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High repetition rate THz characterization at 4th generation X-Ray light sources

Erstgutachter: Prof. Dr. Wilfried Wurth
Zweitgutachter: Prof. Dr. Jan Lösing

Eingereicht von:
Torsten Golz
7014485
Lawaetzweg 9
22767 Hamburg

Betreut von:
Dr. Nikola Stojanovic

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Gutachter/in der Disputation: Prof. Dr. Wilfried Wurth
Prof. Dr. Jan Lüning
Prof. Dr. Daniela Pfannkuche
Prof. Dr. Ulrike Frühling
PD. Dr. Tim Laarmann

Datum der Disputation: 14.09.2018

Vorsitzende des Prüfungsausschusses: Prof. Dr. Daniela Pfannkuche

Vorsitzender des Promotionsausschusses: Prof. Dr. Wolfgang Hansen

Leiter des Fachbereichs Physik: Prof. Dr. Michael Potthoff

Dekan der MIN Fakultät: Prof. Dr. Heinrich Graener
Dedicated to my grandparents Karin and Helmut Mahner, who dedicate their whole life to their family.
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<th>Description</th>
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<tr>
<td>$\Delta\lambda$</td>
<td>Full width at half maximum of the spectrum of the photon pulse</td>
<td>23</td>
</tr>
<tr>
<td>$\epsilon(\lambda_{THz})$</td>
<td>Complex dielectric function</td>
<td>91</td>
</tr>
<tr>
<td>$\gamma$</td>
<td>Lorentz factor</td>
<td>15</td>
</tr>
<tr>
<td>$\lambda$</td>
<td>Wavelength of the radiation generated</td>
<td>23</td>
</tr>
<tr>
<td>$\lambda_c$</td>
<td>Central wavelength of the undulator</td>
<td>15</td>
</tr>
<tr>
<td>$\lambda_U$</td>
<td>Period length of the undulator</td>
<td>15</td>
</tr>
<tr>
<td>$\theta$</td>
<td>Angle between the pointing vector of the undisturbed electron trajectory and the produced radiation or observation position</td>
<td>15</td>
</tr>
<tr>
<td>$BW$</td>
<td>Bandwidth of the created radiation</td>
<td>23</td>
</tr>
<tr>
<td>$n_o$</td>
<td>Ordinary refractive index of the electro-optical crystal at the probe laser wavelength</td>
<td>78</td>
</tr>
<tr>
<td>$N_{Ph}$</td>
<td>Number of photons</td>
<td>12</td>
</tr>
<tr>
<td>$r_{41}(f)$</td>
<td>Frequency dependent electro-optical coefficient</td>
<td>90</td>
</tr>
<tr>
<td>$0.1% BW$</td>
<td>0.1% bandwidth</td>
<td>12</td>
</tr>
<tr>
<td>$2s$</td>
<td>$2\sigma$ Beam size</td>
<td>47</td>
</tr>
<tr>
<td>$\Delta t$</td>
<td>Defined time interval</td>
<td>12</td>
</tr>
<tr>
<td>$\dot{\beta}(t)$</td>
<td>Time dependent variation of the speed of the electrons $\beta$, acceleration</td>
<td>14</td>
</tr>
<tr>
<td>$\epsilon_0$</td>
<td>Vacuum permittivity</td>
<td>14</td>
</tr>
<tr>
<td>$\frac{d^2 I}{d\Omega d\lambda}$</td>
<td>Spectral fluence</td>
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<td>$E_0$</td>
<td>Energy of a resting electron - 0.511 MeV</td>
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</tr>
<tr>
<td>$E_e$</td>
<td>Energy of a moving electron</td>
<td>16</td>
</tr>
<tr>
<td>$E_{THz}$</td>
<td>Electric field of the THz pulse</td>
<td>78</td>
</tr>
<tr>
<td>$f_0$</td>
<td>Frequency of the first transverse optical phonon mode</td>
<td>90</td>
</tr>
<tr>
<td>$f_c$</td>
<td>Central frequency of the laser pulse</td>
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<tr>
<td>$I$</td>
<td>Intensity</td>
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<td>$I(x,y)$</td>
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<td>$I_{hor}$</td>
<td>Intensity of the horizontal polarization of the laser pulse</td>
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</tr>
<tr>
<td>$I_{vert}$</td>
<td>Intensity of the vertical polarization of the laser pulse</td>
<td>81</td>
</tr>
<tr>
<td>$K$</td>
<td>Undulator parameter</td>
<td>15</td>
</tr>
<tr>
<td>$L_{MS}$</td>
<td>Total length of the magnetic structure</td>
<td>53</td>
</tr>
<tr>
<td>$L_u$</td>
<td>Total length of the undulator</td>
<td>52</td>
</tr>
<tr>
<td>$m_e$</td>
<td>Resting mass of an electron</td>
<td>16</td>
</tr>
<tr>
<td>$N_{RP}$</td>
<td>Number of radiating periods</td>
<td>23</td>
</tr>
<tr>
<td>$R$</td>
<td>Distance between the source and the observer</td>
<td>52</td>
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<tr>
<td>$r_{41}$</td>
<td>Electro-optical coefficient</td>
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<td>$S$</td>
<td>Difference signal of the balanced detection</td>
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<tr>
<td>$v_e$</td>
<td>Velocity of the electrons</td>
<td>19</td>
</tr>
<tr>
<td>$v_g(\lambda_p)$</td>
<td>Group velocity of the probe laser pulse</td>
<td>91</td>
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<tr>
<td>$v_{ph}(\lambda_{THz})$</td>
<td>Phase velocity of the THz pulse</td>
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<td>$W$</td>
<td>Near field parameter</td>
<td>52</td>
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<td>$x_0$</td>
<td>Center of gravity with respect to the x-axis</td>
<td>46</td>
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Abstract

Within this work a wholesome approach to the characterization of FEL based THz radiation is made on the example of the THz radiation provided at the THz beamline at FLASH the free electron laser at DESY in Hamburg. A SRW based model of the THz generation from a free electron and the corresponding transport is developed and used to gain insight into the complex intensity profile created by the interplay of the THz undulator and various magnetic edges. An accurate model of the THz beamline is established that allows the precise manipulation of beam size and divergence for subsequent experiments. Based on the agreement with measurements a complete beam transport model for the helical THz undulator, planned at FLASH2 is developed. Furthermore a THz pulse characterization system for high pulse energy high spectral brightness and high pulse energy high bandwidth THz pulses from a free electron laser is developed, set up and thoroughly tested. Based on the linear electro-optical effect the system achieves a broad detection range at few femtosecond time resolution by the interplay of two electro-optical detection setups. The first realizing broadband detection in a scanning electro-optical sampling fashion and the second allowing for a single shot arrival time correction tackling the problem of synchronizing external light sources to large scale accelerators. The system permits the characterization of the electric field of the THz pulses available at the THz beamline at FLASH at a repetition rate of 200 kHz. With the photon efficient design and easy scale-ability the system is suited as a blueprint for other high repetition rate accelerators implementing FEL based THz sources. Lastly the experimental capabilities of the developed system are proven by a model experiment utilizing Strontiumtitanate, perovskite type transition metal oxide. Indications of an ultrafast phase change are found and a possibly mechanism is proposed and discussed based on a series of experiments under varying excitation parameters.
Kurzfassung

Chapter 1

Introduction

FLASH, the free electron laser in Hamburg provides XUV and soft X-ray radiation with outstanding properties to the scientific community around the world. Delivering gigawatt (GW) peak power femtosecond soft X-ray pulses [1, 2, 3], FLASH allowed to gain insight into the electronic structure of gases [4, 5] and the structure of nanostructured non-periodic objects in a single shot [6] at early stages of operation. The scientific advances made by utilizing free electron lasers (FELs), was accompanied by the necessity to characterize the various parameters of the light pulses provided at such facilities. FLASH as the first XUV FEL is operating in a self amplified spontaneous emission (SASE) regime. Inherent to SASE FELs are fluctuations of the pulse parameters on a shot to shot basis, resulting in great effort towards determining pulse energy, spectral content, transverse and longitudinal coherence and the shape of the wave front [7, 8, 9, 10, 11].

The pulse properties are particularly important for time resolved studies, where for example an optical pulse is used to pump and the FEL XUV pulse is used to probe the system [12]. Pump probe experiments at FELs create the opportunity to study the evolution of a process element sensitive on an ultrafast time and atomic length scale. While expanding the scientific possibilities greatly, external laser systems impose challenging boundary conditions and further the need of detailed metrology on both the laser system and the FEL. Next to matching the repetition rate of a superconducting FEL, the main challenges are the synchronization between the laser and FEL pulses, which is crucial for an adequate temporal resolution [13] and a detailed temporal characterization of XUV pulses. Different approaches are made ranging from the analysis of electrons used to generate the radiation to gas phase autocorrelation, THz streaking and plasma based pulse duration monitors [14, 15, 16, 17, 18, 19, 20], while a final online XUV pulse duration monitor remains to be installed.
With the addition of the far infrared or THz undulator [21] a new field of research has become available at Flash. Originally installed as a metrology tool for electron bunches, first applications were utilizing the natural synchronization between the slowly varying, large magnitude electric field of the THz pulse and XUV radiation, by performing single shot XUV pulse duration measurements [14]. The synchronized combination of XUV and THz radiation gives access to a variety of experiments studying electron dynamics in noble gases on ultrafast time scales [22, 23] while bypassing the need for arrival time stabilization. The THz undulator fundamental covers the frequency range of about 1 to 30 THz allowing to access a wide variety of rotational and vibrational modes in gases, solids, liquids and biological systems [24, 25] with intense spectrally bright picosecond THz pulses. The advent of ultrafast laser systems and the associated advent in table-top THz light sources [26, 27, 28, 29, 30, 31] led to a strong increase of scientific activity involving THz radiation. The experimental scope is thereby expanded from interactions of the slowly varying electric field at the carrier frequency with electronic systems to direct excitation of materials at their resonant frequencies aiming for resonant control of matter [32]. Resonant control is pursued in various fields ranging from magnetism, induced phase transition in, for example, transition metal oxides, to superconductivity [33, 34, 35]. In order to disentangle the physical processes excited by the THz pulse from the driving force itself a precise understanding of the THz radiation properties is necessary. Various experiments performed at the THz beamline, ranging from magnetism to ultrafast phase changes, highlight the necessity of precise THz characterization for spectrally intense THz pulses within the ultrafast THz gap in order to extract conclusive results from the measurements. While sufficient characterization is readily available in the case of lower frequencies [36] and at low pulse energy table top sources [37], the characterization of high pulse energy THz radiation at high repetitions rates in the frequency range of 2 – 7 THz is challenging.

The apparatus and techniques developed in the course of this work aim to precisely characterize the THz pulses available for user experiments at the THz beamline at Flash in space and time. A beamline model based on the SRW code is developed in order to predict the spatial intensity profile, beam size and divergence of the THz beam. This will allow to optimize on one hand the acceptance of the metrology tool developed within the course of this work and on the other hand the transmission into complex experimental chambers. The metrology tool aiming for full characterization of the THz pulses in time will open the path to solving the problem of entanglement of the driving force and the evolution of physical processes to be studied, thereby greatly benefiting the scientific progress made at the THz.
beamline at FLASH.

In a final step, aiming to expand the experimental possibilities at the THz beamline further, the developed system is modified for THz driven experiments, opening the path to high resolution field resolved THz driven experiments, effectively transforming the system from a metrology tool to an experimental endstation.
Chapter 2

FEL based THz radiation at FLASH1

2.1 FLASH the Free Electron Laser Hamburg

As the FLASH facility was harboring this work a short introduction into the facility should be given. Shown in figure 2.1 [38] is an schematic overview and a short description of the individual parts of FLASH the Free eLectron LASer Hamburg. It is a 315m long facility consisting out of a linear accelerator and 2 separate electron beamlines, namely FLASH1 and FLASH2, located at DESY the Deutsches Elektronen-Synchrotron. The electron beam is produced by a photo injector laser in a radio-frequency driven electron gun [1]. After the initial acceleration in the rf-gun the electron beam is accelerated using superconducting...
cavities, to a final energy of up to $1.25\, GeV$. As shown in figure 2.1 this happens in several steps with intermediate chicane structures that allow to compress the bunch in time, resulting in a high peak current. After the accelerating stages the electron beam can be directed to either Flash1 or Flash2 utilizing a fast kicker magnet [38]. In order to generate light, the relativistic electron bunches are sent into undulators, magnetic structures with alternating field direction, where spontaneously created radiation (synchrotron radiation) is amplified to the point that it acts back on the electron bunch. The interaction between the strong light field and the electron bunch leads to a deceleration and an acceleration of certain parts of the electron bunch, ultimately creating density modulations on the scale of the light field wavelength. All electrons confined in these so called micro bunches radiate coherently, as the micro bunch size is on the order of the radiated wavelength, creating a strong increase in radiated power. In order for the so called Self Amplified Spontaneous Emission (SASE) principle to work high demands on the electron beam emittance, peak current and energy spread have to be fulfilled [39, 40]. At Flash this results in electron bunches with up to 2.5 kA peak current, an energy spread of 0.2 MeV and a rms bunch length of 10’s of fs [41].

At Flash 1 the main undulator section consists out of 27 m fixed gap undulators. It is designed to produce radiation in the extreme ultraviolet Xuv regime ranging from 4.2 to 52 nm or 24 to 295 eV [38]. In addition, subsequently to the Xuv undulators, a dedicated long wavelength radiator, following referred to as the THz undulator, is installed. The THz undulator is a planar electromagnetic device with period length of 40 cm, a total length of 4455 mm, a maximum field of 1.2 T and 9 full periods with two additional sets of end coils, the first one having $1/8$ and the second one having $1/2$ of the turns of the standard coil [21] [42], making it a 10 period undulator. An overview over a selection of parameters taken from [21] can be found in table 2.1. Electrons injected into this device at the at the nominal Flash energies of 400 to 1250 MeV generate THz radiation in the range of 1.15 to 300 THz or 260 to 1 um [21].

Ultimately the electron beam is separated from the photon beam by a dipole magnet, following called dump magnet, and then send into the electron beam dump [43]. The photon beam is transported further through the photon diagnostics section [7, 44, 45, 46] and into the experimental hall.

At Flash2 the main undulator section consists out of 12 variable gap undulators with a individual length of 2.5 m resulting in a 30 m long undulator section, optimized to generate radiation in the range of of 4 to 90 nm or 13.7 to 310 eV [38]. After the main undulator
Table 2.1: Parameters of the THz undulator at FLASH1 taken from [21]. For further explanation of the $K$ value see section 2.3.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type</td>
<td>electromagnetic</td>
</tr>
<tr>
<td>Gap</td>
<td>40 mm</td>
</tr>
<tr>
<td>Period length</td>
<td>400 mm</td>
</tr>
<tr>
<td>Number of full periods</td>
<td>9</td>
</tr>
<tr>
<td>Total length</td>
<td>4455 mm</td>
</tr>
<tr>
<td>Maximum magnetic field</td>
<td>1.2 T</td>
</tr>
<tr>
<td>Maximum current</td>
<td>435 A</td>
</tr>
<tr>
<td>Maximum K value</td>
<td>49</td>
</tr>
<tr>
<td>Maximum total power</td>
<td>87 kW</td>
</tr>
<tr>
<td>Total weight</td>
<td>4490 kg</td>
</tr>
</tbody>
</table>
section at FLASH2 there is a 3.5 degree bending magnet separating the electron from the X-ray photon beam. In between the bending magnet and the following dump magnet deflecting the electron beam towards the electron beam dump, an approximately 3.2 m long THz undulator is planned. Part of this work will focus on development of sources and transport of THz radiation at FLASH2\textsuperscript{1}. The photon beam is passing through a similar photon diagnostics section as in FLASH1 [47] [48] and further into the experimental hall.

\textsuperscript{1}for further information see chapter 2.7
2.2 Introduction to the THz frequency range

The focus of this work is the characterization of THz radiation produced by 4th generation X-ray light sources on the example of THz at FLASH. In this section a description of the THz frequency range will be given, leading to the differences in generation and application of single cycle and multi cycle THz radiation.

2.2.1 General description

The THz frequency range is situated between the microwave and the infrared spectral range and is, depending on the convention, defined as 0.1 to 10 THz or 3 mm to 30 μm or 0.4 to 41 meV respectively [49]. This wavelength regime was early on of high interest for spectroscopic measurements in solids, liquids and gases, as it covers the energy range of vibrational and rotational degrees of freedom in a multitude of molecules [50]. To this day, Fourier transform infrared (FTIR) spectrometers, for example based on the principle of the Michelson Interferometer [51], are commonly used from biology, chemistry and material science [52, 53, 54]. FTIR spectrometers use sets of continuous wave THz emitters like silicon carbide heating elements, tungsten-halogen or mercury discharge lamps [55]. The main advantage of such emitters is the stable output and broad wavelength range covered, which makes them perfectly suited for infrared spectroscopy [56].

The advent of accelerator based THz sources extended the range of scientific possibilities within the THz range. Bending magnet based THz sources at synchrotrons allow to access the full spectrum throughout the THz frequency range, coupled with a much higher flux than previous emitters and the possibility of polarization manipulation allow for high contrast spectroscopy within short time or with highly diluted samples. Additionally, bending magnet based THz sources at synchrotrons provide pulse THz radiation. With individual electron bunches as its source, the THz radiation, paired with ultrafast laser systems, allows to observe the evolution of processes either utilizing the THz radiation as a probe or observe processes driven by THz radiation, leading to the shift of focus of THz science from static to time resolved spectroscopy and further to manipulation [57, 58, 59, 60].

Cavity based infrared free electron laser closed the gap of high pulse energy, narrow bandwidth THz pulses, left open by broadband bending magnet based synchrotron sources. With pulse energies in the μJ to mJ range and tunability throughout a large frequency range they enable the selective addressing of modes in the THz frequency range. In various facilities
these kind of sources are available in, for example combination with femtosecond laser systems, allowing nonlinear THz / optical pump probe experiments [61, 62, 63, 64].

In order to increase spatial resolution, determined by the optical probe, and achieve element sensitive probing while keeping a femtosecond time resolution in THz driven experiments, narrow band ultrashort extreme ultra violet (XUV) and X-ray pulses are required. 4th generation X-ray light sources provide such pulses on a routine level [1, 65]. When equipped with dedicated THz sources, the stringent requirements on the electron beam in X-ray FEL’s, allow for efficient THz generation.

An alternative possibility of generating THz, being developed in parallel to accelerator based sources, are laser based THz sources [66, 67]. Being fueled by the rapid advance in ultrafast laser systems, so called table top THz systems deliver pulse energies with peak electric and magnetic fields comparable to some accelerator based sources [30]. The high electric and magnetic field strength allows for electron acceleration [68, 14] and in combination with the short pulse duration for impulsively driven spin precessions [69].

The results of the interaction of matter and THz radiation is thereby strongly dependent on the pulse parameters. Next to photon energy, peak field and peak pulse energy, the pulse shape plays a fundamental role [34]. In first order ultrafast THz pulses can be differentiated into single cycle and multi cycle pulses. Following a short description of their individual properties, sources and application will be given.

2.2.2 Single cycle THz pulses

Single cycle pulses carry a large bandwidth exceeding 100% and can therefore cover the so called THz gap. Due to the large bandwidth and the associated coherence of the individual frequency components, single cycle THz pulses can be used to collectively excite phononic motion in matter and probe over a large range of vibrational and rotational modes. Single cycle pulses can be routinely produced by various means with ultrafast laser systems ranging from optical rectification [30, 26, 29] to plasma based sources [70] and spintronic emitters [28] or with accelerators as coherent transition radiation [71] and edge radiation [72].

As an example figure 2.2 shows a schematic of a single cycle THz pulse centered around 2 to 3 THz. The normalized electric field is plotted as a function of time. The electric field has a single field cycle with a wavelength of 150 um. Its corresponding spectrum, calculated via

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2 Further information in the case of FLASH can be found in section 2.5.
3 For further information refer to section 3.5
4 It is to be noted that the electric field trace is multiplied with a blackman-nuttall window in order to create a more realistic transition the sinusoidal field and the surrounding zero line.

---

10
fast Fourier transform, extends up to $10\, THz$. It can be seen that by the time bandwidth limit single cycle pulses carry large bandwidth.

Single cycle pulses are reported to reach electric field strength in the $G\, V/m$ regime accompanied by several $T$ strong magnetic fields both from laser based and accelerator based sources [30, 73]. Electric fields in this range are of great interest for example for biology as they exceed the membrane potentials that are on the order of $10\, MV/m$ [74, 75] or for solid state science as they are in the order of predicted domain switching voltages [34]. Due to their large bandwidth single cycle pulses lack spectral brightness\footnote{Further information on spectral brightness is found in equation (2.2.1).}, which is one of their major disadvantages, in comparison to multi cycle THz pulses achievable with for example dedicated undulator sources at accelerators.

### 2.2.3 Multi cycle THz pulses

Creating multi cycle THz pulses can be achieved by either table top laser based sources or using accelerators. Table top laser based THz generation can be achieved via optical rectification, by employing periodically poled structures [76] [77], by careful manipulation of the driving laser pulse [78] or by difference frequency generation [79]. Using accelerator based sources multi cycle undulator structures are employed either in a single path fashion [21, 36,
80] or utilizing resonator cavities [61, 62, 63, 64]. Furthermore careful manipulation of the electron beam allows to create multi cycle THz pulses via coherent transition radiation [81].

Undulator radiation at accelerator based sources is often characterized by high **Spectral Brightness**. Spectral brightness is defined as the relation between the amount of photons in certain time and frequency interval and is closely related to **Power Spectral Density** used in optics.[add ref] It can described by

\[
Spectral\ brightness = \frac{N_{ph}}{\Delta t \times (0.1\ BW)},
\]

where \(N_{ph}\) equals the number of photons, \(\Delta t\) equals a defined time interval and 0.1% \(BW\) equals 0.1 percent bandwidth. The definition represented in equation (2.2.1) is varied slightly depending on the reference taken but will henceforth be used when referred to spectral brightness. Figure 2.3 shows a schematic of the electric field of a multi cycle THz pulse with a central wavelength of 150 \(\mu m\) and a pulse duration of around 5 \(ps\). With its corresponding spectrum showing a narrow peak around the fundamental frequency.

![Figure 2.3: A Schematic of the electric field of a multi cycle THz pulse with a central wavelength of 150 \(\mu m\) and a pulse duration of around 5 \(ps\). With its corresponding spectrum showing a narrow peak around the fundamental frequency.](image)

with a central frequency of around 2 \(THz\) and 10 period length. The electric field trace is generated as a sinusoidal with a quasi rectangular envelope. The corresponding spectrum shows a narrow peak at the fundamental frequency of 2 \(THz\), carrying almost all spectral intensity. The visible side lobes are resulting from the FFT.

THz pulses with high spectral brightness allow to either selectively probe a certain phonon in a material, giving more detailed information as achieved using a broadband source and
probing partially overlapping vibrational and rotational modes, but more importantly, in our case, allows to selectively drive processes addressing a specific mode in a material. Given the right THz pulse parameters a system can be driven resonantly addressing a single mode, inducing phase changes, domain switching and exotic states of matter [34].
2.3 Basics of undulator radiation

2.3.1 The electric field of a charged particle

One of the main sources of THz radiation, used within this work, is the THz undulator at FLASH1. Therefore a short description of the principles of radiation generation in an undulator is necessary\(^6\). An undulator is a periodic magnetic structure with magnetic poles of alternating polarity. In the simplest case a magnetic field is generated along one plane that causes charged particles traveling at relativistic speeds to undulate around a straight trajectory. A change of direction equals a change in electron velocity in forward direction or an acceleration. Within the moving reference frame of the particle, the acceleration causes a harmonic oscillation, yielding dipole radiation. The emission of dipole radiation peaks in the direction orthogonal to the acceleration and can therefore be described as tangential to the momentary path. Due to the Doppler shift the angle, under which an observer in the laboratory frame detects the radiation changes, changes to narrow cone with an opening angle of \(\theta \approx 1/\gamma\) as depicted in figure 2.4.

The corresponding time dependent electric field \(E(t)\) being observed at a distance \(R(t)\)

\[
\vec{E}(t) = \frac{e}{4\pi\varepsilon_0} \left( \frac{c(1 - \beta^2(t))\vec{n}(t) - c(1 - \beta^2(t))\beta(t)}{R^2(t)(1 - \vec{n}(t) \cdot \beta(t))^3} + \frac{\vec{n}(t) \times ((\vec{n}(t) - \beta(t)) \times \beta(t))}{R(t)(1 - \vec{n}(t) \cdot \beta(t))^3} \right),
\]

(2.3.1)

where \(c\) represents the speed of light in vacuum, \(\varepsilon_0\) represents the vacuum permittivity, \(\beta\) represents the electron velocity relative to the speed of light as \(\beta = v/c\) or \(\gamma = \sqrt{1 - v^2/c^2}\) with \(\gamma\) as the Lorentz factor, \(\vec{n}\) represents the unit vector pointing from the source to the

\(^6\)Please note that a single radiating particle is assumed throughout this section.
observation point and \( \dot{\beta} \) represents the time dependent variation of \( \beta \) and therefore the acceleration. The index \((t)\) describes that all parameters are calculated in retarded time. Equation (2.3.1) can be grouped into 2 different terms. The first term within the brackets is only depending on \( \beta \) and is the so called velocity term. The velocity term is proportional to \( 1/R^2 \) and is therefore rapidly declining with increasing \( R \). The second term within the brackets is depending on \( \dot{\beta} \) and is the so called acceleration term. It is proportional to \( 1/R \) and therefore is the dominant term for larger \( R \) or the so called far field. Furthermore in the so called static case with \( \beta = \dot{\beta} = 0 \) equation (2.3.1) describes the Coulomb law [83].

The Fourier transform of the time dependent electric field allows to calculate the frequency components generated following

\[
E(w) = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{\infty} E(t)e^{iwt} dt, \tag{2.3.2}
\]

where \( w \) represents the frequency, yielding the expression for the frequency dependent electric field \( E(w) \) as

\[
E(w) = \frac{iew}{4\pi\sqrt{2\pi\varepsilon_0 c R}} \int_{-\infty}^{\infty} (n \times (n \times \beta))e^{iw(t'+\frac{R(t')}{c})} dt'. \tag{2.3.3}
\]

Equation (2.3.3) is true for the far field case in which \( R \) is time invariant [83]. As equation (2.3.1) is describing the general electric field properties of radiation produced by charged particles it describes the radiation properties of bending magnets, wiggler and undulators alike and is the basis for the SRW calculations in section 2.6 [84].

### 2.3.2 The undulator equation

Regular magnetic structures, so called undulators, can be employed to generate electromagnetic radiation using relativistic electrons. The electric field of an accelerated relativistic electron can be described by (2.3.1) and (2.3.3). Both equations can be used to acquire inside into the properties of the generated radiation. For the case an undulator, a simpler approach to the central wavelength \( \lambda_c \) can be made by the so called undulator equation. Under the boundary condition of small electron excursion the undulator equation can be derived from the equations of motion for the electron in \( x \) and \( y \) [83]. The central wavelength of an undulator is defined as

\[
\lambda_c = \frac{\lambda_U}{2\gamma^2} \left( 1 + \frac{K^2}{2} + \gamma^2 \theta^2 \right), \tag{2.3.4}
\]

with \( \lambda_c \) as the central wavelength of the radiation generated, \( \lambda_U \) as the undulator period length, \( \gamma \) as the Lorentz factor, \( K \) as the undulator parameter and \( \theta \) as the angle between
the unit vector of the undisturbed electron trajectory and the produced radiation. The Lorentz factor $\gamma$ can be calculated using $\gamma = E_e/E_0$ with $E_e$ the energy of the moving electron or electron beam and $E_0$ the energy of an electron at rest ($0.511 \, MeV$). In order to calculate the expected wavelength of an undulator, the undulator parameter $K$ combining the magnetic field and period length of the undulator has to be known. It can be derived from the equation of motion of electrons in an undulator, details of which can be found in reference [85] or [82]. The undulator parameter or $K$ value is given by

$$K = \frac{eB U \lambda U}{2\pi m_e c},$$

(2.3.5)

with $e$ being the elementary charge, $B_U$ being the peak magnetic field of the undulator, $m_e$ being the mass of an electron at rest and $c$ being the speed of light in vacuum. The $K$ value is a measure for the undulator strength and the maximum angle of excursion of the electrons and thereby the maximum angle under which radiation is emitted from the electron bunch with respect to the central undulator axis, following

$$\theta_{max} \approx \frac{K}{\gamma},$$

(2.3.6)

with $\theta_{max}$ as the maximum angle between the pointing vector of the produced radiation and the central axis of the undulator or the undisturbed trajectory of the electrons, assuming a straight injection of electrons into the undulator [82]. The total opening angle of the radiation is therefore $\pm K/\gamma$. The $K$-value becomes therefore of great importance when considering the output of an undulator. Assuming a $K$ value much smaller than 1 all radiation produced will be within the natural cone of synchrotron radiation of $\pm 1/\gamma$. Therefore a sinusoidal electric field is observed on axis as shown in figure 2.6 a. The Fourier transform of an infinitely long continuous sinusoidal field will yield a single wavelength. As an undulator has a finite length a certain bandwidth $BW$ around the central wavelength is generated following (2.5.1), which can be seen in figure 2.6 b. For the case of $K \gg 1$, as for the THz undulator at Flash1 with a $K$ value of 49, the opening angle $\theta_{max}$ is greater than the natural cone of $\pm 1/\gamma$. Now considering a finite acceptance angle of, for example a beamline, resulting in a finite observation plane at a certain distance, the on axis observation of the electric field generated would not be a continuous sinusoidal, but rather a consecutive train of electric field spikes of alternating polarity. This can be understood best when looking at figure 2.5 from [83] where the electric field and the electron angle are plotted as a function of time. Each time the electron angle is smaller than $1/\gamma$ radiation can be seen on axis. As the electron angle get larger again the cone of radiation is emitted under a larger angle than $1/\gamma$ and no radiation is observable on axis. The undulating electron trajectory results therefore
Figure 2.6: Subfigure a shows the on axis observed electric field over time of the radiation produced by an undulator with a $K$ value of 0.2. The corresponding frequency components can be seen in subfigure b. It can be seen that there is only the fundamental wavelength present as the low excursion of the electron beam, described by $k/\gamma$, creates radiation within the natural cone of $1/\gamma$ leading to a continuous sinusoidal field with a single central wavelength and a narrow bandwidth. Subfigure c shows the on axis observed electric field over time of the radiation produced by an undulator with a $K$ value of 2. It can be seen that the electric field consists out of spikes of alternating polarity that are equally spaced. The corresponding frequency components can be seen in subfigure d. Due to the symmetric spiky structure of the electric field a large amount of odd higher harmonics are produced, which overcome the fundamental in spectral intensity. Figure taken from [82].
in short spikes of detected electric field with alternating polarity. Figure 2.6 c from [82].

Figure 2.5: On axis observed electric field and electron angle as a function of time for an undulator with a $K$-Value much greater than 1. It can be seen that each time the electron angle is smaller than natural cone of synchrotron radiation of $1/\gamma$ electric field can be observed on axis. Due to the undulating electron orbit the electric field observed has a changing polarity. Figure taken from [83].

shows a schematic of a high $K$ value undulator with $K > 1$ and its corresponding frequency components (d). It is apparent that spike-like electric field components, produced by the strong excursion of the electron beam, consists out of a large amount of higher harmonics, which due to the symmetry properties only occur as odd harmonics [82]. Considering the THz undulator and its maximum $K$ value of 49 a large amount of higher harmonics are to be expected and can be measured down into the optical regime, where the THz beamline cutoff, originating from the gold-coated optics, sets the ultimate limit. [86].
2.4 Basics of edge radiation

Edge radiation is one of the main sources of accelerator based THz radiation at Flash. It can be used parasitically to almost every operation of the Flash accelerator as its main contribution is produced by the electron beam dump magnet, which is constantly active to separate the electron from the photon beam. Edge radiation is produced when the longitudinal velocity $\vec{\beta}$ of an electron experiences a sudden change in the transition region between a field free space and a magnetic field. Following equation (2.4.1), the transition is assumed to have little to no influence on the direction of motion, described by the unit vector $\vec{n}$ with $\vec{n}_1 = \vec{n}_2 = \vec{n}$ and can therefore be expressed by the change in velocity of the electron. $\vec{\beta}_1$ is defined as the velocity of the electron before entering the magnetic field and is given as $\vec{\beta}_1 = \vec{v}_1 / c$ and $\vec{\beta}_2$ is defined in analogy as the velocity after entering the magnetic field. The emitted intensity as a function of the frequency and solid angle, the so called Spectral Fluence for edge radiation produced by an electron entering a bending magnet is defined as

$$\frac{d^2 I}{d\Omega d\omega} = \frac{e^2}{4\pi^2 c} \left( \frac{\vec{\beta}_2 \times \vec{n}}{1 - \beta_2^2 n} - \frac{\vec{\beta}_1 \times \vec{n}}{1 - \beta_1^2 n} \right)^2,$$

(2.4.1)

with $I$ as the intensity, $\Omega$ as the solid angle, $e$ as the charge of the electron and $\beta_{1,2}$ the velocity of the electrons and $\omega$ the angular frequency [87]. Equation (2.4.1) shows that the spectral fluence is proportional to the change of the electron velocity. The change of velocity in forward direction when entering a bending magnet is proportional to the magnetic field of the bending magnet and is described by

$$\Delta \beta = \beta_2(s) - \beta_1 = -\frac{eB}{m_c c^2 \gamma} \int_0^s f(s') ds',$$

(2.4.2)

with $s$ as the orbit of the electron as the integration variable, and $f(s) = B(s)/B$ as the magnetic field form factor [88]. Assuming a constant field of $B(s) = B f(s)$ becomes 1 and equation (2.4.2) can be simplified to

$$\Delta \beta = -\frac{eB}{m_c c^2 \gamma},$$

(2.4.3)

which allows to compare the velocity change occurring from different bending magnets or magnetic edges and therefore to compare the spectral fluence for edge radiation of different magnetic edges. Equation (2.4.1) is applicable as long as the transition length $\Delta x$ from field free space to magnetic field is much shorter than the wavelength. The so called long...
wavelength limit can be described by

\[ \Delta x \ll \gamma^2 \lambda \]  \hspace{1cm} (2.4.4)

and gives ultimately a limitation to the approximation towards shorter wavelength [82]. As mentioned before the transition from the field free space to the magnetic field is assumed to have little to no influence on the direction of motion of the electron. This small deflection angle boundary condition can be written as

\[ \Delta x \ll \frac{\lambda_{cs} \gamma^2}{4}, \]  \hspace{1cm} (2.4.5)

where \( \lambda_{cs} \) represents the critical wavelength of the synchrotron radiation of the bending magnet [87]. The critical wavelength is given as \( \lambda_{cs} = \frac{1}{2} \pi R \gamma^3 \) with \( R \) as the radius of curvature of the electron trajectory caused by the bending magnet [89]. Shkvarunets et al. calculated the angular distribution of the edge radiation in horizontal and vertical direction for the case of a sharp magnetic edge where \( \lambda \gg \lambda_{cs} \). The results are presented in figure 2.7. It can be seen that the angular distribution has its maximum at \( 1/\gamma \) and falls off to larger angles. At its center, the axis of electron motion, there is little to no intensity. In conclusion

![Figure 2.7: The angular distribution of the edge radiation created by an electron entering a bending magnet. The intensity in horizontal and vertical direction is plotted as a function of the angle in \( 1/\gamma \) with \( \gamma \) as the Lorentz factor. It can be seen that the intensity has a maximum at \( 1/\gamma \) and falls off to larger angle, with little to no intensity at the center of the distribution. Image taken from [87].](image)

the generation of edge radiation originates from the sudden change of velocity due to the transition of a charged particle from vacuum into a medium or a magnetic field. As large scale accelerators have several magnetic structures ranging from bending magnets to a variety
of undulators and each magnetic edge will produce edge radiation from the same electron bunch, in the case of field free drift space between the magnetic structures the produced edge radiation will be naturally synchronized. Therefore the edge radiation, and partially undulator radiation, from different sources is bound to interfere and create a complex pulse structure. Figure 2.8 shows the results of the calculations of the interference created by two consecutive magnetic fields produced by two small kicker magnets with a separation much larger than the field extend and the comparison with the interference produced by 2 optical transition radiation sources at equal distance performed by Shkvarunets et al. It can be seen that the smooth falloff of the edge radiation profile presented in figure 2.7 is strongly modulated and shows a typical fringe pattern. An extensive study of the interference effects

![Graph showing intensity vs. angle](image)

*Figure 2.8: The angular distribution created by the interference of two coherent edge radiation sources in comparison to the interference of a comparable set of optical transition radiation sources. It can be seen that the interference modulated the smooth falloff of the intensity profile of a the edge radiation and created interference fringes. Image taken from [87].*

can be seen in [90] [88] [91]. In order to acquire a better understanding of the complex THz pulses created by Flash, simulations, using the Synchrotron Radiation Workshop SRW code, have been performed.
2.5 THz generation at FLASH

FLASH1 is equipped with a dedicated long wavelength radiator, the THz undulator, providing frequencies in the range of 1.15 to 300 THz. Figure 2.9 provides a schematic overview of the magnetic structures influencing the THz generation. The electron beam depicted in

![Diagram showing XUV undulators, THz undulator, and dump magnet](image)

Figure 2.9: Schematic overview over the XUV und THz sources present at FLASH. With the XUV undulators in bright and dark blue, the THz undulator in bright and dark red and the electron beam dump magnet in blue as the photon sources. The electron beam is depicted in green. The relativistic electron beam is traveling through the different undulators being deflected on sinusoidal trajectory by the magnetic field, creating photons of specific properties and wavelength depending on the electron beam properties and undulator parameters. Image is courtesy of N. Stojanovic.

green travels at relativistic speed, with an energy of up to 1.25 GeV first entering the XUV undulators, where it produces XUV radiation, with a central wavelength, depending on the electron beam energy. After leaving the XUV undulators the electron beam travels alongside the created photon beam through dispersion free drift space into the THz undulator. The radiation inside the undulator is produced in a single pass of the electron bunch following the principles explained in section 2.3. As there is only dispersion free drift space between the XUV and the THz undulator and the same electron bunch produces both types of radiation, the produced photon pulses are naturally synchronized. After passing through the THz undulator the electron beam travels along another field free drift space before entering the dump magnet. At this point the electron beam gets deflected and separated from the photon beam. When entering the magnetic field of the electron beam dump magnet, the relativistic electron beam creates a strong quasi single cycle radiation, so called edge radiation. The stringent requirements on the electron bunch with respect to the longitudinal bunch length, necessary for short XUV pulses generated with the SASE principle [92], lead to a coherent generation of radiation in the THz regime, as depicted in figure 2.10. In the case of the process of incoherent generation of radiation, different portions of an electron bunch with a longitudinal dimension largely exceeding the generated wavelength are radiating without a specific phase relation to each other. Therefore, on average, no constructive superposition is occurring and the output intensity I scales linearly with the number of radiating particles.
Given that the longitudinal dimension of the electron bunch is in the range of the wavelength of the generated radiation the complete electron bunch can radiate coherently as a single particle. This allows the constructive superposition of the created radiation of each individual particle, leading to a quadratic increase of the output intensity $I$ with the number of radiating particles $N_e$. Ultimately resulting in a strong enhancement in output intensity as the charge of the electron bunches increases.

The THz undulator at Flash1 is a planar electromagnetic device. The produced THz radiation is linearly polarized and due to the electromagnetic nature of the undulator, can be tuned from 1.15 to 300 THz. The spectral bandwidth of the generated radiation depends on the number of radiating periods, which can be described as

$$BW = \frac{\Delta \lambda}{\lambda} = \frac{1}{N_{RP}}, \quad (2.5.1)$$

where $BW$ represents the bandwidth of the photon pulse, $\lambda$ the central wavelength of the photon pulse, $\Delta \lambda$ the full width at half maximum FWHM of the spectrum of the photon pulse and $N_{RP}$ the number of radiating periods \[^7\]. The THz undulator has 10 full periods, following the equation (2.5.1) it can be calculated, that the spectral bandwidth of the THz undulator is 10% under ideal conditions\[^7\]. Several spectra, measured throughout the wavelength range of the undulator using a Princeton Instruments grating spectrometer and a set of appropriate THz filters can be seen in figure 2.11. The spectra are measured with a relatively narrow frequency range around the individual fundamental, therefore possible higher harmonic frequency content, not blocked by the filters, is not visible. An undulator with high $K$ value\[^8\] results in a sharp featured electric field trace and consequently in a large amount of higher harmonics being present in the spectrum, having a fixed phase relation with the fundamental frequency of the undulator. The THz undulator has a $K$ value of 49 leading to high harmonics up to the visible range. Figure 2.12 (a) shows an photograph of the visible high harmonic content of the THz pulse from the undulator. 2 distinct lobes of light can be seen, originating from the turning points of the electrons trajectory inside the undulator as depicted in the schematic in subfigure b. The undulator poles are depicted in dark and bright red, the electron path is depicted in dark green and the visible radiation created at the turning points is depicted in orange. The spacing between the 2 lobes depends on the maximum electron excursion and therefore on the generated wavelength at a given electron beam energy. The electron excursion inside the undulator lies in the horizontal plane, therefore the 2 distinct lobes of light are aligned horizontally. Within the THz

\[^7\]Bandwidth can vary depending on the electron beam parameters.

\[^8\]K $> 1$. For further information refer to section 2.3.
Figure 2.10: The schematic comparison between incoherent and coherent generation of radiation. Electron bunches with longitudinal dimensions largely exceeding the wavelength of the generated radiation, result in an incoherent generation of radiation (a). This is characterized by a linear increase of the output intensity with the number of radiating particles $N_e$ (c). Electron bunches with longitudinal dimensions in the range of the wavelength generated, result in coherent generation of radiation (b), resulting in the generation of radiation with a fixed phase relation and constructive superposition. Coherent generation of radiation is characterized by a quadratic increase of the output intensity with the number of radiating particles $N_e$ (d).
beamline a polarization rotating periscope leads to a vertical alignment of the lobes. After leaving the THz undulator the electron beam, traveling alongside the photon beam, passes a field free drift space before entering the dump magnet, depicted in blue in figure 2.9. The dump magnet deflects the electron beam by 21° in order to separate it from the photon pulses before they are transported to the experimental hall. Due to the electron deflection a large fan of radiation, so called bending magnet or synchrotron radiation, is created [93]. The synchrotron radiation is created tangential to the electron motion, therefore most of the produced synchrotron light generated by the 21° deflection has a larger angle between its poynting vector and the beamline acceptance half angle of \( \approx 0.44^\circ \). When entering the magnetic field of the electron beam dump magnet, an abrupt change in the longitudinal speed of the electrons changes is occurring [94]. Thus another intense light pulse is created. The relativistic electron beam creates a strong quasi single cycle radiation with a central frequency, in the case of FLASH1 of around 1 to 4 THz and a large bandwidth exceeding 100% [90]. The so called edge radiation has a unique feature, it is radially polarized meaning it exhibits a ringlike shape, with electric field components pointing outwards from the center as can be seen in figure 2.13b. Subfigure a shows a recorded

\[ ^9 \text{further information on the beamline acceptance half angle can be found in section 2.6.6} \]
Figure 2.12: A photograph of the visible high harmonic content of the THz pulse created by the THz undulator (a). The 2 distinct lobes visible originate from the turning points of the electron trajectory inside the undulator as it is depicted in the lower schematic with the electron path in dark green and the created visible radiation in orange (b).
Figure 2.13: a A recorded image of the edge radiation produced by the electron beam dump magnet of FLASH1. A clear ring like shape is visible having little to no intensity at the very center. b A schematic of the radial polarization of the edge radiation. The polarization components are linear and pointing outwards from the center of the ring.
image of the edge radiation created by the electron beam dump magnet. The picture was
recorded using a Spiricon Pyrocam III with a pixel size of $85 \times 85 \, \text{um}$ and an effective
pixel spacing of $100 \, \text{um}$. With the radiation focused onto the pyroarray of the camera using
a $100 \, \text{mm}$ focal length off axis parabola, a clear ringlike shape with little to no intensity at
the center is visible. Using a wire grid polarizer it is possible to separate different polariza-
tion components of the edge radiation and create any linear polarization state desired over
a large wavelength range [95]. Polarization control over broadband THz pulses is difficult ,
comparing to the visible range, as birefringend materials transparent for a large wavelength
range, do not exist. Edge radiation is also produced at the entrances and exits of the XUV
undulators and the THz undulator. Additionally the time difference between the electron
bunch and the photon pulse created by it reaching the dump magnet is negligible, resulting
in the created edge radiation appearing as an additional field cycle following the THz field
created by the undulator. The superposition of the different sources creates a highly complex
THz pulse with varying spectral components and varying state of polarization throughout
its pulse duration. Additively the different sources interfere spatially creating a complicated
spatial profile [90].
2.6 SRW calculations

2.6.1 Magnetic Structure and Electron Trajectory

The full characterization of the THz radiation requires a profound understanding of the interaction of different sources of radiation during the process of forming the final THz pulse. In order to be able to disentangle and understand the influence each source of radiation produces, a series of simulations were done. The Synchrotron Radiation Workshop code, henceforth SRW code, is used. The SRW code is an open source software that is used to calculate spectral, spatial and polarization characteristics of radiation produced by relativistic electrons in the near and far field. [96] [84]. The software package was used in the Igor Pro environment version 6.32A [97], which allows to implement the SRW code and call its predefined functions. The SRW script used to calculate the THz output can be found in Appendix A. The magnetic structure of FLASH1 around the THz undulator is modeled as seen in figure 2.15. The coordinate system for the simulations performed with SRW can be found in figure 2.14. The coordinate system is set up in a way that the electron beam travels along the x-axis in positive direction and individual beam profiles are along the y,z-plane. The magnetic field structure is adapted for a beam energy of 600 MeV,

![Figure 2.14: The coordinate system for the SRW calculations. The electron beam travels along the x-axis into the positive direction. Individual beam profiles are along the y,z-plane.](image)

which directly influences the magnetic field strength in both bending magnets included in the simulation. This electron energy is used as it allows to produce THz radiation with a wavelength of 146 μm or 2.05 THz if the undulator field is set to its maximum value of 1.2 T. This frequency is used in the experiment described in section 4.1 and a detailed simulation of the radiation properties is therefore more than appropriate. Subfigure 2.15 a shows the
simulated magnetic field structure in z or vertical direction. The structure starts with a small drift space before the first bending magnet. The magnet has a magnetic field strength of $0.3\,T$ and is used to direct the electron beam on axis into the XUV undulator. The XUV undulators are represented as a 50 pole undulator structure with a maximum magnetic field of $0.47\,T$ and a period length of $23.7\,mm$. The undulator is therefore producing $13.4\,nm$ in the first harmonic. Even though the XUV undulators are much longer, this simplification sufficiently represents their influence in the THz frequency range\textsuperscript{10}. This can be understood as the main contribution to the THz frequency range originates from the edge radiation created at the exit of the XUV undulators from a single electron. A magnified view on the XUV undulator field structure is given in subfigure 2.15 c. Following another field free drift space the magnetic field structure of the THz undulator can be seen. The 9 full period design has a maximum magnetic field of $1.2\,T$ and uses a $\frac{1}{2}$ $\frac{3}{4}$ beginning and end pole design in this representation. This is used to keep the trajectory of the electron beam on the same axis before and after it has passed the THz undulator. At the electron energy of $600\,MeV$, a maximum field of $1.2\,T$ and a period length of $400\,mm$, the THz undulator produces radiation with a wavelength of $146\,um$ or $2.05\,THz$. Subfigure b shows the magnetic field structure in y or horizontal direction. The only non zero field component in this direction is the second bending magnet, the electron beam dump. The beam dump is used to separate the electron from the photon beam. Therefore it is constantly active when the accelerator is in operation. When an electron is entering the $0.56\,T$ strong magnetic field of the dump magnet, a single cycle edge radiation pulse is generated.

In order to simulate the electric field wavefront, a single electron is injected into the system. Therefore the radiation generated in this code is considered fully coherent at all times. The resulting trajectory of the electron in y and z or horizontal and vertical direction, respectively is given in figure 2.16. The electron trajectory is plotted as the deflection in the described plane as a function of the distance traveled through the magnetic structure shown in figure 2.15. In subfigure a the electron trajectory in the horizontal or y direction is depicted. The electron injection is done at about $-43\,mm$ under an angle of approximately $61\,mrad$. Therefore after the first bending magnet the electron trajectory follows the x-axis. After the initial deflection by the bending magnet, the XUV undulator causes a deflection with a maximum amplitude of approximately $\pm 3\,um$. Therefore it can not be seen in subfigure a and is shown in subfigure c. The deflection caused by the THz undulator is about 1000 times larger and has a maximum amplitude of about $\pm 2.4\,mm$. The 10 period oscillation is

\textsuperscript{10}Considering the main influence to be edge radiation at the back edge of the undulator.
Figure 2.15: Magnetic Structure constructed to approximate the section around the THz undulator at FLASH. The structure is adapted for an electron beam energy of 600 MeV, which directly influences the magnetic field strength of both bending magnets depicted. The graphs are plotted with the magnetic field in tesla (T) as a function of the distance in meters (m), beginning from the point of electron injection. Subfigure a depicts the magnetic field in z or vertical direction. The structure consists out of several magnetic elements, namely the first bending magnet, the XUV undulator, the THz undulator and the bending magnet, interleaved with 0-field drift spaces. In subfigure b the magnetic field structure in y or horizontal direction is shown. In this direction the only element implemented is the electron beam dump magnet with a maximum field of 0.56 T. The inlet of subfigure c shows a zoomed in view of the magnetic structure of the XUV undulator.
therefore clearly visible. The deflection in the $z$ or vertical direction is shown in subfigure b. The only deflection in this plane is occurring due to the electron beam dump magnet. The electron beam is deflected with an angle of 21° or 366 mrad as in the case of the FLASH1 electron beam dump magnet. The additional field free drift space placed after the beam dump magnet is used to allow the electron beam to propagate far away from the $y-z$ $0-0$ axis. This is necessary in order not to influence the acquired results, as electrons crossing the defined observation plane, being $yz$ the plane in electric field wavefront is calculated behind the magnetic structure, would generate artifacts that would manifest themselves as additional radiation components. The size of the plane is defined to be 240 by 240 mm.

Figure 2.16: The trajectory of the electron traveling along the magnetic structure shown in figure 2.15. The trajectory is plotted as the deflection over the distance traveled starting form the injection point of the electrons. Subfigure a shows the trajectory in $x$ or horizontal direction. The deflection caused by the XUV undulator is not visible in subfigure a and is presented in subfigure c. Subfigure b shows the deflection in $z$ or vertical direction.

to avoid clipping of the generated wavefront. The distance from the injection point of the electrons to the observation plane is set to be 20 m. The simulation offers various observables to be calculated at the observation plane. In order to calculate the intensity profiles, the observable intensity in dependence of $y$ and $z$ is chosen at a specific wavelength. This allows for instance the calculation of the intensity profile for several wavelength and for higher harmonics.

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2.6.2 Comparison of simulated and measured edge radiation profiles

With the magnetic field structure, the electron trajectory and the plane of observation defined, the groundwork of the simulation is laid. In order to understand the interaction of the different types of radiation produced, and to verify the accuracy of the simulation, a detailed evaluation of the individual radiation sources and their interference is beneficial. In order to observe the edge radiation components separately, the magnetic field of the XUV and THz undulator are set to 0, creating a field free drift space in these sections. This allows to study only the edge radiation of the first bending magnet and the dump magnet. Figure 2.17 shows the intensity profile created by the interference of the different edge radiation components\textsuperscript{11} at a frequency $2.05\, THz$. In addition to the edge radiation ring, a low intensity fan of synchrotron radiation created by the beam dump magnet can be seen towards the lower half of the image. These radiation components are emitted under an angle of up to $21^\circ$ and therefore to a large extend not transported through the beamline and to be discarded. The interference of the edge radiation with the synchrotron radiation fan produces an asymmetric intensity profile within the central ring structure, with a vertical intensity dis-balance\textsuperscript{12}. Apart from the intensity changes in vertical direction a clear ring like structure can be seen with lower intensity at its center. In addition the image shows several sharp rings, that is the fingerprint of two edge radiation sources interfering\textsuperscript{[90]}, with the second source being the first bending magnet, and is also observed at similar facilities\textsuperscript{[72]}, which is a good indication as a first verification of the achieved results. Figure 2.18 shows the horizontal profile of the edge radiation at FLASH1 with a central wavelength of 146 $\mu$m. A small horizontal dis-balance in intensity can be seen, that originates from the interference with the radiation produced from the first bending magnet. The maximum peak brightness is about $18\, photons/s/0.1\%bw\, mm^2$.

In order to compare the simulated intensity profile with the measured result shown in figure 2.13 from section 2.5 the edge radiation is propagated through the beamline and focused using a 250 $mm$ focal length toroidal mirror\textsuperscript{13}. Figure 2.19 shows the focused edge radiation after being transported to the laboratory. It shows a small ring structure with a size of about 1 to 1.2 $mm$, which is larger than figure 2.13 with a size of about 5 pixels and a pitch.

\textsuperscript{11}All profiles are calculated at the observation plane 20 $m$ behind the injection of the electrons into the magnetic structure.

\textsuperscript{12}Please note that the color scale is altered in order to enhance the visibility of the low intensity synchrotron fan.

\textsuperscript{13}Please refer to subsection 2.6.5 for further information on beam transport.
of 100 µm, which can be explained by the longer focal length toroid used in the simulation. This is necessary as the simulation works with 4 inch optics and does not allow large optics with such short focal length. The similarity in shape and explainable difference in size, allow further verification of the simulation. As the undulator is a planar device creating an

![Figure 2.17: The simulated 2-dimensional intensity profile of the edge radiation at Flash1. The profile shows a clear ring-like structure with close to zero intensity in its center.](image)

![Figure 2.18: The simulated horizontal intensity profile of the edge radiation at Flash1.](image)

electron excursion in the y or horizontal plane, the generated radiation is linearly polarized in this plane. Therefore it is of special interest to examine the edge radiation, being radially polarized, only choosing the horizontal polarization to be displayed. This allows to better
Figure 2.19: The simulated 2-dimensional intensity profile of the edge radiation at Flash1 after being transported along the beamline and being focused.

Figure 2.20: The simulated 2-dimensional intensity profile of the horizontal polarization components of the edge radiation at Flash1. It can be seen that out of the naturally radially polarized ring of the edge radiation only two lobes of horizontal polarization with opposite direction remain.
understand the interference effects produced by the interaction of edge radiation and the undulator radiation. Figure 2.20 shows the resulting 2-dimensional intensity profile of the horizontal polarization components of the edge radiation. As the edge radiation is naturally radially polarized, taking only the horizontal polarization components into account, creates two separate lobes that are of equal intensity. The polarization direction of these two lobes are opposite to each other as the polarization components point linearly away from the center. This is important for the interference with the undulator radiation as one lobe will interfere positively, while the other will interfere negatively with the linearly polarized undulator radiation [98, 83]. Comparing the profile in figure 2.20 to figure 2.17, it becomes clear that the edge radiation is indeed radially polarized and when omitting the vertical polarization, all intensity along this direction is gone.

2.6.3 Comparison of simulated undulator radiation profiles

The second important source of THz radiation used in this work is the THz undulator at Flash1. In order to gather inside into the beam profile of the few cycle THz undulator an approach has to be made in order to minimize the influence of the edge radiation created by the electron beam dump magnet. With the current setup of the beamline it is not possible to measure the THz undulator radiation without the influence of edge radiation created by the electron beam dump. This is due to the fact that the electron beam dump magnet at Flash is always active in order to separate the electron beam from the photon beam. The SRW simulation has a similar boundary condition. In order to avoid electrons from passing through the observation plane and creating artifacts that will present themselves as additional radiation components, the electrons need to be deflected. The dump magnet itself creates a single cycle edge radiation pulse. A possible solution can be achieved by eliminating the drift space between the THz undulator and the electron beam dump magnet. Following equation (2.4.1), describing the radiated power is dependent on the momentary change of velocity of the electrons $\vec{\beta}$ and (2.4.3), describing that the loss of velocity is proportional to the magnetic field $B$ or more precisely the momentary change in magnetic field strength $\delta B$\textsuperscript{14} it can be seen that the influence of the edge radiation produced by the electron beam dump is sufficiently masked. This can be understood when having a closer look at $\delta B$. The momentary change in magnetic field at the end of the THz undulator is equal to its field strength, which is $1.2T$ in the presented example, resulting in the generation of edge radiation at the back end of the THz undulator. By eliminating the drift space between the

\textsuperscript{14}equation (2.4.3) assumes the entry into a magnetic field from field free space.
Figure 2.21: The simulated 2-dimensional intensity profile of the THz undulator radiation at FLASH1 without the edge radiation created by the electron beam dump magnet with all polarization components taken into account.

Figure 2.22: Subfigure a shows the horizontal intensity profile of figure 2.21 plotted as the peak brightness as a function of the position on the $z = 0$ axis. While subfigure b, presenting the vertical position, is showing a profile close to the natural bell-like shape of an undulator, subfigure a shows a high degree of asymmetric due to the interference with the horizontal components of the transition undulator radiation.
undulator and the dump magnet the momentary change of the magnetic field is reduced to
\( \delta B = 1.2T - 0.56T = 0.64T \). The influence of the magnetic edge of the dump magnet is
therefore fully masked, on the expense of reducing the edge radiation intensity at the back
edge of the undulator. The second edge of the dump magnet is non relevant as the direction
of emission of the radiation is 21° with respect to the undulator radiation.

Theoretically undulator radiation has a bell like intensity profile in both horizontal and ver-
tical direction [83]. For the THz undulator, the edge radiation created when electrons enter
and exit the THz undulator, so called transition undulator radiation \( \text{TUR} \), will have an
influence on the beam profile, as the produced intensity in the THz regime is high. Figure
2.21 shows the intensity profile of the THz undulator at 146 mm in the plane perpendic-
ular to electron beam propagation taking all polarization components into account. The
profile shows a circular beam shape with an intensity dis-balance along the horizontal axis,
resulting in a lower intensity part of the central shape towards negative positions and a
high intensity part towards positive positions. This results from the interference with the
TUR and with edge radiation created from magnetic edges prior to the THz undulator.
The resulting intensity profile is similar in beam shape to the bell like intensity profile of
an undulator [98] interfering with the horizontal components of the edge radiation shown
before. The additional ring like structures further away from the center of the observation
plane are originating from magnetic edges prior to the THz undulator. Figure 2.22 shows
the horizontal and vertical intensity profile along the \( x = 0 \) and \( z = 0 \) axis in subfigure a
and b, respectively, by plotting the number of photons per second, 0.1 percent bandwidth and
mm² against the horizontal or vertical position. This definition is in analogy to brilliance
often used to describe the beam parameters of accelerators. Comparing subfigure a and
b the influence of the interference becomes apparent. While subfigure b shows a bell like
shape subfigure a shows a reduced intensity towards the negative position and an increased
intensity towards the positive direction. These profiles are in good agreement with studies
performed by Asgekar et. al. [98] about the interference effects on super radiant THz sources
and allow to verify the used simulation.

### 2.6.4 THz beam profile

As the individual results for edge and undulator radiation given by the SRW calculations
are comparable to literature sources it can be concluded, that the magnetic structure and
treatment of the electron trajectory is sufficient to allow the simulation of an approximation
of the complex THz radiation pulses produced by \text{FLASH1}. Therefore in order to simulate
the complex final intensity profile the magnetic structure and electron trajectory presented in figure 2.15 and 2.16 are taken into account. In figure 2.23 the observation wavelength is set to the fundamental of the THz undulator, namely 146 μm. The image represents the intensity of the horizontal polarization and is calculated 20 m behind the injection point of the electrons or about 4.2 m behind the back edge of the beam dump magnet. The central cone of radiation being formed by the THz undulator radiation and the dump magnet edge radiation shows an asymmetric shape. Following the horizontal axis a spatial asymmetry with respect to the beam center similar to figure 2.21 can be seen, spatially ranging from −60 to 60 mm. This main feature originates from the THz undulator main lobe. In addition, one can see the interference due to the THz dump magnet edge radiation being superimposed. This interference creates the low intensity area between −40 and −10 mm as well as the maximum intensity region between +10 and +40 mm. The spatial features originating from the interference, is influenced by the distance between the THz undulator exit and the dump magnet entrance. As the THz beam propagates this distance it expands due to its natural divergence, resulting in an intensity profile spatially further extended than the created edge radiation. Figure 2.24 represents the horizontal profile of figure 2.23 along the \( z = 0 \) axis and allows to examine the complex horizontal intensity profile. The intensity profile is plotted as photons per second and 0.1% bandwidth and mm\(^2\) against the horizontal position. When comparing the profile to the undulator only profile in figure 2.22 a, it can be seen that the initial shoulder like profile of the THz undulator radiation has changed to a two peak like shape with two additional side lobes. The two main peaks are split by a low intensity region originating from the destructive interference of one of the lobes of the edge radiation with the THz undulator intensity profile. The constructive interference between the undulator radiation and the second lobe of the edge radiation leads to the maxima at positive position values. The SRW code allows to observe the intensity distribution of the radiation at any given wavelength by specifying it when defining the observation plane. This allows to observe the high harmonic content produced by the undulator and to have a closer look into possible variations of the beam profile when selecting individual harmonics. Figure 2.25 shows the 3rd harmonic of the THz undulator radiation at 48.66 μm. The 2-dimensional intensity profile is similar to the fundamental presented in figure 2.23. The central cone of radiation in the range of −25 to 25 mm is smaller compared to the fundamental, which can be explained by the natural divergence being much smaller, which leads to less expansion of the beam as it propagates from the source to the observation plane. This creates the situation that the THz
The 2-dimensional intensity profile of the horizontal polarization components at 146 \( \mu \text{m} \) created by the interference of the THz undulator radiation with the edge radiation. The resulting intensity profile shows a strong intensity modulation along the horizontal axis. The beam profile shows, in its horizontal intensity profile, similarities to the undulator profile shown in figure 2.21.

The undulator intensity profile is not exceeding the edge radiation size spatially\textsuperscript{15}. Therefore the resulting beam profile is less complex, missing the valley like structure. A strong intensity dis-balance along the horizontal axis at \( z = 0 \) can be seen, with the difference of having a high intensity region towards the negative position and the low intensity region towards the positive positions. This observation implies that the polarization of the 3rd harmonic is inverted by \( 180^\circ \) with respect to the fundamental, at the position of interaction with the edge radiation. From theory it is expected that every other harmonic has an inverted polarization direction [99], which verifies the simulation. Looking at the horizontal profile generated at the \( z = 0 \) axis the differences in respect to the fundamental intensity profile shown in figure 2.24 become more apparent. The profile in figure 2.26 shows only one strong peak towards negative positions and very little intensity at the equivalent positive positions.

\textsuperscript{15}Despite the smaller edge radiation profile at 50 \( \mu \text{m} \), which is omitted due to its similarity with the previously presented edge radiation profile.
Figure 2.24: The horizontal THz radiation intensity profile at 146 um created by the interference of the edge and the THz undulator radiation shown in figure 2.23. The figure is plotted as the number of photons per second and 0.1% bandwidth and mm² against the horizontal position.

position resulting from the constructive and destructive interference with the two lobes of the edge radiation, respectively. The maximum intensity is about 50% higher than in the fundamental, which is the result of 2 main reasons. At first an undulator with a high K-value, specifically much greater than 1, will have an enhanced harmonic output compared to the first harmonic, which is predicted by theory as shown for the case of $K = 2$ in figure 2.6. As the THz undulator has a K-value of 44 a large amount of higher harmonics are expected. Figure 2.27 shows the simulated spectrum of the THz undulator with the fundamental wavelength tuned to 146 um or 2.05 THz. The simulated spectrum is shown in blue, describing the spectrum emitted by a single electron\(^\text{16}\). It can be seen that next to the fundamental at 2.05 THz higher harmonics appear starting from the second harmonic. This can be explained by the fact that the observation plane used to simulate this spectrum is not infinitely small. Therefore also radiation emitted off axis is observed, leading to the appearance of even harmonics. It can be seen that the 3rd harmonic has an equal intensity in comparison to the fundamental. Additionally due to the smaller natural divergence of the 3rd harmonic, the overall intensity is more confined in space and therefore creates a stronger maximum in interaction with the edge radiation. Furthermore an approach to the high frequency cut-off of coherent radiation generation due to the electron bunch length is made by multiplying the single electron spectrum with the spectrum of Gaussian pulses of varying length from 50 to 150 fs shown in green, violet and dark red, respectively. It can be seen that longer electron bunches reduce the output at higher frequencies. This is a first

\(^{16}\)All simulations are based on a single electron.
Figure 2.25: The 2-dimensional intensity profile of the horizontal polarization components of the 3\textit{rd} harmonic at 48.66 \textit{um} created by the interference of the THz undulator radiation with the edge radiation. The central cone of intensity is smaller with the high intensity region being towards the negative values on the \textit{y}-axis.

Figure 2.26: The horizontal intensity profile at \( z = 0 \) of the 3\textit{rd} harmonic at 48.66 \textit{um}, represented in figure 2.25 created by the interference of the THz undulator radiation with the edge radiation. The profile is plotted as the number of photons per second and 0.1\% bandwidth and \textit{mm}^2 against the horizontal position.
Figure 2.27: The simulated spectrum of the THz undulator at FLASH1 with a fundamental wavelength of 2.05 $THz$ or 146 $um$ for single electron emission and simulating the cut-off induced by a finite length electron bunches from 50 to 150 $fs$. The spectrum is plotted as photons per second and 0.1% bandwidth multiplied with the normalized Gaussian spectrum as a function of the frequency in $THz$. 
indication that varying machine settings, resulting in varying electron bunch length, can have a significant influence on the spectral composition of the THz pulse and therefore on the electric field shape.

2.6.5 THz beam transport at FLASH1

The presented simulations in close proximity to the sources of radiation give first insight into the beam properties. In order to draw final conclusions out of the beam profile simulations the distance between generation of the radiation and experiment needs to be bridged. The SRW code allows, in addition to beam profile simulation at a given point in space, also the simulation of beam transport including several optical elements. The large divergence of the THz radiation, in comparison to the XUV radiation, gives rise to the necessity of recollimation. At FLASH1 this is done at several points along the THz beamline using toroidal mirrors. Figure 2.28 shows a schematic of the design of the THz beamline including the toroidal mirrors and the respective focal lengths [100]. The mirrors marked with M and the respective numbers 1 – 8 are plane mirrors and therefore, in respect to the SRW calculations not of importance. The final mirror P1 is an off axis parabola used in the original design to show the final focal capabilities and will be disregarded. In order to be able to simulate

Figure 2.28: The schematic layout of the THz beamline at FLASH1 taken from [100] including the toroidal T1 – 6 and the plain mirrors M1 – 8. All toroidal mirrors reflect the beam under a 45° incoming and outgoing angle, creating a total deflection of 90°. Mirror P1 is an off axis parabola that was used in the original design by Gensch et. al. to simulate the final focus and will not be treated in the following simulation.

the beam transport properties the distances between the individual components have to be known and can be found in table 2.2. The starting position for the simulations is set to be at 20 m behind the injection point of the electrons or about 4.2 m behind the back edge of the beam dump magnet, equal to all simulations up to this point in section 2.6. From this point on the wavefront simulated by the SRW code will be propagated along the optical
elements until the final point of simulation at about 74 m. This point coincides with the entrance point into the THz pulse characterization setup chapter 3. The beam profile at the

<table>
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</tbody>
</table>

starting position of the simulation can be found in figure 2.23. The wavelength used in the beam propagation is identical with the previously described beam profile analysis, namely 146 \( \mu m \). From this point the beam is propagated backwards to the exit of the beam dump magnet and therefore to the start of the beamline at 15.864 m. Figure 2.29 shows the 2-dimensional intensity profile of the THz radiation at the exit of the dump magnet. A central cone created by the interference of the THz undulator radiation and the edge radiation can be seen. Additionally several ring like structures originating from various magnetic edges and the associated edge radiation can be seen. This profile and the corresponding waveform are the starting point for the beam transport. Propagating the wavefront backwards to the end of the dump magnet has two reasons. First it is not possible to introduce apertures in the process of initial wavefront calculation and second it is necessary to simulate the complete transport throughout the beamline. The SRW code has certain limitations in the way it is used to simulate the beam propagation. When simulating the initial wavefront, the observation plane size chosen, limits the maximum beam size that can be calculated. If the observation plane is chose to small part of the beam profile will be clipped. Similarly, if the beam is propagated the observation plane size limits the maximum observable beam size. In addition to this if the beam expands to a size larger than the observation plane size it will be diffracted at the edges of the observation plane, creating incorrect results. In order to avoid this and to simulate the beamline aperture\(^{17}\), a virtual beamline aperture of 200 \( mm \) is introduced. During each step of propagation the beam will be propagated through this aperture. This prevents possible artifacts due to diffraction at the observation plane edges caused by remaining synchrotron or edge radiation components emitted under a larger

\(^{17}\)It is to be noted that parts of the beamline have an aperture smaller 200 \( mm \).
angle. In order to acquire a detailed characterization of the beam transport the radiation wavefront is propagated in steps of 1 \text{ mm} and a 2-dimensional intensity profile taking only the horizontal components into account is generated. Each image is then analyzed using the second moment method, suited to evaluate the size of an arbitrary beam shape. It is used to calculate the standard deviation $\sigma$ in respect to one of the beam axis, using

$$
\sigma_x = \sqrt{\frac{\int_{-\infty}^{\infty}(x - x_0)^2 I(x, y) \, dx \, dy}{\int_{-\infty}^{\infty} I(x, y) \, dx \, dy}}, \quad (2.6.1)
$$

with $\sigma_x$ as the standard deviation with respect to the x-axis, $x_0$ as the center of gravity of the beam with respect to the x-axis and $I(x, y)$ as the intensity profile, the standard deviation with respect to the x-axis can be calculated. In order to describe the beam size of an arbitrarily shaped laser beam one can use:

$$
2s = 2\sigma_x, \quad (2.6.2)
$$
with $2s$ as the $2\sigma$ beam size, which yields, following the beam profiles along the transport, the graph shown in figure 2.31 [101]. The graph shows the $2s$ beam size in $mm$ calculated using the second moment method, plotted against the beamline position as distance in $m$ from the start of the electron injection. Several positions are marked with $T1 - 6$ representing the positions of the toroidal mirrors inside the beamline. Each toroid has a size of 215 times $150\,mm$ in the horizontal and vertical direction, respectively. Therefore, if the THz radiation intensity profile is exceeding the toroid size, a sudden drop in beam size after the toroid can be seen. A second reason is scattered radiation. The outer rings of the edge radiation intensity profile, being emitted under a larger angle can scatter at the toroid edges and therefore, after additional beam propagation, can be larger than the toroid size. The second moment calculation takes the whole intensity distribution into account. This leads to the fact that low intensity parts of the beam can be distributed over a larger area than the $2s$ beam size implies. Looking at figure 2.29 this can be seen as the low intensity arc towards the negative positions on the x-axis. Figure 2.30 shows a comparison of the intensity profile before and after toroid $T2$. Subfigure a shows the intensity profile before and subfigure b after the toroid $T2$. In close comparison it can be seen that low intensity radiation further from the center of the observation plane than $\pm 75\,mm$ is cut when the radiation is propagated over the toroid. While the central profile remains unchanged the $2s$ beam size is dropping. At the given wavelength of $146\,um$ sudden beam size drops happen at $T2$ and $T3$ even though the beam size at $T3$ is approximately $42\,mm$ and therefore much below the maximum $2s$ beam size of $50\,mm$ $^{18}$. The finite toroid size can ultimately be a limiting factors for the long wavelength transmission through the THz beamline. Apart from the sudden beam size drops the beam size after the first 2 toroids is below $50\,mm$. A tight focus between toroid $T4$ and $T5$ can be seen. At this point a diamond window is mounted to separate the machine and the beamline vacuum. It is indicated as a dotted green line marked with D in figure 2.28. The $2s$ beam size when entering the experimental system described in chapter 3 is $21.5\,mm$, which is in very good agreement with the knife edge measurements performed, yielding a FWHM of $22.1 \pm 6.5\,mm$ or a $2s$ beam size of $18.8 \pm 5.5\,mm$, which can be seen in figure 2.33. The error given represents a 95% confidence interval and originates from the fitting uncertainty, caused by the energy fluctuations at maximum pulse energy. The agreement between simulation and pulse energy, shows that the modeled beamline transport is close the real beam transport at Flash1. Therefore it can be used to model and optimize the incoupling into various experiments as

$^{18}$calculated from the horizontal toroid size considering an angle of incidence of $45^\circ$ and a transmission of $6\sigma$
Figure 2.30: The comparison of the intensity profile before (a) and after (b) toroid T2. Please note that the color map is adjusted to enhance the visibility of the low intensity regions.

done in the case of Castiglioni et al. from 04.2017 by Dr. R. Pan.
Figure 2.31: The 2σ beam size of the THz radiation profile, taking only horizontal components into account, as the beam travels through the THz beamline at Flash1. The positions of the 6 toroidal are indicated with T1 – 6. The toroid size is 215 times 150 mm in horizontal and vertical direction, respectively. Therefore in case of radiation components exceeding the toroid size, a sudden drop of intensity after the toroid can be seen. This also applies for scattered radiation and the outer rings of the edge radiation profile. After an initial collimation of the beam the beam size is kept below 50 mm, with a tight focus between toroid T4 and T5 where a diamond window is mounted, separating the accelerator vacuum from the beamline vacuum.
Figure 2.32: 2-dimensional intensity plots of the THz radiation along the THz beamline at the positions of the six toroids used to collimate the THz radiation. The change of the beam profile along the THz beamline can be seen, marking the change from near to far field region.
Figure 2.33: The fitted knife edge beam size data, acquired at the entrance of the THz pulse characterization tool. The measured data points are presented in blue and fitted using an error function, shown in red. Additionally the 95% confidence interval is plotted in green. The fit results in a FWHM beam size of $22.1 \pm 6.5$ mm, including a 95% confidence interval. The uncertainty in the fit originates from the large pulse energy fluctuations at maximum pulse energy before cutting the beam spatially.
2.6.6 Near-field to far-field transition and source point calculation

When introducing the electric field of a moving point charge in an arbitrary field derived from the Liénard–Wiechert potentials in subsection 2.3 equation (2.3.1), the assumption of large distance $R$ between the source and the observer has been made, describing the so called far field case. This simplified the expression to the second so called acceleration term, being proportional to $1/r$. The SRW code is using the complete expression in order to calculate the generated electric field wavefront and is therefore also taking near-field effects at small $R$ into account. In this case the so called velocity term, being proportional to $1/r^2$ is also taken into account. At a certain distance from the source point the influence of the velocity term is becoming much smaller than the influence of the acceleration term. In order to calculate the transition distance between the near- and the far-field, the parameter $W$, as the near field parameter, described by

$$W = \frac{L_u^2 \theta^2}{2\lambda R},$$

(2.6.3)

can be introduced following the notation of Clarke [83] and Walker [102]. The parameter $L_u$ represents the total undulator length, $\theta$ the maximum angle of radiation observed with respect to the unperturbed electron path and $R$ the distance between the source point and the observer. A $W$ parameter larger 1 defines the radiation to be influenced by near field effects. This can be understood as $W$ equals 1 to represented a $\pi/2$ phase difference between the different radiation components arriving from extreme points of the source. With a phase difference larger than $\pi/2$, more accurately between $\pi/2 + (n*2\pi)$ and $3\pi/2 + (n*2\pi)$, destructive interference occurs. A $W$ parameter larger 1 is therefore describing the near field regime in which constructive and destructive interference occurs, giving rise to the possibility of complex intensity profiles. In order to calculate the $W$ parameter the source position needs to be known. The source position in a magnetic structure with several individual radiation sources that interfere can not simply be put at its center. In order to be able to define the exact source position the radiation profile is first simulated after the magnetic structure, at $20m$ behind the injection point of the electrons, equal to the case of transport through the beamline. In a second step the THz intensity profile is sent through an aperture of $50mm$ diameter, in order to remove the off axis radiation parts, originating from magnetic edges. This allows to isolate the central part of the intensity profile carrying the undulator radiation components that interfered with the edge radiation. This is necessary as the radiation far off axis creating artifacts in the second moment analysis.

\[n = 0; 1; 2; 3;...\]
when propagated back\textsuperscript{20}. After preparing the intensity profile, it is propagated backwards through the magnetic structure in steps of 50 mm creating individual beam profiles in each step, equal to the procedure used to propagate the THz radiation through the THz beamline. The individual beam profiles are then analyzed using a second moment routine which yield the 2s beam size in mm in dependence of the distance from the electron injection, or the start of the magnetic structure, as shown in figure 2.34. The 2s graph shows the evolution of the beam profile with a minimum in size at 7.631 m, marking the source point of the THz radiation. Comparing the minimum with the magnetic structure, shown in figure 2.15, it can be seen that it coincides with the beginning of the THz undulator. This originates from the effective combining from edge radiation and the THz undulator source as predicted by Geloni et al. \cite{90}. A second local minimum can be seen around 12.5 m originating from the electron beam traversing through the electron beam dump. The edge radiation created at the entrance of the dump magnet is, at the point of creation, small in size, as a single electron is used in the simulation. Therefore the corresponding edge radiation intensity is confined in a small space, creating an artifact in the second moment calculation. With the source point defined it is possible to calculate the $W$ parameter. For the comparison with the SRW results presented, the length $L_u$ is substituted with the length of the magnetic structure $L_{MS}$. This can be explained by the fact, that the intensity distribution is a result of the interference of radiation produced by various components in the magnetic structure. The length is therefore defined from the center of the first bending magnet at 0.45 m and the center of the last bending or electron dump magnet at 15.25 m, resulting in 14.8 m. $\theta$ is defined by the finite size of the first toroidal mirror and its distance to the source point and represents the beamline acceptance half angle $\theta_{BL}$. This can be explained by the toroid recollimating the THz radiation and thereby defining the maximum angle under which radiation is observed at any point in the beamline further from the source point than $T1$. This condition is only valid as long as the opening angle of the radiation $\theta_{max}$ defined by equation (2.3.6) is larger than the acceptance of the toroid. The toroid is centered on the 0, 0 axis as is the THz radiation, therefore the beamline acceptance half angle is calculated from the center of the toroid to its edge. Applying these conditions to equation (2.6.3) yields

$$W = \frac{(L_{MS})^2 * (\theta_{BL})^2}{2\lambda R},$$

(2.6.4)

which can be used to calculate the near field parameter for the THz beamline. Given the source point position at 7.631 m and the first toroid at 17.481 m with a effective size of

\textsuperscript{20}Please note that the second moment analysis is sensitive to background radiation.
Figure 2.34: The 2σ beam size of the THz radiation profile, taking only horizontal polarization components into account inside the magnetic structure allowing to identify the source position. The minimum beam size, or the source position can be seen at at 7.631 m coinciding with the exit of the undulator.
150x150 mm\textsuperscript{21} yields a beamline acceptance half angle $\theta_{BL}$ of approximately 7.61 mrad. Figure 2.35 shows the plot of equation 2.6.4 for the simulated wavelength of 146 um against the distance from the source point including the simulated intensity profiles every 10 m. It can be seen that the near field parameter $W$ drops below 1 at approximately 42.5 m behind the source point, or 50.16 m behind the electron injection. Comparing this result with figure 2.31, it can be seen that the transition is occurring between toroid T4 and T5. In comparison to the 2-dimensional beam profile at toroid 4 and 5 from figure 2.32d and 2.32e, respectively, the transition from a structured to a quasi Gaussian beam can be seen, marking the transition from near field to far field [103].

![Figure 2.35: The near field parameter W plotted against the distance from the source point for a wavelength of 146 um including the beam profile simulations every 10 m. A near field parameter above 1 is suggested as the condition for near field effects dominating. W drops below 1 at approximately 42.5 m suggesting the transition to the far field. This is in agreement with the beam profile transition from figure 2.32d and 2.32e.](image)

\textsuperscript{21}physical size of 210x150 mm and a deflection angle of 90°
2.7 Future development - THz at FLASH 2

After the remodeling of the FLASH1 THz beamline and the consecutive comparison of the expected and measured beam size at the entrance of the experimental setup, the developed SRW code can be adapted for FLASH2. FLASH2 is the second electron beamline of the FLASH accelerator. Starting after the accelerating modules FLASH2 features planar variable gap undulators covering the wavelength range of 4 to 90 nm. FLASH2 can be used in parallel to the FLASH1 operation and is therefore increasing the available beamtime for users [38]. In order to enable time resolved experiments, a secondary light source, the pump probe laser, as well as a split and delay unit [104], will be available in the near future. To extent the possibilities of pump probe experiments even further a THz undulator at FLASH2 is planned. Within this section a short outlook on the planned design of the undulator is given alongside the expected beam profile. Based on the simulations and structural constraints, a proposed beam transport to the experimental end station of beamline FL24 is presented including a total beam transport efficiency estimation. All parameters are subject to change and the presented results are acquired at the current state of the project development.

2.7.1 THz beam profile simulations

The THz undulator at FLASH2 is planed to be a helical electro magnetic device, allowing to produce either right hand or left hand circular THz radiation. With the possibility to switch off part of the electro magnetic poles, adds the ability to generate linearly polarized light, similar to FLASH1. The required maximum wavelength, at a maximum electron energy of 1250 MeV, is 100 μm. Due to space constrains the total undulator length will be 3.4 m, with 8.425 mm long periods. A maximum magnetic field of 1.5 T allows to reach the design wavelength at maximum electron energy. Figure 2.36 shows the achieved undulator fundamental in dependence of the magnetic field strength at an electron energy of 1250 MeV. It can be seen that the design wavelength of 100 μm can be reached with the maximum field of 1.28 T. In order to estimate the intensity distribution of the generated THz radiation, hereafter beam profile, simulations are performed using the SRW code introduced in chapter 2. In analogy to the presented procedure a magnetic structure is designed and a single electron is injected into the structure at the desired electron energy. Figure 2.37 shows the 3-dimensional model of the components surrounding the planned THz undulator at FLASH2. In order to accurately simulate the beam profile, the magnetic structure influencing the radiation generation is modeled. Figure 2.38 shows the magnetic structure of
Figure 2.36: The achievable fundamental wavelength of the planned helical THz undulator at FLASH2 as a function of the magnetic field strength for the case of 1250 MeV electron energy.

FLASH2 including the THz undulator in a vertical and b horizontal direction. The vertical magnetic structure starts with a 3.5 degree bending magnet, used to separate the XUV radiation from the electron beam. The bending magnet at this position allows to neglect the edge radiation components created at the magnetic edges along the electron beam transport and especially at the back edge of the XUV undulators. Following the first bending magnet the magnetic field of the THz undulator can be seen. In horizontal direction the magnetic field structure start with the THz undulator. The magnetic field in horizontal direction is shifted by $\lambda_0/4$ with respect to the vertical field, creating a helical undulator and circularly polarized THz radiation. The magnetic structure ends with the electron beam dump magnet with a maximum field of 1.2 $T$ deflecting the electron beam with 21 degree into the electron beam dump.

 Injecting a single electron at 1250 MeV allows to generate a 2-dimensional intensity profile of the generated THz radiation at a chosen wavelength\textsuperscript{22}. Similar to the FLASH1 case, the radiation generated by the THz undulator will interfere with the edge radiation generated at various magnetic edges close to the undulator. Figure 2.39 shows the calculated intensity profile for a fundamental wavelength of 100 um taking all polarization components into

\textsuperscript{22}See chapter 2 for detailed information
account. A central lobe of high intensity is visible with the undulator radiation ranging in $x$ and $z$ direction from $-30$ to $30$ mm. Additionally, low intensity edge radiation rings are visible outside of the central lobe. The distinct structure within the central lobe originates from the interference of the few cycle undulator radiation with the edge radiation created. This can be understood when investigating the edge radiation and the undulator radiation separately. The edge radiation can be investigated by switching the magnetic field of the undulator to zero, effectively disabling it. As the undulator produces in its current setting mainly right hand circular radiation it is beneficial to look at the edge radiation taking only these polarization components into account. Investigating the profile of the few cycle helical undulator separately is not easily possible. A good approximation is made by increasing the period number greatly, resulting in an increase of the photon flux created by the undulator, ultimately reducing the influence of the edge radiation. Figure 2.40 shows the resonant approximation undulator beam profile for the THz undulator with 80 periods at 100 $\mu m$ fundamental wavelength in subfigure a and the edge radiation components observed at 100 $\mu m$ in subfigure b. The resonant helical undulator profile shows a small central cone of about 20 $mm$ diameter with a high intensity. The cone is surrounded by a ring structure originating from the magnetic edges. The edge radiation profile shows the typical ring like structure observed from edge radiation. The shown intensity dis-balance, showing a higher intensity towards the positive directions, can be explained by the interplay of two factors. The first factor is the synchrotron fan created by the beam dump magnet when deflecting the electrons by $21^\circ$, creating the fan towards the lower half of the profile. The dis-balance in horizontal direction originates from choosing only right hand circular polarization to be
(a) The magnetic structure of FLASH2 around the THz undulator in vertical direction.

(b) The magnetic structure of FLASH2 around the THz undulator in horizontal direction.

Figure 2.38: The schematic of the magnetic structure of FLASH2 in the area of the THz undulator shown as the field strength as a function of the distance starting at the electron injection in the SRW simulations.
Figure 2.39: The 2-dimensional intensity profile of the THz radiation created by the THz undulator at FLASH2 taking all polarization components into account. The peak intensity is about 550.

displayed. Comparing the undulator intensity profile shown in figure 2.39 with the intensity profile of the resonant case and the edge radiation, it can be seen that destructively interfering the edge radiation with the resonant undulator radiation, ignoring the intensity difference due to the resonant approach, creates a beam profile closely related to the simulated undulator profile in figure 2.39. The remaining features are to be associated to the low period undulator design.

2.7.2 THz beam transport

Simulating and understanding the generated THz beam profile of the 8 cycle helical THz undulator at the goal wavelength of 100 um is the first step in designing a photon and cost efficient THz transport that can be realized in the FLASH2 tunnel and the corresponding experimental hall. In order to collect as many photons as possible with the mirror size
(a) The 2-dimensional intensity profile of the THz undulator in resonant approximation with 80 periods taking only right hand circular polarization into account.

(b) The 2-dimensional intensity profile of the edge radiation taking only right hand circular polarization components into account.

Figure 2.40: The resonant helical undulator profile, shown in subfigure a, exhibits a small central cone with high intensity, ranging from $-10$ to $10$ in $x$ and $y$, with an additional centro-symmetric ring structure surrounding it. The peak intensity is about 6000. The edge radiation profile of subfigure b, shows the typical edge radiation ring structure. Due to the polarization selection the main intensity is located in a half circle towards the positive direction. The peak intensity is about 60.
of 210 × 150 mm the first collimating toroid needs to be as close to the dump magnet exit as possible. Figure 2.41 shows the top view of the section between the electron beam dump magnet and the PETRA tunnel wall including the proposed beamline schematic in dark blue with the toroid positions in red. The proposed design features a total of 4 mirrors out of which 3 are focusing toroids, shown in red. The design has 3 distinct features. At first the short distance of 1.5 m between the exit of the dump magnet and the first toroid allows to collect the maximum amount of photons. Secondly, the 1.5 m distance between the first and the second toroid, allow to bypass the radiation safety wall, without the necessity of adding additional mirrors to direct the beam transport over or under the wall, reducing the costs significantly while keeping radiation safety unchanged. Furthermore, the short distance between the first and the second toroid allows for a tight intermediate focus, allowing to utilize a small aperture diamond window to separate the accelerator vacuum from the beamline vacuum. Lastly, the proposed design keeps the path difference between the XUV radiation and the THz radiation as small as possible. Table 2.3 shows the positions and radii of curvature of the toroidal mirrors used to re-collimate the beam throughout the transport in the tunnel. The positions of the toroids are given from the injection of the electron into the magnetic structure. From the last toroid on the THz beam is crossing the PETRA3 tunnel and travels about 11 m to the next toroidal mirror located close to the wall inside the FLASH2 hall. In the hall approximately 54 more meters have to be covered from the wall to the experimental endstation. In order to achieve this a total of 3 additional toroidal mirrors are used. Figure 2.42 shows the schematic overview of the experimental hall of FLASH2 and the dummy of the proposed toroid positions in red and the beamline in blue.

\[23\text{This distance is the minimum achievable due to constrains imposed by other components in the area.}\]
Table 2.3: Table of the toroid positions and radii of tangential curvature for the tunnel section of the Flash2 THz beamline.

<table>
<thead>
<tr>
<th>toroid</th>
<th>position [m]</th>
<th>tangential radius [m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>9.237</td>
<td>1.73737</td>
</tr>
<tr>
<td>2</td>
<td>10.737</td>
<td>2.15608</td>
</tr>
<tr>
<td>3</td>
<td>22.487</td>
<td>10.1978</td>
</tr>
</tbody>
</table>

leading to the endstation FL24. Table 2.4 shows the positions and tangential curvatures for the toroids used in the experimental hall section of the THz beamline at Flash2 leading to the endstation of FL24. The final toroid is typically located within the experimental chamber used at a specific experiment and is adapted to the specific needs of the experiment. Propagating the simulated THz radiation using the 6 toroids described in table 2.3 and 2.4 allows to simulate the transverse beam size at various positions throughout the beamline. The simulated beam profile in figure 2.39 is propagated through the beamline in steps of first 5 and after the second toroid 25 cm. Figure 2.43 shows the full width half maximum FWHM beam size in mm as a function of the distance in m from the point of electron injection along the indicated positions of the toroids t1 to t6, as well as the end station es. The graph starts from first toroid at 9.238 m. The beam transport features a tight focus
Table 2.4: Table of the toroid positions and radii of tangential curvature for the hall section of the Flash2 THz beamline.

<table>
<thead>
<tr>
<th>toroid</th>
<th>position [m]</th>
<th>tangential radius [m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>33.487</td>
<td>11.1043</td>
</tr>
<tr>
<td>5</td>
<td>47.437</td>
<td>20.0000</td>
</tr>
<tr>
<td>6</td>
<td>69.487</td>
<td>18.8456</td>
</tr>
<tr>
<td>endstation</td>
<td>87.487</td>
<td>variable</td>
</tr>
</tbody>
</table>

Figure 2.43: The simulated FWHM beam size in mm of the THz radiation at 100 um throughout the THz beamline at Flash2 analyzed using a second moment method. The 6 toroid positions and the end station position are indicated in the top of the graph.
between the first and the second toroid with a minimum FWHM beam size of approximately 10 mm. The tight focus allows to employ a small aperture diamond window in this section, separating the machine from the beamline vacuum. A smaller aperture window reduces the price and makes availability higher. From toroid $t_2$ onward the beam is recollimated between the toroidal mirrors keeping the maximum FWHM beam size under 60 mm allowing to transport $6 \sigma$ of the THz beam with 45° reflection on a toroidal mirror with $210 \times 150$ mm size. A step in beam size is visible at toroid 3 originating from cutting scattered radiation with a transverse size larger than the toroid. Toroid $t_6$ can be adjusted in focal length to create a smaller beam size at the end station, if required by the experiment, for example if spatial constraints are limiting the usable optics size. The current setup creates a FWHM beam size of over 60 mm in order to allow for a small focus if short focal length toroids or off-axis parabolas are used. Figure 2.44 shows the 2 dimensional intensity profiles of the THz radiation at 100 mm at the toroids throughout the THz beamline, leading to the end station. The intensity profile has an initial whirl shape, cut by the beam dump magnet shown in subfigure 2.44a. It is small quasi Gaussian like at $t_3$ and exhibits a small central structure with low intensity side wings on $t_4$ in subfigure 2.44c. The intensity profile on $t_5$ resembles the initial swirl like structure but features smoother transitions between high and low intensity areas. The intensity profile on toroid $t_6$ resembles the profile on toroids $t_2$ featuring a small high intensity region with a quasi Gaussian shape and a low intensity ring to the side. The beam profile at the end station is similar to the profile on toroid $t_4$. It shows a small high intensity region with a half moon shaped lower intensity region surrounding it. The beam shape originates from an interplay of the interference of undulator and edge radiation interference and of clipping on the dump magnet aperture.

### 2.7.3 Beamline transmission and comparison with Flash1

The proposed beamline optics allow to transport the THz radiation at Flash2 to the end station with 6 toroids, keeping the $6 \sigma$ beam size smaller than the toroid size. Apart from the recollimation and transport additional factors influence the overall transmission of the beamline from the creating of radiation inside the undulator to the end station. The main limiting factor is the clear aperture in the electron beam dump magnet. The aperture is $52 \times 68$ mm throughout the dump magnet length of 1.2 m. It is approximated by placing an aperture at the position of the entrance and at the exit of the dump magnet. Figure 2.45 shows the transmission of THz radiation through the dump magnet up to toroid $t_1$ for the THz beamline Flash2 and Flash1. While the Flash2 beamline shows an increasing
(a) The 2-dimensional intensity profile of the THz undulator tuned to 100 um at t2 at 10.737 m.

(b) The 2-dimensional intensity profile of the THz undulator tuned to 100 um at t3 at 22.487 m.

(c) The 2-dimensional intensity profile of the THz undulator tuned to 100 um at t4 at 33.487 m.

(d) The 2-dimensional intensity profile of the THz undulator tuned to 100 um at t5 at 47.487 m.

(e) The 2-dimensional intensity profile of the THz undulator tuned to 100 um at t6 at 69.487 m.

(f) The 2-dimensional intensity profile of the THz undulator tuned to 100 um at the end station at 87.487 m.

Figure 2.44: Two dimensional intensity profiles of a helical undulator tuned to 100 um at the toroids through the THz beamline leading to the end station.
Figure 2.45: Comparison of the simulated THz beamline transmission through the dump magnet at FLASH2 and the dump magnet and the M0 mirror at FLASH1 for several wavelength between 20 and 300 \textmu m. The transmission features a steady increase towards lower wavelength at FLASH2, while the central hole in M0 at FLASH1 reduces the transmission into the beamline at very low wavelength.
transmission at lower wavelength, originating from the smaller divergence at lower wavelength, the FLASH1 beamline shows an increase only to about 50 \( \mu m \). This inconsistency can be explained by the difference in separation of XUV and THz radiation. At FLASH1 the separation is done using a mirror with a central hole of 10 \( mm \) diameter, which collects a part of the THz radiation while the small divergence XUV radiation is passing through the hole. This method results in a reduction of throughput at lower wavelength as the lower divergence results in a smaller beam on the mirror and a larger part of the beam passing through the central hole. At FLASH2 there is no such separation as the electrons and XUV radiation are separated by the 3.5° bending magnet before the THz radiation is created inside the undulator. Therefore the only obstacle between the creating of radiation and the first toroid is the dump magnet aperture, leading to an increased throughput at lower wavelength. Figure 2.46 the transmission through the THz beamline at FLASH1 and FLASH2 from the generation of the radiation to the end station for several different wavelength from 20 to 300 \( \mu m \). The presented graph is the convolution of the dump transmission presented

![Graph](image)

Figure 2.46: Comparison of the simulated THz beamline transmission of FLASH1 and FLASH2 for several wavelength between 20 and 300 \( \mu m \) from the creation in the undulator to the end station, ignoring the reflection on diamond windows.
in figure 2.45 and the transmission along the toroidal system. It can be seen that the graph follows the dump transmission closely with a reduction in overall transmission due to losses of scattered radiation and edge radiation not being transported over the large distance. It can be seen that the transmission of the goal wavelength of 100 \( \mu m \) is about 70\% for the Flash2 beamline. The overall transmission of the proposed beamline at Flash2 is higher or comparable with the Flash1 beamline with a large increase in transmission from 20 to 50 and 100 to 300 \( \mu m \), while using the same amount of toroids and covering an about 20 \( m \) longer distance to the end station. In order to give a complete overview another factor, having an impact on the transmission, needs to be mentioned. The diamond windows separating the machine vacuum from the beamline vacuum. Both beamlines are designed with 1 CVD diamond window\textsuperscript{24} that is reducing the beamline transmission by about 35\% due to reflective losses [105]. Figure 2.47 shows the comparison of the transmission including the

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure2.47.png}
\caption{Comparison of the simulated THz beamline transmission of Flash1 and Flash2 for several wavelength between 20 and 300 \( \mu m \) from the creation in the undulator to the end station.}
\end{figure}

\textsuperscript{24}Flash1 is currently using 2 diamond windows, despite the original design.
20 and 300 $\text{um}$. It can be seen that the maximum transmission is slightly above 50\% for both beamlines and the minimum transmission is 30\% and below 20\% at 300 $\text{um}$ at Flash2 and Flash1, respectively. The goal wavelength of 100 $\text{um}$ has a transmission of about 47\% from the undulator to the end station.
2.8 Conclusion

Within this chapter the Flash accelerator structure is introduced along with the THz frequency range in general. A short overview of THz sources from continuous wave to short pulses is given leading to a division of THz pulses in single and multi cycle pulses focusing on the differences in properties and applications. After introducing the basics of radiation generation by ultrafast particles, the different THz radiation sources utilized within this work are presented. In order to acquire insight into the interaction of the different photon sources an intense study of the THz generation at Flash1 is performed using SRW. In this process the framework of the magnetic structure is introduced and carefully modeled to represent the sections of Flash relevant for the THz generation. In a step by step the different radiation sources and their influence on the THz beam profile are studied, as well as their interaction with each other. The studies are performed at an electron energy of 600 MeV and a THz frequency of about 2 THz, representing parameters used later within this work. Additionally the expected undulator spectrum is simulated with a focus on the high harmonic content for later comparison with measurements. Next, the THz beam transport throughout the THz beamline is simulated and compared to the measured beam size at the entrance of the experimental setup. Based on the good agreement of the simulations and measurements, the possibility to use SRW calculations for the THz beam transport simulations is shown. Consecutively the proposed THz source for Flash2, the second electron beamline of the Flash accelerator is introduced. Its parameters are presented, giving the helical design a special focus. After introducing the boundary conditions imposed by the surrounding elements, including the relevant magnetic structures, the magnetic structure is modeled in SRW. Based on the magnetic system the 2 dimensional intensity profile is presented on the example of 100 μm wavelength, representing the goal wavelength at 1.25 GeV electron beam energy. The specific features of the beam profile are described and, based on a resonant approximation calculation and an edge radiation analysis, explained. After presenting the proposed THz undulator and the resulting intensity profile, the THz beamline proposal is presented. Divided in two main parts, the tunnel and the experimental hall each featuring 3 toroidal focusing mirrors, the proposed THz beamline has a total length of above 80 m from the first toroid to the end station. An optics design is presented and analyzed on the example of 100 μm radiation, allowing to transport the beam with optics of 210 × 150 mm size. Alongside the beam size analysis throughout the transport, the beam profiles at the different toroids as well as the final beam profile at the end station are presented and
a possible explanation for the complex beam profile is given. In a final step the beamline transmission is evaluated throughout a large part of the THz wavelength range and compared to the transmission of the existing THz beamline at Flash1. It is shown that the proposed beamline has an overall high transmission throughout the examined wavelength range and exceeds the transmission of the existing THz beamline at Flash1 throughout almost the entire range.
Chapter 3

THz pulse characterization

Recent advances in laser based THz generation [28, 30, 26, 106, 29, 70] draw more and more attention to the wavelength range covering 0.1-10 THz. The scientific applications employing THz radiation grow rapidly and range from linear to nonlinear dynamic studies in solids, bio materials and liquids addressing the optical phonon modes in this range. With the THz Gap closed [107] with broadband single cycle THz pulses produced with high power laser systems [106] and advances in spintronics [28], it becomes more and more apparent that selectively addressing individual phonon modes with spectrally intense THz pulses remains challenging. 4th generation X-ray light sources combining large scale particle accelerating structures working at MHz repetition-rate with dedicated undulators are able to deliver flexibly tunable narrow band high pulse energy femtosecond to picosecond THz pulses with electric field strength on the order of 100’s of MV/m, routinely available for nonlinear dynamic studies performed within the THz Gap. A recorded signal at such experiments represents the convolution of physical process and driving field. In order to disentangle the possibly complex nonlinear dynamics present at such experiments, a precise understanding of the driving force is necessary.
3.1 Principles of Electro-optical detection

In order to achieve precise understanding of the driving force in THz pump XUV probe experiments, the characterization system, designed to precisely characterize the THz pulses, need to fulfill several requirements that are directly dictated by the THz pulse properties of the Flash1 THz source. The system must therefore have a broadband detection range spanning the working range of the THz undulator at Flash1 and be able to non-distortively measure the electric field trace of the THz pulses. When reviewing the THz pulse properties it becomes apparent that a high dynamic range is necessary over the frequency range of 0 to 10 THz in order to be able to measure the spectrally intense multicycle THz pulse from the undulator including a high amount of the harmonics necessary for a non-distorted measurement and the broadband quasi single-cycle THz pulse created by the electron beam dump magnet.

A technique that can fulfill the given requirements is electro-optical detection, which uses the linear electro-optical or so called pockels effect. The following section follows [108] and [109] and will be dealing with the electro-optical crystals used within the experiments. The pockels effect describes the transient birefringence in linear dependence of an externally applied field. The electric field is in this case supplied by the THz pulse and the focus of investigation. It is possible to utilize the field dependent birefringence to measure the electric field profile by using a linearly polarized laser pulse and modulating its polarization as depicted in figure 3.1. The pockels effect can be found in material without inversion symmetry, like Zinc Telluride ZnTe or Galliumphoshide GaP. GaP and ZnTe have cubic crystal latices with a high symmetry resulting in optical isotropy without an externally applied field. To utilize the pockels effect GaP and ZnTe crystals are cut in a way that the surface is parallel to the (110) plane as shown in figure 3.2. The probe laser and THz pulse are entering the crystal under normal incidence to this plane with the linear electric field polarization parallel to $-110$ axis, yielding the maximum phase retardation between the individual probe laser polarization components [108]. The retardation $\Gamma$ between the ordinary and extraordinary polarization components of the laser pulse can be calculated using

$$\Gamma = \frac{n_o^3 r_{41} E_{THz} \omega_p d}{c}, \quad (3.1.1)$$

Further information can be found throughout chapter 2.

Spectral modification of a THz pulse has a drastic impact on the electric field shape. Please refer to section 3.5 for further information.

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Figure 3.1: The principles of electro-optical detection. A linearly polarized laser pulse is overlapped with an externally applied field, for example a THz pulse. The externally applied field causes a change of birefringence in the electro-optical crystal and leads to a modulation of the polarization of the laser pulse.

Figure 3.2: The schematic of the electro-optical crystal orientation with the (110) plane representing the surface plane of the respective electro-optical crystal. The probe laser and THz pulse enter the crystal under normal incidence with the electric field parallel to the [-110] axis.
where $n_0$ represents the ordinary refractive index of the electro-optical crystal at the probe laser wavelength, $r_{41}$ represents the electro-optical coefficient, $E_{THz}$ represents the electric field of the THz pulse, $\omega_p$ represents the angular frequency of the probe laser pulse and $d$ represents the thickness of the electro-optical crystal. The refractive index $n_0$ can be estimated by the Sellmeier equations for short wavelength where precise refractive index data is available and using the complex dielectric function for the longer wavelength regime [108]. Having a closer look at equation (3.1.1), it can be seen that the phase retardation is linearly dependent on the electric field of the THz pulse, which hold for moderate electric field strength where Kerr effects can be neglected. Recent studies on the influence of the Kerr effect on the spectrum of the probe laser beam in Gallium Phosphide shows that the Kerr effect has a noticeable impact when THz field strength exceed $500 \text{MV/m}$ [110]. Therefore it can be concluded that the Kerr effect can be neglected for THz field strength up to $500 \text{MV/m}$. The phase retardation can consequently be used to directly gain information about the electric field by analyzing the difference between the two polarization directions.
3.2 Sequential electro-optical Sampling

3.2.1 Principles of sequential electro-optical detection with balanced detection

A common way to utilize the electro-optical effect in order to characterize a THz field is the so called sequential electro-optical sampling technique. In this scheme a probe laser pulse with a pulse duration much shorter than a cycle of the THz pulse \( \tau_{\text{probe}} \ll \tau_{\text{THz-cycle}} \) is overlapped with the THz pulse in space and time in an electro-optical crystal. The arrival time between the probe laser pulse and the THz pulse is than varied using for example a delay line. When an overlap in space and time is established in a suitable electro-optical crystal a polarization change of the probe laser pulse is induced. In order to analyze the polarization change various different detection schemes can be used. Figure 3.3 describes the employed balanced detection scheme. In this scheme the linearly polarized probe laser pulse is send through the electro-optical crystal in the absence of the THz electric field. The polarization components are split by a polarization analyzer, for example a wollaston prism. The individual polarization components are detected using identical photo detectors depicted as \( A \) and \( B \). The individual signals are then subtracted from each other creating the final signal. In the balanced mode a half wave plate and a quarter wave plate are used after the electro-optical crystal to equalize the signal intensity in both channels and therefore create a zero difference signal, as depicted in subfigure 3.3 a. In order to achieve perfect balancing the electro-optical crystal and the quarter wave plate are removed. The half wave plate is used to equalize the detected signals in the channels \( A \) and \( B \). After that the electro-optical crystal is reintroduced. An occurring imbalance in the difference signal is now corrected by introducing the quarter wave plate. When a THz field is applied a retardation between the individual polarization components occurs following equation (3.1.1) and resulting in a change of the ratio between the polarization components and an elevated intensity level in one and a decreased intensity level in the other signal channel, as depicted in subfigure 3.3 b and c. The arrival time delay between the THz pulse and the probe laser pulse is then varied in a scanning fashion in order to cover the complete THz pulse length, while recording the individual signals at each point. An integration over the signal on each trace allows the reconstruction of the THz electric field profile. The difference signal \( S \) created by subtracting channel \( A \) and \( B \) is described by [108]

\[
S = A - B = I_{\text{hor}} - I_{\text{vert}} = I_0 \sin(\Gamma),
\]

(3.2.1)
(a) The sequential EOS in the absence of the THz pulse. The intensities in the horizontal and vertical polarization direction are equal and create a zero difference signal.

(b) The sequential EOS in the presence of the THz pulse at a delay $\delta t_1$. The intensities in the horizontal and vertical polarization direction are not equal due to the phase retardation caused by the electric field of the THz pulse and create a positive difference signal.

(c) The sequential EOS in the presence of the THz pulse at a delay $\delta t_2$. The intensities in the horizontal and vertical polarization direction are not equal due to the phase retardation caused by the electric field of the THz pulse and create a negative difference signal.

Figure 3.3: The schematic of the sequential electro-optical sampling principle employing balanced detection. A fs-probe laser pulse is overlapped in time and space with a THz pulse inside a electro-optically active crystal. The horizontal and vertical polarization components of the probe laser pulse are separated with a polarization analyzer and directed to identical photo detectors. The resulting signals $A$ and $B$ are subtracted creating a delay dependent difference signal $S$. 

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where $I_{\text{hor}}$ represents the intensity of the horizontal polarization of the laser pulse measured in one of the channels, $I_{\text{vert}}$ represents the intensity of the horizontal polarization of the laser pulse measured in the other channel and $I_0$ represents the incident laser intensity. Equation (3.1.1) shows that $\Gamma$ is linearly dependent on the electric field of the THz pulse and equation (3.2.1) shows that the measured difference signal is background free and only dependent on $\sin(\Gamma)$ which means that for $\Gamma \ll 1$ the difference signal can be assumed to depend linear on the electric field of the THz pulse. In the case of Flash1 THz pulses can have high electric fields and the assumption of $\Gamma \ll 1$ can not be made, which results in a nonlinear behavior. In section 3.2.2 it will be shown that the individual intensities $I_{\text{hor,vert}}$ are recorded, which allows an estimation of the non-linearity and its effects on the retrieved amplitude spectrum and furthermore the correction of it. Additionally it allows to normalize the laser intensity $I_0$ resulting in a difference signal independent of possible fluctuations of the laser intensity.

### 3.2.2 Experimental realization

Even though the general scheme and the theoretical background for balanced sequential electro-optical sampling seem far from complex, the THz pulse properties impose high demands on the experimental realization. Broadband THz pulses covering the THz gap and ranging from $0.1$ to $10 \, \text{THz}$ require laser pulses shorter than a few $10 \, \text{fs}$ laser pulses to be fully resolved. The large amount of absorption lines in this frequency range, both in gases and solids, results in the need for a careful design of the transport in vacuum. Electro-optical crystals need to be evaluated not only for the strength of the electro-optical effect but also for their broadband detection capability. As different frequency components can have dramatically different spectral brightness a detection system with a high dynamic range and sensitivity is needed in order to accurately characterize the THz pulses from Flash1.

#### 3.2.2.1 Laser source

In order to be able to characterize THz pulses with frequencies up to $10 \, \text{THz}$ the pulse duration needs to be shorter than $50 \, \text{fs}$ FWHM as a cycle length is $100 \, \text{fs}$. The TANGERINE fiber laser system from AMPLITUDE SYSTEMS, used as a $MHz$ repetition rate laser source synchronized to the Flash accelerator, provides pulses with a central frequency of $1030 \, \text{nm}$ and a FWHM bandwidth of approximately $8.3 \, \text{nm}$ as can be seen in figure 3.4. The minimum pulse duration is around $320 \, \text{fs}$ FWHM. Therefore the minimum pulse length is

\[^3\text{FWHM} \approx 2.35 \, \text{sigma}.
\[^4\text{There are also absorption lines in liquids, but these are not relevant for the presented work.}
\[^5\text{following the Nyquist theorem with an oversampling of at least a factor of 2 [111].}
insufficient for the frequency response that the system needs to fulfill. In order to achieve the required pulse duration the probe laser pulse is created by an optical parametric chirped pulse amplifier OPCPA that was developed in collaboration with Class5 Photonics. Detailed description on the theoretical background of the white light generation and the OPA process can be found in the dissertation of Riedel [112] and will be omitted as they were not part of the work performed. The OPCPA uses the TANGERINE fiber laser system as a pump source. Figure 3.5 shows a schematic of the OPCPA with the pump laser pulse entering at the top left (red arrow). The pump beam gets split into two parts using a polarization dependent beam splitter. The splitting ratio can be adjusted by a half wave plate. One part of the beam is directed into the second harmonic generation part of the OPCPA, depicted in green. Where a beta barium borate BBO crystal is used to create the second harmonic as an OPA pump. A dichroic mirror is used to split the second harmonic and the remaining fundamental. The pump beam is afterwards focused through the BBO crystal used in the single stage high gain OPA process.

The second part of the beam is rotated in polarization to match the polarization state of the SHG pump beam and than focused into a yttrium aluminium garnet YAG crystal. When numerical aperture and pulse intensity are adjusted accordingly, an ultra-broadband white light pulse is generated. The spectrum of the white light seed is shown in figure 3.6. It spans over several 100 nm from approximately 700 to 960 nm. The modulation of the spectrum outside this region is originating from the high reflectivity dielectric mirrors used in the setup. The white light is than stretched in time in a way that the desired bandwidth of approximately 50 nm has an equal pulse duration to the second harmonic pump beam. A dichroic mirror is used to deflect the remaining fundamental. The desired spectral components are than overlapped in space and time with the pump beam within the BBO crystal, resulting in an energy transfer from the pump beam to the seed. In this way the amplification happens only over the desired bandwidth yielding the highest spectral brightness. The central wavelength of the amplified beam pulse can be chosen by the variable delay of the white light seed and optimization of the phase matching angle of the BBO. Figure 3.7 shows the spectrum of the amplified OPCPA output. The central wavelength is approximately 850 nm with a FWHM bandwidth of about 50 nm. The spectrum is asymmetric around the central wavelength with a slight tail towards longer wavelength. The amplified pulse is than collected, collimated and further transported out of the OPCPA housing. The OPCPA beam is after transport to the EO-detection system compressed in order to be able to char-

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6Thorlabs UM10-45A
Figure 3.4: The detected spectrum of the tangerine fiber laser with a Gaussian fit showing a FWHM bandwidth of $8.3 \text{ nm}$.

Figure 3.5: Schematic of the OPCPA with its main components. After splitting the beam in two parts, one part is directed into the second harmonic generation (green) and one part into the white light generation (yellow). Both parts are then combined under an angle in the BBO crystal. The geometry is chosen in a way that the pump beam can be dumped and the signal beam can be picked up, collimated and send out of the OPCPA housing (gray).
Figure 3.6: The detected spectrum of the white light seed of the OPCPA.

Figure 3.7: The detected spectrum of the amplified light from the OPCPA. The spectrum is centered around 850 nm with a bandwidth of approximately 50 nm.
(a) Input Frog trace.  
(b) Reconstructed Frog trace.

(c) Autocorrelation of the retrieved Frog trace in blue and the Gaussian fit in red.

Figure 3.8: Frog analysis of the compressed laser pulse.
acterize THz pulses with frequencies up to $10 \, \text{THz}$. Figure 3.8 shows the measured Frog trace in subfigure a used as an input for a Frog retrieval algorithm with the time delay on the horizontal and the frequency on the vertical axis. Subfigure b shows the retrieved Frog trace used for the autocorrelation and analysis of the pulse duration. The autocorrelation of the retrieved Frog trace is represented as blue circles in subfigure c. A Gaussian fit, shown in red, is used to determine the pulse duration of the laser pulse, with the fit residual shown in orange. The fitted full width half maximum FWHM pulse duration is $20.7 \pm 0.8 \, \text{fs}$ and which theoretical allows to measure up to about $21 \, \text{THz}$.

### 3.2.2.2 Beam pointing stability

In order for the amplified probe laser beam to reach to THz pulse characterization tool a distance of approximately $7 \, \text{m}$ has to be bridged. This is, as mentioned before, due to the layout of the laboratory. Figure 3.9 shows the beam pointing stability (green line) measured using the center of mass on a camera, that is used as an alignment reference at the beginning of the THz pulse characterization tool. A peak to peak beam position jitter of up to 200 pixel$^7$’s recorded on the camera$^8$, which translates into a focus movement of more than one beam diameter in the sequential EOS position. This large pointing instability results mainly from a turbulent airflow from the climatization inside the laboratory. The installation of a housing enclosing the THz pulse characterization tool, the beam transport and the OPCPA in addition to a Rayleigh imaging lens system improved the stability, as can be seen in figure 3.9 in purple. The peak to peak pointing jitter is reduced by a factor of 10, which results in a stable focus in the interaction region, necessary to maintain stable overlap while characterizing the THz pulse electric field.

### 3.2.2.3 THz absorptions

With the probe laser pulse compressed and stable in position in the interaction region, the challenges imposed by the THz pulse need to be addressed. THz radiation covering the so called THz gap is of particular interest as it allows to directly excite a variety of phonon modes, laying within this region. At the same time this created high demand on the handling of such radiation. Figure 3.10 shows the normalized absorption of THz radiation through $1 \, \text{m}$ of air$^9$ for the wavelength range of 20 to $200 \, \text{um}^\text{10}$ [113]. In the short wavelength range

---

$^7_1$ The camera is a Basler AcA1920-25gm with a pixel size of $2.2 \times 2.2 \, \text{mm}$.

$^8$ Air composition in %: $\text{H}_2\text{O} : 1.862987 \, \text{CO}_2 : 0.032701 \, \text{O}_3 : 0.00003 \, \text{N}_2\text{O} : 0.00032 \, \text{CO} : 0.00015 \, \text{CH}_4 : 0.000168 \, \text{O}_2 : 20.710864 \, \text{N}_2 : 77.393229$.

$^9$ The spectra is generated using a web based service found under http://spectra-old.iao.ru/
Figure 3.9: Comparison of the OPA beam pointing stability without Rayleigh imaging (normal, petrol) and with Rayleigh imaging (purple). The pointing was evaluated using a camera at the beginning of the pulse characterization tool. The pointing jitter is much smaller when Rayleigh imaging is used.
between 30 and 50 \( \mu m \) a large amount of narrow absorption line can be seen, characterized by peaks to full absorption. Between 50 and 200 \( \mu m \) the major part of frequency components are absorbed, interleaved only by narrow transmission lines. Between 200 and 300 \( \mu m \) the gaps in the absorption become larger and more wavelength components are transmitted through 1 \( m \) of air. The high density of strong absorption is problematic for the characterization of broadband THz pulses for two reasons. First the intensity of different frequency components are attenuated in different ratios changing the spectral composition. The second problem becomes apparent when looking at the retrieved electric field trace. Figure 3.11 shows the electric field of the THz pulse created by the THz undulator and measured in air. The electric field trace shows long lasting field oscillations in the range of several 10\( ps \) created by long lasting dipole type radiation originating from excited molecules. The narrow absorption lines result in distortion of the electric field as they change the spectral composition of the pulse. Making a characterization of the originally generated THz pulse impossible. In order to avoid this, the THz transport and the electro-optical process are done in vacuum.
The transport, specifically deflection and collimation, is realized with reflective optics out of high reflectivity metals or various substrates coated with high reflectivity metals like copper, silver or gold\textsuperscript{11}.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{fig3_11.png}
\caption{The retrieved non jitter corrected electric field trace of the THz pulse produced by the THz undulator. The electric field trace exhibits additional field oscillations due to the narrow absorption lines in air. Exitated molecules create dipole radiation leading to electric field oscillations for several 10 ps.}
\end{figure}

3.2.2.4 Electro-optical crystals

The problem of absorption of the THz radiation continues when trying to identify a suitable electro-optical crystal. In electro-optically active crystals the first transverse optical phonon mode is the main limiting factor for the detection bandwidth. The most common electro-optical crystals are Zinc Tellurite ZnTe and Gallium Phosphide GaP. ZnTe is used for its relatively high electro-optical coefficient $r_{41}$ of 3.9 pm/v [114] and the crystals are readily available. The phonon resonance of ZnTe lies at about 5.3 THz and is therefore limiting the usability to the low frequency range. GaP is of high interest, because its phonon resonance lies at about 11 THz [115], making it a suitable candidate for the broadband detection\textsuperscript{11}.

\textsuperscript{11}If coatings are used the skin depth of the low frequency THz components needs to be taken into account.
required at FLASH1 [116]. The Trade-off of GaP in comparison to ZnTe is the lower electro-optical coefficient of $0.9 \, pm/v$ [114] at frequencies higher than the phonon resonance and about $0.4 \, pm/v$ for frequencies lower than the phonon resonance. From this discrepancy it can be seen that over the large THz frequency range provided by THz undulator and the electron beam dump magnet the electro-optical coefficient $r_{41}$ can not be treated as a constant. Therefore it becomes $r_{41}(f)$ [108, 117], which can be written as

$$r_{41}(f) = d_e \left(1 + \frac{C f_0^2}{f_0^2 - f^2 - i \Gamma_0 f}\right), \quad (3.2.2)$$

where $d_e$ represents the purely electronic influence on the electro-optical coefficient, $f_0 = f_{TO}$ represents the first transverse optical phonon mode, $C$ represents the Faust-Henry coefficient giving the ratio between electronic and ionic part of the electro-optical coefficient at zero frequency and $\Gamma_0$ represents the damping constant of the first transverse optical phonon mode. The individual factors for ZnTe and GaP are taken from Steffen [108] and can be found in table 3.1. In the work of Steffen several parameter sets [116, 118, 119, 120, 121, 122] are used in order to fit experimental refractive index data, where it can be seen that difference are small and ultimately the best fitting parameters are used.

The frequency dependent $r_{41}$ is plotted in figure 3.12 with the results for ZnTe in subfigure a and for GaP in subfigure b. Focusing on the low frequency part between 1 and $10 \, THz$ it can be seen that the electro-optical coefficient of ZnTe is about 10 times higher than for GaP. In the case of ZnTe, $r_{41}$ shows an asymptotic behavior close to the phonon resonance at $5.3 \, THz$ with a drop to $0 \, pm/v$ slightly above $5 \, THz$. From equation (3.1.1) and (3.2.1) it can be seen that, theoretically, with $r_{41} = 0$ no signal is generated, therefore, in the case of ZnTe, $5 \, THz$ marks the detection limit imposed by the electro-optical coefficient, which makes ZnTe unsuited for a broadband detection as it is required for the THz pulses at FLASH1. In the case of GaP $r_{41}$ equals 0 at around $7.5 \, THz$ and therefore significantly before the phonon resonance at $10.98 \, THz$, effectively limiting the detection range. The frequency dependent $r_{41}$ describes only the interaction of the electro-optical crystal with the

<table>
<thead>
<tr>
<th>parameter</th>
<th>ZnTe</th>
<th>GaP</th>
<th>unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>$d_e$</td>
<td>$4.25 \times 10^{-12}$</td>
<td>$1 \times 10^{-12}$</td>
<td>$m/v$</td>
</tr>
<tr>
<td>$C$</td>
<td>$-0.07$</td>
<td>$-0.53$</td>
<td></td>
</tr>
<tr>
<td>$f_0$</td>
<td>$5.3$</td>
<td>$10.98$</td>
<td>$THz$</td>
</tr>
<tr>
<td>$\Gamma_0$</td>
<td>$0.09$</td>
<td>$0.02$</td>
<td>$THz$</td>
</tr>
</tbody>
</table>
Figure 3.12: Comparison of electro-optical coefficient $r_{41}$ in $\text{pm/V}$ for ZnTe and GaP for the THz frequency range of 1 to 200 THz. The transverse optical phonon resonances at around 5 and 11 THz can be seen.

THz pulse throughout the spectral range. In order to achieve a conclusive description of the interaction during electro-optical sampling, the probe laser pulse needs to be considered as well. This can be done by introducing the so called response function $G(\lambda_p, \lambda_{THz}, d_{EOC})$ in dependence of the central probe wavelength $\lambda_p$, the central THz wavelength $\lambda_{THz}$ and the thickness of the electro-optical crystal $d_{EOC}$ [108]. The response function is defined as

$$G(\lambda_p, \lambda_{THz}, d_{EOC}) = \frac{2}{1 + \sqrt{\varepsilon(\lambda_{THz})}} \times \frac{1}{d_{EOC}} \times \int_0^{d_{EOC}} \text{Exp} \left( i2\pi \left( \frac{c}{\lambda_{THz}} \times x \times \left( \frac{1}{v_{ph}(\lambda_{THz})} - \frac{1}{v_g(\lambda_p)} \right) \right) dx, \tag{3.2.3}\right)$$

where $\varepsilon(\lambda_{THz})$ represents the complex dielectric function, $v_{ph}(\lambda_{THz})$ represents the phase velocity of the THz radiation and $v_g(\lambda_p)$ represents the group velocity of the probe laser pulse. In the work of Steffen [108] the dependence of the response function on $\lambda_p$ is hidden inside the group velocity. The possibility to change the probe laser wavelength using the OPCPA, makes the group velocity an interesting parameter to optimize the crystal response within certain limits\textsuperscript{12}. The complex dielectric function is defined as

$$\varepsilon(\lambda_{THz}) = \varepsilon_{el} + \left( \frac{S_0 f_0^2}{f_0^2 - (\omega/\lambda_{THz})^2 - i\Gamma_0/\lambda_{THz}} \right), \tag{3.2.4}\right)$$

where $\varepsilon_{el}$ represents electronic contribution, $S_0$ represents the oscillatory strength, $f_0$ represents the frequency and $\Gamma_0$ represents the damping constant of the transverse optical phonon mode. The second term in equation (3.2.4) represents therefore the lattice oscillation component [108]. The last two terms inside the integral in equation 3.2.3 represent the walk off between the electric field of the THz and the intensity envelope of the probe laser pulse and

\textsuperscript{12}Imposed by the OPA tuning range and the dielectric mirrors used.
give therefore a measure of the interaction length between a specific part of the electric field of the THz, represented by a phase and an amplitude and the total laser pulse. The group velocity can be calculated using

\[
v_g(\lambda_p) = \frac{c}{n(\lambda_p)} \left( 1 + \frac{\lambda_p}{n(\lambda_p)} \frac{dn}{d\lambda_p} \right),
\]

(3.2.5)

where \(n(\lambda_p)\) represents the refractive index of the electro-optical crystal at the probe laser wavelength. The refractive index can be estimated using the Sellmeier equation in the form of

\[
n_{o,e}(\lambda_p) = \sqrt{A_{o,e} + \frac{B_{o,e}}{1 - (C_{o,e}/\lambda_p^2)} + \frac{D_{o,e}}{1 - (E_{o,e}/\lambda_p^2)}}
\]

(3.2.6), where \(A_{o,e}-E_{o,e}\) represent the fitting parameters, \(n_{o,e}(\lambda_p)\) represents the ordinary and extraordinary refractive index and \(\lambda_p\) represents the probe wavelength at which the refractive index is calculated [123]. The resulting coefficients for GaP are \(A_{o,e} = 4.1705, B_{o,e} = 4.9113, C_{o,e} = 0.1174, D_{o,e} = 1.9928\) and \(E_{o,e} = 756.46\). The data taken by Madarasz et al. to fit the sellmeier coefficients for GaP are ranging from 0.2 to 22 \(\mu m\), which is not spanning the entire range of the THz radiation provided by Flash1\textsuperscript{13}. The sellmeier equations can also be given in a form with less parameters as seen in the work of Steffen [108] resulting in refractive index formula for ZnTe in the form of [124]

\[
n(\lambda_p) = \sqrt{4.27 + \frac{3.01\lambda_p^2}{\lambda_p^2 - 0.142}}.
\]

(3.2.7)

The data used by Marple et al. in order to fit the sellmeier equations are scattered in the range of 0.58 to 2.5 \(\mu m\), which is an even smaller range than used in the work of Madarasz for GaP. On the good side, both works cover the wavelength range of the probe laser beam and can be used to calculate the group velocity following equation (3.2.5). Coming back to equation (3.2.3) the only parameter needed to calculate the response function is the group velocity of the THz radiation \(v_{ph}(\lambda_{THz})\). The phase velocity is calculated as

\[
v_{ph}(\lambda_{THz}) = \frac{c}{n(\lambda_{THz})},
\]

(3.2.8)

where \(n(\lambda_{THz})\) represents the refractive index of the electro-optical crystal at the THz wavelength. As mentioned before the sellmeier equations are insufficient to characterize the refractive index of GaP and ZnTe in the low frequency regime. Following the work of

\footnote{Precise data for the refractive index in the long wavelength range are difficult to acquire as sources and detectors remain challenging.}
Leitenstorfer and Steffen the complex index of refraction can be expressed as [117]

\[ n(\lambda_{THz}) = \sqrt{1 + \frac{f_{LO}^2 - f_0^2}{f_0^2 - \left(c/\lambda_{THz}\right)^2 - i\Gamma_0\left(c/\lambda_{THz}\right)}} \times \epsilon_{el}. \]  

(3.2.9)

\( f_{LO} \) represents the frequency of the first longitudinal optical phonon mode and is given as 12.12 \( THz \) [115] for GaP and 6.18 \( THz \) for ZnTe [125], while \( f_0 \) represents the transverse optical phonon mode given above. With the refractive index of the THz radiation being defined, the response function of GaP over the range of 750 to 850 \( nm \) can be calculated. Figure 3.13 shows the response function of GaP over the wavelength range of 30 to 300 \( um \) for an optical probe wavelength of 750, 800, 850 \( nm \), which can easily be reached by the OPCPA and transported by the dielectric mirrors used and 1030 \( nm \) as the wavelength provided by the tangerine fiber laser system in subfigure 3.13 a,b,c,d respectively. Each figure shows the response functions for the crystal thicknesses of 100, 200, 300 and 400 \( um \) in red, green, yellow and blue, respectively. There are two general tendencies visible. First, within each subfigure it can be seen that a smaller crystal thickness results in a broader wavelength range in which the response function is non-zero, resulting in a broader detection bandwidth. Second, throughout the subfigures it can be seen that an increase in the probe wavelength has a similar effect. Both tendencies are directly linked to the difference in group and phase velocity and the resulting walk-off between the THz field and the probe laser electric field envelope. Subfigure 3.13d shows the highest response function value over the complete wavelength range for all crystal thicknesses. Unfortunately the tangerine fiber laser system provides pulses with \( \approx 320 \) fs pulse duration and is therefore unfit to measure high frequency components. In order to achieve broadband detection capability a combination of crystal thickness and probe laser wavelength needs to be used that shows a response function larger 0 over the whole detection range. Subfigure 3.13c shows a response function larger 0 for a crystal thickness of 100 and 200 \( um \) with a probe laser wavelength of 850 \( nm \) and will therefore be used for further evaluation of the electro-optical response. Equation (3.2.2) and figure 3.12 show that the electro-optic coefficient \( r_{41} \) is frequency dependent. Following the notation of Steffen an effective response function \( G_{eff} \) can be introduced combining the frequency dependent \( r_{41} \) and the previously calculated response function. This allows a more accurate estimation of the detection bandwidth. The effective response function is defined as

\[ G_{eff} = G \times r_{41}. \]  

(3.2.10)
Figure 3.13: Comparison of electro-optical response function for GaP for different crystal thicknesses and different probe laser wavelengths. The color coding for the crystal thicknesses is equal for all subfigures.
Figure 3.14 shows the effective response function for GaP for a probe laser wavelength of 850 nm over the wavelength range of 40 to 300 um. The effective response function shows a smooth fall off towards the phonon resonance at 27.3 um for 100 and 200 um crystal thickness. The final electro-optical response that is produced depends on the crystal thickness.

![Graph showing effective response function](image_url)

Figure 3.14: The effective response function of GaP for an optical probe laser wavelength of 850 nm for different crystal thicknesses.

Equation (3.2.3) shows this dependence with respect to the walk-off between the THz and the probe laser inside the crystal. Multiplying the effective response function with the crystal thickness allows to estimate the thickness dependent maximum response over the wavelength range of interest. The so called scaled effective response function is therefore defined as

\[
SG_{eff} = G_{eff} \times d_{EOC}.
\]  

Figure 3.15 shows the scaled effective response function for GaP for the probe laser wavelength of 850 nm. It can be seen that in the long wavelength region crystals with increasing thickness excel in signal intensity. In the short wavelength range a 100 um thick crystal is superior. A 100 um thick crystal shows in addition a very flat response over the whole wavelength range, which is beneficial for the broadband detection. It can be argued that retrieved traces can be corrected with the calculated response functions, but crystals differ in quality and corrections around \(SG_{eff} = 0\) positions lead to artifacts in the retrieved spectra. Based on the frequency dependent electro-optical response function shown in figure 3.12 and the
Figure 3.15: The scaled effective crystal response function for an optical probe laser wavelength of 850 nm in the range of 40 to 300 um for different crystal thicknesses.
scaled effective response function shown in figure 3.15 the THz pulse characterization tool is equipped with a 100 \text{um} thick GaP crystal, offering a broad detection range up to about 40 \text{um} or 7.5 \text{THz} and a flat response.

### 3.2.2.5 Reflections

Gallium Phosphide has as refractive index of about 3.36 in the long wavelength range [126] and about 3.16 in the optical range [127], which lead to reflections at the entrance and at the exit of the crystal, for both probe laser and THz pulse. For the case of normal incidence the reflectance can be calculated using the Fresnel formula

\[ R = \left( \frac{n_1 - n_2}{n_1 + n_2} \right)^2, \quad (3.2.12) \]

where \( n_{1,2} \) represent the the refractive indices of the media that forming the interface. With the refractive index in vacuum equal to 1 the reflections at each interface are about 30\%. This results in approximately 10\% of the initial THz pulse intensity inside the interaction region, being sampled by the probe laser beam again after a double reflection. When considering the optimal crystal thickness of 100 \text{um} the time difference between the original and the reflected THz pulse is approximately 3.3 ps. The total length and therefore the pulse duration of the THz pulse, created by the THz undulator, depends on the generated wavelength. Due to the constructive interference condition, the electron package has to travel the distance of one wavelength further than the light created, for each undulator period[82]. The resulting pulse length can therefore be calculated by the number of radiating periods \( N_{RP} \) times the wavelength \( \lambda_{THz} \), which in turn allows to calculate the pulse duration. In order to be able to measure the undistorted electric field trace the pulse duration must therefore be shorter than the round trip time of the reflection. With a 100 \text{um} thick GaP crystal the wavelength limit is about 100 \text{um}. In order to delay the reflection it is possible to optically bind the 100 \text{um} electro-optically active GaP crystal to a several \text{mm} thick electro-optically inactive GaP crystal\(^\text{14}\). The THz pulse characterization tool employs a 100 \text{um} thick electro-optically active GaP crystal optically bound to a 3 \text{mm} optically inactive GaP crystal. This shifts the first THz reflection by approximately 70 ps. Figure 3.16 shows a jitter corrected electro-optical sampling trace, measured using a combined crystal, showing the electric field produced by the THz undulator at 150 \text{um} using a 50 \text{um} low-pass filter. The remaining reflections with a spacing of about 10 ps originate from the Si-beamsplitter, with a thickness of 380 \text{um}, used to split the THz pulse and direct part of it into the spectral decoding.

\(^{14}\text{<100> cut}\)
branch of the THz pulse characterization tool. The beam splitter is upgraded to a larger aperture, featuring 4 inch clear aperture and a thickness of 525 um separating the reflections to about 17 ps. This allows to measure 10 cycle undulator radiation with more than 500 um and therefore covers the undulator working range. Assuming a delay scan starting with the signal and including the delay range up to the first reflection a frequency resolution of \( \frac{1}{17 \text{ps}} \approx 0.05 \text{THz} \) is reached. Using this configuration allows to detect the electric field trace without the interference cause by reflections inside the electro-optical crystal. The remaining reflections are separated by around 4 ps with a fundamental THz wavelength of 150 um and do not alter the recorded trace.

### 3.2.2.6 Detection scheme

With all the boundary conditions in mind the sequential electro-optical detection system is set up. The sequential electro-optical sampling employs the balanced detection scheme described in section 3.2.1 following equation (3.2.1). Figure 3.18 shows a detailed scheme of the experimental realization of the sequential electro-optical detection. The amplified probe laser beam from the OPA enters from the right and is depicted in dark blue. After entering the setup the OPA gets split into two parts\(^{15}\) and deflected into the chirped mirror pair.

\(^{15}\)Second part not depicted in this figure.
After a total of 18 reflections the pulse is negatively chirped and further directed onto the delay stage depicted in brown. It is used to vary the delay between the probe laser pulse and the THz pulse produced by the THz undulator. The total delay achievable is about 666 ps with a smallest reproducible step of 1 um or $\approx 6.7 \text{ fs}$. After the delay stage, the OPA beam is passing through several optical grade BK7 windows for re-compression. The following 4 mirror pair is necessary for path adjustment with respect to the second part of the setup, which is not depicted in this figure. The OPA beam is than passing through a half wave plate and a polarizer in order to adjust the polarization direction for the EO-process and to adjust the intensity on the final photo diodes. Consecutively the beam enters the vacuum chamber, depicted in gray, through a optical grade vacuum window and gets focused and compressed to the final pulse duration of $\approx 21 \text{ fs}$. The OPA beam gets focused through a hole in the off axis parabola co-linear with the parabola focus into the electro-optical crystal. There it is overlapped with the THz radiation entering from the left, depicted in red. The THz radiation is transported in vacuum with gold coated mirrors and focused with the off axis parabola into the electro-optical crystal. The OPA beam travels through the electro-optical crystal and through a second optical grade vacuum window back into air, where it is recollimated. The OPA transport after the electro-optical crystal is done using silver mirrors instead of dielectric mirrors, as the reflectivity of silver mirrors is practically equal for s- and p- polarization [128] and therefore does not modulate the ratio between the different polarization components. The OPA beam passes through a half and quarter wave plate and finally a wollaston prism that are used for the balanced detection as described in section 3.2.1. Each of the polarization components are than loosely focused onto an individual photo diode. The loose focusing avoids highly excited regions, or hot spots, on the photo diode, that would introduce distortions in the signal due to local depletion of free carriers [129], while reducing the remaining beam position jitter on the photo diodes.

The photo diode signals are passed to a 16 bit $\mu$TCA analog digital converter\textsuperscript{16} (ADC) from STRUCK INNOVATIVE SYSTEME that allows to record the signals with a dynamic range of up to 90 dB. The maximum dynamic range of the ADC is about 98 dB and is reduced due to the positive nature of the signal, leading to an effective range of 15 bit. The ADC samples with up to 125 MS/s and can therefore be used record pulses with the full FLASH repetition rate of 1 MHz\textsuperscript{17}. In order to balance laser intensity on both photo diodes, or more precisely the photo diode signals, both signals are baseline corrected and integrated. This allows an online measure for the photo diode signal in each channel. By subtracting

\textsuperscript{16}SIS8300 MTCA

\textsuperscript{17}If sufficiently fast photo diode is used.
Figure 3.18: A detailed schematic of experimental realization of the sequential electro-optical detection. With the OPA beam entering from the right (dark blue) and the THz radiation entering from the left (red). After compression and polarization cleaning the OPA beam is overlapped in vacuum with the THz radiation inside the co-crystal. The modulated OPA beam is than analyzed using balanced detection in air.
the individual signals one achieves a very sensitive indicator for the balancing. As the signals are integrated over several 100 points small misbalance lead to a large difference signal. By applying micrometer screw driven rotation mounts a high degree of balancing can be achieved. In order to estimate the limits of the detection scheme a correlation measurement between the two individual photo diodes can be performed. In order to do so, the probe laser is send through the sequential electro-optical detection system without the influence of the THz radiation. Several thousand samples are collected, integrated over the signal and plotted. Figure 3.17 shows the integrated values of channel 1 as a function of the corresponding values of channel 2. The correlation plot shows a linear behavior and the linear fit shows an coefficient of determination or $R^2$ value of 0.99958\(^{18}\) [130]. It can therefore be concluded that both individual photo diodes react equal to incoming probe laser pulses of equal intensity.

![Figure 3.17](image)

Figure 3.17: The correlation plot of the photo diode signals from the sequential electro-optical sampling setup. The correlation shows a linear behavior, which can be verified by the linear fit and the resulting $R^2$ factor of 0.99958.

\(^{18}\)Representing that 99.958% of the data can be described by the same linear function.
detection system needs to be evaluated. In order to do so, the acquired signals of channel 1 and 2 are subtracted and normalized to the input laser intensity. In a final step the mean value of the data set is subtracted from each data point in order to baseline correct the resulting data, evaluating $\sin(\Gamma)$ without the presence of THz radiation. The result is plotted in figure 3.19. The standard deviation (SDD) of the resulting data is $\sigma = 6.40899 \times 10^{-4}$ or approximately 0.064%. Ultimately this puts the minimum discernible signal height to $6\sigma = 0.00384$ or 0.38%. This can be understood as the intrinsic noise of the measurement follows a normal distribution. Evaluating the $6\sigma$ level is of importance as 99.73% of the data point are within this range. Data points that are outside of this range can therefore be discerned as signal with statistical significance. This is important, as the experiments presented in chapter 4 aim for small changes in the reflected THz pulse.

![SDD = 6.40899 E-4](image)

Figure 3.19: The normalized difference signal ($\sin(\Gamma)$) of the sequential electro-optical detection without the influence of THz radiation. The standard deviation of the remaining noise is $\sigma = 6.4 \times 10^{-4}$ or 0.064%.
3.2.2.7 Results

The sequential electro-optical detection is set up and ready to characterize THz pulses. Figure 3.20 shows the measured difference signal for a resonant undulator wavelength of $2THz$ measured through a $2THz$ bandpass filter with approximately 15% bandwidth. The curve is plotted as the THz signal as a function of delay, where 0 delay equals the beginning of the delay stage. With a delay step of 20 $nm$ and 900 samples per delay point the corresponding graph consists out of more than 260000 data points. This allows to reduce the THz intensity fluctuation related noise. It can be seen that the structure of the THz field can not be resolved with a high resolution. Only an envelope and the indication of a period of the THz pulse can be seen. In general the resolution is poor. Binning the raw data shown in figure 3.20 allows a better look at the electric field trace and can be seen in the upper part of figure 3.21. The trace is binned with a 66 $fs$ step size equal to the delay steps of the scan. After centering the trace a blackman-nuttall window is applied in order to remove artifacts in the normalized amplitude spectrum shown in the lower half of figure 3.21. The electric field trace shows several oscillations with a period of about 500 $fs$.
corresponding to the resonant wavelength of the undulator at 150 \( \mu m \). Due to the spectral narrowing of the bandpass filter more than the expected 10 periods of electric field can be seen. The amplitude spectrum shows the undulator fundamental at approximately 2 THz. Further spectral components, for example at 1 THz or at 5.9 THz can not clearly identified, as the noise level is about \( 4 \times 10^{-2} \), which is much larger than the noise created by the detection system itself\(^{19}\). This spectral resolution is therefore poor and insufficient for the characterization of the THz pulses and especially for the experiments described in chapter 4. With the noise generated from the detection system being 2 orders of magnitude below

![Binned THz signal trace](image)

**Figure 3.21:** **Upper:** The binned THz signal trace of the THz undulator tuned to 2 THz measured through a 2 \( BP \) filter. A blackman-huttall window is applied to the trace in order to remove artifact from the amplitude spectrum. **Lower:** The amplitude spectrum of the THz signal trace shown above. The undulator fundamental of 2 THz can be seen. Additional frequency components can not be identified without doubt due to the high noise level.

\(^{19}\sigma = 6.4 \times 10^{-4}\)

the noise baseline in the frequency domain the major contribution has to be found at a different position. The lack of resolution of individual electric field cycles in figure 3.20 can originate from two different phenomena. Either the electric field inside the THz pulse is not phase stable and a multi-shot measurement is impossible, or the arrival time of the probe laser pulse and the THz pulse is showing a high uncertainty. Previous work addressed the
topic of laser-FEL timing jitter [94] and found it in the order of several 100 fs peak to peak. Additionally with earlier work being able to resolve the electric field of a band pass filtered THz pulse by streaking [14] it can be excluded that the electric field inside the THz pulse has a different phase from pulse to pulse. Hence the lack of resolution can be accounted to the large arrival time uncertainty between the probe laser beam and the THz pulse.

3.2.2.8 Linearity evaluation

Even though the resolution of the individual electric field cycles is insufficient to precisely characterize the THz field shape and frequency composition, the recorded data allow to evaluate the effect of the high electric field of the THz pulses on the recorded signal. As mentioned in section 3.2.1 the difference of the recorded signals $I_{vert}$ and $I_{hor}$ represents the sine of the retardation $\Gamma$ multiplied with the laser pulse intensity $I_0$. Recording the individual signals $I_{vert}$ and $I_{hor}$ gives direct access to $I_0$ and allows to evaluate the amount of retardation achieved. Figure 3.22 shows the $I_0$ corrected THz signal $\sin(\Gamma)$ with $\Gamma$ as the retardation.

---

A scanning technique utilizing the natural synchronization between the THz and the XUV radiation from FLASH1.
Figure 3.22: The laser input intensity corrected THz signal measured through a $2\,THz$ band pass filter with the undulator tuned to $2\,THz$. The maximum recorded signal is about 0.067, resulting in a retardation $\Gamma = 0.06705$.

The THz undulator is tuned to $2\,THz$ and a $2\,THz$ band pass filter is used. The maximum THz signal $\sin(\Gamma)$ is 0.067 resulting in a retardation $\Gamma$ of 0.06705. The difference between both signals, representing the nonlinearity of the measurement, is therefore 0.00005 or 0.075 % of the signal. It can be concluded that the measurements utilizing electro-optical sampling are always nonlinear. The degree of nonlinearity on the other hand is very small for the presented system. The presented data are recorded with a THz pulse energy of approximately 5 $uJ$ at 150 $um$ measured through a 88 $um$ low pass filter. In this case the recorded signals are far from over-rotation\(^{21}\), allowing to measure pulses with much higher electric field strength. The 100 $um$ thick Gallium Phosphide crystal, used in the THz pulse characterization tool, allows therefore to measure THz pulses with high electric fields with a small amount of nonlinearity, that is corrected for further analysis. For pulse energies much larger than in the presented case the nonlinearity is monitored to prevent falsification of the results by over rotation.

\(^{21}\)Gamma > $\pi/2$
3.3 Single shot spectral decoding

In order to improve the resolution of the sequential electro-optical detection system, the arrival time uncertainty between the THz pulse, produced by the FEL, and the probe laser, needs to be eliminated. In order to do so, the relative arrival time of the THz radiation with respect to the probe laser needs to be measured, to allow the correction of the sequential electro-optical sampling data. Within this section, the single shot arrival time correction system, working with up to 200 kHz repetition rate, and its influence on the retrieved electric field traces will be presented.

3.3.1 Principles of single shot spectral decoding

The basic process in single shot spectral decoding is equal to sequential electro-optical sampling, described in sec 3.2.1 and is used in previous work [131, 132, 108]. An externally applied electric field induces and modulates birefringence of an electro-optically active crystal. When overlapping the externally applied field in space and time with an additional optical laser pulse, the induced birefringence induces a modulation in the laser polarization that can be analyzed and used to characterize the externally applied field, here the THz pulse. The main difference to sequential electro-optical sampling can be seen in figure 3.23. Before overlapping the THz radiation with the probe laser pulse, the probe laser pulse is linearly stretched in time, creating a direct mapping of time to frequency. The THz radiation and the linearly polarized stretched probe laser pulse are overlapped in space and time in a electro-optically active crystal, resulting in frequency dependent polarization modulation. Using a polarization analyzer, allows to transfer the frequency dependent polarization modulation into a frequency dependent intensity modulation. Using a dispersive element, like a grating, allows to transfer the time information, encoded in the frequency, into space, which can be detected with, for example, a CCD-chip.
Figure 3.23: The schematic of the spectral decoding principles. The probe laser pulse is stretched linearly to several picoseconds, creating a time to frequency mapping, before being overlapped with the THz radiation in an electro-optical crystal. This results in a frequency dependent polarization modulation that can be transferred to an intensity modulation using a polarization analyzer. In a final step the frequency dependent intensity modulation is transferred to a position dependent intensity modulation using a dispersive element like a grating. With the linear stretching and the grating analyzer, a time to space mapping is achieved.

A changing arrival time of the THz radiation with respect to the probe laser will hence lead to shift of the intensity modulation on the CCD, allowing to characterize and correct arrival time uncertainties.

3.3.2 Experimental realization

In order for the single shot spectral decoding to provide reliable arrival time information the individual steps of mapping time to frequency, arrival time information encoding, mapping frequency to space and analyzing the space to time relation need to be well-matched. Within the following sections the individual steps in order to achieve an arrival time resolution suited to measure $7.5 \times THz^{22}$ are presented.

3.3.2.1 Mapping time to frequency - laser pulse stretching

The stretching of the probe laser beam allows to create the mapping of time to frequency. In order to be able to track the arrival time uncertainty the time window created must be

\[^{22}\text{Arrival time accuracy better than 60 fs.}\]
larger than the single shot jitter between the THz radiation and the probe laser beam. At the same time, the detector, described in section 3.3.2.3 and 3.3.2.4 imposes limits to the time resolution for very long probe laser pulses. Additionally, a slow long term drift can occur during long lasting sequential measurements. To allow the unambiguous tracing of slow drifts, it is necessary to have a time window even larger than these drift. In reality this is only partially possible as drift times are varying strongly and range from picoseconds per 12 hour shift to picosecond per few minutes\(^ {23}\). With the detector based limit on time resolution, explained in the following section, 5 – 6 ps is found to be a good compromise to achieve a high time resolution and cover a reasonably large drift range unambiguously. In order to be able to easily retrieve the arrival time information a linear mapping is beneficial. Creating a linear chirp\(^ {24}\) over the pulse is possible if the change of refractive index over the bandwidth of the pulse \(dn/d\lambda\) is constant. In reality this is not achieved and higher order dispersion effects need to be taken into account. A common approach to the dispersion introduced by a material is based on the group velocity dispersion \(GVD\), which is defined as

\[
GVD(\omega) = \frac{2}{c} \left( \frac{dn}{d\omega} \right) + \frac{\omega}{c} \left( \frac{d^2n}{d\omega^2} \right). \tag{3.3.1}
\]

The group velocity dispersion takes first and second order effects into account. In order to achieve a large linear chirp over the pulse, the contribution of the first parameter needs to be much larger than the contribution of the second parameter. A large contribution of the second order effect will limit the linear range and therefore the usable time window to trace slow drifts\(^ {25}\). The total induced time delay \(\Delta t\) between two different frequency components \(f_1, f_2\) of the laser pulse can be described by

\[
\Delta t = d_{\text{disp}} \times GVD(f_c) \times (f_1 - f_2), \tag{3.3.2}
\]

where \(d_{\text{disp}}\) represents the thickness of the dispersive material and \(f_c\) represents the central frequency of the laser pulse. Equation (3.3.2) shows that the GVD needs to be sufficiently high in order to keep the the amount of dispersive material small. This can be achieved with several materials like Zinc Selenide and high density flint glass \(SF - 57\). Both material show a linear dispersion for the wavelength range of interest, namely 825 to 875 nm and a high group velocity dispersion of 199.44 and 923.71 fs\(^2/\)mm for \(SF - 57\) and ZnSe respectively \([124, 133]\). ZnSe is advantageous as its GVD is about 5 times higher than for \(SF - 57\), which

\(^{23}\)The later happening rarely.

\(^{24}\)\(df/dT = \text{const.}\)

\(^{25}\)The full time window can be used when careful correction of the nonlinearity is applied to the arrival time data. This adds additional difficulty, which is the reason to aim for a linear dispersion.
results in about 30 mm of material in order to stretch the probe laser beam to more than 5 ps. Figure 3.24 shows the measure auto-correlation in blue with the Gaussian fit in red. The retrieved de-convoluted FWHM pulse duration is $4.9 \pm 0.1$ ps$^{26}$ The linearity of the induced chirp can be checked by performing a spectral decoding measurement. The stretched probe laser pulse and the THz radiation are overlapped in an electro-optical crystal in space and time. A defined delay is than induced in the probe laser beam path, effectively shifting the THz induced intensity modulations on the detector by a certain amount of pixels. Repeating this process and tracing one feature through the complete spectrum of the probe laser pulse on the detector allows to verify the linearity of the chirp, as displayed in figure 3.25. The induced shift in pixel on the detector is plotted as a function of the delay stage position. The delay step between each measurement point is 20 um and 300 single shot measurements are taken and averaged at each point in order to compensate for the arrival time jitter. The data shows a linear behavior and can be fitted with a linear fit model resulting in an $R^2$ value of 0.99703$^{27}$. The disadvantages in using ZnSe are that it is poisonous and not

![Figure 3.24: The auto-correlation and the Gaussian fit of the OPA probe pulse stretched using 30 mm of ZnSe. A de-convoluted FWHM pulse duration of about 4.9 ± 0.1 ps is reached.](image)

$^{26}$The given error represents exclusively the error due to the Gaussian fit.

$^{27}$The influence of the linearity is discussed in subsection 3.3.2.4.
Figure 3.25: The linearity plot of the chirp on the probe laser pulse induced by 30 mm ZnSe. The average pixel shift on the detector is plotted as a function of the delay stage position. The pixel shift shows a linear dependence on the delay stage position and can be fitted using a linear fit function yielding an $R^2$ value of 0.99703 indicating a high degree in linearity as the presented data can be described to 99.7 % with a linear function.
to 6\,ps a total of about 30\,mm of ZnSe is required. With the usage of 6 individual ZnSe windows the amount of interfaces increases and with it the total reflection loss. With the refractive index of \approx 2.5 at 850\,nm \cite{134} the total transmitted intensity after 12 interfaces can be calculated to be around 9\%. Although sufficient for the pilot experiment, a higher transmission is beneficial with respect to future upgrades. SF−57, a high density flint glass, offers a non-toxic alternative to ZnSe that allows for a higher transmission. Unfortunately its GVD is only 199.44\,fs²/mm and therefore approximately 5 times smaller than in the case of ZnSe. Because of this the thickness of the dispersive material needs to be 5 times higher to reach an equivalent pulse stretching comparing to the case of ZnSe. SF−57 is available in large blocks of good optical quality, which allows to use a single piece and reduce the amount of interfaces to 2, yielding an increase in transmission to about 84\%. Figure 3.26 shows the auto-correlation of the OPA probe laser pulse stretched with 150\,mm of SF−57. The Gaussian fit results in a FWHM pulse duration of about 5.2 ± 0.1\,ps and is therefore slightly longer than the pulse duration achieved using ZnSe. Figure 3.27 shows the linearity plot for the SF−57 stretching. The data is plotted as the shift of the THz induced feature on the spectrum of the laser represented as a pixel position on the detector as a function of the delay stage position. The data shows a linear behavior and can be fitted using a linear fit function, resulting in an \( R^2 \) value of 0.99954 indicating a linear dependence of the shift as a function of the induced delay. Comparing figure 3.25 and 3.27 it can be seen that there

Figure 3.26: The auto-correlation and Gaussian fit of the OPA probe pulse stretched with 150\,mm SF−57. The resulting de-convoluted FWHM pulse duration is 5.2 ± 0.1\,ps.
Figure 3.27: The linearity plot for the OPA pulse stretching using 150 mm SF – 57. The shift of the THz induced feature on the spectrum of the probe laser is traced and plotted as the shift on the detector in pixel as a function of the delay stage position. The average pixel shift shows a linear dependence on the stage position and the linear fit yields an $R^2$ value of 0.99954.
is a difference in the degree of linear dependency of the average pixel shift to the induced
delay, which is directly represented by the $R^2$ parameter. While both plots show a linear
dependence the $R^2_{SF-57}$ is higher, indicating a better fit of the linear fit model to the data
and, in return, a higher linear dependence. Combined with the higher transmission and the
non-toxicity, $SF - 57$ allows for an adequate pulse stretching with a linear chirp.

3.3.2.2 Arrival time information encoding - electro-optical crystals

The encoding of the arrival time information is happening inside the electro-optical crystal,
where the electric field of the THz radiation is inducing and modulating birefringence. Given
spacial and temporal overlap, the electric field shape of the THz radiation is imprinted onto
the stretched probe laser pulse as a frequency dependent polarization modulation. In order
for this process to be possible with only a fraction of the THz power incoming into the THz
pulse characterization tool the electro-optical crystal has to be chosen carefully\textsuperscript{28}. The goal
of the single shot electro-optical spectral decoding EOSD is to characterize the arrival time
between the THz and the probe laser pulse for each shot with a high accuracy. This task does
not require a high detection bandwidth, which allows to use an electro-optical crystal with
a higher electro-optical coefficient, $r_{41}$, on the expense of broadband detection. In section
3.2.2.4 the electro-optically active crystals Gallium Phosphide GaP and Zinc Telluride ZnTe
are introduced. Figure 3.12 shows that the $r_{41}$ of ZnTe is about 10 times higher than
for GaP for the frequency range between 0 and 5 THz. Following equation (3.1.1) and
(3.2.1) it can be seen that magnitude of the electro-optical signal is linearly dependent on
$r_{41}$. As an equal measurement principle\textsuperscript{29} is used here a linear dependence of the electro-
optical signal with respect to the THz field can be assumed. Therefore in order to create a
photon efficient detection system for low frequency THz radiation, ZnTe is superior to GaP.
Analogue to GaP, presented in the Electro-optical crystals section 3.2.2.4, the response
function $G$, effective response function $G_{eff}$ and scaled effective response function $SG_{eff}$
can be calculated for ZnTe following equations (3.2.3), (3.2.10) and (3.2.11)\textsuperscript{30}. Figure 3.28
shows the response function, the effective response function and the scaled effective response
function for ZnTe for a probe laser wavelength of 850 nm plotted over the wavelength range
of 70 to 300 um. Each subplot features 3 different crystal thicknesses ranging from 300 um
to 1 mm. The response function and the effective response function show a similar shape
due to the flat $r_{41}$ of ZnTe in the long wavelength range. The $G = 0$ position, marking the

\textsuperscript{28}see Chapter 4 for further information.
\textsuperscript{29}Quasi-balanced detection, analyzing only one branch of the polarization.
\textsuperscript{30}Detailed information can be found in section 3.2.2.4 and are omitted here.
Figure 3.28: Analytic description of the interaction of the probe laser pulse and the THz radiation for the wavelength range of 70 to 300 um inside ZnTe crystals of different thickness, ranging from 300 um to 1 mm. The response function and the effective response function show a similar behavior due to the flat $r_{41}$ in the long wavelength regime. The scaled effective response function shows that 1 mm ZnTe is most effective to detect THz wavelength longer than 125 um.
detection bandwidth, is shifting with the crystal thickness, where a thinner crystal allows for a higher detection bandwidth. The crystal thickness of 1 mm allows to detect THz radiation from a wavelength of approximately 115 \( \mu m \) on. The scaled effective response function allows to determine the most effective crystal thickness for a particular wavelength. It can be seen that a 1 mm thick ZnTe crystal is most efficient for THz wavelength longer than 125 \( \mu m \). The experimental data indicate that preserving or retrieving the original electric field shape is of little to no importance to retrieve the arrival time between THz and probe laser. This can be understood as the detection is in air and the THz pulse passes through a z-cut quartz window when leaving the vacuum chamber. Both air and window absorb part of the frequency components resulting in a distortion of the electric field of the THz pulse. Nevertheless the arrival time can successfully be retrieved. Therefore also a limited detection bandwidth, resulting in a distortion of the recorded field trace, is sufficient. Hence the single shot spectral decoding system is using a 1 mm thick ZnTe crystal in order to create a THz-photon efficient arrival time information encoding.

### 3.3.2.3 Mapping frequency to space - detection with 200 kHz repetition rate

In order to detect the frequency dependent intensity modulations of the stretched probe laser beam introduced by the THz radiation two components are necessary. First, a dispersive element, like a grating, able to separate the different frequency components of the probe laser beam. Second, a detector, like a CCD chip, able to detect the different probe laser wavelengths. In order to be integrated into the THz pulse characterization tool the detector needs to fulfill the requirements for high repetition rate data acquisition\(^{31}\), as it allows to drastically reduce the total acquisition time. While great progress is made towards detectors working at MHz repetition-rates \([135]\), a more readily available detector is used for the THz pulse characterization tool. A Basler sprint mono spl-2048-70km silicon based line camera is used with a National Instruments PCIe-1433 frame grabber module. The camera is a line camera with two rows of 2048 pixels each. Each pixel has a size of 10 \( \times \) 10 \( \mu m \) and a dynamic range of 12 \textit{bit}. The camera can be operated at a maximum rate of 70 \( kHz \) when using 2048 pixels. Reducing the amount of pixels in use, by setting an area of interest of 512 pixels, and using vertical line binning, allows to increase the repetition rate to 217.391 \( kHz \)\(^{32}\). A repetition rate of approximately 200 \( kHz \) is compatible with the Flash1 repetition rate\(^{33}\) and allows to record data within the Flash1 burst. Utilizing the NI frame

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\(^{31}\)Referring to the repetition rates of the Flash accelerator.

\(^{32}\)Calculated with the Basler frame rate calculator \([136]\).

\(^{33}\)When operated at reduced repetition rate.
grabber the camera acquisition can be triggered with a 200 kHz trigger, that is generated by dividing the 1 MHz trigger from FLASH1, resulting in a synchronized acquisition. The grating used is a ruled grating with 300 grooves/mm and a blaze wavelength of 750 nm mounted in a PRINCETON INSTRUMENTS Sp2300i spectrometer. The spectrometer creates a line focus at its exit and the grating disperses in first order 286 nm optical bandwidth over a spacial extend of 27.6 mm[137]. Therefore the bandwidth of the probe laser pulse of approximately 50 nm is dispersed over a length of 4.82 mm, which fits the active area of the line camera of 512 x 10 um = 5.12 mm. The grating can be rotated using a grating turret inside the spectrometer to make sure the appropriate wavelength is imaged onto the line camera. Additionally it allows to use higher dispersion orders, ultimately increase the time resolution of the measurement, but decreasing photon efficiency and overall observed time window. The camera is mounted on an XYZ-stage to allow precise positioning, of the 20 x 5120 um active chip. In addition a tip-and-tilt stage is mounted in order to compensate for focal depth and focal line tilt errors and thereby allow the access to all degrees of freedom as shown in figure 3.29.

Figure 3.29: An image of the Basler line camera spL-2048-70km with it mount and an indication of the available degrees of freedom for alignment.
3.3.2.4 Mapping space to time - timing calibration

The intensity modulated probe laser pulse is dispersed by the grating and focused onto the line camera, where it is recorded with up to \(200 \, kHz\) repetition rate. A change in arrival time between the probe laser beam and the THz radiation produced by the FEL will result in a spatial shift of the intensity modulation on the line camera. In order to associate this shift in pixel with a arrival time change in femtoseconds a timing calibration needs to be performed. The timing calibration factor can be characterized by performing a spectral decoding measurement. Similar to the linearity measurements, the stretched probe laser pulse and the THz radiation are overlapped and a defined delay is induced in the probe laser beam path. This allows to precisely shift the THz induced intensity modulations on the detector\(^{34}\). Moving the THz induced intensity modulations through the complete laser spectrum on the detector allows to measure the space to time mapping. Some of the presented results in section 3.5 are acquired using ZnSe to stretch the probe laser pulse. Therefore the timing calibration for ZnSe is presented in figure 3.30, additionally to the calibration for \(SF - 57\). The presented graphs are based on the data of figure 3.25 and 3.27 but plotted inversely. The induced delay in \(fs\) is plotted as a function of the position on the detector in pixel. The delay step between each measurement point is 20 \(um\) or \(\approx 133 \, fs\) and 300 single shot measurements are taken and averaged at each point in order to average out the arrival time jitter\(^{35}\). The main interest, the timing calibration factor, can be extracted from the slope of the linear fit. Due to the detector, described in the previous section, the spatial resolution is given by the pixel size of 10 \(um\). The timing calibration is therefore given as \(fs/pxl\). It is \(7.95 \pm 0.16 \, fs/pxl\) and marks the upper limit of time resolution of the single shot jitter correction. Figure 3.31 shows the timing calibration plot for the OPA pulse stretching using 150 \(mm\) \(SF - 57\). The induced delay is plotted as a function of the pixel value. The delay step between each measurement is is 50 \(um\) or \(\approx 333 \, fs\) and 300 single shot measurements are taken and averaged at each point in order to compensate the arrival time jitter. The timing calibration factor is \(8.53 \pm 0.1 \, fs/pxl\). This value is higher comparing to the ZnSe stretching, which is expected as the FWHM pulse duration is larger as well\(^{36}\). The time resolution of the single shot arrival time detection can enhanced, by less probe laser stretching, on the expense of overall observed time window. Due to the fact that high resolution measurement with the THz pulse characterization tool can take up to \(30 - 45 \, minutes\) a large time window needs to be observed in order to be able accommodate

\(^{34}\)Influenced by the short and long term jitter.
\(^{35}\)An example of the individual jitter can be found in figure 3.35
\(^{36}\)See section 3.3.2.1 for further information.
Figure 3.30: The timing calibration plot for the OPA pulse stretching using 30 mm ZnSe. The induced delay in fs is plotted against the shift of the modulations of the spectrum on the detector in pixel. The data show a linear dependence and the linear fit allows to define the timing calibration constant of $7.95 \pm 0.16 \text{fs/pixel}$.

Figure 3.31: The timing calibration plot for the OPA pulse stretching using 150 mm SF-57. The induced delay in fs is plotted against the shift of the modulations of the spectrum on the detector in pixel. The data show a linear dependence and the linear fit allows to define the timing calibration constant of $8.53 \pm 0.1 \text{fs/pixel}$.
long term drifts on a picosecond scale. Looking back at the motivation of the single shot arrival time tool, the high resolution sequential electro-optical sampling, it can be seen that figure 3.8 shows a FWHM pulse duration of the compressed probe laser beam of about 21 fs. A time resolution of approximately 8 fs is therefore sufficient to have little impact on the time resolution of the sequential electro-optical sampling\textsuperscript{37}.

3.3.2.5 Evaluation of single shot jitter data

The single shot spectral decoding system is capable of recording data in a burst mode operation with 200 kHz repetition rate. Therefore it matches an available burst mode pattern of FLASH1 and allows for fast data taking. The created intensity modulations are imprinted on the laser spectrum and its associated spectral intensity background as depicted in figure 3.32. The figure shows 10 consecutive bunch trains with a total of 500 consecutive single shot traces. The THz induced modulations are clearly visible over the complete length of the detector and showing the arrival time shift between the individual pulses. The individual trains of modulated laser pulses are interleaved with non modulated laser pulses. This is

Figure 3.32: 500 consecutive single shot spectral decoding traces showing the imprinted arrival time information by intensity modulations over pixels. 10 consecutive pulse trains of 50 laser pulses and 45 THz pulses are shown. The raw data shows the intra-train arrival time uncertainty as well as the inter-train arrival time jitter.

possible because the Tangerine fiber laser system, used to drive the OPA, is able to provide laser pulse trains with 200 kHz quasi-cw, coupled with a triggered acousto-optic modulator, allowing for arbitrarily long pulse trains. The additional unmodulated laser pulses allow to

\textsuperscript{37}Being independent the individual sources are added as sum of squares.
subtract the laser background for each pulse train individually. Taking a single modulated trace, subtracting the pulse train background and plotting it with the intensity as a function of the pixel value allows to directly visualize the THz related intensity modulations. Figure 3.33 shows a background corrected single shot trace. The THz related intensity modulations can be seen between pixel 150 and 400 and show a high signal to noise ratio of about 30 : 1. The raw data presented in figure 3.32 is processed in a two stage process. First all the THz modulation carrying traces and the background traces are separated. In a second step, the background traces of each bunch train are averaged and used for the background subtraction of each individual trace in the corresponding bunch train. Applying this procedure to the spectral decoding data acquired during a sequential electro-optical sampling scan allows to visualize the single shot arrival time jitter. Figure 3.34a shows approximately 55000 single shot spectral decoding traces as a function of the pixel position, taken in about 2 minutes. The intensity modulation is encoded in the color coding, where blue represents low and red

\[\text{Figure 3.33: Background corrected single shot spectral decoding trace using THz radiation from the electron beam dump. The trace is plotted as the intensity as a function of the pixel position. The THz induced intensity modulations can be seen between pixel 150 and 400.}\]
(a) Background corrected single shot arrival time data. About 55000 individual traces are shown. The arrival time jitter can be seen as a shift of minima and maxima between the individual traces.

(b) Single shot jitter data after cross correlation and circular shifting by the retrieved jitter amount. The alignment of minima and maxima indicated the correct retrieval of the arrival time jitter.

Figure 3.34: Comparison between the sorted and unsorted spectral decoding data. The arrival time jitter between the individual single shot traces is retrieved via cross correlation and used in a correction to visualize the successful retrieval.
Figure 3.35: The retrieved single shot jitter data of 400 consecutive spectral decoding traces plotted in fs.
represents high intensity. In order to retrieve the arrival time information cross correlations between one of the individual single shot traces, defined as zero trace\textsuperscript{39}, and all others are performed. The cross correlation has the advantage that the complete spectrum and all of the THz related features are compared, which results in a much more robust method to determine the shift of the THz signal than a simple peak detection. The shift of each trace with respect to the zero trace than applied in a circular shift routine\textsuperscript{40} in order to visualize the jitter corrected single shot data and allow a visual verification of the successful arrival time retrieval. The jitter corrected single shot spectral decoding traces are presented in figure 3.34b. It can be seen that the circular shift with the retrieved jitter data resulted in an alignment of minima and maxima throughout the complete data set as expected, indicating successful arrival time retrieval. The resulting arrival time jitter is represented as a shift in pixel. This shift is now transferred back into time by the spectral calibration factor, introduced in section 3.3.2.4. Figure 3.35 shows the resulting single shot jitter in fs of 400 consecutive single shot spectral decoding traces. During the presented measurement a FEL bunch train length of 40 bunches is used resulting in a total presented measurement time of 1 second. It can be seen that the intra bunch train jitter, referring to the arrival time shift within a 40 bunches train, as well as the inter bunch train, referring to the arrival time between two consecutive bunchtrains can be very high. With the intra bunch train jitter having a more slope-like character the inter bunch train jitter can be characterized by large jumps as in the case around sample 320. Taking this arrival time uncertainty into account, it can be understood why the resolution of the presented sequential electro-optical sampling data without jitter correction in figure 3.20 is so poor. A peak to peak arrival time jitter of almost 350 fs represents a jump in sampling position of about 100 \textmu m, making the sampling of short wavelength components down to 40 \textmu m or 7.5 THz impossible. But with the possibility of measuring the arrival time on a single shot basis the solution is at hand, combining both, the sequential electro-optical sampling and spectral decoding setup to create the THz Pulse Characterization Tool.

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\textsuperscript{39}The zero trace can be chosen arbitrarily. Large drifts through the measurement might require careful choosing at half the maximum drift in order for the cross correlation to function properly.

\textsuperscript{40}The circular shift routine is shifting all vector elements describing each individual spectrum by a certain amount, while keeping the vector length constant by moving the \(n + x\) element after the shift, \(n\) being the vector length, to the position \(x\) of the vector.
3.4 THz pulse characterization tool

The THz pulse characterization is the combination of the high resolution sequential electro-optical sampling system and the single shot spectral decoding arrival time detection system. The combination of both systems allow the arrival time retrieval down to a few-femtosecond scale and the correction of the acquired high resolution. This requires the splitting of both THz and probe laser pulse, the realization of both co-processes at once and most importantly the accurate correlation of the retrieved data. The probe laser is split before entering the respective subsystems and being treated as described in the previous sections of this chapter. Splitting of the THz radiation pulse is realized in vacuum to allow for an undistorted measurement of the electric field shape in the sequential EOS setup. Figure 3.36 shows a photograph of the THz pulse characterization tool with the vacuum chamber in the background and the optical beam paths around it. Within this section a detailed description of the experimental realization, the data correlation and analysis is given.

![Figure 3.36: A photograph of the THz pulse characterization tool with the vacuum chamber in the back right and the optical beam paths in the foreground.](image)
3.4.1 Combining sequential EOS and single shot spectral decoding

In order to utilize the acquired arrival time information to increase the resolution of the sequential electro-optic sampling setup both systems need to be combined, measuring in parallel. This requires the splitting of both the laser and the THz beam and recombination of both with equal path length, as shown in figure 3.37, in order to achieve overlap in space and time. The splitting of the OPA probe laser beam is achieved by a BK7 glass wedge, where the s-polarized beam yields a reflectivity of approximately 9.4% at each interface. The front reflection is directed into the sequential electro-optical detection system. The sequential electro-optical sampling branch of the system remains unchanged from the description in section 3.2.2.6. An additional detailed description is therefore omitted. The remaining OPA probe laser beam is passing through the glass wedge. The reflection occurring at the back surface of the glass wedge is dumped and the remaining 82% of the probe laser intensity is passing into the single shot spectral decoding setup. The laser beam is consecutively directed over a delay stage, allowing precise path length variations down to 2\,\mu\text{m}, before passing through the SF − 57 glass block for temporal stretching. The stretched probe laser beam is then directed through a half waveplate and a polarizer in order to adjust the polarization and allow attenuation. After this the probe beam is focused through the off-axis parabola into the electro-optical crystal, where it is overlapped in space and time with the THz radiation at the sequential electro-optical sampling position. In order to split the THz a 380\,\mu\text{m} thick high resistivity silicon wafer is introduce into the THz beam path inside the EO-vacuum chamber. High resistivity silicon shows a flat transmission behavior at longer wavelength, indicating the lack of strong phonon modes [138]. The combination with a high refractive index allows silicon to be used as a THz beam splitter, without distortion of the electric field shape. Fabry-Perot interference can be avoided by limiting the utilized delay time in the sequential electro-optical sampling setup to less than the round time of the light within the beam splitter. The THz radiation is than passing a z-cut quartz window into air, where it is focused with an off-axis parabola into the Zinc Telluride crystal. When overlapped in space and time with the stretched probe laser beam, the THz radiation induces a frequency dependent polarization modulation on the probe laser pulse, as described in section 3.3.1. The modulated probe laser pulse is passing first through a half and a quarter waveplate, followed by a wollaston prism analyzing the polarization, similar to the balanced detection scheme of the sequential EOS before being focused into the spectrometer. The probe laser

\footnote{The specific resistance is > 3000\,\text{Ohm}\cdot\text{cm.}}

\footnote{In order to linearize the amount of phase retardation as a function of the electric field.}
Figure 3.37: A detailed schematic of experimental realization of the sequential electro-optical detection in combination with the single shot spectral decoding system. With the OPA beam entering from the right (dark blue) and the THz radiation entering from the left (red). The OPA beam is split before entering the sequential EOS (blue) and the single shot spectral decoding (purple). The OPA beam for the spectral decoding is stretched before being overlapped in with the THz in the co-crystal in air. The modulated beam is then directed into the spectrometer and recorded using a line camera.
beam is then spectrally dispersed by a grating in the spectrometer and detected on the line camera, described in section 3.3.2.3. Both individual setups, the sequential electro-optical detection and the single shot spectral decoding system are operated separately via labview. This originates from the µTCA based ADC used in the sequential EO-sampling. The µTCA architecture allows for high data rates but is not yet supporting all devices, which makes it necessary to use an additional computer to operate the line camera and its frame grabber.\textsuperscript{43}

The main problem arising from two free running systems is the simultaneity of data taking and writing and the subsequent correlation of the single shot arrival time data and the corresponding sequential eos signal. The solution is the bunch ID, a 32 bit number that is assigned to each electron package produced in the FLASH accelerator. A dedicated software solution allows to save the bunch ID with the corresponding data, measured in both systems. Using the bunch ID information in a post-mortem analysis allows to precisely correlate the arrival time information with the electric field data.

\textsuperscript{43}A development for a µTCA based frame grabber is ongoing.
3.4.2 Data analysis

There are a multitude of steps involved in processing the raw data streams from the two individual systems before being able to correlate them and correct the arrival time uncertainty, leading to the high resolution electric field trace and the corresponding normalized amplitude spectrum. Even though the individual steps are mentioned in the corresponding sections, a short overview follows. In the first step the sequential electro-optical sampling data from the µTCA based ADC are integrated. This is done by first correcting the background offset of the individual ADC traces. The ADC is set up in a way the 0 line is at $2^{15}$ counts, as the total range is $2^{16}$ corresponding to $\pm 1\, \text{V}$. Following a peak finding routine is used to identify the position of the individual laser pulse signals, coming from the photo diodes, on the ADC trace. After that an integration around the peak positions is performed, greatly enhancing the signal to noise ratio comparing to a simple peak value evaluation. This step reduced the amount of data significantly ensuring time efficient data handling from this point on. In the following step the background signals of each individual trace are identified, averaged and subtracted from the signal carrying probe laser pulses. This completes the first stage of processing for the sequential electro-optical sampling data, resulting in an array with rows of each the bunch ID, followed by the values of the integrated ADC traces. In the coming step the data correlation via bunch ID is performed. The bunch IDs of the sequential EOS data are compared with the bunch IDs of the spectral decoding data. Each pulse trains has its own bunch ID resulting in a number of integrated intensity values with the same bunch ID matching a number of single shot spectral traces with the same bunch ID. When sorting an array is build containing the bunch ID followed by the delay stage position, the integrated signal value from the sequential electro-optical sampling and by the 512 pixel single shot spectral trace. The amount of data is reduced again at this point, as the µTCA acquisition is constantly running with 10 Hz creating a certain amount of unmatched data, being recorded, while, for example, the delay stage in the sequential eos is moving and no spectral data are recorded.

After pre-processing and sorting the arrival time jitter is evaluated. In order to retrieve the single shot jitter the spectral data traces are first normalized to their total intensity in order to equalize laser intensity fluctuations, that would otherwise interfere with the cross correlation. This is done for all traces, including background data. Each laser pulse train is than corrected with its individual background shots before all individual traces get cross

\(^{44}\)Each OPA burst is longer by several pulses, comparing to the FEL. Allowing to have intra burst laser background evaluation.

\(^{45}\)The total intensity is in this case found as the square root of the sum of squares.
correlated to a chosen trace, defined as zero jitter. This results in a vector with all jitter values that is paired in the next step with the integrated ADC values from the \( \mu TCA \). When correcting for the arrival time each individual data point is shifted in time by the corresponding jitter. The jitter value acquired by cross correlation is representing a shift of each individual trace with respect to the zero jitter trace in pixel on the camera. Multiplying the individual pixel shift with the timing calibration factor enables the correction of the data points in time. The combination of camera and spectral calibration factor is therefore also limiting the time resolution of arrival time detection, as the cross correlation only yields shifts of the THz related features on the single shot traces down to one pixel. The arrival time corrected data trace is binned with a 10 fs bin size utilizing a trim mean. This allows to deal with outliers. The data within each bin is sorted, the mean is determined and data points outside of a defined range, here ±40\%, are neglected in forming the final mean value of the bin. The resulting trace is consecutively multiplied with a blackman-nuttall window before calculating the FFT, in order to enhance the dynamic range in expense of frequency resolution, while keeping a flat amplitude response throughout the FFT.

### 3.4.3 Influence of arrival time correction

Combining the single shot arrival time data with the sequential electro-optical sampling data presented in figure 3.20, where the THz undulator is tuned to 150 \( um \) and the radiation is filtered using a 2\( THz \) band pass filter results in the improvement presented in figure 3.38. The figure features 2 distinct data traces presented in blue and red. The blue trace is equal to figure 3.20 and represents the sequential electro-optical sampling data before correcting for the arrival time jitter. Applying the arrival time jitter retrieved from the single shot spectral decoding allows to shift each individual data point in time, creating the red trace, representing the arrival time corrected sequential electro-optical sampling trace. The arrival time corrected trace shows the individual electric field cycles of the THz pulse created by the THz undulator tuned to 2\( THz \) and being spectrally filtered using a 2\( THz \) band pass filter with high resolution. In the process of acquiring sequential electro-optical sampling data, the delay between probe laser pulse and THz radiation is changed in discrete steps. The process of arrival time correction allows to fill the resulting gaps between these steps down to the spectral calibration factor of the spectral decoding setup\(^{46}\), creating a highly sampled data trace. With a linewidth of 9.7 fs RMS spectral features down to approximately 14 \( um \) can be measured, which supports the full detection bandwidth of the 100 \( um \) GaP crystal used.

\(^{46}\)See section 3.3.2.4 for further information.
Figure 3.39: **upper**: The binned THz signal trace of the THz pulse centered around 2 THz, measured through a 2 THz band pass filter. The trace is multiplied with a blackman-hamilton window in order to reduce artifacts in the amplitude spectrum. **lower**: The normalized amplitude spectrum of a 2 THz band pass filtered THz pulse with a central frequency of 2 THz shown above. The spectrum shows the central frequency at 2 THz as well as a leakage of the filter around 3 THz. The signal floor falls off towards 8 THz to a $10^{-3}$ level, which is one order of magnitude below the amplitude spectrum of the uncorrected trace shown in figure 3.21.
With a greatly enhanced time resolution comes a greatly enhances spectral resolution and

![Graph showing THz signal vs time delay]

Figure 3.38: Results of the sequential electro-optical sampling in blue and the result of applying the single shot arrival time correction to said data in red. Applying the arrival time uncertainty information onto the sequential eos data improves the resolution greatly and enables to resolve the individual electric field traces inside the THz pulse.

improvement in the FFT noise floor. Figure 3.39 shows the binned and windowed electric field trace in the upper graph. A reflection of the main pulse originating from the THz beam splitter can be seen between the delay values 252 and 254.5 ps. The blackman-nuttall window is strongly suppressing its amplitude and influence on the FFT. The lower graph of figure 3.39 shows the normalized amplitude spectrum of electric field trace shown above. The amplitude spectrum shows the fundamental of the THz undulator and the center of the band pass filter at $2\, THz$. Additionally frequency components around 3 THz are visible, coinciding with a leakage through the band pass filter. The noise floor within the displayed frequency range is approximately $1 \sim 2 \times 10^{-3}$. Comparing with the uncorrected data displayed in figure 3.21 the noise floor is improved by one order of magnitude and allows now to measure sub-percent level frequency components.
3.4.4 Electric field reconstruction

In order to reconstruct the electric field shape and magnitude of the THz pulses measured, careful de-convolution of the apparatus function, consisting of the scaled effective response function and the laser pulse duration, is necessary. The scaled effective response function is introduced in section 3.2.2.4 and represents both the response of the crystal lattice and electronic structure to the THz pulse, as well as the difference phase and group velocity of the THz and the probe laser pulse. In addition to this the stretching of the probe laser pulse inside the electro-optical crystal can be taken into account. In the work of Steffen [108] the influence of the laser pulse stretching inside the electro-optical crystal, is stated to be negligible for thin crystals of about 100 $\mu m$ thickness. With a different probe laser wavelength used within this work, the influence of pulse stretching needs to be evaluated. Following the work of Steffen [108] the extracted retardation can be expressed as the inverse Fourier transform of the electric field times the effective response function\(^\text{47}\) and the laser pulse width as

$$\Gamma(\tau) = \frac{2\pi}{\lambda_p} n_p^3 d \ast \mathcal{F}^{-1}\{\mathcal{F}_E(f) \ast G_{eff}(f, d) \ast \mathcal{F}_{GLP}(f, d)\}, \quad (3.4.1)$$

with $\mathcal{F}_E(f)$ as the Fourier transform of the electric field, or the spectrum, $\mathcal{F}_{GLP}(f, d)$ as the Fourier transform of the stretched Gaussian laser pulse, $d$ as the crystal thickness and $n_p$ as the refractive index of the electro-optical crystal at the probe laser wavelength $\lambda_p$. The Gaussian laser pulse is defined by

$$GLP = \frac{1}{\sqrt{2\pi}\sigma_s} \exp\left(-\frac{t^2}{2\sigma_s^2}\right), \quad (3.4.2)$$

with $t$ as the time and $\sigma_s$ as the standard deviation of the stretched Gaussian laser pulse. $\sigma_s$ is dependent on the crystal thickness and type and central wavelength of the laser and is defined as,

$$\sigma_s = \sigma_0 \sqrt{1 + \left(\frac{d}{\Delta t^2} \left(\frac{\text{ln}(2) \pi}{\pi^2 (v_g^{-1})}\right)\right)}, \quad (3.4.3)$$

with $\sigma_0$ as the initial standard deviation of the Fourier limited Gaussian probe laser pulse entering the crystal, $\Delta t$ as the time step and $v_g$ as the group velocity. This formalism assumes a Fourier limited pulse entering the crystal. Furthermore the stretching is calculated for the complete crystal length ignoring partial stretching of the laser while passing through the crystal. This will lead to a small overestimation of the strength of the reconstructed electric

\(^{47}\)Or the scaled effective response function.

\(^{48}\)Please note here that $\ast$ refers to multiply. Convoluted terms are represented as $\times$. 

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field trace. Additionally the frequency response needs to be limited to about $7\, THz$ as the effective response function approaches 0 at $7.5\, THz$, resulting in a non-physical amplification of the frequency components around. This is achieved by introducing a Gaussian edge filter to the spectrum with a half width at half maximum of about $1.5\, THz$. This allows to create a smooth transition from the reconstructed spectrum towards 0 and avoids artifacts in the reconstructed electric field, induced by a sharp cut of the spectrum. With these boundary conditions in mind the reconstruction of the electric field trace is a multi step process starting from the measurement signal $S = I_0 \ast \sin(\Gamma)$. The measured signal is processed as reported in section 3.4.2. The binned data is then corrected for the laser input intensity $I_0$ and the sine-function resulting in the phase retardation $\Gamma(\tau)$. As seen in equation (3.4.1) $\Gamma$ is dependent of the inverse Fourier transform of the Fourier transform of the Gaussian laser pulse, the effective response function and the Fourier transform of the electric field to be extracted, as well as the crystal thickness and type and probe laser wavelength. In order to extract the electric field a Fourier transform of $\Gamma$ is performed resulting in

$$F_{\Gamma}(f) = \frac{2\pi}{\lambda_p} n_p^3 d \ast F_E(f) \ast G_{eff}(f,d) \ast F_{GLP}(f,d).$$

(3.4.4)

This allows to de-convolute the individual parameters by dividing the resulting spectrum $F_{\Gamma}(f)$ by the effective response function and the normalized spectrum of the Gaussian laser pulse $F_{GLP}(f,d)$. Further division by the pre-factors $\frac{2\pi}{\lambda_p} n_p^3 d$ allows the obtain the spectrum of the measured electric field$^{49}$. Performing an inverse Fourier transform of the spectrum $F_E(f)$ results in the reconstruction of the measured electric field $E(\tau)$ in phase and amplitude.

Figure 3.40 shows a comparison of the THz induced signal shape in form of phase retardation and reconstructed electric fields and the corresponding spectra. Subfigure 3.40a shows the phase retardation that is measured with a THz pulse with a central frequency of $2\, THz$ and utilizing a $2\, THz$ band pass filter, with the corresponding spectrum in subfigure 3.40b. The spectrum shows the fundamental at $2\, THz$ as well as a small leakage through the filter at $3\, THz$. Furthermore features at 4 and around $6\, THz$ can be seen at small levels. Subfigures 3.40c and 3.40d show the electric field trace and the corresponding spectrum after de-convoluting the influence of the effective response function. Comparing to the phase retardation trace the shape undergoes a slight change featuring a stronger slope in field increase. Within the corresponding spectrum, the de-convolution results in an increase of the higher frequency components, easily visible at $6\, THz$ with an increase from 1 to

$^{49}$The resulting spectrum as well as the final electric field shape are approximations, as the previously mentioned list of boundary conditions need to be taken into account.
(a) Phase retardation of the measured THz pulse. Only a blackman-muttall window is applied.

(b) Spectrum of the electric field trace presented in subfigure 3.40a.

(c) Reconstructed electric field in V/m, corrected for the effective response function $G_{eff}(f, d)$.

(d) Spectrum of the electric field trace presented in subfigure 3.40c.

(e) Reconstructed electric field in V/m, corrected for the effective response function $G_{eff}$ and the stretched probe laser pulse duration GLP.

(f) Spectrum of the electric field trace presented in subfigure 3.40e.

Figure 3.40: Comparison of the influence of the de-convolution of the measured electric field with the effective response function and the stretched probe laser pulse duration, on the example of an electric field trace measured 2THz through a 2THz band pass filter.
2%. The fully de-convoluted electric field trace taking also the laser pulse broadening into account is shown in subfigure 3.40e, with the corresponding spectrum in subfigure 3.40f. By visual comparison to subfigures 3.40c and 3.40d there is no direct difference observable, which can be explained by the short pulse duration and the resulting small influence on the fundamental frequency. The influence on the higher frequency range up to $7 \text{THz}$ is larger but still small comparing to the influence the effective response function has. This can be explained by the short probe laser pulse duration of $20 \text{ fs}$ or about $7 \text{ nm}$ compared to the short wavelength edge of the pulse characterization tool at about $40 \text{ nm}$. In order to allow a better comparison of the influence of the electric field reconstruction on the electric field shape a normalized comparison is shown in figure 3.41. It shows the normalized phase retardation (original) in comparison to the normalized reconstructed electric field taking only the effective response function (resp) and both the effective response function and the laser pulse broadening (full) into account. The normalization allows to acquire inside into the shape change as a result of the reconstruction. A clear change in shape of the signal is visible between the original and the reconstructed signals. The main difference is a steeper rising flank between $-4$ and $0 \text{ ps}$ delay, in the case of the reconstructed field shape as well as a slower fall off of the field magnitude. Due to the normalization in combination with the low frequency fundamental there is no visible difference in shape between the reconstructed electric field taking only the effective response function into account or talking also the laser pulse stretching into account. In order to evaluate the influence of laser pulse stretching, a non normalized comparison is necessary. Figure 3.42 shows the reconstructed electric field traces with (dark red) and without (blue) taking the laser pulse stretching into account. The difference between the two electric field traces is very small showing a difference only in the absolute field magnitude. The difference in peak field is approximately $1.6\%$. The small influence can be associated with the low frequency fundamental and the spectral filter used. This can be understood when comparing the normalized amplitude spectra presented in figure 3.43. It can be seen that the low frequency components between $0$ and $2 \text{ THz}$ are little effected in amplitude. A clear difference can be seen from $3 \text{ THz}$ on, with growing difference towards higher frequencies. At around $6 \text{ THz}$ a factor of $2$ difference can be seen between the original spectrum and the spectra based on the reconstructed electric field traces. The difference between the spectra calculated from the reconstructed electric fields follows the same trend. The influence of the laser pulse broadening is small at low frequencies and becomes more apparent around $6 \text{ THz}$. As stated by Steffen [108] the difference in electric field and spectrum originating from the laser pulse broadening is small for the case of thin
Figure 3.41: The comparison of the normalized phase retardation with the reconstructed electric field only taking the effective response function into account and taking both the response function and laser pulse stretching into account. The start of the individual traces is at around $-4.5 \text{ps}$. 
Figure 3.42: The comparison of the de-convoluted electric field traces with and without taking the laser pulse stretching into account, in dark red and blue respectively.
Figure 3.43: The comparison of the normalized amplitude spectra of the phase retardation and the reconstructed electric field with and without taking the laser pulse broadening into account. It can be seen that the difference between the spectrum based on the phase retardation and the spectra based on the reconstructed electric fields becomes larger at higher frequencies.
crystals. Nevertheless non filtered THz pulses carry a high amount of higher frequency components making corrections for the laser pulse broadening important in order to acquire a good approximation of the electric field shape and magnitude.
3.5 Results of characterized THz pulses

3.5.1 The influence of full spectral content on the electric field shape on the example of a $2\,THz$ trace

It is shown that the arrival time correct is greatly enhancing the time and therefore spectral resolution and allows to characterize the THz pulses throughout the wavelength range of interest, namely 300 to 40 $\mu$m. Figure 3.38 shows a band pass filtered electric field trace with a Gaussian like envelope function. The envelope function is originating from the spectral filtering and is not representative for the unfiltered THz pulses. The THz undulator is a high K device and therefore bound to create a large amount of high harmonic content\textsuperscript{50}, which will have direct influence on the electric field shape. Figure 3.44 shows the measured THz signal of a THz pulse with a central frequency of about $2\,THz$. The data is shown as a dot plot giving insight to the data spread before post processing. Figure 3.45a shows the binned phase retardation trace of a THz pulse with the central frequency of approximately $2\,THz$ that is not spectrally filtered. The THz pulse is beginning around $-2.5\,ps$ delay and lasting until around $4\,ps$. An increase in field amplitude over the first half of the pulse is visible. Additionally it can be seen that the higher harmonics content increases throughout the pulse causing additional spikes superimposed to the $1.8\,THz$ oscillation. A possible explanation for these characteristics are the electron bunch form, which directly influences the amount of electrons radiating coherently and therefore not only the total radiated power but also the spectral composition \cite{15}, as it is indicated in chapter 2 figure 2.27. Superimposed with the 10\textsuperscript{th} cycle of the THz pulse, the strong single cycle THz pulse originating from the electron beam dump magnet can be seen. In subfigure 3.45b the normalized amplitude spectrum of the phase retardation trace of the THz pulse, presented in the upper graph, is shown. The amplitude spectrum shows the fundamental of the THz pulse at around $1.8\,THz$ as well as the odd and even harmonics down to $7.2\,THz$. It is expected to detect the odd harmonics as they are radiated on-axis, but unexpected to detect the even harmonics\textsuperscript{51} as they are radiated off-axis. This explains the general trend of lower amplitude of the even harmonics compared to the odd. Possible reasons for the transport of the even harmonics are the large collection angle of the THz beamline \cite{86} or an off-axis electron beam trajectory through the undulator. Aside the individual harmonics a broadband background signal can be seen, peaking between 2 to $3\,THz$ and falling off

\textsuperscript{50}See section 2.3 for further information.
\textsuperscript{51}See section 2.3 for additional information.
Figure 3.44: The measured THz signal trace of a THz pulse with a fundamental frequency of around 2 THz before binning. The graph is displayed as a dot-plot giving insight into the data-spread.

towards the detection limit of 7.5 THz. This broadband spectral background is originating from the quasi single cycle THz pulse produced by the electron beam dump magnet, which is following the undulator based multi-cycle THz pulse. Figure 3.45a shows that the amount of high harmonic content has a significant influence on the electric field shape. Furthermore, it shows that THz pulses carrying the full spectral bandwidth can be characterized throughout the entire wavelength range of interest in both, time and frequency domain. It is possible to detect spectral components with high spectral brightness as well as broadband features simultaneously. In a next step the electric field reconstruction is to be tested with the THz pulse containing both, spectrally bright undulator harmonics and broadband features from the single cycle dump trace. In order to do so the apparatus function is de-convoluted from the normalized amplitude spectrum of the phase retardation trace shown in figure 3.45. Figure 3.46b shows the de-convoluted normalized amplitude spectrum of a THz pulse with a fundamental frequency of about 1.8 THz, recorded without spectral filtering. Comparing to the original spectrum, an increase of high frequency components can be seen. The third
Figure 3.45: a: The binned phase retardation trace of the THz pulse centered around 1.8 THz. The front edge of the THz pulse can be seen at around −2.5 ps delay. An increase in field amplitude and an increase in high harmonic content is visible throughout the pulse, ending with the electron beam dump single cycle pulse. Additional components after the main pulse, at around 4 ps are the result of remaining gas in the eos chamber. b: The normalized amplitude spectrum of the THz pulse with a central frequency of about 1.8 THz shown above. The spectrum shows the central frequency at around 1.8 THz, additionally the even and odd harmonics up to 7.2 THz are visible on a broadband background originating from the electron beam dump magnet.
Figure 3.46:  

(a) The reconstructed electric field of the measured THz pulse. 

(b) The amplitude spectrum of the reconstructed electric field trace shown in subfigure (a).

Figure 3.46:  

(a) The reconstructed electric field trace in V/m of the THz pulse centered around 1.8 THz. The front edge of the THz pulse can be seen at around −2.5 ps delay. An increase in field amplitude and an increase in high harmonic content is visible throughout the pulse, ending with the electron beam dump single cycle pulse. Additional components after the main pulse, at around 4 ps are the result of remaining gas in the eos chamber. 

(b) The normalized amplitude spectrum of the THz pulse with a central frequency of about 1.8 THz shown above. The spectrum shows the central frequency at around 1.8 THz, as well as a higher amplitude third harmonic. Additionally the second harmonic at about 3.6 THz is visible. The individual harmonics sit on a broadband background originating from the electron beam dump magnet.
harmonic at about 5.4 THz is the dominating frequency, which is conform with the expected harmonic content of a high K undulator. Additionally the fundamental and the second harmonic can be seen in the spectrum, sitting on top of a broadband background originating from the edge radiation. The fourth harmonic visible, in the original spectrum, is cut out by the Gaussian edge filter starting at 6.5 THz. This is necessary as the correction function is approaching an extreme point at 7.5 THz resulting in an incorrect de-convolution. Applying an inverse Fourier transformation allows to re-construct the electric field trace from the de-convoluted amplitude spectrum. The reconstructed electric field trace is shown in subfigure 3.46a. It shows a 11 cycle structure, starting with a narrow cycle originating from the front edge of the THz undulator followed by the main 10 cycle undulator pulse. The main undulator pulse is increasing in electric field strength and high harmonic content throughout the pulse. The pulse finishes with a strong single cycle originating from the electron beam dump magnet superimposed on the last THz undulator field cycle. Additional field components after the main pulse originate from residual gas in the co-vacuum chamber. Comparing to the phase retardation trace an enhancement of the single cycle dump radiation at the back of the pulse is visible, which is in perfect agreement with the increase in high frequency broadband background visible in the normalized amplitude spectrum. Figure 3.46 shows that the apparatus function can be de-convoluted from the spectrum and that the electric field trace can be reconstructed, allowing the THz pulse characterization tool to fully characterize the electric field of a spectrally bright undulator pulse superimposed with a broadband single cycle pulse.

3.5.2 Differences of the electric field shape at similar FEL conditions

The parameters of the free electron laser have a large influence on the THz output. Not only on totals pulse energy, but also on the spectral content and ultimately the shape of the electric field. Figure 3.47 shows the measured THz signal of a THz pulse with the THz undulator tuned to 2 THz. The data is presented as a dot plot before post processing. Figure 3.48a shows the binned phase retardation trace of the data presented in figure 3.47. The FEL parameters, namely electron energy of \( \approx 554 \text{ MeV} \), electron bunch charge of \( \approx 0.53 \text{ nC} \) and orbit through the undulator being 0, 0 on the beam positioning monitors before and after the undulator, were comparable to the settings present during the measurement of the phase

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\(^{52}\)See chapter 2 figure 2.27 for further information.

\(^{53}\)It is to be noted that for the re-construction the amplitude spectrum is used before normalization.
retardation in figure 3.45a, yet shows a difference in shape. The envelope function can be described as rectangular with a slight increase in signal intensity towards the center of the pulse. The increase in signal is accompanied by an increase in high harmonic content, manifesting as additional spikes superimposed with the fundamental oscillation. Another differences between figure 3.48a and 3.45a is the lack of a high intensity single cycle field towards the end of the pulse in figure 3.48a. These differences become of interest when the THz pulse is used as a driving force for a pump probe experiment of any sort aiming at coherent control of a process, like coherent control of magnetism [33]. Any difference in electric field shape\textsuperscript{54} can directly manifest itself in a change of the sample response, making a precise understanding of the driving field necessary to understand the complex physical processes that can be involved. With a change in the shape of the phase retardation

![Image](image.png)

Figure 3.47: The measured THz signal trace of a THz pulse at 2TH\textsubscript{z} with the full spectral bandwidth. The FEL parameters are similar to the settings of figure 3.44 in respect of electron beam energy and charge. The data is presented as a dot plot before any post processing.

\textsuperscript{54}Represented here as a change in the shape of the phase retardation trace.
Figure 3.48:  

(a) Phase retardation of the measured THz pulse. 

(b) The amplitude spectrum of the phase retardation trace shown in subfigure (a). 

Figure 3.48:  

(a) The binned phase retardation trace of the THz pulse centered around 1.9 THz. The front edge of the THz pulse can be seen at around $-3 \text{ ps}$ delay. A quasi square signal envelope with an increase in high harmonic content at the center of the signal trace can be seen. The pulse is ending with the electron beam dump single cycle pulse between 3 and 4 ps. 

(b) The normalized amplitude spectrum of the THz pulse with a central frequency of about 1.9 THz shown above. The spectrum shows the central frequency of approximately 1.9 THz, and the third harmonic at about 5.7 THz, as well as a broadband background originating from the electron beam dump magnet.
Figure 3.49: 

(a) Reconstructed electric field trace of the measured THz pulse.

(b) The amplitude spectrum of the reconstructed electric field trace shown in subfigure (a).

The reconstructed electric field trace of the THz pulse centered around $1.9\, THz$ plotted in $V/m$ as a function of delay in ps. A 12 cycle field trace with a strong increase of third harmonic content at its center can be seen. The normalized amplitude spectrum of the THz pulse with a central frequency of about $1.9\, THz$ shown above. The spectrum shows the central frequency of approximately $1.9\, THz$, and the third harmonic at about $5.7\, THz$, as well as a broadband background originating from the electron beam dump magnet.
normalized amplitude spectrum of the phase retardation trace shown above. The amplitude spectrum shows the fundamental frequency at about $1.9\,THz$ as well as the third harmonic at around $5.7\,THz$. Comparing to 3.45, only the third harmonic at about 5.7 is visible, while even harmonics are not seen in the amplitude spectrum. The broadband spectral background originating from the single cycle edge radiation is present through the range of $1$ to $7.5\,THz$. The comparison of the spectrum of the THz pulses supports the initial assumption that at similar FEL conditions, in respect of electron energy, bunch charge and orbit through the undulator, the spectral composition of the THz pulse can be different. This can become crucial when trying to address specific phonon modes or collective phonon motion in materials in order to induce exotic states of matter and corresponding properties [49]. It is therefore necessary to carefully characterize the electric field shape and the spectral composition before an experiment, even at similar FEL conditions.

Similar differences in spectrum and electric field shape can be observed when comparing the de-convoluted amplitude spectra and the reconstructed electric field traces of figure 3.49 and figure 3.46. The de-convoluted spectrum shows the fundamental and third harmonic of the undulator at $1.9$ and $5.7\,THz$, respectively, with an almost flat broadband background from between $1$ and $7.5\,THz$. Similar to the original spectrum no even harmonics are present. The reconstructed electric field shape differs greatly from the trace presented in figure 3.46. While the electric field shows an initial increase in strength towards the center of the pulse, combined with the increase in high harmonic content, this tendency reverts towards the end. This results in an equal strength of the electric field at the beginning and at the end of the pulse, in contrast to figure 3.46. The reconstructed electric field shown, is therefore a good example why careful characterization of the electric field is necessary on a shift to shift basis, as equal FEL parameters do not necessarily result in equal THz pulses.

### 3.5.3 Broadband detection - single cycle edge radiation

Edge radiation has a strong influence on the overall spectral composition of the THz pulses available at the THz Beamline at FLASH and was used as the main source for the development of the THz pulse characterization tool. Additionally it can not be excluded from the radiation delivered to the experiment, as it covers the complete frequency range available by the THz undulator and is radially polarized, making the selection by polarizer also impossible. On the other hand it can be utilized for both pumping and broadband probing as it covers an ultra broad frequency range in a well defined quasi single cycle electric field. Figure 3.50 shows the measured THz signal of the single cycle edge radiation pulse before post
processing. The data is plotted as a dot plot to give insight into the data spread. Figure 3.51a shows the binned phase retardation trace of the single cycle edge radiation pulse. It is approximately 0.6 ps long, lasting from about −0.5 and to 0.1 ps, corresponding to a frequency of about 1.8 $THz$. Additional field components after the main pulse originate from remaining absorption in the residual gas molecules inside the measurement chamber\textsuperscript{55}, which can also have a slight influence on the electric field shape. The trace shows a single cycle

![Graph showing a dot plot of signal versus delay](image)

**Figure 3.50:** The THz signal trace of the quasi single cycle edge radiation, originating from the electron beam dump magnet. The single cycle pulse is about 0.6 ps long, corresponding to a frequency of about 1.8 $THz$.

behavior with a small shoulder before reaching the maximum positive signal. This feature could also be explained by the electron bunch form factor introduced earlier, but additional measurements would have to be performed to confirm this theory. The lower graph of figure 3.51b shows the normalized amplitude spectrum of the single cycle phase retardation trace shown above. The FFT shows a very broad spectrum centered around 2 to 3 $THz$ with a fall-off towards the detection limit at 7.5 $THz$ and a significant amount of low frequency component. Figure 3.51 shows that the spectrally very broad single cycle radiation produced

\textsuperscript{55}This trace was measured at about 3 mbar pressure.
Figure 3.51: a: The binned phase retardation trace of a quasi single cycle THz pulse originating from the beam dump magnet. The front edge of the THz pulse can be seen at around $-0.5\,\text{ps}$ delay. Additional field components after the quasi single cycle pulse originate from residual gas in the eos chamber. b: The normalized amplitude spectrum of the quasi single cycle pulse shown above. The spectrum shows a broadband frequency range covering the detection window with a central frequency between $2$ and $3\,\text{THz}$. 

(a) Phase retardation of the measured THz pulse. 

(b) The amplitude spectrum of the phase retardation trace shown in subfigure (a).
(a) Phase retardation of the measured THz pulse.

(b) The amplitude spectrum of the phase retardation trace shown in subfigure (a).

Figure 3.52: a: The reconstructed electric field trace of a quasi single cycle THz pulse originating from the beam dump magnet plotted in $V/m$ as a function of delay in $ps$. The front edge of the THz pulse can be seen at around $-0.5$ ps delay. Additional field components after the quasi single cycle pulse originate from residual gas in the eos chamber. b: The normalized amplitude spectrum of the quasi single cycle pulse shown above. The spectrum shows a broadband frequency range covering the detection window with a central frequency between 2 and 3 $THz$. 
by the electron beam dump magnet can be characterized throughout the desired frequency range. Comparing the results to 3.48b shows that the normalized amplitude spectrum is in good agreement with measurements presented. It can therefore be concluded that the system is not only capable of measuring spectrally broadband low brightness components, but also of measuring these components superimposed with narrow band components of high spectral brightness. The de-convolution of the apparatus function and subsequent reconstruction of the electric field is important as the single cycle edge radiation pulse is present at all times. Figure 3.52b shows the de-convoluted normalized amplitude spectrum of the single cycle edge radiation THz pulse. The Gauss edge filter applied after the de-convolution is adjusted to start at 6 THz and therefore shifted by 0.5 THz. This is necessary as the high harmonic components are around 6.5 to 7.5 THz are otherwise dominating the spectral composition, resulting in an un-physical result from the reconstruction of the electric field trace, due to the asymptotic behavior of the correction function around 7.5 THz. This is not the case in spectra featuring the undulator radiation, as the individual harmonics have higher amplitude than the broadband edge radiation, as seen in figure 3.46b. The spectrum is broadband ranging from 1 THz to the detection edge with an increase in higher harmonic radiation around 5 to 6 THz. The reconstructed electric field trace based on the spectrum in figure 3.52b is shown in figure 3.52a. The electric field shape shows a quasi single cycle THz pulse with additional field components following the main pulse as a result of residual gas in the eős chamber. Comparing to the measured phase retardation the reconstructed electric field trace is inverted and shows changes in shape. Most dominant is the shoulder on the rising / falling edge at the beginning of the pulse vanishing in the reconstructed trace. Figure 3.52 shows that apparatus function can be de-convoluted from the single cycle edge radiation pulse and that the electric field trace can be reconstructed.

3.5.4 Measuring at the high frequency detection limit

Gallium Phosphide as the electro-optical detection crystals, allows to measure frequencies up to about 7.5 THz without special characterization of the crystal and careful correction of the measured spectra [28]. In the previous section, it is shown in figure 3.51, that the broadband spectral response that can be achieved is ranging up to approximately 7.5 THz. When tuning the THz undulator to such short wavelength a spectrally bright pulse needs to be measured carrying higher harmonic content outside the detection range. Figure 3.53a shows the measured phase retardation trace of a THz pulse with the THz undulator tuned

Applying a narrow band pass filter is limiting the influence of the broadband edge radiation.

Without re-construction of the electric field.
Figure 3.53: a: The binned phase retardation trace of a THz pulse produced by the THz undulator tuned to 42 um. The trace shows rectangular envelope function with a total of 11 cycles, the front edge radiation of the undulator, 10 period undulator radiation and edge radiation from the electron beam dump magnet superimposed to the last cycle of the undulator based radiation. b: The normalized amplitude spectrum of the trace shown above. The spectrum shows the fundamental of the multicycle undulator pulse at about 6.9 THz. Additionally a high amount of low frequency components can be seen, originating from the single cycle edge radiation.
to 42 \text{um}. The trace exhibits a rectangular envelope function and a total of 11 field cycles. It is comprised of the signal from the front edge single cycle of the undulator at around $-0.7 \text{ps}$ delay, followed by the 10 period undulator radiation overlapping at its end with the single cycle radiation from the electron beam dump magnet. Additional field components from 1 ps delay are originating from absorption in the residual gas inside the experimental chamber. The figure 3.53b shows the normalized amplitude spectrum of the phase retardation trace shown above. The spectrum shows the fundamental of the undulator radiation at approximately $6.9 \text{THz}$. Additionally low frequency components can be seen between the fundamental and approximately $1 \text{THz}$ originating from the single cycle edge radiation. Figure 3.53 shows that the THz pulse characterization tool is capable of characterizing a high spectral brightness THz pulse with frequency components between 0.8 and $7.5 \text{THz}$ centered at $6.9 \text{THz}$. The presented measurement represents a quasi long pass filtered measurement, as the electro-optical crystal does not support the higher harmonics, which can have influence on the measured signal shape. A clean way of measuring in this frequency range can be achieved by using a 33 \text{um} long pass filter. When aiming to characterize high frequency pulses including the harmonic content, changing the electro-optical crystal and adjusting the probe laser wavelength can shift the detection range. Cryogenically cooling Gallium Arsenide allows to reduce the phonon absorptions in the range of 40 \text{um} and opens up the possibility of detection in this range [139] [140]. As the fundamental frequency is higher than the beginning of the Gauss edge filter introduced in the de-convoluted spectrum, the spectrum and hence the electric field shape can not be reconstructed without careful characterization of the eo-crystal and the resulting response function.

### 3.5.5 Measuring low frequencies radiation with high spectral brightness

The maximum achievable wavelength of the THz undulator is directly linked to the electron energy and therefore the wavelength at FLASH1. At a certain point the chance arose to measure at approximately 400 MeV electron energy and therefore reach up to 320 \text{um} as the fundamental of the THz undulator. A fundamental wavelength around 320 \text{um}, allows to test the low frequency response of the system and verify its capabilities in characterize the corresponding electric field. Figure 3.54 shows the measured THz signal before post processing as a dot plot, showing the data spread of the measurement. Figure 3.55 subfigure a shows the binned\textsuperscript{58} phase retardation trace resulting from the measurement of the THz

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\textsuperscript{58} Bin size of 10 fs.
pulse created with the THz undulator tuned to 320 \textmu m, acquired without spectral filtering. The electric field experiences a strong increase in signal strength throughout the pulse with a triangular envelope function. The reduced number of electric field cycles and the strong increase in field strength throughout the pulse can be explained with the electron bunch form factor, that is directly linked to the amount of coherently radiating electron. The electron bunch form factor on its own is dependent on the electron energy as space charge forces are proportional to \( \frac{1}{\gamma^2} \), resulting in a quadratic increase of the repulsive force between 2 relativistic electrons [141]. With increasing space charge effects, highly compressing and transporting a highly compressed electron beam becomes challenging. Therefore it can be assumed, that the peak current of the electron bunch and therefore the amount of coherent radiation produced is significantly reduced. Which can be seen in figure 3.55 at the beginning of the THz pulse. In this case, the increase in electric field visible, can be attributed to a growing density modulation of the electron bunch inside the THz undulator, favoring

\[59\text{The counter action of electric repulsion and magnetic attraction.}\]
the process of coherent emission. A second explanation can be the limited beam pipe aperture size inside the THz undulator. This possibility however is unlikely, as strong single cycle pulses from the front edge of the undulator can be seen, for example in figure 3.47, carrying similar wavelength components. Figure 3.55a shows that the electric field of a THz pulse produced by the THz undulator set to 320 um can be measured. The low frequency fundamental allows to characterize the electric field including many higher harmonics. It is therefore especially interesting to analyze the spectral composition of the pulse. Figure 3.55b shows the normalized amplitude spectrum of the phase retardation trace shown above.

The spectrum shows the fundamental of the THz pulse at around 0.91 THz. Consecutively the third harmonic at around 2.75 THz can be seen, followed by the fifth, seventh, eighth and ninth harmonic, located at 4.46, 5.43, 6.39 and close to the detection edge at 7.19 THz, respectively. Differences in the harmonic frequency with respect to the harmonic number and fundamental occur from a lack of frequency resolution. The third harmonic content is stronger than the fundamental, as expected for a high K-value undulator [82]. In order to give a more accurate representation the amplitude spectrum needs to be corrected for the crystal response function. The individual harmonics sit on a broadband background ranging from 1 to 7 THz. The broadband spectral components originate from the single cycle radiation produced by the electron beam dump magnet. When compared to the single cycle pulse presented in figure 3.51 the spectral cutoff at low frequencies is blue shifted in figure 3.55. This is unexpected as SRW calculations show that the number of low frequency photons within the observation plane is growing with lower electron energies\textsuperscript{60}, as depicted in figure 3.56. Figure 3.56 was calculated by integrating the total photon count on the observation plane behind the electron beam dump magnet at different electron energies. The observation plane has a total size of 480 × 480 mm and the observed wavelength is constant at 375 um\textsuperscript{61}. The magnetic structure of Flash1 presented in figure 2.15 is used to calculate the radiation output of a single electron. It can be seen that the amount of photons per second per 0.1 % bandwidth and per mm\textsuperscript{2} increases exponentially with decreasing electron beam energy. Therefore it is expected that the long wavelength output is increased. The notable discrepancy can possibly be explained by the long electron bunch, reducing the coherent edge radiation. The normalization of the spectrum can be excluded as a reason for the reduction of spectral components between 0 and 1 THz, as the broadband spectral background between 1 and 7.5 THz shows comparable magnitude as in figure 3.48. In order to get an estimate on the spectral composition of the THz pulse entering the GaP crystal

\textsuperscript{60}See section 2.6 for further information.
\textsuperscript{61}This wavelength is chosen as it is closer to the measured fundamental of 0.8 THz.
Figure 3.55: 

(a) Phase retardation of the measured THz pulse with the THz undulator tuned to 320 \( \mu m \). The trace shows a triangular shape with an increasing amount of phase retardation throughout the pulse with about 7 cycles visible.

(b) Amplitude spectrum of the electric field trace shown above. The spectrum shows the fundamental of the THz pulse at approximately 0.91 THz and consecutively the third, fifth, seventh, eighth and ninth harmonic at 2.75, 4.46, 5.43, 6.39 and 7.19 THz, respectively. The third harmonic content is highest in amplitude, with the following harmonics falling off in amplitude. All harmonics are located on a broad spectral background ranging from approximately 1 to 7 THz, originating from the single cycle edge radiation.
Figure 3.56: The integrated photon count on the observation plane of $480 \times 480 \, mm$ at $375 \, um$ simulated using SRW with the single electron emission from the magnetic structure of FLASH1. The integrated photon count shows an exponential increase with the reduction of the electron beam energy.
(a) Electric field trace of the measured THz pulse with a the undulator tuned to 320 \(\mu m\).

(b) Amplitude spectrum of the THz signal shown above.

Figure 3.57: **a:** The reconstructed electric field trace of a THz pulse with the THz undulator tuned to 320 \(\mu m\). The trace shows a increasing electric field strength throughout the pulse with about 9 cycles visible. **b:** The normalized amplitude spectrum of the electric field trace shown above. The spectrum shows the fundamental of the THz pulse at approximately 0.8 to 0.9 THz and consecutively the third, fifth, sevens, eights and times harmonic at 2.6, 4.4, 5.3, 6.3 and 7.2 \(THz\), respectively. The third harmonic content is highest in amplitude, with the following harmonics falling off in amplitude. All harmonics are located on a broad spectral background ranging from approximately 1 to 7 \(THz\), originating from the single cycle edge radiation.
3.5.6 Conclusion

The presented measurements show that THz pulse characterization tool is capable of measuring the spectrally bright THz pulses from the THz undulator superimposed with the broadband single cycle pulse of the electron beam dump magnet. It is shown that THz pulses can be measured throughout the entire wavelength range of interest, namely 1 to 7.5 THz. It is shown that THz pulses can be measured including a large amount of high harmonics within the frequency range up to 7.5 THz. It is furthermore shown, that the THz pulse shape can differ significantly at comparable FEL parameters and that based on this finding, THz characterization is crucial for experiments using THz as a driving source of complex processes. Additionally it is shown that spectral filtering is having a large effect on the THz pulse shape. Spectral components can be identified in percent and sub-percent levels, which allows the study of THz driven dynamics aiming at the generation of higher harmonic content. Limitations of the technique concerning the short wavelength detection can be circumvented by changing the electro-optical crystal and adjusting the probe laser wavelength, which would involve larger changes to the optics and the laser system. To this point, very few experiments aim to use this short wavelength regime, resulting in the dismissal of the adaption of the system.
Chapter 4

High field THz induced dynamics in perovskite type transition metal oxides

Perovskite type transition metal oxides are in focus of research for several decades, with applications ranging from sensors, light emitters, fuel cells and superconductors to hybrid structure solar cells and photonic crystals [142, 143]. When combined with THz radiation the possible applications are widened further. Tunable strong THz pulses with high spectral brightness allow to drive various processes in correlated materials resonantly by addressing phononic motion. Strong multi cycle pulses in the reststrahlen band, available at Flash1, open the door to the manipulation of matter on ultrafast time scales aiming at transient phase changes [34, 49]. This enables not only the manipulation of dielectric properties, like ultrafast conductivity changes, but opens the way to ultrafast domain switching in ferroelectric systems and a possibility for ultrafast non volatile memory. With the THz pulse characterization tool an instrument, able to measure transient changes in the electric field of a THz pulse, is available. Adjusting the existing THz pulse characterization tool to accommodate a sample position allowing for THz field measurements in reflection enables to study the response of transition metal oxides to resonant and non-resonant excitation. Within this chapter the final THz pulse characterization tool upgrade will be presented, accommodating a sample for THz response measurements in reflection. Strontium titanate $SrTiO_3$, short STO, as the transition metal oxide studied, will be shortly introduced, and the experimental results, transient changes on a femtosecond to picosecond time scale will
be shown and discussed.
4.1 Sample Description - $\text{SrTiO}_3$

Transition metal oxides are a group of crystalline materials that are of particular interest for modern THz science, as phase changes, both natural and stimulated, can lead to a large variety of different properties ranging from ferroelasticity and superconductivity to pyroelectricity [144, 145, 146]. Strontium titanate STO is one of the widely used and studied transition metal oxides. It is commonly used as the substrate for transition metal oxide hetero-structures [145] and is readily available in high quality single crystals. At normal conditions it is dielectric with a face centered cubic crystal structure, as shown in figure 4.1. The cubic unit cell is made out of strontium atoms with oxygen at its face centers. The oxygen atoms therefore create an octahedron, with the titanium atom located at its center. The crystalline structure is highly symmetric with the crystal axes $a$, $b$, $c$ being of equal length. Strontium titanate undergoes a series of structural changes when being cooled,

![Diagram of crystalline structure of SrTiO3](image)

Figure 4.1: A schematic of the crystalline structure of strontium titanate under normal conditions. STO shows a cubic structure of strontium (red) with oxygen (blue) face centered on each face of the cube forming an internal octahedron. The titanium atom (green) is located at the center of the oxygen octahedron.

resulting in a drastic change of its properties [145]. Recent studies show that structural changes can also be driven by long term exposure to high electric fields, with magnitudes larger than $1 \text{MV/m}$ [146]. Strong THz pulses can be accompanied by electric fields orders
of magnitude larger [30] and raise therefore the question of ultrafast phase changes and structural control. In the work of Qi et al. simulations on a similar titanate, namely lead titanate PTO, show that strong excitation in phase with the phonon motion allow control over the polarization of the crystalline structure. Narrow band intense THz pulses, available for example at FLASH1, allow to address phonon modes resonantly, creating the necessary handle on structural dynamics [147, 148, 49]. The phonon mode of interest in STO is the so called soft mode, located at approximately 110 $\mu m$ or 2.72 $THz$ [149]. The atomic motion associated with the soft mode is presented in figure 4.2. It is a collective motion of the oxygen octaheders against the central titanium atom, resulting in a shift of the titanium out the the central plane of the oxygen octaheders and therefore creating a net polarization. The resulting structural change breaks the inversion symmetry momentarily, allowing nonlinear phenomena as seen in other titanates, like barium titanate BTO [150]. The recent work of

Figure 4.2: A schematic of the atomic movement due to the soft mode excitation in STO. The central titanium atom and the oxygen octaheders move in opposite directions, resulting in a shift of the titanium atom out of the central plane of the oxygen octaheders.

Kozina et al. [151] shows that excitation with strong THz transient results in a coherent response of the crystal lattice in STO thin films. Pumping with a broadband singly cycle pulse allows to coherently excite a broad range of phonons. On the down side, resonant amplification of triggered processes and their associated phononic motion is impossible. The tunable multi cycle THz pulses available at FLASH1 allow to drive a coherent motion
of the STO soft mode and possibly resonantly amplify the motion. The experiment aims to create a quasi stable phase change of STO into a structure resembling the ferroelectric phase [145]. The change is observed by the transient change in THz field reflected off the sample [152]. Following the work of Qi et al. additional higher frequency components are expected to be emitted by the sample. Given the lack of simulations of the energy surface of STO under strong excitation, the exact frequency remains to be determined. The THz pulse characterization tool can be used to determine both, transient changes throughout the exciting electric field and hence also generated frequency components.
4.2 Experimental description

In order to perform a nonlinear THz driven experiments utilizing the THz pulse characterization tool to visualize transient field changes, a modification is necessary, allowing to accommodate an intermediate sample position. In order to avoid any distortions to the THz field that are not sample related the intermediate sample position needs to be within the vacuum chamber and fit inside the high resolution sequential electro-optical sampling arm of the setup. Figure 4.3 shows the schematic of the THz pulse characterization and the location of the intermediate sample position. The intermediate sample position is located in vacuum behind the THz beam splitter, inside the THz path of the high resolution sequential electro-optical sampling branch of the system. Figure 4.4, shows a detailed scheme of the THz pulse characterization tool with the reflective sample position. It can be seen that
Figure 4.4: A detailed schematic of experimental realization of the THz pulse characterization tool with the accommodated intermediate sample position. With the OPA beam entering from the right (dark blue) and the THz radiation entering from the left (red). The OPA beam is split before entering the sequential EOS (blue) and the single shot spectral decoding (purple). The THz pulse is split using a Si-wafer before being focused into the intermediate sample focus using a 100 mm off-axis parabola. The sample is mounted in a reflective geometry reflecting the beam at 90°. The THz pulse is consecutively recollimated using a second 100 mm off-axis parabola and send back into the original beam path, leading to the electro-optical crystal of the high resolution electro-optical sampling.
the THz pulse coming from the FEL gets split before being send to the sample position. This allows to operate the arrival time characterization branch of the system without any interference by the sample. The THz beam is then focused by a 100 mm off-axis parabola onto the sample. The sample is mounted under 45° reflecting the incoming THz pulse with an angle of 90°. The THz pulse is recollimated using an identical 100 mm of axis parabola and then directed onto the original beam path with an additional mirror. Several filters can be placed either after the focusing parabola, directly before the sample, or between the first 2 mirrors inside the EOS vacuum chamber or on manipulators before the beam enters the EOS vacuum chamber. Placing filters directly before the sample has the advantage that the arrival time detection branch is not influenced by spectral narrowing and is therefore preferred. The other 2 filter positions are also used, in order to have additional flexibility and due to spacial constraints\(^1\). When aiming at nonlinear dynamics, driven by high field or high photon flux, having the maximum intensity on the sample in the smallest achievable focus is necessary. In order to achieve the highest flux on the sample and due to the otherwise added complexity, the experiment is performed in a two step fashion. In the first step a mirror is mounted at the sample position, reflecting the THz pulse, allowing to measure a reference of the THz induced retardation under the given conditions and with the currently used filters. In the second step the sample is mounted in focus and the reflected THz beam is measured. Transient changes to the THz induced retardation trace can be identified by comparing the retardation trace and the normalized amplitude spectrum. It is to be noted that the electric field reconstruction is not performed, as a detailed characterization of the EOS crystal is necessary in order to minimize the error. The discussion of the measurements is therefore limited to the THz signal traces measured\(^2\).

\(^1\)The filter sizes vary between 1 and 4 inch.
\(^2\)Further information of the relation between THz signal and electric field can be found in section 3.4.4.
4.3 Results

4.3.1 Linearly polarized excitation at maximum fluence

The following results were obtained during a dedicated inhouse campaign with the support of collaboration partners. The THz frequency used is $2.72 \, THz$ or $110 \, um$, which is the eigenfrequency of the soft mode in STO. The presented results are color coded showing the reference measurements in red and the STO measurements in black. The measurements are aligned in delay to the negative maximum of the front edge of the undulator, which can be seen at maximum positive delay. In order to drive the phonon mode as depicted in figure 4.2, the polarization of the THz pulse needs to be linear, as the radially polarized edge radiation components would create an excitation in multiple directions with equal strength$^3$. The polarization can be selected using a wire grid polarizer. The polarizer used is an Infraspecs $P01$ with a working range of $0.12$ to $25 \, THz$. The reached extinction ratio is $10^4$. The polarizer is mounted in front of the sample with the option to mount a filter. The filter used to avoid higher harmonic content from the THz undulator itself is a $77 \, um$ low pass filter. Using this filter allows to pump the sample with the fundamental of the THz undulator and broadband low frequency components from the edge radiation. Figure 4.5 shows the comparison of the average binned THz signal trace recorded as a reference and with the STO sample introduced into the beam. The traces are recorded with the maximum available fluence onto the sample. Each trace is formed by averaging 5 individual binned traces, each consisting out of several 100000 individual data points binned with a $10 \, fs$ step. High delay on the traces indicates the probe laser pulse early in delay compared to the THz pulse. Therefore the description of the traces is from high delay to low delay. Looking at the reference (red) in figure 4.5 it can be seen that the THz signal trace starts with a quasi single cycle originating from the front edge of the THz undulator. The front edge single cycle field is followed by 10 field cycles originating from the THz undulator with the last field cycle being superimposed with the single cycle of the electron beam dump magnet. Comparing the reference to the sample trace several differences are apparent. At first the front edge single cycle field at around $11 \, ps$ is strongly absorbed, attenuating the maximum THz signal by more than a factor of 2. Additionally the falloff of the single cycle is shifted in time by several $100 \, fs$. Following this the sample is reacting to the multi cycle field trace. For the first 6 cycles the THz signal traces follows the reference trace with a time shift of about $60 \, fs$ or approximately $\pi/6$. From field cycle 7 onward, at $8 \, ps$ delay, the THz signal trace reflected

$^3$Neglecting the difference in polarization dependent reflectivity at the silicon beam splitter.
of the sample is higher in THz signal and therefore field strength. This effect is amplified drastically from this point on where the magnitude of the THz signal is overwhelming the reference signal by more than a factor of 2. The amplification is lasting through the last 4 field cycles and vanishes after the pulse. The complete process is yet to be understood but following the field trace it may be the case that the strongly absorbed single cycle at the beginning of the pulse creates the coherent phonon motion aimed at, leading to a dipole moment in the sample. The phononic motion is than further amplified by the multi cycle THz pulse at resonance frequency, creating an oscillating dipole that is emitting radiation at its resonant frequency. The quasi immediate suppression of the emitted signal can be explained, as the system at room temperature is strongly favoring the inversion symmetric configuration, which results in high damping of the dipole oscillations and therefore only one additional field cycle at about 6.5 ps. The signal strength is still within the linear regime of

Figure 4.5: The recorded THz signal trace for the reference and STO at 110 um, measured with a wire grid polarizer and a 77 um low pass filter before the sample position. The reference trace is shown in red and the STO trace in black. There are distinct differences visible at the beginning around 11 ps and at the end of the pulse at approximately 7 ps.
the electro-optical detection with a maximum change of 13.37% of the incoming intensity\(^4\).

Figure 4.5 indicates an ultrafast phase change in STO triggered by a strong single cycle THz pulse, similar to the work of Kozina et al. [151] and a resonant amplification of the phononic motion, ultimately leading to a, by more than 100% amplified, THz emission. A second possible explanation can be based upon the ferroelectric configuration described by Sulpizio et al. [145], that naturally occurs at temperatures lower than 23 K. The configuration change leads to a dual well energy surface similar to the surface of lead titanate [34]. A possible explanation for the observed field structure can be that around the 6th field cycle the excursion of the titanium atom against the the oxygen octahedron gets large enough for it overcome the central energy barrier, leading to switching of the dipole moment from positive to negative and vice versa. In order to determine the actual process several steps need to be taken. A detailed analysis and simulation of the energy surface of STO under strong excitation needs to be performed. Additionally studies with atomic resolution, similar to the work of Kozina et al. can bring more fundamental understanding. Unfortunately both is beyond the scope of this work. Looking at the frequency composition of the reference and the STO sample trace a similarly clear difference can be seen. Figure 4.6 shows the normalized amplitude spectrum of the THz signal trace of the reference (red) and the STO (black) shown in figure 4.5. The fundamental frequency of about 2.7 THz can be seen. Additionally low frequency components can be seen for both the reference and STO. The main difference can be seen in the frequency range between 3 and 4 THz. The STO spectrum shows a strong increase in spectral components in this frequency range. In addition an increase in the low frequency range between 1 and 2 THz can be seen. Following the recent work of Kozina et al. [151] the frequency components between 3 and 4 THz could be associated to the soft mode. This partially contradicts the finding of Stirling [149] giving 2.72 THz as the STO soft mode for bulk STO. The change in the soft mode frequency is most likely due to the thin film sample used by Kozina, as different soft mode frequencies were reported for thin films [153]. The generated frequency components can possible be understood as a stiffening of the soft mode when strongly excited [153]. The strong broadband increase in the range between 3 and 4 THz is not fully understood and opens up more questions. The peak at 3.2 THz sitting on top of the broader shoulder is exactly at double the frequency of the peak found at the increase low frequency components between 1 and 2 THz. With the lack of knowledge about the shape of the energy surface of STO under strong excitation, the origin of the individual frequency components can only be speculated. It can therefore only be stated

\(^4\)See equation (3.2.1) for further information
Figure 4.6: The normalized amplitude spectrum of the THz signal traces presented in figure 4.5 for the reference and the sample excited at 110 um at full power using a wire grid polarizer and a 77 um low pass filter. The fundamental of the excitation can be seen at 2.72 THz. In the case of the sample spectrum additional frequency components can be seen between 3 – 4 and 1 – 2 THz.

that additional frequency components, both lower and higher in frequency are generated by the sample when excited by strong THz pulses. In order to verify that the behavior observed in the THz signal and in the corresponding spectrum are nonlinear features originating from strong THz excitation, additional measurements at lower THz fluence need to be evaluated. Furthermore it is proposed, that the observed effect is based on the STO soft mode motion. In order to address the soft mode an excitation with linear polarization is required, which is achieved by the wire grid polarizer. In order to verify the hypothesis a non linearized excitation needs to be evaluated.
4.3.2 Linear excitation with reduced fluence

In order to verify the nonlinear nature of the signal shown in figure 4.5 measurements with reduced THz intensity need to be evaluated. In order to do so, an additional silicon wafer is introduced at normal incidence into the beam path. At normal incidence the silicon wafer reduces the intensity by approximately 50% while not introducing additional absorption lines, as the material is equal to the beam splitter used. Additionally before the sample position a 77 μm low pass filter as well as the wire grid polarizer are mounted, allowing for a low frequency linearly polarized excitation. Figure 4.7 shows the THz signal trace

![Graph showing THz signal trace comparison](image)

**Figure 4.7:** The comparison of the THz signal trace reference and reflected of the sample at reduced fluence with the undulator tuned to 110 μm wavelength. A 77 μm low pass filter and the wire grid polarizer are installed before the sample. To reduce the fluence a silicon wafer is introduced at normal incidence before the beam splitter. The THz signal trace of the sample follows the reference closely while being reduced in amplitude due to the reduced reflectivity of STO. No nonlinear behavior is visible.

comparison between the reference (red) and the STO (black) for the case of reduced fluence. The overall field shape is similar to the maximum fluence case of figure 4.5. The THz signal trace starts around 10 ps with the front edge of the undulator creating a quasi single cycle
THz signal trace. Following the single cycle is the 10 period undulator pulse centered at 110 $\mu m$ or $2.72 \text{THz}$ and therefore at the resonance frequency of the STO soft mode. The last period of the THz signal created by the undulator is overlapped with the single cycle radiation created by the electron dump magnet. The THz signal trace reflected of the STO sample follows the reference trace closely. The main difference observed is the lower THz signal throughout the trace. This can be explained by the reflectivity of the sample of about 80% [152]. Comparing to the high fluence case shown in figure 4.5 there is neither a large absorption at the front edge visible nor an amplification of the THz signal strength towards the end of the pulse. Both missing features features at similar conditions apart from the reduced fluence indicate the nonlinearity of the process observed by the transient changes in THz signal. Looking at the normalized amplitude spectrum in figure 4.8 supports the

![Normalized Amplitude Spectrum](image)

Figure 4.8: The normalized amplitude spectrum of the reference and the STO measurement with 110 $\mu m$ excitation wavelength shown in figure 4.7. A 77 $\mu m$ low pass filter and a wire grid polarizer are mounted before the sample and a silicon wafer is introduced before the beam splitter to reduced the fluence. There are no additional frequency components visible between 3 and 4 or 1 and 2 $\text{THz}$.

impression gained from the THz signal trace. The spectrum of the reference shows the
fundamental frequency of the undulator at $2.72\,T\,Hz$ with a steep falloff towards the $77\,um$ low pass filter edge at around $3.9\,T\,Hz$. Additionally the broadband background originating from the single cycle edge radiation can be seen spanning from around $0.5\,T\,Hz$ up to the filter edge. The sample spectrum follows the reference spectrum closely. Comparing to the high fluence case presented in figure 4.6 no additional frequency components can be seen between 1 and 2 or 3 and $4\,T\,Hz$. There is no indication of a nonlinear process generating additional frequency components. The spectral components at about $5\,T\,Hz$ can be originating from the $TO_2$ mode of STO, that was found for the thin film case to be around $5.4\,T\,Hz$ [151]. The findings at reduced fluence support the possibility of a nonlinear process being triggered at high fluence, leading to an ultrafast phase change.

### 4.3.3 Non-linearized excitation at maximum fluence

The second hypothesis to be evaluated, in order to verify the possibility of driving a nonlinear process via the STO soft mode, is the requirement for an excitation with linearly polarized THz light. In order to create a directed phonon motion similar to the schematic in figure 4.2 it is necessary to have a linearly polarized THz pulse. The interaction of multiple polarization components, as found in the edge radiation, with the sample would lead to an smaller net polarization. This can be understood when realizing the origin of the net polarization is the shift of the titanium atom out of its central position and the associated change towards a ferroelectric phase. As described in the work of Sulpizio [145] this change occurs naturally for certain isotopes at low temperatures, as it becomes energetically favorable. A shift of the central titanium atom not only in vertical but additionally in horizontal direction would possibly lead to an energetically much more unfavorable state of the crystal lattice, which would therefore be suppressed, leading to a very small or no net excitation. Yet again, without detailed knowledge of the energy surface under strong excitation the given explanation remains purely hypothetical. Figure 4.9 shows the THz signal trace of the reference (red) and the sample (black) taken with the undulator tuned to $110\,um$ using a $77\,um$ low pass filter but no polarizer, therefore letting all polarization components of the edge radiation propagate to the sample. The THz signal trace start with the front edge of the undulator at about $11\,ps$ overlapping with the first period of the 10 cycle undulator pulse. The pulse is ending at about $7.5\,ps$ with the single cycle overlapping with the last period of the undulator. The THz signal trace measured with the sample in position follows the reference field closely. Comparing to the signal observed at similar conditions with a wire grid polarizer shown in figure 4.5, there is no absorption of the front edge single cycle
Figure 4.9: THz signal traces of the reference and the sample excited at 110 \textit{um} using a 77 \textit{um} low pass filter and letting all polarization components propagate to the sample. The sample trace follows the reference trace closely with a small decrease of THz signal. Neither an absorption of the front edge nor an amplification of the THz signal are visible.

radiation visible. Furthermore there is no phase shift between the reference and the sample trace observable. Most prominently the enhancement of the THz signal towards the end of the pulse is missing, when all polarization components are propagated over the sample. Figure 4.9 support the hypothesis that the excitation with all frequency components of the edge radiation suppresses effective coupling to the STO soft mode and ultimately the establishment of a phase change leading to a net polarization. Thereby it supports the initial hypothesis of a nonlinear phenomenon based on the resonant excitation of the STO soft mode.
4.3.4 Conclusion

Within this chapter the capabilities of the THz pulse characterization tool for nonlinear THz driven dynamics experiments are shown. The upgrade to accommodate a sample in reflective geometry is elaborated and a suited sample system, strontium titanate, is introduced along with a proposed excitation channel. The strontium titanate soft mode motion is explained alongside its resonant frequency and an experiment to drive the soft mode motion resonantly in order to induce a phase change leading to properties expected by the ferroelectric phase. The presented data at high fluence utilizing a polarization cleaned excitation show large differences between the THz signal of the recorded reference and the sample trace. A hypothesis is presented explaining the observable differences at the beginning and at the end of the recorded traces, based on a phase change towards a ferroelectric structure. Consecutively the hypothesis is tested based on fluence dependent nonlinearity and linearly polarized excitation. It is shown that the additional data support the initial idea and the possibility of an ultrafast phase change that allows resonant excitation of the system and consequent THz signal enhancement\textsuperscript{5}.

\textsuperscript{5}Under the assumption of monochromatic radiation this is directly proportional to the electric field.
Chapter 5

Conclusion and Outlook

The advance in the field of light sources triggers the advance in metrology. This is seen across the complete spectral range provided by laser systems, synchrotrons and free electron lasers. Within the frame of this work great progress was made in the metrology of ultrafast THz pulses at high repetition rates available at the THz beamline at the FLASH facility in Hamburg. Two different approaches are made in order to fully characterize the THz radiation. First a simulation code was developed utilizing the SRW code, allowing to predict the intensity profile of the THz radiation along with its divergence, harmonic content and polarization. The capabilities of the developed code are shown on the example of the FLASH1 THz sources and the associated beamline. It is granting insight into the interaction of the different radiation sources and the resulting beam profile throughout the THz beamline. The developed toolset was already used to calculate the beam transport and incoupling into a complex experimental chamber used in the experiment of Castiglioni et al., effectively coupling the THz radiation through a telescope onto a inch parabola and the subsequent target.

Based on the good agreement between simulation and the presented measurements at FLASH1 a model for a dedicated THz source at FLASH2 was developed. Different undulator designs have been investigated, resulting in the presented helical few period design. Based on this design a study on the resulting intensity profile as well as a beamline optics design proposal are made, accommodating the boundary conditions given by the facility layout. The design study is concluding in a comparison of the transmission through the THz beamlines at FLASH1 and 2 at a variety of wavelengths, showing about 20% increase in long wavelength transmission with the proposed design.

As the second approach, a THz pulse characterization tool was developed. It operates at
In order to extend the capabilities of the THz pulse characterization tool a further upgrade was made. An intermediate sample position was incorporated, allowing to study THz driven lattice dynamics in, for example, perovskite type transition metal oxides. The experimental possibilities were explored on the example of Strontium titanate, by resonant excitation of the soft mode. The studies aimed at a quasi-stable ultrafast phase change into a structure resembling the ferroelectric phase that can be found when cooling STO. Following the scientific advances with transition metal oxides the creation of higher frequency THz radiation was proposed as an indicator for the phase change. The hypothesis was tested with a series of measurements at different excitation frequencies and levels of THz fluence. The results show an increase in higher THz frequency components at resonant excitation and maximum fluence, as well as a decrease in the effect strength at reduced fluence and at varying excitation frequencies. Furthermore a strong enhancement of the trailing part of the reflected THz pulse can be seen that indicates an interplay of the different parts of the THz pulse with the sample, resulting in an initial ultrafast phase change followed by a resonant excitation and an enhanced emission of THz radiation. While time resolved simulation of the energy surface of STO under external excitation need to be performed, the presented results show agreement with literature sources and support the hypothesis of an ultrafast phase change.
followed by a resonant excitation of the soft mode motion. The presented experiment is
the first THz driven - THz resolved experiment performed utilizing the upgraded THz pulse
colorization tool. It shows the possibility of field resolved THz driven experiments with
femtosecond time resolution and resonant excitation at high spectral brightness. The system
can be combined with a femtosecond laser system, expanding the scientific possibilities at
the THz beamline even further.
Appendices
Appendix A

Appendix A - SRW Code for FLASH1

#pragma rtGlobals=1 // Use modern global access method
.
KillWaves /A
// FLASH THz Facility

proc ShT()

SrwUtiKillAllGraphs()

Variable i, nn, n1, n2, n01, n02, n11, n12, Lw1, Lw2, lng2, k, dist, Ffund, Fmin, Fmax, Fund, Nw1, Nw2, caledist, j, printdist, h, l
Variable ING1
Variable E0, c0, m0, q0, Kw1, Kw2, Charge, Mgstep, Mzero, Rt1, Rt2, Rt3, step1, step2, step3, dist1, dist2, dist3, dist4, dist5, dist6, Rt4, Rt5, Rt6, step4, step5, step6
Variable Energy, Plank_eV, kf, dX, dY, pX, pY, ENR, cou, cou1, Mzero2, Mgstep2
String name1, name2, nnw1, nnw2, wrnm, elnm, obsnm, distance, count, count1

nn=1
plank_eV = 4.135669212e-15;
E0 = 0.511;
c0 = 2.99792458e8;
m0 = 9.109389e-31;
q0 = -1.602177e-19;

// geometry for focussing mirrors – distance between mirrors in m

dist1 = 1.5

dist2 = 11.75

dist3 = 11

dist4 = 14

dist5 = 22

dist6 = 18

step1 = 1.5

step2 = 11.75

step3 = 11 // check that dist1, 2, 3 can be devided by steps to natural number !!!!!!!

step4 = 0.5

step5 = 0.5

step6 = 0.5
Rt1 = 2.13737
Rt2 = 1.65608
Rt3 = 10.1978
Rt4 = 11.1043
Rt5 = 20.0
Rt6 = 18.8456

Energy = 600
Charge = 1e-9
// x-ray-undulator
Lw1 = 0.0237
Nw1 = 50
// Thz-undulator
Lw2 = 0.4;
Nw2 = 11

Mgstep = 0.001
Mzero = 0.003

Mgstep2 = 0.001
Mzero2 = 0.003
// z=0 corresponds to the begining of the magnetic structure

dist = 16

kf = 1e3
dX = 480
pX = 500
dY = 480
pY = 500
Make/D /N=(pX, pY) /O w4
n11 = Mzero / Mgstep
n12 = Mzero2 / Mgstep2
\[ n01 = \text{Lw1}/Mgstep/2; \]
\[ n02 = \text{Lw2}/Mgstep2/2; \]
\[ \text{ING1} = 2 \times \text{Mzero} + \text{Nw1} + \text{Lw1}; \]
\[ \text{lng2} = 2 \times \text{Mzero2} + \text{Nw2} + \text{Lw2}; \]
\[ n1 = \text{ING1}/\text{Mgstep} + 1; \]
\[ n2 = \text{lng2}/\text{Mgstep2} + 1; \]
\[ i = 0 \]

SrwInit(1)

// ..............................................................

//-------------------------------X-ray-undulator
//do
Kwl = \text{Lw1} \times q0 \times Bmax1[i] / m0 / c0 / \pi / 2;
Ffund = c0 \times \text{Plank\_eV} / (E0 \times E0 \times \text{Lw1} \times (1 + Kwl \times (Kwl) / 2) / 2.\text{Energy} / \text{Energy}) / k_f;
SrwUtilPhotEnConv(Ffund, 1, 6)
Fmin = 0.7 \times Ffund
Fmax = 1.4 \times Ffund
\text{printf}\_name1, "Mag%d1", i;
SrwMagFieldCreate(name1, 0, ING1, n1);
\text{printf}\_nmw1, "Mag%d1BZ\_fld", i;

//SRW sin generation
SrwMagSin(nmw1, 1, 0, (Lw1) / 1e-3, 0, 0, \text{Nw1}, Bmax1[i], 0, 0);

// Display Mag0BZ\_fld
k = 0;

// Conversion to adiabatic
do
\$\text{nmw1}[k] = 0.5 \times \$\text{nmw1} | k | ;
\$\text{nmw1}[ (n1) - k - 1 ] = 0.5 \times \$\text{nmw1}[ (n1) - k - 1 ];
k = k + 1;
while (k < n1 + n01)
do
  k=k+1;
  $nmw1[k]=0.75*$nmw1[k];
  $nmw1[(n1)−k−1]=0.75*$nmw1[(n1)−k−1];
while (k<n11+2*n01);
/
  // Display  Mag01BZ_fld
  // Display  Mag01BX_fld

//---------------------------THz-undulator
//do
Kw2=Lw2*q0*Bmax2[i]/m0/c0/pi/2;
Ffund=c0*Plank_eV/(E0*E0*Lw2*(1+Kw2*(Kw2)/2)/2/Energy/Energy)/kf;
variable fundamental_thz
fundamental_thz = 1239.84187/Ffund/10^6
SrwUtiPhotEnConv(Ffund,1,6)
Fmin=0.7*Ffund
Fmax=1.4*Ffund
sprintf name2,"Mag%d2",i;
SrwMagFieldCreate(name2,0,lng2,n2);
sprintf nmw2,"Mag%d2BZ_fld",i;
//SRW sin generation
SrwMagSin(nmw2,1,0,Lw2/1e-3,0,0,Nw2,Bmax2[i],0,0);
// Display  Mag01BZ_fld
k=0;
//Conversion to adiabatic
do
  $nmw2[k]=0.5*$nmw2[k];
  $nmw2[n2−k−1]=0.5*$nmw2[n2−k−1];
k=k+1;
while (k<n12+n02)
do
  k=k+1;
\$nmw2[k] = 0.75*nmw2[k];
\$nmw2[n2-k-1] = 0.75*nmw2[n2-k-1];

while (k<n12+2*n02);

// Display Mag02BZ_fld
// Display Mag02BX_fld
//---------------------bending magnets
//
// variable LBM1
LBM1=0.430
SrwMagFieldCreate("BM1",0,LBM1,LBM1*1000)
SrwMagZero("BM1BZ_fld")
SrwMagZero("BM1BX_fld")

// variable SBM1
SBM1 = (0.608/1250)*Energy
SrwMagEdge("BM1BZ_fld",1,0.875,0.150,0,SBM1)
SrwMagEdge("BM1BZ_fld",2,0,0.420,0,SBM1)
SrwMagEdge("BM1BX_fld",1,0.875,0.150,0,0.0)
SrwMagEdge("BM1BX_fld",2,0,0.420,0,0.0)

// Display BM1BZ_fld
// Display BM1BX_fld

//DeletePoints 0,280,BM1BZ_fld
//// Display BM1BZ_fld
//DeletePoints 440,719,BM1BZ_fld
//
// Display BM1BZ_fld
//

//SrwMagEdge("BM1BX_fld",1,0.875,0.150,0,0.0)
//SrwMagEdge("BM1BX_fld",2,0,0,0.420,0,0.0)
//// Display BM1BX_fld

192
// DeletePoints 0,280,BM1BX_fld
// Display BM1BX_fld
// DeletePoints 440,719,BM1BX_fld

// Display BM1BX_fld
// SrwMagFieldCreate("BM2",0,1.25,1250)
// SrwMagZero("BM2BZ_fld")
// SrwMagZero("BM2BX_fld")

//
// SrwMagEdge("BM2BX_fld",1,1.0,0.150,0,1.180)
// SrwMagEdge("BM2BX_fld",2,0.0,1.200,0,−1.180)

variable pBM2,LBM2
LBM2=1.22
pBM2=LBM2*1000
SrwMagFieldCreate("BM2",0,LBM2,pBM2)
SrwMagZero("BM2BZ_fld")
SrwMagZero("BM2BX_fld")

variable SBM2
SBM2 = 1.180/1250*Energy
SrwMagEdge("BM2BX_fld",1,1.0,0.150,0,SBM2)
SrwMagEdge("BM2BX_fld",2,0.0,1.200,0,−SBM2)

// Display BM2BX_fld
// DeletePoints 0,190,BM2BX_fld
// Display BM2BX_fld
// DeletePoints 1221,1410,BM2BX_fld

// Display BM2BX_fld

SrwMagEdge("BM2BZ_fld",1,1.0,0.150,0,0.0)
SrwMagEdge("BM2BZ_fld",2,0.0,1.200,0,−0.0)
// Display BM2BZ_fld
// DeletePoints 0,190,BM2BZ_fld
// Display BM2BZ_fld

193
variable Ld00
Ld00 = 0.49
SrwMagFieldCreate("L00",0,Ld00,Ld00*1000)
SrwMagConst("L00BZ_fld",0.0)
SrwMagConst("L00BX_fld",0.0)

variable Ld0
Ld0 = 0.5
SrwMagFieldCreate("L0",0,Ld0,Ld0*1000)
SrwMagConst("L0BZ_fld",0.0)
SrwMagConst("L0BX_fld",0.0)

variable Ld1
Ld1=4.71
SrwMagFieldCreate("L1",0,Ld1,Ld1*1000)
SrwMagConst("L1BZ_fld",0.0)
SrwMagConst("L1BX_fld",0.0)

variable Ld2
Ld2=3.941
SrwMagFieldCreate("L2",0,Ld2,Ld2*1000)
SrwMagConst("L2BZ_fld",0.0)
SrwMagConst("L2BX_fld",0.0)

variable Ld3
Ld3=2
SrwMagFieldCreate("L3",0,Ld3,Ld3*1000)
SrwMagConst("L3BZ_fld",0.0)
SrwMagConst("L3BX_fld",0.0)
// Display L3BZ_fld

// SrwMagFieldCreate("L4", 0, 0.2, 200)
// SrwMagConst("L4BZ_fld", 0.0)
// SrwMagConst("L4BX_fld", 0.0)

// Display L4BZ_fld

// . . . . . Programme generated field

variable Lmag
Lmag=Ld00+LBM1+LBM2+Ld0+Ld1+Ld2+n11+n12+Ld3
// Lmag=Ld00+LBM2+Ld0+Ld1+Ld2+n11+n12+Ld3
SrwMagFieldCreate("CPBM", Lmag/2, Lmag, Lmag*1000);

SrwMagZero("CPBMBZ_fld")
SrwMagZero("CPBMBX_fld")

Concatenate//o {L00BZ_fld, BM1BZ_fld, L0BZ_fld, Mag01BZ_fld, L1BZ_fld,
    Mag02BZ_fld, BM2BZ_fld, L3BZ_fld} , CPBMBZ_fld
// Concatenate//o {L00BZ_fld, L0BZ_fld, Mag01BZ_fld, L1BZ_fld,
    Mag02BZ_fld, BM2BZ_fld, L3BZ_fld} , CPBMBZ_fld
// SetScale x, 0, Lmag, "m", CPBMBZ_fld

Concatenate//o {L00BX_fld, BM1BX_fld, L0BX_fld, Mag01BX_fld, L1BX_fld,
    Mag02BX_fld, BM2BX_fld, L3BX_fld} , CPBMBX_fld
// Concatenate//o {L00BX_fld, L0BX_fld, Mag01BX_fld, L1BX_fld,
    Mag02BX_fld, BM2BX_fld, L3BX_fld} , CPBMBX_fld
// SetScale x, 0, Lmag, "m", CPBMBX_fld

Display CPBMBZ_fld
Display CPBMBX_fld

195
// Electron beam

// SrwElecFilament("ELBM",1e-3*Energy,Charge,0,0,0,0);
SrwElecFilament("ELBM",1e-3*Energy,Charge
,0,−28.288067104528,61.3693725014440061,0,0);
// 61.3699925004440061
// 0.000007499999939
// SrwElecThick(elnm="_ebm
".0014,150.0,150.0,2.0,0.4,0,0,0,0);

// Electron Trajectory

SrwTrjCreateTransvUnif("Traj","ELBM_ebm","CPBM_mag
",1,2,1,2)

// Mode of Longitudinal Integration

SrwMagPrec("CPBM_mag",3,0.01,0.01,10000,1,0,0);

// Observation Range

end
ENR=Ffund
SrwUtiPhotEnConv(ENR,1,6)
SrwSmpCreate("O", dist);
SrwSmpScanXZE("O_obs", 0, dX, pX, 0, dY, pY, ENR, ENR, 1);
SrwWfrCreate("W", "ELBM_ebm", "CPBM_mag", "O_obs", 2, 1)

//SrWfr2Int("W_rad","PT",7,1,4,1,ENR,0,0,2)
//ModifyImage ($"WPT_xz") ctab= {*,*,Spectrum,1}
//SrWfr2Int("W_rad","IPTht",7,1,2,1,ENR,0,0,2)

// SrWfr2Int("W_rad","IPTvt",7,1,3,1,ENR,0,0,2)
end

string penergy, fundamental_thz_string
penergy=num2str(Energy)
fundamental_thz_string=num2str(fundamental_thz)
SrWfr2Int("W_rad","Ihor",1,1,4,1,ENR,0,0,2)
Save/J/O/P=flash1 Whor_xz as "calculated_initial_at_" +
fundamental_thz_string+ "um_and_" +penergy+ "GeV.txt"

ModifyImage ($"Whor_xz") ctab= {*,*,Spectrum,1}
SrWfr2Int("W_rad","horprof",1,1,2,1,ENR,0,0,2)

//SrWfr2Int("W_rad","PV",2,1,4,2,ENR,0,0,2)
// ModifyImage ($"WPV_xz") ctab= {*,*,Spectrum,1}

// SrWfr2Int("W_rad","IPVht",2,1,2,1,ENR,0,0,0,2)
// SrWfr2Int("W_rad","IPVvt",2,1,3,1,ENR,0,0,2)

//SrWfr2Int("W_rad","PH",1,1,4,1,ENR,0,0,2)
//ModifyImage ($"WPH_xz") ctab= {*,*,Spectrum,1}

//SrWfr2Int("W_rad","IPHht",1,1,2,1,ENR,0,0,2)
//SrWfr2Int("W_rad","IPHvt",1,1,3,1,ENR,0,0,2)

// move beam onto first mirror

SrwOptApertRect("Ap1",52,68,0,0)
SrwOptApertCirc("Ap",110,0,0)
SrwOptApertCirc("Ap2",200,0,0)
SrwOptDrift("D01",-4.5)
SrwOptDrift("D02",1.25)
SrwOptDrift("D1",+0.2236)
SrwOptDrift("D2",+0.0001)
SrwOptDrift("D3",+0.0001)
SrwOptDrift("D4",+3.25)

//SrwOptDrift("D2",+1.2)
//SrwOptApertRect("Ap2",52,68,8,0)
//SrwOptDrift("D3",+1.126)

SrwOptCont("Container98")
  SrwOptContAdd("D01_bli","Container98_bli",2)
  SrwOptContAdd("Ap1_bli","Container98_bli",2)
  SrwOptContAdd("D02_bli","Container98_bli",2)
  SrwOptContAdd("Ap1_bli","Container98_bli",2)
  SrwOptContAdd("D4_bli","Container98_bli",2)

SrwWfrPropagate("W_rad","Container98_bli",2,2,"W1")
  SrwWfr2Int("W1_rad","Ihor",1,1,4,1,ENR,0,0,2)
ModifyImage $("W1hor_xz") ctab= {*,*.. Spectrum,1}
SrwWfr2Int("W1_rad","horprof",1,1,2,1,ENR,0,0,2)
Save/J/O/P= flash1 W1hor_xz as "calculated_behind_the_dump_at_"
  fundamental_thz_string+ "um_and_" +prenery+ "_GeV.txt"
// SavePict/E=−5/B=288 as "rad_0.1"
  mm_behind_aperture_on_first_torroid.png"
end

// SrwOptCont("Container99")
// SrwOptContAdd("D1_bli","Container99_bli",2)
// SrwOptContAdd("Ap1_bli","Container99_bli",2)
SrwOptContAdd("D2_bli","Container99_bli",2)
SrwOptContAdd("Ap2_bli","Container99_bli",2)
SrwOptContAdd("D3_bli","Container99_bli",2)

//SrWfrPropagate("W_rad","Container99_bli",2,2,"W2")
//SrWfr2Int("W2_rad","Ihor",1,1,4,1,ENR,0,0,2)
//ModifyImage $('"W2Ihor_xz"') ctab= {*,*,Spectrum,1}
//SavePict/E=−5/B=288 as "rad_at_first_torroid_50mm_app_Int_xy.png"

/////first torroid — 3m focal length

//SrWfrPropagate("W1_rad","Container1_bli",2,2,"Wd1")
//SrWfr2Int("Wd1_rad","Ihor",1,1,4,1,ENR,0,0,2)
//ModifyImage $('"Wd1Ihor_xz"') ctab= {*,*,Spectrum,1}
//SavePict/E=−5/B=288 as "rad_0.1mm_behind_first_torroid.png"

j=1
//SrWfrPropagate("W1_rad","Container1_bli",2,2,"Wd1")
//SrWfr2Int("Wd1_rad","Ihor",1,1,4,1,ENR,0,0,2)
//ModifyImage $('"Wd1Ihor_xz"') ctab= {*,*,Spectrum,1}
//SavePict/E=−5/B=288 as "rad_0.1mm_behind_first_torroid.png"
// SrwOptContAdd("D3 bli","Container1 bli",2)
// slicing of first 6 m drift space from torroid 1 to torroid 2 (removed13mm drifted due to convenience)
do
   SrwUtiKillAllGraphs()
calcdist=+(step1*j)
// calcdist=+(0.25*j)
// calcdist=1
printdist=9.237+calcdist;
cou = j
cou1 = j+1
sprintf distance,num2str(printdist);
sprintf count,num2str(cou);
sprintf count1,num2str(cou1);

SrwOptDrift("D",+step1)

SrwOptCont("Container")

SrwOptContAdd("Ap2 bli","Container bli",2)
SrwOptContAdd("D bli","Container bli",2)

// Wavefront Propogation

SrwWfrPropagate("Wd"+count+"_rad","Container bli",2,2,"Wd"+count1)
SrwWfrResize("Wd"+count1+"_rad",1,1,1,1,1,2,"Wddd")

// SrwWfr2Int("Wddd_rad","Icomp",7,1,4,1,ENR,0,0,2)
// ModifyImage $("WdddIcomp_xz") ctab= {*,*,Spectrum,1}

200
Save/J/O/P=new_geometrics WddIdcomp_xz as distance+ "_xy_hor_BM_vert_dump_comp_pol_torroids.txt"

SavePic/E=-5/B=288 as distance+"_vert_dump_comp_Int_xy.png"

SrwWfr2Int("Wddd_rad","Ihor",1,1,4,1,ENR,0,0,2)
ModifyImage $("WddIdlor_xz") ctab= {*,* ,Spectrum,1}
Save/J/O/P=new_geometrics WddIdlor_xz as distance+ "_xy_hor_BM_vert_dump_hor_pol_torroids_15.txt"

SavePic/E=-5/B=288 as distance+"_vert_dump_hor_Int_xy.png"

SrwWfr2Int("Wddd_rad","Ivert",2,1,4,1,ENR,0,0,2)
ModifyImage $("WddIdvert_xz") ctab= {*,* ,Spectrum,1}
Save/J/O/P=torroids_dump_aperture WddIdvert_xz as distance+
"_xy_hor_BM_vert_dump_vert_pol_torroids.txt"

SavePic/E=-5/B=288 as distance+"_vert_dump_vert_Int_xy.png"

KillWaves $("Wd"+count+ "X_rae")
KillWaves $("Wd"+count+ "Z_rae")

Save/J/O/U={1,1,1,1}/P=hor_BM_vert_dump_pol_splittet
WdDPV_x as distance+"_x_hor_BM_vert_dump_vert_pol.txt"

Save/J/O/P=hor_BM_vert_dump_pol_splittet WdDPV_xz as
distance+ "_xy_hor_BM_vert_dump_vert_pol.txt"

SavePic/E=-5/B=288 as distance+"_vert_dump_Int_xy.png"

Textbox/N=text0/F=0 *divergence at "+distance
j=j+1
// while (j<120)
while (j<((dist1/step1)+1))

j=1
cou = j
cou1 = j+1

sprintf count, num2str(cou);
sprintf count1, num2str(cou1);
//while (j<4)
\\\\\picture at second torroid position @ 10.85 m

//SrwWfr2Int("Wd_rad","Ihor",1,1,4,1,ENR,0,0,2)
// ModifyImage $("Wdhor_xz") ctab= {*,*,Spectrum,1}

//second torroid - 7 m focal length [remember pos. sign at angle]

SrwOptThinMirTorInit("TM2",210,150,0,0);
  //Rt2= 10.8902 //7
  //12
  SrwOptThinMirTorSetup("TM2",1,Rt2,((Rt2)/2)
  ,+0.785398163,0,0,215,150)
SrwOptCont("Container2")
  SrwOptContAdd("TM2 bli","Container2 bli",2)
  SrwOptContAdd("D3 bli","Container2 bli",2)

SrwWfrPropagate("Wddd_rad","Container2 bli",2,2,"Wd" +count)

//h=2
\\\\\slicing of next driftspace of 2.25m from second to third torroid
  do
    SrwUtiKillAllGraphs()
calc dist =+(step2*j)  
  //calc dist =7.25  
  //calc dist =+(0.25*h)  
  //print dist =15.237+calc dist;  
  print dist =9.237+dist1+calc dist;  
  cou = j  
  cou1 = j+1  
  sprintf distance , num2str(print dist);  
  sprintf count , num2str(cou);  
  sprintf count1 , num2str(cou1);  

SrwOptDrift("D",+step2)  

SrwOptCont("Container")  
  
  SrwOptContAdd("Ap2_bli","Container_bli",2)  
  SrwOptContAdd("D_bli","Container_bli",2)

// Wavefront Propogation
  
  SrwWfrPropagate("Wd" +count+ "_rad","Container_bli",2,2,"Wd" +count1)  
  SrwWfrResize("Wd" +count1+ "_rad",1,1,1,1,2,"Wddd")

//    SrwWfr2Int("Wddd_rad","Icomp",7,1,4,1,ENR,0,0,2)
//    ModifyImage ($("WdddIcomp_xz") ctab= {*,*.*.Spectrum,1}
//    Save/J/O/P=new_geometrics WdddIcomp_xz as distance+ "_xy_hor_BM_vert_dump_comp_pol_torroids.txt"
//    SavePict/E=-5/B=288 as distance+_vert_dump_comp_Int_xy.png"
SrwWfr2Int("Wddd_rad","Ihor",1,1,4,1,ENR,0,0,2)
ModifyImageandalone("WdddIhor_xz")ctab=\{*,*,Spectrum,1\}
Save/J/O/P=new_geometricsWdddIhor_xz as distance+"_xy_hor_BM_vert_dump_hor_pol_torroids_15.txt"
  // SavePict/E=-5/B=288 as distance+"_vert_dump_hor_Int_xy.png"
  
  // SrwWfr2Int("Wddd_rad","Ivert",2,1,4,1,ENR,0,0,2)
  // ModifyImageandalone("WdddIvert_xz")ctab=\{*,*,Spectrum,1\}
  // Save/J/O/P=torroids_dump_apertureWdddIvert_xz as distance+
    +"_xy_hor_BM_vert_dump_vert_pol_torroids.txt"
  // SavePict/E=-5/B=288 as distance+"_vert_dump_vert_Int_xy.png"
  
  // Save/J/O/U={1,1,1,1}/P=hor_BM_vert_dump_pol_splittet
    WddPV_x as distance+"_x_hor_BM_vert_dump_vert_pol.txt"
  // Save/J/O/P=hor_BM_vert_dump_pol_splittet WddPV_xz as
distance+"_xy_hor_BM_vert_dump_vert_pol.txt"
  // SavePict/E=-5/B=288 as distance+"_vert_dump_Int_xy.png"
  // Textbox/N=text0/F=0 "divergence at "+distance
    KillWavesandalone("Wd"+count+"X_rae")
    KillWavesandalone("Wd"+count+"Z_rae")
  j=j+1
  // while (j<145)
  while (j<=(dist2/step2)+1)

SrwWfr2Int("Wddd_rad","Ihor",1,1,4,1,ENR,0,0,2)
ModifyImageandalone("WdddIhor_xz")ctab=\{*,*,Spectrum,1\}
Save/J/O/U={1,1,1,1}/P=new_geometricsWdddIhor_xz as "8"+
  +"_xy_hor_BM_vert_dump_hor_pol_Nw_4_100um_1.txt"
//SrwoptDrift("D4", +2.25)
    //SrwoptContAdd("D4_bli","Container2_bli",2)
//picture at third torroidal position @ 13.1m

//Srwoptwr2Iter("Wdd_rad","Ihor",1,1,4,1,ENR,0,0,2)
    //ModifyImage $("WddIhor_xz") ctab= {*,*,Spectrum,1}

j = 1
    cou = j
    cou1 = j + 1
    sprintf distance, num2str(printdist);
    sprintf count, num2str(cou);
    sprintf count1, num2str(cou1);

//third torroid - 9.5 m focal length [remeber neg. sign at angle]
SrwoptThinMirTorInit("TM3",210,150,0,0);
    SrwoptThinMirTorSetup("TM3",1,Rt3,((Rt3)/2), -0.785398163,0,0,215,150)
    SrwoptCont("Container3")
    SrwoptContAdd("TM3_bli","Container3_bli",2)
    SrwoptContAdd("D3_bli","Container3_bli",2)

SrwoptPropagate("Wddd_rad","Container3_bli",2,2,"Wd" + count)

//1=2
//slicing last 15 m from toroid 3 to hall
    do
        SrwUtiKillAllGraphs()
    calcdist=+(step3*j)
/calcdist = + (0.5 * l )
// calcdist = 15
printdist = 9.237 + dist1 + dist2 + calcdist;
cou = j

cou1 = j + 1

printf distance, num2str(printdist);
printf count, num2str(cou);
printf count1, num2str(cou1);

SrwOptDrift("D", + step3)

SrwOptCont("Container")

SrwOptContAdd("Ap2_bli", "Container_bli", 2)
SrwOptContAdd("D_bli", "Container_bli", 2)

// Wavefront Propogation

SrwWfrPropagate("Wd" + count + "_rad", "Container_bli", 2, 2, "Wd" + count1)
SrwWfrResize("Wd" + count1 + "_rad", 1, 1, 1, 1, 2, "Wddd")

// SrwWfr2Int("Wddd_rad", "Icomp", 7, 1, 4, 1, ENR, 0, 0, 2)
// ModifyImage ("WdddIcomp") ctab = {*/*, Spectrum, 1}
// Save/J/O/P=new_geometrics WdddIcomp_xz as distance+ "_xy_hor_BM_vert_dump_comp_pol_torroids.txt"
// SavePict/E=-5/B=288 as distance+"_vert_dump_comp_Int_xy.png"

SrwWfr2Int("Wddd_rad", "Ihor", 1, 1, 4, 1, ENR, 0, 0, 2)
ModifyImage ("WdddIhor") ctab = {*/*, Spectrum, 1}
Save/J/O/P=new_geometrics WdddIhor_xz as distance+ "_xy_hor_BM_vert_dump_hor_pol_torroids_15.txt"

// SrwWfr2Int("Wddd_rad","Ivert",2,1,4,1,ENR,0,0,2) // ModifyImage $("WdddIvert_xz") ctab= {*,*,Spectrum,1} // Save/J/O/P=torroids_dump_aperture WdddIvert_xz as distance + "_xy_hor_BM_vert_dump_vert_pol_torroids.txt" // SavePict/E=-5/B=288 as distance+"_vert_dump_vert_Int_xy.png"

// Save/J/O/U={1,1,1,1}/P=hor_BM_vert_dump_pol_splittered WddPV_xz as distance+"_x_hor_BM_vert_dump_vert_pol.txt"
// Save/J/O/P=hor_BM_vert_dump_pol_splittered WddPV_xz as distance+ "_xy_hor_BM_vert_dump_vert_pol.txt"
// SavePict/E=-5/B=288 as distance+"_vert_dump_Int_xy.png"
// Textbox/N=text0/F=0 "divergence at "+distance
KillWaves $("Wd" +count+ "X_rae")
KillWaves $("Wd" +count+ "Z_rae")

j=j+1
while (j<((dist3/step3)+1))
// while (1<30)

//SrwOptDrift("D5",+15)
//SrwOptContAdd("D5_bli","Container3_bli",2)
// picture at third torroidal position @ 28.1m – flash II hall

//SrwWfr2Int("Wddd_rad","Ihor",1,1,4,1,ENR,0,0,2) // ModifyImage $("WdddIhor_xz") ctab= {*,*,Spectrum,1}

SrwWfr2Int("Wddd_rad","Ihor",1,1,4,1,ENR,0,0,2)
ModifyImage $("WdddIhor_xz") ctab= {*,*,Spectrum,1}
Save/J/O/U={1,1,1}/P=new_geometrics Wdddhor_xz as "8+" _xy_hor_BM_vert_dump_hor_pol_Nw_4_100um_1.txt"

cou = j
cou1 = j+1

```c
sprintf distance, num2str(printdist);
sprintf count, num2str(cou);
sprintf count1, num2str(cou1);
```

//4th torroid - 9.5 m focal length [remeber neg. sign at angle]

SrwOptThinMirTorInit("TM4",210,150,0,0);

SrwOptThinMirTorSetup("TM4",1,Rt4,((Rt4)/2),+0.785398163,0,0,215,150)

SrwOptCont("Container4")

SrwOptContAdd("TM4_bli","Container4_bli",2)
SrwOptContAdd("D3_bli","Container4_bli",2)

SrwWfrPropagate("Wddd_rad","Container4_bli",2,2,"Wf" + count)

//1=2
//slicing last 15 m from toroid 3 to hall

```c
do
SrwUtiKillAllGraphs()
calcdist=+(step4*j)
//calcdist=+(0.5*l)
//calcdist=15
printdist=9.237+dist1+dist2+dist3+calcdist;
cou = j
cou1 = j+1
```
printf distance, num2str(printdist);
printf count, num2str(cou);
printf count1, num2str(cou1);

SrwOptDrift("D",+ step4)

SrwOptCont("Container")

SrwOptContAdd("A2_bli","Container_bli",2)
SrwOptContAdd("D_bli","Container_bli",2)

// Wavefront Propogation

..............................

SrwWfrPropagate("Wd"+count+"_rad","Container_bli",2,2,"Wd"
 +count1)
SrwWfrResize("Wd"+count1+"_rad",1,1,1,1,2,"Wddl")

// SrwWfr2Int("Wddd_rad","Icomp",7,1,4,1,ENR,0,0,2)
// ModifyImage $("WdddIcomp_xz") ctab= {*/*,Spectrum,1}
// Save/J/O/P=new_geometrics WdddIcomp_xz as distance+"_xy_hor_BM_vert_dump_comp_pol_torroids.txt"
// SavePic/E=-5/B=288 as distance+"_vert_dump_comp_Int_xy.png"

SrwWfr2Int("Wddd_rad","Ihor",1,1,4,1,ENR,0,0,2)
ModifyImage $("Wdddlhor_xz") ctab= {*/*,Spectrum,1}
Save/J/O/P=new_geometrics Wdddlhor_xz as distance+"_xy_hor_BM_vert_dump_hor_pol_torroids_15.txt"

// SrwWfr2Int("Wddd_rad","Ivert",2,1,4,1,ENR,0,0,2)
// ModifyImage $("Wdddlvert_xz") ctab= {*/*,Spectrum,1}
Save/J/O/P=torroids_dump_aperture WdddIvert_xz as distance + "_xy_hor_BM_vert_dump_vert_pol_torroids.txt"
SavePict/E=-5/B=288 as distance+"_vert_dump_vert_Int_xy.png"

Save/J/O/U={1,1,1,1}/P=hor_BM_vert_dump_pol_splittet WdddPV_x as distance+"_x_hor_BM_vert_dump_vert_pol.txt"
Save/J/O/P=hor_BM_vert_dump_pol_splittet WdddPV_xz as distance+ "_xy_hor_BM_vert_dump_vert_pol.txt"
SavePict/E=-5/B=288 as distance+"_vert_dump_Int_xy.png"

Textbox/N=text0/F=0 "divergence at "+distance
KillWaves $("Wd" +count+ "X_rae")
KillWaves $("Wd" +count+ "Z_rae")
j=j+1
while (j<((dist4/step4)+1))
//while (l<30)

j=1
cou = j
cou1 = j+1
sprintf distance, num2str(printdist);
sprintf count, num2str(cou);
sprintf count1, num2str(cou1);

//4th torroid - 9.5 m focal length [remeber neg. sign at angle]
SrwOptThinMirTorInit("TM5",210,150,0,0);
SrwOptThinMirTorSetup("TM5",1,Rt5,((Rt5)/2),
,+0.785398163,0,0,215,150)
SrwOptCont("Container5")
SrwOptContAdd("TM5_bli","Container5_bli",2)
SrwOptContAdd("D3_bli","Container5_bli",2)

SrwWfrPropagate("Wddd_rad","Container5_bli",2,2,"Wd" + count)

// l = 2
// slicing last 15 m from toroid 3 to hall
do
SrwUtiKillAllGraphs()
calcdist = +(step5*j)
// calcdist = +(0.5*l)
// calcdist = 15
printdist = 9.237 + dist1 + dist2 + dist3 + dist4 + calcdist;
cou = j
cou1 = j+1
sprintf distance, num2str(printdist);
sprintf count, num2str(cou);
sprintf count1, num2str(cou1);

SrwOptDrift("D",+step5)

SrwOptCont("Container")

SrwOptContAdd("Ap2_bli","Container_bli",2)
SrwOptContAdd("D_bli","Container_bli",2)

// Wavefront Propogation
.................................

SrwWfrPropagate("Wd" + count + "_rad","Container_bli",2,2,"Wd" + count1)
SrwWfrResize("Wd" + count1 + "_rad",1,1,1,1,2,"Wdd")

// SrwWfr2Int("Wddd_rad","Icomp",7,1,4,1,ENR,0,0,2)
// ModifyImage $("Wdddlcomp_xz") ctab= {*,*,Spectrum,1}
// Save/J/O/P=new_geometrics Wdddlcomp_xz as distance + "_xy_hor_BM_vert_dump_comp_pol_torroids.txt"
// SavePict/E=-5/B=288 as distance + "vert_dump_comp_Int_xy.png"

SrwWfr2Int("Wddd_rad","Ihor",1,1,4,1,ENR,0,0,2)
ModifyImage $("Wdddlhor_xz") ctab= {*,*,Spectrum,1}
Save/J/O/P=new_geometrics Wdddlhor_xz as distance + "_xy_hor_BM_vert_dump_hor_pol_torroids_15.txt"

// SrwWfr2Int("Wddd_rad","Ivert",2,1,4,1,ENR,0,0,2)
// ModifyImage $("Wdddlvert_xz") ctab= {*,*,Spectrum,1}
// Save/J/O/P=torroids_dump_aperture Wdddlvert_xz as distance + "_xy_hor_BM_vert_dump_vert_pol_torroids.txt"
// SavePict/E=-5/B=288 as distance + "vert_dump_vert_Int_xy.png"

// Save/J/O/U={1,1,1,1}/P=hor_BM_vert_dump_pol_splittet WddPV_x as distance + "_x_hor_BM_vert_dump_vert_pol.txt"
// Save/J/O/P=hor_BM_vert_dump_pol_splittet WddPV_xz as distance + "_xy_hor_BM_vert_dump_vert_pol.txt"
// SavePict/E=-5/B=288 as distance + "vert_dump_Int_xy.png"
// Textbox/N=text0/F=0 "divergence at " + distance
KillWaves $("Wd" + count + "X_rae")

KillWaves $("Wd" + count + "Z_rae")

j=j+1
while(j <= ((dist5/step5)+1))
while (l<30)

j=1
cou = j
cou1 = j+1
printf distance, num2str(printdist);
printf count, num2str(cou);
printf count1, num2str(cou1);

//4th toroid - 9.5 m focal length [remeber neg. sign at angle]
SrwOptThinMirTorInit("TM6",210,150,0,0);
SrwOptThinMirTorSetup("TM6",1,Rt6,((Rt6)/2),+0.785398163,0,0,215,150)
SrwOptCont("Container6")
   SrwOptContAdd("TM6 bli","Container6 bli",2)
   SrwOptContAdd("D3 bli","Container6 bli",2)
SrwWfrPropagate("Wdd_rad","Container6 bli",22,"Wd" + count)

//1=2
//slicing last 15 m from toroid 3 to hall
   do
      SrwUtiKillAllGraphs()
   calcdist=+(step6*j)
   //calcdist=+(0.5*l)
   //calcdist=15
   printdist=9.237+dist1+dist2+dist3+dist4+dist5+calcdist;
   cou = j
\( \text{cou1} = j + 1 \)

printf distance, num2str(printdist);
printf count, num2str(cou);
printf count1, num2str(cou1);

SrwOptDrift("D",+step6)

SrwOptCont("Container")

SrwOptContAdd("Ap2_bli","Container_bli",2)
SrwOptContAdd("D_bli","Container_bli",2)

// Wavefront Propogation

SrwWfrPropagate("Wd"+count+"_rad","Container_bli",2,2,"Wd"+count1)
SrwWfrResize("Wd"+count1+"_rad",1,1,1,1,1,2,"Wddd")

SrwWfr2Int("Wddd_rad","Icomp",7,1,4,1,ENR,0,0,2)
ModifyImage $("Wdddlcomp_xz") ctab= {*,*,Spectrum,1}
Save/J/O/P=new_geometrics Wdddlcomp_xz as distance+ "_xy_hor_BM_vert_dump_comp_pol_torroids.txt"
Save/Pic/E=-5/B=288 as distance+:"_vert_dump_comp_Int_xy.png"

SrwWfr2Int("Wddd_rad","Ihor",1,1,4,1,ENR,0,0,2)
ModifyImage $("Wdddlhor_xz") ctab= {*,*,Spectrum,1}
Save/J/O/P=new_geometrics Wdddlhor_xz as distance+ "_xy_hor_BM_vert_dump_hor_pol_torroids_15.txt"

//
// SrwWfr2Int("Wddd_rad","Ivert",2,1,4,1,ENR,0,0,2)
// ModifyImage $("WddIvert_xz") ctab= {*,*,Spectrum,1}
// Save/J/O/P=torroids_dump_aperture WddIvert_xz as distance + "_xy_hor_BM_vert_dump_vert_pol_torroids.txt"
// SavePict/E=-5/B=288 as distance+"_vert_dump_vert_Int_xy.png"

// Save/J/O/U={1,1,1,1}/P=hor_BM_vert_dump_pol_splittet WddPV_x as distance+"_x_hor_BM_vert_dump_vert_pol.txt"
// Save/J/O/P=hor_BM_vert_dump_pol_splittet WddPV_xz as distance+ "_xy_hor_BM_vert_dump_vert_pol.txt"
// SavePict/E=-5/B=288 as distance+"_vert_dump_Int_xy.png"
// Textbox/N=text0/F=0 "divergence at "+distance
KillWaves $("Wd" +count+ "X_rae")
KillWaves $("Wd" +count+ "Z_rae")

j=j+1
while (j<((dist6/step6)+1))
//while (l<30)

end
// Beamline

.................................

do
SrwUtiKillAllGraphs()
calcdist=-(0.05*j) -0.2;
//calcdist=-5.7
printdist=dist+calcdist;
printf distance, num2str(printdist);

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SrwOptDrift("D", calc_dist)

SrwOptCont("Container")

SrwOptContAdd("D_bli","Container_bli",2)

// Wavefront Propogation

SrwWfrPropagate("Wd_rad","Container_bli",2,2,"Wdd")
SrwWfrResize("Wd_rad",1,1,8,1,8,2,"Wdd")

SrwWfr2Int("Wddd_rad","Icomp",7,1,4,1,ENR,0,0,2)
ModifyImage $("WddIcomp_xz") ctab= {*,*,Spectrum,1}
Save/J/O/P=with_aperture WddIcomp_xz as distance+ "
  _xy_hor_BM_vert_dump_comp_pol.txt"
SavePic/E=-5/B=288 as distance+"_vert_dump_comp_Int_xy.png"

SrwWfr2Int("Wddd_rad","Ihor",1,1,4,1,ENR,0,0,2)
ModifyImage $("WddIhor_xz") ctab= {*,*,Spectrum,1}
Save/J/O/P=with_aperture WddIhor_xz as distance+ "
  _xy_hor_BM_vert_dump_hor_pol.txt"
SavePic/E=-5/B=288 as distance+"_vert_dump_hor_Int_xy.png"

SrwWfr2Int("Wddd_rad","Ivert",2,1,4,1,ENR,0,0,2)
ModifyImage $("WddIvert_xz") ctab= {*,*,Spectrum,1}
Save/J/O/P=with_aperture WddIvert_xz as distance+ "
  _xy_hor_BM_vert_dump_vert_pol.txt"
SavePic/E=-5/B=288 as distance+"_vert_dump_vert_Int_xy.png"
j=j+1
while (j<140)

// End of propagation
SrwOptDrift("D2", -1)

SrwOptCont("Container2")
SrwOptContAdd("D1_bli", "Container2_bli", 2)

SrwWfrPropagate("W_rad", "Container2_bli", 2, 2, "Wdl")
SrwWfrResize("Wdl_rad", 1, 1, 8, 1, 8, 2, "Wdd1")

SrwWfr2Int("Wdd1_rad", "Ihor", 1, 1, 4, 1, ENR, 0, 0, 2)
ModifyImage $("Wdd1Ihor_xz") ctab= \{*,*,Spectrum,1\}
Save/J/O/U={1,1,1,1}/P=X100um Wdd1Ihor_xz as "8" + "_xy_hor_BM_vert_dump_hor_pol_Nw_4_100um_1.txt"

end
Appendix B

List of publications

"The THz pulse characterization tool – characterizing THz pulses from 4th generation X-Ray light sources covering the THz Gap" T Golz et al. in preparation (2018)


"Pulse duration of seeded free-electron lasers" P Finetti, H Höppner, E Allaria, C Callegari, F Capotondi, P Cinquegrana, ... Physical Review X 7 (2), 021043 (2017)


"Correlated electronic decay in expanding clusters triggered by intense XUV pulses from a Free-Electron-Laser" T Oelze, B Schütte, M Müller, JP Müller, M Wieland, U Frühling, ... Scientific reports 7, 40736 (2017)
"Simultaneous operation of two soft x-ray free-electron lasers driven by one linear accelerator" B Faatz, E Plönjes, S Ackermann, A Agababyan, V Asgekar, V Ayvazyan, ... New journal of physics 18 (6), 062002 (2016)

"High-field high-repetition-rate sources for the coherent THz control of matter" B Green, S Kovalev, V Asgekar, G Geloni, U Lehnert, T Golz, M Kuntzsch, ... Scientific reports 6, 22256 (2016)

"Development of experimental techniques for the characterization of ultrashort photon pulses of extreme ultraviolet free-electron lasers" S Duesterer, M Rehders, A Al-Shemmary, C Behrens, G Brenner, ... Physical Review Special Topics-Accelerators and Beams 17 (12), 120702 (2014)

Appendix C

Acknowledgements

The list of people that deserve a proper thank you could easily fill a major part of this document, yet I feel like just saying "thanks everybody" is cutting it dramatically short. So I will try to give credit where credit is due. If in any way, you feel like you should have been on this list, thank you and I am sorry for not including you, as most likely you should have been.

I want to start this with my family, without whom I would not have made it past primary school. I still remember my parents training the $1 \times 1$ with me and my brother exploring the path ahead of me while my grandparents helped wherever they could. They all gave me a direction that I follow to this day, even though I might take a metaphorical nap in the shade of a tree every now and then. Thank you very much for allowing me to become the person I am today.

Hopping forward in great leaps there is one person, besides Google and Wikipedia, that brought me through my studies and I am grateful to call him my best friend to this day. Johannes stay as you are and make many more beautiful children with your lovely wife.

Following the chronological red thread I would like to thank my old group leader Jupp, who gave the best DESY tour I’ve ever seen and got me hooked on science. Stefan thank you for bringing me back to FLASH to finish my studies with a Diploma thesis and thank you Nikola for making it such an amazing experience that I wanted to stay for my PhD even though you greatly advised against it. You kept me in your team and furthered my education. Together with Alaa we raised the lab from the ground and spent more nights in there than any of us can count. We had good, bad and ugly times, all of these taught me endlessly. Thank you. Thanks also to our collaborators in Dresden, Michael, Bert and Sergey, who gave a large portion of inspiration to this work, as well as directions where to
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Dimitrios as one of my closest friends you have seen all facets of me during my PhD, we’ve
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all of it. Stay epic buddy. Meatmaster Hauke, you suffered with me and as they say shared
pain is halved pain. By now, because I took forever to write this, you finished, and I can
say shared happiness is definitely doubled. Thanks for being my friend.

Finishing this hopefully complete list I would like to thank my doctor father Wilfried for
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This very last and very special place shall be used to thank the person very special to me. My girlfriend Chrysa. Supporting me during the stressful times of final measurements, the exhausting times of writing and the craze of my defense, you were the constant smile in my life. Thank you from all my heart for going this journey with me and continuing to do so.
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Eidesstattliche Erklärung


Ort, Datum

Unterschrift