Free-Electron Laser at the TESLA Test Facility at DESY: towards a tunable short-pulsed soft X-Ray source

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ABSTRACT

A high peak current, low emittance, short pulse electron beam can produce intense, laser-like radiation in a single pass through a long periodic magnetic structure. The construction of such free-electron lasers (FELs) based on self-amplified spontaneous emission (SASE) has become feasible by recent advances in accelerator technologies. Since SASE FELs do not require any optical components they are promising sources for the generation of intense, sub-picosecond laser pulses which are continuously tunable over a wide wavelength range in the vacuum ultraviolet (VUV) and X-ray region. In the first phase of the VUV-FEL (phase I) at the TESLA Test Facility at DESY, SASE was achieved for the first time in the VUV at wavelengths between 80 and 180 nm. The concept of the VUV FEL at DESY and first experimental results are presented. The second phase of the TESLA Test Facility (phase II), which includes an increase of the electron beam energy to 1 GeV, aims at the construction of a SASE FEL operating in the soft X-ray region. An overview of the current status and the activities toward a soft X-ray FEL user facility is given.

Keywords: X-Ray Laser, Free-Electron Laser, SASE, soft X-Ray, VUV

1. INTRODUCTION

The development of new sources of electromagnetic radiation ranging from radio frequencies to X-rays has led to the discovery of many new phenomena and has had a strong impact on everyday life. The unique properties by which different radiation sources are distinguished, e.g. intensity, wavelength, coherence, time structure, etc., have been exploited in a multitude of research programmes for basic and applied sciences. Progress in source development, such as the advent of lasers, has produced many revolutionary technical, scientific and medical applications, too numerous to be mentioned. Today, lasers dominate new technologies such as telecommunications, and are widely employed in industry. On the other hand, the industrial manufacturing of semiconductor chips with structure sizes below 200 nm provides a tremendous challenge for the development of intense sources in the vacuum ultraviolet (VUV) and soft X-ray region. Due to the high absorbance of radiation in the VUV and soft X-ray region by any material, concepts other than laser resonators utilizing normal-incidence mirrors are required.

Before the experimental verification of synchrotron radiation in 1947,¹ only very limited X-ray sources were available. Synchrotron radiation, emitted by relativistic electrons or positrons undergoing a centripetal acceleration, spans the spectral range from the visible to hard X-rays. The development of storage rings for dedicated synchrotron radiation research has led to 3rd generation facilities with special magnetic devices, so-called wigglers and undulators, and an increase by more than ten orders of magnitude in flux over the last forty years. Quite recently, much effort has been devoted to the development of X-ray lasers. Many different schemes, e.g. high harmonic generation, capillary discharge X-ray lasers, collisional X-ray lasers, plasma-induced lasers, etc., have shown to be capable of producing coherent, laser-like radiation in the VUV and soft X-ray region. While synchrotron radiation is characterized by high repetition rates and weak peak powers, X-ray lasers still have poor repetition rates but extremely high peak powers and short pulse lengths. With the method of high harmonic generation, pulse durations down to the attosecond regime have been demonstrated.^{2,3}

Electrons in a storage ring usually emit incoherent synchrotron radiation. In 1971, John Madey (Ref. 4) noticed that a fixed phase relation between an electron bunch wiggling in an undulator and a resonant radiation field may lead to stimulated emission. This discovery led to the first free-electron laser (FEL) operating in the infra-red. In such an oscillator type FEL, light amplification is reached in a multi-pass setup by using an optical cavity with mirrors. Presently, more than twenty oscillator type FELs are in operation worldwide operating at wavelengths from

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mm down to approximately 200 nm, many of them as user facilities. After successful commissioning, lasing of the European storage ring FEL⁵ at ELETTRA, Trieste, at a wavelength of 190 nm* has been achieved, demonstrating that these sources can be run routinely as user facilities at wavelengths down to the visible and UV. However, FEL oscillators are restricted from operating in the VUV and soft X-ray region due to the optical cavities. In the early 1980s, a scheme was proposed in Refs. 6–8 where stimulated emission of an electron bunch could be induced by the radiation field emitted in the first part of an undulator. Amplification to saturation could then be reached during a single pass through a long undulator. To achieve this process of self amplification of spontaneous emission (SASE) a high-quality electron beam and a long ultra-precise undulator are required. Only recent advances in accelerator technologies have made the generation of these high-quality electron beams possible. Since SASE does not require mirrors or a seed pulse it is, in principle, scalable to X-ray wavelengths. Hence, SASE FELs are promising sources for the generation of tunable, short-pulse, laser-like radiation in the VUV and X-ray region. Their average and peak brilliance will exceed those of state-of-the-art 3rd generation storage rings by many orders of magnitude. Two major projects are aiming at the Å regime. The Linac Coherent Light Source (LCLS)^{9,10} will use part of the linear accelerator at the Stanford Linear Accelerator Center (SLAC). At the Deutsches Elektronen-Synchrotron (DESY), the Technical Design Report[†] (Ref. 11) for the TeV-Energy Superconducting Accelerator (TESLA) with an integrated X-ray facility has recently been presented.

1.1. Principle of the SASE Process

Electron bunches wiggling through an undulator in a storage ring usually radiate incoherently, and the flux is proportional to the number of electrons in the bunch. The idea of a SASE FEL is to improve the electron beam quality such that a large number of electrons in the bunch radiate in phase thus generating coherent radiation which can be, in principle, proportional to the number of emitting electrons[‡] squared. A gain of 10⁵ compared to conventional storage ring undulators can be expected for SASE FELs in the soft X-ray region.

The SASE process starts from noise in the first part of the undulator. An electron bunch with a high peak current, a low emittance, and a small energy spread (< 1%) emits spontaneous radiation thus building up a radiation field. The wavelength λ_n of the fundamental ($n = 1$) and its harmonics[§] ($n \geq 2$) is given by

$$\lambda_n = \frac{\lambda_u}{2n\gamma^2} \left(1 + \frac{K^2}{2} \right), \quad (1)$$

where $\gamma = E_e/mc^2$ is the relativistic factor of the electrons and $K = eB_u\lambda_u/2\pi m_e c$ the undulator parameter with the peak magnetic field B_u and the period length λ_u . If the phase space of the electron bunch is well matched to that of the radiation field, the interaction of the radiation field with the electrons leads to an electron density modulation of the bunch with a periodicity equal to the wavelength λ_n (micro-bunching). This micro-bunching results in an exponential growth of the radiated power $I(z)$

$$I(z) = I_0 e^{z/L_{gain}}, \quad (2)$$

and the maximum power is reached at the saturation length $L_{sat} = 4\pi L_{gain}$. Summarizing, three different regimes can be distinguished in the SASE process. In the first part of the undulator the radiant power increases linearly with the distance (lethargy regime). After micro-bunching has evolved, the radiant power grows exponentially and the radiation becomes (transversally) coherent (gain region). Finally, maximum radiation power is reached after the saturation length L_{sat} .

Although the SASE process is in principle extendable to X-ray wavelengths within the 1 Å region, tight requirements arise for very high-quality electron beams and extremely long (≈ 100 m) high-precision undulators. Only state-of-the-art linear accelerators in combination with laser-driven radio-frequency (RF) electron guns and novel bunch compression schemes are capable to produce such electron beams. Therefore, the development of SASE FELs is strongly coupled with the progress in accelerator technologies.

*see <http://www.elettra.trieste.it/sites/euprojects/fel/>

†see http://tesla.desy.de/new_pages/TDR_CD/start.html

‡In practice, only part of the electrons within the so-called ‘cooperation length’ contribute.

§In a planar undulator, only odd harmonics occur.

Figure 1. Schematic layout of the TESLA Test Facility phase I.

1.2. FEL Projects based on SASE

Since the early theoretical work on the SASE process,^{6–8} considerable theoretical and experimental efforts have been made to design single-pass FELs and study the physics of SASE. Only quite recently, experimental evidence of SASE in the infrared region 5–16 μm has been reported by several groups.^{12–14} A huge step forward has been made by Hogan *et al.*¹⁵ who achieved SASE with a gain up to 10^5 at a wavelength of 12 μm . An 18 MeV electron beam with bunch charges up to 2.2 nC was sent through a 2 m long undulator. A gain length of 25 cm has been determined for the highest bunch charge.

Efforts in reducing the wavelength to the visible began with Babzien *et al.*¹⁶ who observed SASE at 633 nm. A further decrease has been reported by Milton *et al.*¹⁷ who achieved SASE at 530 nm at the Low-Energy Undulator Test Line (LEUTL), Argonne National Laboratory. The latter project benefits from the 650 MeV linear accelerator of the Advanced Photon Source (APS), which employs a laser-driven RF electron gun. An electron beam of 217 MeV was sent through five 2.4 m long undulator modules, giving an output wavelength of 530 nm. The gain length amounted to 1.5 m.

Two decisive milestones on the way to X-ray FELs based on SASE have been achieved in 2000 and 2001. The first FEL output in SASE mode in the VUV at 109 nm (Ref. 18) was observed at the TESLA Test Facility (TTF) at DESY. After adding another four undulator modules at LEUTL, first observation of saturation in the visible (530 nm) and later on in the UV (385 nm) has been reported by Milton *et al.* (Ref. 19).

2. THE FREE-ELECTRON LASER AT THE TESLA TEST FACILITY: PHASE I

At DESY, a longstanding tradition in the fields of accelerator, high-energy, and synchrotron radiation physics has led to the development of the TESLA Test Facility (TTF), which incorporates a VUV FEL operating in SASE mode. 39 institutions from 9 countries contribute to the TESLA project, which aims at the construction of a 500 GeV electron-positron linear collider with an integrated X-ray facility.¹¹ The main objectives of the first phase of the TTF (phase I) are the testing of the superconducting accelerator modules and the demonstration of SASE in the VUV regime. After successful commissioning in 1999, first generation of VUV FEL radiation in SASE mode at a wavelength of around 109 nm was achieved in early 2000.¹⁸ The second half of 2000 and the beginning of 2001 were dedicated to machine studies. FEL operation from early 2001 until February 2002 will focus on the improvement of the electron beam quality, the increase of the FEL gain, detailed photon diagnostics, and first experiments. From February 2002 until the ending of phase I in August 2002, accelerator studies are foreseen.

2.1. Layout of the FEL

The main components of the TTF phase I are depicted schematically in Fig. 1. The injector is based on a laser-driven $1\frac{1}{2}$ -cell RF electron gun operating at 1.3 GHz. Frequency-quadrupled UV laser pulses (262 nm) of a mode-locked Nd:YLF laser generate photoemitted electrons on a Cs_2Te cathode.²⁰ The laser emits a train of pulses synchronized to the RF with a pulse energy of up to 50 μJ and a pulse-to-pulse variation of 2% (rms).²¹ A pulse length of 6(1) ps has been measured with a Streak Camera. The RF electron gun is operated with a peak electric field of 37 MV/m on the photocathode. The gun section is followed by a 9-cell super-conducting cavity (pre-accelerator) which increases the electron energy up to 16 MeV. The electron bunches are further accelerated in the super-conducting cavities also operated at 1.3 GHz. Both 12.2-m-long cryomodules installed in TTF phase I contain eight 9-cell π mode cavities

Figure 2. Time structure of electron bunches at TTF phase I.

and a quadrupole package. Long trains of electron bunches for maximum RF pulse duration of 800 μs were achieved in late 2000. Figure 2 shows the time structure of the electron bunches. The bunch trains have a repetition rate of 1 Hz while the repetition rate of the bunches within a train can be varied between 2.25 MHz, 1 MHz, and 100 kHz, i.e., the number of bunches per bunch train can be varied from 1 up to a maximum of 1800. In order to protect the undulator from demagnetization in case of a beam loss during long bunch train operation, a fast protection system had to be set up. The measured bunch charge and electron beam energy at maximum beam current of around 1800 bunches in a bunch train are shown in Fig. 3.

A bunch compressor, inserted between the two accelerating modules, increases the peak current of the bunches up to 500 A, which corresponds to a bunch length of 0.6 mm (FWHM) for an 1 nC bunch with a Gaussian density distribution. Experimentally, it has been routinely verified²² that a large fraction of the bunch charge is compressed to a length below 0.9 mm (FWHM). Coherent synchrotron radiation (CSR) in the magnetic bunch compressor may have an effect on the emittance and the energy spread at such short bunch lengths.²³

In contrast to undulators installed in synchrotron radiation facilities, relatively long undulators are needed for single-pass FELs to reach saturation. Furthermore, the undulator must provide diagnostic tools and electron optics to guarantee a small divergence of the electron beam and a considerable overlap of the electron and photon beam. The undulator at TTF phase I consists of 3 modules, each 4.4 m long, with a spacing of 0.3 m between adjacent undulators resulting in a total length of 14.1 m. Electron beam diagnostics has been installed before the first and after each undulator, i.e. a total of 4 stations. Each station is equipped with beam position monitors and a system of wire scanners.²⁴ Each undulator module is a permanent magnet device with a fixed gap (12 mm) using a combined function magnet design with a period length λ_u of 27.3 mm and a peak magnetic field B_u of 0.46 T; the resulting undulator parameter K amounts to $K = 1.17$. Due to the fixed gap, the photon energy can only be tuned by varying the electron beam energy. In order to guarantee an overlap of the electron and photon beam along the undulator, the electron beam is focused by integrated quadrupole structures superimposed on the periodic undulator field. Each undulator module contains 10 quadrupole sections which result in 5 full focusing-defocusing (FODO) cells. Furthermore, high precision magnetic fields and an excellent mechanical alignment are required.^{25,26} Each vacuum

Figure 3. Distribution of the electron beam energy and bunch charge within a bunch train. The bunch separation was set to 444 ns (2.25 MHz). Only the values for every fifth bunch are shown. (from Ref. 11)

Figure 4. Layout of the experimental area for photon diagnostics. 1: bending magnet; 2: aperture unit; 3: detector unit; 4: mirror; 5: normal incidence monochromator; 6: ICCD camera; 7: RAFEL chamber; 8: experimental station.

chamber of the undulator modules incorporates 10 beam position monitors and 10 orbit correction coils (steerers), one for each quadrupole. The vacuum tube has a relatively large diameter of 9.5 mm compared to the beam size ($\approx 300 \mu\text{m}$) to reduce wakefield effects. The effect of wakefields on the electron beam has been studied for various beam pipe diameters and different surface roughnesses in an experimental chamber behind the undulator.

An experimental area for photon beam diagnostics is located behind a dipole magnet which separates the electron beam from the photon beam and deflects the electron beam through diagnostic stages into a beam dump. With the help of two beam position monitors before and one behind the dipole magnet the electron beam energy can be measured online for each bunch. The two beam position monitors located before the magnet allow one to measure and correct for the offset position and angle of the electron beam at the entrance of the dipole magnet.²⁷ The distribution of the electron beam energy within a bunch train as shown in Fig. 3 has been recorded with this setup. The energy stability over the bunch train is better than the projected value of 0.1% (rms).

2.2. Photon diagnostics and first results

The layout of the experimental area for the characterization of the FEL photon beam is shown schematically in Fig. 4. With this suite of diagnostics, SASE specific properties - the photon pulse intensity and its angular, spectral and temporal distribution - can be measured on a single pulse basis. Due to the high absorbance of radiation below 200 nm by any material, photon diagnostics in the VUV region becomes extremely challenging. Neither window materials to outcouple the radiation nor attenuating filters are available. Hence, in order to cover the full dynamic range of intensity from spontaneous undulator emission to SASE in saturation, different types of detectors, suitable for the VUV region and for operation under ultra-high-vacuum (UHV) conditions, have to be employed. The detectors and the principle layout of the photon diagnostics unit have been described in detail in Ref. 28.

The SASE process depends crucially on a good on-axis overlap of the electron and photon beam along the undulator. Figure 5 shows the photon intensity measured with a PtSi photodiode²⁹ as a function of the horizontal electron beam position at the entrance of the undulator. The PtSi photodiode was located behind a 0.5 mm aperture (Positions 3 and 2 in Fig. 4, resp.) at about 12 m behind the undulator exit. The intensity observed in a region $\pm 200 \mu\text{m}$ with respect to the optimum beam position shows an enhancement by a factor of more than a 100 compared to the spontaneous radiation. The vertical error bars reflect the statistical fluctuations, which are inherent in the SASE process.

To obtain photon beam profiles, the PtSi photodiode with a 0.5 mm spherical aperture in front was moved in steps of 1 mm through the photon beam. The photon beam profile for SASE is compared to that of spontaneous emission in Fig. 6. For each step, the signal of several pulses was sampled to average out the SASE specific fluctuations. The

Figure 5. Dependence of electron beam position at the entrance of the undulator on the SASE intensity. The squares indicate the mean values. Horizontal error bars represent electron beam position instabilities. Vertical error bars correspond to SASE specific fluctuations. (from Ref. 30)

Figure 6. Photon beam profile of SASE radiation compared to that of spontaneous emission at a distance of 12 m behind the undulator exit. (from Ref. 18)

data points for the spontaneous emission have been multiplied by a factor of 30. As expected, the radiation cone for SASE is much narrower than that for the spontaneous emission, which has an opening angle in the order of $1/\gamma$. The solid lines represent the results of fits to a Gaussian profile. The measured width of 8 mm (FWHM) in SASE mode is larger than the estimated width for SASE in saturation of 4 mm (FWHM). A spatial pulse-to-pulse jitter of the electron beam in the undulator, and therewith the photon beam, could account for this broadening. This averaging over many pulses can be overcome if the fluorescent light of a crystal produced by a single FEL pulse is imaged using a CCD camera. First measurements³¹ have given evidence of a spatial jitter.

The PtSi photodiodes integrate over all wavelengths. Their absolute spectral responsivity $i(\lambda)$ (photocurrent per radiation power) has been determined for quasi cw-mode by the Physikalisch-Technische Bundesanstalt (PTB) at the storage ring BESSY II in Berlin. These data have been used to calibrate the PtSi photodiodes for short pulses. Figure 7 shows the signal of a PtSi photodiode illuminated with a single pulse of the frequency-quadrupled (262 nm) light of the Nd:YLF cathode-laser (see Sec. 2.1) and recorded with a 1 GHz digital storage oscilloscope. The width of the PtSi signal of ≈ 110 ns (FWHM) is due to the response characteristic of the photodiode. The integrated PtSi signal (area under the curve) is related to the pulse energy of the detected light. If we assume that the charge produced by the absorbed light is given by the integrated PtSi signal divided by the $50\ \Omega$ impedance of the oscilloscope, the pulse energy E is given by $E = \frac{\text{PtSi signal}}{i(\lambda) \cdot 50\Omega}$. To verify this assumption, measurements have been performed for several pulse energies and are compared in Fig. 8 with the measured energies of a commercial Joulemeter. The data presented have been taken with two different PtSi photodiodes (16 mm^2 and 100 mm^2 active area) and for two different wavelengths (262 nm and 524 nm). The dotted lines indicate the uncertainty of the commercial Joulemeter. Within the error bars both measurements are in good agreement. Hence, with the help of the spectral responsivity, PtSi photodiodes can be used as calibrated detectors in the VUV and soft X-ray region. They are superior to Si or GaAsP diodes due to the low degradation under radiant exposure in the VUV and soft X-ray region.^{29,32} However, the PtSi signal intensity is limited by an energy density saturation which is wavelength dependent given by the spectral responsivity. For instance, for the tested PtSi photodiodes it has been found out that energy density saturation occurs at $22(8)\text{ nJ/mm}^2$ for 262 nm and at $3(1)\text{ nJ/mm}^2$ for 524 nm.

For the determination of the spectral distribution, the photon beam is deflected by a plane mirror onto the entrance slit of a commercial 1 m normal-incidence monochromator (Pos. 4 and 5 in Fig. 4). The width of the entrance slit can be varied by a precise piezo actuator from 1 to $195\ \mu\text{m}$. For the initial FEL commissioning phase, the monochromator has been equipped with a 1200 lines/mm spherical grating. A fluorescent screen placed in the focal plane of the monochromator is imaged by an intensified charge-coupled device (ICCD) camera through a

Figure 7. Signal of a PtSi photodiode with an active area of 100 mm² illuminated by 7 ps laser pulse at 262 nm.

Figure 8. Comparison of the pulse energies determined from the PtSi signal and a Joulemeter. For further explanation see text. (from Ref. 33)

Suprasil viewport. The ICCD camera is equipped with a micro-channel-plate (MCP) as an intensifier which operates as a fast shutter with exposure times down to 5 ns. This enables one to record the spectral distribution of the FEL radiation emitted by a single bunch within a bunch train.

Such a single pulse spectrum is shown in Fig. 9. The spectrum was taken with a slit width of 195 μm which results in an instrumental bandwidth of 0.17 nm, i.e., the width of the distribution is mainly determined by the SASE process. The wavelength of 111 nm corresponds to an electron beam energy of 231 MeV [see Eq. (1)] which is consistent with the reading of the dipole magnet. An outstanding feature of single-pass FELs is that the wavelength at which SASE occurs scales with the electron energy and, thus, the wavelength is continuously tunable. This is demonstrated in Fig. 10. The electron beam energy has been tuned in several steps between 272 MeV and 181 MeV which corresponds to wavelengths between 80 nm and 181 nm. At any step a SASE search procedure has been performed and a SASE gain above 10^3 has been achieved (at 304 MeV, only spontaneous emission has been observed).

Figure 9. Spectral distribution of FEL radiation in SASE mode emitted by a single electron bunch.

Figure 10. Electron beam energies and the corresponding wavelengths at which SASE has been achieved at the TTF FEL phase I. The figure demonstrates the tunability of a SASE FEL.

Figure 11. Schematic layout of the RAFEL experiment.

2.3. Status of RAFEL

Due to the start up from noise, the radiation emitted from a SASE FEL exhibits a characteristic spiking both in the temporal and spectral domain.[¶] While the instantaneous radiation power distribution will change statistically from pulse to pulse, the integrated power over each pulse is expected to be quite stable, at least at saturation. A regenerative FEL amplifier (RAFEL) experiment has been set up at TTF phase I in order to produce fully coherent VUV laser radiation.

The schematic layout of the RAFEL experiment³⁶ is shown in Fig. 11. Part of the radiation produced by an electron bunch in the undulator is back-reflected by the mirror upstream through the undulator. The spherical grating mounted in the straight section of the bunch compressor area then disperses the radiation and focuses a narrow bandwidth of the pulse back onto the entrance of the undulator. With a distance of 66.4 m between the mirror and the grating, the dispersed pulse overlaps with the next electron bunch when the FEL is operated at a repetition rate of 2.25 MHz. If the photon pulse and the electron bunch overlap properly, the seed pulse dominates the shot noise and is amplified to saturation. The second pulse then has a narrow bandwidth and is fully coherent. Due to the loss factor of about $5 \cdot 10^4$ in the optical system, sufficient SASE gain for the first pulse is required. With a resolving power of $\lambda/\Delta\lambda \approx 10^4$ of the grating the dispersed photon pulse is stretched such that a time jitter of consecutive electron bunches in the order of ± 1 ps can be tolerated.

In the initial commissioning phase (mid 2000 till early 2001), a spherical mirror instead of the spherical grating was mounted in the RAFEL chamber in the bunch compression area. The mirror reduces the losses of the optical system and facilitates a first alignment. Figure 12 shows the signal of a single bunch recorded at the RAFEL chamber behind the undulator. The scattered radiation of a thin wire has been detected with a micro-channel plate (MCP). The radiation pulse produces a first signal on the MCP and 444 ns later after being reflected twice - to the RAFEL chamber in the bunch compression area and back onto the wire - the smaller second peak. Both RAFEL chambers are equipped with external mirrors and a laser-based feedback system that compensates changes of the chamber angle due to vibrations. With this feedback system, angular fluctuations can be kept below an acceptable level of about $1 \mu\text{rad}$. The longitudinal adjustment of both chambers to achieve full overlap of the seed pulse and the subsequent electron bunch is in progress.

[¶]Typical temporal and spectral distributions calculated for a SASE FEL are given in Refs. 34,35.

Figure 12. Oscilloscope trace of the MCP signal in the RAFEL chamber. First peak: signal of the direct photon pulse. Second peak: signal of the twice-reflected photon pulse. For further information see text. (from Ref. 37)

3. TOWARDS A SOFT X-RAY USER FACILITY: TTF PHASE II

Many single-pass FELs operating at wavelengths down to the VUV are currently being tested world wide, and several proposals for VUV and X-ray SASE FELs are underway. The shortest wavelength of 80 nm for which SASE gain has been observed (TTF phase I) still leaves a gap of 3 orders of magnitude to the 1 Å regime as proposed by LCLS/SLAC⁹ and DESY.¹¹ Since the smallest wavelength for which saturation has been achieved so far is 385 nm (Ref. 19) it is obvious that the aim of shorter wavelengths is very challenging and will proceed in several steps. Along the way, further studies of the SASE process and many technical improvements are necessary.

A first approach towards a soft X-ray user facility is represented by the second phase (phase II) of the TTF FEL,^{38,39} which is foreseen to operate at wavelengths between approximately 6 nm and 60 nm in the first harmonic, i.e., the photon energy range 20–200 eV will become accessible. In order to achieve these short wavelengths at TTF phase II, the linear accelerator will be upgraded to 1 GeV by installing four additional cryomodules. Extremely critical parts of the accelerator with respect to the emittance and peak current of the electron beam are the RF photocathode electron gun and bunch compressors. At TTF phase I, a normalized emittance of 4(1) π mmrad has been measured at the exit of the injector while the corresponding value measured in the undulator amounts to 8(2) π mmrad.¹⁸ Calculations have shown that a normalized emittance of 2 π mmrad is required in phase II at the undulator to achieve saturation. The proposed undulator will initially consist of 6 modules with a total length of about 30 m. However, the integrated quadrupole structure (FODO lattice) of the phase I modules (see Sec. 2.1) will be replaced by quadrupole doublets installed between the modules.⁴⁰

With the design parameters given in Table 1, the FEL at TTF phase II promises to provide extremely intense, short-pulsed laser-like radiation in the soft X-ray regime. The peak brilliance will exceed those of 3rd generation

Table 1. Parameters expected for the FEL at the TTF phase II. Values are given for 3 different electron beam energies. (courtesy of M. K. Yurkov)

Parameter	Units		Values		
<i>Electron beam</i>					
Energy	GeV	0.46	0.7	1.0	
Energy spread	MeV		1		
Bunch length (FWHM)	μm		120		
Bunch diameter (FWHM)	μm	235	190	160	
Normalized emittance (rms)	mm mrad		2π		
No. of bunches per train			1–7200		
Bunch separation	ns		111		
Repetition rate	Hz		10		
<i>Undulator</i>					
Period length λ_u	mm		27.3		
Peak magnetic field B_u	T		0.46		
Undulator gap	mm		12		
Length of undulator module	m		4.5		
No. of modules			6		
<i>Photon beam</i>					
Wavelength	nm	30	13	6.4	
Photon energy	eV	41	95	194	
Bandwidth (FWHM)	%	0.62	0.46	0.36	
Beam size at undulator exit (FWHM)	μm	270	220	190	
Beam divergence (FWHM)	μrad	70	40	24	
Peak Power	GW	1.8	2.5	2.8	
Pulse duration (FWHM)	fs	200	200	200	
Pulse energy	mJ	3.6	5.0	5.6	
No. of photons per pulse		$6 \cdot 10^{14}$	$3 \cdot 10^{14}$	$2 \cdot 10^{14}$

Figure 13. Preliminary layout of the experimental hall for TTF phase II.

synchrotrons by more than 8 orders of magnitude, and for the average brilliance there will still be a gain of 4 orders of magnitude.¹¹ The radiation will be polarized and fully coherent in the transverse beam direction. Moderate focusing of the FEL radiation will produce peak power densities sufficiently high to enable non-linear phenomena to be studied. Further focusing will produce power densities at which samples will turn into hot plasmas with properties yet unexplored. Another key feature is the pulse length of 300 fs (FWHM) which is extremely short compared to typical pulse length of 20–200 ps at storage rings. The combination of the FEL with a synchronized infra-red/optical fs source will open up new possibilities of two-color time-resolved experiments.

Figure 13 shows schematically a preliminary layout of the experimental hall. The building is located behind a dipole magnet, which separates the electron and the photon beam, and a collimator section. A massive concrete shielding together with an optical chicane at the entrance of the hall will prevent gamma radiation and neutrons coming from the accelerator from entering the experimental area. A few beamlines will be built so that preparation and alignment of experiments and measurements can be done in parallel. One of the beamlines^{||} will employ a plane-grating monochromator (PGM) designed for a high spectral resolution while the other beamlines will initially provide non-dispersed radiation. The FEL photon beam can be deflected by a set of mirrors into the different beamlines. First estimations on the reflectivity and absorbed energy of different elements favour carbon as an optimal candidate for mirror coatings in the soft X-ray region. Figure 14 presents the absorbed energy per atom for carbon calculated for a single FEL pulse in saturation.⁴¹ The graphs show the results for various angles of incidence at a distance of 40 m behind the undulator exit in the wavelength range 40–300 eV. In the calculation, the expected beam parameters given in Table 1 and the optical parameters of carbon^{42,43} have been taken into account. The results predict tolerable absorbed energies per atom of several 10 meV even for an angle of 3° incidence. For instance, similar calculations for gold predict an absorbed energy per atom of several electronvolts. The steep increase at 250 eV reflects the K-shell absorption of carbon. The maximum average power absorbed by a carbon coated mirror at 2° incidence is only about 2 W and can easily be cooled away. However, for long trains with up to 7200 bunches, a rather high power density occurs during the pulse train. It is therefore essential to choose a mirror substrate with excellent thermal properties, such as Si, in order to avoid a local mirror deformation which could spoil the coherence of the FEL beam.

^{||} This project has been funded by the Bundesministerium für Bildung und Forschung (BMBF).

Figure 14. Energy absorbed per atom in a distance of 40 m behind the undulator calculated for a single FEL pulse. Results are shown for a carbon coated mirror at three different angles of incidence. (courtesy of J. Feldhaus)

The experimental hall houses a cleanroom which will enable a particle-free mounting of vacuum parts. A tunable optical fs laser specially designed for pump & probe experiments will also be set up in a suitable laser hutch.

3.1. Pump & Probe Facility

In order to exploit the short pulse length of the FEL in the soft X-ray region, an optical fs laser system will be synchronized with the FEL for time-resolved pump-probe experiments. This high-power optical laser is currently being developed within the Fifth Framework Programme Of the European Commission.** The laser system consists of a high-power Nd:YLF laser, similar to the photocathode laser (see Sec. 2.1), a tunable Ti:Sapphire seed-pulse oscillator, an optical parametric amplifier (OPA), and a pulse compressor. The project aims at the development of a Pump & Probe facility providing all the infrastructure necessary to perform experiments at the projected beamlines (see Fig. 13). This Pump & Probe Facility with sub-picosecond time resolution will be available for users when the FEL phase II is expected to go into operation (2004).

The most challenging task in the development of the Pump & Probe facility is the synchronization of the optical laser to the FEL pulses with a jitter smaller than the pulse length (300 fs, FWHM). For this purpose an online measurement of the timing between the FEL and optical pulse with the corresponding time resolution is being developed. One source for a time jitter may be an energy variation of the electron bunches. For instance, the electron beam energy varies during long bunch trains by about 0.1% due to the fast-feedforward system acting on the RF phase of the accelerator (see Fig. 3). Due to the dispersive sections in the accelerator (magnetic chicanes), this energy variation may lead to a time jitter of ± 1 ps for the FEL pulses. Since the energy variations are systematic for each bunch train, the correction of the timing for the optical laser by using a similar feedforward scheme should be feasible. A statistical energy jitter on a short time scale, however, could not be corrected for. In this case it is necessary to measure the exact timing for each pulse and to sort the data for different time delays.

In a test experiment⁴⁴ at TTF phase I, the time jitter of the FEL pulses has been measured with respect to the RF master oscillator to which the accelerator and the photocathode laser producing the electron bunches are locked. The schematic layout of the experimental setup is depicted in Fig. 15.

**Institutes participating in the TDR project: Deutsches Elektronen-Synchrotron (DESY) Hamburg, Germany; Max-Born-Institut (MBI) Berlin, Germany; Forschungszentrum Jülich (FZJ), Germany; Dublin City University (DCU), Ireland; Lunds Universitet/Max-Lab, Sweden; Centre National de la Recherche Scientifique Délégation Régionale Ile de France Sud (CNRS/LURE) Orsay, France.

Figure 15. Experimental setup to measure the time jitter of the electron bunches with respect to the 1.3 GHz master oscillator.

The synchrotron light of the bending magnet, which served as a reference for the FEL pulses, has been deflected onto the entrance slit of a synchro-scan streak camera. The streak repetition rate of the camera was synchronized to the sub-divided 108 MHz of the RF master oscillator. The goal of this measurement was to study the time jitter between subsequent bunch trains. For this purpose, the accelerator was operated with single bunches at 1 Hz repetition rate.

Figure 16 shows the temporal distribution of the synchrotron light pulse which corresponds to the electron bunch length. Fitting with a Gaussian function yields a width of 10(1) ps (FWHM). A shot-to-shot variation of the centre position would directly reflect the time jitter with respect to the RF master oscillator. A histogram of the center positions of 100 subsequent pulses together with a Gaussian fit is shown in Fig. 17. The width of the Gaussian of 1.5 ps includes the statistical error and can be regarded as an upper limit for the time jitter. Further measurements with a better resolution are planned during TTF phase I.

Figure 16. Temporal distribution of the synchrotron light emitted by a single electron bunch in the dipole magnet.

Figure 17. Histogram of the centre position of 100 subsequent synchrotron light pulses. The width of the Gaussian fit amounts to 1.5 ps.

3.2. Seeding Scheme

Some experiments, especially those for time-resolved measurements, suffer from the fluctuating, spiky temporal and spectral distribution of the FEL pulse induced by the start-up from noise in the SASE process. A seeding scheme has been proposed in Refs. 34,35 to overcome these inconvenient statistical properties and produce longitudinally coherent, Fourier-limited laser radiation. The concept is similar to that of the RAFEL experiment (see Sec. 2.3). In the soft X-ray region, however, the reflectivity of mirrors near normal incidence vanishes making it impossible to build a feedback system. Hence, the idea is to use two undulators in a row with a narrow-bandwidth grazing-incidence monochromator and an electron bypass in between. In the first undulator, FEL radiation is generated with a power 3 orders of magnitude below saturation and the typical SASE characteristics. The monochromator selects a narrow band of this radiation and seeds the SASE process for the identical electron bunch in the second undulator which then amplifies the radiation to saturation. If the bandwidth of the monochromator is chosen such that the radiation pulse is stretched to overlap the entire electron bunch, the gain process in the second undulator occurs in phase over the whole bunch, and the output radiation will be fully coherent with a narrow temporal and spectral distribution. For a seeded SASE FEL, the spectral brightness will increase by two orders of magnitude compared to a SASE FEL amplifying from shot noise. The monochromator and the electron bypass of the seeding scheme at TTF phase II are currently being designed in collaboration with the GKSS Research Centre Geesthacht, Germany, and the University of Århus, Denmark.

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