New Journal of Physics
The open-access journal for physics

The soft x-ray free-electron laser FLASH at DESY: beamlines, diagnostics and end-stations

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New Journal of Physics **11** (2009) 023029 (16pp)
Received 9 November 2008
Published 17 February 2009
Online at http://www.njp.org/
doi:10.1088/1367-2630/11/2/023029

Abstract. FLASH, the Free-electron LASer in Hamburg, is a worldwide unique source for extremely bright ultra-short laser-like pulses tunable in a wide spectral range in the extreme ultraviolet and soft x-ray region (Ackermann *et al* 2007 *Nat. Photonics* **1** 336–42). To fully exploit the features of this new generation of light sources, a user facility with efficient radiation transport to the experimental area and novel online photon diagnostics capable of characterizing the unique parameters of the FLASH radiation has been built. It serves a broad user community active in many scientific fields ranging from atomic and molecular physics to plasma and solid state physics as well as chemistry and biology. A special focus is placed on the exploitation of the ultra-short FLASH pulses using pump–probe techniques. Thus, the facility is equipped with optical and THz sources synchronized to FLASH. This paper gives a detailed overview of the FLASH user facility.

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Contents

1. Introduction

In mid 2005 the Free-electron LASer in Hamburg (FLASH) started regular user operation [2], providing uniquely intense, short-pulsed radiation that currently can be tuned from 47 to 6.9 nm. Peak and average brilliance of this new free-electron laser (FEL) user facility exceeds both modern synchrotron facilities and laser plasma sources by many orders of magnitude. The soft x-ray output possesses unprecedented flux of about 10^{13} photons per pulse with durations of 10–50 fs and hence, combined with appropriate focusing optics, peak irradiance levels of more than $10^{16}\,\mathrm{W\,cm^{-2}}$ can be achieved [3]. Brilliance, coherence and an ultra-short pulse length down to the femtosecond regime are the outstanding properties opening a new era in the study of soft x-ray radiation–matter interaction and single-particle imaging. The ultra-short FLASH pulses are used to explore the temporal evolution of various processes such as atomic motion, phase transitions, expansion of hot plasmas and chemical reactions. This opens the exciting possibility of making movies of molecules in action instead of static pictures.

Over the past three years FLASH has hosted many international groups who actively explore a diverse range of novel applications including fundamental studies on atoms, ions, molecules and clusters, creation and characterization of warm dense matter, diffraction imaging of nanoparticles, spectroscopy of bulk solids and surfaces, investigation of surface reactions and spin dynamics, and the development of advanced photon diagnostics and experimental techniques (see [3]–[26] and references therein).

Since the first experiments in 2005, FLASH has reached a status of routine operation. The stability and reliability of the FEL have been significantly increased and FLASH recently achieved world record peak and average coherent power at a wavelength of 13.7 nm in the fundamental [1]. The corresponding fifth harmonic wavelength (∼2.7 nm) at power levels of

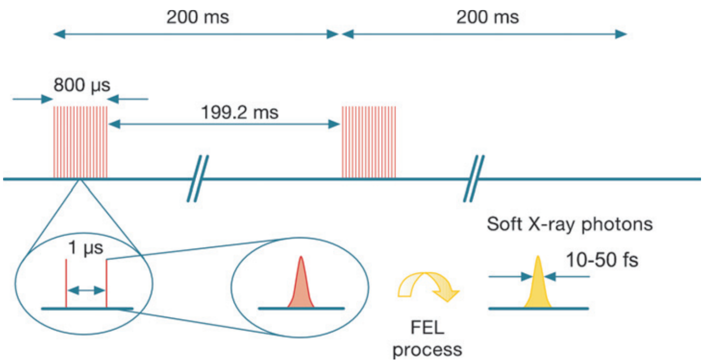

Figure 1. Electron bunch time pattern of FLASH with 5 Hz repetition rate and up to 800 bunches in a 800 μs-long bunch train. The separation of electron bunches within a train can be set to 1, 2, 10 or 100 μs. The pattern is directly transferred to the photon pulses as each electron bunch produces one photon pulse.

about 0.03% is shorter than for any radiation produced so far by plasma-based x-ray lasers at comparable intensity levels and lies well within the 'water window' where biological systems can be imaged and analysed *in vitro*.

The objective of this paper is to give all relevant information on this novel user facility to scientists who may become interested in using FLASH for their own experiments. The paper is organized as follows. Section 2 gives a brief overview on the FEL characteristics and performance. Section 3 describes the layout of the facility including the optical system for beam transport and focusing as well as the experimental stations. Photon diagnostic tools that monitor the essential photon beam parameters are described in section 4, whereas section 5 presents tools for manipulation of the FEL radiation. Finally, section 6 gives an overview of auxiliary light sources that in combination with the FEL, enable advanced multicolour, e.g. pump–probe, experiments. A brief future perspective is given in section 7.

2. FEL characteristics and performance

FLASH is a single-pass FEL lasing in the soft x-ray regime based on a 1 GeV superconducting linear accelerator described in detail in [1] and references therein. A photoinjector generates very high-quality electron bunch trains that are accelerated to relativistic energies of up to 1 GeV and produce soft x-ray radiation during a single pass through a 30 m long undulator, a periodic magnetic structure. The generation of soft x-ray laser radiation is based on the so-called self-amplified spontaneous emission (SASE) process.

Briefly, in the undulator the electron bunches undergo a sinusoidal motion and emit synchrotron radiation. The radiation moves faster than the electron bunch and interacts with electrons further up leading to a charge density modulation within the bunch with a period corresponding to the fundamental in the wavelength spectrum of the undulator. This well-defined periodicity in the emitting bunch enhances the power and coherence of the radiation field exponentially, whereas the electron and the resulting photon bunch travel once through the long undulator without the need for a resonator.

Figure 1 depicts the electron bunch and the resulting photon pulse pattern of FLASH at a repetition rate of 5 Hz. Table 1 summarizes the performance of FLASH in June 2008.

Table 1. Performance of FLASH.

Parameter of FLASH	
Wavelength range fundamental	6.9–47 nm
Higher harmonics	3rd $\sim$ 2.3 nm
	5rd $\sim$ 1.4 nm
Pulse energy average	10–50 μJ
Peak power	several GW
Pulse duration (full-width at half-maximum FWHM)	10–50 fs
Spectral width (FWHM)	0.5–1%
Spot size at the undulator exit (FWHM)	$\sim$160 μm[a]
Angular divergence (FWHM)	90 ± 10 μrad[a]
Peak brilliance	10^{29}–10^{30} photons s^{-1} mrad^{-2} mm^{-2} per 0.1%bw

[a]SASE in saturation at 30 nm.

Since the exponential amplification process in a SASE FEL starts from spontaneous emission (shot noise) in the electron bunch, the SASE FEL radiation itself is of stochastic nature, meaning that individual radiation pulses differ in their intensity, temporal structure and spectral distribution. Therefore, exploitation of the unique properties of the FEL radiation requires suitable pulse-resolved diagnostic tools. Furthermore, online determination of important photon beam parameters, such as intensity, spectral distribution and temporal structure, are mandatory for most user experiments. This requires diagnostics tools that operate in parallel to the user experiments and in a non-destructive way. To fulfill these demands, new diagnostics concepts, such as an online spectrometer and intensity monitors, have been developed for FLASH.

3. Layout of the facility

Figure 2 shows the layout of the user facility with the FEL as well as THz and synchrotron radiation beamlines (see section 6) entering into the hall from the bottom. The experimental hall is positioned 30 m behind the dipole magnet that separates the electron and the photon beam emerging from the undulator in the accelerator tunnel. The approximately 60 m long photon beam transport system delivers the FEL pulses under ultra-high vacuum (UHV) conditions to five experimental stations. Due to the strong absorption of soft x-ray radiation in any material, a completely windowless vacuum system has been designed comprising the FEL, the photon beam transport and the experimental stations, altogether 300 m. In order to make efficient use of the FEL radiation, it can be steered to five different end-stations. However, contrary to synchrotron facilities a single-pass FEL can serve only one experiment at a time. The FLASH beam is delivered directly to the beamlines BL1–BL3 that differ mainly in their focusing optics. The beamlines PG1 and PG2 include a high-resolution monochromator allowing to select an even narrower spectrum from the FEL pulse. Before the separation of beamlines the FEL radiation is passed through an attenuation system based on gas absorption (section 5) and a set of four gas-monitor detectors (GMDs) for intensity and beam position determination (section 4). The BL beamlines are equipped with a variable-line-spacing spectrograph (section 4) that is capable of online determination of the FLASH spectrum in parallel to the user experiments. Due to the strong interest in time-resolved studies at FLASH, the facility provides two additional

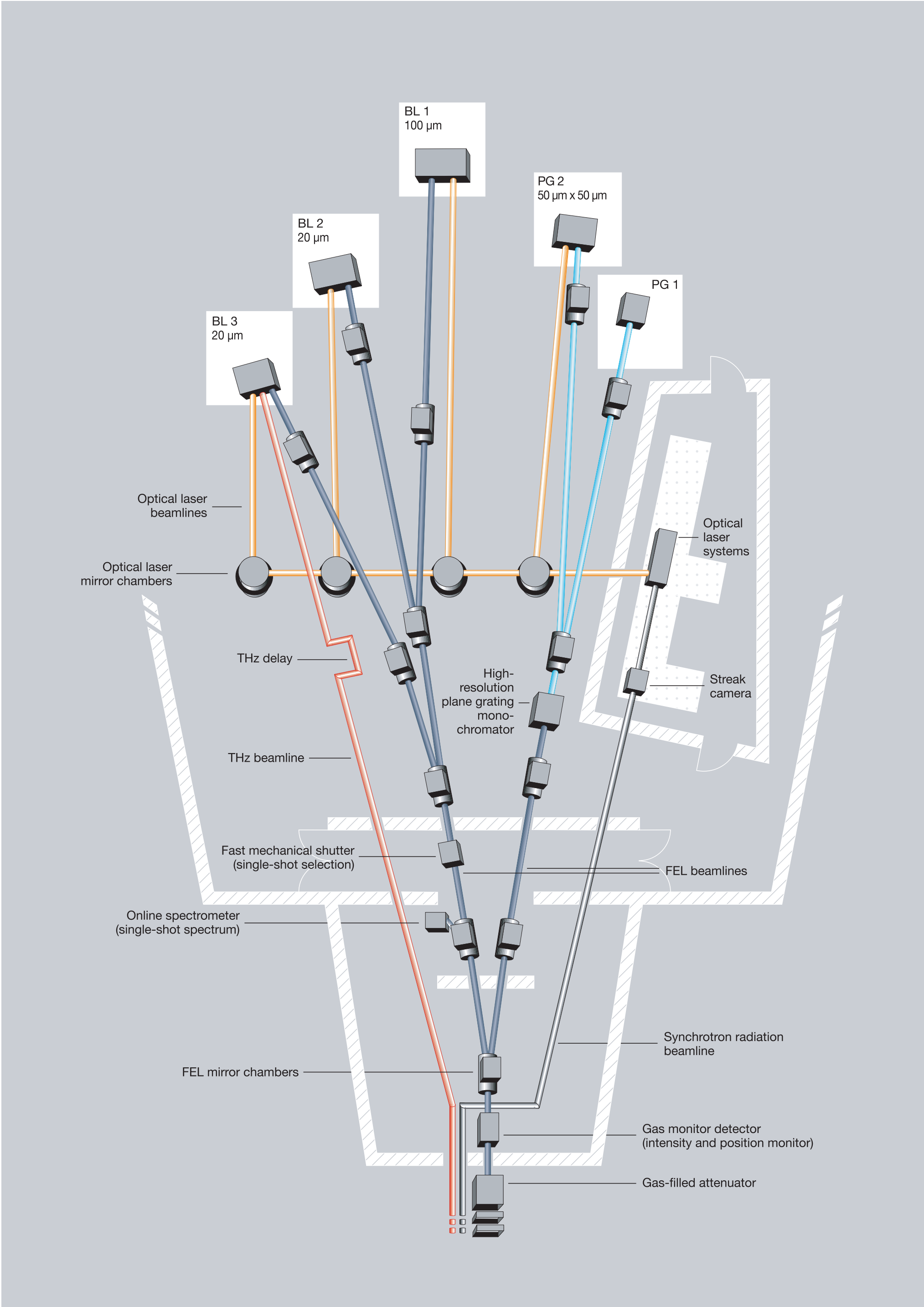

Figure 2. Schematic view of the experimental hall. Beamlines are highlighted by a colour code: 'direct' FEL beam in dark blue, monochromatized FEL beam in light blue, optical laser in orange and THz radiation in red. Different experimental stations are named 'BL' in case of direct FEL beam or 'PG' for the monochromatized FEL beam. Approximate focal sizes are given next to the station name.

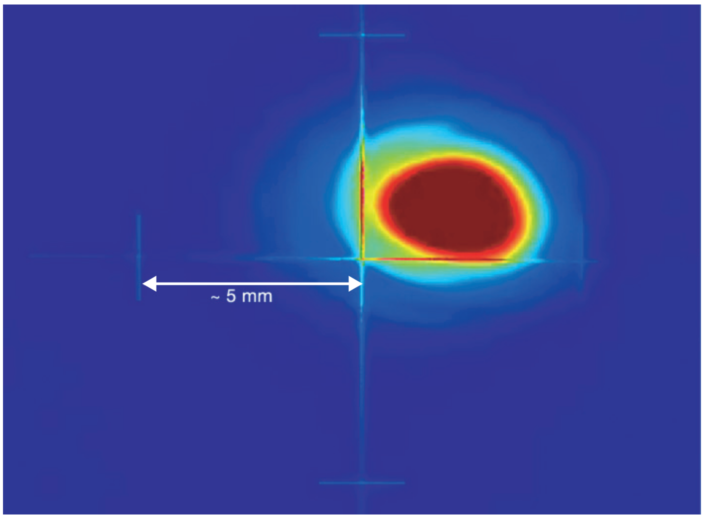

Figure 3. CCD image of the photon beam spot on a Ce:YAG screen.

light sources: a femtosecond optical laser synchronized to the FEL (section 6), situated in a laser hutch depicted in figure 2 and a THz source generated by an additional undulator through which the FLASH electron beam is passed. Both can be combined with FEL pulses for femtosecond time-resolved pump-and-probe experiments.

3.1. Beamlines and end-stations

The photon beam transport system delivers the FEL radiation under UHV conditions via the beam distribution optics to five different end-stations. On its way to the experimental hall the FEL radiation passes two diagnostic units that are located 20 and 25 m, respectively, behind the last undulator segment. Among others the diagnostic units are equipped with apertures ranging between 0.5 and 15 mm. Centering the FEL beam with respect to these apertures ensures a accurate propagation of the photon beam across all beamlines and mirrors towards the experiments. Figure 3 shows the FEL spot on a Ce:YAG fluorescent crystal which is incorporated in the second photon diagnostic detector unit and can be used to determine the beam pointing with the help of a laser engraved cross.

3.1.1. Optical system. The FEL beam is distributed to the different beamlines just by switching one or two plane mirrors. To provide high degrees of reflectivity, avoid the risk of damage due to the high peak powers, and minimize deformation of the mirrors at long bunch trains, very shallow incidence angles of 2 and 3° have been chosen.

The mirrors consist of cooled 0.5 m long silicon or zerodur substrates with high-density carbon coatings and the state of the art low surface roughness amounts to less than 5 Å over the full mirror length. Carbon coatings have been chosen because of their nearly constant high reflectivity between 94 and 96% in the spectral range of the FLASH fundamental, i.e. below 200 eV photon energy.

Downstream of the first pair of mirrors, which creates a beam offset in order to separate potential bremsstrahlung from FEL radiation, the beam can be distributed in two different branches: the ‘direct’ or the ‘monochromator’ branch. The branch leading to BL1, BL2 and

Table 2. Technical specification of the FLASH beamlines.

	BL1	BL2	BL3	PG1	PG2
Monochromatization	–	–	–	Yes	Yes
Optical elements	4	3	5 (4)	8	6
Focusing	Toroidal	Ellipsoidal	Ellipsoidal (none)	KB[a]	Toroidal
Focus size approx. (μm, FWHM)	100	20	20	5	50
Distance undulator end-focus (m)	76	73	72.2	75.2	72.5
Distance last flange-focus (m)	1.281	0.636	0.637	0.758	0.758
Transmission at 13.5 nm (%)	65[b]	64 ± 4	59 ± 6	–	64[c]

[a] Kirkpatrick–Baez.
[b] Calculated.
[c] ∼64% for the zeroth-order diffration of the 200 lines mm^{-1}.

BL3 utilizes the direct FEL beam. The three end-stations offer different focusing schemes leading to more or less intensely collimated FEL beams. BL1 is equipped with a toroidal mirror ($f = 10$ m) providing a focal size of ∼100 μm. At BL2 and BL3 ellipsoidal mirrors ($f = 2$ m) generate focal sizes of ∼20–30 μm. The focusing optics at BL3 can be alternatively retracted, allowing users either to conduct experiments in the non-focused beam with typically 5–10 mm FWHM or to install their own optics. This variety of irradiation conditions from ∼10 mm in the non-focused beam down to ∼2 μm by a back-reflecting spherical multilayer mirror [3] covers the needs of a broad range of scientific fields like plasma physics, cluster science or materials research [27].

For the second branch a high-resolution plane grating monochromator has been built by the University of Hamburg in collaboration with DESY [28] to enable high-resolution spectroscopy at the beamlines PG1 and PG2. Although the radiation pulses of FLASH already offer a narrow inherent bandwidth of ∼1%, there are many scientific areas of investigations that need monochromatic radiation. Two examples are the spectroscopy of highly charged ions [4] or future applications using the secondary emission Raman spectrometer at PG1. The design and performance of the plane grating monochromator was described earlier in detail [28, 29]. Here we only state that optionally the zeroth order including the higher harmonics is deflected to a special diagnostic port. The spot size at PG2 is presently about 50 μm depending on wavelength and monochromator settings. In table 2 the most relevant information on the FLASH beamlines is summarized.

3.1.2. Experimental stations. At the end of the beamlines, a differential pumping stage interfaces the UHV to the user experiments, since the latter might be operated up to pressures about 10^{-5} mbar. The available area for the experimental set-ups is typically 3 m perpendicular and up to 4 m parallel to the beam. Each individual experimental station is equipped with a crate that contains the electronics equipment necessary to interface the experiment to the FLASH data aquisition system. This includes the provision of trigger, time stamp or GMD signals, as well as the possibility to upload experimental data to the FLASH data acquisition (DAQ) system. Furthermore, the crates house beamline-specific touch panels and connectors for the vacuum control and interlock system. Naturally, each station is equipped with all necessities such as cooling water, pressurized air, nitrogen, as well as a gas supply, a separate exhaust system for flammable/toxic gases and the distributor for electrical power. For handling heavy equipment, like experimental chambers, a 10-ton overhead traveling crane with a maximum height below the hook of 6 m is available.

4. Monitoring of the radiation parameters

Most user experiments need online information about important photon beam parameters, such as intensity, spectral distribution and temporal structure. Furthermore, due to the stochastic nature of the SASE process and the resulting pulse-to-pulse fluctuations of the FLASH photon beam, photon diagnostics are required which are capable of resolving each individual pulse within a pulse train. This requires diagnostic tools that operate in parallel to experiments in a non-destructive way. To fulfill these demands, special novel diagnostic tools have been developed.

4.1. Monitoring of the intensity and beam position

A detailed knowledge of the pulse energy of each individual FEL pulse is naturally an essential parameter for almost all user experiments. Depending on the operating conditions of the FEL, the average energy per bunch is typically in the range of 10–50 μJ with peak values up to 170 μJ as shown in table 1. Intensity monitors have to cover the full spectral range from 6.5 to 60 nm as well as the extended dynamic range from spontaneous undulator radiation to SASE in saturation. To accomplish these requirements, a state-of-the-art GMD has been developed [7, 8] to perform a non-invasive measurement of the intensity of each individual pulse within a pulse train. Four GMDs, which are also used to determine the beam position of FLASH for each pulse, are positioned in the FEL beamlines. A set of two GMDs is located at the end of the accelerator tunnel and a second one at the beginning of the experimental hall. Between these two sets of GMDs is a 15 m long gas filled attenuator, providing means to reduce the FEL intensity by many orders of magnitude without changing the accelerator parameters.

Figure 4 shows a scheme of the GMD. When an FEL pulse passes through the ionization chamber of the detector, the gas inside is ionized, and an electric field accelerates the ions upwards and the electrons downwards to be detected by Faraday cups. The absolute number of photons in each shot can be deduced with an accuracy of 10% from the resulting electron and ion currents. Furthermore, the FEL pulse passes between two split electrode plates, allowing the pulse-resolved determination of the horizontal and vertical position of the beam.

The gas in the ionization chamber has a very low pressure of about 10^{-6} mbar, and it is nearly transparent to the FEL pulse that proceeds unaltered to the experimental stations. The display of the GMD in the control system is depicted in figure 5.

4.2. Monitoring of the spectral distribution

Some experiments might not want to monochromatize the FEL radiation because of temporal broadening of the pulse or a reduction of photon flux, but do need the knowledge of the spectral distribution of the individual FEL pulses to interpret their data. For this reason a variable-line-spacing (VLS) grating spectrometer has been designed in collaboration with *Scientific Answers and Solutions* (SAS) in Madison and the *Council for the Central Laboratory of the Research*

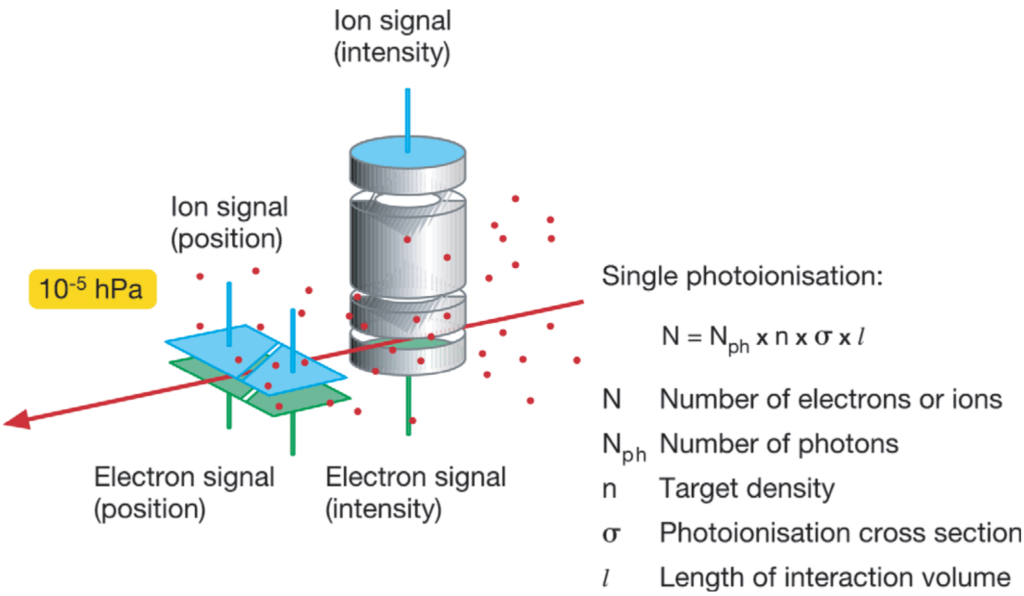

Figure 4. The GMDs provide non-invasive measurements of the shot-to-shot intensity. To the right: a Faraday cup counts the electrons and ions that are produced as the FEL pulse passes through the ionization chamber containing nitrogen or rare gases at very low pressure. To the left: the two split electrodes determine the horizontal position of the beam.

Councils (CCLRC) in Daresbury. The instrument is designed in such a way that the major fraction (∼85–99% depending on wavelength and grating) of the radiation is reflected in zeroth order to the experimental station. Only a small fraction is dispersed in the first order and is used for the online measurement of the spectral distribution. The spectrometer covers the spectral range of FLASH from 6 to 60 nm.

The online spectrometer is installed in the non-monochromatized beamline branch in order to serve the end-stations BL1–3. It can be operated in the 'spectrometer mode' choosing one of the two different VLS gratings described in table 3. Alternatively, a mirror can be used instead of the gratings if no information on the spectral distribution is required. The chamber design allows for x- and z-translations perpendicular to the incident beam as well as pitch, tilt and yaw of the optical element. In the current set-up, the dispersed radiation is focused onto a Ce:YAG single-crystal screen which is then imaged by an intensified CCD camera with an effective pixel size of 12 μm. The gated camera is able to record single-shot spectra with a repetition rate of 5 Hz.

Finally, one should note that the temporal pulse duration can be estimated from the spectral distribution [30]. In this way the online determination of the spectrum complements currently tested concepts to measure the pulse duration of the FEL directly in the time domain [31].

5. Manipulation of the photon beam

In this section three options to manipulate the FEL photon beam are presented, namely gas attenuator, filter foils and a fast shutter. The described developments result from experience

Table 3. Design parameters of the high-energy grating (HEG) and the low-energy grating (LEG) of the online spectrometer.

	HEG	LEG
Central line spacing (lines mm^{-1})	900	300
Working wavelengths (nm)	6–40	20–60
Blaze angle (°)	0.8	1
Coating	Carbon, nickel	Carbon
Theoretical efficiencies (%)	11.5–0.85	10–0.35
(first order of grating)		
Incident angle (°)	2	2
Optical surface (mm^2)	190 × 30	190 × 20
First order angles (°)	74–84	79–83.5
Resolving power (on CCD)	⩾7000	⩾4000
Optimal wavelength (nm)	25	60

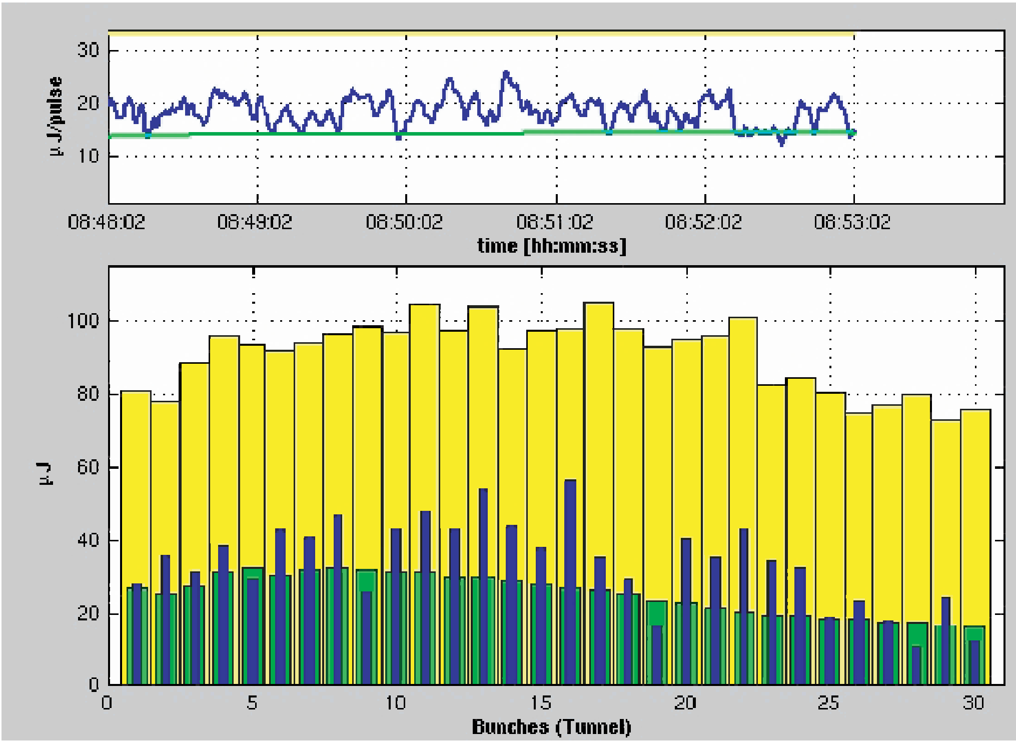

Figure 5. Display of the GMD in the control system. The blue line in the upper part represents the pulse energy (in μJ) averaged over 25 s as a function of time (green line = averaged over longer period). Lower part: the blue bars represent the pulse energy (in μJ) of each bunch of the actual bunch train (yellow bar = maximum value, and green bar = averaged for the respective bunch since start of averaging).

gained in the first phase of FLASH and aim to widen the experimental possibilities. As they do not affect the operation of the accelerator they are all provided in such a way that users can directly access them through the control system interface.

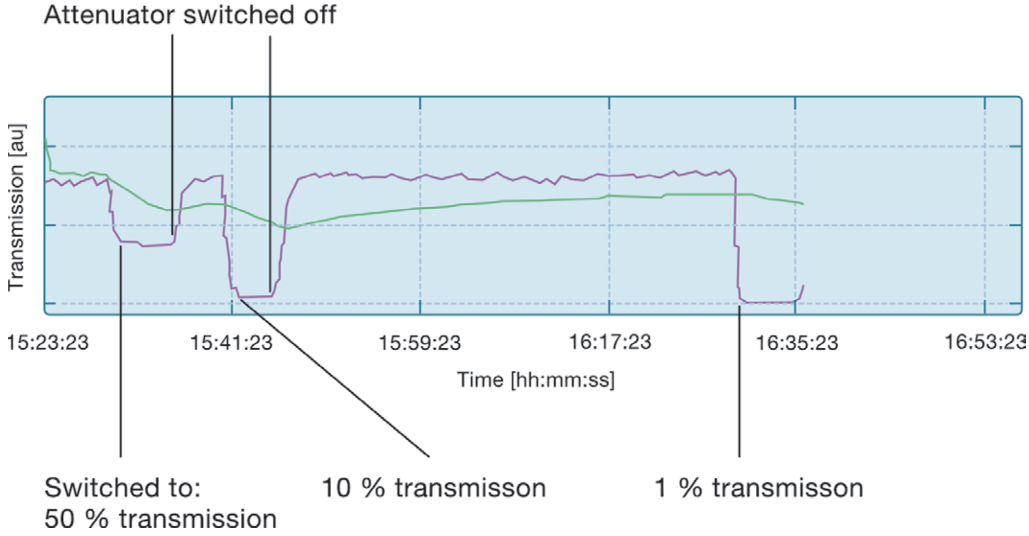

Figure 6. Attenuator performance during an experimental run. The blue curve shows the transmission signal in real time, whereas the green curve displays a time average with a time constant of 30 min.

5.1. *Reduction of photon pulse energy*

Many fields of research in intense photon–matter interaction benefit strongly from the possibility of varying the intensity of light over a large range. For example multiphoton processes in atomic, molecular and cluster physics can investigate the evolution of interaction by varying the laser intensity [3, 9]. To this end, a gas filled attenuator is installed at FLASH, giving the possibility of reducing the photon pulse energy due to photon absorption without changing the beam characteristics [32].

The attenuator consists of a windowless 15 m-long gas-filled tube equipped with two differential pumping units and is installed in front of the experimental hall. The two pairs of GMD in front of and behind the attenuator monitor the transmission of light. The attenuator is operated with either rare gases or nitrogen, each gas used in a certain spectral range.

Nitrogen covers an attenuation range of about four orders of magnitude in the spectral range from 19 to 60 nm. Between 19 and 9 nm, and for shorter wavelengths, one can use xenon and krypton. In order to preserve the beamline vacuum, both sides of the attenuator are terminated by differential pumping stages.

A 'real-life' performance example of the attenuator system is given in figure 6. Within minutes the transmission can be reduced by orders of magnitude and re-established to 100%. This test demonstrates the maturity of the attenuator system. Apart from being indestructible it also offers fast access and flexibility. Furthermore, very recent measurements support the expectation that this attenuation scheme does not degrade the wave front quality, which means it does not spoil the coherence of the pulses.

5.2. *Suppression of FEL harmonics*

Spectrally the FLASH photon beam consists of a strong fundamental and, to a much lesser degree, of higher harmonics [1, 25]. Depending on the experiment it might be desirable to

Table 4. Calculated transmission of different foils in the filter unit for three selected wavelengths of FLASH [33]. For the calculation an additional coverage of a 20 Å oxide layer was assumed for all filters.

Filter	Thickness (Å)	Calc. transmission at 7 nm	Calc. transmission at 13.6 nm	Calc. transmission at 27.3 nm
Al	1009/2000	0.102/0.011	0.058/0.004	0.725/0.585
Si	2161/2739	0.016/0.006	0.679/0.616	0.444/0.364
Zr	1915/2890	0.439/0.291	0.500/0.356	1.2E–7/<1E–10
Nb	2021	0.383	0.353	<1E–10
Mo	2985	0.197	0.159	<1E–10

suppress the higher harmonic content, for example to tell the difference between multiphoton and single-photon processes with harmonics. On the other hand, the suppression of the fundamental and transmission of selected higher harmonics offers the possibility of performing experiments at considerably higher photon energies.

Therefore, a transmission filter unit is installed at beamline BL2, 3.5 m in front of the last focusing mirror. The filter unit consists of two linear motor drives, equipped with up to five different filters each. The filters can be moved perpendicular to the beam and nearly any combination of two filters is possible. For diagnostic purposes a fluorescence screen, a pinhole and several different apertures are installed further downstream of the filters. All filters are produced as cantilever films without any mesh support. The films are fixed on a support frame with an aperture of 10 mm diameter. Table 4 summarizes the properties of the filters installed at the moment in the unit.

First tests of Si and Al filters of different thicknesses at a wavelength of 28 nm showed an effective suppression of the second and third harmonics of the FEL beam. A detailed investigation for a larger variety of foils is currently under way.

5.3. Single pulse selection

Experiments for example in solid state physics [34] or x-ray holography [24] need reliable means to select single FEL pulses, as they need time for either the sample movement to a new spot or detector readout. Therefore, a fast mechanical shutter system is provided at the experimental stations BL1–BL3 [35]. The mechanical layout is shown in figure 7. The set-up allows the selection of single FEL pulses and can be controlled via the software interface or transistor–transistor logic (TTL) signals provided by the user instrumentation. The shutter is able to operate at pulse repetition rates of up to 10 Hz.

6. Additional light sources for advanced multicolour experiments

The FLASH facility offers the unique possibility to use two additional light sources in combination with the FEL, a femtosecond Ti:sapphire laser and a THz radiation source. The benefits from this arrangement are obvious: firstly, the overall spectroscopic range of investigations is significantly enlarged and secondly, time-resolved investigations of sub-picosecond dynamics in matter are feasible by applying pump–probe techniques [26].

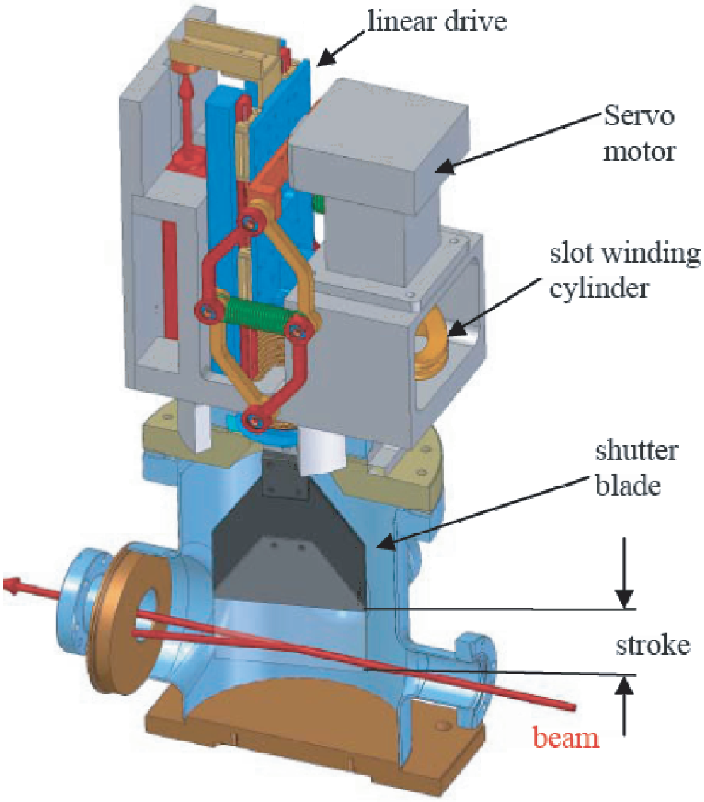

Figure 7. Mechanical layout of the shutter. A programmable logic controller (PLC) is used to steer a servo system based on an electronically commutated (EC) low-voltage motor. To select a bunch-train, the motor is started at the time when one train passes the station. During the following 100 ms (for 5 Hz repetition mode), the cylinder is turned by 180°, leading to a movement of the shutter by 48 mm to the fully open position, thus allowing the passage of the following bunch-train. During the next 100 ms the rotation is continued to the 360° position, thus blocking the next bunch-train by pushing the shutter back to the fully closed position.

6.1. Optical laser system

The optical laser system and the associated infrastructure in the FLASH experimental hall fulfills exceptional requirements. The laser produces ultra-short pulses down to 100 fs pulse duration, if necessary in the same bunch train repetition scheme as the FEL. The system is reliable for long-term measurements, highly automated and remotely controllable from the experiment. The synchronization of the FEL and the optical laser pulses is checked by a streak camera monitoring the arrival time of the optical laser pulse and the synchrotron radiation generated by the electron bunches when they are deflected via a dipole magnet into the dump. The optical laser system is distributed in separate beam lines to four experimental stations namely BL1–BL3, and PG2 as seen in figure 2.

In order to be as flexible as possible a complex laser system was built delivering either femtosecond pulses with the macro pulse structure of the FEL (see figure 1) and moderate pulse energies of 50 μJ (pulse train option) or a few hundred times more intense pulses at 5 Hz (10 Hz) repetition rate (here dubbed the mJ option).

The pulse train option delivers ultrashort pulses with the time structure of the FEL itself. The system was build in collaboration with the Max-Born-Institute in Berlin and it comprises three modular sub-systems: the pump laser is a slightly modified copy of the photo cathode laser of the FLASH accelerator. This Nd:YLF based burst mode laser was optimized to produce pulse trains of up to 800 pulses with a spacing of 1 μs between the individual laser pulses. The pulse trains are produced at 5 Hz, thus delivering up to 4000 pulses s^{-1}. A second laser (Ti:sapphire) is used to provide ultra-short ($\sim$50 fs, 3 nJ per pulse, 108 MHz repetition rate, synchronized to the FEL) pulses. These femtosecond pulses are subsequently amplified by the second harmonic of the Nd:YLF laser in an optical parametric amplifier (OPA). As a result 120 fs (FWHM) near infra-red laser pulses at a wavelength of around 800 nm and a pulse energy of up to 50 μJ with the pulse train structure of the FEL can be produced. This laser is specially suited for high repetition rate experiments like pump–probe experiments in the gaseous phase.

The mJ option, on the other hand, is suited for experiments that need a more intense laser pulse. Therefore a second laser amplifier system is included. The Ti:sapphire oscillator (same oscillator as used for the pulse train amplifier) pulses are amplified by a commercial amplifier based on a chirped pulse amplification (CPA) set-up including a regenerative as well as a 2-pass amplifier (Hidra 25 by Coherent). The maximum laser output amounts to 25 mJ at 120 fs pulse duration (15 mJ, 120 fs at the experimental station).

6.1.1. Challenges of synchronization. The optical laser is synchronized to the radio frequency (RF) source driving the electron accelerator. These reference frequencies are delivered by a 300 m long cable into the laser hutch. The 12th harmonic of the repetition rate of the fs-laser (1.3 GHz) is continuously compared to the reference frequency and if deviations are detected, control electronics adapt the repetition rate of the laser by changing the cavity length with a piezo. Due to a vast number of reasons the FEL itself jitters and drifts with respect to the reference frequency. Thus, the actual timing between the optical laser and FEL has to be monitored. Slow drifts of the timing (averaged over minutes) [36] are monitored by a streak camera (C5680 by Hamamatsu) situated in the laser hutch. Drifts of the FEL with respect to the optical laser are typically less than 1 ps h^{-1} and can be determined with a resolution (averaged over minutes) of better than 100 fs.

Besides the slow drifts fast (random) fluctuations on the order of 250 fs rms are present as well at 5 Hz. These would cause severe problems for pump–probe experiments, keeping in mind that the pulse durations are 100 fs or even shorter (for the FEL). A shot-to-shot (5 Hz) diagnostic based on electro-optical sampling system determines the jitter between the optical laser pulse and the electron bunch with an accuracy below 100 fs rms [37]. The idea of this diagnostic tool is to record the jitter data and provide it to the experimentalists to sort their measured results after the experiment. Thus, the temporal resolution decreases from the actual jitter of the accelerator to the accuracy of the measurement.

6.1.2. Beamlines. Since the experimental end-stations are up to 20 m away from the laser hutch, a dedicated optical beam line system was built to transport the laser pulses of either of the described laser systems to the experiments. To keep a high degree of flexibility the beamline system ends next to the FEL beamline with a window flange such that the experiments can individually direct the laser beam into their UHV experimental chamber. The plane of polarization and attenuation of the beam of about two orders of magnitude can be controlled via the control system from the experiment. In addition the delay of the optical laser with respect to the FEL can be altered (by moving a mechanical delay line) in 20 fs steps within a 3 ns range from the experimental stations as well.

6.2. THz beamline for pump–probe experiments

As a second option for pump–probe experiments, a light source in the THz regime was installed at FLASH and is currently under intensive commissioning [38]. THz pulses between 10 and 200 μm (30–1.5 THz) in wavelength and 300 fs–10 ps in pulse duration are produced by a specially designed planar electromagnetic undulator with nine full periods situated 5 m downstream of the FLASH undulator. A dedicated 65 m long beamline transports the THz radiation into the experimental hall to the station BL3, where it can be combined with the soft x-ray pulses for pump–probe experiments. Since both THz and XUV pulses are emitted from the same electron bunch, they are naturally synchronized on the femtosecond scale. However, it has to be noted that due to its very large divergence, the THz beam has to be repeatedly refocused. As a result, the THz beamline is 4 m longer than its XUV counterpart. For pump–probe investigations this path difference has to be compensated by geometrically redirecting the XUV beam to the experiment to achieve a zero delay. Following this coarse timing overlap, an optical delay line in the THz beamline compensates path differences in order to match the timing of the two pulses or delay them in a controlled way.

7. Near future perspectives

There is a clear wish by users to reach shorter wavelengths, when possible to extend the present range to the water window. In order to achieve this, the safest way is to increase the electron beam energy. Therefore, an increase from 1.0 to 1.2 GeV is foreseen, thus reaching a minimum wavelength of about 4.5 nm. Additional steps to go to even shorter wavelength are being discussed.

Another point that has been under discussion is to improve the stability and quality of pulses. For this purpose, a third harmonic cavity is considered to improve the control of the phase space of the electron pulse. It is expected that this upgrade would enable lasing of the full electron bunch (resulting in up to 200 fs photon pulses with considerably higher photon numbers) as well as maintaining the present short 10 fs mode. Furthermore, the ‘sFLASH’ project aims at seeding the FEL with an external laser at initially 30 nm [39]. The resulting intense and single-mode pulse is foreseen to be synchronized with a pump–probe laser at a femtosecond level and will be delivered in a separate experimental hutch.

In a new proposal (FLASH II), a complete new undulator line is proposed with a separate experimental hall next to the existing one, with space for five more user beamlines. This undulator line would consist of variable gap undulators, thus making it possible to tune the wavelength without changing the electron energy. As a consequence, while delivering one wavelength to the existing FLASH experimental hall, a different wavelength with different pulse spacing and numbers of pulses could be delivered to a second user in the new hall.

Acknowledgments

The authors are indebted to all collaboration partners and the FLASH team at DESY for their contributions. Support of the FLASH user facility through the BMBF programme FSP301-FLASH is greatly acknowledged.

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