Chapter 1
The Soft X-ray Free-Electron Laser FLASH at DESY

E. Plönjes and K. Tiedtke

Abstract FLASH, the Free-electron LASer in Hamburg, is the world's first free electron laser for extremely bright and ultra-short pulses in the extreme ultraviolet and soft X-ray range. Efficient photon beam transport and diagnostics play an essential role in exploiting the features of this new generation of light sources in a large variety of user experiments. A detailed overview of the FLASH user facility is presented.

1.1 Introduction

Since 2005 the Free electron LASer in Hamburg (FLASH) has served as a user facility [1–3], providing highly intense, short-pulsed radiation. 80–6 nm was the design wavelength range, which FLASH and its photon beamlines were originally configured for. Based on user requests a tuning range from 47–6.9 nm was experimentally explored in the first phase. With the upgrade in 2009, the maximum electron energy has been increased from 750 MeV to 1.25 GeV extending the wavelength range down to 4.2 nm [4, 5].

Peak and average brilliance of FLASH exceed 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 pulse durations in the femtosecond range and a high level of coherence. Hence, combined with appropriate focusing optics, peak irradiance levels of more than $10^{16}\ \mathrm{W/cm^2}$ can be achieved.

Over the past decade FLASH has hosted many international groups who actively explore a diverse range of novel applications. These include fundamental studies on atoms, ions, molecules and clusters, creation and characterization of warm dense matter, diffraction imaging of nanoparticles, spectroscopy of bulk solids and

E. Plönjes (✉) · K. Tiedtke
Deutsches Elektronen-Synchrotron, Notkestraße 85, D-22603 Hamburg, Germany
e-mail: elke.ploenjes@desy.de

K. Tiedtke
e-mail: kai.tiedtke@desy.de

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surfaces, investigation of surface reactions and spin dynamics, and the development of advanced photon diagnostics and experimental techniques (see http://www.photon-science.desy.de/facilities/flash/ and references therein).

1.2 FLASH Machine

FLASH is a single-pass free electron laser (FEL) lasing in the soft X-ray regime. The generation of soft X-ray laser radiation is based on the so called self-amplified spontaneous emission (SASE) process [6]. The 1.25 GeV superconducting linear accelerator is described in detail by Ackermann et al. [1] and references therein.

In short, a photo-injector generates very high quality electron bunch trains which are accelerated to relativistic energies of up to 1.25 GeV. They produce laser-like soft X-ray radiation during a single pass through a 30 m long undulator, a periodic magnetic structure. 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 farther up. This leads 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 while the electron bunch travels once through the long undulator without the need for a resonator.

Figure 1.1 depicts the electron bunch and the resulting photon pulse pattern of FLASH at a repetition rate of 10 Hz. Table 1.1 summarizes the performance of FLASH achieved since 2009.

The exponential amplification process in a SASE FEL starts from spontaneous emission (shot noise) in the electron bunch. Therefore, the SASE FEL radiation itself is of stochastic nature and individual radiation pulses differ in their intensity,

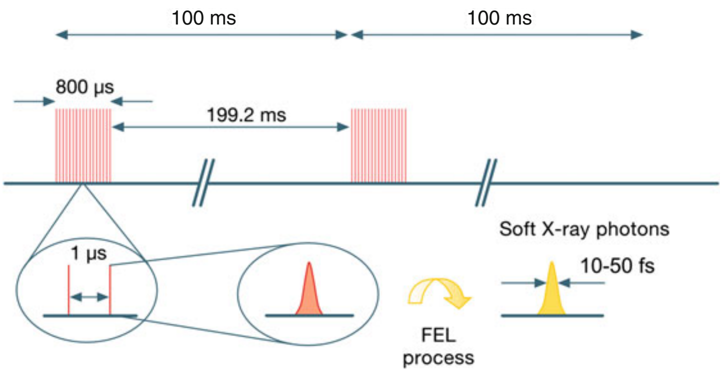

Fig. 1.1 Electron bunch and resulting photon bunch time pattern of FLASH with 10 Hz repetition rate and up to 800 bunches in a 800 µs-long bunch train. Electron/photon bunch separation within a train can be set to 1, 2, 10, or 100 µs

Table 1.1 Performance of FLASH

Parameters of FLASH	
Wavelength range fundamental (measured)	4.2–47 nm
Higher harmonics	3rd $\sim$ 1.4 nm
Pulse energy average	10–250 μJ
Peak power	Several GW
Pulse duration (FWHM)	10–300 fs
Spectral width (FWHM)	0.5–1 %
Angular divergence (FWHM)	$90 \pm 10\,\mu$rad[a]
Peak brilliance	10^{29}–10^{30} photons/sec/mrad^2/mm^2/0.1 % bw

[a]SASE in saturation@30 nm

temporal structure, and spectral distribution. As a consequence, exploitation of the unique properties of the FEL radiation requires suitable pulse-resolved diagnostic tools. 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 which operate in parallel to the user experiments and in a non-destructive way. To fulfill these demands, new diagnostics concepts, such as online spectrometers and intensity monitors, have been developed for FLASH.

1.3 Layout of the Facility

The layout of the FLASH facility takes essential aspects which are unique to SASE X-ray free electron lasers into account. First, in contrast to synchrotrons, FELs are single-pass machines which can serve only one user at a time. Despite this fact, the FLASH beam is delivered to five experimental stations with different characteristics described in detail below. The photon beam can be switched from one station to the other very quickly, thus making very efficient use of the 24-h operation of FLASH. Second, due to the strong absorption of vacuum-ultraviolet and soft X-ray radiation in any material, particularly also in air, a windowless ultra-high vacuum and particle free system has been designed encompassing the FEL, the photon beam transport and the experimental stations, altogether 330 m. The photon beam transport system, which is approximately 75 m long from the undulator to the endstations, includes only grazing incidence optics which cover the wavelength range of FLASH described in Table 1.1. Finally, due to the stochastic nature of the SASE process, FLASH fluctuates significantly from pulse to pulse in its photon beam parameters and user experiments require photon diagnostics which are capable of resolving each individual pulse within a pulse train at all beamlines.

Figure 1.2 shows the layout of the user facility. The FEL, a THz and a synchrotron radiation beamline (see Sect. 1.6) enter into the hall from the bottom of the schematic. The FLASH beam is delivered directly to the beamlines BL1–BL3 which differ in

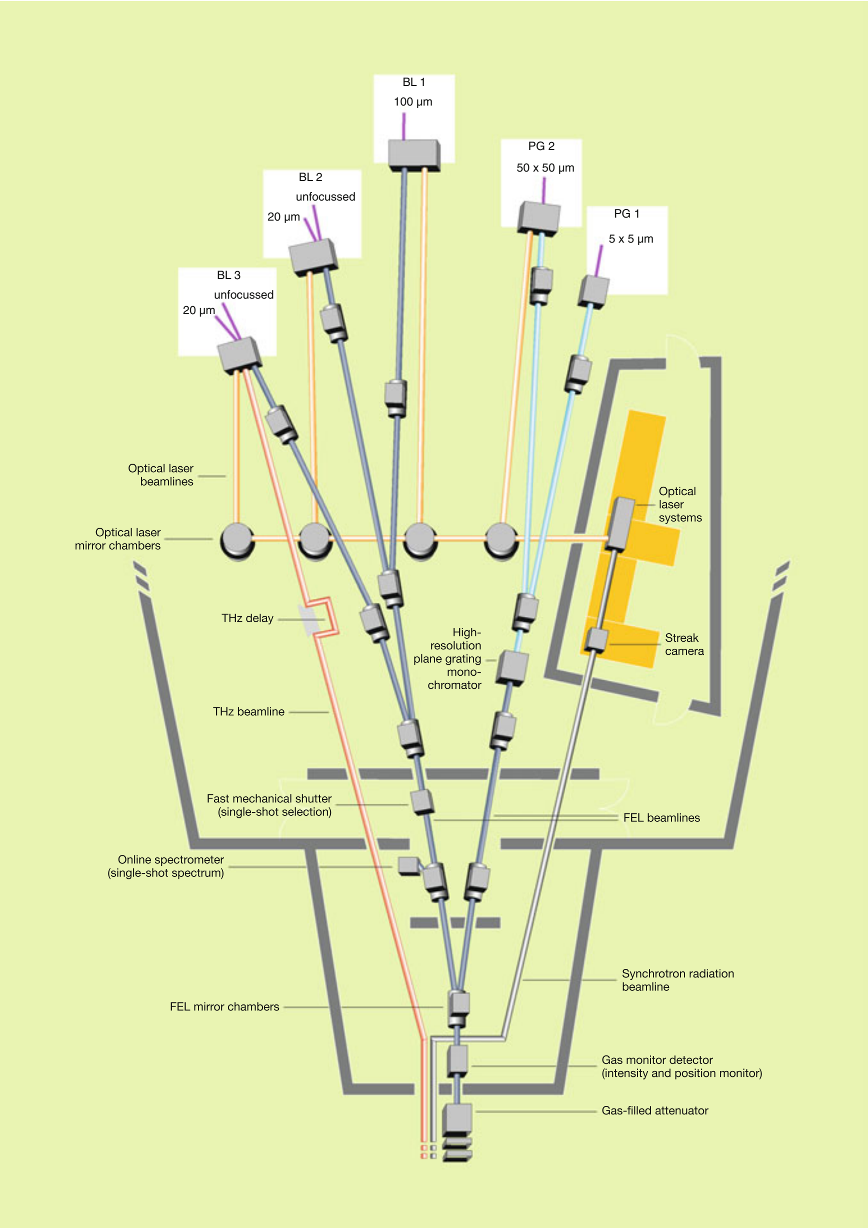

Fig. 1.2 Schematic view of the experimental hall. Beamlines are highlighted by a colour code: 'direct' FEL beam in *dark blue*, monochromatised FEL beam in *light blue*, optical laser in *orange* and THz radiation in *red*. Different experimental stations are named 'BL' in case of direct FEL beam or 'PG' for the monochromatised FEL beam. Approximate focal sizes are given next to the station name

their focusing optics and offer different beam manipulation tools. The beamlines PG1 and PG2 comprise of a high-resolution monochromator allowing the selection of an even narrower spectrum from the FEL pulse.

Before and during the separation of beamlines the FEL radiation passes through a set of photon diagnostics and beam manipulation tools, such as a set of four gas-monitor detectors (GMD) for intensity and beam position determination (Sect. 1.4), an attenuation system based on gas absorption (Sect. 1.5), a set of filters and a fast shutter. The BL beamlines are equipped with a variable-line-spacing spectrograph as well as a detector system based on photoelectron and -ion spectroscopy (Sect. 1.4) for online determination of the FLASH wavelength spectrum in parallel to the user experiments. Due to the strong interest in ultra-fast time resolved studies, the facility provides two additional light sources for femtosecond time-resolved pump-and-probe experiments. A femtosecond optical laser synchronized to the FEL (Sect. 1.6) is situated in a laser hutch depicted in Fig. 1.2 and distributed to the end stations in a separate beamline system. A THz source is generated by a dedicated undulator through which the FLASH electron beam passes subsequent to the XUV undulators.

1.3.1 Layout of the Optical System

The FEL beam is distributed to the five endstations by moving one or two plane mirrors between in and out positions. Most of the beamline system and some of the photon diagnostics have been designed for the originally envisaged wavelength range of 6–80 nm. Downstream of the first pair of mirrors, which creates a beam offset to separate potential Bremsstrahlung from FEL radiation, the beam can be distributed in two different branches: the ‘direct’ or the ‘monochromator’ branch. In the beamline design, particularly when choosing the focusing optics, a large number of different user chambers had to be taken into account. This required a compromise between necessary focal length and reachable focal spot size.

1.3.1.1 Grazing Incidence Optics

Again, in the choice of optics, the large wavelength range and a high flexibility for different user applications had to be taken into account. Thus, grazing incidence optics were chosen for the general layout of the facility. To provide high degrees of reflectivity, avoid the risk of damage due to the high peak powers, and minimize deformation of the mirrors by long bunch trains, very shallow incidence angles of 2° and 3° are used. A total mirror length of 500 mm has been chosen based on a 6σ acceptance for a beam diameter of 3–5 mm (FWHM). The beam divergence strongly depends on wavelength and for the longer wavelength $\geq$30 nm a 6σ acceptance of the optics cannot be expected any more.

The mirrors are silicon (plane) or zerodur (focusing) substrates with high-density carbon coatings. A state of the art low surface roughness amounts to less than 3 Å over the full mirror length for the plane mirrors and less than 5 Å for the focusing optics. Carbon coatings have been chosen because of their nearly constant high reflectivity between 94 and 96 % in the originally anticipated spectral range of the FLASH fundamental of 6–80 nm. The first pair of mirrors, which directs the beam to BL2 has an additional nickel coating and thus allows experiments the carbon K-edge.

1.3.1.2 Multi-layer Optics

In addition to the general endstation layout, users can bring their own focusing optics as part of their experimental chambers. For this purpose, at beamlines BL2 and BL3 (see below) the grazing incidence focusing optics can be retracted, allowing users either to conduct experiments in the non-focused beam with typically 5–10 mm FWHM beam size or to install their own optics. A variety of configurations have been used in past experimental runs. Back-reflecting spherical multilayer mirrors have been used to cover a large range of irradiation conditions from ∼10 mm in the non-focused beam down to ∼2 μm [7] or for THz-XUV pump-probe setups (see Sect. 1.6.2). Extremely small foci down to ≤1 μm have been achieved using off-axis parabolas for warm dense matter studies [8] and other special optics are used for coherent diffraction imaging (see [9] and references therein).

1.3.1.3 Beamlines

BL1, BL2 and BL3 utilize the direct SASE FEL beam. The three end-stations offer different focusing schemes leading to more or less intensely collimated FEL beams. BL1 was originally been equipped with a toroidal mirror ($f = 10$ m) providing a focal spot size of ∼100 μm. Since the vast majority of user experiments require smaller foci than BL1 can offer, this endstation is currently newly equipped with a permanent endstation—the CAMP chamber [10]—which will include a Kirkpatrick-Baez system. This new endstation will be available to users from the middle of 2014.

At BL2 and BL3 ellipsoidal mirrors with focal length $f = 2$ m generate focal sizes of ∼20–30 μm. As described in detail above, at both beamlines the focusing optics can be retracted to install other types of optics.

For the second branch a high-resolution plane grating monochromator has been built by the University of Hamburg in collaboration with DESY [11, 12] to enable high resolution spectroscopy at beamlines PG1 and PG2. Although the photon pulses of FLASH already offer a narrow inherent bandwidth of ∼1 %, many scientific areas require even further monochromatised radiation. Examples are the spectroscopy of highly charged ions [13], measurements of higher-order intensity correlation functions [14], or time-resolved pump-probe X-ray photoelectron spectroscopy [15]. Figures 1.3 and 1.4 depict the calculated photon flux behind the PG beamlines and the resolving power, respectively.

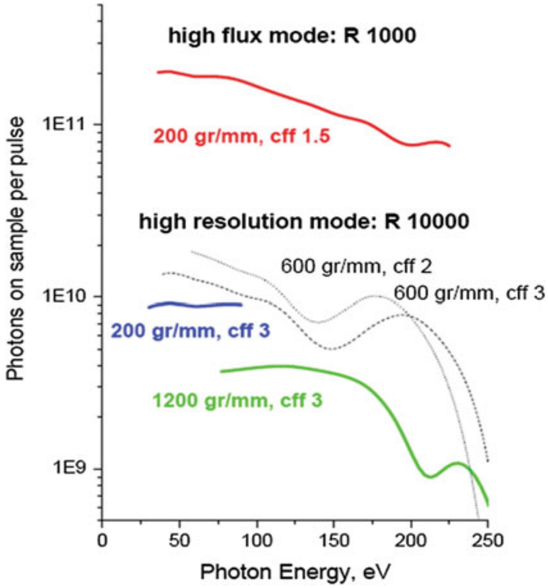

Fig. 1.3 Calculated photon flux behind the monochromator assuming 100 μJ pulse energy at the undulator exit

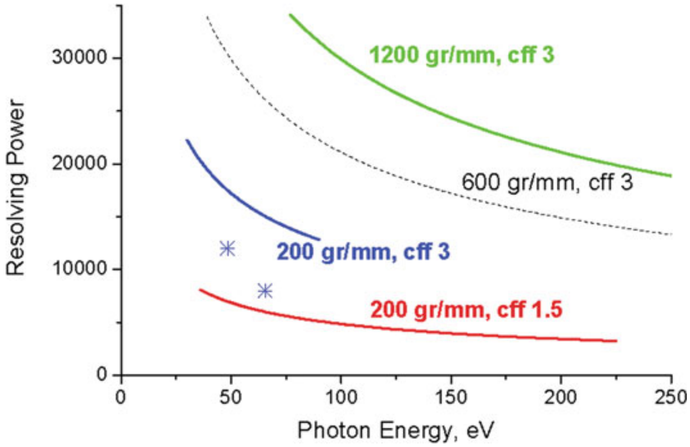

Fig. 1.4 Calculated (*lines*) and measured (*stars*) resolving power. Exit slit set to 20 μm for a constant fixed focus cff = 3 and 35 μm for cff = 1.5

PG1 is equipped with a permanently installed high-resolution double VUV-Raman spectrometer which can be used to study various samples with different techniques, such as resonant inelastic X-ray scattering (RIXS) to probe low-energy elementary (charge, spin, orbital and lattice) excitations in complex solids. The spectrometer employs a double monochromator setup which—along with enhanced stray light

Table 1.2 Technical specifications of the FLASH beamlines

	BL1	BL2	BL3	PG1	PG2
Monochromatisation	–	–	–	Yes	Yes
Optical elements	4	3(2)	5(4)	8	6
Focusing	Toroidal	Ellipsoidal (none)	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 @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}

rejection—allows high energy resolution measurements close to the Rayleigh line. During the first commissioning phase an instrument resolution of 30 meV has been confirmed [16, 17]. The ultimate resolution of below 10 meV should be reached after the commissioning of an improved Kirkpatrick-Baez (KB) focusing optic generating a FEL focal spot of 5 μm (vertically) at the sample position. PG2, on the other hand, is a general purpose monochromator beamline, where users provide their own experimental chambers. The spot size at PG2 is presently about 50 μm depending on wavelength and monochromator settings.

In Table 1.2 the most relevant information on the FLASH beamlines is summarized.

1.3.1.4 Fast Switching Mirror

Switching of beamlines is typically performed between user shifts every 12 or 24 h. The procedure takes several minutes with an accuracy of the position reproducibility in the μm range. However, not all user experiments require a 10 Hz repetition rate of the photon pulse trains. Provided that both user groups require the same FEL parameters, the laser beam could in principle be shared between two beamlines by using a fast switching mirror capable of shifting between pulse trains. Such a system has been developed at FLASH [18] and installed for switching between beamlines BL2 and BL3. It can move the FEL between the two beamlines with a frequency of up to 2.5 Hz and is coupled to the fast shutter (Sect. 1.5) to provide an appropriate FLASH pulse repetition rate. A major design challenge is posed for and met by the system in the repetition accuracy for the mechanical movement. At the reversal points, an accuracy in position of a few μm and in angle of about 1 arcsec is required, because the user endstations are typically 15–20 m downstream of the switching mirror.

1.3.1.5 Experimental Endstations

Up to 2013, FLASH user groups have typically brought their own experimental setups to the beamtimes. In the near future with the addition of FLASH2 (Sect. 1.7) and thus a higher number of available beamlines, several user endstations will be permanently installed. All beamlines end with an interconnection point, which consists of a differential pumping unit interfacing the ultra-high vacuum of FLASH to the user experiments. The latter may be operated with pressures up to 10^{-5} mbar. The experimental area is typically $3.4\,\mathrm{m}^2$ and contains provisions for connection to FLASH signals such as trigger, time stamp, photon diagnostics, the FLASH data acquisition system as well as vacuum control and interlock and gas systems [3].

1.3.2 Characterization of the Optical System

1.3.2.1 Damage of Optical Components

At a free electron laser, high peak powers could potentially render an (costly) optical component useless within fractions of a second [19]. The research of various damage mechanisms caused by this kind of sources is therefore an active field [20, 21]. The empirical data for damage thresholds that exist are often very specific to a certain (synchrotron) beamline and are thus unique in flux and operating wavelength. For these reasons, materials for optics and their coatings employed at X-ray free electron lasers around the world have begun to be studied in a more systematic fashion [21, 22], notably the low Z materials B_4C and SiC [23].

Damage to optical elements at a FEL can be thought of as direct and in-direct: direct damage could be ablation cratering of the surface, distortion due to the heat-load caused by the pulse, etc. In-direct damage mechanisms are more subtle and include damage to multilayers by diffusion or chemical modification of surfaces and layers or changes to the refractive index. Careful monitoring of the beamline performance is thus important and the methods described in Sect. 1.3.2.2 inherently give information that can be used to diagnose the optics.

1.3.2.2 Advanced Beamline Alignment Techniques and Determination of Coherence Properties

For alignment of the FLASH beamlines and focusing optics, wave-front sensors are regularly employed. First, a wave-front sensor by Imagine Optic [24] was used. Meanwhile, two very compact sensors, which include alignment mechanics directly in the system, were developed and extensively tested in a collaboration of DESY and *Laser Laboratorium Göttingen (LLG)* for beamline characterization and optimization both at FLASH [25] and FERMI [26]. They can also be employed by user groups in their experimental setups. The Hartmann-type sensors are largely independent of wavelength in the soft X-ray region and capable of measuring the wave-front of individual FEL pulses. They proved a valuable tool for observing the FEL beam quality as well as the performance of optical elements, such as metal filter foils or the gas attenuator.

In a Hartmann sensor the incoming photon beam is divided into a large number of sub-rays by a pinhole array and monitored in intensity and position on a CCD camera. The incident wave-front is determined by comparing the CCD image to that of a perfect spherical wave generated behind a pinhole for calibration. Ray tracing in upstream direction based on the measured wave-fronts is used to determine focal spot size and position.

In SASE FELs such as FLASH an influence of the stochastic nature of the beam generation process on the degree of spatial coherence is to be expected. Techniques to measure it are necessary and currently under investigation. In particular, 2nd order correlations should be considered for partially coherent sources to achieve reliable beam propagation and in the design of complex optical systems. Several experiments have been carried out so far based on an evaluation of two-beam interference patterns similar to Young's double slit experiment [27–29]. Alternatively, phase space tomography i.e. the reconstruction of the Wigner distribution function from selected two-dimensional intensity profiles along the beam caustic behind a focusing optic, has recently been carried out at FLASH with promising results (see [30, 31] and reference therein). This technique delivers in principle a complete beam characterization including wave-front, propagation and spatial coherence. However, unlike Hartmann wave-front measurements and techniques based on Young's double slit experiment, the Wigner-reconstruction gives only average results and no single pulse information.

1.4 Characterization of the FEL Pulses

Inside the FLASH tunnel a set of photon diagnostics is installed mainly for use by operators during setup of SASE. The FEL beam passes two diagnostic units equipped with apertures ranging between 0.5 and 15 mm and Ce:YAG screens for visualization of the XUV radiation which are located 20 and 25 m behind the last undulator segment. Centering the FEL beam with respect to these apertures ensures an accurate propagation of the photon beam across all beamlines towards the experiments. For fast intensity measurements an MCP tool and one of the GMD detector pairs (see below) are located inside the tunnel, as well as a grating spectrometer [32] and an OPIS (see below) for wavelength calibration.

At the same time, most user experiments need online information about important photon beam parameters, such as intensity, spectral distribution, and temporal structure. Due to the pulse-to-pulse fluctuations of FLASH, photon diagnostics need to be capable of resolving each individual pulse within a pulse train. This requires diagnostic tools which operate in parallel to the experiments in a non-destructive way.

1.4.1 Monitoring of the Intensity and Beam Position

A precise knowledge of the pulse energy of each individual FEL pulse is naturally essential for almost all user experiments. Depending on the operating conditions of the FEL, the average energy per bunch is typically in the range of 10–250 μJ as shown in Table 1.1. Intensity monitors have to cover the full spectral range from 4.2 and below to 80 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 gas monitor detector has been developed [33, 34] to perform a non-invasive measurement of the intensity of each individual pulse within a pulse train.

Four gas monitor detectors, 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 a 15 m long gas filled attenuator is positioned as described in Sect. 1.5. When an FEL pulse passes through the ionization chamber of a GMD 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.

1.4.2 Monitoring of the Spectral Distribution

Some user experiments require pulse-to-pulse knowledge of the spectral distribution of individual FEL pulses to interpret their data. Still, they may not want to use the PG beamline, because of temporal broadening of the pulse or a reduction of photon flux. Three options have been developed for this purpose at FLASH, a variable-line-spacing (VLS) grating spectrometer integrated into the BL beamline branch, an online photoionization spectrometer (OPIS) located in the photon diagnostic section in the FLASH tunnel and a mobile compact spectrometer which can be setup at the endstation or behind user experiments [35].

1.4.2.1 High Precision Online VLS Grating Spectrometer

A variable line spacing (VLS) grating spectrometer installed at the non-monochromatised BL-beamline branch allows to parasitically measure the spectral distribution of the FEL pulses. The optical design of the spectrometer has been carried out in a collaboration of DESY, *Scientific Answers and Solutions* (SAS) in Madison and the *Council for the Central Laboratory of the Research Councils* (CCLRC) in

Daresbury [36]. Making use of two interchangeable plane VLS diffraction gratings the spectrometer covers the wavelength range from 6 to 60 nm. Shorter wavelengths can be reached using second order light. The main vacuum vessel which houses the optics as well as the mechanics for the movement of the gratings have been designed in a joint project of *Helmholtzzentrum Berlin (HZB)* and DESY.

The major fraction of the radiation, ~85–99 % depending on wavelength and grating, is reflected in zeroth order to the experimental station, while only a small fraction is dispersed in first order and used for the online measurement of the spectral distribution. In the current setup, the dispersed radiation is focused on a detector unit containing a Ce:YAG single crystal screen which is 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 10 Hz. Up to now, the instrument has reached a resolving power of 1000 at 25 nm FEL wavelength. In the near future, the gated CCD camera will be complimented by a fast line detector for spectral analysis of pulse trains. Alternatively, a mirror with both, carbon or nickel coating can be moved in place of the gratings if no information of the spectral distribution is requested or if the intensity on the sample is very critical.

1.4.2.2 Online Photoionization Spectrometer

Wavelength measurements with the online photoionization spectrometer (OPIS) are based on photoionization processes of gas targets such as rare gases or small molecules like N_2 or O_2 [37–39]. Since binding energies and photoionization cross sections are precisely known from literature they can be used as a basis for wavelength determination.

An ion spectrometer is used to measure the intensities of different charge states of the created photo-ions. Since the partial cross sections of the different charge states evolve differently with increasing photon energy, the ratios of their corresponding intensities are a unique measure of the photon wavelength in a certain wavelength interval. Literature data of partial cross sections for the different charge states of various rare gases cover basically the full wavelength range of FLASH. The ion spectrometer has two major advantages. The signal intensity is high since the extraction fields collect all ions created by the radiation and it is insensitive against beam position changes.

In electron time-of-flight spectra, the arrival times of the photo-electrons reflect directly their kinetic energy. The electron binding energies of the orbitals from which the photo-electrons are emitted are the only information needed for wavelength determination. Hence, with only a few well known constant quantities the FEL wavelength can be derived over the full wavelength range. This is the main advantage compared to the ion method described above. In addition, more detailed spectral information such as higher harmonics content or the number of FEL modes [3] can, in principle, be deduced as well. On the other hand, the electron signal intensity is lower compared to the ion spectrometer due to limited acceptance angles and it is sensitive to external magnetic and electric fields.

The OPIS device contains a set of time-of-flight spectrometers for detection of photo-ions and photo-electrons, respectively. Since ion and electron signals are measured using fast digitizers, traces of full bunch trains of FLASH can be recorded and it is possible to monitor the spectral distribution resolved for each micro bunch. In addition, the spectrometer is in principle not limited in wavelength range and typical gas target pressures are in the range of 10^{-7} hPa which allow a photon transmission to the user experiment of essentially 100 %. These advantages make OPIS a promising complement to the existing grating spectrometers.

1.4.2.3 Compact Spectrometer

In collaboration with the *CNR-Institute of Photonics and Nanotechnologies* in Padova, a compact and portable spectrometer has been built for real time monitoring of the high-order harmonic contents of the FEL radiation [35]. This spectrometer can be installed at beamline ends or behind user experiments to determine the fundamental and high-order harmonic contents in single-shot operation mode. Its design is based on two flat-field grazing-incidence gratings combined with a EUV-enhanced CCD. The spectrometer covers the spectral range from 1.7 to 40 nm (720–30 eV).

1.4.3 Monitoring of the Temporal Properties

The temporal properties of the photon beam are a key measure of the performance of FELs. The pulse *length* is required to estimate the integral power at the experiment; the pulse *profile* determines the “quality” of the pulse in terms of length and height of the ideal pedestal shape; the pulse *jitter* is a random fluctuation in the arrival time of a pulse and needs to be correlated to another timing event. Thus, for pump-probe experiments it is obviously a crucial parameter. Since the temporal properties of a SASE FEL are going to change on a pulse by pulse basis by an amount that will cause difficulty for many experiments, there is a general need for temporal online diagnostics.

Such tools for the whole parameter range of FLASH are not a straightforward choice since they require intricate setups often with external laser sources. At FLASH, they are currently under intensive development. A choice of techniques like cross-correlation with an optical laser, intensity auto-correlation, reflectivity modulation of a semiconductor by a FEL pulse or the utilization of phase-correlated terahertz radiation has been tested and at this time each has shown their pros and cons. For details see [40] and references therein.

1.5 Manipulation of the Photon Beam

The photon beam can be manipulated by changing FLASH machine parameters. Within the pulse trains, the bunch repetition rate can be varied from single pulse to 1 MHz with up to 800 bunches (see Fig. 1.1), while a wavelength range from 4.2 to 47 nm is available at FLASH with the current machine parameters. Moreover, several options to modify beam properties are incorporated into the beamlines while the machine parameters are kept fixed. These are reduction of the intensity by a gas attenuator, suppression of harmonics using filter foils, and pulse picking with a fast shutter. Users can directly access these beamline components through the control system interface. Finally, two split-and-delay units, one at BL2 and the other at PG2, allow XUV-XUV pump-probe techniques both in the direct FLASH beam and in the monochromatic beam.

1.5.1 Reduction of Photon Pulse Energy

Research on the interaction of intense photon beams with matter benefits strongly from the possibility to vary the FEL intensity continuously over a large range. For this purpose, a gas filled attenuator is installed at FLASH, which gives the option to reduce the photon pulse energy by absorption in various gases. This technique leaves the other beam characteristics unchanged in contrast to changing machine parameters [41].

The attenuator is a windowless 15 m long gas-filled tube which is installed between the FLASH machine tunnel and the experimental hall. 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. Nitrogen covers an attenuation range of about four orders of magnitude in the spectral range of 19–60 nm. Between 19 and 9 nm and for shorter wavelengths Xenon and Krypton are used. Both sides of the attenuator are terminated by differential pumping stages to preserve the beamline vacuum. Within minutes to tens of minutes the transmission can be reduced by orders of magnitude and re-established to 100 %. Wave-front measurements have demonstrated that this attenuation technique does not degrade the coherence properties of the beam.

1.5.2 Suppression of FEL Harmonics

Spectrally, the FLASH photon beam consists of a strong fundamental and, to a much lesser degree, of higher harmonics [1, 42]. Certain experiments desire the suppression of the harmonic content, for example to distinguish between multi-photon and single photon processes due to harmonics. On the other hand, suppression of the fundamental and transmission of selected higher harmonics offers the opportunity

Table 1.3 Calculated transmission of various filter foils for three selected wavelengths of FLASH [43]

Filter	Thickness [Å]	Calc. transmission at 7 nm	Calc. transmission at 13.7 nm	Calc. transmission at 27.3 nm
Al	1000/1980	0.111/0.013	0.063/0.004	0.804/0.651
Si	2210/4190	0.017/4.5E-4	0.687/0.491	0.465/0.235
Zr	2000/2870	0.486/0.354	0.490/0.359	3.0E-8/$<$1E-10
Nb	1970/3840	0.398/0.166	0.369/0.143	$<$1E-10/$<$1E-10
Si_3N_4	3500/5000	0.002/1.2E-4	0.047/0.013	2.2E-5/2.2E-7
C/Al/C	2512/5025/2511	8.3E-6	3.8E-8	5.8E-7

For the calculation an additional coverage of a 20 Å oxide layer was assumed for the filters

to perform experiments at considerably higher photon energies. Also, a very quick reduction of the photon intensity for equipment tests is possible. Both, the BL and the PG branch have filter wheels with a variety of different metal foil filters. All filters are produced as self-supporting films without mesh support on frames with 10 mm diameter apertures. Table 1.3 summarizes the properties of the filters installed typically in the units.

1.5.3 Single Pulse Selection

A rotating fast bunch train shutter, shown in Fig. 1.5, has been developed at DESY for selection of individual photon bunch trains, repetition rates of below 10 Hz, or, in case of one bunch operation, single pulses of FLASH. The shutter contains an aluminum or glassy carbon disk which has six equidistant slits each providing a beam aperture of 20 mm. The disk rotation in vacuum is generated by a special magnetic rotary feed-through combined with a DC-motor outside of the vacuum system. The feed-through couples the rotation of the motor to the disk inside the vacuum without using bellows, mechanical or fluidic couplings. The rotating shutter can be operated through the FLASH control system [44].

1.5.4 Split and Delay Units

At BL2, a grazing incidence split-and-delay unit, which was developed and built in a collaboration of *HZB*, *Universität Münster* and DESY, is incorporated into the beamline to facilitate XUV-XUV pump-probe experiments. The device consists of eight mirrors under 6° grazing incidence which are positioned in a tubular ultra-high vacuum (UHV) chamber with a length of 1800 mm and a diameter of 500 mm.

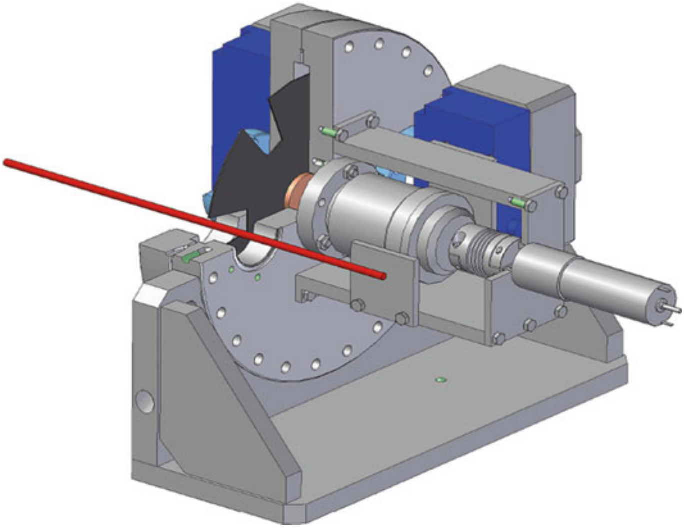

Fig. 1.5 The fast shutter is able to select a single pulses or pulse trains out of the generic 10 Hz repetition rate of the FLASH machine

The entire instrument can be shifted under vacuum to open a clear path through it, in case BL2 is to be used without the autocorrelator.

The FEL beam is split into two parts geometrically on the edge of the first mirror. One half passes a fixed length beam path, while two mirrors are positioned on a parallelogram-based delay stage in the other arm. A delay of –5 to +20 ps can be realized in this instrument with a 1 fs stability/reproducibility. Finally, both beams are recombined at the focus of BL2. The precision of the translation of the delay stage allows interference experiments, autocorrelation measurements of the pulse length of the femtosecond FEL pulses and pump-probe experiments at the user endstation. A detailed technical description can be found in [28, 45] and references therein.

At the plane grating monochromator beamline PG2, a Mach-Zehnder type autocorrelator has been developed by the *Universität Hamburg* and implemented as a XUV split-and-delay line. The device is able to split the pulses and delay them up to ±5.1 ps with a stability in the 200 attosecond range. Both delay arms include an intensity monitor system to measure the beam splitting ratio online. A filter unit in the arms of the delay-line allows a choice of harmonics, as described above, and thus two-colour XUV-XUV pump-probe experiments [46].

The device allows studies of ultra-fast XUV induced dynamics in a site-selective way and it can again be used to monitor the temporal coherence properties of FLASH. In particular, at the monochromator beamline PG2 temporal coherence properties can be measured energy resolved at the expense of lengthening the pulses.

1.6 Additional Light Sources for Advanced Multi-colour Experiments

The femtosecond pulses of FELs make studies of ultra-short processes a particularly attractive area of research at these facilities. More than half of the user experiments use the various options of pump-probe techniques at FLASH. In addition to the split-and-delay units which open up XUV-XUV pump-probe measurements, the FLASH facility offers two additional light sources in combination with the FEL for two-colour pump-probe experiments: a highly advanced optical laser system and a THz radiation source.

1.6.1 Optical Laser System

The optical laser system and the associated infrastructure in the FLASH experimental hall fulfill exceptional requirements [47]. To offer very flexible research opportunities, a complex laser system was built delivering either femtosecond pulses down to 60 fs duration with the macro pulse structure of the FEL (see Fig. 1.1) and moderate pulse energies of 50 μJ (pulse train option) or a few hundred times more intense pulses at 10 Hz repetition rate (mJ-option).

The system is reliable for long-term measurements, highly automated, and remotely controllable from the experiment. Advanced techniques for the synchronization of the optical laser to FLASH are in place. A synchronization scheme with long-term stability is used. It is based on a length-stabilized fiber-distributed optical reference signal with sub-10 fs (rms) timing jitter employing a balanced optical cross-correlator [48].

The pulse train option delivers ultra-short pulses with the same time structure as FLASH. The system was built in collaboration with the *Max-Born-Institute* in Berlin and consists of three modular sub-systems. The pump laser, a slightly modified copy of the photo cathode laser of the FLASH accelerator, is a Nd:YLF based burst mode laser which was optimized to produce pulse trains of up to 600 pulses with a spacing of 1 μs between individual laser pulses. The pulse trains are produced with 10 Hz, thus delivering up to 6000 pulses per second. A Ti:Sapphire oscillator is used to provide ultra-short (∼20 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 ∼60 fs (FWHM) near infrared 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 particularly suited for high repetition rate experiments such as pump-probe experiments in solids (e.g. magnetization dynamics) which yield low count rates for single pulses and thus need a high number of pulses to acquire sufficient signal.

The mJ-option on the other hand is suited for experiments which need a more intense laser pulse. The same Ti:Sapphire oscillator pulses are this time amplified by a commercial amplifier based on a chirped pulse amplification (CPA) setup including a regenerative as well as a 2-pass amplifier (Hidra 25 by Coherent). The maximum laser output amounts up to 20 mJ at 60 fs pulse duration (15 mJ, at the experimental station).

Since the user endstations are up to 20 m distance away from the laser hutch, the optical laser is distributed in a separate dedicated beamline system to four of the experimental stations, namely BL1-BL3, and PG2 as seen in Fig. 1.2 [3].

1.6.2 THz Beamline for Pump-Probe Experiments

As a second option for pump-probe experiments, a planar electromagnetic undulator with 9 full periods producing THz radiation was installed 5 m downstream of the FLASH undulator [49]. It generates THz pulses from 10–330 μm, i.e. 30–0.9 THz, in wavelength and 300 fs–10 ps in pulse duration. The soft X-ray and THz pulses are synchronized on a femtosecond scale since they are emitted by the same electron bunch.

The two pulses are separated and transported in dedicated beamlines to be recombined at endstation BL3 for two-colour pump probe experiments. In its dedicated 65 m long beamline the THz beam is refocused repeatedly owing to its large divergence. As a result, the XUV beamline to BL3, which includes only grazing incidence optics, is 4 m shorter than the THz beamline. Thus, this path difference has to be compensated by redirecting the XUV beam using appropriate multi-layer mirrors in back reflection geometry to achieve 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 both pulses or delay them in a controlled way.

1.7 Near Future Perspectives

Since 2005, the FLASH user facility has been steadily improved, the wavelength range enlarged and new diagnostic tools have been added. The user time at the facility is highly overbooked and possibilities to extend it with the existing FLASH facility are limited. Thus, a major upgrade to expand the facility and double the user capacity is under way. In the FLASH II project, a new tunnel and experimental hall are added to the existing facility as shown in Fig. 1.6 [50, 51]. They will house a new undulator line FLASH2 with up to seven photon beamlines and reserve capacity for a third undulator line FLASH3 as well as other upgrades and extensions. In the future, a seeding scheme will be added to FLASH2 as an alternative to SASE to improve the beam quality.

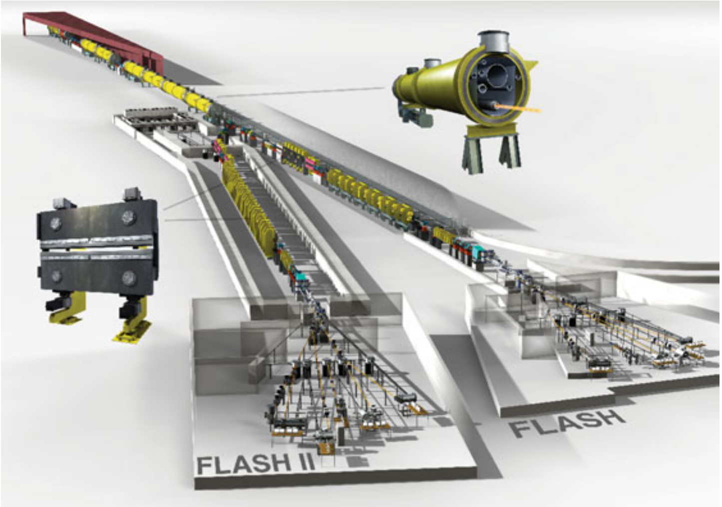

Fig. 1.6 Layout of the FLASH facility including FLASH1 and FLASH2

FLASH II uses to a large extent the existing facility and infrastructure. Modifications needed to the present accelerator which will now drive both undulator lines are minor. Behind the last accelerating module, the beam is switched between the original undulator line now called FLASH1 and the new variable gap undulator line FLASH2. The bunch train can be divided into two bursts, one going straight to FLASH1, the second being kicked to FLASH2. Thus, the electron beam is delivered for both lines with a 10 Hz repetition rate each while varying pulse repetition options are possible. Since FLASH1 has a fixed-gap undulator, the desired FLASH1 wavelength determines the accelerator parameters and the FLASH2 undulator gap is then tuned to the desired wavelength at FLASH2 in a second step.

Similarly to FLASH1, photon diagnostics are positioned in the new FLASH II tunnel behind the dump magnet as well as at the front of the experimental hall. However, contrary to FLASH1, the first two deflecting mirrors are also in the tunnel and radiation shielding will not be necessary inside the new experimental hall. The new hall will allow space for up to seven beamlines [52, 53]. All diagnostic and beam manipulation tools described above, as well as an optical pump-probe laser system and a THz source based on a dedicated undulator will be included into the FLASH2 facility.

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References

1. W. Ackermann et al., Nat. Photonics **1**, 336–342 (2007)
2. V. Ayvazyan et al., Eur. Phys. J. D **37**, 297–303 (2006)
3. K. Tiedtke et al., New J. Phys. **11**, 023029 (2009)
4. S. Schreiber, in *Proceeding of FEL2011*, Shanghai, pp. 164–165 (2011)
5. S. Schreiber, in *Proceedings of FEL2011*, Shanghai, pp. 267–270 (2011)
6. E.L. Saldin, E.A. Schneidmiller, M. Yurkov, *The Physics of Free Electron Lasers*. (Springer, Berlin-Heidelberg, 2000)
7. A.A. Sorokin et al., Phys. Rev. Lett. **99**, 213002 (2007)
8. A.J. Nelson et al., Opt. Express **17**, 18271–18278 (2009)
9. S. Bajt et al., Photon science (2012), http://photon-science.desy.de/annual_report/
10. L. Strüder et al., NIM A **614**, 483–96 (2010)
11. M. Martins et al., Rev. Sci. Instr. **77**, 115108 (2006)
12. M. Wellhöfer et al., J. Opt. A. **9**, 749 (2007)
13. S.W. Epp et al., Phys. Rev. Lett. **98**, 183001 (2007)
14. A. Singer et al., Phys. Rev. Lett. **111**, 034802 (2013)
15. S. Hellmann et al., New J. Phys. **14**, 013062 (2012)
16. N. Gerasimova et al., J. Mod. Opt. **58**, 1480 (2011)
17. A. Rusydi, M. Rübhausen et al., Screening enhanced hole pairing in Spin = 1/2 two-leg ladder compounds unravelled by high-resolution resonant inelastic X-ray scattering at FLASH (in preparation)
18. S. Pauliuk et al., in *Proceedings of EPAC08*, Genoa, pp. 124–26 (2008)
19. A.R. Khorsand et al., Opt. Express **18**, 700–712 (2010)
20. J. Kuba et al., NIM A **507**, 475–78 (2003)
21. S.P. Hau-Riege et al., Appl. Phys. Lett. **93**, 201105 (2008)
22. S.P. Hau-Riege et al., Phys. Rev. E **76**, 046403 (2007)
23. S.P. Hau-Riege et al., Opt. Express **18**, 23933–38 (2010)
24. M. Kuhlmann et al., in *Proceedings of FEL 2006*, Berlin, pp. 794–797 (2006)
25. B. Flöter et al., NIM A **635**, S108–S111 (2011)
26. L. Raimondi et al., in *Proceedings of SPIE Optics + Photonics*, San Diego (2013)
27. A. Singer et al., Phys. Rev. Lett. **101**, 254801 (2008)
28. R. Mitzner et al., Opt. Express **16**, 19909–19 (2008)
29. R. Ischebeck et al., NIM A **507**, 175–180 (2003)
30. T. Mey et al., in *Proceedings of SPIE*, vol. 8778, 87780H1-8 (2013)
31. B. Schäfer et al., in *Proceedings of SPIE*, vol. 8778, 877810-10 (2013)
32. L. Poletto et al., in *Proceedings of SPIE*, vol. 5534, p. 37 (2004)
33. M. Richter et al., Appl. Phys. Lett. **83**, 2970 (2003)
34. K. Tiedtke et al., J. Appl. Phys. **103**, 094511 (2008)
35. F. Frassetto et al., NIM A **635**, S94–S98 (2011)
36. G. Brenner et al., NIM A **635**, S99–S103 (2011)
37. P. Juranic et al., JINST **4**, P09011 (2009)
38. M. Wellhöfer et al., JINST **3**, P02003 (2008)
39. M. Braune, G. Brenner, S. Dziarzhytski, K. Tiedtke, Cross-calibration measurements for online wavelength monitoring at FLASH (in preparation)
40. S. Düsterer et al., Phys. Rev. STAB **17**, 120702 (2014)
41. U. Hahn, K. Tiedtke, in *AIP Conference Proceedings*, vol. 879, pp. 276–282 (2007)
42. S. Düsterer et al., Opt. Lett. **31**, 1750–2 (2006)
43. B.L. Henke, E.M. Gullikson, J.C. Davis (1992) Atomic Data Nuclear Data Tables 54 181, CXRO website, http://henke.lbl.gov/optical_constants/
44. S. Toleikis et al., Photon science (2009), http://photon-science.desy.de/annual_report/
45. M. Wöstmann et al., J. Phys. B: At. Mol. Opt. Phys. **46**, Special Issue: Frontiers of FEL Science 164005 (2013)

46. F. Sorgenfrei et al., Rev. Sci. Instrum **81**, 043107–7 (2010)
47. H. Redlin et al., NIM A **635**, S88–S93 (2012)
48. S. Schulz et al., in *Proceedings of SPIE*, vol. 8778, 87780R1-9 (2013)
49. M. Gensch et al., Infrared Phys. Techn. **51**, 423–25 (2008)
50. B. Faatz et al., NIM A **635**, S2–S5 (2011)
51. K. Honkavaara et al., in *Proceedings of FEL2012*, Nara, pp. 381–84 (2012)
52. M. Kuhlmann et al., in *Proceedings of SPIE*, vol. 8778, 87781A1-7 (2013)
53. E. Plönjes et al., in *Proceedings of FEL2013*, New York (2013)

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