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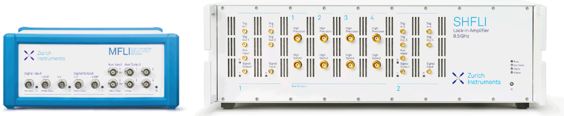

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The FLASH Facility
Current Status In 2018 And Future Upgrade Plans

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Abstract. FLASH is the only high-repetition-rate FEL in the XUV/soft X-ray regime worldwide. Based on superconducting accelerator technology developed at DESY, it can provide up to 8000 pulses/s for experiments in such diverse fields as atomic, molecular, and optical physics, chemistry, condensed matter and nanoscience, life science, warm dense matter research, and FEL physics and technology, including development of new methods and instrumentation. The outstanding opportunities for time-resolved studies at FLASH, which are based on unique pump-probe instrumentation including fully synchronized optical lasers, a large suite of X-ray split-and-delay units, a THz source that is phase stable with respect to the FEL pulses, and sophisticated diagnostics for pulse arrival and duration, attract a large number of eminent researchers in ultrafast science to FLASH. The recent addition of a second FEL line, FLASH2, with variable-gap undulators that enable easy wavelength tuning and novel lasing schemes for users in parallel to the operation of FLASH1, along with the progress in creating and measuring ultrashort single-spike SASE pulses, and the new suite of dedicated state-of-the-art end stations have made FLASH even more attractive to users. To keep FLASH at the forefront of FEL science and technology, an ambitious upgrade program is currently planned. FLASH2020+ foresees operation of two FEL lines, with one line providing externally seeded pulses up to the full repetition rate of FLASH and the second line allowing for flexible novel lasing schemes based on a set of variable undulators. This line will be designed to deliver coherent radiation from THz to soft X-rays. The new ideas are fully in sync with the requirements of the community for breakthrough science with a high-repetition rate XUV/soft X-ray FEL.

INTRODUCTION

Since 2005 the Free electron LASer in Hamburg (FLASH) is serving as a regular user facility [1, 2, 3], providing uniquely intense, short-pulsed radiation that can be tuned from 90 nm to 4 nm at FLASH2 (FLASH1: 50 nm - 4.2 nm), where the lowest achievable wavelength (maximum photon energy) corresponds to a maximum electron energy of 1.25 GeV in the accelerator. Peak and average brilliance of this user facility 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 hence, combined with appropriate focusing optics, peak irradiance levels of more than 10^{17} W/cm^2 can be achieved [4]. Brilliance, coherence and an ultra-short pulse length down to the femtosecond regime are the outstanding properties that opened a new era in the investigation of soft X-ray radiation-matter interaction. Over the past decade FLASH has hosted many international user groups which 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.

MULTI-LINE OPERATION

In April 2016, simultaneous user operation of FLASH1 and FLASH2 started. FLASH2 is a major extension of the soft X-ray free-electron laser FLASH at DESY that turns FLASH into a multi-user FEL facility. A new undulator line

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[*] For the whole FLASH team.

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is located in a separate accelerator tunnel and is driven by the FLASH linear accelerator. First lasing of FLASH2 was achieved in August 2014 with simultaneous user operation at FLASH1. The new FLASH2 experimental hall offers space for up to six experimental end stations in addition to the five station in the FLASH1 hall, some of which will be installed permanently. The wavelength range spans from 90 to 4 nm and down to 0.8 nm in the 5th harmonic. More information of the FLASH2 facility is given in [5]. Details of first lasing at FLASH2 and the general aspects of multi-beam and multi-beamline FEL operation are given in [6, 7, 8]. Even simultaneous multiple lasing in three beamlines including the R&D beamline sFLASH has been demonstrated (see Fig. 1) [9].

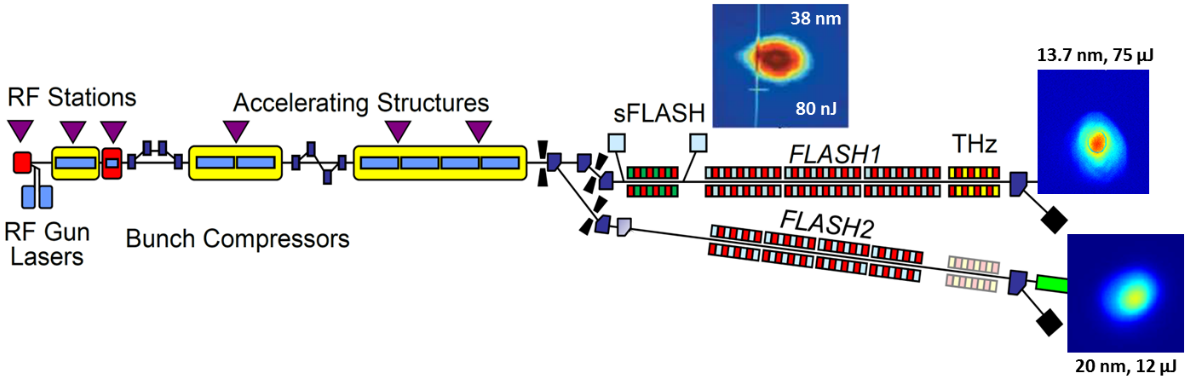

FIGURE 1. Achieving simultaneous multiple lasing of three beamlines (FLASH1, FLASH2, and sFLASH) with two electron bunches. Electron bunch #1 does cascaded lasing in sFLASH at 38 nm and FLASH1 at 13.7 nm with a chicane in between that destroys bunching from the first sFLASH undulator, while bunch #2 lases in FLASH2 at 20 nm wavelength.

FLASHs superconducting linear accelerator can produce bunch trains of up to 800 bunches (at 1 MHz rate) within the 0.8 ms RF flat top at a repetition rate of 10 Hz. In standard operation FLASH is supplied with up to 500 bunches in two bunch trains with independent fill patterns and compression schemes. The intra-bunch train repetition rate can be changed from 1 MHz in steps down to 40 kHz by user demand independent for each undulator beamline. In order to serve both lines with bunch trains at 10 Hz, the train is divided in two sub-trains. These sub-trains are distributed between the two undulator beamlines with a kicker/septum scheme. The RF flat top has to accommodate two sub-trains and a transition period of 50 μs to 100 μs between them. For maximizing the flexibility of SASE operation, the FLASH LLRF system has been adapted to allow splitting the flat top between several sub-trains of bunches with (within boundaries) varying flat top parameters (mainly amplitude and phase) [10].

Although the addition of FLASH2 has increased the available beam time for user experiments, it did not automatically doubled as the wavelength for FLASH1 is still defined by the electron energy in the common FLASH accelerator due to fix gap undulators installed at FLASH1. Therefore the accessible wavelength at FLASH2 ranges only from the given FLASH1 wavelength up to three times the FLASH1 wavelength [5]. As a consequence, it is not always possible to schedule matching user experiments at the same time for FLASH1 and FLASH2.

Another unique feature at FLASH1 is the availability of a fully coherent and tunable THz source (1-30 THz) due to an electromagnetic undulator which is located behind the FLASH1 undulator (not displayed in Fig. 1) [11]. It allows to deliver quasi phase stable THz pulses with respect to the FEL pulses because both pulses originate from the same electron bunch. In order to match the path lengths of both sources the THz pulse can only be combined at the beamline BL3 for XUV-THz pump-probe experiments, or the THz pulse can be used stand-alone in an dedicated THz hutch in the FLASH1 experimental hall [12].

BEAMLINES AT FLASH1 AND FLASH2

Currently, five beamlines at FLASH1 (BL1, BL2, BL3, PG1, PG2) and two beamlines at FLASH2 (FL24, FL26) are in operation, providing largely independent photon beam parameters to the respective experimental halls. A photon beam transport system delivers the FEL pulses to one of the experimental stations in each of the FLASH1 and FLASH2 experimental hall at a time by switching between photon beamlines using a set of plane mirrors. In order to use each FEL beam most efficiently, several experiments are set up at the same time at different beamlines. Usually, one experiment in each experimental hall is online at least for a 24 hour shift and then the beam is switched to another station.

There are several photon diagnostics and beam manipulation tools which are common to all beamlines: gas monitor detector (GMD) as intensity monitors [13], beam position monitors [14], apertures [14], fast shutter [15], filter wheels [14], gas absorber [3], and a co-linear optical alignment laser.

To monitor the spectral distribution of the FLASH pulses there are different concepts for FLASH1 and FLASH2. The bandwidth of the FLASH pulses is typically ~1%, but can vary depending on the setup of the accelerator from 0.4% up to 2%. In addition to the spectrometer used for wavelength setup of FLASH1 inside the tunnel and the PG monochromator beamline, three spectrometers are available for online monitoring of the FEL wavelength. Some user experiments require knowledge of the spectral distribution of the individual FEL pulses to interpret their data, but may not want to use the PG beamlines, because of temporal broadening of the pulse or a reduction of photon flux. Three options have been developed and are available to users for this purpose [15], a variable-line-spacing (VLS) grating spectrometer integrated into the BL beamline branch [16], an online photoionization spectrometer (OPIS) located in the photon diagnostic section in the FLASH2 tunnel [17, 18] and a mobile compact spectrometer which can be setup at the endstation or behind user experiments [19].

Recently, a new device for polarization control in the BL branch of FLASH1 has been installed and commissioned. A four-mirror reflection based polarizer allows the generation of circular polarized light in the wavelength range from about 35 to 13.5 nm. It reaches a degree of circular polarization of up to 90% while maintaining a total transmission above 30% [20].

At all beamlines a synchronized optical laser is available for pump-probe experiments. Details of the optical lasers available at FLASH1 and FLASH2 are described in the next section. In the following sub-sections each of the beamlines and their main features are briefly described.

FLASH1 - Beamline BL1 / CAMP endstation

At this beamline an endstation for imaging, electron- and ion-spectroscopy, and pump-probe experiments is installed to use the non-monochromatic FEL photons in the BL branch. It is equipped with Kirkpatrick-Baez (KB) focusing optics providing a FEL focal spot size of ~6×8 μm^2 (FWHM, hor./ver.). The station has a modular layout allowing combinations of large-area, single-photon counting pnCCD photon-detectors with VMI- and COLTRIMS-type electron- and ion-spectrometers, and ports for various user provided gas jets, particle injectors and fixed target holders [21, 22]. A dedicated collinear laser in-coupling optical setup and additional diagnostics for the FLASH1 optical pump-probe laser systems are available. A multilayer based split-and-delay unit (SDU) which is located in front of the KB system can be used for XUV pump - XUV probe experiments (delay range from -30 ps to +650 ps, multi-layer mirrors @ 13.57 nm wavelength) [23].

FLASH1 - Beamline BL2 / Open-port, XUV split-and-delay unit

This beamline features an open-port where users can also perform XUV pump - XUV probe experiments using non-monochromatic FEL photons. It has a carbon coated ellipsoidal mirror as a focusing optics providing a ~20 μm focus for wavelengths >4.5 nm. This mirror can be retracted to use the unfocussed beam of ~5-10 mm size (FWHM, depending on wavelength) for the full wavelength range of FLASH1 (C and Ni coated optics available). The XUV pump-probe capability is provided by an XUV beam splitter which is located before the focusing ellipsoidal mirror. The SDU is equipped with carbon coated optics limiting the usable wavelength to >5 nm. The time delay between the two XUV pulses can be varied from -3 ps to +15 ps with sub-fs resolution [24]. It also allows fundamental and third harmonic pump-probe configurations by using suitable filters in both XUV pathways.

FLASH1 - Beamline BL3 / Open-port, THz Beamline

This beamline features the same focusing capabilities as BL2 with the restriction that for the unfocussed beam the wavelength restriction of >4.5 nm applies due to solely carbon coated mirrors in beam path. BL3 is the only beamline where pump-probe experiments using THz radiation, either from a THz undulator or edge radiation from the beam dump dipole magnet, are possible. The THz undulator beamline has been designed to provide coherent femtosecond (fs) to picosecond (ps) THz pulses for pump-and-probe experiments in combination with fs XUV pulses from FLASH1. The design of the beamline allows to overlap a XUV FEL pulse and a THz pulse generated by the same electron bunch at the end of BL3. The pulses are therefore naturally synchronized. The THz pulse energies are typically in the microjoule regime. THz radiation with the following parameters is available for pump-and-probe experiments at BL3:

- tunable (from the dedicated THz undulator): 10-300 μm (30-1 THz); up to 100 μJ/pulse; ~10% bandwidth,
- broadband (edge radiation from the last dipole magnet) at 200 μm (1.5 Thz); up to 10 μJ/pulse; ~100% bandwidth,
- synchronized and phase stable to the XUV pulses (down to 5 fs).

FLASH1 - Monochromator Beamline PG2 / Open-port, XUV split-and-delay unit

The XUV monochromator beamline installed at FLASH1 is a high-resolution plane grating monochromator of SX-700 type which allows different classes of experiments to be performed in the fields of gas phase physics, magnetic spectroscopy, high resolution photoelectron spectroscopy, surface chemistry, soft x-ray diffraction and holography. The PG beamline layout permits a free choice of best trade-off between photon flux and resolution. Thus, it provides enough flexibility over the broad parameter range of FLASH1 to enable high resolution applications, pump-probe experiments with control over the temporal-spectral properties at moderate resolution, and high photon flux experiments with the option of harmonic filtering [25, 26]. It is an open-port beamline where the typical focal size is ~50 μm. Due to diamond-like carbon coated optics the usable FEL wavelength in the fundamental ranges from >4.5 nm to 50 nm. The monochromator reaches a resolving power of $>10^4$ and can be used as a high-resolution spectrometer. It also features an XUV split-and-delay unit with variable time delay (±6 ps) for (multicolor) time resolved XUV-pump XUV-probe studies [27].

FLASH1 - Monochromator Beamline PG1 / Raman spectrometer endstation

This beamline also uses the monochromatized beam of the PG branch. It features a two-stage XUV-Raman spectrometer for high-resolution measurements close to Rayleigh line with an energy resolution (design values) from 2-20 meV at 20-200 eV, respectively. It uses Kirkpatrick-Baez (KB) refocusing optics which yields a FEL focal spot of 5 μm (vertically) at the sample in a dedicated sample chamber [28]. The first spectrometer stage has been already commissioned and provides spectral resolution <70 meV at photon energy <100 eV. The implementation of the femtosecond optical laser for time-resolved RIXS experiments is ongoing. The first pump-probe experiment is scheduled at the end of 2018.

FLASH2 - Beamline FL24 / Open-port, KB focusing optics, XUV split-and-delay unit

Beamline FL24 has an open port for user supplied end stations. FL24 covers the entire wavelength range of FLASH2. It is equipped with a KB bending mirror system for focusing, providing an adjustable focus position with focus sizes typically below 10 μm. A grazing incidence XUV split-and-delay unit, a further developed version with shallower angles providing shorter wavelengths, will be installed soon [29]. The newly designed differential pumping section features an out-coupling mirror for wave front sensor measurements [30], while a user experiment is setup, and the possibility of a co-linear in-coupling of an optical pump-probe laser. The KB focussing system can also be retracted providing an unfocussed beam of ~3-10 mm size (FWHM, depending on wavelength).

FLASH2 - Beamline FL26 / REMI endstation (in cooperation with the MPIK Heidelberg)

With a reaction microscope (REMI) all fragments of a photoionization process can be detected by means of a combination of electron and ion time-of-flight spectrometers and a specific arrangement of electric and magnetic extraction fields [31]. Using a coincident measurement technique, a complete set of all the kinematic properties of the products of the photoionization process can be determined in the experiment. Hence, this device is especially suited to investigate the dynamics of various ionization processes of gas phase and liquid targets. With respect to time-resolved experiments employing XUV-XUV pump-probe schemes, a mirror chamber has been recently setup which simultaneously serves as an in-line split-and-delay stage and a focusing device. The time-delay can be adjusted in the range of ±2.7 ps. A focal spot size of 4×5 μm^2 (FWHM) has been achieved. The carbon coated mirrors cover the whole FLASH2 wavelength range above 4.5 nm and the mirror reflectivity is larger than 75% in the wavelength range between 9 and 41 nm. In addition to an optical pump-probe laser a synchronized HHG system providing VUV photons is planned for FL26. These sources will enable high repetition rate, multi-color pump-probe experiments in the near future.

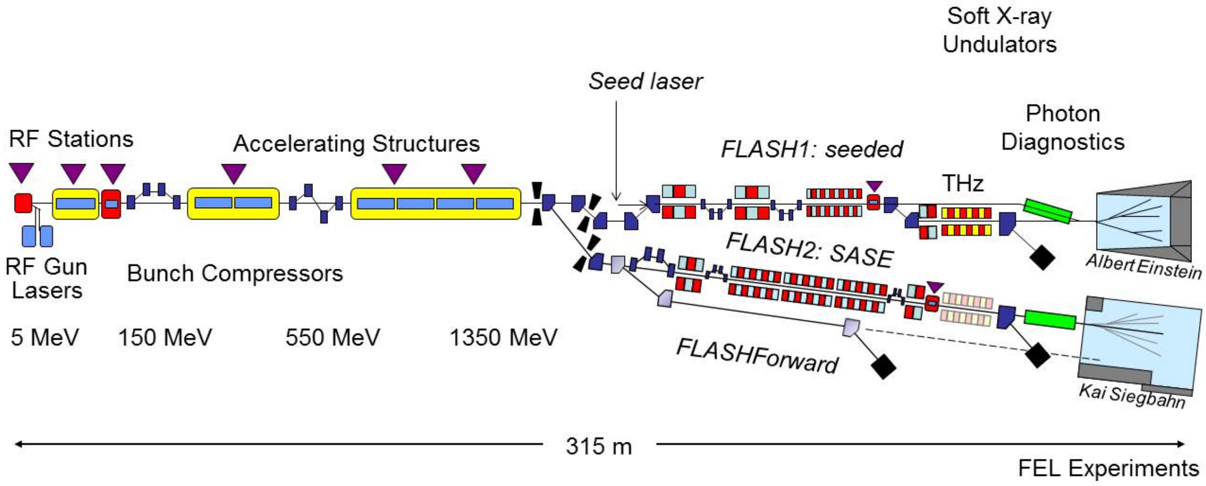

FIGURE 2. Planned FLASH2020+ layout within the present footprint.

OPTICAL LASERS

Two complementary optical lasers are available to user groups at FLASH1 in the FLASH1 experimental hall named '*Albert Einstein*'. First a Ti:Sapphire laser can deliver a high energy pulse (up to 10 mJ, ~60 fs FWHM), albeit the repetition rate is limited to 10 pulses per second. The second laser, based on optical parametric chirped pulse amplification, provides trains of ~20 μJ pulses (~100 fs FWHM) that map exactly onto the complex timing pattern of the FEL delivering several thousand pulses per second in bursts at 10 Hz with a minimum pulse spacing of 1 μs. Both laser systems deliver a central wavelength of 800 nm [32]. Second and third harmonic radiation can be generated at the experimental endstations. Since the FEL and the optical laser are independent sources of femtosecond pulses, the synchronization between both is of vital importance in order to perform well defined pump-probe experiments. The overall timing jitter between the FEL and the optical laser at the endstation is approximately 40 fs rms [33].

The FLASH2 pump-probe laser system has been newly developed. The following list summarizes the most important specifications available at the beamlines FL24 and FL26 in the FLASH2 experimental hall named '*Kai Siegbahn*' in 2018: wavelength at 800 nm (fundamental center wavelength); bandwidth of 100 nm (TL <20 fs); intra-burst repetition rate of 50 kHz with 1-40 pulses in the burst; pulse duration of 15 fs FWHM; pulse energy up to 500 μJ; energy stability <10% pulse-to-pulse peak fluctuation (3% rms). Future upgrades foresee higher intra-burst repetition rates (50, 100, 500, 1000 kHz) at the same average output power as well as variable transform limited pulse durations up to 200 fs and wavelength tuning between 700 and 900 nm. Furthermore, different frequency conversions possibilities into the VIS, IR and UV spectral range are planned in the near future.

FUTURE PLANS

The present FLASH2020+ design (see Fig. 2) foresees to: a) extend the wavelength range, b) provide variable polarization in the fundamental and/or harmonics, c) run a multi-FEL line facility with i) an advanced flexible undulator scheme in one SASE FEL line and ii) with external seeding in the other FEL line (1 MHz burst mode), d) further extend pump-probe capabilities by providing very flexible pump schemes and e) generate ultrashort, sub-femtosecond pulses [34]. In the preparation phase from 2017 to 2020, in addition to finalizing the upgrade plans for the two FEL lines, FLASH1 and FLASH2, it is planned to refurbish two accelerator modules which increases the maximum electron energy to 1.35 GeV. It is also planned to install a variable-polarization afterburner in FLASH2. Furthermore, a new injector laser for FLASH will be developed, which can provide flexible electron bunch patterns at the full repetition rate for simultaneous operation of FLASH1 and FLASH2 with a single gun laser. In FLASH2, an X-band deflecting cavity will be installed downstream the undulators for advanced diagnostics of SASE pulses. The electron beam diagnostics will be upgraded with particular emphasis on low-charge operation required for the shortest SASE pulses. In the FLASH2 experimental hall, a new time-compensating monochromator will be installed [35, 36]. The design for this beamline FL23 has been finalized after intense discussions with the user community. In addition, it is planned to install a THz undulator at FLASH2 and to integrate a THz streaking station in the FLASH2 photon diagnostics section for online pulse duration and arrival time monitoring [37].

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