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FLASH - STATUS AND UPGRADES

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Abstract

FLASH, the Free-Electron Laser at DESY in Hamburg was the first FEL user facility in the XUV and soft X-ray range [1–5]. The superconducting RF technology allows to produce several thousand SASE pulses per second with a high peak and average brilliance. It developed to a user facility with a 1.25 GeV linear accelerator, two undulator beamlines running in parallel, and a third electron beamline containing the FLASHForward plasma wakefield experiment. Actual user operation and FEL research are discussed. New concepts and a redesign of the facility are developed to ensure that also in future FLASH will allow cutting-edge research. Upgrade plans are discussed in the contribution.

FLASH FACILITY

FLASH, the Free-Electron Laser at DESY in Hamburg is a user facility which delivers FEL pulses based on the self-amplified spontaneous emission (SASE) in the wavelength range from 4 to 90 nm for user experiments. The extension of the FLASH facility by a second undulator beamline allows multi-user operation [6, 7]. Both FLASH undulator-beamlines are driven by a common linear accelerator consisting of a laser driven radio-frequency (RF) gun with a photocathode, seven superconducting accelerating modules, a third-harmonic accelerating module, and two bunch compressors. The superconducting technology allows the acceleration of electron bunch trains of several hundred bunches with a spacing of a microsecond or more and a repetition rate of 10 Hz for both beamlines. An electron beam energy of up to 1.25 GeV can be reached. A fast kicker system and a Lambertson septum are used to extract one part to FLASH1 and the other part of the bunch train into the FLASH2 beamline.

The FLASH1 beamline has six fixed-gap undulators, with a length of 4.5 m each. The SASE wavelength of FLASH1 is determined by the electron beam energy. Additionally a planar electromagnetic undulator is installed downstream of the FLASH1 SASE undulators providing THz radiation. The FLASH1 beamline also contains a seeding experiment called sFLASH [8–10].

In the FLASH2 beamline a third bunch compressor was installed in June 2019 to increase the compression flexibility, reduce the effects of space charge and of coherent synchrotron radiation (CSR). The new bunch compressor in the FLASH2 beamline has been commissioned and is now a part of the standard operation. FLASH2 contains twelve variable-gap undulators with a length of 2.5 m each, which allow choosing the wavelength to a certain extend independently from FLASH1 by varying the gap width of the undulators. In order to operate FLASH2 almost independently of FLASH1, a second injector laser and a flexible low level RF system are used. First lasing of FLASH2 was achieved in August 2014 simultaneous to FLASH1 SASE operation. In April 2016, two user experiments, one at FLASH1 and the other at FLASH2, were running in parallel for the first time. Two experiments, requiring different beam parameters, can run simultaneously, since the bunch pattern and compression scheme can be chosen almost independently for FLASH1 and FLASH2 beamlines, allowing to tune the SASE properties specifically for each of the experiments [11].

Figure 1 shows a schematic layout of the FLASH facility with its common accelerator and the two undulator beamlines with their own experimental halls. In addition, a third electron beamline, FLASH3, hosts a pioneering beam driven plasma-wakefield acceleration experiment, FLASH-Forward [12, 13].

An overview of the photon science at FLASH and the evolution of the FLASH facility over the years can be found in [4,5,14]. For more details of the facility and its parameters we refer to [6, 7, 15, 16].

FLASH OPERATION

FLASH has two user periods per year. In 2018, FLASH1 was operated a total of 7103 hours, of which 59% (4189 h) was devoted to FEL user operation, 30% for studies and user preparation, and 11% for general accelerator R&D. FLASH2 was operated 6831 hours, of which 33% (2269 h) was FEL user operation. In 2018 FLASH served beam time for 38 experiments; many wavelengths in the XUV and soft X-ray range from 52 down to 4.4 nm have been realized. In 2018, two photon beamlines have been completed in the FLASH2 Kai Siegbahn experimental hall. This led to an increase of scheduled user experiments in FLASH2, a plus of 50% compared to 2017.

FLASH2 Pump-Probe Laser

The new FLASH2 pump-probe laser system [17] was commissioned in September 2018 with a successful pilot experiment, and is now in routine use. Since most experiments at FLASH1 are indeed pump-probe experiments with optical lasers, for example 58% in the first half of 2018, and 71% in the second half of 2018, the availability of the new pump-probe laser system at FLASH2 significantly increases the number of possible experiments.

New Photon Diagnostics

Another new improvement is a fast line detector for intra-train spectrum measurements named KALYPSO [18] which has been installed in the FLASH1 photon beamline. It offers an online single shot measurement of the SASE wavelength spectrum along the whole bunch train for several hundreds of

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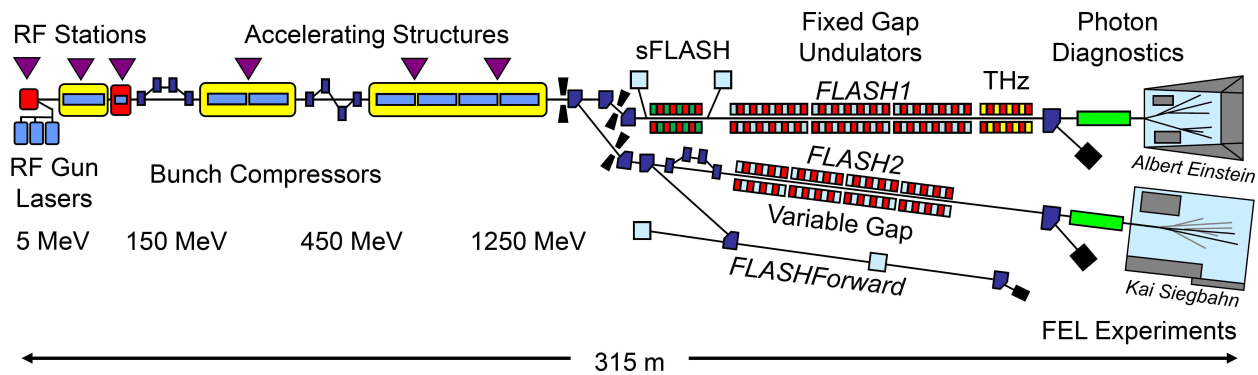

Figure 1: Layout of the FLASH facility (not to scale). Downstream the FLASH2 extraction a bunch compressor was installed in June 2019.

bunches. This optimizes the tuning procedure and monitors the spectral properties of SASE pulses along bunch trains in real time.

Additionally a THz-streaking system is under commissioning at FLASH2 which will allow measure the photon pulse duration.

FLASH Photo Injector

The present RF gun of the FLASH photo injector is in operation since August 2013. In summer 2018, its RF window developed a small vacuum leak in the order of 7×10^{-8} mbar l/s and has been replaced. The window was in operation for two years. The cathodes for the FLASH gun have a thin film of caesium tellurite with a diameter of 5 mm on a molybdenum plug [19]. "The previous photocathode was continuously operated at FLASH for 1413 days with 25 C total charge extracted from the cathode [20].

FLASH's superconducting linac can produce bunch trains of up to 800 bunches within a 0.8 ms RF flat top at a repetition rate of 10 Hz. In standard operation during 2018, FLASH supplied up to 500 bunches divided into two bunch trains with independent fill patterns and compression schemes to each of the two beamlines.

SASE

The variability of the undulators gaps at FLASH2 is an important feature allowing to vary the SASE wavelength within a few minutes per wavelengths step. However, a change of the undulator gap requires adaption of optics, correction magnets, and phase shifters. These parameters have been automatized such that users can control the wavelengths by themselves and can now be incorporated the wavelength into automated scanning scripts. Figure 2 shows an example for a beam energy of 1.1 GeV. FLASH1 was running stable while in FLASH2 SASE was tuned and measurements were taken for 3 different wavelengths : 5 nm, 9 nm and 15.3 nm. For a wavelength of 5 nm the undulator gap is opened to 18.4 mm, while for 15.3 nm SASE radiation the gap width is reduced to 9.3 mm (very close to the minimum). For 15.3 nm a single pulse energy of 1250 uJ has been produced. This corresponds to about 10^{14} photons per pulse.

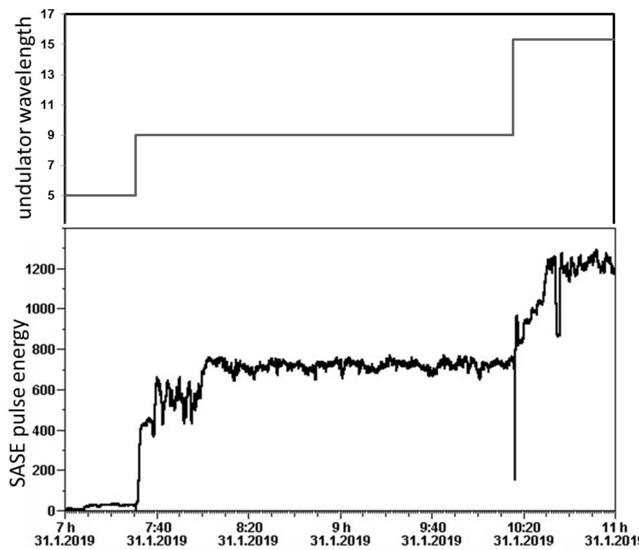

Figure 2: Example of single SASE pulse energy measured at FLASH2 (bottom) as a function of time and the FLASH2 undulator wavelength (top) used. Here the wavelength was increased from 5 to 9 and 15.3 nm while FLASH1 running stable with 5 nm (beam energy: 1.1 GeV).

New Lasing Schemes

Beside the standard SASE operation different lasing schemes have been tested using variable gap undulators at FLASH2. Frequency doubler divides the undulator section into two parts, where the second has the double frequency of the first one. This allows operation with two wavelengths and one of them at shorter wavelengths with respect to standard SASE scheme. Harmonic lasing self seeding (HLSS) amplifies higher odd harmonics and allows to improve spectral brightness of the FEL [21]. Reverse tapering in combination with an afterburner for harmonics of the fundamental has been demonstrated with an enhancement of SASE intensity by several order of magnitude [22]. Using two color lasing, two different arbitrary wavelengths are generated using alternating undulator gap widths [23].

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REFURBISHMENTS

FLASH has been user facility since summer 2005. A refurbishment and upgrade program is in progress to keep FLASH a state-of-the-art FEL [24]. The refurbishment comprises the replace of aged and outdated equipment, but also to adapt the hardware and diagnostics to changed requirements over the years. As an example, the electron beam diagnostics was designed for bunch charges of >1 nC, but FLASH is nowadays routinely operated with 20 to 600 pC. High charge is applied very rarely. Therefore the diagnostics has been upgraded for operation down to 20 pC.

The synchronization system at FLASH has three aspects: Electron Bunch Timing (measured by the bunch arrival time monitors (BAMs)), Laser-to-Laser Synchronization, and the Phase Drift Compensation of the RF-Reference used for Acceleration. The synchronization has been completely refurbished, for the BAM new pick-ups and electro-optical front-ends have been developed. In order to enhance the gain of the intra train bunch arrival time feedback, a normal-conducting S-band cavity was installed. It has a larger bandwidth to improve the arrival time stability below 5 fs. Latest measurements show an improvement of the arrival time stability from 25 fs (rms) to 8.5 fs (rms). The steady state value of the arrival time stability is reached within the first 10 bunches (10 μs for 1 MHz). For details see [25].

For the characterization of the longitudinal properties of the electron bunch and the slice emittance of the FLASH2 bunch a newly designed transversely deflecting X-band structure "PolariX" [26] is foreseen to be installed downstream of FLASH2 undulators in 2020. In June 2019, a prototype of the TDS cavity has been installed in the FLASH3 (FLASH-Forward) beamline.

The two oldest and weakest accelerator modules (module 2 and module 3) will be replaced in 2021 by refurbished modern modules designed as prototypes for the European XFEL, with high gradient cavities. This, together with an optimization of the waveguide distribution system, will provide an energy upgrade from 1.25 GeV to 1.35 GeV.

FLASH 2020+

As part of the DESY strategy process, an upgrade project "FLASH 2020+" has been proposed. The FLASH 2020+ proposal is motivated by the requests of the FEL users, taking into account the technological and beam physics requirements and constraints. The key aspects of the proposal are :

- The replacement of the FLASH1 undulators with variable gap ones, in order to operate both beamlines more independent from each other and thus reduce setup times by minimizing the required beam energy changes.
- The establishment of a high repetition rate seeding at FLASH1, with the goal of 1 MHz.
- The extension of the wavelength (fundamental) range at FLASH2 down to the oxygen K-edge (2.3 nm) to cover the whole water window.
- The exploration of possibilities for novel lasing schemes towards attosecond physics [27].

For more details see [24].

CONCLUSION

FLASH started as the first XUV-FEL user facility. In 2014, with the extension by a second undulator beamline, it became a multi-user facility. To keep FLASH a state-of-the-art FEL, a refurbishment and upgrade program is on-going.

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