ISBN: 978-3-95450-179-3 doi:10.18429/JACoW-FEL2017-MOD02

STATUS OF THE FLASH FEL USER FACILITY AT DESY

K. Honkavaara*, DESY, Hamburg, Germany†

Abstract

The FLASH facility at DESY (Hamburg, Germany) provides high brilliance FEL radiation at XUV and soft X-ray wavelengths for user experiments. Since April 2016, the second undulator beamline, FLASH2, is in user operation. We summarize the performance of the FLASH facility during the last two years including our experience to deliver FEL radiation to two user experiments simultaneously.

INTRODUCTION

FLASH [1–7], the free-electron laser (FEL) user facility at DESY (Hamburg), delivers high brilliance XUV and soft X-ray FEL radiation for photon experiments.

FLASH, originally called the VUV-FEL at TTF2, was constructed in the early 2000s based on the experience gathered from the TTF-FEL operation [8]. The user operation of the FLASH facility started in summer 2005 with one undulator beamline, which is still in use with its original fixed gap undulators (FLASH1). In order to fulfill the continuously increasing demands on beam time and on photon beam properties, a second beamline with variable gap undulators (FLASH2) has been constructed. The first lasing of FLASH2 was achieved in August 2014 [9], and since April 2016 FLASH2 is in regular user operation.

Figure 1 shows an aerial view of the north side of DESY in summer 2016. The FLASH facility with its two experimental halls is in the middle of the picture: the FLASH1 hall ("Albert Einstein") is on the right, the FLASH2 hall ("Kai Siegbahn") on the left.

Figure 1: Aerial view of the north side of DESY. The FLASH facility is in the middle of the picture: the FLASH1 experimental hall is on the right, the FLASH2 hall on the left. Next to FLASH are two experimental halls of the PETRA III synchrotron light source.

* katja.honkavaara@desy.de
† for the FLASH team

This paper reports on the status of the FLASH facility and its performance in 2016/17. Part of this material has been presented in previous conferences, most recently in [7].

THE FLASH FACILITY

Figure 2 shows a schematic layout of the FLASH facility. The seeding experiment sFLASH [10] located upstream of the FLASH1 undulators, and the FLASHForward plasma wakefield acceleration experiment [11], under construction at the FLASH3 beamline, are indicated as well.

The generation of high quality electron bunches is realized by an RF-gun based photoinjector. An exchangeable Cs_2Te photocathode is installed on the back-plane of the normal conducting RF-gun. The presently installed photocathode is in use already more than two years without any significant degradation of the quantum efficiency: the QE is still at an 8% level [12]. The photocathode laser system has three independent lasers [13], allowing a flexible operation and production of electron bunch trains with different parameters (number of bunches, bunch spacing, bunch charge).

The FLASH linac has seven TESLA type 1.3 GHz accelerating modules providing a maximum electron beam energy of 1.25 GeV. The use of superconducting RF cavities allows operation with long RF-pulses, i.e. with long electron bunch trains. The maximum length of the bunch train is defined by the RF flat top of the acceleration modules (800 μs) and of the RF-gun (presently 650 μs). The bunch train repetition rate is 10 Hz, and different discrete bunch spacings between 1 μs (1 MHz) and 25 μs (40 kHz) are possible. The train is shared between two undulator beamlines, allowing to serve simultaneously two photon experiments, one at FLASH1 and the other one at FLASH2, both at 10 Hz pulse train repetition rate.

The RF-gun and the accelerator modules are regulated by an outstanding MTCA.4 based low level RF (LLRF) system [14, 15], which allows, within certain limits, different RF amplitudes and phases for the FLASH1 and FLASH2 bunch trains. The arrival time stability down to a few tens of femtoseconds level is realized by a state of the art optical synchronization system [16].

The production of FEL radiation, both at FLASH1 and FLASH2, is based on the SASE (Self Amplified Spontaneous Emission) process. The electron beam peak current required for SASE process is achieved by compressing the electron bunches in two magnetic chicane bunch compressors at beam energies of 150 MeV and 450 MeV, respectively.

FLASH1 has six 4.5 m long fixed gap (12 mm) undulator modules, FLASH2 twelve 2.5 m long variable gap undulators. A planar electromagnetic undulator, installed downstream of the FLASH1 SASE undulators, provides, on request, THz radiation for user experiments.

ISBN: 978-3-95450-179-3 doi:10.18429/JACoW-FEL2017-MOD02

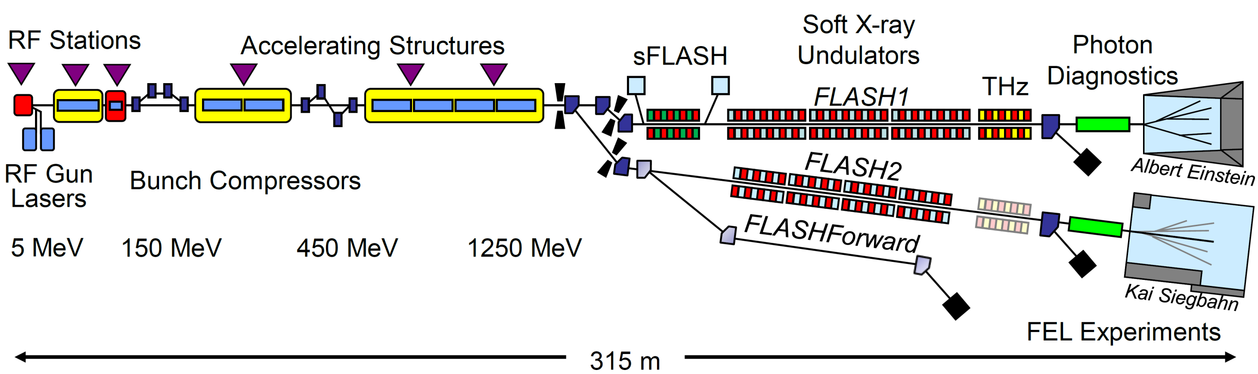

Figure 2: Layout of the FLASH facility (not to scale).

The FLASH1 experimental hall is equipped with five photon beamlines [2], including optical lasers for pump-and-probe experiments, and a THz beamline. The construction of photon beamlines in the FLASH2 hall [17] is on-going. Presently two beamlines are in operation. A pump-and-probe laser will be provided for FLASH2 experiments from early 2018 on.

Since FLASH1 has fixed gap undulators, its wavelength is defined by the electron beam energy. The minimum achievable wavelength in the present layout is 4.2 nm, the maximum one slightly above 50 nm. FLASH2 with variable gap undulators provides FEL radiation at wavelengths between 4 nm and 90 nm.

The typical single photon pulse energies at FLASH1 are from a few tens of µJ to about 100 µJ. At FLASH2, with its variable gap undulators, tuning for high photon pulse energies is easier: single pulse energies above 200 µJ are reached routinely, and pulse energies up to 1 mJ [5] have been achieved using undulator tapering. In addition, the variable gap undulators allow fast wavelength scans, which are not possible at FLASH1.

More details of the FLASH facility are presented, for example, in [3–7]. Photon beamlines and photon diagnostics are described in [2, 17–19]. An overview of the photon science at FLASH can be found in the publication list of [20].

SIMULTANEOUS OPERATION

FLASH1 and FLASH2 beamlines are operated simultaneously with the bunch train repetition rate of 10 Hz. The separation of the bunch trains is realized by using a kicker-septum system downstream of the last accelerating module. A gap of 30 to 50 µs (kicker pulse rise time and LLRF transition time) is needed between the bunch trains.

FEL radiation parameters (photon wavelength, pulse pattern, pulse duration) need to be, as far as possible, independently tunable for FLASH1 and FLASH2 experiments.

The FLASH2 variable gap undulators can adapt to the electron beam energy, which is determined by the FLASH1 wavelength. Consequently the FLASH2 wavelength can be chosen independently of FLASH1: the wavelength range is 1 to 3 times the actual wavelength of FLASH1 [5].

In order to take full advantage of the two undulator beamlines and to allow fast wavelength changes also at FLASH1, it is foreseen to replace the FLASH1 undulators by variable gap ones in the mid-term future.

FLASH has three photocathode lasers. Typically two of them are operated in parallel: one providing the bunch train for FLASH1 and the other one for FLASH2. This has two advantages. First of all, the bunch pattern can be determined independently for both beamlines. Secondly, FLASH1 and FLASH2 can be operated with a different bunch charge. The latter feature, combined with the possibility to use different RF phases, allows different compression of FLASH1 and FLASH2 bunches, and thus different photon pulse durations for FLASH1 and FLASH2 experiments.

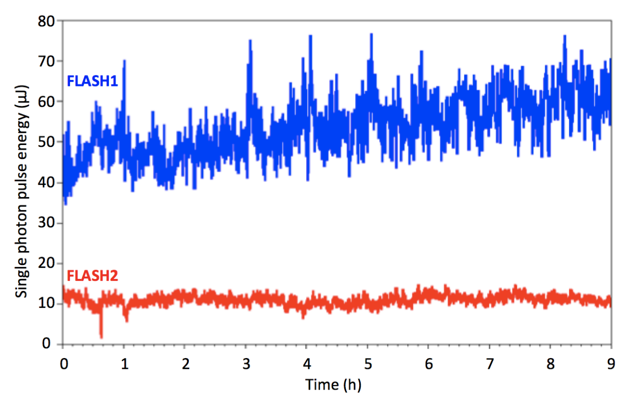

Figure 3: Single photon pulse energy (in µJ) of FLASH1 (blue) and FLASH2 (red) during 9 hours of simultaneous operation. FLASH1: 9.8 nm, 430 pulses in train with 1 µs spacing, electron bunch charge 320 pC. FLASH2: 20.6 nm, 1 pulse, electron bunch charge 70 pC.

Figure 3 shows an example of simultaneous FEL radiation delivery for FLASH1 and FLASH2 user experiments with different parameters. FLASH1 is operated with 430 bunches of 320 pC each at a photon wavelength of 9.8 nm, and FLASH2 with a single bunch of 70 pC at 20.6 nm. The FLASH2 electron bunches are produced by the special photocathode laser dedicated to short pulse operation [13]. Due to the low electron bunch charge used to obtain very short FEL pulses, the photon pulse energy in this case is at a 10 µJ level.

Another example of challenging simultaneous user operation concerns FLASH1 operation with special high charge

ISBN: 978-3-95450-179-3 doi:10.18429/JACoW-FEL2017-MOD02

settings to produce THz radiation combined with delivery of short FEL pulses for the FLASH2 experiment. This was realized by using very different bunch charges: 680 pC at FLASH1 and 140 pC at FLASH2. The two experiments ran in parallel more than 50 hours without interruption, demonstrating that FLASH1 and FLASH2 can be operated simultaneously with a factor five different bunch charges.

The status of simultaneous FLASH1 and FLASH2 operation, including its challenges, is discussed more in detail in [4, 5].

FLASH OPERATION 2016

In 2016 FLASH had two user periods: from January to June (Period 7) and from July to November (Period 8). The user operation of FLASH2 started in April 2016.

Similar to previous user periods, the beamtime was organized with an alternating pattern of user blocks (4-5 weeks) and study blocks (2-3 weeks). In addition, FLASH had two shutdowns: a short one (1.5 weeks) in June 2016, and a longer one (FLASH1 4 weeks, FLASH2 6 weeks) at the end of the year. Both shutdown periods were mainly scheduled for FLASHForward [11] installations.

Total 7333 operation hours were realized at FLASH1, of which 4275 hours (58.3%) were dedicated to user operation, 2284 hours (31.1%) for FEL studies and user preparation, and 774 hours (10.6%) for general accelerator R&D. During user operation, FEL radiation was delivered to experiments 80.7% of the time (3452 h), set-up and tuning of the parameters for experiment requirements took 15.8% (675 h). The downtime during user experiments due to technical and other failures was 3.5% (148 h).

In 2016, FLASH2 had 7010 hours available for beam operation, of which 5365 hours was realized. The remaining 1645 hours FLASH2 was in stand-by due to beam conditions or studies not allowing a parallel FLASH2 beam operation. In total 1570 hours were scheduled for FLASH2 user experiments. This relative low amount of user time is due to the fact that FLASH2 photon beamlines are still under construction, and thus many experiments, for example those requiring a pump-and-probe laser, could not yet take place at FLASH2, but had to be scheduled to the overbooked FLASH1 beamline.

In 2016, FEL radiation was delivered to experiments with wavelengths from 4.2 nm to 38 nm at FLASH1, and between 4.4 nm and 52 nm at FLASH2. The experiments had different demands on pulse pattern (1-500 pulses per train with various pulse spacings), and on photon pulse duration: 43% of them requested pulse durations below 50 fs, 42% 50 to 100 fs and only for 15% the pulse duration was uncritical.

Shortly after the start-up after the summer shutdown 2016, a small vacuum leak developed on the RF-gun window. The exchange of the RF-window (3 days) and its conditioning (6 days) went smoothly, and nominal operation parameters were quickly recovered. Since then the RF-gun is running stable and is routinely operated with a 650 μs RF flat top.

FLASH OPERATION 2017

Similar to the previous year, in 2017 FLASH has two user periods. The first one (Period 9) finished middle of June, and the second one (Period 10) starts in August lasting until Christmas 2017. The shutdown in summer 2017 has been designated to two main tasks: a regular inspection of safety valves of the cryogenic system requiring a warm-up of the superconducting accelerator modules, and the installation of the FLASHForward experiment at the FLASH3 beamline. The FLASH3 beamline is located in the same building as the FLASH2 undulators.

There is no substantial change on beamtime allocation nor on beam parameters compared to the previous years. Since the upgrades of the FLASH2 photon beamlines are still ongoing, only a limited amount of FLASH2 user experiments are scheduled in 2017.

One of the 2017 operational highlights so far has been a user experiment using two FEL pulses with a tunable ns range delay [21]. This was realized by operating FLASH1 with two photocathode lasers at the same time. The experiment used pulse delays of 222 ns and 470 ns to demonstrate feasibility of liquid jet sample delivery for diffraction experiments at high pulse repetition rate.

FEL AND ACCELERATOR STUDIES

Substantial amount of the available beam time (about 30%) is allocated to improve the FLASH performance as an FEL user facility, and to prepare it for the demands of the coming user experiments. In addition, about 10% of the available time is dedicated to general accelerator physics experiments and development, like seeding (sFLASH) and plasma wakefield acceleration (FLASHForward).

In the last two years the efforts on seeding at sFLASH have been concentrated on the high gain harmonic generation (HGHG). Recently the HGHG seeding has been demonstrated of up the 9^{th} harmonic of the seed wavelength of 266 nm [10]. Using the transverse deflecting structure, located downstream of sFLASH undulators, single-shot information of the seeded FEL photon pulse has been successfully extracted [22].

Significant amount of time has been devoted to improve the performance of the facility and to developments of advanced operation modes [21]. Thanks to the variable gap undulators, the FLASH2 performance can be optimized using undulator tapering [23]. Other developments at FLASH2 are related, for example, to reverse undulator tapering [24, 25], harmonic lasing [26–28], and frequency doubling [29].

An on-going development at FLASH1 concerns THz-XUV pump-probe experiments. In order to cope with the different length of the THz and FEL photon beamlines, two electron bunches, with 21.5 ns delay corresponding the path difference between the two beamlines, are produced by a split-and-delay unit installed at one of the standard photocathode lasers [21]. The ultimate goal is to tune the first electron bunch to produce a maximum THz pulse energy,

ISBN: 978-3-95450-179-3 doi:10.18429/JACoW-FEL2017-MOD02

and at the same time optimize the second one for FEL radiation production.

Other continuing developments are, for example, the upgrade of the beam arrival time monitors [30], studies related to electron beam optics [31], and generation of ultra short photon pulses [32, 33].

SUMMARY

The FLASH facility is in regular simultaneous user operation with two undulator beamlines. The 9th user period is successfully completed in June 2017, and after a shutdown designated to a maintenance work on the cryogenic system and installations of FLASHForward, the 10th user period starts in August 2017. The scheduled operation in 2018 is similar to previous years: two 6 months user periods with short shutdowns in January and in July 2018.

FLASH2 is in user operation since April 2016. Due to ongoing construction and upgrades of the photon beamlines, so far only about a dozen of user experiments have taken place. This is foreseen to change in 2018, when pump-and-probe experiments will be possible at FLASH2.

ACKNOWLEDGMENT

We like to thank all colleagues participating in the successful operation, meticulous maintenance, and continuous upgrading of the FLASH facility.

REFERENCES

[1] W. Ackermann *et al.*, “Operation of a free-electron laser from the extreme ultraviolet to the water window”, *Nature Photonics*, **1**, 336, 2007.

[2] K. Tiedtke *et al.*, “The soft x-ray free-electron laser FLASH at DESY: beamlines, diagnostics and end-stations”, *New J. Phys.* **11**, 023029, 2009.

[3] S. Schreiber and B. Faatz, “The free-electron laser FLASH”, in *High Power Laser Science and Engineering*, **3** e20, 2015.

[4] B. Faatz *et al.*, “Simultaneous operation of two soft x-ray free-electron lasers driven by one linear accelerator”, *New J. Phys.*, **18**, 062002, 2016.

[5] J. Roensch-Schulenburg *et al.*, “Experience with Multi-Beam and Multi-Beamline FEL-Operation”, *Journal of Physics: Conf. Series*, **874**, 012023, 2017.

[6] K. Honkavaara *et al.*, “Status of the Soft X-ray FEL User Facility FLASH", in *Proc. 37th Free-Electron Laser Conf.*, Daejeon, 2015, pp. 61-65.

[7] M. Vogt *et al.*, “Status of the Soft X-ray Free Electron Laser FLASH”, in *Proc. 8th Int. Particle Accelerator Conf.*, Copenhagen, 2017, pp. 2628-2630.

[8] V. Ayvazyan *et al.*, “A new powerful source for coherent VUV radiation: Demonstration of exponential growth and saturation at the TTF free-electron laser", *Eur. Phys. J. D*, **20**, 149, 2000.

[9] S. Schreiber and B. Faatz, “First Lasing at FLASH2", in *Proc. 36th Free-Electron Laser Conf.*, Basel, 2014, pp. 7-8.

[10] J. Boedewadt *et al.*, “Experience in Operating sFLASH with High-Gain Harmonic Generation", in *Proc. 8th Int. Particle Accelerator Conf.*, Copenhagen, 2017, pp. 2596-2599.

[11] A. Aschikhin *et al.*, “The FLASHForward Facility at DESY”, *Nucl. Insr. Meth. A*, **806**, 175, 2016.

[12] S. Schreiber *et al.*, “Update on the Lifetime of Cs2Te Photocathodes Operated at FLASH”, in *These Proceedings: Proc. 38th Int. Free-Electron Laser Conf.*, Santa Fe, 2017, WEP003.

[13] S. Schreiber *et al.*, “Simultaneous Operation of Three Laser Systems at the FLASH Photoinjector”, in *Proc. 37th Int. Free-Electron Laser Conf.*, Daejeon, 2015, pp. 459-463.

[14] M. Hoffmann *et al.*, “Operation of Normal Conducting RF Guns with MicroTCA.4", in *Proc. 6th Int. Particle Accelerator Conf.*, Richmond, 2015, pp. 841-843.

[15] M. Omet *et al.*, “Operation Experiences with the MicroTCA.4-based LLRF Control System at FLASH", in *Proc. 6th Int. Particle Accelerator Conf.*, Richmond, 2015, pp. 844-846.

[16] S. Schulz *et al.*, “Femtosecond all-optical synchronization of an X-ray free-electron laser”, *Nature Communications*, **6**, 5938, 2015.

[17] E. Ploenjes *et al.*, “FLASH2 Beamline and Photon Diagnostics Concepts”, in *Proc. 35th Free-Electron Laser Conf.*, New York, 2013, pp. 614-617.

[18] K. Tiedtke *et al.*, “Challenges for Detection of Highly Intense FEL Radiation: Photon Beam Diagnostics at FLASH1 and FLASH2”, in *Proc. 35th Free-Electron Laser Conf.*, New York, 2013, pp. 417-420.

[19] E. Ploenjes *et al.*, “FLASH2: Operation, beamlines, and photon diagnostics‘’, *AIP Conference Proceedings*, **1741**, 020008 2016.

[20] http://photon-science.desy.de/facilities/flash/publications/scientific_publications

[21] S. Schreiber, E. Schneidmiller, and M. Yurkov, “Recent FEL Experiments at FLASH”, in *These Proceedings: Proc. 38th Int. Free-Electron Laser Conf.*, Santa Fe, 2017, TUA01.

[22] T. Plath *et al.*, “Mapping few-femtosecond slices of ultra- relativistic electron bunches”, *Scientific Reports* **7**, 2431, 2017.

[23] E. Schneidmiller, M. Yurkov, “Optimum Undulator Tapering of SASE FEL: from the Theory to Experiment ", in *Proc. 8th Int. Particle Accelerator Conf.*, Copenhagen, 2017, pp. 2639-2641.

[24] E. Schneidmiller and M. Yurkov, "Obtaining high degree of circular polarization at x-ray free electron lasers via a reverse undulator taper", *Phys. Rev. ST Accel. Beams*, **16**, 110702, 2013.

[25] E. Schneidmiller and M. Yurkov, “Background-Free Harmonic Production in XFELs via a Reverse Undulator Taper", in *Proc. 8th Int. Particle Accelerator Conf.*, Copenhagen, 2017, pp. 2618-2620.

[26] E. Schneidmiller and M. Yurkov, “Harmonic lasing in x-ray free electron lasers", *Phys. Rev. ST Accel. Beams*, **15**, 080702, 2012.

[27] E. Schneidmiller *et al.*, “First operation of a harmonic lasing self-seeded free electron laser", *Phys. Rev. Accel. Beams*, **20**, 020705, 2017.

ISBN: 978-3-95450-179-3 doi:10.18429/JACoW-FEL2017-MOD02

[28] E. Schneidmiller *et al.*, "First Operation of a Harmonic Lasing Self-Seeded FEL", in *Proc. 8th Int. Particle Accelerator Conf.*, Copenhagen, 2017, pp. 2621-2624.

[29] M. Kuhlmann, E. Schneidmiller, and M. Yurkov, "Frequency Doubler and Two-Color Mode of Operation at Free Electron Laser FLASH2", in *Proc. 8th Int. Particle Accelerator Conf.*, Copenhagen, 2017, pp. 2635-2638.

[30] M. Viti *et al.*, "Recent Upgrades of the Bunch Arrival Time Monitors at FLASH and European XFEL", in *Proc. 8th Int. Particle Accelerator Conf.*, Copenhagen, 2017, pp. 695-698.

[31] J. Zemella and M. Vogt, "Progress in FLASH Optics Consolidation", in *Proc. 8th Int. Particle Accelerator Conf.*, Copenhagen, 2017, pp. 211-214.

[32] J. Roensch-Schulenburg *et al.*, "Operation of FLASH with Short SASE-FEL Radiation Pulses", in *Proc. 36th Int. Free-Electron Laser Conf.*, Basel, 2014, pp. 342-345.

[33] F. Christie *et al.*, "Generation of Ultra-Short Electron Bunches and FEL Pulses and Characterization of their Longitudinal Properties at FLASH2", in *Proc. 8th Int. Particle Accelerator Conf.*, Copenhagen, 2017, pp. 2600-2603.