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STATUS OF THE FREE-ELECTRON LASER USER FACILITY FLASH

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Abstract

The free-electron laser user facility FLASH at DESY is operating two undulator beamlines simultaneously and delivers XUV and soft X-ray radiation for photon experiments. It is driven by a superconducting linear accelerator. In a shutdown from November 2021 to August 2022 FLASH underwent a comprehensive refurbishment and a substantial upgrade (FLASH2020+). In this paper we summarize the recommissioning of FLASH and its upgraded injector as well as the restart of user operation in 2022. The year 2023 focuses on user operation in order to establish as much as possible beamtime before the next shutdown in 2024.

THE FLASH FACILITY

FLASH is a XUV and soft X-ray free-electron laser (FEL) [1–5] at DESY (Hamburg, Germany). It has been operated as an FEL user facility since summer 2005. The generation of FEL radiation is based on Self-Amplified Spontaneous Emission (SASE). Figure 1 shows an overview of the FLASH facility. The FLASH accelerator consists of a photo-injector with a normal conducting RF-gun, and a linac with superconducting accelerator modules. The superconducting linac allows the acceleration of long bunch trains with several thousand electron bunches per second in 10 Hz bursts of up to 800 μs length. The bunch trains are divided into two parts with, in a certain range, independent RF-properties. A kicker-septum based beam switch yard allows to serve two beamlines in a true parallel fashion. FLASH devides into two undulator beamlines serving two different experimental halls. The FLASH1 undulator beamline has six fixed gap undulators of a length of 4.5 m each. FLASH2 has twelve variable gap undulators of a length of 2.5 m each. Due to fixed gap undulators in FLASH1, the wavelength of the FEL radiation determines the electron beam energy. The advantage of tunable gap undulators in FLASH2 allows to control the undulator parameter K and, in addition, allows for novel techniques for radiation generation. A third beamline has been set-up to host the plasma wakefield acceleration experiment FLASHForward [6]. A seeding experiment Xseed [7] has been set-up to study essential features of external seeding. In order to keep FLASH as a state-of-the-art FEL user facility, a substantial upgrade and refurbishment project FLASH2020+ [8] was initiated. In a first phase during a nine-month shutdown in 2021/22 the FLASH linac was upgraded by replacing two accelerator modules by modern prototype modules of the type used in the European XFEL. They add features already present in most FLASH modules like double row piezo tuning, modern RF couplers, and a waveguide system optimized for better performance and highest energy gain. The new modules increase the energy gain by 100 MeV. A laser heater system has been set-up to reduce micro-instabilities in the electron beam. The 2nd bunch compressor has now a new C-chicane design with a new matching section. The shutdown was also used for refurbishment work, especially for the cryogenic system. The FLASH2 beamline was prepared for installation of an APPLE III type afterburner undulator for variable circular SASE polarization at the third harmonics reaching the oxygen edge.

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COMMISSIONING AND OPERATION

Reestablishing SASE-Operation

The shutdown finished as scheduled 14-Aug-2022. After technical checks and safety inspection, recommissioning of the linac started with cool-down of the superconducting accelerator modules. The cryogenics system has been modified for low pressure operation below 0.5 bar overpressure. A stable 2 K operation was reached 23-Sep-2022. After the cool-down, the superconducting cavities were tuned to resonance, followed by reconditioning of couplers and cavities, testing the coupler interlock system, and the set-up of the low level RF system for stable RF operation. In parallel all magnets and power supplies were brought into operation, while starting-up of the RF-Gun and injector laser systems.

Finally, beam operation started October 2022 to continue commissioning with beam. The commissioning of the accelerator modules with beam and the electron beamline commissioning was an iterative process including LLRF adjustments (vector-sum and energy calibration, cavity phasing and calibration, loaded Q's, Piezo tuners, closed loop operation), commissioning of new electron beam diagnostics and establishment of beam transport through modules. Electron beam transmission to the FLASH2 dump was achieved 12-Oct-2022, and to the FLASH1 dump one day later 13-Oct-2022. One goal of the new linac and beamline design was to improve and stabilize beam operation. This required an extensive work on beam optics and compression schemes. In parallel , the new and refurbished subsystems, especially transverse and longitudinal diagnostics was brought into stable operation.

After the hard work of the whole FLASH team, first lasing was achieved 19-Oct-2022 at FLASH1 and 20-Oct-2022 at FLASH2. The commissioning of photon beam lines started as soon as SASE operation was established accompanied by further shaping electron beam parameters, and further optimizing tools and procedures for operation. A great success

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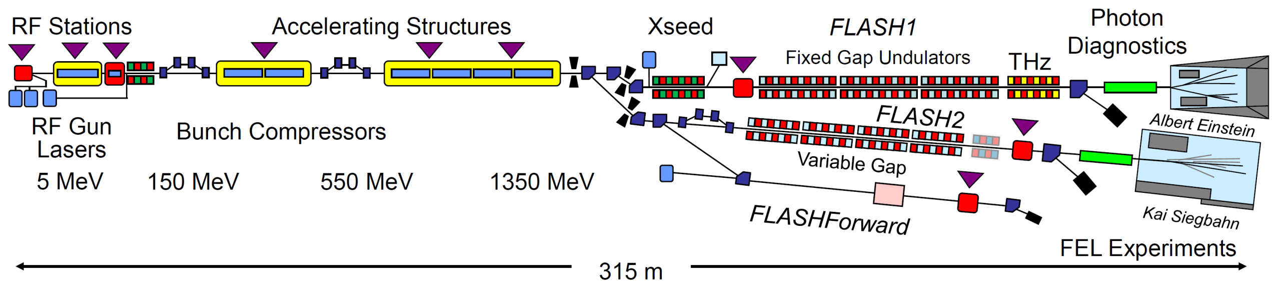

Figure 1: Layout of the FLASH facility.

of the shutdown installations and commissioning was the start of the first photon science experiment the 7-Nov-2022 – as scheduled in 2021.

Recommissioning of the Electron Beamline

All new components required for user operation have been commissioned systematically during the restart of the machine in October 2022. This includes upgraded magnets and magnet power supplies, bunch compressors, controls, machine protection system, master oscillator and master laser oscillators, LLRF, cryogenics, and electron beam diagnostics like toroids for charge measurements, beam position monitors, screens stations, bunch compression monitors, and bunch arrival time monitors including its new electronics. All other systems have been commissioned step by step – whenever possible.

As an example, ten new kicker systems have been installed to achieve a flat horizontal and vertical orbit along the pulse train. Three locations have been chosen: after the RF Gun, in the 1st and 2nd bunch compressor sections [9]. Flatting the orbit is of uttermost importance for many photon experiments and the future external seeding in FLASH1.

The modification of the bunch compressor sections was required to include a laser heater (LH) system before the first compressor and a matching section in the second. The first compressor was moved by 2 m downstream to give place for the laser heater undulator and the laser injection and extraction stations. The former S-chicane of the 2nd bunch compressor was replaced by a shorter, mechanically movable C-chicane. Its shorter now and thus allows to include a matching section with a proper diagnostic section. It now also has the feature to correct the transverse-longitudinal correlation using quads and skew quads in the dispersive arms. To still be able to change the R56, the compressor design includes a movable chicane required for the future seeding operation in the framework of FLASH2020+. For standard SASE operation a working point with a default R56 of about 72 mm was established.

Commissioning of the laser heater started in January 2023. First step was the establishment of an electron beam optics for standard operation with a closed laser heater undulator together with the laser in-coupling-chicane on. After gaining experience in overlapping the laser with the electron beam, we now include the laser heater in standard operation. The laser heater has already been applied for several studies like micro-bunch instabilities [10], and machine learning.

To achieve stable bunch profiles and arrival time conditions, a synchronization system which provides radio-frequency (RF) and optical reference signals to the accelerator subsystems with femtosecond (fs) time stability is required. The heart of the synchronization system is the master oscillator combined with master laser oscillators. After 15 years of successful operation, FLASH's master oscillator has been completely redesigned as part of the FLASH2020+ project. The time jitter in the relevant frequency offset range has been improved from 38 fs to 3 fs [11]. The slow drifts of the RF-phase due to environmental changes have been significantly improved by a system called REFM-opt to re-calibrate the RF reference to the optical reference. RF-phases at the RF Gun, the accelerating modules are now stable within a fraction of a degrees stable for more than a week. The improved stability has been positively noticed by the photon experiments which run usually through a week.

The X-band (12 GHz) transversely deflecting structures PolariX are installed downstream the FLASH2 undulators already in January 2021 [12]. After the shutdown we continued their conditioning and could further increase the RF pulse length. Nevertheless, PolariX is in standard operation and is routinely used for photon experiments and electron beam studies of the longitudinal phase space. Further conditioning to bring the pulse compression cavity XBOC in operation to significantly increase the RF power reducing the resolution down to 5 fs is ongoing in parallel to operation. In a dedicated measurement optimized for short pulses, a temporal resolution of 4.5 fs was already achieved.

Beam Operation 2022 and 2023

In November and December 2022 FLASH was operated 838 hours for FEL photon users. At FLASH1 501 hours of user experiments were realized, at FLASH2 473 hours.

In 2023 we provide as much beam time as possible before the next long shutdown starting in June 2024. In consequence, we reduce the scheduled maintenance to a minimum. A bit more than the usual 60% of the available operation time is dedicated to photon science user experiments, 30% of the beam time is provided to FEL and photon beamline developments. About 10% are used accelerator research and development, which is not related to the FLASH operation as

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an FEL user facility. This includes plasma wakefield acceleration experiments within the FLASHForward project [6], optical klystron studies, microbunching studies [13], studies on an XUV High-Gain FEL Oscillator [14], and 5D phase-space reconstruction of an electron beam [15].

Improving FEL performance for User Operation

Every photon science user experiment has its own requirements of photon pulse properties and demands on quality and stability. We optimize each individual setup in order to fulfill all the requested FEL pulse parameters for the experiments.

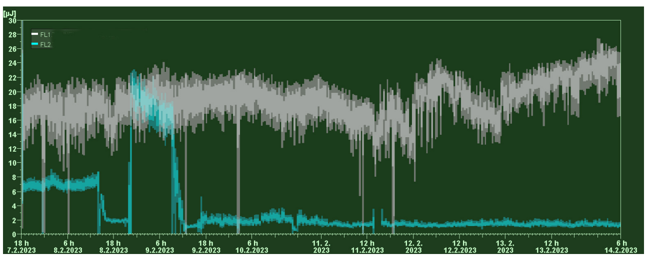

Figure 2: Examples of SASE single pulse energy in two parallel user experiments (gray: FLASH1, light blue: FLASH2) which took place in February 2023.

Figure 2 shows an example of two user experiments which took place in February 2023 in parallel. The experiment at FLASH1 requested a wavelength of 17.7 nm and short FEL pulses belwo 50 fs. To achieve the requested short FEL pulse duration, the electron bunch charge of 120 pC was chosen. After set-up and initial tuning, no further retuning was required. In addition, the downtime during this experiment was 0.4% only. After the initial setup, we delivered 160 hours SASE with an availability of 99.6% to the experiment. Using the feature of FLASH to run two experiments with very different parameters, we usually have in parallel a second user experiment of the same importance. In this example, a user experiment at FLASH2 requesting FEL pulses with a wavelength of 44.3 nm, 49 bunches with a distance of 10 µs (100 kHz) and as short as possible FEL pulse duration has been running, after the initial tuning, for 157 hours with an availability of 96.7% (2.7% tuning, 0.6% down). The ultra-short pulses required single spike lasing. In this case, the short pulse photoinjector laser providing 1 ps laser pulses to relax the bunch compression, running at a small bunch charge of 50 pC to reduce space-charge effects to avoid bunch lengthening was used. In summary, many user experiments request short photon pulses. Single spike lasing [16] has been delivered since years for several user experiments. An important new feature concerning ultra-short pulses has been testes recently: first experimental tests have been successfully performed to overcome the coherence time barrier and to get even much shorter pulses [17].

In general, the complexity of user experiments is rising. Besides the ultra-short pulses, two color operation is becoming increasingly popular. Different lasing schemes in this direction have been tested in the past years at FLASH [18–21]. In October 2021 a new scheme by combining HLSS and two-color lasing to produce the fundamental and the third harmonics with the same photon pulse energy has been delivered to a user experiment [22]. Using standard SASE, the third harmonics is only around 1% of the fundamental.

This is a huge progress for FLASH in delivering photons in advanced modes. This special mode has been set-up this year for a second time for the same experiment with great success.

EEHG IN PARALLEL TO SASE

An important milestone of FLASH was the demonstration of external seeding via Echo-Enabled Harmonic Generation (EEHG) in parallel to SASE in the FLASH2 beamline. The special tailoring of the electron phase space for EEHG is much different to the SASE case. To produce both phase spaces in the same RF-pulse was a major goal. In parallel to SASE in FLASH2, EEHG has been produced at the 9th (29.5 nm), 12th (22.1 nm), 15th (17.7 nm), and 17th (15.6 nm) harmonics. This demonstrates the feasibility of the future FLASH operation concept – an essential feature of the FLASH2020+ project.

OUTLOOK

Besides the preparation of the next phase of the FLASH2020+ project, a few installations are still due this year. Most important are the installation of the afterburner undulator and the new photo injector laser systems. The present two standard laser systems built in cooperation with the Max-Born-Institute Berlin [23] are in continuous operation since April 2004 and have been upgraded in 2010 and 2012 from flashlamp to diode pump systems. Both lasers have been 24/7 in operation for all time since their installation with negligible downtime. Due to the slow but steady aging, the development of new laser systems have been triggered in 2019. A prototype has been built, implemented at XFEL and will be installed at FLASH and PITZ in this year.

The next phase of the FLASH2020+ project has the goal to install external seeding in the FLASH1 beamline to provide transversely and longitudinal coherent circular polarized XUV and soft X-rays photon pulses, and to improve the production of ultra-short photon pulses towards the attosecond range in FLASH2. In the upcoming shutdown in 2024/2025 we will refurbish the FLASH1 electron and photon beamline to realize external seeding.

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REFERENCES

[1] W. Ackermann *et al.*, "Operation of a free-electron laser from the extreme ultraviolet to the water window", *Nat. Photonics*,

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vol. 1, pp. 336–342, 2007.
doi:10.1038/nphoton.2007.76

[2] B. Faatz *et al.*, “Simultaneous operation of two soft x-ray free-electron lasers driven by one linear accelerator”, *New J. Phys.*, vol. 18, p. 062002, 2016.
doi:10.1088/1367-2630/18/6/062002

[3] J. Rossbach, J. R. Schneider, and W. Wurth, “10 years of pioneering X-ray science at the free-electron laser FLASH at DESY”, *Physics Reports*, vol. 808, pp. 1–74, 2019.
doi:10.1016/j.physrep.2019.02.002

[4] K. Honkavaara, and S. Schreiber, “FLASH: The Pioneering XUV and Soft X-Ray FEL User Facility ”, presented at the 39th Int. Free Electron Laser Conf. (FEL’19), Hamburg, Germany, Aug. 2019, paper THP074, pp. 734–737.
doi:10.18429/JACoW-FEL2019-THP074

[5] K. Honkavaara, C. Gerth *et al.*, “Status of the Free-Electron Laser User Facility FLASH”, presented at FEL’22, Trieste, Italy, Aug. 2022, paper MOP37, to be published.

[6] R. D’Arcy *et al.*, “FLASHForward: plasma wakefield accelerator science for high-average-power applications”, *Phil. Trans. R. Soc. A*, vol. 377, p. 20180392, 2019.
doi:10.1098/rsta.2018.0392

[7] S. Ackermann *et al.*, “First Demonstration of Parallel Operation of a Seeded FEL and a SASE FEL”, presented at FEL’22, Trieste, Italy, Aug. 2022, paper TUP41, to be published.

[8] M. Beye *et al.*, “FLASH2020+, Conceptual Design Report”, DESY, Hamburg, 2020.
doi:10.3204/PUBDB-2020-00465

[9] M. Vogt, J. Zemella, J. Roensch-Schulenburg, and S. Schreiber “Recommissioning of the FLASH Injector and Linac”, presented at IPAC’23, Venice, Italy, May 2023, paper TUPL022, this conference.

[10] D. Samoilenko *et al.*, “First Beam Heating Studies with the Laser Heater for FLASH2020+”, presented at IPAC’23, Venice, Italy, May 2023, paper SUPM094, this conference.

[11] M. Urbanski *et al.*, “An upgraded universal frequency divider module for the new FLASH2020+ RF reference generation system”, presented at IPAC’23, Venice, Italy, May 2023, paper WEODB1, this conference.

[12] M. Vogt *et al.*, “RF Commissioning and First Beam Operation of the PolariX Transverse Deflecting Structures in the FLASH2 Beamline”, presented at FEL’22, Trieste, Italy, Aug. 2022, paper WEP22, to be published.

[13] P. Amstutz and M. Vogt, “Advances in a Perturbation Theory for the Microbunching Instability in Free-Electron Laser Injectors”, presented at IPAC’23, Venice, Italy, May 2023, paper WEPL183, this conference.

[14] M. Asatria *et al.*, “Simulation Studies on an XUV High-Gain FEL Oscillator at FLASH”, presented at IPAC’23, Venice, Italy, May 2023, paper SUPMO92, this conference.

[15] S. Jaster-Merz *et al.*, “5D phase-space reconstruction of an electron beam”, presented at IPAC’23, Venice, Italy, May 2023, paper WEODB2, this conference.

[16] J. Roensch-Schulenburg *et al.*, “Operation of FLASH with Short SASE-FEL Radiation Pulses”, in *Proc. FEL’14*, Basel, Switzerland, Aug. 2014, paper TUB04, pp. 342–345.

[17] E. A. Schneidmiller *et al.*, “Experimental test of a new method of generation of ultrashort pulses in X-ray FELs”, presented at IPAC’23, Venice, Italy, May 2023, paper TUPL30, this conference.

[18] J. Feldhaus *et al.*, “Efficient frequency doubler for the soft X-ray SASE FEL at the TESLA Test Facility”, *Nucl. Instrum. Meth. Phys. Res. Sect. A*, vol. 528 (2004) 471-475.
doi:10.1016/j.nima.2004.04.134

[19] E. A. Schneidmiller and M. V. Yurkov, “Harmonic lasing in x-ray free electron lasers”, *Phys. Rev. Spec. Top. Accel. Beams*, vol. 15, p. 080702, 2012.
doi:10.1103/PhysRevSTAB.15.080702

[20] E. Schneidmiller and M. V. Yurkov, “Studies of Harmonic Lasing Self-seeded FEL at FLASH2”, in *Proc. IPAC’16*, Busan, Korea, May 2016, pp. 725–728.
doi:10.18429/JACoW-IPAC2016-MOPOW009

[21] E. Schneidmiller *et al.*, “Two-Color Operation of FLASH2 Undulator”, in *Proc. FEL’19*, Hamburg, Germany, Aug. 2019, pp. 168–171. doi:10.18429/JACoW-FEL2019-TUP055

[22] J. Roensch-Schulenburg *et al.*, “A combination of harmonic lasing self-seeded FEL with two-color lasing”, presented at FEL’22, Trieste, Italy, Aug. 2022, paper MOP41, to be published.

[23] I. Will, H. I. Templin, S. Schreiber, and W. Sandner, “ “Photoinjector drive laser of the FLASH FEL”, *Opt. Express*, vol. 19, p. 23770, 2011. doi:10.1364/OE.19.023770