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STATUS REPORT OF THE SUPERCONDUCTING FREE-ELECTRON LASER FLASH AT DESY

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Abstract

The free-electron laser in Hamburg (FLASH) is a high brilliance XUV and soft X-ray SASE FEL user-facility at DESY. FLASH's superconducting linac can accelerate several thousand electron bunches per second in 10 Hz bursts of up to 800 µs length. The long bunch trains can be split in two parts and shared between two undulator beamlines. During 2020, FLASH supplied, in standard operation, up to 500 bunches at 10 Hz in two bunch trains with independent fill patterns and compression schemes. The FLASH2 undulator beamline comprises variable gap undulators that allow different novel lasing schemes. A third beamline accommodates the FLASHForward plasma wakefield acceleration experiment. We report on the FLASH operation in 2019 - 2021 and present a few highlights.

INTRODUCTION

FLASH [1–4] at DESY (Hamburg, Germany) is a free-electron laser (FEL) user facility. FLASH consists of a photoinjector, a superconducting linac, two undulator beamlines (FLASH1 with fixed gap undulators and FLASH2 with variable gap ones), and two experimental halls. The schematic layout is shown in Fig. 1. In addition, FLASH hosts a seeding experiment Xseed [5], and a plasma wakefield acceleration experiment FLASHForward [6].

The production of FEL radiation is based on the SASE (Self Amplified Spontaneous Emission) process. The photon wavelength of FLASH1, due to fixed gap undulators, is defined by the electron beam energy. With a maximum energy of 1.25 GeV, the shortest fundamental wavelength, which FLASH1 can provide for user experiments is 4.2 nm, looking into the water window. The maximum wavelength is slightly above 50 nm. FLASH2 with variable gap undulators provides FEL radiation at wavelengths between 4 nm and 90 nm.

Table 1 shows typical FLASH operating parameters. Note, that these parameters are not all achieved simultaneously, but indicate the overall span of possible SASE parameters. The superconducting linac allows RF flat-tops of up to 0.8 ms running with a repetition rate of 10 Hz. In order to keep the lifetime of the RF-gun and its RF-window reasonably long, RF-gun RF pulse is usually limited to 0.6 ms. FLASH always serves two beamlines within a burst. A burst is divided into two segments separated by 50 to 70 µs. The separation is used by the kicker-system to ramp-up and the low-level RF system to change amplitude and phase of the RF-pulses between the segments. This scheme allows a flexible adjustment of bunch compression adapted to the specific requirements of the experiments in the two beamlines. In addition, charge and bunch spacing are adjusted to different needs. Besides the standard 1 MHz operation, many other intra-train frequencies are possible. The flexibility of beam parameters in the two beamlines is also supported by three photoinjector laser systems [7, 8] being all three simultaneously on the beamline to be chosen at will.

Table 1: FLASH Parameters 2019 - 2021

Electron Beam		
Energy	MeV	380 - 1250
Bunch charge	nC	0.02 - 1.2
Bunches / train		1 - 500
Bunch spacing	µs	1 - 25
Repetition rate	Hz	10
FEL Radiation		FLASH1; FLASH2
Wavelength (fundamental)	nm	4.2 - 51; 4.0 - 90
Average single pulse energy	µJ	1 - 500; 1 - 1000
Pulse duration (fwhm)	fs	< 30 - 200
Spectral width (fwhm)	%	0.7 - 2 ; 0.5 - 2
Peak power	GW	1 - 5
Photons per pulse		10^{11} - 10^{14}
Peak brilliance	⋆	10^{28} - 10^{31}
Average brilliance	⋆	10^{17} - 10^{21}

⋆ photons / (s mrad^2 mm^2 0.1 % bw)

In order to keep FLASH a state-of-the-art FEL user facility, an upgrade project "FLASH2020+" has been launched [9].

USER OPERATION

FLASH has been operated as an FEL user facility since summer 2005: first ten years with one undulator beamline only, and since spring 2016 with two undulator beamlines.

The year 2019 was a standard operation year with 7476 h of beam operation. Of these, 4601 h were devoted to user experiments, 1988 h to FEL studies and preparation of user experiments, and 887 h to accelerator physics developments. Thanks to the simultaneous user experiments at FLASH1 and FLASH2 (about 40% of the user time), a total of 6502 h of beamtime could be provided for user experiments: 3710 h at FLASH1 and 2792 h at FLASH2.

Also in 2020, the originally allocated beamtime for user experiments was about 4600 h. However, due to the Covid-

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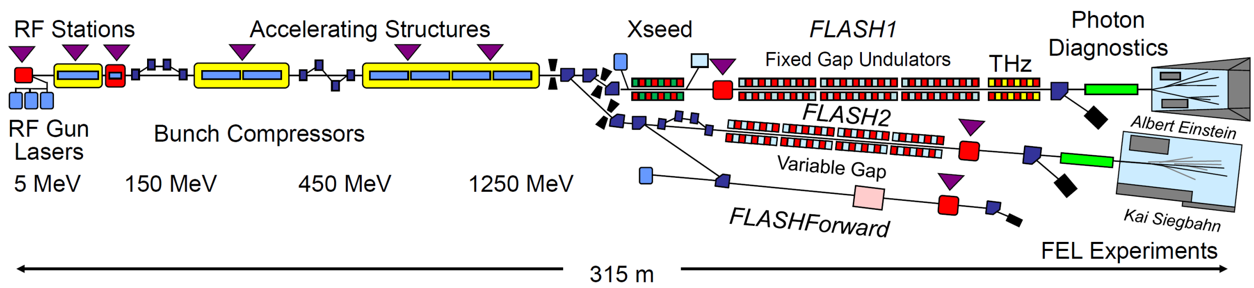
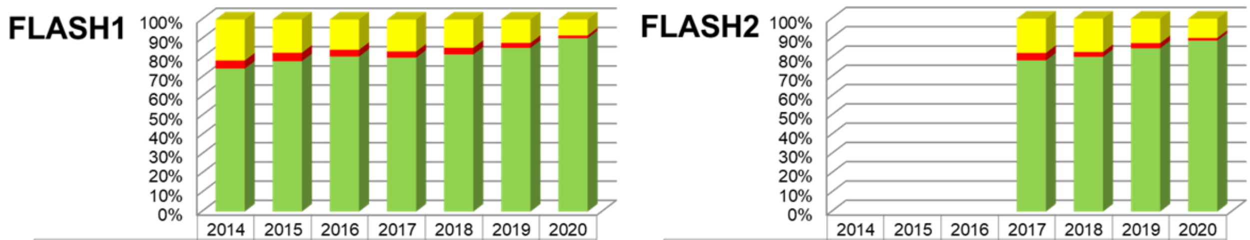


Figure 1: Schematic layout of the FLASH facility in 2021 (not to scale).



	2014	2015	2016	2017	2018	2019	2020
set-up (%)	21.3%	17.3%	15.8%	16.6%	14.7%	12.2%	8.3%
down (%)	4.2%	4.4%	3.5%	3.2%	3.5%	2.6%	1.4%
SASE delivery (%)	74.4%	78.3%	80.7%	80.2%	81.8%	85.2%	90.3%

	2014	2015	2016	2017	2018	2019	2020
set-up (%)				17.8%	17.2%	12.6%	10.0%
down (%)				3.8%	2.5%	2.7%	1.3%
SASE delivery (%)				78.4%	80.3%	84.7%	88.7%

Figure 2: FLASH1 and FLASH2 operation statistics during user experiments in 2014-2020. Definitions: set-up = accelerator set-up plus SASE tuning to achieve specific needs for user experiments; SASE delivery = users have SASE with requested or agreed parameters; Down = no SASE or beam during delivery or set-up.

19 lockdown, two user blocks in spring and early summer 2020 had to be canceled, and thus 17 from the 36 experiments, had to be postponed to 2021. After having established health safety measures, the user operation was resumed in August 2020 with a rearranged schedule. Unfortunately, due to travel restrictions and other Covid-19-related issues, some experiments had to be canceled in the second half of 2020 as well. In some cases the users could join the experiments from remote.

In 2020, despite of restrictions due to the Covid-19 pandemic, the FLASH accelerator could deliver beam for 5101 h. Of these, 3024 h were devoted to user experiments. Due to reduced scheduling possibilities under the pandemic conditions, parallel user experiments at FLASH1 and FLASH2 were only rarely possible. In total FLASH1 had 1979 h user operation and FLASH2 1356 h. In addition, FLASH also provided 1732 h of beam time for FEL related studies and preparation of user experiments and another 345 h for accelerator R&D, mostly for the FLASHForward experiment. Moreover, additional beamtime (about 350 h) was provided to FLASHForward in parallel to FLASH1 user experiments.

The beamtime for users includes also the time required for set-up and tuning the experiments. Every experiment has its own wish list of photon properties and demands high quality and stable beams. The FLASH team has worked hard on streamlining all related procedures, and has succeeded in enhancing both the beam stability and the delivery reliability. The evolution of the beam operation statistics over the last years is shown in Fig. 2. Thanks to careful analysis and optimization set-up procedures combined with a change to weekly schedule in which each experiment is conducted five or six days in a row, the set-up and tuning in 2020 could be pushed down to a record low of 8 to 10% of user beamtime. In addition the downtime due to technical or other failures during user experiments reached a low 1.4% (FLASH1) and 1.3% (FLASH2).

The goal in 2021 is to provide as much as possible beamtime before a long shutdown. Unfortunately restrictions under the pandemics still hamper especially user experiments, and thus also in the first half of 2021 some experiments had to be canceled or again rescheduled.

HIGHLIGHTS

Single Spike Operation

SASE radiation is transversely coherent, but in the longitudinal phase space, several randomly generated spikes appear to form the radiation pulse. Using special techniques to produce a very high electron bunch compression to the femtosecond level allows to produce SASE radiation with close to one longitudinal mode, called “single spike” [8].

The operation with single spike SASE pulses is requested by a rising number of photon experiments; in 2021, FLASH already provided single spikes to two user experiments.

The single spike duration depends on beam energy, undulator parameters, and, most important, on the desired radiation wavelength. The spike length τ is estimated using the gain length given by electron beam properties and undulator parameters with $\tau = C \cdot \lambda_{\text{rad}}$ [10]. For FLASH2, the parameter $C = 0.7(3)$ fs/nm; λ_{rad} is the SASE radiation wavelength.

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Two Color Lasing for Pilot Experiment

A two-color operation mode has been tested at FLASH2 using the alternating gap-scheme of the twelve variable gap undulators. The two color lasing scheme has been successfully provided for a pilot-experiment. The scheme is based on alternating undulator gaps, where the first and all even undulator segments are set on resonance for the base wavelength $\lambda_1 = 10$ nm, and the odd segments to $\lambda_2 = 13$ nm. To provide flexibility, the second wavelength has been scanned between 9.9 and 13.7 nm, which is a feature used by experiments. The alternating gap-scheme has the advantage that the source positions of the two FEL beams are close to each other which makes it easier to handle them in the experiment. In addition, the amplification is more efficient since the segments with the respectively "wrong" wavelength still act as bunchers.

PolariX TDS at FLASH2

At FLASH1 a transverse deflecting structure called LOLA is installed upstream of the SASE undulators but downstream of the Xseed seeding experiment. It serves together with a kicker and an off-axis screen as an on-line monitor for the electron bunch length during experiments with the possibility to measure the whole phase space [11, 12]. This monitor is in continuous operation, especially during short pulse operation with sub-50 fs (rms) bunches.

To implement a similar system into the FLASH 2 beamline, a project has been accomplished in collaboration between PSI, CERN, and DESY to design, build and install a new type of a TDS called PolariX (Polarizable X-band Transverse Deflecting Structure) [13, 14]. The beamline downstream of the FLASH2 undulator section underwent a significant remodeling [15] followed by the installation two PolariX TDSs (Fig. 3).

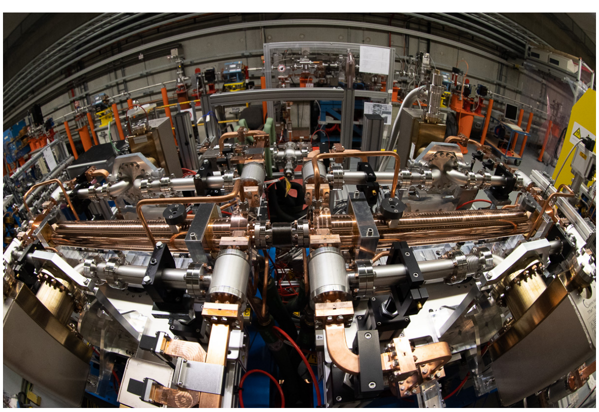

Figure 3: Top view of the two newly installed PolariX TDSs. The beam direction is from right to left, the last FLASH2 SASE undulator is visible on the right hand side (yellow girder).

As LOLA in FLASH1, the PolariX reconstructs the electron bunch longitudinal phase space and monitors the temporal profile of the electron with a resolution of a few femtoseconds. Compared to LOLA, the new structure has the ability to freely choose the direction of polarization, and because its installed after the SASE undulators, to estimate the photon pulse duration – similar to LOLA for the Xseed experiment. Both PolariX structures are fed by the same 6 MW klystron. An XBOC (X-band Barrel Open Cavity) pulse compressor [16] is used to quadruple the power to 24 MW. The PolariX structures and all waveguide components saw high-power RF for the first time after installation into FLASH2. In-situ conditioning is well in progress, so far, stable operation has been achieved at a power of 3 MW. During conditioning, first commissioning with beam has already possible. For the first time at FLASH2, the longitudinal phase space of electron bunches could be measured directly with a resolution of 10 fs. See reference [15] for details.

Examples of FLASH Scientific Highlights

From the many recent user experiments performed we pick two examples. A study on ultrafast photocatalytic reaction combined photoemission measurements in a time-resolved optical laser pump - FEL probe experiment with theoretical modeling. The experiment succeeded in describing the light induced reaction of light induced reaction of CO to CO_2 on the surface of an oxide-photocatalyst [17]. The subject of another experiment was related to absorption of XUV pulses from FLASH in plasmas with an extremely high density of free electrons. The FEL pump - FEL probe experiment used a split-and-delay unit. The intense first FLASH pump pulse turned a thin aluminum foil into a plasma with electron temperatures above 100,000 K, while the second, delayed FLASH probe pulse was used to determine the absorption of this plasma in the XUV range. The results contribute to a better understanding of astrophysical processes in the interior of stars [18].

OUTLOOK

A nine months shutdown for refurbishments and upgrades within the FLASH2020+ project is scheduled from late 2021 to summer 2022. The shutdown will be used to refurbish the cryogenic system, and to exchange two accelerator modules to increase the linac energy to 1.35 GeV. In addition, an upgrade of the bunch compressors and installation of the afterburner APPLE III undulator are planned.

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REFERENCES

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

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Phys., vol. 18, p. 062002, 2016. doi:10.1088/1367-2630/18/6/062002

[3] K. Honkavaara and S. Schreiber, "FLASH: The Pioneering XUV and Soft X-Ray FEL User Facility", in *Proc. 39th Int. Free Electron Laser Conf. (FEL'19)*, Hamburg, Germany, Aug. 2019, pp. 734–737. doi:10.18429/JACoW-FEL2019-THP074

[4] J. Rönsch-Schulenburg, K. Honkavaara, S. Schreiber, R. Treusch, and M. Vogt, "FLASH - Status and Upgrades", in *Proc. 39th Int. Free Electron Laser Conf. (FEL'19)*, Hamburg, Germany, Aug. 2019, pp. 776–779. doi:10.18429/JACoW-FEL2019-FRA03

[5] L. Schaper *et al.*, "XUV and Soft X-Ray External Seeding at FLASH: Activities and Future Plans", presented at the 12th Int. Particle Accelerator Conf. (IPAC'21), Campinas, Brazil, May 2021, THPAB115, this conference.

[6] G. Loisch *et al.*, "FLASHForward: beam-quality preserving plasma wakefield acceleration at high average power", presented at the 12th Int. Particle Accelerator Conf. (IPAC'21), Campinas, Brazil, May 2021, paper WEPAB114, this conference.

[7] I. Will *et al.*, "Photoinjector drive laser of the FLASH FEL", *Optics Express*, vol. 19, p. 23770, 2011. doi:10.1364/OE.19.023770

[8] J. Roensch-Schulenburg *et al.*, "Operation of FLASH with Short SASE-FEL Radiation Pulses", in *Proc. 36th Int. Free Electron Laser Conf. (FEL'14)*, Basel, Switzerland, Aug. 2014, paper TUB04, pp. 342–345.

[9] E. Allaria *et al.*, "FLASH2020+ plans for a new coherent source at DESY", presented at the 12th Int. Particle Accelerator Conf. (IPAC'21), Campinas, Brazil, May 2021, paper TUPAB086, this conference.

[10] S. Düsterer *et al.*, "Development of experimental techniques for the characterization of ultrashort photon pulses of extreme ultraviolet free-electron lasers", *Phys. Rev. ST Accel. Beams* vol. 17, p. 120702, 2014. doi:10.1103/PhysRevSTAB.17.120702

[11] M. Roehrs *et al.*, "Time-resolved electron beam phase space tomography at a soft x-ray free-electron laser", *Phys. Rev. ST Accel. Beams*, vol. 12, p. 050704, 2009. doi:10.1103/PhysRevSTAB.12.050704

[12] M. Yan *et al.*, "First Realization and Performance Study of a Single-Shot Longitudinal Bunch Profile Monitor Utilizing a Transverse Deflecting Structure", in *Proc. 2nd Int. Beam Instrumentation Conf. (IBIC'13)*, Oxford, UK, Sep. 2013, paper TUPC36, pp. 456–459.

[13] P. Craievich *et al.*, "Novel *X*-band transverse deflection structure with variable polarization", *Phys. Rev. Accel. Beams*, vol. 23, p. 112001, 2020. doi:10.1103/PhysRevAccelBeams.23.112001

[14] B. Marchetti *et al.*, "Experimental demonstration of novel beam characterization using a polarizable X-band transverse deflection structure", *Sci. Rep.*, vol. 11, p. 3560, 2021. doi:10.1038/s41598-021-82687-2

[15] F. Christie, J. Roensch-Schulenburg, S. Schreiber, M. Vogt, and J. Zemella, "Redesign of the FLASH2 Post-SASE Undulator Beamline", presented at the 12th Int. Particle Accelerator Conf. (IPAC'21), Campinas, Brazil, May 2021, paper TUPAB104, this conference.

[16] R. Zennaro, M. Bopp, A. Citterio, R. Reiser, and T. Stapf, "C-band RF Pulse Compressor for SwissFEL", in *Proc. 4th Int. Particle Accelerator Conf. (IPAC'13)*, Shanghai, China, May 2013, paper WEPFI059, pp. 2827–2829.

[17] M. Wagstaffe *et al.*, "Ultrafast Real-time Dynamics of CO Oxidation Over an Oxide Photocatalyst", *ACS Catal.*, vol. 10, pp. 13650–13658, 2020. doi:10.1021/acscatal.0c04098

[18] S. M. Vinko *et al.*, "Time-resolved XUV Opacity Measurements of Warm-Dense Aluminium", *Phys. Rev. Lett.*, vol. 124, p. 225002, 2020. doi:10.1103/PhysRevLett.124.225002