ISBN: 978-3-95450-247-9 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2024-MOPG16

FLASH STATUS — FEL USER FACILITY BETWEEN TWO UPGRADE SHUTDOWNS

Mathias Vogt*, Ingmar Hartl, Katja Honkavaara, Marion Kuhlmann,
Juliane Rönsch-Schulenburg, Lucas Schaper, Siegfried Schreiber, Rolf Treusch, Johann Zemella
Deutsches Elektronen-Synchrotron DESY, Germany

Abstract

FLASH, the XUV and soft X-ray free-electron laser user facility at DESY, is in the transitional period between two substantial ("long") upgrade shutdowns (LSDs) within the FLASH2020+ upgrade project. FLASH consists of a common part FLASH0 (injector & superconducting linac), two FEL beamlines (FLASH1/2) and an experimental beamline FLASH3, accommodating the plasma wakefield experiment FLASHForward. The first LSD (2021/22) was aimed at upgrading FLASH0 and install an APPLE-III undulator in the otherwise unchanged beamline FLASH2, enhancing the third harmonic at flexible output polarization. The next LSD (2024/25) will focus on the complete exchange of the FLASH1 beamline to allow for externally seeded operation in the range from 60 nm down to 4 nm at 1 MHz repetition rate (600 µs trains at 10 Hz).

We report on the operation between the two shutdowns which was, to a large extend, dedicated to FEL operation for users and on the commissioning of the new features implemented in the last shutdown.

FLASH AFTER THE 2021/22 SHUTDOWN

FLASH the *Free-electron LASer in Hamburg* [1–5] at DESY is an FEL user facility with two FEL undulator beamlines (FLASH1/FLASH2), with wavelengths in the extreme ultraviolet (XUV) and soft X-ray, driven by a common injector and superconducting linac (FLASH0). FLASH1 and FLASH2 are in separate tunnels, but FLASH2 shares the tunnel with an experimental beamline FLASH3 used by the plasma wakefield acceleration experiment FLASHForward [6]. FLASH is currently in-between two long shutdowns (LSDs) (2021/22 & 2024/25) of the FLASH2020+ [7–10] upgrade and refurbishment project. The essential goal of the project is to keep FLASH at the forefront of XUV & soft X-ray FELs by increasing the beam energy, enhancing the operability and stability and converting the FLASH1 beamline to an externally seeded FEL in the full (fundamental) wavelength range from 3.8 nm to 70 nm while preserving the excellent SASE performance of the FLASH2 beamline. The first LSD (2021/22) was dedicated to the upgrade of FLASH0 and the installation of a polarized 3rd-harmonic afterburner undulator at the end of the undulator string at FLASH2. This first upgrade phase and the initial recommissioning are described in [4, 9, 11]. In the second phase (LSD 2024/25) the FLASH1 SASE beamline (the original "FLASH") will be converted to enable external seeding [10, 12–15] employing the High Gain Harmonic Generation (HGHG) [16, 17] and the Echo Enabled Harmonic Generation (EEHG) [18, 19] modes. The time between the two LSDs from September 2022 to June 2024 was reserved to re-commissioning of the machine and the new features and last but not least to user operation with an already upgraded injector/linac. Here we describe FLASH operations in the aforementioned intermediate state between 1st and 2nd LSD. See also Fig. 1.

The upgraded FLASH0 consists of an electron source, a 1st superconducting L-band (1.3 GHz) acceleration stage (module ACC1) with 3rd harmonic longitudinal linearizer (ACC39), a laser-heater [20] section, a 1st bunch compression chicane (CBC1) followed by a transport channel (DBC1) capable of optimized beam transport or alternatively 5 screens with optimized phase advances for controlling the optics mismatch and measuring the transverse emittances, a 2nd acceleration stage (modules ACC2,ACC3), a 2nd bunch compression chicane [21, 22] (CBC2) followed by a transport channel (DBC2) for beam transport or alternatively quadrupole scans, and finally FLASH's "main-linac" consisting of 4 more superconducting L-band modules ACC4/5/6/7. Adjacent to FLASH0 is the beam separation into the two FEL beamlines FLASH1/2.

The e^- source is a normal-conducting 1.6-cell L-band photo-cathode RF-gun with a Cs_2Te photo-cathode. The gun supports RF pulses with usable flat tops of more than 600 µs at a repetition frequency of 10 Hz and a gradient of about 50 MeV/m resulting in a momentum of 5.6 MeV[1] at the gun exit. The electron bunches are created by two new injector lasers NEPAL F1 and NEPAL F2: The NEPAL (NExt generation PhotocAthode Laser) [23] laser system comprises a passively modelocked Yb:fiber oscillator, three Yb:fiber pre-amplifiers (YDFAs), four Yb:YAG power amplifiers and a 4th harmonic generation stage, generating picosecond pulses at 257 nm wavelength and of up to 5 µJ. The laser pulses are spatially shaped to truncated Gaussian shape using an aperture and relay-imaged to the photocathode. Three acousto-optic modulators (AOMs) are used for pulse-picking the appropriate burst-pattern, whose envelope can be arbitrarily shaped. A spectral shaper between the first two YDFAs enables generation of flexible pulse-shapes. We currently use short pulses of about 1 ps duration for single-spike SASE and 5 ps rms for standard operation. With two active beamlines we generate two bunch sub-trains, each from one of the two lasers, with quite variable bunch properties (charge, bunch-length, bunch-frequency) but in case

* vogtm@mail.desy.de

[1] $c \equiv 1$, of course.

ISBN: 978-3-95450-247-9 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2024-MOPG16

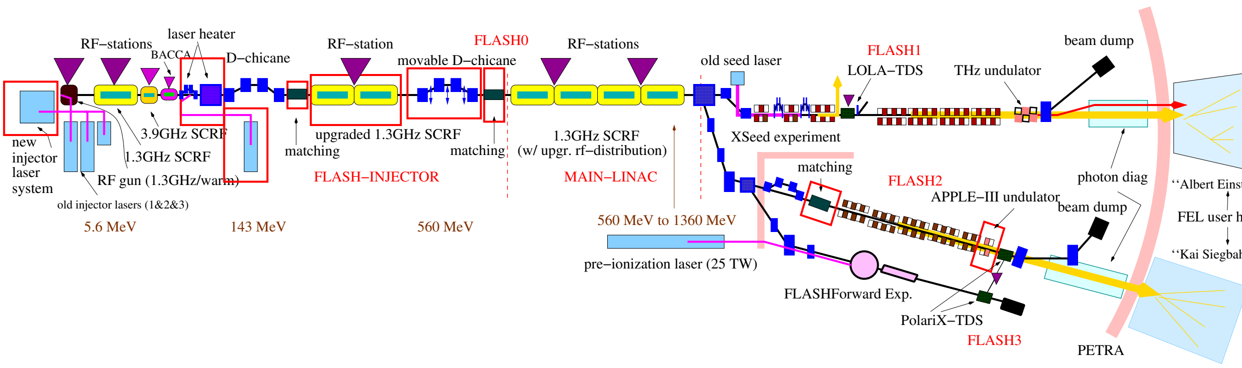

Figure 1: Schematic sketch of FLASH between LSD 2021/22 and 2024/25 (not to scale). Installations of LSD 2021/22 are boxed in red.

of a laser trip, the other laser can take over its sub-train with still reasonable variability.

FLASH is usually operated with bunch repetition frequencies of 40 kHz to 1 MHz. But the lasers are capable of creating full-length trains with bunch repetition frequency of 3 MHz at 10 Hz. The superconducting L-band modules (ACC1/2/3/4/5/6/7) are strings of 8 nine-cell niobium 1.3 GHz cavities embedded in a common cryostate with separate couplers per cavity and an embedded superconducting quadrupole/steerer pack. The 3rd harmonic linearizer (ACC39) is a string of 4 scaled down nine-cell niobium 3.9 GHz cavities in a seperate customized cryostate. These modules are from various phases of the development of SRF at DESY and are potentially all slightly different in all imaginable aspects. Hence the distribution of the modules puts certain constraints on the achievable E-profile and the beam-optics. The original modules ACC2 and ACC3 have been replaced by high-gradient modules which where carefully refurbished spares from the XFEL production line [9, 24]. They constitute the main part of the FLASH2020+ energy upgrade. The laser-heater and the 1st bunch compressor are operated at 143 MeV and the 2nd bunch compressor is usually operated at 560 MeV, but for specialized operation at highest energies can be operated above 580 MeV due to the excellent performance of ACC2/3. The laser heater consists of a small dedicated in-coupling chicane for the 532 nm laser-heater laser, and an undulator for the laser/bunch interaction, both in the dispersion free region downstream of ACC39. The over-folding of the E-modulation is performed in CBC1. CBC1 is a conventional 4-dipole chicane with flat vacuum chamber and variable M_{56} from 120 mm to 250 mm, run routinely in 2023/24 between 150 mm to 170 mm. CBC2 is a 4-dipole chicane with round vacuum chamber and corrector quadrupoles/skew-quadrupoles to ameliorate transverse-to-longitudinal correlations inside the bunches [21, 22]. Both chicanes are followed by optical matching sections to re-match bunches into the design optical functions and measure the transverse bunch emittances [11]. The remaining 4 SRF modules, driven pairwise by independent RF stations, constitute the FLASH "main linac" and are capable of accelerating the beam from 585 MeV to 1365 MeV

The extraction into FLASH2 uses vertical kickers that deflects the FLASH2 sub-train into the horizontally deflecting channel of a Lambertson septum. The sub-train for FLASH1 is basically not affected.

FLASH1 is still in its original layout [1]. The FLASH1 beamline starts with a section for transverse collimation followed by a dogleg that enables energy collimation. Downstream of the dogleg is the section for the Xseed experiment, used to gain experience in operation of HGHG and EEHG seeding for the post-upgrade operation. Next is a section for optics matching and longitudinal diagnostics using the 2.856 GHz transverse deflecting structure LOLA [25, 26], a DC switch-yard towards a dispersive beamline for full reconstruction of the longitudinal phase space (invasive mode) as well as a kicker to extract single bunches to an off-axis screen for online bunch length measurement (non-invasive mode). The six 4.5 m long original fixed gap main FLASH1 SASE undulators follow the LOLA section. Downstream of the SASE undulators, still in the common e^-/photon beamline, is an electromagnetic undulator that radiates in the THz regime. When the e^- bunch caries enough charge and features a pronounced current spike, the charge in the spike radiates coherently resulting in THz radiation pulse energies of several tens of µJ. Finally the e^- beam is deflected by a tilted dipole into a transversely coupled beamline which blows up and rotates the beam before it hits the vacuum window towards the beam dump, capable of disposing 100 kW of beam power.

FLASH2 [2] is the newer of the two SASE beamlines of the FLASH facility. Downstream of the Lambertson septum is an intricate arc that creates the necessary horizontal separation from FLASH1 required by the two seperate tunnels. This arc also houses transverse and energy- collimation for FLASH2 and the DC switch-yard to FLASH3. FLASH2 has an independent bunch compression chicane, a 4-dipole chicane with variable M_{56} from 7 mm to 20 mm (and 0). Following is a matching section directly upstream of the SASE undulator section of twelve 2.5 m long variable gap undulators. In the 2021/22 LSD the most downstream undulator was moved up-front the undulator string to create space for a new variable gap 3rd harmonic APPLE-III

ISBN: 978-3-95450-247-9 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2024-MOPG16

undulator [27] as an afterburner with controllable photon polarization. Downstream of the afterburner are two 12.0 GHz transverse deflecting structures PolariX [28–30]. Next a horizontal dipole separates the e^- beam from the photons. Thus the screens for on-axis (invasive) and off-axis (non-invasive, with a kicker) operation of PolariX have horizontal dispersion. Finally the beam is deflected downwards into a coupling-free dump beamline with dispersion matching, beam blow up and beam rotation. FLASH2 with its versatile undulator system is best fitted for short pulse operation [31].

OPERATIONS 2023-2024

User Operation

The year 2023 was mainly dedicated to user operation to compensate for the two LSDs 2021/22 and 2024/25. 8227 h of beam operation, that is 94% of the year, were achieved. Almost 4996 h (61%) were spent for operation for official FEL users, about 2563 h (31%) for machine & photon beamline development (including commissioning of the features introduced by the 1st LSD), and for preparation of FEL user operation, and about 668 h (8%) for general accelerator research & development.

In FLASH2, SASE radiation was provided to users at 3.5 nm with a final beam energy of $E_{\text{final}} = 1365$ MeV for a whole week in FLASH2. The gradients of ACC2 and ACC3 were increased so that the energy at CBC2 reached 585 MeV. Including off-crest compression of about 16° $\Rightarrow A_{23} = 457$ MeV), and the main linac stations (at on-crest) were increased to to their limits $A_{45} = 325$ MeV, $A_{67} = 430$ MeV. In this set up we even reached 3.2 nm in studies. During the last 1.5 weeks before the IPAC, FLASH was running again at highest energies in FLASH2 with *fundamental* wavelengths between 4.7 nm and 5.3 nm and with active 3rd harmonic afterburner in circular polarization (both helicities). The wavelengths reached in the 3rd harmonics correspondingly are between 1.55 nm and 1.75 nm. One key aspect of the tuning is to get rid of the linearly polarized 3rd harmonic content from the main undulators. Another great success is that the FLASH RF was running stable and without big interruptions at this high energies with HV pulses optimized (shortened/decreased) for a more "sustainable" working point which was established just a few weeks before the user run.

Commissioning Highlights

Since early 2024 the new injector lasers are in operation. They offer a variety of new features that had and have to be commissioned in development shifts spread along the run year. The bunch pattern- and charge control is much more flexible so that in principle each one of the lasers can drive both sub-trains with different parameters and with a flexible bunch gap for kicker rise time and RF flat top transition. Both lasers are capable of producing pulses of variable (rms) length from 1 ps to >5 ps. The new laser heater was taken into operation and its effect on micro-bunching and SASE pulse energy were verified. Moreover, the FLARE experiment [32] combines the laser heater laser with a split and delay unit to let both pulses interfere within the bunch to promote extremely short sub-structures that radiate extremely short photon pulses. In the Xseed section an experiment [33] was installed an is still ongoing to prove the feasibility of a resonator FEL in the XUV. Close to the IPAC deadline XRAY already achieved a complete pass through the resonator. The APPLE-III afterburner in FLASH2 has been commissioned and used to commission special polarization-sensitive photon diagnostics. This will be described in more detail in [34]. The new layout of the CBC2 chicane allows at least partial compensation of transverse-to-longitudinal correlations inside the bunch. We have started commissioning this feature [22].

FLASH had a very successful run from November 2022 until now and the whole team is looking forward to the 2nd LSD starting June 10th 2024.

ACKNOWLEDGMENTS

We dedicate this article to the memory of our colleague Siegfried Schreiber (1959 - 2024). He was an extraordinary sharp scientist, a great inspiration to his team, and a great fighter for the future of the FLASH facility.

REFERENCES

[1] W. Ackermann *et al.*, "Operation of a free-electron laser from the extreme ultraviolet to the water window", *Nat. Phot.* 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] J. Rönsch-Schulenburg *et al.*, "Status of the Free-Electron Laser User Facility FLASH", presented at the 14th Int. Particle Accelerator Conf. (IPAC'23), Venice, Italy, May 2023, paper TUPL020. doi:10.18429/JACoW-IPAC2023-TUPL020

[5] 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

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

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

[8] L. Schaper *et al.*, "Flexible and Coherent Soft X-ray Pulses at High Repetition Rate: Current Research and Perspectives",

ISBN: 978-3-95450-247-9 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2024-MOPG16

Appl. Sci., vol. 11, p. 9729, 2021. doi:10.3390/app11209729

[9] M. Vogt, "The FLASH 2020+ Upgrade Project", presented at SRF'23, Grand Rapids, MI, USA, June 2023, paper TUIAA02.

[10] E.Allaria *et al.*, "FLASH2020+ Plans for a New Coherent Source at DESY", presented at the 12th Int. Particle Accelerator Conf. (IPAC'21), Campinas, SP, Brazil, May 2021, paper TUPAB086. doi:10.18429/JACoW-IPAC2021-TUPAB086

[11] M. Vogt, J. Zemella, J. Rönsch-Schulenburg, and S. Schreiber, "Recommissioning of the FLASH Injector and Linac", presented at the 14th Int. Particle Accelerator Conf. (IPAC'23), Venice, Italy, May 2023, paper TUPL022. doi:10.18429/JACoW-IPAC2023-TUPL022

[12] M. Vogt, J. Zemella, "The New FLASH1 Beamline for the FLASH2020+ Project", presented at the 13th Int. Particle Accelerator Conf. (IPAC'22), Bangkok, Thailand, June 2022, paper TUPOPT006. doi:10.18429/JACoW-IPAC2022-TUOPT006

[13] P. Niknejadi *et al.*, "Integrating Sustainable Computational Strategies in Light Source Accelerator Upgrades", presented at the 15th Int. Particle Accelerator Conf. (IPAC'24), Nashville, TN, USA, May 2024, paper MOPG17, this conference.

[14] F. Pannek *et al.*, "Mitigation of Beam Instabilities in the Echo-Enabled Harmonic Generation Beamline for FLASH2020+", presented at the 12th Int. Particle Accelerator Conf. (IPAC'21), Campinas, SP, Brazil, May 2021, paper FRXA06. doi:10.18429/JACoW-IPAC2021-FRXA06

[15] Ph. Amstutz, M. Vogt, "Micro Bunching Studies for the FLASH2020+ Upgrade Using a Semi-Lagrangian Vlasov Solver", presented at the 13th Int. Particle Accelerator Conf. (IPAC'22), Bangkok, Thailand, June 2022, paper WEPOMS037. doi:10.18429/JACoW-IPAC2022-WEPOM037

[16] L. H. Yu, "Generation of Intense UV Radiation by Subharmonically Seeded Single-Pass Free-Electron Lasers", *Phys. Rev. A*, vol. 44, p. 5178, 1991. doi:10.1103/PhysRevA.44.5178

[17] E. Allaria *et al.*, "Highly coherent and stable pulses from the FERMI seeded free-electron laser in the extreme ultraviolet", *Nat. Photonics*, vol. 6, p. 699, 2012. doi:10.1038/nphoton.2012.233

[18] D. Xiao and G. Stupakov, "Echo-enabled harmonic generation free electron laser", *Phys. Rev. Spec. Top. Accel. Beams*, vol. 12, p. 030702, 2009. doi:10.1103/PhysRevSTAB.12.030702

[19] E. Allaria *et al.*, "Amplified Emission of a Soft-X Ray Free-Electron Laser Based on Echo-Enabled Harmonic Generation", presented at the 10th Int. Particle Accelerator Conf. (IPAC'19), Melbourne, Australia, May 2019, pp. 2230–2232. doi:10.18429/JACoW-IPAC2019-WEXXPLM1

[20] C. Gerth *et al.*, "Layout of the Laser Heater for FLASH2020+", presented at the 12th Int. Particle Accelerator Conf. (IPAC'21), Campinas, SP, Brazil, May 2021, paper TUPAB111. doi:10.18429/JACoW-IPAC2021-TUPAB111

[21] M. Vogt and J. Zemella, "A New 2nd Bunch Compression Chicane for the FLASH2020+ Project", presented at the 12th Int. Particle Accelerator Conf. (IPAC'21), Campinas, SP, Brazil, May 2021, paper TUPAB102. doi:10.18429/JACoW-IPAC2021-TUPAB102

[22] J. Zemella and M. Vogt, "First Commissioning of the Corrector Quadrupoles in the 2nd Bunch Compression Chicane at FLASH", presented at Ithe 15th Int. Particle Accelerator Conf. (IPAC'24), Nashville, TN, USA, May 2024, paper MOPG16, this conference.

[23] Chr. Mahnke *et al.*, "Novel Photocathode Lasers for the Hard- and Soft- X-ray Free Electron Lasers EuXFEL and FLASH", to be presented at the 41st International Free Electron Laser Conf. (FEL'24), Warsaw, Poland, August 2024.

[24] D. Kostin *et al.*, "SRF Accelerating Modules Upgrade for FLASH Linac at DESY", presented at SRF'23, Grand Rapids, MI, USA, June 2023, paper MOPMB082.

[25] Ch. Behrens, "Measurement and Control of the Longitudinal Phase Space at High Gain Free-Electron Lasers", presented at FEL'11, Shanghai, P.R. China, 2012, slides THOCI1.

[26] M. Yan *et al.*, "First Realization and Performance Study of a Single-Shot Longitudinal Bunch Profile Monitor Utilizing a Transverse Deflecting Structure", presented at IBIC'13, Oxford, UK, Sep. 2013, paper TUPC36, pp. 456–459.

[27] M. Tischer *et al.*, "Development of an APPLE-III undulator for FLASH-2", *J. Phys.: Conf. Ser.* 2380, 01201, 2022. doi:10.1088/1742-6596/2380/1/012017

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

[29] 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

[30] P. González Caminal, "Beam-Based Commissioning of a Novel X-Band Transverse Deflection Structure with Variable Polarization", *Phys. Rev. Accel. Beams* vol. 27, p. 032801 2024. doi:10.1103/PhysRevAccelBeams.27.032801

[31] J. Rönsch-Schulenburg *et al.*, "Operation of FLASH with Short SASE-FEL Radiation Pulses", presented at FEL'14, Basel, Switzerland, Aug. 2014, paper TUB04, pp. 342–345.

[32] Ph. Amstutz *et al.*, "Towards Short-Pulse Generation at FLASH via Laser-Assisted Electron Bunch Manipulation", presented at the 15th Int. Particle Accelerator Conf. (IPAC'24), Nashville, TN, USA, May 2024, paper MOPG65, this conference.

[33] M. Asatrian *et al.*, "Simulation Studies on an XUV High-Gain FEL Oscillator at FLASH", presented at the 14th Int. Particle Accelerator Conf. (IPAC'23), Venice, Italy, May 2023, paper TUPL097. doi:10.18429/JACoW-IPAC2023-TUPL097

[34] J. Rönsch-Schulenburg *et al.*, "Generation of Short Wavelength at Variable Polarization in FLASH2", to be presented at the 41st International Free Electron Laser Conf. (FEL'24), Warsaw, Poland, August 2024.