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FLASH STATUS 2024 — FEL OPERATION FOR USERS AND UPGRADE SHUTDOWN

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Abstract

FLASH, the XUV and soft X-ray free-electron laser, is currently undergoing the 2nd of two long upgrade shutdowns within the FLASH2020+ project. The 1st half of 2024 was dedicated to user operation. The upgrade shutdown started in June 2024, and we plan to come back to beam operation in August 2025.

Here we will discuss the operational highlights of the first half of 2024, briefly describe the new features being implemented, and report on the shutdown status.

INTRODUCTION

FLASH [1–6] is an FEL user facility operating in the extreme UV and soft X-ray regime and is currently in the second of a series of two substantial upgrade shutdowns within the FLASH2020+ upgrade project [7–13].

FLASH (Fig. 1) consists of a common injector and linac section (FLASH0) driving two FEL beamlines (FLASH1/2) and an experimental beamline (FLASH3) accommodating the FLASHForward [14] plasma wakefield acceleration experiment. FLASH0 was upgraded in the first long shutdown (LSD 2021/22) while the second, currently ongoing long shutdown (LSD 2024/25) is dedicated to converting FLASH1 from a SASE (*Self Amplified Spontaneous Emission*) beamline (the original TTF2/FLASH beamline) to a beamline for externally seeded FEL operation in *High Gain Harmonic Generation* mode (HGHG) [15, 16], and *Echo Enabled Harmonic Generation* mode (EEHG) [17, 18].

FLASH0 consists of a normal conducting 1.3 GHz 1.6-cell RF-gun with a Cs_2Te photo cathode driven by a UV injector laser system capable of producing trains of up to 800 bunches at 1 MHz bunch repetition frequency (variable) with a train repetition frequency of 10 Hz (fixed). The injector laser system has been completely replaced and upgraded during the LSD 2021/22 [19]. The injector lasers can now produce up to 2400 bunches per 800 µs train at 3 MHz. Standard operation in the run period 2023/24 (from November 2022 to June 2024) was with RF pulses of up to 550 µs duration with at most 1 MHz bunch repetition frequency. However, the RF control (LLRF) requires a leading beam-loading-free section of the flat top of ~15 µs duration, and the "pulse-length feedback", used to accurately keep the temperature of the gun cavity tuned requires another ~15 µs, so that the *effective* gun flat top is typically 30 µs shorter, i.e. in 2024 it was only up to 520 µs long.

The FLASH0 electron acceleration system is comprised of 7 cryo modules containing 8 superconducting 1.3 GHz 9-cell niobium cavities each. The superconducting electron acceleration technology enables the long bunch trains that FLASH0 is capable of providing. The RF pulse is typically split into two separate flat-tops divided by a typically 70 µs transition time. The bunches are accordingly split into two sub-trains supported by the two flat-tops and that are distributed between the two FEL beamlines by a kicker/septum beam separation. Adaption of the RF flat-tops as well as rising flange of the kicker are hidden in the transition time. Thus both FLASH1 and FLASH2 can be served at 10 Hz with sub-trains of at most $(520 - 70 = 450)$ bunches at 1 MHz in total.

The bunches are compressed (in configuration space) in two stages by imprinting a longitudinal energy chirp on each bunch in the RF cavities and then letting the bunch tail close up to the head in the longitudinal dispersion of two magnetic chicanes (BC1/2). During the LSD 2021/22, the injector lasers were upgraded, a laser heater [20, 21] was installed, the two original accelerating modules between BC1 and BC2 have been replaced by two specially refurbished EU-XFEL prototype modules [22], the 2nd bunch compression 6-dipole chicane was replaced by a movable 4-dipole chicane [23, 24], and an additional diagnostic section was installed for optics-matching after BC2. Moreover, a 3rd harmonic afterburner undulator with controllable polarization has been installed in FLASH2. A comprehensive description of the layout of FLASH in the run period 2023/24 can be found in [4, 5, 9, 25].

On February 22nd in 2000 ,i.e. 25 years ago, around 04:47 (paper-logbook entry) first SASE lasing at 108.3 nm was found at the TTF-FEL, which later (Summer 2005, i.e. 20 years ago) became the FLASH user facility [6]. Since then FLASH has been continuously extended, refurbished, and upgraded, the latest upgrade being the current FLASH2020+ project [12, 13].

FLASH OPERATION IN 2024

In 2024, the FLASH facility delivered beam for 3774 h. Of these, 1886 h were devoted to user experiments, 1103 h to FEL studies and preparation of user experiments, and 785 h to accelerator R&D (Fig. 2). The beam time for users includes the time required for set-up and tuning. The FLASH team has streamlined the corresponding procedures. As a result, a record low of 6.7% at FLASH1 and 8% at FLASH2 of user beam time required for initial set-up and tuning was achieved in 2024. For comparison, 21% were required for tuning in 2014, 12% in 2019. In 2024, the availability of the

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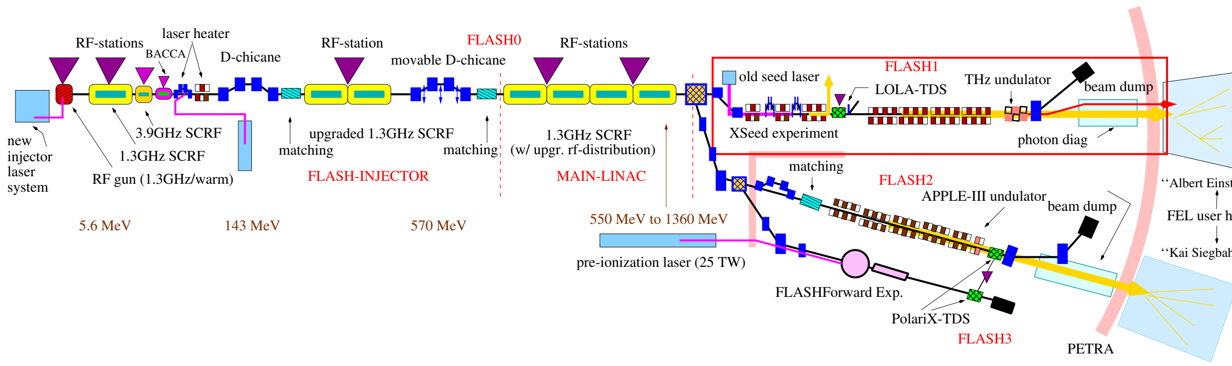

Figure 1: Schematic view of FLASH in 2024. The part in the red rectangle (FLASH1) was completely removed and is being rebuild during the ongoing shutdown.

facility was at 98.1% overall. The downtime for users was 2.3% at FLASH1 and 1.8% at FLASH2.

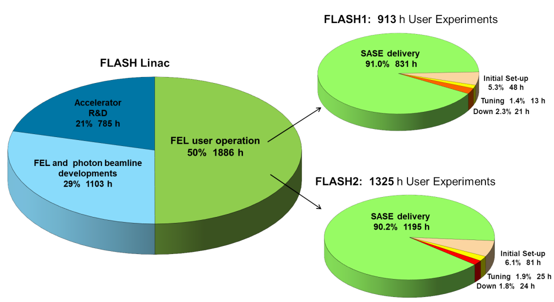

Figure 2: FLASH 2024 run statistics.

Stable and reliable user operation at a maximum *e*-beam energy of 1350 MeV was established and SASE pulses with wavelengths down to 3.2 nm in the fundamental could be achieved with pulse energies of about 6 µJ. In May 2024 FLASH was operated completely stable at 1350 MeV for 4 weeks. During this period the first user experiments that employed FEL radiation with variable polarization at the 3rd harmonic from the afterburner undulator in FLASH2 have been performed successfully [26]. The APPLE-III-type afterburner undulator [27] in FLASH2 can be seen as a prototype for the radiators to be installed in the seeding beamline FLASH1 during the currently ongoing shutdown.

A new access mode designed to enhance the efficiency "net experimental hours" over "hours for facility setup" for special classes of experiments was tested at FLASH2. In the *standardized access mode* (SAM) five different user experiments were performed within 2 weeks using the same FEL setup and the same photon end station with only minor re-tuning. During the SAM test, FLASH2 was set up for FEL pulses of 3.8 nm and 5.4 nm with bandwidths below 0.5% and pulse durations of about 50 fs.

The highest power consumers at the FLASH facility are the RF stations and the cryogenic plant. In April 2024 the setting of the RF stations and the RF controllers were optimized in order to reduce the power load and at the same time preserving the maximum *e*-beam energy and the possible number of bunches. The power consumption required for operation of FLASH with all RF stations was reduced from 825 kW to 620 kW, thus by about 25%.

The accelerator R&D experiment FLARE [28, 29] (a collaboration of the TU Dortmund University and DESY) has proven that by "local overheating" the part of the *e*–bunch that is capable of lasing can be conveniently controlled. They used a special laser heater set-up with a beam splitter and a two-path interferometer to create an effectively "sand-clock" shaped laser amplitude profile and which can be shifted over the *e*–bunch to select the lasing region. Moreover, they have shown that with used hardware can create a local extra chirp so that upstream compression creates a local controllable current spike.

The XRAY oscillator FEL experiment [30] (a collaboration of University of Hamburg and DESY) demonstrated a transversely fully closed cavity for soft X-ray in the pre-upgrade beamline FLASH1. A complete round trip along the cavity has been performed. The possibility of future experiments (e.g. at FLASH2) is being investigated.

The beam driven plasma wake-field acceleration experiment FLASHForward [14], located in the experimental beamline FLASH3, demonstrated the acceleration of a 1200 MeV FLASH beam to an energy of 1700 MeV within a 500 mm plasma cell and thus an energy gain of 500 MeV. FLASHForward has also studied the stability of the plasma when MHz bunch trains are being accelerated.

THE 2024/25 LONG SHUTDOWN

FLASH2020+ was initiated to enhance the quality of the FEL radiation for the experimentalists. The first stage aimed at increasing the photon energy range of the fundamental deeper into the water window (4.4 nm to 2.3 nm) by upgrading the *e*-beam energy from FLASH0, enhance the 3rd harmonic content, and provide controllable photon polarization at FLASH2, and establish better control of the *e*-beam to enable seeding in the second step. The second step, performed in the current shutdown is the conversion of the FLASH1 beamline from SASE to external seeding with longitudinally

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Figure 3: Photograph of the emptied, freshly painted FLASH1 tunnel as of February 2025.

fully coherent FEL pulses at MHz repetition rate in bursts at 10 Hz. Figure 3 shows the (almost) completely empty FLASH1 tunnel — a prerequisite to the actual upgrade. The second step (Fig. 4) includes installation of three new chicanes, two modulator undulators, two seed lasers and their laser beam transport system, a modern variable gap radiator section consisting of 3 planar and 1+5 APPLE-III-type undulators with controllable polarization. For low energy *e*-beamlines like FLASH1 (and FLASH2) the undulator focusing (APPLE-III: both planes) can significantly deteriorate the *e*-beam transport up to exponential blow up of the envelope. We are analyzing the mechanism and are developing an automated procedure for optimal compensation [31, 32]. A transverse deflecting RF structure [33, 34] for longitudinal diagnostics is being installed downstream of the radiators. In order to separate the *e*-beam dump system from the FEL photon beam diagnostic, remove the geometrical coupling due to the old dump beamline, generate space for the reused THz undulator, generate space for potentially installing a post-compressor chicane to enhance the THz output of the undulator, and to disentangle the THz beamline from the FEL photon beamline, the dump pit was moved ~2 m to the portside. A comprehensive description of the design of the post-upgrade FLASH1 beamline can be found in [11–13]. While this conference is ongoing, the installation of the new FLASH1 beamline in the tunnel is in its final phase, and the shutdwon will end early August this year.

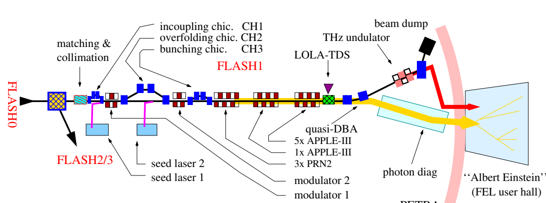

Figure 4: Schematic view of the FLASH1 design after the shutdown.

CONCLUSION

For FLASH the year 2024 was divided between 6 months of user run and the beginning of the long shutdown 2024/25. The user run was very successful with low tuning- and high up-time. In addition several accelerator R&D experiments were successfully performed. The shutdown, dedicated to the upgrade of the beamline FLASH1 within the FLASH2020+ project, started in June 2024. The FLASH1 tunnl was completely emptied and the installation of the new beamline for external seeding is currently ongoing. In February 2025 FLASH had the "25 years of SASE" anniversary. We are looking forward to restart FLASH with *e*-beam in early August this year.

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We would like to thank all our colleagues at DESY for their continuous dedication in operation, maintenance and upgrade of the FLASH facility that made the 1st half of 2024 a successful run and was and is *the* key ingredient in the ongoing shutdown : "teamwork makes the beam work".

REFERENCES

[1] W. Ackermann *et al.*, "Operation of a free-electron laser from the extreme ultraviolet to the water window", *Nat. 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. 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", *Phys. Rep.*, vol. 808, pp. 1–74, 2019. doi:10.1016/j.physrep.2019.02.002

[4] M. Vogt *et al.*, "The FLASH user facility between two upgrade shutdowns", presented at the 41st Int. Free Electron Laser Conf. (FEL'24), Warsaw, Poland, Aug. 2024, paper TUP123-TUA, not yet published.

[5] M. Vogt *et al.*, "FLASH status — FEL user facility between two upgrade shutdowns", in *Proc. IPAC'24*, Nashville, TN, USA, May 2024, paper MOPG16, pp. 335–338. doi:10.18429/JACoW-IPAC2024-MOPG16

[6] K. Honkavaara, and S. Schreiber, "FLASH: The pioneering XUV and soft X-ray FEL user facility", in *Proc. FEL'19*, Hamburg, Germany, Aug. 2019, paper THP074, pp. 734–737. doi:10.18429/JACoW-FEL2019-THP074

[7] M. Beye *et al.*, "FLASH2020+, conceptual design report", DESY, Hamburg, Germany, Rep. PUBDB-2020-00465, 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", *Appl. Sciences*, vol. 11, no. 20, p. 9729, 2021. doi:10.3390/app11209729

[9] M. Vogt, "The FLASH2020+ upgrade project", in *Proc. SRF'23*, Grand Rapids, MI, USA, Jun. 2023, paper TUIAA02, and slides https://accelconf.web.cern.ch/srf2023/talks/tuiaa02_talk.pdf. doi:10.18429/JACoW-SRF2023-TUIAA02

[10] E.Allaria *et al.*, "FLASH2020+ plans for a new coherent source at DESY", in *Proc. IPAC'21*, Campinas, SP, Brazil, May 2021, paper TUPAB086. doi:10.18429/JACoW-IPAC2021-TUPAB086

[11] M. Vogt, J. Zemella, "The New FLASH1 beamline for the FLASH2020+ project", in *Proc. IPAC'22*, Bangkok, Thailand, Jun. 2022, paper TUPOPT006. doi:10.18429/JACoW-IPAC2022-TUPOPT006

[12] L. Schaper *et al.*, "Combining SASE and external seeding at high repetition rate: FLASH upgrade status", presented at the 16th Int. Particle Accelerator Conf. (IPAC'25), Taipei, Taiwan, Jun. 2025, this conference.

[13] E. Ferrari *et al.*, "Status of the seeding upgrade for FLASH2020+ project", presented at the 16th Int. Particle Accelerator Conf. (IPAC'25), Taipei, Taiwan, Jun. 2025, this conference.

[14] 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

[15] 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

[16] 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

[17] 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

[18] E. Allaria *et al.*, "Amplified emission of a soft X-ray free-electron laser based on echo-enabled harmonic generation", in *Proc. IPAC'19*, Melbourne, Australia, May 2019, pp. 2230–2232, paper WEXXPLM1. doi:10.18429/JACoW-IPAC2019-WEXXPLM1

[19] Chr. Mahnke *et al.*, "Novel photocathode lasers for the hard- and soft- X-ray free electron lasers EuXFEL and FLASH", presented at the 41st International Free Electron Laser Conf. (FEL'24), Warsaw, Poland, Aug. 2024, paper WEAC04, not yet published.

[20] C. Gerth *et al.*, "Layout of the laser heater for FLASH2020+", in *Proc. IPAC'21*, Campinas, SP, Brazil, May 2021, paper TUPAB111. doi:10.18429/JACoW-IPAC2021-TUPAB111

[21] Ph. Amstutz, Chr. Gerth, *et al.*, "Improvements in FLASH operation through the use of the laser heater", presented at the 16th Int. Particle Accelerator Conf. (IPAC'25), Taipei, Taiwan, Jun. 2025, paper MOPB059, this conference.

[22] D. Kostin *et al.*, "SRF accelerating modules upgrade for the FLASH linac at DESY", in *Proc. SRF'23*, Grand Rapids, MI, USA, Jun. 2023, paper MOPMB082. doi:10.18429/JACoW-SRF2023-TUIAA02

[23] M. Vogt and J. Zemella, "A new 2nd bunch compression chicane for the FLASH2020+ project", in *Proc. IPAC'21*, Campinas, SP, Brazil, May 2021, paper TUPAB102. doi:10.18429/JACoW-IPAC2021-TUPAB102

[24] J. Zemella and M. Vogt, "First commissioning of the corrector quadrupoles in the 2nd bunch compression chicane at FLASH", in *Proc. IPAC'24*, Nashville, TN, USA, May 2024, paper MOPG16. doi:10.18429/JACoW-IPAC2024-MOPG16

[25] M. Vogt, J. Zemella, J. Rönsch-Schulenburg, and S. Schreiber, "Recommissioning of the FLASH injector and linac", in *Proc. IPAC'23*, Venice, Italy, May 2023, paper TUPL022. doi:10.18429/JACoW-IPAC2023-TUPL022

[26] J. Rönsch-Schulenburg *et al.*, "Generation of short wavelength at variable polarization in FLASH2", presented at the 41st Int. Free Electron Laser Conf. (FEL'24), Warsaw, Poland, Aug. 2024, paper TUP179-FRA, not yet published.

[27] M. Tischer *et al.*, "Development of an APPLE-III undulator for FLASH-2", *J. Phys. Conf. Ser.*, vol. 2380, no. 1, p. 012017, Dec. 2022. doi:10.1088/1742-6596/2380/1/012017

[28] Ph. Amstutz *et al.*, "Towards short-pulse generation at FLASH via laser-assisted electron bunch manipulation", in *Proc. IPAC'24*, Nashville, TN, USA, May 2024, paper MOPG65. doi:10.18429/JACoW-IPAC2024-MOPG65

[29] Ph. Amstutz *et al.*, "Generation of short current spikes by laser modulation at FLASH", presented at the 16th Int. Particle Accelerator Conf. (IPAC'25), Taipei, Taiwan, Jun. 2025, paper MOPB060, this conference.

[30] M. Asatrian, E. Ferrari, W. Hillert, V. Miltchev, and G. Paraskaki, "Simulation studies on an XUV high-gain FEL oscillator at FLASH", in *Proc. IPAC'23*, Venice, Italy, May 2023, pp. 1946–1949. doi:10.18429/JACoW-IPAC2023-TUPL097

[31] J. Zemella, M. Vogt, B. Faatz, and Z. Chen, "Automatic electron optics compensation for FODO lattices affected by undulator focusing", presented at the 41st Int. Free Electron Laser Conf. (FEL'24), Warsaw, Poland, Aug. 2024, paper TUP124-WEB, not yet published.

[32] J. Zemella *et al.*, "Parametric optics for FUDU lattices with strongly focusing undulators", presented at the 16th Int. Particle Accelerator Conf. (IPAC'25), Taipei, Taiwan, Jun. 2025, paper WEPM100, this conference.

[33] Ch. Behrens, "Measurement and Control of the longitudinal phase space at high gain free-electron lasers", presented at the 33rd Int. Free Electron Laser Conference (FEL'11), Shanghai, P.R. China, 2011, ISBN: 9783954501175, slides THOCI1, accelconf.web.cern.ch/FEL2011/talks/thoci1_talk.pdf.

[34] M. Yan *et al.*, "First realization and performance study of a single-shot longitudinal bunch profile monitor utilizing a transverse deflecting structure", in *Proc. IBIC'13*, Oxford, UK, Sep. 2013, paper TUPC36, pp. 456–459.