UPGRADE OF THE HIGH REPETITION RATE FEL FLASH TO ALLOW SIMULTANEOUS SASE AND EXTERNAL SEEDING OPERATION

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Abstract

The Free-Electron Laser FLASH at DESY has provided more than 20 years XUV and soft x-ray SASE radiation for user experiments. In order to keep FLASH as a state-of-the-art FEL, the refurbishment and upgrade project FLASH2020+ was launched. The latest upgrade has been a complete replacement of the FLASH1 beamline in a 14 months shutdown in 2024/25. The new external seeded FLASH1 will provide fully coherent radiation at up to MHz bunch repetition rate (burst). Moreover, the new APPLE-III type undulators enable full polarization control. In addition, FLASH1 hosts, as before, a THz source. FLASH2 continues unchanged in SASE operation. The commissioning of the upgraded facility started in August 2025, and since November FLASH2 is back in user operation. Commissioning of seeding at FLASH1 continues in parallel to FLASH2 user experiments.

INTRODUCTION

FLASH [1–5], the XUV and soft x-ray Free-Electron Laser (FEL) user facility at DESY (Hamburg, Germany), has been more than two decades the worldwide pioneering FEL Facility. In early 2000's, SASE (Self Amplified Spontaneous Emission) lasing in the wavelengths from 80 nm to 120 nm [6–8], and its feasibility for photon experiments [9, 10], was demonstrated at the TTF-FEL [11], driven by the TESLA Test Facility (TTF) 250 MeV superconducting linac [12]. Already then an elongation of the superconducting linac (TTF2) was prepared. VUV-FEL at TTF2 [13] was constructed in the first half of 2000's. It started user operation in summer 2005, and was renamed to "FLASH". The design energy of 1 GeV was reached in 2007, allowing lasing down to 6.5 nm [14]. In 2010, an additional (7$^{\text{th}}$) accelerating module was added to the linac to reach beam energy of 1.25 GeV and photon wavelength down to 4.1 nm [15].

To meet the continuously increasing demands of the user experiments on beam parameters and beam time, it was decided to extend the FLASH facility with a second undulator line driven by the same superconducting linac, but located in a separate building with an attached experimental hall. Since summer 2014 two undulator lines (FLASH1 and FLASH2) are operated in parallel, and in April 2016, the user operation started also at FLASH2.

In order to keep FLASH as a state-of-the-art FEL user facility, the next refurbishment and upgrade project FLASH2020+ [16, 17] was launched in 2018. The main goals were to establish a high repetition rate seeding (1 MHz) at FLASH1, and to extend the wavelength range at FLASH2 down to the oxygen K-edge (2.3 nm). The first upgrade shutdown, to increase the electron beam energy up to 1.35 GeV took place from November 2021 to August 2022. An APPLE III undulator operated as a third-harmonic afterburner was installed to FLASH2 in autumn 2023, enabling SASE radiation with variable, in particular circular, polarization. The high repetition rate seeding at FLASH1 has been realized within the second long shutdown from June 2024 to July 2025. This paper reports the status of the FLASH facility after the latest upgrades.

FLASH LAYOUT

FLASH consists of a photoinjector, a superconducting linac, two undulator lines and two experimental halls. A schematic layout of the facility after the 2024/25 shutdown is shown in Fig. 1.

A high quality, bunched electron beam is produced by a normal conducting RF-gun with a Cs_2Te photocathode and UV injector laser system. A new upgraded laser system [18] has been in routine operation since 2024. A laser heater [19], crucial for the seeded operation, was installed during the 2021/22 shutdown. The superconducting linac has seven TESLA type 1.3 GHz accelerator modules with eight 9-cell Niobium cavities each [20]. A third harmonic module (3.9 GHz) downstream of the first accelerating module linearizes the longitudinal phase space. In the 2021/22 shutdown the two oldest modules (ACC2 and ACC3) were replaced by new refurbished XFEL prototype modules [21] to reach the electron beam energy of 1.35 GeV [22]. The use of superconducting RF allows long RF pulses (up to 800 μs) and thus long electron bunch trains. Several discrete bunch spacing between 3 MHz and 50 kHz are possible. The bunch train repetition rate is 10 Hz. Two C-shape bunch compressors are used to compress the electron bunches at the beam energies of 143 MeV and 560 MeV. The second bunch compressor is a new movable 4-dipole chicane [23].

Until June 2024 FLASH was operated with two SASE undulator beamlines. In the shutdown 2024/25 the old FLASH1 beamline was completely dismounted, including the tunnel infrastructure. After the infrastructure refurbishment, a complete new electron beamline designed for external HGHG (High-Gain Harmonic Generation) [24, 25] and EEHG (Echo-Enabled Harmonic Generation) [26, 27] seeding has been installed. The FLASH1 photon diagnostics has been refurbished and upgraded as well. The FLASH1 hosts, as before, also a THz source: an electro-magnetic undulator, in use at FLASH since 2007, producing radiation between 1 and 300 THz. In order to ensure an adequate THz output, a

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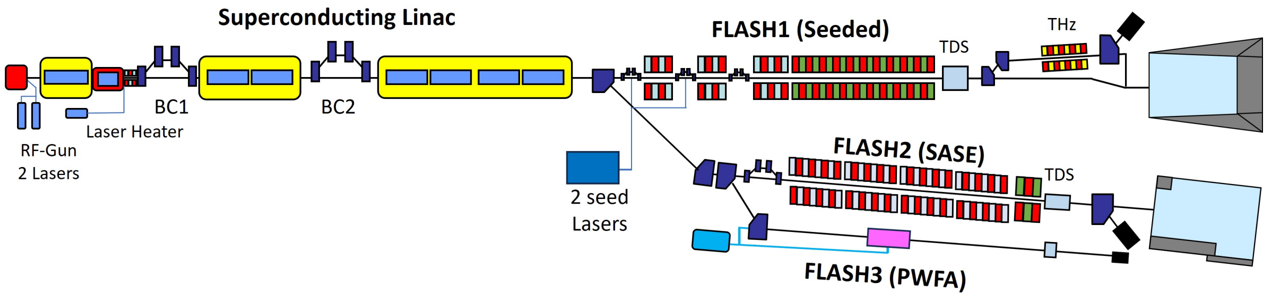

Figure 1: Schematic layout of the FLASH Facility in 2026 (not to scale). The total length is about 315 m.

post-compressor chicane is scheduled to be installed in 2027 upstream of the THz undulator.

FLASH2 is preserved as a SASE FEL facility. It has an additional bunch compressor downstream of the extraction beamline, and long undulator section of twelve 2.5 m long planar variable gap undulators. A third harmonic afterburner undulator (APPLE-III) [28] was installed downstream of the main undulators in autumn 2023, extending the photon wavelength range and providing polarized photons [29]. Longitudinal phase space is characterized by a transverse deflecting structure [30].

The FLASH2 undulator building hosts also a third electron beamline with a plasma wakefield acceleration (PWFA) experiment FLASHForward [31]. Recently FLASHForward has demonstrated, for example, a plasma injector scheme, where the strong accelerating fields of a plasma accelerator negate the space-charge-driven emittance growth of a newly generated electron bunch [32].

SEEDED FLASH1

In the 2024/25 shutdown, FLASH1 electron beamline was completely reconstructed to enable external HGHG and EEHG seeding. The new configuration consists of two seed lasers [33] and their laser beam transport system [34], three vertically bending magnetic chicanes, two planar modulator undulators, and a radiator section consisting of 3 planar and 6 APPLE-III undulators (similar to FLASH2 afterburner undulator) with a controllable polarization. More details of the concept of the seeded beamline can be found, for example, in Refs. [35, 36]. A transverse deflecting RF structure [37], which has been used since 2004 in various positions in the FLASH electron beamline, is now installed downstream of the radiators. Downstream of the TDS, the FEL pulses are separated from the electron beam and passed over a new photon diagnostic section before transported into the FLASH1 experiment hall. From the separation point the electron beam is transported through the THz undulator into the beam dump.

Using the HGHG and EEHG concepts with the tunable seed laser in the range from 297 nm to 317 nm, coherent FEL radiation from 60 nm down to 4 nm can be generated (Fig. 2). Overview of the expected photon parameters can be found in Ref. [38].

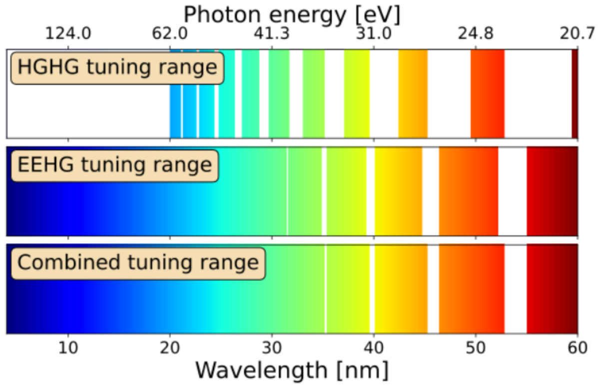

Figure 2: Wavelength range of seeded FLASH1.

SIMULTANEOUS OPERATION

FLASH has over 10 years experience on simultaneous operation of two undulator beamlines. The first lasing of FLASH2 in August 2014 was realized with a simultaneous SASE delivery for photon users at FLASH1, and since 2016 FLASH1 and FLASH2 have been routinely operated in parallel for FLASH1 and FLASH2 users, both at 10 Hz bunch train repetition rate, and having different photon parameters (photon wavelength, pulse pattern, pulse duration).

Simultaneous operation is realized with a kicker-septum system downstream the last accelerator module. Flat-top kickers kick the FLASH2 part of the bunch train vertically into the deflecting channel of a Lambertson septum. The septum deflects the beam horizontally into the FLASH2 beamline. The FLASH1 part of the bunch train goes straight to FLASH1. With the new injector lasers, in use since 2024, the two bunch trains can be set up independently, i.e. with different bunch charges and bunch patterns, not only by splitting the trains between the two lasers, but also with both trains on one single injector laser. This allows production of two electron bunch trains with different parameters to accommodate the different requirements for the user experiments at FLASH1 and FLASH2. A gap of some tens of μs (kicker pulse rise time and LLRF transition time) is needed between the two bunch trains. The LLRF system permits, in certain limits, different accelerating amplitudes and phases for the FLASH1 and FLASH2 bunch trains. This feature, together with different bunch charges, allows lasing at FLASH1 and FLASH2 with different photon pulse durations. More about the simultaneous operation of two SASE beamlines can be found, for example, in Ref. [2].

The longitudinal phase space for HGHG/EEHG seeding and for SASE is very different, and there have been doubts if the phase space can be tailored for both cases within the same RF-pulse. Already before the 2024/25 shutdown we demonstrated (XSeed experiment at FLASH1) that HGHG [39] and EEHG [40] are possible simultaneous to SASE operation at FLASH2. Moreover we demonstrated recently that the upgraded FLASH1 beamline can be operated with HGHG and EEHG seedings in parallel to sophisticated SASE operation for user experiment at FLASH2.

COMMISSIONING

Commissioning of the upgraded facility started in August 2025. First the injector and accelerator modules were taken back to operation, then FLASH2. In parallel, FLASH1 technical commissioning (magnets, undulators, seed lasers, laser beamlines, photon diagnostics) was carried out. The first electron beam was transported into the new FLASH1 beamline on 28-Aug-2025, and up to dump only one day later.

In autumn 2025, FLASH2 was prepared for the user operation, including commissioning of the photon beamlines. SASE radiation was produced with different wavelengths between 4 nm and 85 nm. The user experiments at FLASH2 started in November 2025 and until end of March 2026, we have provided over 2000 hours of SASE radiation for 11 different experiments with a very high availability: the average downtime during user operation has been only around 1%.

The commissioning of the seeded FLASH1 has continued in parallel to the FLASH2 user operation. The first HGHG seeding was achieved early December 2025 and the first EEHG seeding in January 2026. Both seeding working points were prepared and operated parallel to user operation at FLASH2 without any perturbations to the user's experimental program.

OUTLOOK

After a 3 weeks shutdown in April 2026 (installation of the last APPLE-III radiator, and two additional chicanes for advanced lasing modes [41]), the seeding commissioning at FLASH1 continues in parallel to FLASH2 user experiments. The goal in the next months is to characterize and improve HGHG/EEHG radiation parameters, to generate longer pulse trains, to commission the FLASH1 photon beamlines as well as to establish a robust seeding set-up and operation, including tuning procedures and tools.

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