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FLASH: STATUS AND UPGRADE

M. Vogt*, S. Schreiber, J. Zemella
Deutsches Elektronen-Synchrotron DESY, Germany

Abstract

FLASH, the Soft X-Ray and Extreme-UV Free Electron Laser at DESY, is undergoing a substantial upgrade and refurbishment project, called FLASH2020+. The project will finally enable external seeded and SASE FEL operation for a wavelength range down to 4 nm with the EEHG method. This is achieved in two long shutdowns from November 2021 to August 2022 and from June 2024 to August 2025. Key ingredient of the upgrade were installation of a laser heater, replacing two early TTF-type L-band SRF accelerating modules by modern, high-gradient XFEL-type modules, redesign of the 2nd bunch compressor, and complete redesign of the FLASH1 beam line for HGHG/EEHG seeding.

This talk will report on the project and the status of FLASH after the first shutdown with emphasis on beam dynamics aspects.

FLASH

This contribution is a modified version of a contribution [1] to the 21st International Conference on Radio-Frequency Superconductivity, held this June in Grand Rapids, MI, USA. There the emphasis was on the energy upgrade, while this contribution emphasizes certain beam dynamics aspects of the FLASH2020+ Upgrade.

FLASH [2–8] is a superconducting high-gain vacuum-ultraviolet (VUV) / soft X-ray free-electron laser (FEL), operated mainly as a photon user facility with up to two beamlines operated simultaneously. FLASH is segmented into three functional beamlines: the common injector and linac FLASH0, preparing and accelerating bunch trains suitable for the FEL process, and the two FEL beamlines FLASH1 and FLASH2 which finalize and diagnose the bunch preparation, accommodate the FEL process each in their own internal undulator beamline, and finally dispose of the spent beam in a beam dump. The FLASH3 beamline is used by the plasma wake field acceleration experiment FLASHForward [9] which can be activated *alternatively* to FLASH2 by powering a DC dipole. The FLASH accelerating RF consists of 7 L-band (1.3 GHz) superconducting modules of 8 9-cell Tesla-type cavities.

At the moment FLASH is undergoing a substantial upgrade and refurbishment project, called FLASH2020+ (see next section). The first of two shutdowns started November 2021 and ended August 2022 successfully and the second scheduled to start June 2024 and to end August 2025, is being prepared now.

The original FLASH injector (before the upgrade) consisted of a normal-conducting photo-cathode 1.6-cell RF-gun (1.3 GHz), an accelerating L-band module (ACC1), a third harmonic linearizer (ACC39) operated at 3.9 GHz, a BACCA longitudinal feedback cavity [10], the first bunch compression chicane, two more L-band accelerating modules (ACC2,ACC3), and the second bunch compression chicane — at that time an S-type 6-dipole chicane.

The bunches are produced in up to three trains mapped to the three injector lasers.

In its standard setting, the RF-gun is operated with approximately 5 MW and produces a 600 µs flat top. The bunch at the exit of the gun then has a momentum of 5.6 MeV/"c" FLASH0 can therefore provide up to 6000 bunches per second (in 10 trains) at 1 MHz bunch repetition frequency and 10 Hz pulse repetition frequency. If the RF pulse is split between two sub-trains (for FLASH1 and FLASH2), a minimum of 70 µs has to be subtracted for transient effect of the extraction kicker and for interpolating between the RF parameters of the two flat tops which are otherwise within certain ranges independent.

The third harmonic linearizer ACC39 is typically operated in decelerating mode with a nominal set point is 19.5 MeV.

The first bunch compression chicane is a 4-dipole C-chicane designed for bending angles from 15° (longitudinal dispersion M_{56} =120 mm) to 15° (M_{56} =255 mm). Prior to the upgrade it used to be operated at a typical deflection angle of 18° (M_{56} =181 mm). Downstream of the chicane used to be a comfortably equipped transverse diagnostics and matching section.

Before the upgrade, the second (ACC2) and third (ACC3) L-band Module were among the weakest in FLASH. Well tuned they were capable of (together) providing an E-gain of 304 MeV at an off-crest angle of up to 30°, i.e. an effective total amplitude of at most 350 MeV

In addition prior to the first shutdown, the second bunch compression chicane was a 6-dipole (S-type) chicane blocking the space for proper a proper second beam re-match upstream of the "main-linac".

The FLASH0 "main-linac" consists of four L-band modules (ACC4/5/6/7). The maximum attainable energy gain of the main linac is about 800 MeV so that the maximum e^--beam energy of FLASH was ~1250 MeV

Downstream of the last module the combined collimation and switch-yard section starts. Switching between FLASH1 and FLASH2 is achieved via a kicker-septum scheme with two vertically deflecting flat top kickers, deflecting the FLASH2 sub-train into the horizontally deflecting channel of a DC Lambertson septum. In order to achieve the required stability for the kicked bunches, the gap between the bunch trains needs to be >70 µs to cover the kicker rise-time *and* the damping of the initial ringing.

* vogtm@mail.desy.de

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The FLASH1 beamline was originally designed and optimized for SASE FEL operation.

The FLASH2 beamline also provides SASE FEL radiation. It consists of an extra bunch compression chicane (called FL2BC1), a transverse diagnostic section capable of performing a quad-scan, the 12 variable gap FLASH2 undulators, the PolariX TDS [11–13], the horizontal photon/electron separator dipole which also generates the dispersion for the longitudinal phase space mapping with PolariX, the vertical dump dipole and finally the dump beamline.

Downstream of the separators of FEL and electron beam, both tunnels (FLASH1/2) are equipped with photon diagnostics, i.e., screens, pulse energy detectors, and spectrometers for tuning the FEL. Then the FEL beams are delivered to the two experimental halls: Albert Einstein Hall (FLASH1), and Kai Siegbahn Hall (FLASH2). Both halls contain further photon diagnostics, hardware for photon beam manipulation [14], and of course the experimental end-stations.

The history of FLASH is nicely covered in Ref. [5, 8].

THE FLASH2020+ UPGRADE

To keep FLASH at the forefront of science, an ambitious upgrade and refurbishment project, called FLASH2020+ [15–17], was started in 2020. The goals are to replace outdated hardware, and at the same time upgrade the FLASH facility to stay attractive and competitive for at least the next 15 years.

Motivation

FLASH is currently the only superconducting FEL in the wavelength regime from VUV to soft X-ray. In its current injector configuration it can provide ~ 5000 bunches per second producing SASE FEL radiation from 60 nm down to ~4 nm with pulse durations from some tens to several hundreds of fs and with pulse energies from some µJ to ~1 mJ. Part of the motivation for the upgrade was to extend the wavelength range towards shorter wavelengths. In fact ~4 nm is just the upper end of a wavelength range, called "the water window", which is of special interest to many of the users. The energy upgrade will allow to reach higher beam energies and thus create photons of shorter wavelengths <4 nm In addition, so called *afterburner* undulators can significantly enhance the 3rd harmonic content of the FEL radiation, thereby extending the usability of the third harmonic down to ~1.3 nm.

SASE is a powerful production mechanism of FEL radiation however, it is a stochastically seeded process, with notable shot-to-shot fluctuations of the photon spectrum and potentially several uncorrelated modes (spikes) in a single bunch. Thus the longitudinal coherence of SASE FELs is rather low. The FEL process can however also be externally seeded with a highly coherent external laser pulse. It has been decided that FLASH1 should ultimately cover the wavelength range from ~4 nm to ~60 nm with external seeding in High Gain Harmonic Generation mode (HGHG) [18, 19] for the longer wavelengths and Echo Enabled Harmonic Generation mode (EEHG) [20, 21] for the shorter wavelengths.

Many pump-probe experiments at FLASH1 make use of the THz undulator that produces radiation in the THz regime using the spent electron bunches from the FLASH1 FEL undulators. This was quite successful with bunches tweaked to be a little more spiky than necessary for standard SASE operation, but still compatible with producing useful SASE pulse energies. A beam optimized for high stability, efficient HGHG/EEHG operation however, is not likely to generate decent THz pulse energies. Therefore a post compressor chicane will almost surely be required at some stage to optimize the THz radiation.

In order to reliably provide beams with high quality and stability for seeding in FLASH1 and SASE in FLASH2, the operability of FLASH needs an upgrade too. The design includes more and improved sections with transverse diagnostics to match the incoming beam to a downstream optics which is optimized for best performance, more appropriate locations for the transverse deflecting structure LOLA [22, 23], an intra-train orbit feed forward to remove the systematic part of intra train orbit correlations, quad/skew-quad corrector packs in the new designed second bunch compression chicane for removing systematic longitudinal to transverse correlations within the bunches, a laser heater [24] to ameliorate the unwanted micro-bunching effects [25], and of course a upgraded diagnostics at all levels. All these measures will make the operation of FLASH more systematic and predictable.

The Injector Upgrade

The first shutdown 2021/22 was dedicated to upgrading and refurbishing the injector section of FLASH0. Figure 1 shows a schematic layout of FLASH *after* the first upgrade shutdown 2021/22. Installation of two new injector lasers was started. All components of the laser beamlines that require access to the accelerator tunnel have been installed during the shutdown. The new lasers are scheduled to be commissioned by the beginning of next year.

Kickers have been installed to reduce the systematic (short term reproducible) orbit slopes over the bunch train, between gun ad ACC1, and around the two chicanes. Downstream of BACCA, space has been generated to install an incoupling chicane for the laser heater laser, an undulator for the actual energy modulation process, and the necessary surrounding lattice elements (quadrupoles, steerers, screens). The laser heater installation has been completed in the shutdown and it is already commissioned to a large extent. We have achieved transverse and temporal overlap, optimized the undulator gap for the actual beam energy. We have observed the heating process, i.e., increased slice energy spread in the heated part of the bunch, directly by both LOLA and PolariX, and by observing the expected reduction of the micro-bunching gain and the FEL gain.

In order to make space for the laser heater the first Burch compression chicane (*now called FL0BC1*) had to be moved about 2 m downstream. Thereby the space for the transverse

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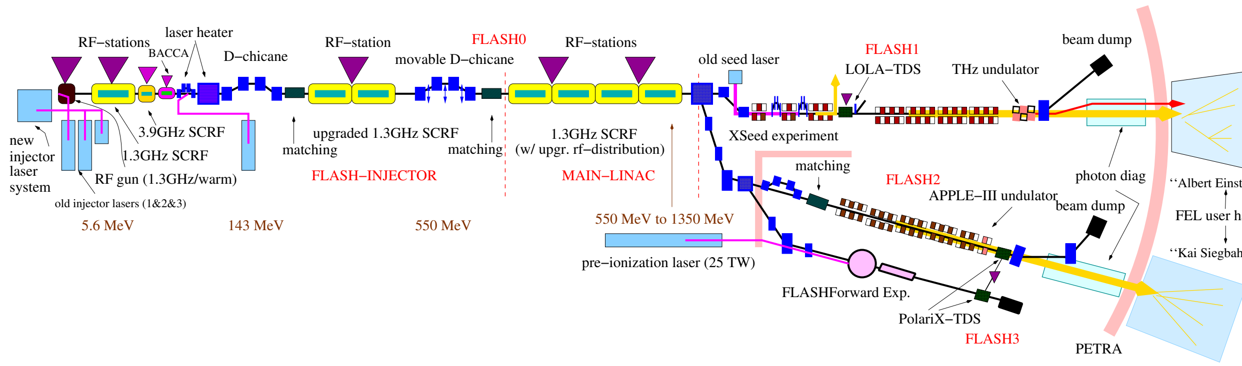

Figure 1: Schematic layout of FLASH (not to scale) after the first shutdown 2021/22.

diagnostics and matching section (between FL0BC1 and the *fixed position* of ACC2) was reduced. This required an updated concept for measuring emittance and mismatch amplitude as well as for re-matching into the design optics [26].

During the first shutdown 2021/22 two of the oldest, and weakest, TTF-type L-band modules were replaced by newly refurbished, XFEL-type modules PXM2.1 and PXM3.1 [27]. We now routinely achieve an E-gain of around 417 MeV at an off-crest phase of at most 25° which suggests an effective total amplitude of ~460 MeV. This allows to operate FL0BC2 at 560 MeV — 110 MeV more than the before the energy upgrade.

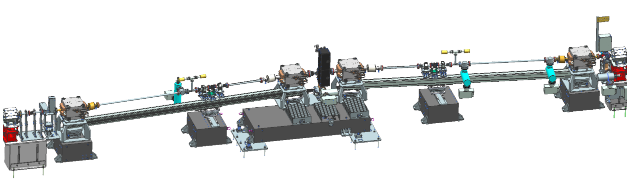

Figure 2: 3D CAD model of FLASH's 2nd bunch compression chicane FL0BC2

The section around the second bunch compressor chicane (*now called FL0BC2*) was completely redesigned in order to generate space for a proper diagnostics and re-matching section, capable of performing symmetric quads-cans and multi-quad-scans. The old (horizontal) 6-dipole S-shaped chicane with flat vacuum chamber was replaced by a new, shorter, C-shaped design with round vacuum chambers and skew-quad/BPM/quad packs in the two chicane legs [28]. Figure 2 shows at 3D CAD model of the new chicane FL0BC2. The inner dipoles are movable on rails so that the chicane is tunable from 0° to 6° (nominal 5°) with maximum a M_{56} of ~100 mm (nominal ~70 mm). The magnet packs in the chicane legs consist of a quadrupole, followed by a beam position monitor, followed by a skew-quadrupole, in one leg and the mirror image of the pack in the other leg. The goal is to employ the horizontal chicane dispersion in the quadrupole to reduce linear longitudinal-to-horizontal correlations inside the bunch, the combined action of horizontal dispersion in skew-quad and quad to reduce linear longitudinal-to-vertical correlations inside the bunch [28–30].

The new chicane could so far only be commissioned in part: Transmission with various magnet currents from 0.5° to 5° and the corresponding nominal slider positions is perfect. With the nominal deflection angle of 5° the compression factor for given bunch chirp is in the right ball park. Since mid-August the new FL0BC2 is routinely operated at 560 MeV.

In Early October 2022 commissioning with beam started for about 3.5 weeks prior to the first user run with the new injector [26]. Since then we take more and more features into operation during the regular FEL studies.[1] In the short time we managed to establish beam transport through both beamlines, commission a large part of the new updated diagnostics, match the beam from the gun to the design optics upstream of FL0BC1, correct the dispersion in injector and linac, and get the intra train orbit feed forward into operation.

The FLASH1 Upgrade Towards External (HGHG/EEHG) Seeding

The second shutdown 2024/25 was originally scheduled to convert FLASH1 into an externally seeded beamline for HGHG and EEHG operation, preserve the capability of providing also saturated SASE, and preserve the capability of producing THz radiation of high pulse energy simultaneous to seeding and/or SASE for pump-probe experiments in the Albert Einstein Hall. Figure 3 shows FLASH after this stage of the project has completely been finalized. The FLASH1 beamline is described in some detail in Ref. [31] with emphasis on the seed radiator section and in Ref. [32] with emphasis on the remaining parts. We refer to this original design as *stage-FULL*. However it turned out that in the 2024/25 shutdown, not all goals can be achieved. Instead a reduced design, called *stage-0* will be implemented at first. It enables HGHG and EEHG seeding with slightly reduced performance but in particular will not provides SASE in saturation at shortest wavelengths or high THz pulse energies.

The first new section downstream of the septum will be a transverse diagnostic and matching section. The first modulator section contains a laser incoupling chicane FL1CH1 for the first seed laser, an undulator (1st modulator) in which

[1] studies explicitly aiming at improving the FEL operation of FLASH.

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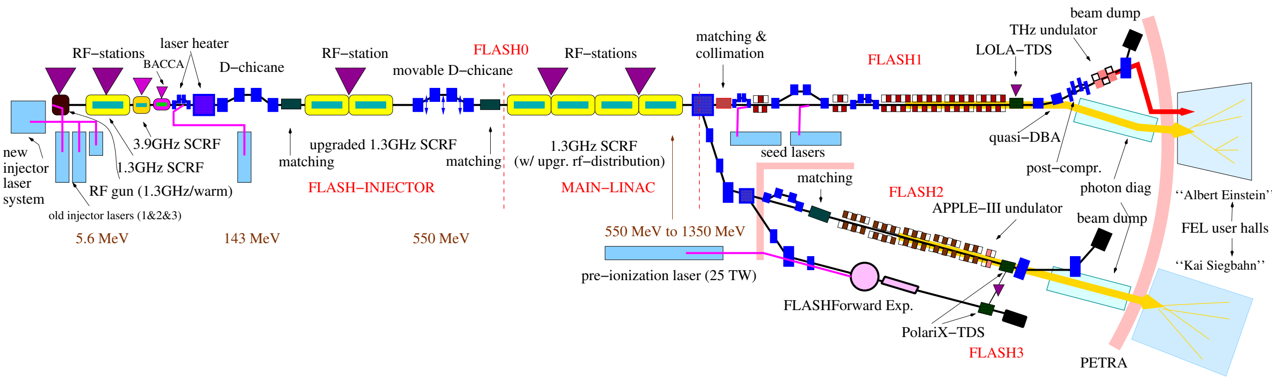

Figure 3: Schematic layout of FLASH (not to scale) after the shutdown 2024/25 (Stage-Full).

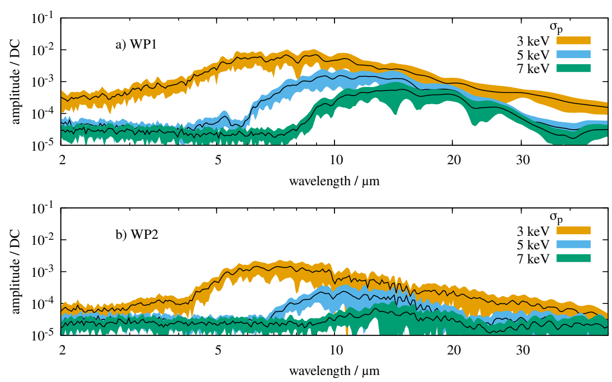

Figure 4: Microbunching simulations using a realistic shot-noise model for two compression working points with the semi-Lagrangian code SelaV$_{1D}$

the electron bunch becomes energy-modulated by laser 1, and the so-called *over-folding* chicane FL1CH2 to strongly over-fold the energy modulation from the first laser in EEHG mode. The over-folding chicane also serves for coupling seed laser 1 out and for coupling seed laser 2 in. The second modulator section contains a second undulator to modulate the incoming phase space, and the so-called *bunching* chicane FL1CH3 that is used to shear the doubly modulated structure in order to create sharp spikes in the charge distribution — with potentially very high harmonic content. Downstream follows the radiator section, with its (originally) 11 helical APPLE-III undulators.

Seeded FEL operation is much more severely perturbed by microbunching than SASE. We have performed start-to-end simulations to minimize the impact of microbunching in FLASH1. In particular we have developed a code, SelaV$_{1D}$ [33], that describes the evolution of the longitudinal phase space density by low-noise backward tracking (semi-Lagrangian method) of a tree-based grid. The tree-based grid allows extreme fine resolution for the ϵ-support of the exotic FEL densities without wasting memory on unpopulated areas. Figure 4 compares too compression working points (WPs), a heuristically designed WP and a carefully optimized WP, by means of microbunching spectra provided by SelaV$_{1D}$ simulations, starting the microbunching from realistic shot-noise without the artifacts of macro particle tracking. Each WP shows three different slice energy spreads (intrinsic, moderate laser heater, cranked up laser heater). It becomes clear that the microbunching amplitude can be kept small ($\sim 10^{-4}$) in the relevant wavelength regime with moderate energy spread if a suitable wP is chosen.

Downstream of the radiators follows the new location for LOLA downstream of the radiators. One key aspect of the new FLASH1 beamline is to disentangle the photon beamline from the spent electron beamline, and eliminate geometrical coupling. A quasi double bend achromat structure (qDBA) will divert the beam by 5° to the port side[2]. In order to post-compress the "soft" seed beam for enhanced THz output, stage-FULL includes a 4th chicane FL1CH4 [32] between the qDBA and the actual THz undulator. Finally the beam is transported into the dump via a coupling-free beamline much alike the FLASH2 dump line.

The CDR [15] foresees for FLASH2, the installation of the PolariX TDS, the installation of a helical third harmonic afterburner undulator (APPLE-III) and not further specified modifications for advance lasing schemes. PolariX is installed and operational although not yet at full RF power (conditioning was slower than expected), the afterburner will be installed this fall.

Stage-Full vs. Stage-0

As mentioned before not all features of the FLASH1 upgrade (stage-FULL) can already be achieved in the 2024/25 shutdown. However, the so called stage-0, to be implemented 2024/25, was designed by *delaying* features in way that allows implementation at a later stage with minimal effort. Features that do not immediately affect the primary goal of external seeding were delayed. This includes the ability to saturate SASE at short wavelengths and high pulse-energy THz radiation. Only 6 of the 11 APPLE-III radiators will be installed at first, the first three radiators will be replaced by recycled planar Xseed [34] radiators as buncher, 2 more will be left empty at first. The post-compressor chicane FL1CH4 and some THz related electron beam diagnostic will be delayed. The intersections of the radiators will not equipped

[2] *in beam direction* left

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with wire-scanners in the first implementation. The space will however be reserved.

CONCLUSION

FLASH was and is a competitive FEL user facility. The FLASH2020+ upgrade will extend the wavelength range and make FLASH the only *seeded* VUV / soft X-ray FEL capable of supplying several thousand FEL pulses per second. The first upgrade shutdown was successfully finished and user operation was established after a very short commissioning phase. The second shutdown planning is within schedule. The originally planned second stage of the upgrade will not be fully achievable after the next shutdown. However, delayed features can without exception be implemented later. We are looking forward to the next step of the FLASH2020+ upgrade.

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