THE FLASH 2020+ UPGRADE PROJECT

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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 externally seeded and SASE FEL operation for a wavelength range down to 4 nm with the EEHG method. A key ingredient of the upgrade was replacing two early TTF-type L-band RF cryo accelerator modules by modern, high-gradient XFEL-type ones. The beam energy range of the injector has been increased by 100 MeV. This was achieved in the first of two long shutdowns from November 2021 to August 2022. The energy increase together with an afterburner APLLE III type undulator for variable circular polarization in the FLASH2 beamline will make it possible to reach the oxygen K-edge (530 eV). This talk will report on the project and the first shutdown with emphasis on the upgraded modules.

FLASH

FLASH [1–7] 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, house the FEL process each in their own internal undulator beamline, and finally dispose of the spent beam in a beam dump. Figure 1 shows a schematic layout of FLASH *before* the first upgrade shutdown 2021/22. FLASH2 can be disconnected from FLASH0 in a radiation-safety compliant way, so that maintenance on FLASH2 is possible while the FLASH0/1 complex is operated with beam. FLASH1 on the other hand shares the tunnel building with FLASH0 so that FLASH0 and FLASH1 are operationally permanently connected. There is in fact a third experimental beamline (FLASH3) which is extracted from FLASH2 and is placed in the FLASH2 tunnel. The FLASH3 beamline is used by the plasma wake field acceleration experiment FLASHForward [8] which can be activated *alternatively* to FLASH2 by powering a DC dipole. The FLASH accelerating RF is based on L-band (1.3 GHz). The L-band systems except for the RF-gun are superconducting modules of 8 nine-cell niobium cavities. They were designed and built in various stages of the TESLA/TTF/FLASH/XFEL SRF development process [9]. Apart from the L-band modules FLASH includes four more RF systems. The superconducting 3.9 GHz third harmonic linearizer, and three normalconducting RF systems operatied at 2.856 GHz (American S-band) for the transverse deflecting structure (TDS) LOLA [10, 11], 3.0 GHz (S-band) for the *b*eam *a*rrival time *c*ompensation *ca*vity BACCA [12], and 12.0 GHz (X-band) for the PolariX TDS [13–16].

At the moment FLASH is undergoing a substantial upgrade and refurbishment project, called FLASH2020+ (see next section). Some sub-projects of FLASH2020+ have already been accomplished 2019-2020, but the major remodeling phases are two long (> 1/2 year) shutdowns. The first shutdown started November 2021 and ended August 2022 successfully and the next, 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 superconducting TTF-type L-band module (ACC1), the third harmonic linearizer (ACC39) which contains 4 Tesla-type but scaled down nine-cell niobium cavities operated at 3.9 GHz, the BACCA longitudinal feedback cavity, the first bunch compression chicane, two more TTF-type L-band 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. The two "standard lasers" are in operation since almost 15 years and still constitute the backbone of the low-energy part of the injector system concerning stability and reliability. However, it is feared that at some stage the will become non-maintainable. The two standard lasers produce pulses with a Gaussian longitudinal profile with about 4.5 ps and 6.5 ps rms duration. The third "short pulse" laser produces pulses of between 0.8 ps and 1.6 ps rms duration. The beam spots on the CS_2Te cathode are approximately flat circular spots with a typical diameters in operation of 0.7 mm to 2.0 mm for laser 1 and 2 and 0.5 mm to 1.5 mm. The two standard laser are operated in burst mode and each can produce pulse trains of up to 800 µs at 10 Hz with variable pulse repetition rates between 40 kHz and 1 MHz while the third laser is operated in continuous mode and allows to extract arbitrary bunch patterns from a 1 MHz raster.

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[1] It can therefore generate 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 interpolating between the RF parameters of the two flat tops which are (within certain ranges) independent.

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[1] we know of course that $c \equiv 1$:-)

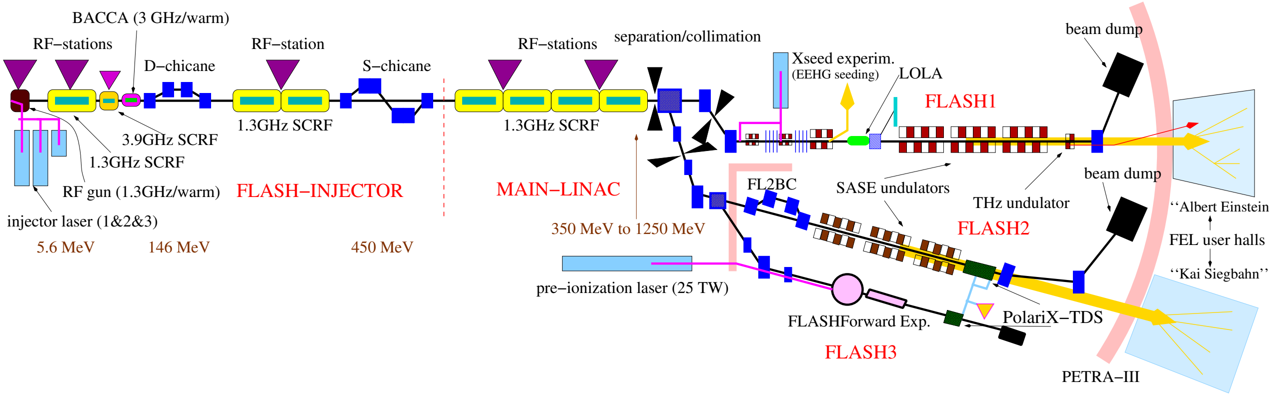

Figure 1: Schematic layout of FLASH (not to scale) prior to the first upgrade shutdown 2021/22.

The first L-band Module (ACC1) is, as mentioned before, an old TTF-type module — with a quadrupole doublet at the exit of the module. It is only operated with moderate gradient which yields a (beam-energy) E-gain of around 160 MeV at a (compressing) off-crest phase of at most 10° requiring an effective total amplitude of $\sim$163 MeV. The doublet is still needed for matching the space charge dominated beam from the gun into the design lattice, since the adjacent FLASH-type linearizer (ACC39) has *no* magnet-pack installed.

ACC39 is typically, operated in decelerating mode with an effective total amplitude of 18 MeV to 20 MeV. The 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 was typically operated at the central angle of 18° (M_{56} =181 mm). The standard beam energy for the bunch compressor used to be 146 MeV. Downstream of the chicane was a comfortably equipped transverse diagnostics and matching section.

Before the energy upgrade, the second (ACC2) and third (ACC3) L-band Module were among the weakest in FLASH. Let us only mention here that well tuned the 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 Both modules were and are driven by the same RF station (ACC23)

Also 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 matching upstream of the “main-linac”.

The FLASH0 “main-linac” consists of four L-band modules (ACC4/5/6/7) connected pairwise to two RF stations (ACC45 & ACC67). The first three are relatively modern TTF-type modules, while ACC7 is prototype of the modules produced for the European XFEL. Since it turned out that a FODO optics in the periodic parts of the machine is preferable due to its relaxed sensitivity and improved chromatic behavior, the XFEL-type modules have only have magnet packs with *one* quadrupole.

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.

The FLASH1 beamline which so far is optimized for providing SASE (self amplified spontaneous emission) FEL radiation to the FLASH1 experimental hall (Albert Einstein Hall). It consists of a dogleg for energy collimation, an experimental section Xseed [17] for gaining experience with external seeding in preparation for FLASH2020+ a diagnostic section including the LOLA TDS to map the longitudinal phase space into x/y space on a screen, the fixed gap main SASE undulators from the original FLASH, an electromagnetic THz undulator that uses the spent FEL beam, and finally the photon/electron separation (tilted dump dipole) and the (coupled!) FLASH1 dump beamline.

The FLASH2 beamline provides SASE FEL radiation to the experimental hall (Kai Siegbahn Hall). It consists of the extraction beamline that is also used for collimation and houses the extraction dipole (DC) to the FLASH3/FLASHForward, an extra bunch compression chicane (called FL2BC1), a transverse diagnostic section capable of performing a quadscan, the 12 variable gap FLASH2 undulators, a longitudinal diagnostic section including the PolariX TDS, the horizontal photon/electron separator dipole which also creates the dispersion for the longitudinal phase space mapping with PolariX, the vertical dump dipole and finally the FLASH2 beam dump.

After the separation of the FEL beam from the electron beam, both tunnels (FLASH1/2) are equipped with photon diagnostics, i.e. screens, pulse energy detectors, and spectrometers for tuning the FEL. Both tunnels are bounded by a “natural” radiation safety (double-) wall namely the PETRA tunnel walls. The photon beam pipes cross the PETRA tunnel into the adjacent experimental halls (Albert Einstein and Kai Siegbahn). Both halls contain further photon diagnostics, hardware for photon beam manipulation [18], and of course the experimental end-stations. While the electron beamlines gun-to-dump measure approximately 255 m, the complete FLASH1/2 facilities including the photon beamlines are both about 315 m long.

Each of the two beam dumps is capable of taking a total average beam power of 100 kW, which is by far more than what is needed for standard operation with < 5000 bunches per second with ~400 pC at <1.4 GeV.

The history of FLASH starting from the early Tesla Test Facility (TTF) [19] to the current FLASH is nicely covered in Ref. [4, 7]. More technical details on the electron beamlines of FLASH prior to the first upgrade shutdown, i.p. on the beamlines FLASH1 and FLASH2 can be found in Ref. [20, 21]. The photon diagnostic is explained in Ref. [18].

THE FLASH2020+ UPGRADE

To keep FLASH at the forefront of science, an ambitious upgrade and refurbishment project, called FLASH2020+ [22–24], 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 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 smaller 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. The electron bunch then needs to be prepared to contain a sufficiently long smooth part with just the right charge density to create enough FEL gain for amplifying the seeded pulse or one of its harmonics.

Today’s short pulse quantum lasers normally produce radiation for the infrared to the (near) ultraviolet. In the most simple case of external seeding, called High Harmonic Generation (HHG), the harmonic content of the seed laser itself is excited at the cost of substantial attenuation of the seed pulse energy. If the seed pulse energy is low one needs more FEL gain, which in the end diminishes the contrast to the SASE pedestal. Thus the preferred methods are based on high harmonics generation in the high-gain regime, i.e. in the FEL itself. The two methods to be implemented in FLASH1 in order to cover (almost) the complete wavelength range accessible with SASE, are High Gain Harmonic Generation (HGHG) [25, 26] and Echo Enabled Harmonic Generation (EEHG) [27, 28].

In a later stage of the project FLASH2 is planned to be modified to implement advanced FEL schemes.

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 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, high contrast HGHG/EEHG operation however, is not likely to generate decent THz pulse energies. Therefore a post compressor chicane will almost surely[2] 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 to be upgraded 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 longitudinal diagnostics LOLA, 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 [29] to ameliorate the unwanted micro-bunching effects [30], 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 FLASH0, in fact mainly the injector section. Here we will summarize the changes to the lattice not concerning the two new modules for ACC2/3 which will be treated in the next subsection. Figure 2 shows a schematic layout of FLASH *after* the first upgrade shutdown 2021/22. Installation of two new injector lasers was started. A new annex to the building which contains the injector bunker (called “tunnel”) was built and the installation of the laser has begun. 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.

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[2] i.e. with probability 1.

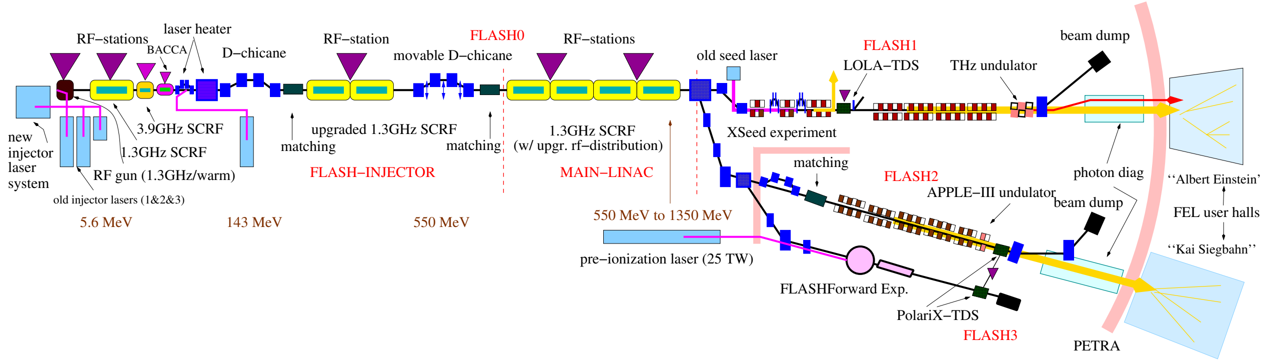

Figure 2: Schematic layout of FLASH (not to scale) after the first shutdown 2021/22.

Kickers have been installed to reduce the systematic (short term reproducible) orbit slopes over the bunch train: A horizontal and vertical kicker between gun and ACC1 to remove the orbit slope inside the laser heater undulator. A horizontal and vertical *pair* in each of the sections downstream of the compressor chicanes to reduce the slopes building up from time dependent transverse (dipole) coupler kicks in the modules and thus improving the intra train stability of the SASE in FLASH2 and, even more important, the overlap with the seed laser(s) in FLASH1. 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 micro-bunching gain and of 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 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 [31]. In addition the screen stations in the laser heater section, in FL0BC1 and downstream have been updated.

The locations of the supports for modules ACC2 & ACC3 were left unchanged in order to minimize the necessary modification to the cryogenics supply lines.

The section around the second bunch compressor chicane (*now called FL0BC2*) was completely remodeled: One goal was to generate space for a proper diagnostics and rematching section, capable of performing symmetric quadscans and multi-quad-scans. Since the space between ACC3 and ACC4 (the first module of the main linac) is fixed, the chicane had to be redesigned [32]. 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. 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 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 [33]. The BPM is used to minimize the steering of the quad/skew-quad pack, but can conveniently be used to measure beam-energy drifts at the location of the chicane. Figure 3 is a photography of the FL0BC2 chicane after completion. Due to lack of time between the end of the hardware commissioning and the start of the user operation, the new chicane could only be commissioned (with beam) in part: Transmission with nominal magnet currents for 5° and nominal slider position for 5° is perfect, and the compression factor for given bunch chirp is in the correct range. The new FL0BC2 is now routinely operated at 550 MeV.

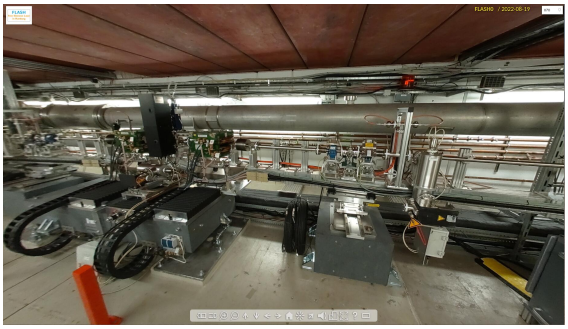

Figure 3: The new movable 2nd bunch compressor chicane FL0BC2 after the first shutdown.

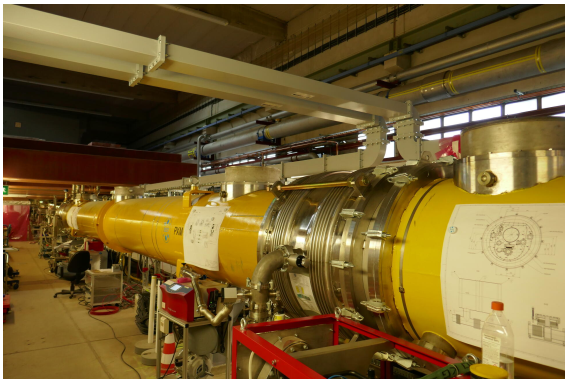

Figure 4: The two new modules PXM2.1 (ACC2) and PXM3.1 (ACCC3) and their cryogenic interconnection *during* the 2021/22 shutdown June 2022.

The Energy Upgrade

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 [9]. The new modules were originally build as prototypes for the module series production of the European XFEL, but were completely reassembled and equipped with high gradient cavities. Figure 4 shows both new modules allready installed in the tunnel during the shutdown. The cavities in ACC2 and ACC3 have maximum gradients from 29 MeV/m to 34 MeV/m, and from 24 MeV/m to 34 MeV/m respectively. The high gradient cavities and an optimized power distribution via the wave guide system, driven by a 10 MW multi beam klystron makes this RF station the most powerful in FLASH. Warm and initial cold conditioning in FLASH was successful and we are now *very slowly* moving towards the operational limits of the modules. The primary goal is to not compromise the high quality of the modules by too quickly raising the amplitude set points. We routinely achieve an E-gain of around 407 MeV at an off-crest phase of at most 25° which suggests an effective total amplitude of ~450 MeV or an effective average gradient of ~26.7 MeV/m. We also run at an E-gain of ~407 MeV and an off-crest phase of 30° which suggests an effective total amplitude of ~470 MeV or an effective average gradient of ~28 MeV/m. This allows to operate FL0BC2 at 550 MeV — 100 MeV more than the before the energy upgrade. The energy was measured with SASE radiation in the fixed gap (fixed K) undulator of FLASH1 and a high precision photon spectrometer in the PG beamline of FLASH1.

In Early October 2022 commissioning with beam started for about 3.5 weeks prior to the first user run with the new injector [31]. 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 gun part of the intra train orbit feed forward into operation. Since then we take more and more features into operation during the regular FEL studies.[3]

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, and at the same time preserve the capability of producing THz radiation of high pulse energy for pump-probe experiments in the Albert Einstein Hall. Figure 5 shows FLASH after this stage of the project has completely been finalized. The FLASH1 beamline is described in some detail in Ref. [34] with emphasis on the seed radiator section and in Ref. [35] 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. It enables HGHG and EEHG seeding but not with the full performance. We will briefly discuss stage-0 in the next subsection.

The old FLASH1 beamline starting after the FLASH1/2 septum dipole will be completely removed from the tunnel. The dogleg, so far used for energy collimation will not be installed again. Therefore the FLASH1 beamline will move in-line with FLASH0. The first new section downstream of the septum will be a transverse diagnostic and matching section FL1DIAG to prepare the bunches to match well inside the first EEHG modulator section FL1MOD1. FL1MOD1 contains a laser incoupling chicane FL1CH1 for the first seed laser, an undulator in which 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 as uncoupling for seed laser 1 and as incoupling for seed laser 2. The next section, FL1MOD2, contains a second undulator to modulate the incoming phase space with its substructure due to the over-folded first modulation, 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. FL1RADI is the radiator section, downstream of FL1MOD2, which is designed to contain 11 helical APPLE-III undulators, tunable to resonance with the selected harmonic and supporting the actual FEL amplification. Next is the new location for LOLA. By moving it downstream of the radiators one may, at least in SASE mode, be able to resolve the lasing part of the bunch by its modified energy profile. One key aspect of the new FLASH1 beamline is to disentangle the photon beamline from the spent electron beamline. A quasi double bend achromat structure (qDBA) will divert the beam by 5° to the port side[4]. In order to post-compress the “soft” seed beam for enhanced THz output, stage-FULL includes a 4th chicane FL1CH4 [35] between the qDBA and the actual THz

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

[4] *in beam direction* left

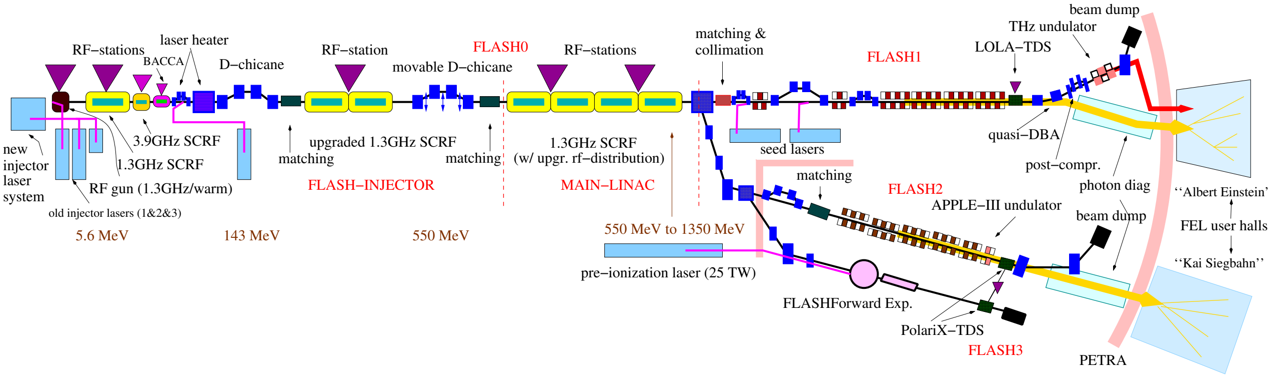

Figure 5: Schematic layout of FLASH (not to scale) after the shutdown 2024/25 (Stage-Full).

undulator. Finally the beam is transported into the dump via a coupling-free beamline much alike the FLASH2 dump line.

The CDR [22] foresees for FLASH2, the installation of the PolariX TDS, the installation of a helical third harmonic afterburner undulator (APPLE-III) and not further speecified 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, and the advanced lasing schemes are still in the conceptual design phase.

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 implementd 2024/25, was designed by *delaying* features in way that allows implementation at a later stage with minimal effort. Stand alone features that can be implemented without tunnel access (i.e. without a shutdown) were put on hold first. This includes the upgrade of the FLASH1 pump-probe laser system and the new photon beamline FL11. Next, 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 saves a couple of radiators, and 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 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 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. In particular the replacement of the old ACC2 & ACC3 by freshly refurbished XFEL prototypes was very successful enabling an increase of the final energy of the injector by 100 MeV. 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.

ACKNOWLEDGMENTS

We thank all the people from the FLASH team and the FLA2020+ project who made the FLASH2020+ upgrade possible. In particular we thank the people and groups that worked on preparing, performing the 1st shutdown, and on re-commissioning FLASH after the 1st shutdown and to those preparing the 2nd shutdown.

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