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STATUS OF THE SUPERCONDUCTING SOFT X-RAY FREE-ELECTRON LASER USER FACILITY FLASH

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Abstract

The XUV and soft X-ray free-electron laser FLASH at DESY is capable of operating two undulator beamlines simultaneously with up to several thousand bunches per second. It is driven by a normal conducting RF photo-cathode gun and a superconducting L-band linac. FLASH is currently undergoing a substantial refurbishment and upgrade program (FLASH2020+). The first 9-months installation shutdown started in November 2021. Here we report on the operation in 2021 and present main upgrades during the ongoing shutdown.

THE FLASH FACILITY

The superconducting XUV and soft X-ray FEL (free-electron laser) facility FLASH at DESY [1–5] can provide up to 500 bunches per train at 10 trains per second. Each train is typically divided into two sub-trains for the two beamlines with a variable transition time to cover the rise time of the extraction kickers and the adaption between the RF flat tops for the sub-trains. The bunches are generated in a normal conducting 1.3 GHz RF-photo-cathode gun using a Cs_2Te cathode and 3 independent injector lasers [6, 7] capable of producing bursts of UV pulses with up to 1 MHz[1]. Laser 1 and 2 generate equally spaced pulses with a duration of 4.5 ps and 6.5 ps (rms) respectively, while laser 3 can generate arbitrary pulse patters within a 1 MHz raster and rms pulse durations from 0.8 ps to 1.6 ps. Each laser has an independent attenuation system. Laser 1 and 2 share a common BSA (beam shaping aperture) optimized to produce beam spots on the cathode suited for medium to high bunch charges, while laser 3 has an independent BSA adapted (reduced bore diameters) in particular to low charges. Therefore the bunch charges and temporal patterns for the two beamlines can be chosen rather independently, while keeping the space charge effects in the injector to a large extent comparable.

FLASH uses seven TESLA-type superconducting 1.3 GHz RF-modules with 8 cavities with 9 cells each for beam acceleration. Bunch compression is realized in two stages: A first RF-module plus a 3rd harmonic linearizer followed by the first C-type dipole chicane operated at 146 MeV; and two more superconducting RF-modules followed by the 2nd S-type dipole chicane operated at 450 MeV. The following 4 RF-modules constitute the main linac and allow acceleration up to 1250 MeV and under certain conditions deceleration down to 380 MeV. All RF stations are equipped with versatile LLRF (low level RF) controllers suited for long pulse operation and capable of generating distinct RF flat tops for the two sub-trains allocated for the two undulator beamlines. The flexible laser- and LLRF systems generate a great amount of freedom to meet the different needs of independent experiments at the two undulator beamlines.

Table 1: FLASH 2021 Operational Parameters

Parameter (e^-,γ)		FLASH1	FLASH2
beam energy	GeV	0.38 – 1.25	
bunch charge	pC	20 – 1000	
$\varepsilon^{1\sigma}_{\perp,n}$ (inj)	µm	0.5 – 1.0	
bunches/sec.		1 – 5000	
undul. gap		fixed	variable
undul. period	mm	27.3	31.4
photon pulse energy	µJ	1 – 500	1 – 1000
photon wavelength	nm	4.2 – 51	4 – 90
spectr. width (FWHM)	%	0.7 – 2	0.5 – 2
pulse duration (FWHM)	fs	< 30 – 200	
photons/pulse		10^{11} – 10^{14}	
average brilliance	(∗)	10^{17} – 10^{21}	
peak brilliance	(∗)	10^{28} – 10^{34}	

(∗): s^{-1} $mrad^{-1}$ mm^{-1} /0.1%bw

The sub-trains for the two beamlines are separated with a kicker/septum scheme consisting of 3 vertical flat top kickers and a horizontal Lambertson (DC) septum. The extraction beamline into FLASH2 contains a DC dipole to potentially send beam into a 3rd beamline (FLASH3) that houses the FLASHForward plasma wakefield acceleration experiment [8, 9]. For the time being FLASH2 and FLASH3 can only be operated exclusively. FLASH1 has six 4.55 m long fixed gap undulators while FLASH2 has twelve 2.39 m long variable gap undulators. Both undulator beamlines are dedicated SASE (self-amplified spontaneous emission) FELs. FLASH1 also houses a seeding experiment Xseed [10] in preparation of the seeding beamline to be built for the FLASH2020+ upgrade project [11–13]. In addition FLASH1 contains a THz undulator that uses the spent e^-–beam from the FEL to generate THz radiation for pump-probe experiments. Both beamlines contain transverse deflecting RF structures for longitudinal diagnostics: An S-band structure (LOLA) [14] located *upstream* of the main-undulators (downstream of Xseed) in FLASH1; and two variable polarization X-band structures (PolariX) [15–17]

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[1] up to 3 MHz is possible in 5 Hz operation. And the 3 inj. lasers could be interleaved and sent to one beamline

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downstream of the undulators in FLASH2. Finally the beams are dumped in two dumps, each capable of taking 100 kW of beam power which is far beyond our typical operational range. Table 1 summarizes the most essential parameters of the run year 2021.

2021 OPERATIONS

In January 2021 the two PolariXes have been installed in the FLASH2 beamline. Since then their RF components have been conditioned and the system has become a valuable tool for tuning FLASH2 [17]. The run year 2021 was ended by the first of two long shutdowns within the FLASH2020+ project. Still more than 6700 h of beam time were achieved with an availability of 97%. The actual beam time distribution is shown in Fig. 1.

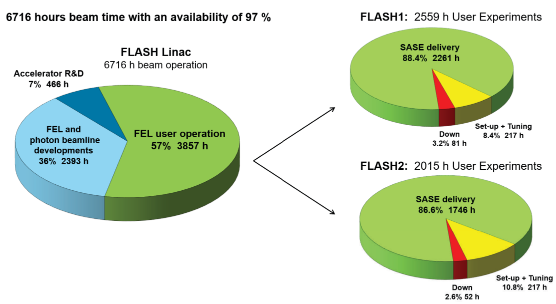

Figure 1: FLASH operations statistics 2021.

The beam time in FLASH is divided as follows: About 60% of the beam time should be reserved for FEL photon user experiments, 30% for machine- and photon beamline development dedicated to improve the performance and the operation of the facility, and 10% for *general* accelerator science and R&D. Machine set up and tuning is performed prior to every experiment, whenever experimental parameters are changed, and of course whenever necessary after an interruption. Beam time for each photon user experiment is scheduled contiguously, with preferably one experiment per week per beamline.

Downtime (~3%) in 2021 was dominated by a couple of major events. Some of them caused by manufacturing nonconformities, others by aged hardware, and a non-negligible fraction by external power-glitches that tripped sensitive equipment. Most faults from the first two categories can and will be addressed by hardware upgrades during the present shutdown. The trips of special equipment due to power-glitches have been analyzed and measures to mitigate the impact of power-glitches will be taken where possible with reasonable effort.

Highlights

An experiment analyzing the relaxation timescales in core level photo excited molecules, required simultaneous lasing at 17.7 nm and 5.9 nm, both with maximum attainable pulse energy, with pulse durations below 50 fs, for 40 bunches at a bunch frequency of 100 kHz. On the one hand it has been shown that HLSS (harmonic lasing self-seeded) [18, 19] is a good candidate for high pulse energy in the 3rd harmonic, but unfortunately the fundamental wavelength is mostly eroded in this scheme and the remains cannot even be transported to the photon experiment since the focal points of the two different colors are far away from each other. On the other hand, two-color lasing [20] based on alternating undulator gaps offers the possibility to generate the focal point of both wavelength close to each other, but the underlying physics does not take advantage of the harmonic relation of the two wavelengths to and hence lacks the high output power in the 3rd harmonic. Therefore, a mixture of both configurations was chosen at FLASH2: The first 3 undulators were set to to 17.7 nm to allow the fundamental wavelength to gain bunching on the fundamental and the 3rd harmonic generation. The downstream undulators were set up with alternating gaps for two-color lasing for increasing the pulse energy of the fundamental as well as the 3rd harmonic and get a source point at a similar position at the end of the undulator beamline. It should be noted that at given beam energy the dynamical range of the wavelength (determined by the undulator gap) is about a factor of 3, i.a.w. two-color lasing at fundamental and 3rd harmonic is at the edge of what is possible by design in FLASH2. Pulse energies of about 30 µJ for the 17.7 nm and several µJ for the 5.9 nm where achieved. The photon pulse duration was estimated and tuned using the PolariX transverse deflecting structure in FLASH2. The PolariX measurements suggested that the pulse duration was in fact < 50 fs. The experiment will be described and analyzed in greater detail in [21].

In a proof of principle experiment it was shown for the first time worldwide, that a simultaneous operation with SASE in one beamline (FLASH2) and HGHG external seeding in a second beamline (Xseed in FLASH1) driven by a common accelerator is possible [22]. The electron beam phase space required for seeding is quite different from the one required for SASE. It turned out that at FLASH the range for varying the RF-parameters of the accelerating modules between the flat top regions for the beam for FLASH1 and FLASH2 is sufficient to tailor electron bunches with the required longitudinal properties for HGHG seeding simultaneous to SASE lasing. While Xseed was seeding one bunch per train, trains of 200 bunches were lasing in FLASH2.

THE CURRENT 2021/22 SHUTDOWN

FLASH is currently in an upgrade shutdown within the FLASH2020+ project [11–13]. The shutdown is also used for general refurbishments like upgrade of the cryogenic facility and the cooling water systems. It started November 2021 and beam operation will resume in September 2022. This first of two "long shutdowns" is dedicated mostly to the upgrade of the FLASH injector (FLASH0). Figure 2 shows a sketch of FLASH *after* this shutdown.

A new injector laser system is being installed.

The first bunch compressor chicane is shifted downstream to generate space for a laser heater [23] right before the

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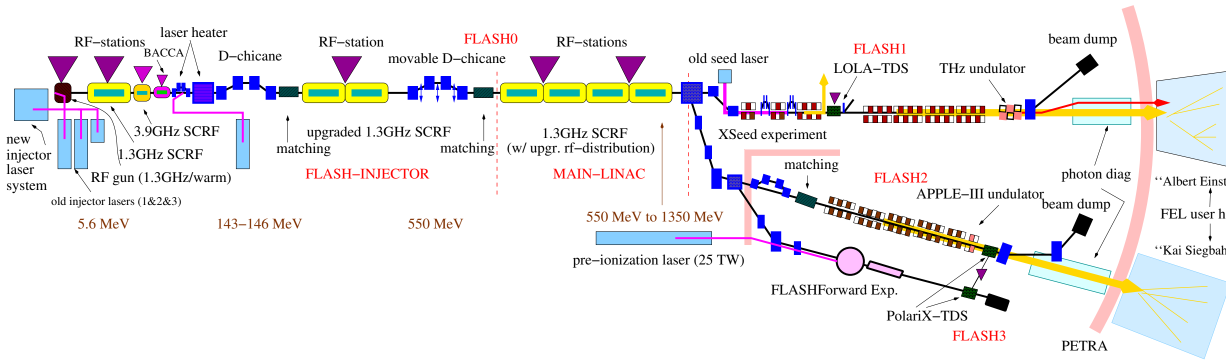

Figure 2: Sketch of FLASH after successful completion of the 2021/22 shutdown (not to scale).

chicane. In order to generate the required space the matching section downstream of the chicane had to be optimized and shortened. For performing an optimal four-screen measurements of emittance and betatron mismatch, the optics will have to be temporarily modified from the transport optics used in standard operations. The laser heater beamline consists of a vertical 4-dipole-bump around the in-coupling mirror followed by an undulator — both in a dispersion free beamline. The over-shearing of the laser-induced energy modulation will be performed in the first compressor chicane, which also provides the out-coupling bump for the spent laser beam. This set up will be able to increase the intrinsic slice energy spread from the natural 3 keV to about 10 keV. Micro-bunching studies [24] suggest that this will suffice to diminish the micro-bunching gain substantially.

The two RF-modules between the 1st and the 2nd bunch compression chicane have been replaced by refurbished XFEL prototype modules with an excellent performances in terms of cavity gradients. Moreover the RF-distribution systems of the first two of the main-linac modules have been optimized and upgraded to the standard of the other modules. These two upgrades are expected to increase the maximum attainable beam energy by at least 100 MeV to 1.35 GeV. In addition the cryogenic system undergoes a major refurbishment.

A weak point of the previous design was the absence of a matching section between the first and the second compression stage. Therefore the old S-type chicane was taken out and a new, shorter C-type chicane is currently being installed. The new chicane has two combined quad/skew-quad packs in its dispersive arms to allow for correcting longitudinal-to-transverse intra bunch correlations. However, these magnets require a round vacuum chamber, so that either the chicane can only be used at one *fixed* deflecting angle ($\rightarrow M_{56}$), or the chicane needs to be mechanically movable so that the vacuum chamber can follow the beam for varying deflection angles. The latter option is being installed at FLASH and Fig. 3 shows the current status of the assembly.

In FLASH1 the Xseed experiment is being upgraded with new diagnostics and movable quadrupoles.

In FLASH2 space has been generated for a helical APPLE-III 3rd harmonic afterburner undulator. The last planar undu-

Figure 3: Current assembly status of the 2nd compression chicane (02.06.2022).

lator has been moved upstream to the start of the undulator string. The last two upstream matching cells have been upgraded with new diagnostics: a bunch compression monitor (diffraction radiator), a bunch arrival time monitor, and an additional OTR screen. All modifications in the upstream sections of FLASH2 have been successfully finished. The delicate new vacuum chamber for the afterburner will be installed during the current shutdown, while the actual afterburner is scheduled for 2023. Since the beamline is already being prepared in this shutdown, installing the undulator should be possible within a 2 weeks time slot.

Recommissioning of FLASH facility with beam is scheduled to start in September 2022.

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