ISBN: 978-3-95450-184-7 doi:10.18429/JACoW-IPAC2018-TUPMF090

STATUS OF THE SUPERCONDUCTING SOFT X-RAY FREE-ELECTRON LASER FLASH AT DESY

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Abstract

FLASH, the free-electron laser (FEL) user facility at DESY, deliverers high brilliance XUV and soft x-ray FEL radiation for photon experiments since summer 2005. In 2014 and 2015 a second beamline, FLASH2, has been commissioned in parallel to user operation at FLASH1. FLASH's superconducting linac can produce bunch trains of up to 800 bunches within a 0.8 ms RF flat top at a repetition rate of 10 Hz. In standard operation during 2017 FLASH supplied up to 500 bunches in two bunch trains with independent fill patterns and compression schemes. Since mid 2017 initial commissioning of a third experimental beamline, accommodating the FLASHForward plasma wakefield acceleration experiment, has started. We report on the highlights of the FLASH operation in 2017/2018.

THE FLASH FACILITY IN 2018

FLASH (Free electron LASer in Hamburg) is a XUV and soft X-ray FEL with two independent undulator beamlines (FLASH1 and FLASH2) driven by a common warm photo cathode RF-gun and common 1.3 GHz superconducting injector- and main linac [1–10] (see Fig. 1). A detailed overview of the history and the technical evolution of the FLASH facility can be found in [9], a more detailed description of the principal layout of FLASH can be found in [10], and for a table of the most recent run parameters see [2]. Here we only describe the systems that have been upgraded or otherwise modified in the last year or that are essential to understand this report.

The Cs_2Te photo cathode [11] of the RF-gun can be driven by three independent UV injector lasers [12]. The two "standard" lasers (1 & 2) are typically used to generate bunches with up to 2 nC at up to 1 MHz (uniform) intra-train repetition rate and a train repetition rate of 10 Hz. They produce UV pulses with an rms duration of 4.5 ps and 6.5 ps respectively at the cathode. The third "short-pulse" laser (3) can produce arbitrary patterns within a 1 MHz raster of UV pulses with variable duration from 0.8 ps to 1.6 ps. Typically laser 3 generates bunch charges from 30 pC up to 0.4 nC. With these three injector lasers FLASH can provide a multitude of different bunch and/or bunch charge patterns.

To allow user experiments with the highest attainable temporal resolution, it is not sufficient to accurately monitor the bunch arrival time data. In addition, the arrival time jitter within each bunch train must actively be controlled. The bunch arrival time is measured by the Beam Arrival time Monitors (BAMs) [13–15]. This data is made available to the photon experiments for offline correction. The bunch arrival time jitter is predominantly caused by bunch-to-bunch energy fluctuations from the residual roughness of the RF flat top, which are converted into arrival time fluctuations via the longitudinal dispersion in the magnetic bunch compressor chicanes. The first RF module generates the strongest effect since for given fluctuation δE, the relative $\delta E/E_0$ is of course highest at low reference energy E_0. For example, relative amplitude jitter of 0.5×10^{-4} in the first L-band module with an energy gain of ~160 MeV generates 30 fs arrival time jitter after the first chicane at 146 MeV with an $R_{5,6}$ of 180 mm. However, the measured bunch arrival time can be fed back to the LLRF (low-level RF) system of the corresponding RF transmitter, thereby actively reducing the energy fluctuations and hence the arrival time fluctuations. At the FLASH injector this is implemented at the first 1.3 GHz module where it is routinely used in SASE operation. The high quality factor of the superconducting cavities, however, limits the bandwidth of the system. The residual energy fluctuations are typically small so that no high gradients are required for the feedback system. Thus a warm wide-band 3 GHz cavity with 4 cells, named BACCA [16], was developed and installed in the 2017/2018 winter shutdown. The goal for enhancing the bandwidth of the arrival time feedback with BACCA is to reduce the jitter below 10 fs. The section between the 3rd harmonic linearizer module and the first magnetic chicane has been completely rebuild to accommodate BACCA. In particular the formerly used all-in-one matching triplet (three quadrupoles on one common iron yoke) has been replaced by three separate quadrupoles. Thereby the capability to transversely match the space charge dominated beam from the gun into a well defined optics was significantly enhanced.

The superconducting technology of the FLASH linac allows an RF flat top duration of up to 800 μs, and thus a maximum of 8000 bunches per second to be transported in FLASH. In order to serve both undulator beamlines with bunch trains at 10 Hz, the train is divided in two sub-trains. These sub-trains are distributed between the two undulator beamlines with kicker/septum scheme, employing two vertical flat top kickers and a Lambertson DC septum. The RF flat top has to accommodate two sub-trains and a transition period of 50 μs to 100 μs between them. For maximizing the flexibility of SASE operation, the FLASH LLRF system has been adapted to allow splitting the flat top between several sub-trains of bunches with (within boundaries) varying flat top parameters (mainly amplitude and phase). Thus the transition time between the sub-trains does not only allow the kicker to reach its flat top but also allows to vary and stabilize the RF flat top parameters. Potentially stronger RF

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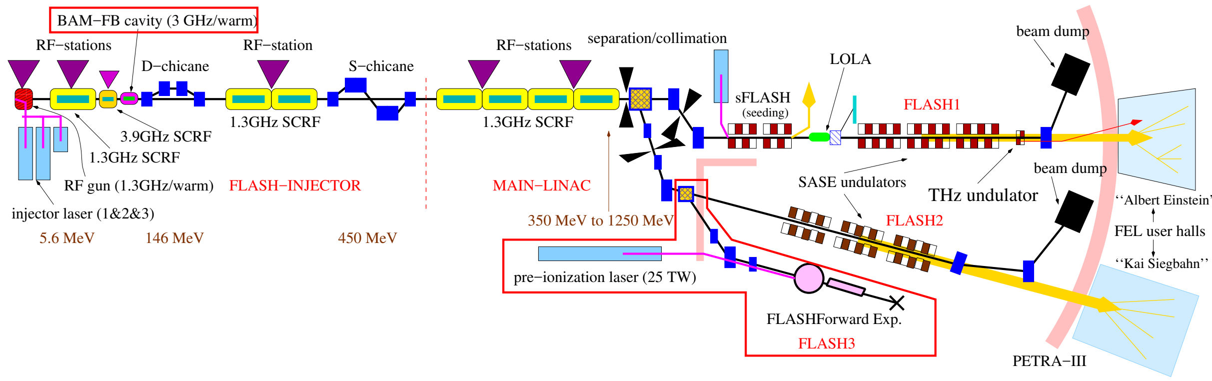

Figure 1: The FLASH facility (not to scale).

variation between sub-trains requires longer transition times. Details of the FLASH1/FLASH2 separation can be found in [8, 17].

The installation of a third beamline (FLASH3) housing the FLASHForward plasma-wakefield acceleration experiment [18, 19] was completed recently. The first electron beam was extracted to FLASH3 in end of August 2017. Meanwhile the commissioning of FLASHForward beamline concluded, and the first studies with plasma are expected soon. At the moment the FLASH3 extraction consists of two DC dipoles of 4 deg deflection angle each, installed at the exit of the FLASH2 extraction arc. Hence for the time being FLASH2 and FLASHForward cannot be run in parallel. In the future, however, the DC dipoles will be replaced by pulsed dipoles with a 100 μs half-sinusoidal excitation. Then it will be possible to extract two (drive- & witness-) bunches at the end of the last sub-train with a gap of about 50 μs between the last non-FLASH3 bunch and the FLASHForward bunches.

HIGHLIGHTS OF USER OPERATION

Parallel double beamline operation (FLASH1 together with FLASH2/3) is now routine. Whenever the program and the machine condition allows, both undulator beamlines are set up and tuned for SASE.

In 2017 FLASH1 was operated 6967 hours. The operation time was distributed between photon users (65%), general accelerator R&D (7%), and FEL studies, i.e. machine development to improve FEL operation, FEL beamline commissioning, and preparation for photon user runs (28%). 80% of the photon user time was SASE delivery, 17% was set-up and tuning, and 3% downtime.

Since the photon beamlines at FLASH2 and/or their end-stations were partly still being commissioned or under construction and since the optical pump laser for optical/XUV pump-probe experiments at FLASH2 was not yet operational in 2017, and since FLASH1 is operated with fixed gap undulators, thereby defining the machine energy, only part of the available time could be scheduled for FLASH2 user experiments. In 2017 at FLASH2 total of 1899 hours was devoted to user operation, with 1327 hours to user experiments and 572 hours to methods and instrumentation developments. The remaining FLASH2 beamtime was used for FEL studies, including FLASHForward commissioning and studies in FLASH/FLASH1 which preclude FLASH2 operation.

The short pulse injector laser [12, 20, 21] is routinely requested by users aiming for shortest pulse duration rather than highest pulse energy. With this device single spike lasing (and almost-single spike lasing) has been achieved in FLASH2 (FLASH1) [22].

The variable gap undulatosr of the FLASH2 beamline allow a great flexibility in setting up new FEL schemes [23]. In particular HLSS (Harmonic Lasing based Self Seeding) [24] has been successfully established for photon users. HLSS means that the FEL process is started at a longer wavelength where the gain length is short, and that after some undulator segments, still in the exponential gain regime, the undulator gaps are adjusted (opened) for a higher harmonic which is then brought into saturation. Thereby the pulse energy as well as the spectral brightness and the coherence time are increased.

The FLASH1 beamline contains, downstream of the SASE undulator, an electromagnetic (tunable) undulator for radiation in the THz regime. This device enables THz/XUV pump-probe experiments at FLASH1. However, since the path-length of the THz beamline is longer, due to the required refocusing along the transport, the THz beam is delayed by ≈ 21.5 ns. In [2, 23] we have reported about initial tests with a laser pulse doubler that splits the UV pulse from injector laser 1 into two pulses with a time delay of exactly 28 RF buckets (≈ 21.5 ns). Without this pulse doubler the only way to establish THz/XUV pump-probe is artificially lengthening the XUV path-length which turned out detrimental for the majority of experiments at the photon beamline equipped for THz/XUV pump-probe. The pulse doubler hardware is now fully commissioned and is permanently installed in injector laser 1. Under standard conditions, the pulse doubler itself can easily be operated without expert knowledge on the laser system. However, tuning the double pulses so that the 1st bunch produces mainly THz radiation and hardly any XUV while the 2nd bunch significantly lases in the XUV

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(as sketched in Fig. 2) is not straight forward and is subject of an ongoing study.

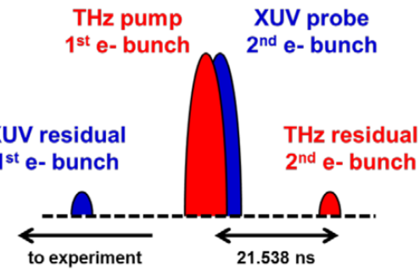

Figure 2: XUV/THz Pulse structure with active THz (injector laser) Pulse doubler.

SHORT-TERM UPGRADES

So far the FLASH2/3 complex does not have any bunch length measurement equipment operational. The THz radiator/spectrometer system [25] announced in [2] has been installed and commissioning is ongoing.

Inspired by the success of the X-band Transverse Deflecting Structure (TDS) longitudinal diagnostics at LCLS [26], a collaboration of CERN, DESY and PSI was founded with the task of developing and producing a modular X-Band TDS system that is able to fulfill the requirements on a longitudinal short pulse diagnostics in various accelerator environments [27, 28] (see Fig. 3). The TDS has recently been given the name “PolariX-TDS”. At FLASH, for the time being, 2 installations are envisioned: First, the prototype will be installed for the FLASHForward experiment downstream the plasma cell [29]. Second, after successful commissioning of the prototype, a cascade of two PolariX-TDSs will be installed in FLASH2 downstream of the last FLASH2 SASE undulator [20]. In order to allow FLASH2 PolariX-TDS operation with long bunch trains, a fast kicker is needed to deflect the streaked bunch onto a screen. The necessary resolution in time and energy and the limited amount of space require substantial optics changes in that section [20].

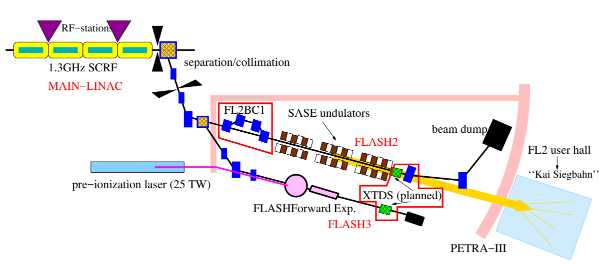

Figure 3: Upcoming modifications to the FLASH2/3 beamlines.

In order to preserve FLASH as an attractive XUV/ soft X-ray FEL an upgrade program (called FLASH 2020+) is being pursued. For a possible scenario of upgrades focused on the accelerator aspects, see [30]. In preparation for such a possible upgrade a third bunch compressor chicane is planned to be installed in FLASH2 downstream of the FLASH3 extraction. With this additional chicane it will be possible to relax the compression at low energy and in particular ameliorate the CSR effects from the FLASH2 extraction arc.

ACKNOWLEDGMENT

We would like to thank all the colleagues at DESY and from the collaborating institutes for their continuous dedication in operation, maintenance and upgrade of FLASH and in particular during the construction and commissioning of the FLASHForward beamline.

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