STATUS OF THE SOFT X-RAY FREE ELECTRON LASER FLASH

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Abstract

The superconducting free-electron laser user facility FLASH at DESY in Hamburg routinely produces several thousand photon pulses per second. The operational parameters cover a wavelength range from 4 nm up to 90 nm with pulse energies from several µJ up to 1 mJ and with pulse durations of several hundred fs down to a few fs. The FLASH injector and linac drive two undulator beamlines (FLASH1, FLASH2) and therefore FLASH is capable of serving 2 independent experiments with photon pulse (sub-) trains of several 100 bunches at the full train repetition frequency of 10 Hz. In this paper we summarize the highlights of user operation at FLASH1/2 and the study program (machine development and FEL optimization) of the FLASH facility.

INTRODUCTION

The superconducting soft X-ray free-electron laser user facility FLASH [1–7] (Free electron LASer in Hamburg) at DESY, Germany is driven by a normal conducting RF photo cathode gun (RF-gun) and a superconducting linac consisting of seven 1.3 GHz (L-band) accelerating modules with eight TESLA-type 9-cell cavities each. The superconducting modules are capable of producing 800 µs long accelerating flat tops every 100 ms. The three UV injector lasers [8] are in their standard set up capable of producing 800 µs long pulse bursts of 800 pulses (1 MHz) at 10 Hz which are converted to bunch trains of up to 800 bunches at the Cs_2Te photo cathode [9] inside the RF-gun. These bunch trains are compressed to typically 0.8 to 2.5 kA peak current in two stages and accelerated to up to 1250 MeV. The minimum energy for SASE (self amplified spontaneous emission) operation in 2016 was 350 MeV. Downstream the linac the bunch trains are distributed between two undulator beamlines (FLASH1/FLASH2) with a kicker-septum scheme. To allow for the finite rise time of the kicker, the bunch trains have to be generated as two sub-trains with a typical separation of 50 to 70 µs. A detailed overview of the history and the technical evolution of the FLASH facility can be found in [6] and a more detailed description of the layout can be found in [7]. Figure 1 sketches the FLASH layout including a new electron beamline to be installed in summer. Table 1 shows typical FLASH parameters obtained during user operation and studies. The parameters of the FLASH1 and FLASH2 undulators are given in [1, 3].

USER OPERATION

FLASH1 and FLASH2 are routinely operated simultaneously [10] and user operation in FLASH2 started in April

Table 1: FLASH Parameters 2016/2017

electrons :	FLASH1	FLASH2	
beam energy	350 - 1250	400 - 1250	MeV
charge	0.1 - 1.2	0.02 - 1	nC
emittance (×)	1.4		µm
peak current (†)	0.8 - 2.5		kA
energy spread (∘)	0.2	0.5	MeV
bunches / train (∗)	1 - 500		
bunch spacing	1 - 25		µs
train rep. freq.	10		Hz

(×) : gun, $\beta\gamma\varepsilon_{x,y}$, 1 nC, on-crest, 90% rms
(†) : after compression (∘) : entrance undulator
(∗) : up to 600 (FLASH1 xor 2) possible in 2017

photons :	FLASH1	FLASH2	
λ (fund.)	4.2 - 51	4 - 90	nm
pulse energy (⋆)	1 - 500	1 - 1000	*J*
pulse duration (fwhm)	<30 - 200	< $10^{(*)}$ - 200	fs
spectral width (fwhm)	0.7 - 2.0	0.5 - 2.0	%
peak power	1 - 5		GW
peak brilliance	10^{28} - 10^{31}		(+)
photons /pulse	10^{11} - 10^{14}		

(⋆) : average, single pulse (∗) : estimated
(+) : photons/(s mm^2 mrad^2 0.1%bw)

2016. With FLASH2 we expect to almost double the user time in the near future, however the FLASH2 experimental hall is not yet fully equipped. Installation work at the FLASH2 photon beamlines is still ongoing. Moreover, the pump/probe laser for FLASH2 will not be ready for users until 2018. Since many time resolved experiments (52 % in 2016) require such an optical laser, they still have to be scheduled at the overbooked FLASH1 beamlines. Thus user operation in FLASH2 can not yet be scheduled as regularly as in FLASH1. This will change in the near future with the completion of the FLASH2 photon beamlines and the pump/probe laser.

In 2016 a total of about 7300 h were scheduled for the operation of FLASH1. About 60 % of this time was dedicated to photon experiments while 30 % was scheduled for FEL studies (machine development and photon beamline commissioning). The remaining 10 % were scheduled for general accelerator R&D. The systematics behind the scheduling of FLASH operations is explained more in detail in [3]. During the photon user runs about 81 % of the time SASE with the requested parameters was delivered to user experiments. About 16 % of the time was needed for tuning and machine set up and the down time during user runs was 3.5 %.

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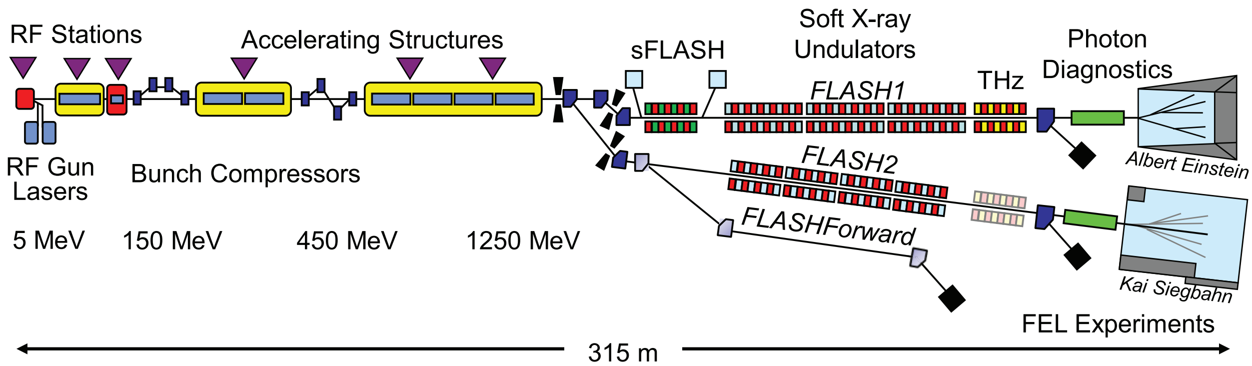

Figure 1: The FLASH facility (not to scale).

In July 2016, after a short scheduled shutdown, preceded by more than a year of stable RF-gun operation, the RF-window from the waveguide to the input coupler developed a small vacuum leak and had to be exchanged. The exchange and the conditioning went smoothly and the nominal operation parameters were quickly recovered. The RF-gun is running very stable since then and since the beginning of 2017 we operate it at 650
,μs flat top length. In addition, another problem, not related to the RF-gun occurred in summer 2016. A vacuum leak developed in the electron beamline downstream of the gun at a bellow between a bunch charge monitor (toroid) and the warm-cold transition into the first L-band module. The vacuum pressure could be maintained until repair to an acceptable level in order not to spoil the photocathode of the RF-gun and the superconducting cavities of the L-band module. The bellow was finally repaired during a scheduled shutdown December 2016.

In 2016 user experiments were performed with wavelengths from 4.2 nm to 38 nm (FLASH1) and up to 52 nm (FLASH2). About 43 % of the users requested pulse durations below 50 fs, 42 % requested 50 to 100 fs and only 15 % considered the pulse duration uncritical. In addition the proposals asked for 1-500 bunches per train with various bunch repetition frequencies between 1 MHz and 100 kHz. In general more than 80 % of the experiments are pump/probe (either optical/XUV, THz/XUV or XUV/XUV), thus many requests include THz radiation from an electromagnetic undulator downstream the FLASH1 main SASE undulator, optical pump/probe laser, or split-and-delay units for the FEL beam. Additional requests are for small bandwidth, photon-energy scans and other.

A user experiment was made with injector laser 1 *and* injector laser 2 both set up for one undulator beamline (FLASH1) with delays in the range of 222 ns, tunable in 1.3 GHz buckets, to mimic the 4.5 MHz bunch repetition frequency of the European XFEL. It could be shown that the experiment under study performed well with the enhanced pulse frequency. Moreover, delays of around 470 ns were also successfully tested.

HIGHLIGHTS OF STUDIES

A study is on-going as preparation for experiments using the radiation from the THz undulator in FLASH1 as pump and the XUV from the FEL as probe. The THz radiation is transported through a separate beamline. Since the THz beamline is about 21.5 ns longer than the FEL beamline, an additional about 7 m long delay has to be introduced in the FEL beam path in order to overlap THz and FEL-radiation in time for pump/probe experiments. This delay is presently introduced via a normal incidence back-reflecting multilayer mirror, which has substantial drawbacks. The alternative approach is to provide an additional "THz bunch" 21.5 ns ahead of the "FEL bunch" in order to simplify THz-pump/XUV-probe experiments. A pulse splitter with a delay line for the second bunch was installed in the injector laser beamline. The double bunches were transported successfully through the machine and used to generate THz radiation. The aim will be to prepare the leading bunch to produce only marginal XUV but high THz pulse energies while the trailing bunch does the opposite.

The seeding team has successfully performed HGHG seeding at the 7th and 8th harmonic of a 266 nm seed pulse [11]. Moreover they have transported the seeded FEL beam to an experimental hut outside the FLASH tunnel where the FEL radiation was characterized.

Photon pulse duration measurements employing THz streaking of photo-electrons [12] have been performed on SASE and seeded FEL beams. A permanent installation of a THz streaking diagnostics is planned in FLASH2 in this or the next year.

Studies on shortest possible photon pulses were performed using injector laser 3 which is designed for variable laser pulse duration in the range of 0.7 to 1.7 ps (rms) [13]. This allows bunch compression to the level of a few fs. For comparison: injector laser 1/2 generate 4.5/6.5 ps (rms) long laser pulses. The pulse durations estimated from the measured wavelength- and temporal spectra were well below 30 fs. Moreover, various user experiments were provided with SASE from short, low-charge bunches from injector laser 3.

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PLANS FOR THE SUMMER SHUTDOWN

This summer, FLASH will have a 6 week shutdown needed to perform regular maintenance at the cryogenics system. During this time several upgrades will be installed at FLASH.

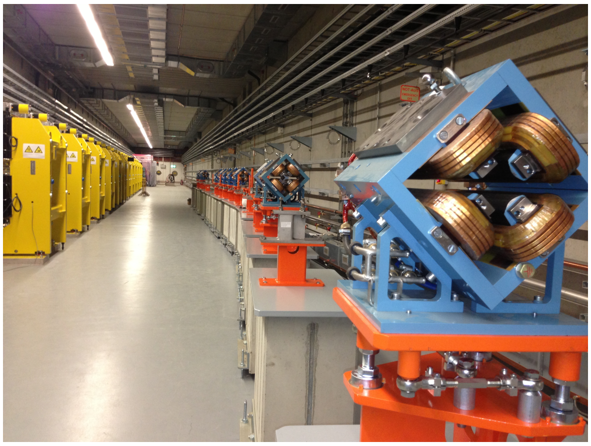

Figure 2: The FLASH2 tunnel (in beam direction) with the FLASH2 undulators to the left and magnets/magnet supports for the FLASHForward experiment in the FLASH3 beamline to the right.

In order to further stabilize the arrival time of the bunches in the undulator, an S-band cavity with large bandwith [14] has been developed to assist the beam based arrival time feedback of the first superconducting, i.e. narrow-band, L-band module in minimizing the arrival time jitter. The cavity will be installed in a section downstream the first module and upstream the first magnetic chicane. In addition we will replace an old all-in-one triplet quadrupole magnet in this section by three separate quadrupoles. This will enhance our capabilities to match the beam from the RF-gun into the design optics of the linac.

At FLASH2 we plan to establish online monitoring of the bunch length using a THz radiator (screen) and a spectrometer. This requires the installation of a fast kicker and of moving the existing off-axis screen and spectrometer downstream.

The major part of the shutdown work, however, will be the installation of the extraction from the FLASH2 arc into the FLASH3 beamline to be used by the plasma wake field acceleration experiment FLASHForward [15] and the installation of the actual beamline in the FLASH2 tunnel. Figure 1 shows a sketch of the upgraded FLASH facility including the FLASH3 beamline and Fig. 2 is a photograph of the FLASH2 tunnel including the already installed components of the FLASH3 beamline.

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