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

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Abstract

FLASH, the superconducting free-electron laser at DESY delivers up to several thousand photon pulses per second with wavelengths ranging from 52 nm down to 4.2 nm and with pulse energies of up to 500 μJ to photon users at the FLASH1 beamline. In 2014 and 2015 a second beamline, FLASH2, has been commissioned in parallel to user operation at FLASH1. FLASH produces bunch trains of up to 800 bunches in 0.8 ms with a train repetition rate of 10 Hz. Each train can be split in sub-trains for FLASH1 and FLASH2, such that both beamlines receive bursts of bunches with full 10 Hz. Operational highlights are the SASE energy record of 600 μJ at 15 nm in FLASH2, and the first simultaneous SASE lasing of three undulator systems: FLASH1 (13.7 nm), sFLASH (38 nm), and FLASH2 (20 nm). sFLASH is the seeding experiment in the FLASH1 beamline. On April 8th 2016, FLASH has for the first time simultaneously served users at both beamlines, FLASH1 and FLASH2.

THE FLASH FACILITY

The superconducting soft X-ray free-electron laser FLASH [1–8] at DESY in Hamburg consists of four separate functional units: (1) an injector-linac capable of producing up to 8000 bunches per second with charges typically varying from 20 pC to 1.2 nC and compressed in two stages to typically 0.8 to 2.5 kA at an energy of 450 MeV, (2) a superconducting L-band main-linac capable of accelerating the beam up to 1250 MeV, or even decelerate it to 350 MeV, and (3 & 4) two electron beamlines (FLASH1 & FLASH2), each with a collimation section, a beam diagnostics section, a undulator section accommodating the SASE FEL process, an electron dump section, a photon diagnostics section, and ending into two separate experimental halls, where the FEL beam can be sent to several photon beamlines for the user experiments.

A detailed overview over the history and the technical evolution of the FLASH facility can be found in [5]. The injector consists of a normal conducting RF photo cathode gun (RF-gun) equipped with 3 separate injector lasers [9, 10], and two superconducting linac sections interleaved with magnetic chicanes for bunch compression. The first stage consists of an L-band (1.3 GHz) module with 8 TESLA-type 9-cell cavities for acceleration and a third-harmonic (3.9 GHz) module for linearizing the energy/time-of-flight correlation of the longitudinal phase space density. The second stage consists of two L-band modules. The two chicanes are operated at beam energies of 146 MeV and 450 MeV respectively. The main-linac consists of four L-band modules driven by two RF stations, and a switch-yard at the final energy distributing the sub-trains between the two beamlines. The switch-yard is based on two vertical flat top kickers, a focusing channel amplifying the kick and transforming it into a 20 mm vertical offset, and a horizontally Lambertson septum deflecting the FLASH2 beam by 6.5°. A key difference between the FLASH1 and FLASH2 beamlines are their main SASE undulators. FLASH1 has fixed gap undulators and thus the photon wavelength can *only* be varied by changing the beam energy. FLASH2 has variable gap undulators which allow varying the photon wavelength by about a factor of 3 at constant beam energy. Moreover they facilitate various types of tapering for enhancing the FEL output power. FLASH1 is additionally equipped with an experimental section for seeded FEL operation sFLASH. A more detailed description of the layout can be found in [6]. Table 1 shows typical FLASH parameters.

USER OPERATION

In the present operation scheme the FLASH run year is divided into two *user periods* with several *user blocks* of 4-5 weeks, interleaved by study blocks of 2-3 weeks. Since, presently, most of the photon beamlines in operation do not have permanent end-stations, the length of the study blocks is to a large extent determined by the time needed to change the experimental setups. The total available beam time is distributed between photon user experiments (60%), FLASH studies, i.e. machine development and photon beamline development (30%) and general accelerator R&D (10%). Typically one or two shutdowns per year for maintenance and technical modifications are scheduled. Every user experiment has its own set of beam parameters. For the last two user periods, period 6/7 (June-December 2015 / January-June 2016) the requested wavelengths were distributed approximately as 15%/20% below 7 nm, 70%/60% between 7 nm and 21 nm, and 15%/20% above 21 nm. The requested bunch patterns were: single or few bunches 60%/15%, maximum bunch number (at 1 MHz) 20%/35%, and multi-bunch (enhanced bunch spacing) 20%/50%. In both user periods about one third of the users requested 50 fs or less photon pulse duration. In user period 6 about 3000 h were dedicated to user experiments. FEL radiation was delivered 78% of the user time to the expermients and 16% of the time was used to tune the FEL so that the photon parameters meet the demands of the experiments. Downtime due to technical failures was 4% and an additional 2% was caused by a lightning strike in June 2015 which damaged the personnel interlock system leading to several days of interruption of

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Table 1: FLASH Parameters 2015/2016

electrons :	FLASH1	FLASH2	
beam energy	350 - 1250	400 - 1250	MeV
charge	0.02 - 1.2		nC
emittance (×)	1.4		mm mrad
peak current	0.8 - 2.5		kA
bunches / train (∗)	1 - 400		
bunch spacing	1 - 25		μs
train rep. freq.	10		Hz
(×) : $\beta\gamma\varepsilon_{x,y}$, 1 nC, on-crest, 90% rms			
(∗) : up to 580 (FLASH1+FLASH2) possible in 04/2016			
undulator :	FLASH1	FLASH2	
type	planar		
gap	fixed	variable	
period	27.3	31.4	mm
undul.-K_{rms}	0.9	0.7 -1.9	
$\langle\beta_{x,y}\rangle$	10	6	m
segment length	4.5	2.5	m
num. of segments	6	12	
photons :	FLASH1	FLASH2	
λ (fund.)	4.2 - 52	5 - 90	nm
pulse energy (⋆)	1 - 500	1 - 600	μJ
pulse duration (fwhm)	<30 - 200		fs
spectral width (fwhm)	0.5 - 2.0		%
peak power	1 - 5		GW
peak brilliance	10^{28} - 10^{31}		(+)
average brilliance	10^{17} - 10^{21}		(+)
(⋆) : average, single pulse			
(+) : photons/(s mm^2 mrad^2 0.1%bw)			

the beam operation. During the first four months of 2016 the downtime has been on the level of 3%. Since June 2014, the RF-gun, which caused a significant amount of downtime in the past, runs stable with a gradient of almost 54 MeV/m (equivalent to a forward power at the coupler of ≈5 MW and an average power for 30 kW) and with slowly increased RF flat top duration. The recently achieved value is 600 μs (580 μs usable for beam).

During RF studies on high gradient and high beam loading in November 2015, after changing the loaded Q of the cavities, the most downstream cavity (or its coupler) of the most downstream module developed a field emitter. Since then operating the cavity at more than ≈15 MeV/m is impossible due to unacceptably high dark current losses. The situation did not improve over the last months and it was decided to slightly detune the cavity by 500 Hz for high energy operation. Despite the partial loss of one of the best cavities we were able to tune the energy up to 1.25 GeV to deliver 4.2 nm FEL radiation in the water window important for some user experiments.

User operation at FLASH2 started on April 8th 2016 in parallel to FLASH1 user operation. The first official the user experiment at FLASH2 was carried out at 13 nm wavelength with 11 pulses per train and up to 100 μJ pulse energy. In parallel FLASH1 delivered FEL radiation to an experiment at 10 nm with 400 pulses per train and up to 140 μJ.

FLASH1/FLASH2 SIMULTANEOUS OPERATION

FLASH1 and FLASH2 are routinely operated simultaneously since mid 2014. Because of the restrictions due to its fixed gap undulators user operation at FLASH1 requires regular changes of the beam energy. The extraction into FLASH2 is very sensitive to energy mismatch and thus it is crucial for simultaneous operation that FLASH2 is set up systematically from the beginning at every energy change necessary for FLASH1.

Making use of the variable gap undulators, wavelength changes in FLASH2 at constant beam energy can, in principle, be performed within minutes. However, at shortest possible wavelengths in FLASH2 requiring a large undulator gap, i.e. at wavelengths equal to FLASH1 more tuning time is required, and so far the pulse energy at shortest achievable wavelengths is not yet fully satisfactory.

Tapering is now routinely used to enhance the pulse energy and studies on optimized tapering schemes are ongoing.

The commissioning of the photon diagnostics for FLASH2 is fairly well advanced. Several screens, a multi channel plate detector (MCP) and a gas monitor detector (GMD) for online pulse resolved energy measurement, and two spectrometers, an online gas ionization based spectrometer and a (destructive) grating spectrometer, are already operational. Moreover, starting in May, a second photon beamline with a permanent end-station will be operational at FLASH2.

Multi bunch operation was established for FLASH2 in December 2015. FLASH1 and FLASH2 are now operated routinely in parallel with long bunch trains in various bunch patterns. Figure 1 shows an example with 250 bunches sent to each beamline. Figure 2 shows 400 pulses in FLASH2 with a wavelength of 22.9 nm and an average pulse energy of 130 μJ. In October 2015 a record value of 600 μJ was measured at FLASH2 at 15 nm in single bunch mode at 1100 MeV.

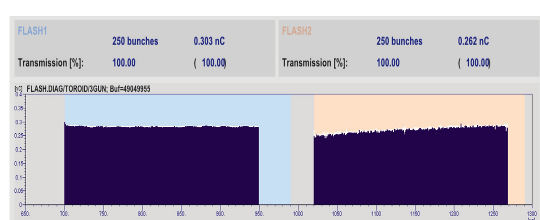

Figure 1: Example of a bunch pattern with 250 bunches in FLASH1 and 250 bunches in FLASH2. Both with 1 μs bunch-spacing.

STUDIES

Machine development beam time in FLASH is used to commission, optimize and maintain hardware, software and

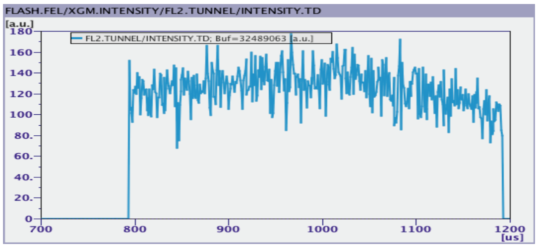

Figure 2: 400 photon pulses in FLASH2 at a wavelength of 22.9 nm with on average 130 μJ. The horizontal axis is the intra train time in μs. The vertical axis is the pulse energy in μJ.

operational procedures. The program is scheduled so that whenever adequate, studies are performed on both FEL beamlines independently and in parallel. A significant fraction of the study time in FLASH2 was used to commission the photon diagnostics. Electron diagnostic hardware, installed in FLASH2 but also foreseen for the European XFEL, was characterized with beam. In addition several general accelerator experiments have been performed during study time. Some highlights of them are:

Experiments with two bunches in the same RF bucket have been performed in preparation of a beam-driven plasma wakefield experiment, FLASHForward [11] located in the FLASH3 beamline which is under construction in the FLASH2 tunnel. A pulse stacker was inserted into the injector laser beamline and double bunches with varying charges and phase separations were created and transported through the complete linac into the transverse deflecting structure LOLA [12] in FLASH1.

Studies on the generation of ultra short FEL pulses [13] were performed despite of technical problems with the commercially produced short pulse injector laser. Using one of the two standard injector lasers photon pulse durations of 10-30 fs were achieved with bunches of 45 pC.

The experimental seeding setup at FLASH (sFLASH) operates currently in the high-gain harmonic generation mode (HGHG) seeded by 266 nm laser pulses. Characterization of the seeded FEL pulses at 38 nm and below is ongoing in the spectral and temporal domain. The generated pulse energy is 70-100 μJ and the upper limit for the relative spectral width is below 10^{-3} (rms), limited by the resolution of the sFLASH spectrometer.

Cascaded and simultaneous lasing of three SASE undulators [14] was achieved in a setup with one bunch sent to to FLASH2, lasing at 20 nm, and a second bunch lasing first in the sFLASH undulator (SASE, not seeded) at 38 nm and then, after recovering during passage through $\approx$20 m of beamline, lasing again in the FLASH1 main SASE undulator at 13.7 nm.

On May 1st 2016, more than 1000 μJ were achieved in FLASH2 during studies using an optimized version of quadratic tapering [15].

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