STATUS OF THE SOFT X-RAY USER FACILITY FLASH

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Abstract

Since 10 years FLASH at DESY (Hamburg, Germany) has provided high brilliance FEL radiation at XUV and soft x-ray wavelengths for user experiments. Recently FLASH has been upgraded with a second undulator beamline, FLASH2, whose commissioning takes place parallel to user operation at FLASH1. This paper summarizes the performance of the FLASH facility during the last user period from January 2014 to April 2015.

INTRODUCTION

Since summer 2005, FLASH [1–4], the free-electron laser (FEL) user facility at DESY (Hamburg), has delivered high brilliance XUV and soft X-ray FEL radiation for photon experiments. In order to fulfill the continuously increasing demands on the beam time and on the photon beam properties, FLASH is now upgraded with a second undulator beamline (FLASH2), being the first FEL facility worldwide operating simultaneously two undulator lines. The first lasing of FLASH2 was achieved in August 2014 [5]. A brief history of FLASH from a superconducting accelerator technology test facility [6] to a soft x-ray FEL user facility can be found in [3] and references therein.

Figure 1 shows an aerial view of the north side of the DESY area in summer 2014. The FLASH facility with its two experimental halls is in the middle: the FLASH1 hall (recently named as "Albert Einstein") is on the right, the new FLASH2 hall ("Kai Siegbahn") on the left. Next to FLASH are the experimental hall of the PETRA III synchrotron light source (left) and the construction site of PETRA III extension (right).

Figure 1: Aerial view of the FLASH facility. The FLASH1 experimental hall is on the right, the new FLASH2 hall on the left.

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This paper reports the status of the FLASH facility and its performance during the 5th user period in 2014/15. Part of this material has presented also in previous conferences, most recently in [4].

FLASH FACILITY

Up to 800 μs long trains of high quality electron bunches are generated by an RF-gun based photoinjector. An exchangeable Cs_2Te photocathode [7] is installed on the backplane of the normal conducting RF-gun. The photocathode laser system has two independent lasers, a third one is in the commissioning phase [8]. The bunch train repetition rate is 10 Hz, and different discrete bunch spacings between 1 μs (1 MHz) and 25 μs (40 kHz) are possible.

A linac consisting of seven superconducting TESLA type 1.3 GHz accelerating modules accelerates the electron beam up to 1.25 GeV. The linearization of the energy chirp in the longitudinal phase space is realized by a module with four 3.9 GHz (third harmonic of 1.3 GHz) superconducting cavities downstream the first accelerating module. The RF-gun and the accelerator modules are regulated by a sophisticated MTCA.4 based low level RF (LLRF) system [9, 10]. The electron beam peak current of the order of a few kAs is achieved by compressing the electron bunches by two magnetic chicane bunch compressors at beam energies of 150 MeV and 450 MeV, respectively.

The use of superconducting technology allows operation with long RF-pulses, i.e. with long electron bunch trains. The bunch train can be shared between the two undulator lines, allowing to serve simultaneously two photon experiments, one at FLASH1 and the other at FLASH2, both at 10 Hz pulse train repetition rate. The separation of the two bunch trains is realized by using a kicker-septum system downstream the last accelerating module.

The production of FEL radiation, both at FLASH1 and FLASH2, is based on the SASE (Self Amplified Spontaneous Emission) process. FLASH1 has six 4.5 m long fixed gap (12 mm) undulator modules, FLASH2 twelve 2.5 m long variable gap undulators. Later, FLASH2 can be upgraded with hardware allowing a seeded operation. A planar electromagnetic undulator, installed downstream of the FLASH1 SASE undulators, provides, on request, THz radiation for user experiments. A place for a THz undulator is available also at FLASH2.

A schematic layout of the FLASH facility is shown in Fig. 2. More details of the FLASH facility and its subsystems can be found, for example, in [3, 4], and references therein. Photon beamlines and photon diagnostics are described in [2, 11, 12].

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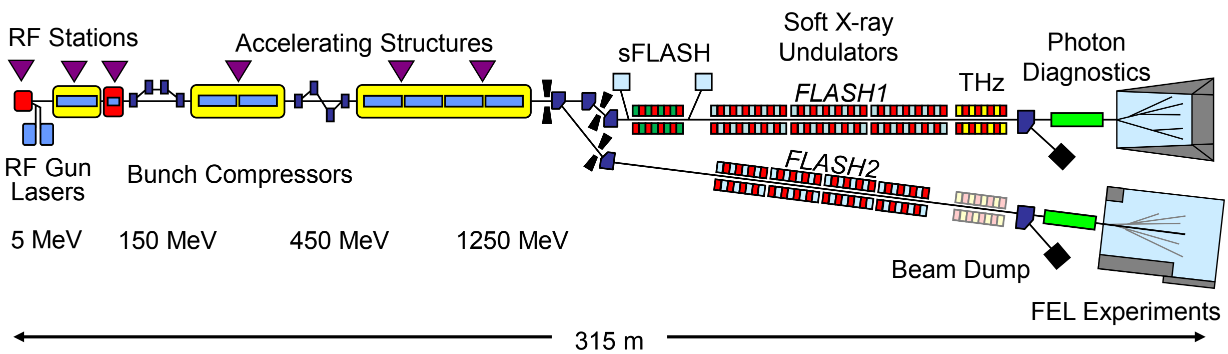

Figure 2: Layout of the FLASH facility (not to scale).

Simultaneous Operation

Each photon experiment has its own demands on the photon beam parameters concerning, for example, photon wavelength, pulse pattern, and pulse duration. In order to fully use the capacity of two undulator lines, the parameters of FLASH1 and FLASH2 need to be, as far as possible, independently tunable.

FLASH1 has fixed gap undulators, and therefore the electron beam energy of the FLASH linac is defined by the photon wavelength required at FLASH1. Thanks to the FLASH2 variable gap undulators providing wavelength tunability by up to a factor of 4, the FLASH2 wavelength can be adapted to the fixed electron beam energy. However, in order to take full advantage of the two undulator lines and to allow fast wavelength changes also at FLASH1, it is desirable to replace the FLASH1 undulators by variable gap ones in the future.

Unequal pulse pattern and pulse duration at FLASH1 and FLASH2 is realized by using two independent photocathode lasers in parallel. This allows production of two electron bunch trains with different parameters (number of bunches, bunch spacing, bunch charge) within the same RF-pulse. A gap of 30 to 50 µs (kicker pulse rise time) is needed between the bunch trains. The LLRF system permits, in certain limits, different accelerating amplitudes and phases for the FLASH1 and FLASH2 bunch trains. This feature, together with different bunch charges, allows lasing at FLASH1 and FLASH2 with different photon pulse durations.

An example of simultaneous operation with different parameters is shown in Fig. 3: FLASH1 has a train of 112 electron bunches with a bunch charge of 0.2 nC, and simultaneously FLASH2 is operated with one bunch of 0.4 nC. The electron beam (1.2 GeV) is not only transported through both beamlines, but both are also simultaneously lasing with wavelengths of 4.5 nm (FLASH1) and 5.5 nm (FLASH2).

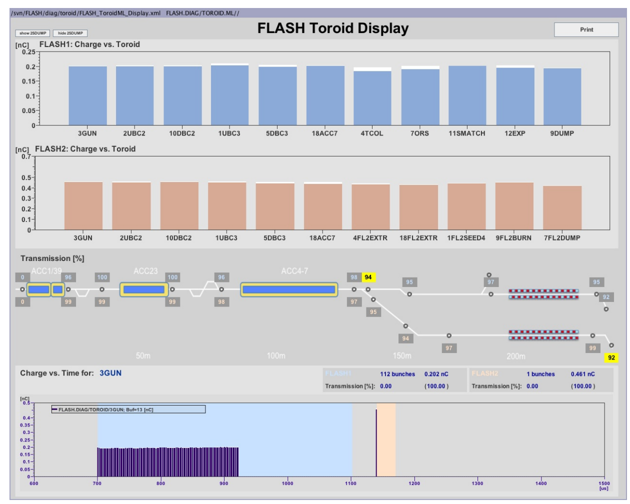

Figure 3: Example of simultaneous operation of FLASH1 and FLASH2. FLASH1 (blue): 112 electron bunches, bunch charge 0.2 nC. FLASH2 (salmon): single bunch with a charge of 0.4 nC.

FLASH1 OPERATION

During the 5th user period from January-27, 2014 to May-3, 2015 (462 days), 10180 hours of beam operation have been realized: 5628 hours (55%) were dedicated to photon user experiments, and 4552 hours (45%) for FEL and accelerator studies. The scheduled weekly maintenance took 199 hours, the yearly approval of the personnel interlock system 81 hours, and the Christmas shutdown 307 hours. Due to a vacuum leak in the RF-gun window, an additional 321 hours off time was accumulated in April 2014. As a consequence, one user experiment was postponed from April 2014 to April 2015.

After a 3 weeks shutdown in May 2015, to complete the radiation shielding between FLASH1 and FLASH2 tunnels with an additional 1000 tons of sand, the FLASH beam operation continued on May-26, 2015. The second half of 2015 will be dedicated to the 6th period of user experiments. From now on, FLASH will have two 6 months user periods per year.

User Operation

Table 1 shows the FLASH1 operating parameters in 2014-2015. These parameters are not all achieved simultaneously, but indicate the overall span of the performance.

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Table 1: FLASH1 Parameters, 5th User Period 2014/15

Electron beam		
Energy	MeV	345 - 1250
Bunch charge	nC	0.08 - 1
Bunches / train		1 - 500
Bunch spacing	µs	1 - 25
Repetition rate	Hz	10
FEL radiation		
Wavelength (fundamental)	nm	4.2 - 52
Pulse energy	µJ	10 - 500
Pulse duration (fwhm)	fs	< 50 - 200
Peak power	GW	1 - 3
Photons per pulse		10^{11} - 10^{13}
Peak brilliance	*	10^{29} - 10^{31}
Average brilliance	*	10^{17} - 10^{21}

* photons / (s mrad^2 mm^2 0.1 % bw)

Similar to previous user periods, the 5th period was organized with an alternating pattern of user blocks (4 weeks) and study blocks (2-3 weeks). The time between the user blocks is also required to exchange experimental set-ups. In the near future, the exchange time for certain types of experiments will be significantly reduced, when two permanent end-stations will be in regular operation: the CAMP end-station for imaging and pump-probe experiments at BL1, and a Raman spectrometer at the PG1 beamline.

During the 5th user period the uptime of the FLASH facility was 96%. In total 4256 hours of FEL radiation was delivered to 32 experiments (25 external, 6 in-house, and one industry experiment). This corresponds to 75% of the total time reserved for user operation. 21% of the user time was used to tune the photon beam parameters to meet the versatile demands of the experiments.

FEL radiation at more than 50 different photon wavelengths between 4.3 nm and 52 nm was delivered to experiments. About 40% of experiments was carried out with a single photon pulse (10 Hz repetition rate), about 20% requested as many pulses as possible. Other desired a multi-pulse operation with a lower intra-train pulse repetition rate (100 kHz or 200 kHz). In addition many experiments require photon pulses shorter than 50 fs or with a small bandwidth (<1%). Arrival time stabilization to the 20 to 40 fs level is also often requested.

Some examples of realized parameter combinations are a single pulse operation at 4.3 nm, 400 pulses (1 µs pulse spacing) at 7.8 nm, 40 pulses (10 µs spacing) at 15 nm, and 60 pulses (5 µs spacing) at 52 nm. For all the cases, the pulse train repetition rate was 10 Hz.

Figure 4 shows the average photon pulse energy during 12 hours of FEL radiation delivery for a user experiment. The fundamental wavelength of the radiation is 9.9 nm. The experiment was carried out at the 3rd harmonics of it (3.3 nm) with 400 photon pulses per train. An example of the pulse energy along the pulse train is shown in Fig. 5.

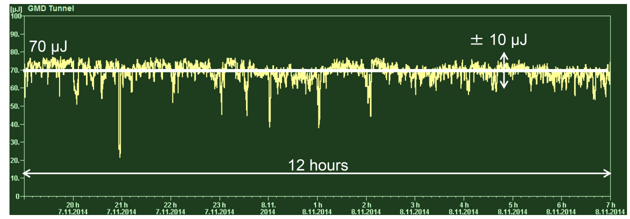

Figure 4: Average photon pulse energy during 12 hours of FEL radiation delivery. Photon wavelength 9.9 nm, 400 photon pulses per train, pulse train repetition rate 10 Hz, photon beamline aperture 3 mm.

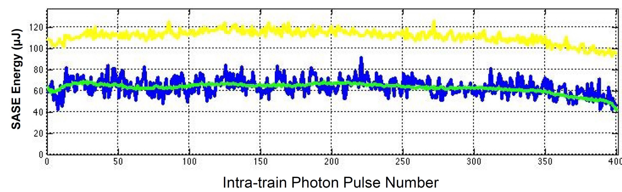

Figure 5: Pulse energy of 400 photon pulses in one train, pulse spacing 1 µs (1 MHz), photon wavelength 9.9 nm. Blue: Actual value, Green: Average, Yellow: Maximum.

Since FLASH1 has fixed gap undulators, the change of the photon wavelength requires the change of electron beam energy. As a consequence a substantial amount of tuning time is needed for wavelength changes (roughly one third). This time will be significantly reduced, when variable gap undulators are available also at FLASH1. Besides wavelength changes, tuning is also required to provide high photon pulse energies (>100 µJ per pulse), to adjust photon beam pointing, and to set up and keep operation with long pulse trains or with very short photon pulses. Additional tuning is also needed, when special FEL radiation properties (e.g. a narrow bandwidth) or parallel delivery of THz radiation are requested.

Two or three user experiments are simultaneously installed at different photon beamlines. Typically, three to five beam time blocks of 24 to 48 hours are reserved for each experiment. Only occasionally an experiment, due to its own constraints, is able to run continuously over several days. Since every experiment has its own parameter set, time (4-8 hours) is reserved for parameter change and tuning at the beginning of each beam time block. This scheduled tuning corresponds to about 20% of the total user time.

The total tuning time can be significantly reduced, when the same experiment runs continuously over a longer period. Two examples to demonstrate this are an experiment of 7 days in December 2014 (11.5 nm, single pulse), and an other one running 10 days in April 2015 (60 pulses, four different wavelengths between 44 nm and 52 nm). In the former case, the FEL radiation delivery was 96%, tuning 2%, and downtime 2% of the total time reserved for the experiment. In the latter one, the distribution was 87% delivery, 11% tuning (including wavelength changes), and 2% downtime.

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FEL and Accelerator Studies

In addition to FEL user operation, FLASH beam time is allocated to FEL and accelerator studies. Study time is used to improve the FLASH performance as an FEL user facility, and to prepare it for the demands of the coming experiments, including also the photon beamlines. Time is reserved for general accelerator physics experiments and developments as well.

Examples of tasks carried out during the study periods are upgrades of the LLRF and the optical synchronization systems, preparation of reference settings for the user operation, and training of the operators. Time is also allocated, for example, to electron beam optics studies [13, 14], and to generate ultra short bunches [15, 16]. The latter uses a special short-pulse (~1 ps) photocathode laser system, and very low electron bunch charge (down to 20 pC) with the goal to produce single-spike, longitudinally fully coherent photon pulses with duration below 10 fs.

An other example of experiments carried out during study periods is the seeding experiment sFLASH, which is located upstream of the FLASH1 SASE undulators since 2010. During the first years sFLASH concentrated on HHG (High Harmonics Generation) seeding [17]. Later also other seeding schemes like HGHG (High Gain Harmonic Generation) have been investigated [18, 19]. In addition, sFLASH hardware has been used to study suppression of FEL radiation by seeded microbunching instabilities [20].

Many of the accelerator physics developments carried out at FLASH have been related to the European XFEL [21], concerning, for example, electron beam diagnostics [22], and operation of accelerating modules with XFEL operation parameters. A new project, FLASHForward, focusing on the plasma-based acceleration, has recently started its hardware installations at the third FLASH electron beamline, and already performed first tests of the production of "driver" and "witness" bunches.

COMMISSIONING FLASH2

Beam commissioning of FLASH2 started in spring 2014. The first lasing was achieved on August 20, 2014 at a wavelength of 40 nm [5]. During the following months, lasing with several wavelengths has been established. Figure 6 shows an example of an FEL beam spot on a YAG screen at a wavelength of 5 nm.

In January 2015, FLASH2 demonstrated fast tunability with the variable gap undulators: the wavelength was changed from 6 nm to 13.5 nm within 30 minutes with a wavelength step of 0.5 nm, i.e. 2 minutes per step.

From mid January 2015 to mid April 2015, FLASH2 had a 3 months shutdown to finalize the installation of photon beam diagnostics in the FLASH2 tunnel. After the re-establishment of the electron beam and SASE operation, the first FEL beam was transported to the experimental hall in June 2015. In the experimental hall, the installation of photon beamlines is on-going, and the first pilot experiments are

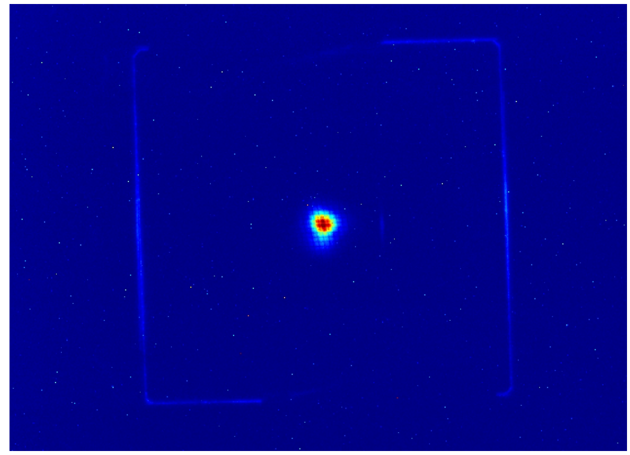

Figure 6: FLASH2 FEL radiation spot on a YAG screen. Photon wavelength 5 nm. The diffraction pattern is caused by a MCP mesh inserted upstream of the screen.

foreseen later this year. The FLASH2 beam commissioning continues in 2015 parallel to FLASH1 user operation.

More details of the FLASH2 commissioning, and of the simultaneous FLASH1 and FLASH2 operation, can be found in [23].

SUMMARY AND OUTLOOK

FLASH1 has successfully completed its 5th user period. After a short shutdown in May 2015, the 6th user period started in June 2015 continuing to the end of 2015. Two user periods of 6 months each are scheduled for the year 2016.

The FLASH2 beam commissioning started in spring 2014 and takes place in parallel to the FLASH1 user operation. First lasing was achieved in August 2014. The first FLASH2 pilot photon experiments are expected late 2015, and regular user operation in 2016.

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