FLASH: FIRST SOFT X-RAY FEL OPERATING TWO UNDULATOR BEAMLINES SIMULTANEOUSLY

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Abstract

FLASH, the free-electron laser user facility at DESY (Hamburg, Germany), has been upgraded with a second undulator beamline FLASH2. After a shutdown to connect FLASH2 to the FLASH linac, FLASH1 is back in user operation since February 2014. Installation of the FLASH2 electron beamline has been completed early 2014, and the first electron beam was transported into the new beamline in March 2014. The commissioning of FLASH2 takes place in 2014 parallel to FLASH1 user operation. This paper reports the status of the FLASH facility, and the first experience of operating two FEL beamlines.

INTRODUCTION

FLASH [1–4], the free-electron laser (FEL) user facility at DESY (Hamburg), delivers high brilliance XUV and soft X-ray FEL radiation for photon experiments.

The TESLA Test Facility (TTF) Linac [5], constructed at DESY in mid 1990's and operated until end of 2002, was originally dedicated to test the feasibility of high gradient superconducting accelerator technology in the framework of the TESLA linear collider project [6]. In addition, it was used to drive a SASE (Self Amplified Spontaneous Emission) free-electron laser pilot facility TTF-FEL [7, 8] at photon wavelengths from 80 nm to 120 nm [9, 10] to demonstrate the feasibility of SASE FELs in the VUV range. Based on the experience gathered from the TTF-FEL operation, FLASH – originally called VUV-FEL at TTF2 – was constructed in 2003-04.

The first lasing of FLASH at 32 nm was achieved in January 2005 [11]. Since summer 2005 FLASH has been operated as an FEL user facility, being the first facility in the world delivering VUV and XUV FEL radiation for photon experiments. During 2005-2007, FLASH delivered FEL radiation in wavelengths from 13 nm to 47 nm (fundamental), entering the water window with the 3rd and 5th harmonics [1]. An energy upgrade to 1 GeV in summer 2007 extended the range to the soft X-rays with wavelengths down to 6.5 nm [12, 13]. The next upgrade [14], accomplished in 2009/10, led to major modifications of the facility, including, for example, the installation of third harmonic RF cavities to linearize the longitudinal phase space and an energy upgrade to 1.25 GeV. This allowed lasing with wavelengths down to 4.1 nm [15], entering thus the water window also with fundamental wavelengths.

The most recent upgrade to include a second undulator beamline has been carried out in 2011-14, mostly parallel to the FLASH user operation. After a shutdown in 2013 to connect the new beamline to the FLASH linac, the operation re-started in August 2013. Since February 2014, FLASH is back in user operation. The beam commissioning of the second undulator beamline (FLASH2) has started in March 2014.

This paper reports the status of the FLASH facility, and the first experience of operating two undulator beamlines. Part of the material discussed here has been presented in previous conferences, most recently in [4].

Table 1: FLASH Parameters 2014

Electron beam		
Energy	MeV	380 - 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 - 45
Average single pulse energy	µJ	10 - 500
Pulse duration (fwhm)	fs	< 50 - 200
Spectral width (fwhm)	%	0.7 - 2
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)

FLASH FACILITY

The layout of the FLASH facility is shown in Fig. 1. The first undulator beamline, being in operation since 2004, is referred to FLASH1, the new one to FLASH2. Table 1 shows typical FLASH operating parameters. These parameters are not all achieved simultaneously, but indicate the overall span of the performance.

A superconducting linac driven by an RF-gun based photoinjector provides a train of electron bunches: the maximum bunch train length is 800 µs, and it can be shared between the two undulator beamlines. Several discrete bunch spacings between 1 µs (1 MHz) and 25 µs (40 kHz) are possible. The bunch train repetition rate is 10 Hz. The typical bunch charge ranges from 80 pC to 1 nC.

The photocathode laser system has two independent lasers, both based on an actively mode-locked pulse train oscillator with a linear chain of fully diode pumped Nd:YLF ampli-

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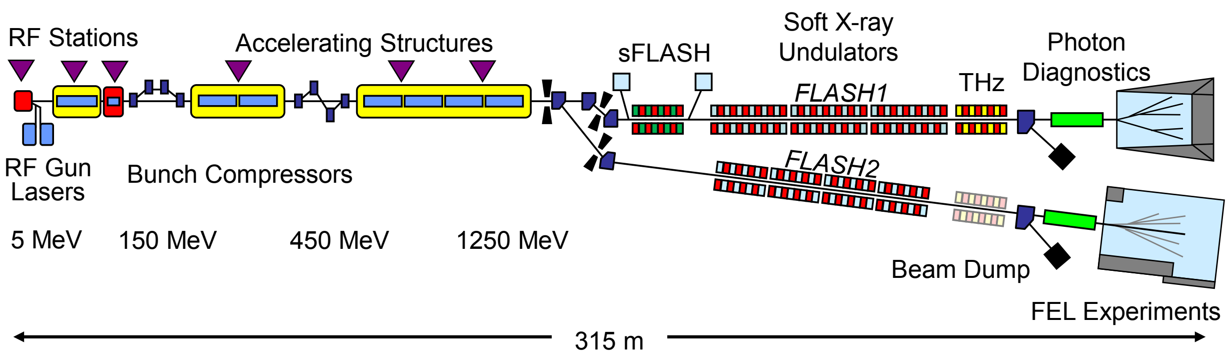

Figure 1: Layout of the FLASH facility (not to scale).

fiers followed by frequency quadrupling to the UV [16, 17]. During simultaneous operation, one of the lasers is used to produce the electron bunch train for the FLASH1 beamline, the other one for FLASH2. The duration of the Gaussian shaped laser pulse is fixed to 6.5±0.1 ps (rms). For certain experiments, especially in order to produce very short electron bunches [18], a third laser system is in the testing phase. This laser provides UV-pulses with an adjustable duration of 0.8 ps to 2 ps (rms), easing thus the compression of electron bunches.

An exchangeable cathode, consisting of a thin Cs_2Te film on a molybdenum plug [19], is installed on the backplane of the RF-gun. During the last years, severe hardware problems have occurred related to the RF-gun and its RF-window [4, 20]. During the 2013 shutdown, a new RF-gun has been installed and was successfully taken into operation in autumn 2013. Unfortunately, a vacuum leak developed at the RF-window, and the window had to be replaced in April 2014. New RF-gun design options and new RF-window types are being tested with a goal to increase their lifetime considerably.

The FLASH linac consists of seven superconducting TESLA type accelerating modules. Each module has eight 9-cell niobium cavities operated at 1.3 GHz. The maximum achievable electron beam energy is 1.25 GeV. A module with four 3.9 GHz (third harmonics of 1.3 GHz) superconducting cavities is installed downstream the first accelerating module to linearize the energy chirp in the longitudinal phase space. In order to achieve the peak currents required for the lasing process, electron bunches are compressed by two magnetic chicane bunch compressors at beam energies of 150 MeV and 450 MeV, respectively.

The RF-gun and the accelerator modules are regulated by a sophisticated low level RF (LLRF) system. During the 2013 shutdown, the LLRF system of the accelerator modules has been upgraded to a new powerful and fast digital system using MTCA.4 specifications [21]. The upgrade of RF-gun LLRF system is scheduled late 2014. Details of the new LLRF system and its performance at FLASH can be found in [22].

A kicker-septum system is now installed downstream the last accelerator module. Flat-top kickers with a total deflection angle of 2.2 mrad kick the FLASH2 part of the bunch train vertically into the deflecting channel of a Lambertson septum. The septum deflects the beam horizontally by 6.5° into the FLASH2 beamline. The FLASH1 part of the bunch train goes straight ahead to the FLASH1 collimator and undulator section. The septum magnet with the FLASH1 and FLASH2 beamlines is shown in Fig. 2.

The FLASH1 and FLASH2 bunch trains are within the same RF-pulse. This allows to serve both beamlines with a bunch train repetition rate of 10 Hz. The two trains, one for FLASH1 and the other one for FLASH2, are separated by a gap of some tens of µs. The minimum gap width is determined by the kicker pulse rise time, and is about 30 µs.

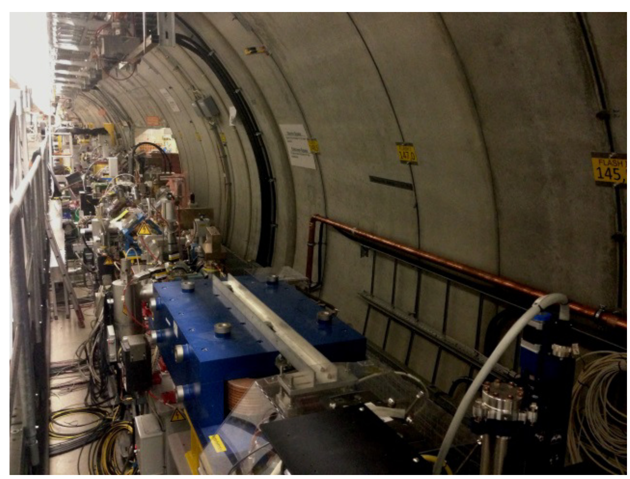

Figure 2: Separation of FLASH1 (straight) and FLASH2 beamlines (to the right). The blue magnet is the Lambertson septum.

The FLASH1 electron beam passes through six 4.5 m long fixed gap (12 mm) undulator modules producing FEL radiation based on the SASE process. The undulators consist of permanent NdFeB magnets, the undulator period is 27.3 mm, and the peak K-value 1.23. The FLASH2 beamline has twelve 2.5 m long variable gap undulators with an undulator period of 31.4 mm.

At FLASH1 a transverse deflecting structure is installed upstream of the SASE undulators. It serves together with a

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kicker and an off-axis screen as an on-line monitor for the electron bunch length and shape [23]. This monitor is now in continuous use, especially during short pulse operation.

In the FLASH1 beamline, a planar electromagnetic undulator is installed downstream of the SASE undulators to produce, on request, THz radiation. Later, a THz undulator will also be installed into the FLASH2 beamline.

Both FLASH1 and FLASH2 have a sophisticated photon diagnostics section providing a possibility to measure and characterize the photon beam parameters. In the FLASH1 experimental hall, five photon beam lines are available for user experiments. Photon diagnostics and photon beamlines of FLASH1 are described in [2, 24]. Since FLASH1 is not yet equipped with permanent end-stations, each experiment has to provide and install its own measurement hardware. The first permanent end station (CAMP instrument) is under preparation at beamline BL1. The operation of FLASH2 starts initially with 2-3 photon beamlines, and the new experimental hall foresees place for finally up to seven beamlines. The aim is to provide several fixed end-stations for photon users. The FLASH2 photon beamlines and diagnostics are described in [24, 25].

A seeding experiment sFLASH [26], with four variable gap undulators, is installed between the collimation section and the SASE undulators in the FLASH1 beamline. In the FLASH2 beamline, a place for seeding hardware is reserved upstream of the undulators. Investigations of the optimal seeding scheme for FLASH2 are on-going. Initially the FLASH2 operation will start with SASE having similar parameters as FLASH1.

OPERATION STATUS OF FLASH1

After the shutdown to connect the FLASH2 beamline to the FLASH linac, the operation started in August 2013.

A ground settlement of the FLASH1 beamline of up to 10 mm was expected due to the heavy load of the new FLASH2 buildings, including a 6 m deep and 80 m long triangle-shaped space between FLASH1 and FLASH2 buildings, which was filled with some kilotonnes of sand for radiation safety reasons. Due to delays in FLASH2 civil construction, the settlement occurred late, mainly in summer 2013. As a consequence, the final survey and re-alignment of FLASH1 undulators coincided with the commissioning of the linac and caused a significant delay of about one month for beam commissioning. A stable FEL operation was established by end of 2013, including commissioning of the photon beamlines, which had to be re-adjusted as well.

A highlight of the commission phase was the successful increase of the average single FEL pulse energy up to 540 µJ. This is a new record at FLASH, and has been achieved at a photon wavelength of 8.7 nm. A new electron beam optics [27, 28], allowing simultaneous operation of FLASH1 and FLASH2, has been implemented. Substantial amount of time was used also to commission the new LLRF system, new magnet controls, and upgrades of the timing system.

The 5th user period started in February 2014. As in the previous user periods, the photon experiments have requested a large variety of beam parameters. Experiments requiring 400 pulses per train with 1 µs spacing at the wavelength of 7.8 nm, 50 pulses per train with 5 µs spacing at 42 nm, and a single pulse in the water window at 4.3 nm are examples of the diversity of beam parameters realized in the last months. In addition many experiments require photon pulses shorter than 50 fs (fwhm) or with a small bandwidth (<1%). Arrival time stabilization to the 20 to 40 fs level is also often requested.

A vacuum leak on the RF-window of the RF-gun was detected in March 2014, and the window was promptly exchanged at the next opportunity in April. Due the required conditioning of the RF-window, one user experiment had to be postponed. Nevertheless, the the user run could be continued with shorter RF-pulses to serve users with a few bunches per train only. During the following weeks, the RF-gun pulse length has been slowly increased, and a length of 500 µs has been re-established. The user operation continued in June 2014 according to the schedule with a stable RF-gun operation.

COMMISSIONING STATUS OF FLASH2

The construction of the building hosting the new FLASH2 undulator line started in autumn 2011. The civil construction took significantly longer than expected and was finished only early summer 2013, almost half a year later than originally scheduled. The construction of the new experimental hall has been finalized in spring 2014.

Figure 3: FLASH2 undulator beamline with twelve variable gap undulators.

The installation of the FLASH2 extraction beamline and its connection to the FLASH linac took place in spring and early summer 2013. The mounting of the FLASH2 electron beamline, including the undulators (see Fig. 3), was finished in January 2014. Devices for basic photon diagnostics, such an MCP detector to measure the photon pulse energy, a Ce:YAG crystal for beam profile and position measurements,

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and a wavelength spectrometer, have also been installed already. Technical commissioning of FLASH2 components, for example, magnet power supplies and variable gap undulators, started early 2014. The control and timing systems have been upgraded to allow simultaneous operation of FLASH1 and FLASH2.

After connecting the FLASH2 personnel interlock system, the official permission for FLASH2 beam operation was given February 7, 2014. Due to the FLASH1 user operation, dedicated beam time for FLASH2 had been restricted to a few days only until simultaneously operation was established. The first electron beam was transported into the FLASH2 extraction beamline on March 4, 2014, and beam transport up to the dump was achieved on May 23, 2014.

Figure 4 shows the FLASH1 and FLASH2 electron beams on a screen at the septum entrance; the upper one is the kicked beam to be deflected to FLASH2, the lower one the beam going straight to FLASH1.

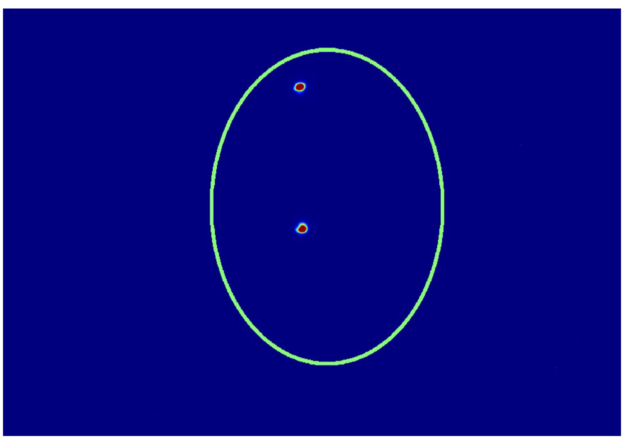

Figure 4: FLASH1 (lower) and FLASH2 (upper) electron beams on a screen at the septum entrance. The beam separation is 16 mm.

End of May 2014, the simultaneous operation of FLASH1 and FLASH2 has been established, and starting with June, the FLASH2 beam commissioning has taken place, whenever possible, parallel to the FLASH1 user operation. This increases significantly the time available for FLASH2 beam commissioning.

The on-going commissioning is mainly related to the electron beam diagnostics and to the beam loss and machine protection systems. The setting up of the beam optics to provide a stable, loss-free beam transport is under way [29]. In order to avoid radiation damage on the permanent undulator magnets, the first beam operation has been carried out with open undulator gaps. First lasing is expected soon.

OPERATION OF TWO UNDULATOR BEAMLINES

The FLASH linac uses superconducting accelerator technology, which allows operation with long RF-pulses, i.e. with long electron bunch trains. The bunch train can be shared between the two undulator beamlines, giving the possibility to serve simultaneously two photon experiments, both at 10 Hz pulse train repetition rate. Since roughly half of the photon experiments request operation with a few pulses per train only, it is feasible to organize experiments such that both undulator beamlines are efficiently used.

Two separate injector lasers are used in parallel to produce two electron bunch trains within the same RF-pulse with different parameters. The two trains are separated by a gap of some tens of μs (kicker pulse rise time). The number of bunches as well as the bunch spacing can be selected independently for both trains, taking into account the total available RF-pulse length of 800 μs. In addition, the electron bunch charge can be different in the two trains. This feature, together with the flexible LLRF system, which is able to provide in certain limits different accelerating amplitude and phase for the two trains, allows FLASH1 and FLASH2 experiments with different pulse durations. Since the electron bunches are accelerated and compressed by the same linac, the practical feasibility of different parameters is constrained by beam dynamics of the bunch compressors (space charge related collective effects) and the acceptance of the beam optics in terms of beam energy.

FLASH1 has fixed gap undulators, and therefore the electron beam energy of the FLASH linac is defined by the wavelength of the FLASH1 experiment. Thanks to the variable gap undulators, the FLASH2 wavelength can be typically tuned by a factor of 2-3 and hence be adapted, at a fixed electron beam energy, to the requirements of the FLASH2 experiment. In the future, it is planned to exchange the FLASH1 undulators to variable gap ones as well.

During the last months, we have gathered our first experience to operate the FLASH1 and FLASH2 beamlines simultaneously. We have successfully established FLASH2 electron beam operation during FLASH1 photon user experiments. For example in July 2014, FLASH1 delivered a photon beam to a user experiment at 4.3 nm, while the FLASH2 electron beam was simultaneously transported up to the dump and used for commissioning of electron beam diagnostics, without disturbing the FLASH1 operation.

Operation with two injector lasers is well-established and applied routinely. The control and timing systems as well as operation procedures have been upgraded and commissioned. In order to allow smooth simultaneous operation of both beamlines, it is important to set up the FLASH linac at the same time for FLASH1 and FLASH2 operation. This includes, for example, the beam orbit in the common beamline between the kicker and the septum. In the first meters downstream of the septum, the two electron beamlines are very close to each other (Fig. 2), and cross-talk through stray fields of the magnets has to be taken into account as well.

SUMMARY AND OUTLOOK

After connecting the FLASH2 beamline to the FLASH linac, the 5th period of user FEL experiments at FLASH1 started in February 2014, continuing until April 2015.

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The FLASH2 beam commissioning started in March 2014 and mainly takes place in parallel to the FLASH1 user operation. First lasing and SASE operation is expected soon. The first FLASH2 pilot photon experiments are expected in 2015, and regular user operation in 2016.

With FLASH2 in operation, the user capacity of FLASH will be significantly increased. The variable gap undulators will ease photon wavelength changes in FLASH2, and, together with two injector lasers and the flexible LLRF system, allow parallel operation of FLASH1 and FLASH2 with to a certain extent independent parameters.

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