STATUS OF THE FEL USER FACILITY FLASH

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Abstract

The free-electron laser FLASH at DESY has been upgraded and extended its wavelength range down to 4.1 nm. Beside the increased electron beam energy to 1.25 GeV, another important upgrade is the installation of 3.9 GHz superconducting RF cavities in the injector. They are used to shape the longitudinal electron beam phase space. Now, significantly more FEL radiation energy per pulse up to several hundreds of microjoules is achieved. Moreover, the system allows to adjust the FEL pulse duration, from long pulses of more than 200 fs (FWHM) to short pulses of 50 fs (FWHM). The upgraded FLASH facility shows an excellent performance in terms of FEL radiation quality and stability as well in operation reliability. The 3rd user period started in September 2010.

Table 1: FLASH parameters 2011.

Electron beam		
Energy (max.)	MeV	1250
Bunches / train		1 - 500
Bunch spacing	μs	1 - 25
Repetition rate	Hz	10
FEL radiation		
Wavelength (fundamental)	nm	4.1 - 45
Average single pulse energy	μJ	10 - 400
Pulse duration (FWHM)	fs	50 - 200
Spectral width (FWHM)	%	0.7 - 2
Peak power	GW	1 - 3
Peak brilliance	*	10^{29} - 10^{31}
Average brilliance	*	10^{17} - 10^{21}

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

INTRODUCTION

FLASH [1–3] is a single-pass high-gain SASE-FEL at DESY (Hamburg, Germany). The upgrade in 2009/10 led to major modifications of the facility, including an energy upgrade to 1.25 GeV allowing now lasing with wavelengths down to 4.1 nm, the installation of third harmonic RF cavities to linearize the longitudinal phase space, and the realization of a seeding experiment sFLASH.

The third FEL user period started as scheduled on Sep. 2, 2010. In the one year period until Sep. 12, 2011, 217 days are devoted to user experiments ranging from diffraction imaging to atomic physics and femto-chemistry. By now, the experiments carried out at FLASH have resulted in 150 publications, many of them in highly ranked journals. [4]

We summarize here the present status of the upgraded FLASH facility. Part of the material presented here has been already discussed in proceedings of previous conferences [3, 5].

FLASH LINAC

A schematic layout of FLASH is shown in Fig. 1, and some of its main parameters are listed in Table 1.

Electron bunch trains are produced by a laser driven RF-gun (1.3 GHz, 5 MW klystron, RF pulse length 900 μs (design), repetition rate 10 Hz). The photocathode laser system is consists of a mode-locked pulse train oscillator with a chain of diode-pumped Nd:YLF amplifiers. [6] The UV laser beam is guided to a $\mathrm{Cs_2Te}$ cathode [7], which is inserted to the backplane of the RF-gun.

In spring 2010, the RF window separating the gun vacuum and RF waveguides caused a continuous high trip rate, and therefore has been exchanged in June 2010. After a month of conditioning, the FLASH linac was back in operation with a reduced RF pulse length of 150 μs. Since then, the RF pulse length has been steadily increased and is now at 550 μs. A new improved RF window is in preparation.

The number of bunches in a train as well as the spacing between the bunches can be varied: several discrete spacings between 1 μs (1 MHz) and 25 μs (40 kHz) are possible. The maximum number of bunches at a given frequency is limited by the RF pulse length. The electron bunch charge is variable. Typically, a range from 0.1 nC to 1.5 nC is used for FEL operation.

FLASH has seven superconducting accelerating modules, 6 TESLA-type modules and 1 XFEL-prototype. Each module has 8 niobium 1.3 GHz cavities. They are powered by four RF stations (three 5 MW klystrons, and one 10 MW multibeam klystron). In addition, a module with four 3.9 GHz superconducting cavities – the third harmonics of 1.3 GHz – is installed in the injector. The phase and amplitude of the accelerating field – the vector sum of all cavities fed by one klystron – is regulated by FPGA based low level RF systems providing feedback and feedforward features. This also includes intra-train longitudinal feedback for stabilization of the compression process and arrival time. [8–10]

The SASE FEL radiation is produced by six 4.5 m long fixed gap undulators (permanent NdFeB magnets, period 27.3 mm, K = 1.23). An additional planar electromagnetic undulator to produce radiation in the THz wavelength range is installed downstream the SASE undulators. The FEL radiation – as well as the THz and synchrotron radiation from the last dipole – is transported to the experimental hall over a distance of more than 60 m. Details of the photon beamline and photon diagnostics are in [2].

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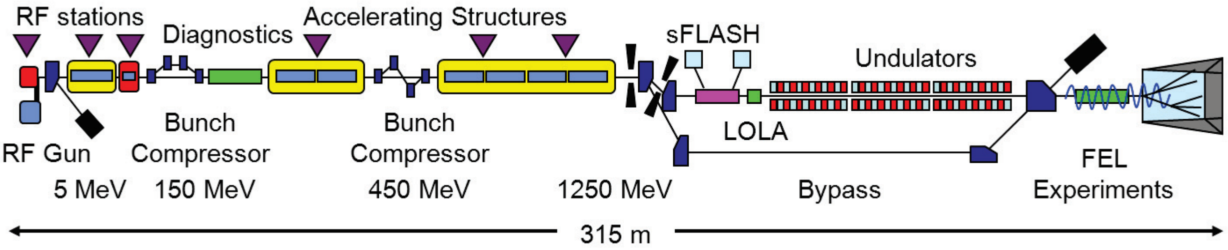


Figure 1: Layout of the FLASH facility (not to scale).

Between the collimation system and the SASE undulators, sFLASH, an experiment for seeded FEL radiation is installed. It consists of a seed laser beam line including an HHG source, an undulator section of 10 m with four variable gap planar undulators, and a photon beam line. [11]

LASING AT 4.12 nm

During the last upgrade, a 7th superconducting accelerating module has been added to the FLASH linac. Lasing at 4.45 nm has been achieved quickly early June, 2010. In September 2010 the electron beam energy has been pushed to 1.25 GeV with an improved low level RF system. The beam energy is now sufficient to lase for the first time in the water window with the fundamental. Figure 2 shows the wavelength spectrum centering at 4.12 nm. This is above the carbon 1s-absorption edge (4.4 nm).

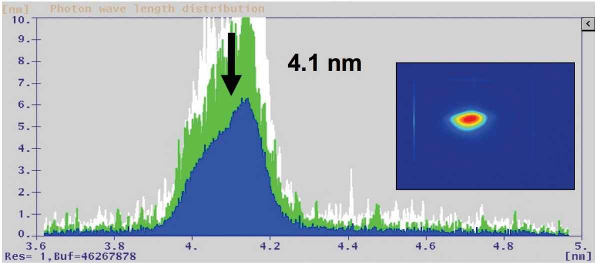


Figure 2: SASE FEL radiation at 4.12 nm measured with a spectrometer. The transverse photon beam profile on a Ce:YAG screen is shown as well.

FLASH uses silicon carbide mirrors to transport the FEL radiation to the five experimental stations. These mirrors absorb the radiation which is inside the water window and therefore cannot be used for these wavelengths. Fortunately, some of them have a partial Nickel coating. The reflectivity of Ni is not as good as silicon carbide, but has a negligible absorption for wavelengths within the water window. An in-house experiment using a wavelength of 4.3 nm has been performed in spring 2011.

BUNCH COMPRESSION

A peak current in the kA-range is required for the lasing process. At FLASH, this is achieved by compressing the electron bunch by two magnetic chicane bunch compressors. In order to remove the RF induced curvature in the longitudinal phase space, a module with four superconducting 3.9 GHz cavities has been installed downstream of the first accelerating module.

Without the phase space linearization, the compression leads to a high current spike with a long tail. Since the tail, which does not contribute to lasing, contains most of the charge (80 to 90 %), it is difficult to measure and adjust the properties of the lasing part of the bunch. This together with the complicated beam dynamics makes SASE tuning a challenging task.

When the injector is operated with the 3rd harmonic module, the longitudinal shape of the compressed bunch is more regular and therefore tuning is much easier. A larger fraction of the bunch charge develops a high peak current and contributes to the lasing process. Therefore, significantly more FEL radiation energy per pulse is achieved. Moreover, the electron bunch length can be adjusted. Short bunches are realized with low charge. For instance, 50 fs (rms) is achieved with charges below 200 pC. With higher charges between 0.5 to 1 nC, the bunch length is usually >100 fs (rms). The expected photon pulse duration is roughly half the electron bunch duration.

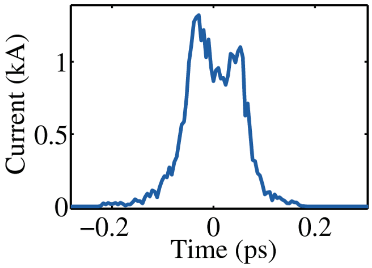


Figure 3: Longitudinal electron bunch profile measured with LOLA. The bunch length is 55 fs (rms), charge 0.2 nC.

The transverse deflecting RF cavity LOLA provides an excellent tool to characterize the compression process. [12] It is located close to the SASE undulators and has also a dispersive section to measure the longitudinal phase space. Figure 3 shows a measured longitudinal electron bunch profile. In this example, the duration of the electron bunch is 55 fs (rms) with a bunch charge of 0.2 nC. High precision spectrometers and experiments to measure the photon pulse duration are in a commissioning phase.

SASE PERFORMANCE

Some typical FEL radiation parameters are listed in Table 1. The performance is different for each photon wavelength, and it differs also depending on the electron bunch charge and the used bunch compression scheme. Therefore the parameters shown should be taken as an indication of the overall span of the performance.

For the 3rd user period, a total of 75 proposals for experiments have been reviewed, 29 of them have been accepted, and 333 12-hour user shifts have been scheduled. The user experiments are arranged in 8 blocks of usually 4 weeks each. Between the user blocks, 2 to 3 weeks are used to dismount the previous and mount and adjust the new experiments. This time is also used for machine and FEL physics related studies to improve the facility, and to prepare it for the next user block.

Every experiment has its own demands on the properties of the FEL radiation in terms of photon wavelength, FEL pulse energy and duration, number of pulses and pulse spacing, and spectral bandwidth. About half (47 %) of the scheduled user shifts request single pulse operation, the second half (53 %) multi pulse operation with different pulse patterns. Many experiments have also demands on the pulse duration: 28 % of user shifts request ultra-short pulses with a duration of 50 fs (FWHM) or below, and 54 % between 50 and 100 fs (FWHM). Only for 18 % the pulse duration is less critical.

During the third user period we have so far delivered more than 30 different wavelengths between 4.7 nm and 44.6 nm. In addition an in-house experiment has been carried out at 4.3 nm. About one third of user experiments have requested wavelengths below 10 nm, another third have been carried out with wavelengths around 13.5 nm, – this mainly because of the availability of multilayer mirrors for this wavelength –, and the last third with wavelengths longer than 20 nm.

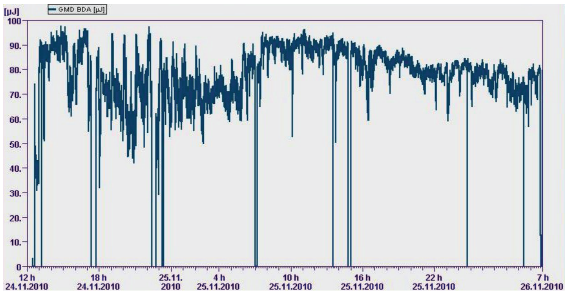
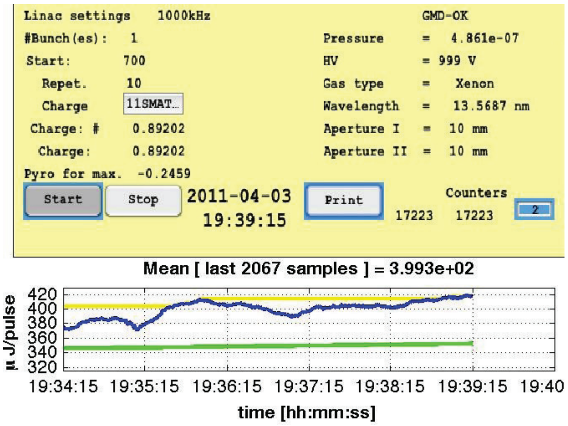


Figure 4: Average single pulse photon energy over 43 h, 200 pulses in a 1 MHz train, repetition rate 10 Hz, photon wavelength 4.8 nm.

Up to 300 photon pulses per train with different pulse patterns have been delivered to user experiments. Examples of long train operation are experiments with 200 pulses at 4.8 nm and with 300 pulses at 6.9 nm. In both cases, the spacing between the pulses was 1 μs (1 MHz) and the average single pulse energy 80 to 100 μJ. Figure 4 shows the average single photon pulse energy during the first experiment mentioned above. This also demonstrates the capability of FLASH to run stable beam over many shifts providing at the same time with a high SASE level, long bunch trains, and short wavelengths. Other examples of multi-bunch operation at high SASE level are experiments with 50 bunches (1 MHz) at wavelengths of 15.8 nm and 14.6 nm with average single pulse energy of 200 to 300 μJ.

Since the average photon pulse energy depends on the number of electrons participating in the lasing process, the higher the bunch charge the higher the average single photon pulse energy. The average single pulse energy for electron bunch charges below 0.2 nC is typically 10-30 μJ. When the bunch charge is around 1 nC, average single photon pulse energies up to 400 μJ have been achieved. An example is shown in Fig. 5.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Aperture I = 10 mm
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Mean [last 2067 samples] = 3.993e+02

Figure 5: Photon pulse energy (blue) measured by the gas monitor detector. The maximum (yellow) and averaged (green) data are shown as well. Single bunch, 13.6 nm.

In addition to FEL radiation, two optical lasers (800 nm) are available for pump-and-probe experiments: A burst mode Nd:YLF laser, and a high power Ti:Sapphire laser. More details of these lasers systems are in [13]. About 40 % of the experiments use the optical lasers. In one beamline, THz radiation in the wavelength range of 10 to 230 μm is also available. So far, five user experiments have used the THz radiation, and one of them has performed three-color pump-and-probe measurements using the FEL, THz, and the optical radiation.

Operational Issues

During the first seven users blocks of the 3rd period FEL radiation has been delivered in average 76 % of the time to the experiments, a total of 3300 h. Tuning of the FEL radiation properties and setting up the accelerator has taken 19 % of the time, 1 % of the time has been used for sched-

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uled weekly maintenance. The total downtime has been 4 % yielding to an uptime of 96 % – a remarkable improvement compared to the 1st and 2nd user period, where it was only 87 % and 93 % respectivly.

Infrastructure failures, especially power cuts and disturbances of cooling water, air conditioning and temperature stabilization systems are the main sources of downtime, causing 16 % of the total downtime. The downtime due to the 1.3 GHz RF-stations is now reduced significantly: only 9 % of the total downtime is assigned to them. This is mainly due to exchange of the two old RF-stations and further upgrades of the systems. The downtime caused by the 3.9 GHz RF-station is 5 %. Other significant downtime is caused by failures of the control system (10 % of the total downtime), the low level RF regulation system (8 %), and the photon beam line components (7 %). Contribution of other subsystems, e.g. the photocathode laser, magnet power supplies, or cryogenics, is small (less than 5 % each). About 30 % of the downtime is caused by single incidents happening only once or rarely. For example, operational and maintenance mistakes belongs to this category as well as failures where the real cause could not been unambiguously identified.

At least two experiments, located at different beamlines, run in parallel. In addition, collaborations are often formed to share beamlines. In this case, the second user uses the spent photon beam of the first one. The photon beam is switched between beamlines after one or two 12-hour shifts. Only some experiments use longer blocks in a row. Since the experiments have often very different requirements on the FEL radiation, the switching between them requires always a substantial change of the electron beam parameters. Therefore, the machine settings are often changed once or even twice per day.

During the 3rd user period, 34 % of the tuning and set-up time has been used for wavelength changes, 20 % for standard SASE tuning (pulse energy, photon beam position, pulse pattern), 18 % for short pulse operation, 6 % for operation with long bunch trains, and 5 % for tuning narrow photon bandwidth and exact wavelength. Set-up and tuning after maintenance and technical failures, including also adjustments for special feedbacks (like bunch arrival time) has taken the remaining 17 %.

Table 2 shows the distribution between FEL radiation delivery, tuning and set-up, maintenance, and downtime. The difference between blocks is partly due to different amount of downtime, but more important due to different requirements of experiments. The more demanding the experiments are and the more often the wavelength or other beam parameters have to be changed, the more time is needed - and scheduled - for tuning. In fact, 54 % of the tuning time has been scheduled in advance. In addition, some contingency shifts (5-10 % of the beam time) have been scheduled to have the possibility to react flexible on unexpected user demands or to compensate lost beam time due to machine problems or issues with the user experiments. If we compare the beam time originally scheduled for experiments with the time when FEL radiation is actually delivered (down- and tuning times subtracted), we have 101 % SASE delivery in average, i.e. some experiments get even more beamtime than scheduled.

Table 2: SASE delivery, tuning, and set-up, scheduled maintenance and downtime during the 3rd user period.

Block	**Length** (days)	**SASE** (%)	**Tuning** (%)	**Maint.** (%)	**Down** (%)
1	19	84	11	1	4
2	29	77	20	1	2
3	28	64	29	1	6
4	29	82	14	2	2
5	18	74	21	0	5
6	29	71	20	2	7
7	29	80	15	1	4
Total	181	76	19	1	4

SUMMARY AND OUTLOOK

After the upgrade, the 3rd FEL user period started as scheduled beginning of September 2010. Lasing with a wavelength of 4.12 nm in the water window has been achieved. FLASH has successfully delivered SASE FEL radiation for experiments with wavelengths from 4.3 nm to 45 nm with average pulse energies up to several hundreds of microjoules. A 3.5 months shutdown is scheduled autumn 2011 for civil construction work to prepare the building for a second undulator beamline (FLASH2) [14]. Start of the 4th FEL user period is foreseen spring 2012.

ACKNOWLEDGMENT

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REFERENCES

[1] W. Ackermann et al., Nature Photonics **1** (2007) 336.

[2] K. Tiedtke et al., New J. Phys. **11** (2009) 023029.

[3] S. Schreiber et al., Proc. FEL 2010, pp. 198 (TUOBI2)

[4] http://hasylab.desy.de/facilities/flash/publications/selected_publications/

[5] K. Honkavaara et al., Proc. IPAC2010, pp. 1290 (TUOARA01)

[6] S. Schreiber et al., THPA18, these proceedings.

[7] S. Lederer et al., THPA19, these proceedings.

[8] W. Koprek et al., Proc. FEL 2010, pp. 537 (THOAI2)

[9] C. Schmidt et al., THPA26, these proceedings.

[10] S. Schulz et al., WEPA08, these proceedings.

[11] V. Miltchev et al., TUPA04, these proceedings.

[12] C. Behrens et al., THOCI1, these proceedings.

[13] H. Redlin et al., Nucl. Instr. Meth. A **635** (2011) S88.

[14] B. Faatz, TUPA22, these proceedings.