STATUS OF THE FREE-ELECTRON LASER USER FACILITY FLASH

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Abstract

FLASH, the FEL user facility at DESY (Hamburg, Germany), is operated with an electron beam energy up to 1 GeV corresponding to a photon wavelength down to 6.5 nm. FLASH consists of an electron source to generate a high quality electron beam, a superconducting linac of six TESLA type accelerating modules, and an undulator section to produce laser like coherent FEL radiation. About half of the beam time is scheduled for the FEL users, and the other half for accelerator and FEL physics studies. Experience gathered at FLASH is important not only for further improvements of the FLASH facility itself, but also for the European XFEL and for the R&D effort of the International Linear Collider (ILC).

INTRODUCTION

FLASH is a free-electron laser (FEL) user facility at DESY (Hamburg, Germany). It is driven by a 1 GeV superconducting linac consisting of six TESLA type accelerating modules. The production of FEL radiation is based on self-amplified spontaneous emission (SASE). FLASH provides ultrashort radiation pulses (femtosecond range) with an unprecedented brilliance. It is a world-wide unique light source in the vacuum ultraviolet (VUV) and soft x-rays wavelength range.

FLASH originates from the TESLA Test Facility (TTF), which was constructed and operated at DESY in the framework of the TESLA Collaboration. In the late 90's a free-electron laser was integrated to the TTF linac. The resulting TTF-FEL was in operation until end of 2002 providing FEL radiation in the photon wavelength range from 120 nm to 80 nm [1, 2]. In the following years, it has been upgraded and commissioned to a state-of-the-art single-pass high-gain SASE-FEL: FLASH [3, 4]. FLASH is an FEL user facility since summer 2005. The first two years, it was operated in the wavelength range from 47 nm to 13 nm. The installation of a sixth accelerating module in summer 2007 increased the electron beam energy to 1 GeV allowing lasing with wavelengths down to 6.5 nm.

FLASH is also an important test facility for the future projects based on superconducting accelerator technology, like the European XFEL [5] and the International Linear Collider (ILC) [6].

Part of the material reported here has already been presented and discussed in the proceedings of previous conferences [7, 8, 9, 10, 11, 12, 13].

Table 1: FLASH Parameters

Electron beam		
Energy	MeV	370 - 1000
Peak current	kA	1-2
Emittance, norm. (x,y)	μmrad	1.5 - 2
nb. of bunches / train		1 - 800
Bunch train length	ms	up to 0.8
Rep. rate	Hz	5
FEL radiation delivered to experiments		
Wavelength (fundamental)	nm	6.8 - 47
Average single pulse energy	μJ	10 - 100
Spectral width (fwhm)	%	~ 1
Pulse duration (fwhm)	fs	10 - 50
Peak power	GW	1 - 5
Peak brilliance	*	10^{29} - 10^{30}

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

FLASH LINAC

FLASH consists of an electron source to generate a high quality electron beam, a superconducting linac of six TESLA type accelerating modules, and an undulator section to produce FEL radiation. Figure 1 shows a schematic layout of the linac.

Electron bunches are produced by a laser driven RF gun. The RF gun is a 1.5 cell normal conducting copper cavity operated at 1.3 GHz. The photocathode laser is based on a mode-locked pulse train oscillator with a chain of single-pass Nd:YLF amplifiers. The initial infra-red wavelengths are converted to ultraviolet (262 nm). The laser beam is guided to a Ce_2Te cathode, which is inserted to the backplane of the RF gun. The maximum accelerating gradient on the photocathode is 46 MV/m.

The number of bunches in the bunch train as well as the bunch spacing can be varied: several distinct spacings between 1 MHz and 40 kHz are possible. The maximum number of bunches per macro-pulse is 800 (1 MHz bunch spacing). The macro-pulse repetition rate is presently fixed to 5 Hz. The electron bunch charge is variable from 0.1 nC to 3 nC. During FEL operation charges between 0.5 nC and 1 nC are typically used. Some main electron beam parameters are listed in Table 1.

FLASH uses TESLA type superconducting accelerating modules. Each module consists of eight 9-cell standing wave Niobium cavities with a fundamental frequency of

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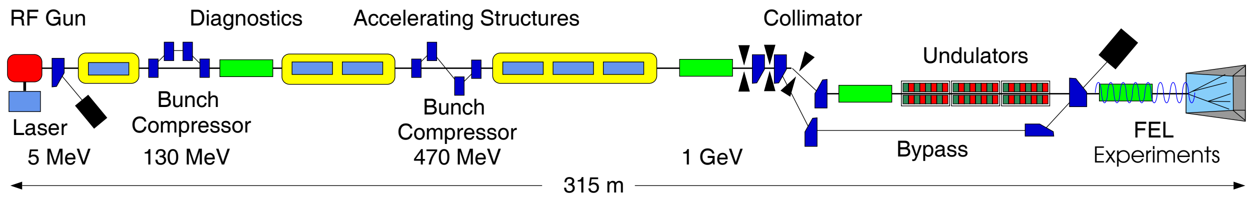

Figure 1: Layout of the FLASH linac including the experimental hall (not to scale).

1.3 GHz. Each cavity has a length of about 1 m and is equipped with a RF power coupler, a pickup probe, two high order mode couplers, and a stepper motor based tuning system. Cavities are mounted into a 12 meters long cryo-module together with a quadrupole magnet doublet, two corrector magnets, and a beam position monitor. Cavities of some of the modules have also piezo tuners. The module is bath-cooled by superfluid Helium to 2 K.

The first accelerating module is located about 1 m downstream of the RF gun exit. It boosts the initial 5 MeV beam energy to 130 MeV. Space charge forces due to RF focusing may cause transverse emittance growth. In order to avoid this unwanted effect, the first four accelerating cavities are operated with a moderate gradient of 12-15 MV/m.

The electron beam energy is increased to 470 MeV by two accelerating modules, which are located between the bunch compressors. Further three modules accelerate the electron beam up to 1 GeV. The modules are operated with accelerating gradients between 20 MV/m and 25 MV/m. Four cavities of the sixth module reach gradients above 30 MV/m.

Four RF stations, consisting each of a klystron, a high voltage pulse transformer, a pulsed power supply (modulator), and a low level RF system, are used to power the RF gun and the accelerating modules. The modulators are bouncer type and provide 1.5 ms long HV pulses. The RF gun and the first module are both operated by a 5 MW klystron. The third 5 MW klystron is shared between the second and the third module. The last three modules have a common RF station with a 10 MW multi-beam klystron. A linear waveguide distribution system is used for the five first modules. Therefore the operation gradient of these modules is limited by the weakest cavity in the module. The sixth module has a new combined type waveguide distribution based on asymmetric shunt tees allowing adjustment of the power for each cavity pair individually. Thus the performance of the complete module can be optimized, assuming that both cavities in a pair have similar performance. More details can be found in [14].

A dedicated low level RF (LLRF) system is developed to regulate the gradient (vector sum) and phase of the RF gun and the accelerating modules. The RF gun and the first accelerating module are controlled by an FPGA (field programmable gate array) based system. A careful regulation of them is especially important, since electron beam properties, and thus the stability of the complete linac, are mainly determined at low electron beam energies. The other accelerating modules use DSP (digital signal processor) based systems.

FLASH uses similar superconducting accelerating modules and RF systems as will be used for the European XFEL and for the ILC, providing thus an important test bench for these future facilities.

PRODUCTION OF SASE FEL RADIATION

At FLASH the production of FEL radiation is based on self-amplified spontaneous emission (SASE). The most relevant electron beam parameters for this process are peak current and transverse emittance: the former has to be high enough and the latter simultaneously small enough.

The required peak current of ~ 2 kA is achieved by compressing the electron bunch by two magnetic chicane bunch compressors. Due to emittance optimization, the initial electron bunch having a length of about 2 mm is relatively long. When a long bunch is accelerated off-crest, a nonlinear energy chirp is produce along it. The following compression process leads therefore to a non-symmetric bunch shape with a leading spike of a high peak current and a long tail.

The transverse emittance is optimized in the injector. In order to achieve a small emittance, the accelerating gradient on the cathode is as high as possible, the space charge effects are compensated by a solenoid magnet, and the laser parameters as well as the steering of the electron beam through the first accelerating module are optimized. A typical normalized projected transverse emittance of a 1 nC bunch (on-crest acceleration) is around 2 mm mrad [15]. In the present operation mode with a leading high current spike and a long tail, the slice emittance of the spike, not the projected emittance of the entire bunch, is the relevant parameter for the lasing process. A description and results of the slice parameter measurements at FLASH can be found in [16].

Six 4.5 m long undulator modules consisting of a periodic structure of permanent NdFeB magnets are installed after the collimation section to produce SASE FEL radiation. The undulator has a fixed gap of 12 mm, its peak magnetic field is 0.48 T, the undulator period 27.3 mm, and the K-value 1.23.

The produced FEL radiation is transported from the accelerator tunnel to the experimental hall, where the user experiments are placed. More details of the photon beam lines and photon diagnostics can be found in [17].

OPERATIONAL ISSUES

FLASH is operated 7 days per week, 24 hours per day. Beam time is organized into blocks: four week user experiment blocks are sandwiched between three weeks blocks of FEL physics studies, improvements of the FLASH facility, and preparation of the next user block. Two or three times per year a dedicated beam time of a couple of weeks is scheduled for general accelerator physics studies and developments related to future projects.

During the second user period from November 26, 2007 to August 16, 2009, 50 % of the time has been scheduled for user experiments, and 42 % for studies and developments. The remaining 8 % have been reserved for maintenance periods 1-2 times per year.

During the scheduled user experiments, FEL radiation has been delivered in average 75 % of the time to experiments, totally about 5700 hours during the second user period. Tuning of the FEL radiation properties has taken 14 %, and the start-up after maintenance or failures 1 % of the time. The total downtime due to technical failures or other incidents has been 7 %. 3 % of the time has been used for the scheduled weekly maintenance. The total up-time of the facility during the second user period was 93 %.

The time distribution of individual user blocks differs from each other, as can be seen in Table 2. The difference is partly due to different amount of downtime, but more important due to different requirements of the user experiments. The more demanding the experiments are and the more often the wavelength has to be changed, the more time is needed - and scheduled - for tuning.

Table 2: Time distribution between SASE FEL radiation delivery, tuning, linac set-up, maintenance, and downtime during the user blocks of the second user period. Blocks 1-5 and 7-10 are four weeks long, the length of blocks 6, 11 and 12 is three weeks.

Block	**SASE** (%)	**Tuning** (%)	**Set-up** (%)	**Maint.** (%)	**Down** (%)
1	71	14	2	4	9
2	79	13	1	4	3
3	75	16	1	2	6
4	67	24	1	2	6
5	69	18	2	1	10
6	68	21	1	3	7
7	81	12	1	2	4
8	78	13	1	3	5
9	79	13	1	3	4
10	75	12	1	2	10
11	75	7	1	2	15
12	90	5	0	1	4
Total	75	14	1	3	7

Downtime

Downtime discussed here considers the twelve blocks of user experiments during the second user period. The study periods are excluded from the downtime statistics, since during these periods the linac and its subsystems are often operated in unusual conditions.

About one third of the downtime (34 %) is related to the RF stations. Almost 80 % of this downtime is caused by failures of two old RF stations, which have been in operation already more than ten years. These two aged stations will be exchanged to new ones during the coming upgrade shutdown. It is also worth to mention that during the user blocks 3 and 12 the downtime due to RF stations has been only 3 % of the total downtime.

In order to reduce the downtime due to failures of the photocathode laser system, presently 8 %, a second laser will be available after the upgrade shutdown. The old laser is partly flash-lamp pumped, whereas the new one is fully diode pumped, which will reduce the downtime caused by broken flash-lamps.

Infrastructure failures, especially power cuts and disturbances of cooling water, air conditioning and temperature stabilization systems, have caused 18 % of the downtime. Other significant sources for the downtime are failures of the magnet power supplies (8 %), photon beamline components (5 %), control system (4 %), and cryogenics (4 %), as well as low level RF regulation (3 %).

About 16 % of the downtime is caused by single incidents happening only once or very rarely. For example, operational and maintenance mistakes, and technical interlocks of the RF gun belongs to this category. No downtime is caused by the superconducting cavities, and the downtime due to the RF power couplers is also negligible ($\sim$1% of the total downtime).

SASE PERFORMANCE AND USER EXPERIMENTS

Some typical FEL radiation parameters are listed in Table 1. The performance is different for each photon wavelength, and therefore the parameters shown should be taken as an indication of the overall span of the performance.

Some of the operational highlights of the second user period have been an experiment using the fifth harmonic of 7.97 nm (1.59 nm), a continuous running of five days at 7 nm with a bunch train of 100 bunches, and a three weeks run at 7 nm with 30 bunches and average FEL radiation pulse energy up to 50 μJ. The 7 nm wavelength corresponds to electron beam energy of about 950 MeV.

Since summer 2005, 77 proposals for user experiments have been accepted and experiments ranging from diffraction imaging to atomic physics and molecular biology, have been successfully carried out [18]. Every experiment has its own demands on the properties of the FEL radiation in terms of photon wavelength, FEL pulse energy, pulse repetition rate, spectrum bandwidth, and stability. Tuning of these properties has taken 14 % of the time during the user blocks.

More than half of the total tuning time has been needed for wavelength changes (55 %). Since FLASH has a fixed gap undulator, a change of the photon wavelength requires always a change of the electron beam energy. In addition to adjustments of the gradients and phases of the accelerating modules, the wavelength change procedure includes an adjustment of the beam optics and a correction of the orbit through the undulator. During the second user period the wavelength has been changed about 140 times, and more than 30 different wavelengths between 6.8 nm and 40.5 nm have been delivered to the experiments. The most requested wavelengths have been the the shortest ones (7-8 nm), and the ones around 13.5 nm, the latter is due to the availability of multilayer mirrors for this wavelength.

Part of the tuning time (17 %) has been required to increase the average pulse energy of the FEL radiation, or to correct the transverse position of the photon beam. Some experiments have also special demands, like an exact wavelength or a narrow bandwidth of the wavelength spectrum. This kind of quality tuning has taken 8 % of the tuning time. Tuning is also needed after technical failures (7 %) and weekly maintenance (6 %). 5 % of the tuning has been related to changes on the number of bunches in the bunch train or the bunch repetition rate. The rest of the tuning has been characterization of FEL radiation properties.

ACCELERATOR AND FEL STUDIES

As mentioned above, 42 % of the beam time during the second user period has been scheduled for studies. This time includes also periods reserved for improvements of the FLASH facility itself, and the preparation for the next user experiments. About one fourth of the study time has been especially dedicated to developments related for future projects like the European XFEL and the ILC.

About 20 % of all studies has been related to low level RF regulation, especially to control and measurement algorithms and developments of hardware components. A substantial amount of time has been used for developments of electron beam diagnostics devices, especially beam position monitors, as well as a new synchronization system based on beam arrival time monitors and optical links. An other important study issue has been a long-term follow-up of the properties of the Ce_2Te photocathodes. Beam time has also been scheduled for experiments developing new methods for longitudinal electron bunch diagnostics using an optical replica synthesizer and coherent infrared undulator radiation as well as for studies related to THz radiation and micro-bunching.

Preparation of an experiment to operate the FLASH linac with full beam loading (up to 9 mA electron beam current) has been going on since spring 2008. Dedicated beam time of two weeks is reserved for this experiment in September 2009. [19, 20]

Improvements of the FLASH facility are recently concentrated on stability and feedback issues as well as on tuning procedures. One important study subject has been electron beam orbit control, especially in the undulator section. Part of the time has been used for developments on photon diagnostics devices and preparation of the photon beam lines for the user experiments. A new THz radiation beam line has been commissioned as well.

UPGRADE 2009/10

Major modifications of the FLASH facility will take place during a 5 months upgrade shutdown starting end of September 2009.

A seventh TESLA type superconducting accelerating module [21] will be installed downstream of the sixth module. The place for this module has been foreseen already in the original design of the FLASH linac. By this upgrade, the electron beam energy will be increased up to 1.2 GeV allowing lasing at wavelengths below 5 nm.

As mentioned above, RF curvature causes a non-symmetrical longitudinal bunch shape. This can be removed by third harmonic RF cavities, and therefore a module with four superconducting cavities operated at 3.9 GHz (third harmonic of 1.3 GHz) [22] will mounted after the first accelerating module. When the third harmonic module is in full operation, a larger fraction of the electron bunch can contribute to the lasing process leading to longer FEL pulses with higher energy per pulse. Switching the module off leads to the similar electron bunch shape and FEL pulse length as FLASH has now.

An other new installation is an experiment for seeded FEL radiation: sFLASH [23]. It consists of a seed laser system, an undulator section of 10 meters, and a photon beam line to transport the FEL radiation to an experimental hutch located outside the FLASH tunnel. In order to realize this experiment, 40 meters of the FLASH electron beam line between the collimator section and the SASE undulators will be reconstructed.

The RF gun has been in continuous operation over the last six years. It shows some aging effects, and will be replaced by a new gun with an improved cooling scheme facilitating the operation at high average power levels. Its waveguide system will be prepared for a possible operation with a 10 MW klystron in the future.

The first accelerating module is one of the oldest TESLA type modules, and it is foreseen to replace it during the shutdown by a cryo-module furnished with new high performance cavities. This upgrade increases operating gradients of the last four cavities in the module, and thus helps to compensate the energy loss, which will be caused by the operation with the third harmonic module.

In addition, upgrades of the RF stations and waveguide distribution are scheduled. Two old RF stations will be replaced by new ones, and an additional RF station will be included. After the upgrade, the fourth and fifth accelerating module have a common RF station (5 MW klystron), while the last two modules will be operated by one 10 MW multi-beam klystron. The seventh accelerator module has an XFEL type combined waveguide distribution, and thus the performance of its each cavity pair can be optimized, as already is the case for the sixth module.

SUMMARY

FLASH is a world-wide unique light source in the VUV and soft x-rays wavelength range providing ultrashort FEL pulses with a high brilliance. It is driven by a 1 GeV superconducting linac with six TESLA type accelerating modules, and provides therefore an important test bench for the future projects using superconducting accelerator technology.

During the second FEL user period from end of November 2007 to middle of August 2009, FEL user experiments with photon wavelengths between 40.5 nm and 6.8 nm have been successfully performed. Significant amount of beam time has also been scheduled for accelerator and FEL physics studies as well as for technical developments.

After an upgrade shutdown starting end of September 2009 and the following commissioning period, the third FEL user period is expected to start in summer 2010.

ACKNOWLEDGMENT

We like to thank all colleagues, both at DESY and at the collaborating institutes, who are participating in the development, operation, and maintenance of FLASH.

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