OPERATION OF FLASH AS AN FEL USER FACILITY

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Abstract

FLASH, the FEL user facility at DESY, is operated with an electron beam energy up to 1 GeV corresponding to a photon wavelength down to 6.5 nm. The full year 2008 is dedicated to beam operation: about half of the time is scheduled for FEL users, and the rest for accelerator and FEL physics studies. Operational experience gathered at FLASH is very important not only for further improvements of the FLASH facility itself, but also for the European XFEL and for the ILC R&D effort. This paper reports our experience to operate FLASH as a user facility.

INTRODUCTION

FLASH is a free-electron laser (FEL) user facility at DESY (Hamburg, Germany). It is a high-gain single-pass FEL based on self-amplified spontaneous emission (SASE). FLASH is a world-wide unique light source providing ultrashort radiation pulses (femtosecond range) with an unprecedented brilliance.

FLASH is based on the TTF-FEL [1] operated at DESY until end of 2002 with a photon wavelength range from 120 nm to 80 nm [2, 3]. The first lasing of FLASH at 32 nm was achieved in January 2005 [4]. Since summer 2005, FLASH is an FEL user facility. The first two years it provided FEL radiation for user experiments with photon wavelengths from 47 nm to 13 nm [5]. An energy upgrade to 1 GeV in summer 2007 extended the wavelength range down to 6.5 nm. The second user period started end of November 2007.

The complete year 2008, as well as the first half of 2009, is dedicated to beam operation. About half of the time is scheduled for FEL user experiments. The other half is shared between accelerator and FEL physics studies, and maintenance periods.

The experience gathered at FLASH is important not only for further improvements of the FLASH facility itself, but also for the European XFEL project [6] and for the R&D effort of the International Linear Collider (ILC) [7]. We report here our experience to operate FLASH as a user facility. Part of this material has already been presented in [8] and [9].

PRODUCTION OF ELECTRON BUNCHES

Figure 1 shows a schematic layout of the FLASH linac.

A laser driven pulsed RF-gun provides up to 800 electron bunches per bunch train. The macro-pulse repetition rate is 5 Hz. The photocathode laser is based on a mode-locked pulse train oscillator synchronized to the 1.3 GHz of the accelerator. A chain of single-pass Nd:YLF amplifiers provides enough power to convert the initial infra-red wavelengths 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 RF-gun is a 1.5 cell normal conducting L-band cavity (1.3 GHz). The maximum accelerating gradient on the photocathode is 46 MV/m, and the electron beam energy at the gun exit ∼5 MeV.

Table 1: Some 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
Undulator		
Period	cm	2.73
Gap	mm	12
Peak magnetic field	T	0.48
K		1.23
Total length	m	27.3
FEL radiation		
Wavelength	nm	47 - 6.5
Average pulse energy (typ.)	μJ	10 - 50
Average pulse energy (max)	μJ	70
Bandwidth (fwhm)	%	∼1
Pulse duration (fwhm)	fs	10 - 50
Peak power	GW	1 - 5
Peak spectral brilliance	*	10^{29} - 10^{30}

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

The number of bunches in the bunch train as well as the bunch spacing can be varied: the standard spacing is 1 MHz, other spacings like 500 kHz, 250 kHz, or 100 kHz have been realized as well. The electron bunch charge is variable to a certain extend. During FEL operation, a charge between 0.5 nC and 1 nC is used. Some main electron beam parameters are listed in Table 1.

FLASH uses TESLA type accelerating modules. Each module contains eight superconducting niobium 9-cell cavities, a quadrupole doublet with integrated steerers and a beam position monitor. The first accelerating module boosts the electron beam energy to 130 MeV. In order to reduce space charge effects, its first four cavities are operated with a moderate gradient (12-15 MV/m). The first bunch compressor is followed by two modules (ACC2 and

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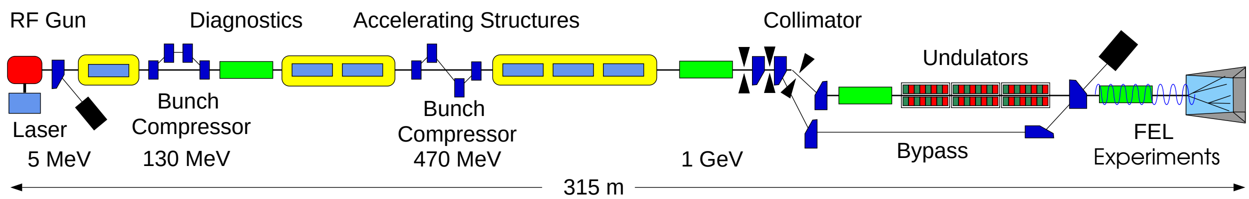

Figure 1: Layout of the FLASH linac including the experimental hall (not to scale).

ACC3), which accelerate the beam energy up to 470 MeV. After the second bunch compressor, three modules (ACC4, ACC5, and ACC6) further increase the electron beam energy up to 1 GeV.

The accelerating module at the position ACC6 is a new module installed in summer 2007. At the same time, the module at position ACC3 was replaced by a new one. The performance of both new accelerating modules is excellent. Both of them reach an average gradient of 25 MV/m, and four cavities of the sixth module even more than 30 MV/m.

PRODUCTION OF SASE FEL RADIATION

In the SASE process the radiation amplification starts from shot noise in the electron beam. The interaction of the electron bunch with the undulator magnetic field leads to a periodic charge density modulation of the electron bunch. Once this "micro-bunching" is induced, many electrons within the bunch start to radiate coherently with the resonant wavelength. This wavelength depends on the electron beam energy and the properties of the undulator (period, gap, magnetic field).

A high-gain single-pass SASE FEL like FLASH requires a long undulator system. Six 4.5 m long undulator modules consisting of a periodic structure of permanent NdFeB magnets are installed after the collimation section. The undulator has a fixed gap of 12 mm. Some main undulator parameters are listed in Table 1.

The most relevant electron beam parameters for the SASE process are peak current and transverse emittance: the peak current has to be high enough and the emittance simultaneously small enough.

Two magnetic chicane bunch compressors are used to achieve the required peak current of 1-2 kA. The compression process requires a linear energy chirp along the bunch introduced by off-crest acceleration. However, to optimize the transverse emittance in the RF-gun, the initial electron bunch is relatively long ($\sim$2 mm), and when it is accelerated off-crest by the sinusoidal RF field of the first accelerating module, a non-linear energy chirp is produced. Therefore, the compression leads to a longitudinal bunch shape with a leading spike of a high peak current and a long tail. The shape of the spike can be adjusted to some extend by varying the compression ratio between the two bunch compressors.

The RF curvature can be removed by third harmonic accelerating cavities (3.9 GHz). In summer 2009, it is planned to install a module with four superconducting 3.9 GHz cavities [10] upstream of the first bunch compressor. With this third harmonic module, it is expected to achieve a more regular longitudinal shape of the compressed bunch. The advantage will be a better and easier control of the SASE process together with a significant increase in SASE FEL radiation energy (a factor of 10 is predicted [11]). However, the FEL pulse duration is expected to increase simultaneously from the present value of a couple of 10 fs to $\sim$200 fs [11]. When the third harmonic module is switched off, FLASH can still be operated in the femtosecond mode, and also intermediate modes are anticipated.

The transverse emittance is optimized in the injector: the photocathode laser parameters are carefully adjusted, the accelerating gradient on the cathode is as high as possible, the transverse space charge effects are compensated by a solenoid magnet, and the steering of the electron beam through the first accelerating module is optimized. A typical transverse emittance of a 1 nC bunch (on-crest acceleration) is around 2 mm mrad [12].

In the present operation mode (femtosecond mode) with a leading spike and a long tail, the slice emittance of the high peak current 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 [13].

The produced SASE FEL radiation is transported from the accelerator tunnel to the experimental hall via a specially designed beam line including photon diagnostics devices to determine the photon pulse energy, the transverse position, and the wavelength. In the experimental hall, where the user experiments are placed, the radiation can be guided to five different beam lines. However, only one line can be served at a given time.

SASE Performance

Some typical FEL radiation parameters are listed in Table 1. The performance is different for each photon wavelength: each wavelength has different beam optics and – more important – a different bunch compression scheme. Therefore, the parameter range shown in Table 1 should be taken as an indication of the overall span of the performance. A complete characterization of the SASE radiation at 13.7 nm can be found in [5].

With the present undulator design having a fixed gap, the photon wavelength can only be varied by changing the electron beam energy. After the energy upgrade in summer 2007, electron beam energies up to 1 GeV are now available corresponding to photon wavelengths down to 6.5 nm. The lasing with this world record wavelength of SASE FELs was observed in the beginning of October 2007 for the first time [8, 9].

An other milestone was also achieved in October 2007: lasing with a complete bunch train of 800 bunches. The electron beam energy was 685 MeV corresponding to a photon wavelength of 13.4 nm. The average power of the photon beam was 56 mW.

Some of the operational highlights of this user period have been an experiment using the fifth harmonic of 7.97 nm (1.59 nm), and a continuous running of five days at 7 nm with a bunch train of 100 bunches for two experiments.

OPERATIONAL ISSUES

FLASH is operated 24 hours per day, 7 days per week. The FEL user experiments are grouped into blocks of four weeks. Between two user blocks, a block of three weeks is reserved for improvements of the FLASH facility, and for FEL physics studies. Three times per year a dedicated beam time of 2-3 weeks is scheduled for general accelerator physics studies and technical developments.

During the period from November 26, 2007 (beginning of the second user period) to September 7, 2008 (end of the fifth user block within the second period), 49 % of the time has been scheduled for user experiments, 38 % for accelerator and FEL physics studies, and the rest for maintenance, including a maintenance period of 3 weeks in May 2008.

During the user blocks, FEL radiation has been delivered in average 73 % of the time to experiments. The rest of the up-time is used to tune FEL radiation properties (17 %) and to start-up the accelerator after maintenance or failures (1 %). The total downtime due to technical failures or other incidents is 6 %. The scheduled weekly maintenance takes 3 % of the time.

The time distribution of individual user blocks differs from each other (Table 2). For example, during the second user block the FEL radiation was delivered 79 % of the time, when in the fourth block its proportion was only 67 %. The difference is partly due to different amounts of the downtime, but more important due to different requirements of the user experiments. The more demanding the experiments are, the more time is needed for tuning.

Stability is an important issue to ensure continuous delivery of high quality FEL radiation. Many measures, like installation of low noise magnet power supplies, replacement of the old master oscillator, as well as temperature stabilization and reduction of electro-magnetic interference of the injector low level RF (LLRF) system racks, have already been taken. Several other actions are on-going including, for example, improvements of the LLRF phase and amplitude regulation, and developments of feedbacks to compensate drifts of electron beam parameters (energy, charge, arrival time, bunch compression, orbit).

Table 2: Time distribution between SASE FEL radiation delivery, tuning, linac set-up, maintenance, and downtime during the user blocks from November 26, 2007 to September 7, 2008. Each block has a length of four 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
Total	73	17	1	3	6

Downtime

Downtime discussed here considers the five user blocks since November 2007. During FEL and accelerator study periods, the linac is often operated in unusual conditions. Therefore, the study periods are not representative for a standard FEL operation, and thus excluded from the downtime statistics.

About one third of the downtime (31 %) is related to failures of RF-stations (modulators, transformers, klystrons, preamplifiers, waveguides). Presently, four RF-stations are used to operate the FLASH linac: the RF-gun and the first accelerating module (ACC1) are operated by a 5 MW klystron each, ACC2 and ACC3 have a common 5 MW klystron, and the other three accelerating modules are fed by one 10 MW klystron. The modulators and transformers of RF-gun and ACC1 have been in operation already more than ten years. The two other RF-stations are of a newer type and have been in operation since 2004. During the last two years, the downtime due to RF-stations has been reduced significantly: in 2006-2007 it still caused more that 50 % of the total downtime. The reduction to the present 31 % is achieved especially by improving the start-up and reset procedures. A further improvement is expected, when the two aged modulators will be replaced during the shutdown in 2009.

Infrastructure failures, especially power cuts and disturbances of cooling water, air conditioning and temperature stabilization systems, have caused 11 % of the downtime. Magnet power supplies have been the source for 8 % of the downtime. In order to reduce the downtime due to failures of the photocathode laser (presently 7 %), a second laser system is in preparation.

Other downtime sources are low level RF regulation (5 %), and occasional failures of photon beamline components (7 %) and control (4 %) and cryogenic (3 %) systems. About 17 % 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 and accelerating cavity couplers belong to this category.

The RF-system for the normal conducting RF-gun is especially demanding in terms of power transmitted to the gun cavity and reflected from it. During one of the user blocks, substantial amount of the downtime was caused by spikes in the reflected RF-power detected at the RF-gun klystron.

User Experiments

Every user experiment has its own demands on the properties of the FEL radiation in terms of photon wavelength, pulse energy, pulse repetition rate, spectrum bandwidth, and stability. As mentioned above, 17 % of the time during the five user blocks has been used for tuning of these properties.

Usually, two user experiments, placed at different photon beam lines, run in parallel. The photon beam is changed from one experiment to another typically every 12 hours. In order to minimize the time required for tuning, the experiments are scheduled – whenever possible – to have similar FEL radiation properties. However, even with this, the change of, for example, the photon wavelength or the bunch pattern is often required between user shifts.

More than half of the total tuning time is needed for wavelength changes (57 %). Since FLASH has a fixed gap undulator, a change of the photon wavelength requires 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. Different wavelengths may also require different bunch compression schemes. A standard wavelength change with well-known accelerator settings takes in average two hours. Substantially longer tuning times are needed for wavelengths delivered for the first time, as well as for short wavelengths, especially if high photon pulse energy is required simultaneously. During the five user blocks the wavelength has been changed more than 60 times, and totally 24 different wavelengths between 7 nm and 27 nm have been delivered to the experiments.

Every now and then tuning is required to increase the FEL radiation energy, or to correct the transverse position of the photon beam. 15 % of the tuning time is used for this kind of standard tuning. A typical average FEL pulse energy delivered to user experiments is between 10 and 30 μJ. Occasionally even higher pulse energies (up to 50 μJ) has been provided.

Some experiments have special demands concerning the FEL radiation quality, like an exact wavelength or a narrow bandwidth of the wavelength spectrum. This kind of quality tuning takes presently 8 % of the tuning time, but its amount is likely to increase with the increasing demands of the experiments.

About half of the experiments request a single bunch operation (5 Hz FEL pulse repetition rate). The majority of the other experiments uses 10 to 30 electron bunches per bunch train. A couple of experiments have been carried out with longer bunch trains ($\sim$100 bunches). Setting up the long bunch train lasing have taken 4 % of the total tuning time.

Tuning is also required after technical failures (5 %) and after weekly maintenance (7 %).

SUMMARY AND OUTLOOK

FLASH is a world-wide unique light source providing ultrashort FEL pulses with a high brilliance.

After the energy upgrade in summer 2007, the design electron beam energy of 1 GeV was reached in September 2007, and two other milestones in October 2007: lasing at a wavelength of 6.5 nm – a new world record for a SASE FEL – and lasing with a complete bunch train of 800 bunches.

The second FEL user period started end of November 2007, and since then FEL user experiments with more than 20 different wavelengths between 27 nm and 7 nm have been successfully performed.

During user experiments FEL radiation has been delivered in average 73 % of the time. Tuning of FEL radiation parameters has taken 17 % of the time. The downtime due to technical failures or other incidents has been 6 %. The rest of time has been used for weekly maintenance (3 %) and start-up (1 %).

A long shutdown is scheduled for the second half of 2009. Several modifications of the FLASH facility are planned to take place during the shutdown. A third harmonic module with four 3.9 GHz superconducting cavities will be installed in the injector. An other major modification is the installation of an experiment for seeded VUV radiation (sFLASH) [14] requiring a modification of the complete 40 m long electron beam line between the collimators and the SASE undulators. In addition, it is planned to exchange the RF-gun, and to install a seventh accelerating module to further increase the electron beam energy. Upgrades for the RF-stations and waveguide systems are scheduled as well. After a commissioning period, the third FEL user period is expected to start in spring 2010.

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