STATUS OF FLASH

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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 shutdown in summer 2007 was followed by a three month commissioning and study period. A new run of FEL experiments started in November 2007. 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. Here we report the present status of FLASH as an FEL user facility.

INTRODUCTION

FLASH is a SASE (self-amplified spontaneous emission) free-electron laser at DESY (Hamburg, Germany).

The functionality of SASE FELs has been demonstrated by the TTF-FEL [1] operated at DESY in 2000-2002 with photon wavelengths from 120 nm to 80 nm [2, 3]. Based on the experience from the TTF-FEL operation, a new FEL facility, FLASH, was constructed in 2003-04. The first lasing at 32 nm was achieved in January 2005 [4]. From summer 2005 to spring 2007, FLASH has been operated as an FEL user facility with photon wavelengths in the range from 47 nm to 13 nm [5]. In summer 2007 FLASH was upgraded to its design energy of 1 GeV allowing lasing down to 6.5 nm [6]. After a commissioning phase in autumn 2007, the second period of FEL user operation started in November 2007.

About half of the beam time is scheduled for FEL user experiments. The other half is shared between accelerator and FEL physics studies, and maintenance periods. FLASH serves also as a pilot facility for the European XFEL project [7].

PRODUCTION OF ELECTRON BUNCHES

Figure 1 shows a schematic layout of the FLASH linac. The main parameters are listed in Table 1.

Up to 800 electron bunches are produced by a laser driven RF-gun. The standard bunch spacing is 1 MHz, other spacings like 500 kHz, 250 kHz, or 100 kHz, have been realized as well. The macro-pulse repetition rate is 5 Hz. The electron bunch charge can be varied to a certain extend. During the FEL operation, a charge between 0.5 nC and 1 nC is typically used.

Table 1: FLASH parameters

Electron beam		
Energy	MeV	370 - 1000
Peak current	kA	1-2
Emittance, norm. (x,y)	μm rad	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)	%	$\sim$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 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 on the backplane of the RF-gun. When necessary, the cathode can be exchanged to a fresh one. The RF-gun is a 1.5 cell normal conducting copper cavity (1.3 GHz). The maximum accelerating gradient on the photocathode is 46 MeV, and the electron beam energy at the gun exit 5 MeV.

The electron beam energy is boosted to 130 MeV by a TESLA type accelerating module (eight superconducting niobium 9-cell cavities). In order to reduce space charge effects, the first four cavities are operated with a moderate gradient (12-15 MV/m). The first bunch compressor is followed by two further TESLA type accelerating modules. The latter of them has been replaced by a new one in summer 2007 allowing now beam energies up to 470 MeV at the second bunch compressor. The three last accelerating modules increase the electron beam energy up to 1 GeV. The last module has been installed in summer 2007.

The performance of both new accelerating modules (at

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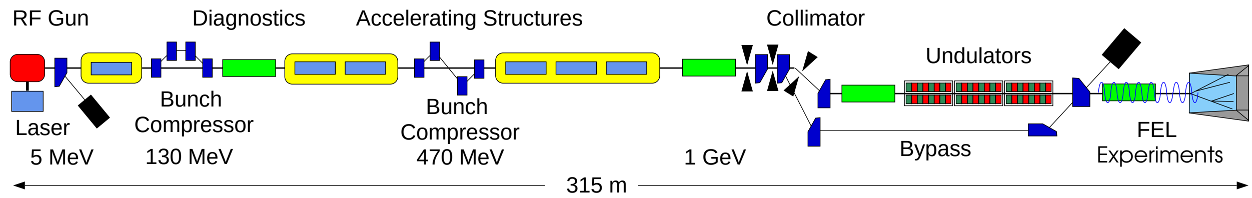

Figure 1: Layout of the FLASH linac including the experimental hall (not to scale).

positions ACC3 and ACC6) 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. [6]

Two magnetic chicane bunch compressors are used to achieve the 1-2 kA peak current required for the SASE process. Due to a relative long ($\sim$ 2 mm) initial electron bunch combined with a sinusoidal RF field of the accelerating module, an energy chirp is produced, when the electron bunch is accelerated off-crest in the first module. The compression of the bunch by the bunch compressors 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 a third harmonic module (3.9 GHz), which will be installed between the first accelerating module and the first bunch compressor in summer 2009. This will lead to a more regular longitudinal shape of the compressed bunch.

Besides the peak current, also the transverse emittance plays a role in the SASE process. The 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. In the present operation mode, 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.

FEL RADIATION

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 peak magnetic field is 0.48 T. The undulators have a fixed gap of 12 mm and a period of 27.3 mm.

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.

Due to the fixed gap undulator, 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 first time observed in October-5, 2007 (see Figure 2).

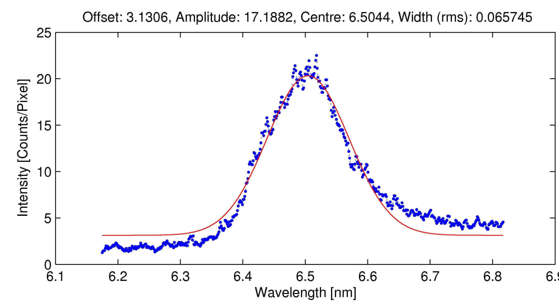

Figure 2: One of the first measured spectra of SASE FEL radiation at a wavelength peaking at 6.5 nm: a new world record. The spectrum is averaged over 125 photon pulses.

An other milestone was achieved in October-21, 2007: lasing with a complete bunch train of 800 bunches. The photon wavelength was 13.4 nm, and the average power 56 mW.

Typical FEL radiation parameters are listed in Table 1. Note that the parameter set is different for each photon wavelength, and the parameter range shown in Table 1 indicates the overall span of performance. The performance for an individual wavelength depends much on the bunch compression scheme and beam optics applied.

OPERATION AS A USER FACILITY

The second FEL user period started end of November 2007. Since then FEL radiation with 20 different wavelengths between 27 nm and 7 nm has been delivered to experiments.

Some of the operational highlights have been a run at 7 nm with a bunch train of 100 bunches and an experiment using the fifth harmonic of 7.97 nm (1.59 nm).

Operational Issues

FLASH is operated 24 hours per day, 7 days per week. The FEL user experiments are organized in blocks of four weeks. Between user blocks, three weeks are reserved for FEL physics studies and improvements of the FLASH facility. In addition dedicated beam time (2-3 weeks) is scheduled three times per year for general accelerator physics studies and instrumentation developments.

During the period from November-26, 2007 (beginning of the second user period) to July-20, 2008 (end of the fourth user block), 47 % of the time was scheduled for user experiments, 37 % 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 was delivered 73 % of the time to experiments. The rest of the up-time was 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 was 6 %. The scheduled weekly maintenance took 3 % of the time.

About half of the downtime is related to failures of RF-stations, infrastructure (water, electricity), and magnet power supplies. Other downtime sources are the low level RF regulation, and occasional failures of the photocathode laser, the photon beamline components, the control system, and the cryogenic system. About 15 % of the downtime is caused by single incidents happening only once or very rarely.

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 the reflected RF-power at the gun klystron.

Continuous actions are taken to reduce the downtime. For example, improvements on the start-up and reset procedures of the RF-stations are realized. This has already reduced the downtime by a considerable amount. A replacement of aged modulators (RF-gun and the first accelerating module), which are difficult to maintain, is scheduled for 2009 shutdown. To ensure the operation of the injector, a conditioned backup RF-gun is stored, and a second photocathode laser system is in preparation.

Stability is an other important issue. Many measures, like installation of low noise magnet power supplies, and replacement of the old master oscillator, are already 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 on beam energy, arrival time, bunch compression, charge, and orbit.

FEL Radiation Delivered to Experiments

Every 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 four user blocks since November 2007 has been used for tuning of these properties.

Most of the tuning time is needed for wavelength changes (58 %). Since FLASH has a fixed gap undulator, a change of the photon wavelength requires a change of the electron beam energy. In addition to the adjustments of the gradients and phases of the last three accelerating modules, the wavelength change procedure includes the adjustment of the beam optics and the correction of the orbit through the undulator as well. 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 a high photon pulse energy is required simultaneously.

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

Apertures can be inserted to the photon beam to improve the pointing stability. The radiation pulse energies referred above are values for two 10 mm apertures. When smaller apertures are applied, the delivered pulse energy decreases accordingly. If an attenuation of the FEL radiation is required, a gas-absorber can be used.

Some experiments have special demands concerning the FEL radiation quality, e.g. an exact wavelength or a narrow bandwidth of the wavelength spectrum. This kind of quality tuning has presently taken 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 use 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 lasing for these experiments have taken 5 % of the total tuning time.

SUMMARY AND OUTLOOK

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

Since November 2007, FEL user experiments with 20 different wavelengths between 27 nm and 7 nm has been successfully performed. The present user period continues until end of April 2009.

During the long shutdown in 2009 several modifications of the FLASH facility are planned. 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) [8] requiring a modification of the complete electron beam line between the collimator and SASE undulators (∼ 40 meters). 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.

ACKNOWLEDGMENT

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