

FLASH OPERATION AS AN FEL USER FACILITY

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Abstract

The free-electron laser FLASH at DESY operates as a user facility providing coherent 10 to 50 femtosecond long laser radiation in the wavelength range from 47 nm to 6.8 nm with an unprecedented brilliance - many orders of magnitude higher than conventional facilities. The SASE radiation contains also higher harmonics. The third and fifth harmonics have successfully been used by FEL experiments, in the latter case with a shortest wavelength of 1.59 nm. In addition, FLASH serves as a pilot facility for the European XFEL. Part of the beam time is reserved for general accelerator studies which also includes ILC related studies.

INTRODUCTION

The free-electron laser facility FLASH at DESY (Hamburg, Germany) is a high-gain single-pass FEL based on self-amplified spontaneous emission (SASE). It consists of a photo-injector, a superconducting linac with TESLA type accelerating modules, an undulator section, and an experimental hall, where the FEL experiments are located. FLASH provides coherent 10 to 50 femtosecond long laser radiation in the wavelength range from 47 nm to 6.8 nm for user FEL experiments with an unprecedented brilliance.

FLASH is an FEL user facility since summer 2005. It started with a maximum electron beam energy of 800 MeV allowing lasing with photon wavelengths down to 13 nm [1]. An additional accelerator module was installed in summer 2007 increasing the energy to 1 GeV corresponding to a minimum photon wavelength of 6.5 nm [2, 3].

The second user period started end of November 2007 and will continue until autumn 2009. About half of the time is scheduled for FEL user experiments. The other half is shared between accelerator and FEL physics studies, which concentrate on improvements of the FLASH facility, and developments related to the European XFEL [4] and the International Linear Collider [5]. A shutdown is scheduled for autumn 2009 to upgrade the FLASH facility [6].

Part of the material presented here has already been discussed in [2, 7, 8].

FLASH LINAC

Figure 1 shows a schematic layout of the FLASH linac.

Electron bunch trains with up to 800 bunches are generated by a laser driven RF gun. The driving laser is based

on an actively mode-locked pulse train oscillator and chain of single-pass Nd:YLF amplifiers. The RF gun is a 1.5 cell normal conducting L-band cavity with a Cs₂Te cathode inserted to its backplane.

FLASH uses TESLA type superconducting accelerating modules. Each of them consist of eight 9-cell niobium cavities operated at 1.3 GHz. The first bunch compressor is located after the first accelerator module, where the electron beam energy is 130 MeV. The next two modules accelerate the beam up to 470 MeV. After the second bunch compressor the electron beam energy is increased up to 1 GeV by three further modules. The last module has been installed in summer 2007. At the same time, the third module was replaced. Both new modules reach an average gradient of 25 MV/m. Four cavities of the sixth module go even beyond 30 MV/m approaching the ILC goal.[2]

The electron bunch charge is variable to a certain extent. During FEL operation, a charge between 0.5 nC and 1.2 nC is typically used, the maximum charge per bunch is ~ 3 nC. The number of bunches in the train can be varied from single to a few hundred, as well as the bunch spacing, e.g. 1 MHz, 250 kHz, or 100 kHz. The bunch train repetition rate is 5 Hz.

PRODUCTION OF SASE FEL RADIATION

The most important electron beam parameters for the SASE lasing process are transverse emittance, peak current, and energy spread. The transverse emittance has to be small enough: a typical projected rms emittance at FLASH for a 1 nC bunch (on-crest acceleration) is around 2 mm mrad [9]. In order to reach a peak current of ~ 2 kA, the electron bunch is compressed by two magnetic chicane bunch compressors. In the present operation mode, a non-linear bunch compression leads to a longitudinal bunch shape with a high current leading spike, and a long tail. Hence, only a fraction of the bunch contributes to the lasing process ($\sim 20\%$): the part, which has simultaneously a high peak current, a small emittance, and a small energy spread. As a consequence, the produced FEL radiation pulses are extremely short: 10 to 50 fs depending on the compression scheme applied.

The SASE FEL radiation is produced by a long undulator section of six 4.5 m long undulator modules consisting of a periodic structure of permanent NdFeB magnets. The undulator has a fixed gap of 12 mm, and a period of 27.3 mm. The FEL radiation is transported from the accelerator tunnel to the experimental hall, where the photon beam lines are located.[10]

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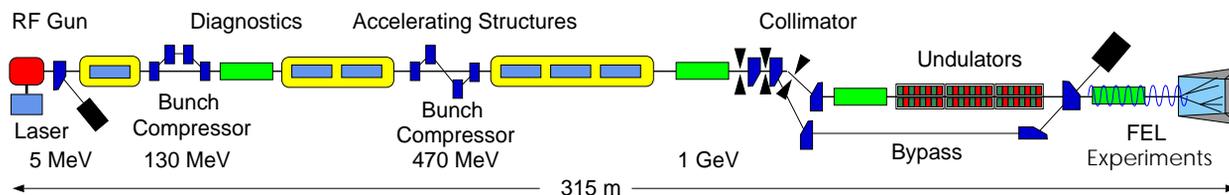


Figure 1: Layout of the FLASH linac including the experimental hall (not to scale).

SASE PERFORMANCE

The present wavelength range for user experiments is from 47 nm to 6.8 nm. Since FLASH uses fixed gap undulators, the photon wavelength is determined by the electron beam energy. The SASE performance is somewhat different for each wavelength depending on the beam optics and bunch compression scheme. A typical average FEL pulse energy delivered to experiments is between 20 and 40 μJ . Occasionally even higher pulse energies, up to 100 μJ , have been provided. The peak power of the photon pulses is 1 to 5 GW.

In addition to radiation at the fundamental wavelength, the FEL radiation contains also higher harmonics. Although their pulse energy is significantly smaller than that of the fundamental radiation ($\sim 0.5\%$ for the third harmonic), user experiments have successfully been carried out with the third and fifth harmonics. So far, the shortest used wavelength is 1.59 nm.

A high brilliance is important for FEL experiments. The peak brilliance of FLASH reaches $10^{29} - 10^{30}$ photons/s/mrad²/mm²/(0.1% bw). This is several orders of magnitudes higher than any other light source in this wavelength range presently in operation.

OPERATIONAL ISSUES

FLASH is operated 24 hours per day, 7 days per week. The beam time is organized in blocks of four weeks of FEL user experiments, sandwiched by 3 weeks of FEL studies. The first two weeks of the FEL studies are dedicated to further develop and improve the FLASH facility. The third week is used to set-up the facility according to the requirements of the following user experiments. In addition to this scheme, beam time is reserved for general accelerator physics studies and technical developments.

From the start of the second user period November 26, 2007 to April 26, 2009, 47% of the time has been scheduled for user experiments, 43% for accelerator and FEL physics studies, and the remaining 10% for maintenance.

During user time, FEL radiation has been delivered in average 74% of the time to experiments. The remaining up-time is used to tune FEL radiation properties (16%), and to start-up the accelerator after maintenance or failures (1%). The total downtime has been 6% only, and the scheduled weekly maintenance 3%. During the two most recent user blocks in spring 2009, the SASE delivery has

been 78%, tuning 13%, and downtime 5% yielding in an uptime of 95%.

The largest amount of the down time has been due to failures of RF stations (modulators, transformers, klystrons, preamplifiers, waveguides). Fortunately, during the last two years, the downtime due to RF stations has been reduced significantly: in 2006-2007 it still caused more than 50% of the total downtime, during the second user period this value has been reduced to 28%, and during the recent two user blocks in 2009 it was only 7%. This is due to improved maintenance schemes and improved automation of standard procedures. Another significant downtime source are infrastructure failures, especially power cuts and disturbances of cooling water, air conditioning, and temperature stabilization systems, which have caused 11% of the down time. Other down times have mainly been due to magnet power supplies (9%), photocathode laser (8%), photon beam lines (8%), cryogenics (6%), and control system issues (5%).

Stability is an important issue to ensure continuous delivery of high quality FEL radiation. Especially for pump-probe experiments, a stable arrival time of the FEL pulses is crucial. During the last years, several actions have been taken to improve the stability. For example, a new master oscillator has been installed in May 2008. A new optical synchronization system based on the beam arrival time detection is presently in a test phase. Other measures are the temperature stabilization of low level RF (LLRF) electronics racks, improvements of LLRF phase and amplitude regulations, and developments of feedbacks to compensate drifts of electron beam parameters (energy, charge, arrival time, bunch compression, orbit).

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, spectral width, and stability. As mentioned above, 16% of the time has been used for tuning of these properties. The more demanding the experiments are, the more time is typically needed - and also scheduled - for tuning.

Since the beginning of the first user period in summer 2005 the FLASH facility has steadily improved in performance. This has often been driven by user experiments continuously evolving in difficulty and complexity. A fruitful cooperation between experiments and the ma-

chine leads to many successful experiments which otherwise would not be possible.

About half of the total tuning time is required for wavelength changes. During the second user period, the wavelength has been changed about 120 times, and more than 30 different wavelengths between 6.8 nm and 40.5 nm have been delivered. Due to the fixed gap undulator, a change of the photon wavelength requires a change of the electron beam energy including adjustments not only of the gradients and phases of the accelerating modules, but also of the beam optics and the orbit through the undulator. Different wavelengths may also require different bunch compression schemes.

Every now and then tuning is required to increase the FEL radiation energy, or to correct the transverse position of the photon beam. Some experiments have tight tolerances on the photon wavelength or on the spectral width requiring dedicated tuning. Tuning is also occasionally needed when the bunch pattern is changed, as well as after technical failures and maintenance days.

ACCELERATOR AND FEL STUDIES

Dedicated beam time is scheduled for general accelerator studies two or three times per year. These studies are typically related to developments for future projects, like the European XFEL and also the ILC.

About one fourth of all studies are related to low level RF, especially to control and measurement algorithms and hardware developments. A substantial amount of time has been used for beam position monitor developments, and also for a long-term follow-up of the properties of the Cs₂Te photocathodes. Experiments to develop new methods for longitudinal electron bunch diagnostics using an optical replica synthesizer [11] and coherent infrared undulator radiation [12] are on-going, as well as studies related to THz radiation and micro-bunching.

An experiment to operate the FLASH linac with a beam current of 9 mA within a 800 μ s long pulse train is under preparation. The final experiment is scheduled for September 2009.[13]

The FEL studies concentrate presently on stability and feedback issues, as well as on tuning procedures, and on the electron beam orbit control through the undulator. Part of the time is used for improvements of the photon beam lines and developments of photon diagnostics devices [10]. A special beam line for THz radiation produced by the above mentioned infrared undulator is under commissioning. The aim is to provide THz radiation for user experiments in the future.

SUMMARY AND OUTLOOK

FLASH is a world-wide unique light source providing ultrashort FEL pulses with a high brilliance for user experiments. During the second user period, user experiments with more than 30 different wavelengths between 6.8 nm

and 40.5 nm have been successfully performed. Besides the FEL user experiments, beam time has been scheduled for improvements of the FLASH facility and for general accelerator physics studies and developments.

Up to now, the experiments lead to more than 50 publications, with about half of them in highly ranked journals.[14]

The FLASH facility will be upgraded in autumn 2009. During a five months shutdown, major modifications will take place. The beam energy will be increased to 1.2 GeV. Four superconducting third harmonic cavities assembled in a module [15] will be installed to linearize the longitudinal phase space providing more flexibility in bunch shaping. Another new installation is an experiment for seeded FEL radiation (sFLASH) [16] requiring a modification of the complete 40 m long electron beam line between the accelerating modules and the undulators. After a commissioning period, the third FEL user period is expected to start in summer 2010.

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