FEL USER FACILITY FLASH

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Abstract

The free-electron laser user facility FLASH at DESY, Germany has finished its second user period scheduled from November 2007 to August 2009. More than 300 days have been devoted for user operation. In addition, a large part of beam time has been allocated for machine studies to further improve the facility, including beam time for XFEL and ILC R&D. FLASH provides trains of fully coherent 10 to 50 femtosecond long laser pulses in the wavelength range from 6.8 nm to 40.5 nm. The SASE radiation contains also higher harmonics; several experiments have successfully used the third and fifth harmonics. The shortest wavelength used is 1.59 nm. We summarize the second period of user operation at FLASH.

INTRODUCTION

FLASH is the free-electron laser (FEL) user facility at DESY (Hamburg, Germany) [1]. It is driven by a superconducting linac with TESLA type accelerating modules. The production of FEL radiation is based on self-amplified spontaneous emission (SASE). FLASH provides trains of fully coherent very short (10 to 50 femtosecond) laser pulses with an unprecedented brilliance. The photon wavelength range is from the vacuum ultraviolet (VUV) to soft x-rays. FLASH is also an important test facility for the future projects based on superconducting accelerator technology, like the European XFEL [2] and the International Linear Collider (ILC) [3].

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 [4].

Here we summarize our operation experience during the second user period from November 2007 to August 2009. Part of this material has already been presented in proceedings of previous conferences [5, 6, 7, 8, 9, 10, 11].

After the second user period, the FLASH facility has been upgraded, and is now in the commissioning phase. Details of the FLASH upgrade can be found in [12, 13].

FLASH LINAC

Figure 1 shows a schematic layout of the FLASH linac.

Electron bunch trains are produced by a laser driven RF gun. Spacing between bunches in a train is variable: different spacings between 1 MHz and 40 kHz are possible. The number of bunches in a train can be varied from 1 up to 800 (1 MHz bunch spacing). The maximum train length is 800 μs. During the second user period the bunch train repetition rate has been fixed to 5 Hz. Electron bunch charges between 0.5 nC and 1 nC are typically used in FEL operation, although charges up to 3 nC are possible as well.

The photocathode laser is based on a mode-locked pulse train oscillator with a chain of single-pass diode and flash-lamp pumped Nd:YLF amplifiers. The electron beam is produced with a Ce_2Te cathode inserted via a load-lock system to the backplane of the RF gun. The RF gun is a 1.5 cell normal conducting copper cavity operated at 1.3 GHz.

Six TESLA type superconducting accelerating modules are used to accelerate the electron beam energy up to 1 GeV. Eight 9-cell standing wave Niobium cavities with a fundamental frequency of 1.3 GHz are mounted into each of the 12 meters long cryo-modules. Modules are bath-cooled by superfluid Helium to 2 K. The first accelerating module boosts the initial 5 MeV beam energy to 130 MeV. After the first bunch compressor, two modules increase the energy to 470 MeV. The last three modules downstream of the second bunch compressor further accelerate the electron beam up to the maximum energy of 1 GeV. The accelerating gradients of the cavities are typically between 20 MV/m and 25 MV/m. Four cavities of the sixth module reach gradients above 30 MV/m.

The accelerating modules are powered by three RF stations consisting of a klystron (two 5 MW klystrons and one 10 MW multibeam klystron), a high voltage pulse transformer and a pulsed power supply (modulator). In addition, the RF gun has its own RF station with a 5 MW klystron. The gradient and phase (vector sum) of the RF gun and the accelerating modules are controlled by a dedicated low level RF (LLRF) regulation system: the RF gun and the first accelerating module by an FPGA (field programmable gate array) based system, and the other modules by DSP (digital signal processor) systems.

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

PRODUCTION OF SASE FEL RADIATION

A high quality electron beam is required to produce SASE FEL radiation. The most relevant electron beam parameters for the lasing process are transverse emittance and peak current. The transverse emittance is optimized in the

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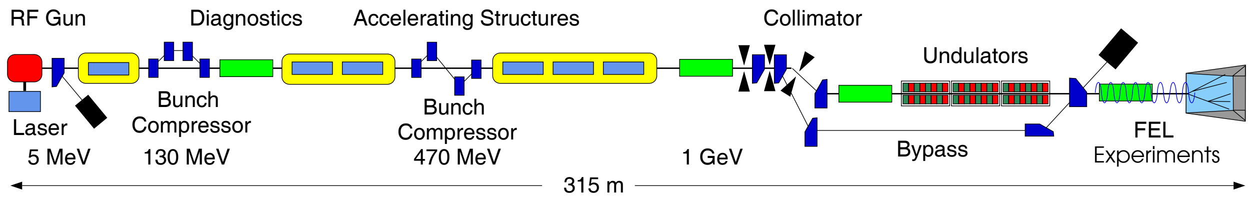

Figure 1: Layout of the FLASH linac during the second user period (not to scale).

injector. At FLASH a typical normalized projected transverse emittance of a 1 nC bunch (on-crest acceleration) is below 2 mm mrad [14]. The required peak current of about 2 kA is reached by compressing the electron bunch by two magnetic chicane bunch compressors. The compression scheme leads to a non-symmetric bunch shape with a leading spike of a high peak current and a long tail. This is due to a non-linear energy chirp along the bunch, which is produced when the initially long electron bunch (about 2 mm) is accelerated off-crest by the first accelerating module.

The SASE process requires a long undulator section. FLASH has six 4.5 m long undulator modules consisting of a periodic structure of permanent NdFeB magnets. Each undulator has a fixed gap of 12 mm, peak magnetic field of 0.48 T, the undulator period 27.3 mm, and the K-value 1.23. Due to fix gap undulators, the wavelength of the produced FEL radiation is determined by the electron beam energy. Thus, the electron beam energy has to be adjusted whenever the photon wavelength needs to be changed.

Stability is an important issue to ensure continuous delivery of high quality FEL radiation. During the last years, several actions have been taken to improve the stability of the FLASH facility. For instance, improvements on the master oscillator system and LLRF phase and amplitude regulations have been carried out. A new optical synchronization system based on the beam arrival time detection is in a test phase, and developments of beam based feedbacks to compensate drifts of electron beam parameters (energy, charge, arrival time, bunch compression, orbit) are ongoing.

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 [15].

SASE PERFORMANCE

A typical average FEL pulse energy delivered to experiments is between 20 and 50 μJ. Occasionally higher pulse energies, up to 100 μJ, have been provided. The peak power of the photon pulses is 1 to 5 GW, and the peak brilliance 10^{29} - 10^{30} photons/s/mrad^2/mm^2/(0.1% bw).

During the second user period, FEL radiation with wavelengths from 6.8 nm to 40.5 nm has been delivered to the user experiments. The most requested wavelengths have been 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.

FEL radiation contains also higher harmonics. Although their pulse energy is significantly smaller than the fundamental radiation ($\sim$ 0.5 % for the third harmonic), user experiments have successfully used the third and fifth harmonics. The shortest wavelength used is 1.59 nm (the fifth harmonics of 7.97 nm).

Due to the non-linear bunch compression scheme, only a fraction of the electron bunch contributes to the lasing process ($\sim$ 20 %): the part which has simultaneously a high peak current, a small energy spread, and a small emittance. Therefore, the produced FEL radiation pulses are extremely short, in the range of 10 to 50 fs depending on details of the compression scheme applied.

OPERATIONAL ISSUES

FLASH is operated 7 days per week, 24 hours per day. A typical operation schema consists of four weeks blocks dedicated to user experiments sandwiched between three weeks blocks of study and improvement periods.

During the second user period from November 26, 2007 to August 16, 2009, more than 300 days have been scheduled for user experiments. This corresponds to 49 % of the total time; 30 % has been reserved for FEL physics studies, including improvements and the preparation of the next user block. The scheduled off-time (11 %) includes weekly maintenance (typically 8 hours every week) and a longer maintenance period 1 to 2 times per year. The remaining 10 % has been dedicated for general accelerator physics studies and other developments.

The total up-time of the FLASH facility during the second user period has been 93 %. During the scheduled user experiments, FEL radiation has been delivered in average 78 % of the time to experiments, totally about 5700 hours. Tuning of the FEL radiation properties has taken 14 %, and the start-up after maintenance or failures 1 % of the time. The 7 % downtime is due to technical failures or other incidents.

About one third of the downtime has been related to the RF stations. Most of it has been caused by failures of two old RF stations, which have been replaced during the upgrade shutdown by new modern ones. An other major downtime source causing 18 % of the downtime is infrastructure failures, especially power cuts and disturbances of cooling water, air conditioning, and temperature stabilization systems. The photocathode laser system, magnet power supplies, photon beamline components, control system, cryogenics, and low level RF regulation are other subsystems contributing considerably to the downtime, between 8 % and 3 % each.

Since every user 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, beam parameters need to be adjusted to each experiment. More than half of the total tuning time has been needed for wavelength changes (55 %). As mentioned above, FLASH has a fixed gap undulator. Therefore, a change of the photon wavelength requires always a change of the electron beam energy, including 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. Part of the tuning time has been required to increase the average pulse energy of the FEL radiation; and to correct the transverse position of the photon beam. Tuning is also mandatory when experiments have special demands, like an exact wavelength or a narrow bandwidth of the wavelength spectrum.

SUMMARY

FLASH is a world-wide unique light source in the VUV and soft x-rays wavelength range providing ultrashort FEL pulses with high brilliance.

During the second user period from end November 2007 to mid August 2009, many FEL user experiments with fundamental photon wavelengths between 6.8 nm and 40.5 nm have been successfully performed. Experiments have also successfully used the third and fifth harmonics of the FEL radiation, the shortest wavelength being 1.59 nm (the fifth harmonics of 7.97 nm). More than 100 publications on experiments performed at FLASH have been published in high level journals.

The up-time of FLASH during user experiments has been 93 %, and about 5700 hours of FEL radiation has been delivered to the experiments. In addition, a significant amount of beam time has been allocated to machine studies to further improve FLASH, as well as to developments related to future projects like the European XFEL and ILC.

After a long shutdown from autumn 2009 to early 2010, the considerably upgraded FLASH facility is now in the commissioning phase. [13] The third FEL user period is expected to start late summer 2010.

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