FLASH UPGRADE AND FIRST RESULTS

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Abstract

The free-electron laser facility FLASH at DESY, Germany finished its very successful 2^{nd} user period late summer 2009. Recently FLASH has been upgraded. The 3^{rd} user period starts in September 2010. In many aspects the upgraded FLASH is an FEL with a new quality of performance. It can provide thousands of FEL pulses per second with wavelengths approaching the carbon 1s absorption edge and the water window. The extension of the photon wavelength range is realized by increasing the electron beam energy up to 1.2 GeV by adding a 7^{th} superconducting accelerating module. The dynamics behavior of the electron beam is improved by installing 3^{rd} harmonic superconducting RF cavities. In addition, an experiment for seeded FEL radiation, sFLASH, is integrated to the FLASH linac. Recently, FLASH achieved a beam energy above 1.2 GeV and lasing at 4.45 nm with a remarkably improved performance.

INTRODUCTION

FLASH [1] is a single-pass high-gain SASE-FEL at DESY (Hamburg, Germany). It has been operated as an FEL user facility since summer 2005. During its first user period, the photon wavelength range was from 47 nm to 13 nm. The first energy upgrade took place in summer 2007: with the installation of a sixth accelerating module the electron beam energy was increased to 1 GeV allowing lasing with wavelengths down to 6.5 nm.

During the second user period from late 2007 to August 2009 more than 300 days of beam time have been devoted to user experiments. Many experiments ranging from diffraction imaging to atomic physics and biology have been successfully carried out resulting in more than 100 publications in highly ranked journals. [2]

The last upgrade of FLASH from September 2009 to February 2010 lead to major modifications, mainly an energy upgrade to 1.2 GeV, the installation of third harmonic RF cavities to linearize the longitudinal phase space, and the realization of a seeding experiment, sFLASH.

We describe here the main modifications and upgrades of the FLASH facility, and their effects on the FLASH performance. Part of the material presented here has been already discussed in proceedings of previous conferences [3–5].

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FLASH LINAC

A schematic layout of FLASH, as it is after the upgrade, is shown in Fig. 1.

Electron bunch trains are produced by a laser driven RF gun. The photocathode laser is based on a mode-locked pulse train oscillator with a chain of single-pass fully diode pumped Nd:YLF amplifiers. The UV laser beam is guided to a Cs_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.

The maximum electron bunch train length is 800 μs thus allowing up to 800 bunches with 1 MHz bunch spacings. Several other discrete bunch spacings between 1 MHz and 40 kHz are possible. In a special mode, 3 MHz can be provided as well. The bunch train repetition rate is now increased from 5 to 10 Hz. The electron bunch charge is variable from about 0.1 nC to 3 nC. The normalized projected transverse rms emittance of a 1 nC bunch (on-crest acceleration) is below 2 mm mrad [6].

FLASH uses TESLA type superconducting accelerating modules. Each 12 m long cryo module has eight 9-cell niobium cavities operated at 1.3 GHz.

The production of FEL radiation is based on self-amplified spontaneous emission (SASE). Besides the small transverse emittance, a high peak current is required for the lasing process. Therefore, the initially long electron bunches are compressed by two magnetic chicane bunch compressors to obtain a peak current in the kA range. The SASE FEL radiation is produced by six 4.5 m long undulator modules. Permanent NdFeB magnets generate a peak magnetic field of 0.48 T with a K value of 1.23 and an undulator period of 27.3 mm. The undulators have a fixed gap of 12 mm. The FEL radiation is transported to the experimental hall over a distance of more than 60 m, where the user experiments are located. Details of the photon beamline and photon diagnostic devices are described in [7].

More details of FLASH and its operation as an FEL user facility before the upgrade can be found, for example, in [4, 8].

ENERGY UPGRADE AND LASING AT 4.45 nm

A seventh TESLA type accelerating module has been added to the FLASH linac to increase the electron beam energy from 1 to 1.2 GeV. The new module is a prototype module for the European XFEL [9]. This module has new high quality cavities and provides an energy gain of up to

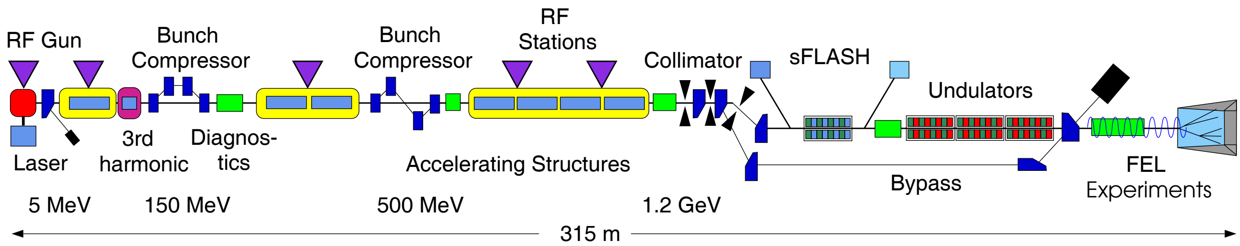

Figure 1: Layout of the FLASH linac after the upgrade (not to scale).

240 MeV. Like several other modules, it is equipped with Piezo-tuners. More details of the module and its performance can be found in [10].

With an electron beam energy of 1.2 GeV, lasing with a photon wavelength of 4.45 nm has quickly been achieved early June, 2010. Single photon pulse energies well above 100 μJ show the remarkably improved performance of the upgraded facility.

The wavelength of 4.45 nm approaches the carbon 1s absorption edge and the water window. Although the whole water window is not yet reachable by the fundamental FEL radiation, it is now within the range of the third harmonic wavelength.

In addition to SASE at 4.45 nm, up to now various wavelengths between 13 nm and 26.5 nm have been used for photon beam line commissioning purposes.

BUNCH COMPRESSION AND THE THIRD HARMONIC MODULE

The required peak current of about 2 kA is achieved by compressing the electron bunch by two magnetic chicane bunch compressors. The compression process leads to a non-symmetric longitudinal bunch shape with a leading high current peak and a long tail (roll-over compression). This is due to a non-linear energy chirp, which is produced along the bunch, when the initially long bunch is accelerated off-crest by a sinusoidal RF field of the accelerating module located upstream of the bunch compressor. In this case, only a fraction of ($\sim$20 %) the compressed electron bunch contributes to the lasing process: the part of the bunch which has simultaneously a high peak current, a small transverse emittance, and a small energy spread. Due to the complicated beam dynamics involved, mainly due to collective effects like coherent synchrotron radiation, and space charge effects in the bunch compressors, the collimator, and dogleg section, the adjustments is delicate and requires continuous fine tuning.

On the other hand, since only a small longitudinal part of the bunch is involved, the duration of the produced radiation pulses is extremely short (10 to 50 fs).

In order to remove the RF induced curvature, a module with four superconducting cavities operated at 3.9 GHz (third harmonic of 1.3 GHz) has been installed downstream of the first accelerating module during the upgrade shutdown. The third harmonic module has been designed and constructed within a collaboration between DESY and FNAL. The first demonstration of its capability to linearize the longitudinal phase space has been succeeded early May 2010 [11], and since then, it has been in routine operation.

When the injector is operated with the third harmonic module, the longitudinal shape of the compressed bunch is more regular and therefore tuning gets easier. A larger fraction of the bunch charge develops a high peak current and contributes to the lasing process. A significant increase in FEL radiation pulse energy is predicted by simulations. [12] This has also been experimentally demonstrated: single photon pulse energies of a couple of hundred microjoules are now reached.

For example, in the case of an initial bunch charge of 1 nC, the FEL pulse duration is predicted to be about 70 fs (fwhh). Shorter pulse durations are expected to be realized with lower bunch charges – equivalent to the previous applied roll-over compression scheme, but now without the development of long tails. [12, 13] Lasing has been experimentally verified for several bunch charges between 0.1 and 1 nC.

Although smaller bunch charges can be produced by the electron source, most of the beam diagnostics and instrumentation devices may not work properly below 100 pC. For instance most BPMs have been designed for bunch charges above 0.5 nC. In parallel to the development effort for the European XFEL, an upgrade of many diagnostic devices is foreseen.

To tune the facility to the desired FEL performance, a characterization of the compression process is important. The transverse deflecting RF cavity provides an excellent tool for this. LOLA, as the transverse deflecting structure of FLASH is called, has been moved from its old location upstream of the collimator to a new location between the sFLASH experiment and the SASE undulators. A dispersive section for phase space measurements (energy – time correlation) has been added. Details on the set-up and first experimental results on electron pulse length and energy spread measurements are presented in [14].

High precision spectrometers [15] and experiments to measure the photon pulse length are in the commissioning phase. Results are expected soon.

SFLASH SEEDING EXPERIMENT

Another new important installation is sFLASH – an experiment for seeded FEL radiation. This experiment is designed and constructed by the University of Hamburg in collaboration with DESY. It is located in the FLASH linac between the collimator and the transverse deflection structure LOLA, upstream of the SASE undulators. In order to realize this experiment, 40 meters of the FLASH electron beam line has been reconstructed. sFLASH consists of a seed laser beam line including an HHG source, an undulator section of 10 meters with four variable gap planar undulators, and a photon beam line to transport the FEL radiation to an experimental hutch located outside the FLASH tunnel. The seed source uses a single shot (10 Hz) high power laser system to generate higher harmonics (HHG) with a wavelength of 38 nm in an appropriate gas cell. Recently, sFLASH reached its first SASE lasing at 38.4 nm. Seeding is expected soon. A detailed description and the present commissioning status is in [16, 17].

INJECTOR

The RF gun has been replaced during the shutdown. The new gun has been tested and operated at the photoinjector test facility PITZ at DESY-Zeuthen. Its main feature is a reduced dark current by a factor of ten [18] due to the new CO_2 cleaning procedure. In addition, an improved cooling scheme allows operation with more RF power. The RF station and the waveguide system have been prepared for an upgrade to a 10 MW multi-beam klystron in the near future.

Unfortunately, the RF window separating the gun vacuum and RF waveguides (partially filled with SF_6 gas at normal pressure), caused a continuous high trip rate. The RF window has been exchanged in June 2010. After a month of conditioning, the FLASH linac was back in operation early July with a reduced RF pulse length of 150 μs. It is expected, that the RF pulse length is steadily increased with conditioning time until full performance is reached.

A second photocathode laser system has been broad into operation. The new system is now fully diode pumped with an improved stability in single pulse energy and phase. It includes new types of Pockels cells and drivers for 3 MHz operation. The old flashlamp pumped laser system is being upgraded as well.

The third harmonic module deaccelerates the electron beam and thus decreases the beam energy. In order to compensate this energy loss, the first accelerating module upstream of the third harmonic module has been replaced. The new module has new high performance cavities, and can thus be operated with significantly higher accelerating gradients (180 MeV energy gain). All the cavities are also equipped with piezo-tuners.

RF AND LLRF SYSTEMS

The RF power is provided by several RF stations consisting of a klystron, a high voltage pulse transformer, a pulsed power supply (modulator, bouncer type), and a low level RF (LLRF) regulation system.

The RF stations feeding the RF gun and the first accelerating module have been completely rebuilt. An additional RF station has been added to optimize the power distribution among the modules. Now all RF stations have similar modern hardware. This eases the operation and maintenance, and thus improves the overall reliability.

The RF gun, the first module, the second and third module together, as well as the fourth and fifth module together have a 5 MW klystron each (see Fig. 1). One 10 MW multibeam klystron feeds the sixth and seventh module. In addition the third harmonic module has its own 3.9 GHz RF system.

All new accelerating modules – modules 1, 6, and 7 – have the new XFEL-type waveguide distribution. It uses asymmetric shunt tees replacing the scheme with hybrids. [19] This allows an adjustment of the power for each cavity pair individually. As a consequence, the operation of a module is not limited any more by the weakest cavity, and thus optimization of the performance of the complete module is obtained.

The phase and amplitude of the accelerating field – the vector sum of all cavities fed by one klystron – is regulated by a low level RF system (LLRF) with feedback and feedforward features. All RF stations are now being upgraded to a modern FPGA (field programmable gate array) based LLRF regulation system. This also includes intra train longitudinal feedback for stabilization of the compression process and arrival time. [20, 21]

OTHER UPGRADES

A survey of the complete linac has been carried out. All accelerator components, have been realigned when necessary. Especially the realignment of the undulator section resulted in an improved pointing accuracy in respect to the photon beamlines.

Upgrades of the control system and infrastructure (water and cryogenics systems) have been accomplished as well.

Important upgrades have been realized in the photon beam lines and photon diagnostics. From the operational aspect, one important upgrade is the set-up of two new photon spectrometers allowing on-line measurements of the photon wavelength spectra.

SUMMARY

The free-electron laser user facility FLASH has been upgraded. The upgrade shutdown has been finished in schedule mid February 2010. After the technical commissioning of all components, and the cool down of the superconducting accelerating modules, the electron beam operation has been established in April 2010. Lasing with a wavelength of 4.45 nm has been achieved early June 2010.

Commissioning of the complete facility, including the photon diagnostics and beam lines, is continuing. The 3rd

FEL user period starts early September 2010.

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