

## FLASH UPGRADE

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### Abstract

The free-electron laser user facility FLASH at DESY has been upgraded. The upgrade started in autumn 2009 after almost 2 years of a very successful second user period. The beam energy is increased to 1.2 GeV by installing a seventh superconducting accelerating module. The new module is a prototype for the European XFEL. Among many other upgrades, third harmonic superconducting RF cavities are installed in the injector. The main purpose is to linearize and - to a certain extent - to shape the longitudinal electron beam phase space improving the dynamics behavior of the beam. The seeding experiment sFLASH is being commissioned, an important step forward to establish seeded FEL radiation for user experiments. After the ongoing commissioning, the third user period is scheduled to start late summer 2010. In many aspects FLASH will be an FEL with a new quality of performance: a wavelength approaching the carbon edge and the water window, tunable pulse width, and with thousands of pulses per second. This report summarizes the recently finished upgrade and reports on the results of the ongoing commissioning and the expected performance as a free electron laser user facility.

### INTRODUCTION

FLASH [1], the free-electron laser (FEL) user facility at DESY (Hamburg, Germany), finished its second user period mid August 2009 [2, 3]. During  $\sim 300$  days devoted to user experiments, several tens of experiments ranging from diffraction imaging to atomic physics and molecular biology have been successfully carried out [4].

A period of five weeks from mid August to end September 2009 was devoted to an experiment to operate the FLASH linac with full beam loading using  $800 \mu\text{s}$  long electron bunch trains and a beam current of 9 mA. The first half of the time was used to prepare the FLASH linac and its subsystems for the long bunch train operation, and the second to the beam operation. The data-analysis of the experiment is still ongoing and the results will be published later.

An upgrade of the FLASH facility has taken place from autumn 2009 to early 2010. During a 5 months shutdown, several major modifications have been realized, among them an energy upgrade to 1.2 GeV, and installation of third harmonic RF cavities to linearize the longitudinal phase space. In this paper, these upgrades and their effects on

the performance of the FLASH facility are described. Part of this material has been already published in proceedings of previous conferences [3, 5].

### FLASH LINAC

FLASH consists of an electron source to generate a high quality electron beam, a superconducting linac of TESLA type accelerating modules, and an undulator section to produce FEL radiation. Figure 1 shows a schematic layout of FLASH, as it is after the upgrade described in this paper.

Electron bunch trains are produced by a laser driven RF gun. During the second user period, the bunch train repetition rate has been fixed to 5 Hz, but is now increased to 10 Hz. The maximum train length is  $800 \mu\text{s}$  and the spacing between the bunches in a train variable: several discrete spacings between 1 MHz and 40 kHz are possible. Operation with long bunch trains allows FLASH to produce thousands of FEL pulses per second.

The RF gun is a 1.5 cell normal conducting L-band cavity with a  $\text{Ce}_2\text{Te}$  cathode inserted on its backplane. The new photocathode laser is based on a mode-locked pulse train oscillator with a chain of single-pass fully diode pumped Nd:YLF amplifiers.

FLASH uses TESLA type superconducting accelerating modules. Each 12 m long cryo-module has eight 9-cell niobium cavities operated at 1.3 GHz. Modules are bath-cooled by superfluid Helium to 2 K.

The SASE (self-amplified spontaneous emission) FEL radiation is produced by a 30 m long undulator section. The undulators consist of a periodic structure of permanent Nd-FeB magnets and have a fixed gap of 12 mm. The produced radiation is guided via a photon transport line to the experimental hall, where the user FEL experiments are located [6].

FLASH - as it was before the upgrade - and its operation as an FEL user facility are described in more detailed, for example, in [2, 3].

### ENERGY UPGRADE

Room for seven TESLA type accelerating modules has been foreseen already in the original design of the FLASH linac. During the upgrade shutdown, a seventh accelerating module has been added to the end of the existing module chain. The new module is a prototype module for the European XFEL [7] with an energy gain of more than 200 MeV. More details of the module and its performance can be found in [8].

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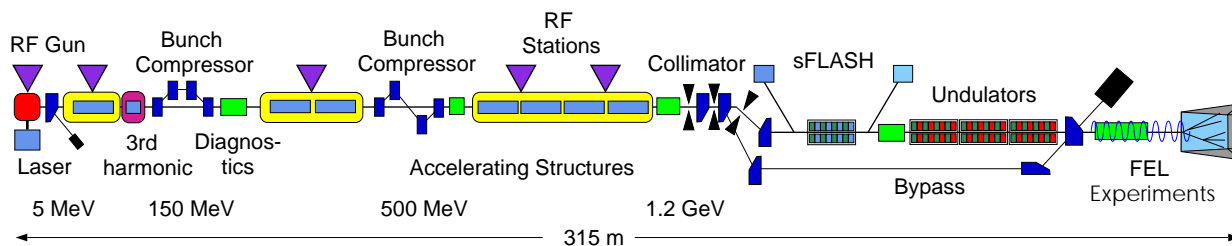


Figure 1: Layout of the FLASH linac after the upgrade (not to scale).

The achievable electron beam energy of the upgraded FLASH linac has been demonstrated beginning of May 2010: an electron beam has been accelerated to 1.2 GeV (on-crest acceleration) corresponding to a photon wavelength just below 5 nm. The demonstration of the lasing with the shortest achievable wavelength is foreseen in June 2010.

## BUNCH COMPRESSION AND THE THIRD HARMONIC MODULE

At FLASH, the electron beam peak current of about 2 kA is required for the lasing process. It is reached by compressing the electron bunch by two magnetic chicane bunch compressors. Due to off-crest acceleration of the initially relative long electron bunch by a sinusoidal RF field of the accelerating module, a non-linear energy chirp is produced along the bunch. Therefore, the compression process leads to a non-symmetrical longitudinal bunch shape with a leading high current peak and a long tail. Only a fraction of the compressed 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. As a consequence, the duration of the radiation pulses is very short: in the range of 10 to 50 fs.

The RF curvature can be removed by third harmonic cavities. During the upgrade shutdown, a module with four superconducting cavities operated at 3.9 GHz (third harmonic of 1.3 GHz) is installed downstream of the first accelerating module. The third harmonic module has been designed and constructed within a collaboration between DESY and FNAL. More details, including commissioning status, are in [9].

The longitudinal shape of the compressed bunch is expected to be more regular when operating the linac with the third harmonic module. As a consequence, a larger fraction of the bunch charge develops a high peak current, and thus contributes to the lasing process. A significant increase in FEL radiation pulse energy is predicted by simulations. On the other hand, for a charge of 1 nC, the FEL pulse duration is expected to increase to  $\sim 200$  fs. Shorter pulse lengths can be realized when a lower bunch charge is used. The demonstration of lasing with third harmonic module in operation is foreseen in summer 2010.

With the third harmonic module switched off, FLASH is operated, as before, in the short (femtosecond) pulse

mode. Intermediate modes are also anticipated providing more flexible beam parameters for user experiments.

## SFLASH SEEDING EXPERIMENT

A seeding experiment, sFLASH, is designed and constructed by the University of Hamburg in collaboration with DESY. Its goal is to demonstrate the applicability of seeded FEL radiation for user experiments.

The sFLASH experiment is located in the FLASH linac between the collimator and SASE undulators. In order to realize it, 40 meters of the FLASH electron beam line has been reconstructed. The experiment consists of a seed laser beam line, an undulator section of 10 meters with four variable gap undulators, and a photon beam line to transport the FEL radiation to an experimental hutch located outside the FLASH tunnel. A detailed description of sFLASH and its present commissioning status is in [10].

## OTHER UPGRADES

The RF gun has been replaced by a new gun commissioned and tested at the photoinjector test facility PITZ at DESY-Zeuthen. The new gun has by a factor of ten reduced darkcurrent [11]. An improved cooling scheme allows an operation with more RF power.

The first accelerating module - one of the oldest TESLA type modules - has been replaced by a cryo-module furnished with new high performance cavities. This upgrade increases operating gradients of the module, allowing thus to compensate the energy loss caused by the third harmonic module. The new cavities are equipped with piezo-tuners, which eases operation with long electron bunch trains.

The RF stations feeding the RF gun and the first accelerating module have been upgraded: the old modulators and transformers are exchanged by modern ones, and the complete electronics has been upgraded. Now all RF stations have similar modern hardware facilitating the operation and maintenance, and thus improving the overall reliability.

In order to optimize the operation with seven accelerating modules, a fifth RF station is connected to the FLASH linac. The RF gun and the first module is operated by one 5 MW klystron each. The RF station and the waveguide system of the RF gun have been, however, prepared to an operation with a 10 MW klystron in the future. The second

and third module have one common 5 MW klystron, as well as the fourth and fifth module. The sixth and seventh module are operated by one 10 MW multibeam klystron. The third harmonic module has its own 3.9 GHz RF system.

The low level RF (LLRF) system regulating the phase and amplitude of the accelerating modules have been upgraded. Now all modules are controlled by a similar modern FPGA (field programmable gate array) based system. In addition, the cabling of the injector LLRF electronics has been revised to improve stability, and a second master oscillator has been installed as a backup.

A transverse deflecting RF cavity is an important tool to measure the longitudinal structure of electron bunches as well as the slice beam parameters. The FLASH transverse deflecting structure, previously located downstream the accelerating modules, is moved to a new location close to the SASE undulators. In order to allow a complete measurement of the longitudinal phase space, a dispersive section has been added.

The photon beam lines and the photon diagnostics have been upgraded as well. One of the most important upgrades for the FLASH operation is a photon spectrometer allowing on-line measurements of the photon wavelength.

The injector corrector magnets have been replaced by new magnets with a low remnant field. The photocathode laser system has been upgraded: a new diode pumped laser system is now in operation, and the old laser system, which will be upgraded in the near future, stays as backup. A survey of the complete linac has been carried out, and all accelerator components, including the SASE undulators, are realigned when necessary. Upgrades of the control system and infrastructure (water and cryogenics systems) have been accomplished as well.

## STATUS AND OUTLOOK

The upgrade shutdown has been finished in schedule mid February 2010. The following two months have been devoted to the technical commissioning of the linac and its subsystems, including, for example, commissioning of magnet power supplies, conditioning of the RF gun, cool-down of the accelerating modules, and adjustments of the RF and LLRF systems. Electron beam operation has been established in April 2010, and the first lasing is expected in June 2010. The long bunch train operation restarts as well in the summer. The third FEL user period is scheduled to start late summer 2010.

## SUMMARY

The free-electron laser user facility FLASH has been upgraded, and is now in the commissioning phase. The upgraded facility will be in many aspects an FEL with a new quality of performance. Its shortest photon wavelength is expected to be just below 5 nm, it provides thousands of FEL pulses per second and has to some extent tunable photon pulse length. The seeding experiment sFLASH, inte-

grated to the FLASH linac, is an important step forward to establish seeded FEL radiation for user experiments in the future.

## ACKNOWLEDGMENT

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