sFLASH - FIRST RESULTS OF DIRECT SEEDING AT FLASH*

J. Bödewadt†, A. Azima, F. Curbis, H. Delsim-Hashemi, M. Drescher, E. Hass, U. Hipp,
T. Maltezopoulos, V. Miltchev, M. Mittenzwey, M. Rehders, J. Roßbach,
J. Rönsch-Schulenburg, R. Tarkeshian, M. Wieland, University of Hamburg, Germany
S. Bajt, S. Düsterer, K. Honkavaara, T. Laarmann, H. Schlarb, DESY, Hamburg, Germany
S. Khan, DELTA, Dortmund, Germany
R. Ischebeck, PSI, Villigen, Switzerland

Abstract

The free-electron laser facility FLASH at DESY (Hamburg) was upgraded during a five month shutdown in winter 2009 [1]. Part of this upgrade was the installation of a direct seeding experiment in the XUV spectral range. Beside all components for transport and diagnostics of the photon beam in and out of the accelerator environment, a new 10 m long variable gap undulator was installed upstream of the existing FLASH undulator system. The seed pulses are generated within a noble gas jet by focusing 40 fs long Ti:Sa laser pulses into it resulting a comb of higher harmonics. In the first phase of the experiment the 21st harmonic of the 800 nm drive laser will be used to seed the FEL process. The commissioning of the experiment has started in April and the first results are expected after the FLASH commissioning period mid of summer 2010. The experimental setup and the commissioning procedures as well as first result will be presented.

INTRODUCTION

The FEL user facility FLASH consists of a 1.2 GeV superconducting linac and 27 m long fixed-gap undulator, producing XUV pulses based on the SASE principle with variable pulse length. During the upgrade in 2009 some major modifications and installations of new components were made e.g. a new RF gun, a 7th accelerator module, new RF systems and 3rd harmonic superconducting RF cavities [2] to name but a few. In addition, 40 m of the electron beamline between the energy collimator and the existing SASE undulators were modified to install a new variable-gap undulator system for a direct seeding experiment.

Direct Seeding With High Harmonics

So far, XUV and X-ray radiation produced by FEL facilities was generated using the SASE principle to achieve high peak intensities at the GW level. In this operation mode the laser pulses consist of a number of uncorrelated longitudinal modes due to the start-up of the amplification process from shot noise of the electron bunch. The results are a reduced longitudinal coherence and shot-to-shot fluctuation of 18% (rms) [3]. Another limitation for time-resolved user experiments is the arrival time jitter of the electron bunches and the photon pulses respectively. Although some of these pump-probe experiments can measure the arrival time of each individual photon pulse with an acurracy of 40 fs (rms) to sort the experimental data afterwards [4] [5], this method has its own limitations. Other approaches reducing the arrival time jitter measuring the electron bunch arrival time with fs temporal resolution and applying a feedback on the RF systems to stabilize accelerating gradients and phases of each individual accelerating module [6]. The obvious solution to have a high temporal resolution for pump-probe experiments is to get the pump and the probe pulses from the same source. If in addition the experiments need high XUV intensities a directly seeded FEL is presently a promising way to achieve these requirements. The XUV seed pulses for such an experiment are delivered by the generation of higher harmonics (HHG) of near-infrared (NIR) laser pulses in rare gases [7]. The first seeding experiment with an HHG source was performed at SCSS [8] in 2008 showing the possibility of combining the advantages of an FEL and a high coherent XUV source. At FLASH the direct seeding with higher harmonics below 40 nm is presently under study and first pump-probe experiments with this seeded FEL are going to be performed soon. One of the key challenges of seeding is to establish the six-dimensional overlap between electrons and seed photons within the undulator, namely the transverse position and angle of both beams in vertical and horizontal plane, the longitudinal overlap and the spectral overlap. In addition, a matched transverse beam size of photons and electrons guaranties an optimal utilization of the seed pulse energy. Numerical studies were performed in order to set the tolerances for the seeding at sFLASH [9].

EXPERIMENTAL SETUP

The general layout of the sFLASH installation is shown in Fig. 1. The two laboratories adjacent to the FLASH tunnel and the sheath tubes which support the vacuum beam pipes for the photon beams were erected in previous shutdown periods.

Laser System, Seed Source and HHG Diagnostics

The seeding source based on HHG is driven by a CPA laser system at a repetition rate of 10 Hz matching the rate

---

* Supported by the Federal Ministry of Education and Research of Germany under contract 05 ES7GU1

† corresponding author: joern.boedewadt@desy.de

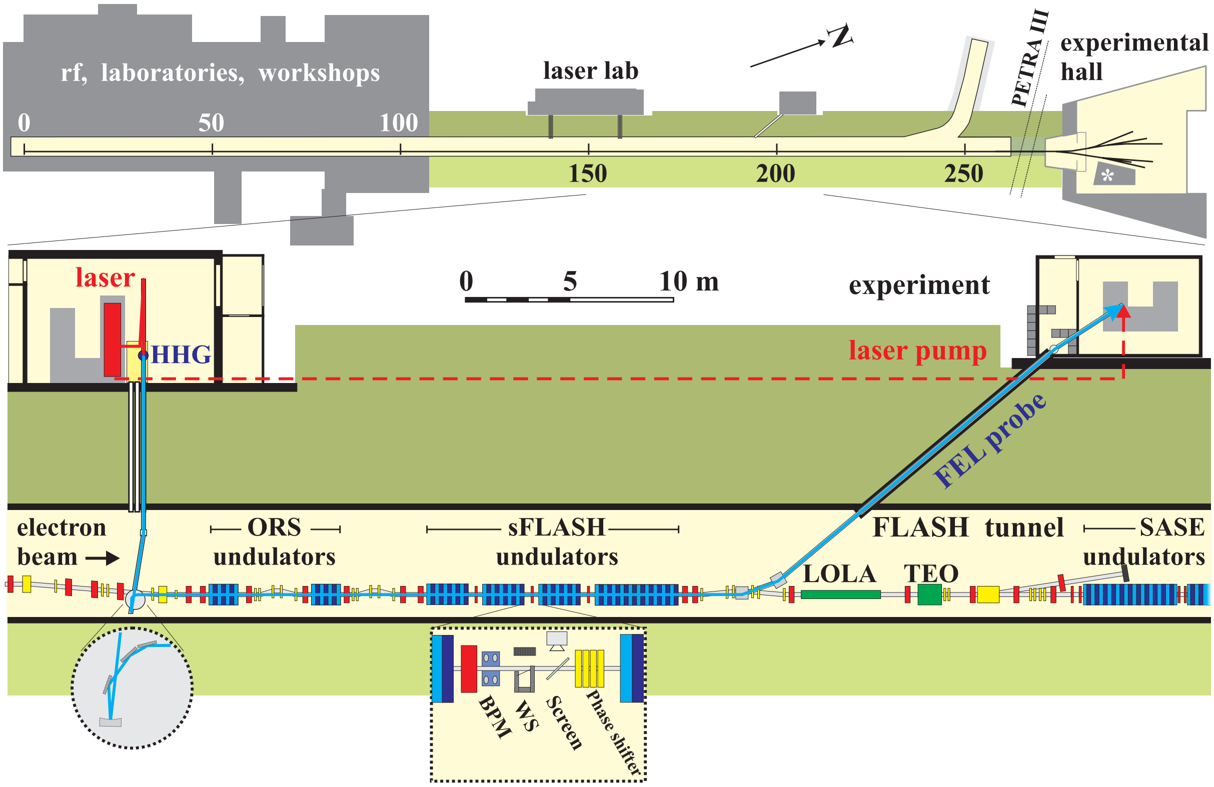

Figure 1: The FLASH facility (top) comprises a 260 m long tunnel housing the linac and undulators of a SASE FEL, followed by an experimental hall. A 40 m long section (bottom) preceding the SASE undulators was modified to accommodate four additional undulators for sFLASH. Seed pulses from the HHG source in the building adjacent to the FLASH tunnel are aligned to the electron beam at the last dipole of the accelerator energy collimator (left). At the undulator exit, the electron beam is displaced while the FEL radiation is sent by mirrors to an experimental hutch. Delayed laser pulses will be sent directly to the hutch for pump-probe applications (dashed line). Also shown are dipole magnets and steerers (yellow), quadrupoles (red) and devices for longitudinal bunch diagnostics (ORS, LOLA and TEO). The dashed bordered boxes show detailed views of the seed injection and the undulator intersections.

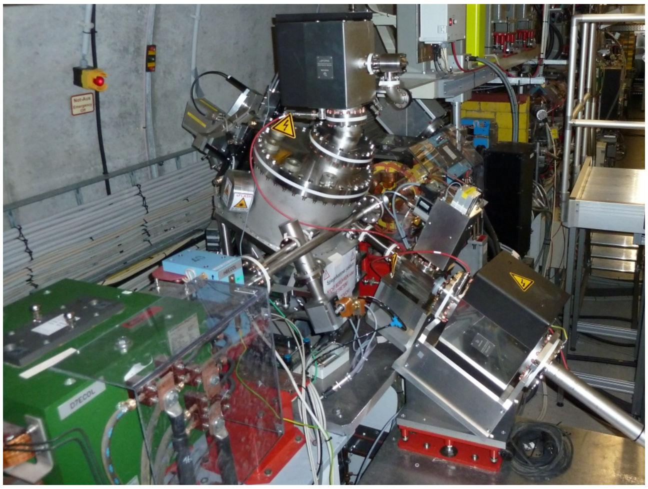

Figure 2: View of the second mirror chamber of the seed injection beamline.

of bunch trains at FLASH. Pulses from a Ti:Sapphire oscillator, that is synchronized to the 1.3 GHz master oscillator clock of the accelerator RF, are amplified in a combined regenerative and multipass-amplifier. It produces ultra short (35 fs) pulses with a pulse energy of up to 50 mJ. The mean pulse energy stability is in the order of a few percent being at the limit given by the flash lamp driven pump laser of the amplifier system. Roughly 20 mJ are transported to the HHG vacuum chamber that is located in a pit beneath the optical table (see Fig. 3), where the HHG is carried out in a noble gas filled capillary. The remaining pulse energy can be guided in a dedicated laser beamline to the experimental container at the end of the seeding setup. This enables measurements on the temporal properties of the seeded radiation. The XUV beam is directly steered into the accelerator tunnel, or for diagnostic purposes of the generated harmonic comb back onto the optical table by means of two triplet mirror systems. Here, an XUV spectrometer for the spectral characterization as well as an imaging setup for the measurement of the XUV beam near- and far field are available. In a first step, the 21st harmonic of the Ti:Sa laser at 32 eV or 38 nm will be used for seeding. Under the present conditions, the HHG source delivers a well collimated beam with a divergence of 0.5 mrad (FWHM) and a pulse energy in the order of a few nJ contained in the 21st harmonic. First preliminary wave front measurements using a Hartmann Sensor indicate a well behaved and undistorted wave front of the required harmonic 21.

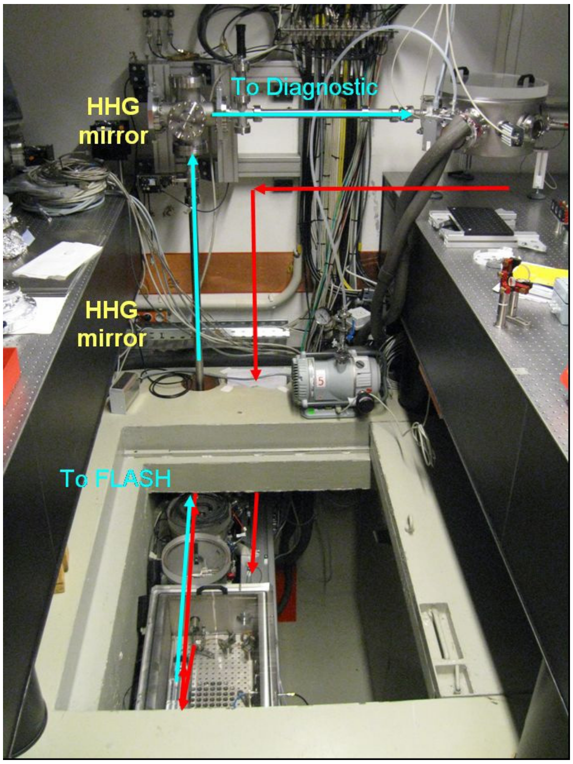

Figure 3: View into the pit where the HHG source is adapted to the transport beamline to the accelerator tunnel.

Injection Beamline

In order to transport and focus the XUV radiation of the HHG source into the sFLASH undulator a dedicated 12 m long beamline is installed at the end of the energy collimator section of the linac. The last dipole magnet of this energy collimator bends the electron beam by 3.5 ° and gives the possibility to align the photon beam to the e-beam reference axis. One UHV mirror chamber steers the beam to the level of the e-beam using a grazing incidence at 13.9 °. Another mirror chamber focuses the XUV beam using a multilayer normal incidence spherical mirror and deflects the beam with a mirror triplet with 14.1 ° grazing incidence at each mirror finally onto the undulator axis. The grazing mirror substrates are coated with TiB4C for wavelengths around 38 nm and with MoB4C for 13 nm. The exchange of these mirrors is remotely controlled. XUV focusing can be done by six different mirrors (see Fig. 2) giving the option of two different wavelengths (Si/Sc and Mo/Si multilayer coating) and three different focal lengths (f1 = 6.25 m; f2 = 7 m; f3 = 8.5 m). From simulations the overall transmission of the beamline, taking all polarization effects into account, is about 8% at 38 nm. The alignment of the XUV beam with the electron beam will be done by changing the transverse position of the focal mirror and by tilting the first grazing incidence mirror. Assuming a tolerance for the radiation power of the seeded FEL of 5% the simulation shows a maximum acceptable offset of 35 μm and a maximum angle of 20 μrad for the two beam with respect to each other. Based on that numbers the position and angle adjustment tolerances for the photon beam were set to 10 μmm and 5 μmrad respectively.

Transverse Overlap Diagnostics

Along the sFLASH undulator beamline several diagnostic tools are used to measure the transverse position and profile of the electron or the photon beam respectively. Eight beam position monitors (BPM) [10] and eight optical transition radiation (OTR) screens are used to measure the transverse electron beam parameter and to match the electron beam in the seeding undulator. Two OTR stations are equipped with the standard optics developed for TTF2 [11]. The others use specially designed solutions for the particular geometries, two at the diagnostic stations of the optical replica experiment (ORS) [12], and four in the sFLASH undulator. The latter optics is also used to image a cerium-doped YAG crystal which converts the XUV radiation from the HHG source into visible light. With that it will be possible to directly measure the transverse overlap of the XUV and the electron beam.

Longitudinal Overlap Diagnostics

The temporal overlap of the electron bunches and the laser pulses will be found with using two methods. Firstly, a streak camera based approach will be employed that simultaneously measures the remnant 800 nm laser and undulator radiation from the electron beam. Later, a finer resolution ORS-based [12] system will be used in which the 800 nm laser imprints an energy modulation onto the electron beam, which will be used to produce a coherent radiation signal [13]. The streak camera is placed close to the electron beamline in a special shielded container to protect the electronics against radiation damages. A remotely controlled optical beamline guides the synchrotron light from an electro-magnetic undulator and the 800 nm laser light to the entrance slit of the camera. Different sets of band-pass and neutral-density filters allow attenuating the two beams to get equal intensities within a certain bandwidth. The coarse temporal overlap (1 ns) will be measured with a photo-multiplier or a photo diode. After that the two pulses need to be found with the largest time window (500 ps) of the streak camera in order to increase the resolution consecutively to about 1 ps. From this point on a fine scan of the temporal overlap with step sizes of a few ten femtoseconds will be done.

Undulators and Electron Beamline

sFLASH comprises a 10 m long undulator section. Unlike the FLASH undulators, these are variable-gap devices.

Three 2 m long U32 undulators are followed by a 4 m long U33 undulator. The latter is a previously decommissioned device which is reused for sFLASH after refurbishment [14]. Undulator parameters are listed in Table 1. Both types are hybrid structures built with NdFeB magnets and Vanadium Permendur poles. An intersection of 700 mm length is placed between the undulators which contains the quadrupole, diagnostic components, an ion getter pump, and a compact electromagnetic phase shifter. The latter corrects the gap-dependent phase advance from one undulator to the next. Additionally, a set of small air coils is located upstream of all undulators in order to compensate residual field integrals. The undulator vacuum chamber uses the achievements of XFEL [15] (see Fig. 4). Taking into consideration the vertical size of the vacuum chamber (8.6 mm) and the minimum desired undulator gap size (9 mm), a sophisticated support and holder system was to adjust and maintain the position of the chamber within the undulator gap.

Table 1: Parameters of sFLASH undulators

	U32	U33
Min. gap [mm]	9.0	9.8
Period length [mm]	31.4	33
No. of poles	120	240
Length [m]	2	4
K value	2.72	3.03

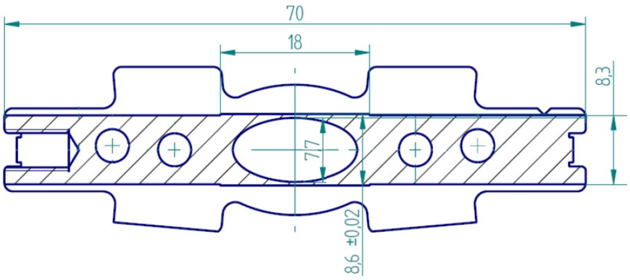

Figure 4: Cross-section of the undulator vacuum chamber

FEL Beamline and Photon Diagnostics

After the undulator section, the electron beam is vertically displaced by a magnetic chicane and the FEL radiation is extracted by a deflecting mirror. The photon beamline continues with the first diagnostic block equipped with a Ce:YAG screen and two cameras, then a second switching mirror allows to send the radiation either into the diagnostic branch (that includes intensity monitor and XUV-spectrometer [16]) or into the experimental hutch outside the tunnel where time-resolved pump-probe studies can be performed with high temporal resolution. A port for an alignment laser is placed before the first diagnostic block. The mirrors are plane amorphous carbon coated silicon substrates with grazing incidence at 3.33 ° for the first chamber and 5 ° for the second. The reflectivity at this angle is typically better than 85%. A portion of the mirrors has larger roughness resulting in the attenuation on the detectors [17].

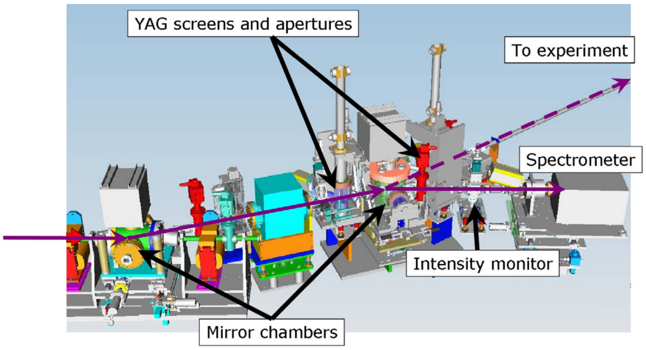

Figure 5: Layout of the diagnostic branch. The FEL radiation, coming from left, is deflected in the first mirror chamber and through a diagnostic unit. The second mirror chamber allows to send the beam either to an intensity monitor and an XUV-spectrometer or to the experimental hutch outside the accelerator tunnel.

Pump-Probe Beamline and Lab

Two 40 m long pump laser beam pipes were built connecting the laser laboratory for the seed laser and the experimental hutch. Both pipes will be evacuated to avoid distortions of the infrared laser beam. The installation work for the user laboratory is finished and the vacuum photon beamline for the seeded FEL is completed and ready to connect the first experimental set ups. The first experiments are going to characterize the seeded FEL pulses and to perform first tests on the temporal resolution that can be expected for later pump-probe experiments.

COMMISSIONING RESULTS

Since March 2010 all described components were installed and technically commissioned. Dedicated beam time was arranged to get the individual devices and procedures for finding the transverse and the temporal overlap into operation.

Seed Source and Transport

The source was installed successfully at the entrance of the injection beamline. Following alignment of the harmonics to the first diagnostics in the linear accelerator area, spectra of the HHG frequency comb of Argon source were recorded. Figure 6 shows the result of such a measurement. The transport beamline was aligned using the following procedure. One alignment laser beam was placed coaxial to the electron beamline and was centred thought the undulator chamber. After this all screens were aligned to this beam axis and markers were set. The FEL extraction mirror chambers were aligned in order to centre the beam on the spectrometer slit. A second alignment laser beam placed on the laser table of the HHG drive laser was send through the complete injection beamline including the HHG source chambers. The two injection beamline mirror chambers iteratively were aligned until this second beam was centred on all marked positions.

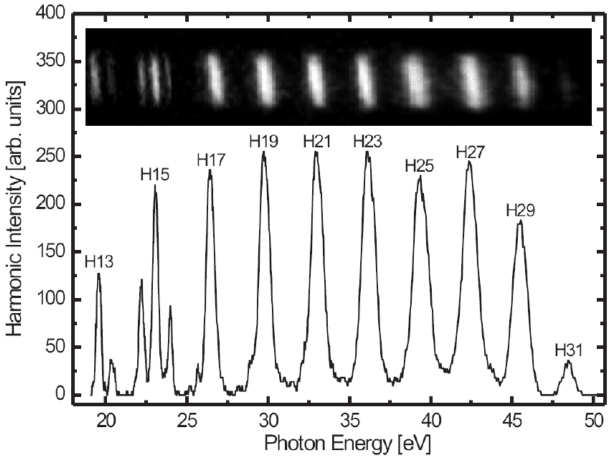

Figure 6: The high-harmonics spectrum of the sFLASH seed Argon source. The 21st harmonic will be used as the seed for sFLASH.

Overlap Diagnostics

The new transverse beam monitors for electron and XUV photon diagnostics are in operation and were integrated in the standard operation tools of the FLASH control system. Figure 7 shows the beam profile of the XUV beam at the entrance of the sFLASH undulator. The streak camera for adjusting the temporal overlap of the electron and the seed pulses of the order of a few picoseconds is operating remotely controlled without any problems in terms of system crashes due to radiation dose.

Undulator System

Regarding the order of the three U32 undulators, the one with the best magnetic field error properties should be placed in the beginning of the seeding section. In the present case, all U32 easily meet the magnetic specification. Differences in their field quality are insignificant in this respect. Therefore, the sequence of the devices has been chosen such that the gap dependence of the residual downstream kick of one undulator is at least partly compensated by the upstream kick of the following undulator. The remaining kicks are corrected by one set of steering coils shared by both devices. Owing to a slim design of the undulator vacuum chamber [18], chamber and undulator could be successfully aligned with respect to each other, even with a nominal space of only 0.15 mm at each side while preserving the minimum magnetic gap [14]. During the commissioning period the complete undulator system was tested. Beam-based orbit response measurements for each undulator module for varying gap sizes were performed in order to create correction tables for horizontal and vertical air coils.

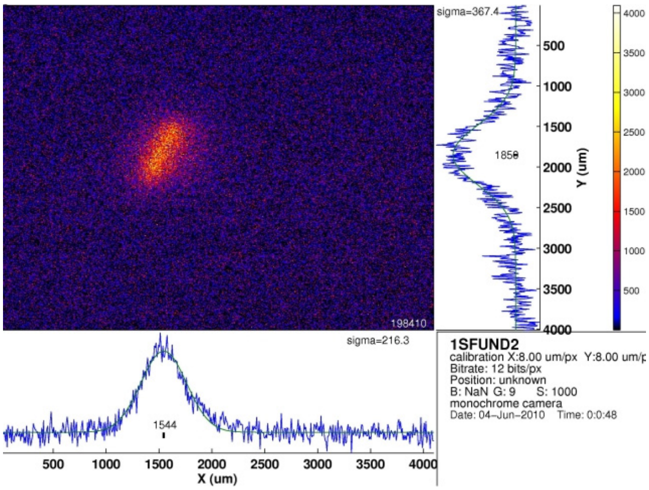

Figure 7: Beam size measurement of the XUV beam at the undulator entrance using a Ce:YAG screen.

FEL Diagnostics

First tests of the FEL diagnostics after installation were performed using the higher harmonic beam from the seed source. Figure 8 shows the spectrum of the source at the XUV spectrometer following the sFLASH undulator. The reduction of the intensity of the adjacent harmonics is due to the narrow bandwidth of the reflectivity from the normal incident focal mirror in the injection beamline.

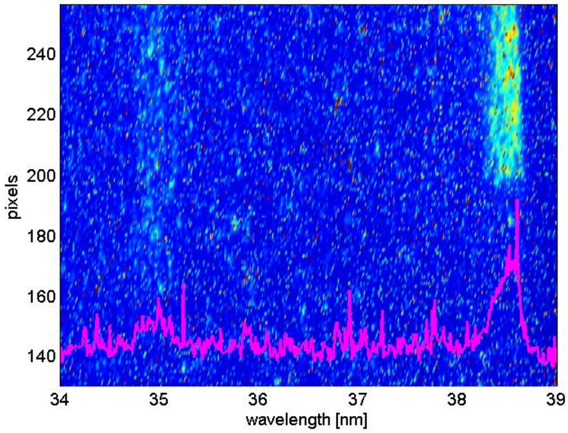

Figure 8: First spectrum of the seed source measured at the FEL diagnostic branch.

CONCLUSION AND SUMMARY

Presently a direct seeding experiment in the XUV spectral range is going to be commissioned at FLASH. All hardware components auch as new variable-gap undulators, vacuum beamlines for injecting the seed beam and extracting the FEL beam plus the diagnostics to establish transverse and longitudinal overlap were installed during the shutdown period in winter 2009/2010. The HHG source operating with Argon is able to deliver seed pulses at wavelength around 38 nm over many hours of beam time. The XUV spectrometer and the intensity monitor in the FEL diagnostic branch were tested and first spectra from spontaneous undulator radiation have been taken. Currently the procedures to find the six-dimensional overlap are improved. The first seeded operation of the system is planned for September 2010 after the first user period at FLASH.

ACKNOWLEDGMENTS

Without the help from many groups at DESY (among them FLA, HASYLAB, MCS, MEA, MIN, MKK, MPY, MVS, ZBAU and ZM) the preparation and commissioning of all sFLASH components would not be conceivable. Their support is gratefully acknowledged. Special thank also to Volker Ziemann for the help during the recommissioning of the ORS beamline components. The project is supported by BMBF under contract No. 05 ES7GU1.

REFERENCES

[1] S. Schreiber et al., *FLASH upgrade and first results*, these proceedings, TUOBI2

[2] K. Flöttmann et al., *Generation of ultrashort electron bunches by cancellation of non-linear distortions in the longitudinal phase space*, TESLA-FEL-2001-06.

[3] W. Ackermann et al., *Operation of a free-electron laser from the extreme ultraviolet to the water window*, Nature Photonics 1 (2007), 336.

[4] A. Azima et al., *Jitter reduced pump-probe experiments*, Proceedings DIPAC'07, Venice, 337.

[5] T. Maltezopoulos et al., *Single-shot timing measurement of extreme-ultraviolet free-electron laser pulses*, 2008 New J. Phys. 10 033026

[6] F. Löhl et al., *Measurement and stabilization of the bunch arrival time at FLASH*, Proceedings EPAC'08, Genoa, 3360.

[7] C. Winterfeldt et al., *Optimal control of high-harmonic generation*, Rev. Mod. Phys. 80 (2008), 117.

[8] G. Lambert et al. *Injection of harmonics generated in gas in a free-electron laser providing intense and coherent extreme-ultraviolet light*, Nature Physics 4 (2008), 296.

[9] V. Miltchev et al., *Tolerance studies on the high harmonic laser seeding at FLASH*, Proceedings FEL'08, Gyeongju, 235.

[10] N. Baboi et al., *Beam position monitor calibration at the FLASH linac at DESY*, Proceedings of PAC'07, Albuquerque, 3937.

[11] K. Honkavaara et al., *Design Of OTR Beam Profile Monitors For The TESLA Test Facility, Phase 2 (TTF2)*, Proceedings of PAC'03, Portland, 2467

[12] S. Khan et al., *Results from the optical replica experiments at FLASH*, Proceedings FEL'08, Gyeongju, 497.

[13] R. Tarkeshian et al., *Femtosecond temporal overlap of injected electron beam and EUV pulse at sFLASH*, Proceedings IPAC'10, Kyoto, 915.

[14] M. Tischer et al., *Undulators of the sFLASH experiment*, Proceedings IPAC'10, Kyoto, 3114.

[15] M. Altarelli et al. (Eds.), *The european X-ray free electron laser*, Technical Design Report, DESY 2006-097

[16] McPerson 248/310G; http://www.mcphersoninc.com

[17] F. Curbis et al., *Photon diagnostic for the seeding experiment at FLASH*, Proceesings FEL'09, Liverpool, 754.

[18] H. Delsim-Hashemi et al., *Status of the sFLASH undulator system*, Proceedings FEL'09, Liverpool, 500.