EXPERIMENTAL LAYOUT OF 30 nm HIGH HARMONIC LASER SEEDING AT FLASH*

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Abstract

Since 2004, the Free-electron-LASer at Hamburg (FLASH) has operated in the Self-Amplified Spontaneous Emission (SASE) mode, delivering to users photon beams with wavelengths between 6.5 nm and 40 nm. In 2009, DESY plans to install a 3.9 GHz RF acceleration section for the production of electron bunches with high peak currents ($\sim$kA), but ten times larger pulse durations compared to the present configuration. The relaxed timing requirements of the new configuration make it possible to externally seed FLASH with high harmonics of an optical laser (sFLASH). The aim of the project is to study the technical feasibility of seeding a free-electron-laser (FEL) at 30 nm with a stability suited for user operation. sFLASH will use 10 m of gap-tuneable undulators installed upstream of the fixed-gap SASE-undulator. A chicane behind the seeding undulators will allow extracting the output radiation for a careful characterisation and for first pump-probe experiments with a resolution of the order of 30 fs by combining the FEL and the optical laser pulse.

INTRODUCTION

Currently FLASH operates in the SASE regime and produces EUV pulses of sub-10 fs duration [1]. Due to its start-up from noise, the SASE radiation consists of a number of uncorrelated modes resulting in reduced longitudinal coherence and shot-to-shot fluctuations (about 18 % rms [1]) of the output pulse energy. One possibility to decrease the magnitude of these fluctuations is, with the help of a 3.9 GHz RF cavity [2], to produce much longer ($\sim$200 fs) radiation pulses, so that more modes contribute to the FEL output. However, in this case the increased EUV pulse length might not fit to the needs of ultrafast time resolved experiments. An alternative is to operate FLASH as an amplifier of an injected seed from a high harmonic generation (HHG) source. This approach gives several benefits compared to SASE. It makes possible to achieve higher shot-to-shot stability at GW-power level with a pulse duration given by the seed pulse of the order of 20 fs FWHM. The longitudinal coherence is expected to be greatly improved. The FEL output is synchronized with the external seed laser, thus enabling precise pump-probe experiments to be performed. As sketched in Fig.1, sFLASH will be installed at the end of the linac, upstream of the existing fixed-gap SASE-undulators. With the help of a dedicated optical beamline, the HHG seed will be inserted through the collimator section, making use of the electron beam offset of about 20 cm. After amplification in the sFLASH variable-gap undulators, the output radiation is separated from the electrons by means of a mirror mounted in a small magnetic chicane downstream. The photons are then reflected towards the experimental area outside the FLASH tunnel. An experiment recently performed by a French-Japanese collaboration in SPring-8 Compact SASE Source [13] has successfully demonstrated HHG seeding at 160 nm. The goal of sFLASH is to study the technical feasibility of the seeding at shorter wavelengths and how to reliably realize it for user operation. In the following the main components of the experimental setup will be reviewed.

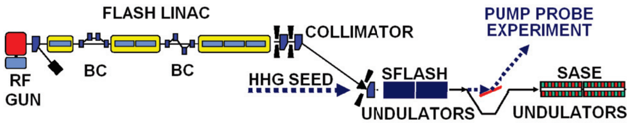

Figure 1: Schematic layout of the seeding experiment (not to scale), *BC* stands for bunch compressor stage.

ELECTRON BEAMLINE

General Requirements

The aim for a stable seeded operation in the 30-13 nm range imposes certain requirements for the design of the experimental layout and for the electron beam parameters. It is mandatory to obtain a reproducible six-dimensional, $\{x, y, x', y', t, \lambda\}$, overlap between the seed and the electron bunch. Therefore, the beamline must include proper diagnostics and instrumentation to maintain the overlap within the desired tolerances, which according to the studies performed with GENESIS [3], are of the order of $30\ \mu\mathrm{m}$ and $20\ \mu\mathrm{rad}$ in the transverse plane. In order to minimize the impact of the timing jitter, the electron bunch length should be of the order of 260 fs rms, even though the state-of-the-art synchronisation system (see below) can restrict the jitter to less than 40 fs rms. Such operation mode can be realized only after the installation of the 3^{rd} harmonic (3.9 GHz) RF cavity. sFLASH has to run in parallel to and without disturbing the SASE operation. The SASE-undulators are fixed-gap devices and the SASE wavelength, given by the electron energy, is defined by the users. Therefore, for tuning the resonant wavelength of sFLASH one needs variable gap undulators. Moreover, the total undulator length has to assure that saturation can be reached at all

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seeding wavelengths. Finally, since the HHG seeding will share the same beamline with other setups (e.g. ORS [6] and LOLA[7]), one has to provide compatibility between the different experiments.

Beamline Layout

The final layout of the electron beamline in the seeding section is illustrated in Fig.2. It consists of four planar variable-gap undulators of 10 m total length, separated by 70 cm intersections. The undulators, except the first one, are of the same type as those installed in the PETRA III synchrotron radiation source [4] with a period of 31.4 mm and a length of 2 m. The first undulator is a 4 m long PETRA II type [5] with 33 mm period. In order to extend the wavelength range, an undulator vacuum chamber with a vertical size of 9 mm will be installed. The transverse focussing, accomplished by movable quadrupoles placed in-between the undulator segments, allows an average β-function of the order of 8 m. Figure 3 shows the β-function along the seeding beamline calculated with the help of the code ELEGANT [8]. The apertures of both the collimator (located upstream sFLASH undulators, see Fig.1) and the vacuum chamber have been considered in the design of the electron optics in order to assure full transmission without losses. The electron beam diagnostics will be realized using wire scanners, optical transition radiation (OTR) and Ce:YAG screens and beam position monitors. The wire scanners and screen stations, together with additional instrumentation (BPM, microchannel plates), will be compacted in a common diagnostic block. The idea is to make these devices usable for both electron beam and HHG radiation diagnostics. This feature is critical for finding and keeping the overlap between electrons and the seed. From this point of view the two diagnostic blocks located before and after the first undulator (see Fig.2) are of particular importance. The three electromagnetic phase shifters will compensate the shift between the phase of the electron transverse velocity and the electromagnetic field, introduced by the drift between undulators.

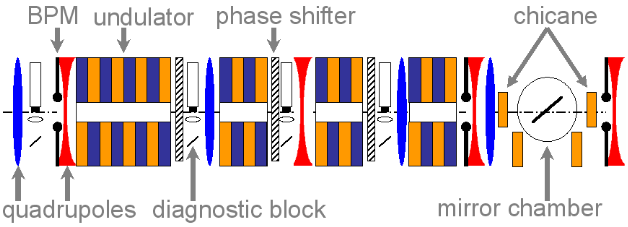

Figure 2: Schematic layout of the electron beamline in the seeding section.

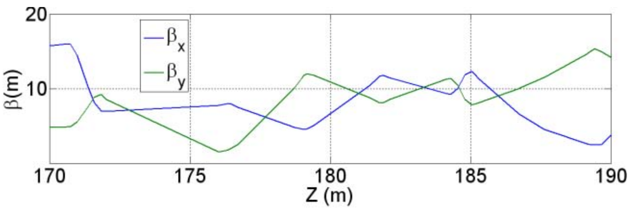

Figure 3: β-function along the sFLASH beamline

Synchronisation

Mandatory for a stable seed operation is an excellent timing overlap between the electron bunches and the HHG pulses. To achieve 40 fs rms timing jitter the electron bunch arrival time has to be actively stabilized using an intra-pulse train feedback [10] regulating the gradient of the accelerating modules prior to the first bunch compressor stage. For the feedback, the electron bunch arrival time is detected by sampling a fast transient signal from a broadband pickup using laser pulses from a femtosecond stable optical synchronization system [11]. The seed laser system is locked with femtosecond precision to the optical synchronization system using a two-color balanced optical cross-correlator currently under development [12].

HHG SOURCE

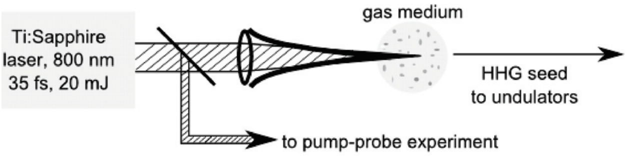

Figure 4: Schematic layout of the HHG source.

Figure 4 schematically shows the HHG source: Optical laser pulses (800 nm, 20 mJ, 35 fs) are splitted into two parts. The first part can be used for pump-probe experiments while the second part is focused onto a pulsed gas jet (argon) in order to create higher-order odd harmonics [9]. The harmonics are guided to the sFLASH undulator to seed the electron bunches. The seeding laser and the FLASH photocathode laser will be synchronized to better than 40 fs rms, thus guaranteeing temporal overlap between the seed pulse and the electron bunch.

SEPARATION OF PHOTONS AND ELECTRON BEAM

At the exit of the undulator section a magnetic chicane separates the electron and the photon beam vertically. The radiation is directed into a grazing incidence spectrometer using a set of amorphous carbon coated Si plane mirrors that exhibit very high radiation stability [14]. The reflectivity of the optics at grazing angles of 5° is typically larger than 85 %. The spectrometer (McPherson 248/310G, 1-meter focal length) incorporates an entrance slit adjustable from 5 to 500 μm in front of the gold coated grating with 1200 grooves·mm^{-1}, blazed at 20 nm and 3° angle of incidence. The 40 mm microchannel plate detector assembly is mounted perpendicular to the exit beam of the instrument tangent to the Rowland circle. This way the spectra can be recorded on a single-shot basis with large dynamic range. Data readout is done by a fibre taper connected to a CCD. The CCD can be scanned along the Rowland circle to position any wavelength between 1 nm and 35 nm at the centre of the detector. The array-detector equipped system will provide approximately $\lambda/\Delta\lambda$ = 1000 at 13 nm and 30 nm wavelength position. Finally, the undulator gap is tuned so that the undulator radiation and the seed are spectrally matched in the spectrometer. The photon beamline design allows for switching the light between the spectrometer branch and the experimental hutch. Here, the seeded FEL is combined with part of the naturally synchronized optical seed in order to perform pilot pump-probe experiments with a resolution of the order of 30 fs.

FEL SIMULATIONS

The performance of the above described experimental setup has been investigated with GENESIS in its time dependent mode. The example below studies the amplification of the 27$^{\mathrm{th}}$ harmonic of the fundamental 800 nm pulse. The considered FEL parameters are summarized in Table1. One has to note that 1 nJ energy in the resonant harmonic, corresponding to about 50 kW seed power, is a very pessimistic assumption, which might be considered as a worst case scenario. The graph in Fig.5 shows linear and logarithmic plots of the radiation power at the onset of the nonlinear regime (after three undulator modules) as a function of the position inside the pulse. The seeded part (at around s=35 μm) is amplified to a GW power level and exceeds the SASE power (head and tail) by about three orders of magnitude. The EUV pulse length of about 24 fs FWHM corresponds to that of the seed with some lengthening due to longitudinal slippage effects.

Table 1: Electron beam and seed parameters

Energy, E_0	850 MeV
Peak current, I_0	1500 A
rms bunch length, σ_z	80 μm
rms energy spread	0.2 MeV
Normalized rms emittance, ϵ_n	2 mm mrad
seed pulse duration, FWHM	20 fs
wavelength, λ_r	30 nm
energy in the harmonic	1 nJ

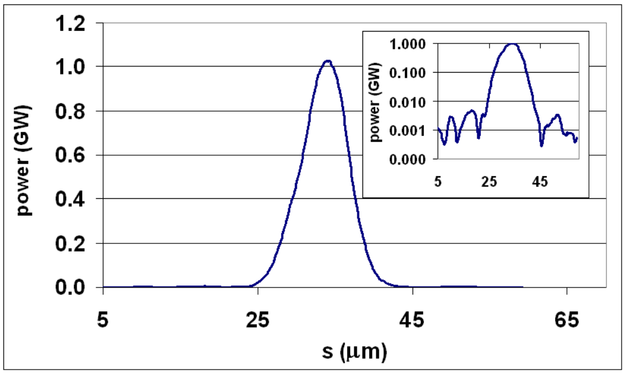

Figure 5: Linear and logarithmic plot (inset) of the radiation power at the onset of the nonlinear regime as a function of the local distance in the bunch

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