STATUS OF THE OPTICAL REPLICA SYNTHESIZER AT FLASH

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Abstract

A novel laser-based method to measure the longitudinal profile of ultrashort electron bunches, known as the Optical Replica Synthesizer (ORS) [1] is currently implemented at the free-electron laser FLASH at DESY. The paper describes its technical layout and the status of the project.

INTRODUCTION

The characterization of ultrashort electron bunches is of utmost importance for the operation and optimization of linac-based free-electron lasers such as FLASH (the Free electron LASer at Hamburg) [2], the European XFEL [3] and other future x-ray radiation sources. Urgent need for single-shot characterization of ultrashort bunches also arises from the upcoming laser-plasma accelerators (e.g. [4]), where shot-to-shot stability is a yet unsolved problem. In either case, methods to measure unambiguously the bunch charge, emittance and energy spread as function of the longitudinal coordinate at a rate of typically 10 Hz are desired. Such a method should be robust enough for routine operation and should not prevent the beam from further use. The required time resolution should be significantly better than the presumed bunch duration of a few 10 fs. In view of pump-probe experiments, a laser-based method would allow to obtain the shot-to-shot arrival time of x-ray probe pulses relative to the laser pump pulses.

FLASH is a high-gain free-electron laser (FEL), based on the principle of self-amplified spontaneous emission (SASE). Electron bunch trains (1-800 bunches, repetition rate 1-10 Hz, bunch charge 0.5-1 nC) from a laser-driven photo injector are accelerated by a 1.3-GHz superconducting linear accelerator to 700 MeV, resulting in a world-record FEL radiation wavelength of 13 nm. With an additional acceleration module installed in the spring shutdown 2007, a beam energy of 1 GeV and a radiation wavelength of 6 nm should be achievable in the near future. In order to reach high peak currents of several 1000 A, as required by the SASE process, the bunches are accelerated slightly off the rf-voltage crest, thus introducing an energy chirp, and are subsequently compressed employing energy-dependent path length differences in two magnetic chicanes (bunch compressors). This procedure results in a bunch profile consisting of a spike, which is believed to be a few 10 fs in duration, followed by a tail which is due to the nonlinearity of the rf voltage and extends over several ps.

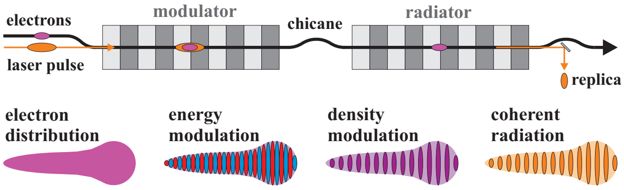

Figure 1: Principle of the Optical Replica Synthesizer: laser-electron interaction in an undulator causes an electron energy modulation, which is converted into a density modulation and gives rise to a coherent radiation pulse that resembles the original electron distribution (hence “replica”).

In order to verify the theoretical understanding of bunch properties and to optimize them for FEL operation, several methods to study the longitudinal bunch profile have been devised and employed at FLASH:

- In collaboration with SLAC, a 2.9-GHz transversely deflecting rf structure has been installed, which streaks individual bunches in vertical direction [5]. After an additional horizontal kick, these bunches hit an optical transition radiation (OTR) screen viewed by a CCD camera. Under normal operation conditions, the temporal resolution is limited to 25 fs (rms) by the vertical beam size.
- Electro-optical sampling with several decoding methods [6] has been applied, where a laser pulse passing through a birefringent crystal (ZnTe or GaP) is sensitive to the electric field distribution of a nearby electron bunch. The time resolution is limited by transverse-optical lattice vibrations in the crystal, Using GaP, temporal structures of 50 fs (rms) can be resolved [7].
- The infrared spectrum of synchotron radiation or transition radiation from electron bunches has a strong coherent component at wavelengths comparable or longer than the bunch structure, see e.g. [8], and there is no intrinsic limit in time resolution. However, the infrared spectrum allows only to obtain the bunch form factor (i.e. the square of the Fourier-transformed charge distribution) and not the bunch shape itself.
- A novel method to determine the structure of electron bunches with a resolution of a few fs, the optical replica synthesizer, is the topic of this paper.

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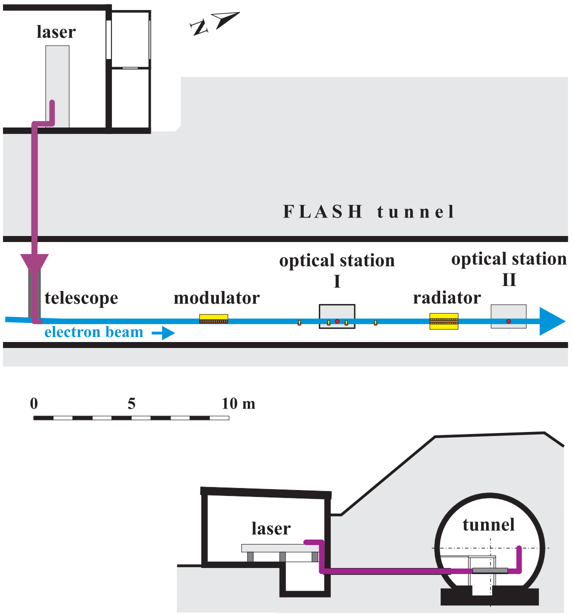

Figure 2: Footprint and cross section of the ORS setup comprising a laser system outside the FLASH tunnel, two undulators (modulator and radiator) and two optical stations. Only the chicane magnets are shown. The SASE undulator starts 22 m downstream of optical station II.

PRINCIPLE OF OPERATION

The optical replica sythesizer (ORS) proposed in 2004 [1] is based on the modulation of the energy of electrons with Lorentz factor γ, co-propagating with a laser pulse in an undulator (the "modulator" with period λ_{U} and field parameter K), which is tuned to the laser wavelength λ_{L}:

$$\lambda_{\mathrm{L}} = \lambda_{\mathrm{U}} \left(1 + K^2/2\right)/2\gamma^2 . \quad (1)$$

As sketched in Fig. 1, a subsequent magnetic chicane converts the energy modulation into a density modulation with a periodicity of λ_{L}, which gives rise to coherent radiation in a second undulator (the "radiator"), again tuned to λ_{L}. When the laser pulse covers the whole electron bunch, the shape of the coherent radiation pulse closely resembles the bunch shape (hence the name "optical replica").

Methods to fully characterize coherent pulses at typical laser wavelengths are readily available, e.g. FROG, GRENOUILLE or SPIDER. All of them combine autocorrelation and spectral information to reconstruct the temporal amplitude and phase. The GRENOUILLE [9] is essentially an SHG-FROG (frequency-resolved optical gating [10]), using second-harmonic generation) which is particularly simple and robust, and thus well suited to be remotely operated in the FLASH tunnel.

The time resolution of ORS is ultimately given by the laser wavelength (2.6 fs for $\lambda_{\mathrm{L}} = 775$ nm). The smearing effect of slippage, i.e. the fact that electrons lag behind the light field by one wavelength per undulator period, can be eliminated by an unfolding procedure.

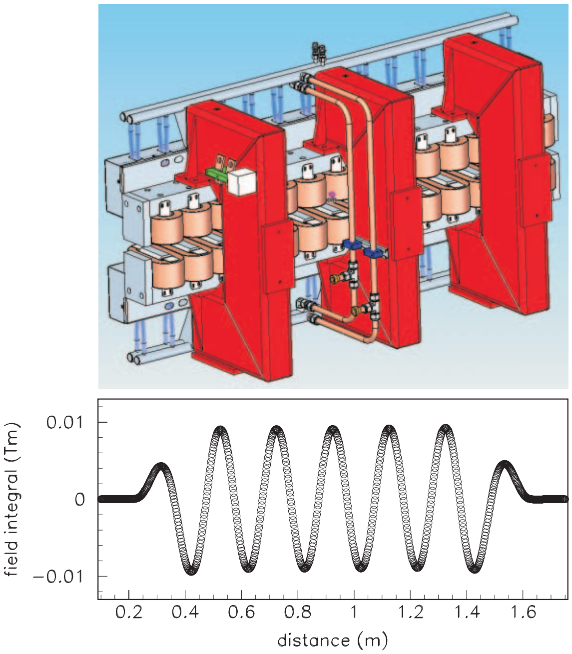

Figure 3: Three-dimensional sketch of the modulator and example of a magnetic measurement, the evolution of the first field integral along the undulator axis.

TECHNICAL LAYOUT

The ORS setup comprises a laser system and two undulators, each followed by an optical station for diagnostics purposes (see Fig. 2). The laser system will be installed in a recently erected laser building adjacent to the FLASH tunnel. An Erbium-doped fiber laser, pumped by laser diodes at 980 nm, has an output of 100-fs pulses at 775 nm after frequency doubling. These pulses enter a regenerative Ti:sapphire amplifier (Clark CPA-2001), based on chirped-pulse amplification and pumped by a Nd:YAG laser at 532 nm. This system is capable of producing pulses at a repetition rate of 1 kHz with 0.85 mJ per pulse and 150 fs duration (fwhm). For the ORS, however, the stretcher/compressor system is tuned to 2 ps and the required repetition rate is that of FLASH (5-10 Hz).

After travelling about 12 m in air and focussed by a set of remotely adjustable lenses, the laser pulses enter the FLASH vacuum through a back-tangent port of an existing dog-leg chicane, about 9 m upstream of the modulator. Although a Galilei-type two-lens telescope would be sufficient, a telescope of three lenses (one fixed and two movable over a distance of 1 m) is used to allow for more flexibility in the adjustment of the beam waist diameter and position.

The two electromagnetic undulators (modulator and radiator, Fig. 3) were designed, assembled and tested at Scanditronics Magnet AB, Sweden. Their magnetic gap is 40 mm wide and their period length is 200 mm with 14 dipoles powered by four separate circuits, one circuit powering dipole number 3 to 12 (5 periods) in series, one circuit

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for the dipoles 2 and 13, and two separate circuits for the dipoles 1 and 14, i.e. the end poles of the device. The undulator parameter is $K = 5.7$ at the nominal field of 0.31 T on the beam axis, the maximum field is 0.5 T. Moving a Hall probe along the undulators in 2 mm steps, the resulting first and second field integrals were measured to be smaller than $(50 \pm 5) \cdot 10^{-6}$ T m and $(20 \pm 1.5) \cdot 10^{-5}$ T m^2, respectively. The magnetic field of the modulator is vertical, i.e. electrons are deflected horizontally and interact with the horizontally polarized laser field. Following a chicane formed by four dipole magnets, the radiator field is horizontal in order to produce vertically polarized coherent radiation at 775 nm, which is discriminated from the laser light by a polarizer (alternatively, a higher undulator harmonic could be employed to distinguish between laser and radiator light [1]).

Two optical diagnostics stations are installed, both comprising an optical table and an OTR chamber with a set of different foils viewed by a CCD camera in order to analyze the laser and electron beam profile and their relative position. Station I at the center of the chicane between modulator and radiator allows to image laser and modulator radiation with a CCD camera and to measure their respective arrival times with fast photodiodes in order to establish and optimize the transverse and temporal laser-electron overlap. At Station II, coherent radiation from the radiator can be imaged, analyzed with a power meter and photodiodes. Finally, these pulses are focussed onto a GRENOUILLE in order to determine their temporal characteristics (and thus the bunch profile).

SIMULATIONS

A numerical simulation of the replica process was performed in the time domain, using the FEL code GENESIS 1.3 [11] to calculate the energy modulation of the electrons in the modulator as well as the electric field of the coherent output of the radiator. The magnetic chicane is modelled by a tranfer matrix. Figure 4 shows an arbitrary current profile of the electron bunch at the modulator entrance (solid line) and the electric field amplitude of the coherent pulse leaving the radiator (dots). Confirming earlier results [1], the optical pulse is indeed an excellent replica of the electron distribution. The discrepancies (slight broadening and smearing) are due to the slippage of electrons with respect to the light emitted by the radiator. Since this effect is known, it can be accounted for in the retrieval algorithm.

STATUS AND OUTLOOK

By the end of June 2007, the laser building will be completed, and both undulators and other ORS-related hardware will be installed in the FLASH tunnel. During recommissioning of FLASH, starting in August, the laser system will be installed. As a first step, the laser beam focussed by the telescope will be sent back to the laser lab, where a "virtual" beam waist allows to study the properties of the beam at the position of the modulator. The next step is to establish the laser-electron overlap in the modulator and finally to extract coherent radiation from the radiator.

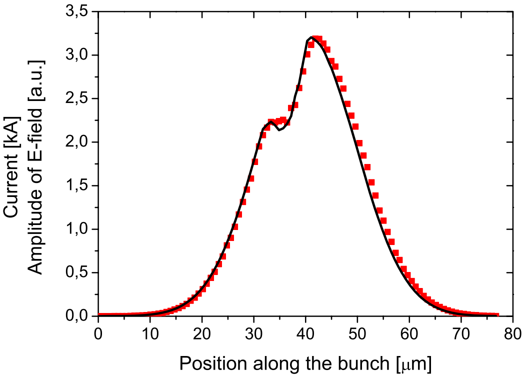

Figure 4: Longitudinal distribution of the assumed bunch current (solid line) and calculated electric field (dots) of the coherent pulse emitted by the radiator.

In addition to the ORS, the newly created infrastructure (a laser building with 150 m^2 lab space, tubes connecting the lab to the FLASH tunnel, the possibility to inject a laser collinearly with the electron beam, and two undulators) opens up the whole field of manipulating relativistic electrons with laser pulses.

ACKNOWLEDGEMENTS

It is a pleasure to acknowledge the invaluable help of all DESY groups involved in the FLASH shutdown activities, the work done by the technical groups of the Institut für Experimentalphysik (University of Hamburg), the contributions of R. Ruber and M. Johnson (Uppsala University) and the support through the SU-UU-KTH FEL-center.

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