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Technical aspects of the integration of the optical replica synthesiser for the diagnostics of ultra-short bunches into flash at desy

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Introduction

Monitoring and tuning the bunch properties are essential for the reliable operation of linac-based SASE free-electron lasers such as FLASH [2], XFEL [3], and LCLS [4]. This need has triggered the development of new diagnostic methods based on a transversely deflecting cavity [5] or electro-optical sampling [6]. The Optical Replica Synthesiser (ORS), a complementary scheme that was introduced in reference 1, is similar to an optical klystron FEL seeded by an infrared laser as is shown in figure 1. In the modulator the interaction of the laser with the transversely oscillating electrons causes an energy modulation. A dispersive section turns this energy modulation into a density modulation at the wavelength of the light. In a following radiator undulator the micro-bunched beam radiates coherently and the emitted light pulse has the same longitudinal profile as the electron beam. Hence the name optical replica synthesiser.

The optical replica pulse is analysed in a FROG (frequency resolved optical gating) device [7], which is based on recording the spectrally resolved signal of the auto-correlation. Subsequent application of a pulse retrieval algorithm reveals both amplitude and phase of the incident electric field and thus of the longitudinal profile of the electron bunch. A very compact second harmonic FROG device, Grenouille [8], which performs the analysis, is available commercially.

Following up on the signing of a letter of intent by DESY and the vice-chancellors of three Swedish universities in Uppsala and Stockholm the recently established SU-KTH-UU Free Electron Laser Centre has entered a collaboration with DESY to design and implement a prototype of the ORS in FLASH in order to establish the feasibility of the device for the X-FEL. In this note we present the status of the project as of August 2006.

Space and time

The ORS will be installed in the beam line of FLASH between the collimating dog-leg and the VUV-undulator. The seed laser will be coupled in into the beam line just downstream of the dog-leg where a vacuum window is available. The modulator will be located about 10 m downstream of the vacuum window. The magnets will fit into 1.5m long unoccupied sections between quadrupoles and other equipment and the magnet gap of 40mm is sufficiently large to allow installation without modifying the existing beam pipe. The chicane consisting of four standard dipole magnets will also fit in between consecutive quadrupoles and can be mounted without breaking the vacuum. The housing of the extraction coupling mirror and some extra diagnostic for beam size measurements and alignment of laser and electron beam will require some vacuum intervention.

The distance between the modulator and the radiator will be on the order of 15m and it should indeed be short, because collective effects such a plasma oscillations [9] perturb the micro-bunching, caused by modulator, before it can generate the optical replica pulse in the radiator. The replica pulse in this case would not be a faithful replica of the electron bunch profile.

The laser system will be placed outside the linac tunnel with the shortest possible laser transfer line. For that an additional tunnel into the beam-tunnel will be drilled near the dog-leg. The installation of the ORS in the beam line is foreseen for a shutdown during spring 2007 which will be followed by commissioning and operating until the self-seeding option for FLASH will be installed in the beam line between the collimating dog-leg and the undulator.

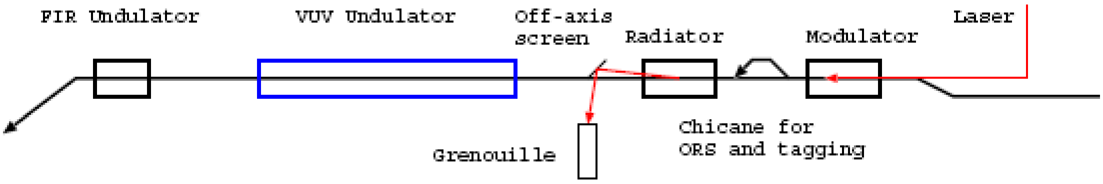

Figure 1: Schematic view of the Optical Replica Synthesiser

Seed laser

The seed laser will be based on an 1550 nm Erbium fiber oscillator that can be synchronised to the RF system of the linear accelerator. This oscillator has recently been constructed and the first, preliminary tests show that it is functioning properly. Stable mode locking is achieved and the pulse has the desired characteristics regarding pulse energy and spectral width. A schematic diagram of the Erbium fiber laser is shown in figure 2. As a next step the pulses will be compressed and frequency doubled. Subsequently the active synchronisation will be implemented and its effect on the laser operation will be tested.

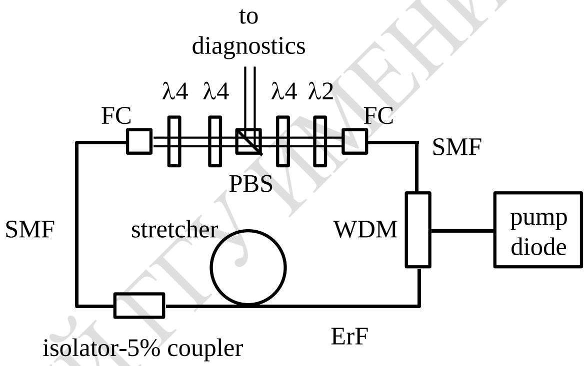

Figure 2: Schematic view of the Erbium fiber oscillator. FC: fiber coupler; SMF: single mode fiber; ErF: Erbium fiber, PBS: polarising beam splitter, WDM: wavelength division multiplexer, λ/4: quarter lambda plate, λ/2: half lambda plate.

As an amplifier we will use an existing Clark-MXR CPA2001 Ti:Sapphire laser from Stockholm University. The interfacing of the home-built oscillator and the amplifier will start soon. The choice for this amplifier is mainly motivated by budgetary reasons, as the CPA2001 is a highly compact laser system that is not easily adapted to this particular application. On the other hand, it has performed very reliably in our lab, with little maintenance and without major malfunctions for many years. The doubled output pulses of the Erbium fiber oscillator will be stretched before injection into the Ti:Sapphire amplifier cavity. We will attempt to use the stretcher currently installed inside the CPA2001. This means that we will have to separate the two layers of the CPA2001 in order to gain access to the lower level. No modifications of the amplifier cavity or the compressor are envisaged and only slight changes of control electronics are necessary, predominantly in the Pockels cell driver. The normal operating frequency of the CPA2001 is 1 kHz, but it can easily be reduced to 1-10 Hz to match the frequency of FLASH.

A seed laser intensity of about 4.5 GW/cm^2 is necessary to achieve required energy modulation of the electron bunch in a five period modulator undulator [1]. If we account for reflection losses during transport, the estimated maximum pulse energy of the modified CPA2001 laser system will be approximately 700 μJ inside the accelerator vacuum tube. The pulse length will be set to about 2 ps to attain a stable temporal overlap between the laser pulse and the electron

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bunch. This is achieved by deliberately misaligning the compressor of the CPA2001. The resulting longitudinal chirp on the laser pulse is not expected to influence the operation of the ORS significantly.

In order to estimate the beam diameter inside the modulator undulator we have performed a straightforward calculation using Gaussian optics. The results of this calculation, in which the beam is focussed by a Galilean telescope consisting of two achromatic lenses with focal lengths of 1.0 m and -0.8 m separated by 0.26 m, are shown in figure 3. The beam from the CPA2001 was assumed to be diffraction limited with an initial diameter of 6 mm (FWHM). From figure 3 we can see that a beam diameter of about 0.8 mm (FWHM) can be expected at the position of the modulator undulator located about 10 m downstream from the second telescope lens. This leads to a laser peak intensity of about 45 GW/cm^2 a factor of ten in excess compared to what should be required. A more realistic simulation that takes into account the transversal mode structure of the femtosecond pulses is under way using commercial beam propagation software. This simulation will also address the transport form the CPA2001 laser system to the focussing telescope.

In principle even higher laser intensities could be reached by focussing tighter, but here we are limited by the requirement that the intensity is essentially constant over the entire length (ca. 1.5 m) of the modulator and by the dimensions of the input vacuum window (16 mm diameter). Furthermore, the laser beam should easily accommodate the whole electron bunch, which has a diameter of 0.1-0.2 mm (FWHM), even while it is performing its oscillatory motion in the modulator, and by making the diameter of the seed laser beam too small we may simply become too sensitive to the pointing stability of the laser system. In any case, the distance between the laser and the modulator is so large that probably active beam position stabilisers are required to maintain spatial overlap between the laser and the electron beam for extended periods of time. Existing beam position monitors and screens will be used to monitor the spatial overlap between the laser and the electron beams. Diagnostic stations to monitor the laser before the vacuum window as well as after the radiator undulator are foreseen, but not yet finalised.

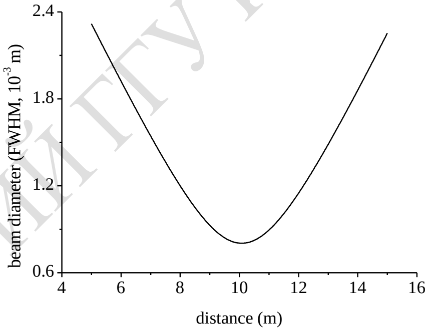

Figure 3: Seed laser beam diameter as a function of the distance to the focussing telescope showing a focus of 0.8 mm diameter (FWHM) inside the modulator.

One point of concern is the presence of a spatial chirp and / or a tilted wavefront on the CPA2001 seed laser pulse. At the moment it is not entirely clear how this will affect the detailed micro-bunching process or the subsequent analysis of the radiator pulse using the Grenouille FROG apparatus. We will perhaps be forced to take steps to correct the seed laser pulse for these imperfections.

Undulator and chicane

The undulators for the modulator and radiator with period l_0 and $K=93.4B_0l_0$ must fulfil the FEL resonance condition $\lambda=l_0(1+K^2/2)/2\gamma^2$ with an IR laser operating at $\lambda = 780$ nm and beam energies $E = \gamma mc^2$ between 500 and 1000 MeV. Together with the constraint to be shorter than 1.5m we arrive at electromagnetic magnets that have 5 full periods plus two extra periods to zero the field-integrals with a period of 20 cm and a peak field B_0 below 0.5 T. In order to allow separating

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the high power seed laser from the weaker replica pulse by a polariser we will have one horizontal and one vertically polarised undulator. Both magnets are now ordered from Scanditronix in Sweden and will be delivered to DESY in spring 2007. The support structure for the undulators to move them in and out of the beam line will be designed by staff at DESY.

The standard steering dipoles with a peak excitation of $33x10^{-3}$ Tm are sufficient for chicane to provide an R_{56} of up to 0.3 mm. The transverse offset (ca. 10 mm) of the beam in the chicane can also be used to insert a mirror and extract a major portion of the seed laser pulse to avoid irradiating downstream equipment and disturbing the weak replica pulse.

Laser diagnostics

Once the replica pulse is generated in the radiator undulator it has to be extracted from the beam pipe and transported to the diagnostic section with the Grenouille. Presently we are discussing several options to extract the light, either by pointing the radiator undulator at a downstream off-axis mirror. This option, however, would introduce significant wavefront distortion and is not favoured. In another option we add a second chicane downstream of the radiator with steering magnets to steer around an off axis screen. A third option would be to insert a mirror with a hole into the beam pipe such that the electron beam can pass the mirror, but the IR pulse is deflected out. These options will be scrutinised in the coming months.

The placement of the Grenouille either in the accelerator tunnel or in the new laser housing has not been decided yet. Placement of the Grenouille inside the tunnel has the advantage of a shorter beam path for the replica pulse as well as easier alignment and construction,
but access to the tunnel during accelerator operation is impossible and parasitic operation without impeding other activities is, of course, much favoured.

Conclusions and prospects

We have taken the first steps towards implementing the ORS in FLASH at DESY. Ordering the magnets which have a long lead time was the first major step and building the laser will be the next, together with solving all the other issues that we only mentioned in passing.

The infrastructure of lasers and undulators created for the ORS provides a fertile ground for further experiments with beams and lasers, especially regarding synchronisation. For example, using the FIR-undulator that will be installed downstream of the VUV-undulator as the radiator instead of the original radiator will allow to generate a coherent light pulse at the wavelength of the seeding laser close to the experimental hall where it can be cross-correlated with an external laser used for pump probe experiments. This will yield information about the relative timing of the external laser and the bunch arrival time, which also caused the VUV-pulse. In this way the relative timing between VUV-pulse and external laser can be determined.

Furthermore, passing the micro-bunched electron beam after the chicane through an optical transition radiation screen, will yield information about the bunching and this signal can be used for tuning.

Abstract. In this paper we present an overview of current status of the Optical Replica Synthesiser at DESY. The method is based on producing an "optical copy" of the electron bunch with its subsequent analysis with optical techniques [1]. To this end, a near-IR laser beam is superimposed on the electron beam in the first undulated of an optical klystron. In the following dispersive section the laser-induced energy modulation is transformed into a density modulation. The modulated electron bunch then produces a strong optical pulse in the second undulator. Analysis of this near-IR pulse (the optical copy) then provides information about the profile, the slice emittance and the slice energy spread of the electron bunch. We discuss the implementation of such a measurement set-up at the FLASH facility at DESY and investigate the influence of various parameters on the performance of the device. Topics we address include the dispersive chicane, as well as the requirements for the seed laser pulses and the detection and analysis of the near-IR pulse.

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