A SETUP FOR SINGLE SHOT ELECTRO OPTICAL BUNCH LENGTH MEASUREMENTS AT THE ANKA STORAGE RING*

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Abstract

Single shot electro optical bunch length measurements, in particular using spectral decoding (EOSD), are foreseen for the ANKA storage ring. In order to resolve fast changes of bunch deformation and structure during the low-α_c-operation (2-15 ps rms bunch length). The EOSD technique uses a chirped laser pulse to probe the field induced birefringence in an electro optical crystal. The laser pulse is then analyzed in a single shot spectrometer. To obtain the birefringence modulation one can either use the near field of the electron bunch (placing the crystal close to the electron bunch in the UHV system of the storage ring), or the far field (coherent synchrotron radiation in the THz range at a THz-/IR-Beamline). We give an overview of the experimental setup in the ANKA storage ring and present the specifications of the probe laser developed at the Paul Scherrer Institute in Switzerland.

MOTIVATION

During the low-α_c-operation of the ANKA storage ring in Karlsruhe, the momentum compaction factor α_c is reduced drastically to compress the bunches in order to generate coherent synchrotron radiation (CSR) in the THz range [1]. Previous measurements have shown a beam current dependent bunch lengthening and deformation effect at ANKA in this special operation mode [2] [3]. In addition to that, the CSR exhibits a bursting behaviour [4] which could be caused by dynamic changes of the longitudinal bunch shape (e. g. microbunching). Currently we measure the bunch shape with a streak camera which requires us to average the bunch profile over many revolutions to obtain a sufficient signal to noise ratio, thus we cannot resolve any expected dynamic effects on shorter timescales.

SINGLE SHOT ELECTRO OPTICAL SPECTRAL DECODING (EOSD)

During the past few years, following the first very promising bunch length measurements at FELIX [5] single shot electro-optical bunch length measurements have been performed at linear accelerators such as FLASH and LCLS [6]. The underlying principle is the following (see Fig.1): A laser pulse probes the field induced birefringence in an electro-optical crystal (EO-crystal) and is then analyzed. A thorough discussion of the technique can be found here [6].

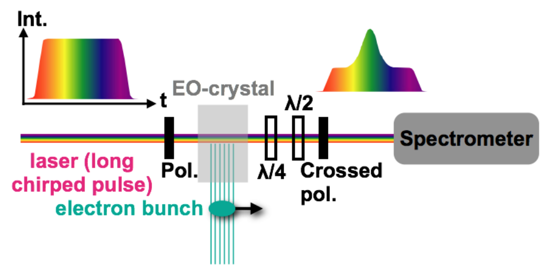

Figure 1: Principle of spectral decoding using the crossed polarizer scheme. The long, chirped, linearly polarized laser pulse is sent through the EO crystal while an electron bunch passes a few mm from the crystal. With the help of wave plates and a crossed polarizer the longitudinal profile of the bunch is intensity modulated onto the laser pulse and then analyzed in a spectrometer.

For single shot measurements the laser has to be chirped in order to be longer than the electron bunch. The well know relation between time and wavelength of a chirped pulse allows for the reconstruction of the temporal profile of the electric field from the measured spectrum.

The probing electric field can either be the Coloumb field of the electron bunch directly (near field) or coherent synchrotron radiation (CSR) emitted by a short electron bunch (far field). For the first option the electro-optical crystal has to be placed inside the electron vacuum chamber with a distance of only a few mm from the electron beam, so the field is strong enough. For the second option, CSR in the THz range is used at a beam line where the laser and the CSR co-propagate through the EO-crystal. This has already been shown at the ANKA storage ring with an earlier setup in [7]. For this method the CSR beam needs to be focused down inside the crystal to achieve a sufficient electrical field strength.

Laser System

EOSD measurements bring along certain requirements for the laser system to be fulfilled. These are: modelocking operation, synchronization to the storage ring radio frequency, a sufficient spectral width, and the pulse length must be tunable over a wide range. The exact requirements are discussed in more detail later on. At the Paul-Scherrer Institute (PSI) in Switzerland an Yb-doped modelocked fibre laser system has been developed specifically for EOSD measurements [8]. It consists of a compact Yb-doped fiber oscillator that is synchronized RF system via a

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phase-locked loop (PLL). The repetition rate is then lowered by an acousto-optic modulator (AOM) and the pulses are non-linearly amplified in a subsequent fiber amplifier to obtain a sufficiently high pulse energy (up to 20 nJ) and a wider spectrum. The central wavelength of the amplified spectrum lies at 1050 nm for which a better phase matching between the laser and the probing field inside the EO crystal can be achieved than with a Ti:Sa laser at 800 nm. This allows us to use thicker crystals which yield a stronger modulation.

The typical spectrum of the fibre oscillator has a FWHM of only about 25 - 30 nm. So in order to obtain a wider spectrum which will increase the resolution that can be achieved, a non-linear amplification effect is used (self-phase modulation) in the fibre amplifier. This increases the usable spectral bandwidth to about 90-100 nm.

The lowering of the repetition rate by a pulse picker with an AOM is required to ensure that single shot measurements are possible as the detector of the spectrometer has a minimum exposure time of 1.4 μs, so we want to make sure that only one pulse arrives at the detector during that time.

The laser pulses required for the EOSD measurements need to be chirped, which means that the frequency inside a laser pulse either increases (up-chirp) or decreases (down-chirp) along the pulse. This allows us to measure the spectrum of the pulse and then convert back to the time domain (calibration is required). When a short Fourier-transform limited pulse passes through a material (e. g. a long optical fibre) with linear dispersion it stretches in the time domain and becomes chirped, if the pulse energy is very high non-linear effects can also occur. Linear chirp introduced this way can be controlled by a grating compressor. The bunch length during the low-α_c-operation at ANKA can be varied between about 2-15 ps (RMS values), so the laser pulse length, which is usually stated using FWHM values, needs to be tunable over a wide range as well (about 10-70 ps FWHM).

In order to achieve temporal overlap between the laser pulse and the electric field of the electron bunch inside the EO crystal, the laser system needs to be actively synchronized to the revolution frequency of the electron bunches (2.7 MHz for ANKA) with a sub-ps accuracy. The repetition frequency of mode-locked fiber lasers is given by the length the light has to pass inside the oscillator, which in our case consists of a compact free-space and fiber part. To achieve such an accurate synchronization not the revolution frequency but the storage ring radio frequency of 500 MHz is used. This means the oscillator repetition frequency needs to be a subharmonic of 500 MHz, but also an harmonic of 2.7 MHz (which is 500 MHz divided by the harmonic number of ANKA: 184) The constraints upon the oscillator repetition rate are then given by the dividers of harmonic the number which factorizes into 23×8. So the options are rather limited with 500 MHz / 8 = 62.5 MHz or its multiples and 500 MHz / 23 = 21.7 MHz. The original PSI system is optimized for 50 MHz, so the two options either meant to decrease the oscillator length by a free-space-equivalent of 1.2 m or increase it by 6.7 m. After careful consideration of the required fiber and free-space lengths in the oscillator, the first option with 62.5 MHz was chosen and the reduction was achieved entirely by making the fiber part shorter by about 80 cm (light propagation in fiber is about 1.5 times slower than in free space).

In collaboration with PSI their original laser system has been adjusted to our needs, was assembled, and tested at PSI. It will be installed at ANKA within the next few weeks. Synchronization to a 500 MHz RF signal has been achieved and maintained over several days. Figure 2 shows first spectra recorded at the output of the oscillator and of the subsequent amplifier. The pulse picker reduced the repetition rate to about 1 MHz, which is the maximum frequency to work with the exposure time of the spectrometer. Additional fine tuning of the settings to achieve a wide, stable and smooth amplified spectrum will be required once the system is installed at ANKA.

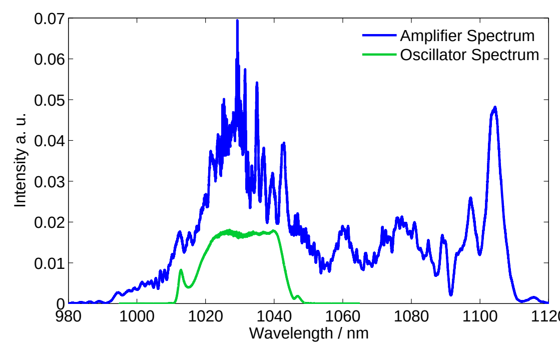

Figure 2: First measurements of the spectrum at the oscillator and amplifier output after the assembly. The repetition frequency was 1 MHz for the amplifier. Additional fine tuning of oscillator and amplifier settings and alignment will be required to obtain a smoother amplified spectrum that remains very stable from shot to shot. The usable bandwidth is from 1000 nm to 1090 nm.

SET UP AND SIMULATIONS

While EOSD with CSR has successfully been performed at synchrotron light sources before [9]; the near field option for which the EO crystal has to be mounted on a retractable sledge placed inside the UHV system of the storage ring has not yet been done. The planned measurements at the ANKA storage ring include the installation of such an EO monitor after far field measurements at an IR beam line have been carried out. The EO monitor will follow the compact design of the one used at PSI and DESY [10] where laser is coupled in and out via optical fibers and the crystal can be moved closer to the electron beam on the sledge without changing the timing of the laser. The wave-plates and polarizers are also included in a free space part of the monitor, the connection to the UHV is done via a vacuum window.

There are two feasible placement options for the EO monitor in the storage ring, either looking at the electron beam from above (vertical placement) or from the inside of the ring (horizontal placement). For those two geometries the field seen by an observer 5 mm from the beam center has been simulated. This distance was picked because preliminary measurements with a scraper have shown that the beam life time reduction at 5 mm distance from the beam is tolerable, even though still noticeable. The temporal profile of the electric field of a relativistic line charge is given by the convolution of the field generated by a single electron and the distribution of the line charge. For the conditions present at a synchrotron (high relativistic γ-factor and a bunch length of more than 100 fs), the field of a single electron can be assumed as delta function in comparison to the charge distribution thus the convolution does not introduce any broadening effects and the profile of the electric field in a certain distance from the line charge equals the distribution of the line charge itself. For ANKA, the beam size at the possible location for the EO monitor which is in one of the straight sections is in the order of $\sigma_x \approx 1.5$ mm (horizontally) and $\sigma_y \approx 0.1$ mm (vertically), while $\sigma_z \approx 0.6 - 4.5$ mm (2-15 ps; longitudinally). So the approximation of a line charge is questionable, especially considering the horizontal beam size. To get a rough approximation of the effect of the horizontal beam size on the electric field seen by an observer at a fixed position 5 mm from the bunch center, the fields of line charges with different distances and charges (forming an envelope of the horizontal bunch profile) and hence a shift in time due to the field retardation have been summed up and are depicted in Figure 3 for both geometry options with an unpertubed bunch length of 1 ps RMS. While for a vertical observer the electric field is only slightly disturbed for a horizontal observer the field broadens to 5.5 ps. For an original length of 10 ps a broadening to 11.3 ps is predicted. The simulations suggest that the broadening effect for a horizontal observer can be assumed by quadratic addition of 5.4 ps to the original pulse length. So clearly the vertical placement is more suitable for short bunch length measurements. However the larger contribution to the ring impedance provides a challenge in this case.

CONCLUSION

EOSD seems to be a promising technique for single shot bunch length measurements during low-α_c-operation at the ANKA storage ring. We are expecting to be able to perform single shot bunch length measurements with a sub-ps resolution over a wide range of bunch lengths and currents during the low-α_c-operation. After the installation of the laser system at ANKA first measurements with CSR are planned to adjust the laser settings to an optimum and study systematics of the set up. Meanwhile a compact EO monitor will be installed in a straight section of the storage ring during the winter shutdown at the end of 2011, so near-field measurements can be carried out in 2012.

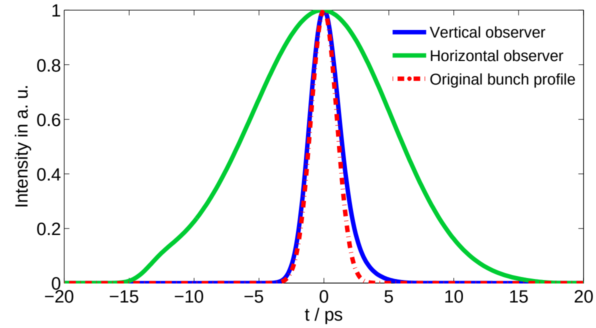

Figure 3: Comparison of the options with a horizontal or vertical placement of the EO crystal in a distance of 5 mm from the electron beam. For an original bunch length of 1 ps RMS the elongation due to the horizontal beam size for the different geometries is shown. Where for the vertical observer the projected longitudinal profile stretches only slightly, it stretches to 5.5 ps RMS for the horizontal observer which makes this geometry unsuitable for short bunch length measurements.

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