

# ELECTRO OPTICAL SAMPLING OF COHERENT SYNCHROTRON RADIATION FOR PICOSECOND ELECTRON BUNCHES WITH FEW pC CHARGE

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## Abstract

Electro Optical (EO) sampling is a promising nondestructive method for measuring ultra short (sub-ps) electron bunches. The FEMTO slicing experiment at the Swiss Light Source modulates about 3 pC of the 5 nC electron bunch longitudinally. The coherent synchrotron radiation (CSR) emitted by this substructure was sampled by 100 fs long pulses from an Yb fiber laser in EO crystals of gallium phosphide. The broadening of this ps long structure over four turns of the synchrotron could be measured with sub-ps resolution.

## INTRODUCTION

Femto slicing [1] is a technique to manipulate the temporal profile of a long (some 10 ps) electron bunch in a storage ring with a short pulse laser (100 fs). The very high electric field of the laser pulse (up to  $10^9$  V/m) modulates the energy of the electrons in a slice of the length of the laser pulse. After the first dispersive section this pure energy modulation is transferred into a longitudinally one. The resulting electron distribution consists of two humps containing the low and the high energy sliced electrons and a central dip, from where the sliced electrons have been removed (see Fig. 1). The dip will lead to an enhancement of synchrotron radiation in the millimeter wavelength range (THz) emitted at following dipole magnets of the storage ring.

To measure the time structure of synchrotron radiation pulses electro optical measurement techniques, developed for electron bunch length measurements, can be used. These techniques employ birefringence an electric field induces in an electro-optically active crystal like gallium phosphide (GaP) to transfer the time structure of the electric field onto a laser pulse which can be measured with fs accuracy. It has been shown that sub-ps electron bunches of some 100 pC charge can be measured with about 200 fs resolution applying the spectral decoding technique [2, 3] by using the Coulomb field of the relativistic electron bunch directly. By imaging and focusing the coherent radiation emitted from the electron bunch onto the crystal, the resulting field strength can be enhanced leading to larger EO signals [4].

In this paper we present results of the first direct measurements of coherent synchrotron radiation pulses from the sliced electron bunches at the Swiss Light Source (SLS) in time domain. We applied the technique of electro optical spectral decoding using a ytterbium fiber laser [5] which has been synchronized to the SLS rf master clock.

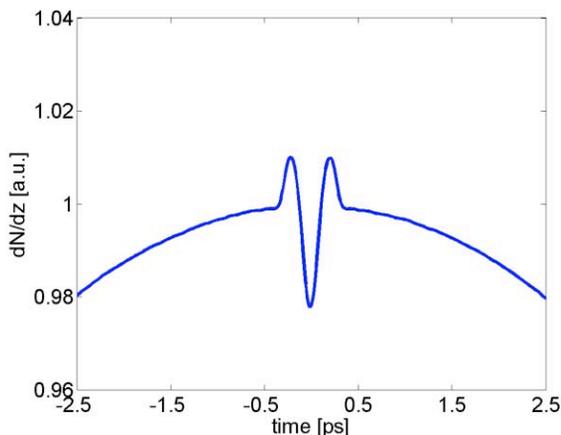


Figure 1: Charge distribution of the sliced electron bunch at the SLS right after the slicing.

## FEMTO-SLICING AT THE SLS

The FEMTO slicing setup at the SLS is used to generate sub-ps hard x-ray pulses for pump-probe experiments at the  $\mu$  XAS beam line. The slicing setup consists of a modulator (wiggler) for energy modulation, chicane dipoles for pulse separation, and a radiator (in-vacuum undulator).

A laser pulse from a regenerative Ti:Sa amplifier (30 fs rms, 2 kHz, 2.5 mJ, 800 nm) overlaps with the co propagating electron bunch in the modulator and induces an energy exchange between the laser pulse and the electron bunch. Depending on the relative phase between the two pulses, the electrons can either gain or lose energy. Since the electron bunch in the SLS storage ring is about 35 ps (rms) long, only a small number of electrons is energy modulated. According to simulations, a laser pulse energy of 2 mJ provides a maximum energy modulation of 1% (24 MeV) within this slice. The core bunch contains 5 nC and the slicing efficiency is about  $6 \cdot 10^{-4}$  which leads to a charge of the modulated particles of approximately 3 pC.

The chicane between modulator and radiator induces a spatial ( $\pm 2$  mm) and angular ( $\pm 0.5$  mrad) horizontal offset of the sliced beam at the radiator center which is used to separate the fs x-ray pulse for the ps background in the  $\mu$  XAS beam line. Additionally the chicane is a dispersive element which transfers the pure energy modulation in to a longitudinally one which is slightly broader than the initial modulation. X-ray diffraction measurements on high-amplitude phonon dynamics of photoexcited

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bismuth are consistent with an effective x-ray pulse length of  $140 \pm 30$  fs FWHM [6].

After passing the FEMTO slicing experiment the modulation has the typical bipolar shape as shown in figure 1. One hump contains the electrons which gained energy and the other one the electrons which lost energy. Both are separated by a dip from which the modulated electrons have been removed. Due to the linear momentum compaction factor of the SLS storage ring, this modulation smears out from turn to turn and finally vanishes (see Fig. 5 for particle tracking simulations). For a comprehensive description of the FEMTO slicing experiment at the SLS see [6, 7].

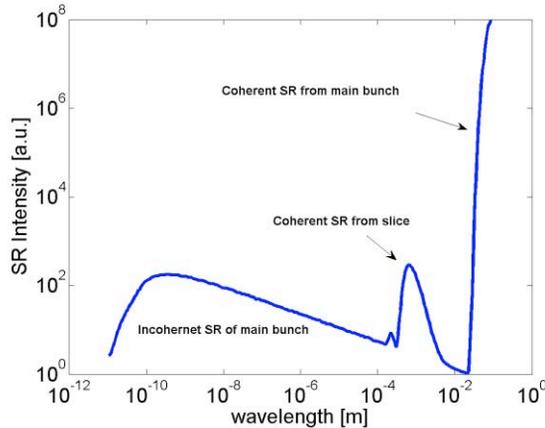


Figure 2: Spectrum of the synchrotron radiation emitted by the sliced electron bunch.

The spectrum of the synchrotron radiation (SR) emitted by the sliced bunch is depicted in figure 2. The core bunch generates incoherent SR, while the FEMTO-sliced particles radiate coherently at wavelength in the order of the slicing length. Therefore the SR spectrum is coherently enhanced in the THz range, where the radiation intensity is proportional to the square of the number of emitting electrons.

## ELECTRO OPTICAL DETECTION

Electro optically active crystals like GaP become birefringent in the presence of an electric field. Electro optical detection techniques use this effect to measure fast changing electric fields by sampling the change in birefringence with short laser pulses. This techniques can be used to measure the temporal profile of electron bunches by sampling their Coulomb field or the emitted coherent synchrotron or transition radiation.

For small electric fields (up to MV/m), the EO effect is dominated by the Pockels effect and linear with the electric field strength. For a properly oriented GaP crystal and electric field direction, the two orthogonal polarized components of a laser oriented along the principal axes of the EO crystal receive a relative phase retardation of

$$\Gamma = \frac{\omega d}{c(n_1 - n_2)} = \frac{\omega d}{c} n_0^3 r_{41} E_{THz}, \quad (1)$$

where  $\omega$  is the angular frequency of the laser,  $d$  the thickness of the EO crystal, and  $n_1$  and  $n_2$  are the refractive indices along the principal axes.  $n_0$  is the refractive index of the (isotropic) crystal at vanishing

electric field,  $r_{41}$  its electro optic coefficient, and  $E_{THz}$  the applied electric field.

With suitable optical elements this relative phase shift or polarisation rotation can be transferred into an amplitude modulation of the transmitted laser light. For all measurements reported in this paper the setup and the electric field strength were such that the change in transmitted laser light is linear in the applied electric field strength.

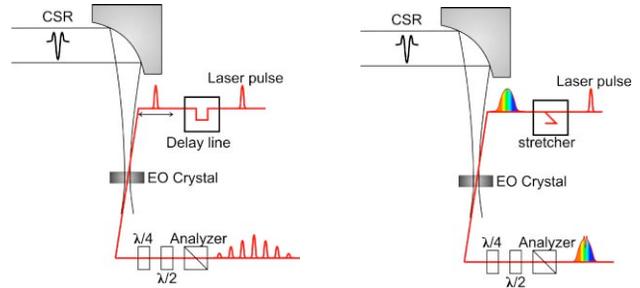


Figure 3: Scheme of the setup for EO sampling (left) and spectrally decoded detection (right).

Results from two different electro optical techniques are reported in this paper: electro optical sampling using a variable delay (Fig. 3, left) and single shot measurements using electro optical spectral decoding (Fig. 3, right).

For the electro optical sampling (EOS) a short ( $\approx 100$  fs) laser pulse is sent through the crystal in parallel with the electric field pulse of the CSR and the relative delay for consecutive laser pulses is changed to sample the longitudinal profile of the THz field pulse. Since the profile is not measured in a single shot, this technique is sensitive to fluctuations of charge and profile as well as arrival time jitter between CSR and the laser pulse.

Spectrally resolved electro optical decoding (EOSD) is a single shot technique, where the broadband laser pulse is stretched in a dispersive material or grating stretcher, resulting in a known frequency vs. time relation. The laser pulse is now longer than the THz field pulse and only a part of the chirped laser pulse is modulated in the EO crystal. This intensity modulation can be retrieved measuring the spectrum of the laser pulse using a spectrometer. Due to frequency mixing between the laser and the THz field pulse, signal distortions become a problem for short pulses and strongly stretched laser pulses. For the Yb doped fiber laser used here significant distortions are expected for field pulses shorter than  $\approx 300$  fs (rms).

For a more comprehensive description of electro optical detection techniques and theory see [3, 8].

## EO-SETUP AT THE INFRARED BEAMLINE

The measurements presented here were done at the infrared beamline [9] of the Swiss Light Source (SLS). The 2.4 GeV electron beam emits synchrotron radiation in a 1.4 T dipole magnet. The SR is collected by a slotted mirror over an angle of 61 mrad (corresponding to a source length of 350 mm) and transported over 9 m by three times 1 to 1 imaging optics to the experimental area outside the accelerator bunker. At the experiment the SR is focused by a 250 mm off-axis paraboloid mirror onto a

5 mm thick GaP crystal (Moltech, Berlin), leading to a focal spot of 5-10 mm.

The EO probe laser is a self built amplified ytterbium fiber laser system [5] synchronized to the SLS rf master clock, delivering 10 nJ pulses at 1 MHz with a useful bandwidth of about 120 nm centered at 1050 nm. Since FEMTO slicing of the electron bunch is done with an independently synchronized Ti:Sa laser, the laser to laser stability and the relative jitter plays a decisive role for pulse length measurements. This jitter determines how long the chirped laser pulse has to be in order to ensure a temporal overlap. It can be deduced from a cross correlation between the two lasers. The relative jitter between the two lasers was measured to about 50 fs (rms).

The Yb fiber laser pulses were chirped to about 100 fs (rms) in a grating compressor for the sampling and 3 ps (rms) for the SD measurements, respectively. They were sent via a polarizer under a slight angle through the GaP crystal. After passing the crystal the laser was directed through a quarter waveplate, a half waveplate, and an analyzing polarizer to an optical fiber. All measurements were done with the half waveplate  $2-4^\circ$  away from crossed polarizer settings to ensure good linearity in the measured signals. For the EO sampling the pulses were detected by an InGaAs photodiode (ET-3010, EOT) and the readout and averaging was done by an oscilloscope. For EOSD a spectrometer (Andor Shamrock 303i) equipped with an InGaAs camera (Andor iDus490-1.7) was used.

## RESULTS

Figure 4 shows EO sampling measurements for several round trips. The EO setup is sensitive enough to detect up to turn 3, which according to beam tracking simulations is already a few ps long, providing a much weaker THz signal than turn 0. For EO sampling measurements the laser is delayed by a delay stage in steps of 100 fs and each data point is averaged over 100 shots. The CSR is extracted at the infrared beamline, which is located about three quarters of a round trip in the SLS storage ring after the FEMTO slicing experiment. Due to the SLS momentum compaction factor, the modulation is already several times longer than directly after the laser interaction and it gets further broadened for every additional turn, as seen in the simulated longitudinal charge distribution of the sliced electron bunch shown in figure 5 [10].

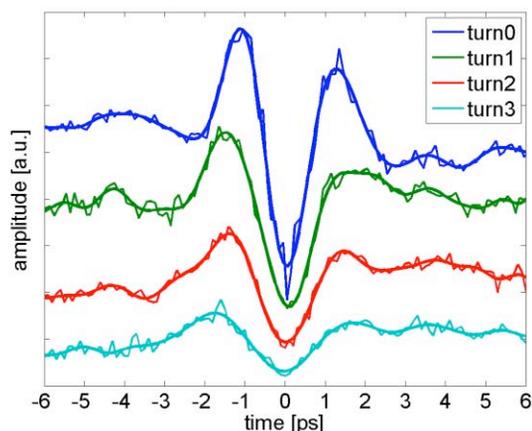


Figure 4: EO sampling measurements of turn 0 to 3.

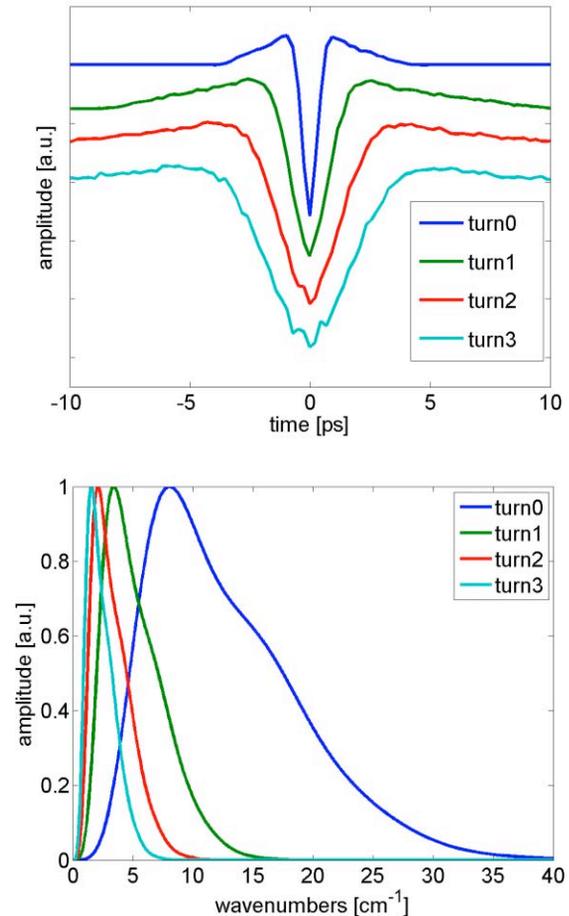


Figure 5: (top): Charge distribution of the sliced bunches from turn 0 to turn 3; and (bottom) the corresponding spectra.

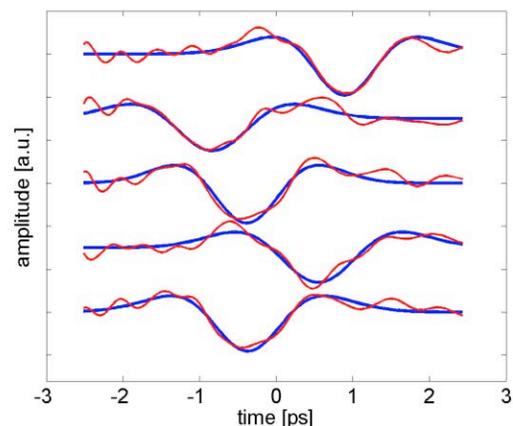


Figure 6: Five consecutive EOSD measurements of turn 0 (red); the blue line shows a fitted double Gaussian distribution.

The signal from the dip in turn 0 has been measured to 510 fs (rms) and increases to about 800 fs (rms) at turn 3. However, large fluctuations of consecutive shots at a single EO sampling point in the central region of the bunch indicate a significant timing jitter between the sampling laser and the sliced electron bunch. In order to reduce these effects, single shot measurements were performed for turn 0 using EO spectral decoding.

A set of single shot EOSD measurements is shown in figure 6. The red line indicates the measurement and the blue one a double Gaussian fit. The pulse length is  $365 \pm 50$  fs (rms), which is clearly shorter than it has been determined to 510 fs (rms) from EO sampling measurements for turn 0. Large fluctuations in the arrival time of the sliced electron bunch could be measured with EOST resulting in a jitter of 630 fs (rms) for 500 shots, which leads to a significant distortion and a corresponding broadening of the sampling results. Although a clear source for this comparatively large arrival time jitter at the IR beamline could not be identified so far, the slicing laser to EO laser jitter, which has been measured to 50 fs rms is definitely not the dominating source. Amplitude and phase jitter of the storage ring rf, timing distribution as well as mechanical vibrations in the IR beamline are major suspects.

The arrival time can be determined and corrected for each single shot EOSD measurement before averaging leading to an improved signal to noise ratio without introducing additional pulse broadening as shown in figure 7. From the modulation a maximum field strength of 20 kV/m at the crystal can be derived.

The spectrum of the sliced bunch of turn 0 at the IR beamline measured with an IR spectrometer (Bruker IFS 66 V) shows a strong suppression of wavelengths longer than 10 nm as compared to the spectrum derived from the simulated particle distribution (blue curve of Fig. 8, top). Taking this into account by an assumed transfer function of the IR beamline, the measured longitudinal profile for turn 0 is in excellent agreement with the simulated distribution (Fig. 8, bottom).

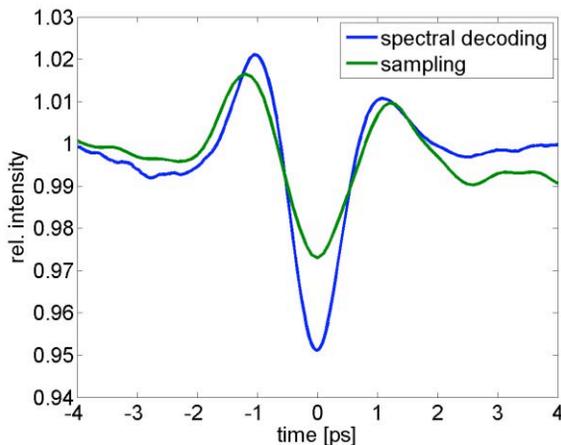


Figure 7: Arrival time jitter corrected average of 500 EOSD measurements of turn 0 and the corresponding sampling measurement.

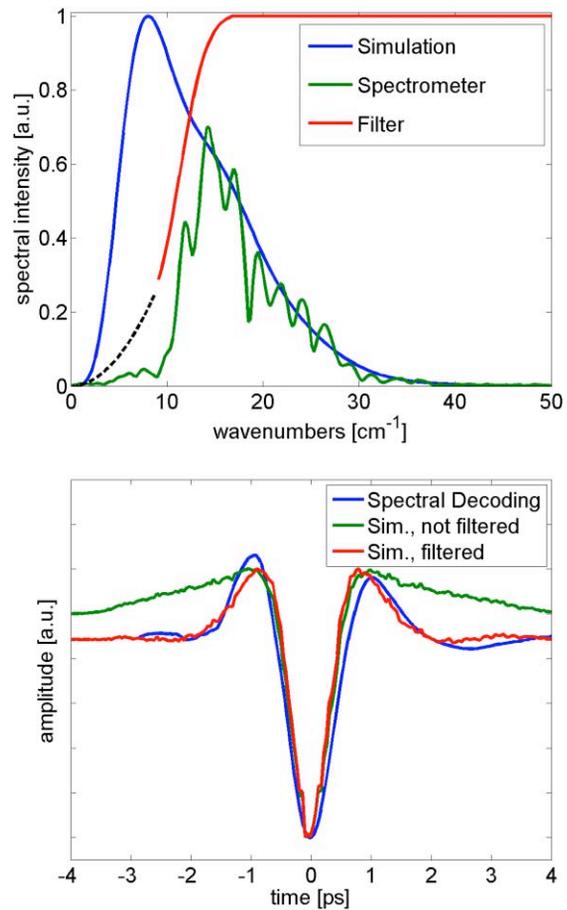


Figure 8: top: measured spectrum of the sliced bunch at turn 0 highpass filter (green), the spectrum derived from particle tracking simulations (blue), and the assumed transfer function of the IR beamline, the measured longitudinal profile for turn 0 is in excellent agreement with the simulated distribution (Fig. 8, bottom). bottom: EOSD measurement function of the IR beamline, the measured longitudinal profile for turn 0 is in excellent agreement with the simulated distribution (Fig. 8, bottom).

## CONCLUSION

The longitudinal time structure of coherent synchrotron radiation pulses from a sub-ps modulation containing a charge of approximately 3 pC was determined in a single shot EO spectral decoding measurement at the IR beamline of the SLS. The measured longitudinal profile of the field pulse is in good agreement with particle tracking simulations. Further experiments to find the source of the relatively large arrival time jitter are in preparation.

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