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HIGH REPETITION-RATE ELECTRO-OPTIC SAMPLING: RECENT STUDIES USING PHOTONIC TIME-STRETCH

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Abstract

Single-shot electro-optic sampling (EOS) is a powerful characterization tool for monitoring the shape of electron bunches, and coherent synchrotron radiation pulses. For reaching high acquisition rates, an efficient possibility consists in associating classic EOS systems with the so-called *photonic time-stretch* technique. We present several setups that may be used for adding the time-stretch functionality to existing EOS systems, and focus on experimental tests made in two situations. At SOLEIL, we present a setup which is optimized for high SNR recording of THz CSR pulses. At KARA (Karlsruhe Research Accelerator), the storage ring of the test facility and synchrotron radiation source ANKA at KIT, we show how the time-stretch strategy can be tested using almost no modification of an existing spectrally-encoded EOS system. Finally we present recent results on CSR and the microbunching instability that have become accessible using photonic time stretch.

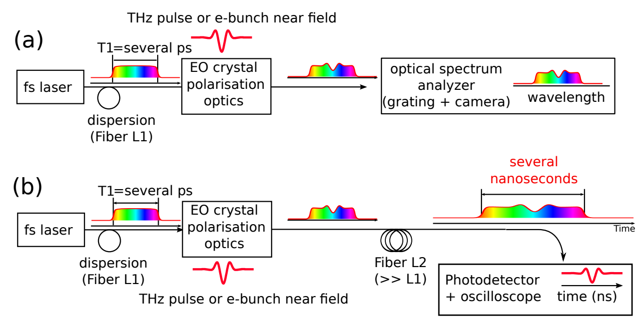

Figure 1: Principles of (a) usual spectrally-encoded EOS (b) photonic time-stretch EOS. In both cases a chirped laser pulse is modulated by the electric pulse under investigation, and the main difference concerns the readout. In classical spectral encoding, the output spectrum is recorded using a single-shot optical spectrum analyzer (usually composed of a grating and a camera). In photonic time-stretch, a long fiber (typically few kilometers-long) stretched the output signal, so that it can be recorded by a single pixel photodetector and an oscilloscope (typically with few GHz bandwidth).

INTRODUCTION: HIGH REPETITION RATE EOS

Single-shot Electro-Optic Sampling [1] (EOS) is an efficient technique for monitoring electron bunch shapes [2–4] by recording the electric field in the near-field of the bunch, and is also capable of recording the Coherent Synchrotron Radiation emitted by the electrons [5]. The principle (Fig. 1a) consists of modulating a stretched laser pulse with the electric pulse to be characterized. As a result, the information is imprinted in the spectrum of the laser pulse, and the information can be retrieved by recording the spectrum shape. In classical spectral encoding EOS, the spectrum is typically recorded using a diffraction grating and a camera.

Although this technique is particularly efficient, operation of EOS at high repetition rates (1 MHz or more) remined up to recently a largely open challenge. The main bottleneck in high-speed EOS was the readout part, as commercial linear cameras are typically limited to the 100 KHz range. Two approaches to this problem have been undertaken recently: (i) one direction has been to develop specific cameras that can operate at several Megahertz, the KALYPSO project at Karlsruhe Institute of Technology [6, 7], (ii) a second research direction has been devoted to an alternate type of readout: photonic time-stretch [8–10].

In photonic time-stretch EOS [8–10], the output pulse (Fig. 1b) is dispersed in a long fiber (typically with few kilometers length). As a result, the EOS signal appears as slowed-down replica of the THz electric field, and can be recorded using a single pixel commercial photodetector and an oscilloscope (or acquisition board) with few GHz bandwidth. The acquisition rate can thus be pushed to the hundreds of MHz range, using commercial devices.

Historically, the photonic time-stretch technique has been introduced by the B. Jalali team in 1999 [11, 12] for increasing the bandwidth of A/D digitizers in general. Variants of the technique have also been widely used for recording optical spectra at hundreds of MHz rates [13] (a technique known as Dispersive Fourier Transform, or DFT), as well as high repetition-rate imaging [14–16].

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We present here result using the photonic time-stretch approach in the context of single-shot EOS. We present results at SOLEIL on free-propagating THz CSR pulses, and at KARA on near-field EOS of electron bunches.

RESULTS AT SOLEIL: ANALYSIS OF THZ CSR BURSTS

We first performed a test at SOLEIL in 2013 [8], where we could record THz Coherent Synchrotron Radiation (CSR) pulses in single bunch mode, at 850 KHz repetition rate. This first experiment has been performed in conditions of high electron bunch charge, in order to reduce as much as possible the SNR requirement.

Then we started to study the microbunching instability, by monitoring the CSR pulses in more challenging situations. First we considered nominal-alpha regimes at less intense current. Then we aimed at recording the CSR pulses on low-alpha mode, i.e., the prefered mode for users of CSR.

This led us to upgrade our time-stretch setup, with the aim to increase the sensitivity.

Detectivity Enhancement using "Near Extinction" Scheme with Balanced Detection

We first upgraded our laser system by adding a home-made Ytterbium amplifier. This allowed us to test the EOS configuration know as *near extinction*. Data analysis revealed that the strategy was indeed efficient for increasing the EOS signal. We also noticed that the SNR was essentially limited by the noise of the optical source.

In order to go further, and attempt approching shot-noise limited detection, a main challenge was to manage the optical noise of the laser source, and we thus searched a way for performing EOS while canceling out the laser source noise.

In a slightly different context, in Ref. [17], Ahmed Savolainen and Hamm presented a trick that allows a *near-extinction EOS setup* to provide two complementary outputs. Balanced detection can thus be perfomed ar the same time as near-extinction EOS, opening the way to a drastic noise reduction.

In practice, this upgrade could be performed by adding a set of Brewster plate just after the EO crystal, and using the two ports of the output polarizer. This setup is represented in Fig. 2, and a detailed characterization of the EO setup can be found in Ref. [9].

Results: Long Bunch and Short Bunch Modes

In Fig. 3, we displayed a typical series of THz pulses during a CSR burst in nominal-alpha (i.e., long bunch) mode. 5 bunches are simultaneously recorded in this experiment. These CSR pulses are produced by the microbunching instability, and are observed above a threshold for the bunch charge. As expected from theory, below threshold, the average shape of the electron bunch is unable to radiate coherently, as the emission is shielded by the vacuum chamber.

The situation is different with short electron bunches. If their size is sufficiently small, they can radiate CSR even below the threshold of the microbunching instability. Hence two regimes are expected in this case. Below the microbunching instability threshold, we expect a CSR radiation due to the "shortness" of the electron bunch. Above threshold, we expect also an emission due to the appearance of microstructures in the bunch. This scenario is displayed in Fig. 4, and studied in detail in Ref. [10].

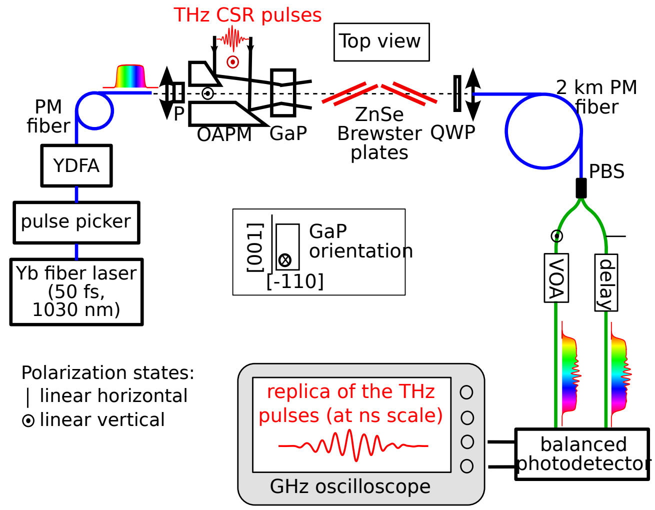

Figure 2: Photonic time-stretch setup designed for high sensitivity EOS. The EO modulation is performed in the Gallium Phosphide crystal. Then the time-stretch is provided by the 2 Km-long fiber. As a result, we obtain a "replica" of the THz pulses, on the oscilloscope, that are "slowed down" in time, with a factor of the order of 150-200. See Ref. [9] for details.

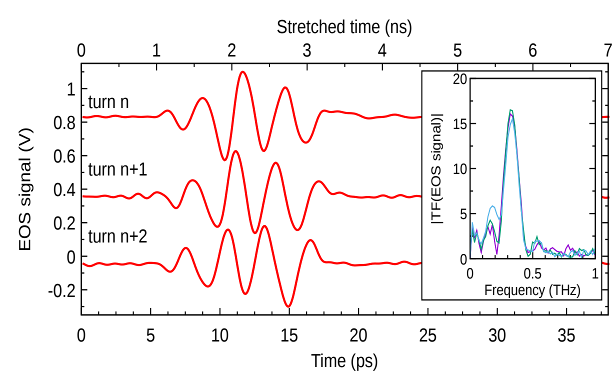

Figure 3: Series of CSR pulses obtained with long electron bunches (15 ps RMS), above the microbunching instability threshold.

PRELIMINARY RESULTS AT KARA: ELECTRON BUNCH NEAR-FIELD

In parallel, we started a joined PhLAM-ANKA/KARA collaboration aiming at testing the possibility to perform photonic time-stretch on a near-field electron-bunch EOS system. For this preliminary test, we did not specifically adapt the ex-

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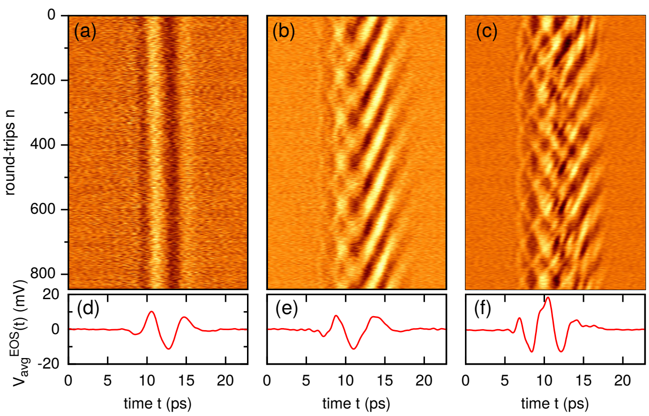

Figure 4: Series of CSR pulses obtained with short electron bunches in the so-called *low alpha* mode. (a): below, and (b), (c) above the microbunching instability threshold. (d), (e), (f): averages of the EOS signals. See Ref. [10] for details.

isting EOS setup. We mainly replaced the single-shot optical spectrum analyzer by a 2 km HI1060 fiber, followed by an amplified InGaAs photodetector (Discovery Semiconductor DSC-R412).

We optimized the dynamic range of the detection, by added an Ytterbium-doped fiber preamlifier before the stretching fiber. In order to subtract the reference laser pulses (without EOS signal) we proceeded in an analog way. We fed the two balanced detector inputs with successive laser pulses (with and without EOS signal). The stretch factor was M=80, and we low-pass filtered the data at 5 GHz at the processing stage.

A typical series of EOS signals (at each turn in the ring) is represented in Fig. 5. Although we did not work specifically on the SNR optimization, we can already see dynamical features as a global oscillation at the synchrotron frequency, and even the appearance of microstructures (at the right), which may be attributed to the microbunching instability.

Data analysis showed guidelines for further SNR improvement. The SNR is still limited by the available laser power. We thus expect improvements in the next experimental shifts, by optimizing the losses in the EOS setup. A second foreseen possibility is a modification of the EOS setup for cancelling out the laser common noise, using balanced detection technique of Ref. [9].

CONCLUSION, FUTURE DIRECTIONS

Photonic time-stretch appears as a viable candidate for high-repetition-rate acquisition of single-shot EOS signals. The acquisition rate can in be extended in principle up to the hundreds of MHz range (i.e., the typical repetition rate of laser oscillators). Tests can be made on existing EOS systems, with minimal modifications of the EOS part. When needed, SNR can be significantly improved by a slight modification of the EOS design for performing balanced detection [9].

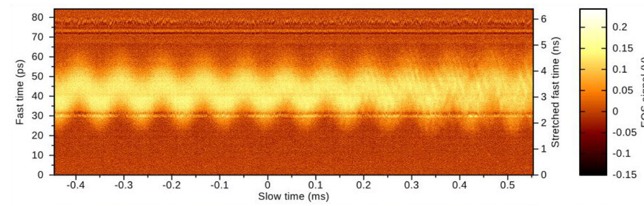

Figure 5: Preliminary result: Time-stretch EOS recording of the electron-bunch near-field at KARA, at each turn (i.e., at 2.7 MHz acquisition rate). Left vertical scale (Fast time) corresponds to the input time, Right vertical time (Stretched time) corresponds to the time at oscilloscope input. Horizontal time scale corresponds to the number of round-trips.

Future works concern the improvements of time-stretch EOS performances for specific applications. Detection of free-propagating THz pulses requires high-sensitivity. Detection of electron bunch near-fields can required high dynamic range, when small structures (i.e., due to the microbunching instability) are the object of interest. Another important direction consists of performing time-stretch EOS at the 1550 nm wavelength, in order to take advantage of the widely developed high-quality (and low-cost) components of the telecommunication market.

Finally, another important question concerns the comparison of the performances of camera-based spectrally-encoded EOS, with photonic time-stretch, in order to evaluate their respective best domains of application.

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