EXTENSION OF EXISTING PULSE ANALYSIS METHODS TO HIGH-REPETITION RATE OPERATION: STUDIES OF THE “TIME-STRETCH STRATEGY”

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Abstract

We examine how the “photonic time-stretch strategy” can be used to upgrade existing FEL Electro-Optic Sampling (EOS) setups to high repetition rates. Tests made at SOLEIL showed a capability of 88 MHz acquisition rate of single-shot EOS signals. The time-resolution limits is found to be identical to the limits of classical spectral encoding. Technically, time-stretch EOS systems can be build from existing spectral encoding systems, by adding an output optical device.

BRIEF REVIEW OF THE SPECTRAL ENCODING AND TIME-STRETCH METHODS

Spectrally Encoded Electro-optic Sampling (Time to Wavelength Conversion)

A powerful technique to analyze electron bunch shapes (or short THz pulses produced, e.g., by CSR) consists to convert the temporal information into the spectral domain of a laser pulse [1–6] (spectral encoding). The principle is displayed in Fig. 1. The spectral information is analyzed by a single-shot optical spectrum analyzer, which is composed of a grating and a CCD or CMOS camera. Although very efficient and widely used for electron bunch diagnostics, this strategy present a limitation in term of acquisition rate, because of the speed limitation of currently available cameras (typically hundreds of kilo frame/s). Hence it will be challenging to use further this technique in high-repetition rate FELs (as well as LINACs, storage rings, etc.).

Time Stretch Strategy (Time-to-time Conversion)

The photonic time-stretch technique has been developed in a different context than accelerator physics [7]. The idea consists in converting the ultrafast signal under investigation into a “slowed-down” replica. This is two-step process (Fig. 2). First the pulse is encoded into the spectral domain (as for the classical spectral encoding method). The second step consists in using dispersion in a long fiber, so that the optical spectrum is converted back into the time domain. Using a sufficient length of fiber, the output replica can be easily stretched up to the nanosecond domain, and thus can be recorded using a photodetector and an oscilloscope. This technique can typically reach tens to hundreds of MHz acquisition rates.

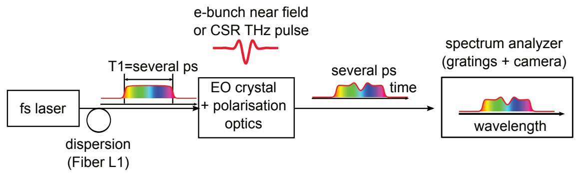

Figure 1: Classical electro-optic detection with spectral encoding. The pulse information is encoded into the spectral domain and recorded using a single-shot spectral analyzer. The main acquisition rate limitations stems from the camera used in the spectrum analyzer.

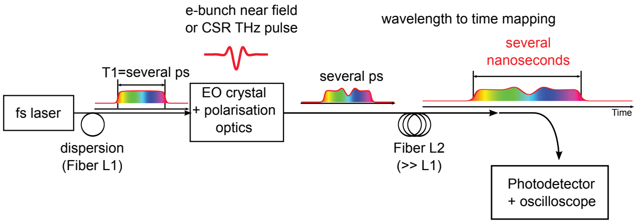

Figure 2: Principle of electro-optic sampling with time-stretch: a “slowed-down” replica of the bunch shape (or THz pulse) is produced. The output signal is recorded using a single pixel detector and an oscilloscope.

EXPERIMENTAL TESTS OF THE TIME-STRETCH EOS STRATEGY AT SOLEIL

We have explored the possibility to use this method to record electric fields produced by electron bunches at SOLEIL. Instead of probing the near-field electric field of an electron bunch, we attempted to detect the CSR THz pulses emitted by the electron bunch. As for the SLS EOS system [3], we used a GaP crystal and a 1040 nm mode-locked Yb fiber laser. The complete time-stretch setup is detailed in Ref. [8].

A typical series of single pulse is represented in Fig. 3. The stretch factor between the THz pulses and the oscilloscope pulses is $M = 190$ (i.e., 1 ps correspond to 190 ps at the oscilloscope input). The acquisition rate was fixed by the laser repetition rate (88 MHz). This speed enabled to study the CSR pulses emitted at the AILES beamline in

ISBN 978-3-95450-134-2

single bunch (0.85 MHz repetition rate), and 8 bunch (6.8 MHz).

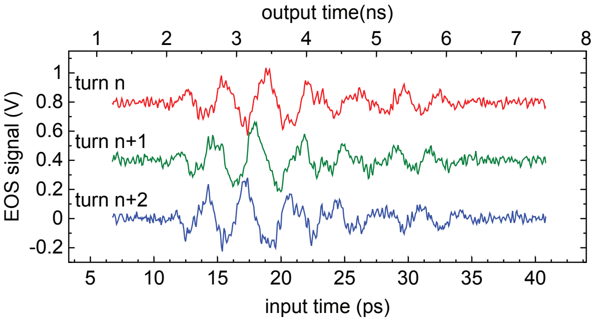

Figure 3: Typical EOS recording of successive THz CSR pulses emitted at SOLEIL every 1.2 μs. See [Roussel *et al.*, Scientific Reports 5, 10330 (2015)], for the detailed experimental setup. The stretch factor is $M = 190$. Note that the acquisition rate (88 Mega pulses/s) was well above the requirement of this recording.

TIME-STRETCH VERSUS SPECTRAL ENCODING METHODS: PERFORMANCES

Acquisition Speed

In the time-stretch technique, the use of a "single pixel" detector and an oscilloscope enables to reach much higher acquisition speeds. For the data shown in Fig. 2, the detector has a 20 GHz bandwidth, and the oscilloscope bandwidth is 30 GHz. It can thus be considered as equivalent to a spectrometer equipped with a camera with ≈20 GHz pixel clock.

Temporal Resolution/Bandwidth: Numerical Results

In addition to the crystal performances, it is well-known that spectral encoding method presents a limitation in temporal resolution that is due to the conversion process (from time to wavelength). Hence we have also examined the temporal resolution of the time-stretch strategy and compared it to the spectral encoding case.

Let us remember that the temporal resolution in the classic spectral encoding case is:

$$T_{res} \approx \sqrt{T_0 T_S}, \tag{1}$$

with T_S the duration of the stretched pulse at the crystal input, and T_0 the compressed pulse duration of the laser.

In order to compare the two methods, we have computed the output signal to a sine modulation of the crystal birefringence. We assume that the dispersion in the fibers is linear, and neglect nonlinear effects, and we compute the ouput modulation amplitude versus the modulation frequency f_m. As a main result (Fig. 4), the bandwidth (and thus the temporal resolution) were found to be the same for both the time-stretch and the spectral encoding methods.

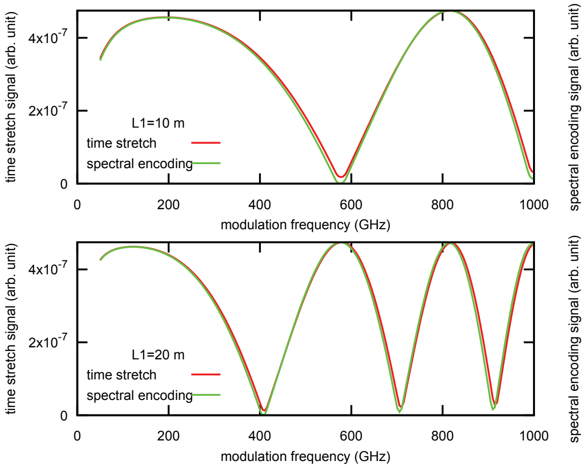

Figure 4: Comparison of the frequency responses (amplitude versus frequency) calculated in the case of spectral encoding (green curve) and time-stretch (red curves). (a) $L_1 = 10$ m and (b) $L_1 = 20$ m. $L_2 = 2000$ m. For other parameters, see Ref. [8].

CONCLUSION

The time-stretch strategy can be an alternative to the classical spectral encoding method, when high repetition rate electron bunches are used. From the experimental point of view, a time-stretch system can be obtained using an existing spectral encoding EOS system, by a relatively straighforward upgrade. Moreover no loss of performance is expected concerning the temporal resolution.

This strategy can also be potentially applied to any diagnostics for which an information can be encoded onto a laser pulse, as, e.g., transient reflectivity [9].

APPENDIX: DETAILS OF THE EXPERIMENTAL SETUP

In the case of CSR detection at SOLEIL, we used a setup optimized for sensitivity to the electric field. Hence, instead of using directly the setup presented in Fig. 2, we build a variant allowing to perform a balanced detection (at the analog level) between the two outputs of the EOS polarizing cube beam-splitter. This setup is shown in Fig. 5.

ACKNOWLEDGMENT

The work was supported by the ANR (Blanc 2010-042301) and the LABEX CEMPI project (ANR-11-LABX-0007). The CERLA is supported by the French Ministère chargé de la Recherche, the Région Nord-Pas de Calais and the FEDER. The project used HPC resources from GENCI TGCC/IDRIS (2013-x2013057057, 2014x2014057057).

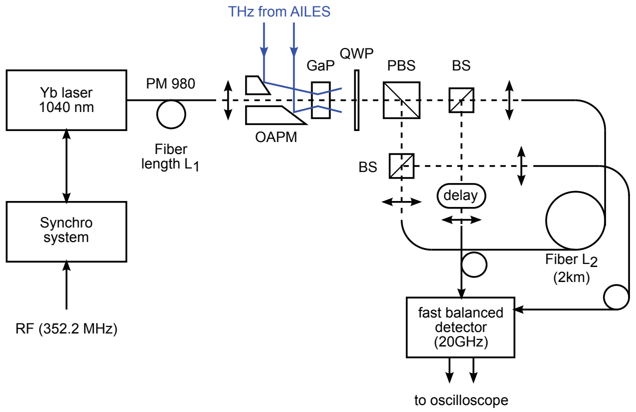

Figure 5: Detail of the experimental setup (from Ref. [8]). (P): polarizer, (OAPM): off-axis parabolic mirror, (PBS): polarizing beam splitter, (BS): non-polarizing beam-splitter. Expect the fiber with length L_1, all fibers are HI1060. L_1 = 10 m, and L_1 = 2 km.

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ISBN 978-3-95450-134-2