Echantillonnage Electro-Optique monocoup à cadence multi-MHz, en utilisant la technique d'étirage temporel (time-stretch).

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LAL, 8 décembre 2015

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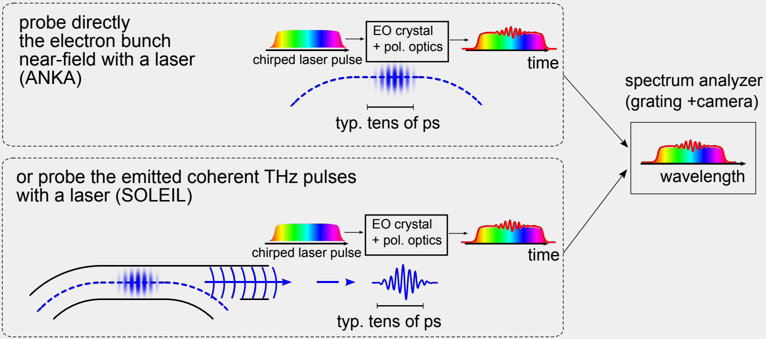
Single-shot electro-optic sampling using spectral encoding

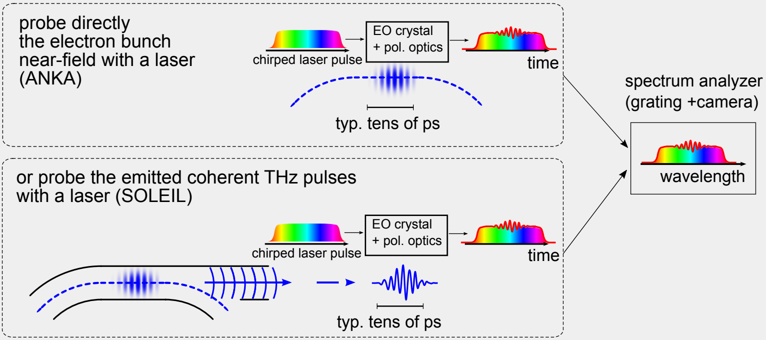
Time to spectrum conversion



First demonstration (THz pulses): Jiang and Zhang, Appl. Phys. Lett. 72, 1945 (1998)
Electron bunch: Wilke et al. , PRL 88, 124801 (2002)
CSR pulses (SLS): F. Mueller et al. PRSTAB 15, 070701 (2012)
Inside a storage ring (ANKA): N. Hiller et al., MOPME014, Proc.IPAC'13, Shanghai, China (2013).

Single-shot electro-optic sampling using spectral encoding

Time to spectrum conversion

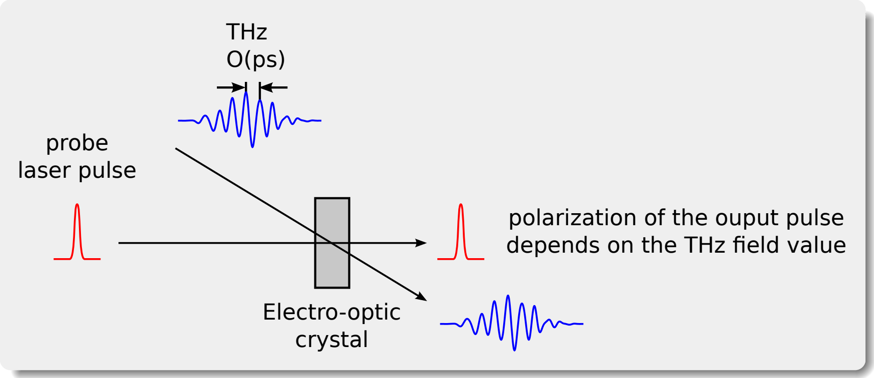


+: single-shot, pico/sub-picosecond resolution
-: repetition rate limited by camera aquisition rate

$\Rightarrow$ Upgrade to high repetition rate?

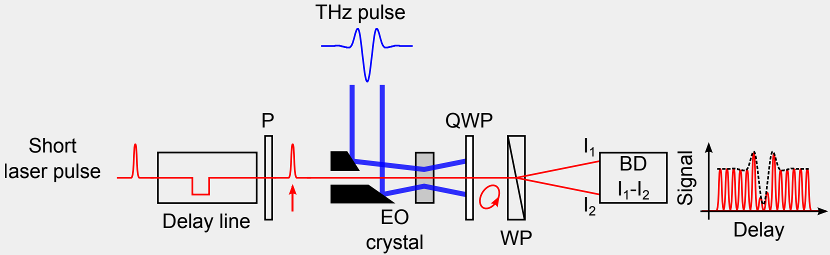
Electro-Optic detection principle

- The **Pockels effect**:
  An external e-field modifies the refractive indexes of a birefringent crystal.
- The induced birefringence is probed using a laser pulse.



Existing EO setups and their limitations: based on delay scan

Scanning-type electro-optic sampling (EOS)

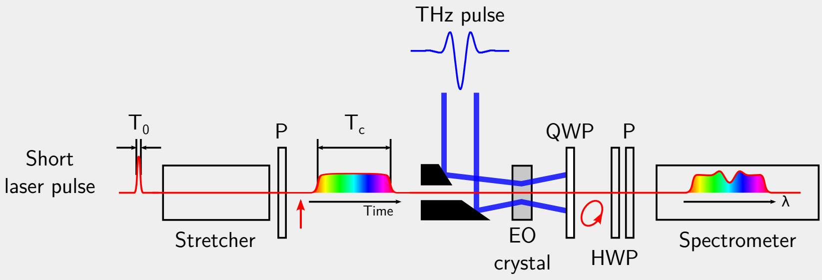


[Yan *et al.*, Phys. Rev. Lett. **85**, 3404 (2000)], [Katayama *et al.*, App. Phys. Lett. **100**, 111112 (2012)]

- Balanced detection $\rightarrow$ high sensitivity (+)
- Not single-shot (-)

Existing EO setups and their limitations: based on spectral encoding

Spectrally-encoded electro-optic detection (EOSD)

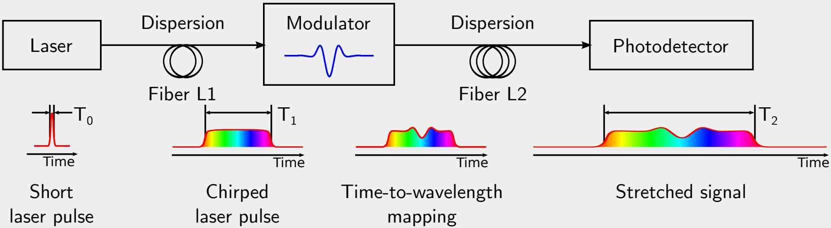


[Wilke *et al.*, Phys. Rev. Lett. **88**, 124801 (2002)], [Müller *et al.*, Phys. Rev. ST Accel. Beams **15**, 070701 (2012)], [Hiller *et al.*, IPAC'13, p. 500 (2013)]

- Resolution $\approx \sqrt{T_0 T_C}$
- No balanced detection (-)
- Single-shot (+)
- Acquisition rate: 100 kHz max. (-)

Photonic Time-Stretch

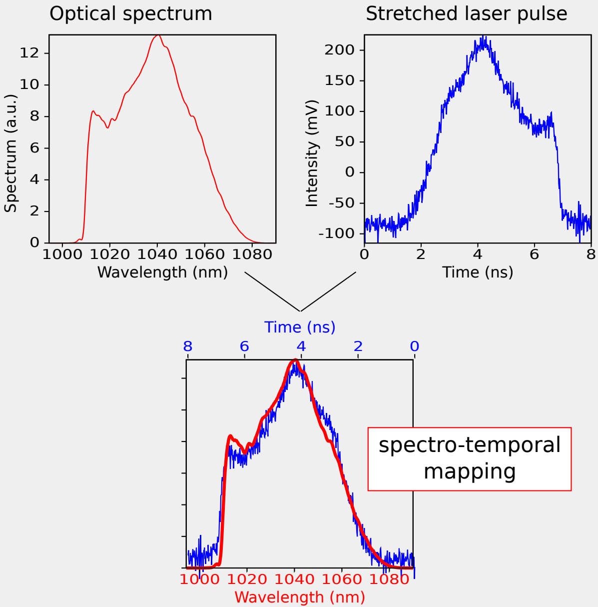
Principle



[Coppinger, F. *et al.*, IEEE Transactions on Microwave Theory and Techniques, **47**, 1309 (1999)], [Han, and Jalali, Journal of Lightwave Technology, **21**, 3085 (2003)]

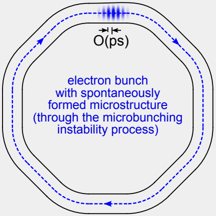
- Stretch factor: $T_2 = MT_1 = (1 + L_2/L_1)T_1$
- Resolution: $T_{min} = \sqrt{8\pi\beta_2 L_1} \approx \sqrt{T_0 T_1}$
- Photodetector speed: up to 70 GHz
- Possibility of balanced detection [Wong *et al.*, Journal of Lightwave Technology, **29**, 3099 (2011)]

Wavelength-to-time mapping



Application to the detection of coherent synchrotron radiation in storage rings

Emission of CSR during the microbunching instability

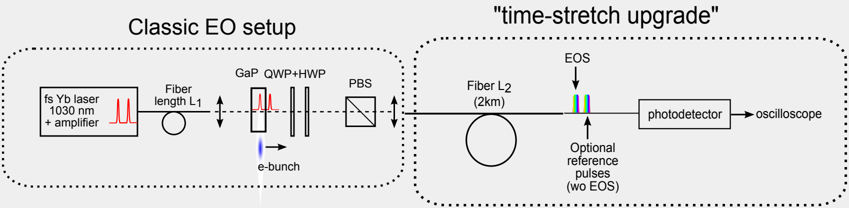


- Coherent synchrotron radiation in the THz frequency domain: sub-ps/ps structures,
- At high-repetition rate: revolution frequency in the MHz range.

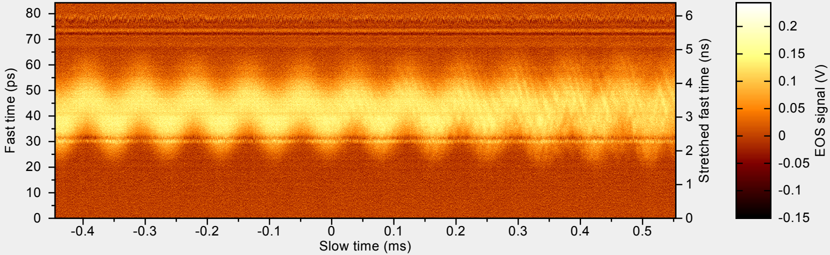
Electro-optic strategy for THz CSR pulse measurements in storage rings:

UVSOR-II: [Katayama *et al.*, App. Phys. Lett. **100**, 111112 (2012)]
SLS: [Müller *et al.*, Phys. Rev. ST Accel. Beams **15**, 070701 (2012)]
ANKA: [Hiller *et al.*, IPAC'13, p. 500 (2013)]

"Photonic time stretch" upgrade at ANKA (EOS of the e-bunch near field)

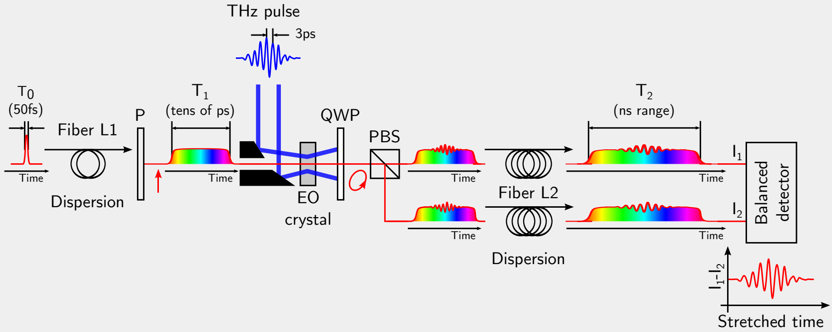


Bunch shape near field recorded at each turn in the ANKA storage ring (every ~ 363 ns)

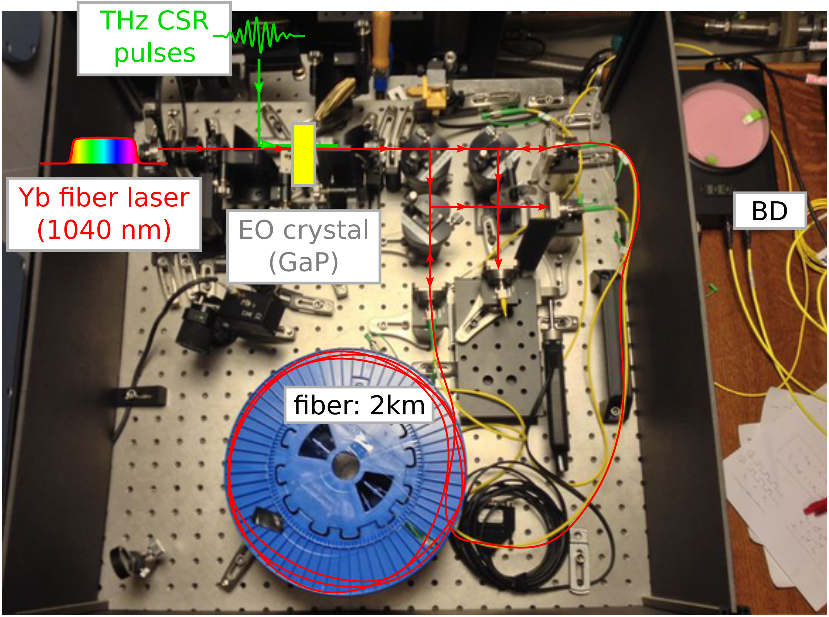


EOS of CSR pulses at SOLEIL

Time stretch spectrally-encoded EOS with balanced detection

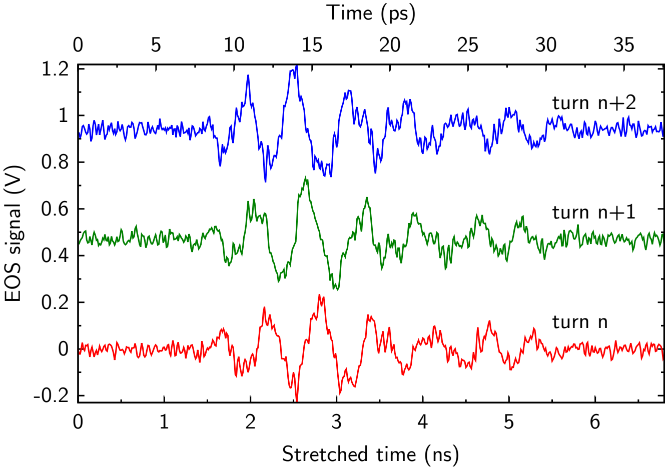


TS-EOSD setup on the AILES infrared beamline



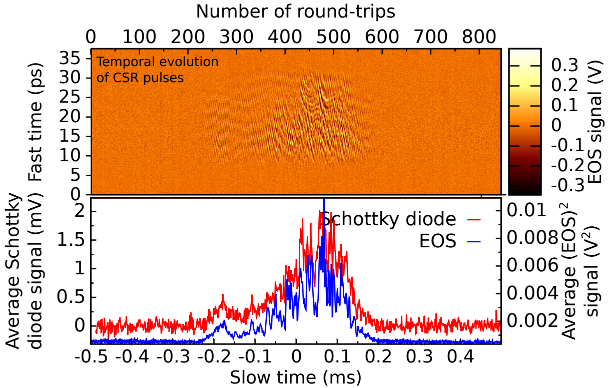
Successive single-shot CSR pulses recordings

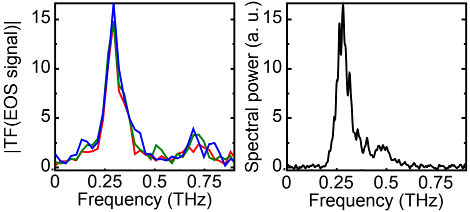
Synchrotron SOLEIL, single-bunch, nominal-alpha operation,
$I = 15$ mA (above microbunching instability threshold)



Fiber lengths: $L_1 = 10$ m, $L_2 = 2$ km $\rightarrow$ Stretch factor $M = 1 + L_2/L_1 = 201$

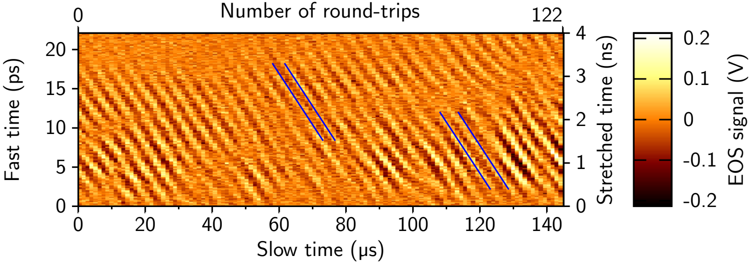
Comparison with traditional CSR measurements



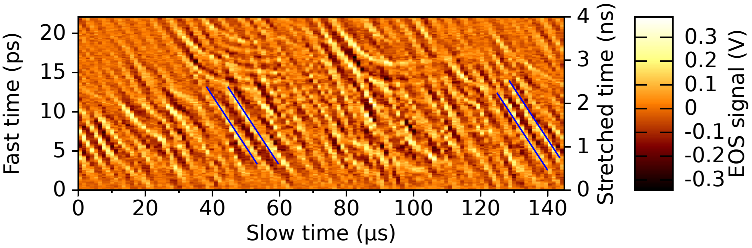


Details of temporal evolution of the CSR pulses

- Beginning of the burst

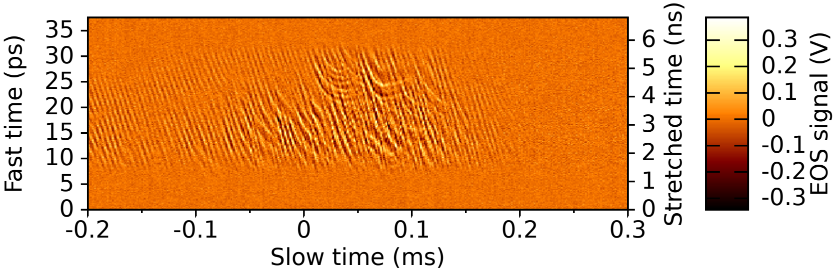


- Burst peak

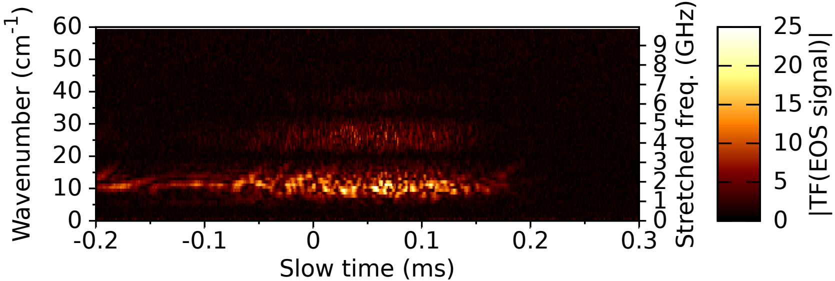


Temporal evolution of the CSR spectrum

- Temporal evolution of the CSR pulses ($L_1 = 10$ m)

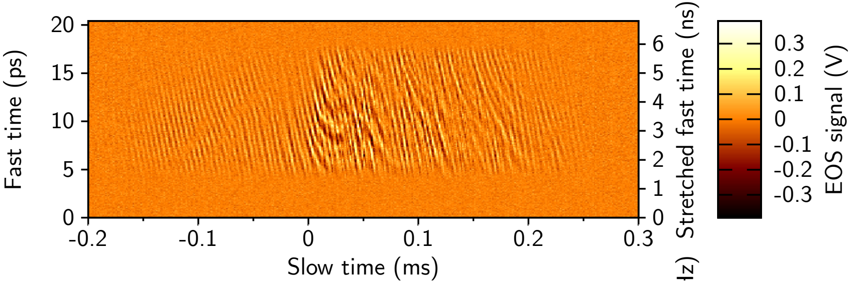


- Fourier transform of the EO signal ($L_1 = 10$ m)

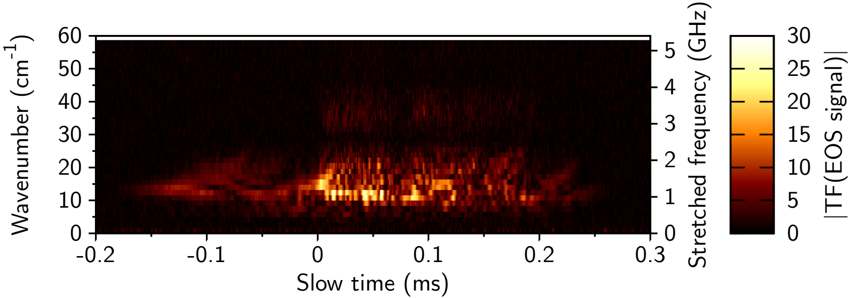


Temporal evolution of the CSR spectrum

- Temporal evolution of the CSR pulses ($L_1 = 5$ m)

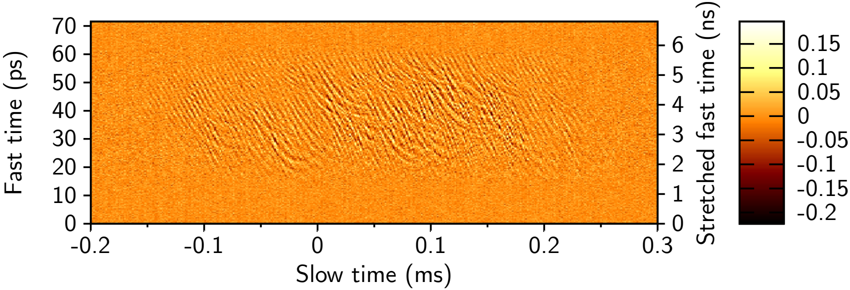


- Fourier transform of the EO signal ($L_1 = 5$ m)

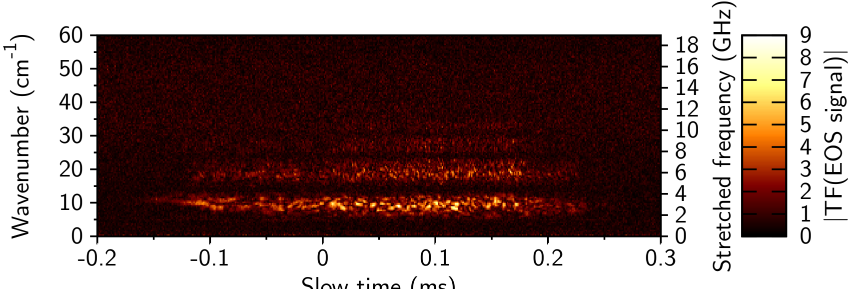


Temporal evolution of the CSR spectrum

- Temporal evolution of the CSR pulses ($L_1 = 20$ m)

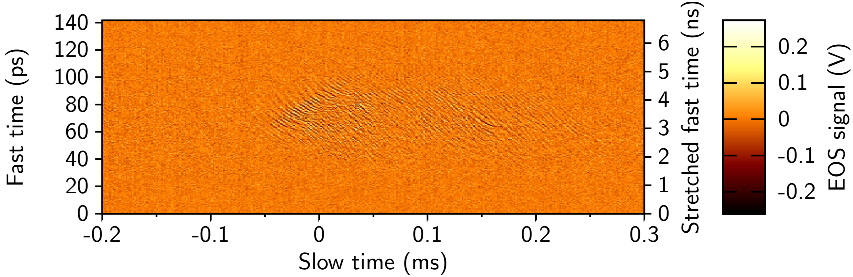


- Fourier transform of the EO signal ($L_1 = 20$ m)

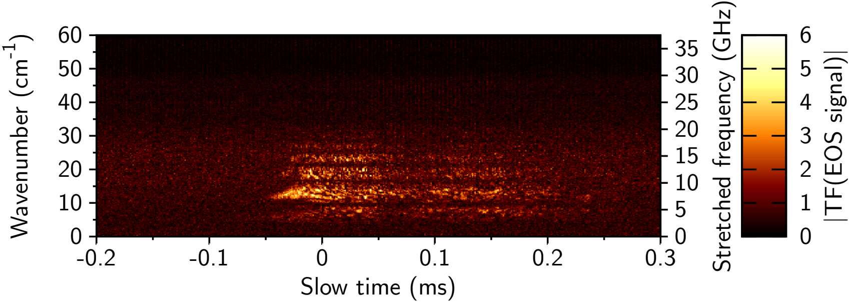


Temporal evolution of the CSR spectrum

- Temporal evolution of the CSR pulses ($L_1 = 40$ m)



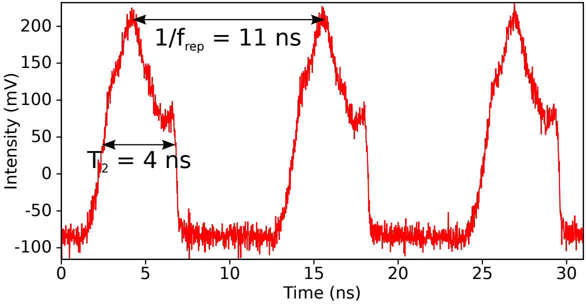
- Fourier transform of the EO signal ($L_1 = 40$ m)



Trade-off between acquisition rate and stretch factor

Final stretch pulse duration T_2:

$$T_2 = \left(1 + \frac{L_2}{L_1}\right) T_1 = M T_1$$



Bandwidth limitation and acquisition time window

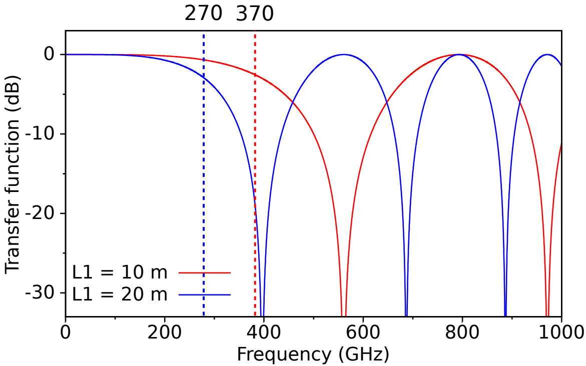
Transfer function of the photonic time-stretch:

$$\begin{aligned} H(f_m) &= \cos^2\left(2\pi^2\beta_2 \frac{L_2}{M} f_m^2\right) \\ &\approx \cos^2\left(2\pi^2\beta_2 L_1 f_m^2\right) \end{aligned}$$

Bandwidth at 3 dB:

$$\nu_{max} = \sqrt{\frac{1}{8\pi\beta_2 L_1}} \propto \sqrt{\frac{1}{T_0 T_1}}$$

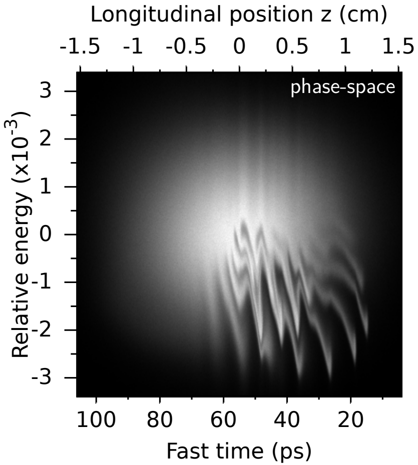
L_1 (m)	T_1 (ps)	ν_{max} (GHz)
10	25	370
20	47	270

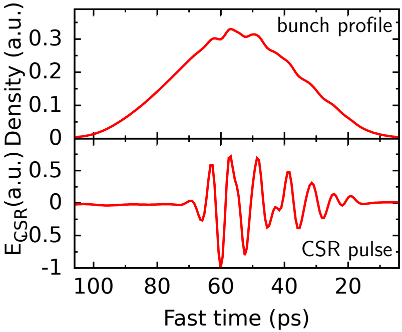


From phase-space to THz CSR pulse

Simulations of the longitudinal electron bunch dynamics under the influence of the shielded CSR wakefield using macro-particles code.

[Evain *et al.*, Europhys. Lett. **98**, 40006 (2012)], [Murphy *et al.*, Part. Accel. bf 57, 9 (1997)]

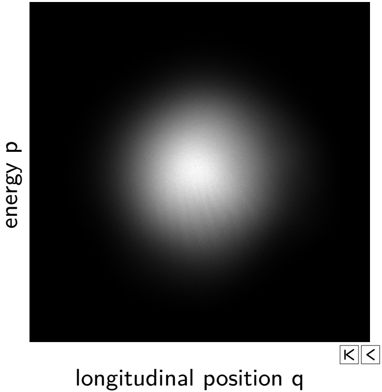




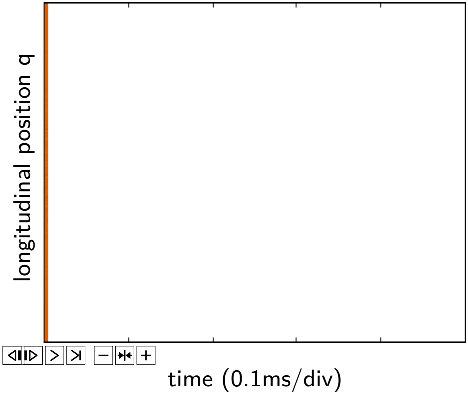
Note: THz electric field → may be viewed as a "high-pass filter"

Temporal evolution of THz CSR pulses

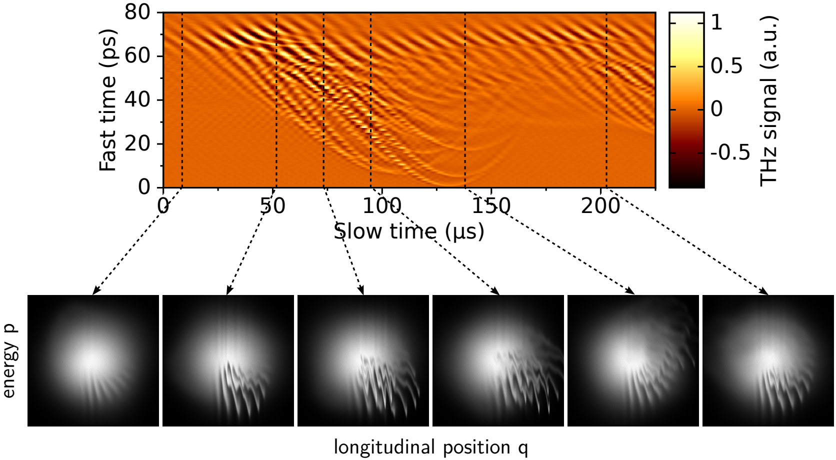
Longitudinal phase-space:



CSR wakefield:



Temporal evolution of THz CSR pulses



Conclusion

Experimental results

- A relatively simple upgrade of existing single-shot EOS setups can enable high-acquisition rates (easily up to many tens of Mega pulses/s).
- The strategy works for monitoring either electron bunch near field, and THz CSR radiation

Test of the model

- Qualitative good agreements with the simulations based on macro-particles tracking combined with shielded CSR wakefield.

Some open questions

- Use in EOS setups of high rep. rate LINACs?
- Possibility to use the "time-stretch upgrade" in other diagnostics? (e.g., transient reflectivity).

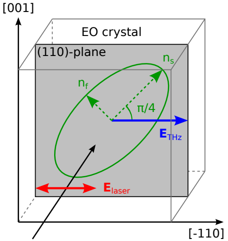
Current works

- Improvement of SNR, Bandwidh, time window
- Systematic studies of the microbunching instability

E. Roussel et al, Scientific Reports **5**, 10330 (2015)

Characteristics of the TS-EOSD setup

- Electro-optic effect in the GaP crystal → phase retardation $\Delta\Phi$



$$\Delta\Phi = \frac{2\pi d}{\lambda} n_0^3 r_{41} E_{THz}$$

- Balanced detected signal:

$$I_{det} = I_0 \sin\Delta\Phi \approx I_0 \Delta\Phi$$

- Sensitivity of the setup:
  Minimum phase retardation $\Delta\Phi_{min} = 3.2 \cdot 10^{-3}$ radians
  → Theoretical electric field sensitivity = 3.7 kV/m