High repetition-rate electro-optic sampling of CSR and bunch shapes: recent studies using photonic time-stretch

Serge Bielawski
PhLAM, Université Lille 1, France
on behalf of the SOLEIL-PhLAM-ANKA collaborations

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Introduction: PhLAM-SOLEIL and PhLAM-ANKA collaborations

PhLAM Lab.
- Nonlinear optics, fiber development
- Nonlinear dynamics, instabilities

SOLEIL
- Synchrotron radiation facility (storage ring)

ANKA (now KARA)
- Synchrotron radiation facility (storage ring)
- Test facility
Initial motivation: studies of the microbunching instability

- Emitted electric field → affects other electrons

- CSR wakefield [Murphy et al., Part Acc 57, 9 (1997)] (and possibly others wakefields)

- Typical num. simulation (by E. Roussel, with SOLEIL parameters):

  - Observed in many storage-rings: ALS (Berkeley), BESSY, MLS and ANKA (Germany), Canadian Light Source (Canada), DIAMOND (UK), ELETTRA (ITALY), SOLEIL (France), UVSOR (Japan)...
  - Opportunity?: Intense source of coherent THz radiation (typ. > 10000 times normal SR)

CSR instability theory [Venturini & Warnock, PRL89, 224802 (2002)]
First (indirect) observations in storage rings: ALS [PRL 88, 254801 (2002)], and BESSY [PRL 89, 224801 (2002)]
Measurement strategies at SOLEIL and ANKA: near-field vs far-field

**PhLAM-SOLEIL:** record far-field emission (at the THz beamline)

- coherent THz pulse
- THz detection system

**ANKA:** record the near field

- electric field probe

+ Easy to place/develop a detector far from the e\textsuperscript{−} bunch
+-/- Only access to fast-evolving field component

?? low field expected => requires a good sensitivity (V-kV/cm)

?? Challenging to place something near the e\textsuperscript{−} bunch
++ “Very direct” measurement
+-/- Intense electric field, but need high dynamic range (microstructure relative amplitude is small)

In both cases, need: (i) few ps resolution, (ii) single-shot, (iii) MHz+ rep. rate
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2. Results at SOLEIL: microstructures observed in the far-field

3. Preliminary results at ANKA (near-field)
Electro-Optic sampling of THz pulses: principle

- The electric field modifies the birefringence of a crystal.
- The THz-induced birefringence is probed using a laser pulse.

Add a polarizer (and optional waveplates) → electro-optic modulator.
Single-shot EO sampling → spectral encoding?

Time to spectrum conversion

CSR THz pulse

EO crystal + polarisation optics

fs laser
dispersion (Fiber L1)

T1=several ps

several ps

time

CSR THz pulse

EO crystal + polarisation optics

fs laser
dispersion (Fiber L1)

T1=several ps

several ps

time

wavelength

T1=several ps

EO crystal
+ polarisation
optics

fs laser

dispersion (Fiber L1)

T1=several ps

EO crystal
+ polarisation
optics

FS laser
dispersion (Fiber L1)

CSR THz pulse

EO crystal + polarisation optics

fs laser
dispersion (Fiber L1)

T1=several ps

several ps

time

wavelength

Challenge: repetition rate, as commercial cameras ≤ 150 K line/s*

(*) e.g., Sensorinc 2048R 157 K lines/s, (2048 pix/12 bits)


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 EO sampling → spectral encoding?**

**Time to spectrum conversion**

- **fs laser**
- dispersion (Fiber L1)
- **EO crystal + polarisation optics**
- **CSR THz pulse**
- **spectral analyzer** (gratings + camera)
- **wavelength**

**For increasing the acquisition rate: two main directions**

- **Work on the electronic part:** develop a new generation of high-repetition rate cameras. KALYPSO project at KIT/ANKA. See 12:40 Talk by L. Rota.
- **Work on the optical part (this talk).**
Main idea: **photonic time-stretch**, introduced by B. Jalali and coworkers
Coppinger et al., IEEE Trans. on Microwave Theory & Techniques, 47, 1309 (1999)

On the oscilloscope, we obtain a replica of the THz pulse that is “temporally stretched” by a factor $M = 1 + L_2/L_1$.
Example: $L_1 = 10$ m and $L_2 = 2$ km $\Rightarrow M \approx 200$.
$\Rightarrow 5$ GHz on the oscilloscope corresponds to 1 THz at the input.
Some setup options for high signal-to-noise ratio

Balanced detection between the two polarizer ports: **Laser noise cancellation**

EO crystal between polarizers “close to extinction”: **High responsivity**

- **Incompatible strategies?**
Setup for single-shot recording of radiated THz pulses (at SOLEIL)

Notes:

- Balanced detection for noise cancellation (laser and ASE)
- Introduction of Brewster plates (with transmission \( T \)) allows the sensitivity to be increased by an arbitrary factor \( 1/\sqrt{T} \). [Ahmed et al., Rev. Sci. Instr. 85, 013114 (2015)].
PhLAM/SOLEIL high-sensitivity time-stretch EOS setup

- Yb fiber laser (50 fs, 1030 nm)
- Balanced photodetector (20 GHz)
- GHz oscilloscope

- 2 km PM fiber
- ZnSe Brewster plates
- GaP Xtal
- Parabolic mirror
- QWP
- Polar splitter
- PPM fiber polar.
- PM fiber

operation “near extinction” ⇒ high responsivity
AND balanced detection ⇒ ASE noise reduction

PhLAM/SOLEIL high sensitivity time stretch

1030 nm pulses from fiber laser (12 nJ)

EO crystal (GaP)
4 Brewster plates
QWP

polarization maintaining fiber (2 km)

To photodetectors

60cm

Setup realized @PhLAM/Lille University

Eléonore Roussel
Christophe Szwaj
Clément Evain
Marc Le Parquier
Serge Bielawski

CSR experiment with the SOLEIL team:
Laurent Manceron
Jean-Blaise Brubach
Marie-Agnès Tordeux
Jean-Paul Ricaud
Lodovico Cassinari
Marie Labat
Marie-Emmanuelle Couprie
Pascale Roy
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1. Time-stretch EOS: principles, setups, performances

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CSR bursts recordings at SOLEIL in nominal alpha mode (15 ps RMS, normal user operation)

**Thz CSR field from 1 bunch (every turn, i.e., \(\approx\) every microsecond) \(\ell = 12\ mA\)**

<table>
<thead>
<tr>
<th>Time (ps)</th>
<th>Stretched time (ns)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>-0.2</td>
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<tr>
<td></td>
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</tr>
<tr>
<td></td>
<td>0.8</td>
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</tbody>
</table>

**Notes**
- Stretch factor = 200
- 5 GHz low-pass filtering \(\rightarrow\) 1 THz limitation.
- RMS noise level corresponds to \(\approx\) 1.25 V/cm over the first 0-300 GHz band.
Photonic time-stretch EOS

Results at SOLEIL: CSR

Results at ANKA/KARA: near-field

CSR bursts recordings at SOLEIL in nominal alpha mode (15 ps RMS, normal user operation)

THz electric field versus time, at each turn

19/10/2015, 1:29:15, exp2/C4Trace00023.trc LP 5 GHz 0

-1.6 -1.58 -1.56 -1.54 -1.52 -1.5
 0
 0.5
 1
 1.5
 2
 2.5
 3
 3.5
 4
 4.5
Fast time (ps)
Stretched fast time (ns)
Slow time (ms)

12 mA per bunch
8 bunches (one displayed here)
nominal alpha
bunch length 15 ps.
CSR bursts recordings at SOLEIL in nominal alpha mode (15 ps RMS, normal user operation)

Note: possibility to monitor the CSR from several bunches simultaneously. Here: 8 bunches (4 displayed):

12 mA per bunch, nominal alpha.
Electron bunches with much higher charge → more irregular

Actually the first recordings, in 2013 [Roussel, et al. Scientific Reports 5, 10330 (2015)]
Note the lower SNR obtained at this time (no Brewster plates, balanced detection only).
Comparison: time-stretch EOS vs standard diode detector

CSR versus round-trips

I = 15 mA

Average Schottky diode signal (mV)

Temporal evolution of the CSR pulses

Number of round-trips

Average (EOS)² signal (V²)

Fast time (ps)

Stretched time (ns)

Slow time (ms)
New stringent tests of theoretical models

Physical ingredients for the *microbunching instability*:
- Longitudinal dynamics of electrons
- Each electron is subjected to the CSR wakefield created by the others

EM field created by accelerated electrons: [Murphy et al., Part Acc 57, 9 (1997)]
Comparison with theory

Example of high charge (long bunch) at SOLEIL

Longitudinal phase-space:

CSR wakefield:

- Energy $p$
- Longitudinal position $q$
- Time (0.1ms/div)
Comparison with theory: long bunch mode

- Photonic time-stretch EOS
- Results at SOLEIL: CSR
- Results at ANKA/KARA: near-field

Graph showing THz signal as a function of fast time (ps) and slow time (µs), with energy and longitudinal position indicated.

- THz signal (a.u.)
- Fast time (ps)
- Slow time (µs)
- Energy p
- Longitudinal position q
Photon time-stretch EOS

Results at SOLEIL: CSR

Results at ANKA/KARA: near-field

Short bunch operation at SOLEIL [C. Evain et al., PRL 118, 054801 (2017)]

3 ps RMS, low alpha, 209 bunches.

**Experiment**

Numerical simulation

~0.7e9 particles - 512CPU

Note: trade-off between rep. rate and SNR

If acquisition rate ↑ = laser pulse energy ↓ = SNR ↓

- Best SNR expected for 48 nJ (here 12 nJ)

- Here 10 EOS shapes/turn (5 bunches + 5 dark references)

- 8.6 × 10^6 EOS traces/s (for 4.3 × 10^6 bunches/s)
Near-field EOS + time stretch: preliminary tests (ANKA-PhLAM)

Already existing ANKA single-shot electro-optic sampling setup

fs Yb laser
1030 nm + amplifier
Fiber length L1
GaP QWP+HWP
PBS
e-bunch

single-shot spectrum analyzer KALYPSO (grating + ultrafast camera developed at KIT)

N. Hiller et al. Electro-Optical Bunch Length measurements at the ANKA Storage Ring”, MOPME014, Proc. IPAC’13, Shanghai, China (2013)

remote location
pulse analysis (OSA or Photonic time-stretch)
1030 nm laser source
35 m fiber for pulse stretching

near-field EOS system (GaP, waveplates, PBS)

EOS output signal
ANKA-PhLAM time-stretch setup for near-field recording

 Already existing ANKA single-shot electro-optic sampling setup

- fs Yb laser 1030 nm + amplifier
- Fiber length L1
- GaP QWP+HWP
- PBS
- e-bunch
- fast balanced photodetector
- oscilloscope

Photonic time-stretch readout

- YDFA
- SM Fiber (2km)
- fast balanced photodetector

remote location

N. Hiller et al. Electro-Optical Bunch Length measurements at the ANKA Storage Ring'', MOPME014, Proc. IPAC’13, Shanghai, China (2013)

near-field EOS system (GaP, waveplates, PBS)

EOS output signal

1030 nm laser source

35 m fiber for pulse stretching
Electron bunch near-field (ANKA)


![Graph showing EOS signal vs time with raw data and high-pass filtered curves]
Electron bunch near-field at each turn (ANKA)

We can record electron bunch structure evolution :-) 

1 turn every 360 ns  
Stretch factor=80

Note: there is room for future SNR improvement
→ increase optical power  
→ balanced detection for common mode noise cancellation
Near-field microstructure vs coherent emission (CSR)?

- Photonic time-stretch EOS
- Results at SOLEIL: CSR
- Results at ANKA/KARA: near-field

![Graph showing near-field microstructure vs coherent emission](image)

Time (ps) vs. Stretched time (ns) with Numbers of round-trips.

Relativistic electron bunch

Coherent THz pulse (far field)

Near field diode detector

Photonic time-stretch

THz detector (V)

Time (ms)
Conclusion

Electro-optic sampling + photonic time stretch

- Free-propagating THz pulses, at SOLEIL
  Special design allows sensitivities in the few V/cm range for 300 GHz BW
- Electron bunch shapes (near field EOS): preliminary tests at ANKA.

Current/expected limits

- Bandwidth: exactly identical to spectral encoding
- SNR: almost shot-noise limited with 50 nJ laser pulses (50% shot-noise/50% thermal noise for our detector).
- Acquisition rate: O(100) MHz range trivial (limited by available laser rep. rate)
- Trade-off between SNR and acquisition rate (SNR depends on optical power).

Future directions, open questions

- Time-stretch vs camera readouts, vs situations?
- Systematic studies of the microbunching/CSR instability
- Useful (or not) in high-rep. rate machines? e.g. high-rep. FELs?
- Cost reduction, e.g., using 1550 nm wavelength, lower ADC bandwidth, etc.
### Authors of the work

**PhLAM (Lille University, France)**
- Clément Evain, Eva Burkard, Marc Le Parquier, Éléonore Roussel, Christophe Szwaj, Serge Bielawski

**SOLEIL (France)**
- Lodovico Cassinari, Jean-Blaise Brubach, Marie-Emmanuelle Couprie, Laurent Manceron, Jean-Paul Ricaud, Marie-Agnès Tordeux, Pascale Roy

**ANKA/LAS, Karlsruhe Institute of Technology (Germany)**
- Edmund Blomley, Erik Bruendermann, Andrii Borysenko, Stefan Funkner, Nicole Hiller, Michael Nasse, Gudrun Niehues, Patrik Schönfeldt, Marcel Schuh, Sophie Walter, Johannes Leonard Steinmann, Anke-Susanne Müller

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Photonic time-stretch EOS

Results at SOLEIL: CSR

Results at ANKA/KARA: near-field

Transfer function: time-stretch EOS vs spectral encoding

Time-stretch vs spectral encoding: Numerical simulations, using a THz sine wave at EOS input.

Analytical expression:

\[ H(f_m) \approx |\cos\left(2\pi^2 \beta_2 L_1 f_m^2 \right)|, \quad (1) \]

with \( T_1 = \beta_2 L_1 \) the laser duration on the electro-optic crystal, and \( f_m \) the modulation frequency.
Example of spectroscopic measurement made with CSR

SOLEIL AILES team (PhD of J. Barros).

For the same S/R ratio:
- Acquisition time = 45 minutes with CSR
- Acquisition time >10 hours using normal SR

Coherent THz pulses emitted by short bunches (low-alpha)

Production of THz CSR with stable power (no bursts)

- Bunch duration ≈ 3 ps
- Low charge (≈ 100 less than in normal-alpha)
- More bunches (209 here, 8 in previous slides)
- Routine user mode (few weeks/year)

Repartition of the 208 electron bunches over the ring (i.e., over 300 m, or 1.2 μs)
Short bunches: below and above the microbunching instability threshold

CSR electric field vs time

Average THz spectrum
Photonic time-stretch EOS
Results at SOLEIL: CSR
Results at ANKA/KARA: near-field

IPAC 2014, TUPRI042:
Crossed-polarizers + amplifier

8 bunches (all bunches recorded, 4 bunches displayed here, 12 mA/bunch)

6.85x10^6 CSR pulses/second (but the EO system is actually recording at 88 M pulses/second)
Balanced detection only

Noise equivalent to \( \approx 18 \text{ V/cm} \) over 1 THz BW.
# Simulation parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>nominal $\alpha$</th>
<th>low $\alpha$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy</td>
<td>2.75 GeV</td>
<td>2.75 GeV</td>
</tr>
<tr>
<td>Revolution time</td>
<td>1.181e-6 s</td>
<td>1.181e-6 s</td>
</tr>
<tr>
<td>Energy spread</td>
<td>1.017e-3</td>
<td>1.017e-3</td>
</tr>
<tr>
<td>Bunch length</td>
<td>4.59e-3 m</td>
<td>0.918e-3 m</td>
</tr>
<tr>
<td>Synchrotron frequency</td>
<td>4640 Hz</td>
<td>928 Hz</td>
</tr>
<tr>
<td>Synchrotron damping time</td>
<td>3.27 ms</td>
<td>3.27 ms</td>
</tr>
<tr>
<td>Bending magnet ROC</td>
<td>5.36 m</td>
<td>5.36 m</td>
</tr>
<tr>
<td>Parallel plate $h$</td>
<td>1.25 cm</td>
<td>1.25 cm</td>
</tr>
</tbody>
</table>
processors on Ada for a mesh of 896 × 896 points (i.e. around 30 minutes on 128 processors for 1000 synchrotron periods of transient).

Figure 2.15: Scaling curves of the VFP code for a mesh of 1920 × 1920. The number of iterations per second versus the number of processors is shown for different processors: Curie Thin Nodes, Curie Fat Nodes, Idris Ada.
Synchrotron radiation spectrum of one electron on a circular trajectory

for an electron on a circular trajectory: $P_{1e^-} (\mu W) \approx 0.68E^4 / \rho^2$ ($E$ in GeV)

see e.g. H. Wiedemann, particle accelerator physics, Springer (1993), Jackson, classical electromagnetism
Detectivity enhancement + balanced detection
Noise-cancelling effect of the balanced detection

Noise versus delay line adjustment
SNR increase using Brewster plates

Noise-equivalent input electric field, with and without Brewster plates. (data are low-pass filtered to 400 GHz).