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

Serge Bielawski
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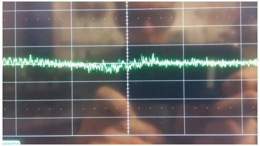
on behalf of the SOLEIL-PhLAM-ANKA collaborations

IBIC 2017, Grand Rapids

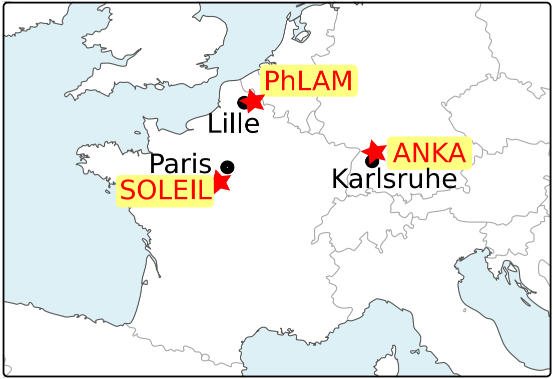


SOLEIL SYNCHROTRON

PhLAM

KIT Karlsruher Institut für Technologie

Introduction: PhLAM-SOLEIL and PhLAM-ANKA collaborations



PhLAM Lab.

- Nonlinear optics, fiber development
- Nonlinear dynamics, instabilities

SOLEIL

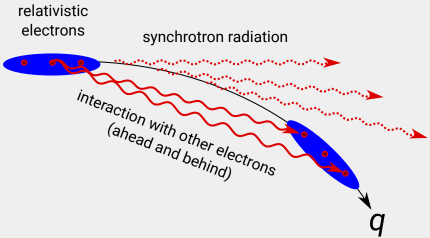
- Synchrotron radiation facility (storage ring)

ANKA (now KARA)

- Synchrotron radiation facility (storage ring)
- Test facility

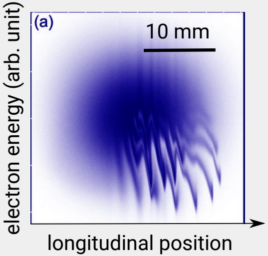
Initial motivation: studies of the microbunching instability

Emitted electric field
→ affects other electrons



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

→ spontaneous formation of microstructures.



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

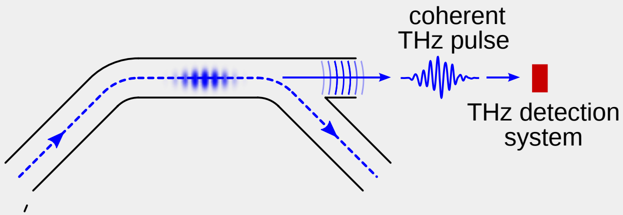
- Observed in many storage-rings: ALS (Berkeley), BESSY, MLS and ANKA (Germany), Canadian Light Source (Canada), DIAMOND (UK), ELETTRA (ITALY), SOLEIL (France), UVSOR (Japan)...
- limitation
- Opportunity?: Intense source of coherent THz radiation (typ. $>$ 10000 times normal SR)

CSR instability theory [Venturini & Warnock, PRL89, 224802 (2002)]

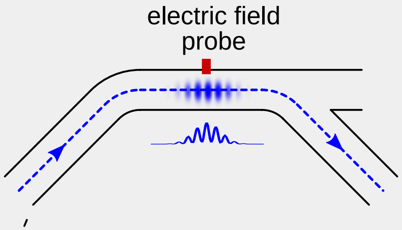
First (indirect) observations in storage rings: ALS [PRL 88, 254801 (2002)], and BESSY [PRL 89, 224801 (2002)]

Measurement strategies at SOLEIL and ANKA: near-field vs far-field

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



ANKA: record the near field



- \+ Easy to place/develop a detector far from the e^- *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^- *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

Table of Content

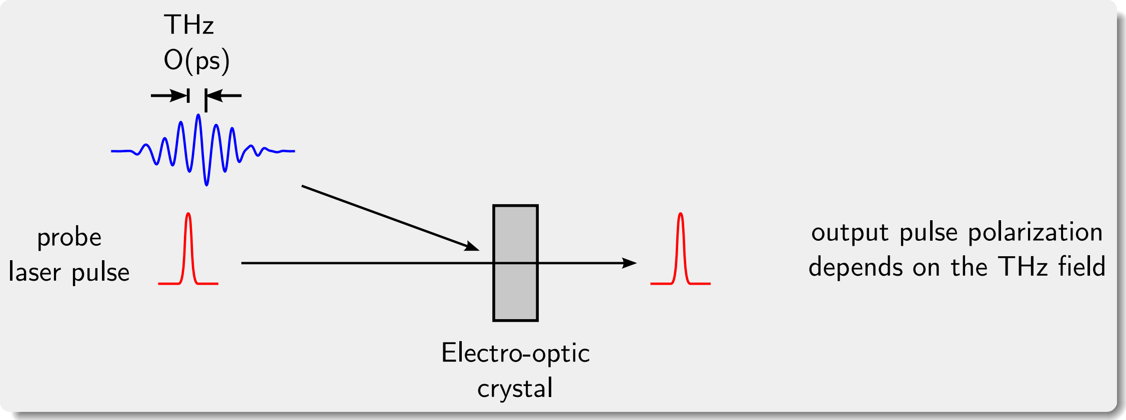
1. Time-stretch EOS: principles, setups, performances

2. Results at SOLEIL: microstructures observed in the far-field

3. Preliminary results at ANKA (near-field)

Electro-Optic sampling of THz pulses: principle

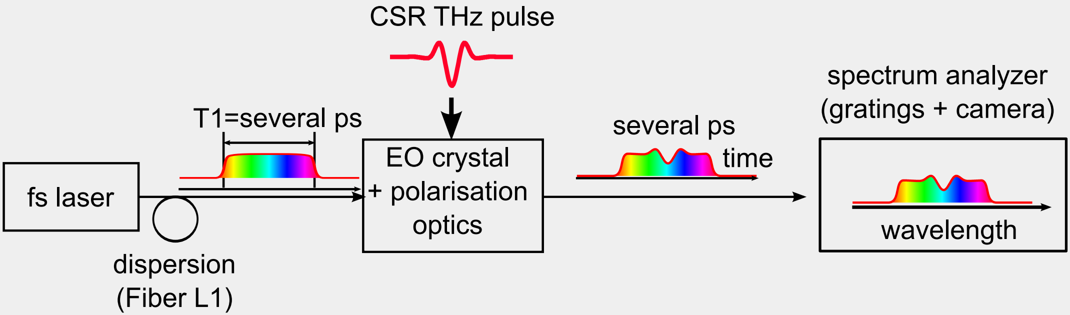
- The electric field modifies the birefringence of a crystal.
- The THz-induced birefringence is probed using a laser pulse.



Add a polarizer (and optional waveplates) → electro-optic modulator.

Single-shot EO sampling → *spectral encoding ?*

Time to spectrum conversion



:-) single-shot, pico/sub-picosecond resolution

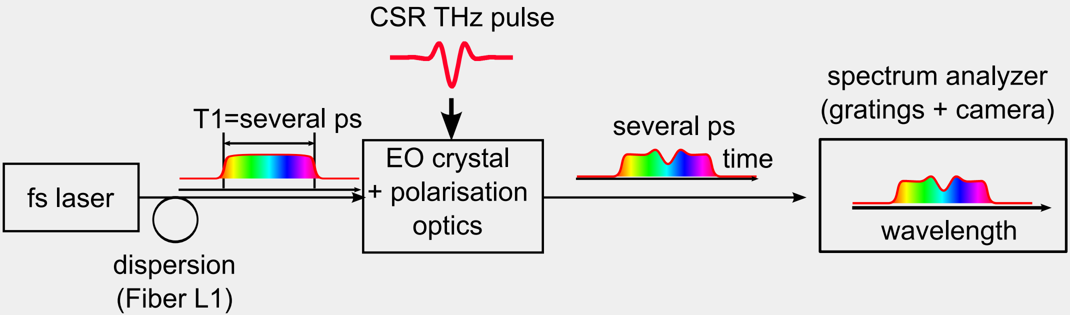
Challenge: repetition rate, as commercial cameras ≤ 150 K line/s*

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

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 EO sampling → *spectral encoding ?*

Time to spectrum conversion

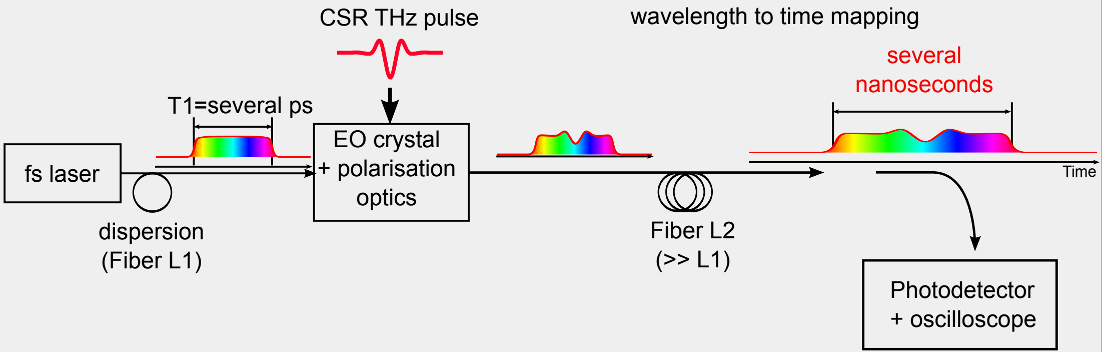


For increasing the acquisition rate: two main directions

- 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).

Single-shot electro-optic sampling at high repetition rate

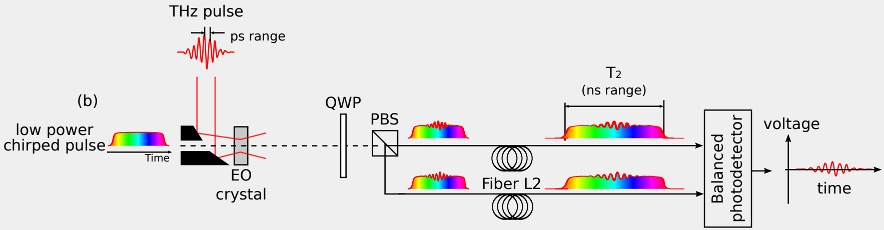
Main idea: photonic time-stretch, introduced by B. Jalali and coworkers
Coppinger et al., IEEE Trans. on Microwave Theory & Techniques, 47, 1309 (1999)



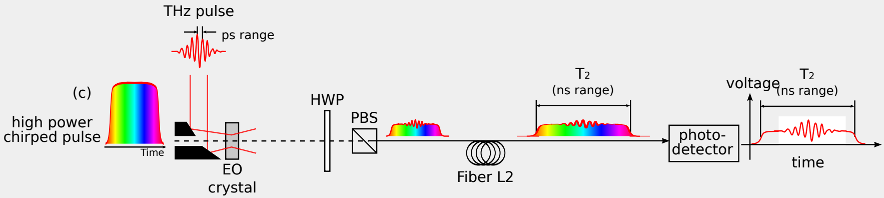
On the oscilloscope, we obtain a replica of the THz pulse that is "temporally stretched" by a factor $M = 1 + L_2/L_1$.
Example: $L_1 = 10$ m and $L_2 = 2$ km $\Rightarrow M \approx 200$.
$\Rightarrow$ 5 GHz on the oscilloscope corresponds to 1 THz at the input.

Some setup options for high signal-to-noise ratio

Balanced detection between the two polarizer ports: Laser noise cancellation

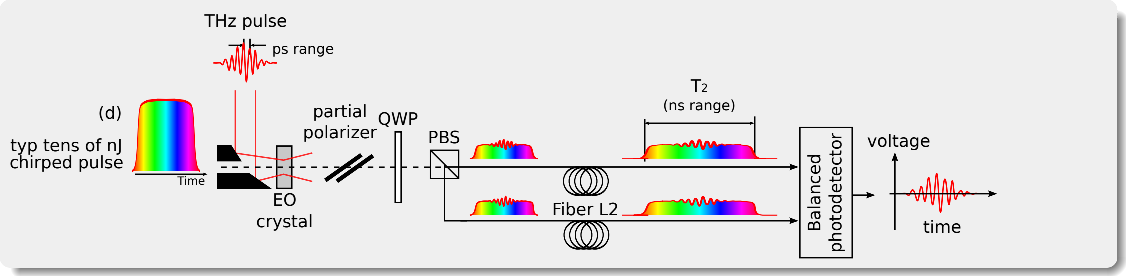


EO crystal between polarizers "close to extinction": High responsivity



- Incompatible strategies?

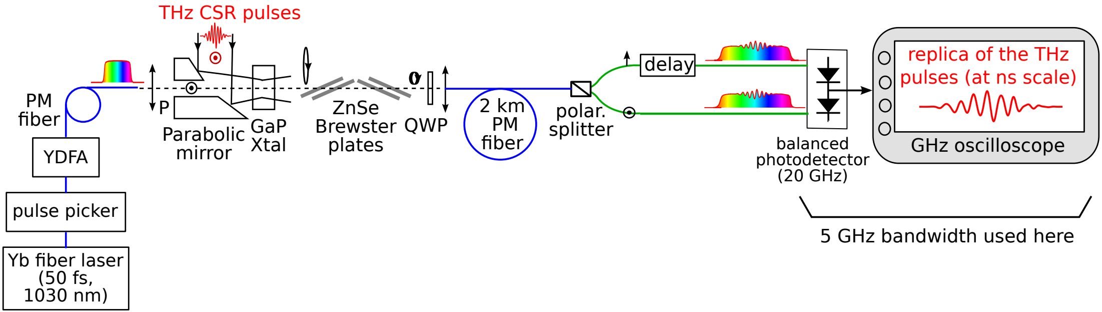
Setup for single-shot recording of radiated THz pulses (at SOLEIL)

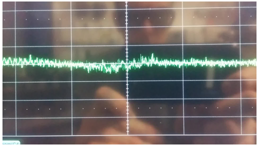


Notes:

- 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

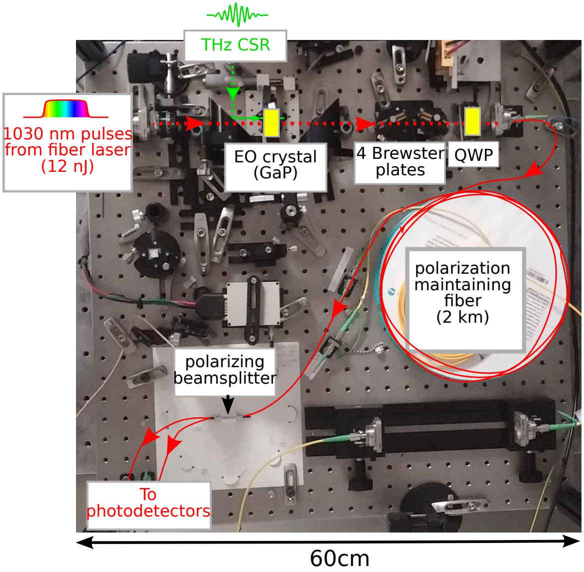




- operation “near extinction” ⇒ high responsivity
- AND balanced detection ⇒ ASE noise reduction

[C.Szwaj et al., Rev. Sci. Instr. 10, 10311 (2016)]

PhLAM/SOLEIL high sensitivity time stretch



Setup realized @PhLAM/Lille University
[C.Szwaj et al., Rev. Sci. Instr. 10, 10311 (2016)]

Eléonore Roussel
Christophe Szwaj
Clément Evain
Marc Le Parquier
Serge Bielawski

CSR experiment with the SOLEIL team:
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Marie-Agnès Tordeux
Jean-Paul Ricaud
Lodovico Cassinari
Marie Labat
Marie-Emmanuelle Couprie
Pascale Roy

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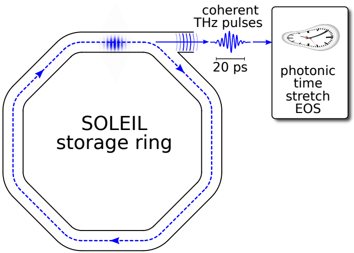
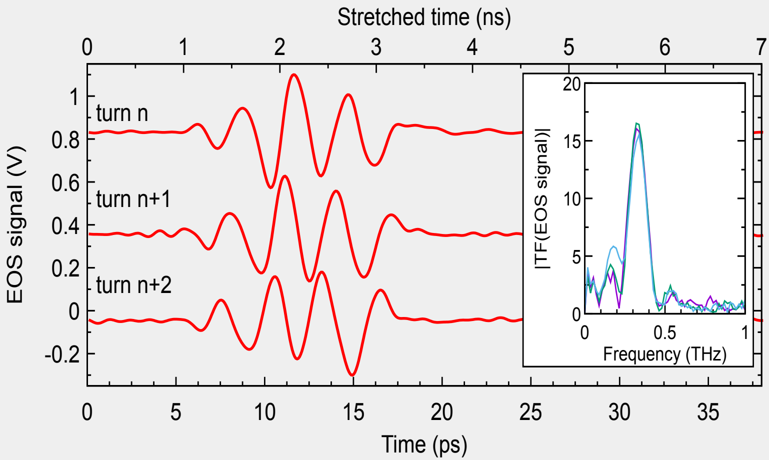
3 Preliminary results at ANKA (near-field)



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., ≈ every microsecond) $I = 12$ mA

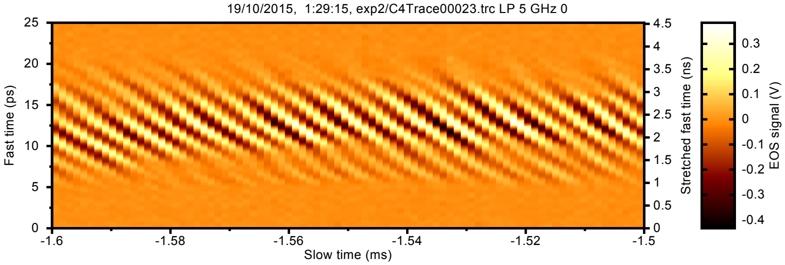


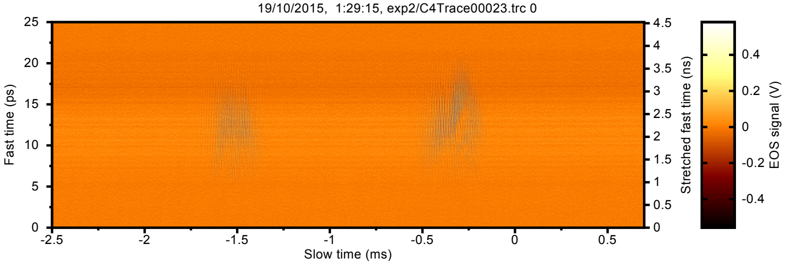
Notes

- Stretch factor =200
- 5 GHz low-pass filtering → 1 THz limitation.
- RMS noise level corresponds to ≈ 1.25 V/cm over the first 0-300 GHz band.

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

THz electric field versus time, at each turn

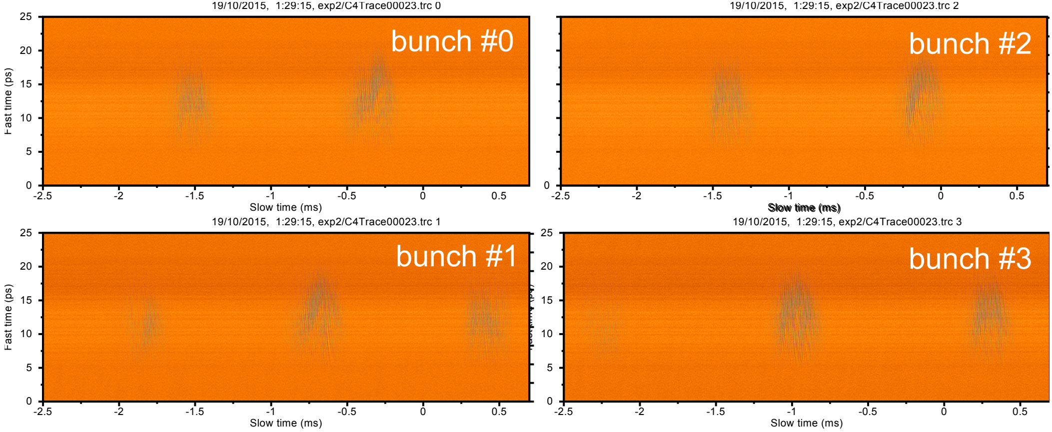




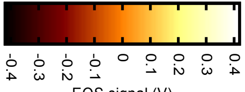
- 12 mA per bunch
- 8 bunches (one displayed here)
- nominal alpha
- bunch length 15 ps.

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):

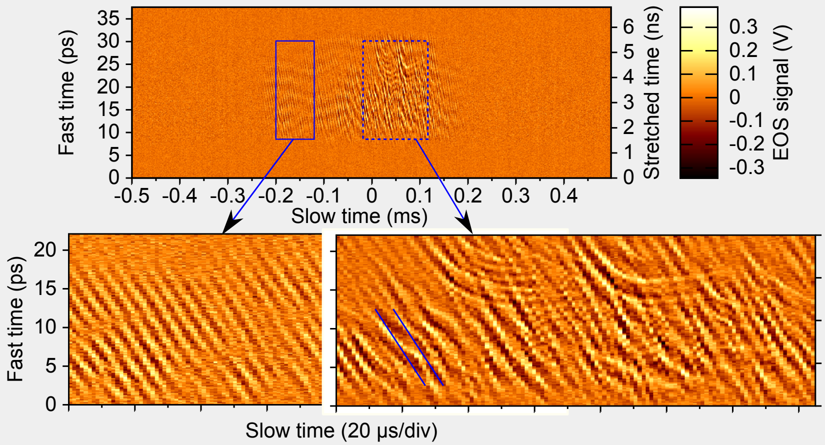


12 mA per bunch, nominal alpha.



Electron bunches with much higher charge → more irregular

CSR pulse shape evolution versus round-trips $I = 15$ mA

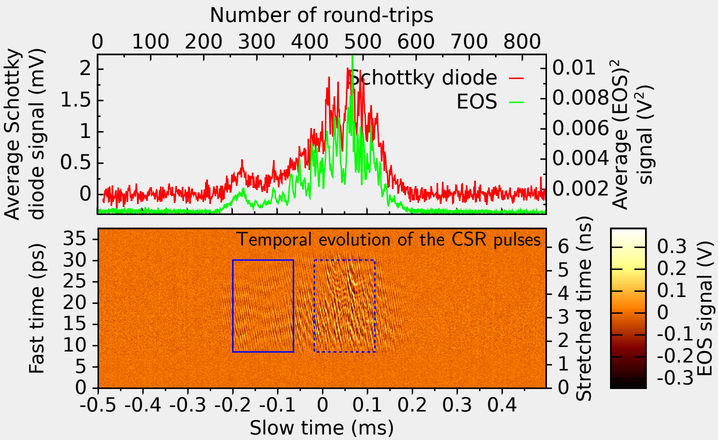


Actually the first recordings, in 2013 **[Roussel, et al. Scientific Reports 5, 10330 (2015)]**
Note the lower SNR obtained at this time (no Brewster plates, balanced detection only).

Comparison: time-stretch EOS vs standard diode detector

CSR versus round-trips

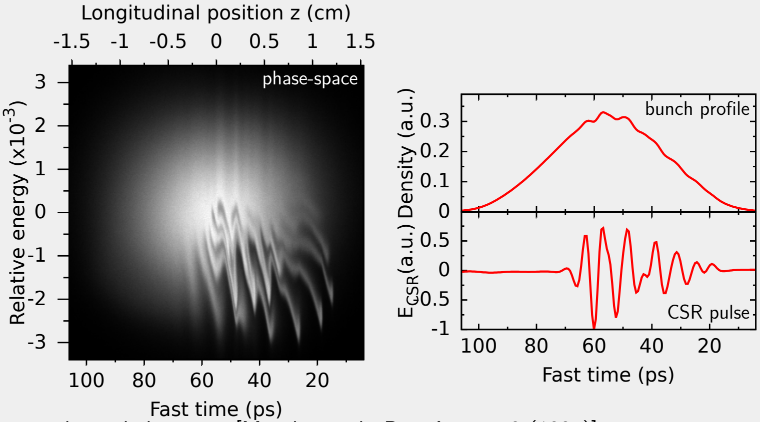
$I = 15$ mA



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

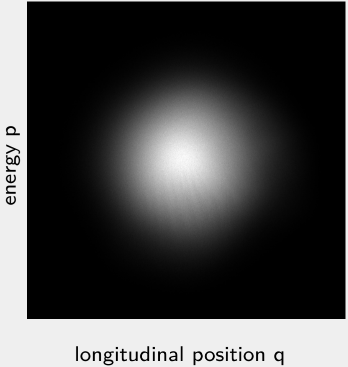


EM field created by accelerated electrons: [Murphy et al., Part Acc 57, 9 (1997)]

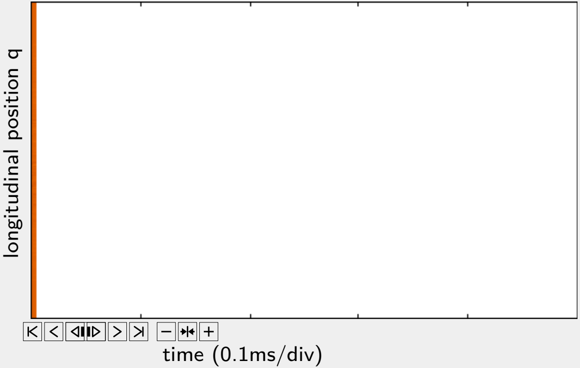
Comparison with theory

Example of high charge (long bunch) at SOLEIL

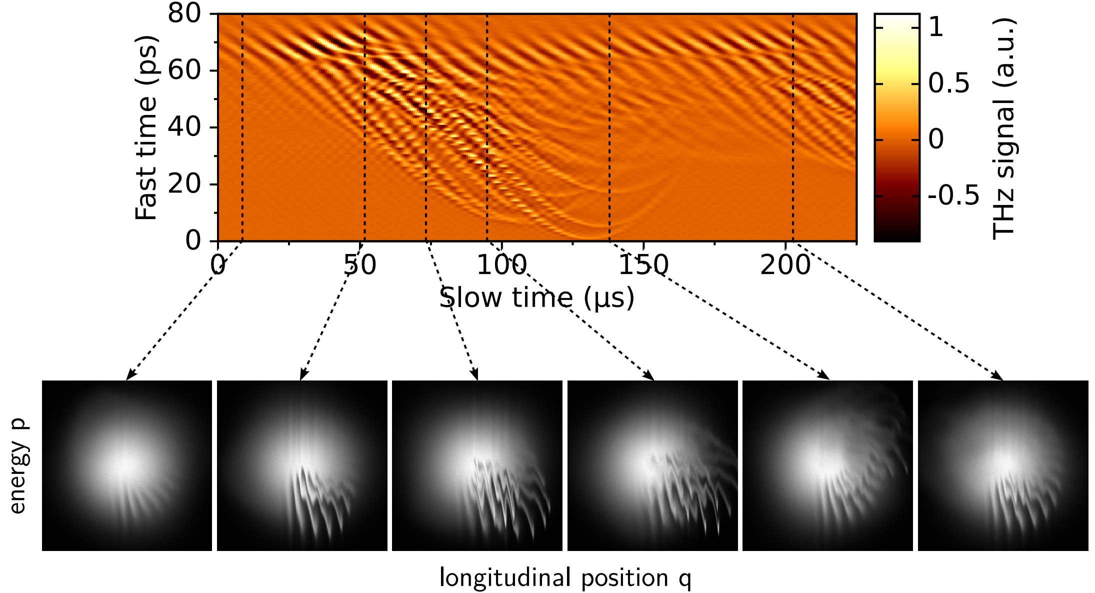
Longitudinal phase-space:



CSR wakefield:



Comparison with theory: long bunch mode

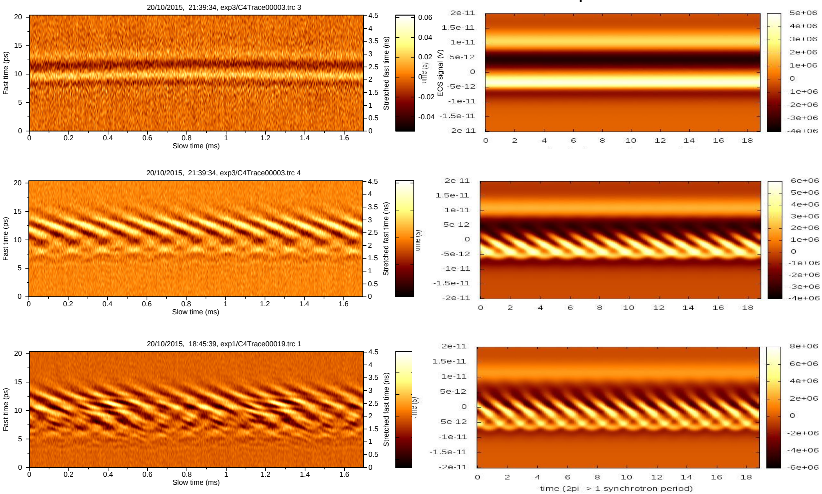


Short bunch operation at SOLEIL [C. Evain et al., PRL 118, 054801 (2017)]

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 ↘

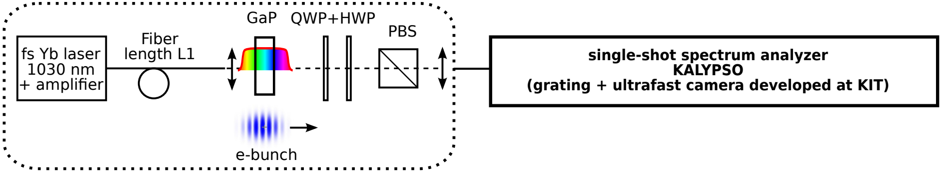
⟹ SNR ↘

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

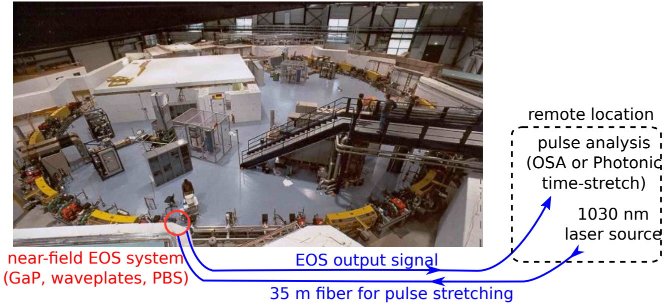
- Here 10 EOS shapes/turn (5 bunches + 5 dark references)
- 8.6×10^6 EOS traces/s (for 4.3×10^6 bunches/s)

Near-field EOS + time stretch: preliminary tests (ANKA-PhLAM)

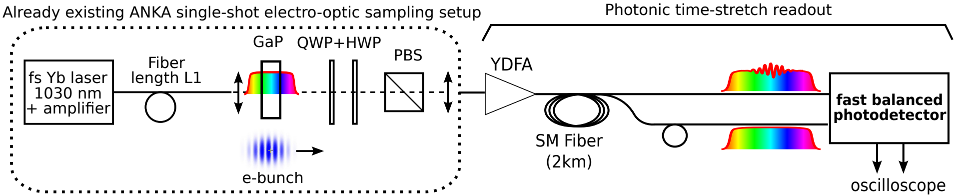
Already existing ANKA single-shot electro-optic sampling setup



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



ANKA-PhLAM time-stretch setup for near-field recording



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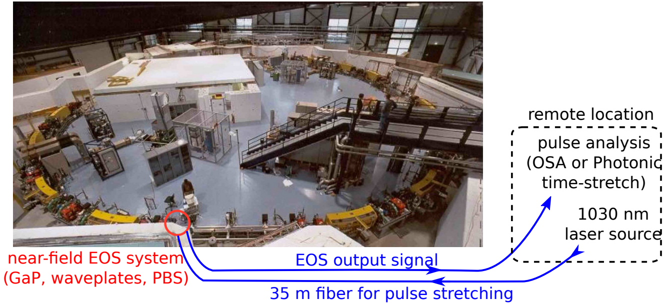
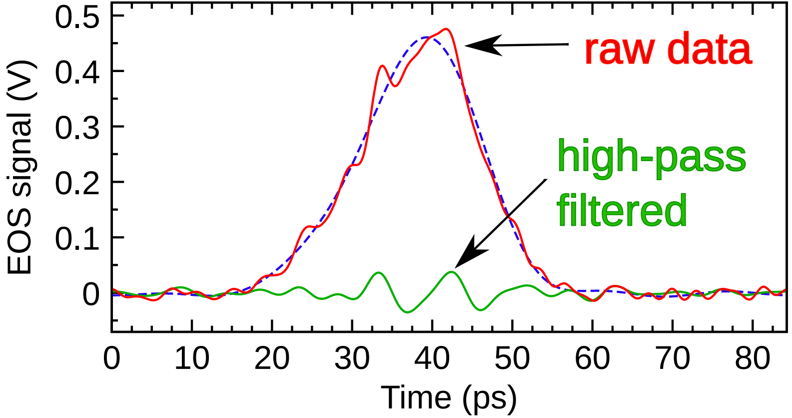


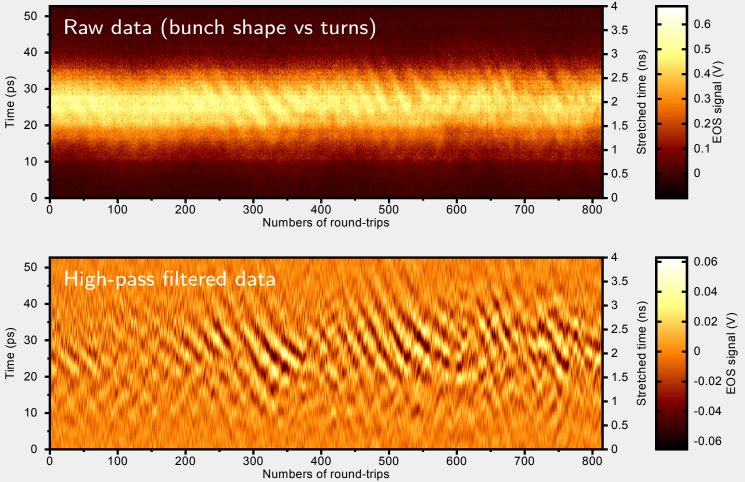
Electron bunch near-field (ANKA)

PhLAM: Clément Evain, Marc Le Parquier, Eléonore Roussel, Christophe Szwaj, Serge Bielawski.
ANKA: 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



Electron bunch near-field at each turn (ANKA)

We can record electron bunch structure evolution :-)

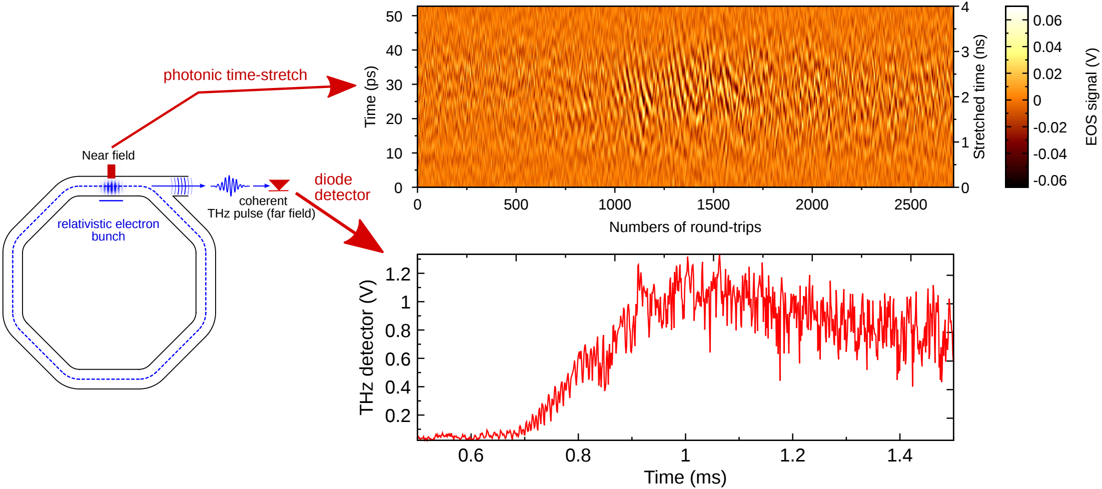


1 turn every 360 ns
Stretch factor=80

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)?



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.

Curent/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

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- Clément Evain, Eva Burkard, Marc Le Parquier, Eléonore Roussel, Christophe Szwaj, Serge Bielawski

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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

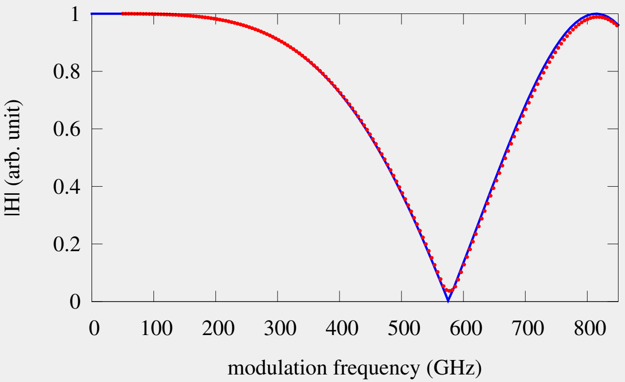
Acknowlegements

- J. Raasch, P. Thoma, A. Scheuring, M. Hofherr, K. Ilin, S. Wünsch, M. Siegel (KIT, Germany)
- M. Hosaka, N. Yamamoto, Y. Takashima, H. Zen, T. Konomi, M. Adachi, S. Kimura, and M. Katoh (UVSOR team, Japan)

Fundings: LABEX CEMPI, CPER photonics for society.

Transfer function: time-stretch EOS vs spectral encoding

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



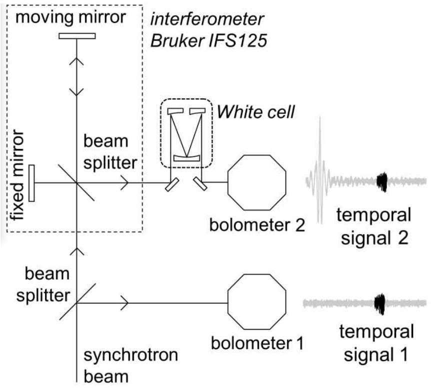
Analytical expression:

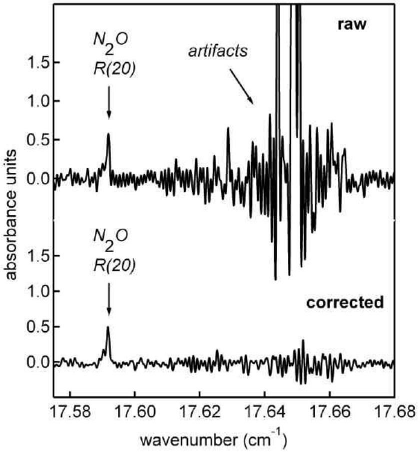
$$H(f_m) \approx \left|\cos\left(2\pi^2 \beta_2 L_1 f_m^2\right)\right|, \qquad (1)$$

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:

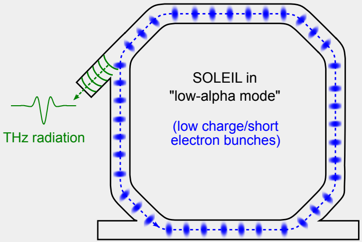
- Acquisition time= 45 minutes with CSR
- Acquisition time >10 hours using normal SR

[Toward highly stable Terahertz Coherent Synchrotron Radiation at th e synchrotron SOLEIL J Barros et al 2012 J. Phys.: Conf. Ser. 359 012002]

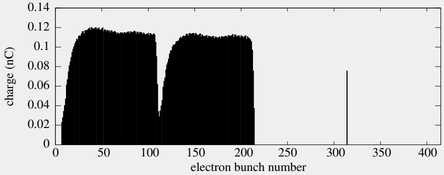
Coherent THz pulses emitted by short bunches (low-alpha)

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)

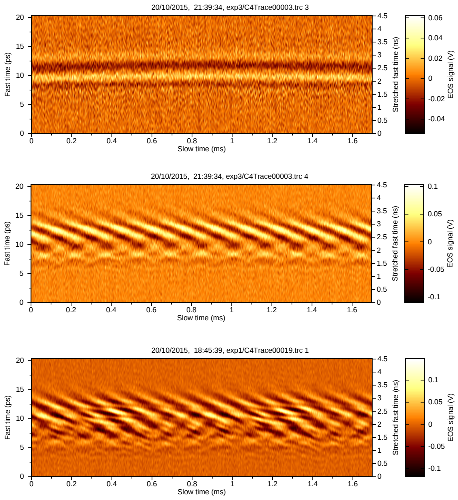


Repartition of the 208 electron bunches over the ring (i.e., over 300 m, or 1.2 μs)

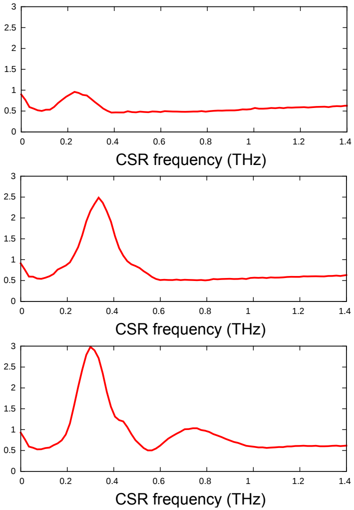


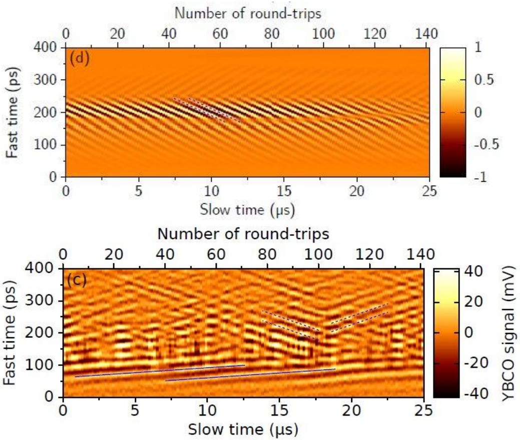
Short bunches: below and above the microbunching instability threshold

CSR electric field vs time



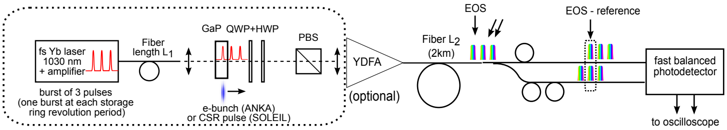
Average THz spectrum



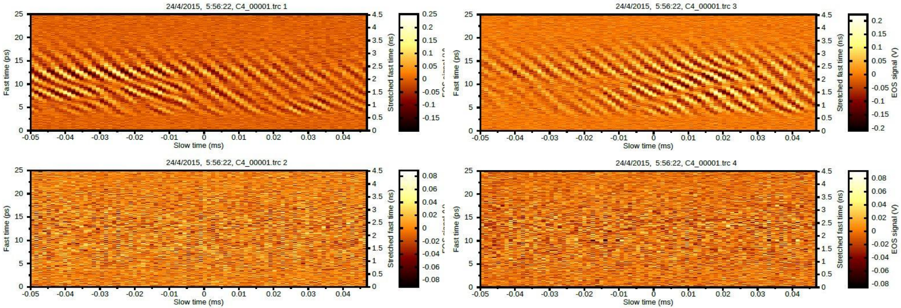


IPAC 2014, TUPRI042:

Crossed-polarizers+amplifier

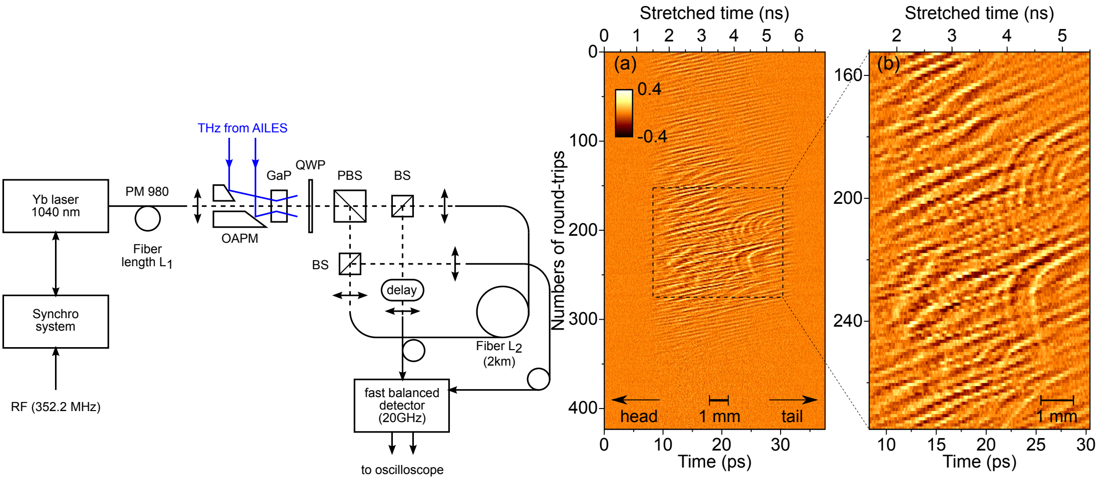


8 bunches (all bunches recorded, 4 bunches displayed here, 12 mA/bunch)



6.85×10^6 CSR pulses/second (but the EO system is actually recording at 88 M pulses/second)

Balanced detection only



Noise equivalent to ≈ 18 V/cm over 1 THz BW.

Simulation parameters

	nominal α	low α
Energy	2.75 GeV	2.75 GeV
Revolution time	1.181e-6 s	1.181e-6 s
energy spread	1.017e-3	1.017e-3
bunch length	4.59e-3 m	0.918e-3 m
synchrotron frequency	4640 Hz	928 Hz
synchrotron damping time	3.27 ms	3.27 ms
bending magnet ROC	5.36 m	5.36 m
parallel plate h	1.25 cm	1.25 cm

VFP

$$\frac{\partial f}{\partial \theta} - p\frac{\partial f}{\partial q} + [q - I_c E_{wf}(q)]\frac{\partial f}{\partial p} = 2\varepsilon\left[f(q,p,\theta) + p\frac{\partial f}{\partial p} + \frac{\partial^2 f}{\partial p^2}\right]. \qquad (2.20)$$

processors on Ada for a mesh of 896 × 896 points (i.e. around 30 minutes on 128 processors for 1000 synchrotron periods of transient).

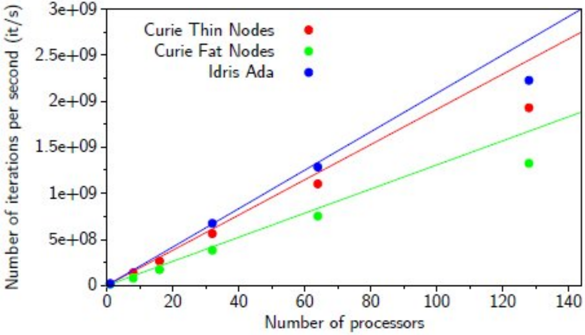
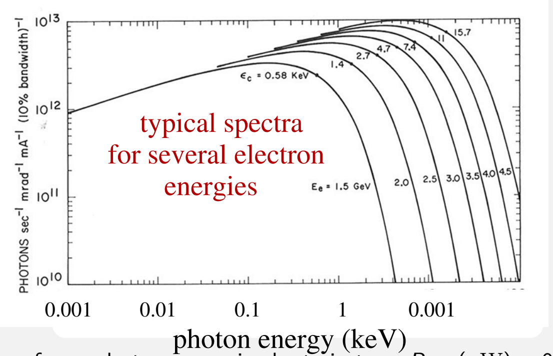


FIGURE 2.15: *Scaling curves of the VFP code for a mesh of 1920 × 1920. The number of iterations per second versus the number of processors is*

Synchrotron radiation spectrum of one electron on a circular trajectory

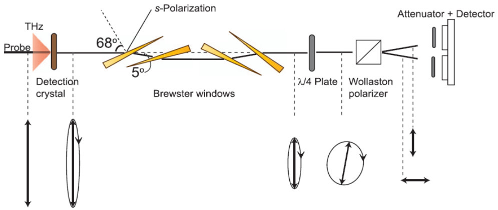


for an electron on a circular trajectory: $P_{1e-}(\mu\mathrm{W}) \approx 0.68E^4/\rho^2$ (E in GeV)

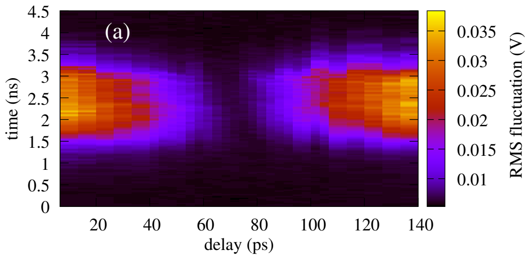
see. eg: H. Wiedemann, particle accelerator physics, Springer (1993), Jackson, classical electromagnetism

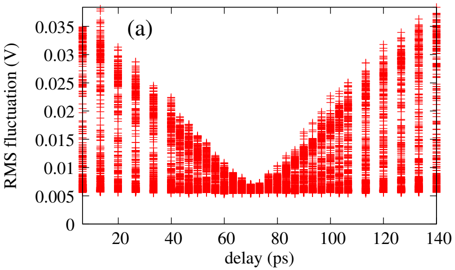
Detectivity enhancement + balanced detection

013114-2 Ahmed, Savolainen, and Hamm Rev. Sci. Instrum. **85**, 013114 (2014)



Noise-cancelling effect of the balanced detection





Noise versus delay line adjustment

SNR increase using Breswter plates

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