Microbunching Instability in Relativistic Electron Bunches: Direct Observations of the Microstructures Using Ultrafast YBCO Detectors

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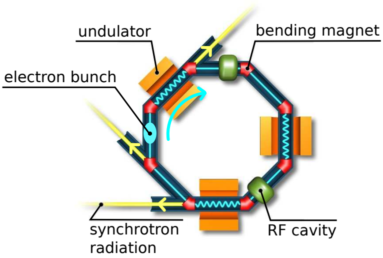
Microbunching instability (CSR instability) in storage rings

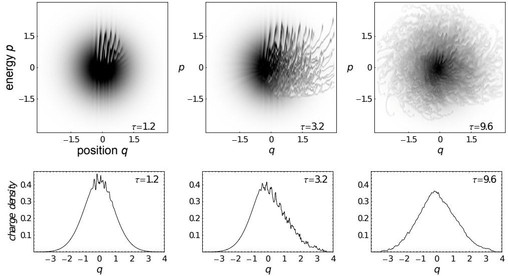


Bunch dynamics :

- If charge density $>$ density threshold, interaction between the electron bunch and its radiation (wakefield)
  $\Rightarrow$ microbunching instability
- Strong THz emission: $> 10^5$ times stronger than normal synchrotron radiation.

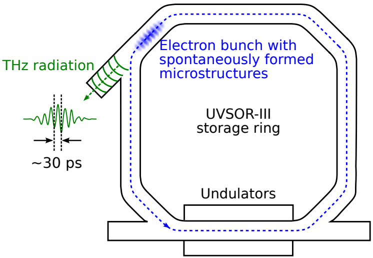
Pattern formation in the longitudinal phase-space:

- Appearance of microstructures with erratic behaviors in space and time.



[Venturini et al., Phys. Rev. ST Accel. Beams **8**, 014202 (2005)]

Microbunching instability (CSR instability) in storage rings



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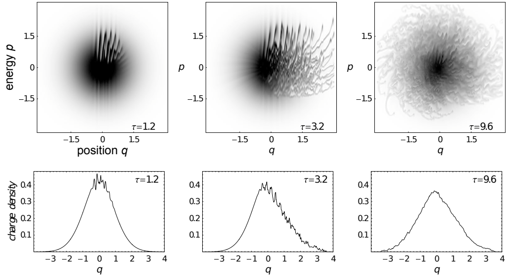
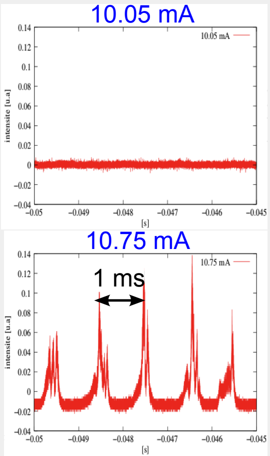


[Venturini et al., Phys. Rev. ST Accel. Beams **8**, 014202 (2005)]

Indirect experimental observations of the "microstructures"

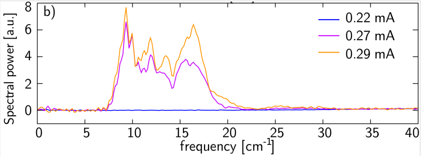
Classical observations using slow detectors, e.g. bolometers, Schottky diodes, etc. at ALS, ANKA, BESSY, DIAMOND, ELETTRA, MLS, SOLEIL, UVSOR.

CSR signal vs. time



courtesy of Synchrotron SOLEIL

Optical spectrum with FTIR spectrometer

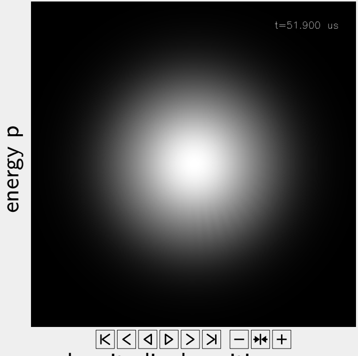


[Evain et al., Europhysics Letters **98**, 40006 (2012)]

- Instability threshold
- Irregular emission of CSR in the THz domain
- Characteristic wavenumber O(mm)

Longitudinal phase-space evolution

UVSOR-III, $I = 120$ mA



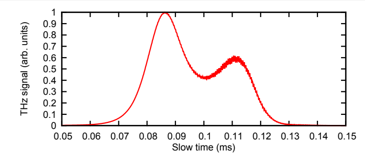
longitudinal position q

—

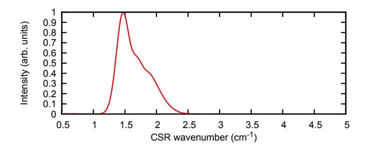
Bunch length $\sigma_z = 30$ mm
Round-trip time $T_0 = 0.177$ μs
Damping time $\tau_d = 32.36$ ms
Synchrotron frequency $f_s = 23.1$ kHz

"Traditional" observations

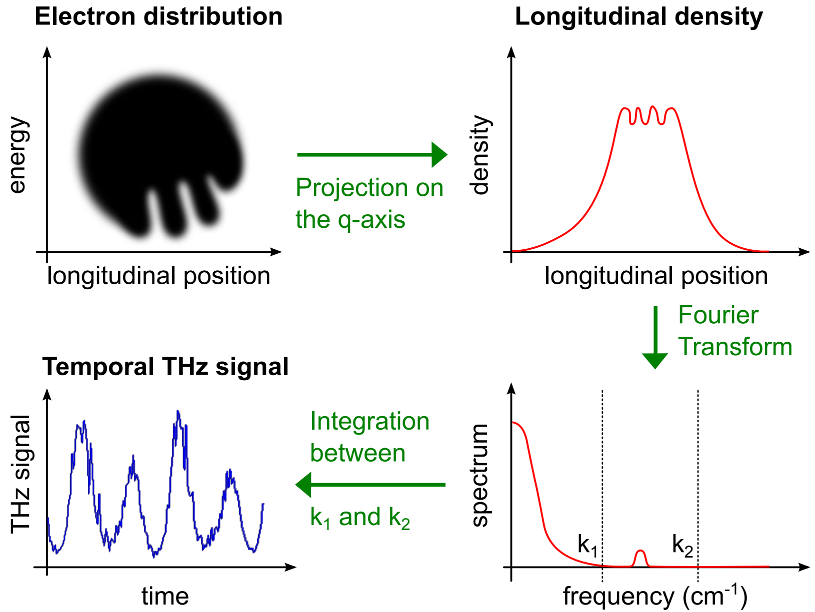
- Coherent THz signal (may be recorded with a bolometer or a diode)



- Average CSR spectrum (may be recorded with a FTIR spectrometer)

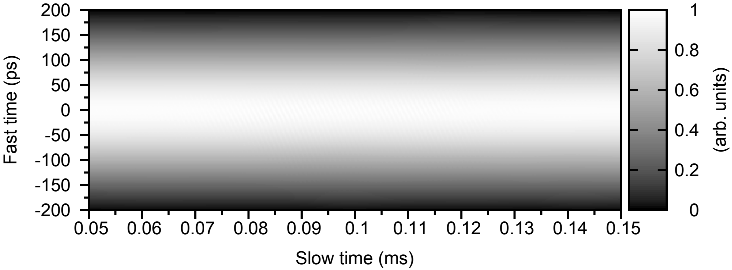


[Venturini and Warnock, Phys. Rev. Lett. 89, 224802 (2002)], [Murphy et al, Part. Acc. (1997)]


Electron distribution
energy
longitudinal position
Projection on
the q-axis
Longitudinal density
density
longitudinal position
Fourier
Transform
spectrum
k_1
k_2
frequency (cm^{-1})
Integration
between
k_1 and k_2
Temporal THz signal
THz signal
time

Other possible (?) observable quantities...

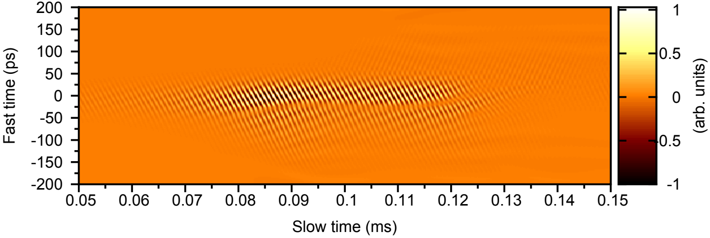
- Longitudinal profile $\rho(q,t) = \int_{-\infty}^{+\infty} f(q,p,t)dp$
  (may be recorded with a streakcamera)



with *fast time* $\equiv$ position along the longitudinal direction in the bunch and *slow time* $\equiv$ number of round-trips.

Other possible (?) observable quantities...

- THz electric field $E_{CSR}(q,t) = \int_{-\infty}^{+\infty} \rho(q',t) W(q-q') dq$ (may be viewed as a "high-pass filter")



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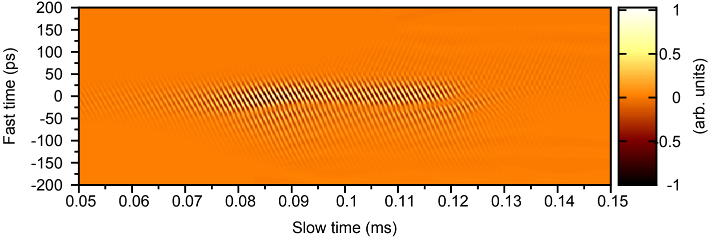


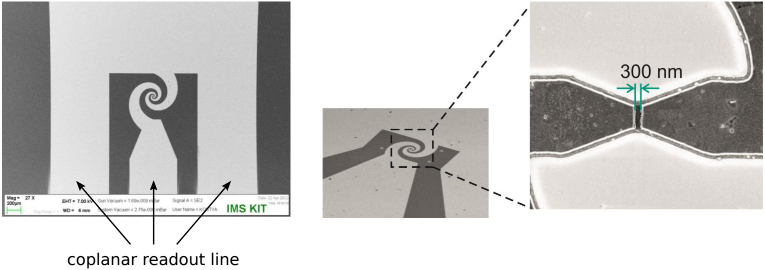
with *fast time* $\equiv$ position along the longitudinal direction in the bunch and *slow time* $\equiv$ number of round-trips.

$\rightarrow$ size of microstructures: 16-33 ps (30-60 GHz)

1. Introduction to the microbunching instability in relativistic electron bunches
2. A high-T_C $YBa_2Cu_3O_{7-x}$ detector for THz CSR pulses
3. Recordings of CSR pulses @ UVSOR-III using a YBCO detector

- Thin-film fabrication using pulsed-laser deposition (PLD).

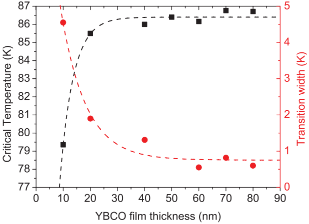
- Patterning of detecting element, planar antenna and co-planar readout using electron-beam lithography (ELB), ion beam (IBE) and wet etching.



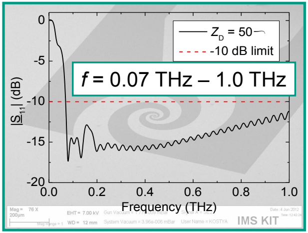
courtesy of J. Raasch, KIT, Germany

Detector integration to hybrid antenna

- Critical temperature well above the liquid nitrogen temperature

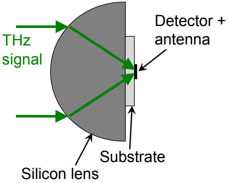


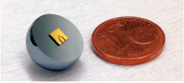
- Coupling efficiency higher than 90%



[P. Probst et al., Phys. Rev. B **85**, 174511 (2012)]

- Integrated lens antenna



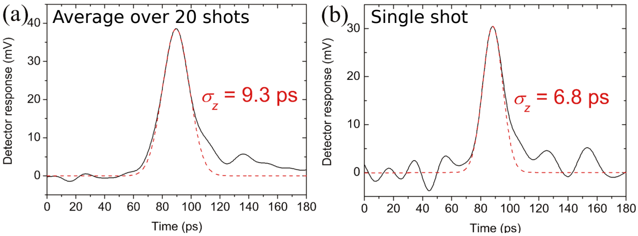


- Detector block

courtesy of J. Raasch, KIT, Germany

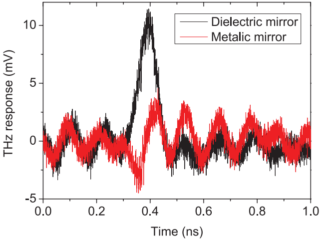
Detection of THz CSR pulses using a YBCO detector

- Temporal response of 15 ps FWHM



[Thoma, P. et al., Applied Physics Letters **101**, (2012)]

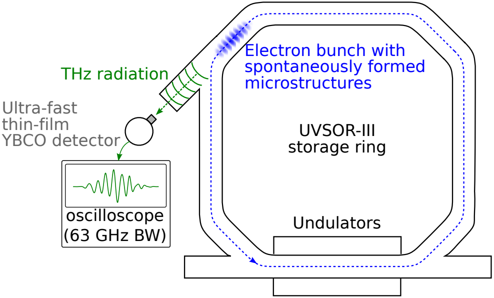
- Zero-bias conditions sensitive to electric field



[P. Probst et al., Phys. Rev. B **85**, 174511 (2012)]

1. Introduction to the microbunching instability in relativistic electron bunches
2. A high-T_C $YBa_2Cu_3O_{7-x}$ detector for THz CSR pulses
3. Recordings of CSR pulses @ UVSOR-III using a YBCO detector

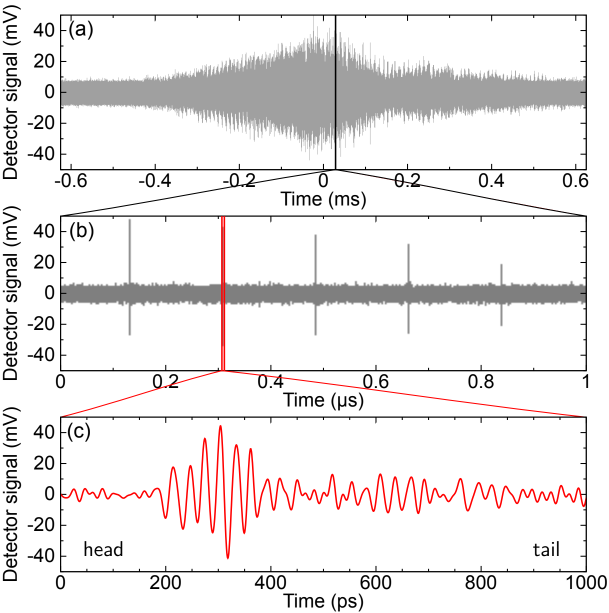
Experiments @ UVSOR-III: setup



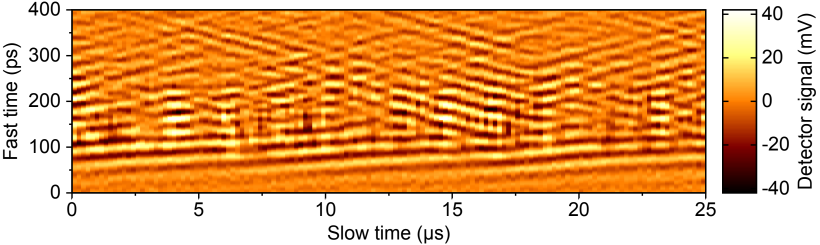
- UVSOR-III, 600 MeV, single-bunch and nominal alpha mode, I=60-65mA
- Detection on BL6B with a ultra-high speed thin-film YBCO detector connected to a 65 GHz BW oscilloscope

  [P. Probst et al., Appl. Phys. Letters, **98**, 043504 (2011)], [P. Thoma et al., IEEE Transactions on Terahertz Science and Technology, **3**, 81 (2013)]

Experimental results: CSR electric field (envelope + carrier !) turn-by-turn

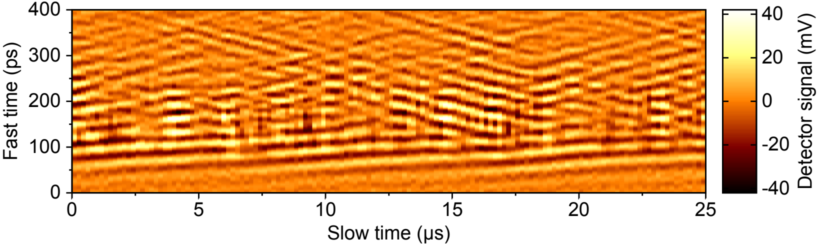


- Above the microbunching instability threshold, $I = 62$ mA

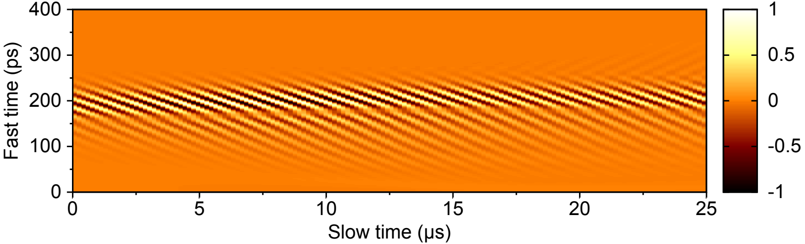


Interpretation of the drifting structures using numerical simulations...

- Experiment



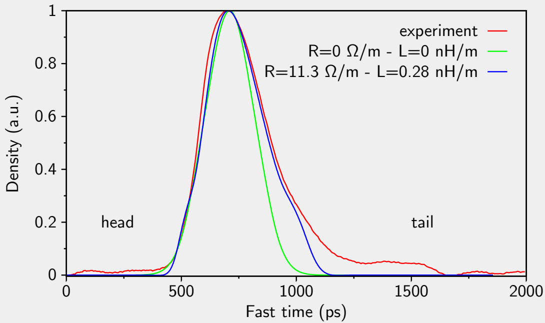
- Numerical simulation



$\Rightarrow$ Strong discrepancy: absence of the slow drifting structure in the lower part !

Take into account :

- the asymmetric bunch profile (by adding resistive and inductive impedances + the robinson damping)

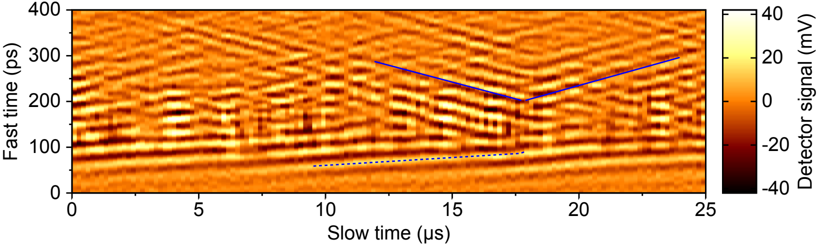


- the effect of shot noise due to the finite number of electrons N_e in a bunch

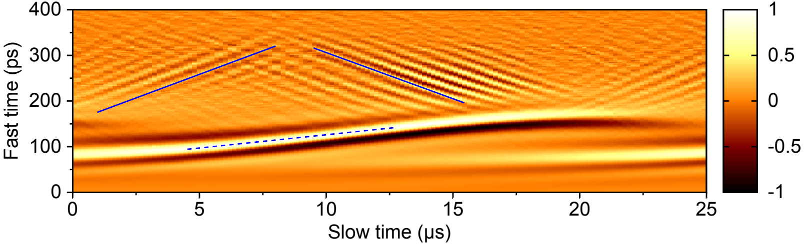
New numerical results with shielded CSR wakefield + R and L impedances

Above the microbunching instability threshold

- Experiment, $I = 62$ mA

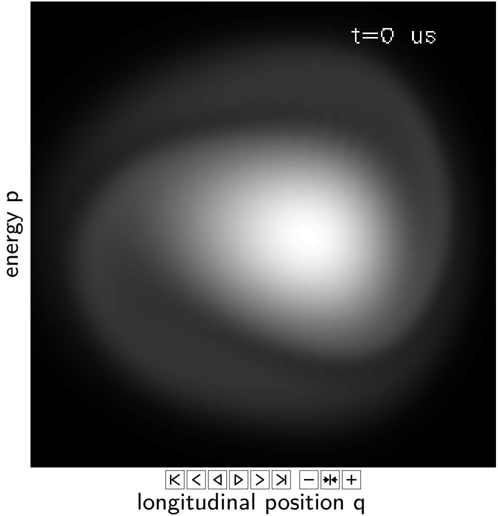


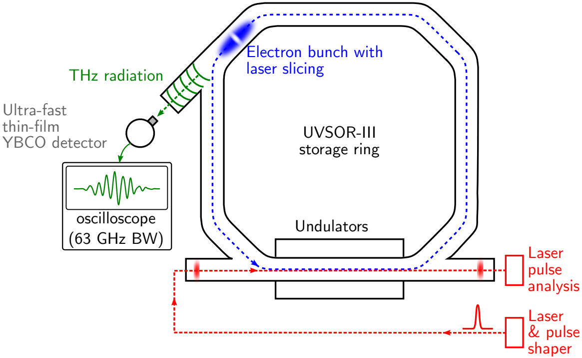
- Numerical simulation, $I = 120$ mA ($R = 11.3\ \Omega/\text{m}$, $L = 0.28$ nH/m)



What happens in the longitudinal phase-space ?

Above the microbunching instability threshold, $I = 120$ mA, taking into account the shielded CSR wakefield + R and L impedances



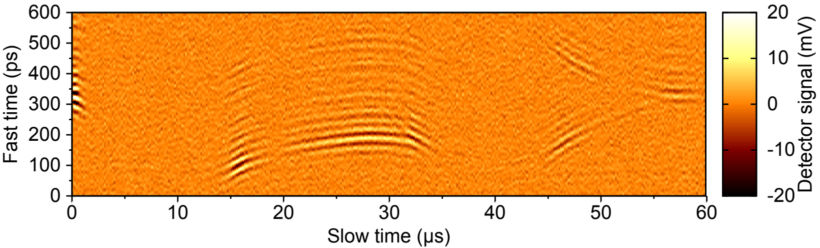


- UVSOR-III, 600 MeV, single-bunch and nominal alpha mode
- Beam current below the microbunching instability threshold $I < 55$ mA
- Laser pulses @ 800 nm, pulse duration $\approx$ few ps
- Interaction in undulator U1 and detection on BL6B

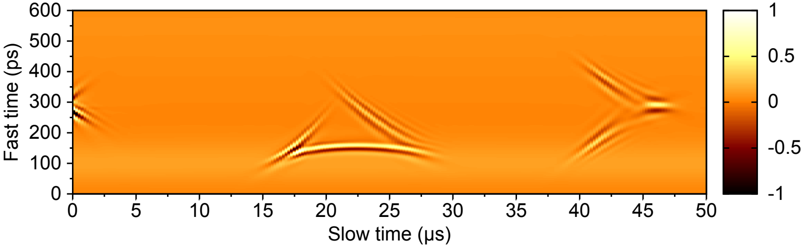
Results in condition of laser slicing

Below the microbunching instability threshold, with slicing (laser duration: 12 ps)

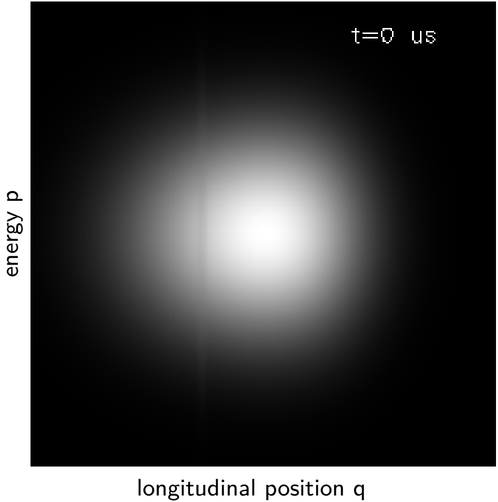
- Experiment, $I = 42$ mA



- Numerical simulation, $I = 60$ mA

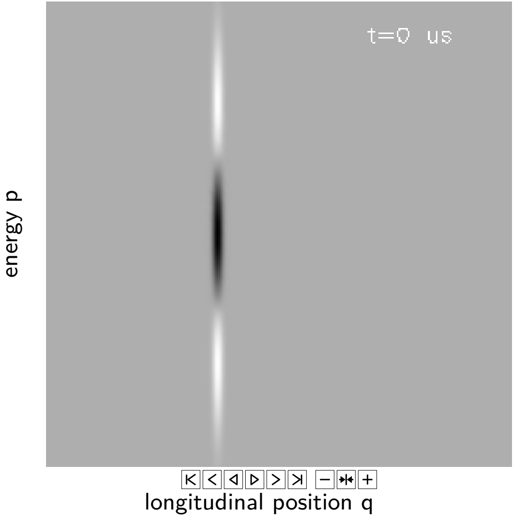


Below the microbunching instability threshold, $I = 60$ mA, with slicing (laser pulse duration: 12 ps)



What happens in the phase-space ?

Below the microbunching instability threshold, $I = 60$ mA, with slicing (laser pulse duration: 12 ps)



Conclusion

Experiments

- First recordings of the envelope and carrier of the CSR pulses, turn-by-turn, at 30-60 GHz during the microbunching instability,
- Study of the electron bunch response to a laser-slicing.
- Note: it is also possible to monitor the emitted THz field with EOS setup, see MOPB005, MOPB006.

Comparison experiments/numerical simulations

- Highlight discrepancies between experiments and most used model,
- Require more ingredients in the model, e.g., the resistive and inductive impedances.

Outlook

- Application: CSR spectroscopy system with picosecond time resolution.
- Extension of this detection method, by biasing the detector, to record pulses envelopes at a similar speed.

[Roussel et al., Phys. Rev. Lett. **113**, 094801 (2014)], [Roussel et al., Proceedings of IPAC2014, TUPRI042 (2014)]

Collaborations

The PhLAM's Non-Linear Dynamics group (France)

S. Bielawski, C. Evain, M. Le Parquier and C. Szwaj.

The UVSOR team (Japan)

M. Adachi, M. Hosaka, M. Katoh, S. Kimura, M. Shimada, Y. Takashima, T. Tanikawa, N. Yamamoto and H. Zen.

The KIT team (Germany)

M. Hofherr, K. Ilin, J. Raasch, A. Scheuring, M. Siegel, P. Thoma and S. Wünsch.