Steady State Microbunching and related activities at the Metrology Light Source

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Helmholtz Zentrum Berlin

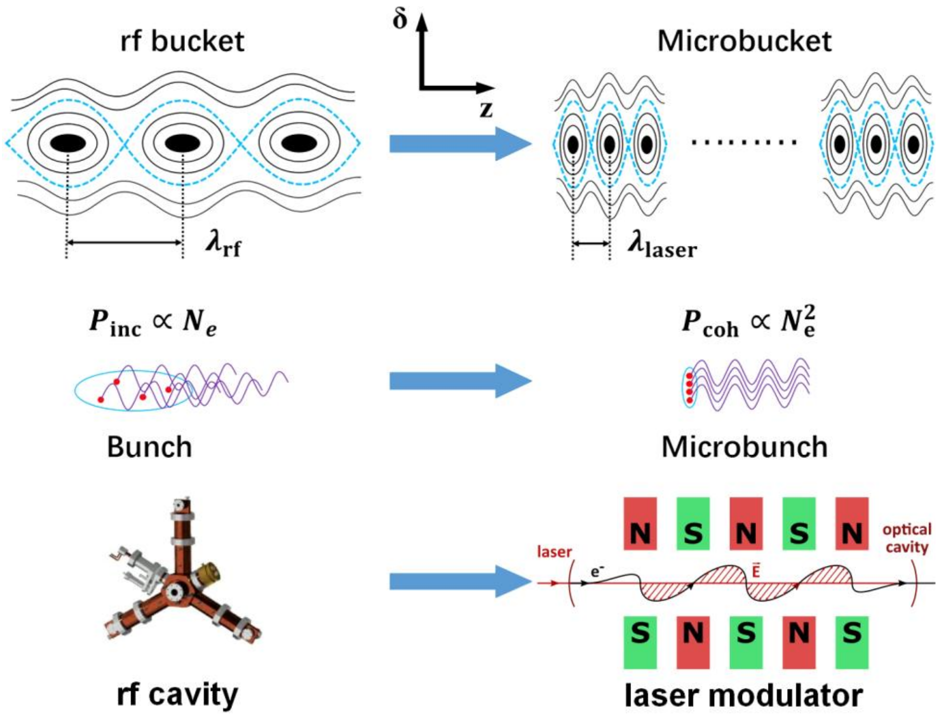
The Mechanism of Steady-State Microbunching (SSMB)

Motivation: Demand for high power light sources for science and industrial applications (e.g. photolithography for computer chip manufacturing)

Steady-State Microbunching (SSMB):
Coherent radiation from microbunched electron beams inside a storage ring [1]

- ➔ Combining high peak power and high repetition rate
  → high average power
- ➔ Coherent radiation at wavelengths up to the EUV range
- ➔ Principle: Scale down longitudinal focusing mechanism that creates electron bunches
- ➔ Proof-of-Principle (PoP) experiment at the MLS to prove the basic mechanism behind SSMB

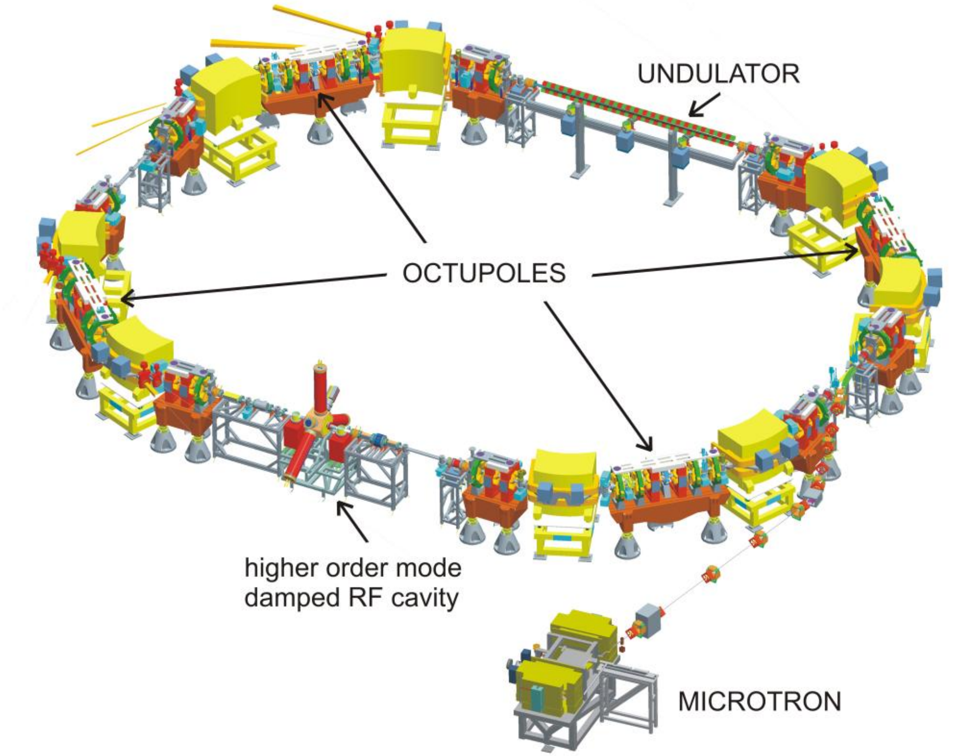
➔ SSMB promises high average power EUV source



[1] D. F. Ratner and A. W. Chao, Steady-State Microbunching in a Storage Ring for Generating Coherent Radiation, Phys. Rev. Lett. **105**, 154801 (2010).
DOI: 10.1103/PHYSREVLETT.105.154801

The Metrology Light Source (MLS)

- Owner: German national metrology institute (PTB)
- First storage ring optimized for low alpha operation (short bunch operation → coherent THz emission)
- Additional sextupole and octupole magnet families to control higher order momentum compaction
- Low alpha for SSMB: $|\alpha| < 2 \cdot 10^{-5}$

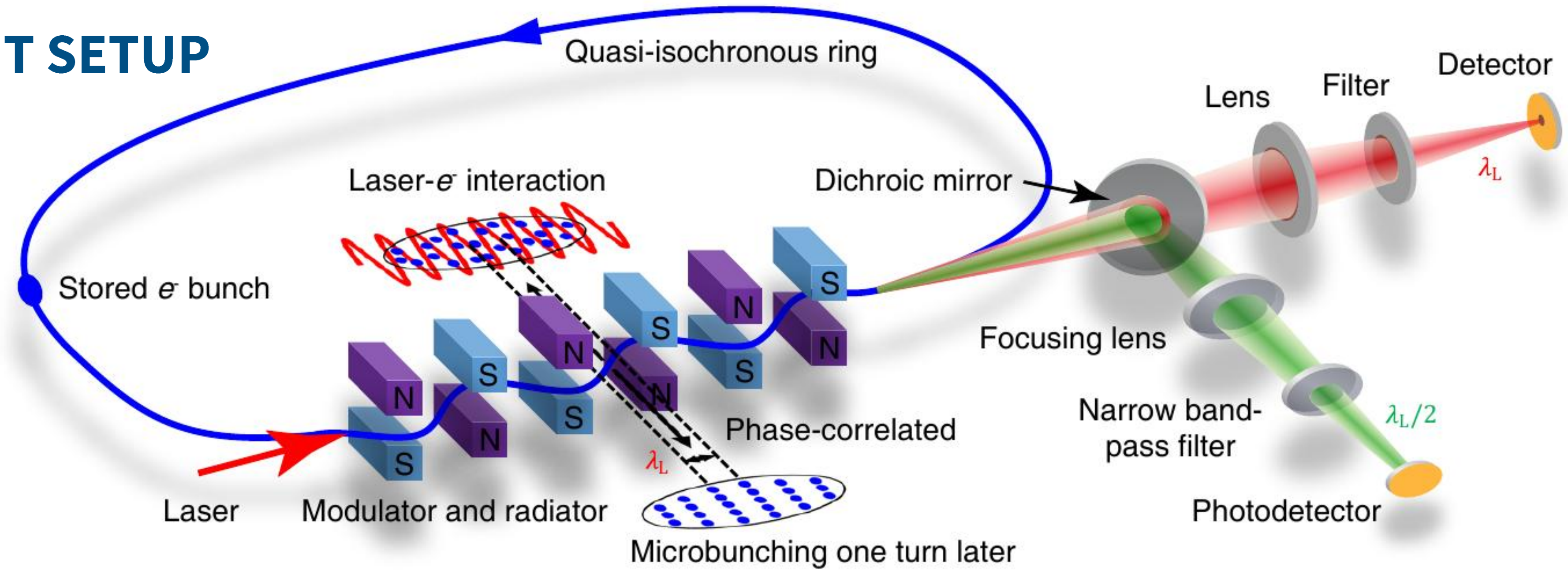


Circumference	48 m
Electron energy	105 MeV – 629 MeV
Intensity range	Single electron (1 pA) up to 200 mA
Undulator	Single U125

→ MLS is uniquely suited for SSMB proof-of-principle experiment

SSMB POP EXPERIMENT SETUP

PoP Phase I Laser	
Wavelength	1064 nm
Pulse length	5 ns FWHM
Pulse energy	~ 100 mJ
Repetition rate	1.25 Hz

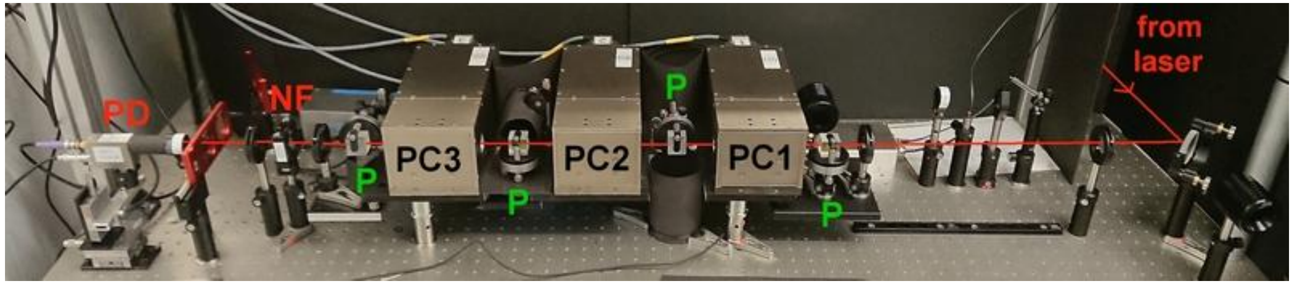


PoP "Phase I": laser repetition rate 1.25 Hz
→ single-shot modulation

2019: First coherent signal observed on second undulator harmonic

2021: First detection on the fundamental wavelength with Pockels cell detection setup

Detectors: Fast InGaAs (1064 nm) and Si (532 nm) photodiodes

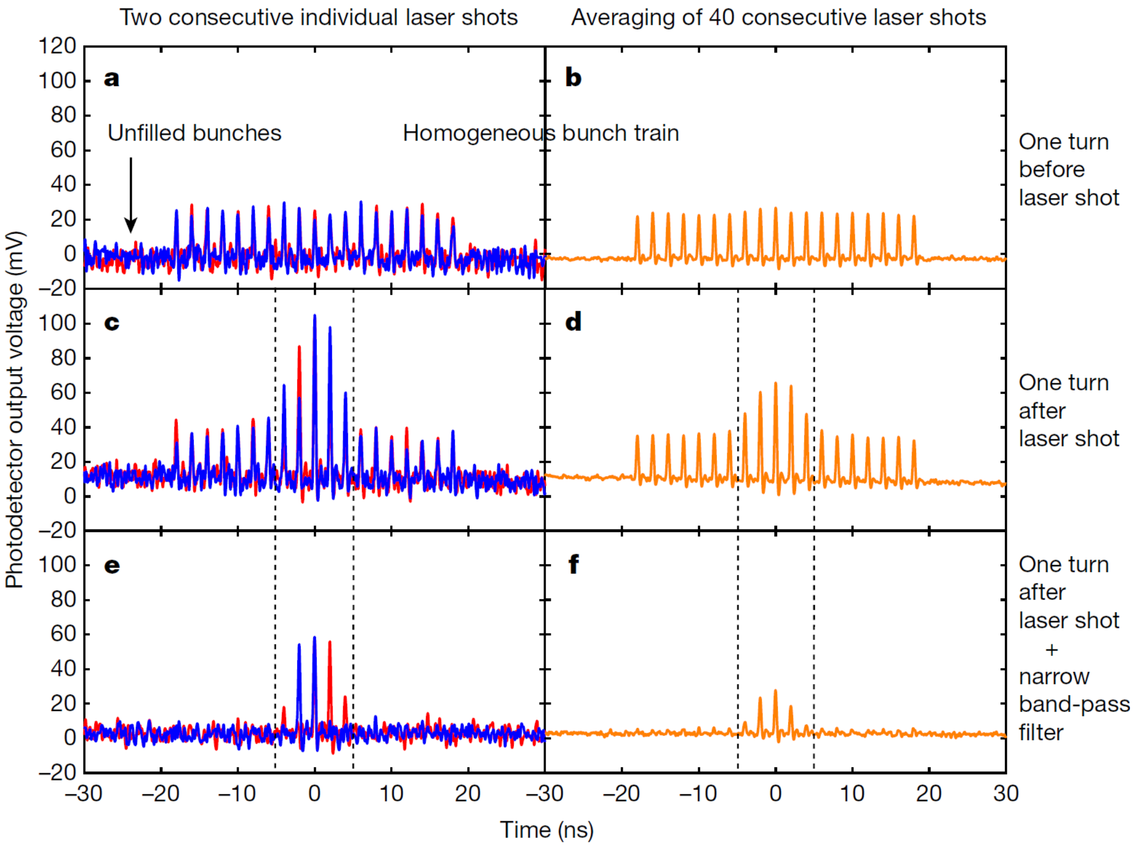


➔ **Initial findings published in *Nature* [2]**

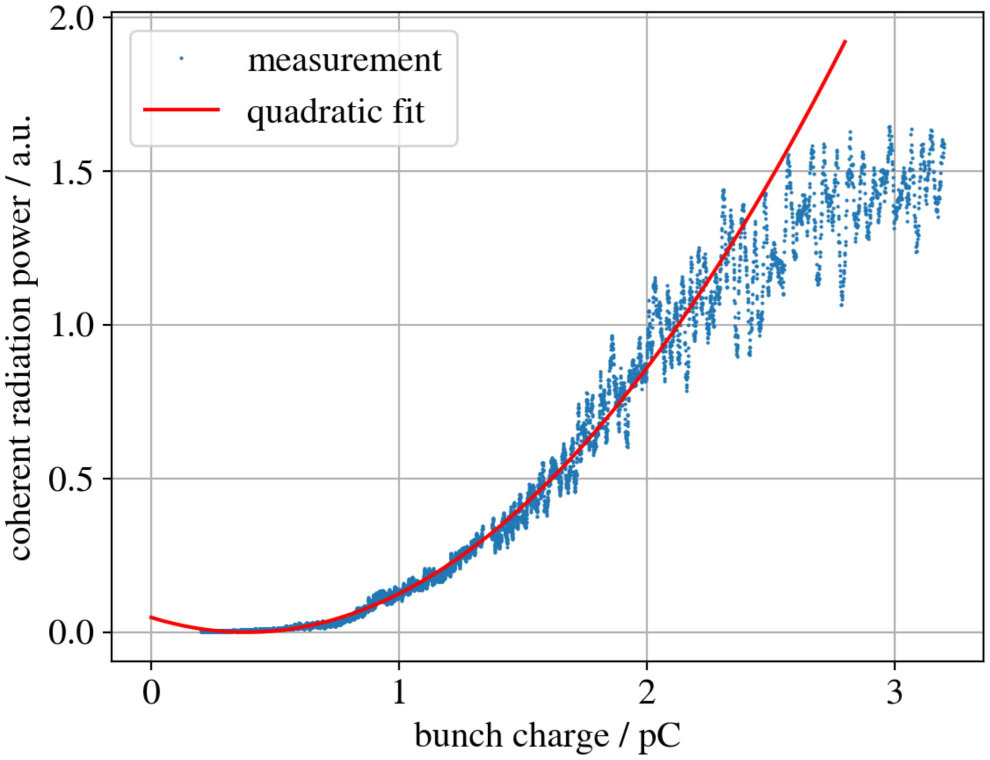
[2] X. Deng *et al.*, First experimental demonstration of the mechanism of steady-state microbunching, Nature **590**, 576–579 (2021).
DOI: 10.1038/s41586-021-03203-0

DETECTED COHERENT EMISSION FROM MICROBUNCHING

Increased radiation intensity with narrow bandwidth for modulated bunches one turn after laser interaction



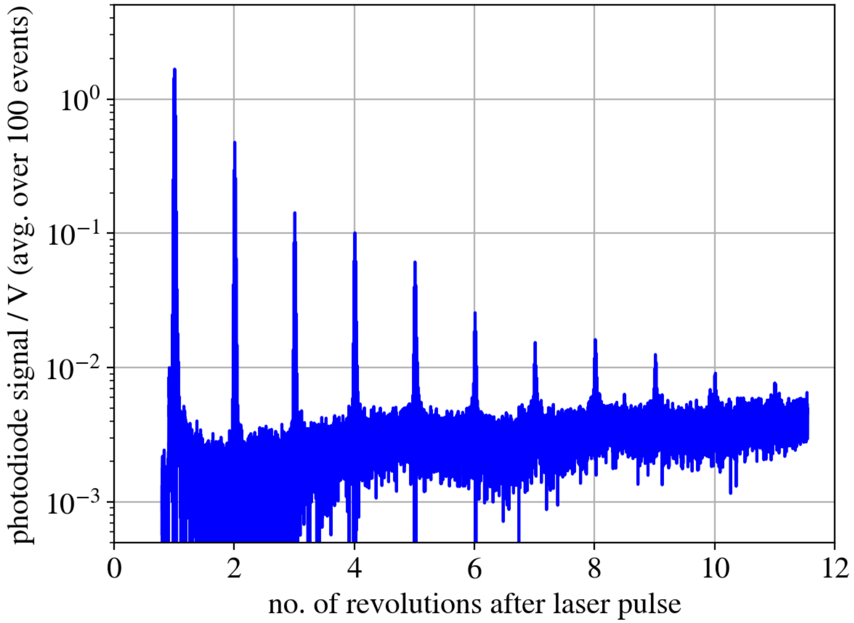
Quadratic scaling of coherent radiation power with electron bunch charge



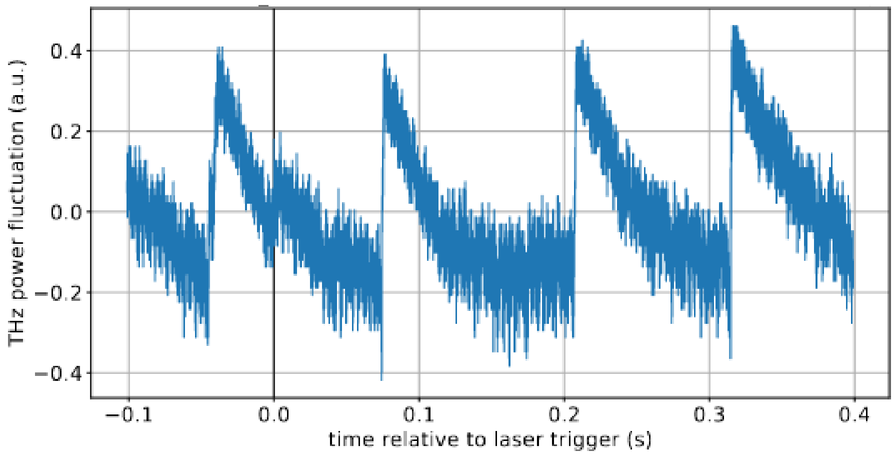
➔ Coherent nature of radiation confirmed

RESULTS OF SSMB STUDIES ON THE FIRST UNDULATOR HARMONIC

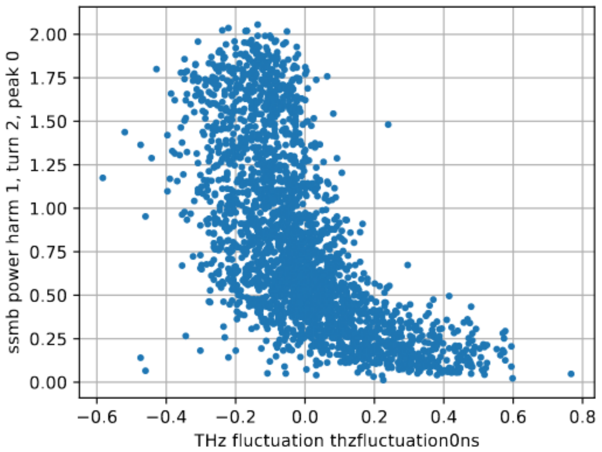
- Since first harmonic detection is possible, investigations can be set up more reliably and reproducibly, and can span a broader parameter range.
- Coherent emission can survive for multiple revolutions, in some cases for up to 30 revolutions. This high number is unexpected, and may indicate that the microbunching generation is more robust than expected.



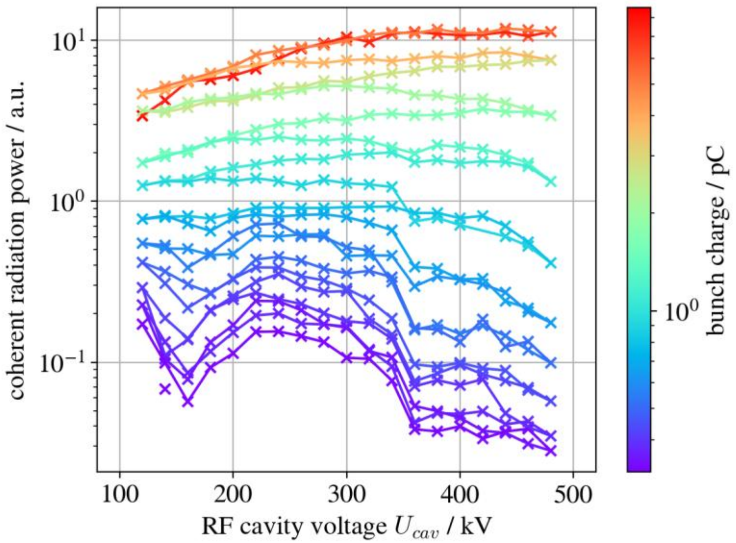
Coherent THz radiation bursting in SSMB state with influence of SSMB laser



Anticorrelation between THz bursting and SSMB signal strength



Unexpected dependence on rf cavity voltage



ALPHA BUCKET DYNAMICS FOR SSMB

- Low momentum compaction: Higher orders of alpha function

$$\alpha(\delta) = \alpha_0 + \alpha_1\delta + \alpha_2\delta^2 + \ldots \quad \text{with} \quad \delta = \Delta p/p_0$$

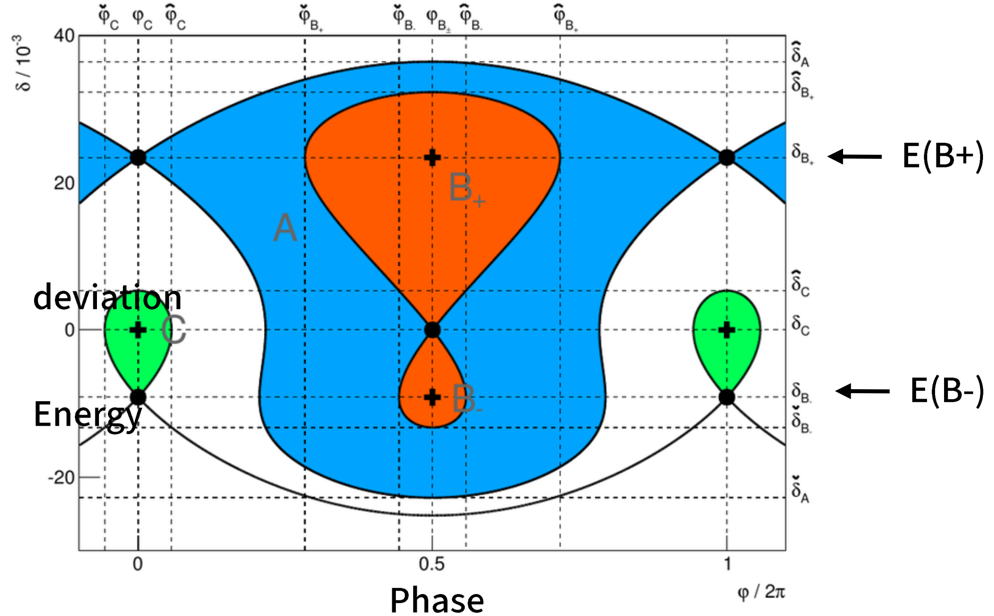
become important
→ alpha buckets at same phase but different energy [3]

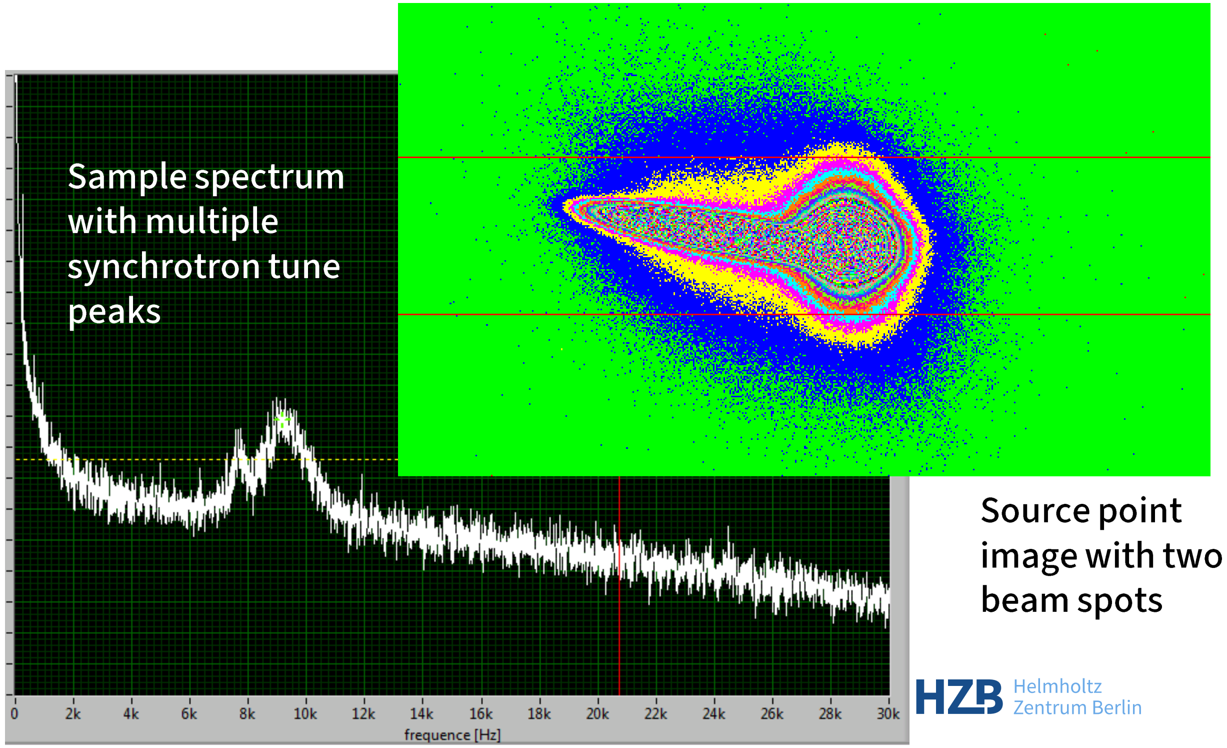
- Coherent signal only observed in a specific alpha bucket state → why?

- Complicated phase space in the SSMB state
  - ➢ Ongoing investigations in experiment
  - ➢ Simulations necessary

→ Nonlinear longitudinal phase space is crucial for the generation of microbunching for SSMB

Longitudinal phase space in low-alpha





Sample spectrum with multiple synchrotron tune peaks

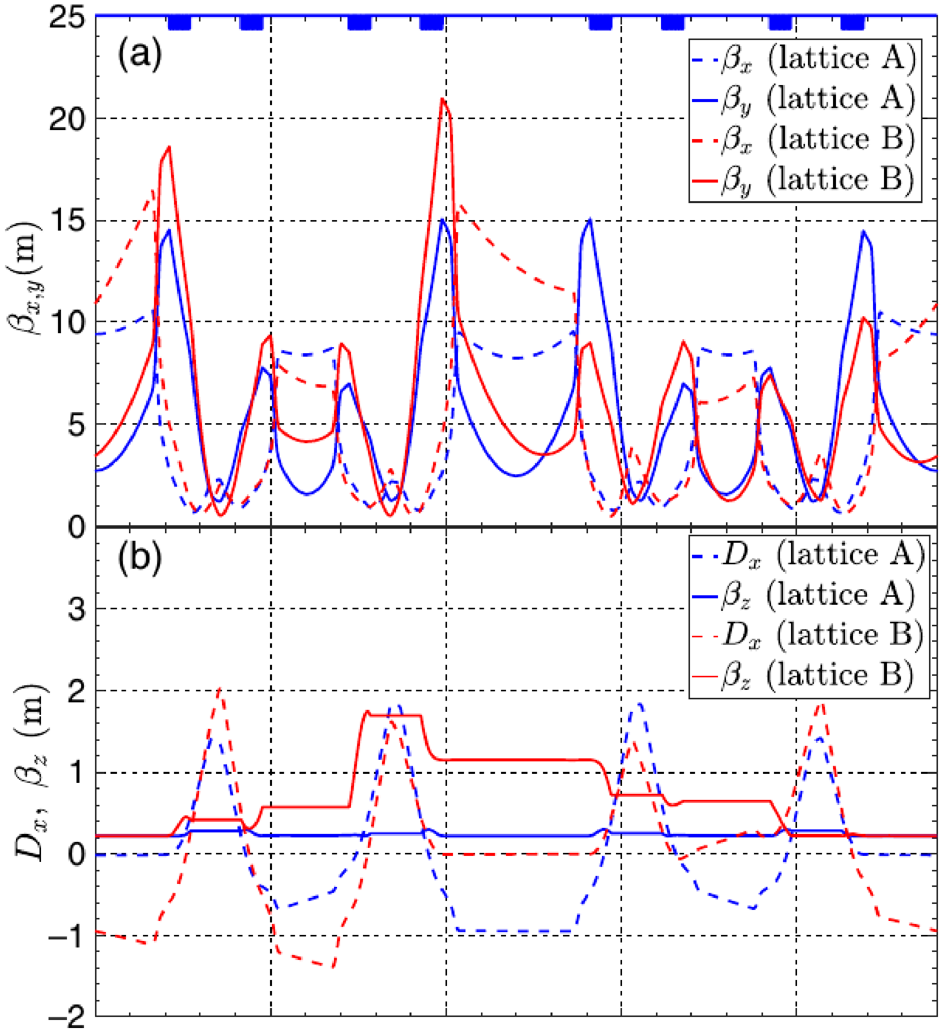
Source point image with two beam spots

[3] M. Ries, Nonlinear Momentum Compaction and Coherent Synchrotron Radiation at the Metrology Light Source, Dissertation, Humboldt-Universität zu Berlin (2013). DOI: 10.18452/16979

BUNCH LENGTHENING DUE TO LOCAL MOMENTUM COMPACTION

- Momentum compaction: $\alpha = \frac{\Delta C/C_0}{\Delta p/p_0} = \frac{1}{C_0}\oint \frac{D_x(s)}{\rho(s)}\mathrm{d}s$
- Stochastic nature of synchrotron radiation emission:
  "Local" momentum compaction $\tilde{\alpha}(s_1,s_2) = \frac{1}{C_0}\int_{s_1}^{s_2} \frac{D_x(s)}{\rho(s)}\mathrm{d}s$
- Classical bunch length formula $\sigma_z \propto \sqrt{|\alpha|}$ invalid
  if local momentum compaction varies around the ring → increase in energy spread and bunch length at low synchrotron tunes
- Experimental investigation at the MLS: comparison between standard low alpha lattice ("Lattice A") and lattice with strong variation of dispersion ("Lattice B", "high partial alpha")

→ **Fundamental effect limiting bunch shortening so far experimentally not confirmed**



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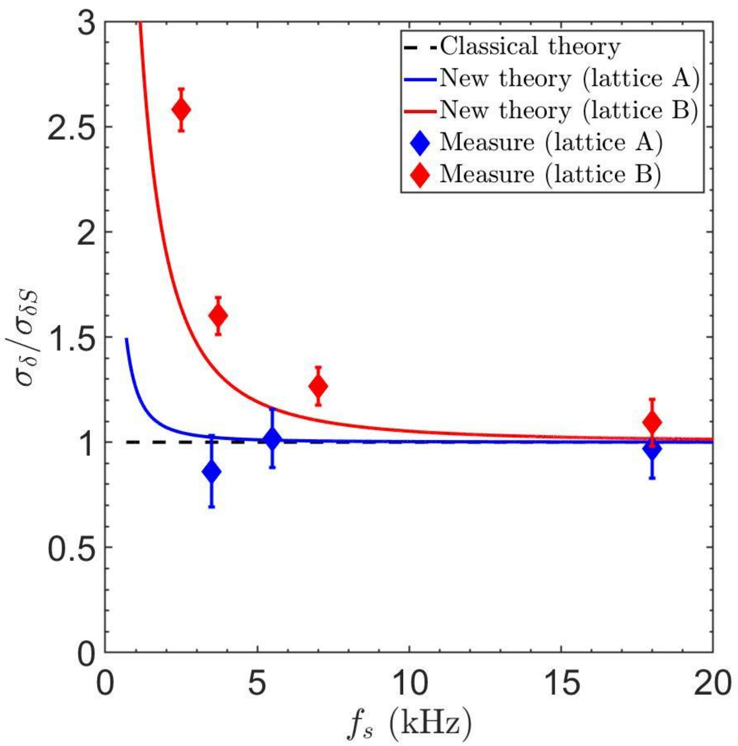
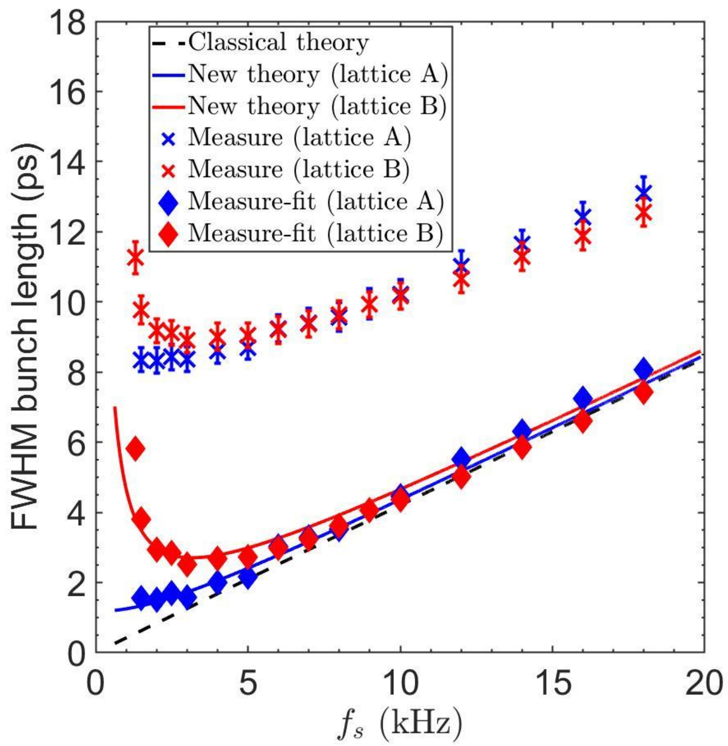
Experimental verification at the Metrology Light Source [4]

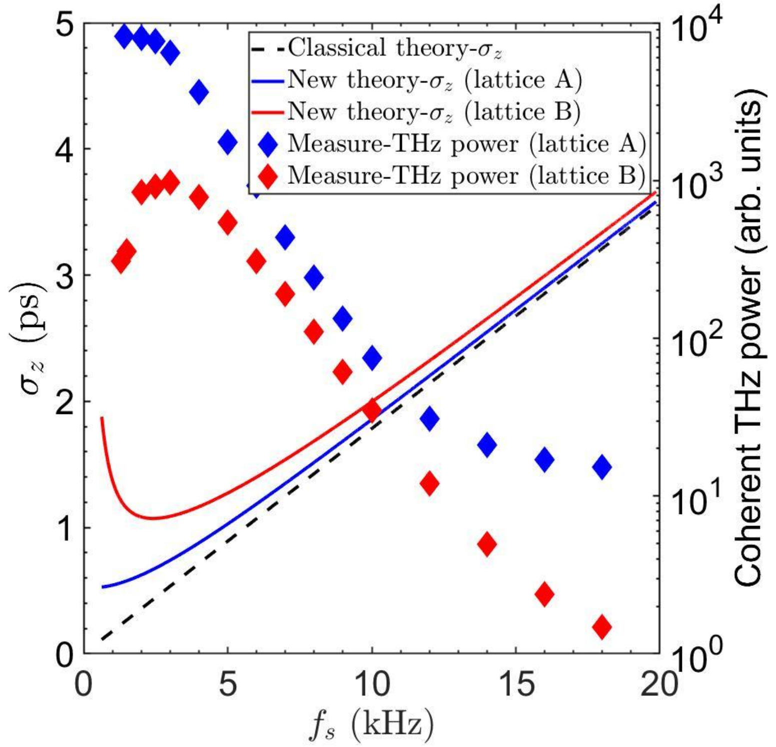
Direct measurement of energy spread:
Compton backscattering



Direct measurement of bunch length:
Streak camera (resolution limited)



Indirect measure of bunch length:
Power of coherent THz emission



synchrotron tune $f_s \propto \alpha$

[4] X. J. Deng *et al.*, Breakdown of classical bunch length and energy spread formula in a quasi-isochronous electron storage ring, Phys. Rev. Accel. Beams **26**, 054001 (2023).
DOI: 10.1103/PhysRevAccelBeams.26.054001

➔ **Multiple independent measurements support theoretical expectation**

Conclusion & Outlook

- SSMB PoP experiment at the MLS has shown coherent radiation from microbunches and is now reproduced routinely
- Flexibility of MLS allows studies of many effects relevant for SSMB
  - alpha buckets
  - bunch lengthening due to partial momentum compaction
- Important next steps:
  - Continue exploring longitudinal phase space in the SSMB state
  - Support experimental work with simulations
  - Investigate conditions for radiation stability
- SSMB PoP phase II:
  - Goal: Modulate electron beam turn-by-turn for up to 1000 revolutions to achieve a quasi-steady state
  - High repetition rate laser under construction and optimization at laser lab in Wuhan, China
  - Exact experiment plan, detection setups still have to be finalized
- Long term perspective:
  - Continuation of PoP experiments and possible first application at MLS successor machine MLS II
  - Final goal: Construction of dedicated SSMB storage ring facility by Tsinghua University, Beijing

Thank you for your attention!

Acknowledgment to all members of the SSMB PoP collaboration team:

Helmholtz-Zentrum Berlin (HZB):
Jörg Feikes, Arnold Kruschinski, Ji Li, Aleksandr Matveenko, Markus Ries, and others

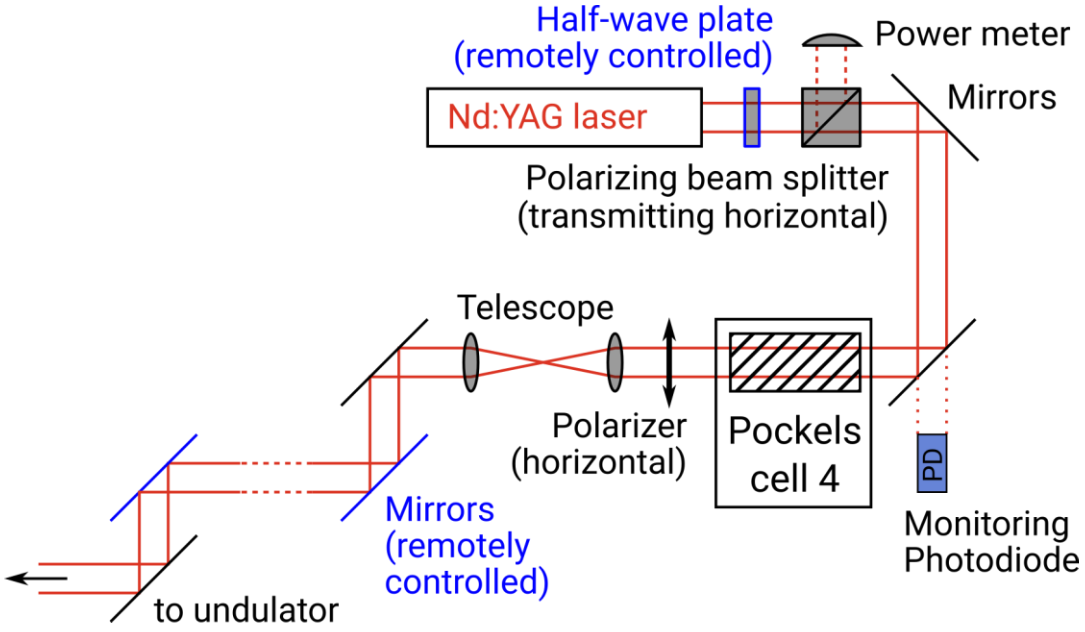
Physikalisch-Technische Bundesanstalt (PTB):
Arne Hoehl, Roman Klein, and others

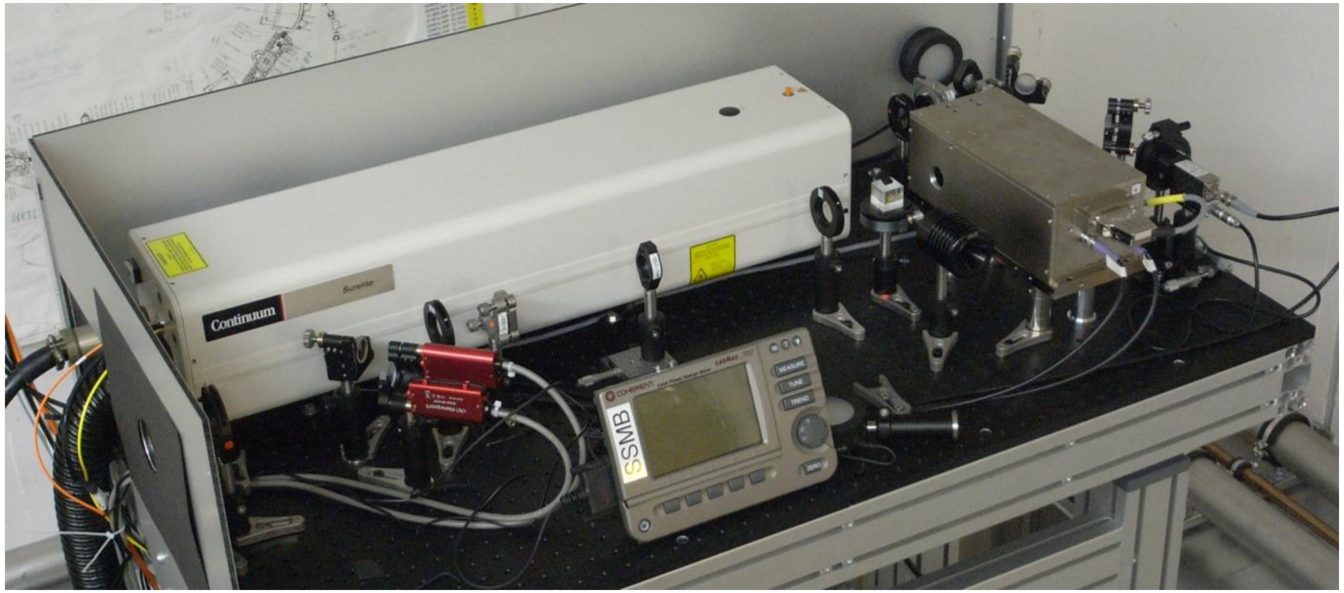
Cooperation partners in China, led by Tsinghua University, Beijing:
Alex Chao, Xiujie Deng, Wenhui Huang, Lixin Yan, Chuanxiang Tang, and many others

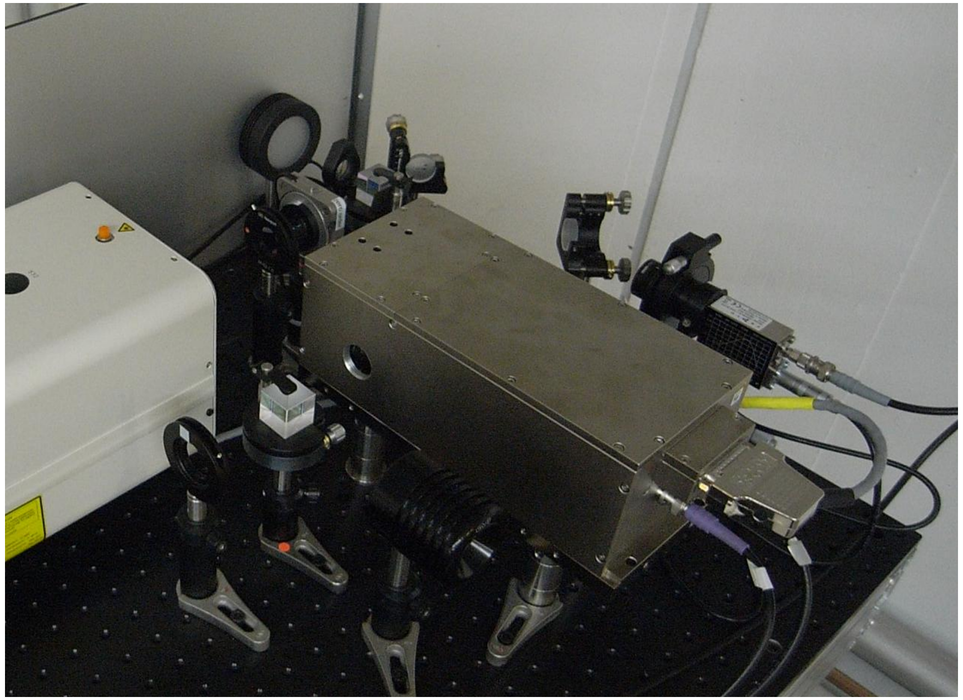
Backup

LASER SETUP FOR SSMB

- Commercial Continuum Surelite laser system
- August 2021: Installation of an additional Pockels cell (“Pockels cell 4”) to supress stray light from the cw seeder laser

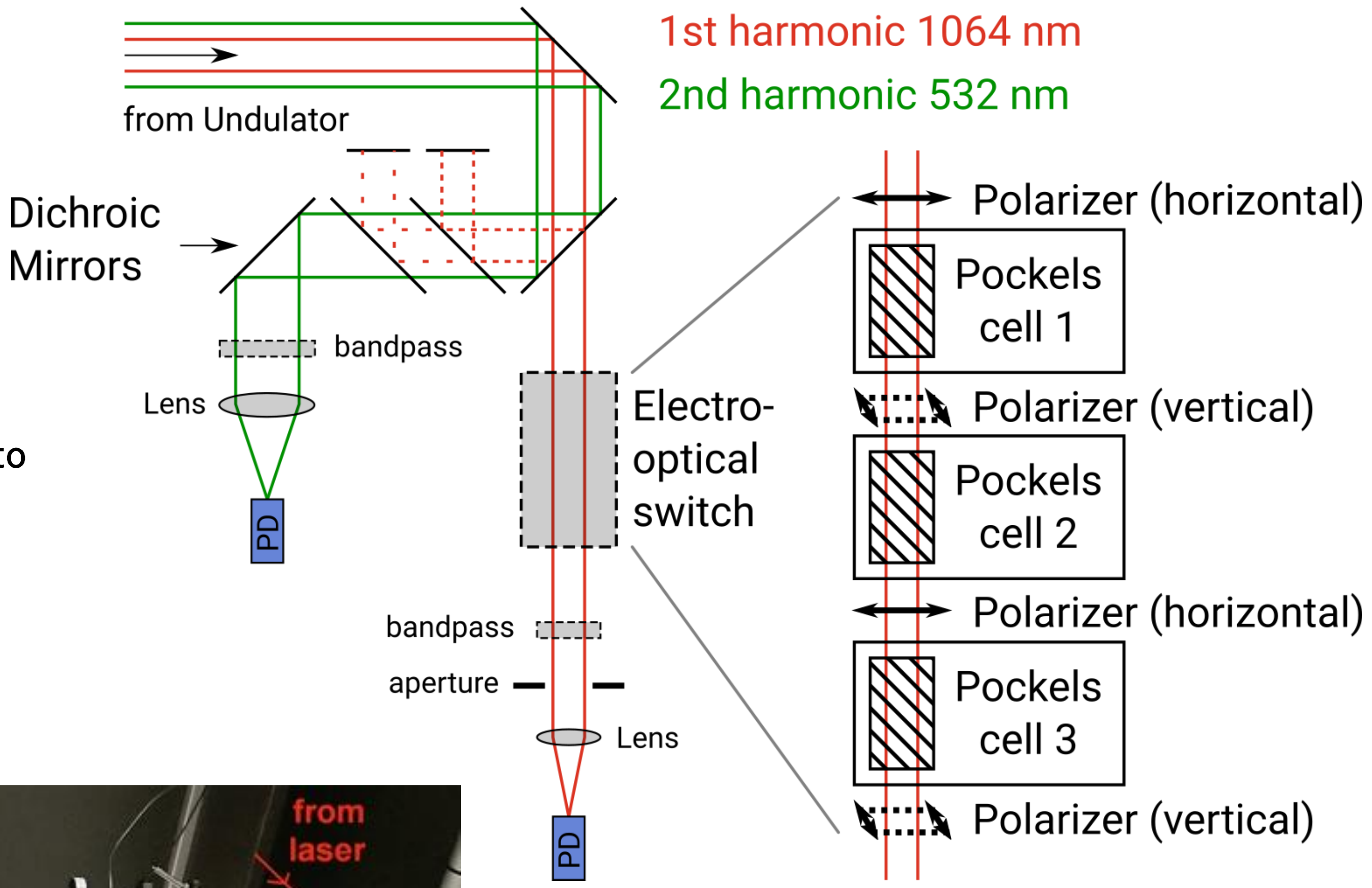


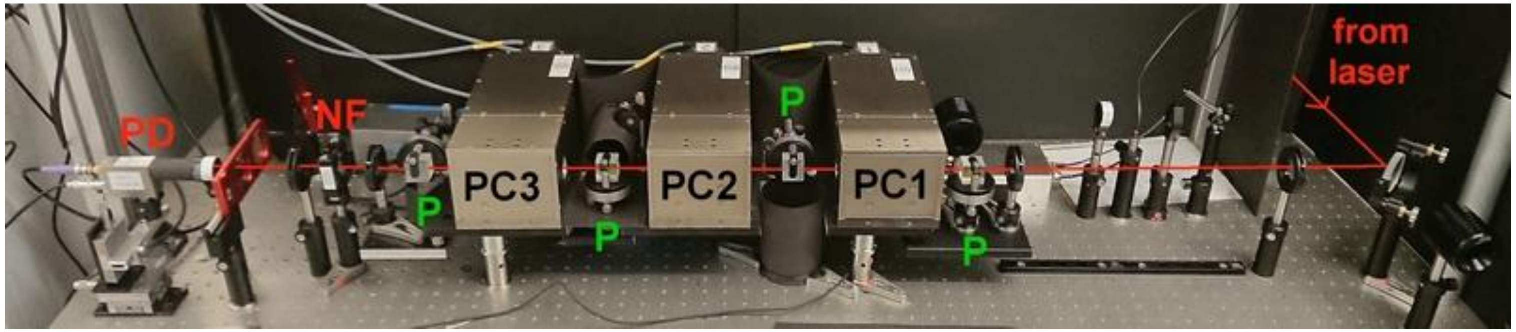




FIRST HARMONIC DETECTION

- Development for Master’s thesis
- Pockels cells as fast optical switches
- 3 stages needed for attenuation of 10^-9
- Can also use Pockels cells as variable attenuators to improve detector dynamic range
- Installed at the beamline in April 2021
- Considering expansion with grating spectrograph





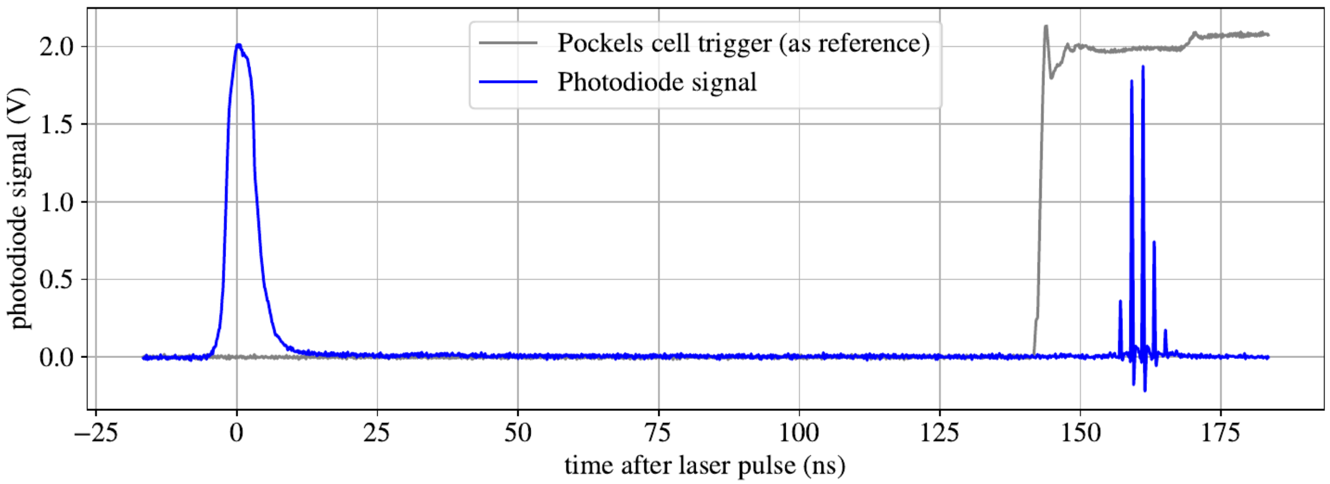
FIRST HARMONIC SSMB SIGNALS

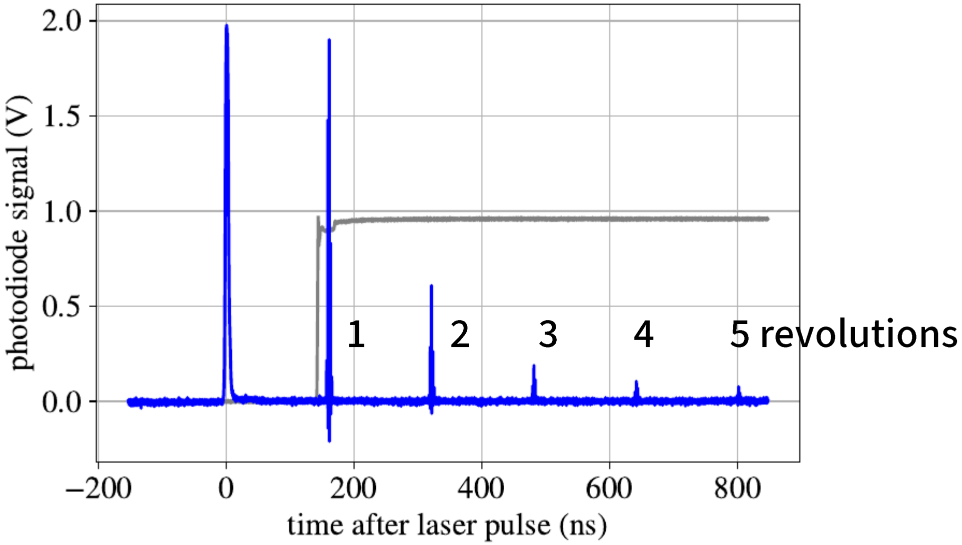
- > 2 orders of magnitude stronger signals than on second harmonic → better statistics
- Coherent signal can be reproduced and optimized more reliably → good reproducibility
- Machine parameters can be varied over a wider range without losing the signal → wider parameter space can be investigated
- Coherent signal is present also on later revolutions → unexpected!

→ Now we can do systematic analyses of the SSMB state!

Laser pulse

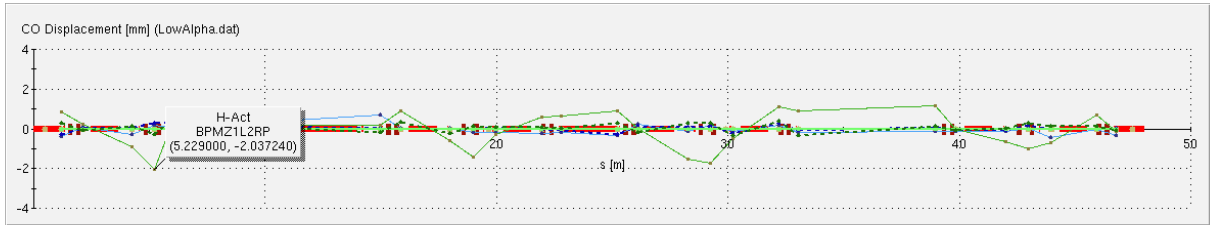
Coherent radiation of bunches modulated by laser

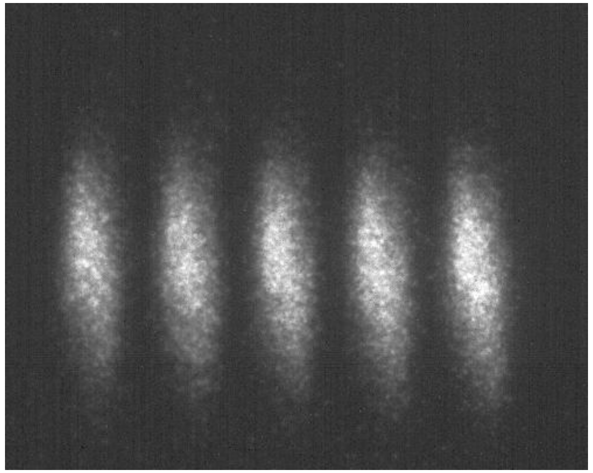




Bunch length measurements in alpha buckets with streak camera

B- bucket



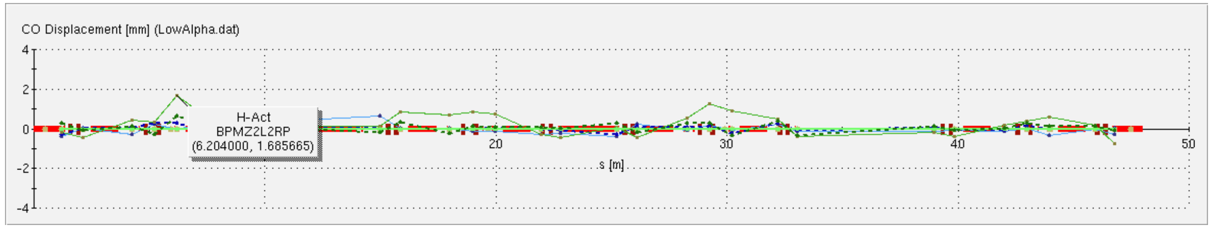


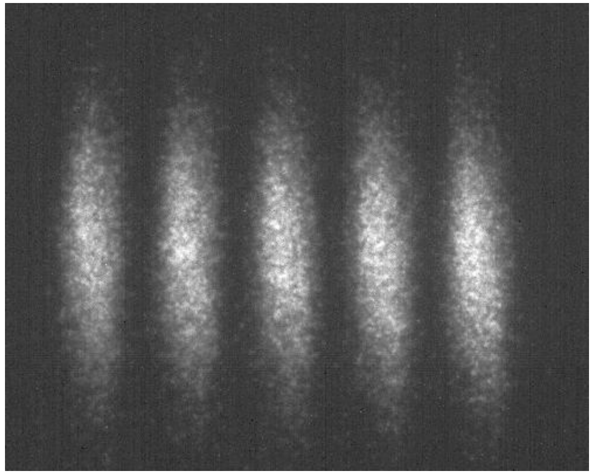
Time

(≈ 10 ps)

- Shorter bunch length
- coherent signal is observed

B+ bucket

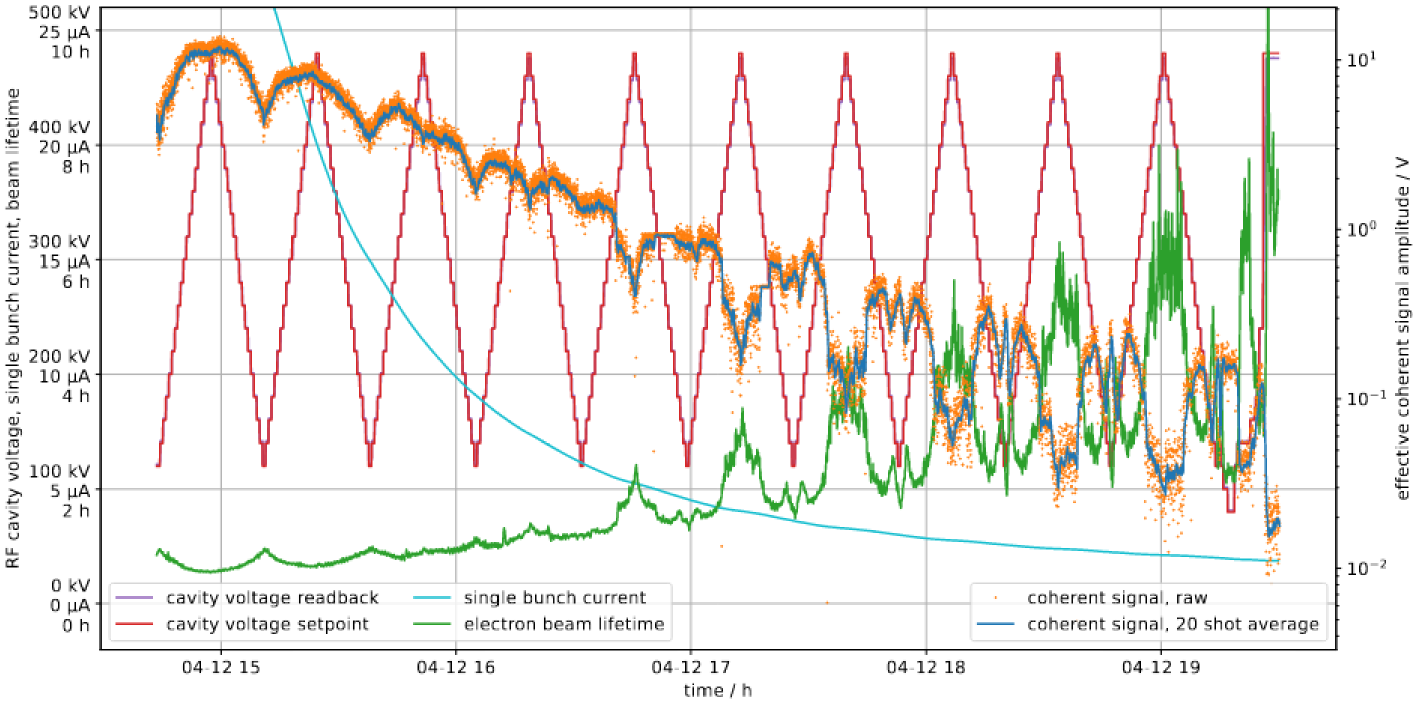


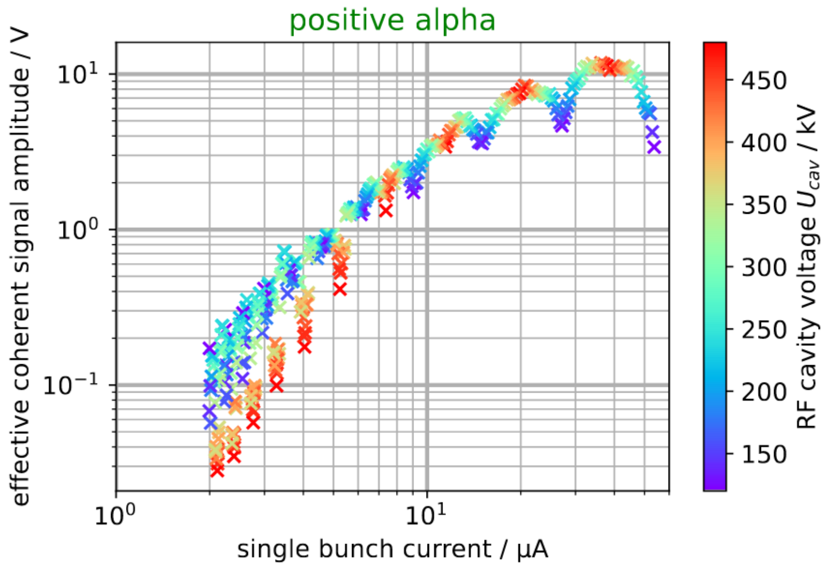


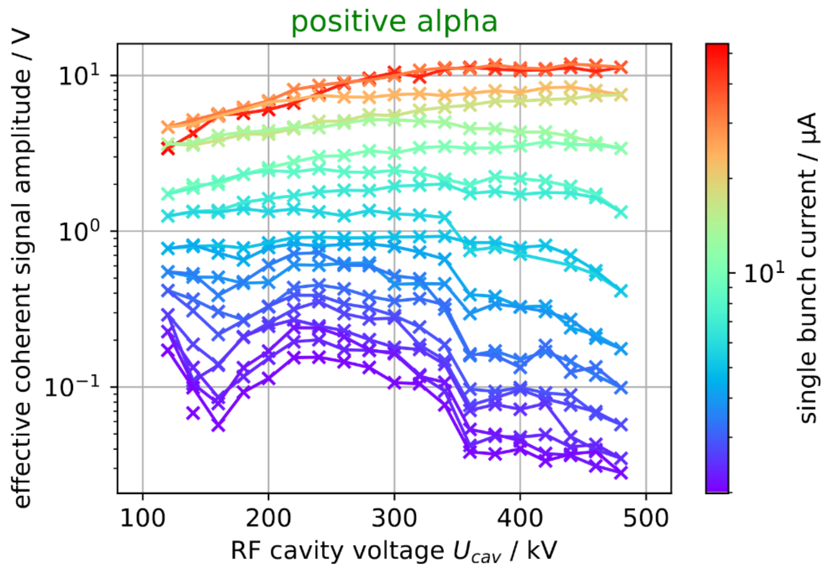
- Longer bunch length
- **no** coherent signal observed

Dependence of SSMB amplitude on cavity voltage

- Naïve expectation: Higher RF cavity voltage → shorter bunch → stronger SSMB signal
- But observed is a breakdown of SSMB amplitude below a current threshold and above a voltage threshold
- Similar observation for coherent THz emission 2009-2014







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