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Exploring the Dynamics of Steady State Microbunching in a Proof-of-Principle experiment at the MLS

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MT Student Retreat 2022

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)

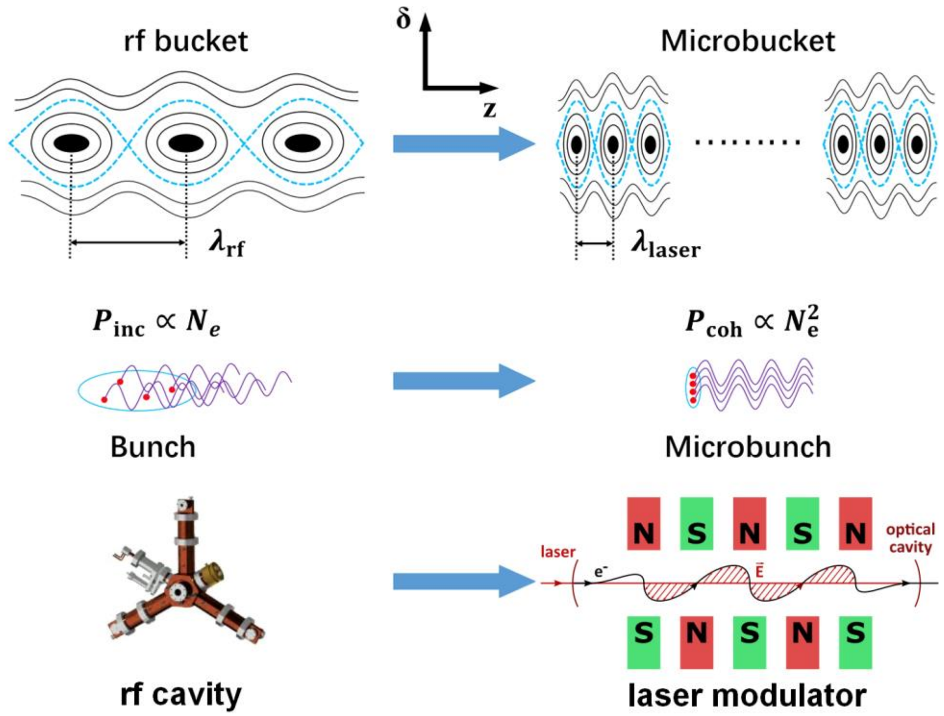
Steady-State Microbunching (SSMB):
Coherent radiation from microbunched electron beams inside a storage ring [1]

➔ Combining high peak power and high repetition rate (high avg. power)

➔ Coherent radiation at wavelengths up to the EUV range

➔ Principle: Scale down longitudinal focusing mechanism that creates electron bunches

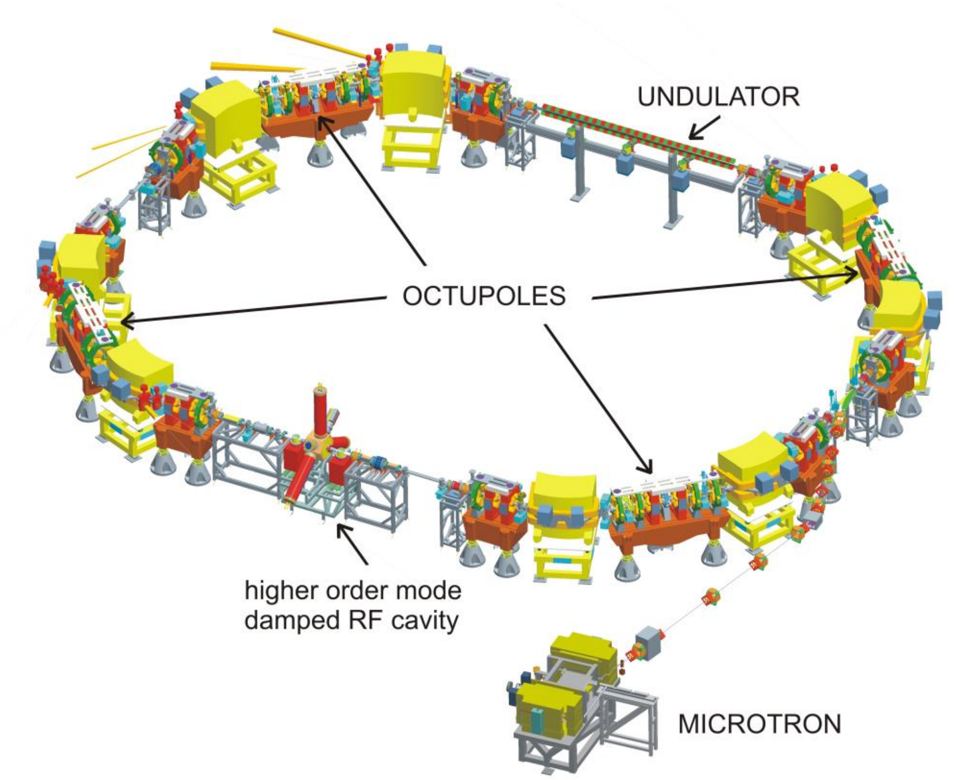
➔ Proof-of-Principle (PoP) experiment at the MLS to prove the basic mechanism behind SSMB



[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)

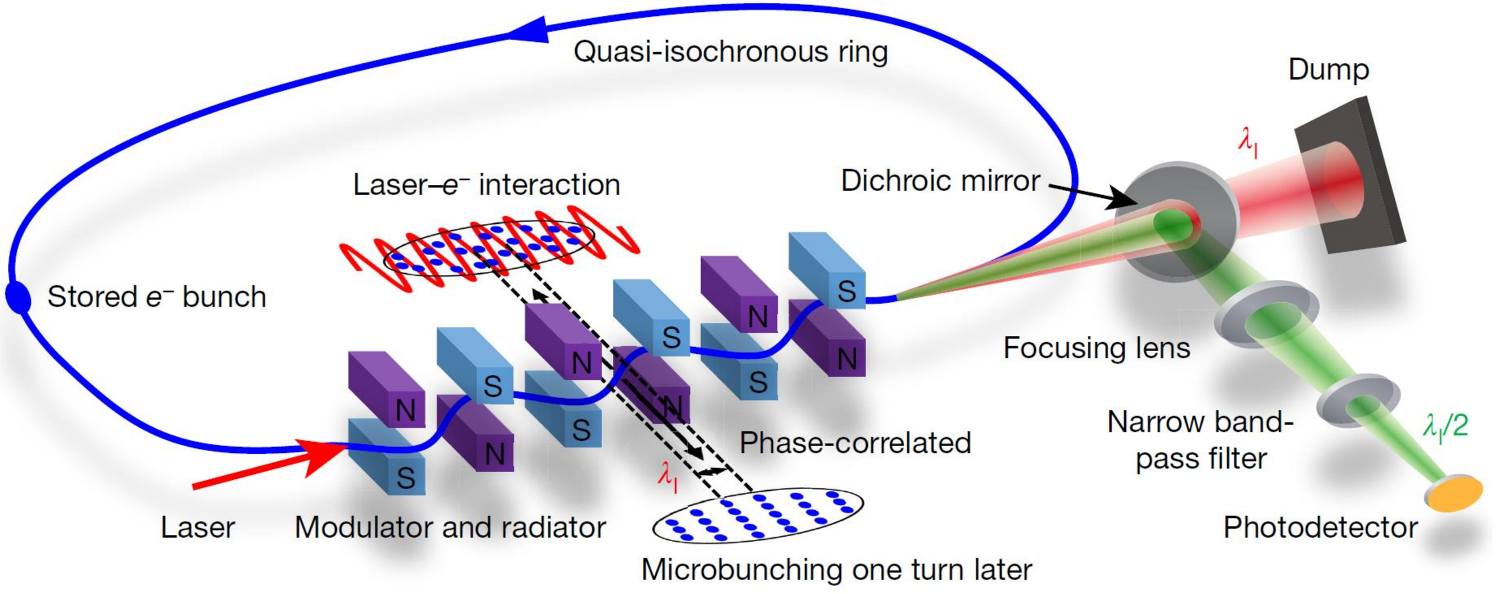
- Full time user operation machine
- Owner: National metrology institute (PTB)
- First storage ring optimized for low-alpha operation
- Additional Sextupole and Octupole families to control higher order momentum compaction
- Low alpha for SSMB: $|\alpha| < 2 \times 10^{-5}$



Circumference	48 m
Electron energy	105 MeV – 629 MeV
RF frequency	500 MHz
Revolution period	160 ns
Momentum compaction factor	$|\alpha| < 0.05$
Undulator	Single U125

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 (fundamental wavelength detection not yet possible as detector is saturated by the modulation laser)

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

→ Initial findings allowed for publication 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

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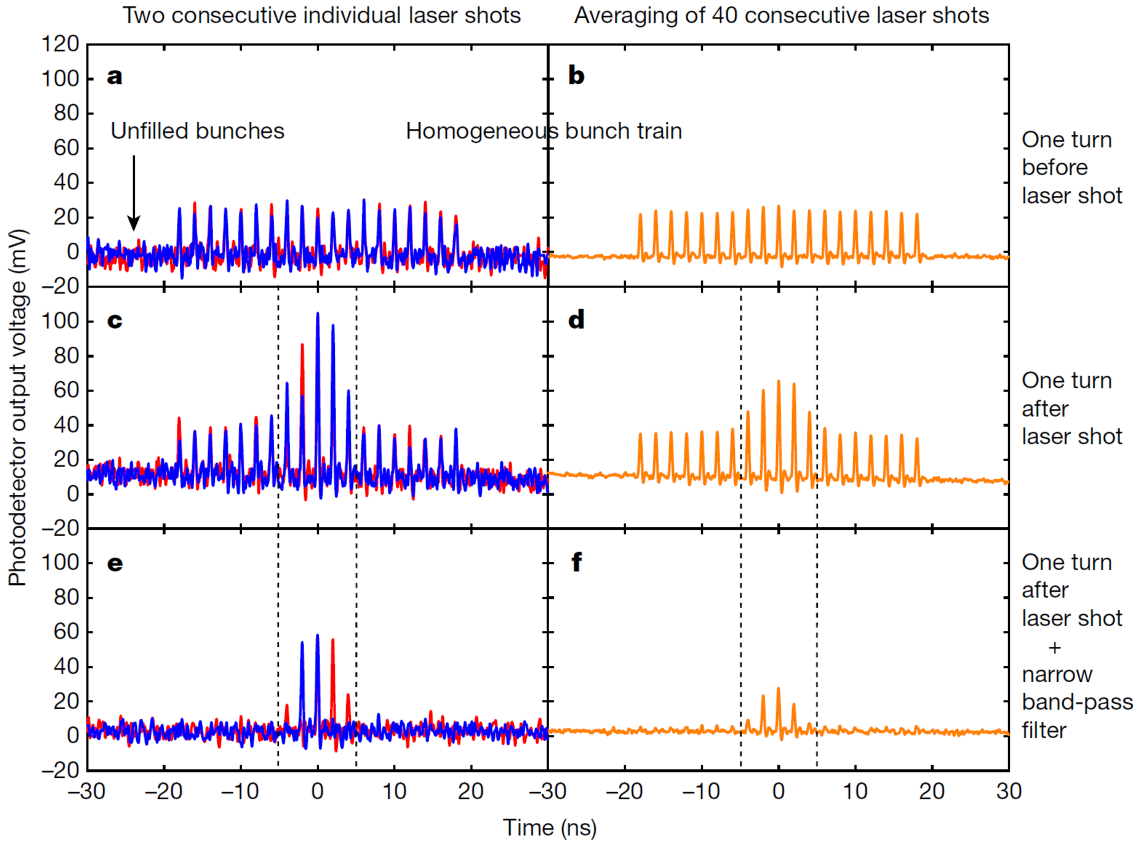
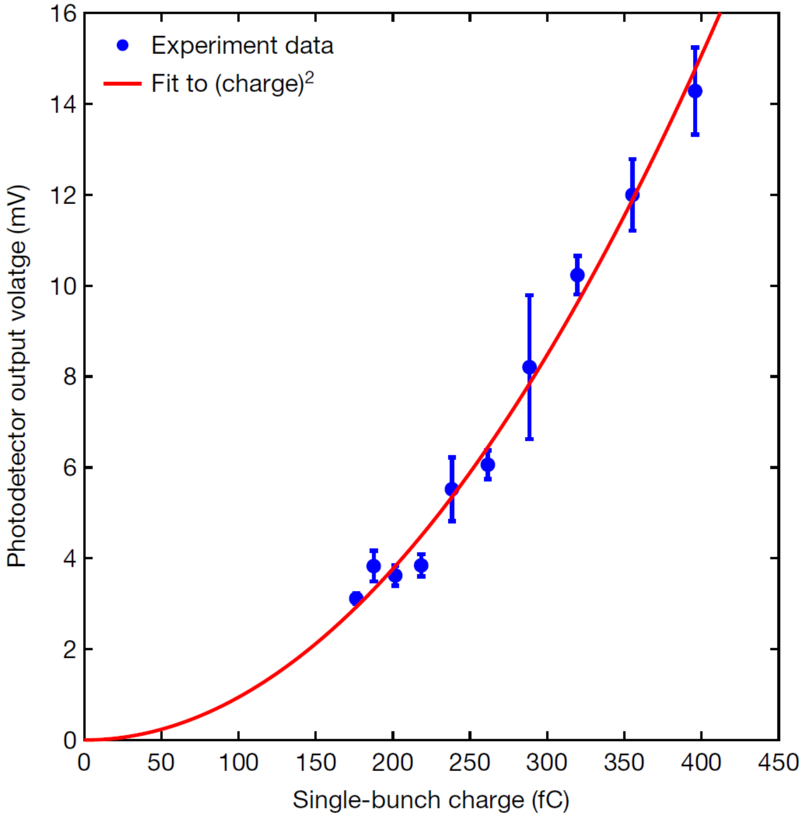
Results of SSMB experiments
on the second undulator harmonic

Weak but clear signal: increased radiation intensity with narrow bandwidth

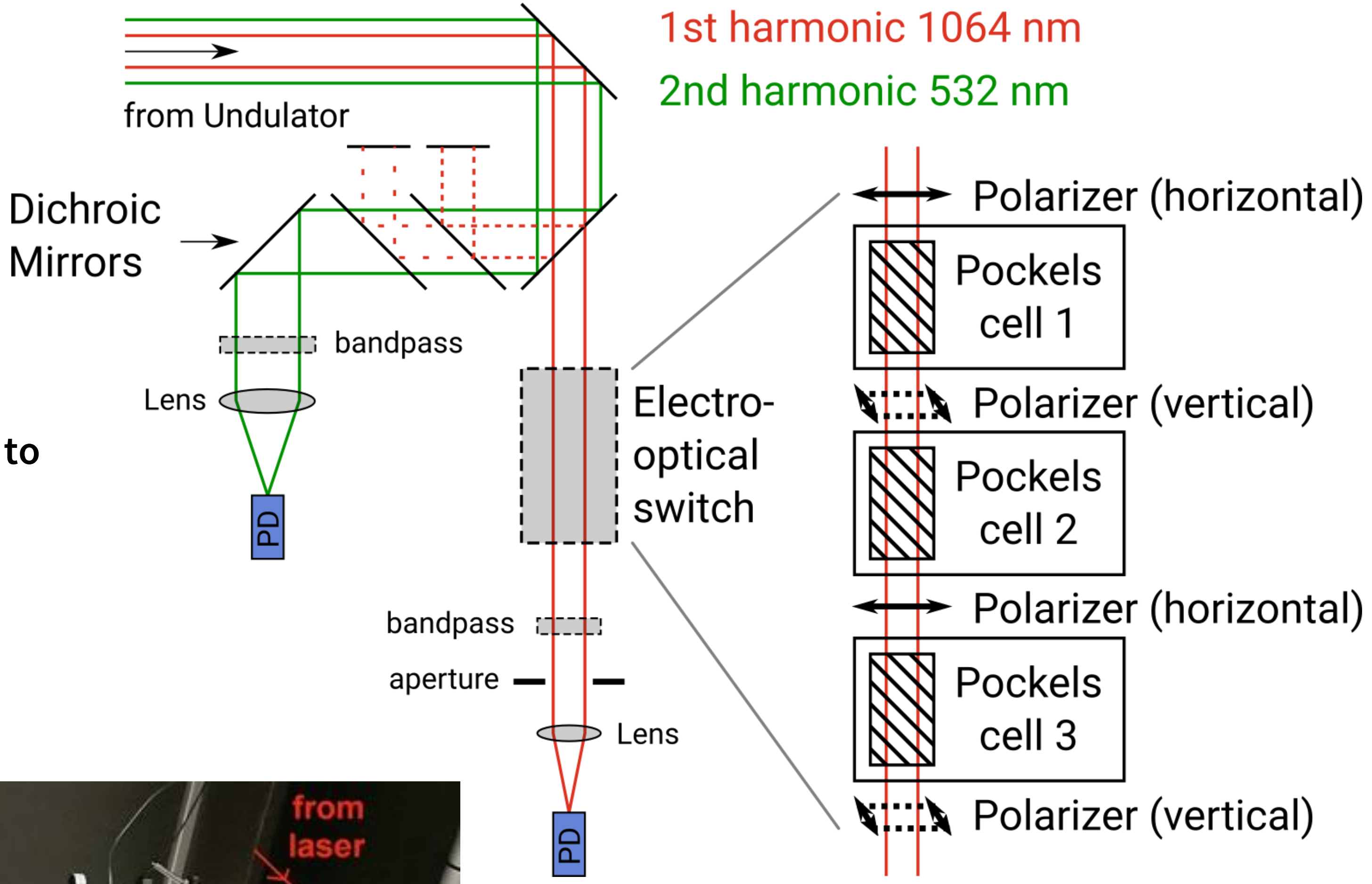


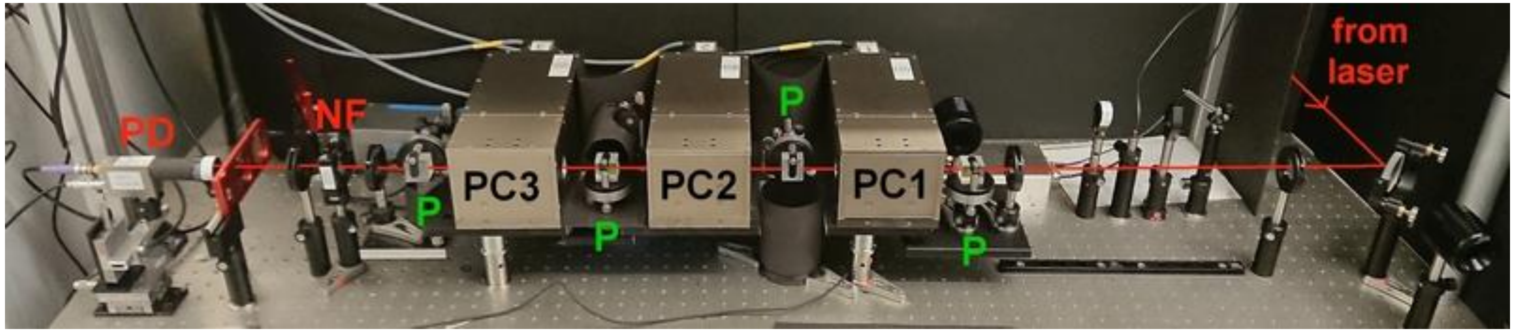
Quadratic current scaling characteristic of coherent radiation confirmed



FIRST HARMONIC DETECTION

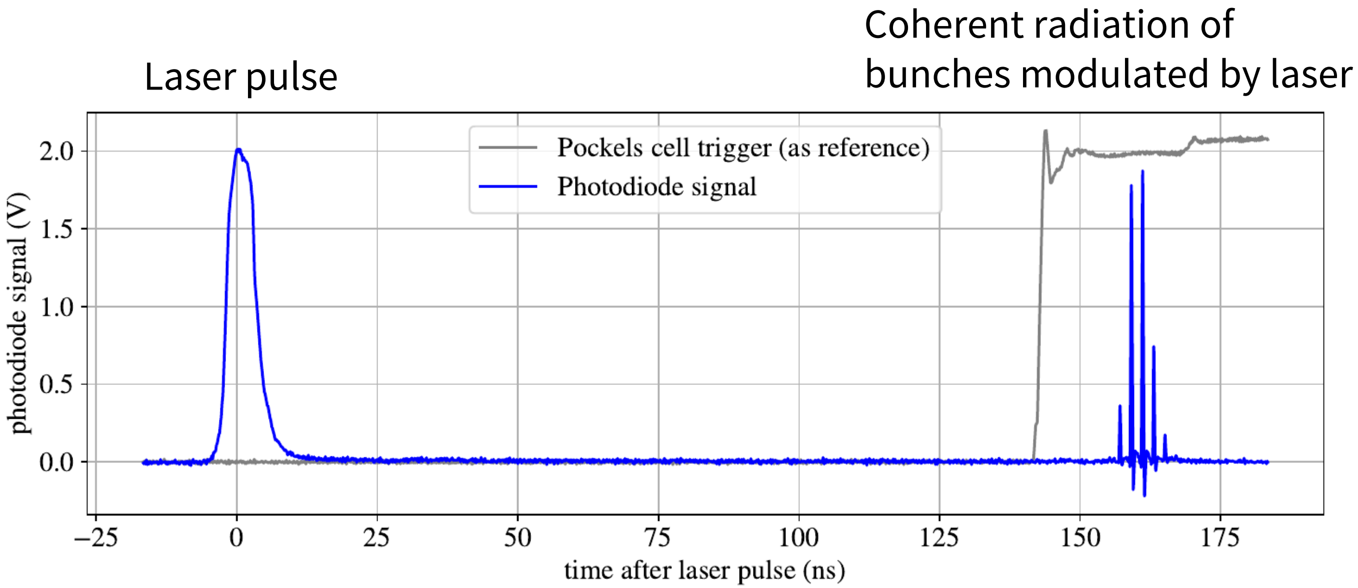
- Development for Master's thesis
- Pockels cells as fast optical switches
- 3 stages needed for attenuation of 10^-9
- Can also use Pockels cells as variable attenuators to improve detector dynamic range
- Installed at the beamline in April 2021
- Considering expansion with grating spectrograph

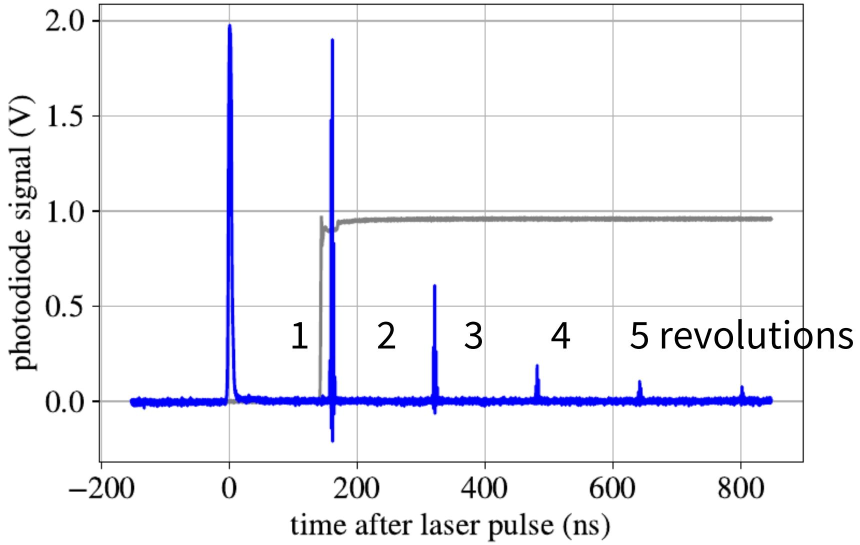




SSMB SIGNALS ON THE FIRST HARMONIC

- > 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!

Alpha bucket dynamics for SSMB

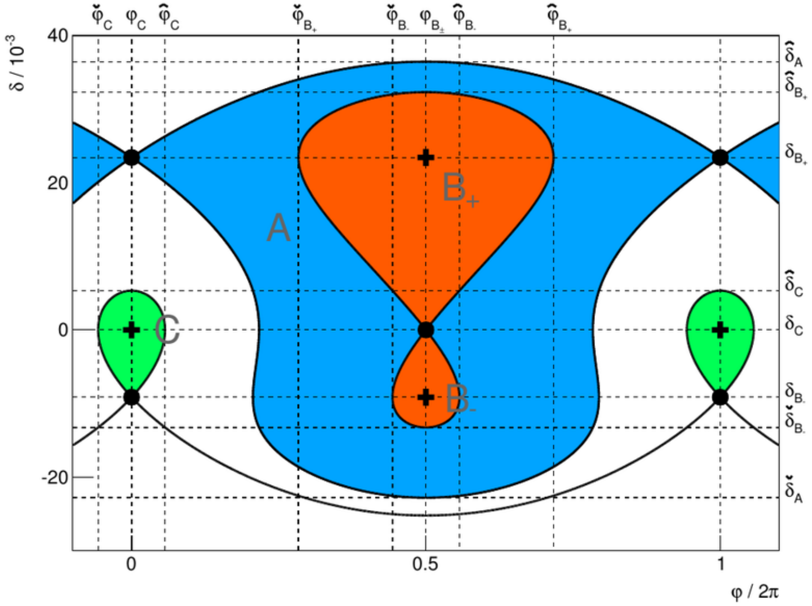
- Low momentum compaction: Higher orders of alpha function

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

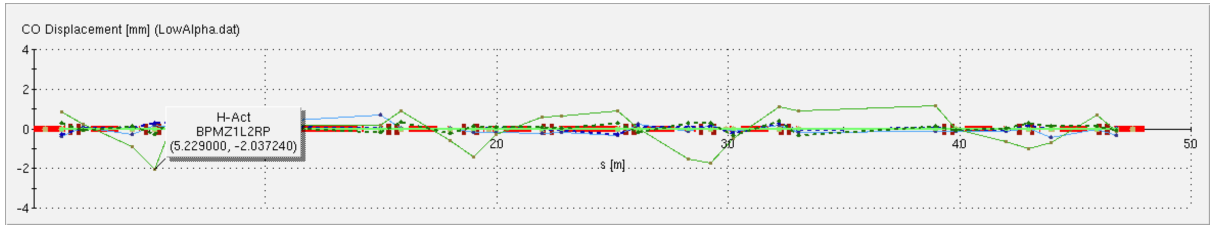
  become important → alpha buckets [3]

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

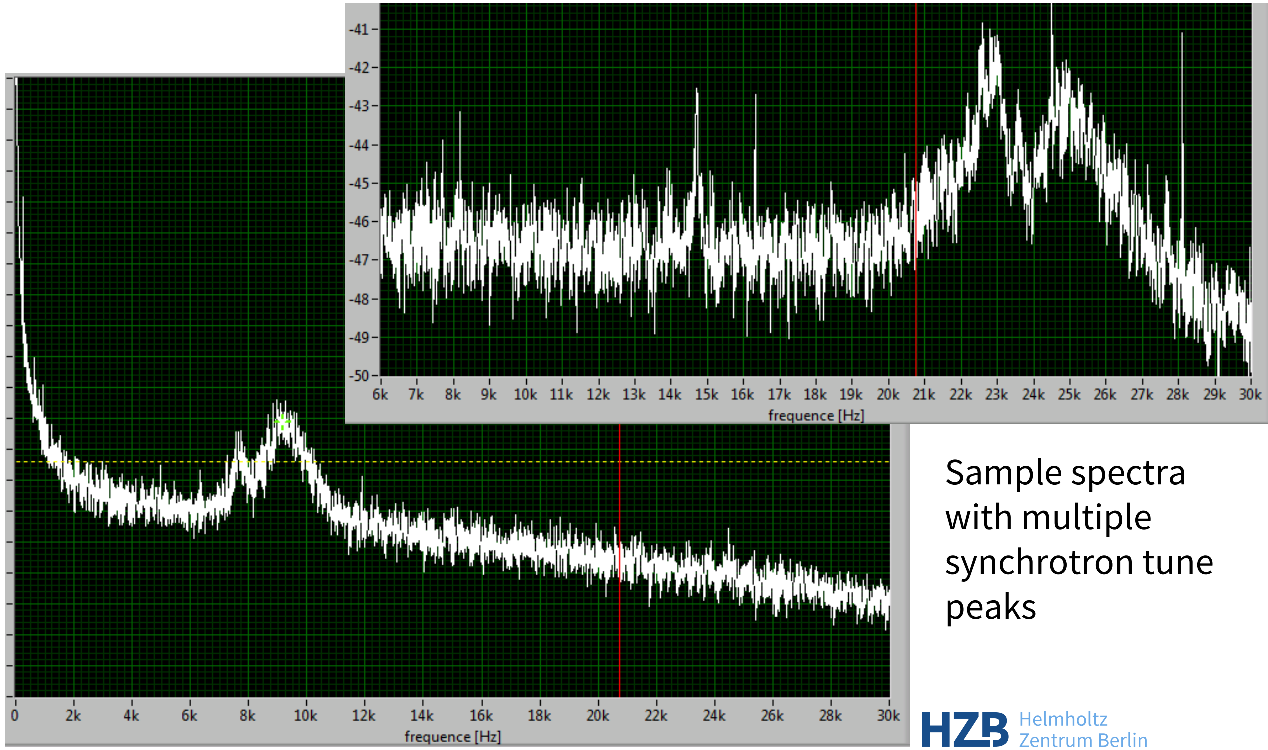
- Complicated phase space in the SSMB state
  - ➢ Ongoing investigations in experiment
  - ➢ Simulations necessary



Longitudinal phase space in low-alpha



Typical electron orbit in B- bucket



Sample spectra with multiple synchrotron tune peaks

[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

Conclusion

- Coherent radiation from a microbunched electron beam in a storage ring has been successfully proven
- New first order detection setup allows the continuation of the SSMB PoP experiment
- Important next steps:
  - ➢ Continue exploring longitudinal phase space in the SSMB state
  - ➢ Support experimental work with simulations
  - ➢ Investigate conditions for radiation stability

- Perspective for SSMB:
  - ➢ Continuation of PoP experiments and possible first application at MLS successor machine MLS II
  - ➢ Long term: Construction of dedicated SSMB storage ring facility by Tsinghua University, Beijing

Thank you for your attention!

The SSMB PoP collaboration team

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

Physikalisch-Technische Bundesanstalt (PTB):
Arne Hoehl, Roman Klein, Jana Puls

Tsinghua University, Beijing:
Alex Chao, Xiujie Deng, Wenhui Huang, Lixin Yan, Chuanxiang Tang, Huan Wang, Zizheng Li, Yao Zhang, Zhilong Pan

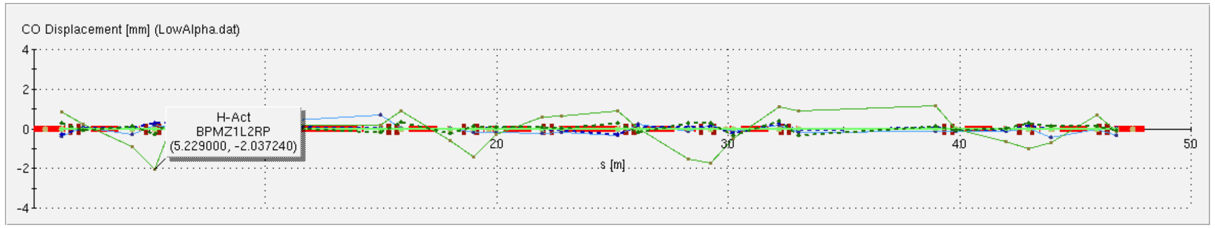
National Tsing Hua University, Hsin-Chu:
Hao-Wen Luo, Poshun Wu, Ci-Ling Pan, Make Ying

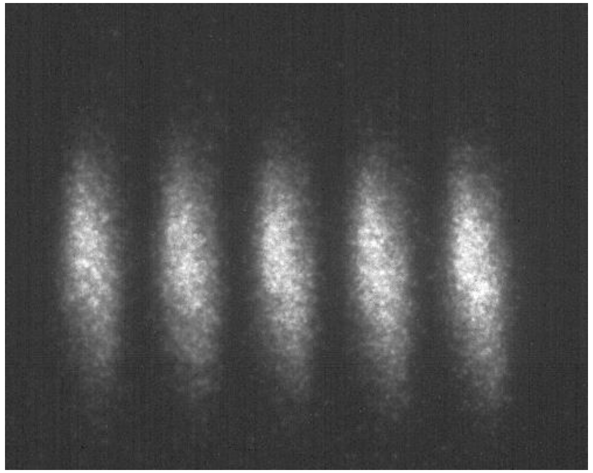
Shanghai Synchrotron Radiation Facility:
Bocheng Jiang, Chao Feng, Xiaofan Wang, Changliang Li, Weishi Wan

Backup

Bunch length measurements in alpha buckets with streak camera

B- bucket



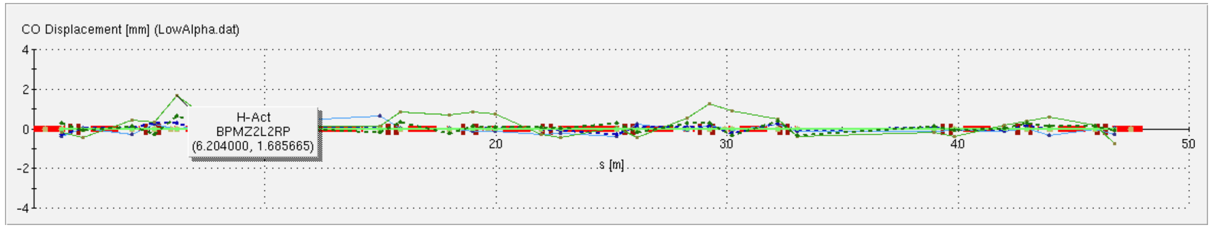


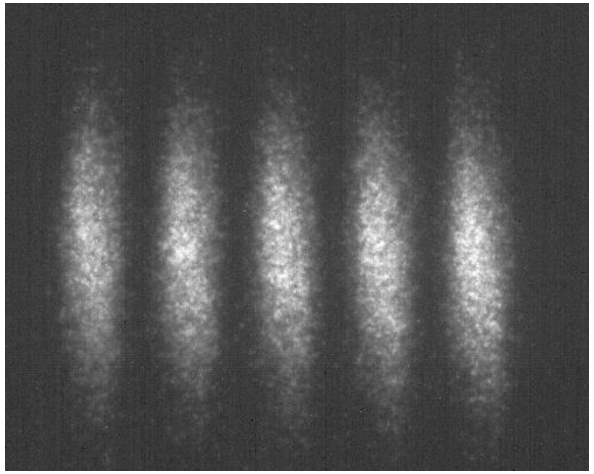
Time

(≈ 10 ps)

- Shorter bunch length
- coherent signal is observed

B+ bucket

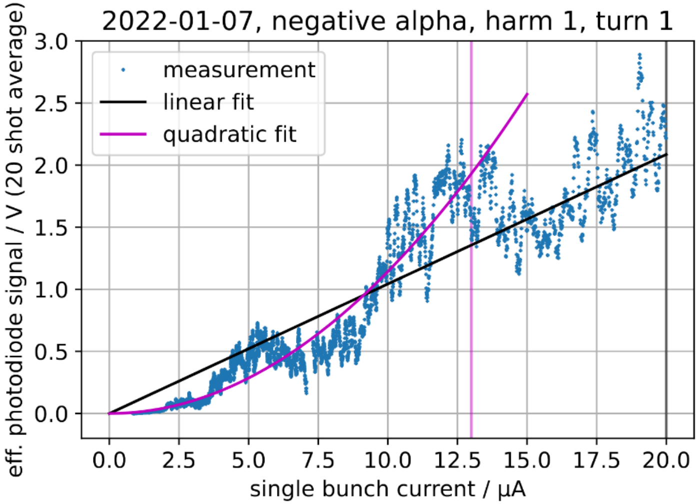


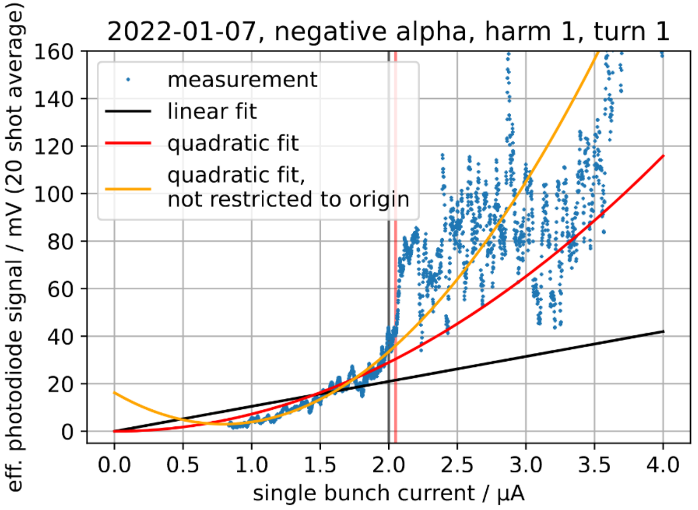


- Longer bunch length
- **no** coherent signal observed

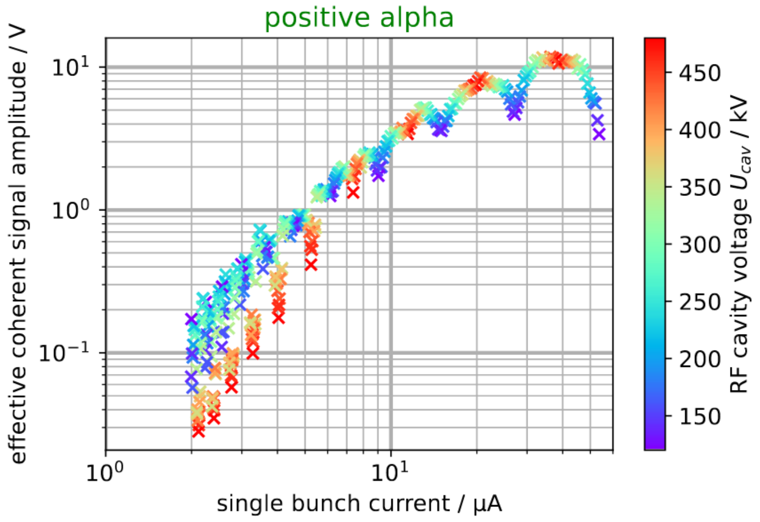
Latest measurements of SSMB on the first harmonic

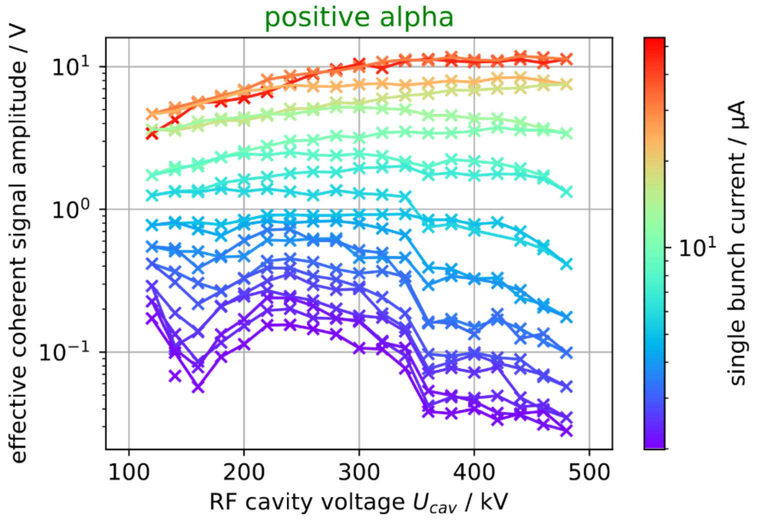
Current scaling on the first harmonic





Influence of accelerating cavity voltage on SSMB signal amplitude





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