Steady State Microbunching in Storage Rings – Proof of Principle Results at MLS

LEAPS FIRST WG2 Workshop 2020

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based on slides by A. Chao

SSMB Collaboration

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Recent conference reports by the collaboration

Joerg Feikes, VUV and EUV Metrology Workshop 2019, First experiment towards steady state micro bunching successfully performed at the Metrology Light Source

Changliang Li et al., IPAC19, Lattice design for the reversible SSMB

Zhilong Pan, FEL 2019, A Storage Ring Design for Steady-State Microbunching to Generate Coherent EUV Light Source

Chuanxiang Tang, IPAC2020, First experimental demonstration of the mechanism of steady-state microbunching

Xiujie Deng, EUVL2020, High-power EUV light source based on steady-state microbunching mechanism

SSMB Collaboration[2,3]

- An initial task force has been established at Tsinghua University to promote SSMB research with the goal of developing an SSMB storage ring.
- Three main tasks:
  1. Proof-of-principle (PoP) experiment
  2. Lattice design for SSMB ring[4-6]
  3. Resolve related technical issues

The First SSMB Collaboration Meeting at Tsinghua University, Beijing, 21st July, 2017

[2] C. Tang, et al., An Overview of the Progress on SSMB, in Proceedings of FLS18, Shanghai, China, 2018.

[3] A. Chao, et al., A Compact High-power Radiation Source Based on Steady-state Microbunching Mechanism, SLAC Technical Report No. SLAC-PUB-17241, 2018.

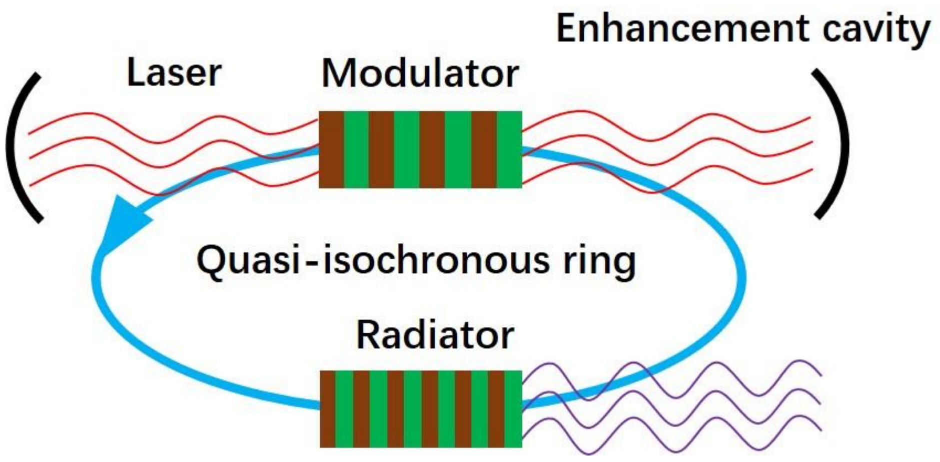
[4] T. Rui, et al., Strong Focusing Lattice Design for SSMB, in Proceedings of FLS18, Shanghai, China, 2018.

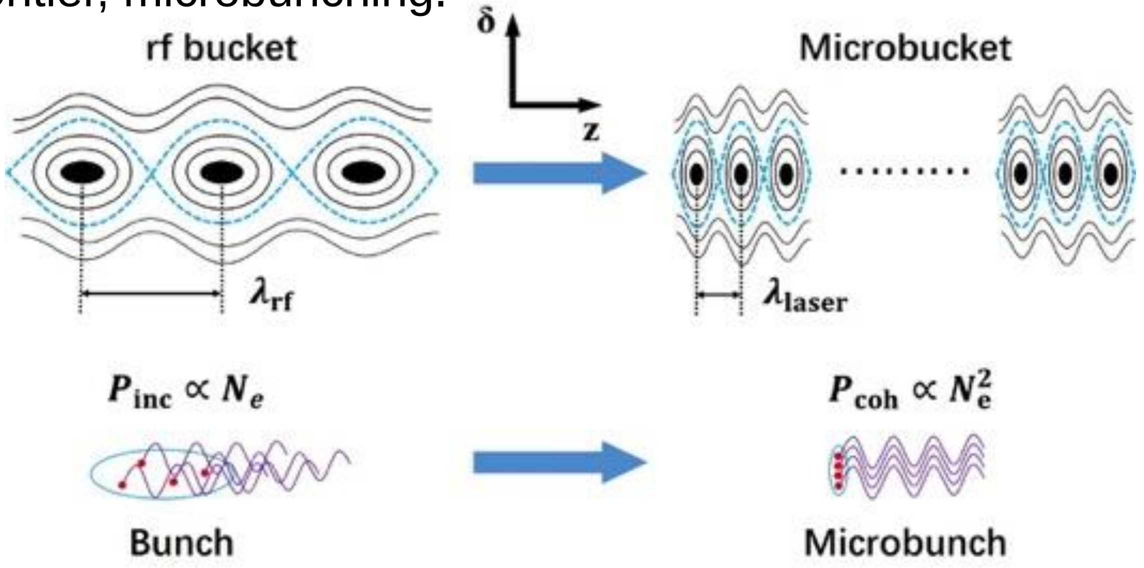
[5] Z. Pan, et al., A Storage Ring Design for Steady-state Microbunching to Generate Coherent EUV Light Source, in Proceedings of FEL19, Hamburg, Germany, 2019.

[6] C. Li, et al., Lattice design for the reversible SSMB, in Proceedings of IPAC19, Melbourne, Australia, 2019.

What is steady-state microbunching (SSMB)[1]?

- Why is FEL so successful? FEL is a game changer. Since the advent of the FEL, the name of the game of radiation source has shifted to the new fertile frontier, microbunching.





- FELs are single-pass devices. **SSMB aims for microbunching in storage rings**. The main difference from a conventional storage ring is to replace the RF cavities by laser modulators. --- The 6 orders of magnitude extrapolation asks for a proof-of-principle test.
- Two key ingredients of SSMB: microbunching for high N_e^2 **peak power,** steady state for high repetition rate.
- SSMB is not an FEL. **No consecutive energy heating/emittance growth**. No FEL mechanism invoked.
  Laser modulator is the key – causing microbunching and maintaining steady-state.
  Radiator is only a passive device, much shorter than that in a high-gain FEL, e.g. a simple dipole.

[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).

Potential of SSMB

- Microbunching is a longitudinal phenomenon. SSMB focuses on **longitudinal dynamics**. This is parallel to the present efforts by the community of **diffraction-limited rings**, which focus on the **transverse dimension**.

  notice: the diffraction limit defines the end of the development towards smaller source points transversely

  -> there is no more potential for machine development in that direction beyond

  -> in contrast in the longitudinal direction the limit is still many **orders** away (*m* -> µ*m*) giving room for decades of

  future science and developments in longitudinal compactification

- Features of SSMB: high-average-power, continuous-wave, **narrow-band** radiation, at wavelengths ranging from the THz to IR, EUV.
- This implies tremendous potential in accelerator photon science and industry applications, for example the **EUV lithography**. High-power EUV source is urgently needed for the high volume manufacturing of EUV lithography and this is one of the main driving force behind recent SSMB developments.

Proof-of-Principle experiments at MLS

A **PoP experiment** was succesfully performed at the Metrology Light Source, Berlin by a collaboration of Tsinghua, HZB and PTB.

Phase-I

- Test of SSMB mechanism in the steady-state isochronous environment of a stored electron beam.
- With very limited resources, use existing MLS, add an existing available single-shot laser.
- Demonstrated SSMB mechanism at MLS, May 2019, a critical milestone.

Experiment is very demanding:

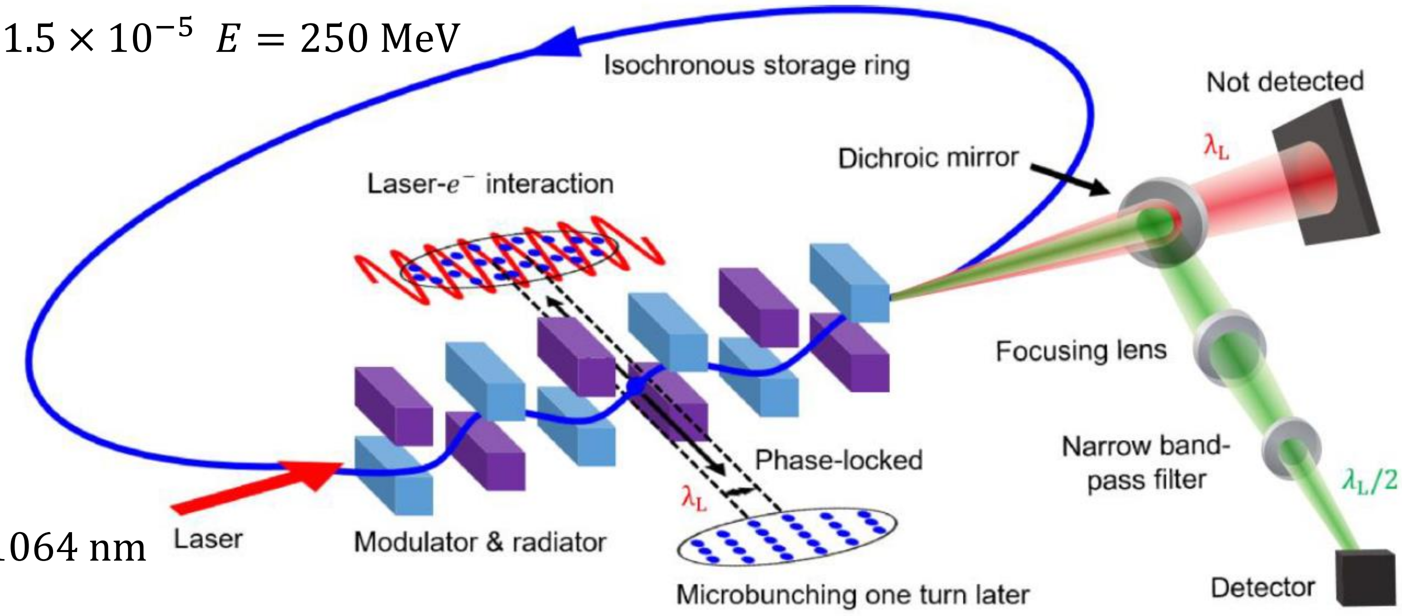
- very **high precision setting** needed for many machine parameter simultaneously
- full understanding of all relevant micro structure smearing effects is essential
- some parameters cannot be measured to the needed accuracy –> **multi-dimensional scans** needed
- stability of these quantities over time (~h) critical
- stability of the beam laser system (overlap, laser jitter) critical
- unexpected physical effects appeared (impact of non-linearities)

-> often we needed several days of trial to achieve coherent emission

SSMB PoP Phase I[7]

Electron beam is stored in an isochronous configuration at MLS. The beam is modulated by a single-shot laser. The laser is turned off, the beam makes one turn and returns to the modulator, which now serves as the radiator in the next turn. The ring must have a high precision and stability to store the beam in isochronous condition and to maintain phase space correlations for microbunching after a full turn.

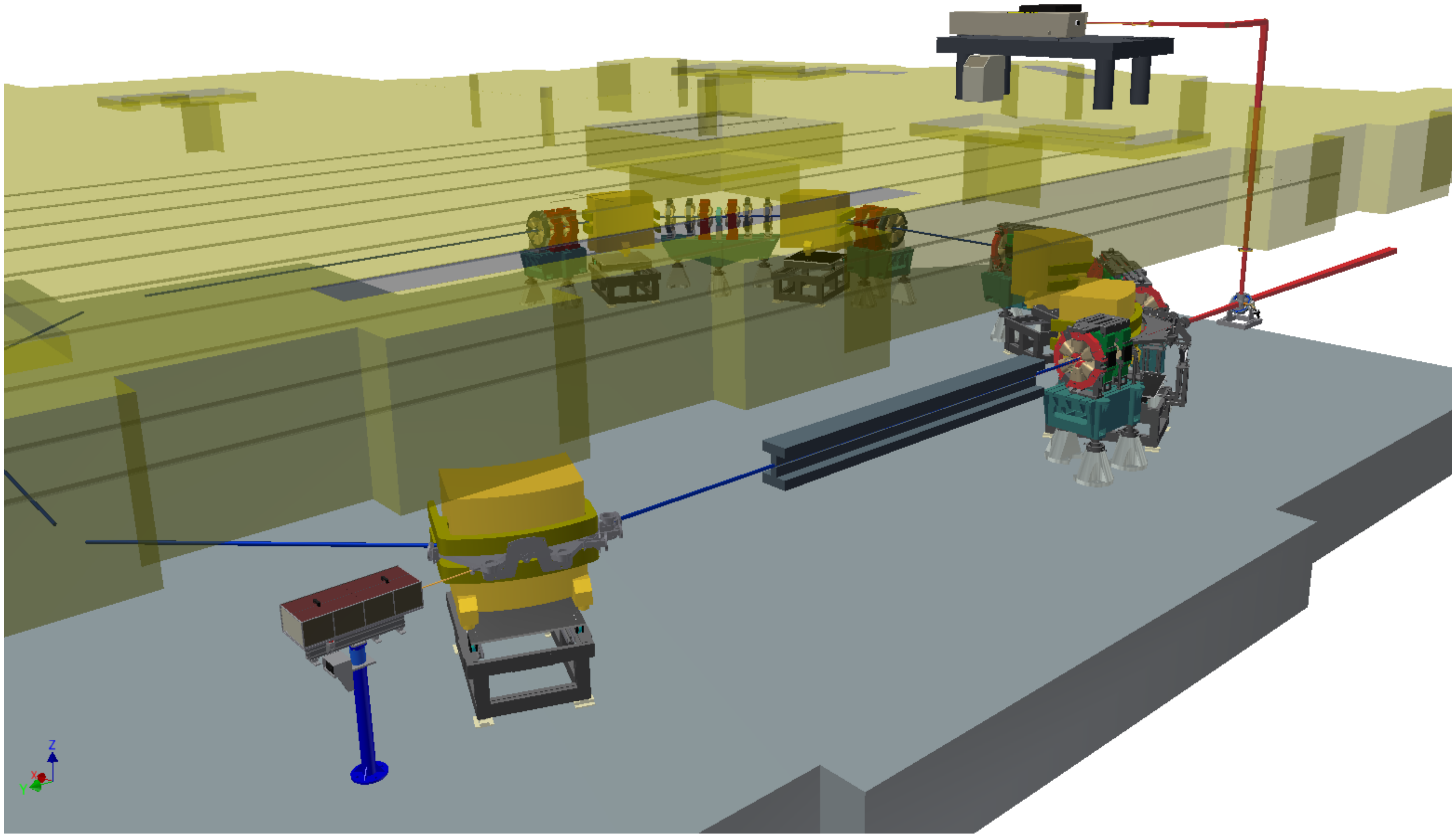
$C = 48\ \mathrm{m}$ $\alpha \approx -1.5 \times 10^{-5}$ $E = 250\ \mathrm{MeV}$



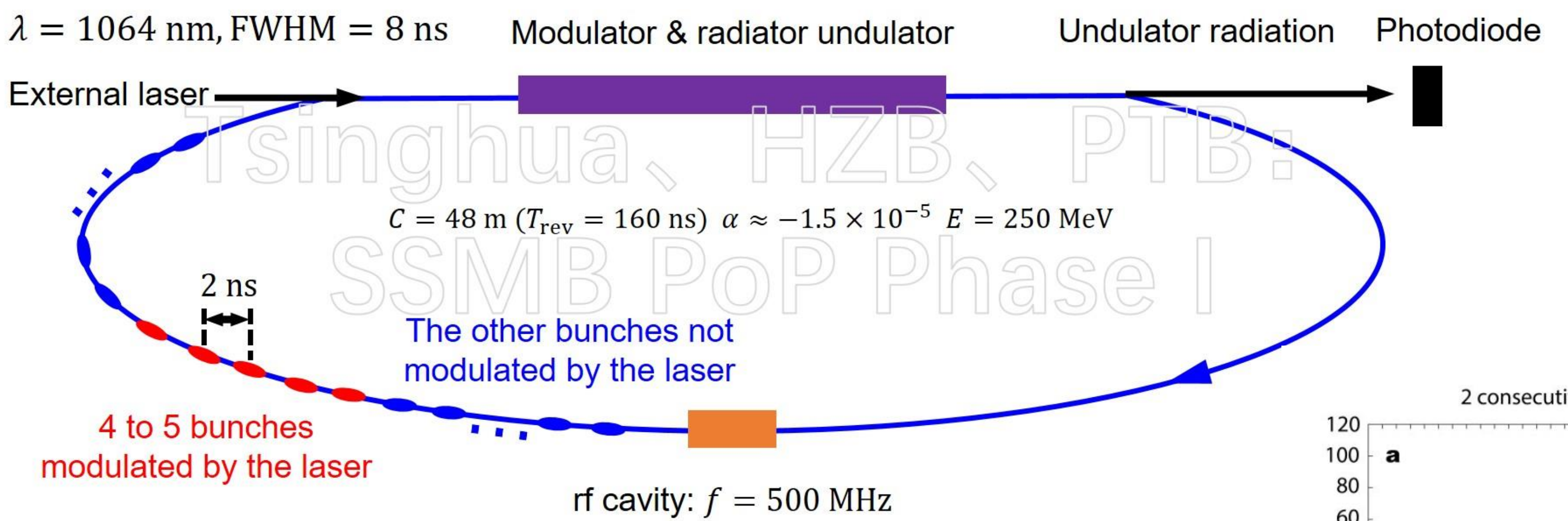
$\lambda = 1064\ \mathrm{nm}$

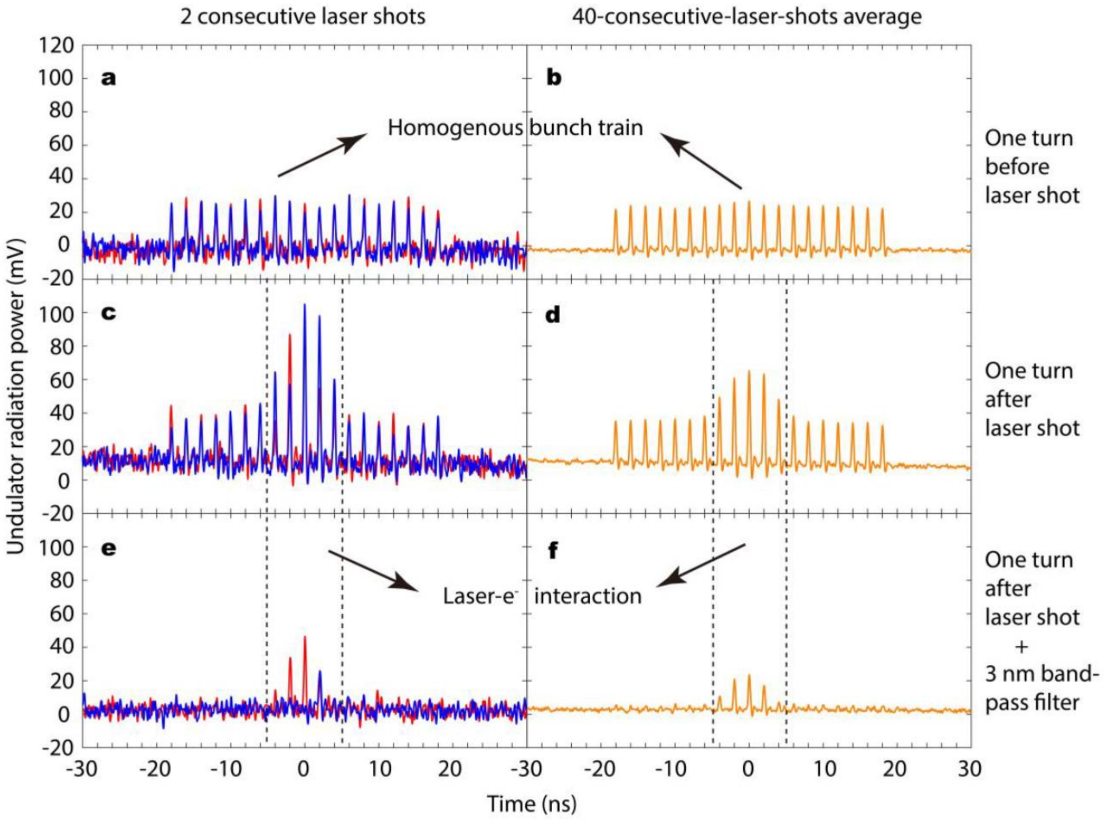
[7] X. Deng, A. Chao, J. Feikes, A. Hoehl, W. Huang, R. Klein, A. Kruschinski, J. Li, A. Matveenko, Y. Petenev, M. Ries, C. Tang and L. Yan, First Experimental Demonstration of the Mechanism of Steady-state Microbunching, under review.

established optical path for Compton Back Scattering measurements used for an improvised SSMB setup



Success after two years of efforts

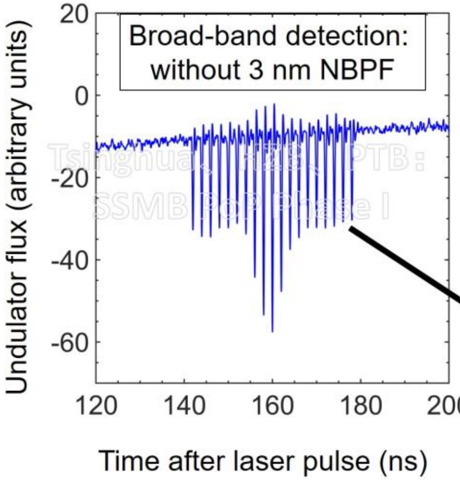




- The undulator radiation (2nd harmonic) intensity amplification of the **4 to 5 bunches in the middle of the bunch train** one turn after modulated by the laser indicates the formation of microbunches and generation of coherent radiation.
- One important feature of the coherent radiation: narrow-banded.

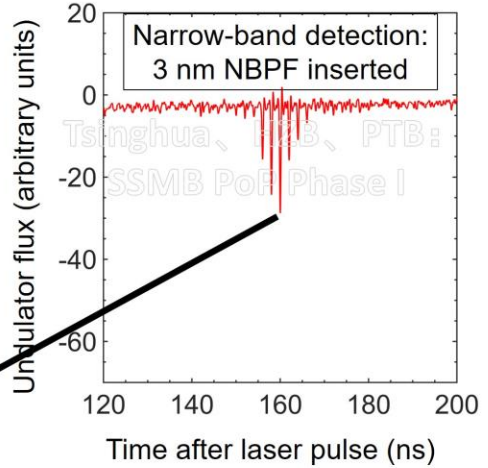
- The quadratic beam current scaling of the coherent radiation demonstrates unequivocally the formation of microbunching as well as its small band width
- The coherent signal comes from 2^{nd} harmonic radiation. 1. harmonic radiation is blocked together with the Laser light. **Fundamental mode is expected to have a much higher radiation power**

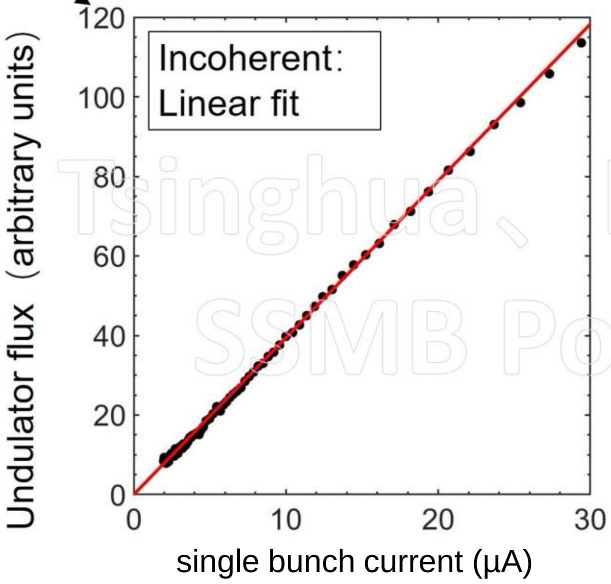
-> detection scheme for 1. harmonic component using pockelt cells to block the laser is in preparation

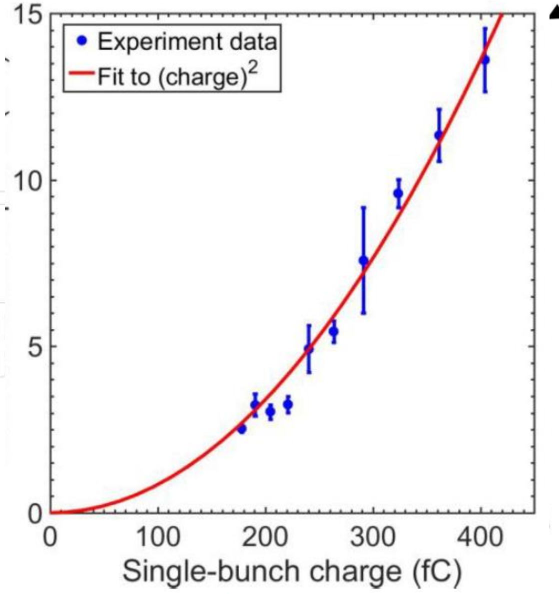


Broad-band incoherent radiation of usual bunch

Narrow-band coherent radiation of microbunches



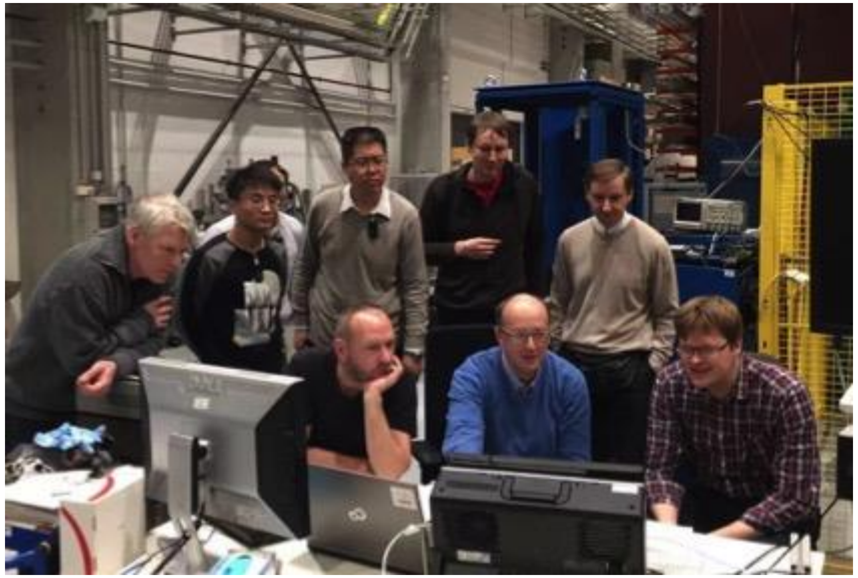


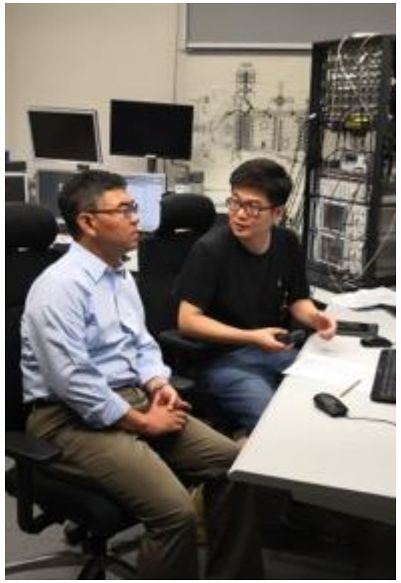


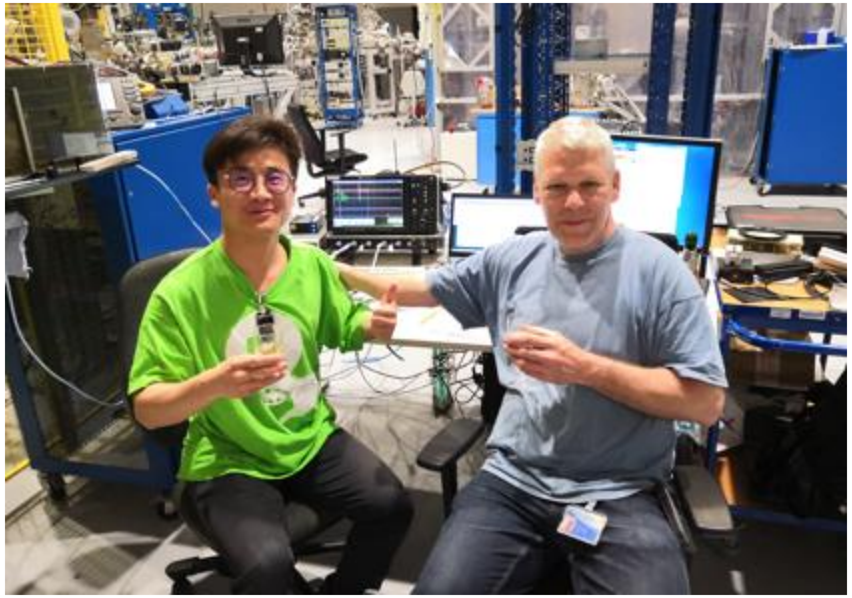
Significance of SSMB PoP Phase I

- Our PoP test is essentially different from the other single-pass microbunching experiments. The key point here is to demonstrate that in a touchy isochronous storage ring, a microbunched electron beam can stay microbunched with definitive microbunching phase.
- Once the one-turn microbunching phase is established with the electron beam stored stably in the required storage ring lattice, a multi-shot laser is expected to provide the microbunching bucket for 1000 turns in Phase-II using the same ring configuration but replace the single-shot laser by a 1000-shot laser.
- The Phase-I experiment demonstrates phase stabilization in the optical wavelength range, validating the scaling from RF buckets to optical microbuckets and microbunches.

Acknowledgement





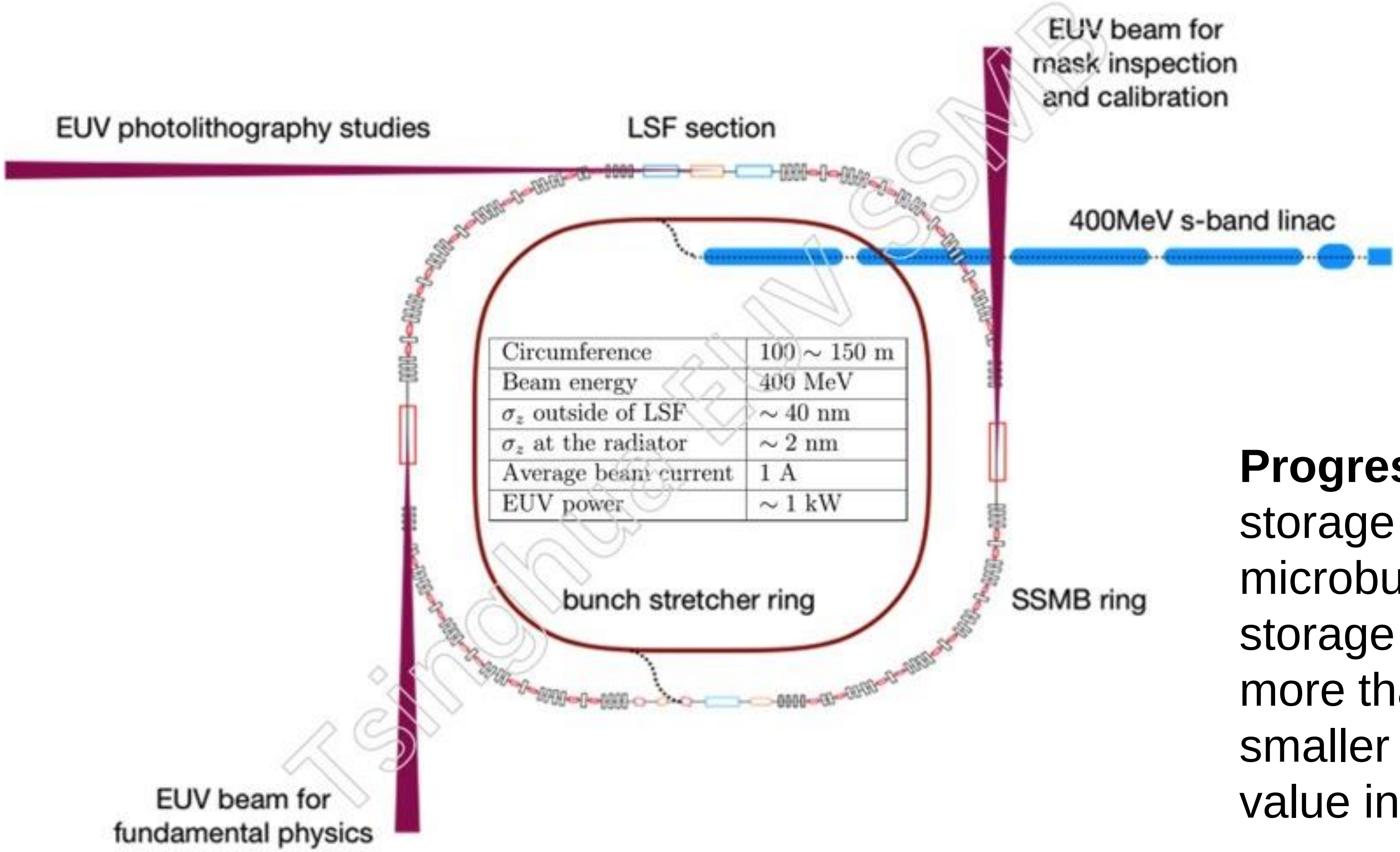


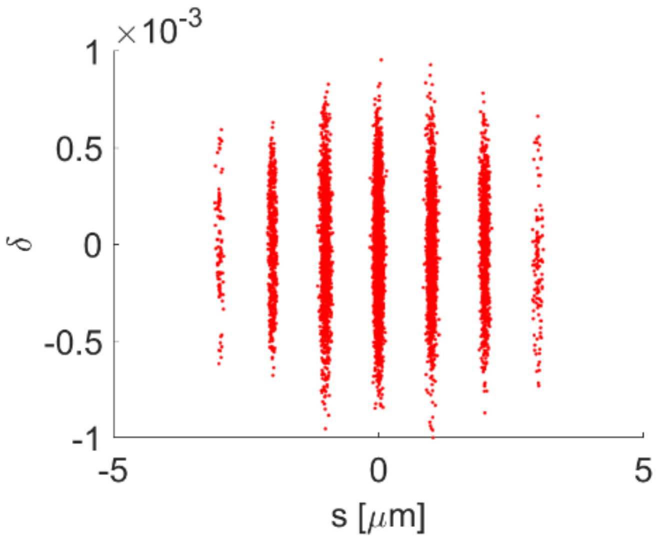
Phase-II (planned)

- Replace the single-shot laser by a 1000-shot laser, but use the same MLS ring lattice.
- Can test only a quasi-SSMB. Microbunch lifetime ~ 1000 turns. Full SSMB requires a dedicated ring and a CW laser.
- The SSMB Collaboration plans to launch Phase-II. Very unfortunately delayed by COVID19.

Future perspective: Dedicated SSMB storage ring near Bejing

- Envisioned Tsinghua strong focusing storage ring:





Progress on lattice design: stable storage of $\sigma_t \sim 0.1$ fs @ 400 MeV microbunches for the first time in a storage ring.[12] The bunch length is more than three orders of magnitude smaller than the present achievable value in storage rings.

[12] Z. Pan, et al., Low alpha storage ring design for steady-state microbunching to generate EUV radiation, under review.

Summary

- The Steady-State Microbunching in storage rings has the potential of starting a new era of accelerator photon science from THz, IR, to EUV.

- The mechanism of SSMB has been demonstrated experimentally in electron storage ring MLS. It is the first key advance of developing an SSMB high-power coherent radiation source.

- SSMB PoP Phase II is under preparation and will be conducted in the near future.

- Lattice design and technical components for a dedicated SSMB storage ring are ongoing, with good progress being made.