High-power EUV Light Source Based on Steady-state Microbunching Mechanism

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On behalf of the SSMB Collaboration

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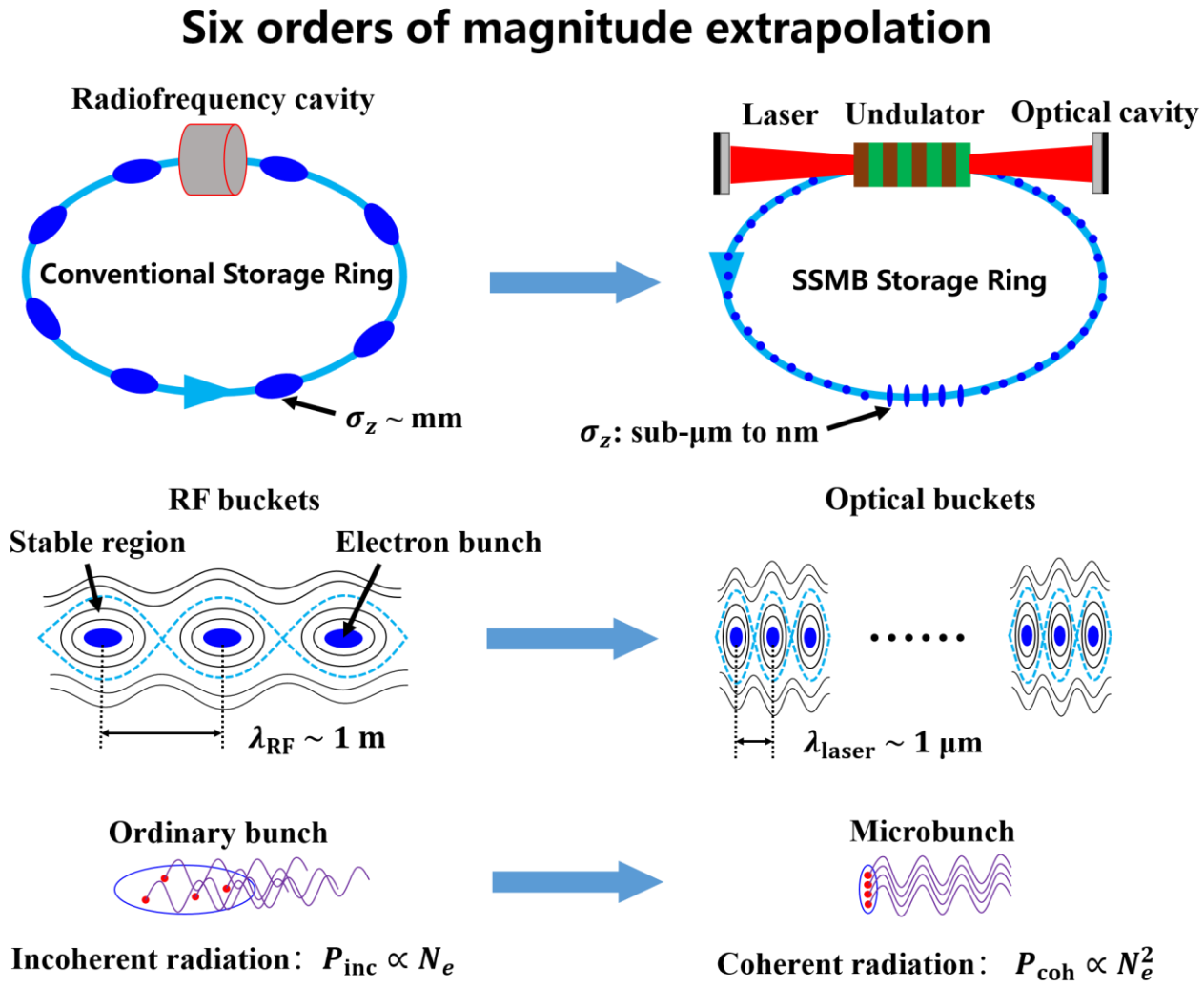
Steady-state Microbunching (SSMB)[1]: electron storage ring from radiofrequency-focusing to laser-focusing

- Replace the conventional RF cavity in an electron storage ring by laser modulator.
- Two key ingredients:
  - **microbunching for high peak power temporally coherent radiation**
  - **steady state for high repetition rate.**
- Two features combined to support a high-average-power, high-repetition-rate or continuous-wave and narrow-band radiation, at wavelengths ranging from the THz region to the EUV.



[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).

SSMB EUV Source for Lithography

- **High average power**: the power aimed is > 1 kW per tool, each facility should be able to incorporate multiple tools;
- **Narrow-banded and collimated**: the radiation spectrum bandwidth is < 2% and has a well collimated angular spread < 0.1 mrad, which should help to reduce the number of reflection mirrors and thus increase the EUV power transport efficiency;
- **Continuous wave output**: the temporal structure of the radiation is truly CW, this minimizes the chip damage problem;
- **Clean radiation**: the radiation is clean and carries no debris, so that mirrors do not get contaminated and do not require frequent replacements;
- **Good scalability**: $\lambda_r = \frac{(1+K^2/2)}{2\gamma^2}\lambda_u$, easy to scale to shorter wavelength. Offer possibility for the EUVL Extension - Blue-X.

SSMB Collaboration

- An initial task force has been established at Tsinghua University, in collaboration with researchers from China, Germany, the USA, and elsewhere, to promote SSMB research with the goal of developing an **EUV SSMB storage ring**.

- Three main tasks:
  1. Proof-of-principle (PoP) experiment
  2. Lattice design for EUV SSMB ring
  3. Resolve related technical issues

Some Literature Review for Interested Readers

➢ SSMB Scenarios:

- D. F. Ratner and A. W. Chao, Steady-State Microbunching in a Storage Ring for Generating Coherent Radiation, Phys. Rev. Lett. 105, 154801 (2010).
- A. Chao, et al., High Power Radiation Sources using the Steady-state Microbunching Mechanism, in Proceedings of IPAC16, Busan, Korea, 2016.

➢ SSMB Collaboration:

- C. Tang, et al., An Overview of the Progress on SSMB, in Proceedings of FLS18, Shanghai, China, 2018.
- A. Chao, et al., A Compact High-power Radiation Source Based on Steady-state Microbunching Mechanism, SLAC Technical Report No. SLAC-PUB-17241, 2018.

➢ SSMB proof-of-principle experiment:

- 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.
- C. Tang, First Experimental Demonstration of the Mechanism of Steady-state Microbunching, Talk at IPAC2020.
- A. Chao, Steady-State Microbunching in Storage Rings: a new source of radiation, Talk at BESSY Matter and Technology Annual Meeting 2020.
- J. Feikes, Steady State Microbunching in Storage Rings – Proof of Principle Results at MLS, Talk at LEAPS FIRST WG2 Workshop 2020.

➢ Lattice design for EUV SSMB ring:

- 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.
- T. Rui, et al., Strong Focusing Lattice Design for SSMB, in Proceedings of FLS18, Shanghai, China, 2018.
- C. Li, et al., Lattice design for the reversible SSMB, in Proceedings of IPAC19, Melbourne, Australia, 2019.

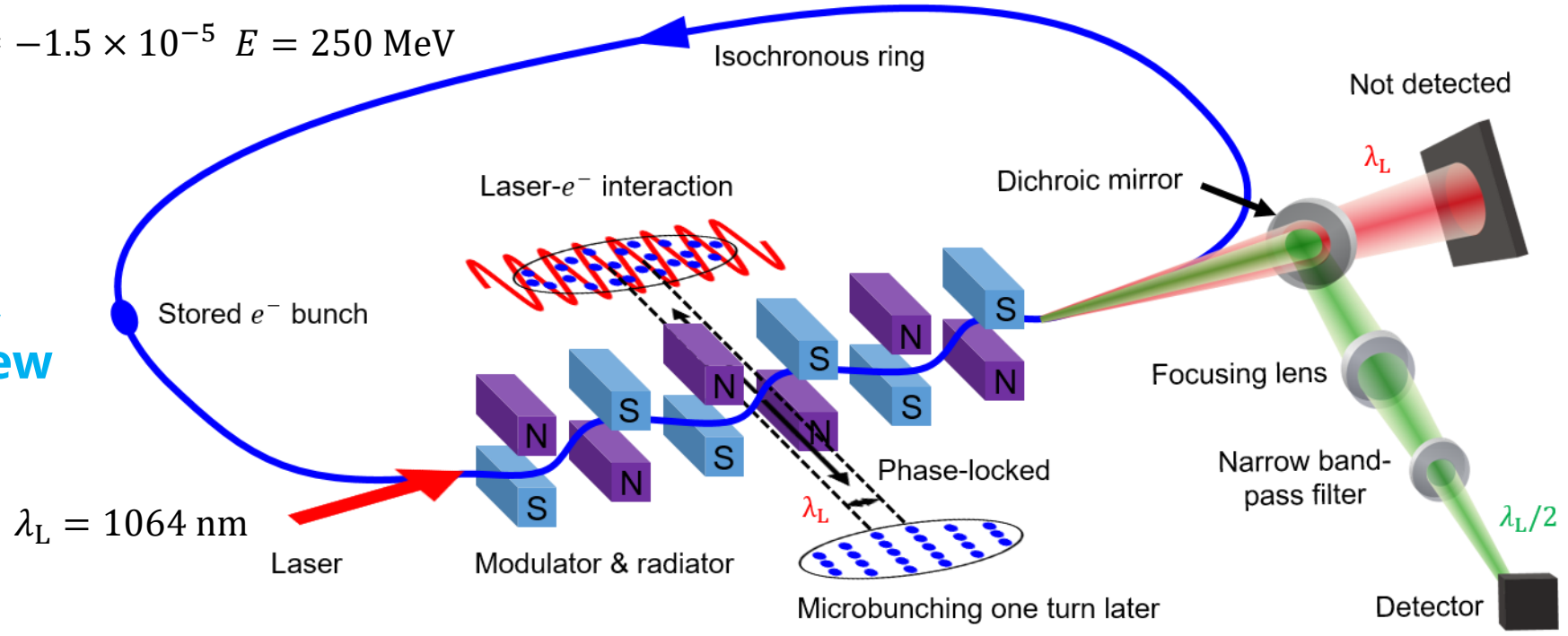
➢ SSMB beam dynamics study:

- Deng, X. J., Chao, A. W., Feikes, J., Huang, W. H., Ries, M., & Tang, C. X. Single-particle dynamics of microbunching. Phys. Rev. Accel. Beams 23, 044002 (2020).

SSMB PoP Experiment[2]: a collaboration work of Tsinghua, HZB and PTB at the MLS

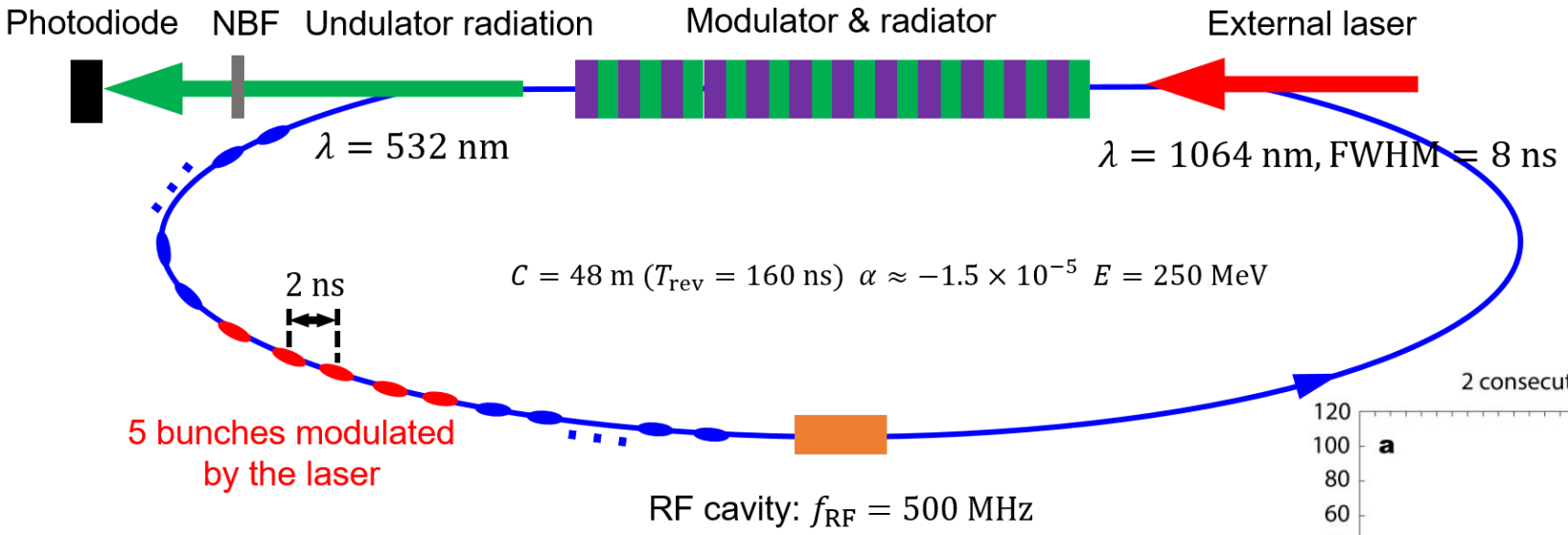
Electron beam is stored in an isochronous configuration at MLS. The beam is modulated by a single-shot laser. The laser is turned off, the beam makes one turn and returns to the modulator, which now serves as the radiator in the next turn. **The ring must have a high precision and stability to store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

Submitted, under review



[2] 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.

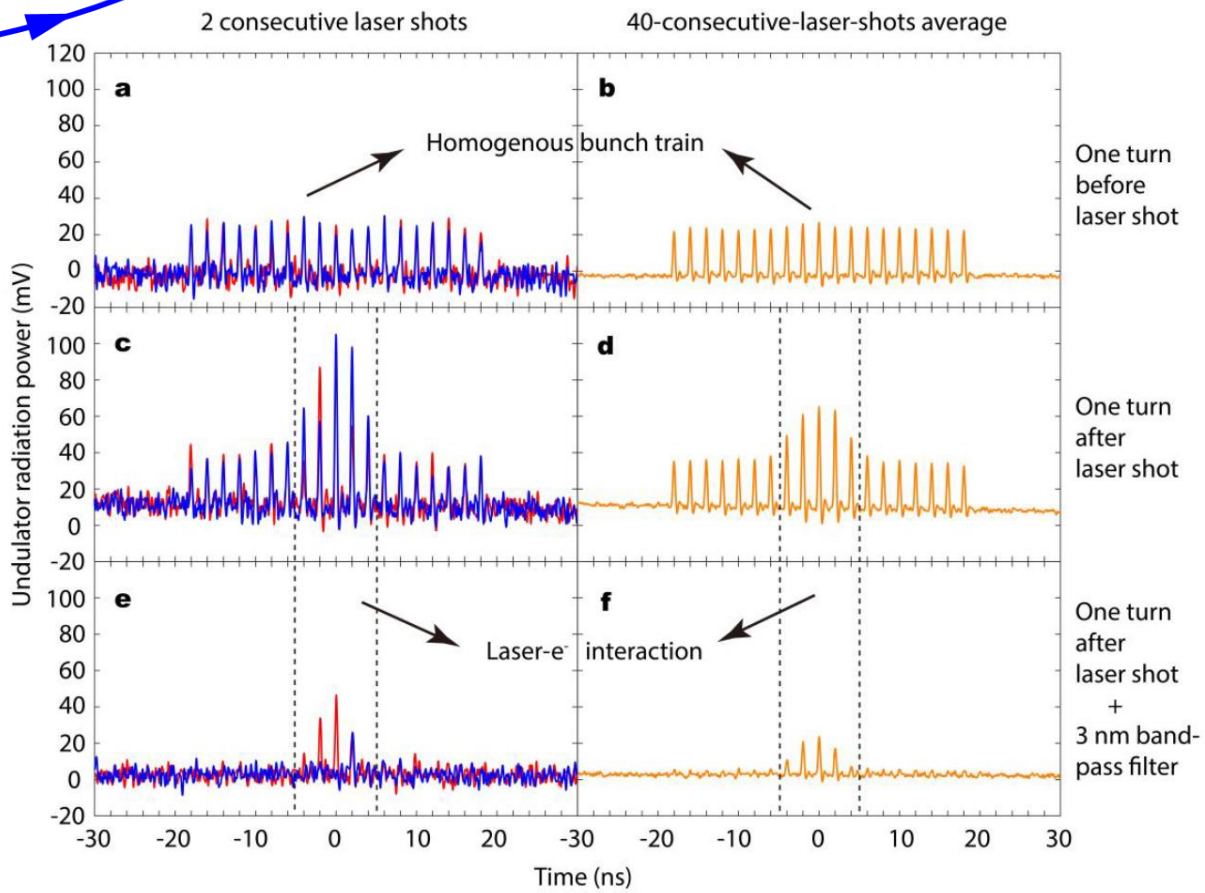
Success after Two Years of Efforts[2]



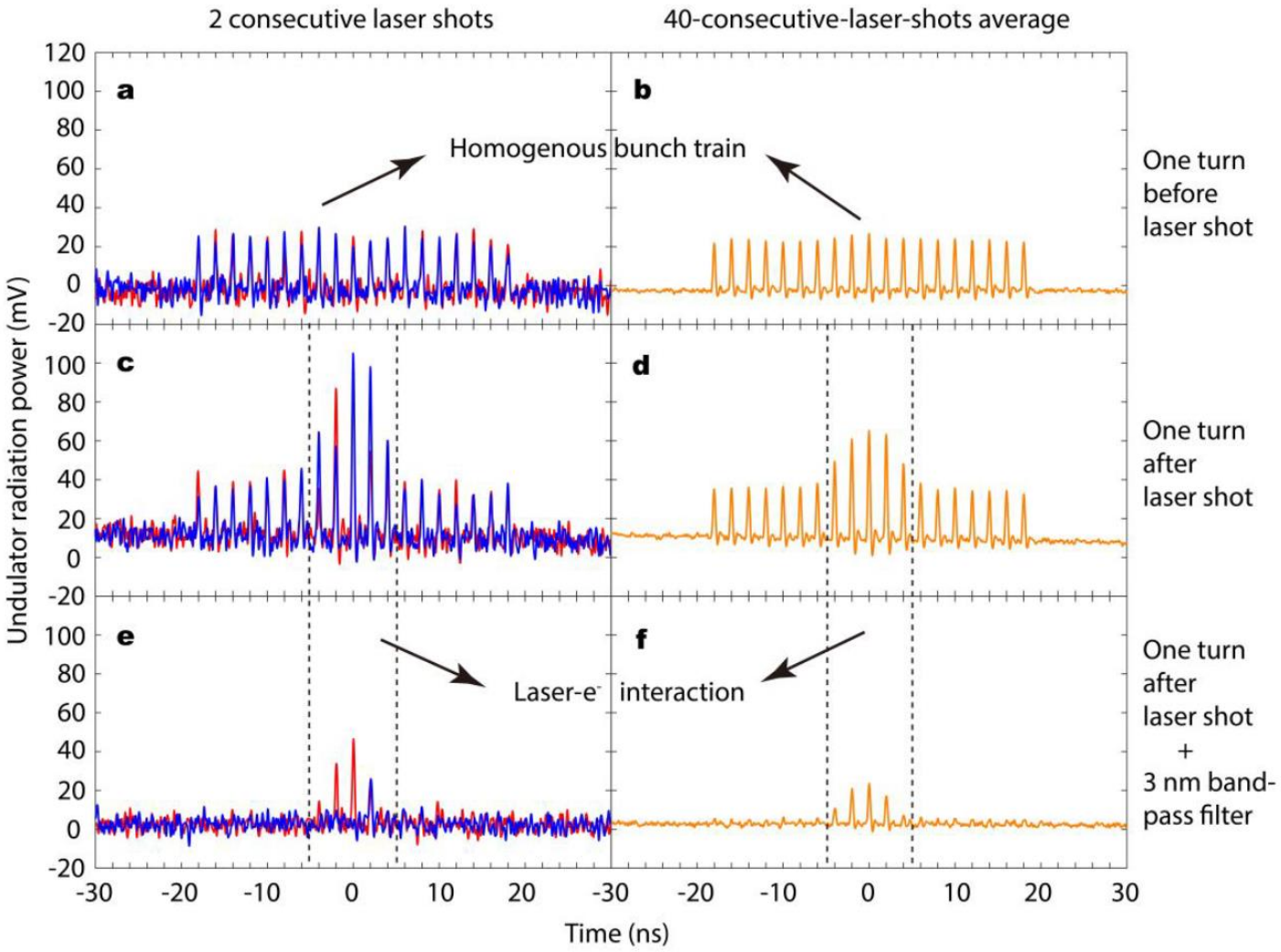
[2] X. Deng, A. Chao, J. Feikes, A. Hoehl, W. Huang, R. Klein, A. Kruschinski, J. Li, A. Matveenko, Y. Petenev, M. Ries, C. Tang and L. Yan, First Experimental Demonstration of the Mechanism of Steady-state Microbunching, under review.

Submitted, under review

- The undulator radiation intensity amplification of the **5 bunches in the middle of the bunch train** one turn after laser modulation indicates the formation of microbunches and generation of coherent radiation.
- One important feature of the coherent radiation: **narrow-banded**.



The **quadratic bunch charge dependence**, together with the **narrowband feature** of the coherent radiation, **demonstrates unequivocally the microbunching formation**.[2]



[2] 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.

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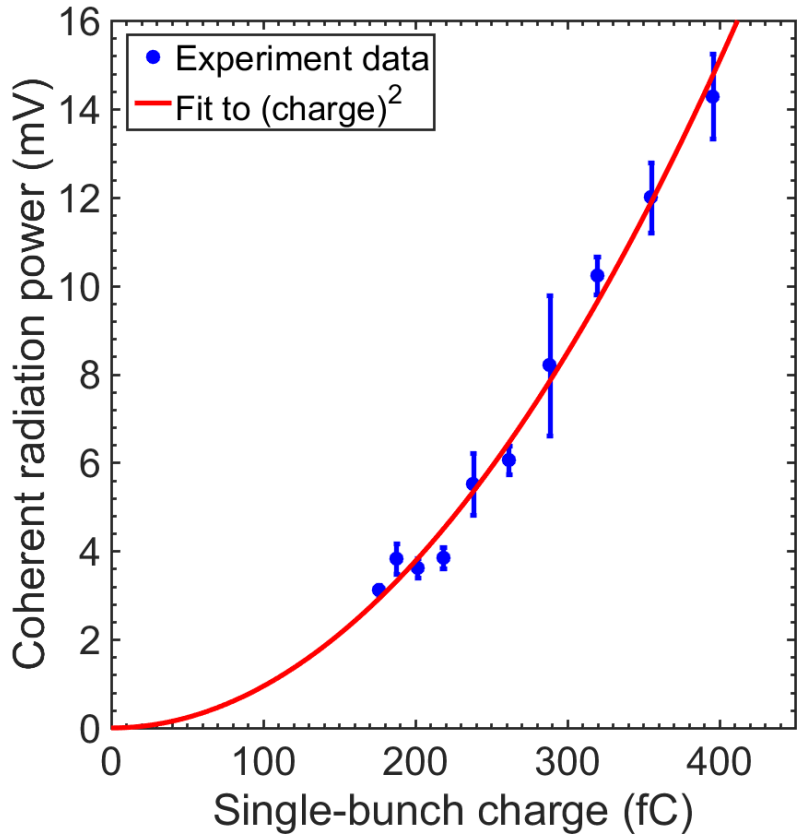


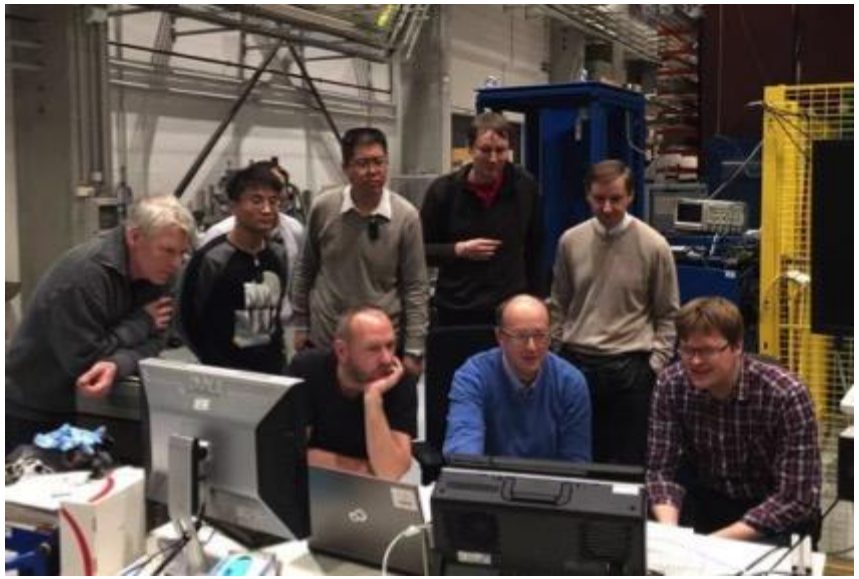
Significance of the SSMB PoP Experiment

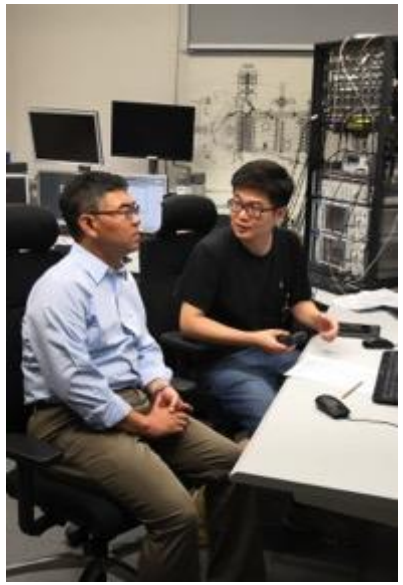
- The returning to the same location of modulation to microbunch and radiate has the significance, and in fact the requirement, that **the storage ring must be capable of storing a microbunched beam turn after turn.**

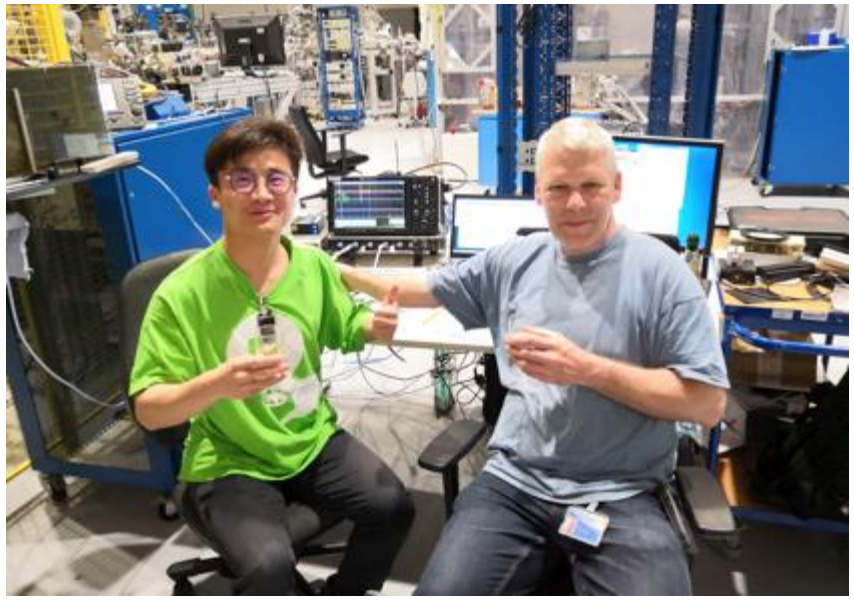
- The success of the demonstration manifests the robustness of theoretical models and the viability of accelerator technology to **encourage SSMB as a user facility.** The achieved optical longitudinal focusing in a storage ring represents **an important advancement in accelerator physics.**

- **It is the first key advance of developing an SSMB-based high-power EUV light source.**

Two Years Efforts Condensed in Two Slides

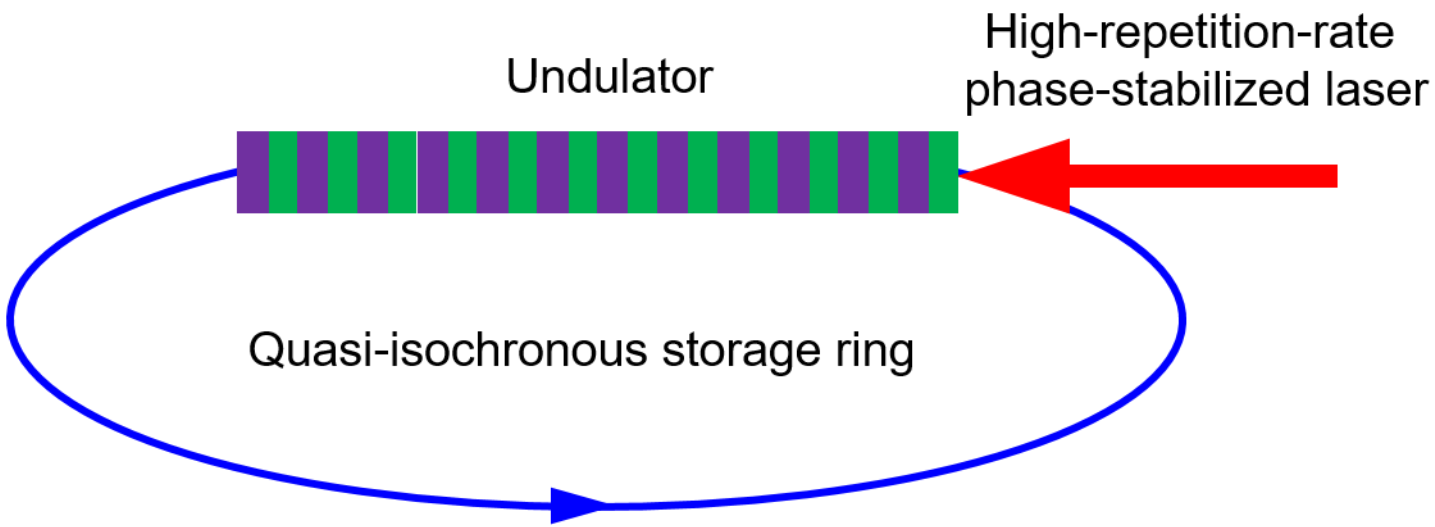


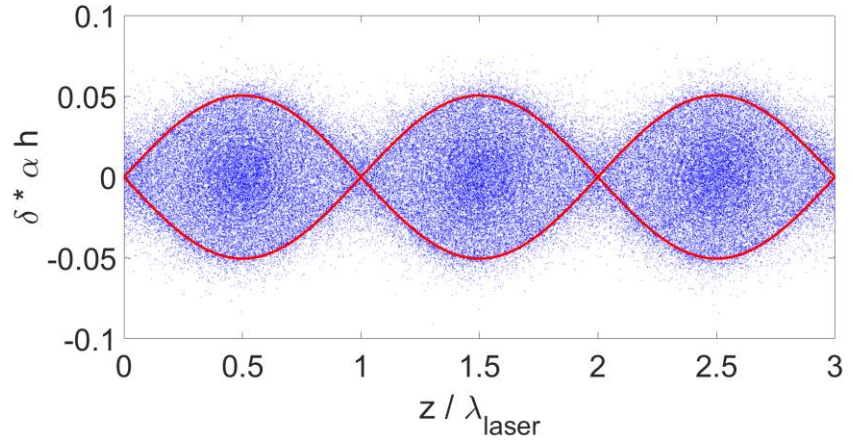


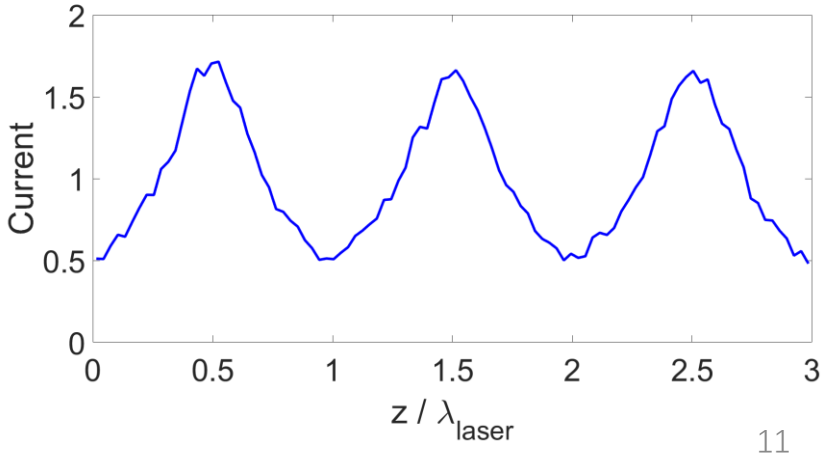


Future Perspective: PoP Phase II planned at the MLS

- With the laser-electron phase locked on a turn-by-turn basis, the next step is an establishment of stable microbuckets and **maintaining of the microbunching for multiple turns**.



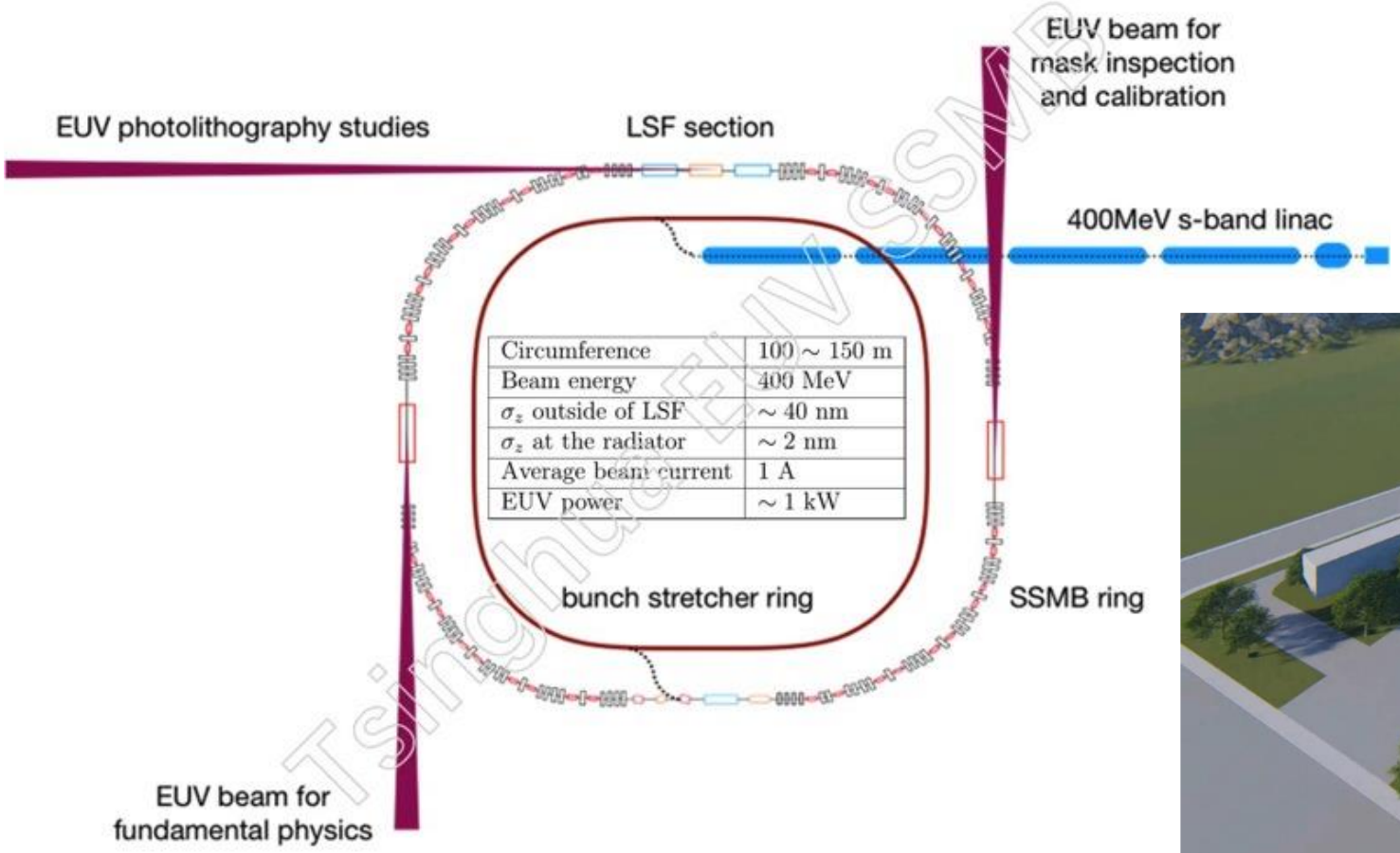




- It is to be accomplished by using a **high-repetition-rate phase-stabilized laser to interact with the electron beam turn by turn**.

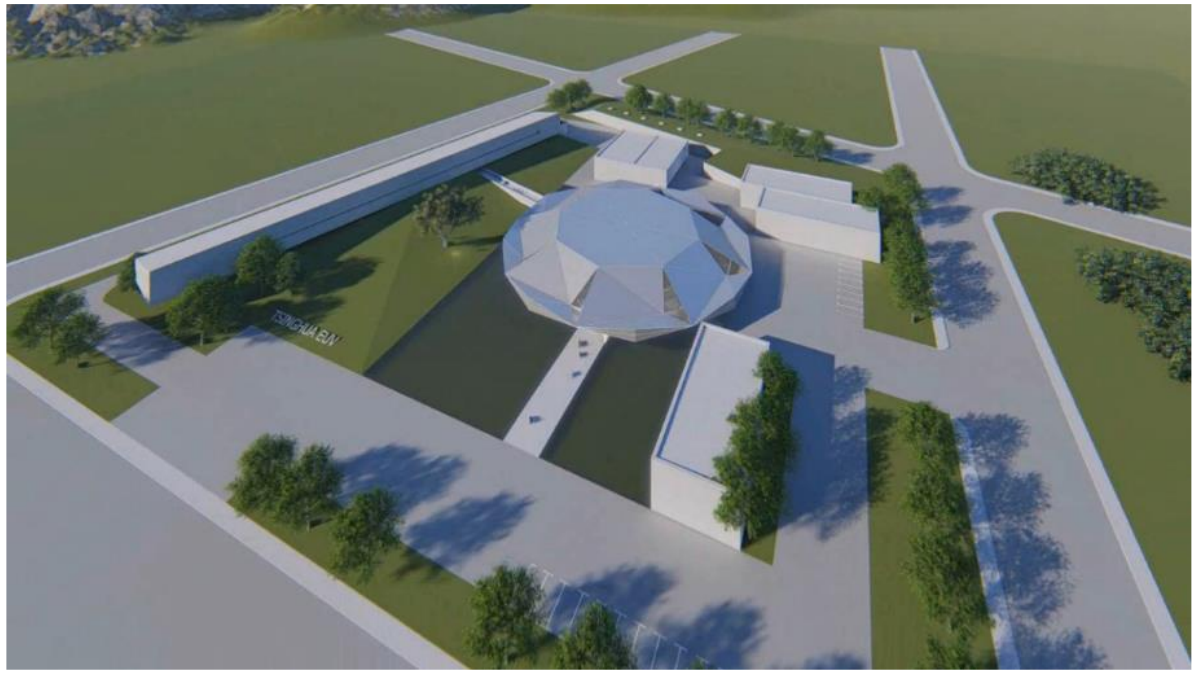
Future Perspective: EUV SSMB storage ring

- Envisioned Tsinghua EUV SSMB storage ring:



Circumference	100 ~ 150 m
Beam energy	400 MeV
σ_z outside of LSF	~ 40 nm
σ_z at the radiator	~ 2 nm
Average beam current	1 A
EUV power	~ 1 kW

Progress on lattice design: first-stage lattice design of EUV SSMB ring succeeded.[3] **The steadily stored bunch is more than four orders of magnitude shorter than the present typical bunches in storage rings.**



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

Summary

- **SSMB** is a promising **high-power EUV radiation scheme** and has potential advantages for applications in EUVL.
- **The mechanism of SSMB has been demonstrated the first time worldwide in an electron storage ring**. It is the first key advance of developing an SSMB high-power EUV radiation source, which has the potential of starting a new era of accelerator photon science and offer new possibilities for EUV lithography light source.
- **SSMB PoP Experiment Phase II** is under preparation and will be conducted at the MLS in the near future.
- Magnet lattice design for envisioned **Tsinghua EUV SSMB storage ring** is ongoing, with very good progress achieved.

Acknowledgement

- Thank the SSMB Proof-or-principle Experiment Group, especially our colleagues of HZB and PTB (Berlin), for the efforts in the past two years devoted to the SSMB PoP experiment.

- SSMB PoP Experiment Group:
  - Tsinghua University: Alex Chao[1], Xiujie Deng, Wenhui Huang, Chuanxiang Tang*, Lixin Yan
  - Helmholtz-Zentrum Berlin (HZB): Jörg Feikes†, Arnold Kruschinski, Ji Li, Aleksandr Matveenko, Yuriy Petenev, Markus Ries
  - Physikalisch-Technische Bundesanstalt (PTB): Arne Hoehl, Roman Klein

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