Progress of Tsinghua SSMB EUV Light Source Development

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On behalf of the SSMB Collaboration

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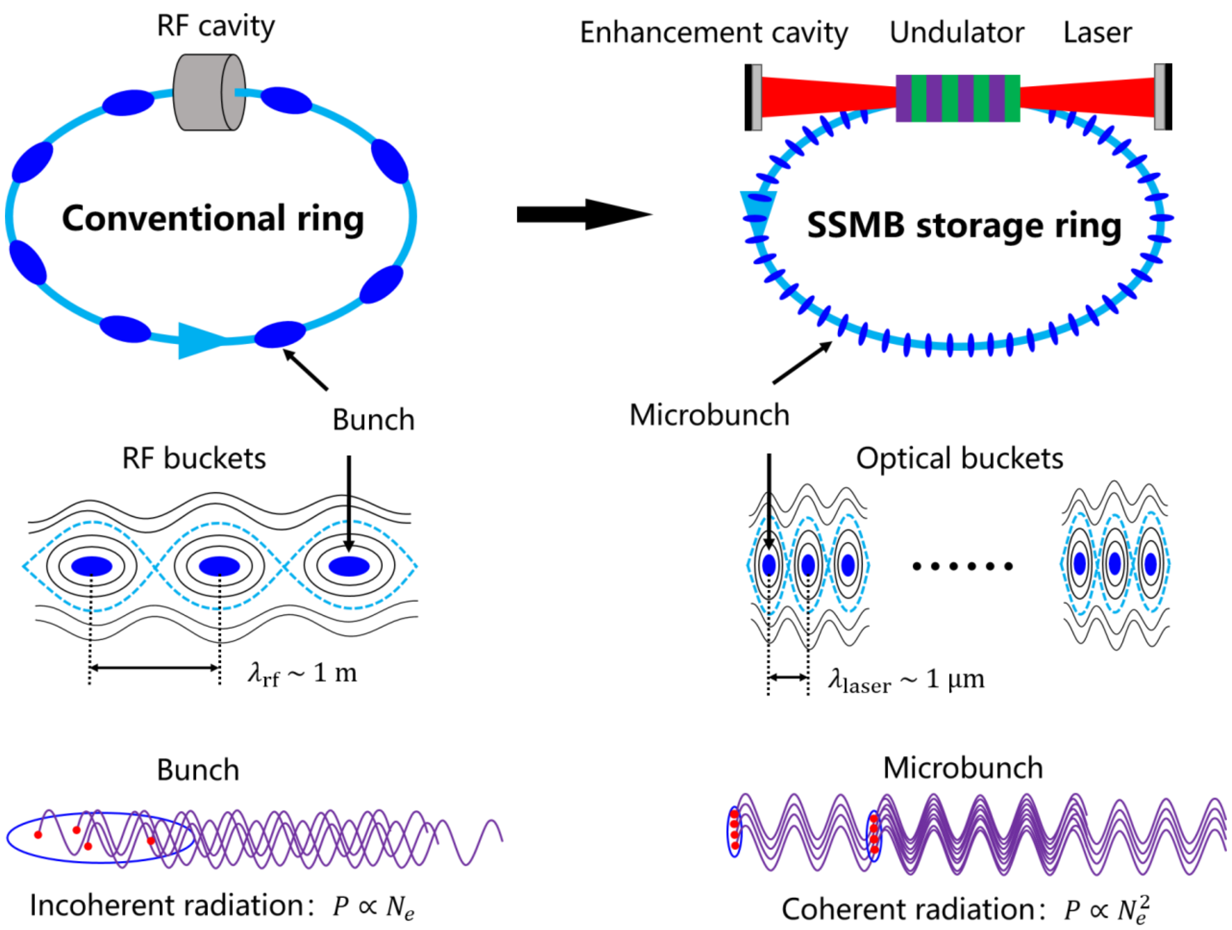
Steady-state Microbunching (SSMB)[1]: from microwave to laser

- **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 high-average-power radiation, at wavelengths ranging from the THz region to the EUV.**

6 orders of magnitude extrapolation



[1] D. F. Ratner and A. W. Chao, 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;
- **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.

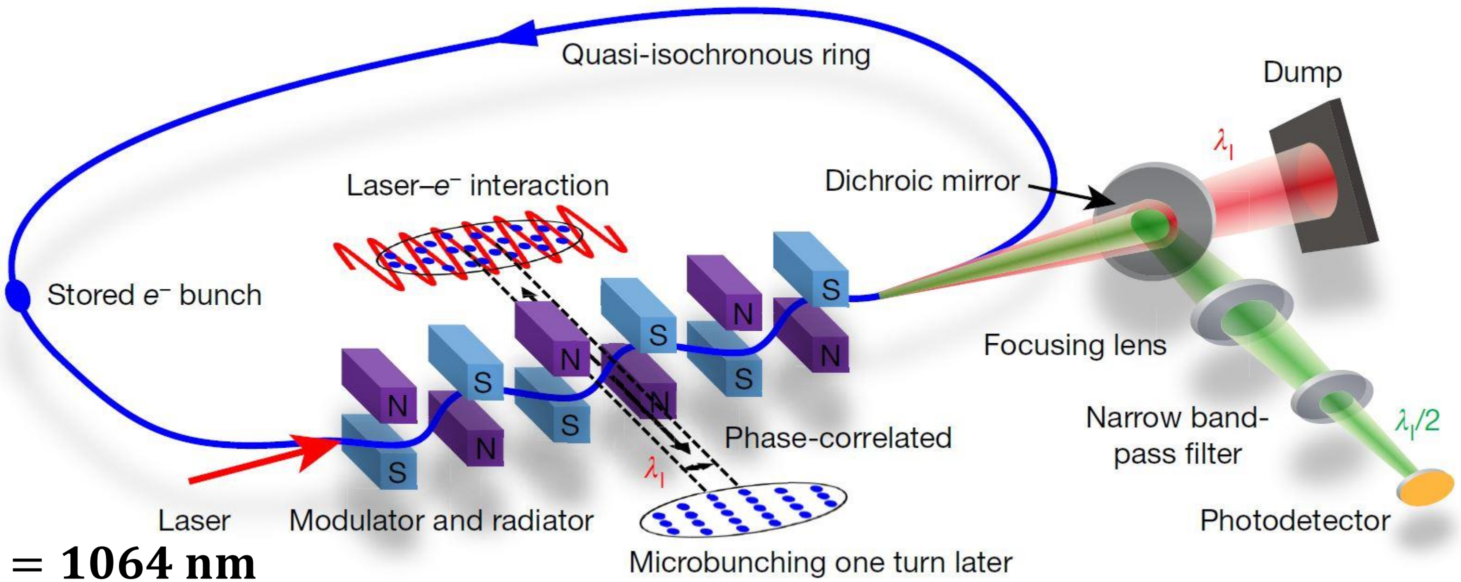
SSMB Collaboration

- **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**

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

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



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

Article

Experimental demonstration of the mechanism of steady-state microbunching

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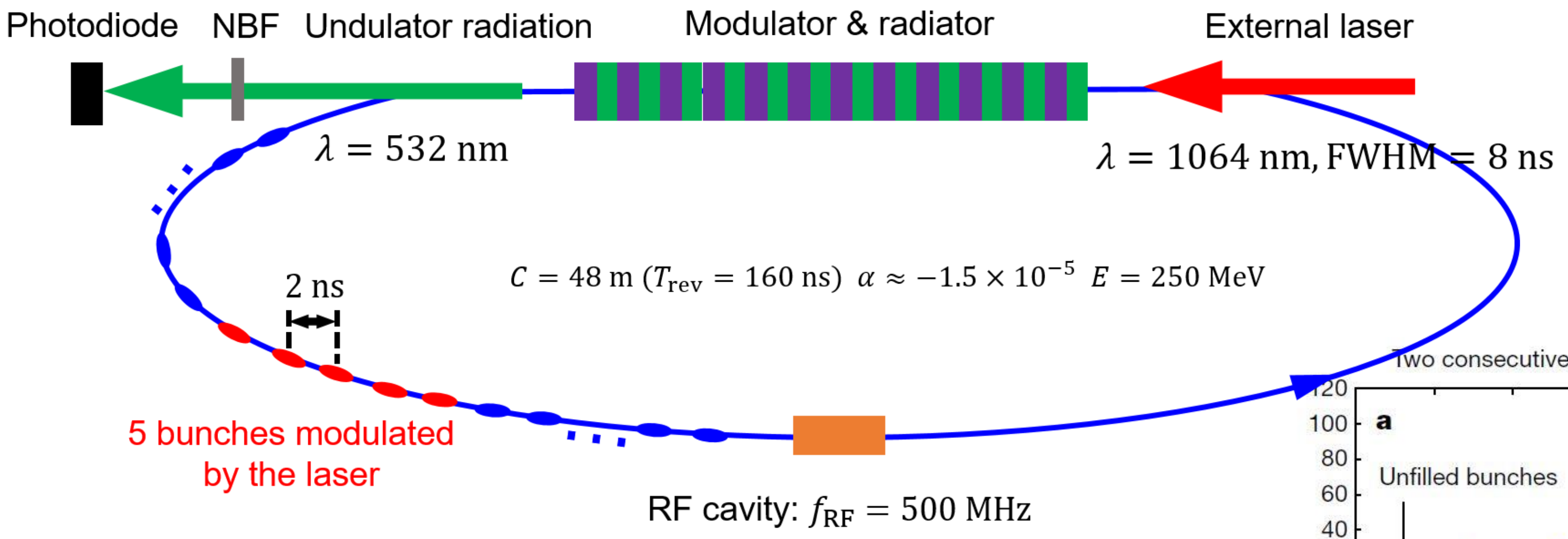
The use of particle accelerators as photon sources has enabled advances in science and technology[1]. Currently the workhorses of such sources are storage-ring-based synchrotron radiation facilities[2–4] and linear-accelerator-based free-electron lasers[5–14]. Synchrotron radiation facilities deliver photons with high repetition rates but relatively low power, owing to their temporally incoherent nature. Free-electron lasers produce radiation with high peak brightness, but their repetition rate is limited by the driving sources. The steady-state microbunching[15–22] (SSMB) mechanism has been proposed to generate high-repetition, high-power radiation at wavelengths ranging from the terahertz scale to the extreme ultraviolet. This is accomplished by using microbunching-enabled multiparticle coherent enhancement of the radiation in an electron storage ring on a steady-state turn-by-turn basis. A crucial step in unveiling the potential of SSMB as a future photon source is the demonstration of its mechanism in a real machine. Here we report an experimental demonstration of the SSMB mechanism. We show that electron bunches stored in a quasi-isochronous ring can yield sub-micrometre microbunching and coherent radiation, one complete revolution after energy modulation induced by a 1,064-nanometre-wavelength laser. Our results verify that the optical phases of electrons can be correlated turn by turn at a precision of sub-laser wavelengths. On the basis of this phase correlation, we expect that SSMB will be realized by applying a phase-locked laser that interacts with the electrons turn by turn. This demonstration represents a milestone towards the implementation of an SSMB-based high-repetition, high-power photon source.

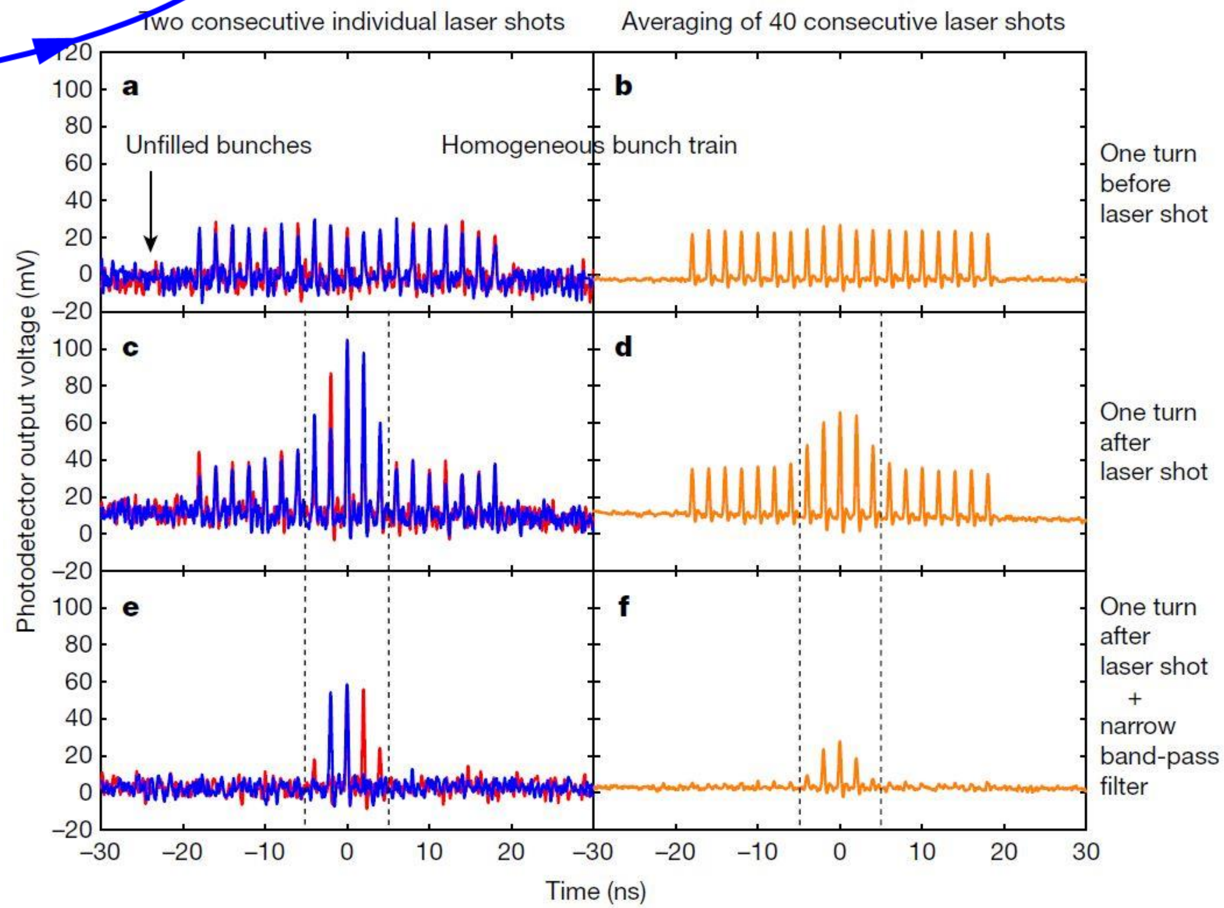
X. Deng, et al., Nature 590, 576–579 (2021).

[2] X. Deng, et al., Experimental Demonstration of the Mechanism of Steady-state Microbunching, *Nature* 590, 576–579 (2021).

Experimental Results

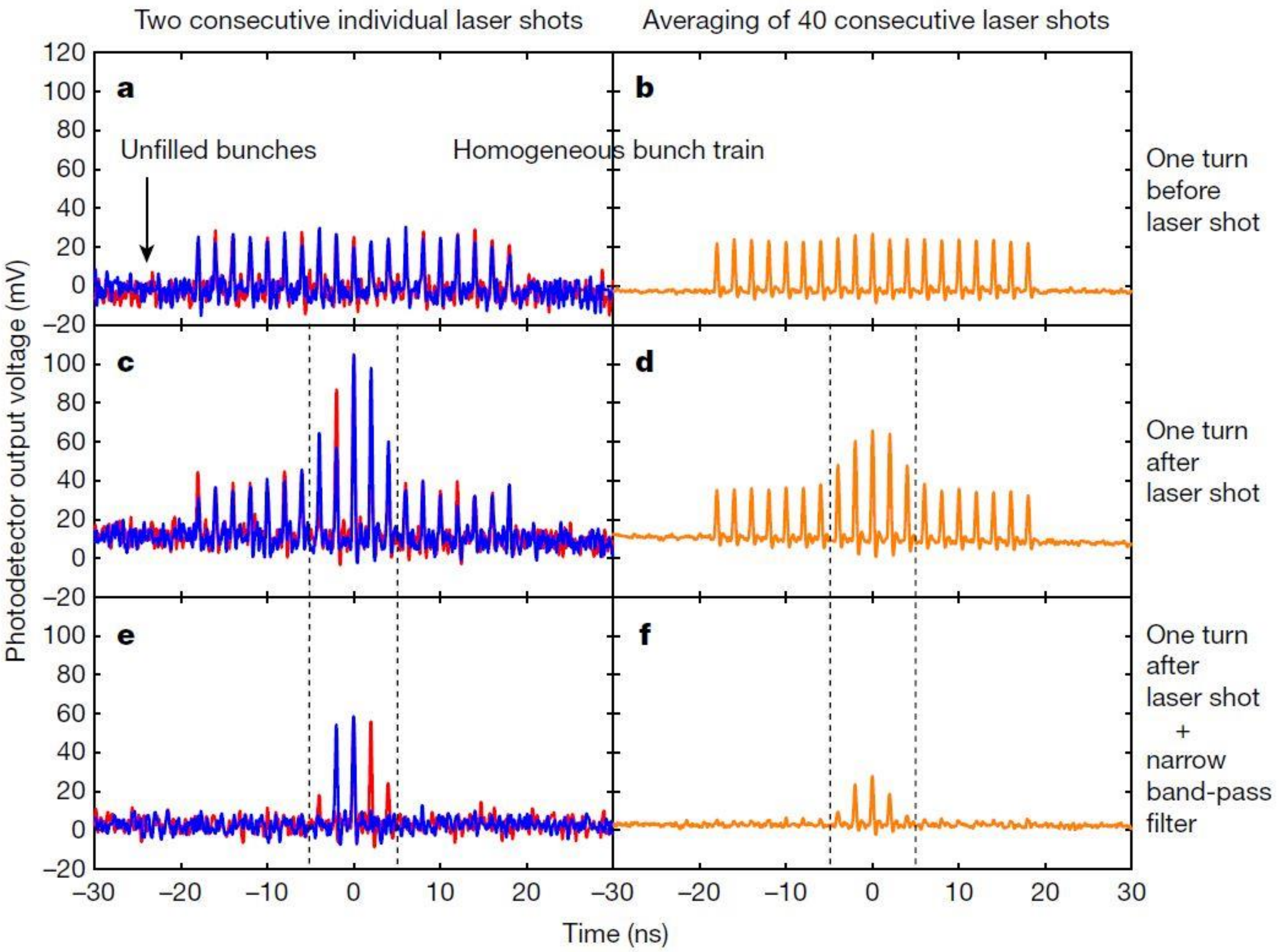


Nature 590, 576–579 (2021)



- **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 the microbunching formation



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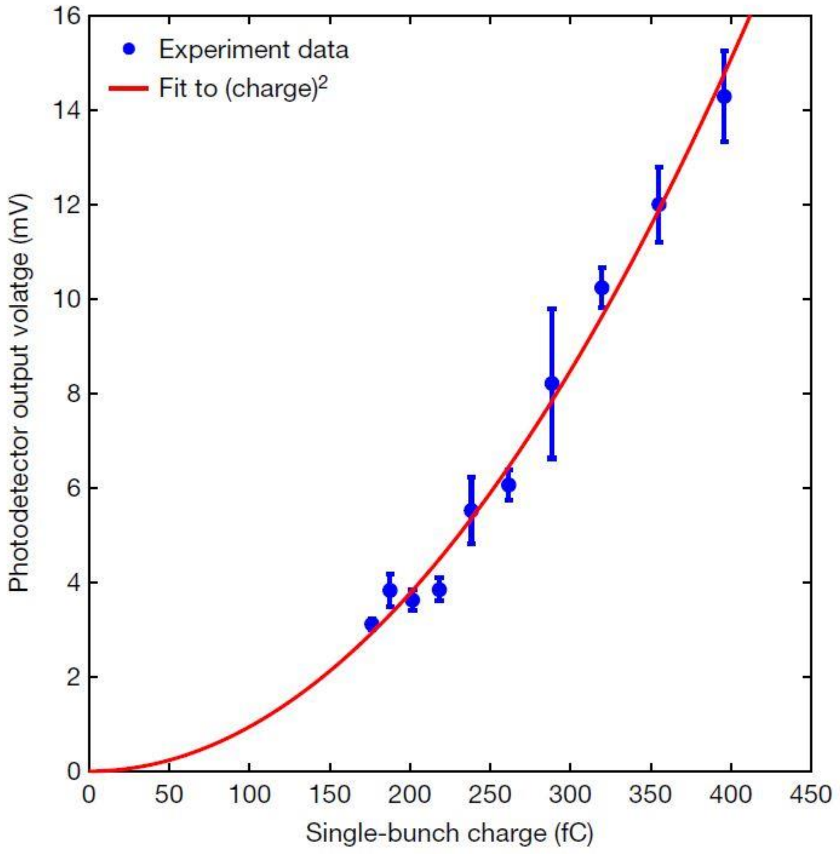
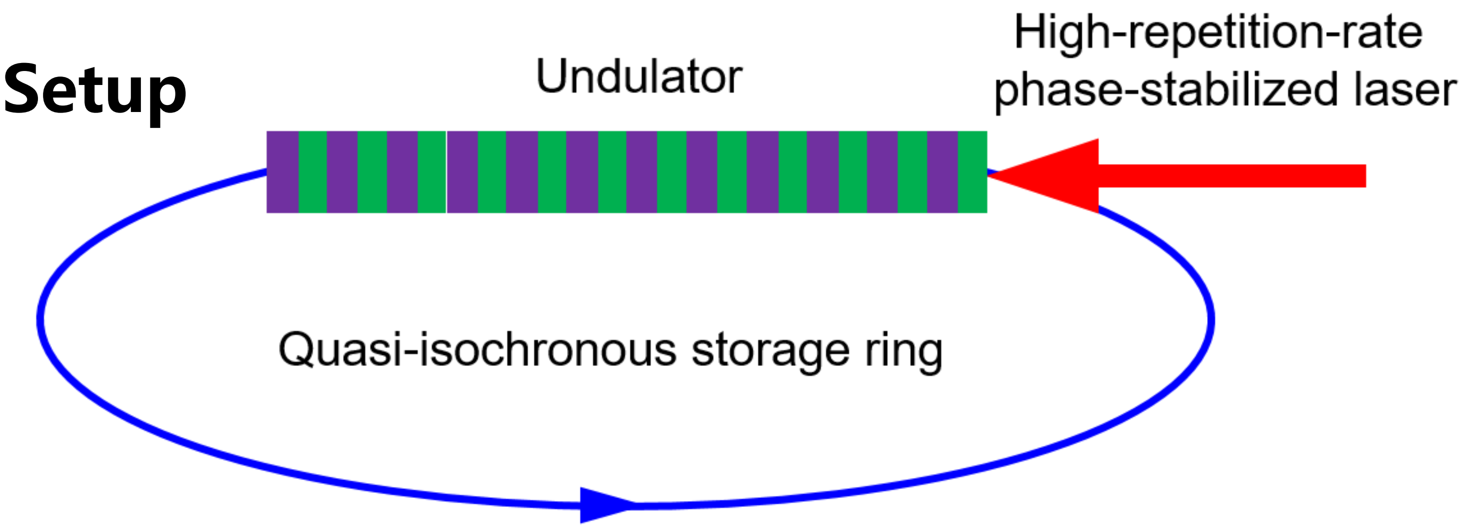
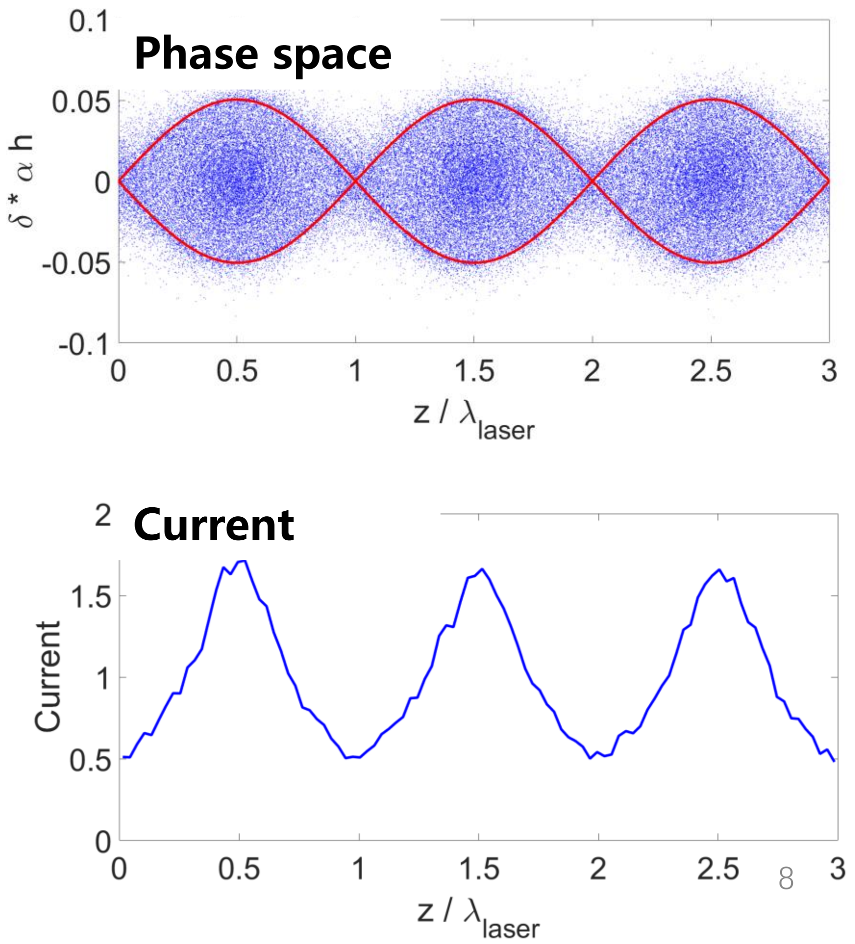


Future Perspective: PoP Phase II at the MLS

- **On the basis of phase I, the next step is to sustain the microbunching for multiple (~1000) turns to reach a quasi-steady state, by replacing the laser used in Phase I with a high-repetition phase-locked laser**

Setup

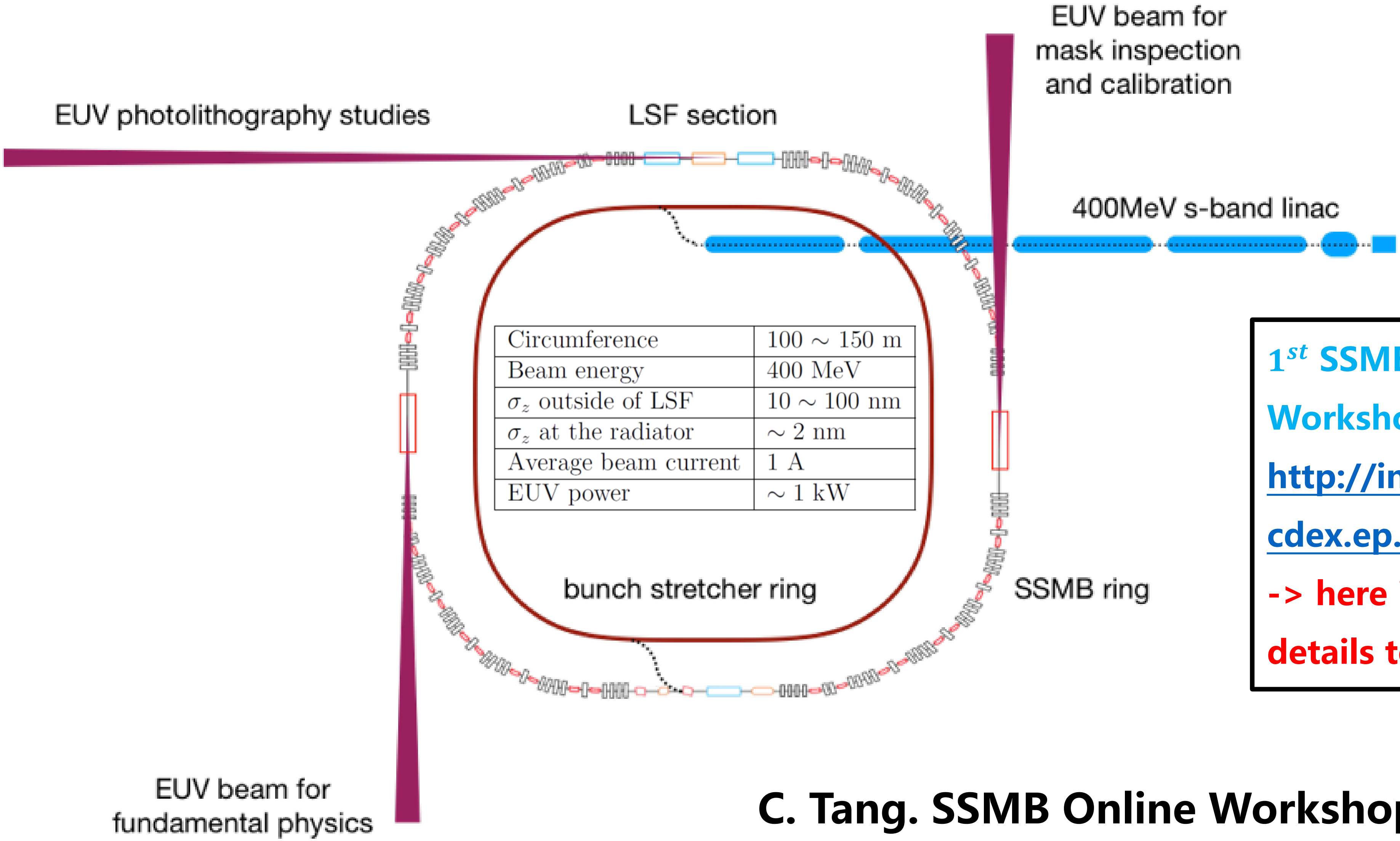




- **Dedicated laser system development completed**
- **Hopefully the experiment can be launched in the second half of this year**

Future Perspective: Tsinghua EUV SSMB Ring

- **Status:** **under in-depth study and trying to get fund**



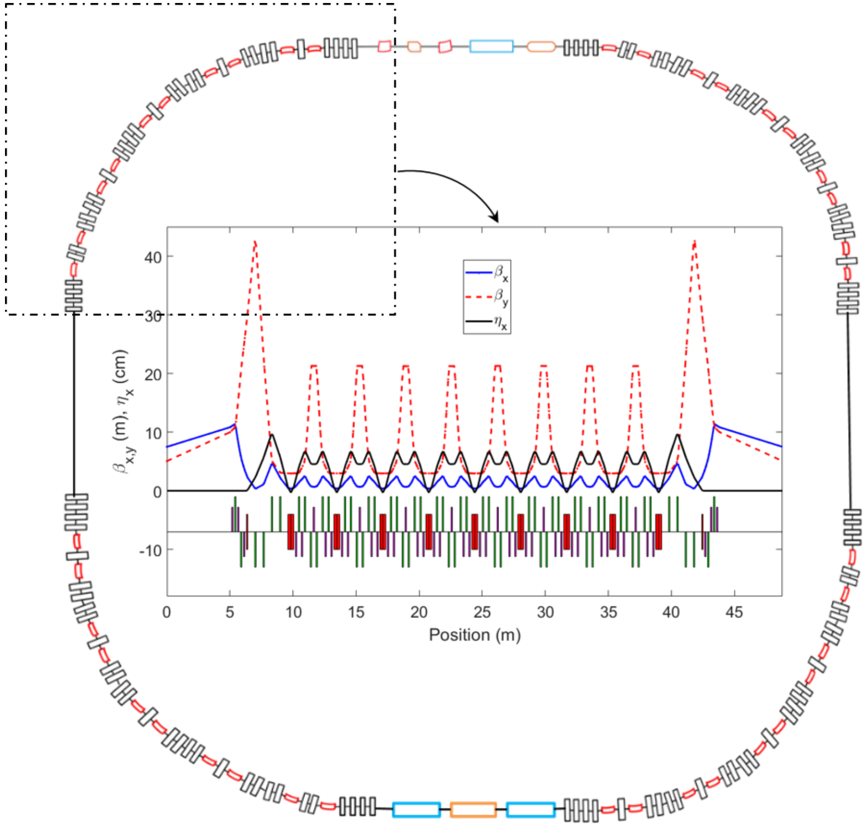
Circumference	100 ∼ 150 m
Beam energy	400 MeV
σ_z outside of LSF	10 ∼ 100 nm
σ_z at the radiator	∼ 2 nm
Average beam current	1 A
EUV power	∼ 1 kW

1^{st} SSMB Light Source Online Workshop, 7-9 December, 2020
http://indico-cdex.ep.tsinghua.edu.cn/event/38/
-> here interested can find many details to this project !

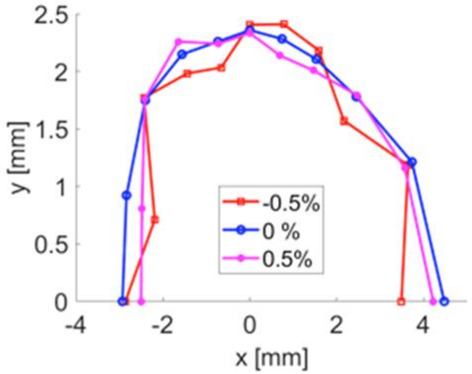
C. Tang. SSMB Online Workshop, 2020.

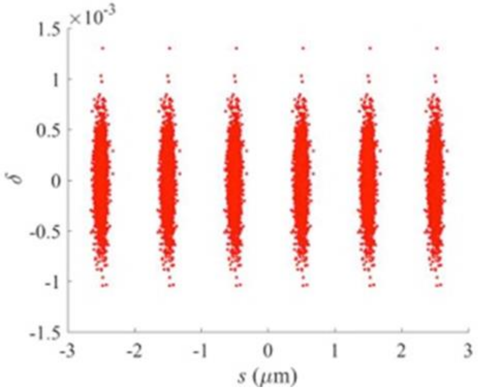
Magnet Lattice Design

- **Progress: storage of 3 nm microbunches @ 400 MeV for the first time in a storage ring. The bunch length is more than four orders of magnitude smaller than the present achievable value in storage rings.**



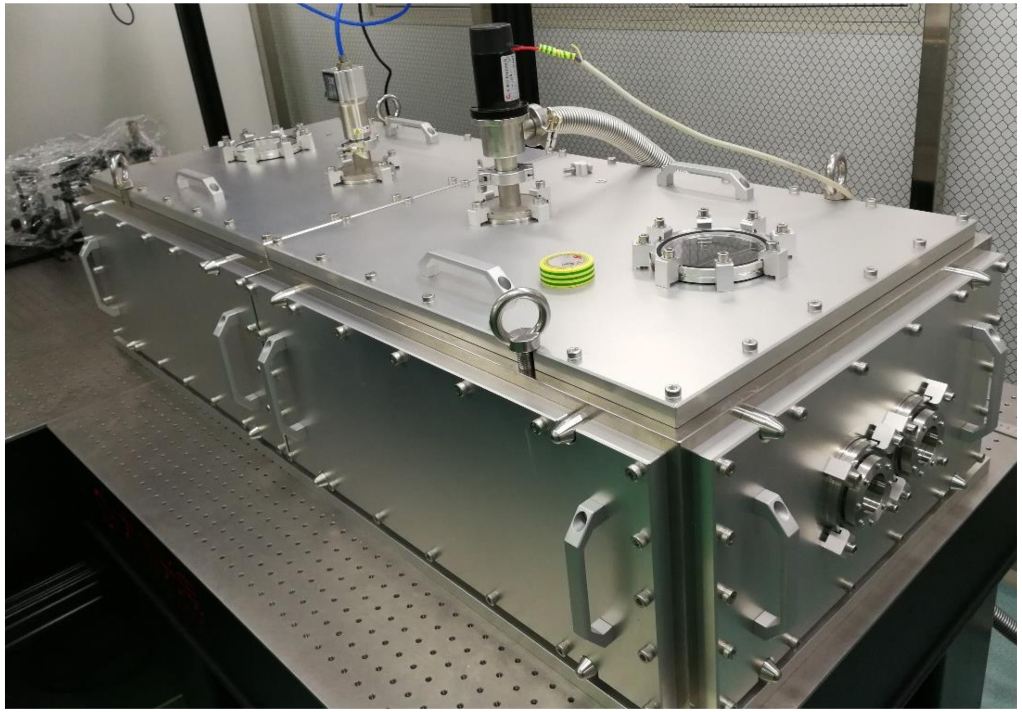
Parameters	Value
Circumference [m]	195.2
Tunes(x/y)	25.58/5.80
Chromaticity(x/y)	0.001/0.001
Beam energy [MeV]	400
Phase slippage factor η	1.0e-6
Second order Phase slippage factor η_2	6.0e-6
Energy spread	2.0e-4
Natural emittance [pm]	84.2
Energy loss per turn [keV]	1.5

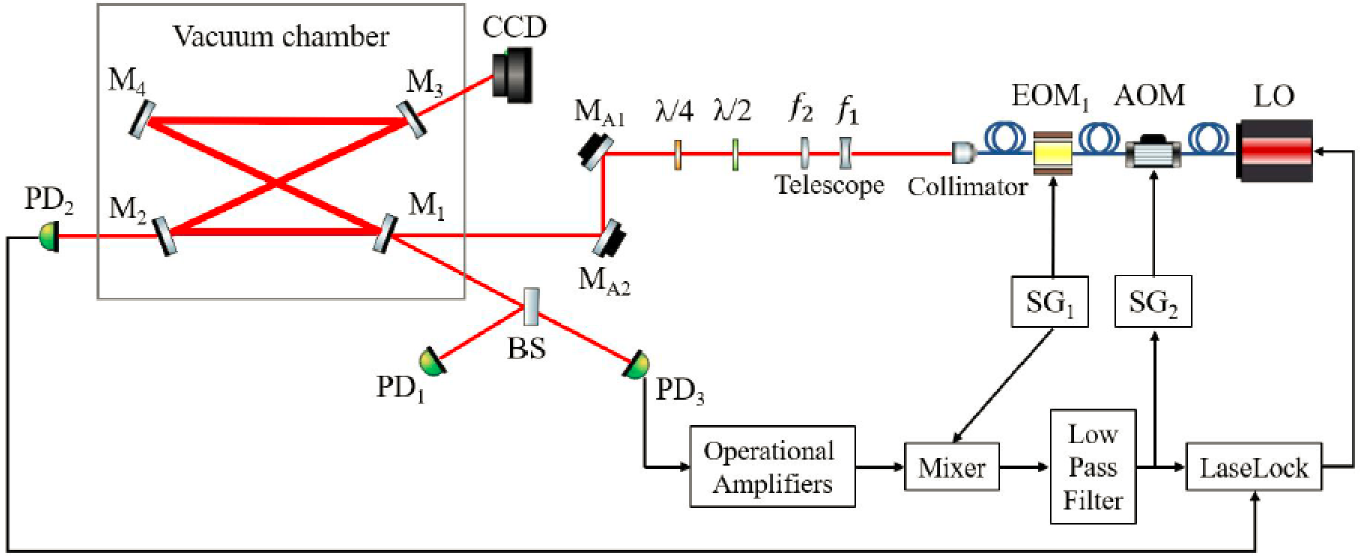


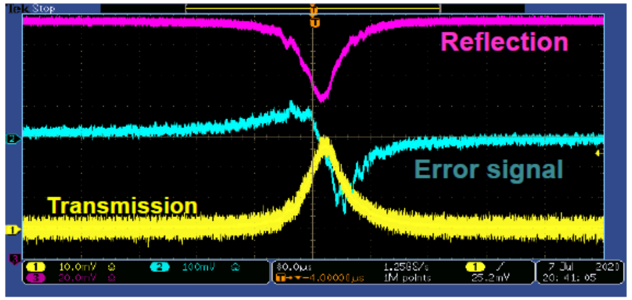


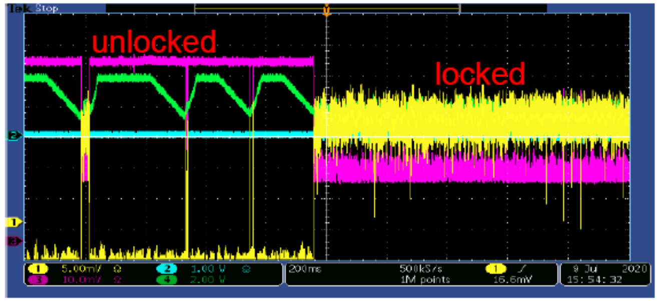
Z. Pan. et al., SSMB Online Workshop, 2020.

Optical Enhancement Cavity









- **Cavity T-Box at Tsinghua (> 100 cavity gain)**

Future plan: wavelength ~ 1 um, CW mode, stored power ~ 1 MW

L. Yan. & H. Wang. SSMB Online Workshop, 2020.

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 source.
- **SSMB PoP Experiment Phase II** is under preparation and will be conducted at the MLS in the near future.
- Magnet lattice design and optical enhancement cavity development for the envisioned **Tsinghua EUV SSMB storage ring** is ongoing, with very good progress achieved.

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, et al., Experimental Demonstration of the Mechanism of Steady-state Microbunching, *Nature* 590, 576–579 (2021).
- J. Feikes, Progress Towards Realisation of Steady-State Microbunching at the Metrology Light Source, Talk at IPAC2021.
- 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.

➢ 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., et al., Single-particle dynamics of microbunching. Phys. Rev. Accel. Beams 23, 044002 (2020).
- Deng, X. J., et al., Widening and distortion of the particle energy distribution by chromaticity in quasi-isochronous rings. Phys. Rev. Accel. Beams 23, 044001 (2020).

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