High-Power SSMB-EUV Source Development at Tsinghua University

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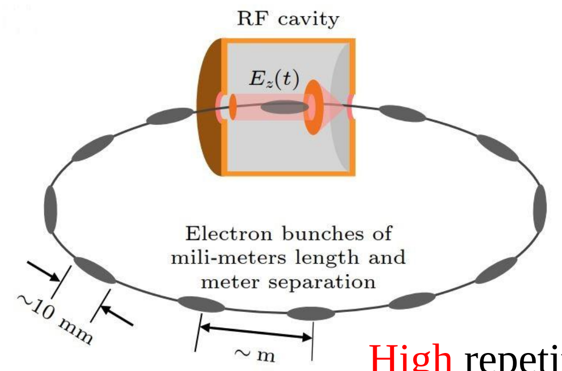
On behalf of the SSMB Collaboration

2022 Source Workshop, Held Online, October 24-27, 2022.

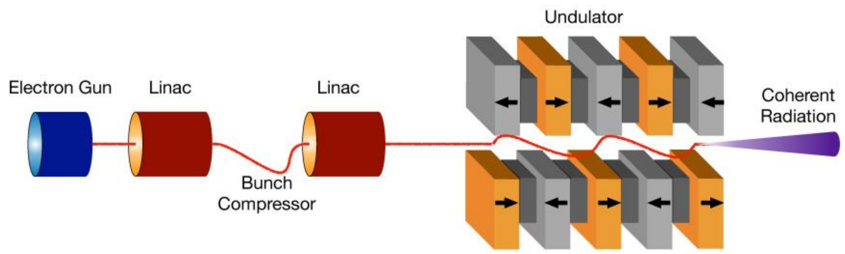
Steady-state microbunching (SSMB)

Synchrotron Radiation



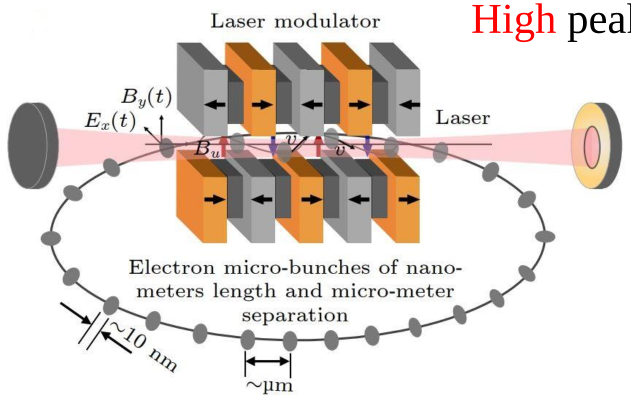
High repetition rate
Low peak power

Free-Electron Laser



Low repetition rate
High peak power

SSMB

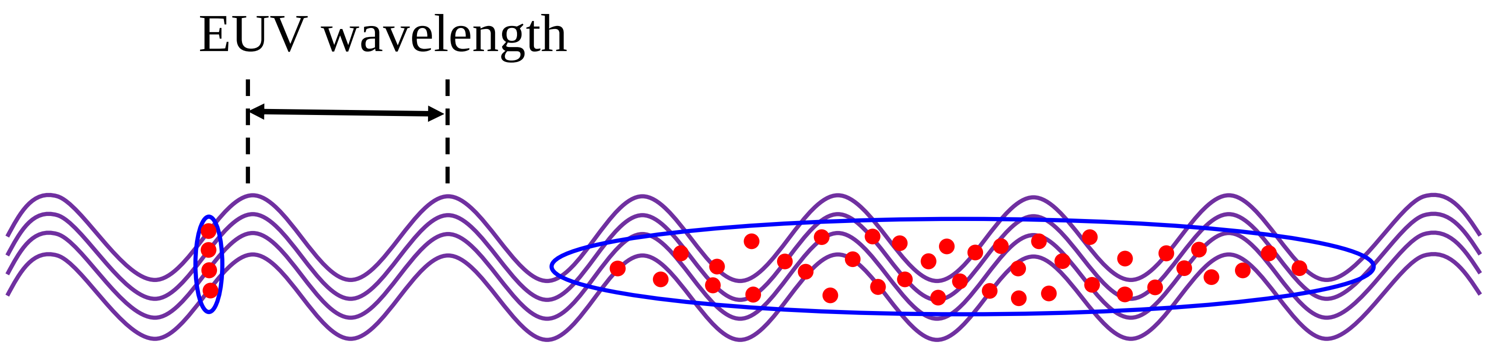


High repetition rate
High peak power

Two features combined leads to high average power!

D. F. Ratner and A. W. Chao, Phys. Rev. Lett. 105, 154801 (2010).

Radiation Power Enhancement by Microbunching



Microbunch

Coherent radiation

$P \propto N^2$

Conventional bunch

Incoherent radiation

$P \propto N$

$E = \mathrm{A}(e^{i\phi_1} + e^{i\phi_2} + \cdots + e^{i\phi_N})$

$P \propto |E|^2$

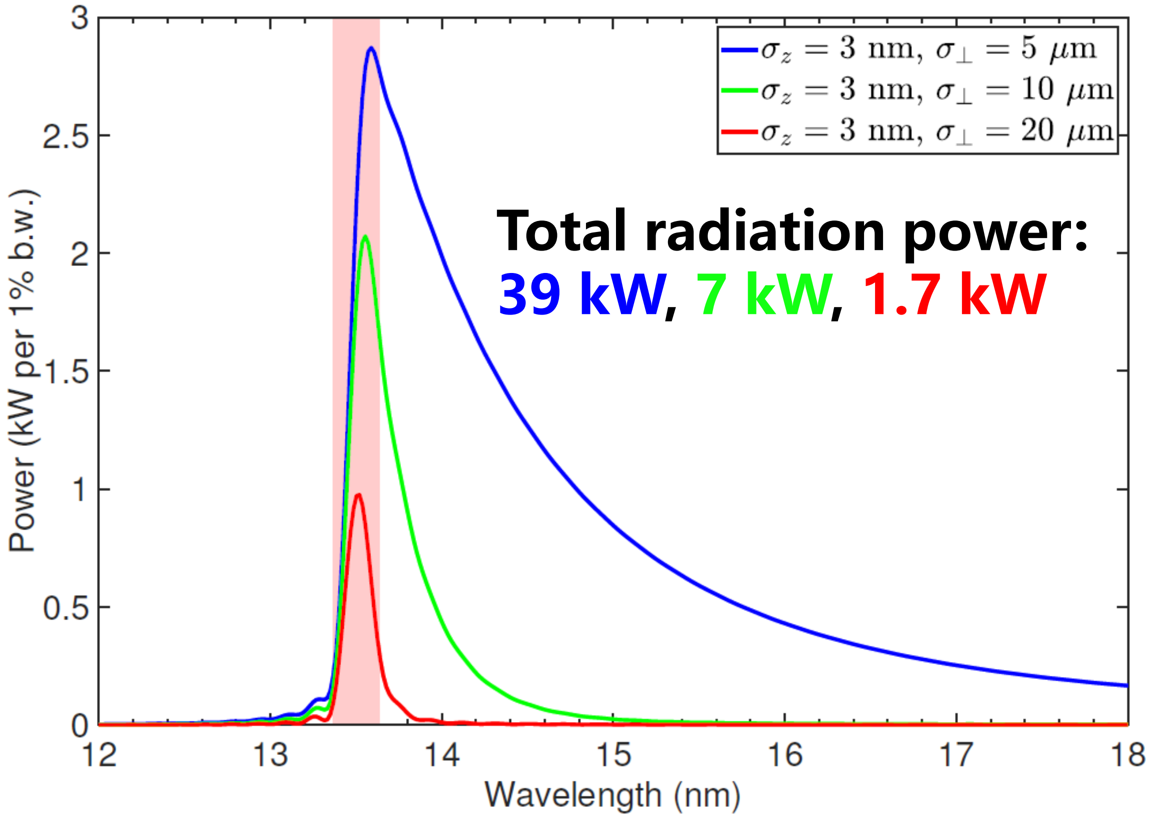
Note that the coherence here means longitudinal or temporal coherence

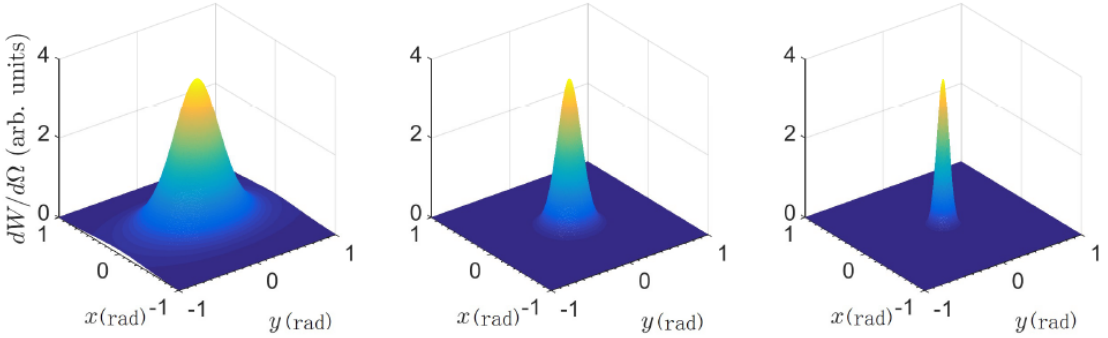
Radiation Characteristics of EUV SSMB

- **SSMB can generate EUV radiation with an average power larger than 1 kW, provided that an average current of 1 A and bunch length of 3 nm microbunch train can be formed at the radiator**

$$\left.\frac{\Delta\omega_{e^{-1}}}{\omega_0}\right|_{\perp} \approx 1.7\%,$$

$$\left.\theta_{e^{-1}}\right|_{\perp} \approx 0.21\ \mathrm{mrad}.$$





Deng, X. J., et al. Average and statistical property of coherent radiation from steady-state microbunching. to be appear in Journal of Synchrotron Radiation.

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 or quasi-CW;
- **Clean radiation**: the radiation is clean and carries no debris;
- **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.

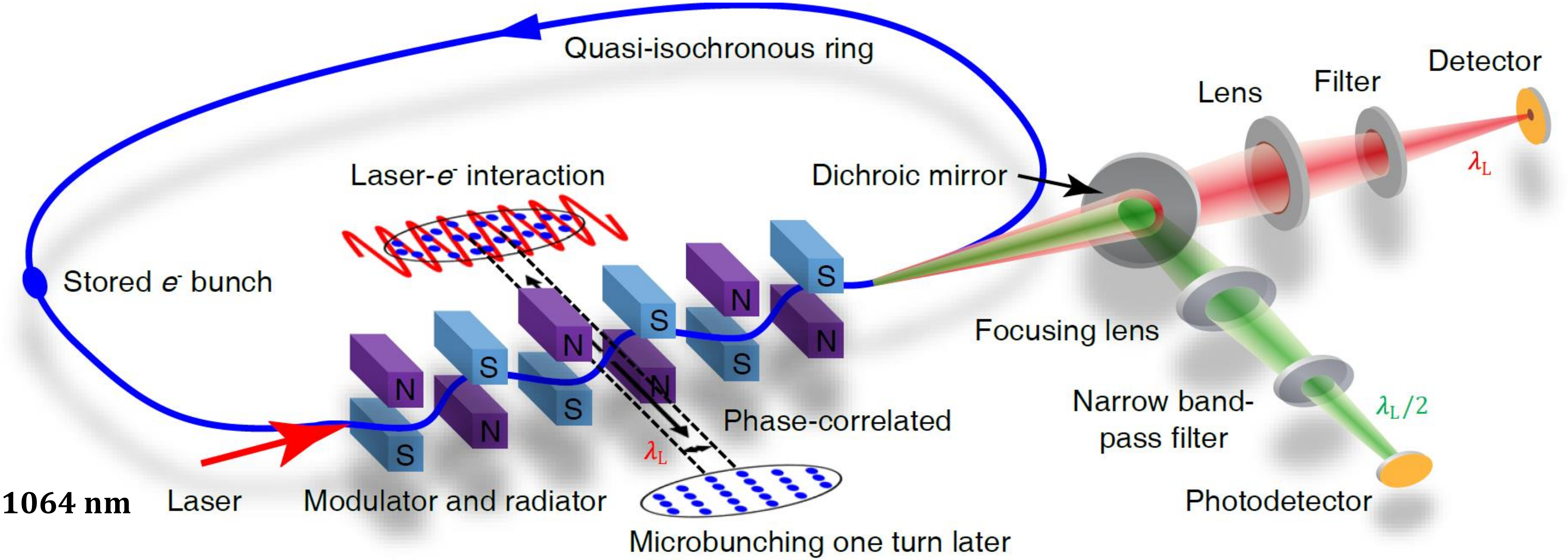
SSMB Collaboration

- **A task force has been established at Tsinghua University, in collaboration with researchers from different institutes, to promote SSMB research and develop 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**

PoP Experiment (Tsinghua, HZB & PTB)

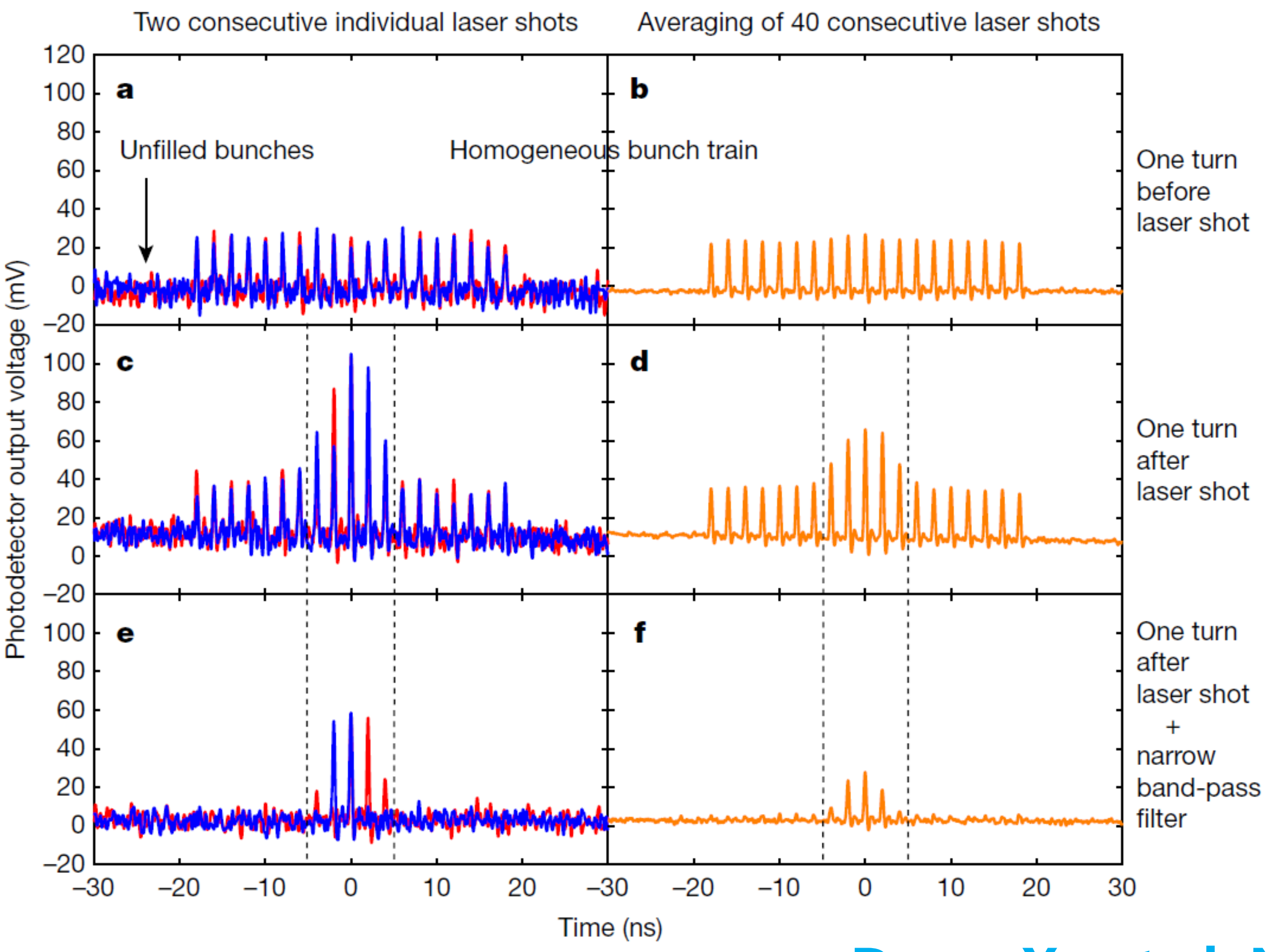
$C = 48\ \mathrm{m}$ $\eta \approx -2 \times 10^{-5}$ $E = 250\ \mathrm{MeV}$

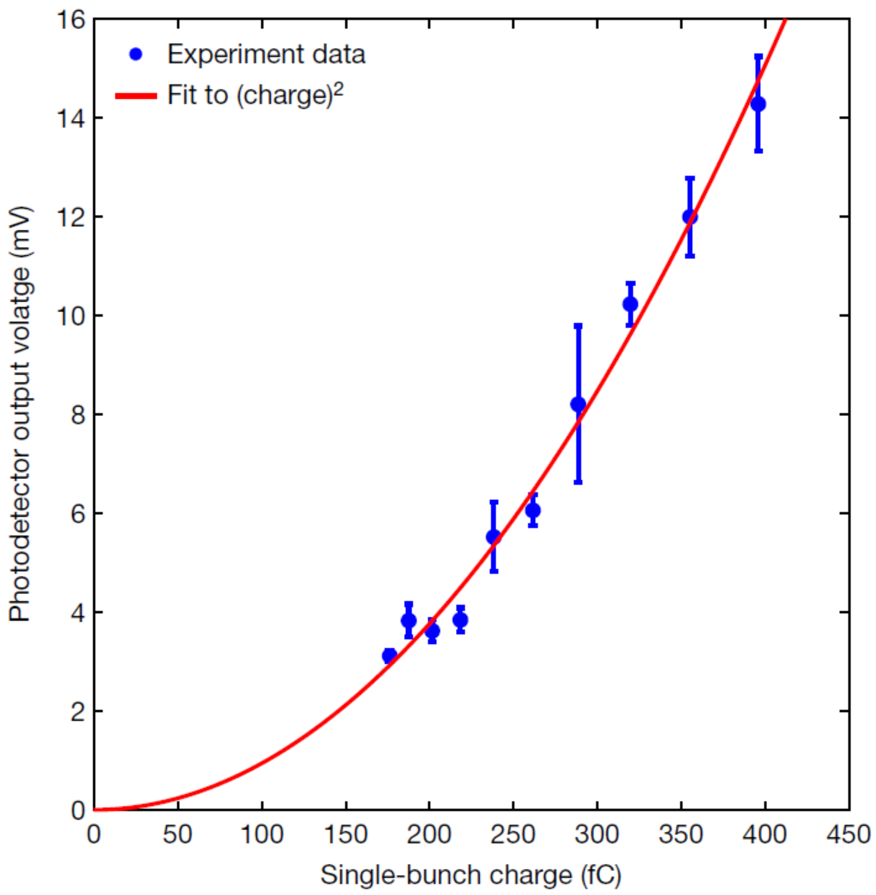


$\lambda_L = 1064\ \mathrm{nm}$

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

The quadratic bunch charge dependence, together with the narrowband feature of the coherent radiation, demonstrates unequivocally the microbunching formation



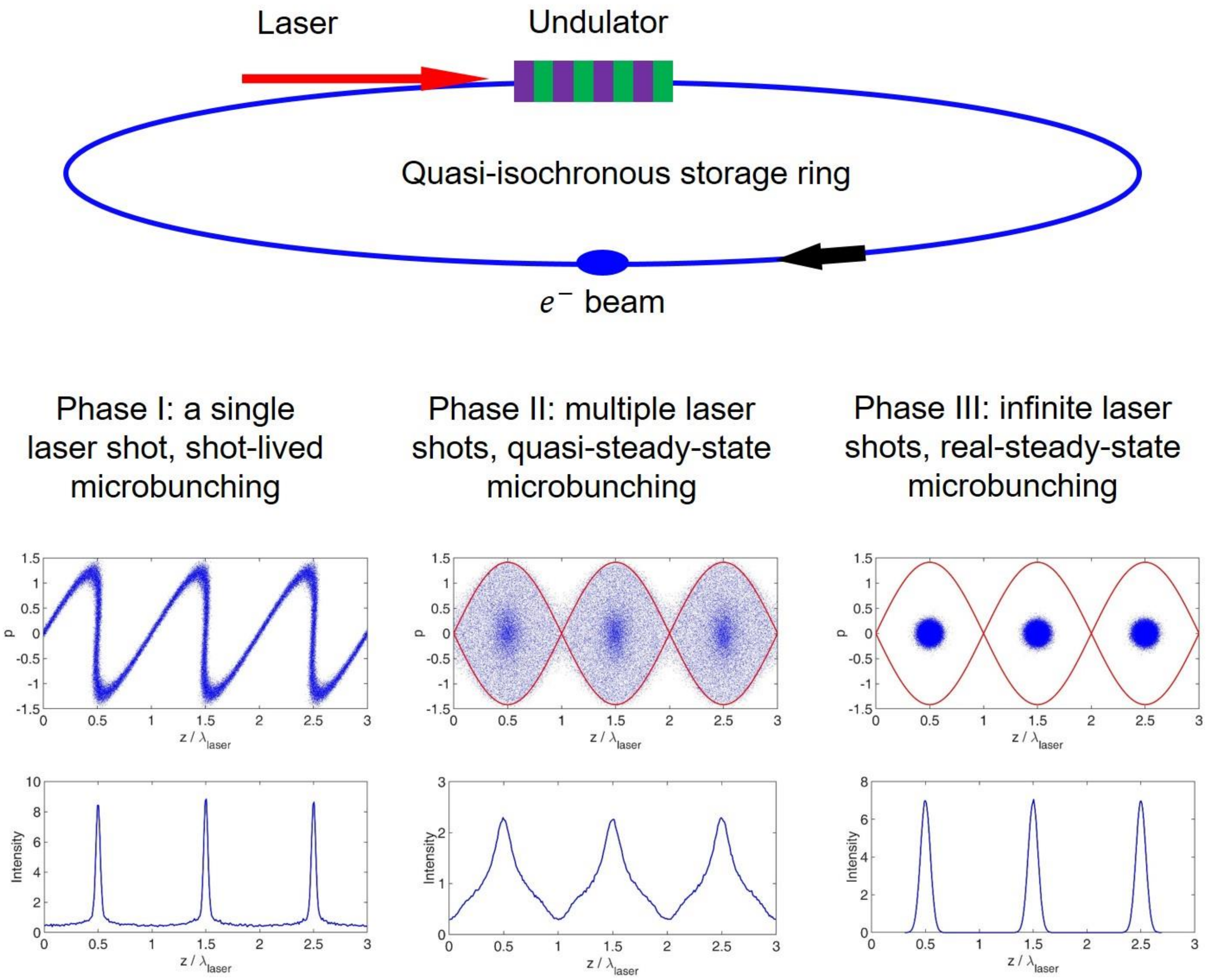


Deng, X., et al. Nature 590, 576–579 (2021).

Next step: PoP Phase II at the MLS

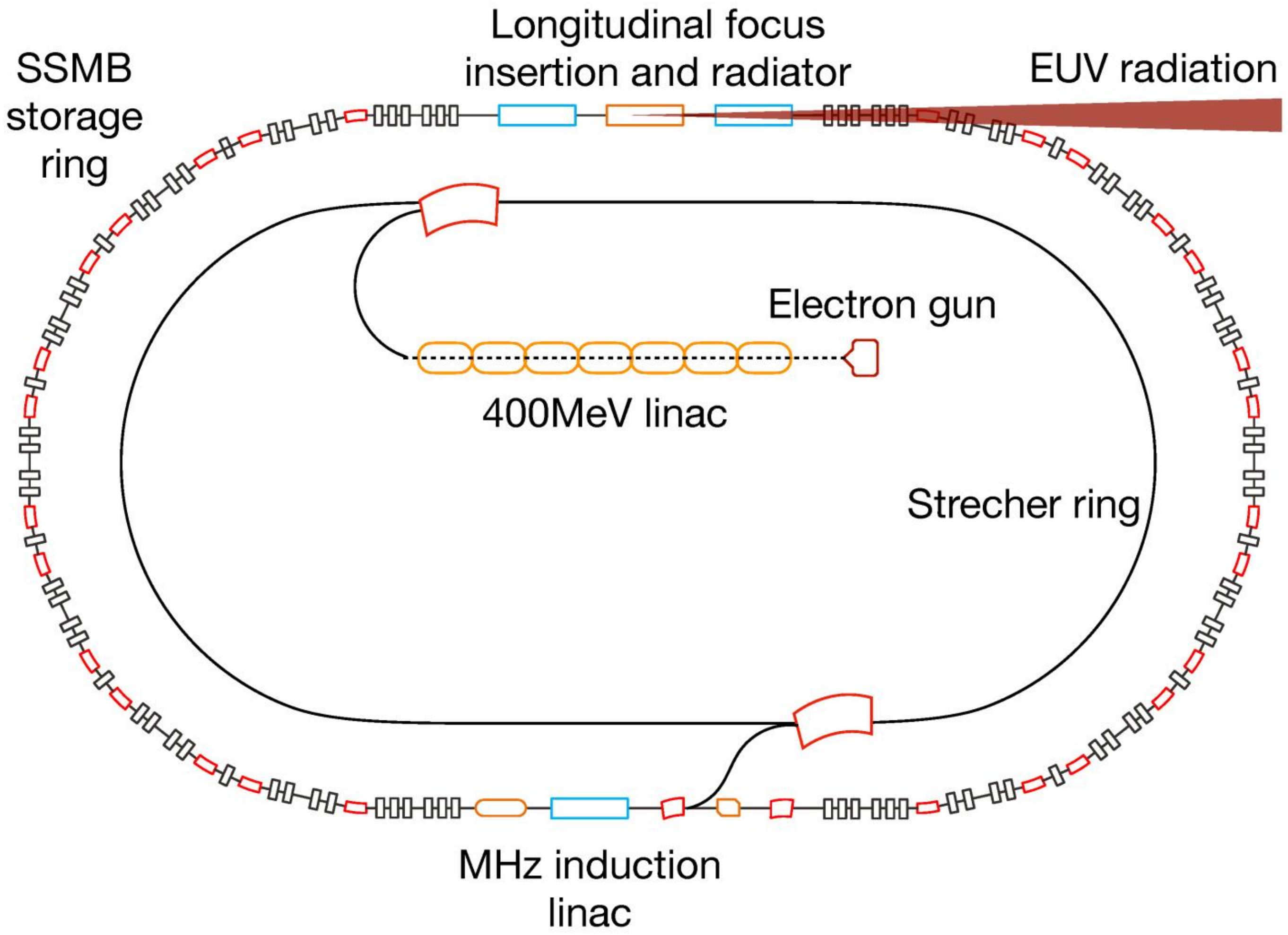
- **On the basis of phase I, the next step is to sustain the microbunching for multiple (~1000) turns to reach a quasi-steady state, by replacing the present laser with a high-repetition phase-locked laser**

- **Hopefully the experiment can be launched early next year**



Future Perspective: Tsinghua EUV SSMB Ring

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

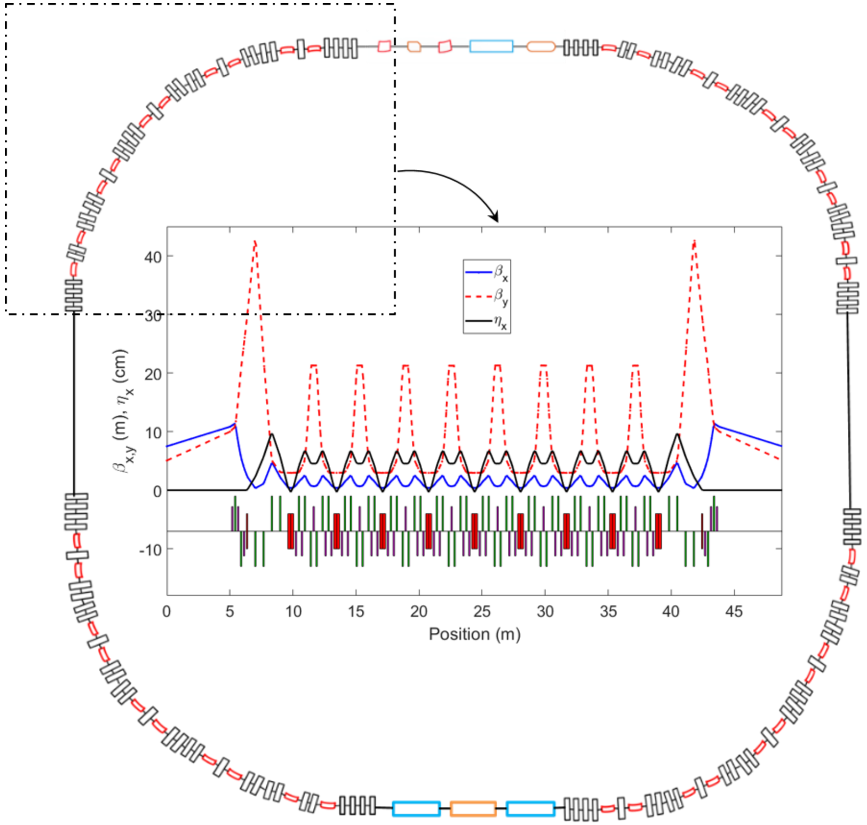


Parameter	Value	Unit
Circumference	~150	m
Electron energy	≥ 400	MeV
Current	≥ 1	A
Radiation wavelength	5 - 100	nm
13.5 nm EUV power (within 2% bandwidth)	> 1	kW
EUV photon flux (within 0.1 meV)	> 10^{13}	photons/s

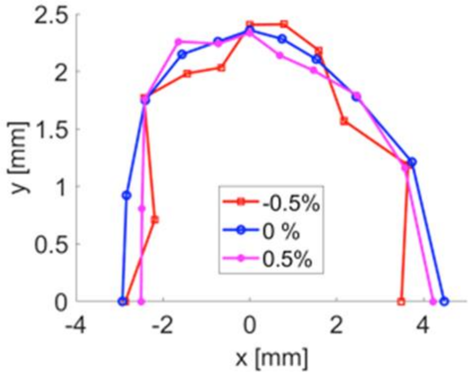
C. Tang. 2021 Source Workshop.

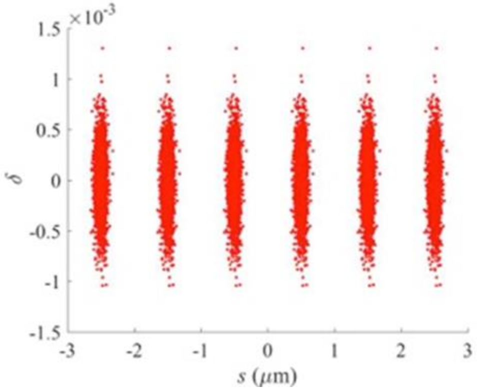
Magnet Lattice Design

- **Progress: storage of 3 nm microbunches @ 400 MeV for the first time in a storage ring. The bunch length is five 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

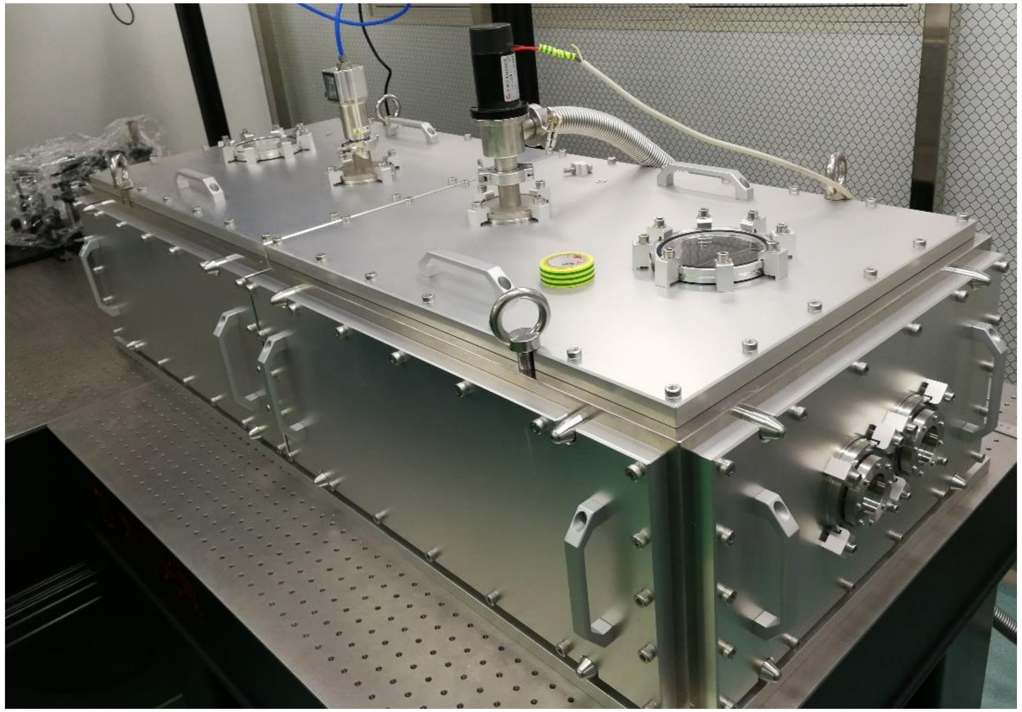


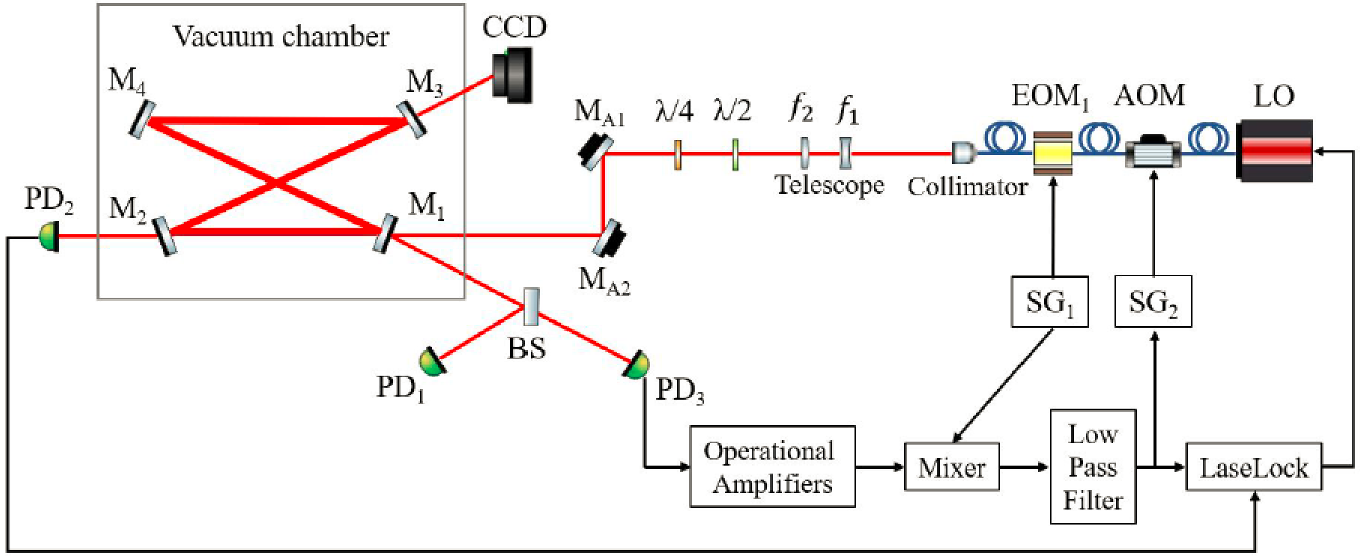


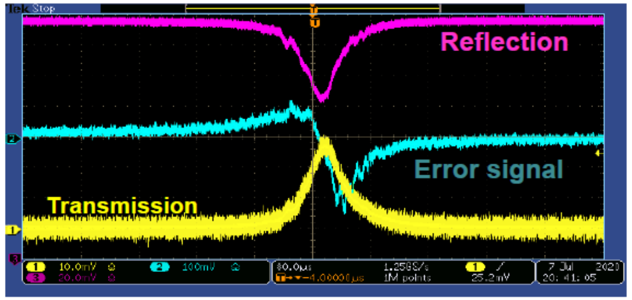
This storage ring design can be more compact after optimization, the circumference can be as small as 100 m.

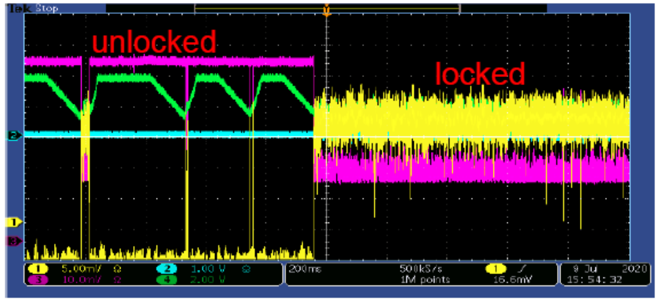
Z. Pan. et al., SSMB Online Workshop, 2020.

Optical Enhancement Cavity









- Cavity T-Box at Tsinghua (a couple of 10 kW now)

Long-term goal: stored power ~ 1 MW

L. Yan. 2021 Source Workshop.

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**.

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

- Accelerator lattice design and optical enhancement cavity development for **Tsinghua EUV SSMB storage ring** is ongoing, with encouraging progress being 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.

SSMB proof-of-principle experiment:

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

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.

SSMB radiation:

- Deng, X. J., et al. Average and statistical property of coherent radiation from steady-state microbunching. to be appear in Journal of Synchrotron Radiation (2022).

SSMB beam physics:

- Deng, X. J., et al., Single-particle dynamics of microbunching. Phys. Rev. Accel. Beams 23.4 (2020): 044002.
- Zhang, Y., et al. Ultralow longitudinal emittance storage rings. Phys. Rev. Accel. Beams 24.9 (2021): 090701.
- Deng, X. J., et al. Courant-Snyder formalism of longitudinal dynamics. Phys. Rev. Accel. Beams 24.9 (2021): 094001.
- Deng, X. J., et al. Harmonic generation and bunch compression based on transverse-longitudinal coupling. Nucl. Instrum. Methods Phys. Res. A 1019 (2021): 165859.
- Tsai, C-Y., et al. Coherent-radiation-induced longitudinal single-pass beam breakup instability of a steady-state microbunch train in an undulator. Phys. Rev. Accel. Beams 24.11 (2021): 114401.
- Tsai, C-Y. Theoretical formulation of multi-turn collective dynamics in a laser cavity modulator with comparison to Robinson and high-gain free-electron laser instability. Phys. Rev. Accel. Beams 25.6 (2022): 064401.