Update of Tsinghua SSMB EUV Light Source Development

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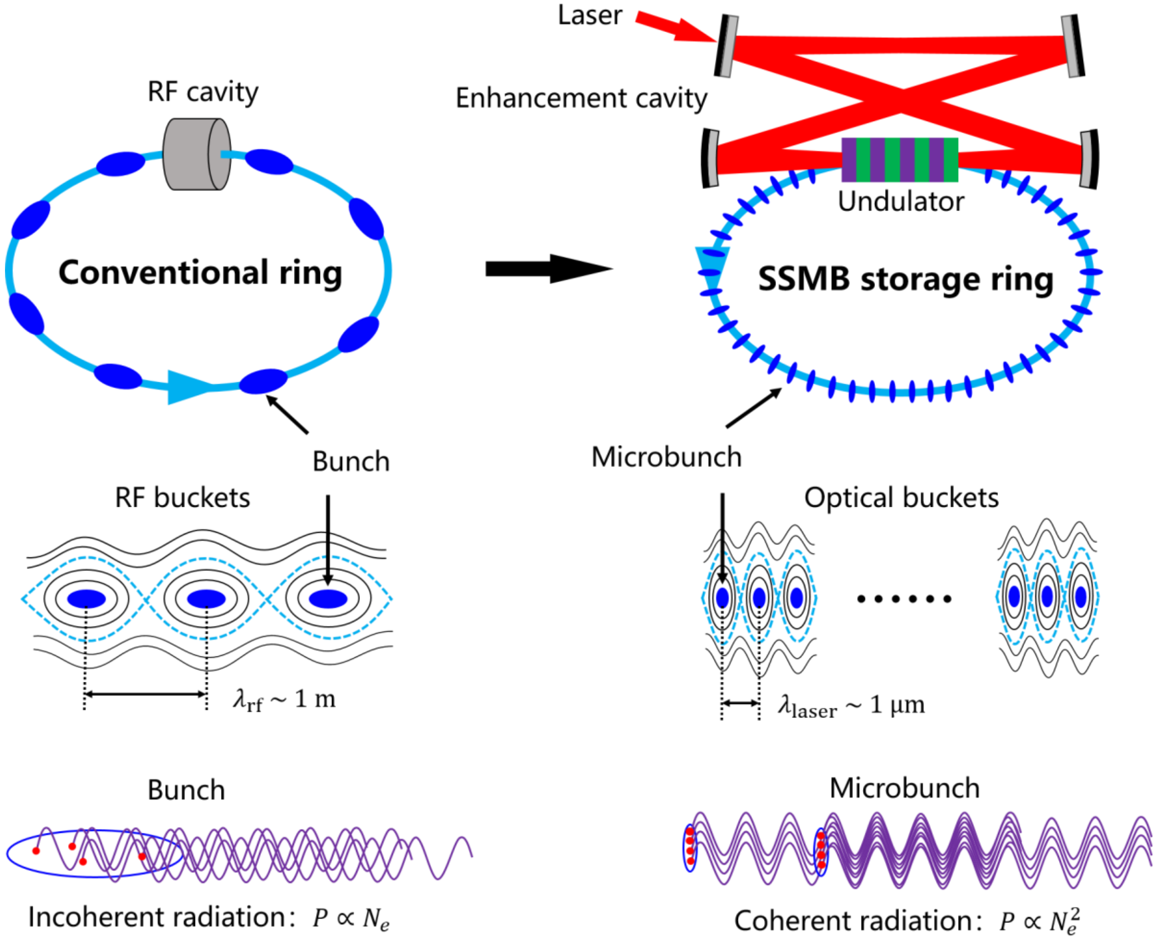
On behalf of the SSMB Collaboration

2022 EUVL Workshop, Held Online, June 4-9, 2022.

Steady-state microbunching (SSMB)

- **Electron storage ring-based**
- **Bunching system: laser modulator, instead of RF cavity**
- **Two key ingredients**
  - **microbunching for strong coherent radiation**
  - **turn-by-turn steady state for high repletion rate**
- **High-average-power narrow-band coherent radiation, with wavelength ranging from THz to EUV**

6 orders of magnitude extrapolation



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;**

- **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

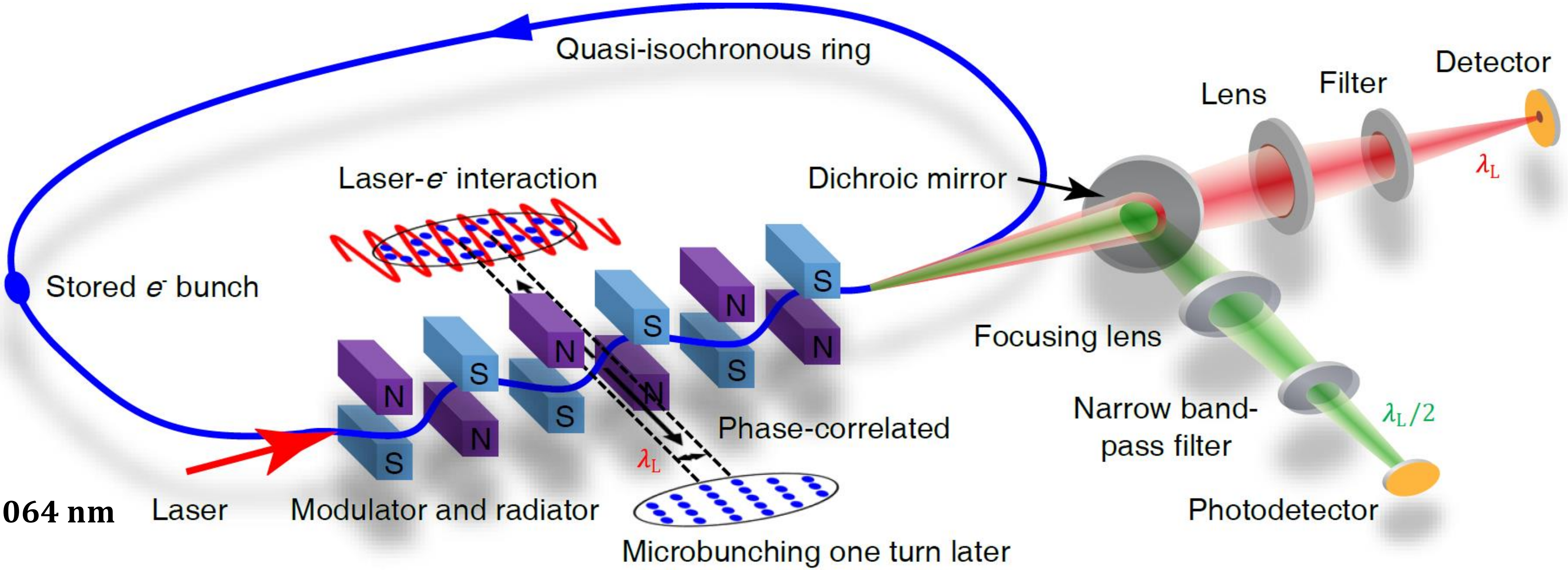
- **A task force has been established at Tsinghua University, in collaboration with researchers from different institutes, to promote SSMB research and develop an EUV SSMB storage ring**

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

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

PoP Experiment (Tsinghua, HZB & PTB)[7]

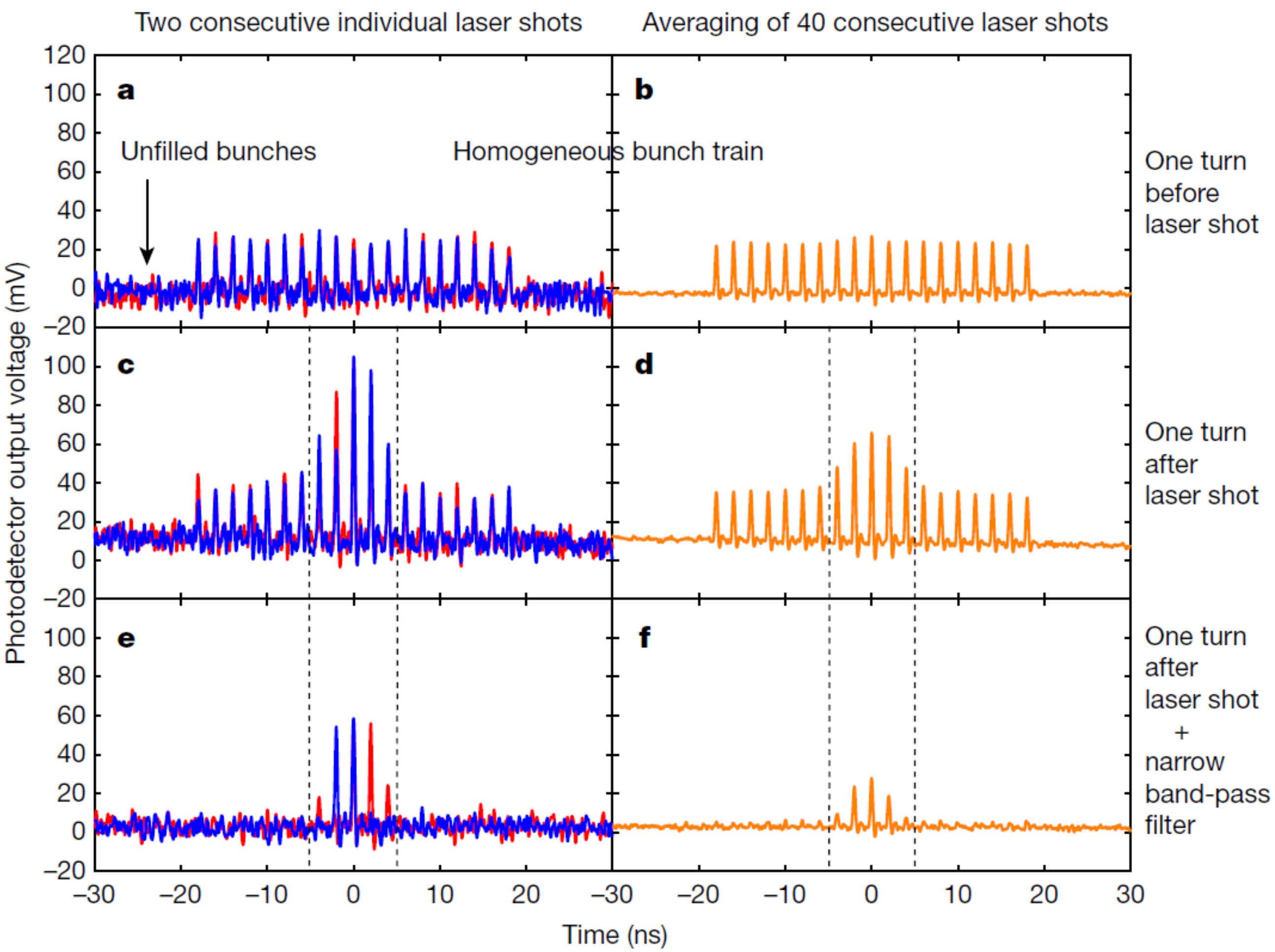
$C = 48\ \mathrm{m}$ $\eta \approx -2 \times 10^{-5}$ $E = 250\ \mathrm{MeV}$

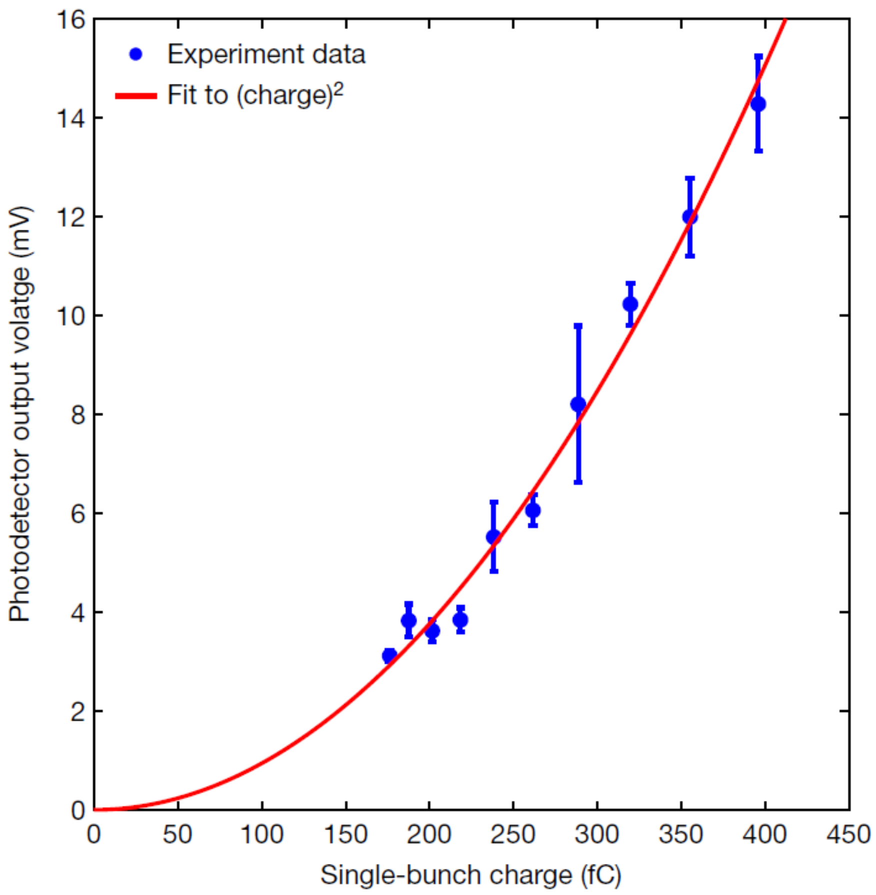


$\lambda_L = 1064\ \mathrm{nm}$

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



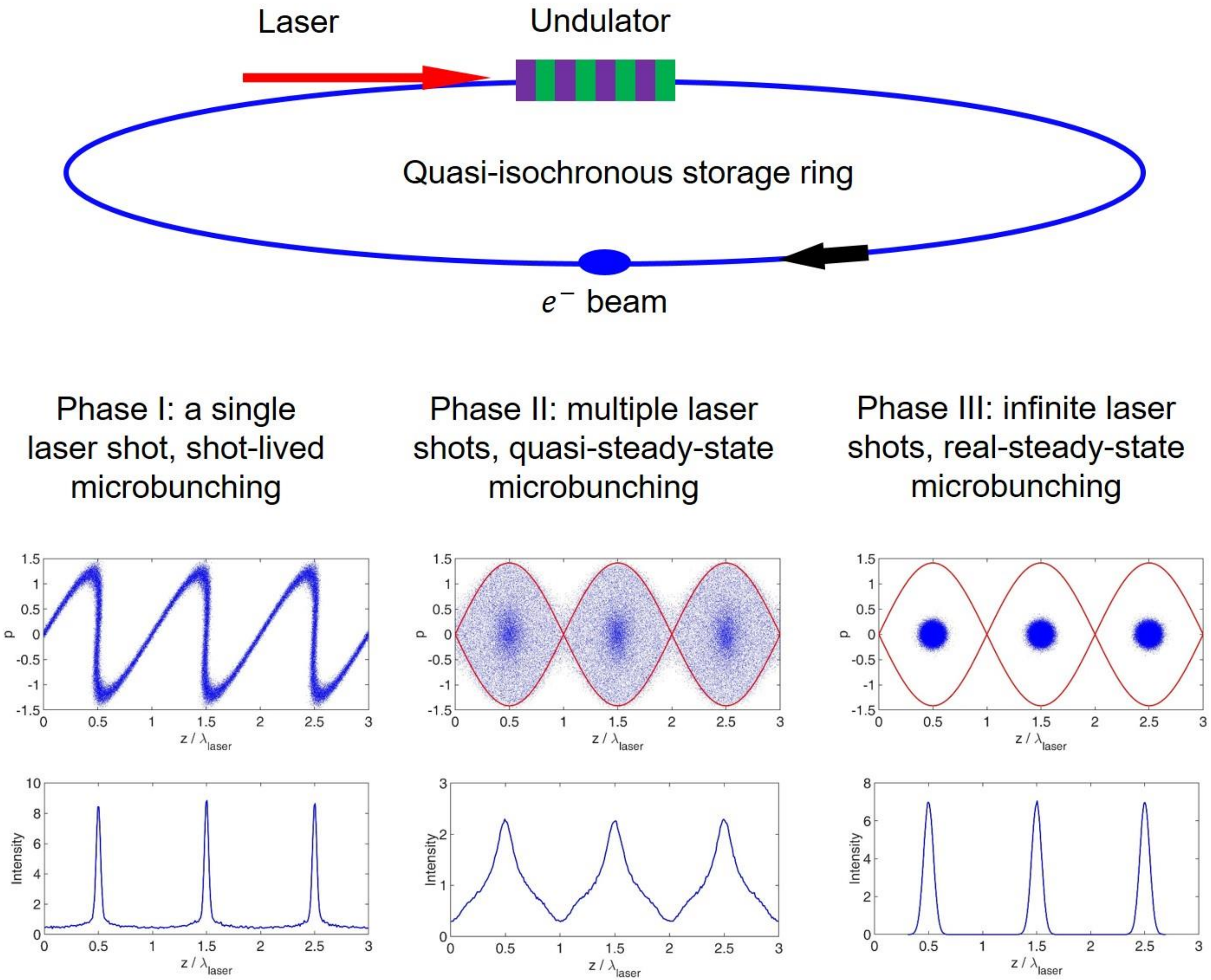


Deng, X., et al. Nature 590, 576–579 (2021).

Future Perspective: PoP Phase II at the MLS

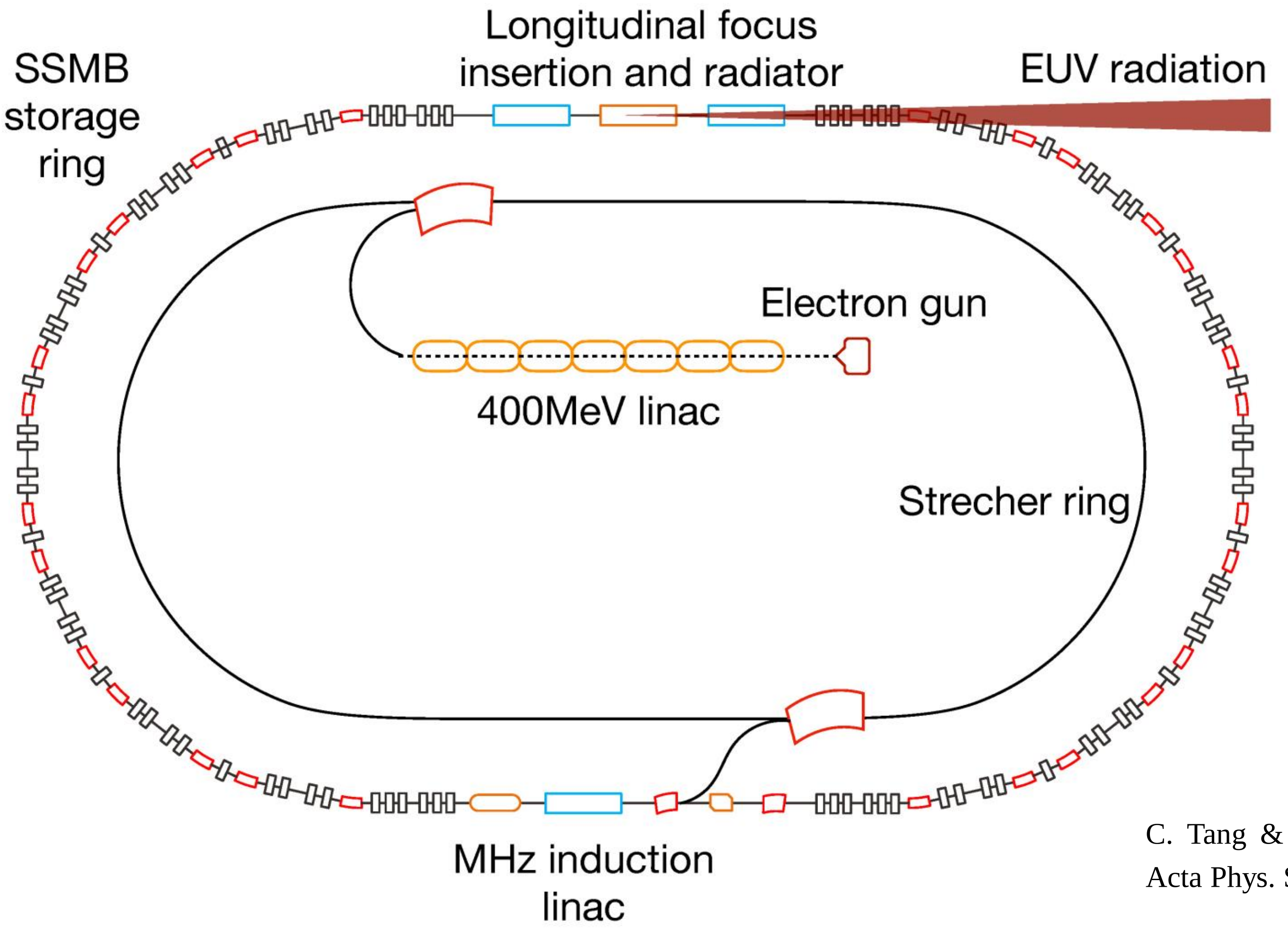
- **On the basis of phase I, the next step is to sustain the microbunching for multiple (~1000) turns to reach a quasi-steady state, by replacing the laser used in Phase I with a high-repetition phase-locked laser**

- **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



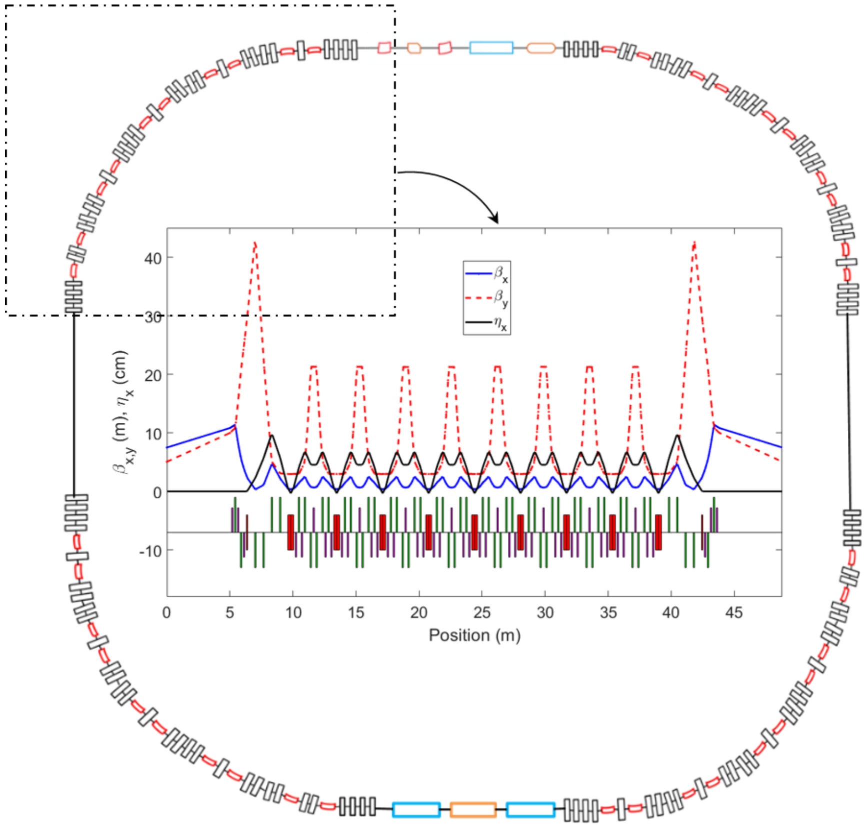
1^{st} SSMB Light Source Online Workshop, 7-9 December, 2020
http://indico-cdex.ep.tsinghua.edu.cn/event/38/
-> here interested can find many details to this project !

C. Tang & X. Deng. Steady-State Micro-Bunching Accelerator Light Source. Acta Phys. Sin. (2022).

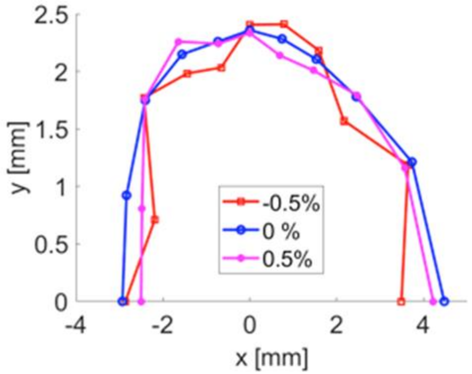
C. Tang. 2021 Source Workshop.

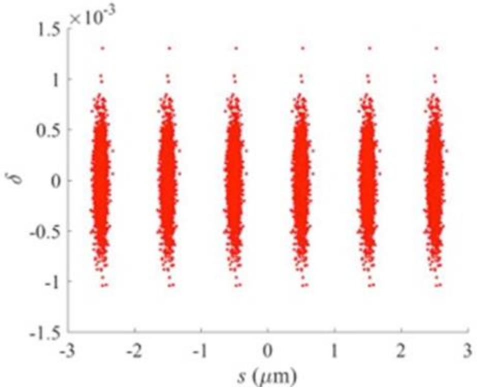
Magnet Lattice Design

- **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.

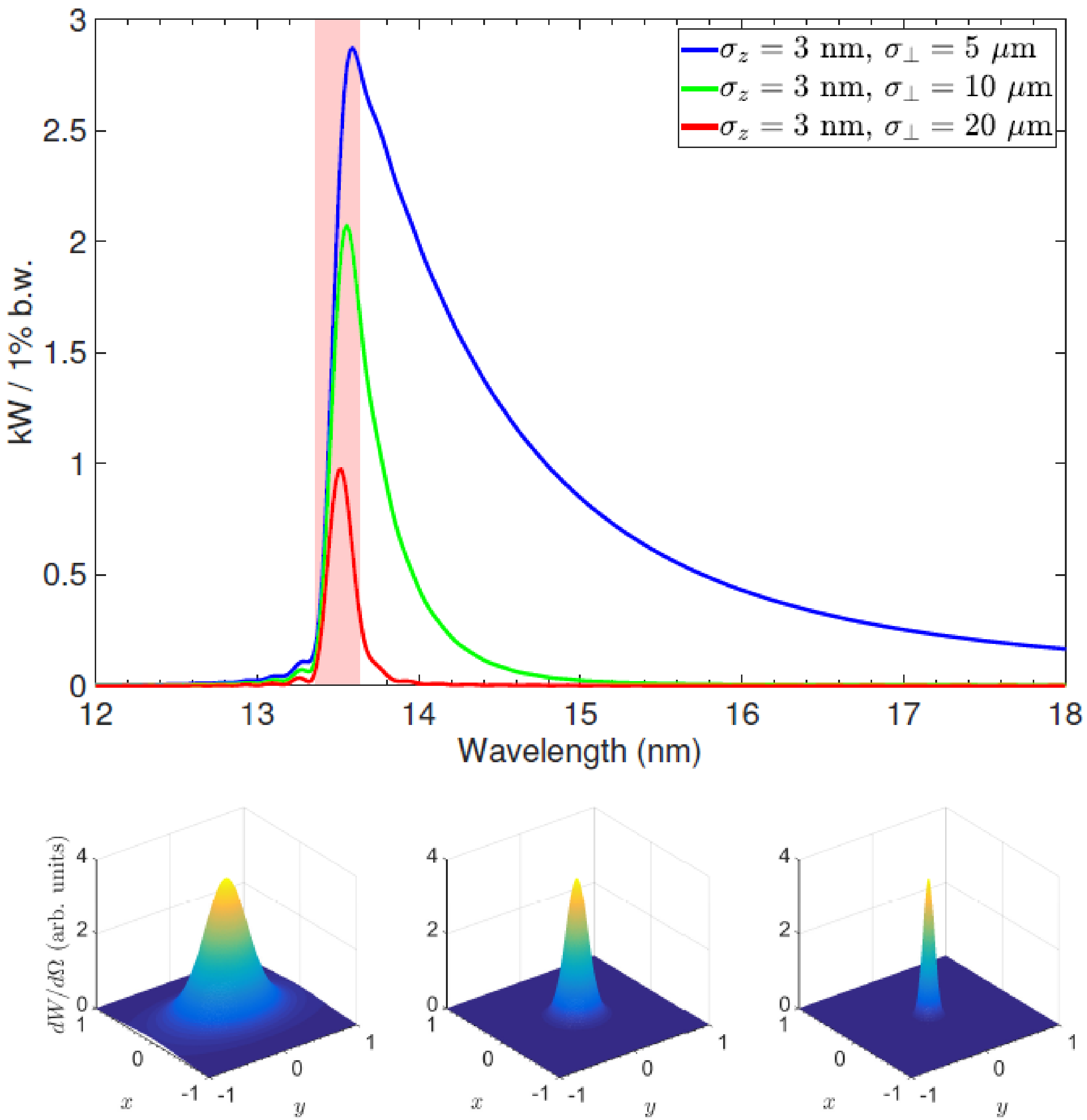
Z. Pan. et al., SSMB Online Workshop, 2020.

Radiation Characteristics of EUV SSMB

- **Our results show that an average power 1 kW EUV radiation can be obtained from an SSMB ring, provided that an average current of 1 A and bunch length of 3 nm microbunch train can be formed at the radiator**

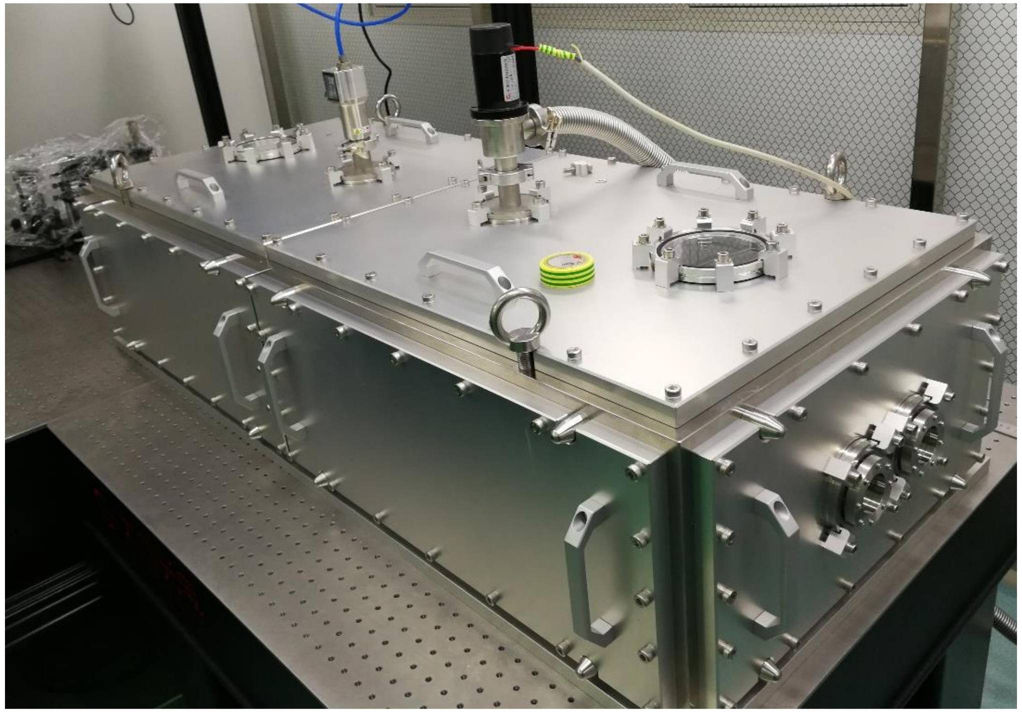
$$\left.\frac{\Delta\omega_{e^{-1}}}{\omega_0}\right|_{\perp} \approx 1.7\%,$$

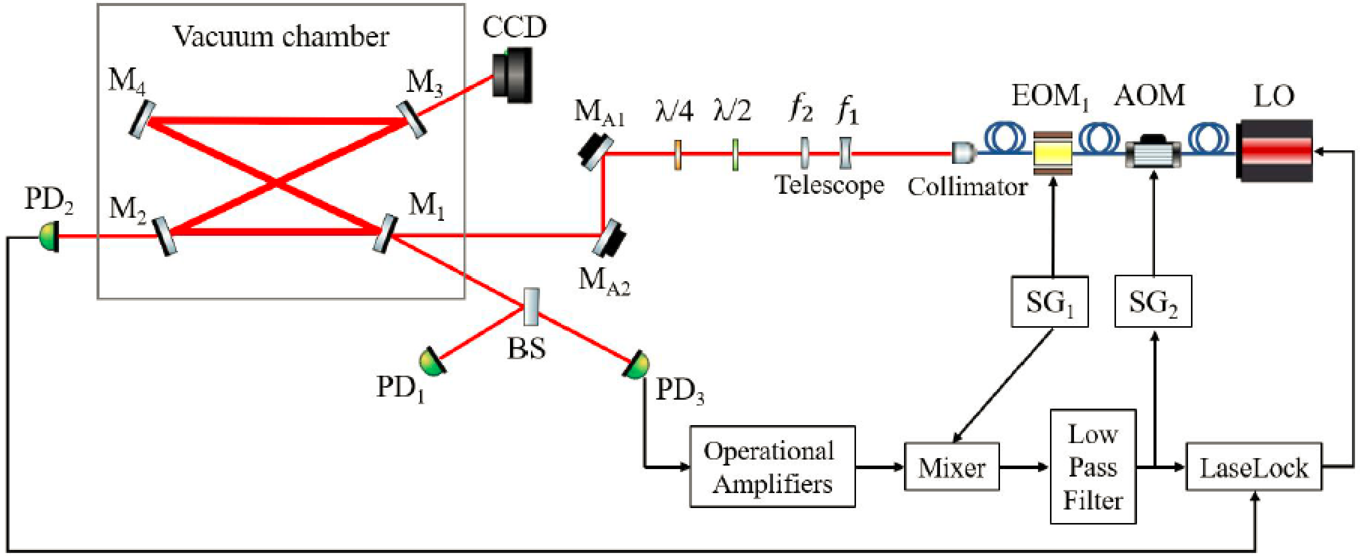
$$\left.\theta_{e^{-1}}\right|_{\perp} \approx 0.21\ \mathrm{mrad}.$$

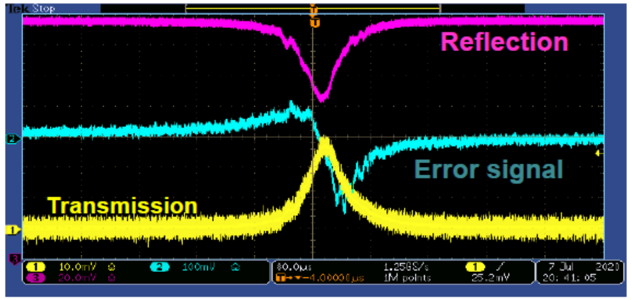


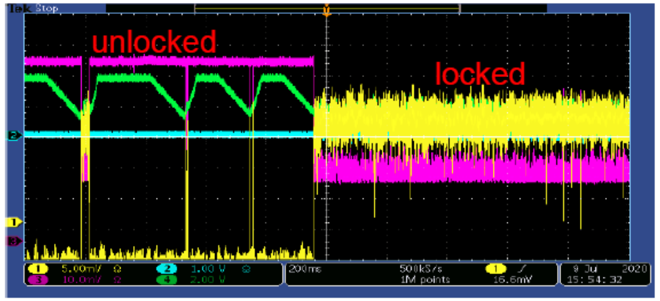
Deng, X. J., et al. Average and statistical property of coherent radiation from steady-state microbunching. submitted to Journal of Synchrotron Radiation.

Optical Enhancement Cavity









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

Future plan: wavelength ~ 1 um, 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.
- C. Tang & X. Deng. Steady-State Micro-Bunching Accelerator Light Source. Acta Phys. Sin. (2022).

➢ 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.

➢ 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. submitted to Journal of Synchrotron Radiation (2022).

➢ SSMB beam physics:

- Deng, X. J., et al. Harmonic generation and bunch compression based on transverse-longitudinal coupling. Nucl. Instrum. Methods Phys. Res. A 1019 (2021): 165859.
- 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., Single-particle dynamics of microbunching. Phys. Rev. Accel. Beams 23, 044002 (2020).
- 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, accepted for publication Phys. Rev. Accel. Beams

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