清華大學
Tsinghua University

Development of SSMB EUV Light Source at THU

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On behalf of the THU SSMB Task Force

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- Accelerators Based EUV Light Sources
- Brief Introduction of SSMB
- THU SSMB-EUV Light Source: Design, Beam Physics , EUV Light, and Key Technologies
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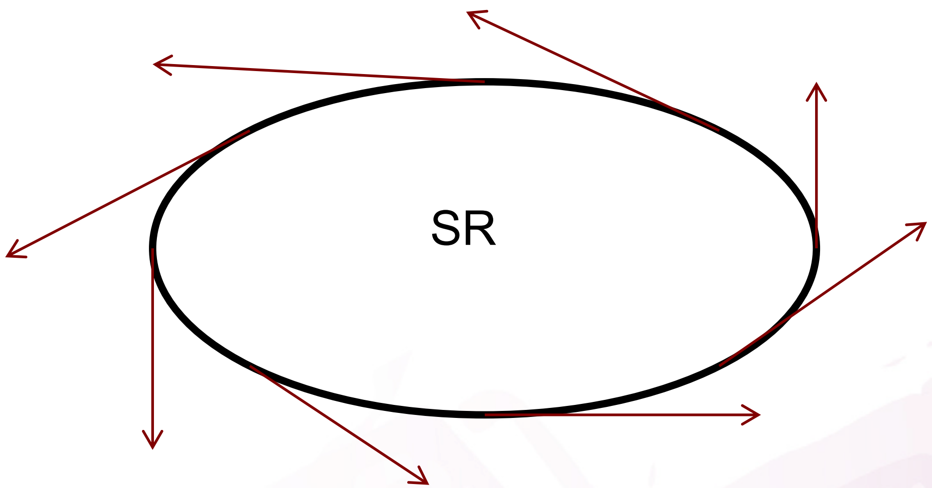
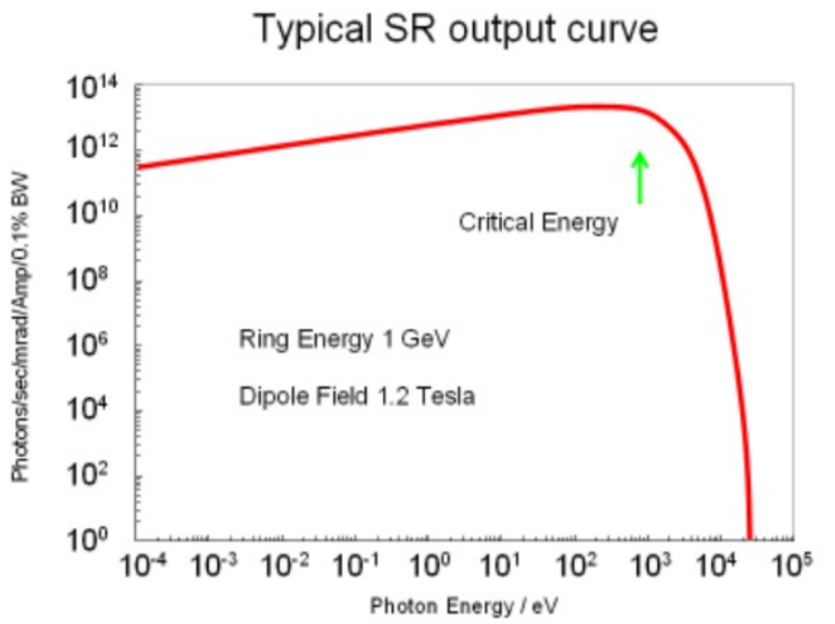
Power of Synchrotron Radiation





The power radiated in a storage ring：

$$P(kW) = 88.47E^4(GeV)I(A)R^{-1}(m)$$

With an undulator: Power $P_T[\mathrm{kW}] = 0.633E^2[\mathrm{GeV}]B^2[\mathrm{T}]L[\mathrm{m}]I[\mathrm{A}]$

Resonant wavelength $\lambda = \frac{\lambda_u}{2\gamma^2}\left(1 + \frac{K^2}{2} + \gamma^2\theta^2\right)$

The typical power radiated in a storage ring is ~kW, and it will be much lower at a narrow band of a special wavelength .

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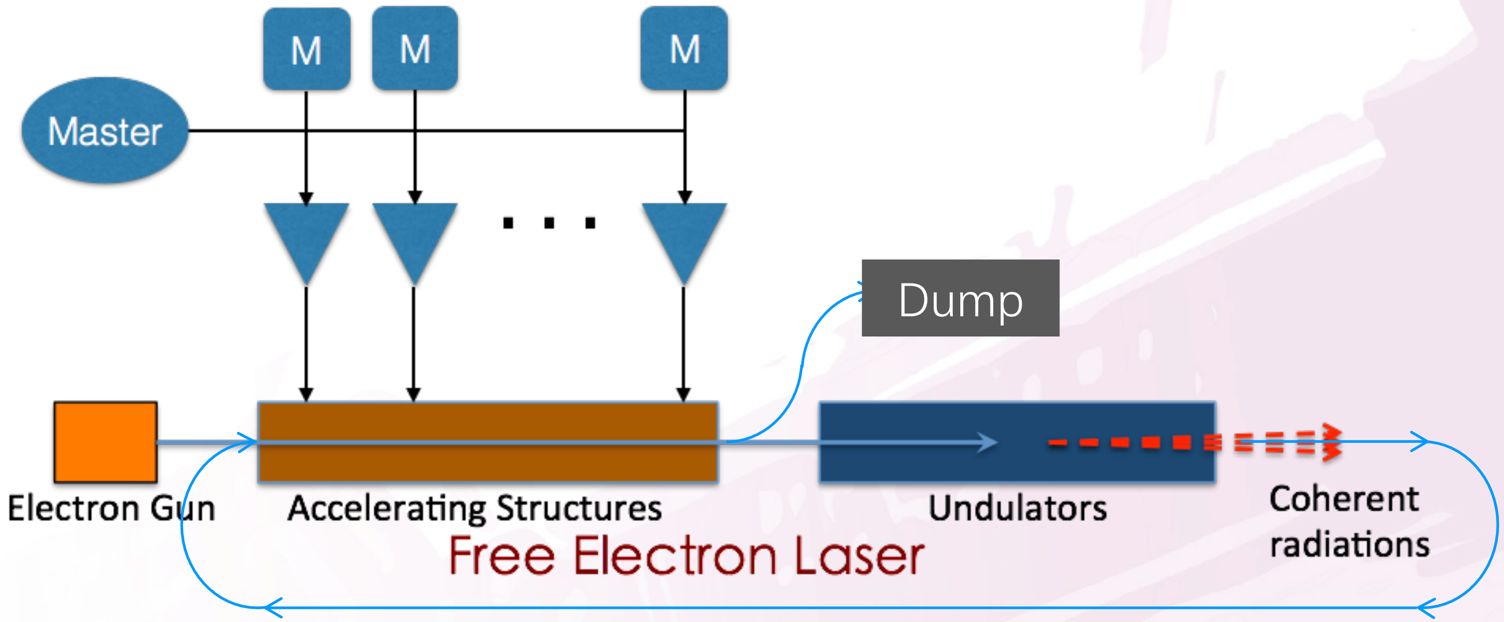
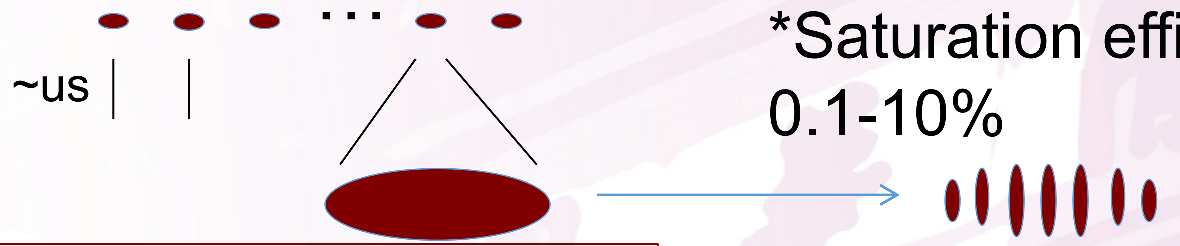
High rep-rate FEL based on SRF linacs and ERL





*Saturation efficiency: 0.1-10%

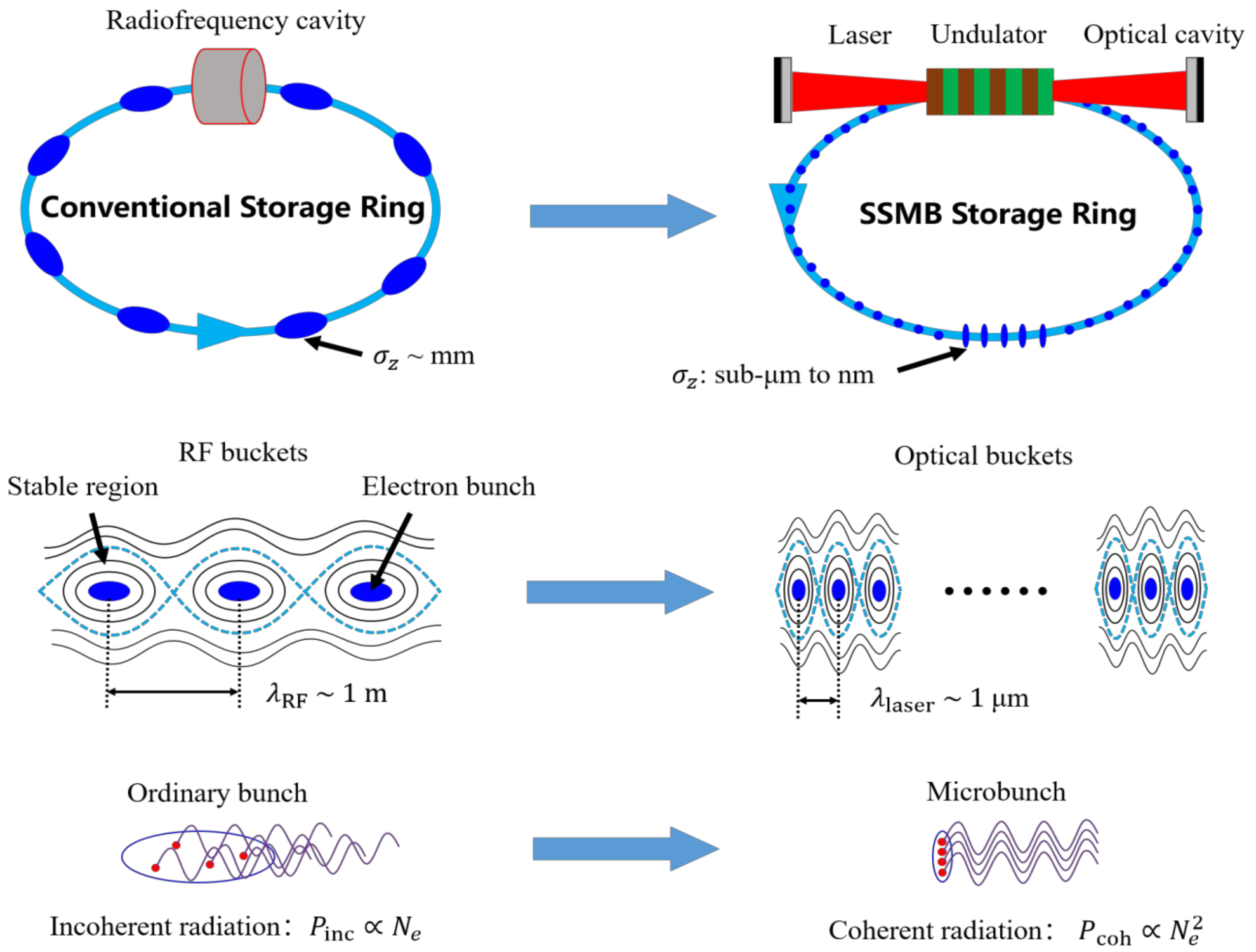
Radiation Power at a very narrow bandwidth : ~10 kW

*Opt. Commun. 50, 373 (1984)
New J. Phys. 17, 063036 (2015)
Phys. Rev. Accel. Beams 19, 020705 (2016)

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.

Six orders of magnitude extrapolation



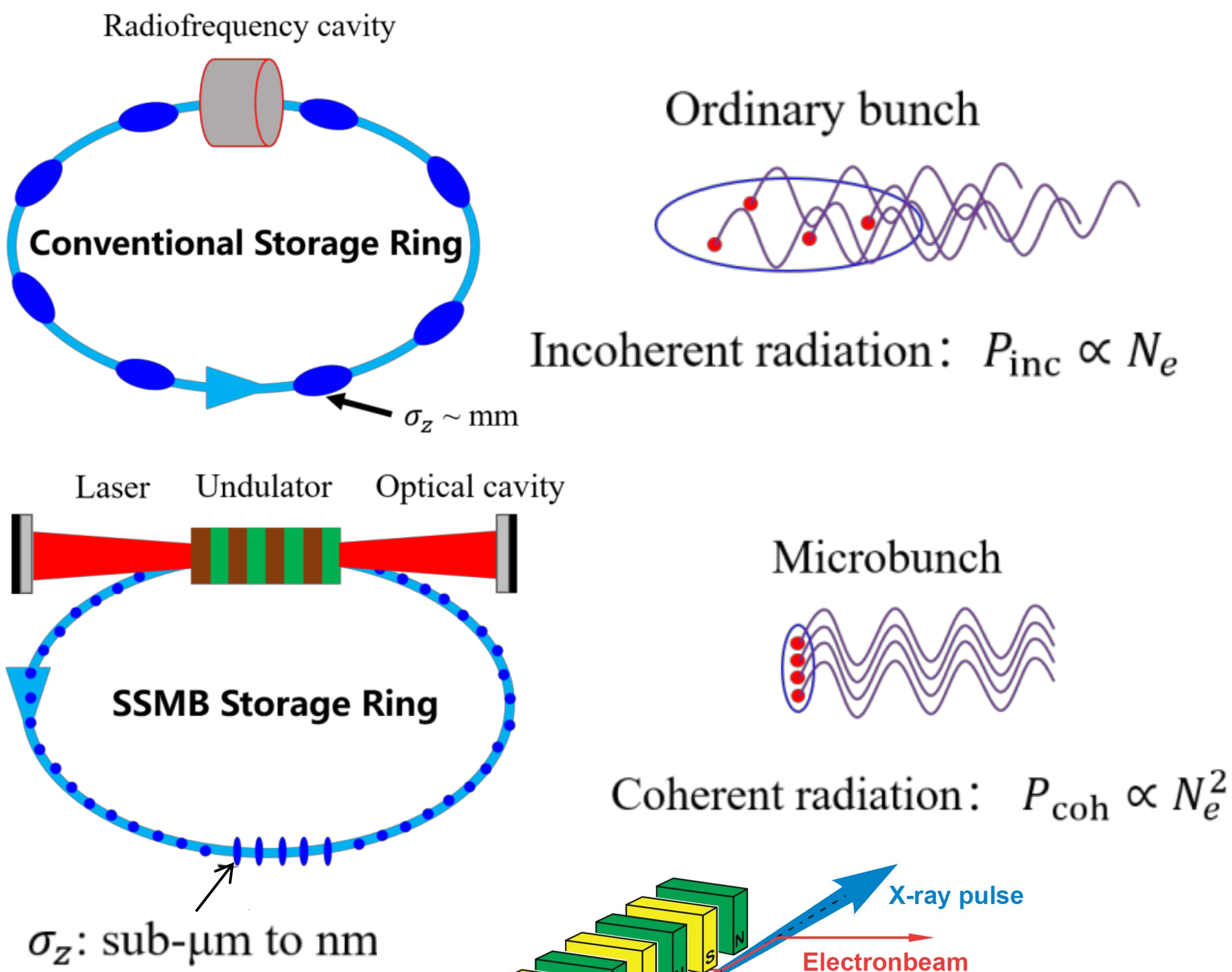
[1] D. F. Ratner and A. W. Chao, Steady-State Microbunching in a Storage Ring for Generating Coherent Radiation, Phys. Rev. Lett. 105, 154801 (2010).

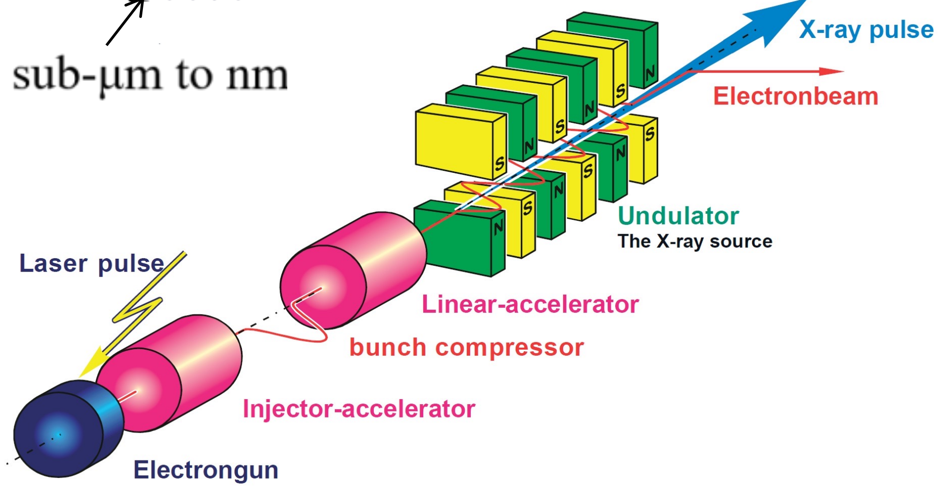
SSMB is Unique

- From SR：
  - **DLSR**： transversal coherent
  - **SSMB**：longitudinal coherent
- From FEL：
  - **FEL: Microbunching is from collective instability, need long undulator, and the MB can not be maintained long term.**
  - **SSMB: MB is from the active longitudinal focusing of the Laser in the modulator, a turn-by-turn steady-state.**

Challenges of beam physics in SSMB

bunch length
mm (ps)-> µm (fs) -> nm (as)
longitudinal beam physics





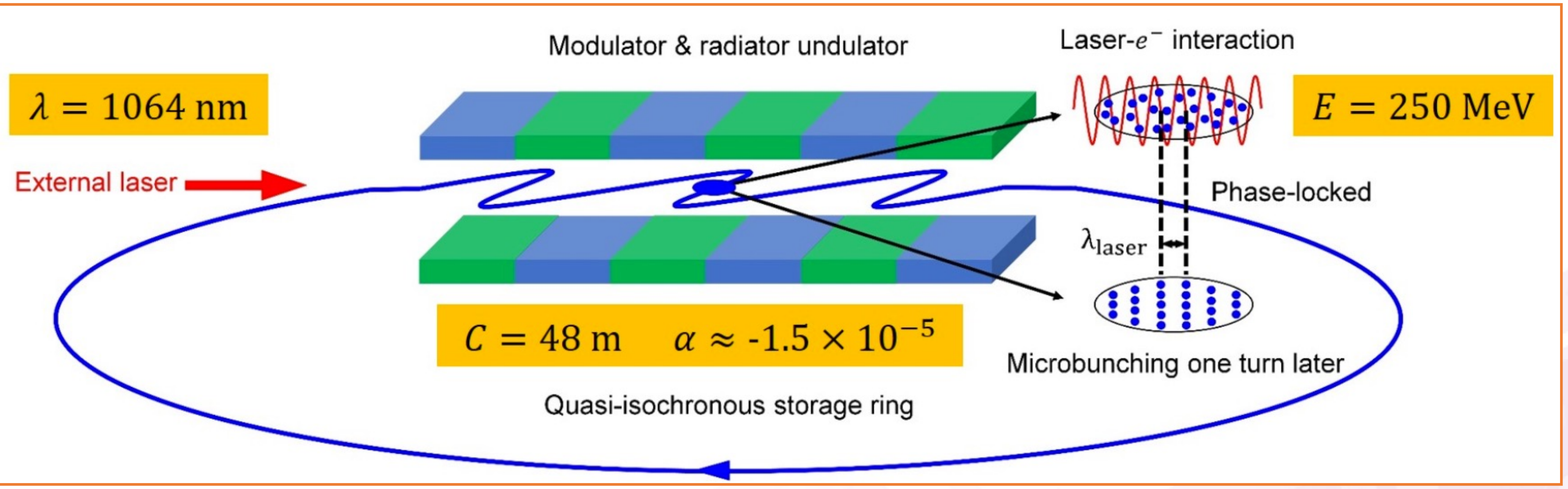
SSMB Collaboration[2,3]

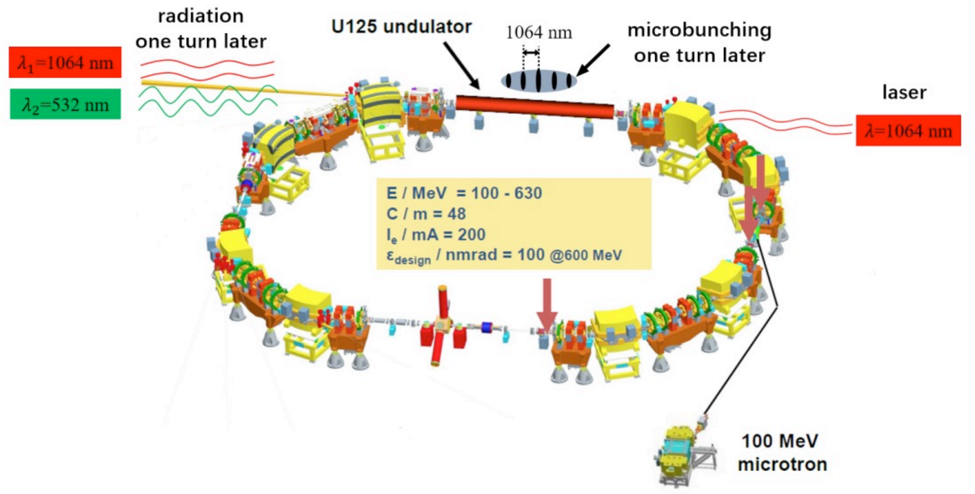
- An initial task force has been established at Tsinghua University, in collaboration with researchers from China, Germany, the USA, and elsewhere, to promote SSMB research with the goal of developing an SSMB storage ring.
- Three main tasks:
    1. **Proof-of-principle (PoP) experiment**
    2. Lattice design for SSMB ring[4-6]
    3. Resolve related technical issue

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

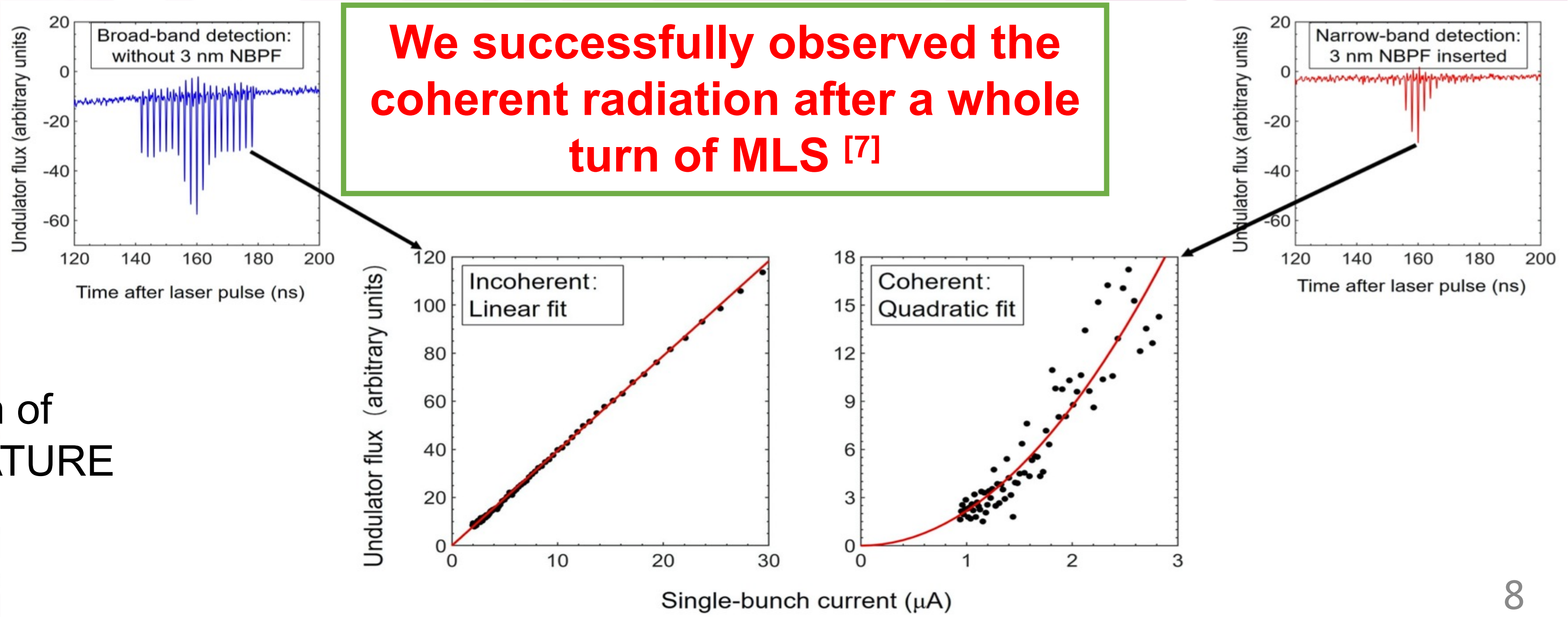
[2] C. Tang, et al., An Overview of the Progress on SSMB, in Proceedings of FLS18, Shanghai, China, 2018.
[3] A. Chao, et al., A Compact High-power Radiation Source Based on Steady-state Microbunching Mechanism, SLAC Technical Report No. SLAC-PUB-17241, 2018.
[4] T. Rui, et al., Strong Focusing Lattice 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.

SSMB PoP Phase I





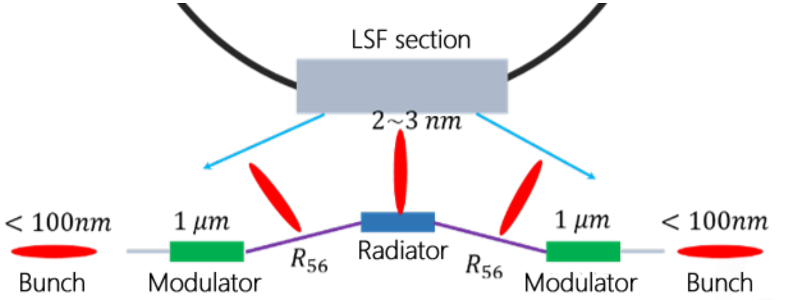
We successfully observed the coherent radiation after a whole turn of MLS [7]



[7] X J Deng et al, Experimental demonstration of the mechanism of steady-state microbunching , NATURE Vol590 , 25February2021

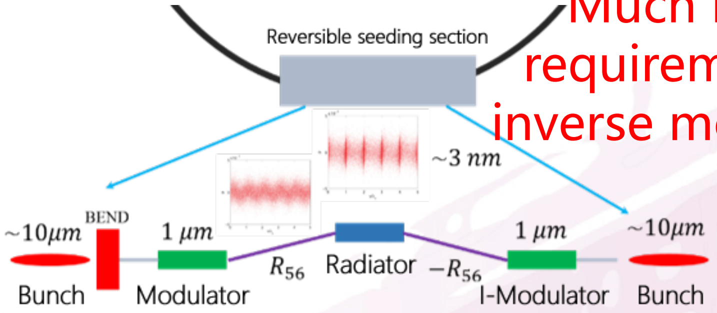
Schemes for high power EUV radiation

Longitudinal strong focusing

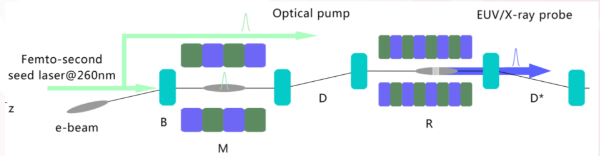


- Continue optimizing the lattice
- Analyze the impact of high order TL coupling on dynamic aperture
- Deeper study on single particle motion and collective effect, get steady 2-3 nm bunch
- Error analysis. Investigation of injection. Obtain a complete strategy for EUV

Reversible seeding



Much higher requirements on inverse modulation

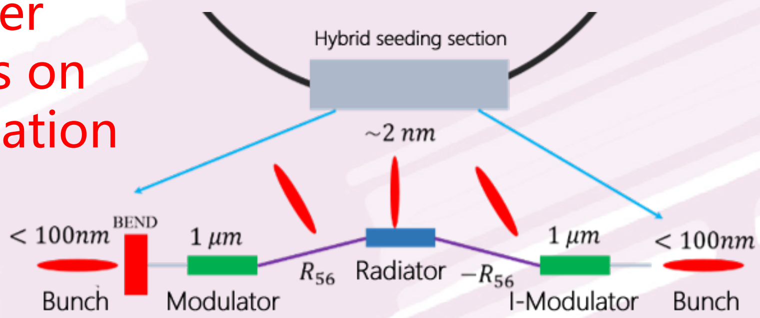


ADM

- Realize ultral-short beam and high harmonic at radiator by emittance exchange
- Reversible coupled lattice for bunch compression, chirp removement
- Error, collective effect analysis

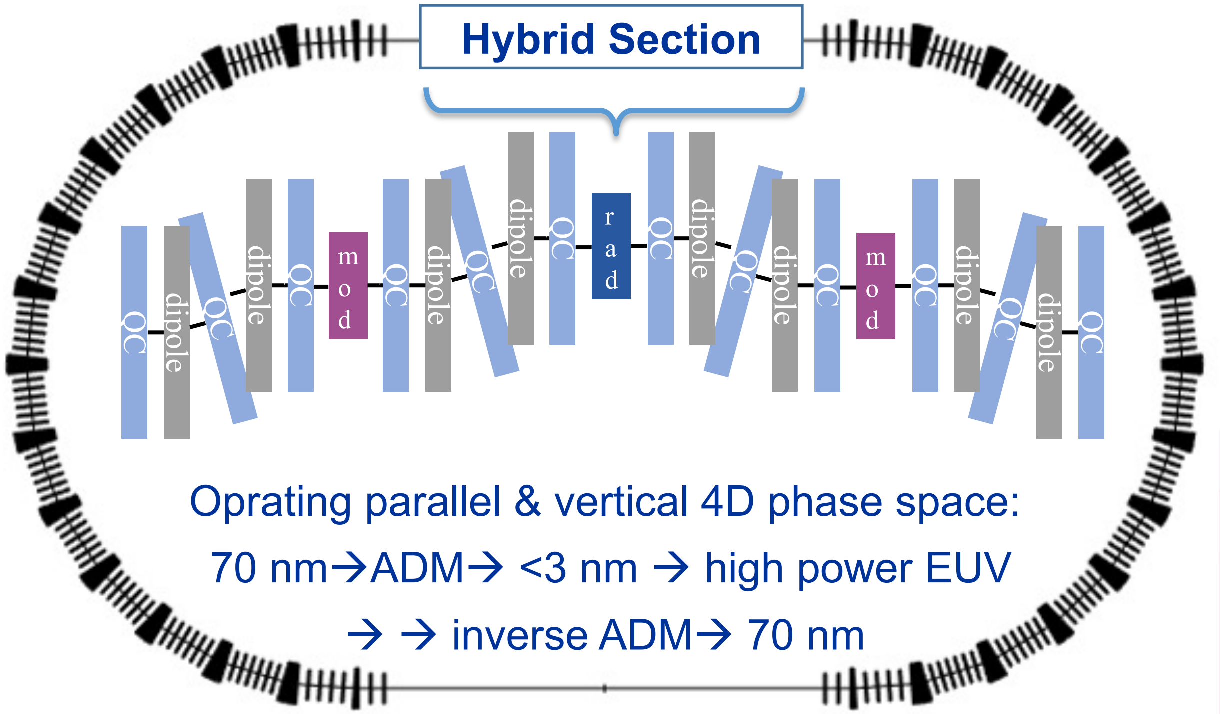
C. Feng, Z. T. Zhao, Sci. Rep. 7, 4724 (2017)
C. Li, C. Feng, B. Jiang PRAB 23, 110701 (2020)

Hybrid

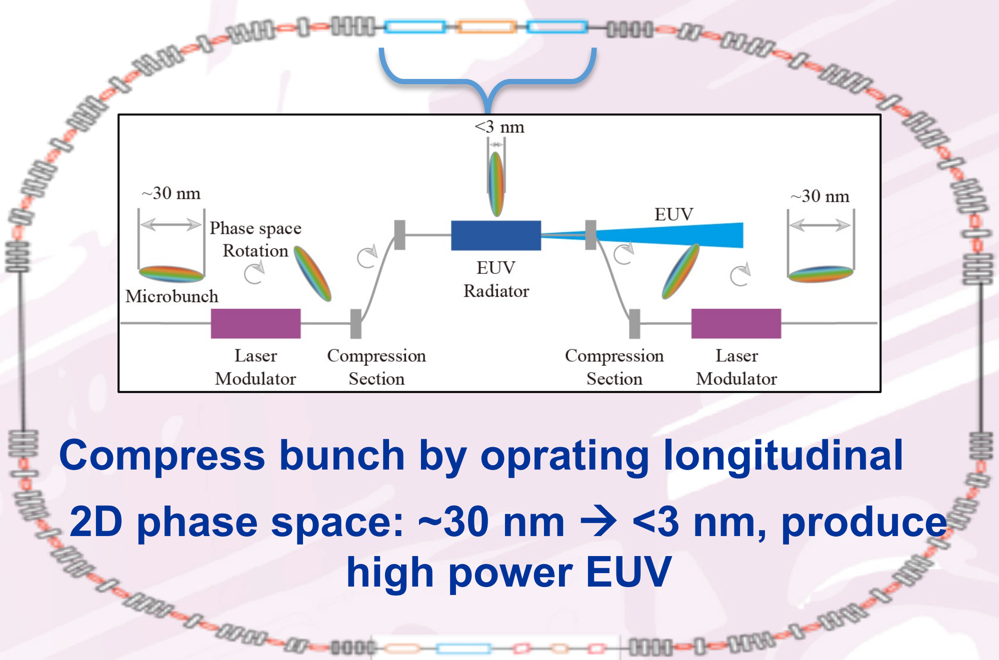


- Hybrid lattice combining low alpha and reversible seeding
- Take advantage of both schemes, get high power EUV at a low averaged current

Two SSMB Schemes Designed: Hybrid and LSF

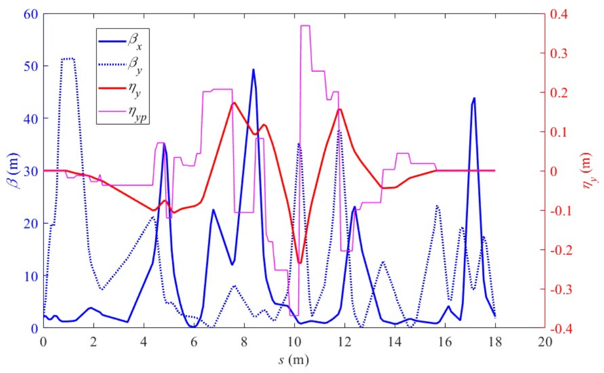


Oprating parallel & vertical 4D phase space:
70 nm→ADM→ <3 nm → high power EUV
→ → inverse ADM→ 70 nm



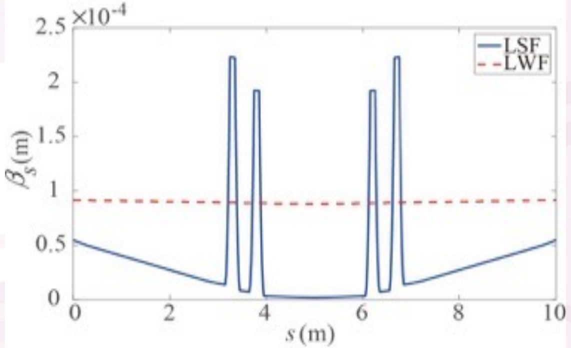
Compress bunch by oprating longitudinal 2D phase space: ~30 nm → <3 nm, produce high power EUV

Ring Lattice

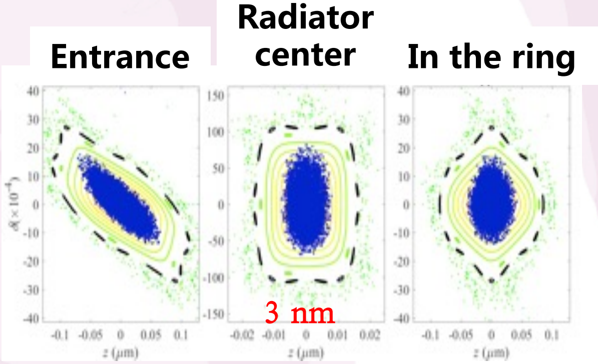


Optics of Hybrid section

ADM requires low vertical emittance, which is natural in a planar lattice!



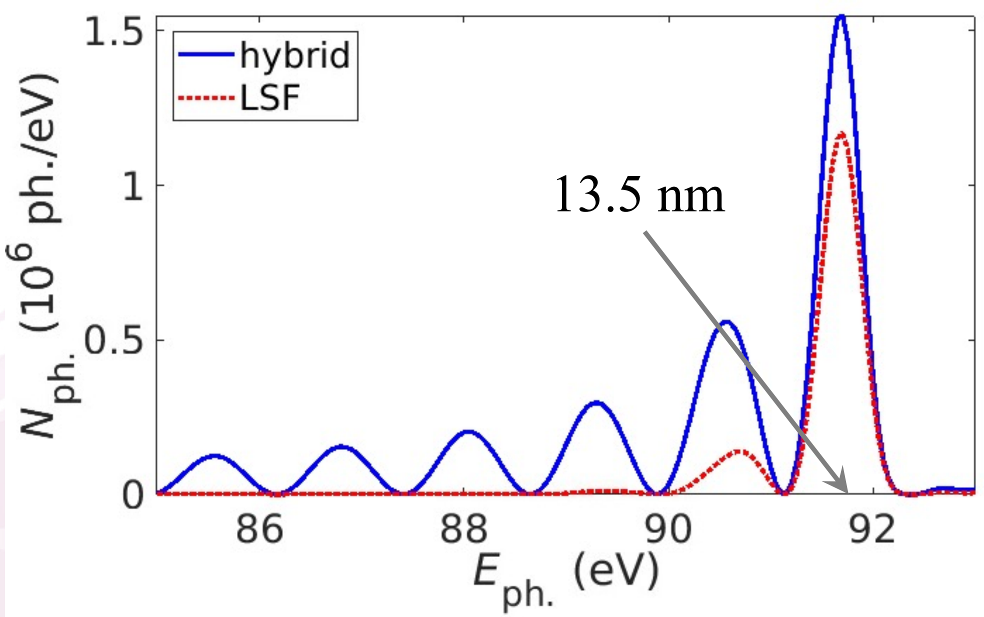
Optics of LSF section

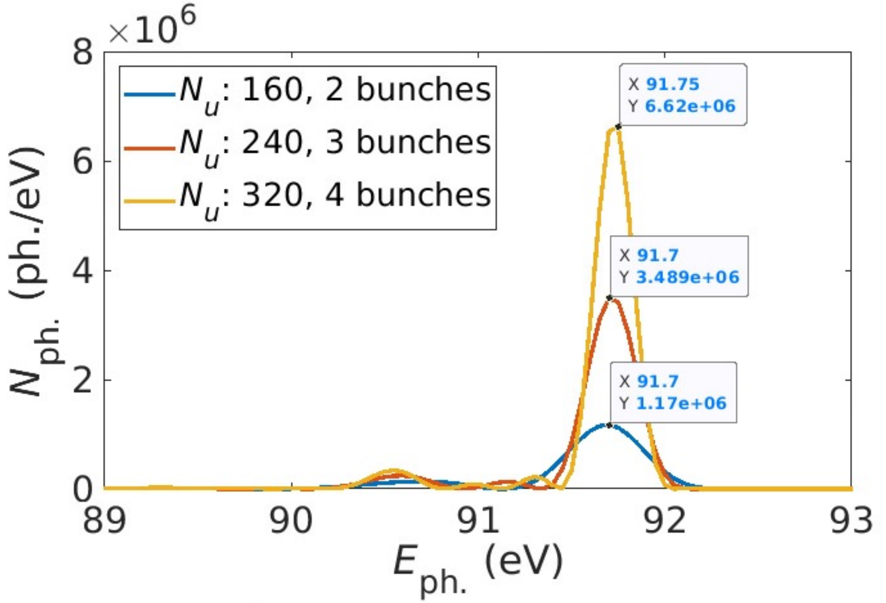


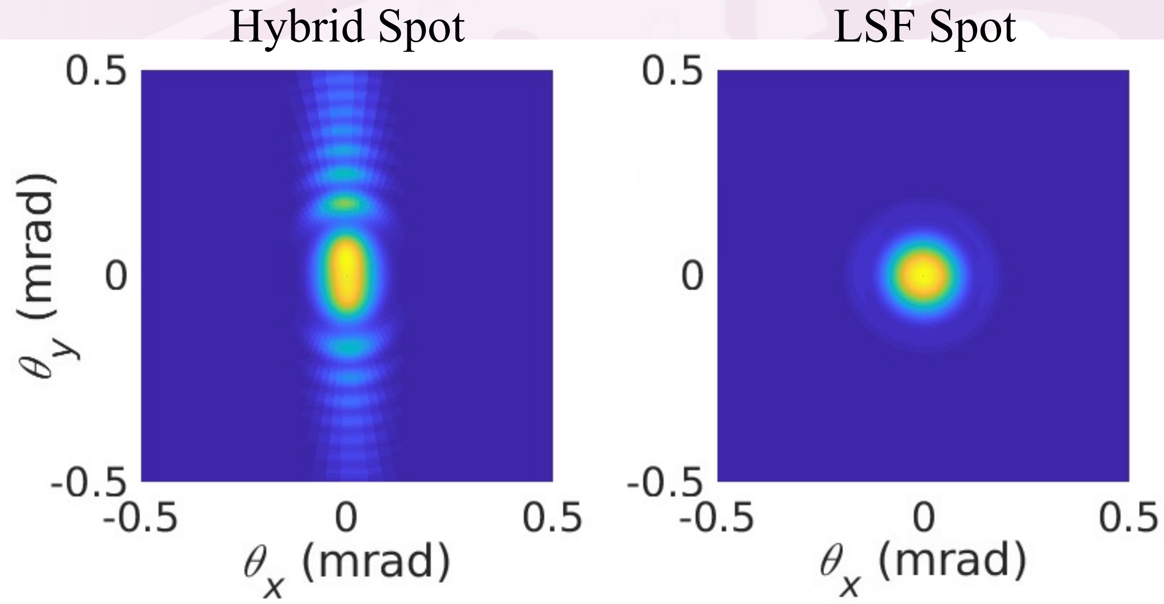
Longitudianal phase space

EUV Radiations of the Hybrid and LSF Schemes

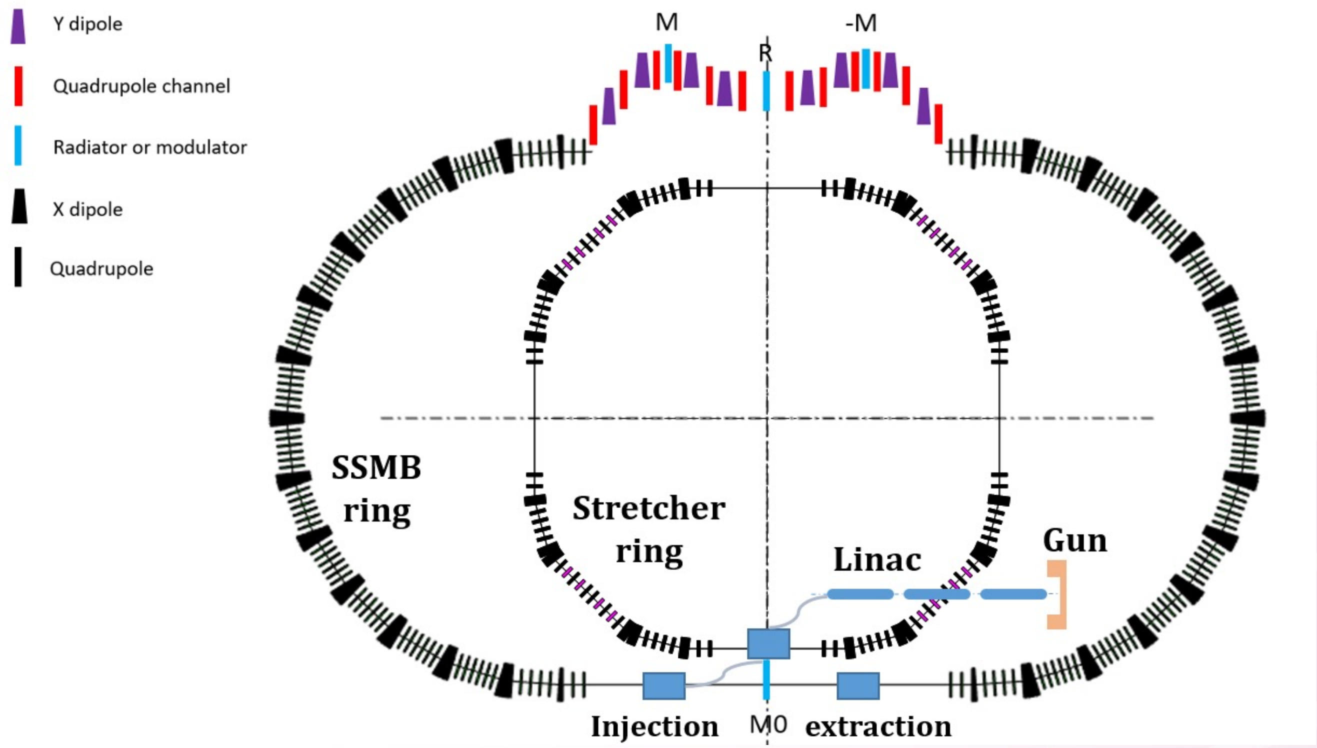
Paras.	Hybrid	LSF
Ratio	40%	88%
Power (W)	4200	2451
Mode	CW	Pulsed (Dutyfactor: 1%)







Hybrid Design of the SSMB-EUV Storage Ring



Parameters	Value
Circumference	138.43 m
Beam energy	400 MeV
Tunes (x/y)	0.23/0.21
Momentum compaction factor	-4.05×10^{-6}
Energy loss per turn	0.71 keV
Damping time (x/y/z)	539.9/542.1/271.6 ms
Energy spread	1.91×10^{-4}
Natural emittance	181.5 pm

- The electrons will be produced by Photocathode gun.
- Accelerated to 400 MeV by Linac accelerator.
- Stretched by a large R56 ring, and became coasting beam after circling about 200 turns in the ring.
- Injected to SSMB ring, with super small equilibrium bunch length under 100 nm
- Further compressed to 3 nm, generate kWs EUV radiation.

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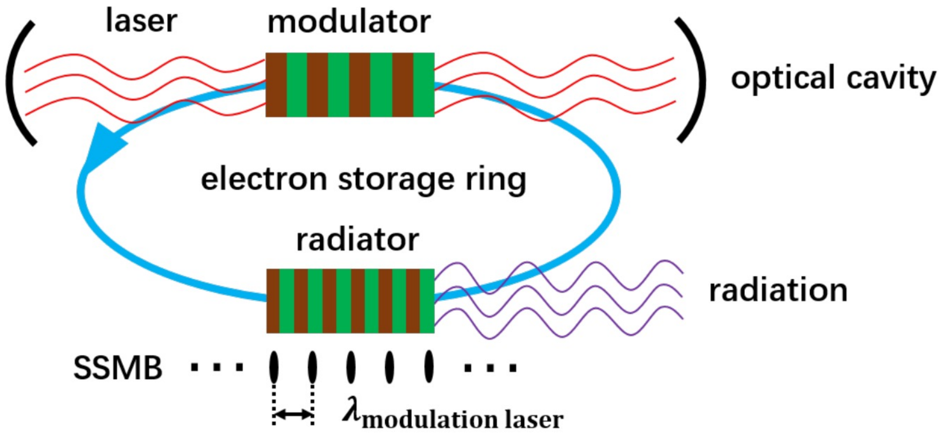
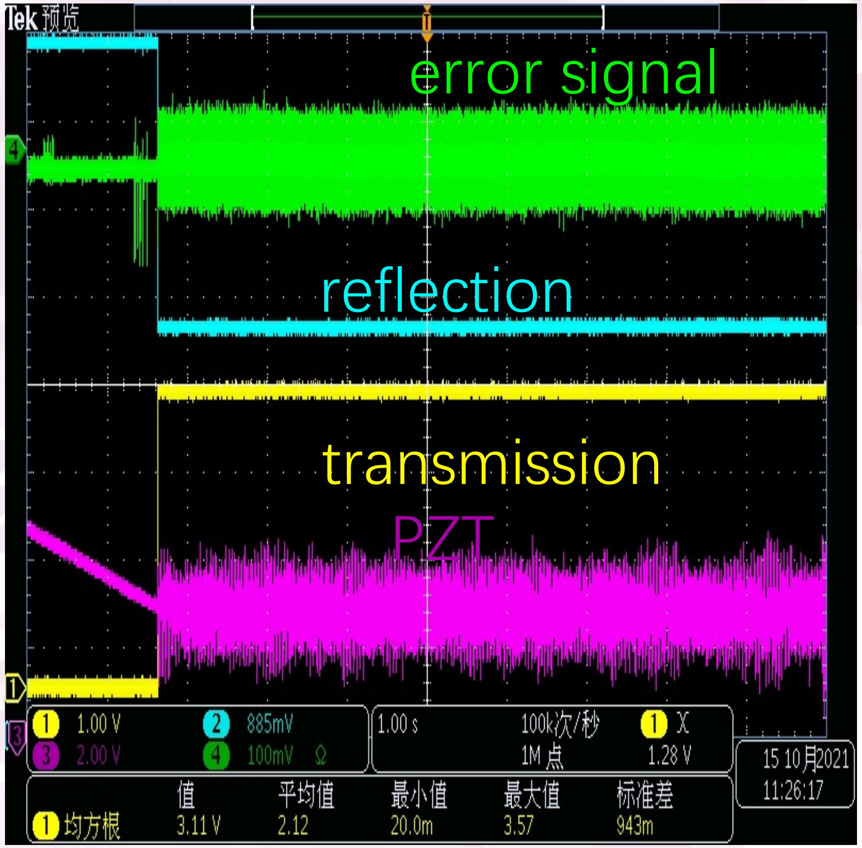
Key Technology- OEC

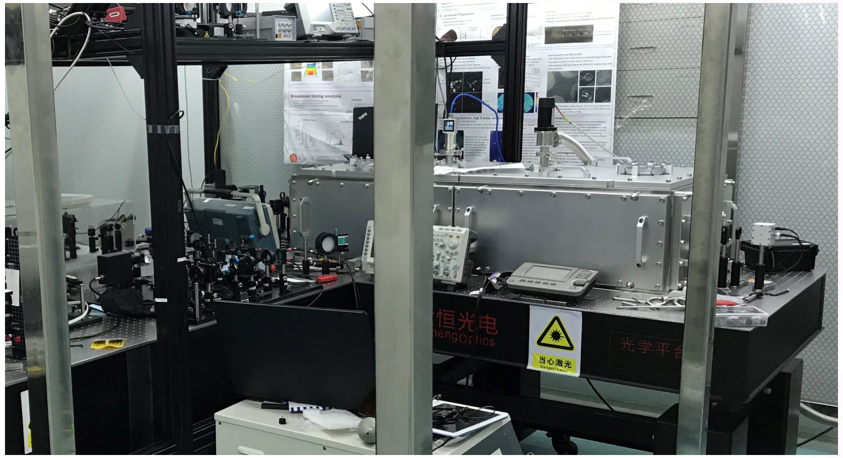


Yan's Talk

- Injection power: ~130W
- Cavity gain: ~10,000
- OEC power: ~1MW



A First OEC experiment setup (>100 cavity gain)



Coupling efficiency: ~45%

OEC Power stability: ~0.5%

Summary

- SSMB is one kind of brand new light source, its storage ring is focus on longitudinal phase space, nanometer bunch length physics, longitudinal strong focus, ultra-low whole ring and partial momentum compression factors.
- SSMB EUV is a potential light source with kW power for EUV and even blue-X lithography, with relatively low price.
- The SSMB principle has been proved experimentally, and an SSMB-EUV light source has been designed at THU, which can provide more than 4 kW EUV light power . The OEC for SSMB is nearly ready.

Thanks for your attention!