清華大學
Tsinghua University

6th EUV-FEL WORKSHOP

Recent progress of SSMB EUV light source project at Tsinghua University

Zhilong Pan

On behalf of Tsinghua SSMB Task Force

2022.01.18

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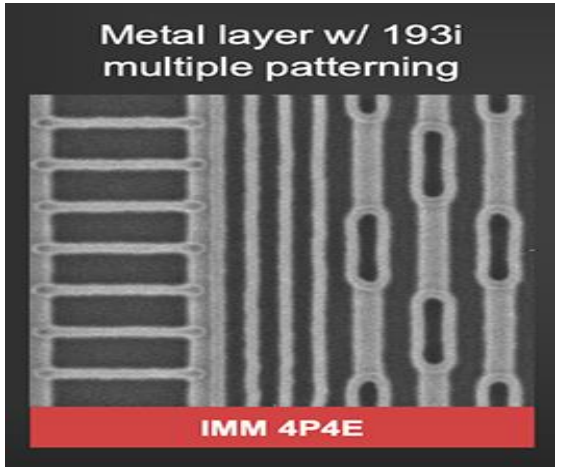
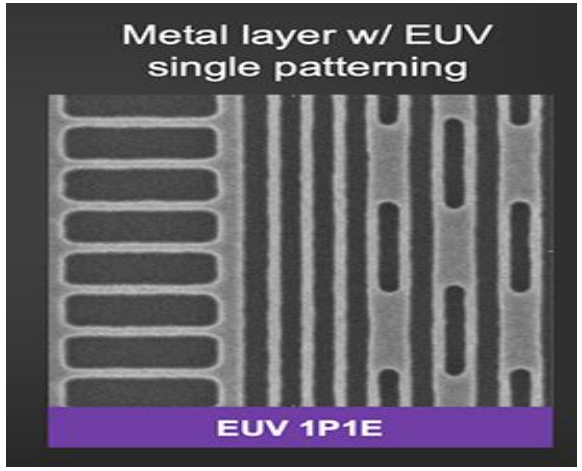
The history of EUV lithography

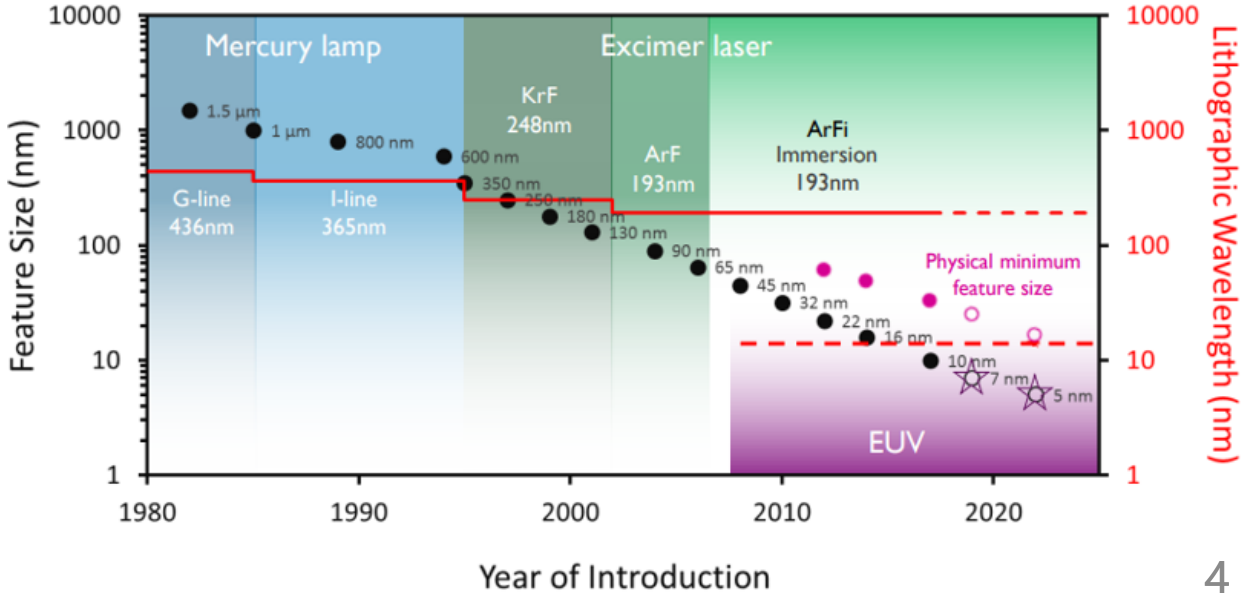
- EUV lithography：began from 1980s, EUV LLC was found in 1994
- EUVL is the most advanced technology for node 7 nm or below, can signifi-cantly simplify the lithography process compared to the DUV lithography.
- Several EUV light sources were proposed, LPP-EUV succeeded in 2004 and extended to industry afterward.



193 nm: 4 masks needed

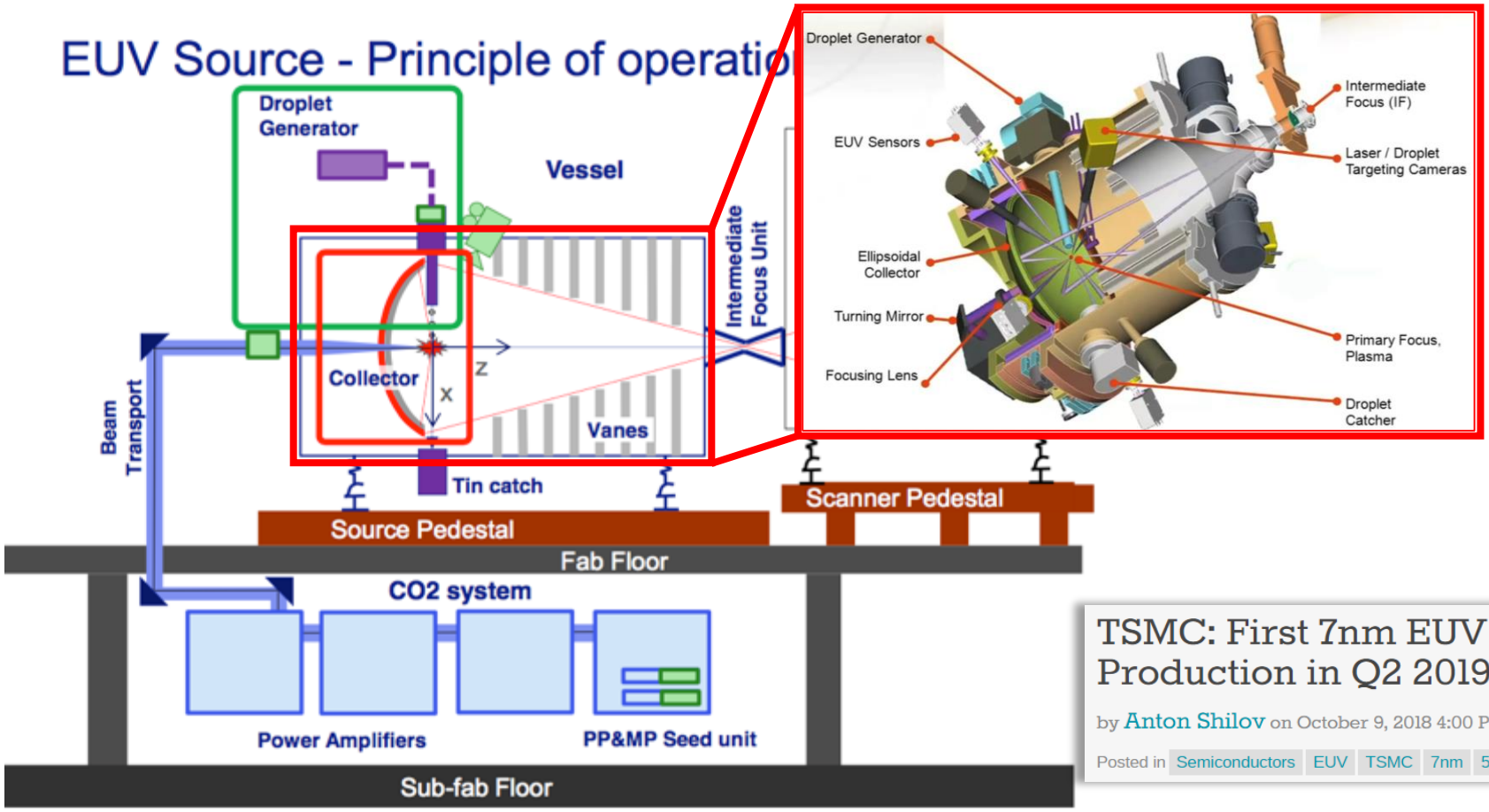


EUV: 1 mask needed



The history of EUV lithography

- **ASML has achieved huge success in LPP-EUV route**
- **Next generation EUVL: need 1 kW or higher power EUV light source**



nodes		power needed
7 nm	→	250 W
5 nm	→	350 W
3 nm	→	500 W
2 nm	→	1 kW

The future?

TSMC: First 7nm EUV Chips Taped Out, 5nm Risk Production in Q2 2019

50 Comments

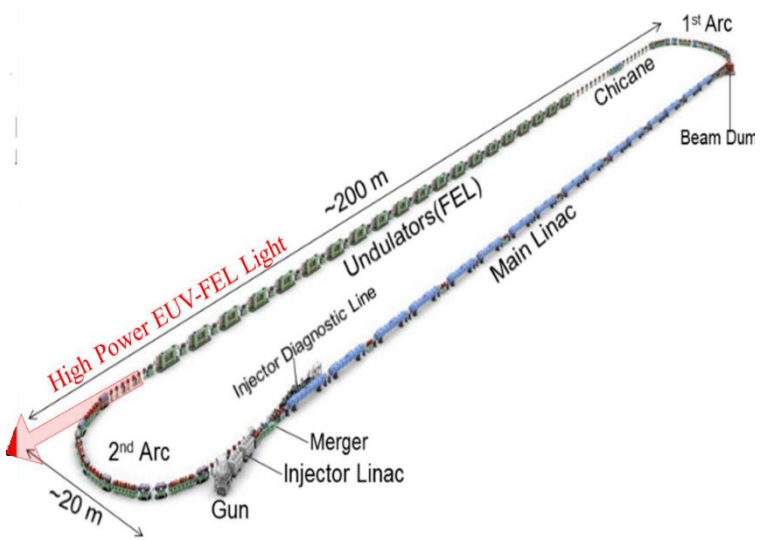
by Anton Shilov on October 9, 2018 4:00 PM EST

+ Add A Comment

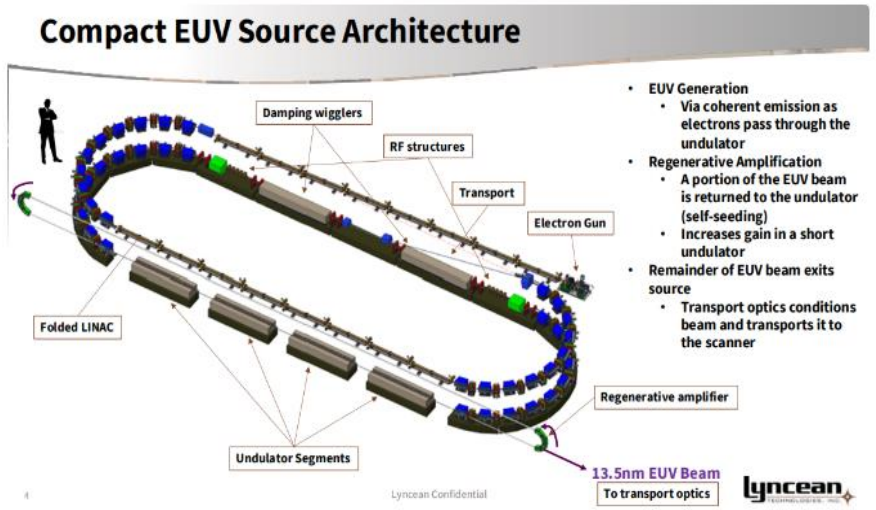
Posted in Semiconductors EUV TSMC 7nm 5nm CLN7FF CLN5

1 kW EUV light source

- **Several proposals to generate ~1 kW EUV**
- **ERL-FEL: Energy recover Linac based FEL technology. (KEK)**
- **Ring-FEL: Ring based FEL technology. (Lyncean Company)**
- **SSMB: Ring based, Steady State Microbunching mechanism. (THU)**
- **ERL-SSMB: ERL based steady-state microbunching mechanism. (SSRF)**

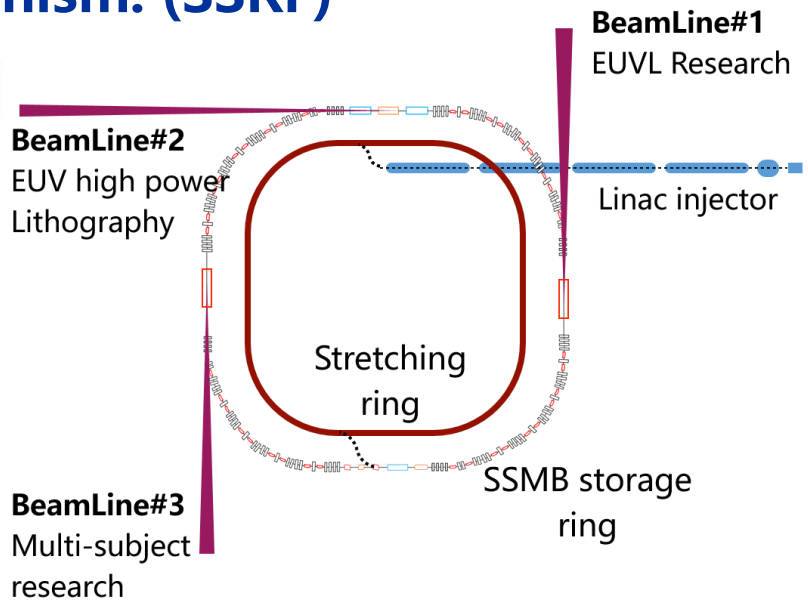


ERL-FEL



2021年1月Lyncean公布的13.5nm EUV光源的设计方案

Ring-FEL



SSMB

2021 N. Nakamura 5th EUV-FEL workshop

2021 R. Loewen 5th EUV-FEL workshop

2021 C. Tang EUVL source workshop

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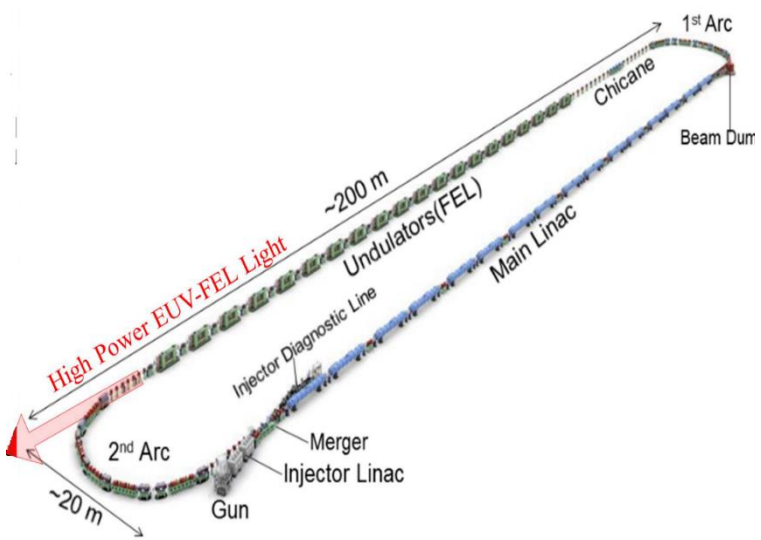

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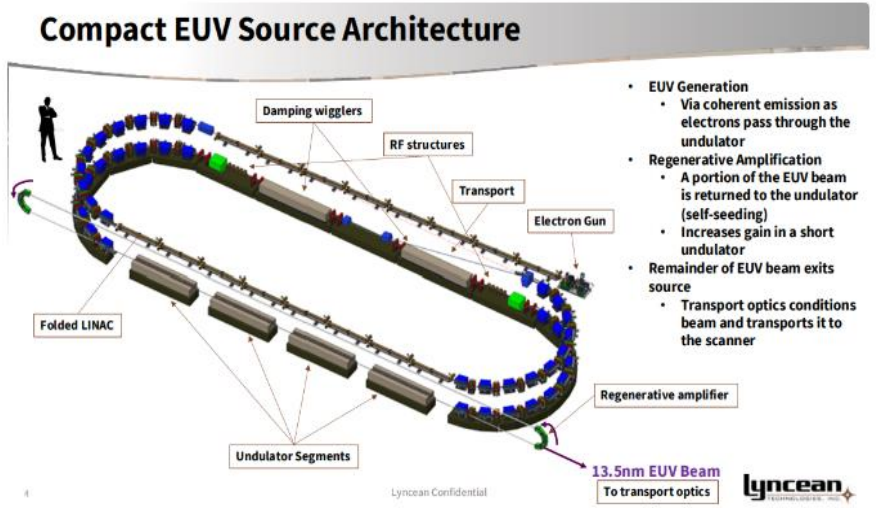

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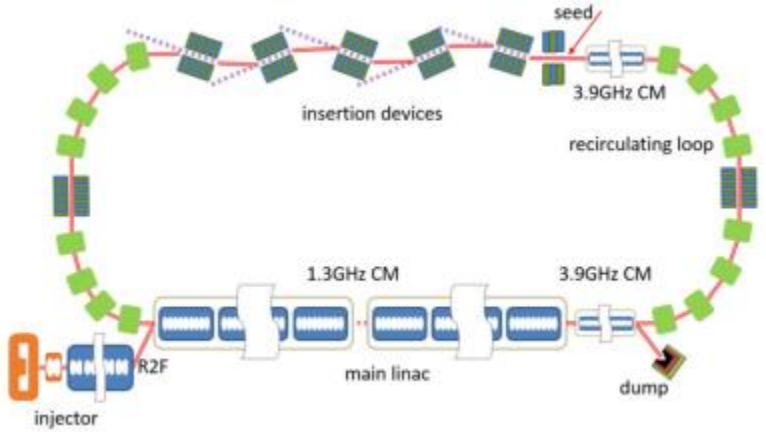


ERL-SSMB

2021 N. Nakamura 5th EUV-FEL workshop

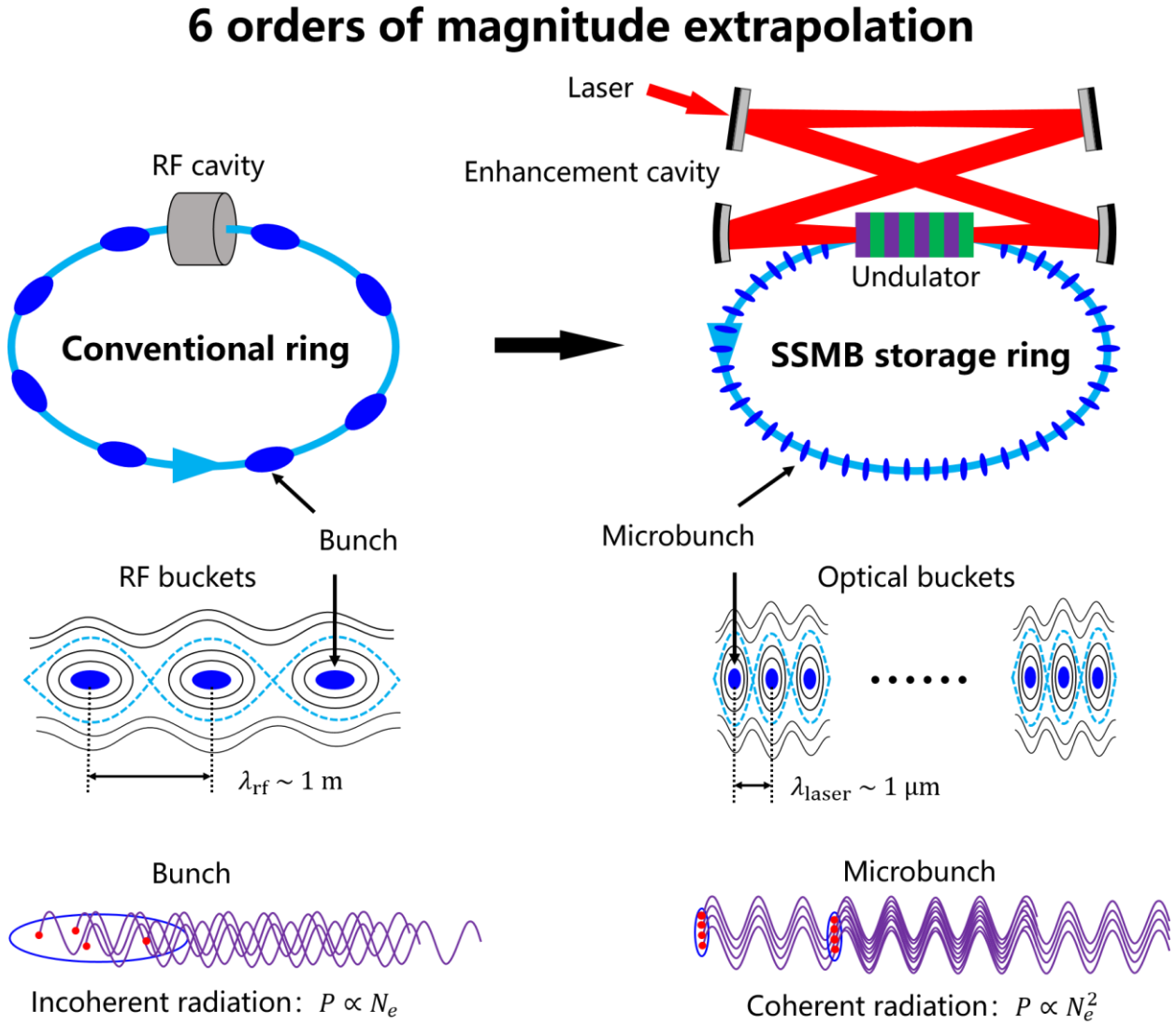
2021 R. Loewen 5th EUV-FEL workshop

2021 Z.T. Zhao scientific reports

Contents

Steady-state Microbunching (SSMB)

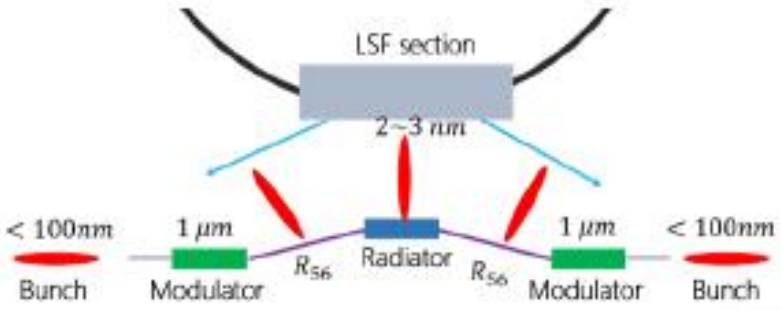
- Electron storage ring-based
- Bunching system laser modulator, instead of RF cavity
- Two key points
  - microbunching for strong coherent radiation
  - turn-by-turn steady state for high repetition rate
- High average power, high repetition rate coherent radiation, with wavelength ranging from THz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



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

Schemes for high power EUV radiation

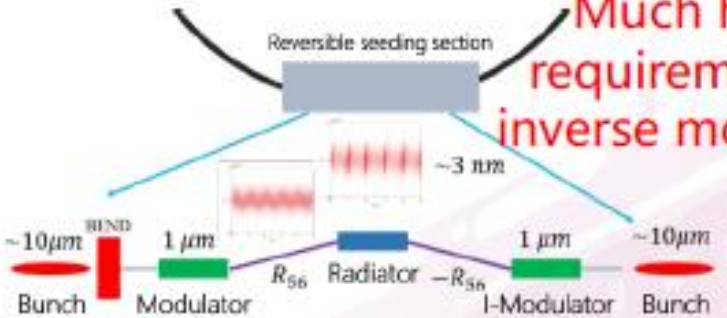
Longitudinal strong focusing



- Low-alpha ring (~100 nm bunch) + longitudinal strong focusing (~3nm)
- Required laser power: hundreds MW, pulsed, Duty rate: 1%
- Pulse power : several kW, average power : several tens W

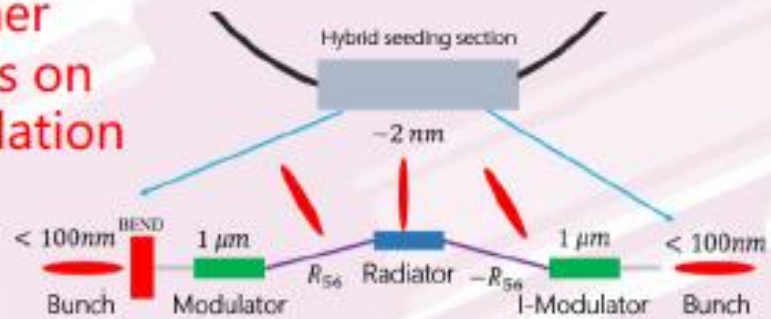
Reversible seeding

Much higher requirements on inverse modulation



- normal ring + ADM compress (~3nm)
- Required laser power: ~1 MW
- Low bunching factor, coasting beam (@10A)
- Average power : ~ kW

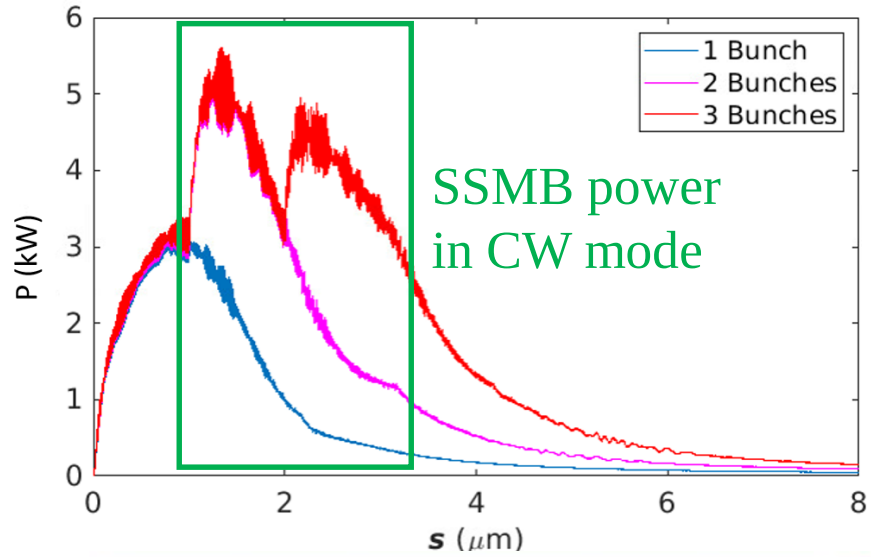
Hybrid

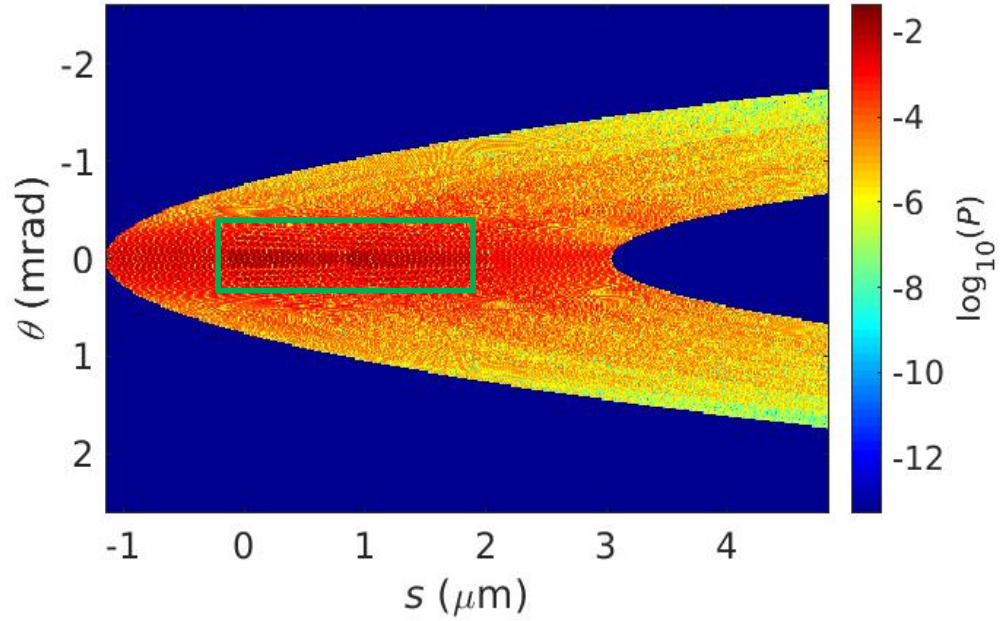


- Low-alpha ring (~100 nm bunch) + ADM compress (~3nm)
- Required laser power: ~1 MW
- high bunching factor
- Average power : ~ kW (@1A)

EUV radiation property

Paras.	Hybrid	LSF
Ratio	40%	41%
Power (W)	4200	3292
Mode	CW	Pulsed (Duty factor: 1%)





- Modulation laser wavelength: 1 um. So as the bunch separation
- The radiation will be CW
- Narrow band, Nu ~ hundreds

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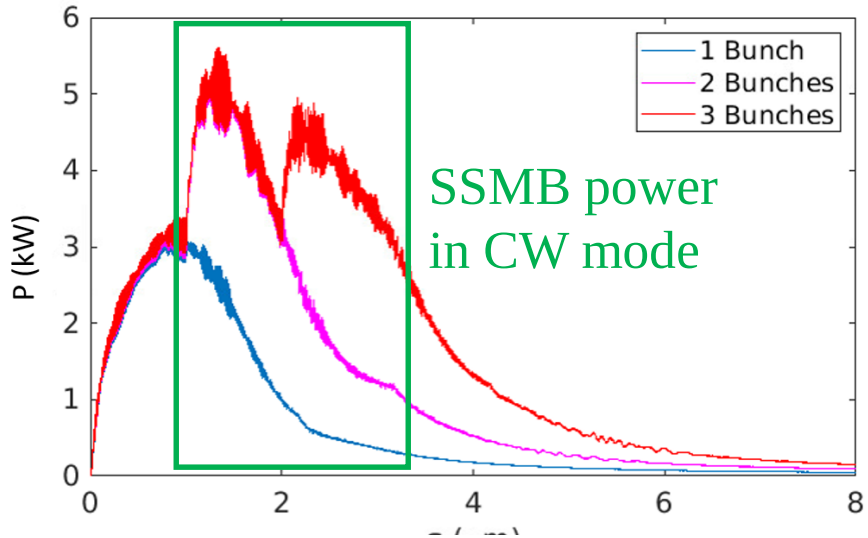
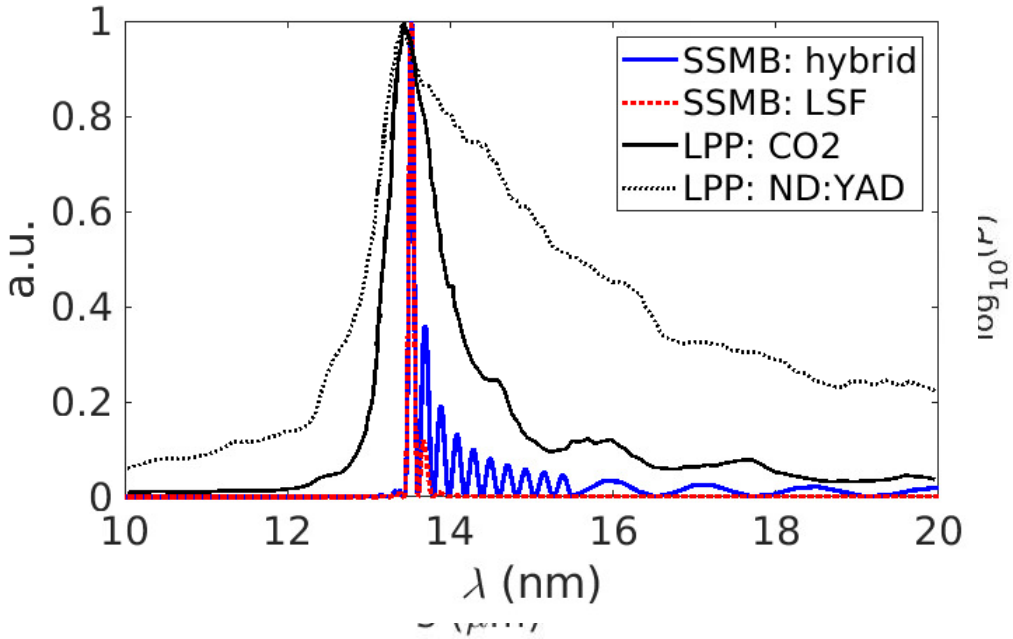
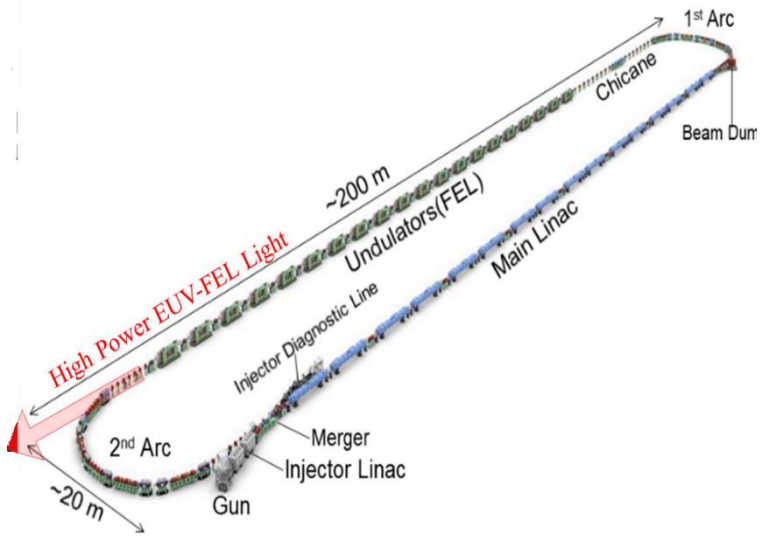




Comparison with other schemes



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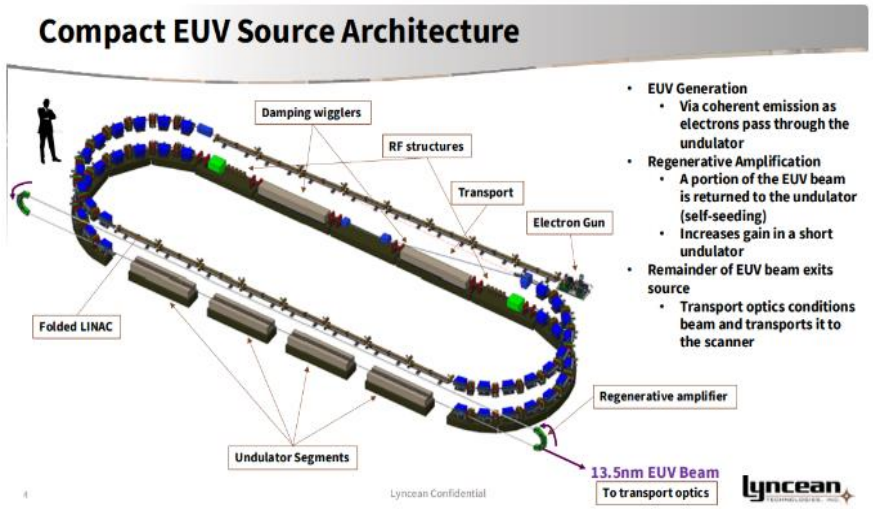

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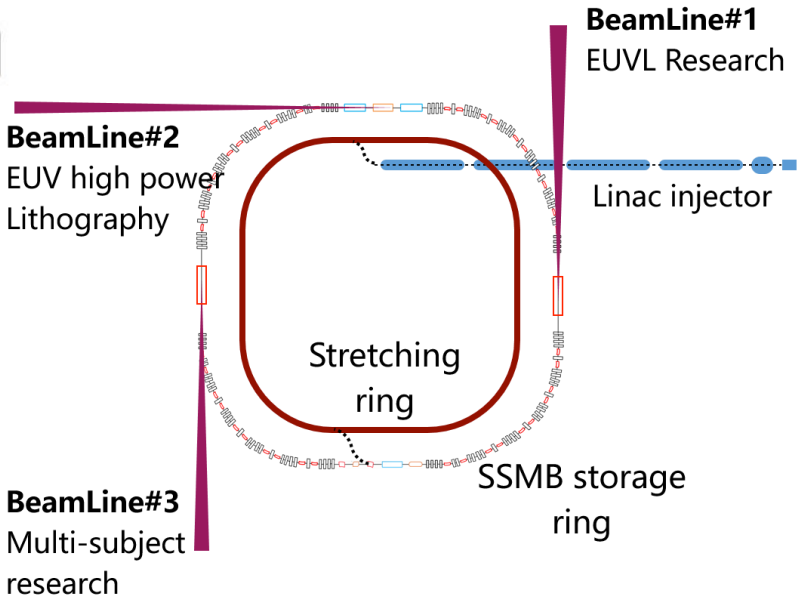

SSMB

- ☐ ~hundreds meter undulator
- ☐ Super-conductivity Linac
- ☐ average power : ~kW to 10kW
- ☐ Test facility commissioning

- ☐ ~tens meter undulator
- ☐ Ring-based, strong damping
- ☐ average power : ~kW
- ☐ Conceptual design

- ☐ ~several meter undulator
- ☐ Ring-based, steady-state
- ☐ average power : ~kW
- ☐ Conceptual design

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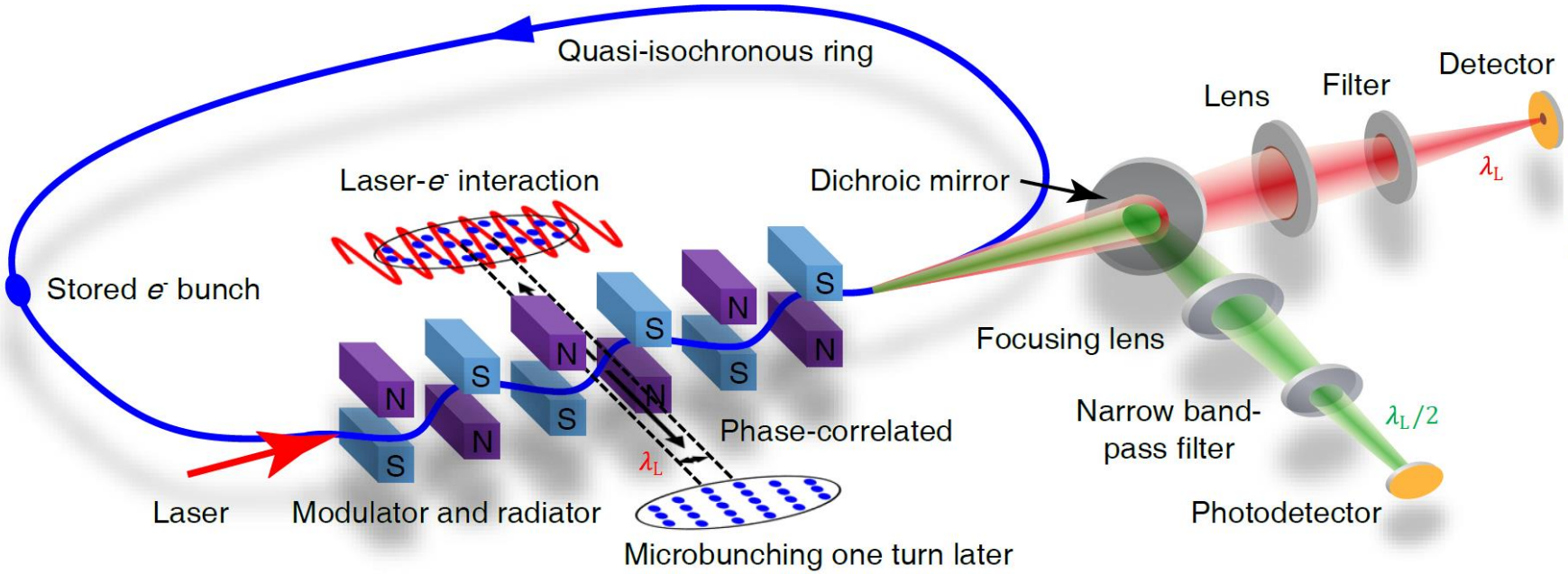
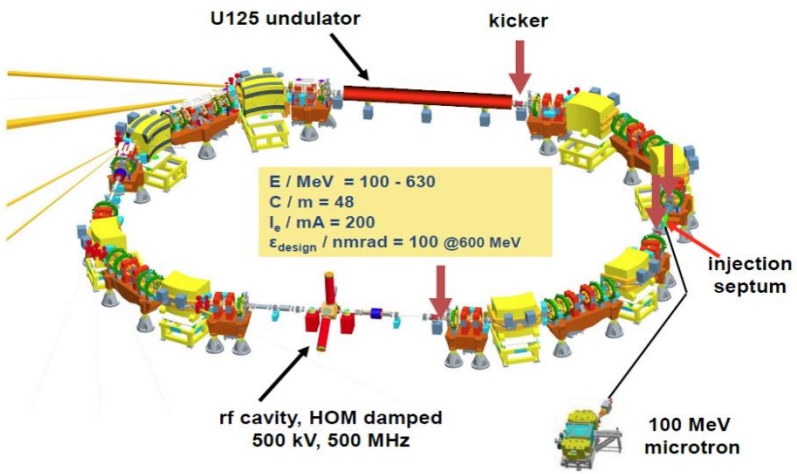
Proof-of-principle experiment





- Phase I: modulate one turn, observe CSR afterward
- Collaboration with HZB &PTB
- Experiment is achieved at MLS

- Phase II: modulate thousands turns, keep MB each turn.
- Hopefully can be finished in 2022

- Phase III: true SSMB, keep MB to steady-state
- Under consideration

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

Proof-of-principle experiment

- **The experiment result has published in *Nature***
- **And the News & views said:**

News & views

Experimental physics

Accelerator-based light sources get a boost

Alexander Brynes

The structure of matter can be explored using the light emitted by particle accelerators. An experiment demonstrates how the properties of two such light sources – synchrotrons and free-electron lasers – can be combined. See p.576

…operties of matter …rt scales of length …eng *et al.*[1] report a …ment on an acceler- …apabilities of these machines even further, potentially yielding applications in a next-generation chip-etching technology called extreme-ultraviolet litho-graphy[2] and an advanced imaging method known as angle-resolved photoemission spectroscopy[3].

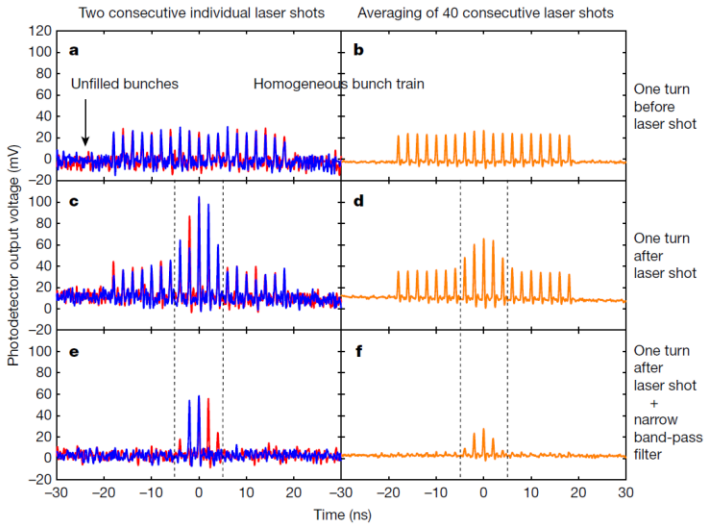
Article

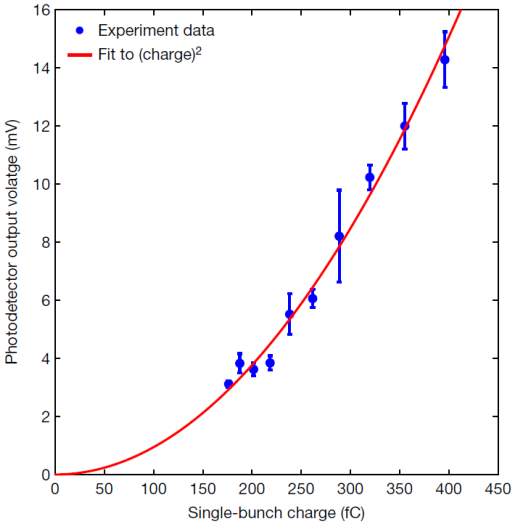
Experimental demonstration of the mechanism of steady-state microbunching

https://doi.org/10.1038/s41586-021-03203-0
Received: 27 March 2020
Accepted: 7 January 2021
Published online: 24 February 2021
Check for updates

Xiujie Deng[1], Alexander Chao[2,3], Jörg Feikes[4]✉, Arne Hoehl[5], Wenhui Huang[1], Roman Klein[5], Arnold Kruschinski[4], Ji Li[4], Aleksandr Matveenko[4], Yuriy Petenev[4], Markus Ries[4], Chuanxiang Tang[1]✉ & Lixin Yan[1]

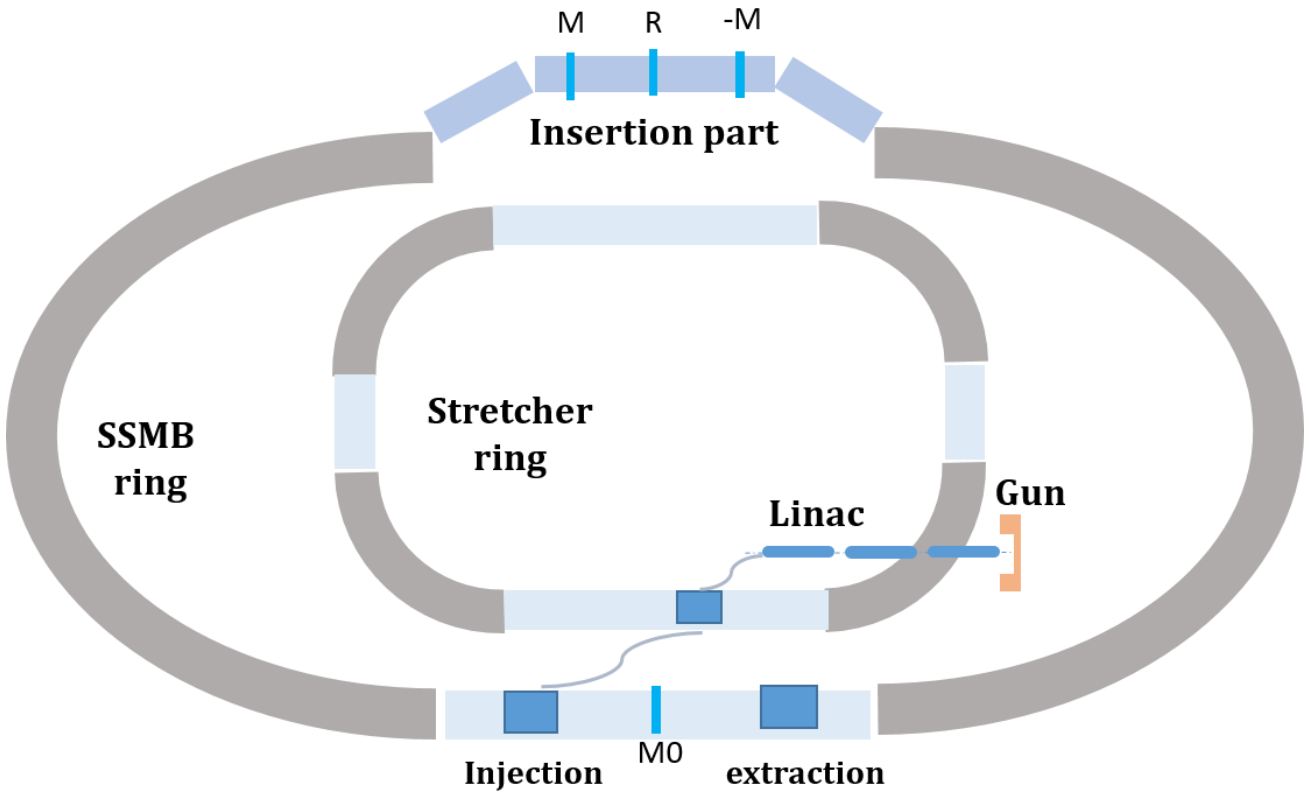
The use of particle accelerators as photon sources has enabled advances in science and technology[1]. Currently the workhorses of such sources are storage-ring-based synchrotron radiation facilities[2–4] and linear-accelerator-based free-electron





*** X. Deng, C. Tang*, et al. Experimental demonstration of the mechanism of steady-state microbunching. Nature 590, 576 (2021).**

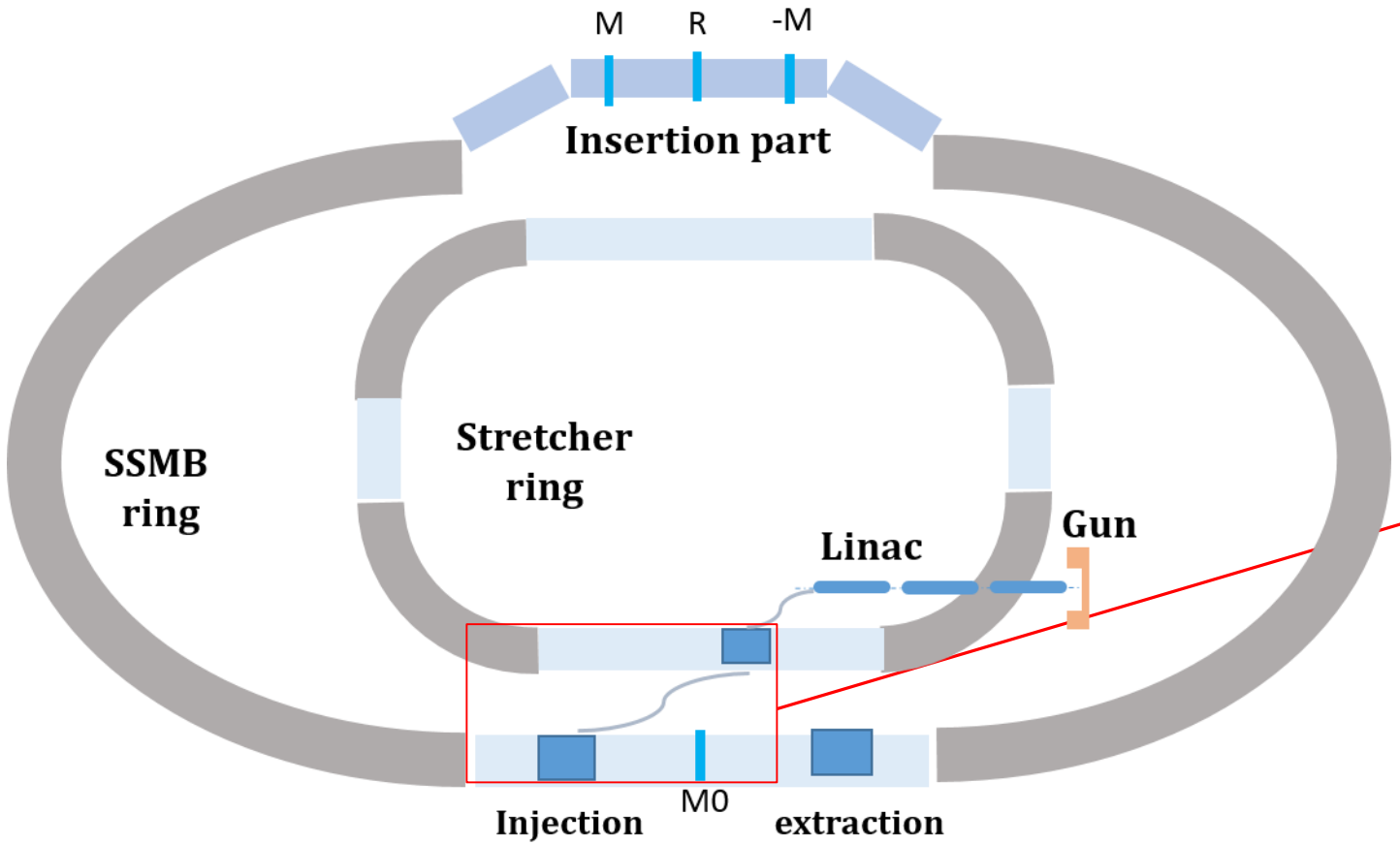
THU SSMB-EUV light source project

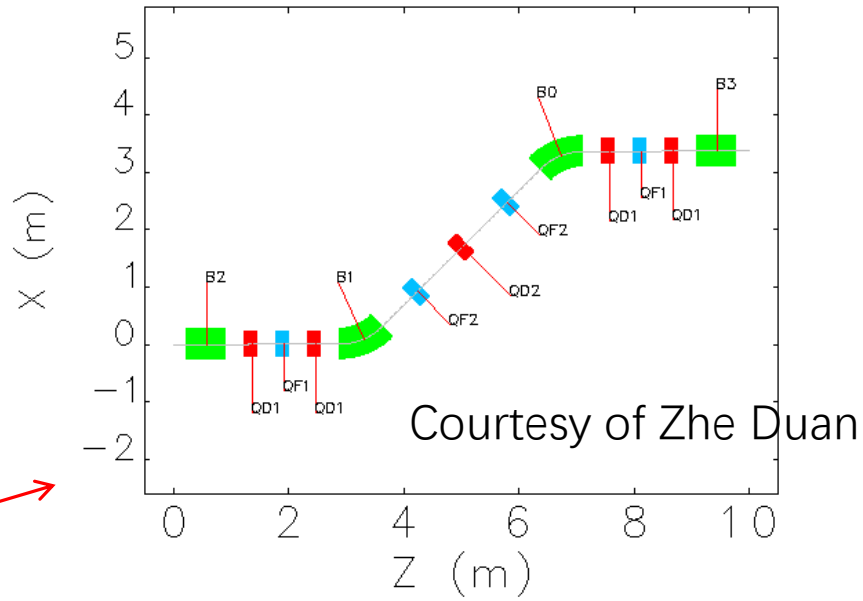


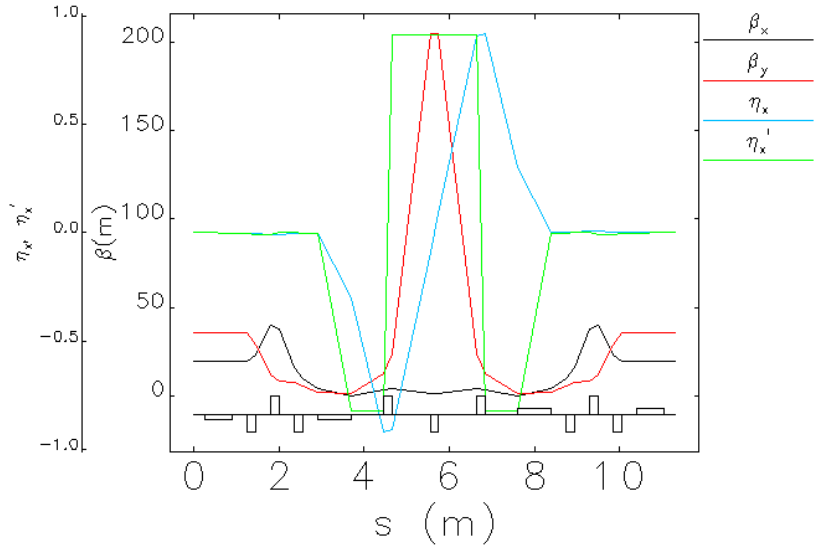
Parameters	Value	Units
Circumference	138.43	m
Beam enerfy	400	MeV
Tunes （x/y）	0.23/0.21	
α_c	-4.05×10^{-6}	
Damping time (x/y/z)	539.9/542.1/271.6	ms
Energy spread	1.91×10^{-4}	
Natural emittance	181.5	pm
Bunch length	74.1	nm

- The electron bunches will be produced by Photocathode gun
- Accelerated to 400 MeV by Linac and then stretched by a large R56 Ring for about 200 turns, became a coasting beam finally.
- Injected to SSMB ring, compressed to ~3 nm, and generate kWs EUV radiation.

THU SSMB-EUV light source project

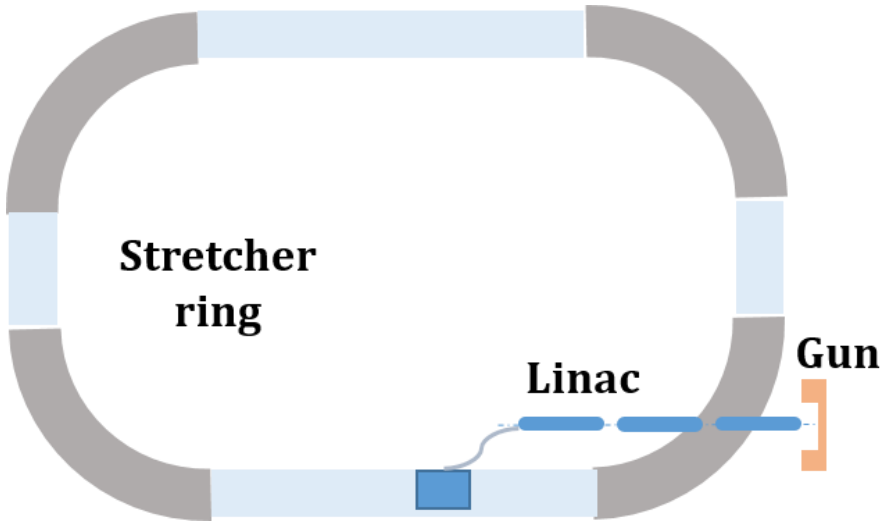


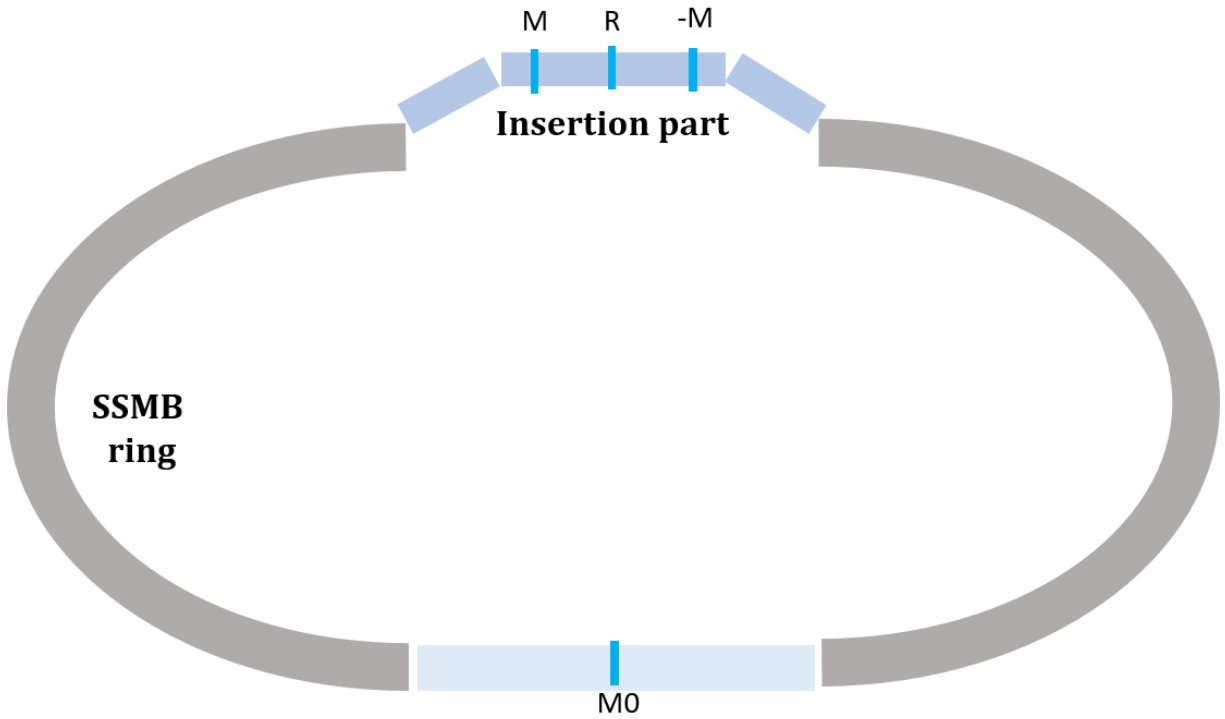




- Achieved injection transfer line and kicker design.
- Achieved extraction beam dump design.
- Start to end simulations are ongoing

THU SSMB-EUV light source project

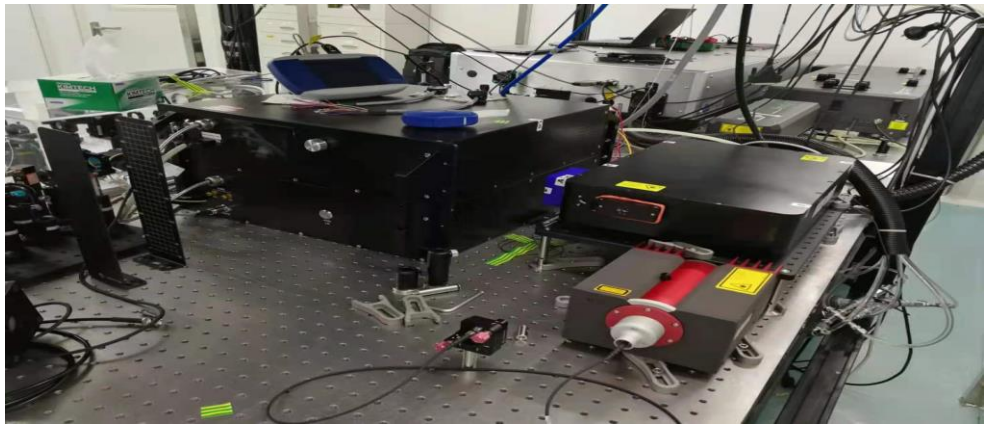




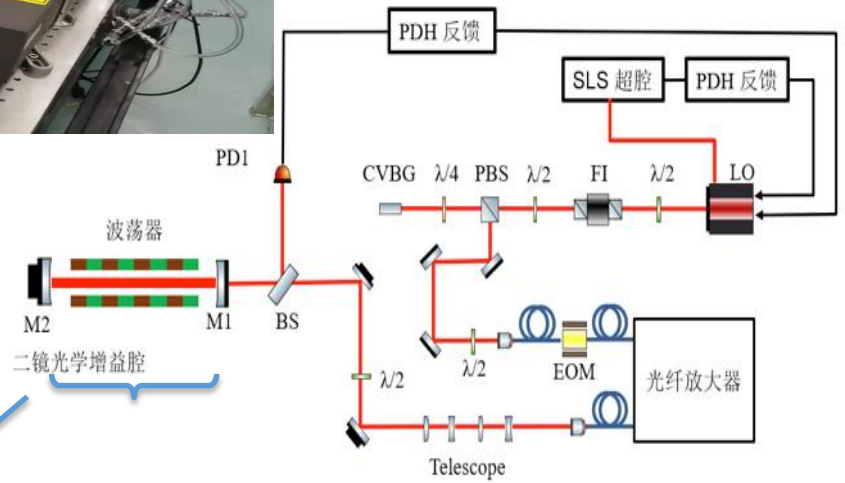
- Achieved Linac and stretching ring design, the energy spread of coasting beam can be below 0.05% (beam loading effects considered).
- Top-up injection scheme is considered, to maintain the stability of EUV power

- Achieved SSMB main ring design, the bunch length in ring will be less than 100 nm.
- Achieved hybrid insertion design, the electron bunch can be compressed to 3nm, can generate > 1kW power
- Multi-particles effects are studying, nonlinear optimization is on going

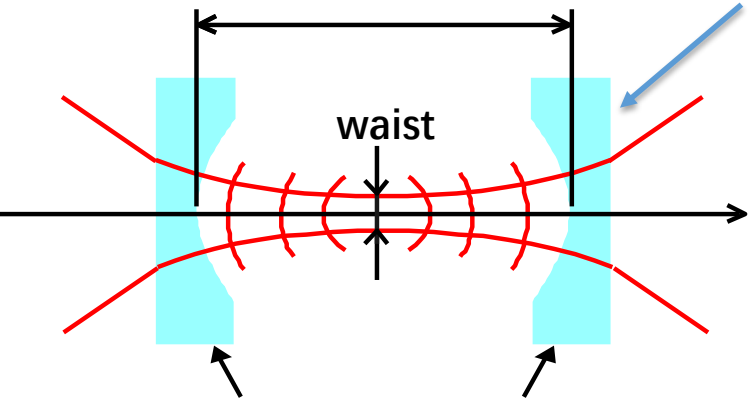
Key technology- high power optical cavity



Test bench for high power two mirror optical cavity experiment



Two mirror optical enhancement cavity

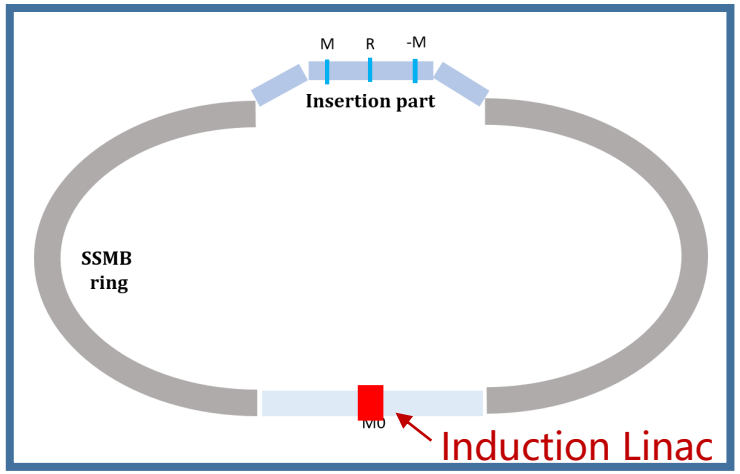


- Two-mirrors system has been set up,
- Phase I:10 kW average power, ongoing
- Phase II: 1MW average power

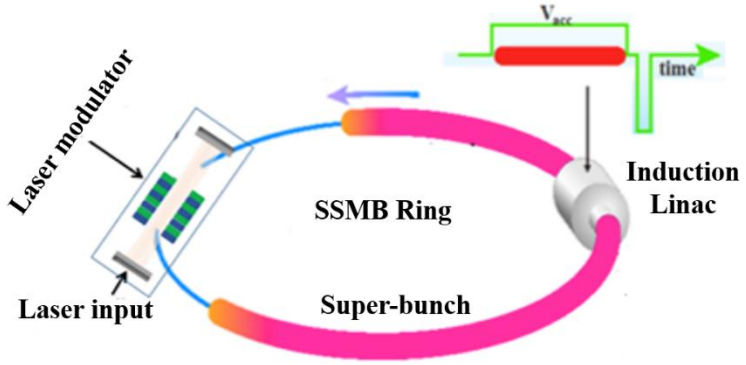
Cavity parameters

Parameters	Design target
wavelength	1064 nm
structure	Two-mirror
length	5 m
Operation mode	CW mode
Average power	~1MW
Q	~10000
Input laser power	130 W

Key technology- induction Linac design



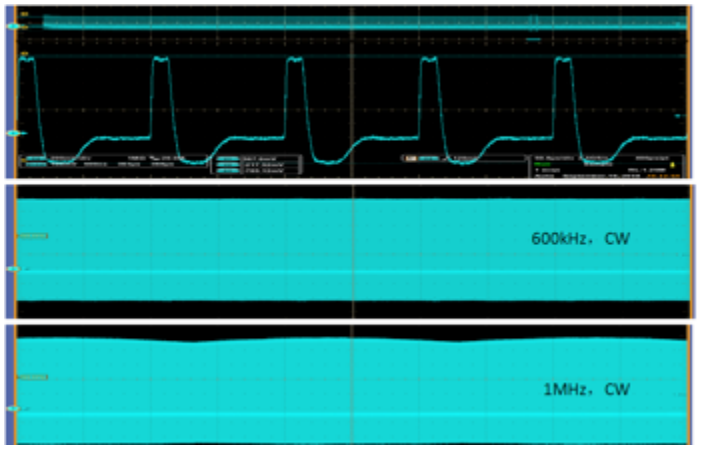
—— the synchrotron radiation loss will be supplied by induction Linac



- Achieved 1 MHz repetition rate、1 kV voltage, with 100 ns flap top

Prototype of induction Linac

High repetition rate test



Pulse type in High repetition rate mode

Contents

Summary

- SSMB is one kind of brand new light source, with the potential to produce kW EUV power, in relatively low price

- The proof-of-principle experiment for SSMB have been implemented successfully, the next stage experiments will begin in 2022.

- A SSMB-EUV light source has been designed at THU, with designed EUV power higher than 1kW, and some key technologies are nearly ready.

Thanks for your attention!