清華大學
Tsinghua University

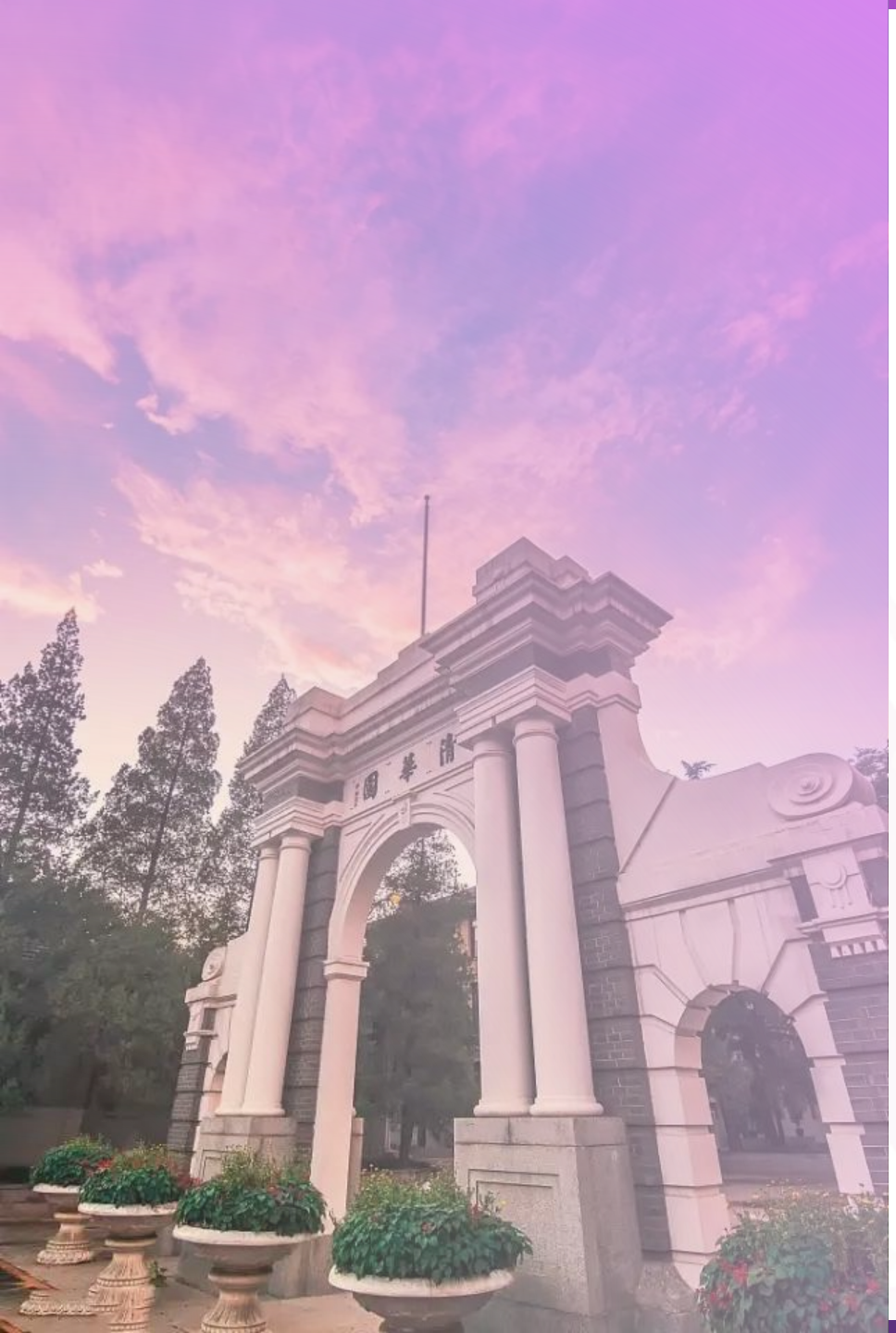
"Extreme Storage Rings" Workshop (ESRW22)

Recent progress on a Steady-State MicroBunching light source at Tsinghua University

Renkai Li

On behalf of the THU SSMB Team

2022.02.01

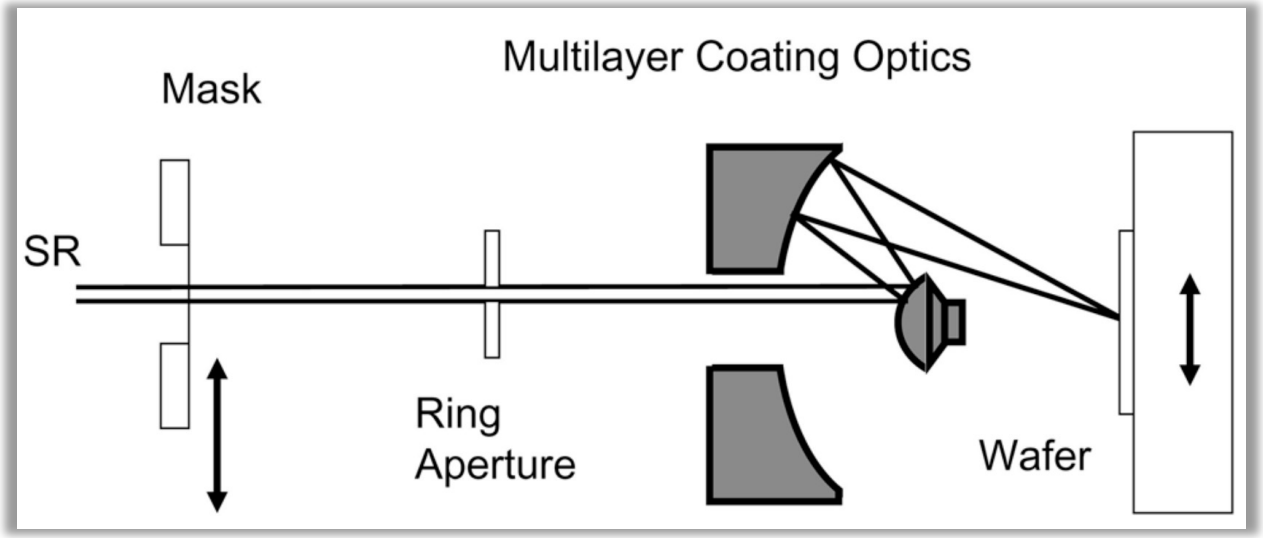


Outline

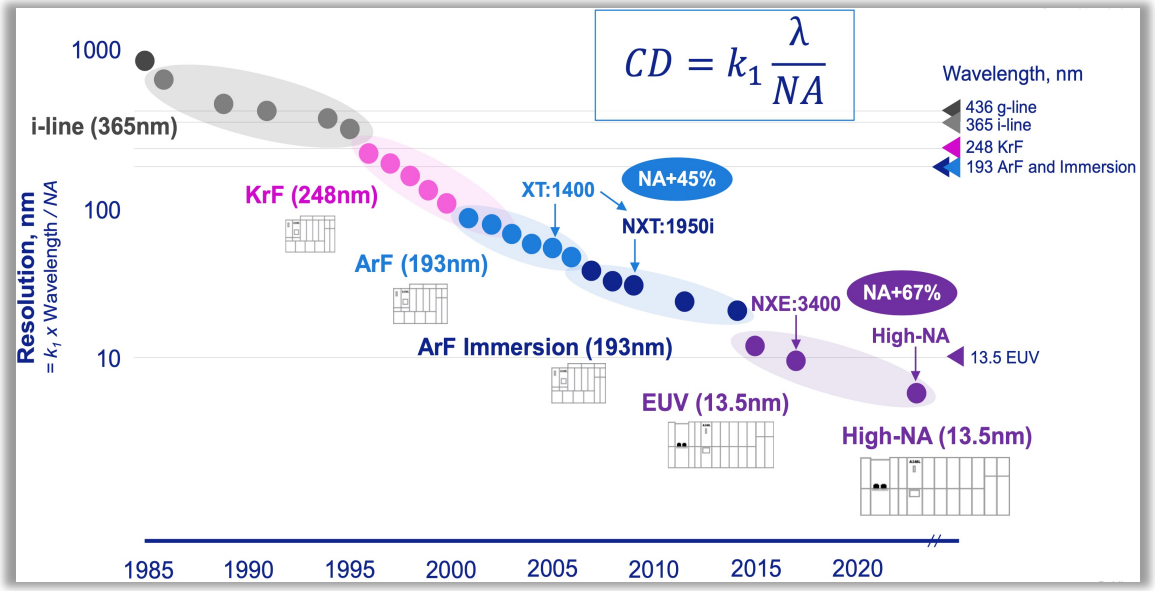
- Introduction
- SSMB mechanism
- SSMB-EUV project
- Summary

Light sources for EUVL

- Shorter wavelength and high power radiation highly desirable for lithography
- Lithography R&D using SRs kicked off in 1980s
- Working wavelength for lithography converged to ~13 nm together with optics



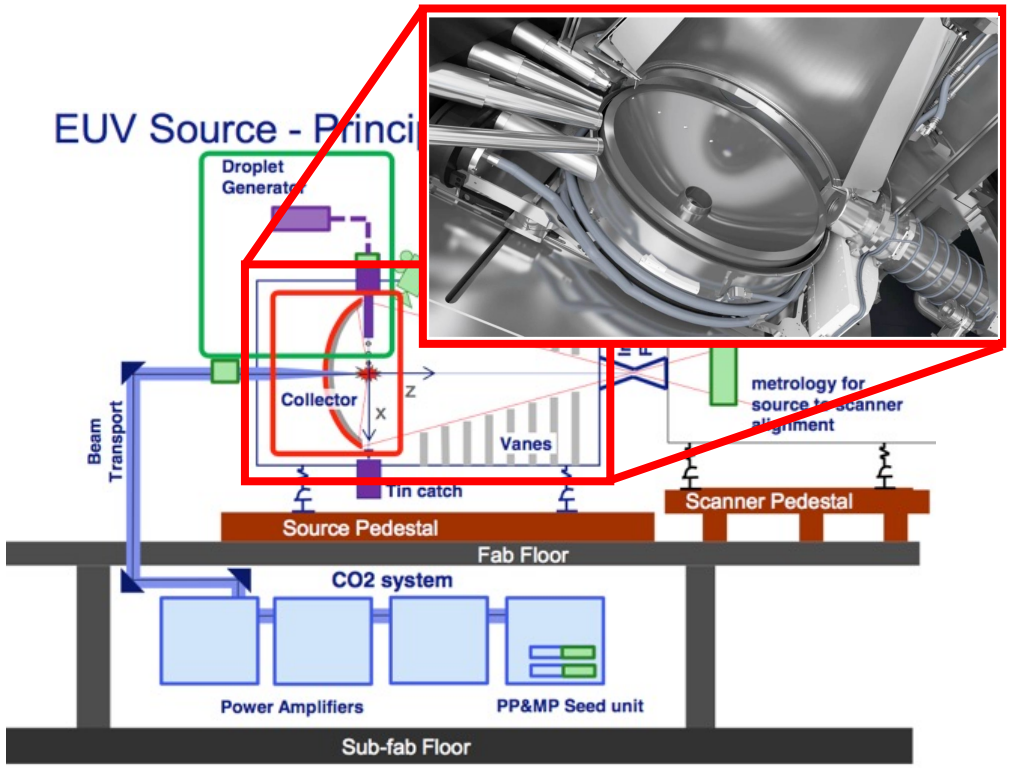
X-ray reduction lithography - H. Kinoshita et al. (1986)

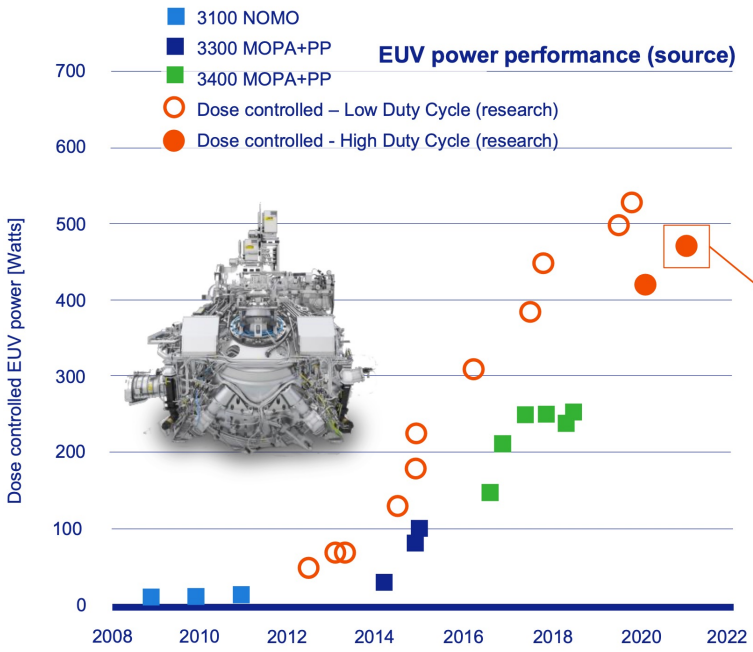


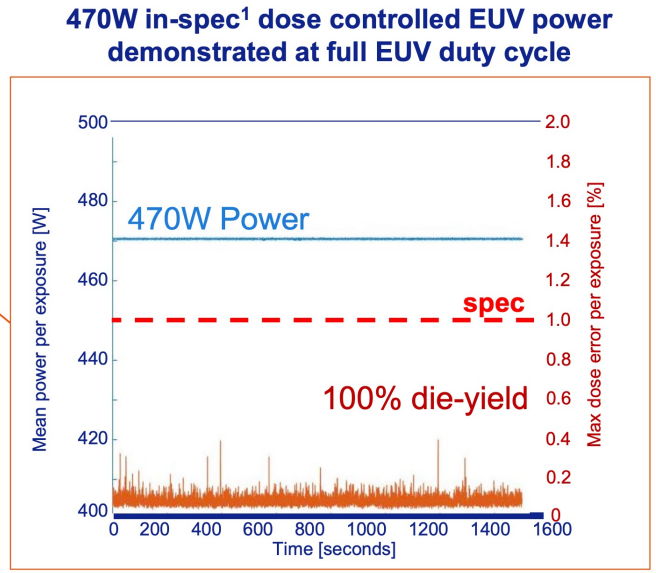
Jan van Schoot et al., 2021 EUVL Workshop

LPP source

- Laser-produced plasma (LPP) source developed into commercial product
  - High power CO_2 laser drives liquid Sn droplet to generate 13.5 nm light
- Continuing LPP R&D toward higher power (250 W in product and ~500 W demonstrated in lab)





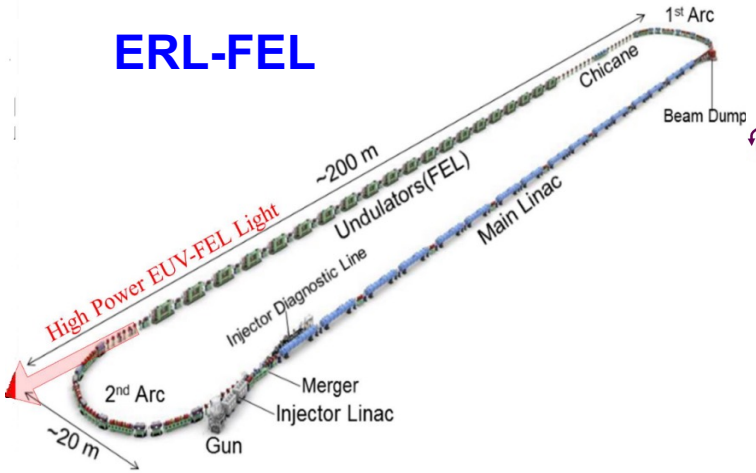


Jan van Schoot et al., 2021 EUVL Workshop

High power accelerator EUV source

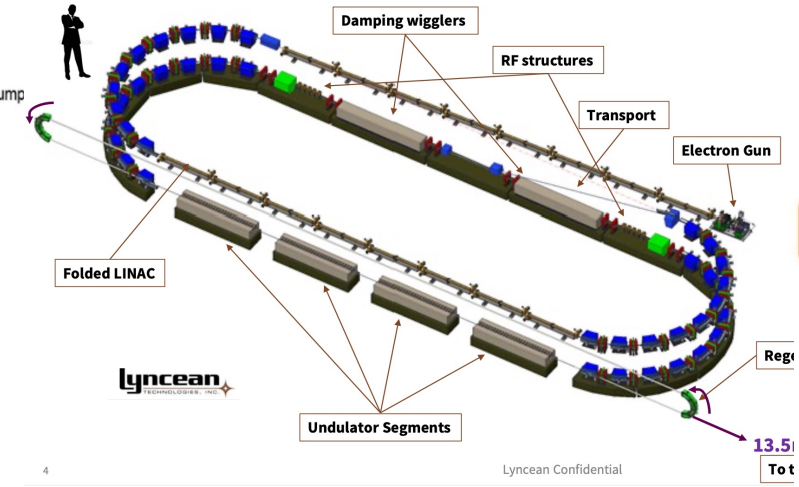
- **Accelerator-based EUV source for lithography :**
  - **Clean, potential for >1 kW, multiple beamlines, extendable to shorter wavelength**
  - **Cost, scale, temporal structure, matching optics to downstream**

ERL-FEL



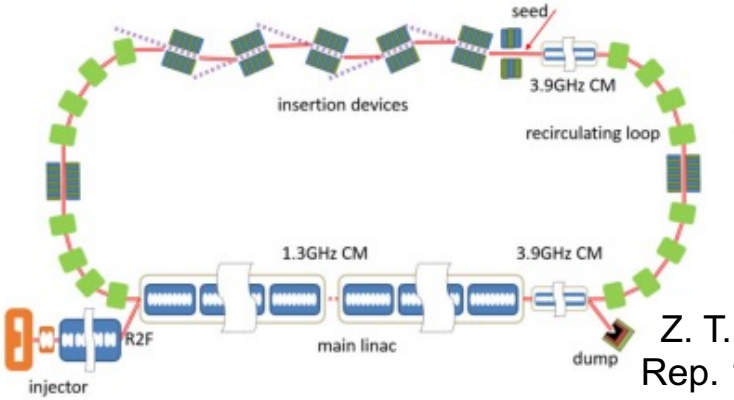
N. Nakamura, 2015 EUVL Workshop

Regen. Amplifier



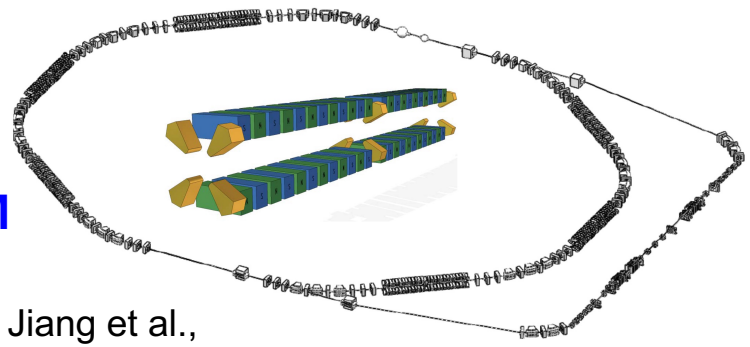
Rod Loewen, 2021 EUVL Workshop

ERL+ Angular Dispersion Modulation

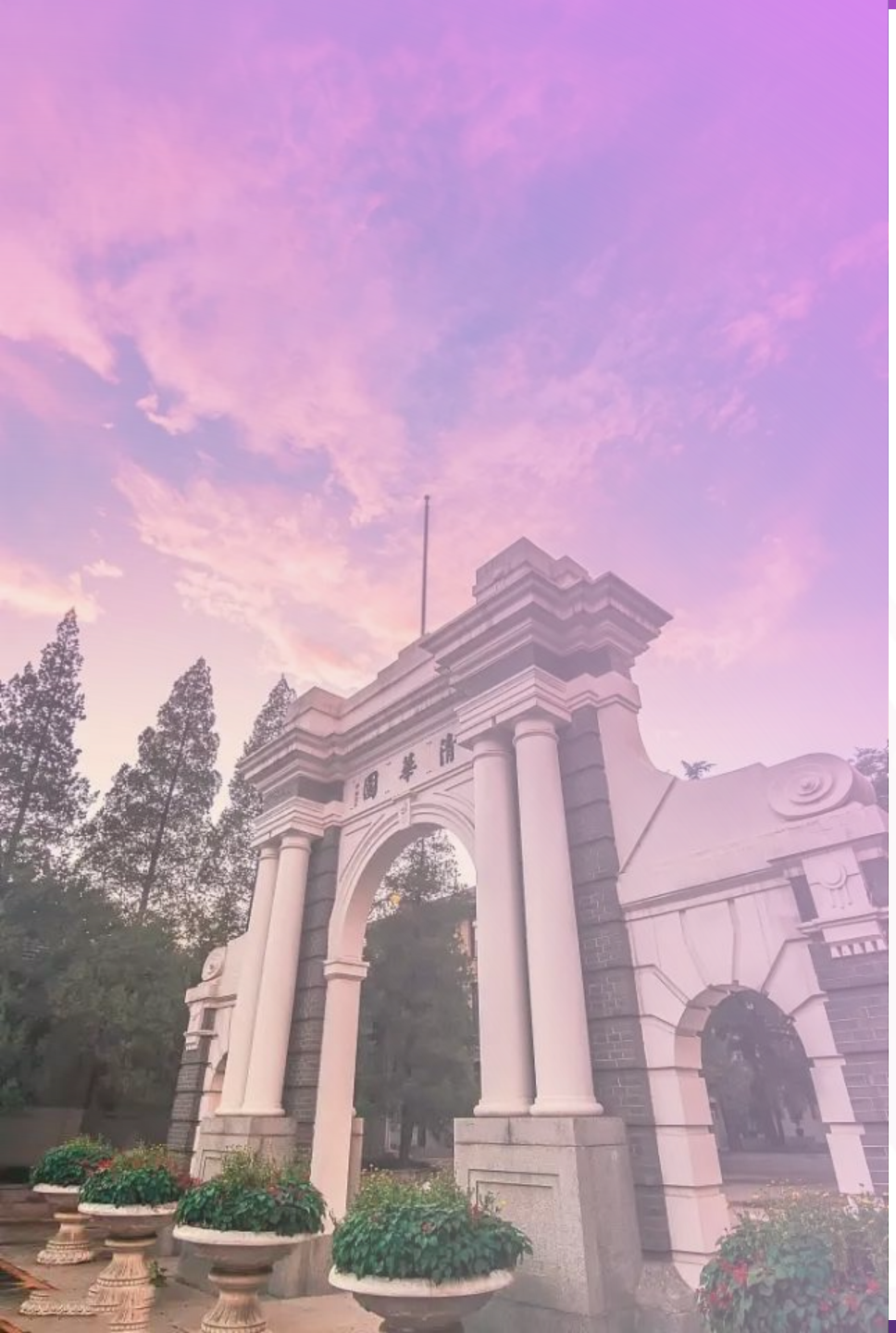


Z. T. Zhao et al., Sci. Rep. 11, 23875 (2021)

SR+ADM



B. Jiang et al., arXiv:2110.08987



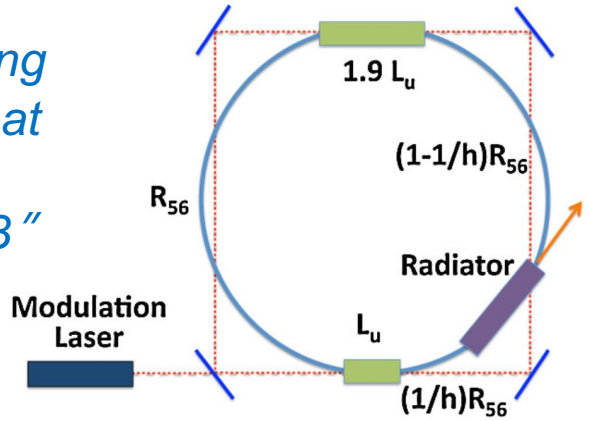
Outline

- Introduction
- **SSMB mechanism**
- SSMB-EUV project
- Summary

Steady-state Microbunching (SSMB)

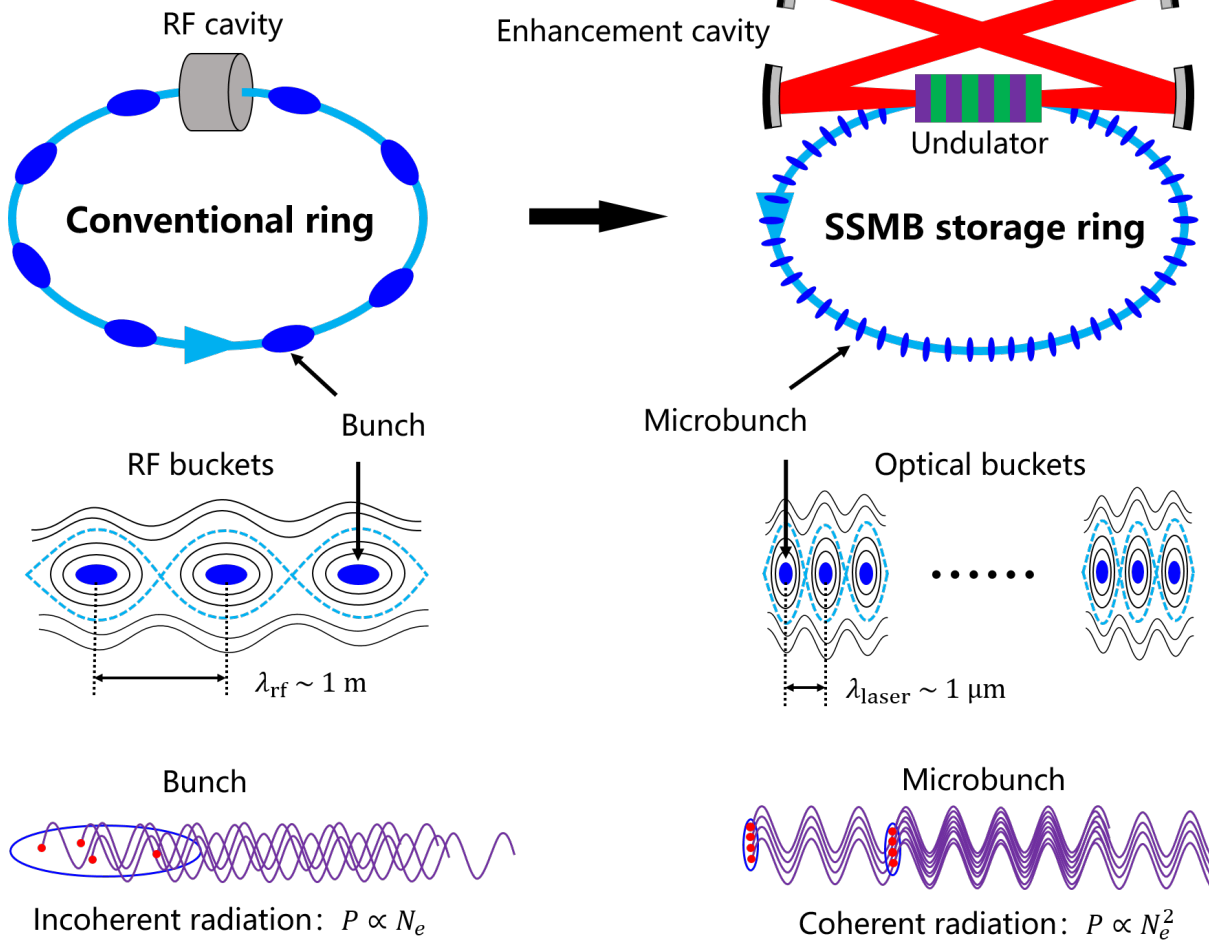
- **Concept proposed by D. Ratner and A. Chao, PRL 105, 154801 (2010).**

"the microbunching (MB) is permanent at the radiator, so we consider this SSMB"



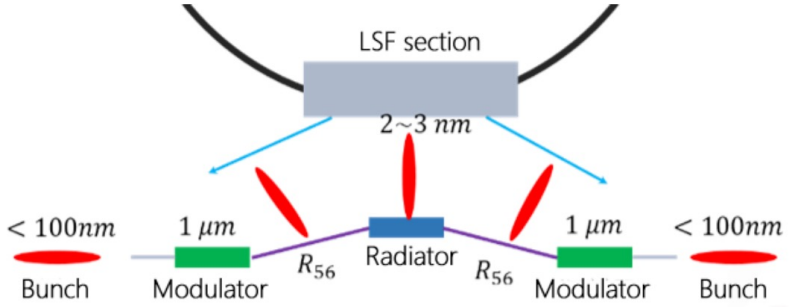
- **Aiming at combining the high rep-rate of SR and high peak power of FEL**
- **Using optical cavity replace RF cavity + compatible lattice**
- **Generate high average power, high rep-rate to CW coherent radiation, at wavelengths from THz to EUV even beyond**

6 orders of magnitude extrapolation



Schemes for high power EUV radiation

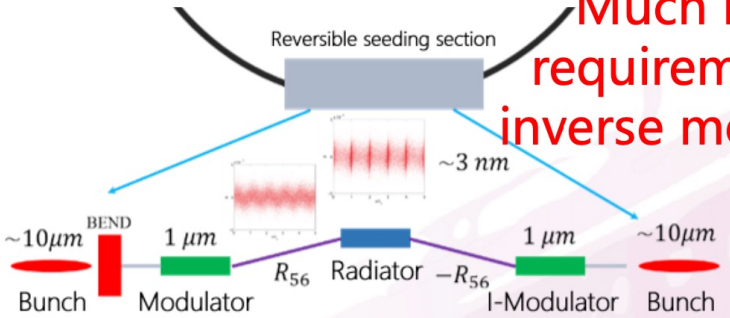
Longitudinal strong focusing



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

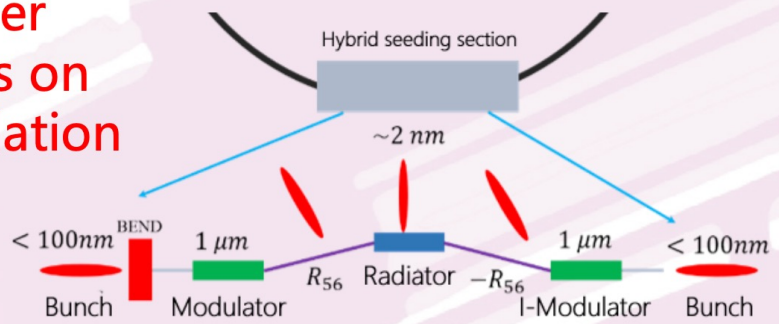
Reversible seeding

Much higher requirements on inverse modulation

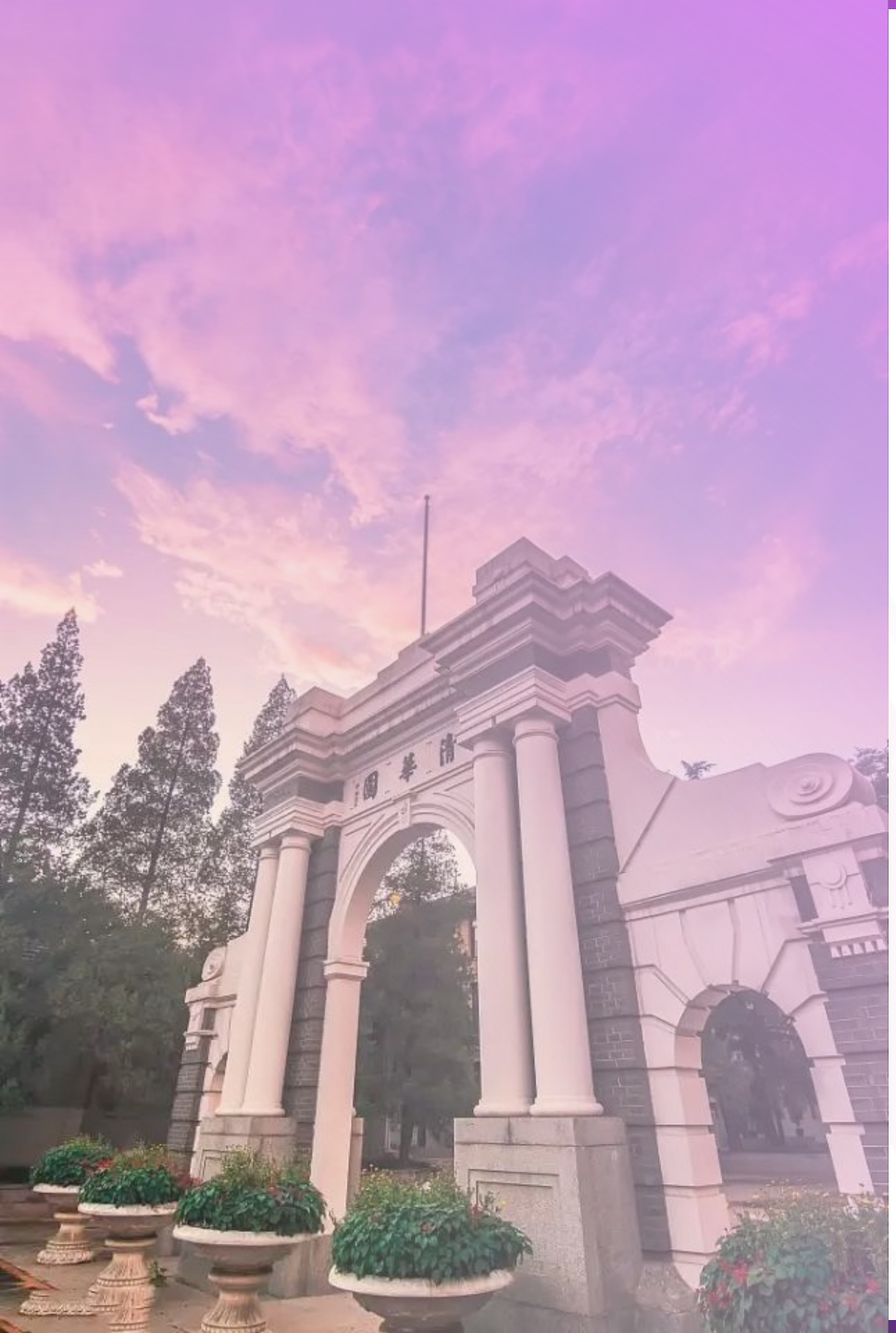


- Regular SR + ADM compression (~3nm)
- Required laser power: ~1 MW
- Low bunching factor, coasting beam (@10A)
- Average power : ~ kW

Hybrid



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



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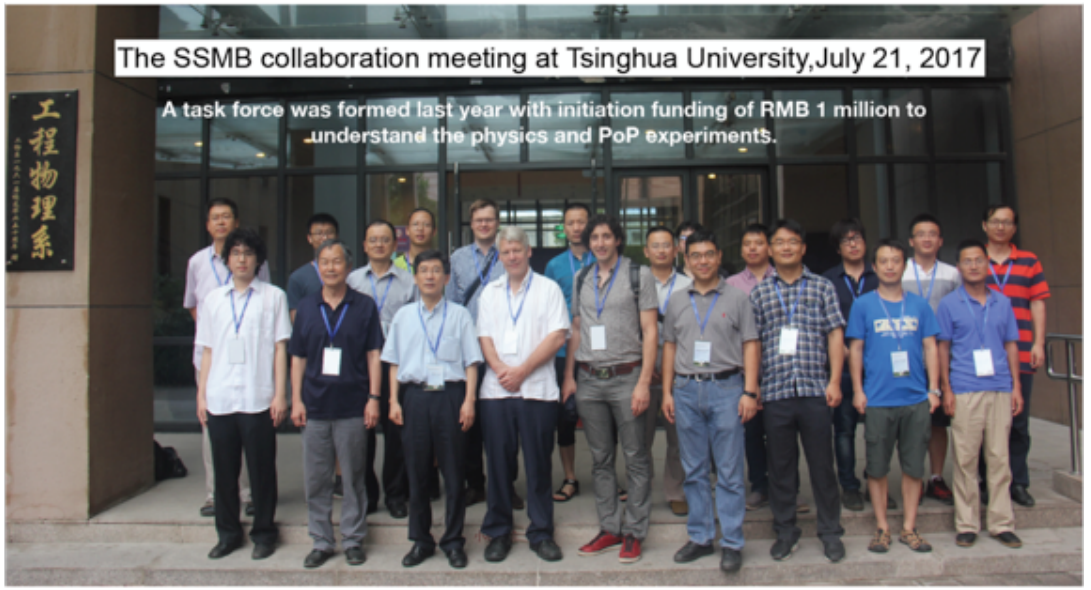
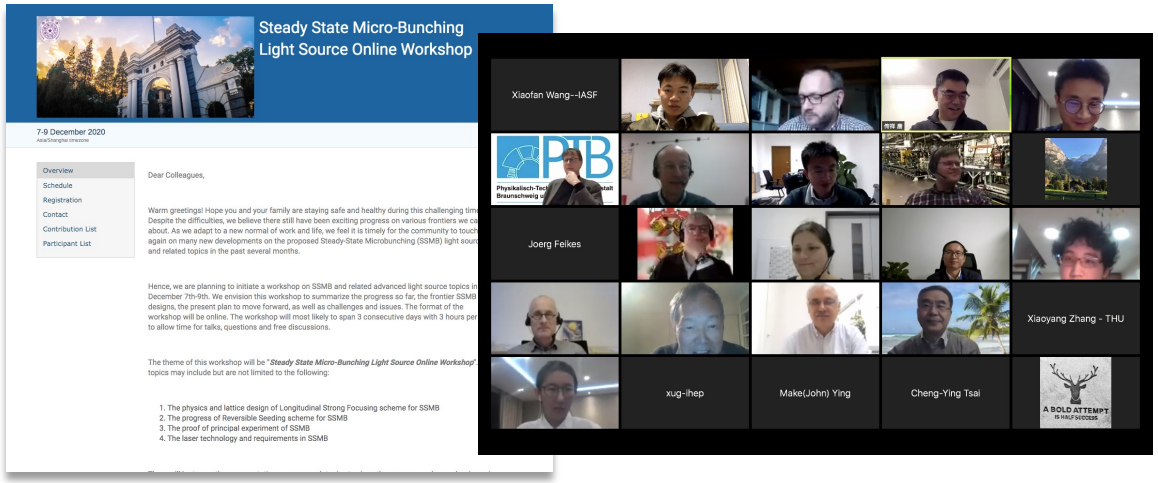
SSMB taskforce at Tsinghua

- Kick-off meeting in July 2017 with colleagues from China, Germany, France, U.S., South Korea etc.
- R&D on SSMB physics, technologies and a research facility
- Supported by Tsinghua University Initiative Scientific Research Program and NSFC

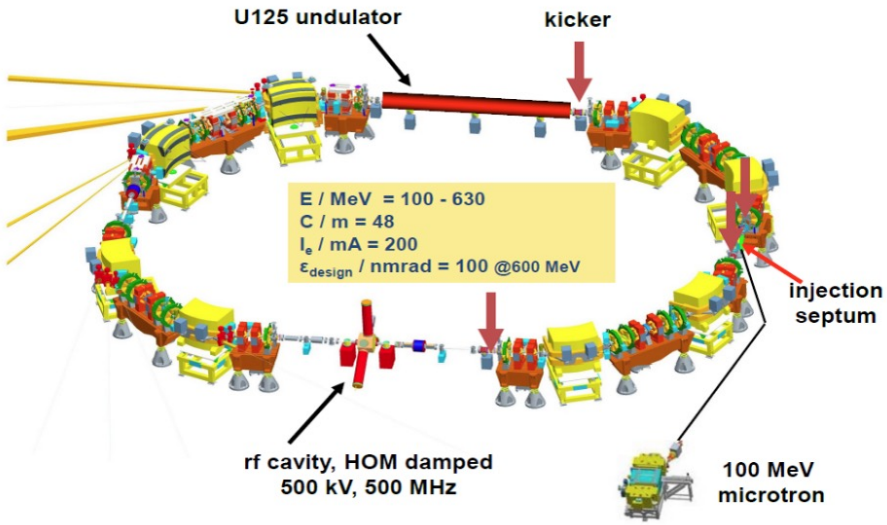


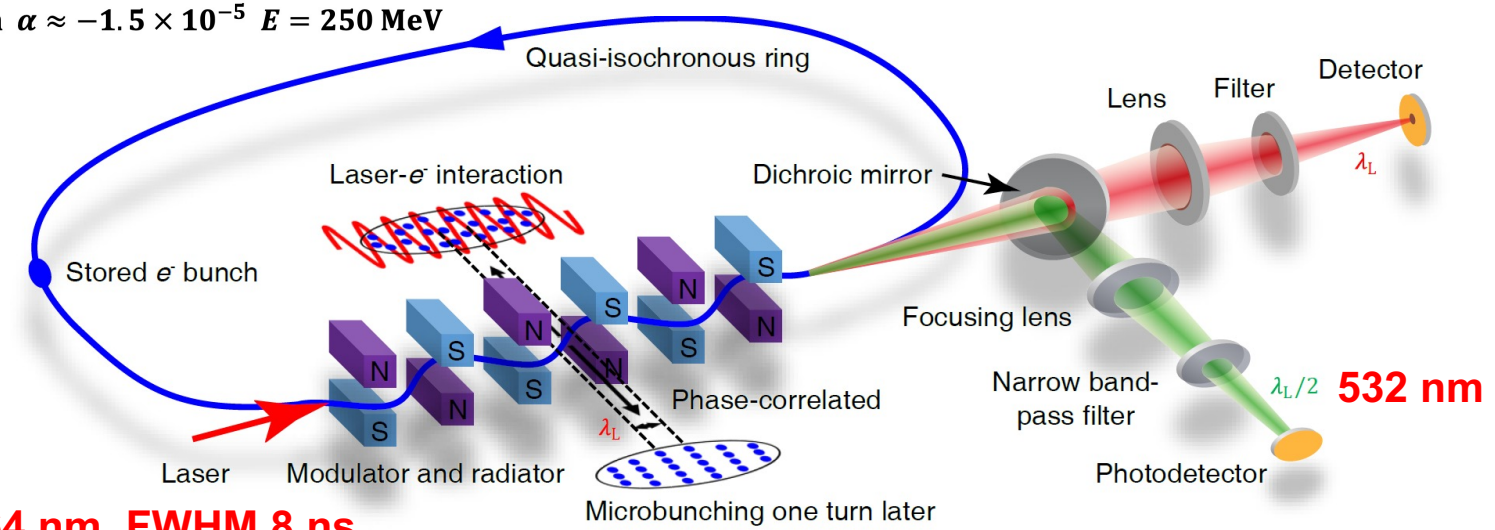
First SSMB Light Source Workshop (Online), Dec. 7-9, 2021
80+ participants from 20 institutes worldwide



Proof-of-principle experiment

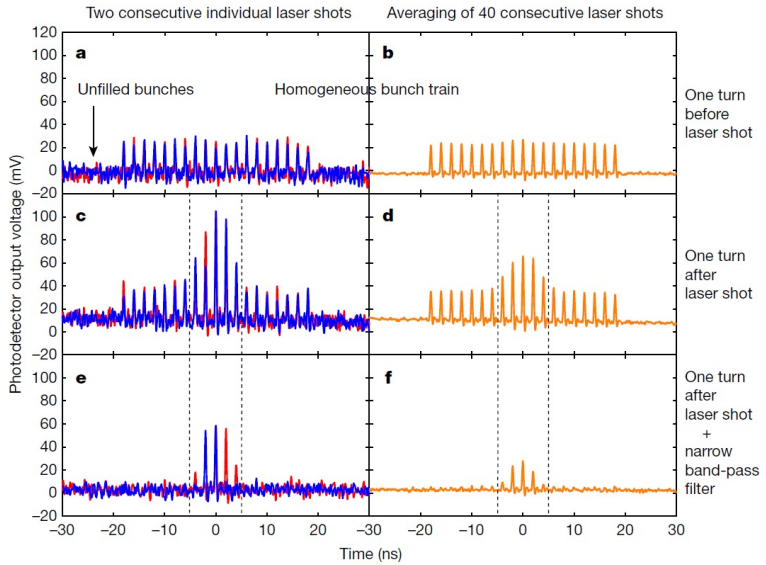
$C = 48\ \mathrm{m}\ \ \alpha \approx -1.5 \times 10^{-5}\ \ E = 250\ \mathrm{MeV}$

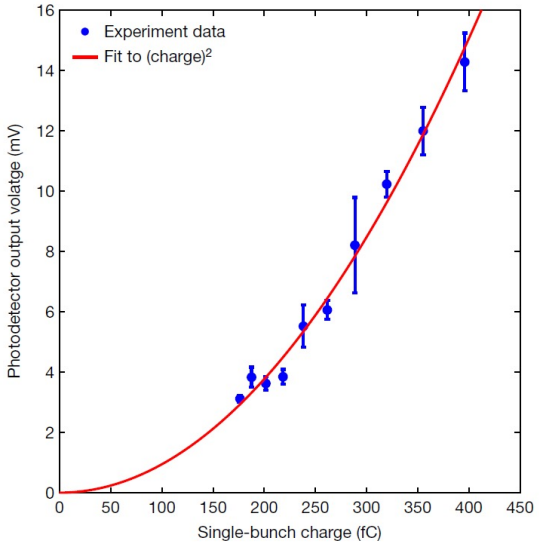




1064 nm, FWHM 8 ns

- **Phase I Goal: generate and maintain MB for at least one turn**
- **Modulate once, observe CSR afterwards**
- **Collaboration with HZB & PTB**
- **Experiment carried out at MLS**





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

Proof-of-principle experiment

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 accelera
and technology[1]. Currently
synchrotron radiation faci

News & views

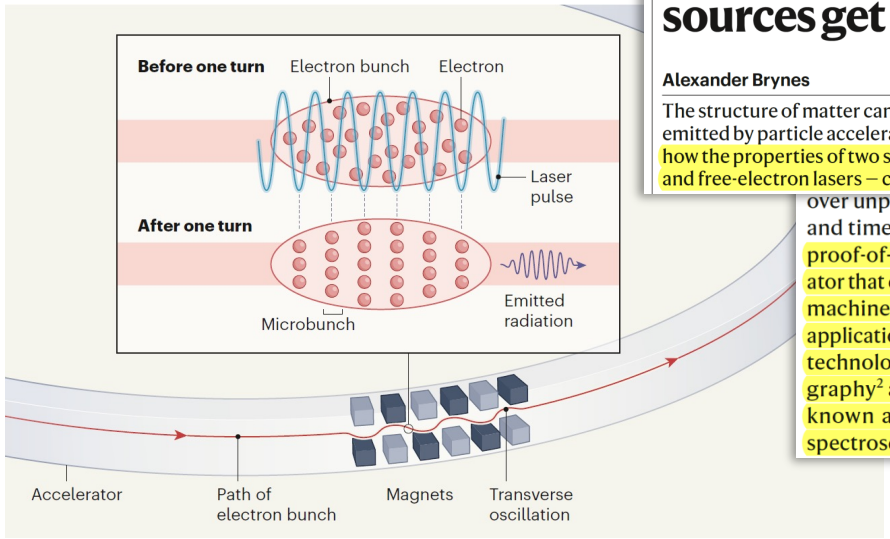
Experimental physics

Accelerator-based light sources get a boost

Alexander Brynes

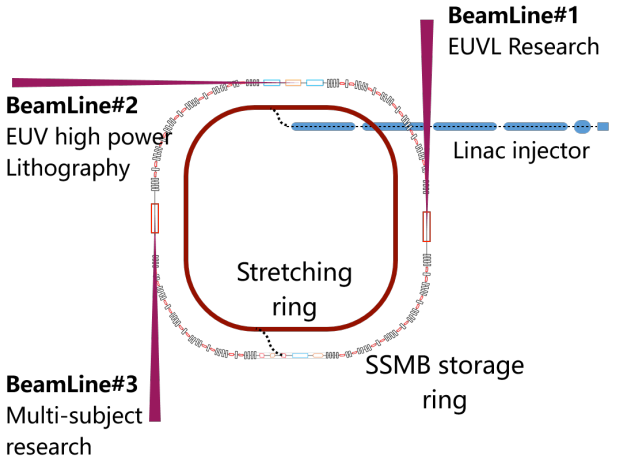
The structure of matter can be explored using the light emitted by particle accelerators. An experiment demonstrates how the properties of two such light sources – synchrotrons and free-electron lasers – can be combined. See p.576

over unprecedentedly short scales of length and time. On page 576, Deng *et al.*[1] report a proof-of-principle experiment on an accelerator that could extend the capabilities of these machines even further, potentially yielding applications in a next-generation chip-etching technology called extreme-ultraviolet lithography[2] and an advanced imaging method known as angle-resolved photoemission spectroscopy[3].



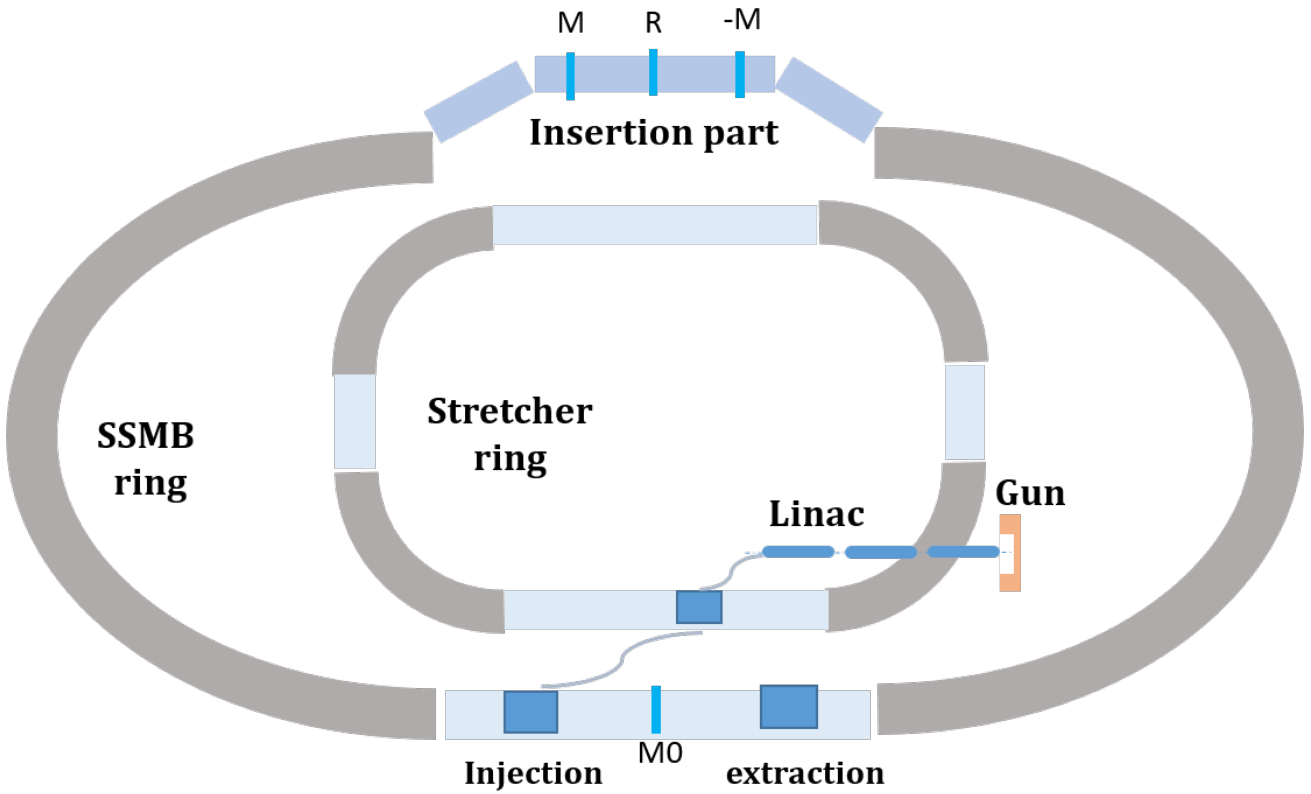
Deng, X. et al., *Nature* 590, 576 (2021).

- **Phase I: MB at long wavelength can be created and maintained for one or few turns**
- **Phase II: modulate thousands of turns, maintain MB each turn**
- **Laser and diagnostics are being tested**
- **Scheduled beamtime in 2022**
- **Phase III: dedicated SSMB research facility for true SSMB, keep MB to steady-state**



- *A dedicated SSMB EUV research facility under design and study at Tsinghua*
- *For studying SSMB physics and provide 3 beamlines for EUV and EUVL research*

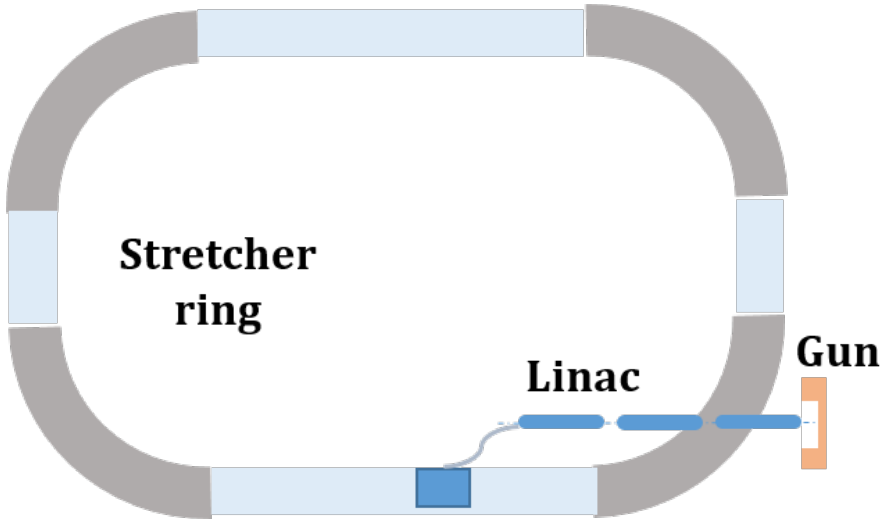
THU SSMB-EUV light source project

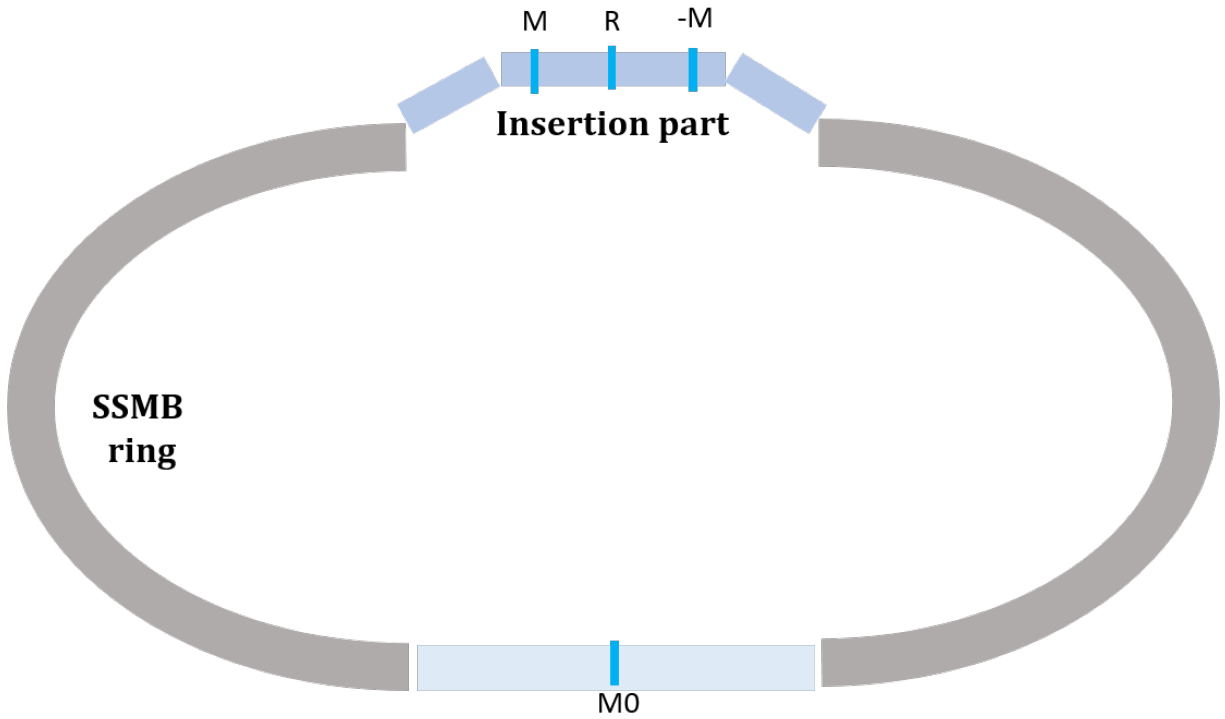


Parameters	Value	Units
Circumference	138.43	m
Beam energy	400	MeV
Tunes（x/y）	0.23/0.21	
α_c	-4.05×10^{-6}	
Damping time (x/y/z)	539.9/542.1/271.6	ms
Energy spread	1.91×10^{-4}	
Natural emittance	181.5	pm
Bunch length	74.1	nm

- Injector based on a photocathode rf gun in marco-pulse mode at ~1 A beam current
- Accelerated to 400 MeV (strong beam-loading) and then stretched by the stretcher ring (large R_{56}) for about 200 turns to a CW coasting beam
- Injected into SSMB main ring, compressed to ~3 nm, and generate kW EUV radiation

THU SSMB-EUV light source project



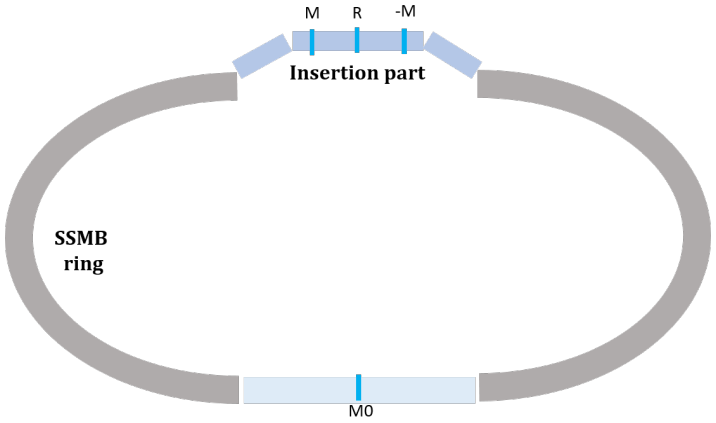


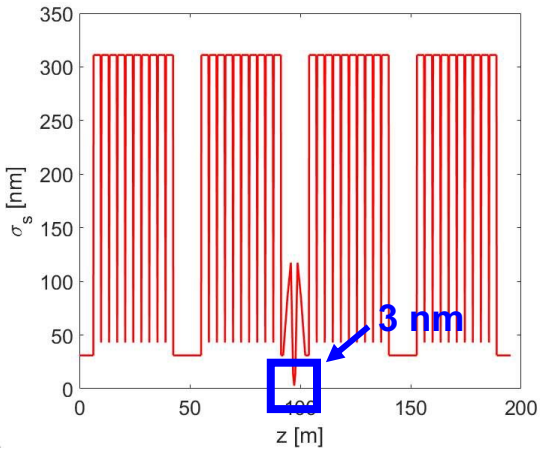
- Completed initial linac and stretcher ring design, the energy spread of coasting beam can be below 0.05% (control the beam loading effects)
- Top-up injection scheme being considered, to maintain the stability of EUV power

- Completed initial main ring design, the bunch length can be maintained at less than 100 nm.
- hybrid insertion option, electron bunches can be compressed to 3 nm and generate > 1kW power
- Multi-particles effects are being studied, nonlinear optimization is on going

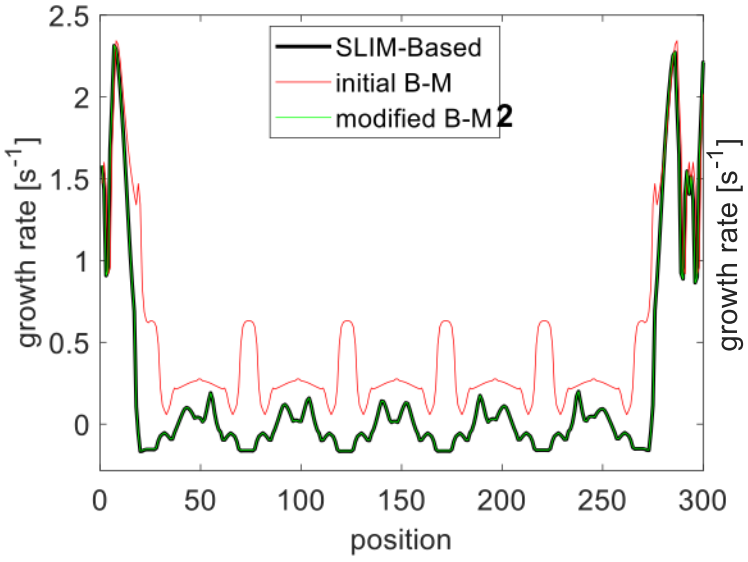
IBS effects in SSMB

- In a SSMB SR, electron beams contain **fine structures** - nm beamlets with um spacing, at low emittance and relatively low beam energy
- Bunch length of nm beamlets vary significantly along the ring
- A new code is under development to calculate IBS growth rate for SSMB – taking into account longitudinal beam dynamics and T-L coupling
- Lattice optimization with IBS effects included is on-going

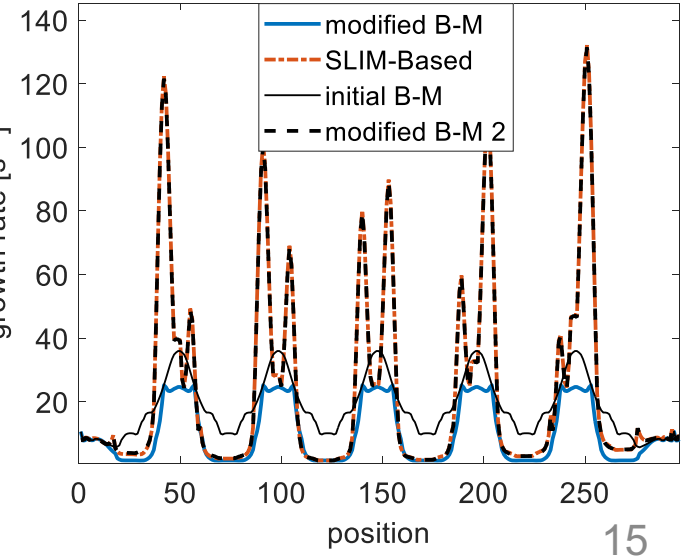




Longitudinal growth rate



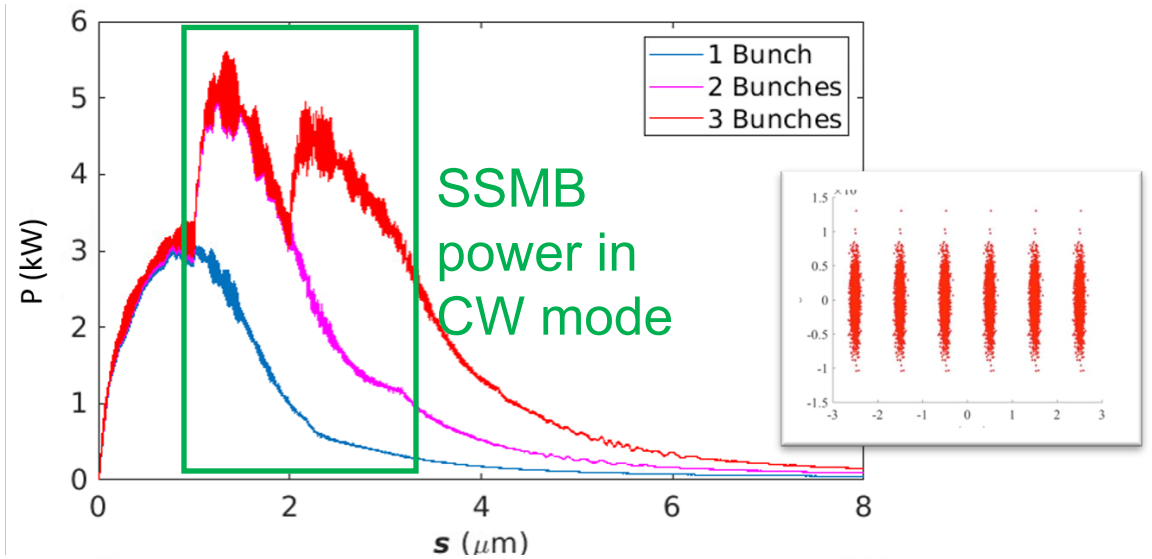
Transverse growth rate

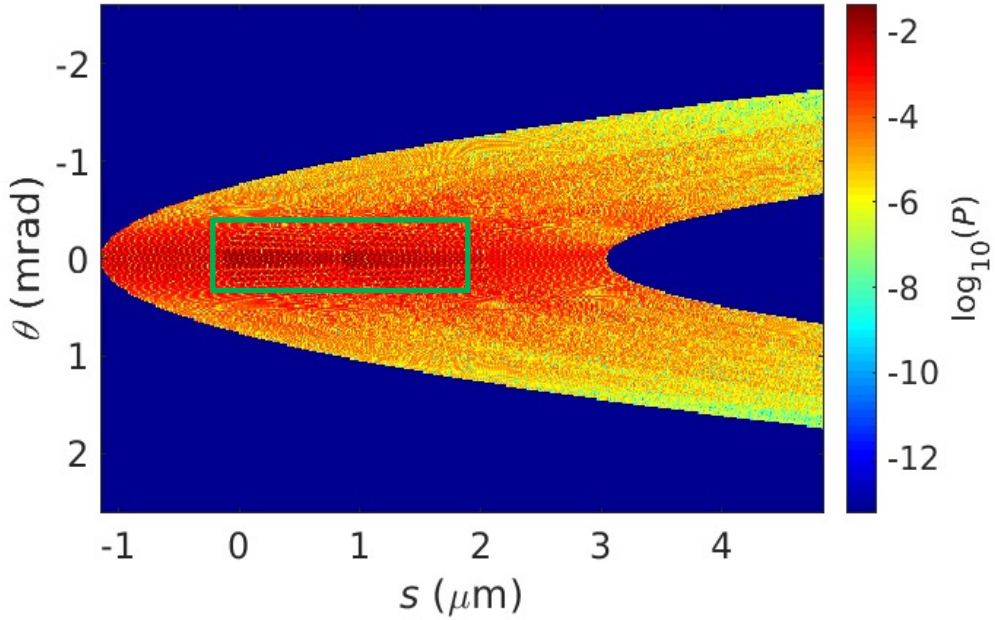


Calculate EUV radiation property

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

- **Modulation laser wavelength: 1 um, so is the beamlet separation**
- **The radiation will be CW**
- **Narrow band, N_u ~ hundreds**





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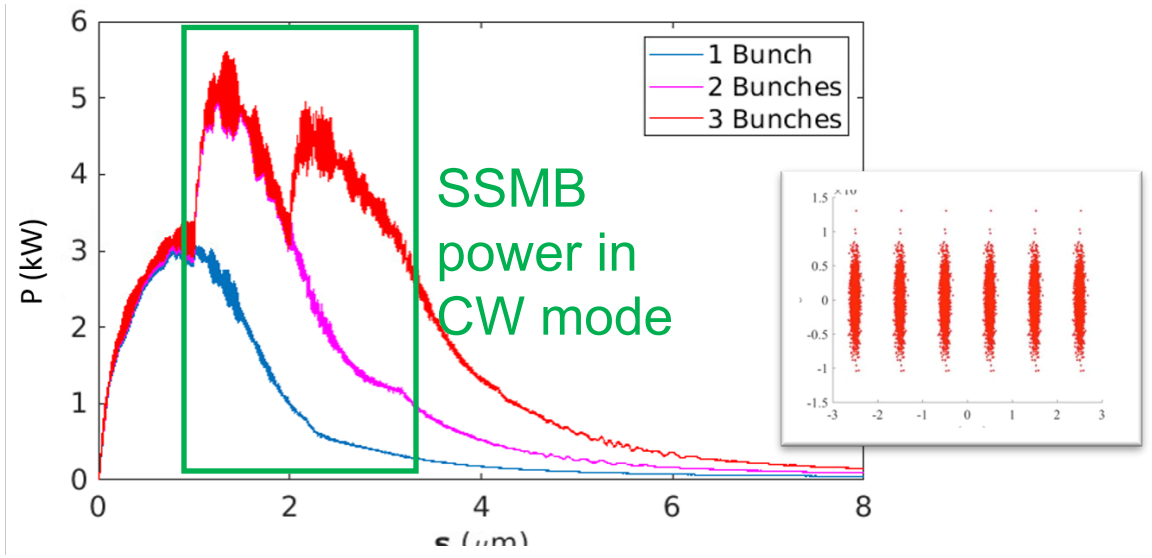
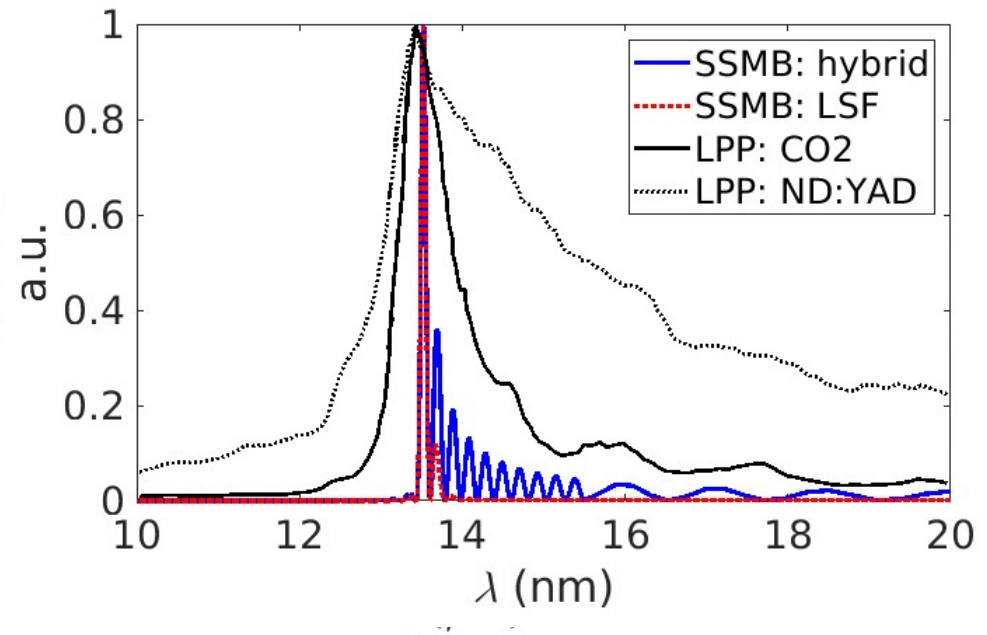
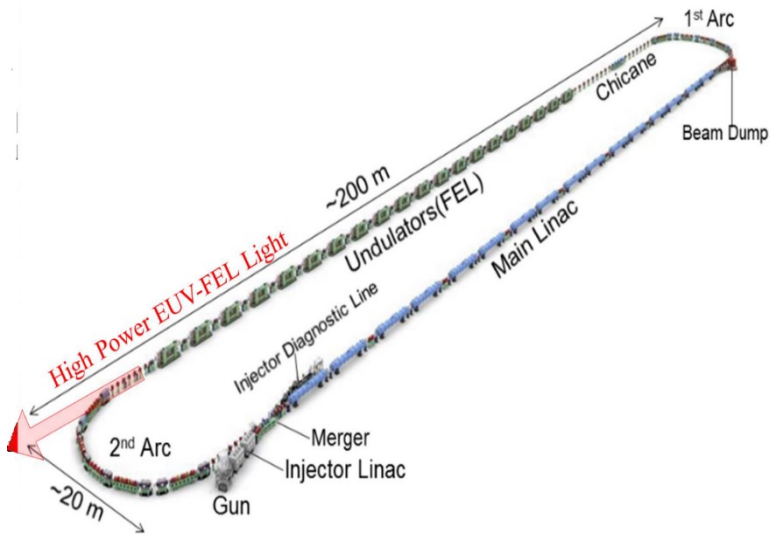
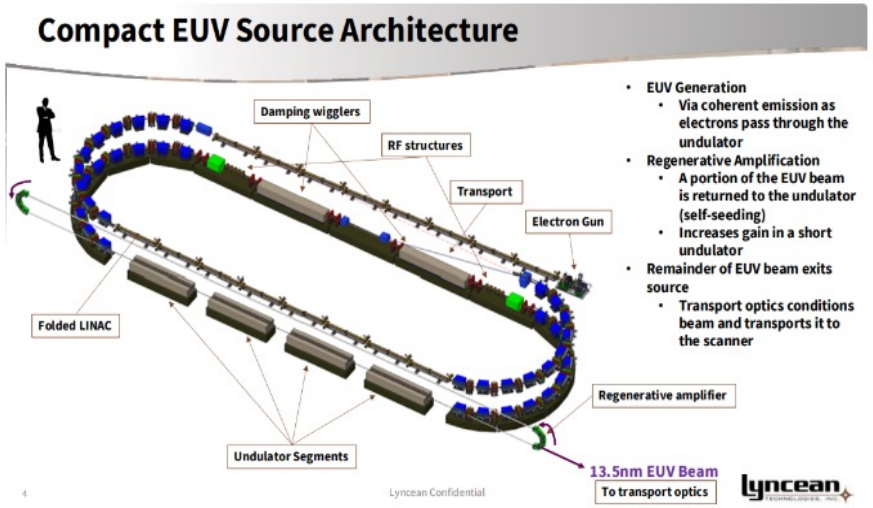
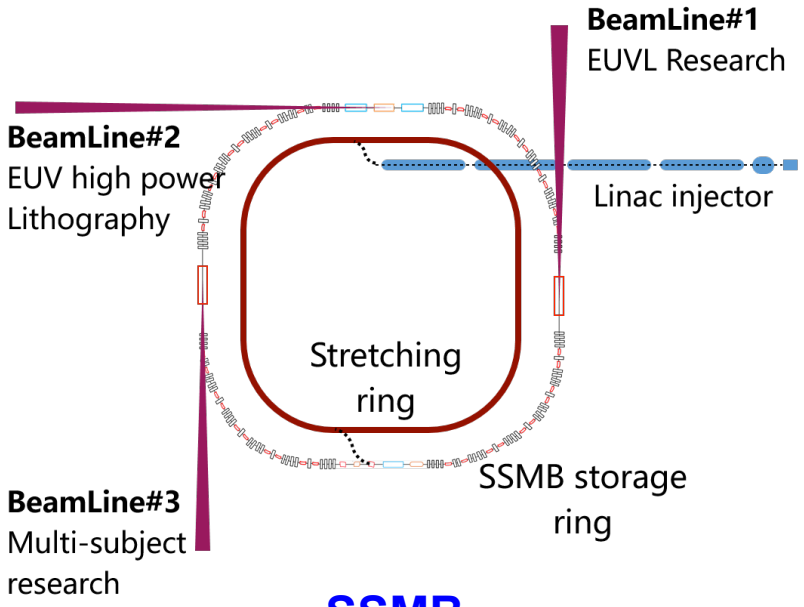




Comparison with other schemes







ERL-FEL

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

Regen. Amplifier

- ~tens meter undulator
- Ring-based, strong damping
- Optical cavity at 13.5 nm
- average power : ~kW
- Conceptual design

SSMB

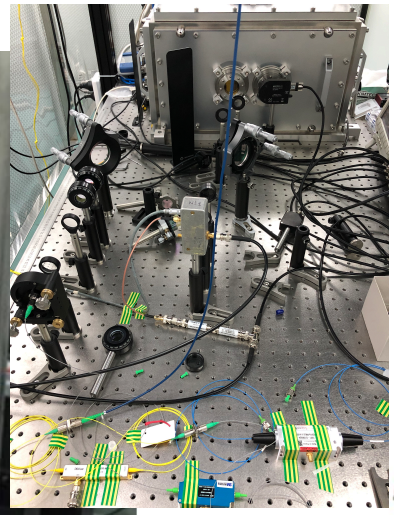
- ~several meter undulator
- Ring-based, steady-state
- average power : ~kW
- Conceptual design

2021 N. Nakamura 5th EUV-FEL workshop

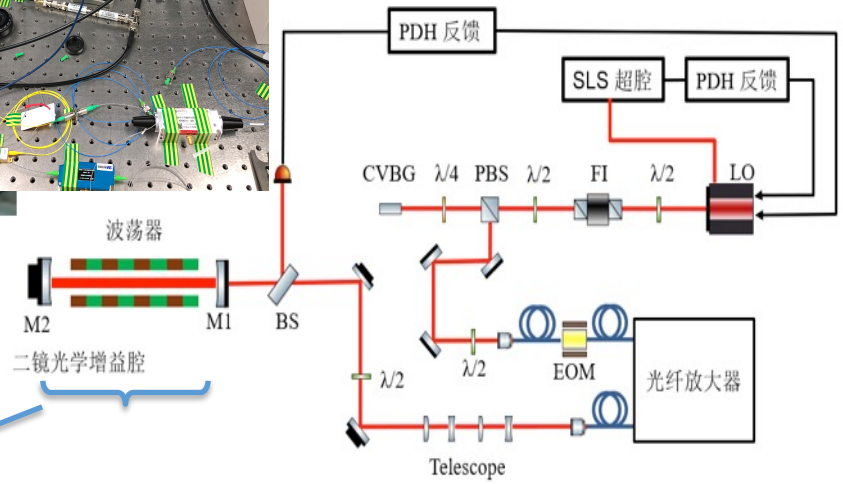
Rod Loewen, 2021 EUVL Workshop

2021 C. X. Tang, EUV Source workshop

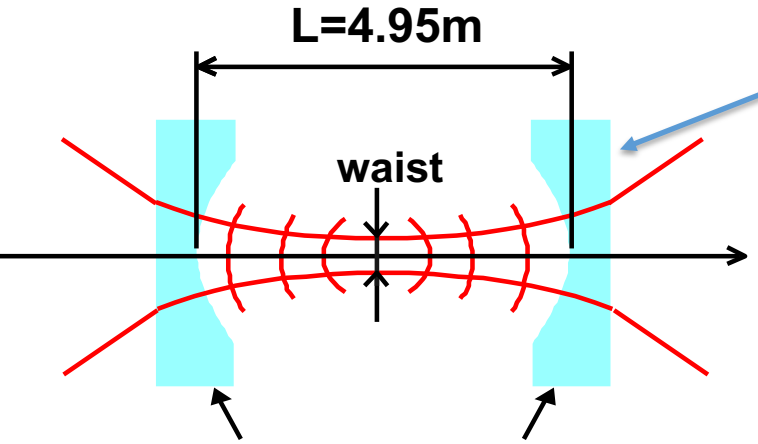
Key technology - optical cavity



Test bench for a high-power two- mirror optical cavity experiment



Two-mirror optical enhancement cavity

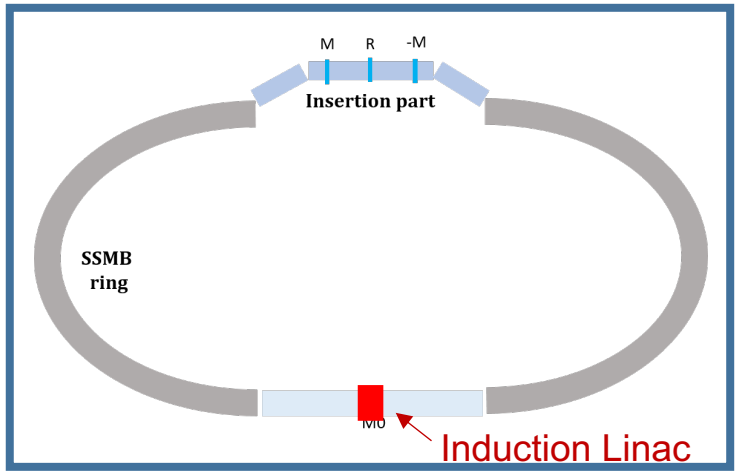


- The two-mirror test system has been set up
- Phase I: 10 kW average power, ongoing
- Phase II: 1MW average power

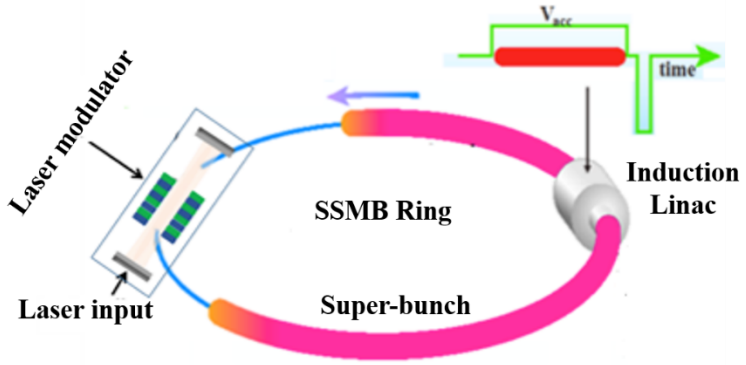
Cavity parameters

Parameters	Design specs
wavelength	1064 nm
configuration	Two-mirror
cavity length	4.95 m
operation mode	CW mode
average power	~1 MW
Q	~10000
input laser power	130 W

Key technology - induction linac



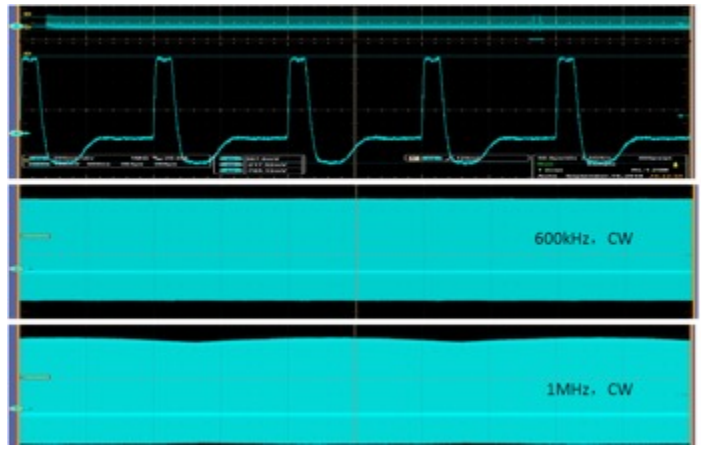
—— the synchrotron radiation loss will be compensated for by the induction linac



- A prototype cavity has been built and tested
- 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

Summary

- SSMB is a unique and new concept light source, with potential to produce kW EUV power at relatively low cost
- Very challenging as well as interesting physics and technologies
- The POP: Phase I for SSMB completed successfully with collaborators, and Phase II is underway – laser, diagnostics and e-beam preparation
- A SSMB EUV light source is under study at THU - physics, key techniques and design of a research facility - aiming at kW EUV output
- Will benefit tremendously from discussion, suggestion, and collaboration

Thank you for your attention!