Storage Ring EUV Light Source based on Steady-state Microbunching Mechanism

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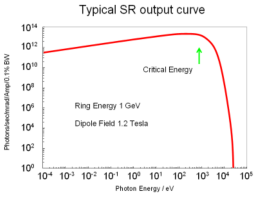
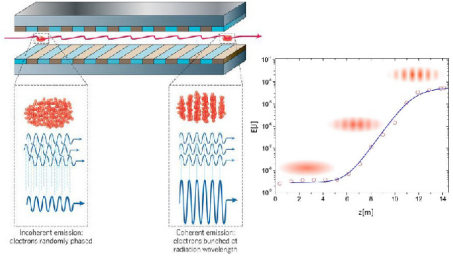
Overview

Accelerator light source workhorses

- Storage rings: high repetition rate, low peak power

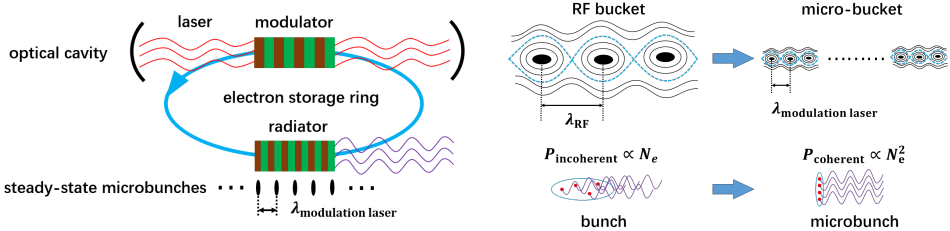


- Free electron lasers: high peak power, low repetition rate



Steady-state microbunching (SSMB) [1]

- Microbunching for high peak power and steady-state for high repetition rate, two features combined lead to the idea of SSMB:



- Remarkable feature of SSMB: high average power narrow-banded temporal coherent radiation with wavelength ranging from THz to EUV.

[1] Ratner and Chao, PRL 105, 154801 (2010)

Potential advantages of applying SSMB for EUV lithography

- **High average power**: the power aimed is > 1 kW per tool, each facility should be able to incorporate multiple tools.;
- **Narrow-banded and collimated**: the radiation spectrum bandwidth is $< 1\%$ and has a well collimated angular spread ≤ 0.1 mrad, which should help to reduce the number of reflection mirrors and thus increase the EUV power transport efficiency;
- **Truly continuous wave**: the temporal structure of the radiation is truly CW, this minimizes the chip damage problem;
- **Clean radiation**: the radiation is clean and carries no debris, so that mirrors do not get contaminated and do not require frequent replacements during operation;
- **High stability**: storage ring source has the advantage of a good stability, which helps to increase the machine availability and qualified production rate;
- **High efficiency**: higher wall-plug electricity to EUV conversion efficiency than LPP source expected;
- **Reasonable price**: storage ring technology is mature and the average price for each tool is expected to be reasonable;
- **Good scalability**: easy to scale to shorter wavelength $\lambda_r = \frac{1+K^2/2}{2\gamma^2}\lambda_u$.

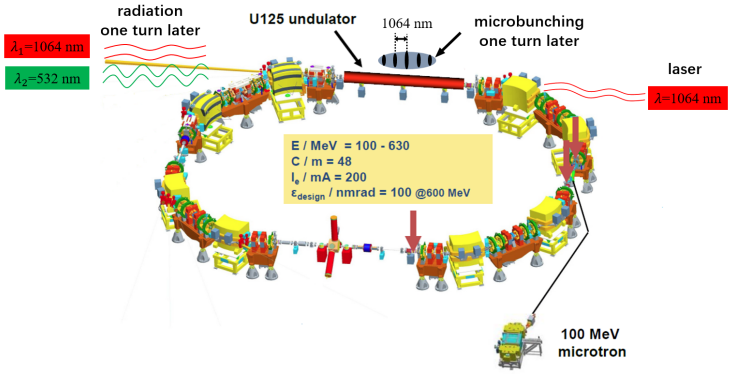
The SSMB task force in Tsinghua [2]

- A task force has been established in Tsinghua University collaborating with institutes from China, Germany and the USA since 2017 to promote the SSMB research with a final goal of designing and building an EUV SSMB storage ring at Tsinghua ;
- The first collaboration meeting was held on July 21^{th}, 2017 and regular SSMB work meetings since then;
- Main tasks of the collaboration at this moment:
  - prove the SSMB work principle;
  - dedicated EUV SSMB lattice design;
  - address related technical challenges.

[2] C. Tang et al., Proc. FLS 2018, Shanghai, China, pp. 166-170.

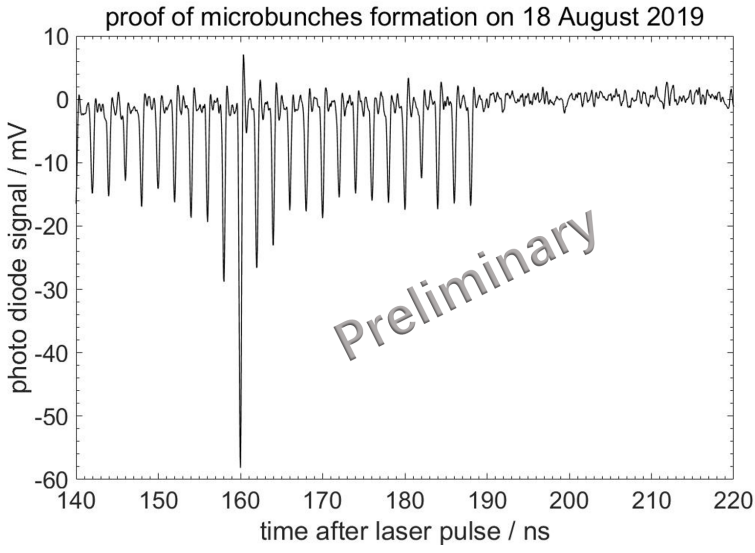
Proof-of-principle experiment phase I [3]

- Conducted at the Metrology Light Source (MLS) in Berlin. A collaborative work of Tsinghua, HZB and PTB:
  - formation of microbunches and generation of coherent undulator radiation;
  - study various parameters, physical effects and investigate radiation characteristics;
  - define the starting point of the SSMB PoP experiments.



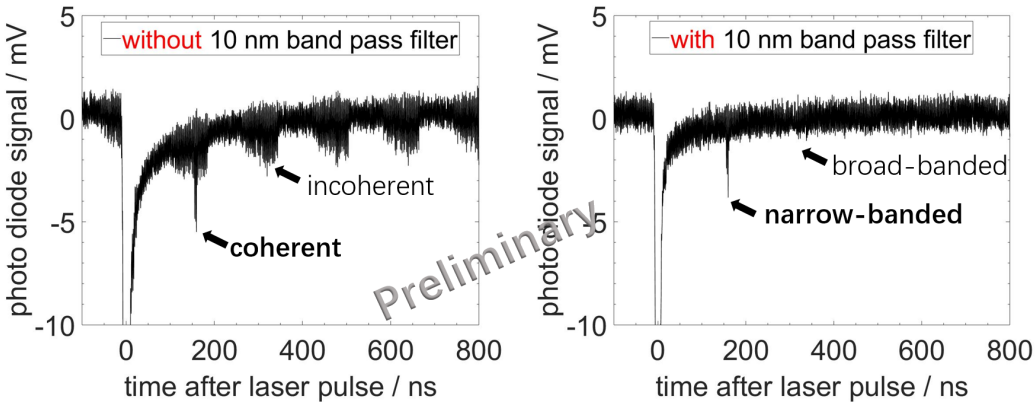
[3] X. Deng et al., Proc. IPAC 2018, Vancouver, Canada, pp. 4583-4586

Experiment result: second harmonic (unpulished)



The coherent radiation from microbunches is narrow-banded:

$\frac{\delta\lambda}{\lambda} = \frac{1}{n_{\text{harmonic}} N_\mu}$, $N_\mu \gg N_u$ (unpublished)



The above two slides contain the hard efforts of the SSMB PoP team during the past two years

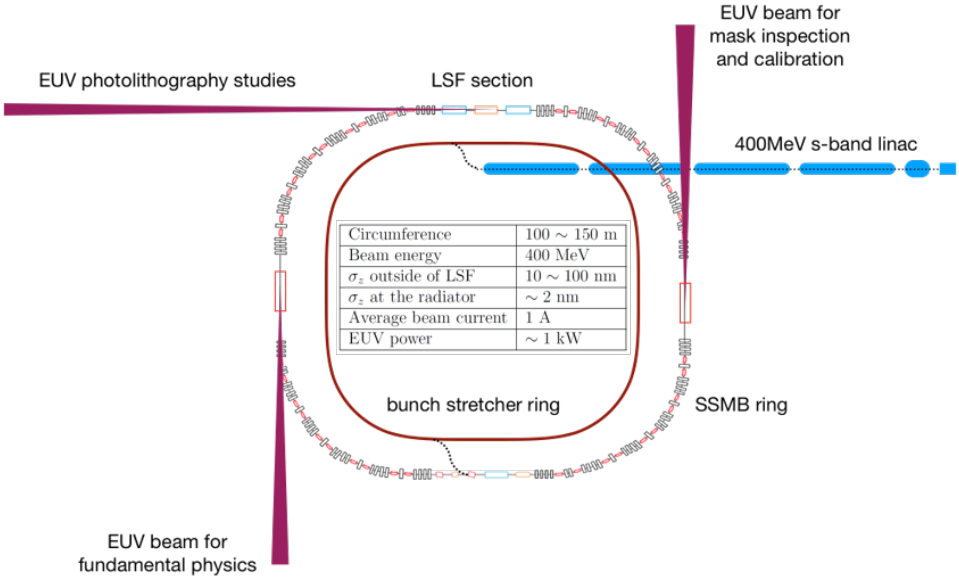
- Tsinghua: Alex Chao[4], Xiujie Deng, Wenhui Huang, Chuanxiang Tang, Lixin Yan;
- HZB: Jörg Feikes, Ji Li, Aleksandr Matveenko, Yuriy Petenev, Markus Ries;
- PTB: Arne Hoehl, Roman Klein.

[4] also at SLAC

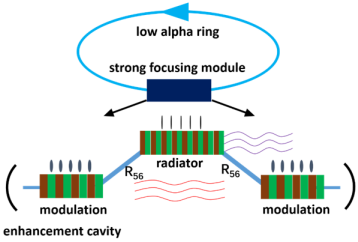
Significance of the experiment

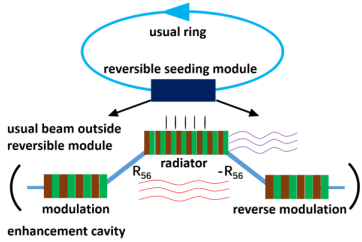
- Alex Chao: "the key to our test is to demonstrate that microbunching is doable in the environment that has the potential of maintaining steady state. ... Our test is not to be confused with the other single shot tests. It is one order of magnitude more difficult."
- Jörg Feikes: "it is similar to the first Apollo missions which were sent only into the orbit of earth, done several times before with other rockets, but with the difference that the Apollo module had the potential to continue further to the moon."
- It is the first experiment worldwide confirming that energy modulation of electron beam induced by an externally applied laser can conserve and convert to density modulation to form microbunches after a complete revolution in a storage ring. The first key step towards SSMB: it is from 0 to 1, the later steps are from 1 to 1000 to 10^6 ...

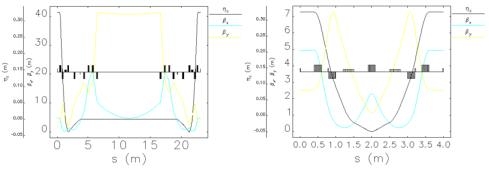
Envisioned Tsinghua EUV SSMB

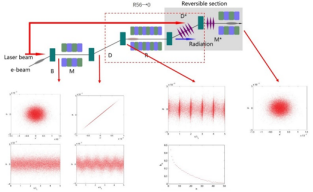


Two lattice approaches: longitudinal strong focusing [5] and reversible seeding [6]









[5] T. Rui et al., Proc. FLS 2018, Shanghai, China. & Z. Pan et al., Proc. FEL19, Hamburg, Germany.
[6] C. Li et al., Proc. IPAC19, Melbourne, Australia, pp.1507-1509.

Related technique challenges

- High storage power ($\sim$ 1 MW) optical enhancement cavity;
- High repetition rate ($\sim$ MHz) induction acceleration unit;
- Power supply stability requirement on some of the magnets maybe more demanding than the now electromagnet available. Permanent magnet?
- ...

Summary

- SSMB was proposed years ago to generate high average power narrow-banded temporal coherent radiation and has many potential advantages when applying for EUV lithography.
- An initial task force has been established in Tsinghua collaborating with other institutes to promote the SSMB research with a final goal of designing and building an EUV SSMB storage ring at Tsinghua;
- Recently important progress has been achieved by the SSMB PoP team (Tsinghua, HZB, PTB) on the PoP experiment at the MLS in Berlin.
- Dedicated EUV SSMB lattice design and efforts to resolve related technical challenges for a real machine are ongoing.
- Much further work needed.