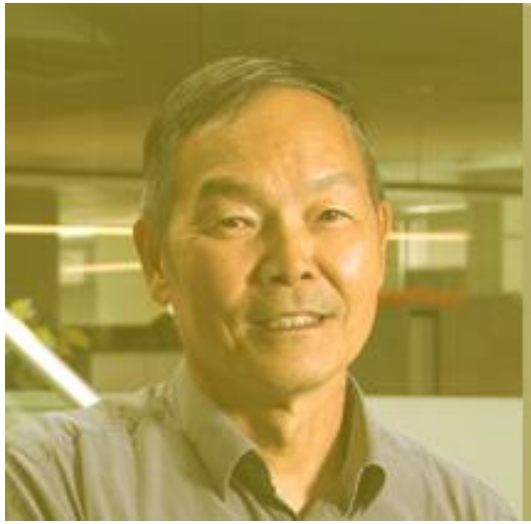

Special Topics in Accelerator Physics

Celebrating the Distinguished Career of Professor ALEX CHAO

Status of the steady-state microbunching (SSMB) studies at Tsinghua University

Renkai Li

on behalf of Prof. Chuanxiang Tang

Tsinghua University

Oct. 25, 2019

清華大學 Tsinghua University

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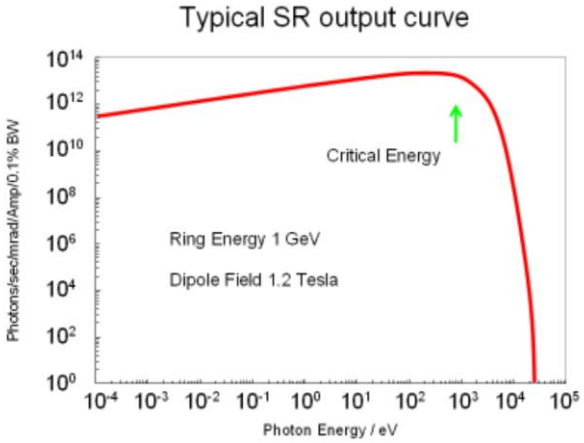
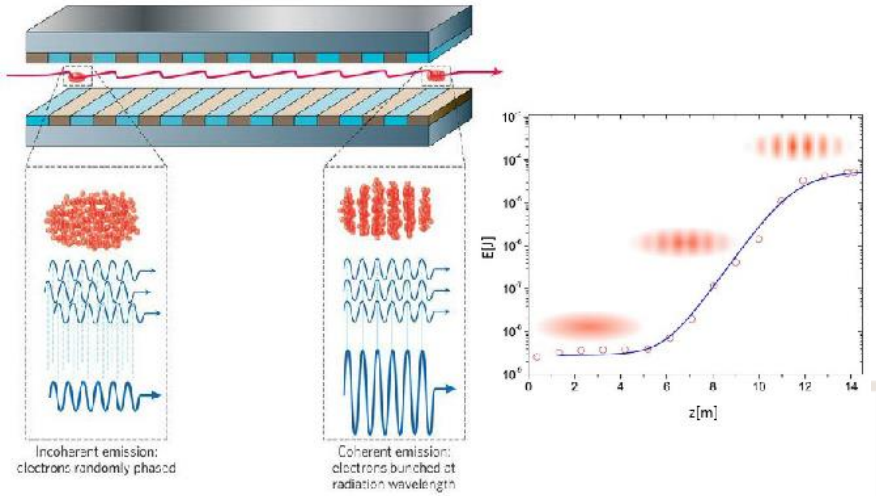
- Introduction
  - tremendous potential, task force at Tsinghua
- Research progress
  - proof-of-principle experiment
  - dedicated EUV SSMB lattice design
  - related technique challenges
- More status and next step
  - related studies at other places
  - next step and summary
- Alex and Tsinghua

Accelerator light source workhorses

- Storage rings: high repetition rate, low peak power

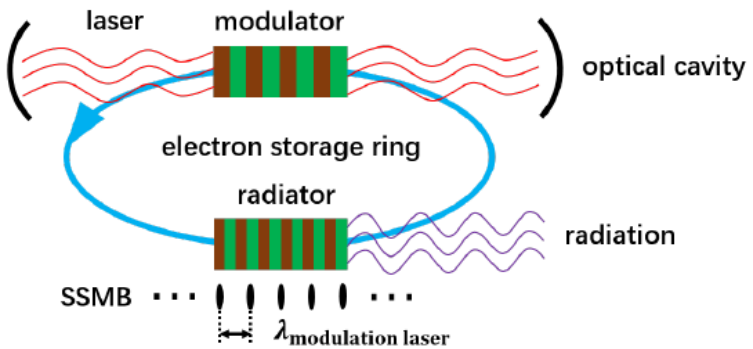


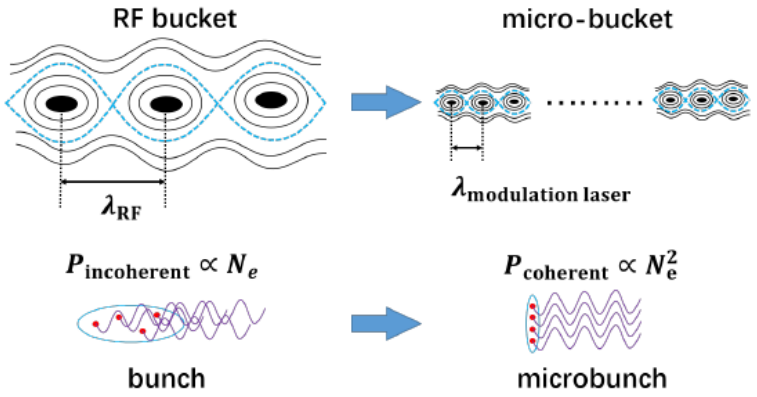
- Free electron lasers: high peak power, low repetition rate



Steady-state microbunching (SSMB)

Microbunching for high peak power and steady-state for high repetition rate, two features combined lead to the idea of SSMB (Ratner and Chao, PRL 2010):





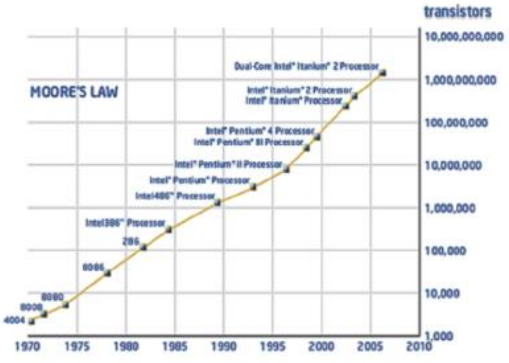
Remarkable feature of SSMB: high average power narrow band coherent radiation with wavelength ranging from THz to EUV.

Tremendous potential of SSMB

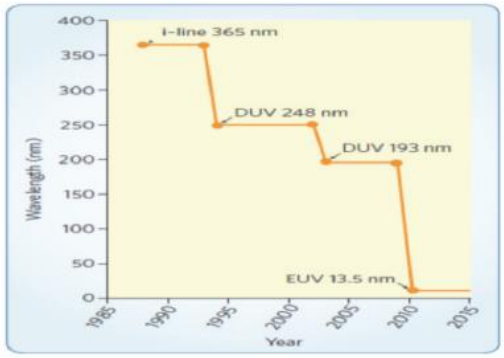
- A good candidate for the next generation light source:
  - the synchrotron light source community is intensively studying and building the low transverse emittance rings now. SSMB, on the other hand, focuses on the longitudinal emittance.
  - exciting accelerator physics of SSMB:
    longitudinal strong focusing dynamics and novel 6D PS manipulation schemes;
    many physical effects negligible in usual storage rings;
    collective effects study of steady-state microbunches.

- KW level EUV source is urgently needed by semiconductor industry for lithography. SSMB is one of the promising schemes (sc FELs, ERLs, etc.) resolving this issue.

	Year	Transistors
4004	1971	2,250
8008	1972	2,500
8080	1974	5,000
8086	1978	29,000
286	1982	120,000
386™ processor	1985	275,000
486™ DX processor	1989	1,180,000
Pentium® processor	1993	3,100,000
Pentium II processor	1997	7,500,000
Pentium III processor	1999	24,000,000
Pentium IV processor	2000	42,000,000



[Courtesy: 林合俊 陳虹宇 周展弘 陳玟儒 吳萱郁, 2014]



[Courtesy: 林合俊 陳虹宇 周展弘 陳玟儒 吳萱郁, 2014]

The SSMB task force at Tsinghua

- 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 on July 21st, 2017 and more than ten work meetings have been held since then;

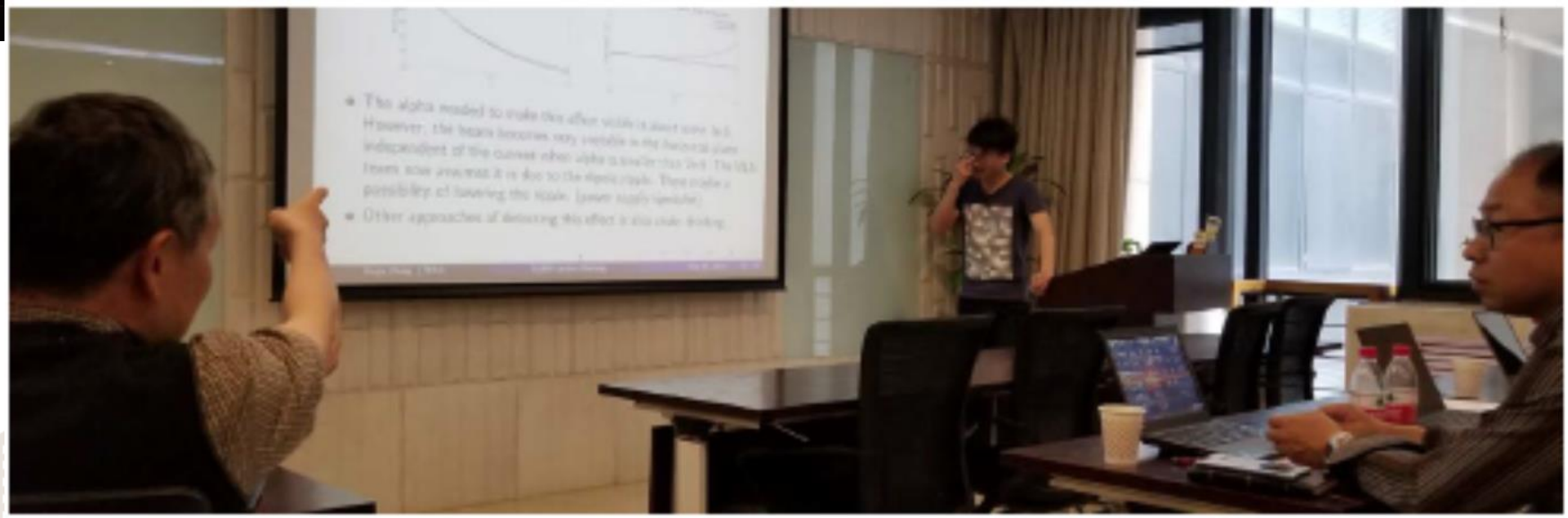
- Main tasks of the collaboration at this moment:

  - prove the SSMB work principle: from single-pass to quasi-steady-state to real steady-state microbunching. Performed at the MLS in Berlin, with HZB and PTB;

  - dedicated EUV SSMB lattice design: strong focusing and reversible schemes;

  - address related technical challenges: high repetition rate induction linac, MW storage power optical enhancement cavity, etc.

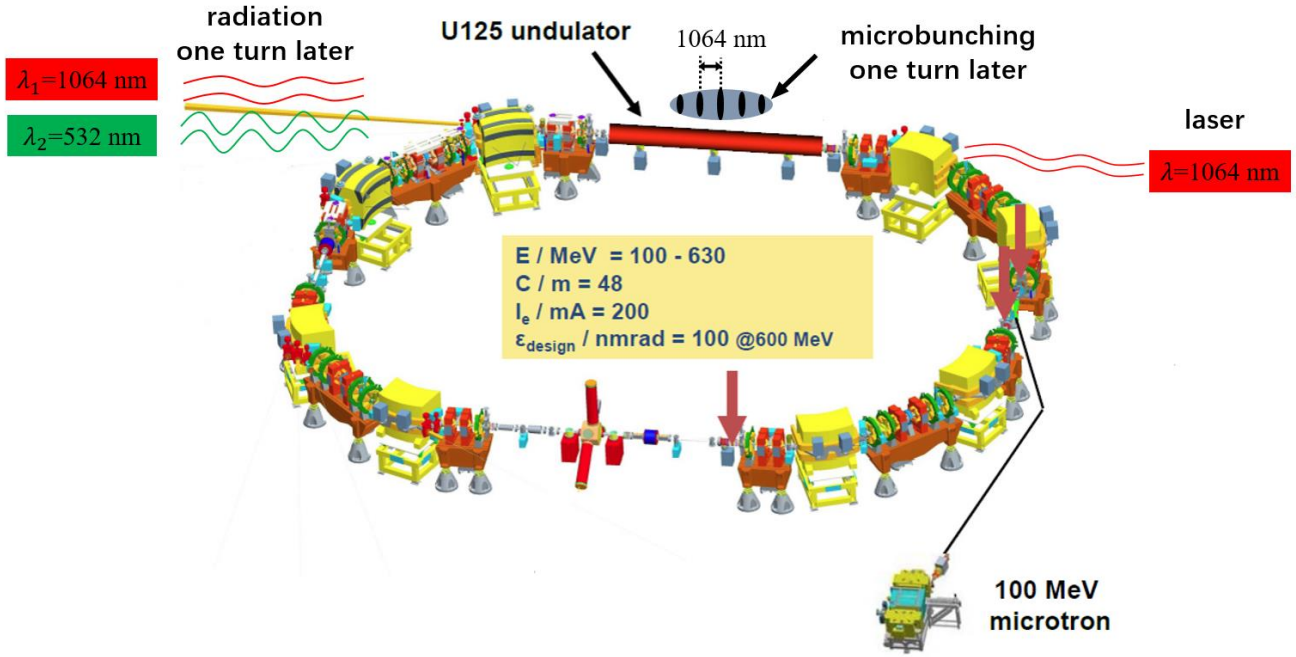
SSMB meetings



SSMB meetings

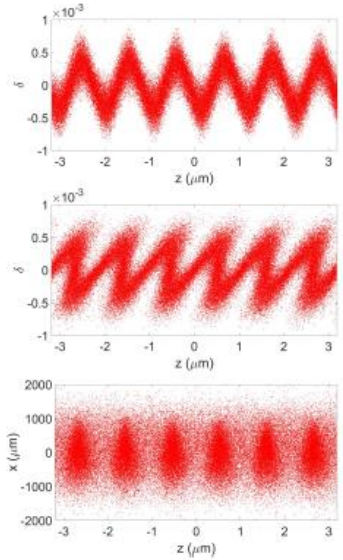
Proof-of-principle experiment phase I

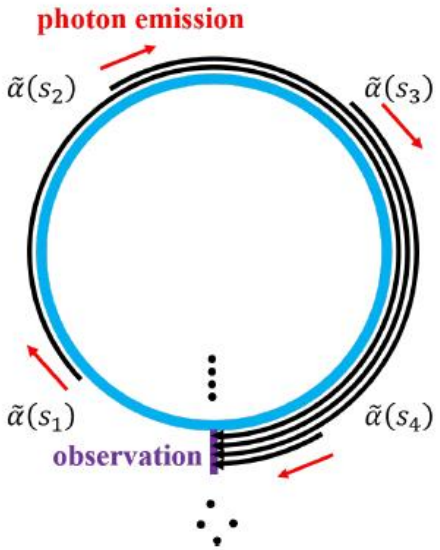
- Electron beam modulated by a pulse laser in the undulator and microbunching one turn later with the goal of:
  - formation of microbunches and generation of coherent undulator radiation from them;
  - study the influences of various parameters, physical effects and investigate the radiation characteristics;
  - define the starting point of the SSMB PoP experiments and establish the possibility of PoP Phase II at the MLS.

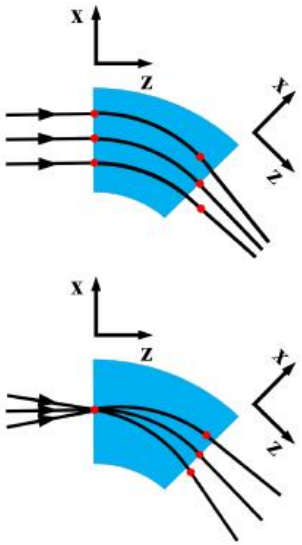


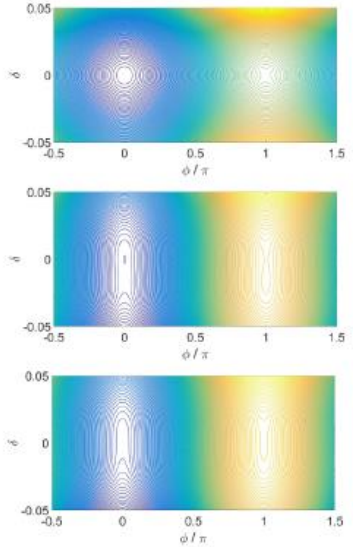
Related physical effects

- energy modulation convert to density modulation by dispersion;
- longitudinal quantum radiation excitation;
- linear and nonlinear transverse-longitudinal coupling;
- nonlinear momentum compaction;
- coherent synchrotron radiation, etc.
- some of the effects experimentally verified for the first time (paper being prepared).



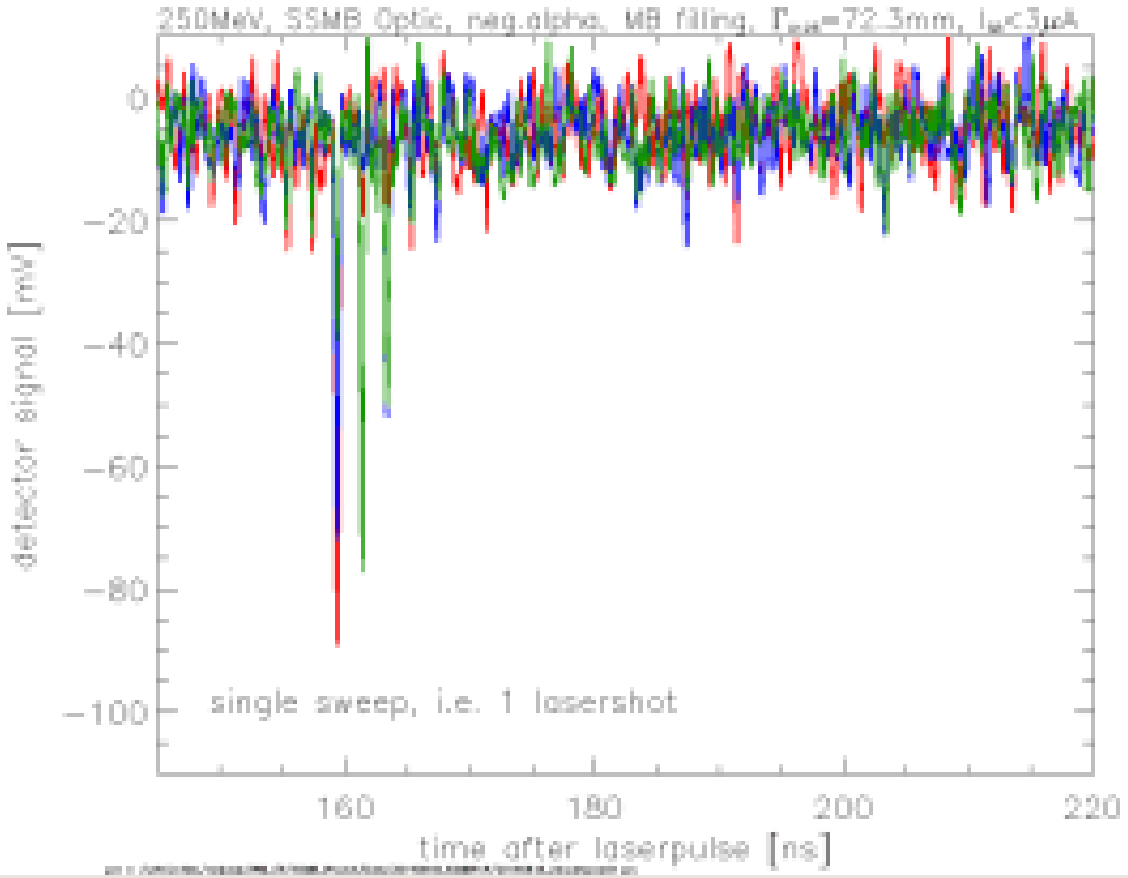






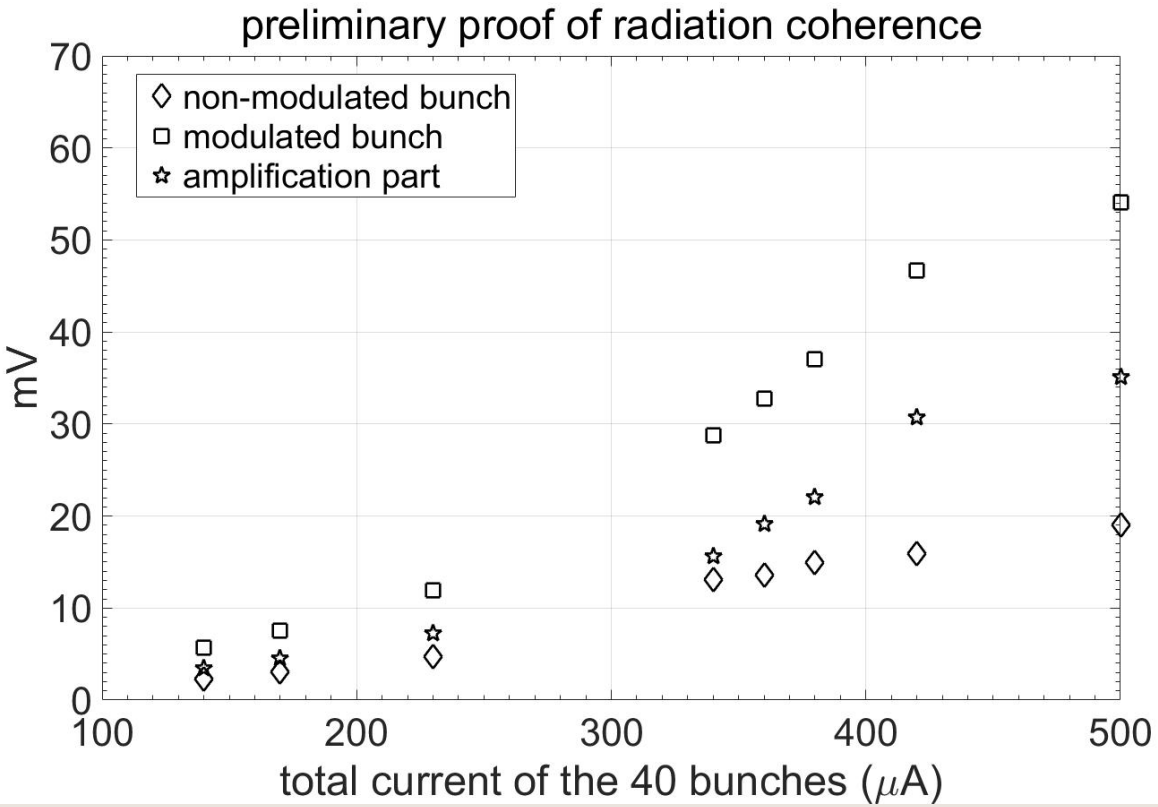
Experiment result (unpublished)

- After seven visits of the group members to the MLS for preparation and participation since November, 2017 and four dedicated rounds of SSMB experiments since the beginning of 2019, we finally succeeded on August 18th, 2019!



Experiment result continued (unpublished)

- nonlinear scaling of the amplification signal v.s. beam current indicates the quadratic characteristics of coherent radiation, microbunching!
- collective effects emerge at higher current and degrade the microbunching which also fits with our understanding.



Significance of the experiment

- Alex Chao: **it is challenging to provide SSMB** because the storage ring needs to be designed and operated accordingly. It is not something to be taken for granted. **The recent proof-of-principle test at Berlin, however, established its feasibility.** In that experiment, the beam stays microbunched for one revolution. Once it completes one revolution, we think it can be made to complete 1000 revolutions. The rest will then be optimization.

- 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**. The storage ring must provide the potential of steady state. As we know well, this environment is a subtle one, not easy to achieve. When SSMB was proposed initially, there were questions concerning this issue. What we demonstrated this time is that even in the environment of a storage ring that stores a beam in the SSMB state, the beam can still be made to microbunch and radiate one turn later. **Our test is not to be confused with the other single shot tests. It is one order of magnitude more difficult.**

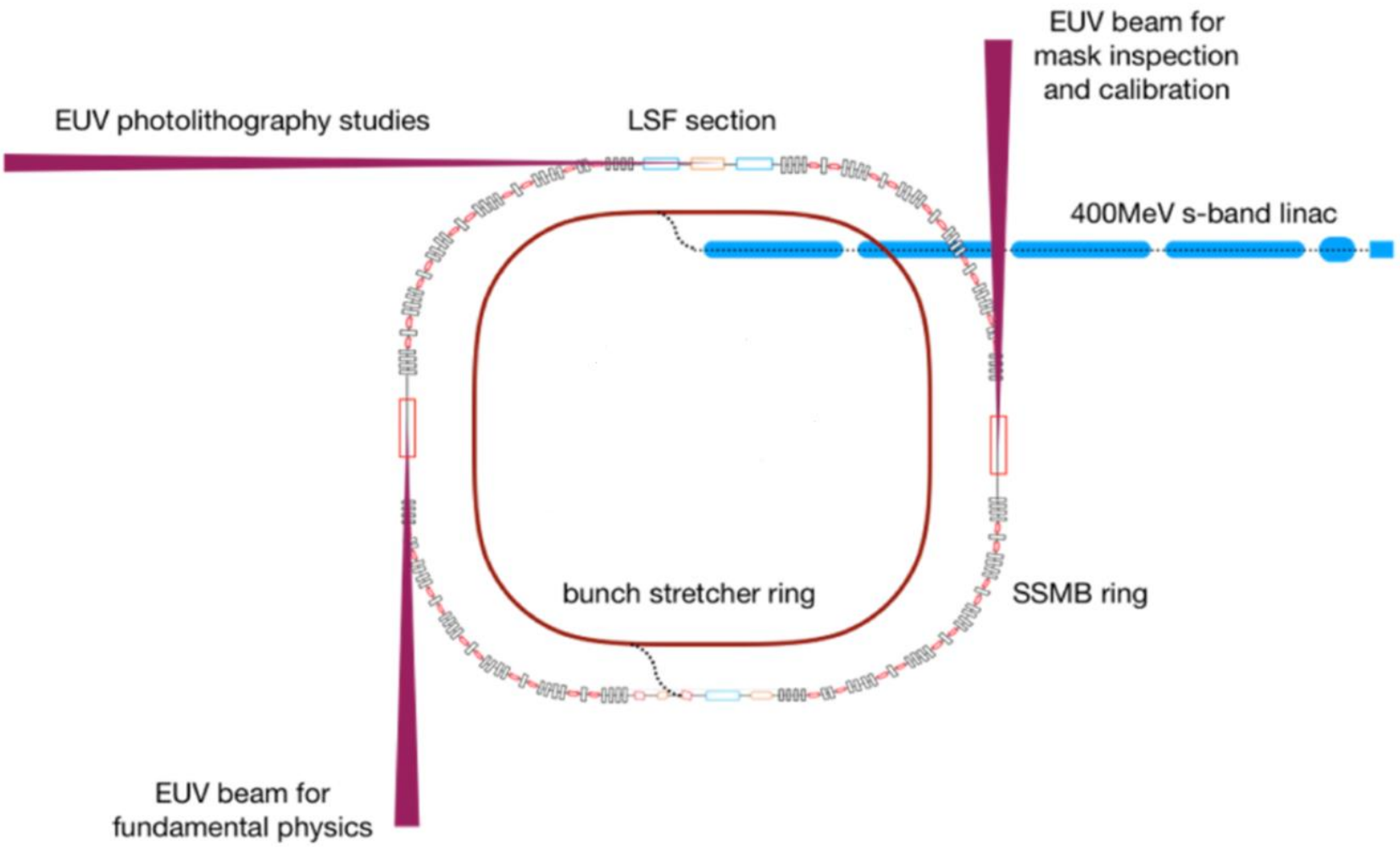
Significance of the experiment (continued)

- 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.**

- The first experiment using a whole ring to convert energy modulation into density modulation to form microbunches. The first step towards real SSMB.

- Our understanding of the storage ring beam dynamics still applies at sub-μm level, offering us great confidence of pushing SSMB to even shorter wavelength range like EUV.

The envisioned Tsinghua EUV SSMB ring



Related technique challenges

- longitudinal strong focusing module;
- collective effects of the SSMB ring: 100 W, 1 kW or more?
- requirement on power supply stability of some magnets maybe one order of magnitude higher than now available;
- long electron beam pulse injection;
- high storage power optical enhancement cavity;
- timing and synchronization system;
- ...

More status

- From Jörg Feikes: **both institutions (HZB+PTB) agreed that we can continue with our experiment at least 3 years and that we will get all necessary funding to buy our own laser and to build up a new robust experimental setup.** ... This program is seen as a purely academic program together with Tsinghua and the other institutes and we will hire a PhD and preferably two master students (fundings are available) and also Bachelors when available. **In this way we are following the Tsinghua academic approach.**
- **Dortmund University** (S. Khan), Germany is closely following our work.
- We are going to report the status of the SSMB research and recent important progress of the PoP experiment on the 2019 International Workshop on EUV and Soft X-Ray Sources to be held Nov. 4^{th}-6^{th} in Netherlands.
- The first SSMB workshop is under planning and hopefully can be held at Tsinghua soon.

Next step

- Team building: gradually build a world leading academic team, Tsinghua faculty;
- Continuous steady dedicated funding to support the SSMB research in Tsinghua;

- More SSMB work meetings and workshops to promote the SSMB research;
- Proof-of-principle experiment phase II;
- More in-depth study of lattice design and collective effects;
- Resolve technical issues as soon as possible.

Summary

- SSMB can generate high average power coherent radiation and has tremendous potential in both science and industry applications.
- An initial task force has been established in Tsinghua 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 collaboration about the PoP experiment at the MLS in Berlin. PoP phase II is under discussion and planning;
- SSMB is a promising candidate to be the next generation advanced light source and the work of the SSMB collaboration is attracting more and more attention from both the academic circle and industry;
- Much further work needed.

Oct. 2019, Tsinghua campus

Dr. Chen Senyu and Dr. Zhao Zhentang would like to express their sincere gratitude to Alex for friendship and collaboration over many years, and more to come!

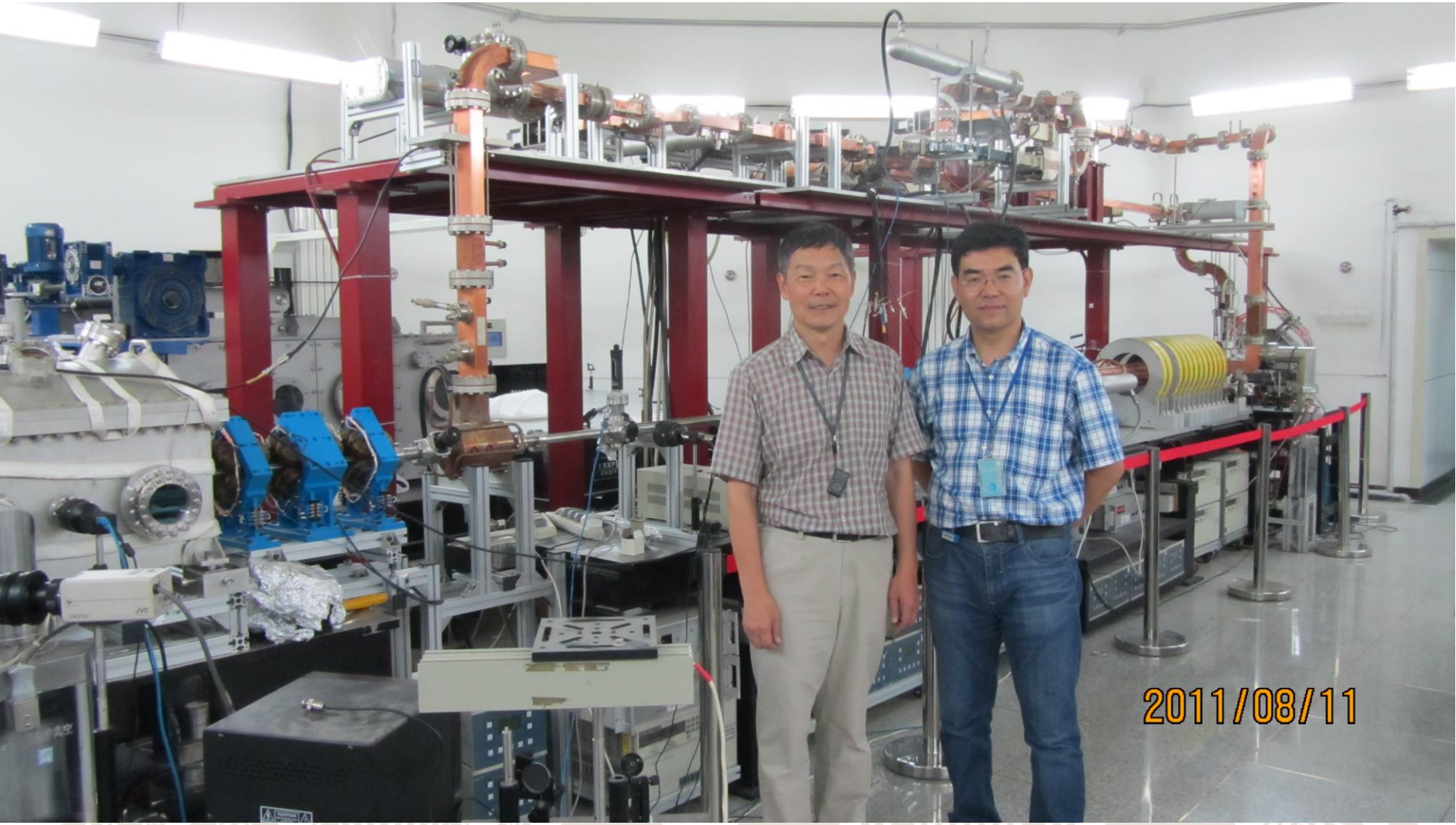
Renkai Li Chuanxiang Tang Wenhui Huang Bochen Jiang

Alex Senyu Chen Zhentang Zhao

2002, Nuctech, Minyun, Beijing

Juwen Yuzheng Lin Alex

2011, Tsinghua Thompson scattering X-ray source



2006, Yang-zhou

Thanks, Alex!

2019, the Yellow Mountain

2006, OCPA school, Yang-zhou

2009, 1st OCPA Topical Accelerator School, Tsinghua

2019, 6th OCPA Topical Accelerator School, Tsinghua