Storage Ring Based Steady State Microbunching

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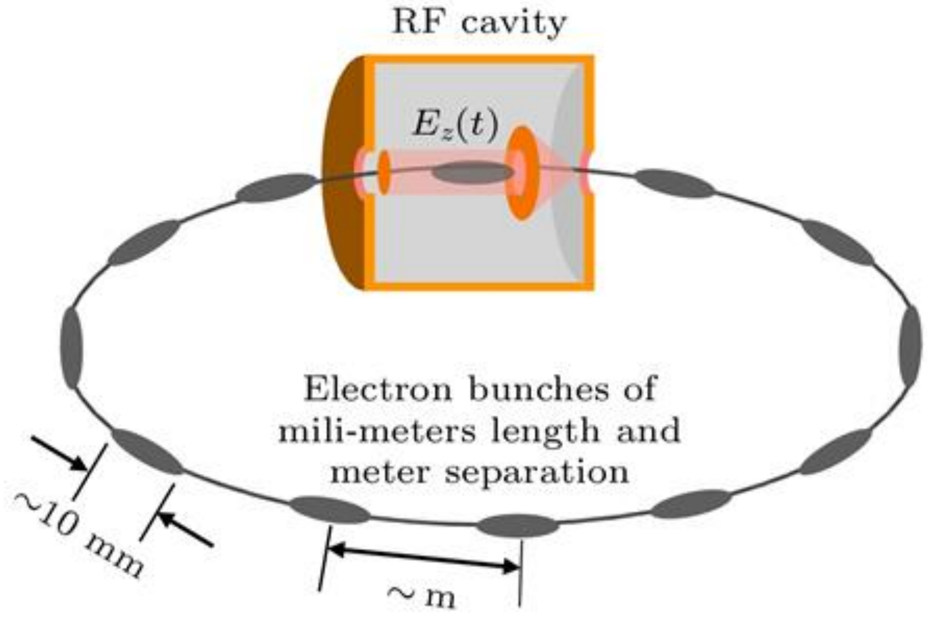
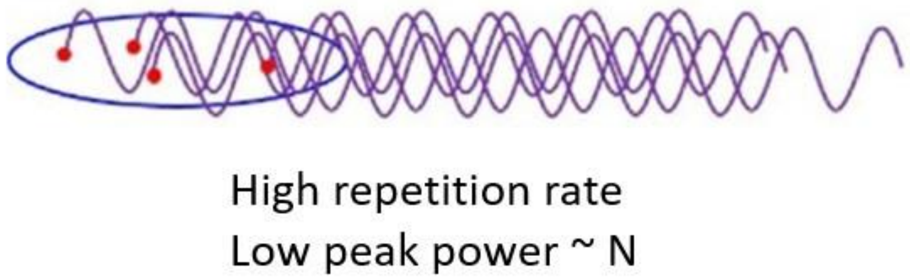
ICFA Beam Dynamics Workshop on Future Light Sources, Lucerne, Switzerland, 2023

There are currently two main approaches in advanced light sources.

Approach 1 3rd- and 4th-generation synchrotron radiation facilities:

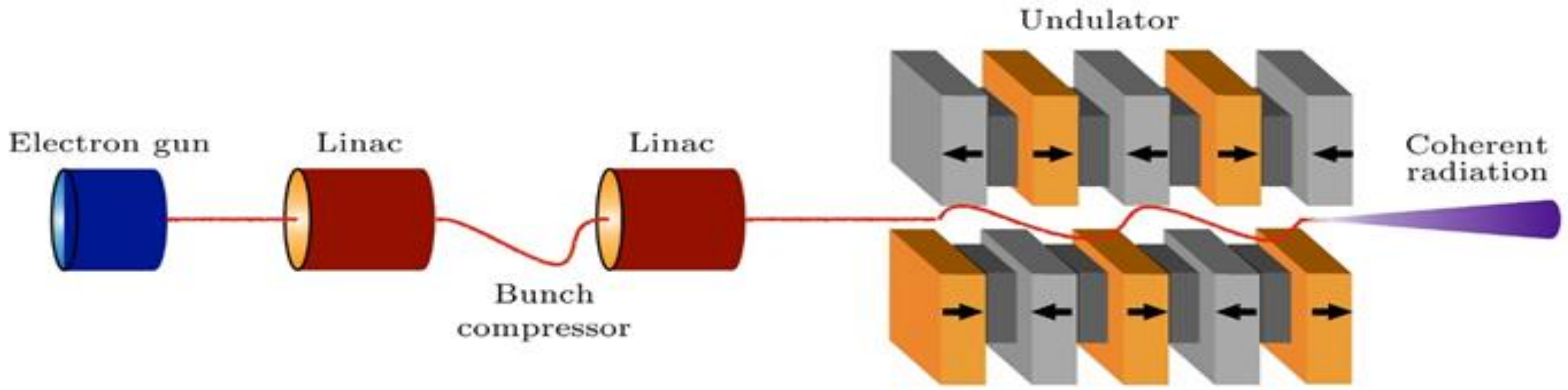


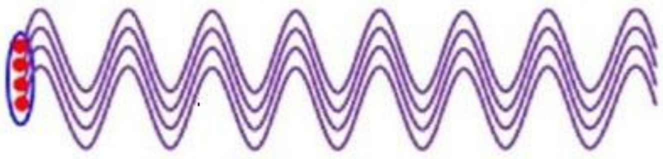


Bunch length >> radiation wavelength

Radiation is incoherent

Approach 2 A free electron laser:





Low repetition rate

High peak power ~ N^2

A linac and a long undulator are used. The beam gets microbunched towards the end of the FEL.

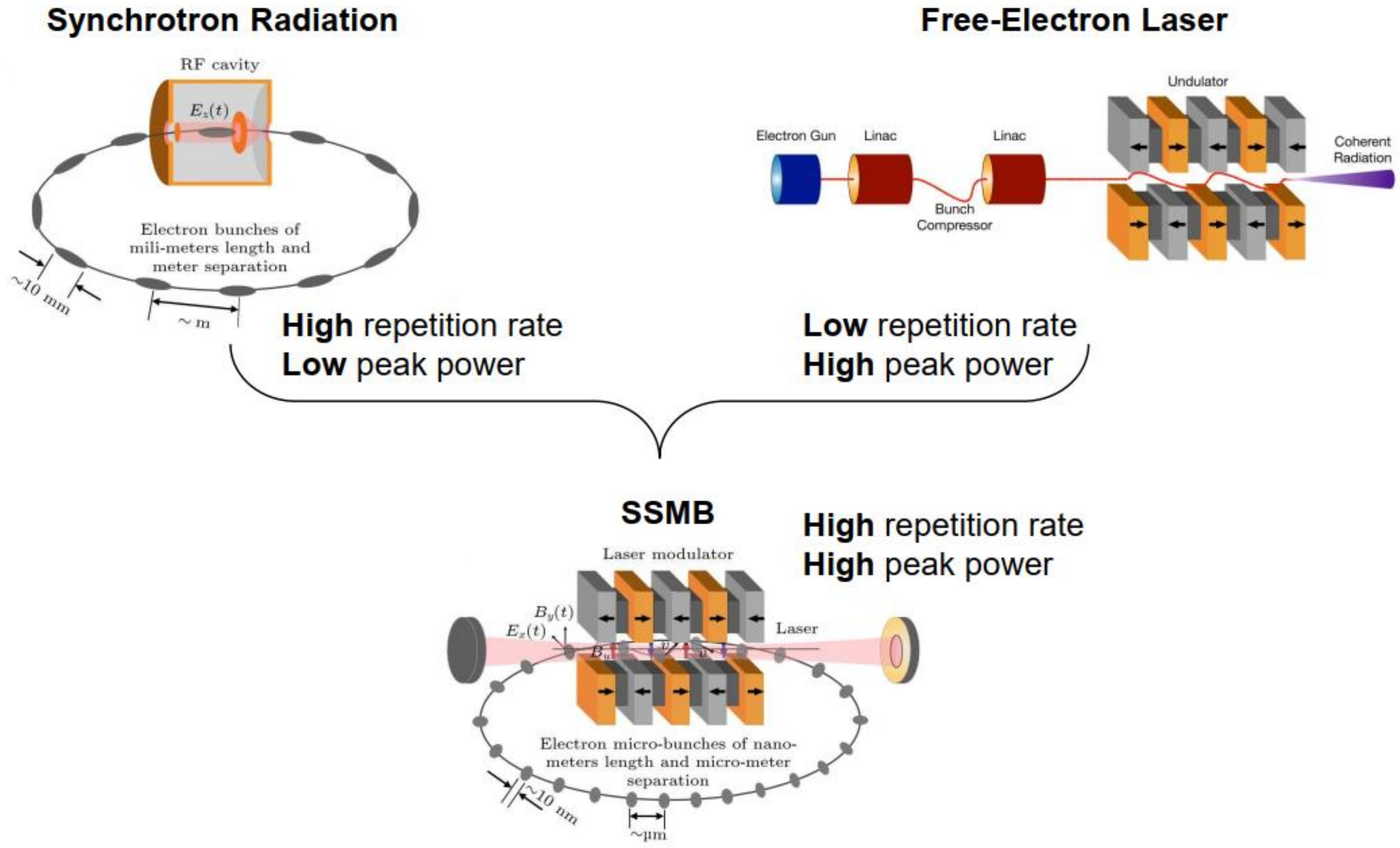
Radiation is coherent.

One approach has high repetition rate but low peak power. The other approach has high peak power but low repetition rate.

Net radiation power ∝ (repetition rate) x (peak power).

Combine the two approaches. The new approach would invoke a storage ring for high repetition rate and a microbunched beam for high peak power.

10^6 extrapolation.



D.F. Ratner, A.W. Chao, Phys. Rev. Lett. (2010)

There is a catch:
The beam must be microbunched, and stays microbunched as it circulates the storage ring in steady state.

A straight insertion of an FEL in a storage ring will not work. The FEL disrupts the mirobunching beam dynamics.

SSMB is not an FEL. It is closer to a third-generation storage ring, just replacing the RF by a laser modulator.

SSMB Scenarios

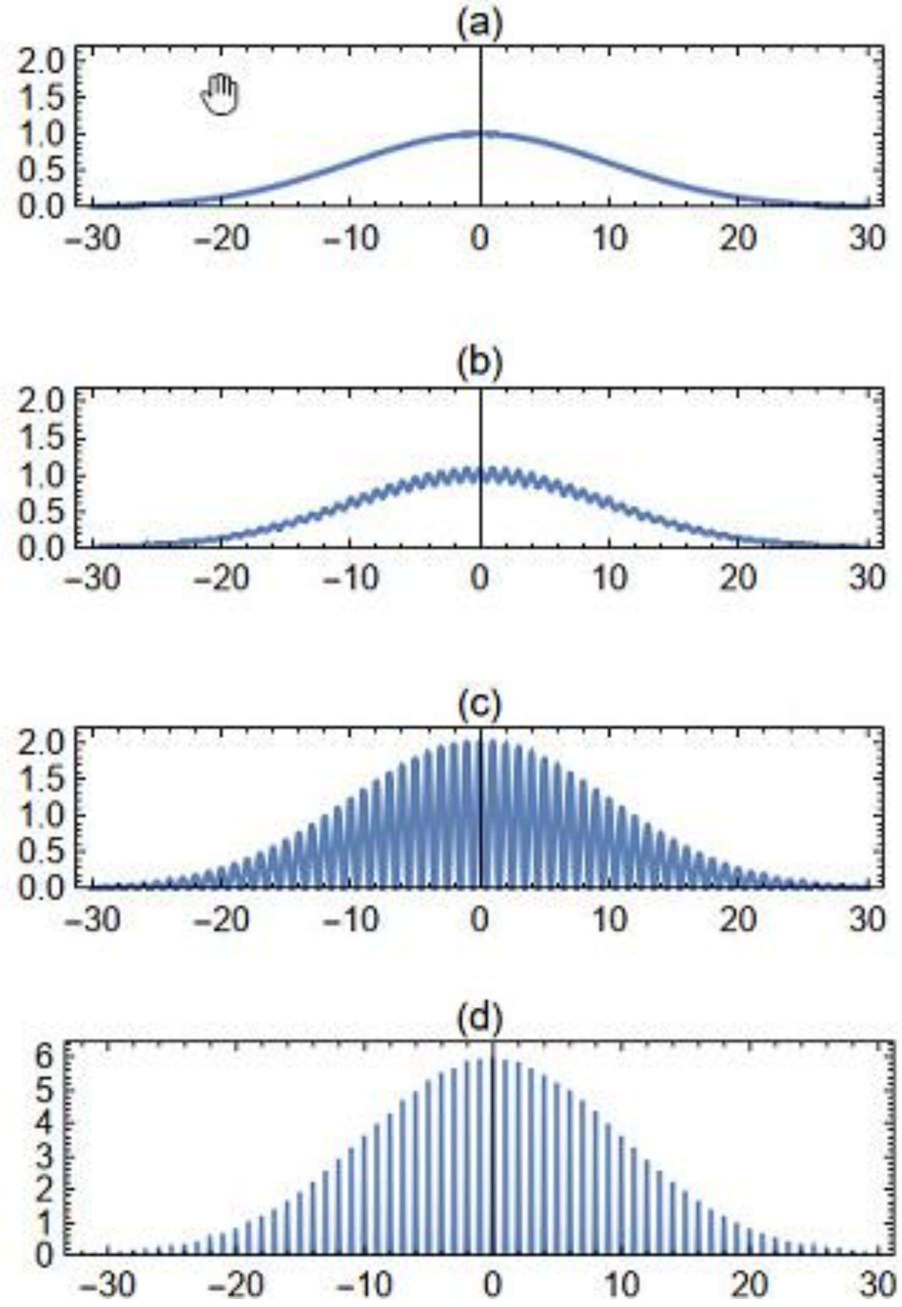
Depending on its targeted radiation wavelength, there are several SSMB scenarios.

(a) Gaussian beam in an RF bucket of a conventional ring

(b) Potential-well of RF bucket is slightly distorted by a laser modulation
--- for IR or THz radiation

(c) Potential-well distortion increased to 100%
--- for amplification of IR or THz radiation by a factor N

(d) Microbunches shrink when modulation depth provides overfocusing
--- for high harmonic generation to reach DUV, EUV, soft Xray



Potential-well distortion SSMB

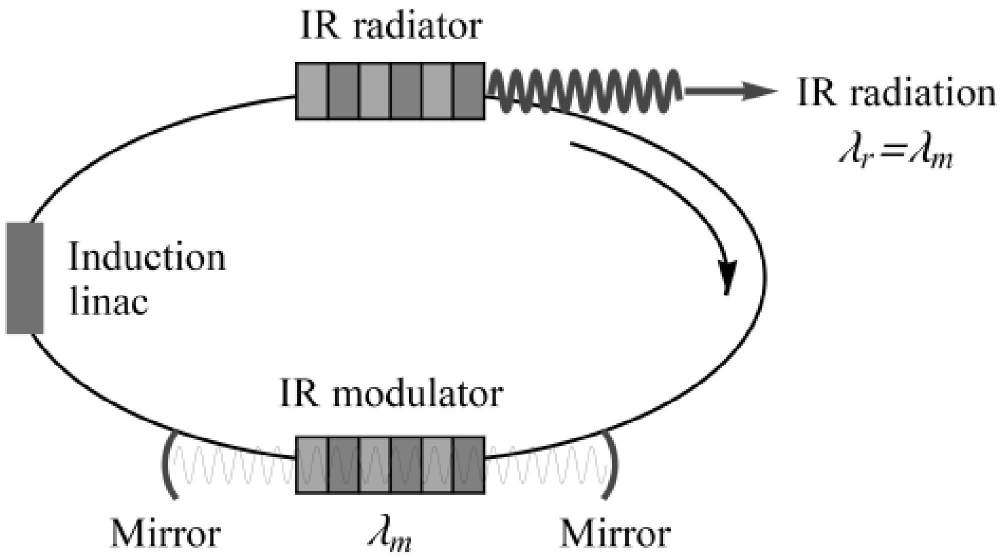
- No additional requirements from SSMB. ➔ Readily available using existing storage rings.
- Very slight modulation provides respectable IR radiation.

$$P_{ave} = \frac{\pi}{\epsilon_0 c}|\mathcal{B}|^2 \xi [JJ]^2 N_u I_{ave} I_{peak}$$

e.g. a 1% modulated beam can produce 25 W average power.

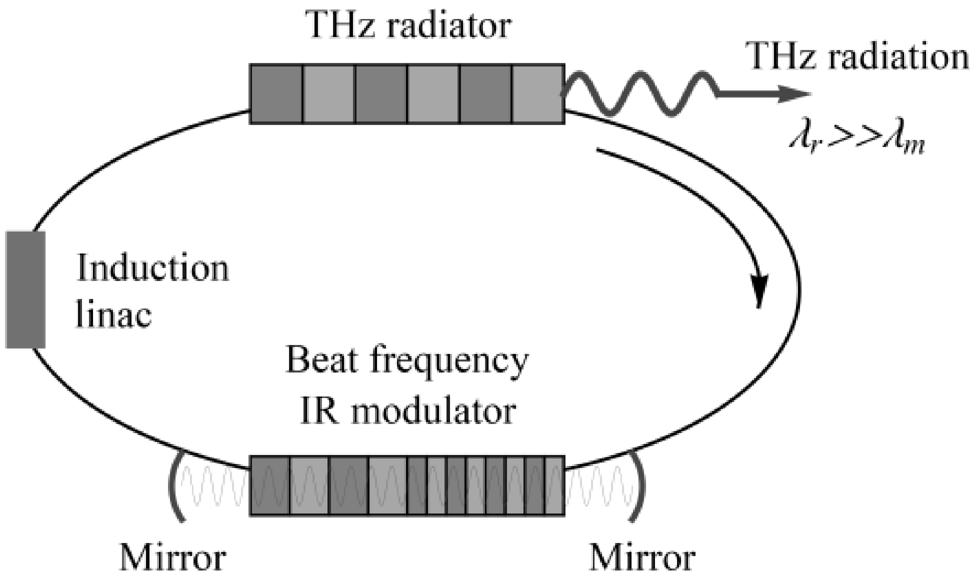
Amplifier SSMB

- By increasing the modulation depth, this scenario can be very powerful source of IR.
- Weakness is that its radiation wavelength is limited to IR, $\lambda_r = \lambda_m$.
- The SSMB proof-of-principle test at the MLS is an amplifier SSMB. This scenario already has an existing prototype.



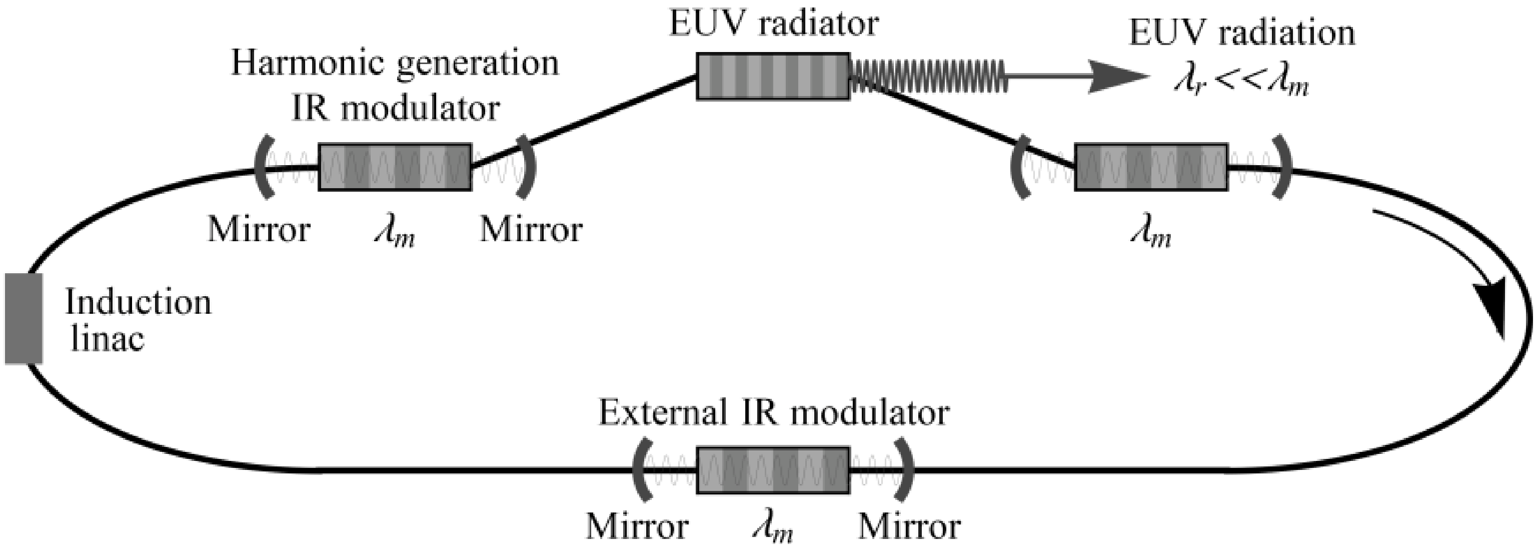
THz SSMB

- Replace the modulator undulator by a dual undulator.
- Radiation amplifies the beat frequency of the two resonant frequencies of the dual undulator.
- $\lambda_r >> \lambda_m$.
- A conventional ring can be used without much additional technology.



Harmonic generation SSMB

- To reach DUV, EUV, soft Xray, an additional step of harmonic generation is needed,
- R&D is on-going.
- Two modulators sandwiching the radiator does the harmonic generation.
- $\lambda_r << \lambda_m$.



FEL-ERL based scenario

- This scenario uses an FEL to do the microbunching.
- Implementing a superconducting linac and adding an ERL, steady state is reached not by reusing the electrons but by reusing the electron energy.
- Its microbunching beam dynamics and that of the SSMB are quite similar.

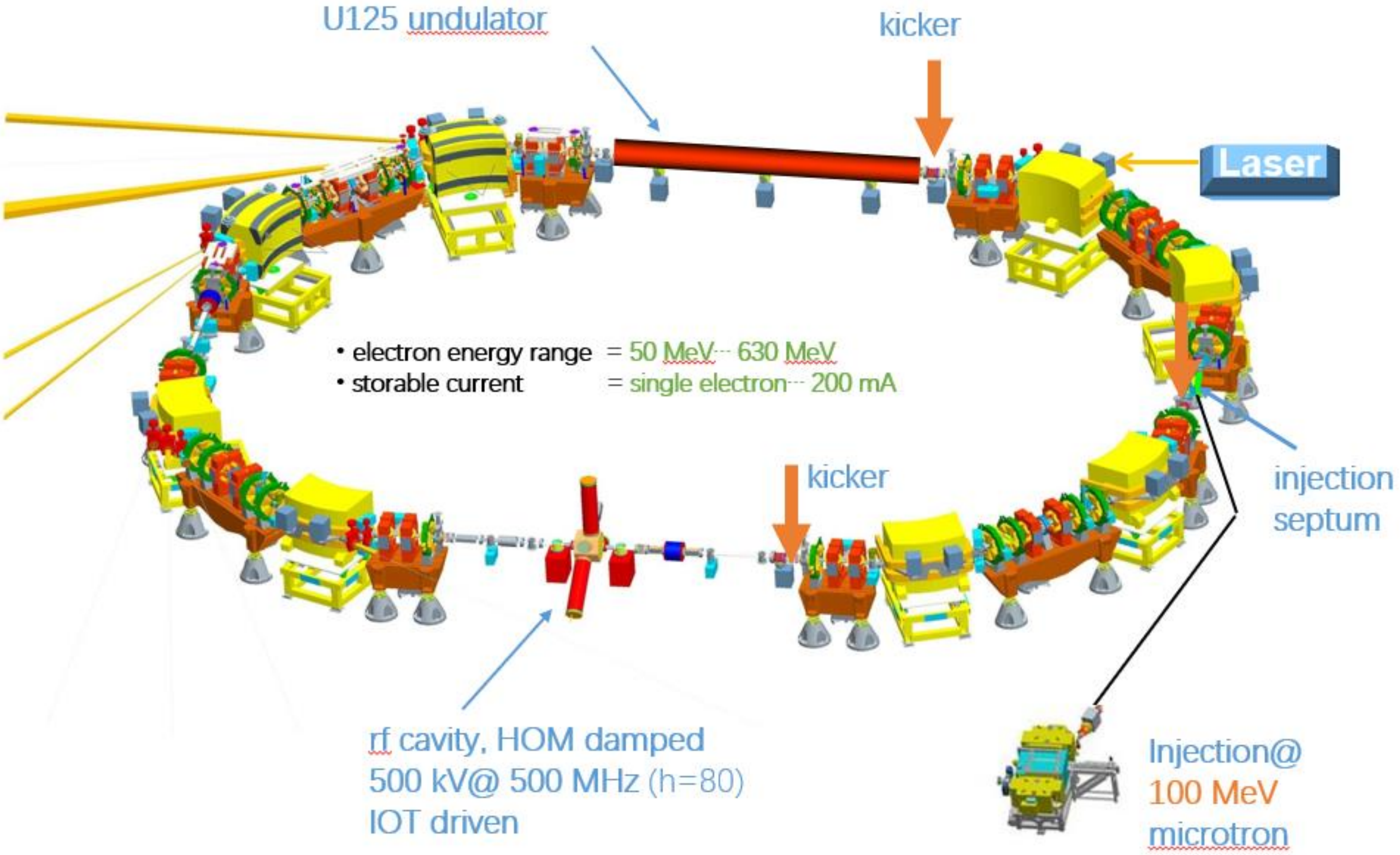
C. Feng, Z.T. Zhao, Sci. Rep. (2017)

Proof of principle experiments

Metrology Light Source MLS,
Berlin

C.X. Tang, et al., FLS Workshop, 2018
J. Feikes, et al., IPAC 2021

MLS - the storage ring

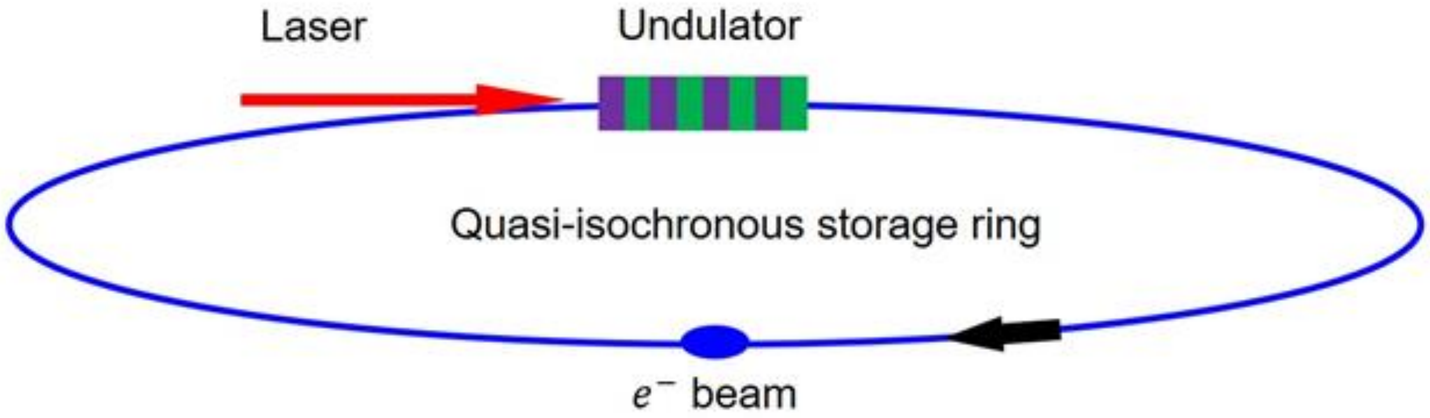


- electron energy range = 50 MeV··· 630 MeV
- storable current = single electron··· 200 mA

Three phases conceived of the SSMB planning:

Phases I and II are proof of principle tests using the existing ring MLS.

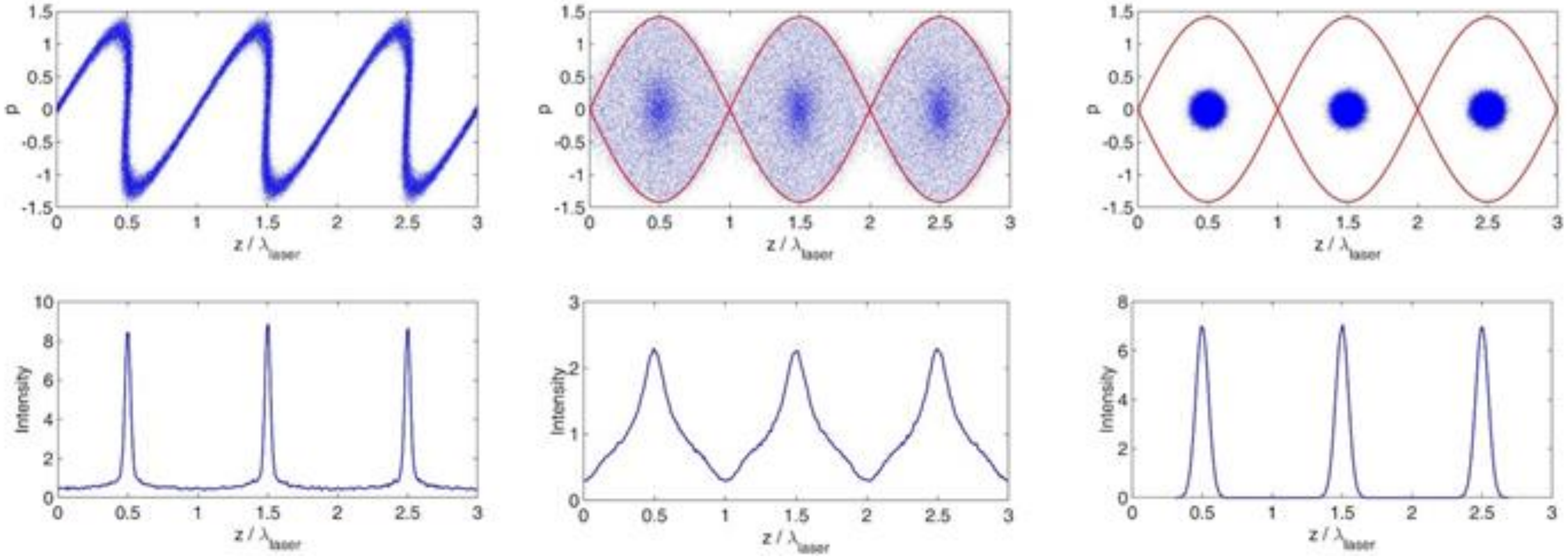
Phase III is a dedicated ring, presently under a design effort.



Phase I: a single laser shot, shot-lived microbunching

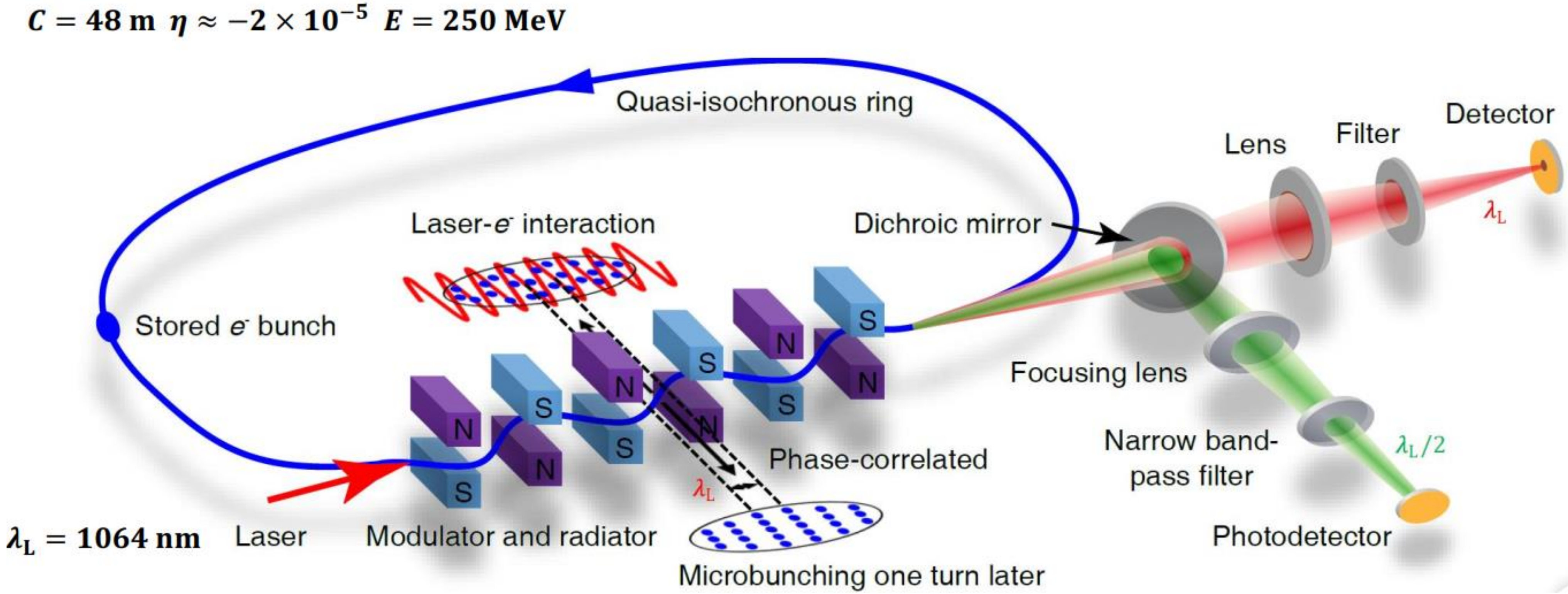
Phase II: multiple laser shots, quasi-steady-state microbunching

Phase III: infinite laser shots, real-steady-state microbunching



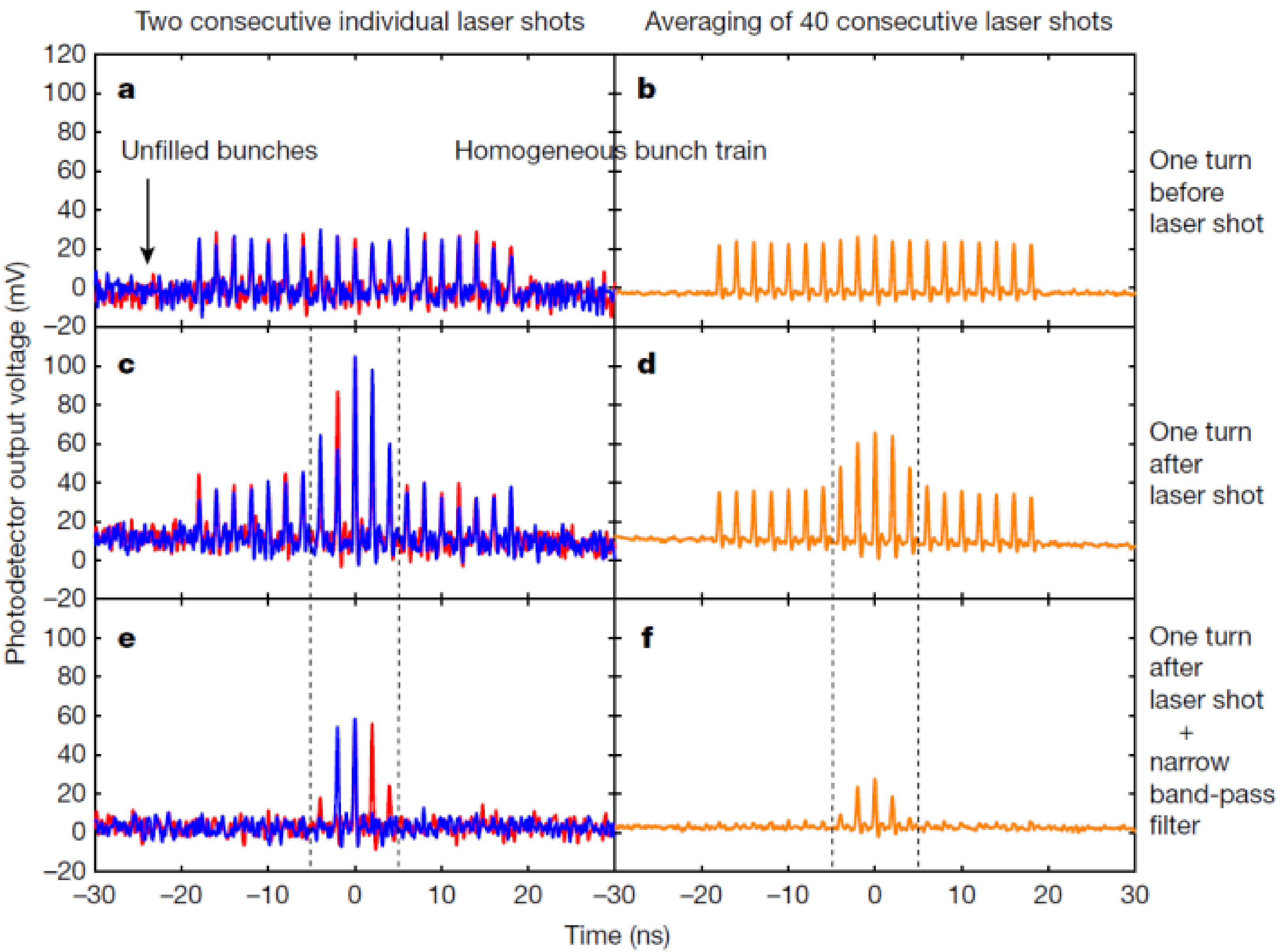
Phase I proof of principle test

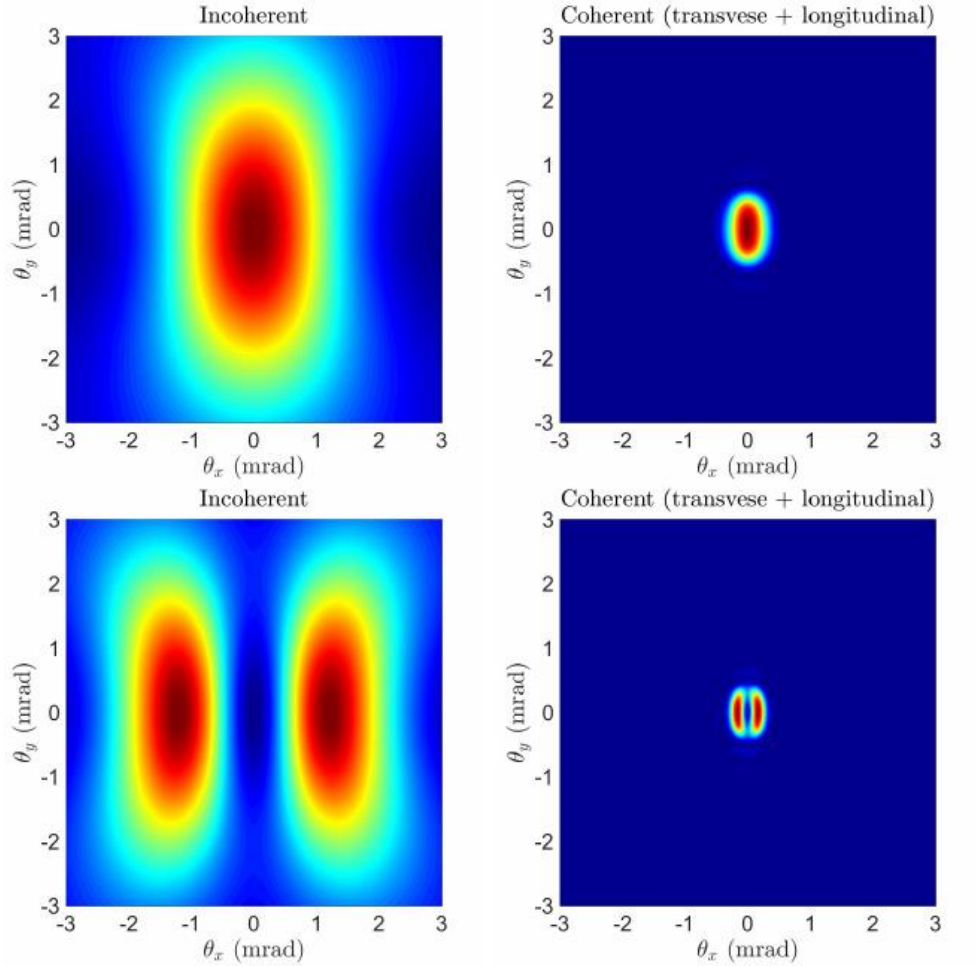
After the beam is stably stored in the ring, a single-shot IR laser is fired to excite the beam with energy modulation. A precision semi-isochronous storage ring optics causes the beam to microbunch at its next turn. The modulating undulator then serves as the radiator in the subsequent turns of the beam. SSMB is detected by the coherent radiation of the microbunched beam for multiple turns.



- A 19-bunch beam is stored in the ring, detecting 19 incoherent synchrotron radiation peaks.
- A laser shot is fired, affecting 5 in the middle of the 19 bunches.
- On the next turn of the beam, the 5 bunches get microbunched, yielding their enhanced radiation.
- When a frequency filter is installed in front of the detector, incoherent signal disappears, only coherent signal remains,

X.J. Deng, et al., Nature (2021)





The coherent radiation is expected also to have a narrower angular spread.

Left column: incoherent undulator radiation (Upper: fundamental 1064 nm, Lower: second-harmonic 532 nm).

Right column: coherent SSMB radiation.

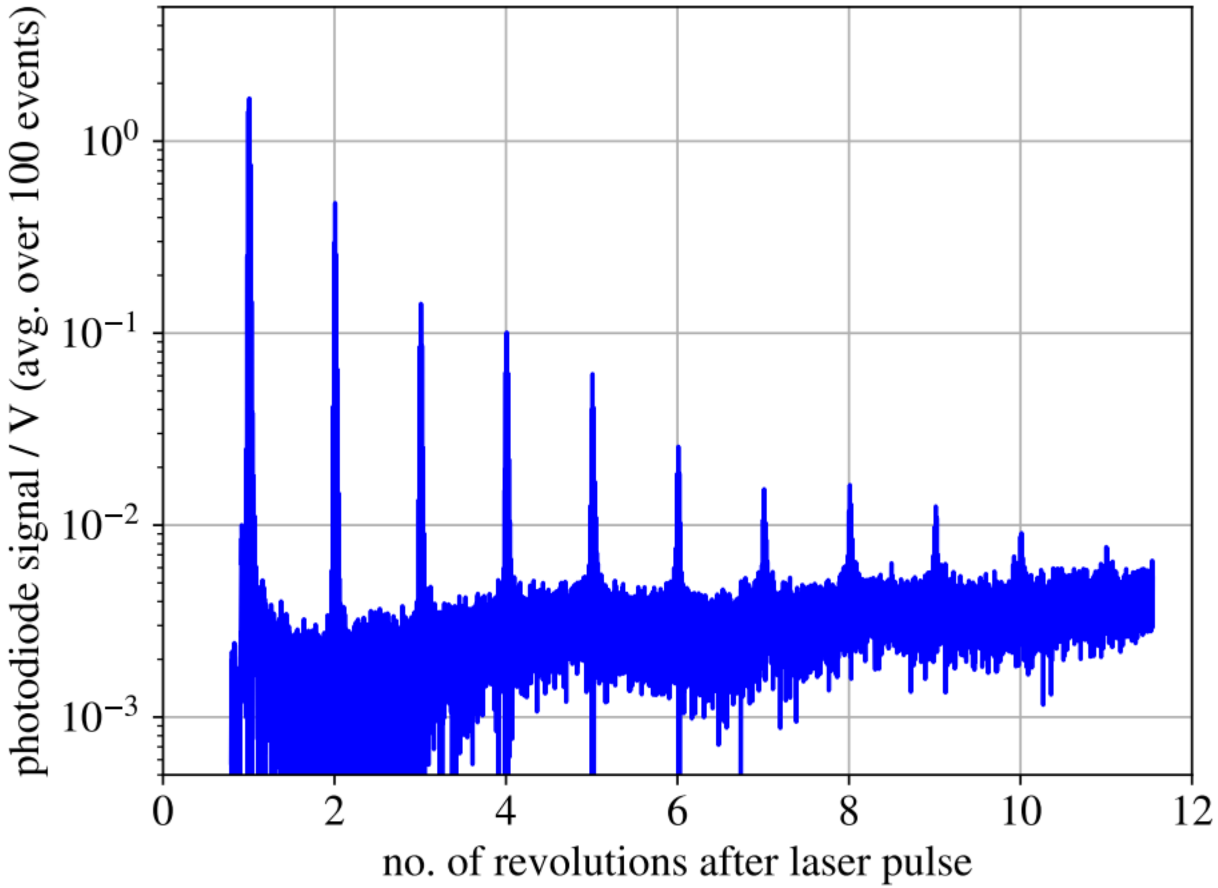
X.J. Deng, A. Chao, this workshop, TP4P29

After the laser shot, the microbunching structure lasts for several revolutions without additional laser shots.

The microbunched beam is very robust.

10^6 extrapolation of present understanding is applicable down to micro-scales.

A.~Kruschinski, et al., IPAC 2023



Phase II proof of principle experiment

- This multi-turn result is very encouraging. A single shot of the laser produces microbunches for several revolutions.
- If we continue the laser shots, it is expected that the microbunched beam will continue to circulate around the ring in a steady state.
- This is what the phase-II experiment aims to demonstrate. The single-shot laser is to be replaced by a high repetition laser. A quasi-steady-state SSMB is expected.

Harmonic generation SSMB design effort

Applications to DUV, EUV, and soft Xray require harmonic generation.

Present design contains the following ingredients:

- Two modulators sandwiching the radiator
- Two modulations cancel each other, constituting a reversible insertion

D. Ratner, A. Chao, FEL Conf. 2011
C.L. Li, et al., IPAC 2011

- Adopts a clever angular dispersion scheme to reduce the required laser power

C. Feng, Z.T.Zhao, Sci. Rep. (2017)

- Adopts a generalized strong focusing scheme to compress the beam in 6D phase space with transverse-longitudinal coupling.

Z.Z. Li, et al., to be published, PRAB, 2023
X.J. Deng, PRAB (2020)

- Bunch compression is done solely in the insertion section. A small momentum compaction factor is not required, thus relaxing the storage ring design.

X.J. Deng, et al., this workshop, TU4P28

- SSMB storage ring lattice design
  - Optimization
  - Dynamic aperture
  - Intrabeam scattering

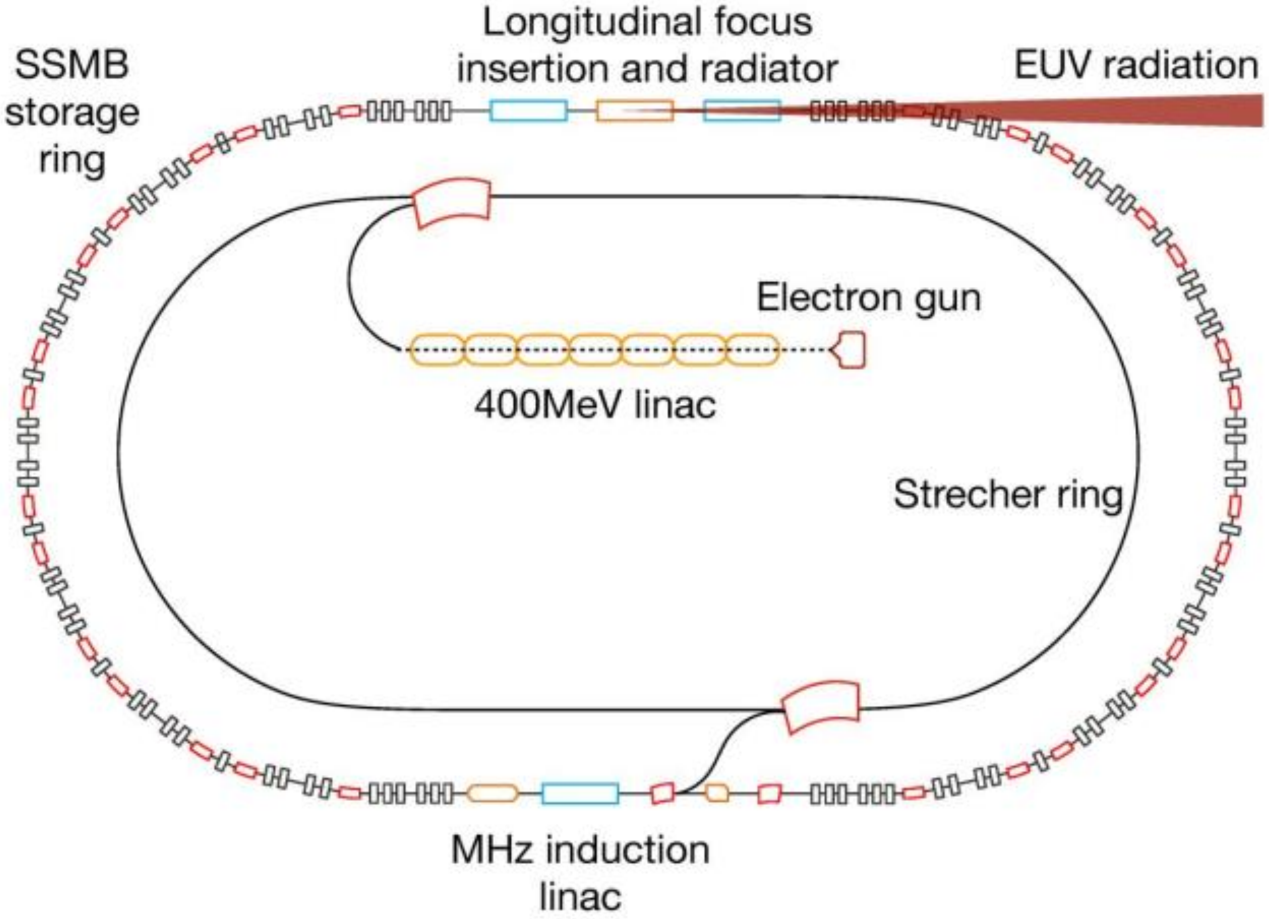
Z.L. Pan et al., FEL Conf. 2019

Z.L. Pan, this workshop, TU1B2

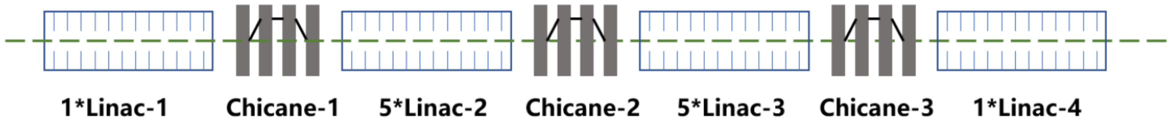
- Collective effects
  - Intrabeam scattering
  - Coherent synchrotron radiation
  - Resistive wall
  - Robinson instability

C.Y. Tsai, X.J. Deng, this workshop, TU4P31

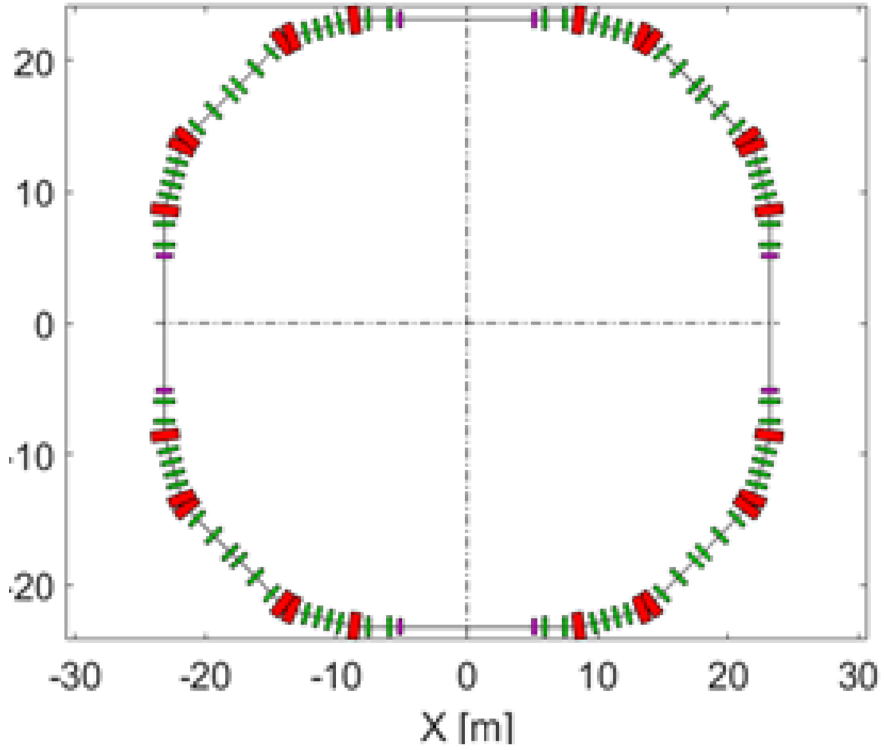
J.Z. Tang, in preparation



- Injector system
  - High quality gun
  - Wakefield compensation linac

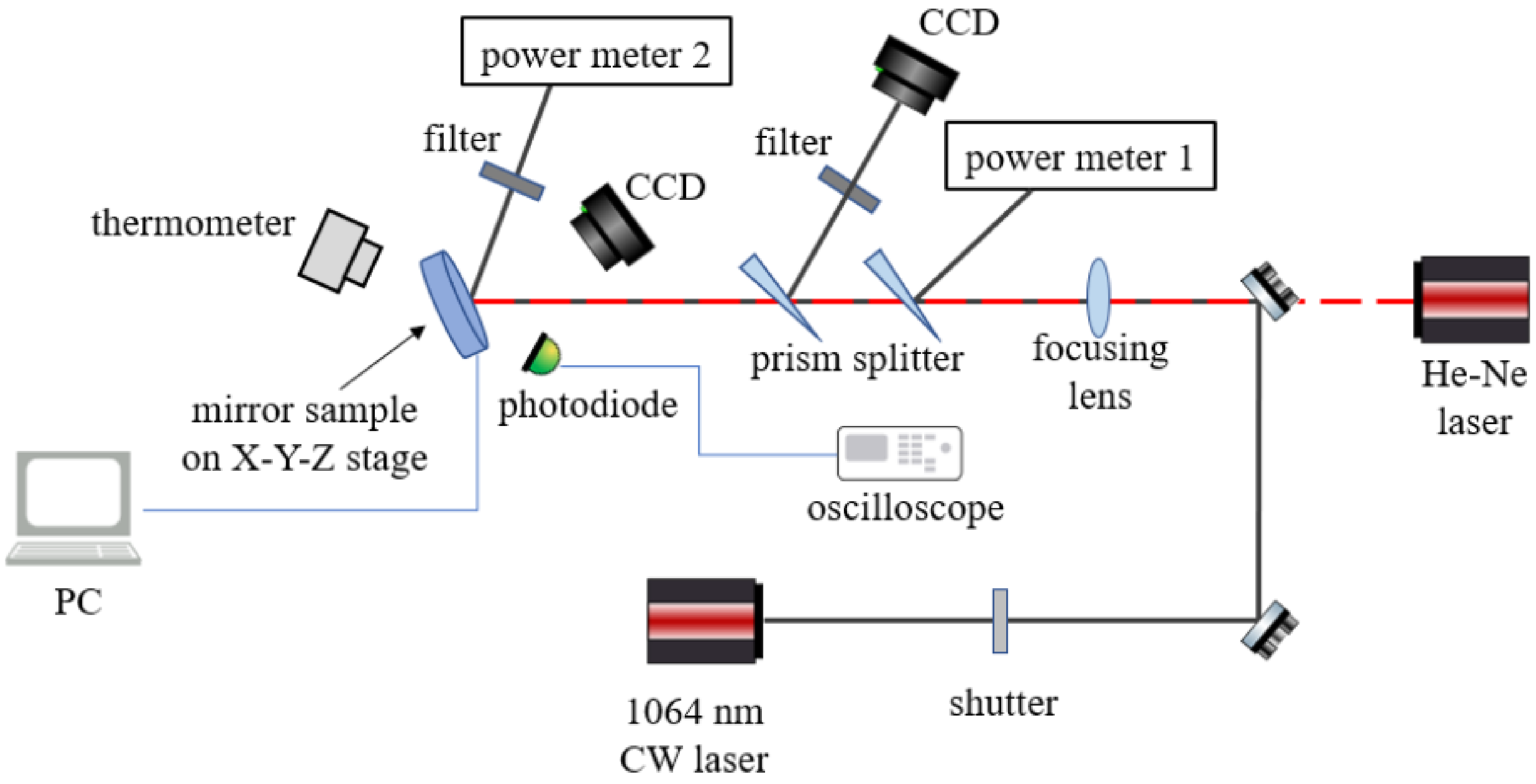


Stretcher ring



X.Y. Zhang, et al., IPAC 2023

- Laser system
    - Seed laser
    - Optical cavity is demanding
        - H. Wang, et al., IPAC 2023



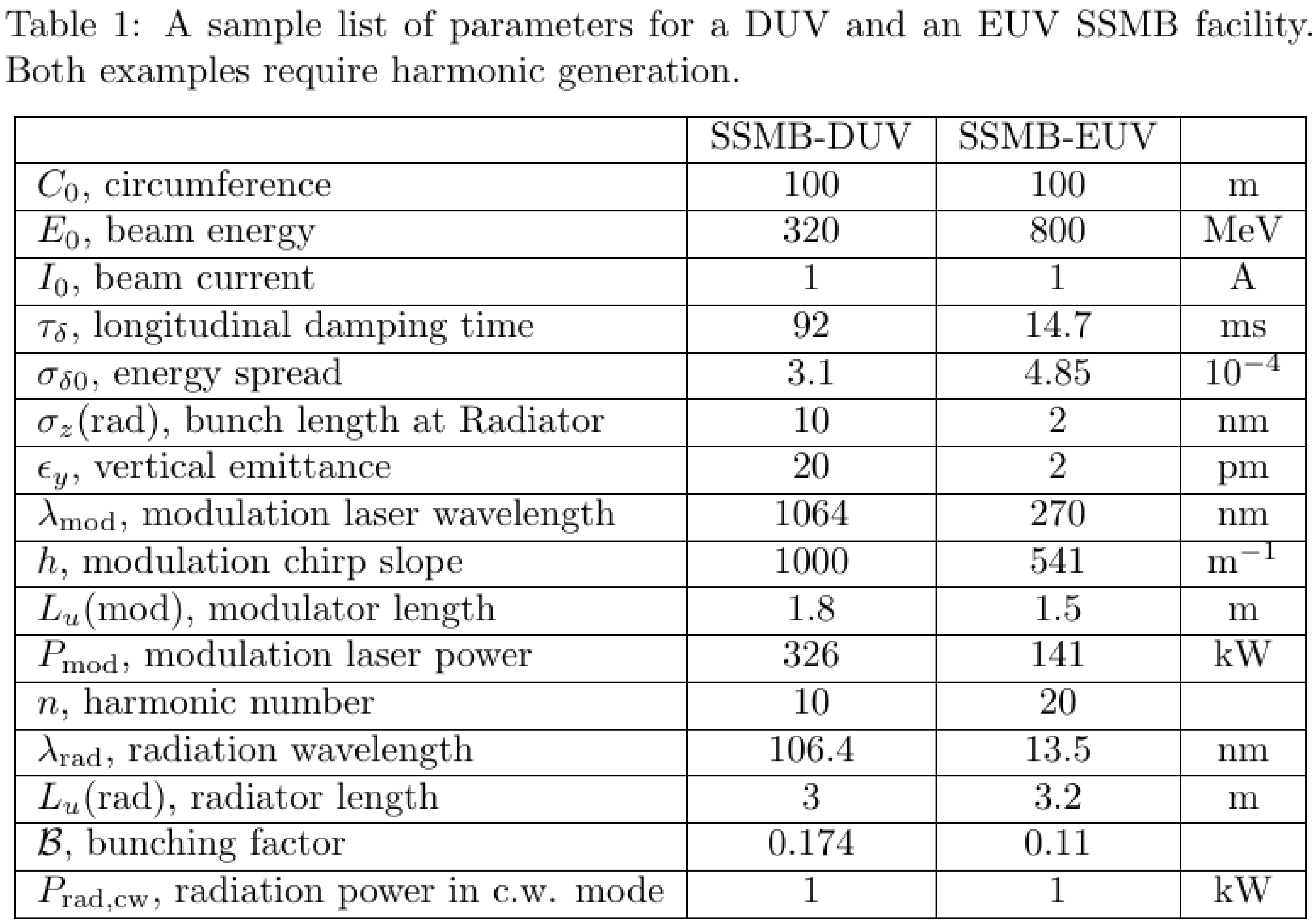


Table 1: A sample list of parameters for a DUV and an EUV SSMB facility. Both examples require harmonic generation.

	SSMB-DUV	SSMB-EUV	
C_0, circumference	100	100	m
E_0, beam energy	320	800	MeV
I_0, beam current	1	1	A
τ_δ, longitudinal damping time	92	14.7	ms
$\sigma_{\delta 0}$, energy spread	3.1	4.85	10^{-4}
σ_z(rad), bunch length at Radiator	10	2	nm
ϵ_y, vertical emittance	20	2	pm
λ_{mod}, modulation laser wavelength	1064	270	nm
h, modulation chirp slope	1000	541	m^{-1}
L_u(mod), modulator length	1.8	1.5	m
P_{mod}, modulation laser power	326	141	kW
n, harmonic number	10	20	
λ_{rad}, radiation wavelength	106.4	13.5	nm
L_u(rad), radiator length	3	3.2	m
$\mathcal{B}$, bunching factor	0.174	0.11	
$P_{\text{rad,cw}}$, radiation power in c.w. mode	1	1	kW

X.J. Deng, et al.,
this workshop,
TU4P28

Summary

1. Proof of principle Phase I experiment successfully demonstrated the feasibility of the SSMB approach. Phase II experiment is being reinitiated at MLS after a 3-year COVID pause.

2. There are several scenarios of the SSMB light sources.
   a) An amplifier scenario uses a conventional storage ring, readily available as a powerful IR source.
   b) THz scenario requires a conventional storage ring plus a dual undulator.
   c) Harmonic generation SSMB is in active R&D. Design parameters are being formulated and forthcoming.