9th Low Emittance Rings Workshop

Low Longitudinal Emittance and Steady-State Micro-Bunching Storage Rings

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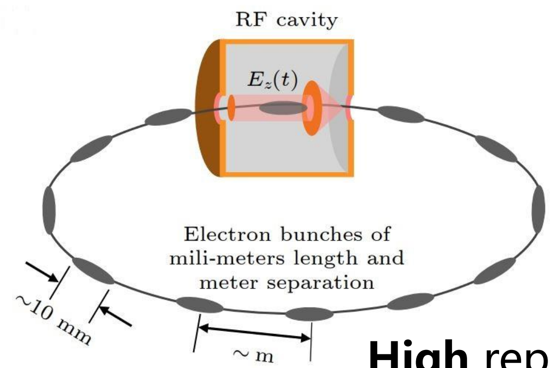
14.02.2024

Outline

- **A brief introduction of SSMB**
- **Three lattice scenarios of SSMB light source**
- **SSMB proof-of-principle experiments**

Steady-State Micro-Bunching（SSMB)

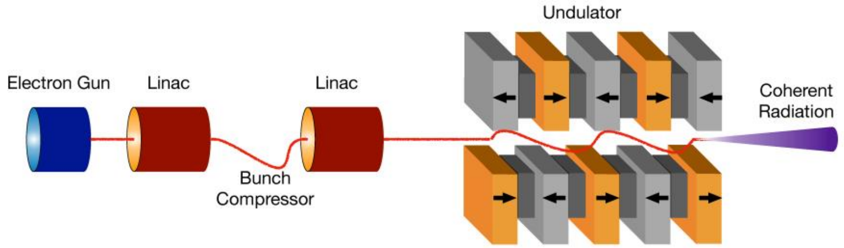
Synchrotron Radiation



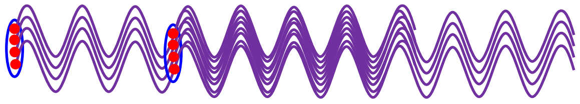
High repetition rate
Low peak power

Incoherent $P \propto N_e$

Free-Electron Laser



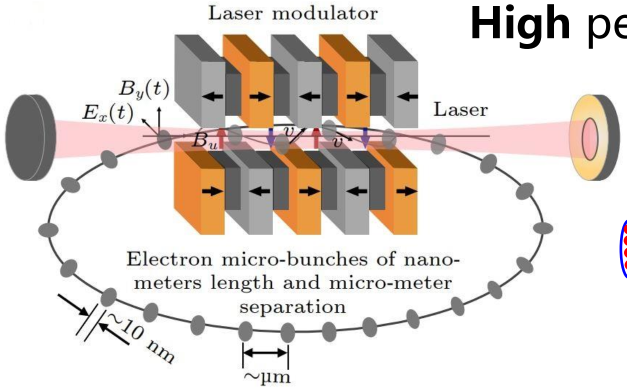
Low repetition rate
High peak power

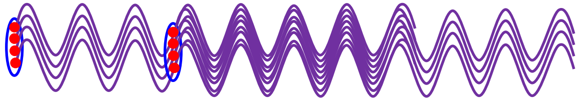


Coherent $P \propto N_e^2$

SSMB

High repetition rate
High peak power



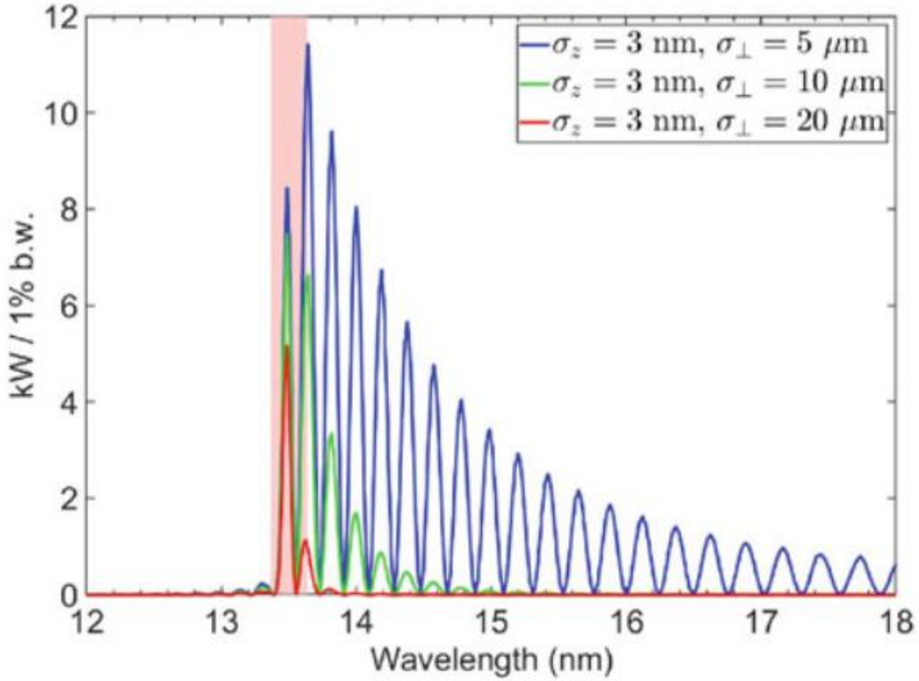


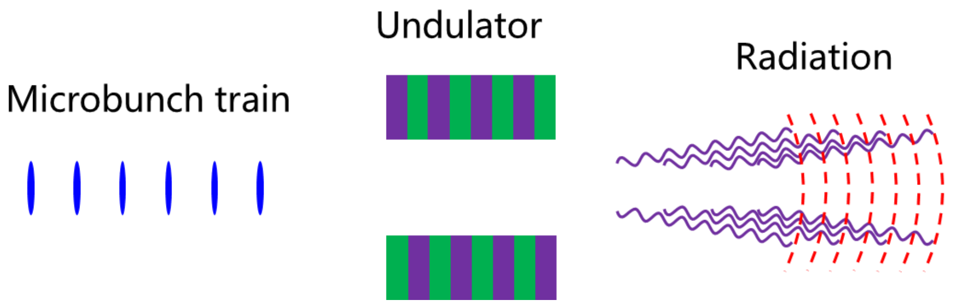
Coherent $P \propto N_e^2$

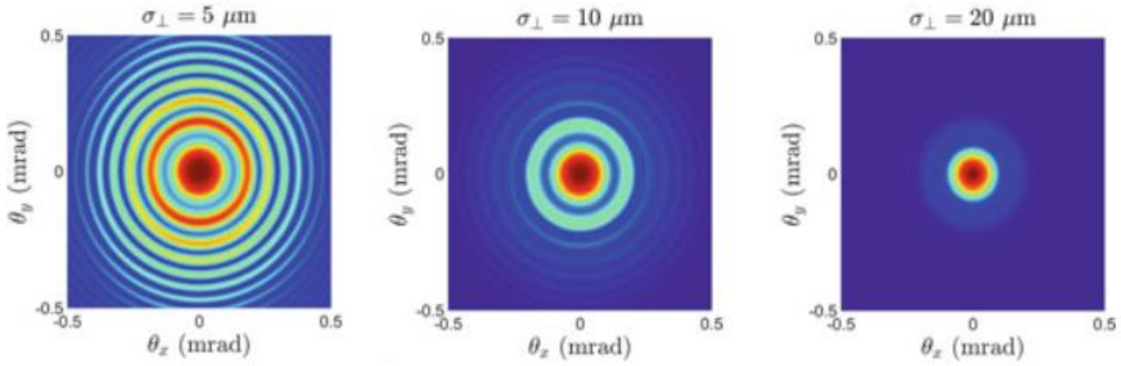
D. F. Ratner and A. W. Chao, Phys. Rev. Lett. 105, 154801 (2010).

Radiation Characteristics of SSMB Light Source

- **High average power (>1 kW EUV)**
- **Narrow-banded (1% level)**
- **Collimated (0.1 mrad level)**
- **Quasi-continuous waveform**





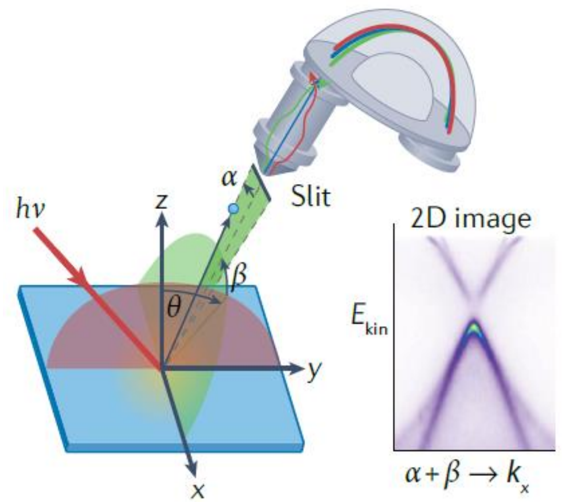


X. J. Deng et al. J. Synchrotron Rad. (2023). 30, 35–50. X. J. Deng, PhD Thesis.

Potential Applications of SSMB Light Source

- **ARPES:**
  - **High photon flux: >10^{13} phs/s within 1 meV energy bandwidth**
  - **Tunable wavelength: extendable to soft X-ray**
  - **CW waveform: minimize space charge-induced energy shift, spectral broadening and distortion of photoelectrons**

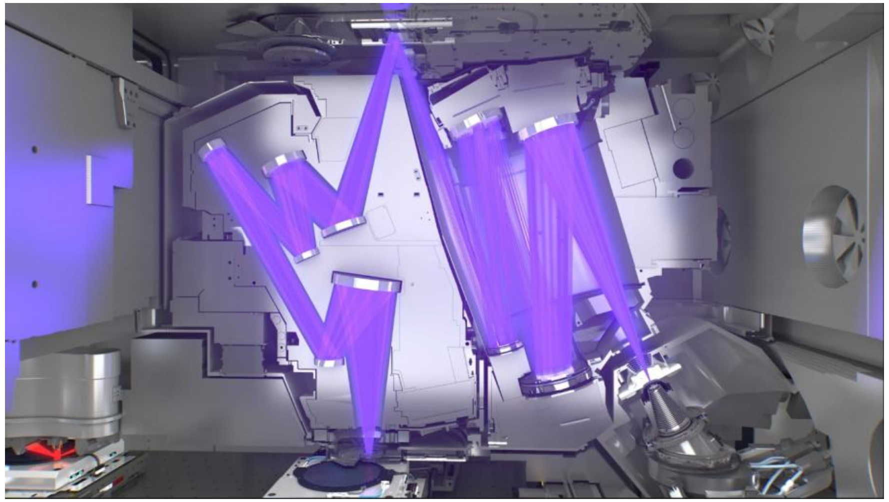
- **EUV Lithography:**
  - **High average power: the power aimed is > 1 kW per tool**
  - **Clean radiation and CW waveform**
  - **Good scalability: $\lambda_r = \frac{(1+K^2/2)}{2\gamma^2}\lambda_u$, easy to scale to shorter wavelength. Offer possibility for the EUVL Extension**



Figure@Zhang

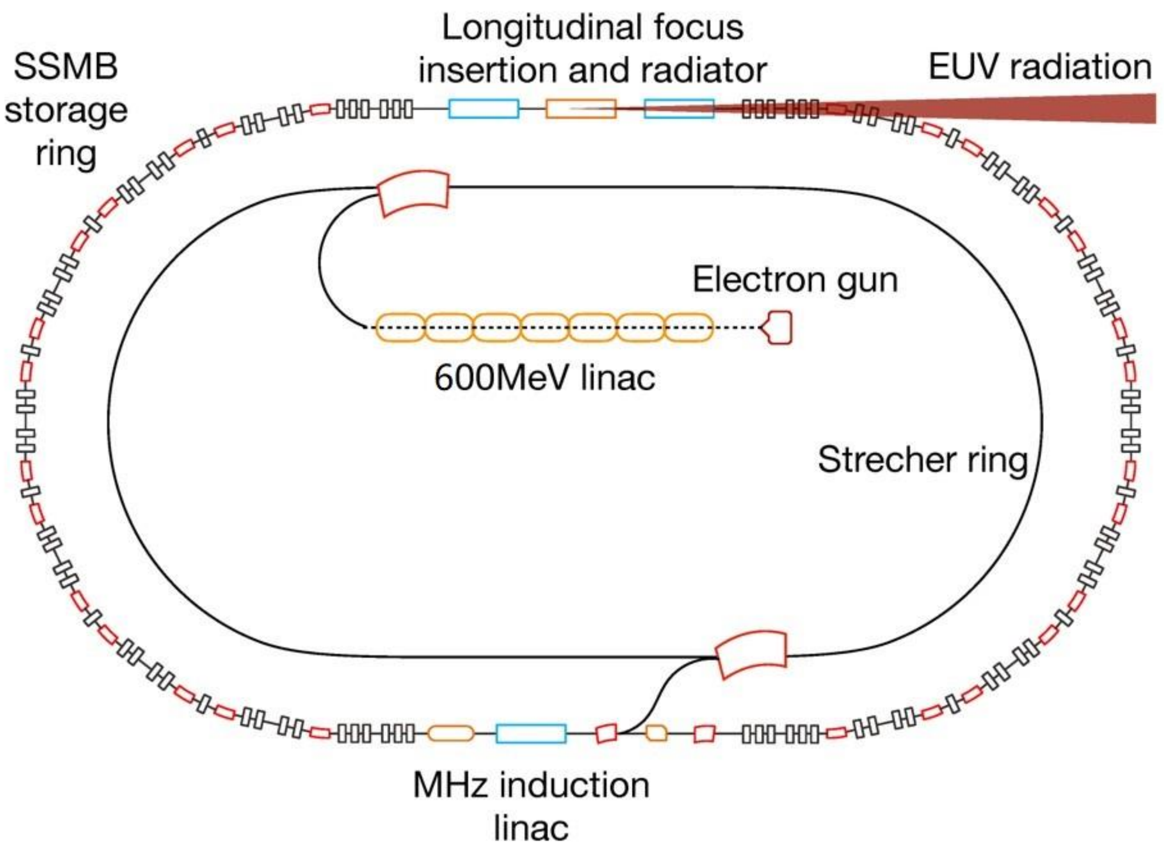
$0.67^{11} = 1.2\%$

Figure@ASML



Tsinghua EUV SSMB Storage Ring

- **A task force has been established at Tsinghua University since 2017, in collaboration with researchers from different institutes, to promote SSMB research and develop an EUV SSMB storage ring**



Parameter	Value
Circumference	150 ~ 200 m
Electron energy	~ 600 MeV
Current	⩾ 1 A
Radiation wavelength	5 – 100 nm
13.5 nm EUV power **(in 2% bandwidth)**	> 1 kW
EUV photon flux **(within 1 meV)**	> 10^{13} photons/s

C. Tang et al, FLS2018-THP2WB02.
C. Tang & X. Deng Acta Phys. Sin., 2022, 71(15): 152901.

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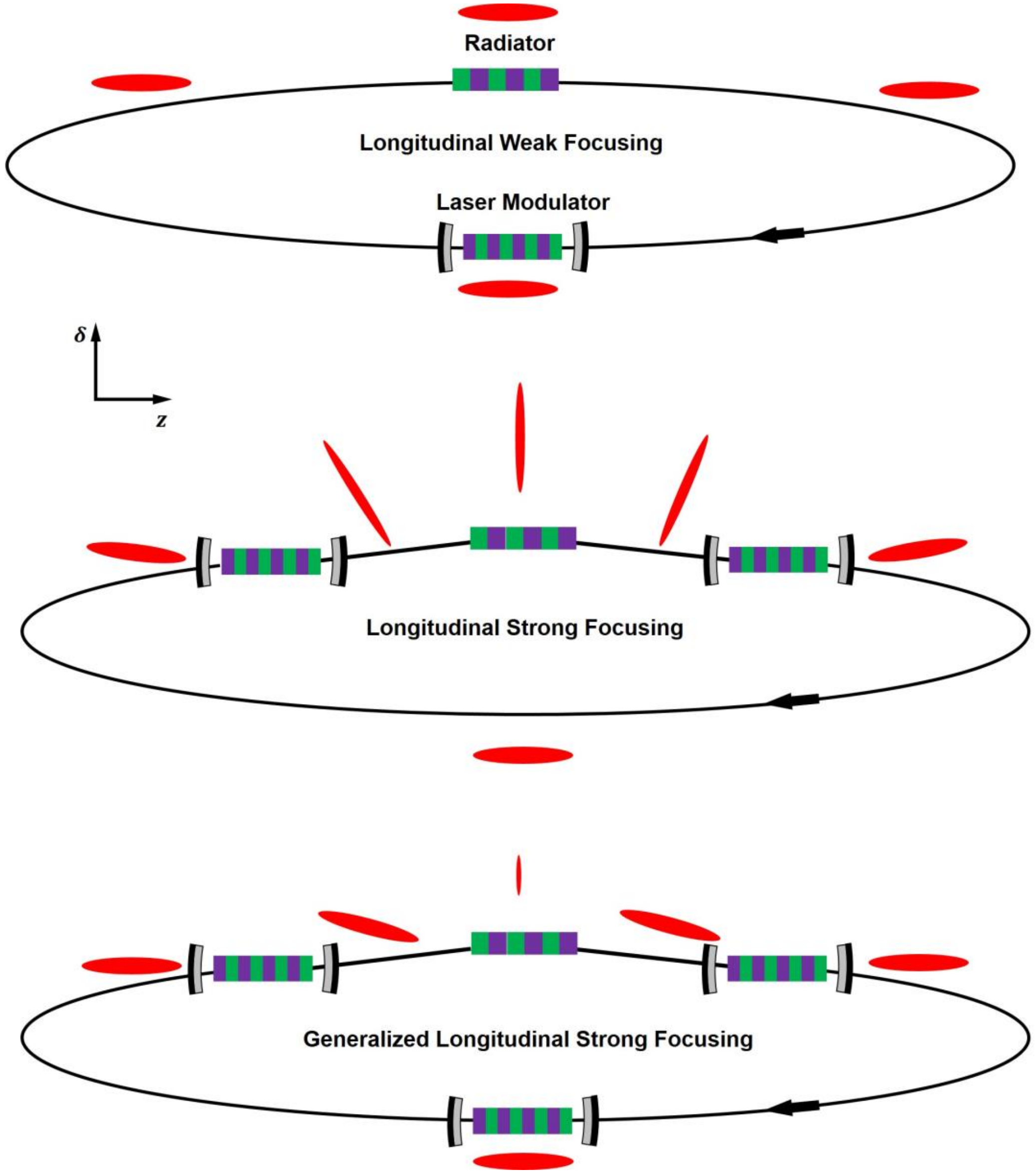
- **SSMB proof-of-principle experiments**

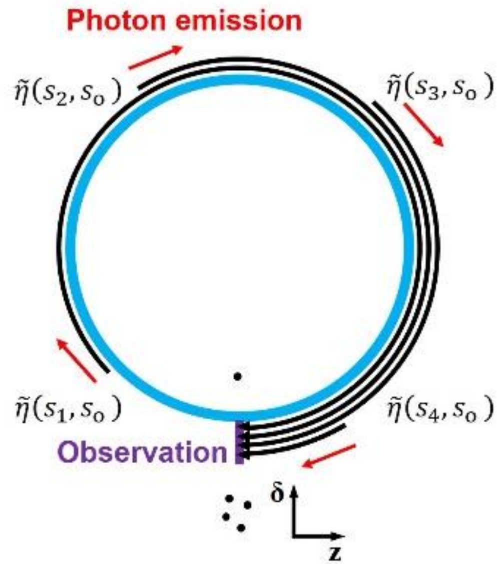
Three Lattice Scenarios

- **Longitudinal weak focusing**: target radiation wavelength ≳100 nm
- **Longitudinal strong focusing**: target radiation wavelength can be as short as ~13.5 nm, but the required modulation laser power is too high such that the optical cavity can only work in a pulsed mode
- **Generalized longitudinal strong focusing**: target radiation wavelength can be as short as ~13.5 nm. In addition, we aim to operate the optical cavity in a high duty cycle or CW mode such that the average output radiation power can be very high



Realize Short Bunch in a Weak Focusing Ring

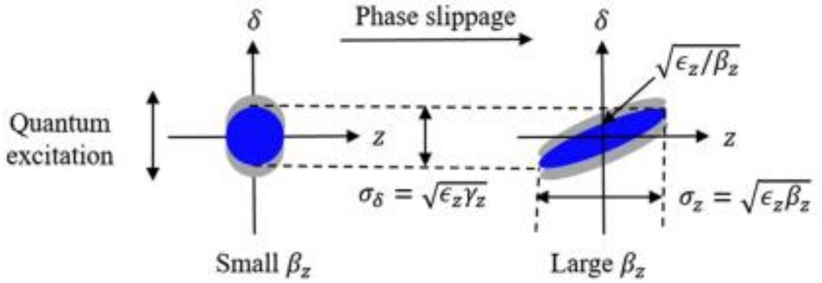
- **A classical method is to implement a quasi-isochronous or low-alpha lattice, as $\sigma_z \propto \sqrt{|\eta|}$. This scaling breaks down however when η is close to zero. There exists a bunch length limit, arising from the stochasticity of photon emission time/location. Energy spread will diverge when we push bunch length to this limit. To get a short bunch, both the global and local phase slippage should be minimized**



PHYSICAL REVIEW ACCELERATORS AND BEAMS **24,** 094001 (2021)

Courant-Snyder formalism of longitudinal dynamics

X. J. Deng,[1,*] A. W. Chao,[2,3] W. H. Huang,[1] and C. X. Tang[1]

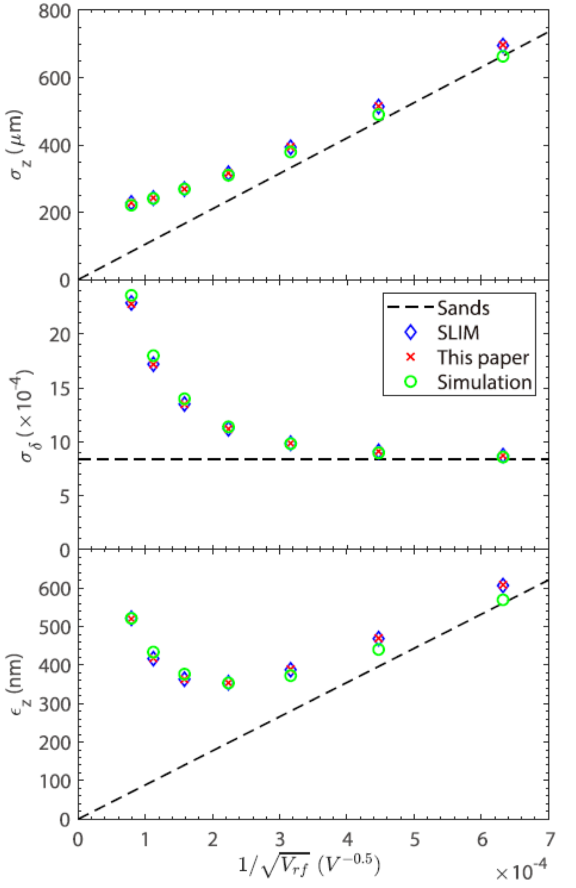


$$\epsilon_z \equiv \langle J_z \rangle = \frac{55}{96\sqrt{3}} \frac{\alpha_F \bar{\lambda}_e^2 \gamma^5}{\alpha_L} \oint \frac{\beta_z(s)}{|\rho(s)|^3} ds$$

$$\beta_z(s_j) = \frac{\mathbf{M}_{12}(s_j)}{\sin\Phi_z} = \frac{-\eta C_0 + \tilde{\eta}(s_j, s_{\mathrm{RF}})\tilde{\eta}(s_{\mathrm{RF}}, s_j) h C_0^2}{\sin\Phi_z}$$

$$\tilde{\eta}(s_2, s_1) = \frac{1}{C_0}\int_{s_1}^{s_2}\left(\frac{D_x(s)}{\rho(s)} - \frac{1}{\gamma^2}\right) ds$$

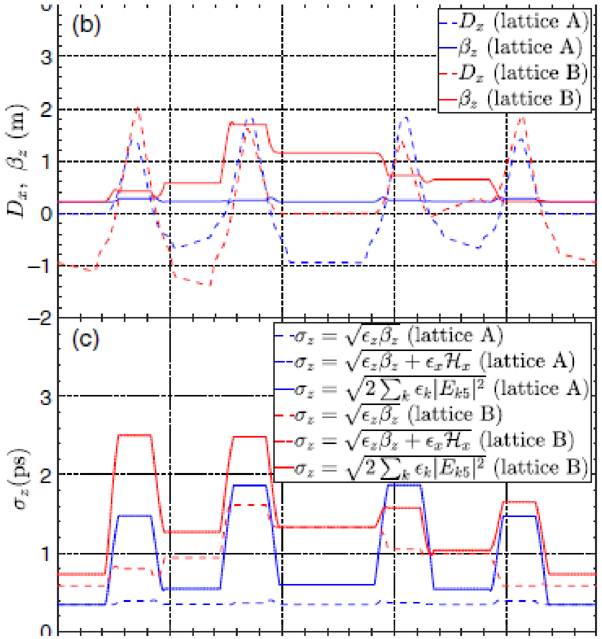
$$\sigma_{z,\mathrm{limit}} = \sigma_{\delta S}\sqrt{\langle \tilde{\eta}^2(s_j, s_{\mathrm{RF}})\rangle_\rho C_0}$$



Experimental Confirmation at the MLS

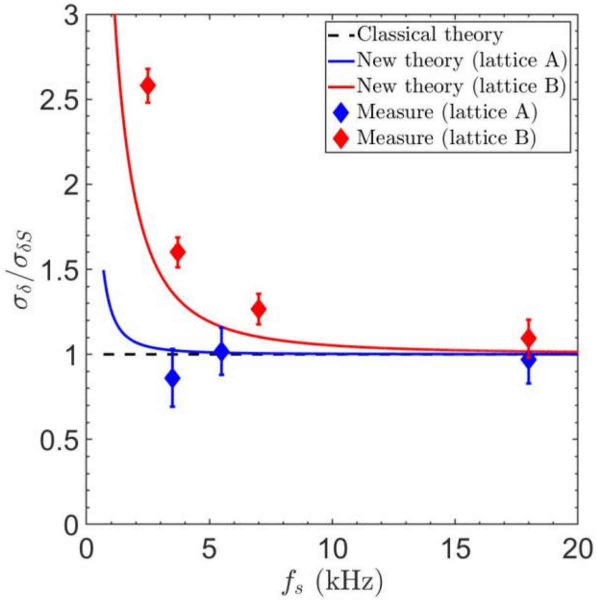
- **Bunch length saturation and energy widening when pushing the global η close to zero**

Two low-alpha lattice optics prepared, with different local phase slippages

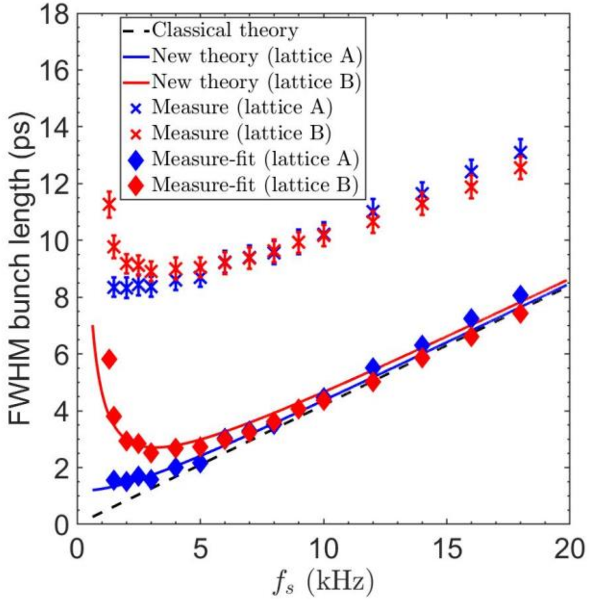


$\sqrt{\langle\tilde{\eta}^2(s_j, s_{\mathrm{rf}})\rangle_\rho}$	1.6×10^{-3}	Lattice A
$\sigma_{z,\mathrm{limit}}$	34 μm (115 fs)	Lattice A
$\sqrt{\langle\tilde{\eta}^2(s_j, s_{\mathrm{rf}})\rangle_\rho}$	6.7×10^{-3}	Lattice B
$\sigma_{z,\mathrm{limit}}$	142 μm (469 fs)	Lattice B

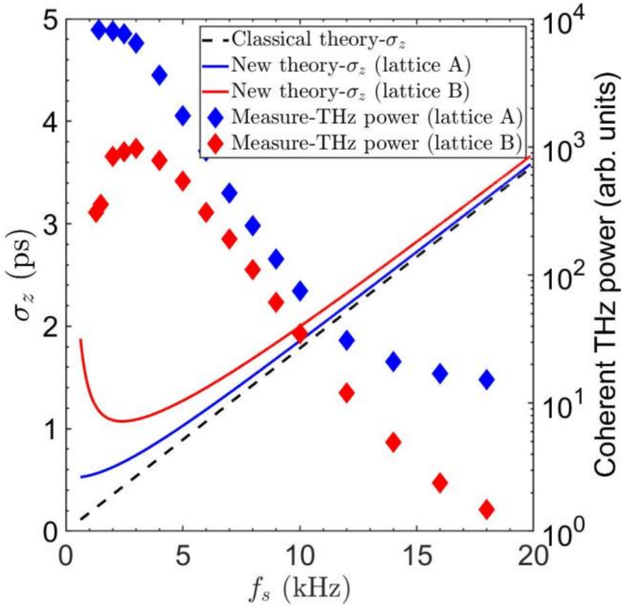
Result: Compton backscattering measurement of energy spread



Result: streak camera measurement of bunch length



Result: coherent THz radiation power measurement



PHYSICAL REVIEW ACCELERATORS AND BEAMS **26,** 054001 (2023)

Breakdown of classical bunch length and energy spread formula in a quasi-isochronous electron storage ring

X. J. Deng,[1,*] A. W. Chao,[2,3] J. Feikes,[4,†] A. Hoehl,[5] W. H. Huang,[1] R. Klein,[5,‡]
A. Kruschinski,[4] J. Li,[4] M. Ries,[4,§] and C. X. Tang[1]

Theoretical Minimum Longitudinal Emittance

- **Longitudinal beta function is the key**

$$\epsilon_z \equiv \langle J_z \rangle = \frac{55}{96\sqrt{3}} \frac{\alpha_F \lambda_e^2 \gamma^5}{\alpha_L} \oint \frac{\beta_z(s)}{|\rho(s)|^3} ds$$

$$\mathbf{S}(\alpha) = \begin{pmatrix} \cos\alpha & \rho\sin\alpha & 0 & 0 & 0 & \rho(1-\cos\alpha) \\ -\frac{\sin\alpha}{\rho} & \cos\alpha & 0 & 0 & 0 & \sin\alpha \\ 0 & 0 & 1 & \rho\alpha & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 \\ -\sin\alpha & -\rho(1-\cos\alpha) & 0 & 0 & 1 & \rho\left(\frac{\alpha}{\gamma^2} - \alpha + \sin\alpha\right) \\ 0 & 0 & 0 & 0 & 0 & 1 \end{pmatrix}$$

$$\mathbf{E}_{III}(0) = \frac{1}{\sqrt{2}} \begin{pmatrix} \frac{i-\alpha_{z0}}{\sqrt{\beta_{z0}}} D_{x0} \\ \frac{i-\alpha_{z0}}{\sqrt{\beta_{z0}}} D'_{x0} \\ 0 \\ 0 \\ \sqrt{\beta_{z0}} \\ \frac{i-\alpha_{z0}}{\sqrt{\beta_{z0}}} \end{pmatrix} e^{i\Phi_{III0}}$$

$$\begin{aligned} \beta_z(\alpha) \equiv \beta_{55}^{III}(\alpha) &= 2|\mathbf{E}_{III5}(\alpha)|^2 = 2|\left(\mathbf{S}(\alpha)\mathbf{E}_{III}(0)\right)_5|^2 \\ &= \left(\sin\alpha \frac{\alpha_{z0}}{\sqrt{\beta_{z0}}} D_{x0} + \rho(1-\cos\alpha)\frac{\alpha_{z0}}{\sqrt{\beta_{z0}}} D'_{x0} + \sqrt{\beta_{z0}} - \rho\left(-\alpha + \sin\alpha\right)\frac{\alpha_{z0}}{\sqrt{\beta_{z0}}}\right)^2 \\ &\quad + \left(-\sin\alpha \frac{1}{\sqrt{\beta_{z0}}} D_{x0} - \rho(1-\cos\alpha)\frac{1}{\sqrt{\beta_{z0}}} D'_{x0} + \rho\left(-\alpha + \sin\alpha\right)\frac{1}{\sqrt{\beta_{z0}}}\right)^2. \end{aligned}$$

Optimal conditions in the middle of dipole for theoretical minimum

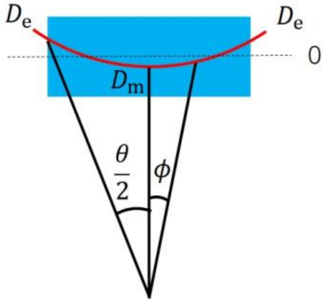
$$\boxed{\alpha_{z0} = 0,\ \beta_{z0} \approx \frac{\rho\theta^3}{120\sqrt{7}},\ D_{x0} \approx -\frac{\rho\theta^2}{40},\ D'_{x0} = 0,}$$

$$\epsilon_{z,\min}[\mathrm{nm}] = 4.61 E_0^2[\mathrm{GeV}]\theta^3[\mathrm{rad}]$$

- **The above optimal conditions however are not easy to satisfy for all the bending magnets in practice. A more practical or useful scaling is (each half-bend is isochronous)**

$$\sigma_{z,\min}[\mu\mathrm{m}] \approx 4.93\rho^{\frac{1}{2}}[\mathrm{m}]E_0[\mathrm{GeV}]\theta^3[\mathrm{rad}],$$

$$\epsilon_{z,\min}[\mathrm{nm}] \approx 8.44 E_0^2[\mathrm{GeV}]\theta^3[\mathrm{rad}].$$



Y. Zhang et al. Phys. Rev. Accel. Beams 24, 090701 (2021). X. J. Deng, PhD Thesis. X. J. Deng et al. Phys. Rev. Accel. Beams 24, 094001 (2021) & 26, 054001 (2023).

Longitudinal Weak Focusing SSMB Light Source

- **An example parameters set for a high-power infrared radiation source is presented**

- **The limitation of this scheme is that the target radiation wavelength cannot be as short as EUV or soft X-ray, since then the required phase slippage factor or laser power will be too demanding**

$$\beta_{zS} \approx \sqrt{\frac{\eta C_0}{h}}$$

For lattice design details, refer to:
Z. L. Pan, FLS2023-TU1B2.

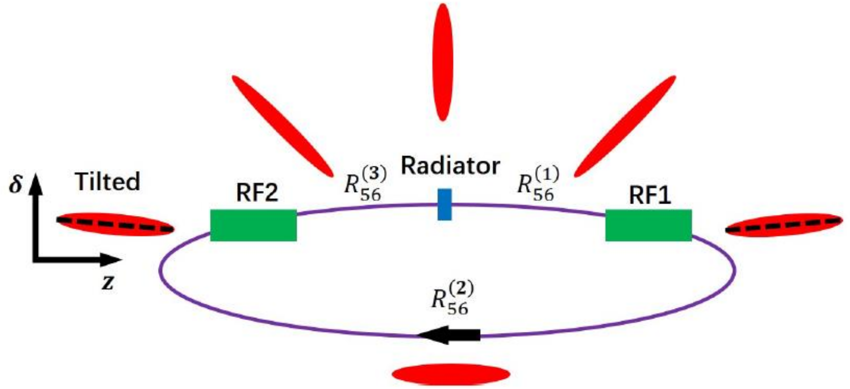
Parameter	Value
Circumference	~ 50 m
Electron energy	~ 250 MeV
Phase slippage factor	~ 4e-6
Number of bending magnets	~ 15
Modulation laser wavelength	~ 1 um
Modulation laser power	~ 20 kW
Bunch length	100 ~ 200 nm
Radiation wavelength	~ 1 um
Radiation power	~ 1 kW @ 0.5 A

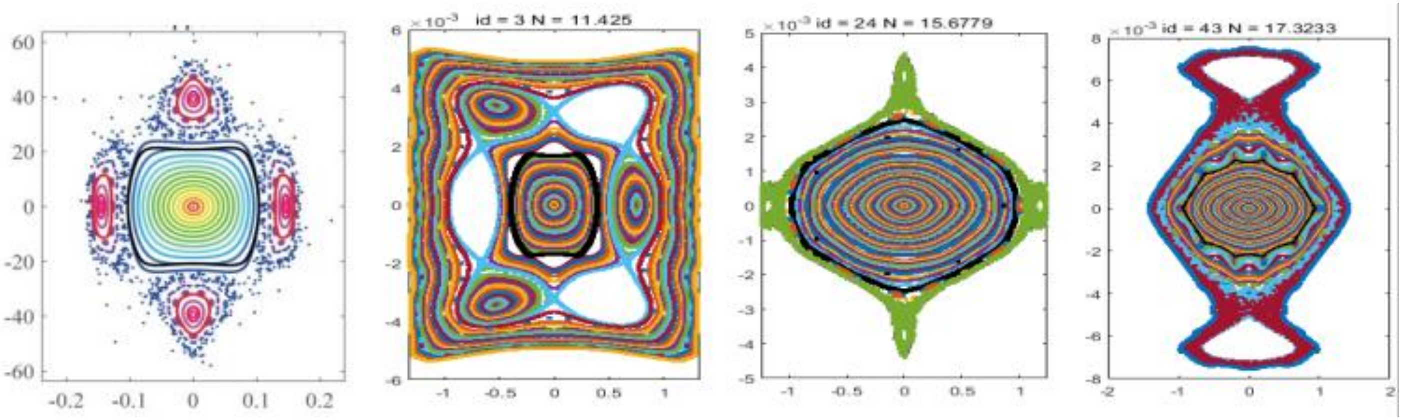
Longitudinal Strong Focusing

- **Control of longitudinal beta function is still the key, the difference here is that the synchrotron tune is not limited to be much smaller than 1, and there is more freedom to tailor the longitudinal beta function**

$$\epsilon_z = \frac{55}{96\sqrt{3}} \frac{\alpha_F \bar{\lambda}_e^2 \gamma^5}{\alpha_L} \oint \frac{\beta_z(s)}{|\rho(s)|^3} ds \qquad \sigma_z(s_i) = \sqrt{\epsilon_z \beta_z(s_i)}$$

- **One subtlety is that the choice of RF/laser modulator kick strength and R56 of different sections is more complex than that in a weak focusing ring, since now the dynamical system is strongly chaotic**



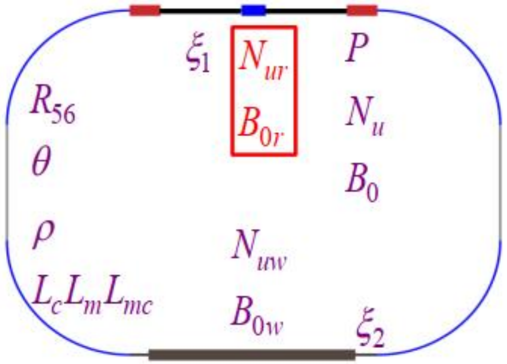


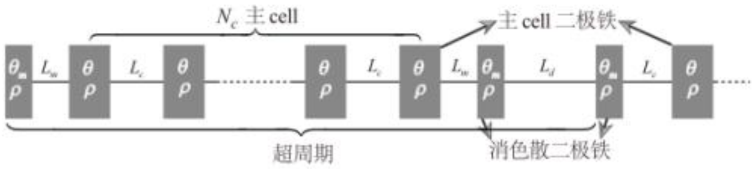
Typical longitudinal phase space topology

Y. Zhang, PhD Thesis, Tsinghua University, Beijing, China.
X. J. Deng et al. Phys. Rev. Accel. Beams 24, 094001 (2021).

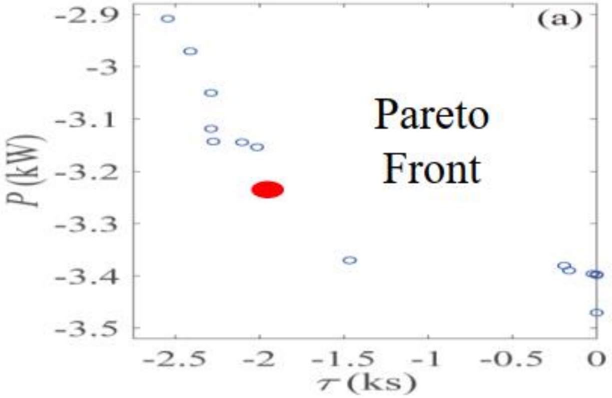
Longitudinal Strong Focusing SSMB Light Source

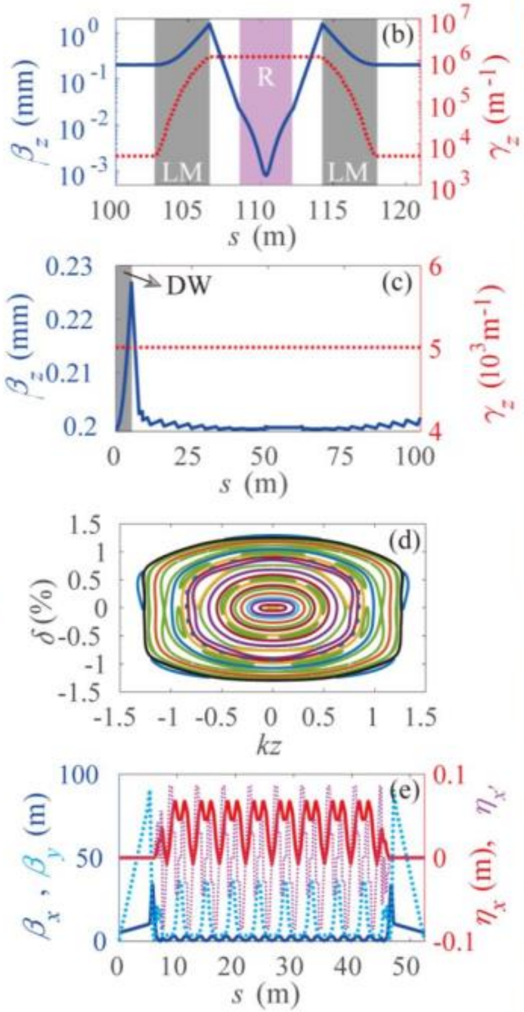
- ☐ 2LMs+DW+11BA(4 supper cells)





- ☐ MOGA(目标: 辐射功率/Touschek寿命, 17变量)





Paras.	Value
P_{laser}	300 MW
ε_x	24 pm
ε_s	4.68 pm
σ_{srad}	2.10 nm
σ_{drad}	2.20E-3
σ_{sring}	28.30 nm
σ_{dring}	1.65E-4
Iwidth	1.09E-2
τ_{DL}	388 ms
U_0	756 eV
I	1 A
τ_{touschek}	2000 s
P_{EUV}	3200 W

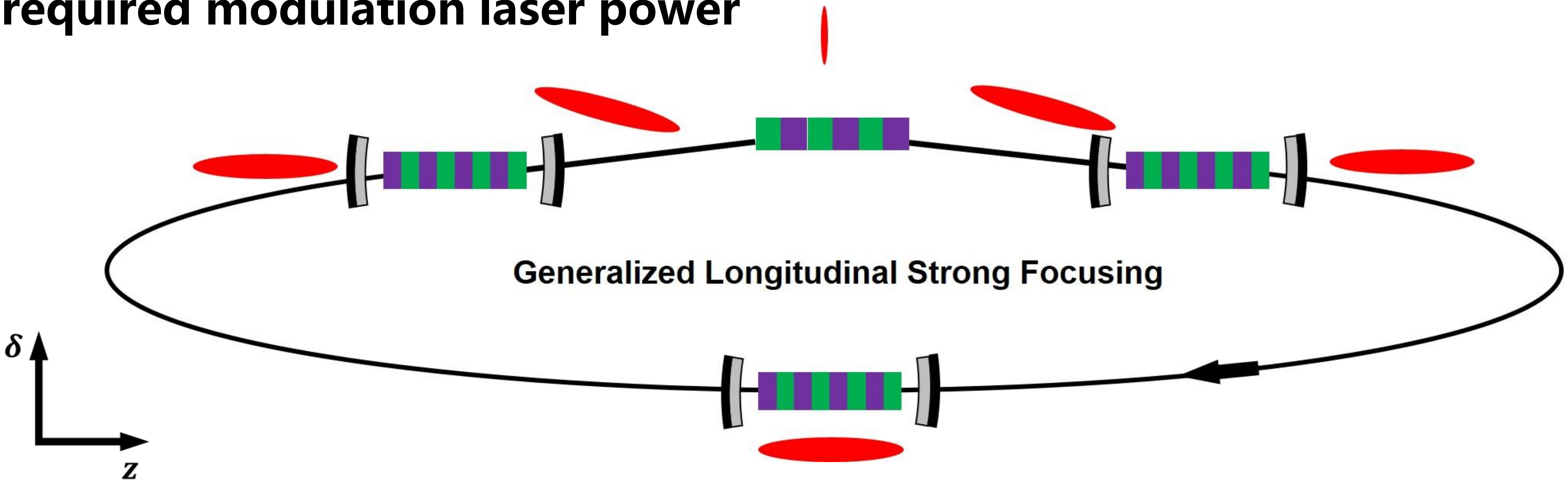
- **This scheme works and can realize a bunch length as short as nm, thus generating coherent EUV radiation. The issue is that it requires a high modulation laser power, thus limits the duty factor of the optical cavity and average output radiation power**

Slide from Y. Zhang

Y. Zhang, PhD Thesis, Tsinghua University, Beijing, China.

Generalized Longitudinal Strong Focusing

- Two modulators sandwiched by a radiator. The second modulator cancels the modulation imprinted by the first modulator. The beam in the ring can be a mircobunched beam, or a coasting beam
- Transverse-longitudinal coupling scheme is applied for bunch compression. The ultrasmall vertical emittance in a planar storage ring is taken advantage of to lower the required modulation laser power



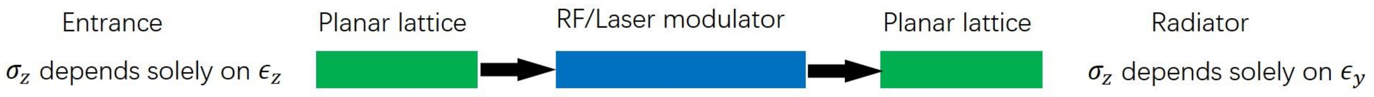

PHYSICAL REVIEW ACCELERATORS AND BEAMS **26,** 110701 (2023)

Generalized longitudinal strong focusing
in a steady-state microbunching storage ring

Zizheng Li,[1] Xiujie Deng,[1] Zhilong Pan,[1] Chuanxiang Tang,[1,*] and Alexander Chao[2,3,†]

Trans.-Long. Coupling for Bunch Compression

- **It is a partial emittance exchange**



$$\sigma_z(\mathrm{Mod}) = \sqrt{\epsilon_z\beta_z(\mathrm{Mod}) + \epsilon_y\mathcal{H}_y(\mathrm{Mod})} \quad \sigma_z(\mathrm{Rad}) = \sqrt{\epsilon_y\mathcal{H}_y(\mathrm{Rad})} \quad h^2(\mathrm{Mod})\mathcal{H}_y(\mathrm{Mod})\mathcal{H}_y(\mathrm{Rad}) \geq 1$$

- **The modulators are placed at dispersive location, and quantum excitation there will contribute to the vertical emittance**

$$\Delta\epsilon_y(\mathrm{Mod}) = 2 \times \frac{55}{96\sqrt{3}} \frac{\alpha_F \lambda\!\!\!^{-}{}_e^2 \gamma^5}{\alpha_V} \frac{\mathcal{H}_y(\mathrm{Mod})}{\rho_{0\mathrm{Mod}}^3} \frac{4}{3\pi} L_u$$

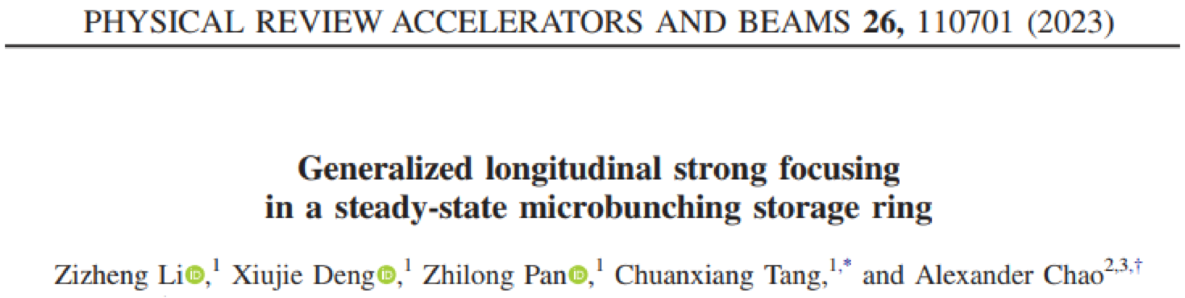
- **If the vertical emittance is mainly from quantum excitation of modulators, the self-consistently scaling of required modulation laser power is then**

$$P_L[\mathrm{kW}] \approx 5.67 \frac{\lambda_L^{\frac{7}{3}}[\mathrm{nm}] E_0^{\frac{8}{3}}[\mathrm{GeV}] B_{0\mathrm{Mod}}^{\frac{7}{3}}[\mathrm{T}]}{\sigma_z^2(\mathrm{Rad})[\mathrm{nm}] B_{\mathrm{ring}}[\mathrm{T}]}$$

X. J. Deng PhD Thesis, Tsinghua University, Beijing, China.
X. J. Deng et al, NIMA 1019 (2021): 165859. arXiv:2311.11052

Generalized Longitudinal Strong Focusing SSMB

- **An example parameters set for a high-power EUV source is presented. This is currently the scheme we adopt for high-power EUV generation**
- **Some key points: IBS optimization and precision control of x-y coupling**
- **Nonlinear dynamics optimization of this scheme is ongoing**



PHYSICAL REVIEW ACCELERATORS AND BEAMS **26**, 110701 (2023)

Generalized longitudinal strong focusing in a steady-state microbunching storage ring

Zizheng Li,[1] Xiujie Deng,[1] Zhilong Pan,[1] Chuanxiang Tang,[1,*] and Alexander Chao[2,3,†]

Parameter	Value
Circumference	150 ~ 200 m
Electron energy	~ 600 MeV
Peak current	~ 5 A
Average current	~ 1 A
Vertical emittance	~ 5 pm
Modulation laser wavelength	~ 500 nm
Modulation laser power	~ 600 kW
Radiation wavelength	13.5 nm
Peak radiation power	~ 5 kW
Average radiation power	~ 1 kW

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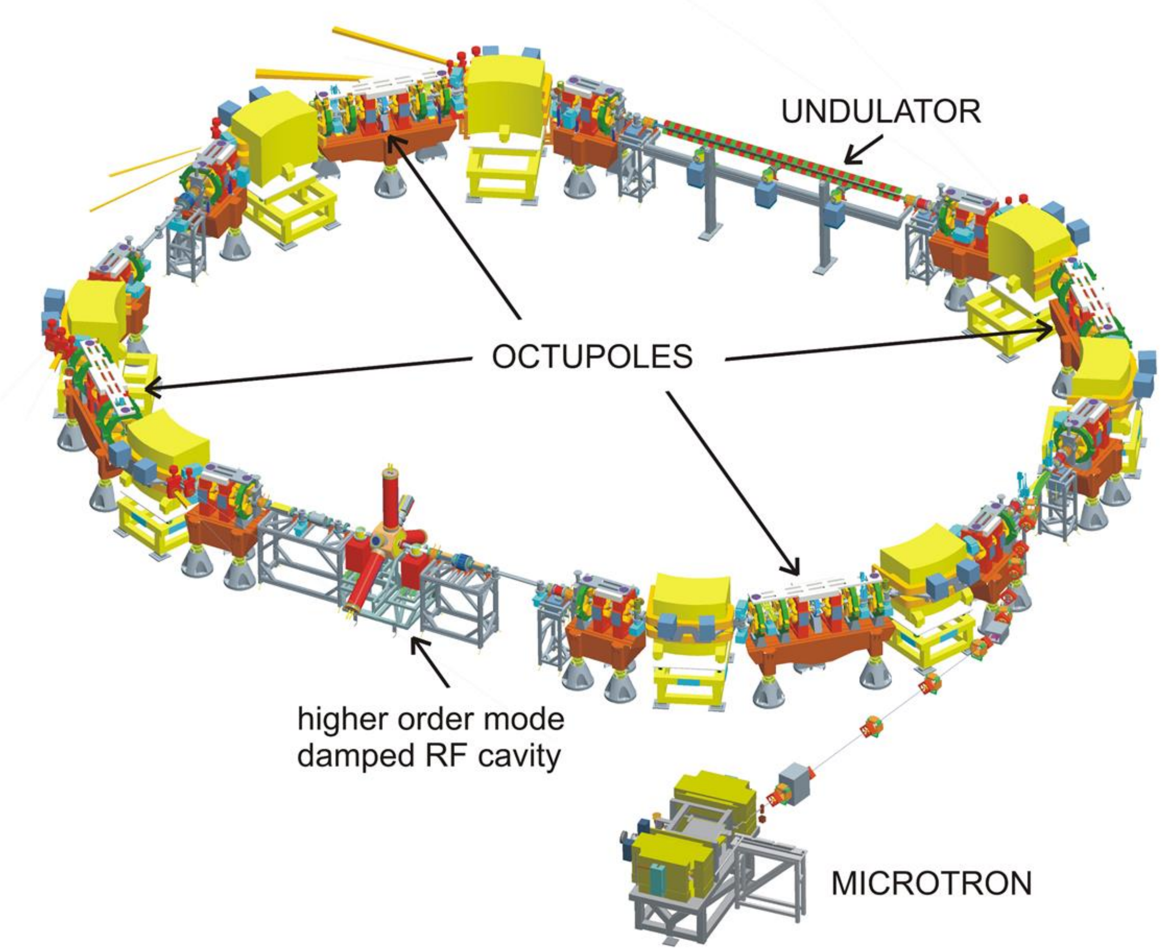
- **Three lattice scenarios of SSMB light source**
- **SSMB proof-of-principle experiments**

The Metrology Light Source (MLS) Storage Ring

- **Operated by HZB and owned by PTB, located in Berlin**

Machine Parameter	Standard	SSMB PoP
Circumference	48 m	
Energy	629 MeV	250 MeV
Bunch charge	400 pC	< 1 pC
Momentum compaction	0.03	$< 2 \times 10^{-5}$

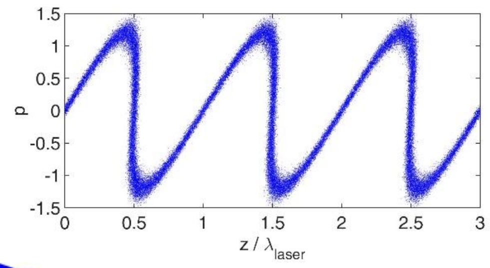


SSMB Proof-of-principle Experiment at the MLS

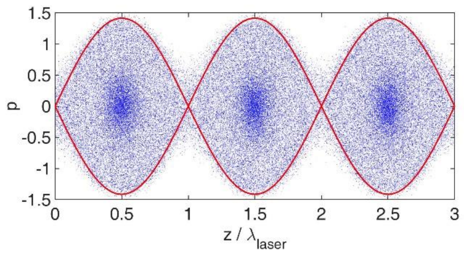
- **A collaboration of Tsinghua, HZB and PTB**

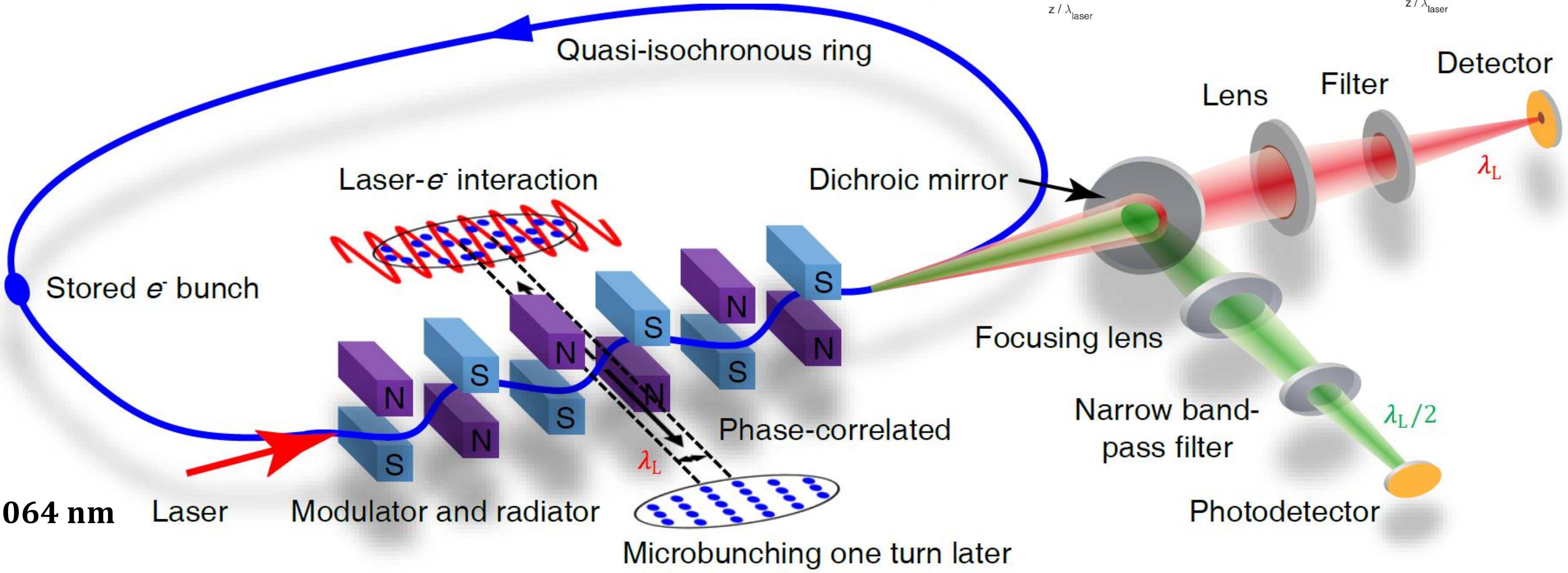
$C = 48\ \mathrm{m}\quad |\eta| \lesssim 2\times 10^{-5}\quad E = 250\ \mathrm{MeV}$

Phase I (current stage)



Phase II (in preparation)

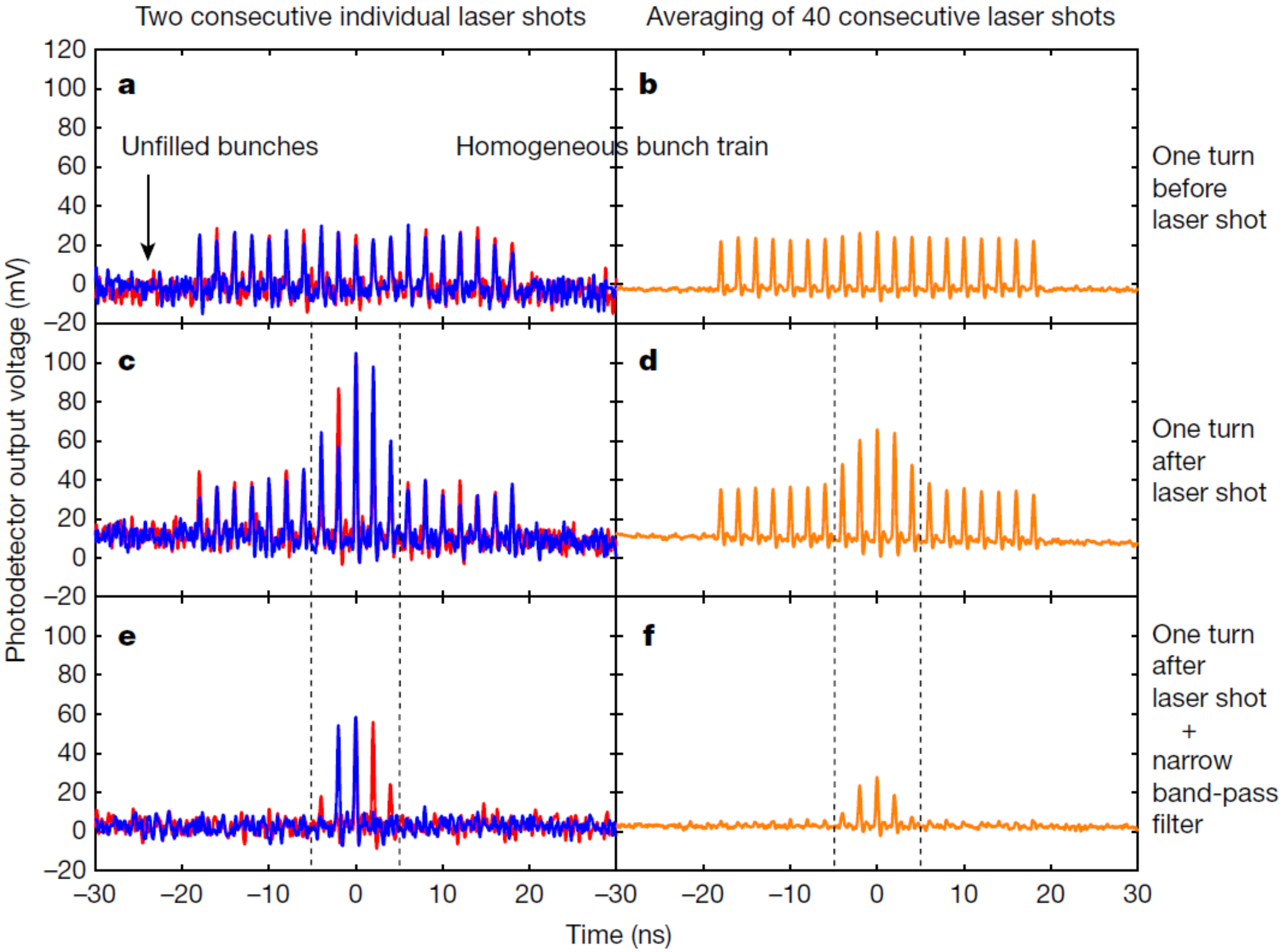




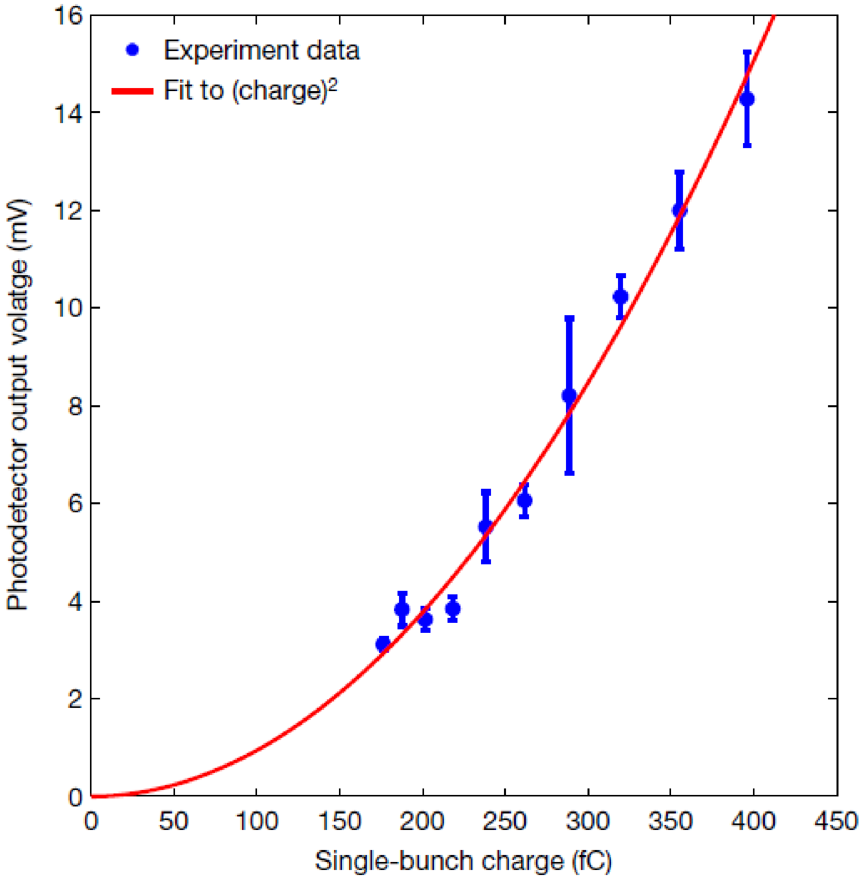
$\lambda_{\mathrm{L}} = 1064\ \mathrm{nm}$

Experimental Results

Narrow-band coherent radiation generation from microbunching



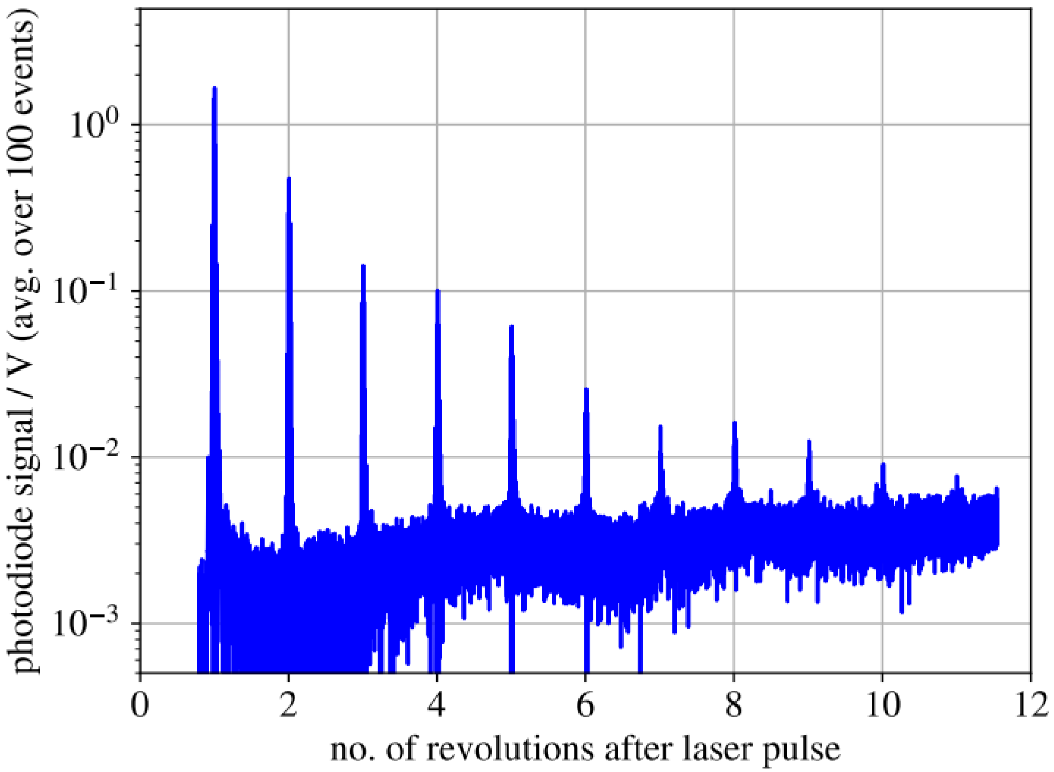
Quadratic charge scaling of coherent radiation power



X. J. Deng, et al. Nature 590, 576–579 (2021).

Experimental Results

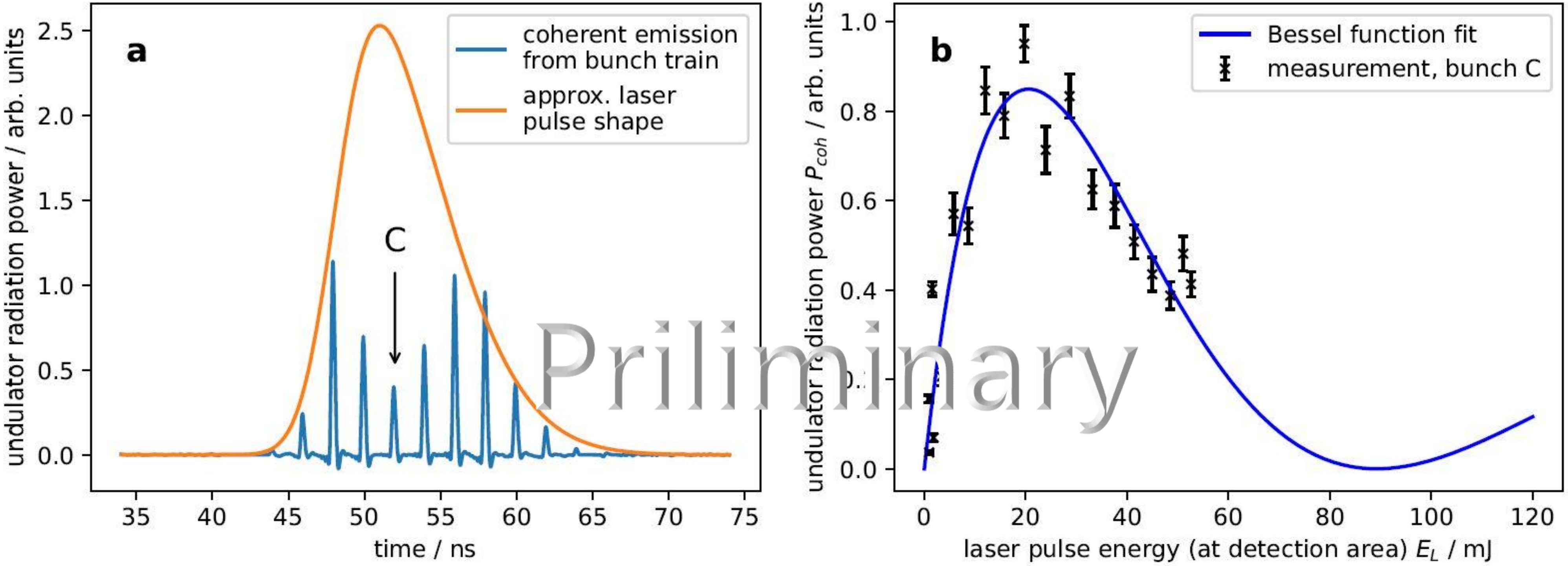
Preservation of microbunching for multiple revolutions



A. Kruschinski, et al. IPAC2023, MOPA176.

Recent Results: impact of modulation laser power

$$b_{n,m} = J_n(nk_L m\eta C_0 \boxed{A}) \exp\left\{-\frac{(nk_L)^2}{2}\left[4\epsilon_x\mathcal{H}_x \sin^2(m\pi\nu_x) + 4\epsilon_y\mathcal{H}_y \sin^2(m\pi\nu_y) + (m\eta C_0\sigma_\delta)^2\right]\right\}$$

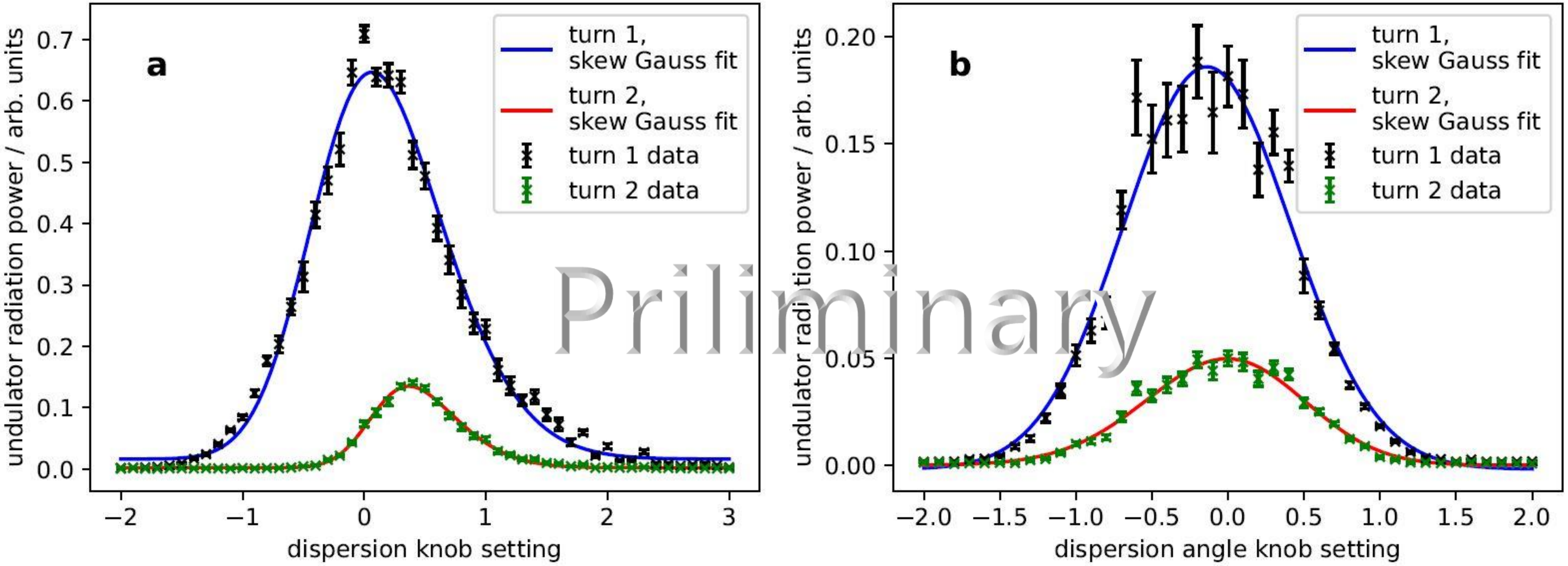


A. Kruschinski, et al. Next steps towards steady-state microbunching: confirming the theoretical foundation, to be published.

Recent Results: impact of x-z coupling

$$b_{n,m} = J_n(nk_L m\eta C_0 A)\exp\left\{-\frac{(nk_L)^2}{2}\left[4\epsilon_x \boxed{\mathcal{H}_x} \sin^2(m\pi\nu_x) + 4\epsilon_y\mathcal{H}_y\sin^2(m\pi\nu_y) + (m\eta C_0\sigma_\delta)^2\right]\right\}$$

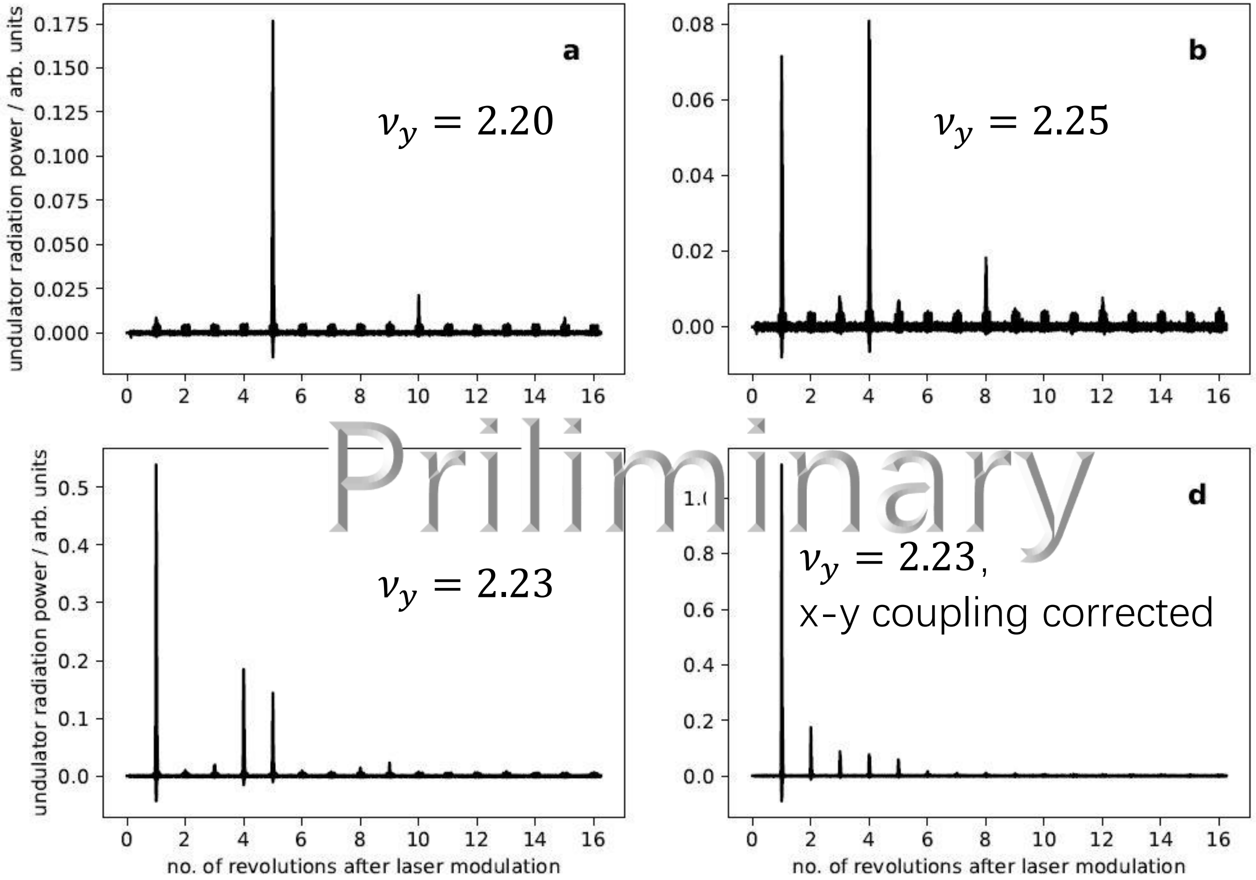
$$\mathcal{H}_{x,y} = \gamma_{x,y}D_{x,y}^2 + 2\alpha_{x,y}D_{x,y}D'_{x,y} + \beta_{x,y}D'^2_{x,y}$$



A. Kruschinski, et al. Next steps towards steady-state microbunching: confirming the theoretical foundation, to be published.

Recent Results: impact of y-z coupling

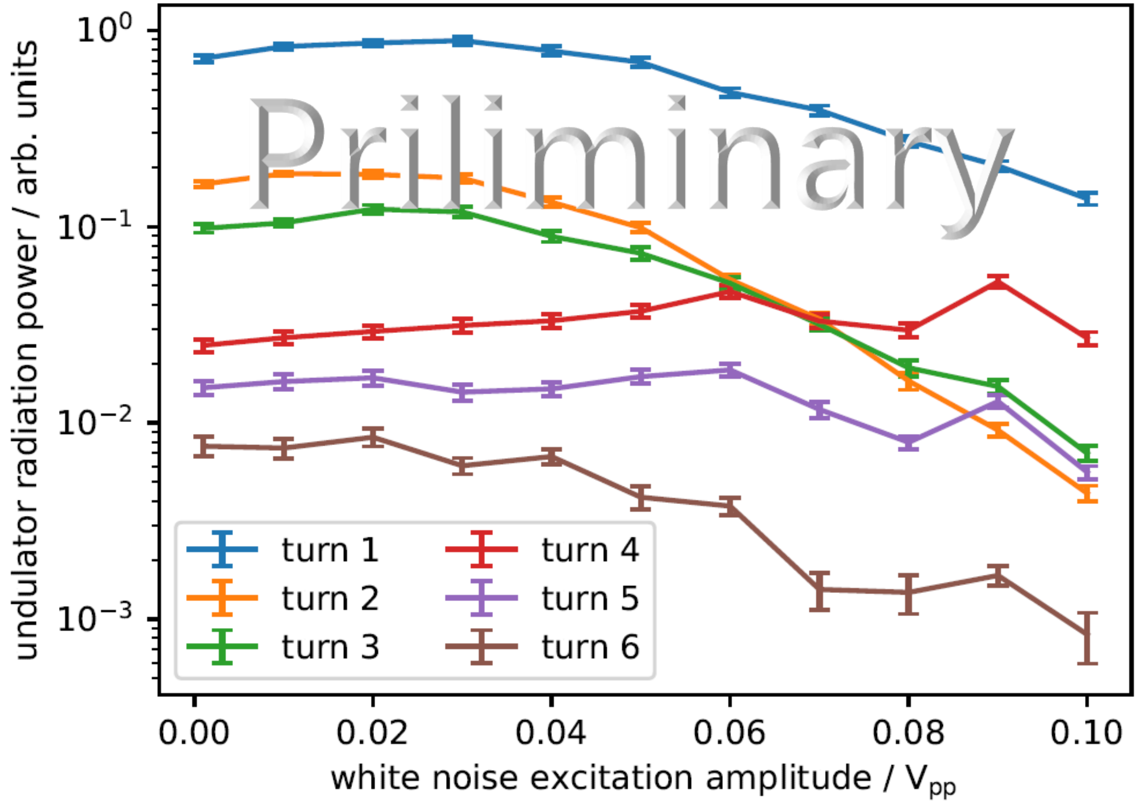
$$b_{n,m} = J_n(nk_L m\eta C_0 A)\exp\left\{-\frac{(nk_L)^2}{2}\left[4\epsilon_x\mathcal{H}_x\sin^2(m\pi\nu_x)+4\epsilon_y\mathcal{H}_y\sin^2(m\pi\nu_y)+(m\eta C_0\sigma_\delta)^2\right]\right\}$$



A. Kruschinski, et al. Next steps towards steady-state microbunching: confirming the theoretical foundation, to be published.

Recent Results: impact of y-z coupling

$$b_{n,m} = J_n(nk_L m\eta C_0 A)\exp\left\{-\frac{(nk_L)^2}{2}\left[4\epsilon_x\mathcal{H}_x\sin^2(m\pi\nu_x) + 4\epsilon_y\mathcal{H}_y\sin^2(m\pi\nu_y) + (m\eta C_0\sigma_\delta)^2\right]\right\}$$



A. Kruschinski, et al. Next steps towards steady-state microbunching: confirming the theoretical foundation, to be published.

Implication of the SSMB PoP Experiment Results

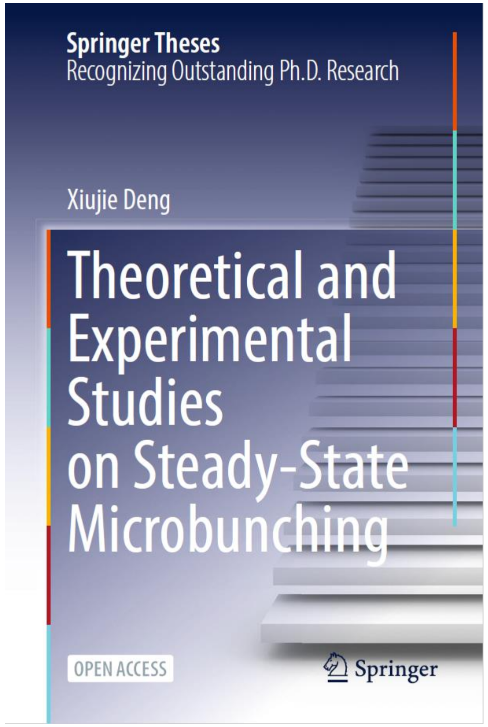
- It is the first time that such a precise (sub-laser wavelength) turn-by-turn beam dynamics is demonstrated in a storage ring

- These findings demonstrate:
  - the theoretical foundation of SSMB is correct
  - the ultrahigh precision turn-by-turn control of electron beam phase space as required by SSMB can indeed be realized in a real machine

Summary

- **SSMB is a new accelerator light source mechanism which promises high-average-power narrow-band radiation with wavelength extendable to soft X-ray, and could provide new opportunities for EUV lithography and high-resolution ARPES**
- **The development of a high-power SSMB EUV light source is ongoing in Tsinghua University, with encouraging results being achieved**
- **The mechanism of SSMB has been demonstrated the first time at the MLS**

For readers who want to know more technical details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- Years efforts of the SSMB PoP Group, and the Tsinghua SSMB group

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Thanks for your attention!