An overview of the Steady State Microbunching R&D effort initiated at Tsinghua University

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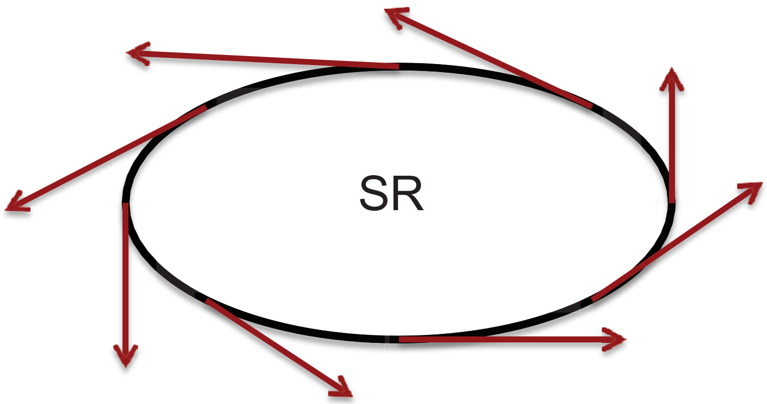
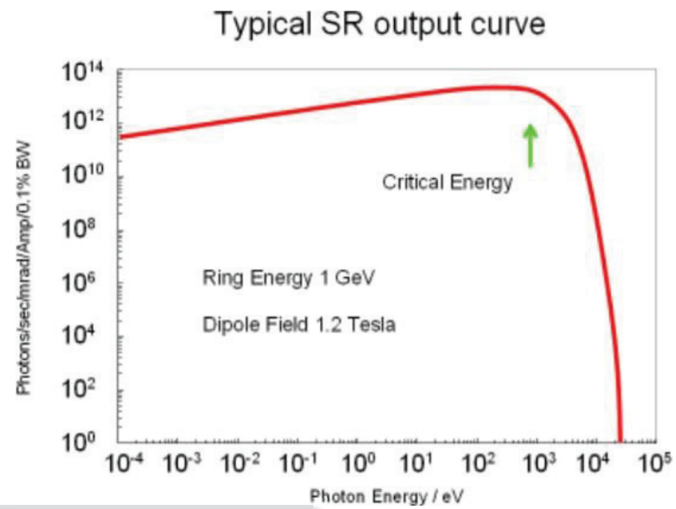
Power of Synchrotron Radiation





The power radiated in a storage ring：

$$P(kW) = 88.47E^4(GeV)I(A)R^{-1}(m)$$

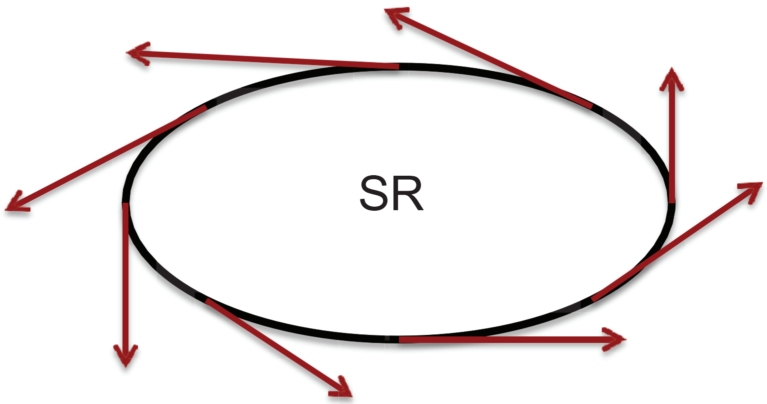
With an undulator: Power $P_T\,[\mathrm{kW}] = 0.633E^2[\mathrm{GeV}]B^2[\mathrm{T}]L[\mathrm{m}]I[\mathrm{A}]$

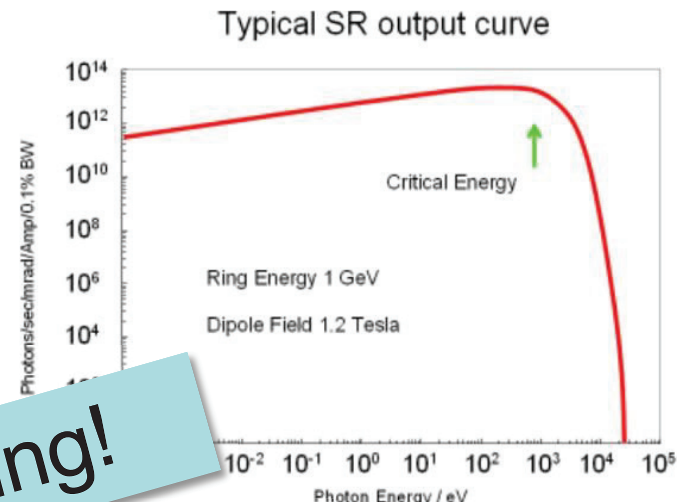
Resonant wavelength

$$\lambda = \frac{\lambda_u}{2\gamma^2}\; 1+\frac{K^2}{2}+\gamma^2\theta^2$$

The typical power radiated in a storage ring is ~kW, and it will be much lower at a narrow band of a special wavelength .

Power of Synchrotron Radiation





No micro-bunching!

The power radiated in a storage ri…

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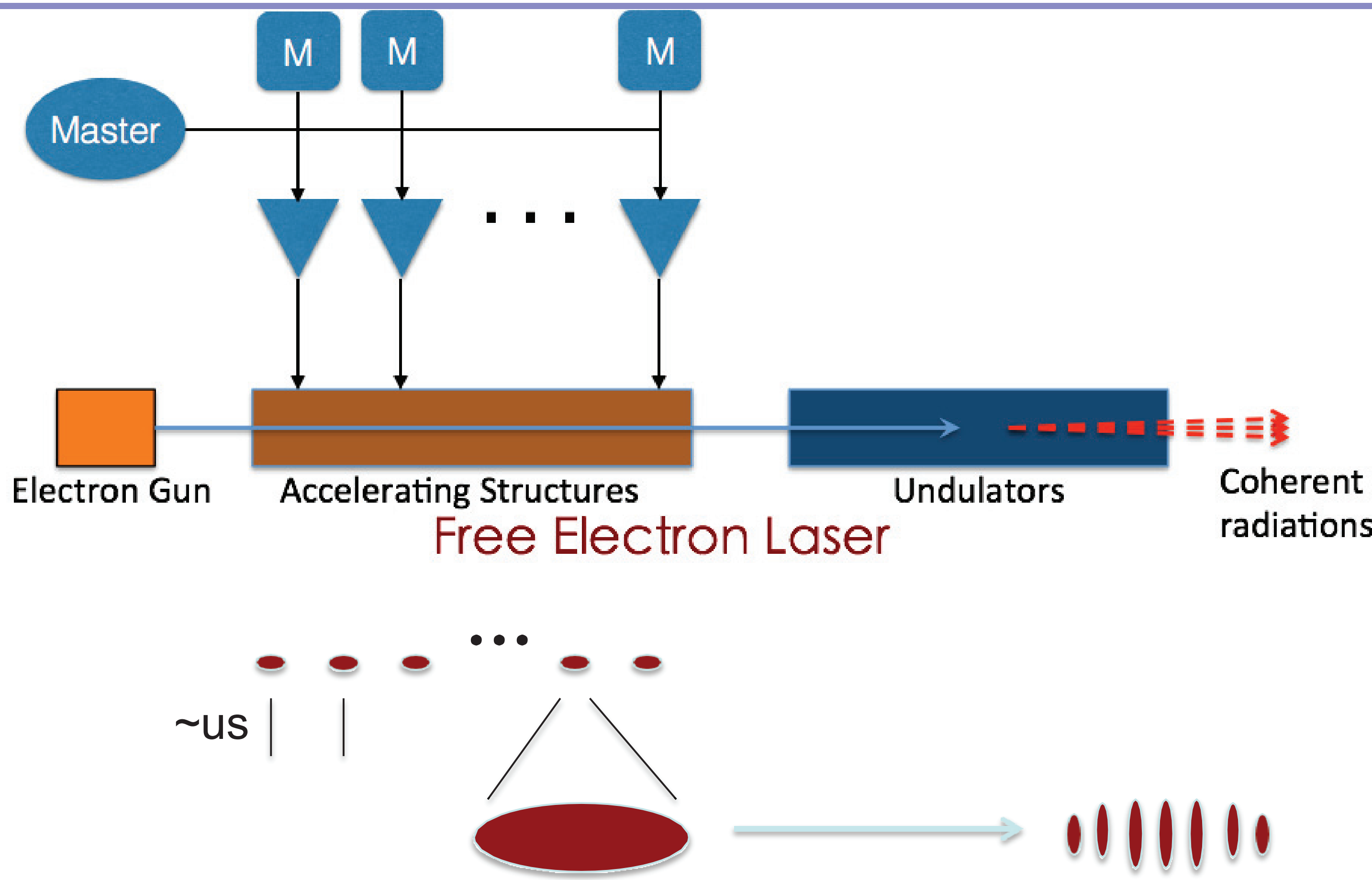
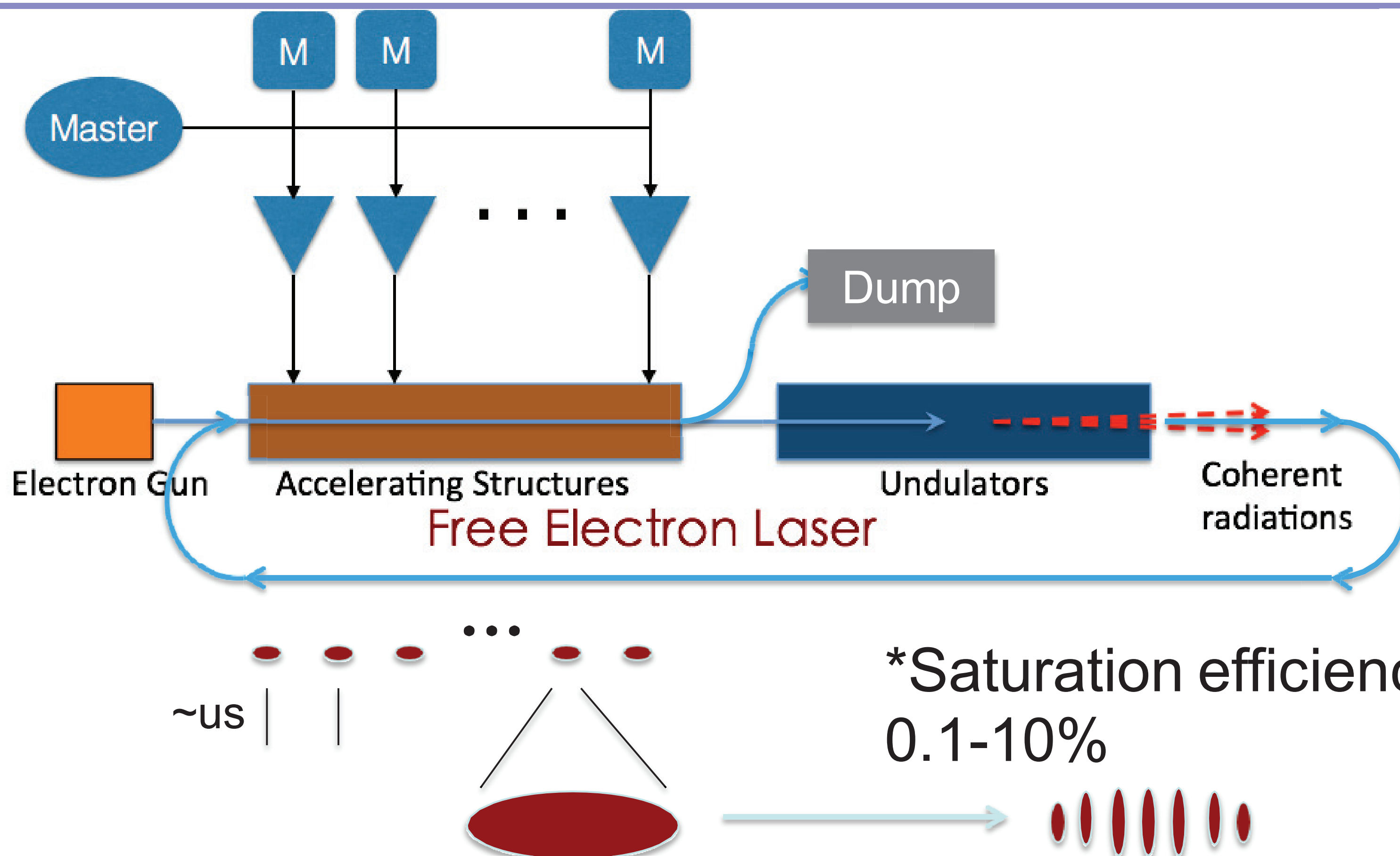
The typical power radiated in a storage ring is ~kW, and it will be much lower at a narrow band of a special wavelength .

High rep-rate FEL based on SRF linacs and ERL



High rep-rate FEL based on SRF linacs and ERL



*Saturation efficiency: 0.1-10%

Radiation Power at a very narrow bandwidth : ~10 kW

*Opt. Commun. 50, 373 (1984)
New J. Phys. 17, 063036 (2015)
Phys. Rev. Accel. Beams 19, 020705 (2016)

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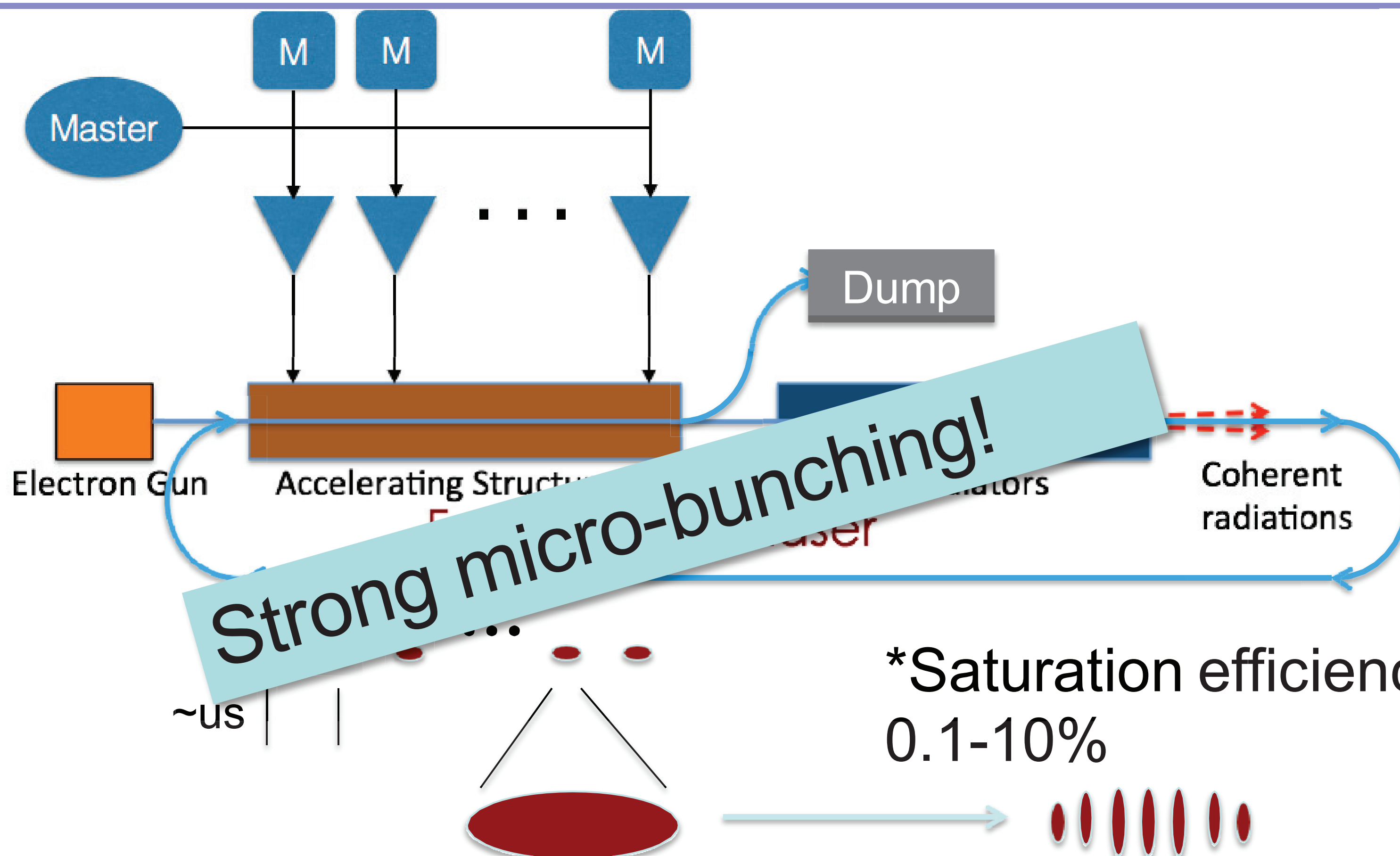
High rep-rate FEL based on SRF linacs and ERL



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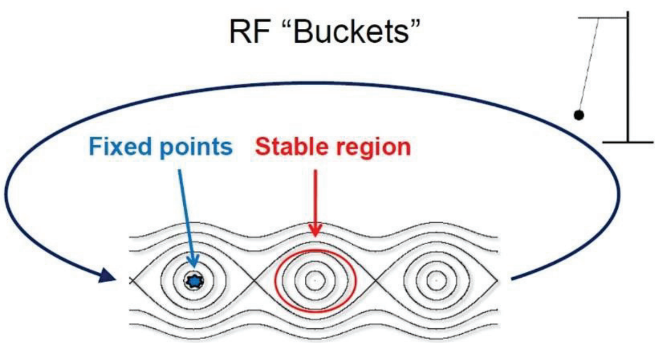
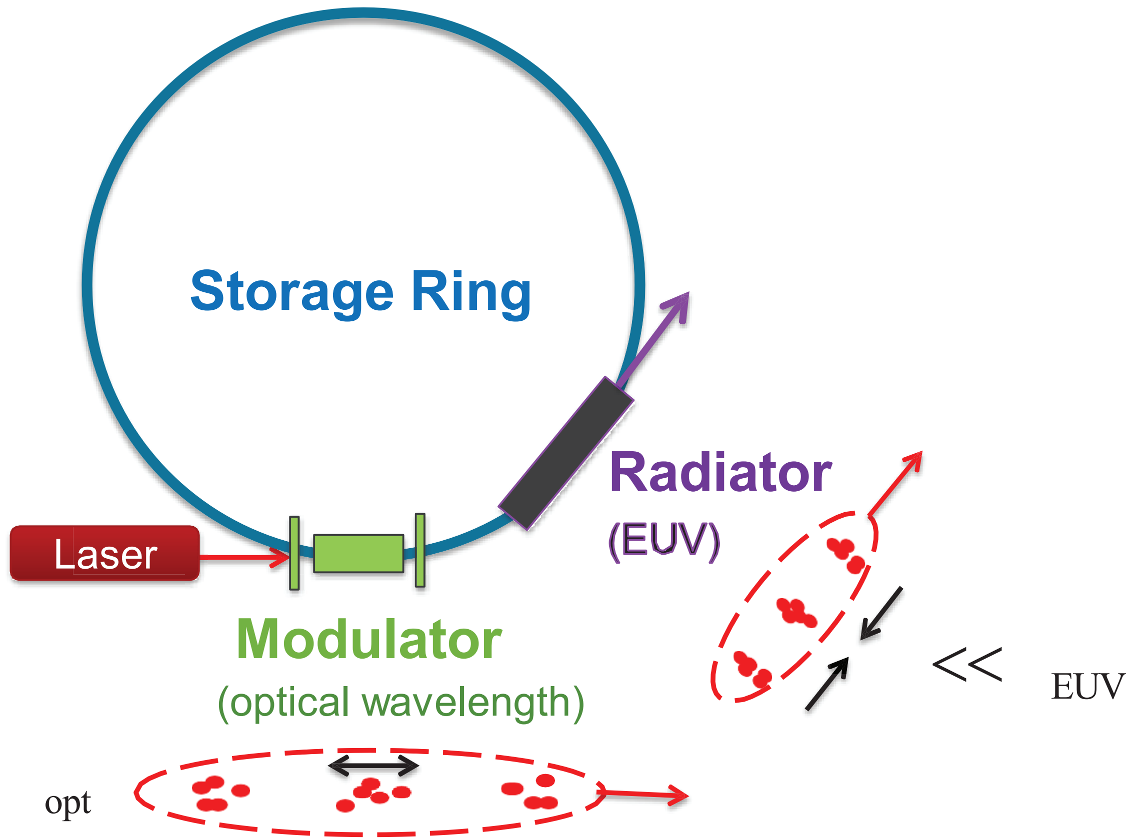
CSR based on SSMB ring



- The natural idea of SSMB is a scaling from microwave to optical, i.e. using laser modulator to replace RF to microbunch the beam and let it stay in a steady state.



Courtesy of Ratner & Chao

PRL 105.15 (2010): 154801

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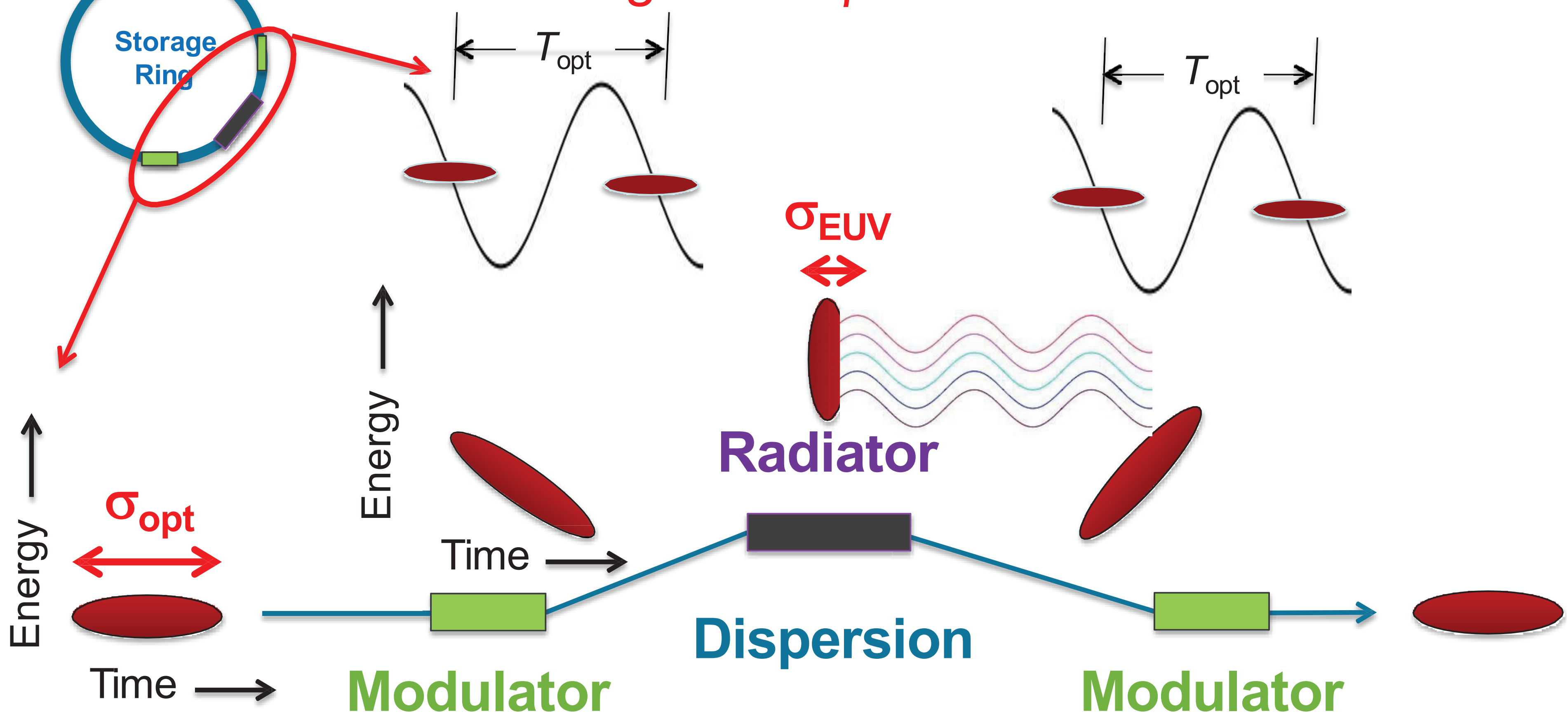
CSR based on SSMB ring

Small longitudinal β-function at radiator



Courtesy of Ratner & Chao

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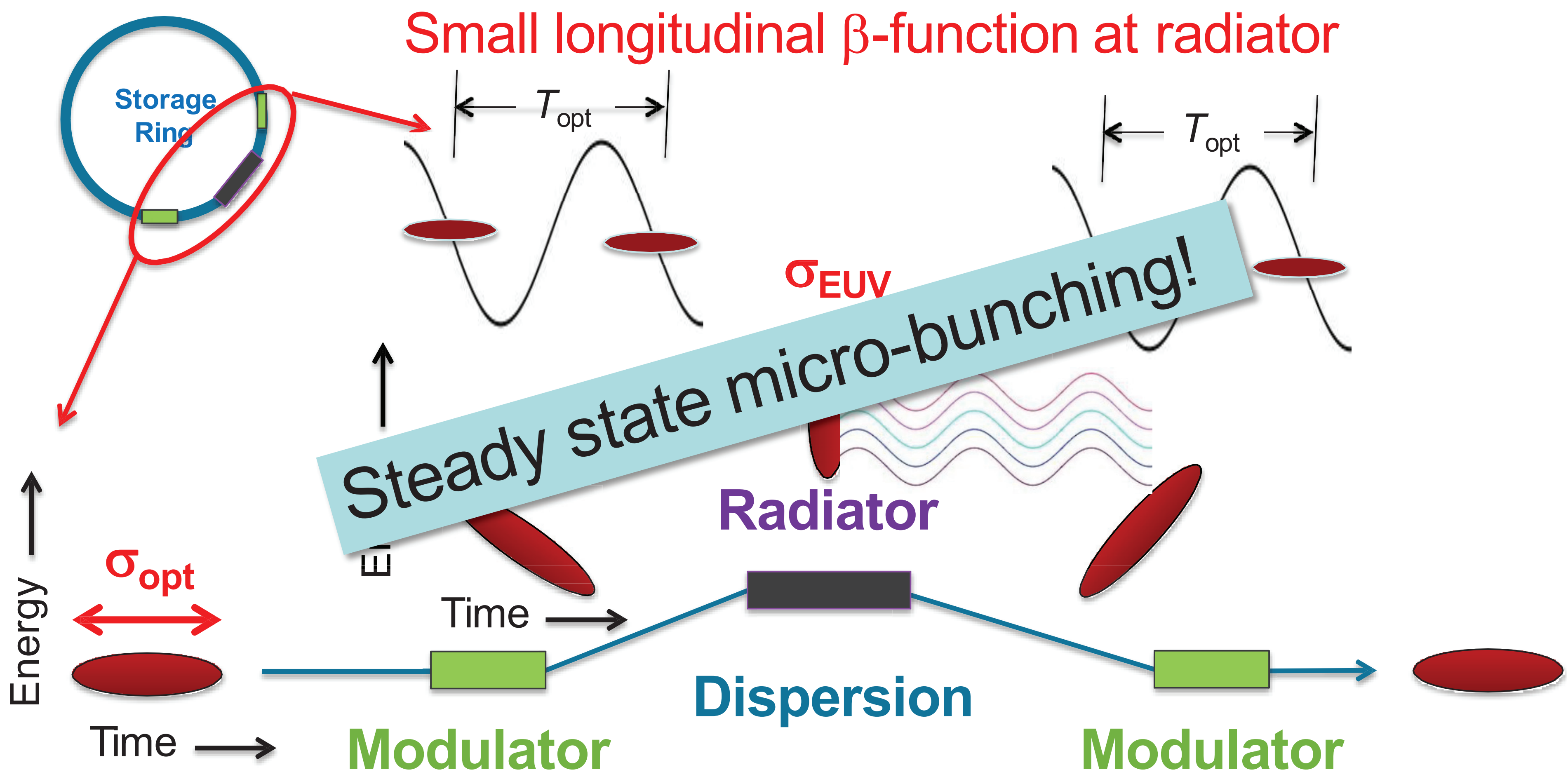
CSR based on SSMB ring

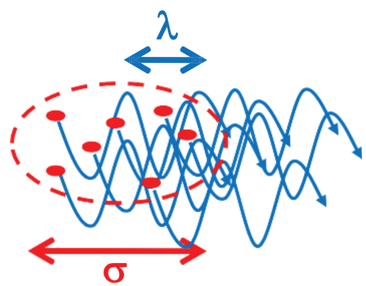


Courtesy of Ratner & Chao

PRL 105.15 (2010): 154801

CSR power of SSMB

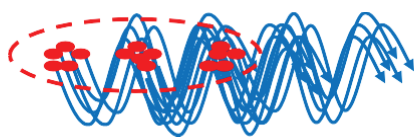
Shot Noise



Number of electrons

$$P_{rad} \propto \mu N_e$$

Microbunching



$$P_{rad} \propto \mu N_e^2$$

Compare SSMB with FELs and conventional storage rings:

	f[GHz]	bunch length	microbunch length	$N_{\rm bunch}$	$N_{\rm coh}$	$f N_{\rm bunch} N_{\rm coh}$
Conv. storage ring	0.3	1 mm		10^{11}	1	0.3×10^{11}
Supcond. FEL	1	1 mm	$< 1\ \mu$m	10^9	10^7	10^{16}
SSMB	3×10^5		$< 1\ \mu$m	10^5	10^5	3×10^{15}

Courtesy of Ratner & Chao

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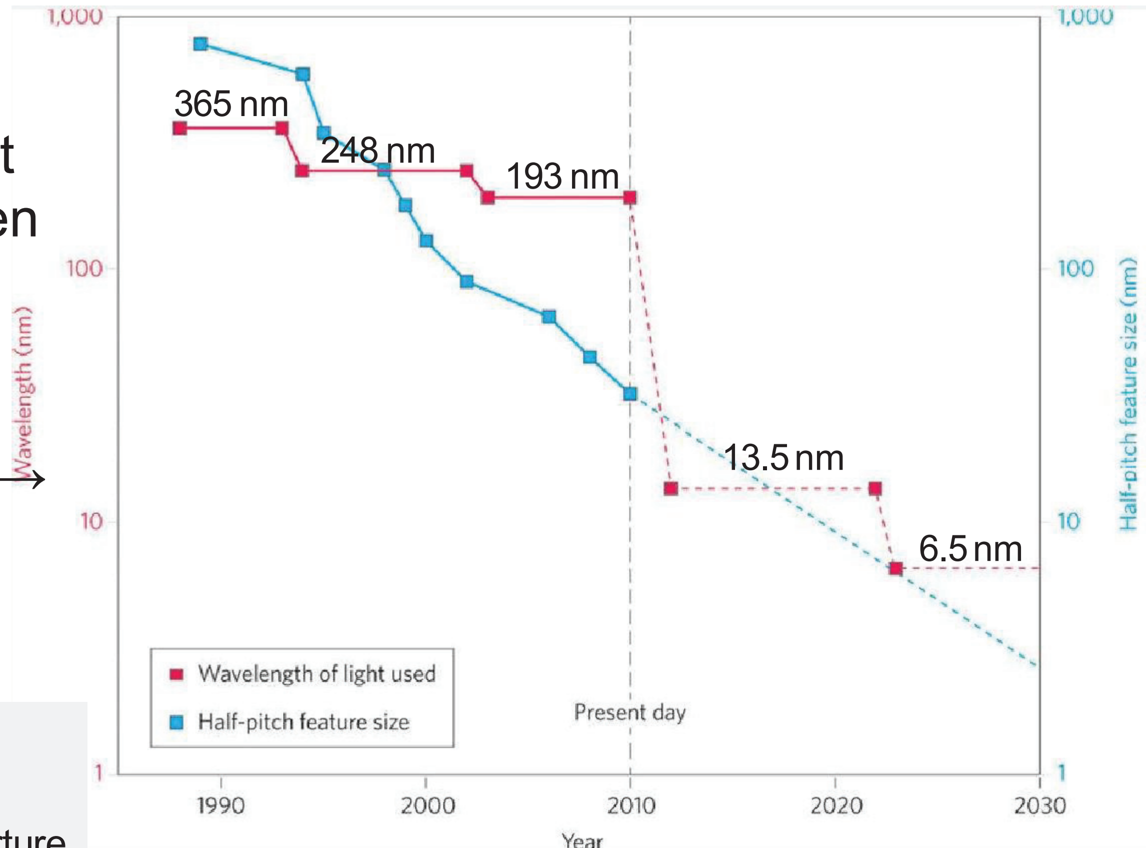
Demands for High Average Power

✧ kW level EUV light source for lithography:



Moore's law:

The number of transistors that could be fit on a chip of a given size at an acceptable cost doubles every two years.

- Denser integrated circuits → less power, lower cost
- Lithography → better resolution

$$R = k\frac{\lambda}{\text{NA}}$$

R	is resolution,
λ	is wavelength,
NA	is numerical aperture,
k	is constant.

Advances in X-Ray/EUV Optics, Components, and Applications (2006)
Nature Photonics, 4(12), 809-811

Exciting Accelerator Physics of SSMB

- Dig the potential of longitudinal coherence of electron beam in electron storage rings;
- Longitudinal dynamics study, for example longitudinal strong focusing;
- Novel 3D phase space manipulation schemes;
- Many interesting effects which can be ignored in traditional storage rings;
- Collective effects study of steady state microbunches;
- …

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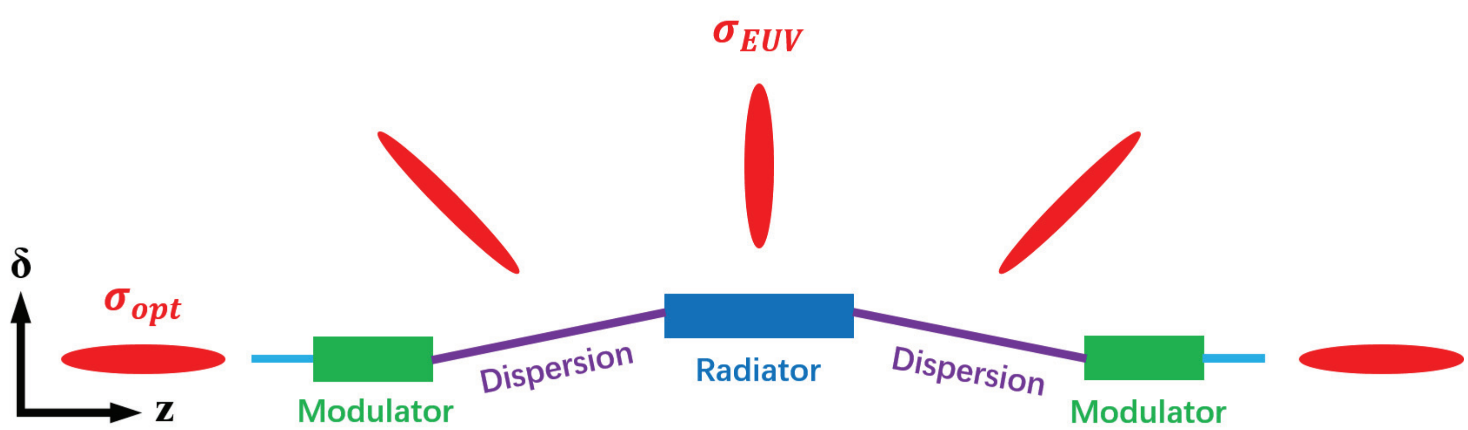
Current Status of SSMB Research

- Several different scenarios have been proposed and some preliminary theoretical study has been done since the first publication of the idea of SSMB;
- A dedicated taskforce has been established in Tsinghua University with the promote of **Chao** recently;
- Lattice design efforts of two SSMB approaches are being pursued in parallel by the collaboration:
  - Strong focusing SSMB;
  - Reversible seeding SSMB.
- PoP experiment is being prepared on MLS, the radiation source of the German national metrology institute (PTB).

Longitudinal Strong Focusing SSMB

- Low alpha + longitudinal strong focusing SSMB:
  - Fist use low alpha lattice to reduce bunch length since $\sigma_{z,Sands} \propto \sqrt{\alpha}$;
  - Then apply longitudinal strong focusing to compress the bunch length further;
- Schematic configuration and the longitudinal phase space evolution of one strong focusing SSMB super-period:



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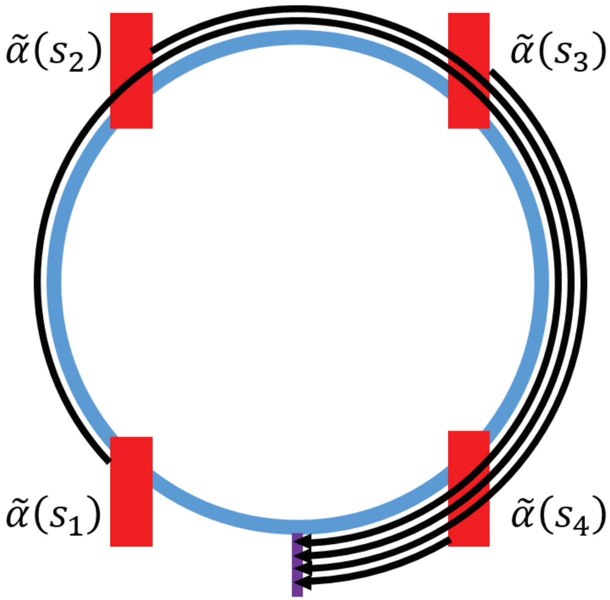
Longitudinal Quantum Radiation Excitation



Partial alpha:

$$\tilde{\alpha}(s_j) = \frac{1}{C_0}\int_{s_j}^{observation\ point} \frac{\eta(s)}{\rho(s)} ds$$

- The relation $\sigma_{z,Sands} \propto \sqrt{\alpha}$ breaks down when alpha approaches zero;
- A stochastic fluctuations of where the photoemission takes place produces a fluctuation of path length of one revolution, thus resulting in a bunch length limit and an extra energy spread.

Shoji, Yoshihiko, et al. PRE 54.5 (1996): R4556.

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Bunch Length Limit Caused by Partial Alpha

- Stochastic difference equation:

$$\begin{pmatrix} \frac{\delta E}{E_0} \\ \delta\tau \end{pmatrix}_n = A_{damping\ matrix} \begin{pmatrix} \frac{\delta E}{E_0} \\ \delta\tau \end{pmatrix}_{n-1} + \begin{pmatrix} \frac{\Delta E}{E_0} \\ \Delta\tau \end{pmatrix}_n - \begin{pmatrix} \left\langle \frac{\Delta E}{E_0} \right\rangle \\ \langle \Delta\tau \rangle \end{pmatrix}$$

where δ means relative to the barycenter and Δ means change in one turn.

- Equilibrium bunch length limit:

$$\sigma_{z,lqe} = \sigma_{\delta,Sands} C_0 \sqrt{I_\alpha}$$

$$I_\alpha = \frac{1}{C_0^2} \left\langle \left[\int_{s_j}^{watch\ point} \frac{\eta(s)}{\rho(s)} ds - \langle \tilde{\alpha} \rangle C_0 \right]^2 \right\rangle$$

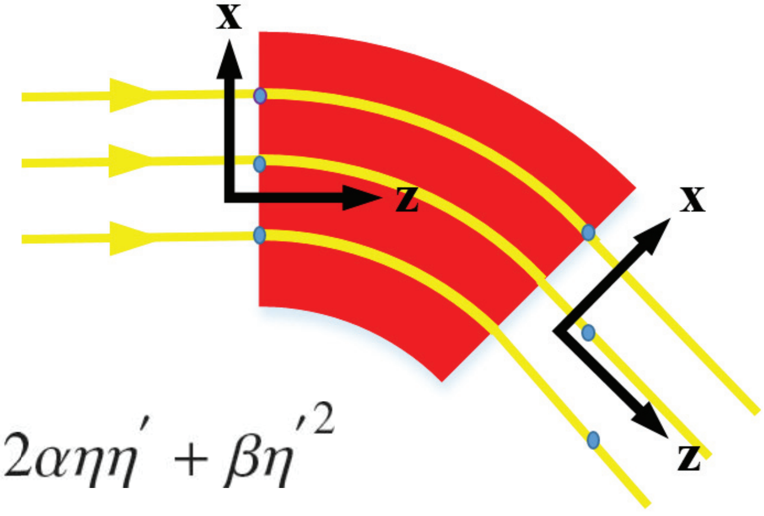
First Order Transverse Longitudinal Coupling

- Particles with different betatron amplitudes and phases pass bending magnets on different trajectories, resulting in longitudinal displacement differences and a bunch length limit (Shoji, Yoshihiko. PRSTAB 7.9 (2004): 090703):

$$\delta L = \int_{s_S}^{s_S+L_0} [x(s)/\rho(s)]ds$$

$$x(s) = \sqrt{\varepsilon_{\mathrm{CSI}}\beta(s)}\sin\psi(s)$$

$$\sigma_{hlc} = \sqrt{\varepsilon H},\ with\ H = \gamma\eta^2 + 2\alpha\eta\eta' + \beta\eta'^2$$



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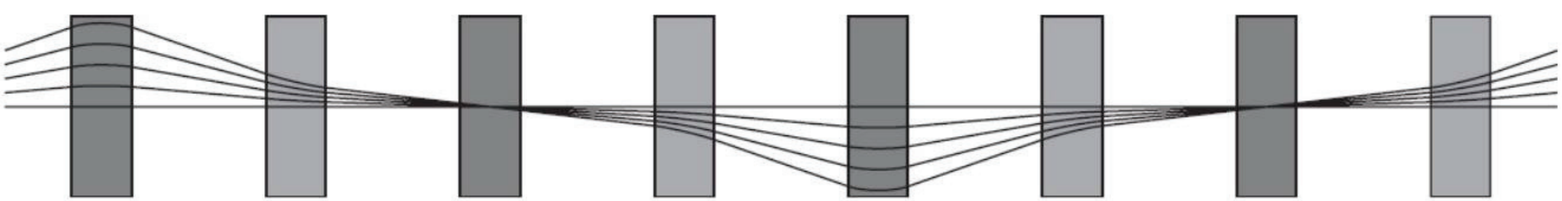
Second Order Transverse Longitudinal Coupling

- Oscillation amplitude based trajectory length is related to chromaticities due to symplectic condition (Etienne Forest. Beam dynamics, 1998):

$$\Delta L_n = \int_w^{w+nL_0} [\sqrt{(1+\frac{x(s)}{\rho(s)})^2 + x'^2 + y'^2} - 1] ds$$

$$\Delta C = \lim_{n\to\infty} \frac{1}{n} \Delta L_n = -2\pi (J_x \xi_x + J_y \xi_y)$$



Courtesy of J. Scott Berg

Second Order Transverse Longitudinal Coupling

- In a storage ring, the RF always makes sure the particle synchronize with it in average sense by longitudinal focusing. A shift of fixed point (synchronous) energy (momentum) will be introduced to fight against this path length shift (Shoji, Yoshihiko, et al. PRSTAB 8.9 (2005): 094001):

$$\delta = -\frac{1}{\alpha_p}\frac{\Delta C}{C_0}$$

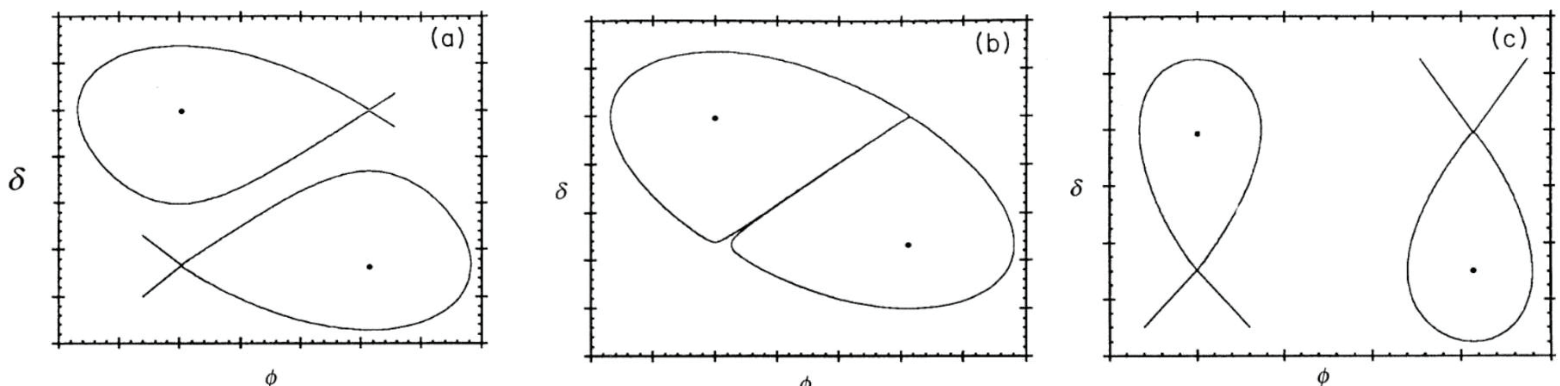
- Due to this effect, the energy spread will be enlarged by chromaticities in a low alpha ring.

Nonlinear Momentum Compaction

- Momentum compaction function:

$$\alpha(\delta) = \alpha_0 + \alpha_1\delta + \alpha_2\delta^2 + \cdots$$

- When α_0 approaches zero, the higher order terms will play bigger roles and transform the traditional RF-buckets to α-buckets (Robin, David, et al. PRE 48.3 (1993): 2149.):



- It can be well controlled using sextupoles and octupoles to get a high enough bucket height to guarantee a long enough quantum lifetime.

Influences of Different Effects

- Until now, we have introduced several single particle effects important for strong focusing SSMB:
  - Longitudinal quantum radiation excitation;
  - First order transverse longitudinal coupling;
  - Second order transverse longitudinal coupling;
  - Nonlinear momentum compaction.

Poster: Xiujie Deng et, al. WEP2PT018

- To get a concrete feeling of these effects, we investigate their influences on MLS, the first low alpha storage ring optimized for coherent THz radiation (Feikes, J., et al. PRSTAB 14.3 (2011): 030705).

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Metrology Light Source

Wüstefeld, Godehard, et al. TU5RFP005, PAC09

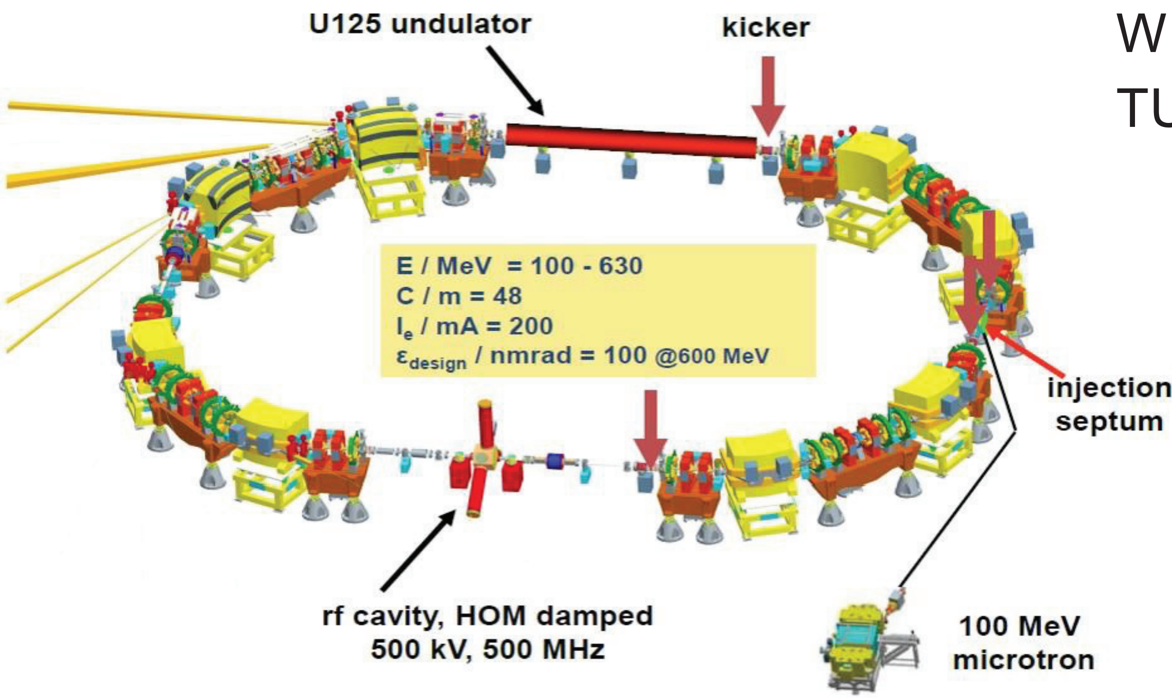
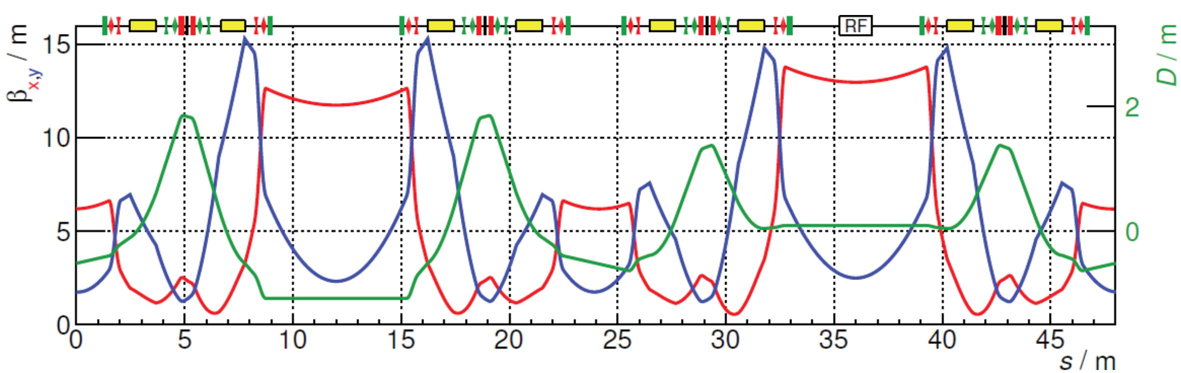


Table 1: Main MLS Parameters

parameter	value
injection energy	105 MeV
max. energy	630 MeV
circumference	48 m
optics	4 cell double bend
rf-frequency	500 MHz
max. rf-voltage	500 kV
hor. / vert. tune	3.2 / 2.2
short / long straigth	2.5 m / 6 m
rms-bunch length	5 mm to 0.5 mm



Low alpha (1.3e-4) optics

Markus, PhD thesis, 2014

Longitudinal Quantum Radiation Excitation

- Bunch length limit caused by partial alpha on MLS is about 36um@630MeV at low alpha mode. It should be carefully treated in lattice design for EUV SSMB.
- This effect is caused by the dispersion in dipoles cooperated with the stochastic quantum radiation, possible ways to proceed:
  - Minimizing dispersions at all dipoles;
  - Lowering beam energy;
  - Dividing the ring into N_{iso} isochronous sections, the fluctuations of partial momentum compaction will be reduced by a factor of N_{iso}^2 ;
  - Adopting the reversible seeding scheme for the EUV radiation.

First Order Transverse Longitudinal Coupling

- The largest bunch length limit due to 1^{st} order horizontal longitudinal coupling on MLS is 450um@630MeV at low alpha mode, which means this effect can easily smear microstructures in many places of the storage ring.

- However, this effect can be helpful in some sense since very short bunch occurs only at specific locations and this will help mitigate the damages caused by collective effects like CSR and IBS (Courtesy of Markus Ries).

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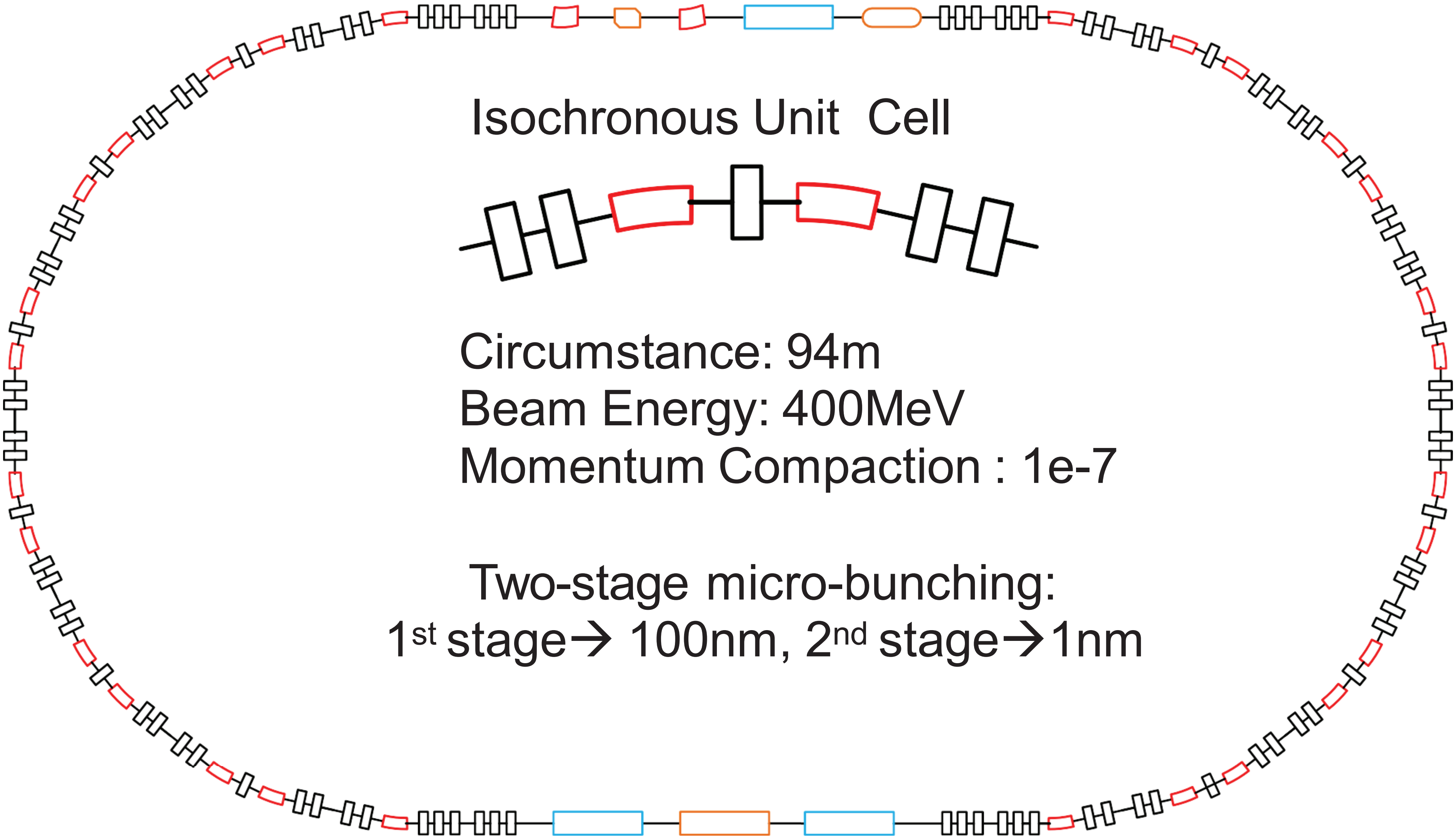
Strong Focusing Lattice Design of SSMB

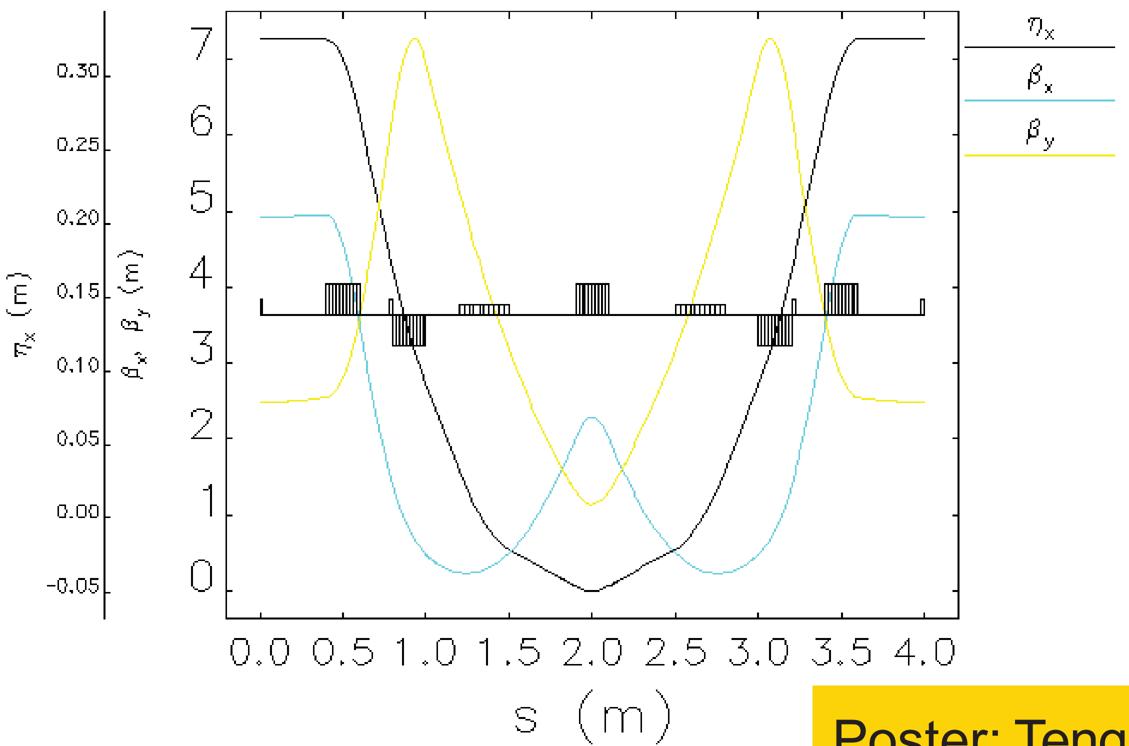


Isochronous Unit Cell

Circumstance: 94m
Beam Energy: 400MeV
Momentum Compaction : 1e-7

Two-stage micro-bunching:
1st stage→ 100nm, 2nd stage→1nm

Dedicated Lattice Design



- Abandon the achromatic condition to make chromaticity correction not too hard.

Poster: Tenghui Rui et, al. WEP2PT014

- Minimize the effect of longitudinal quantum radiation excitation by canceling the momentum compaction within each dipole.

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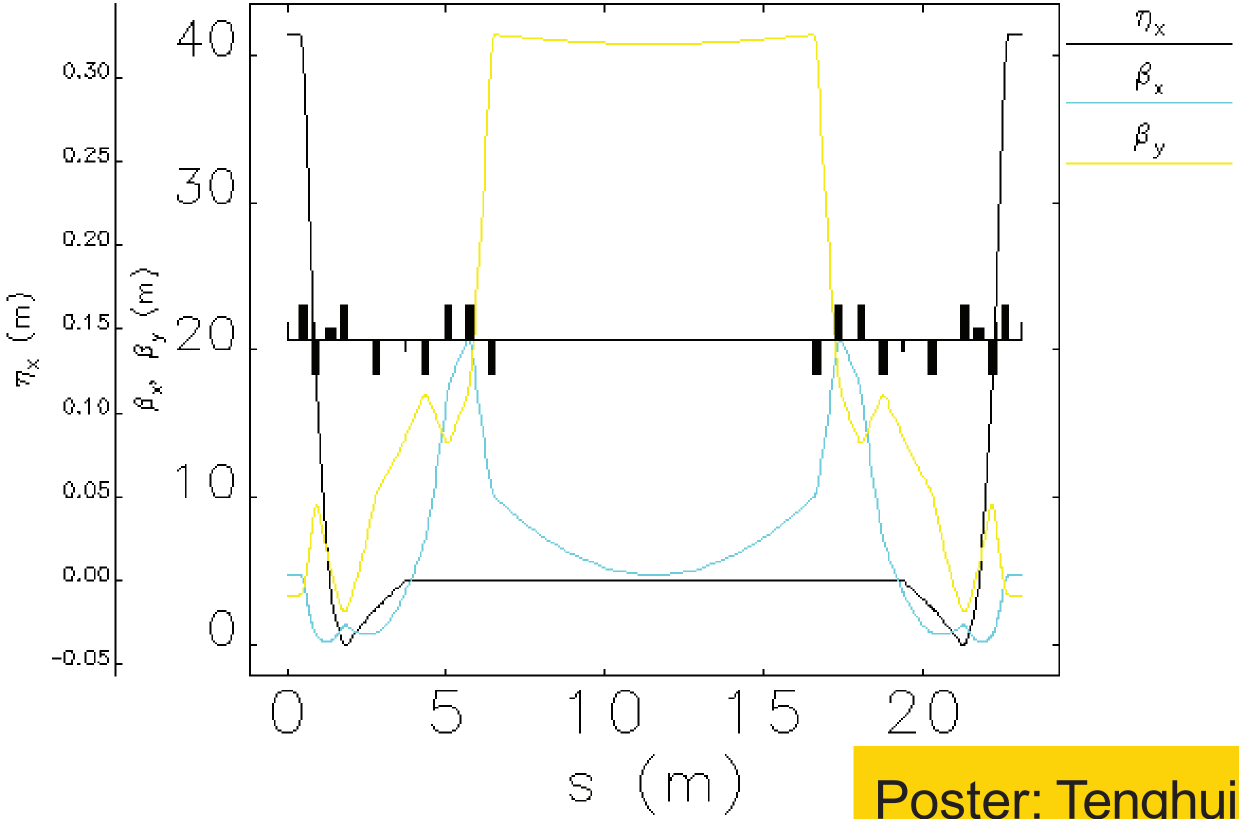
Dedicated Lattice Design



- Low dispersion and small beta function at most places combined lead us to a low emittance ring.

Poster: Tenghui Rui et, al. WEP2PT014

- Dispersion suppression section for insertion devices to avoid the first order horizontal longitudinal coupling.

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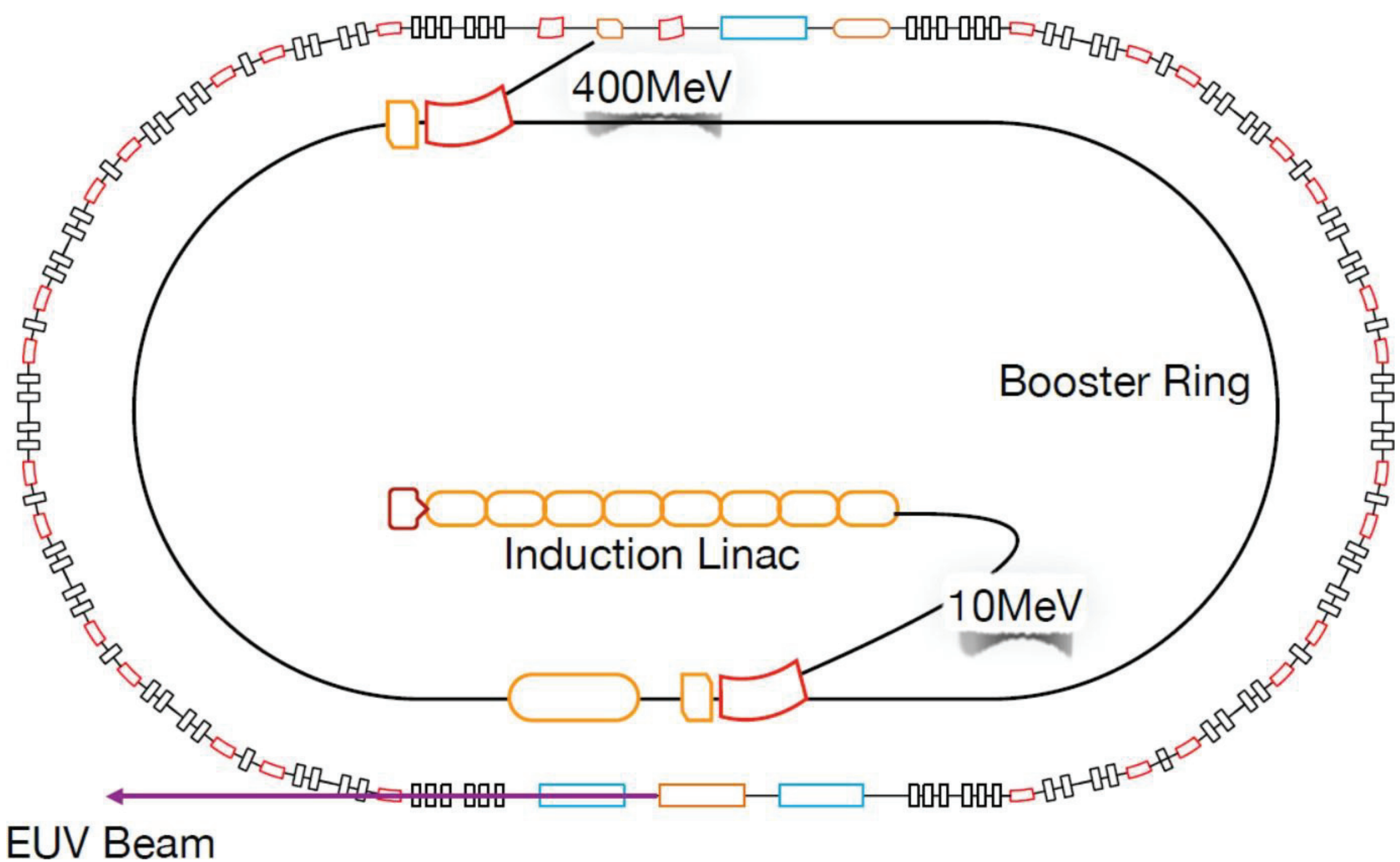
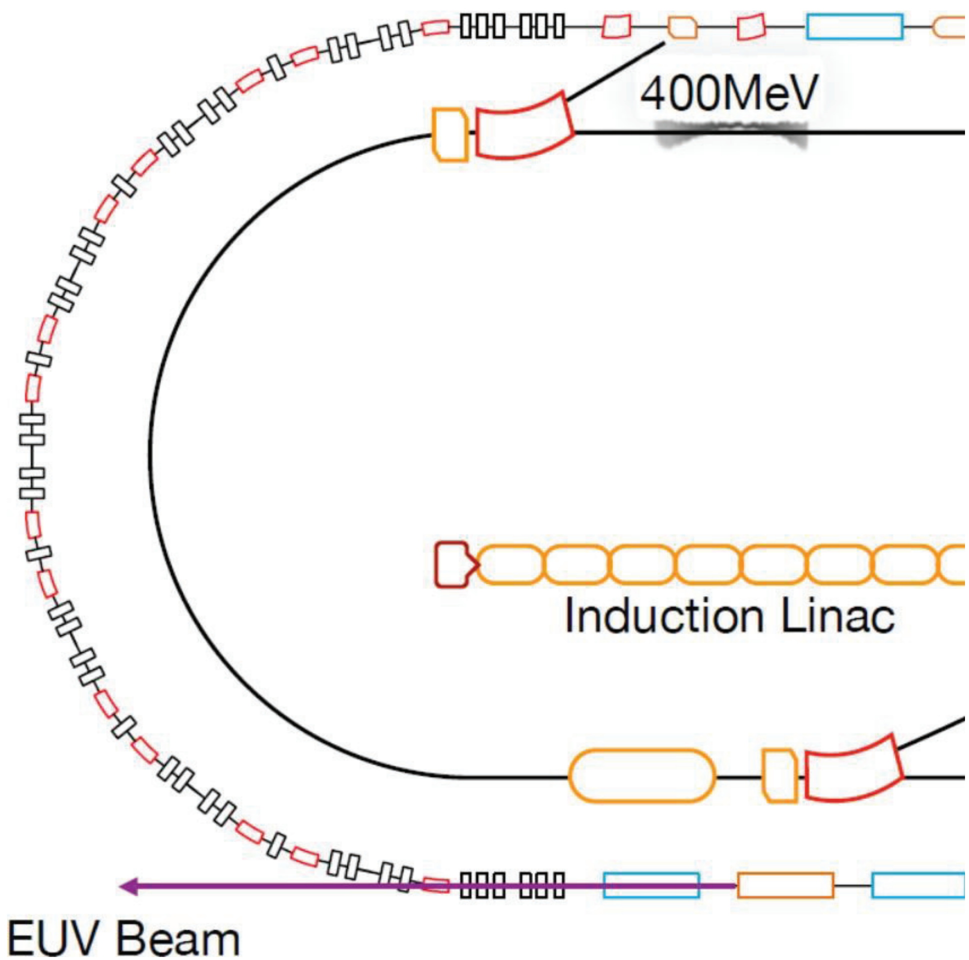
Comparison with MLS

- Bunch length limit caused by longitudinal radiation excitation:
  - MLS: 36um@630MeV
  - Dedicated design: 500nm@630MeV
- Largest bunch length limit caused by 1st order coupling:
  - MLS: 450um@630MeV
  - Dedicated design: 8um@630MeV
- Nonlinear momentum compaction terms are under optimization;
- As mentioned earlier, to reach EUV radiation, a strong focusing cell is needed in addition.

A sketch of strong focusing SSMB EUV light source



Storage Ring Dedicated for SSMB



Main Parameters

- Circumference: 94m
- Beam Energy: 400MeV
- Momentum Compaction: <1e-7m
- Two-stage micro-bunch generation
  1st stage: ~100nm
  2nd stage: ~1nm

Main Components

- Modulator
- Radiator
- Kicker
- Induction linac
- Injection/Extraction Septum Magnet

Main Structures

- Isochronous unit cell
- Conventional undualtor buncher
- Undulators for Longitudinal strong focusing

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It is just the beginning…

- It can be anticipated **coherent synchrotron radiation** and **intra beam scattering** will be the two dominant collective effects since now we have short bunch and low emittance at the same time.
- As a result of these considerations, the number of electrons per microbunch is limited to about **4000** in the present design.

- Future work:
  - ➢ Optimization of higher orders of the momentum compaction;
  - ➢ Detail design of the longitudinal strong focusing cell;
  - ➢ Simulation of microbunching with dynamic aperture effect.

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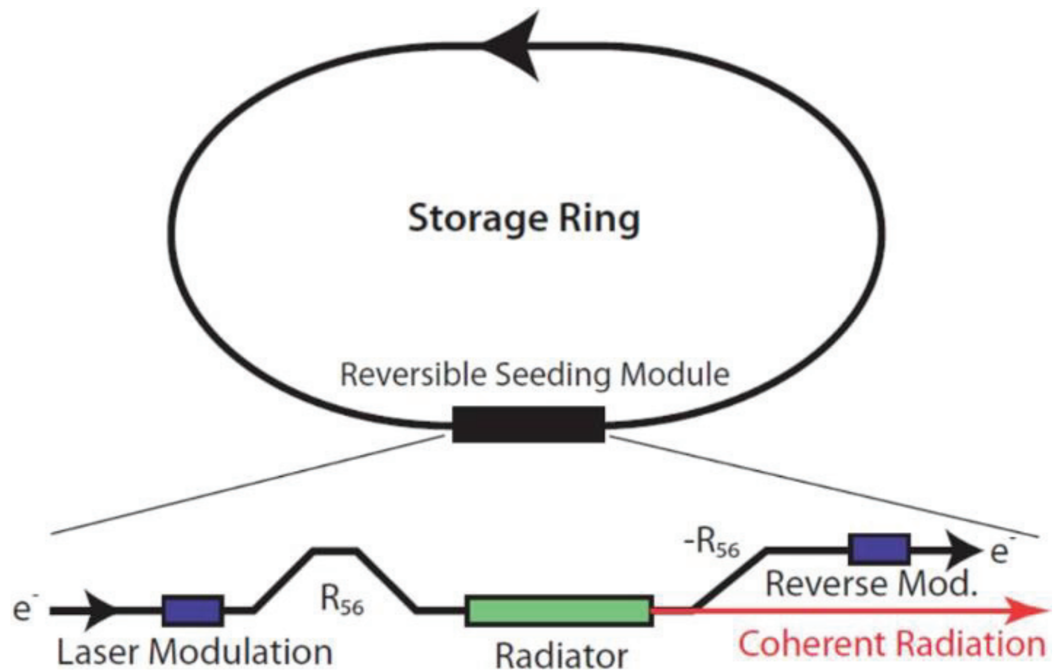
Reversible seeding SSMB

- Few additional requirements (no need of low alpha) on the lattice outside of the insertion since the beam microbunches only within the radiator;
- Careful design to realize perfect cancellation of the seeding module.

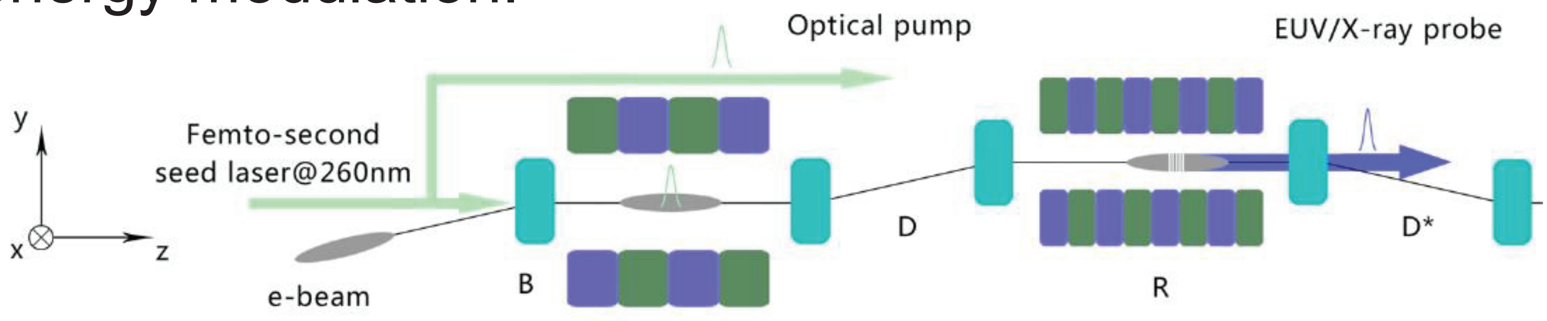


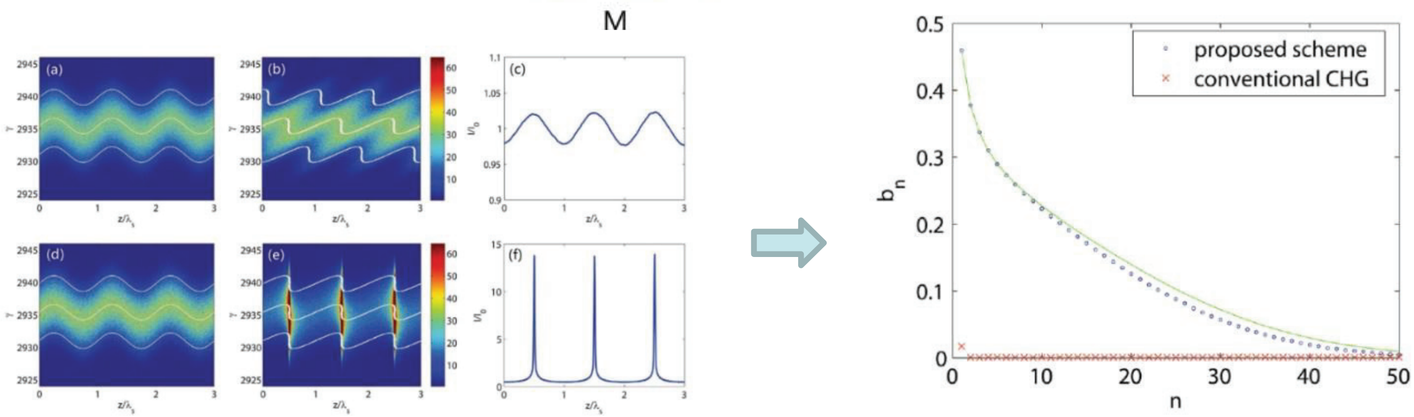
Ratner, Daniel, and Alex Chao. No. SLAC-PUB-14718. 2011.

Poster: Chao Feng et, al. WEP2PT017

A Novel Seeding Method

- Making full use of the characteristic that the vertical emittance is much smaller than the horizontal one in usual storage rings to realize large bunching factor with small energy modulation.



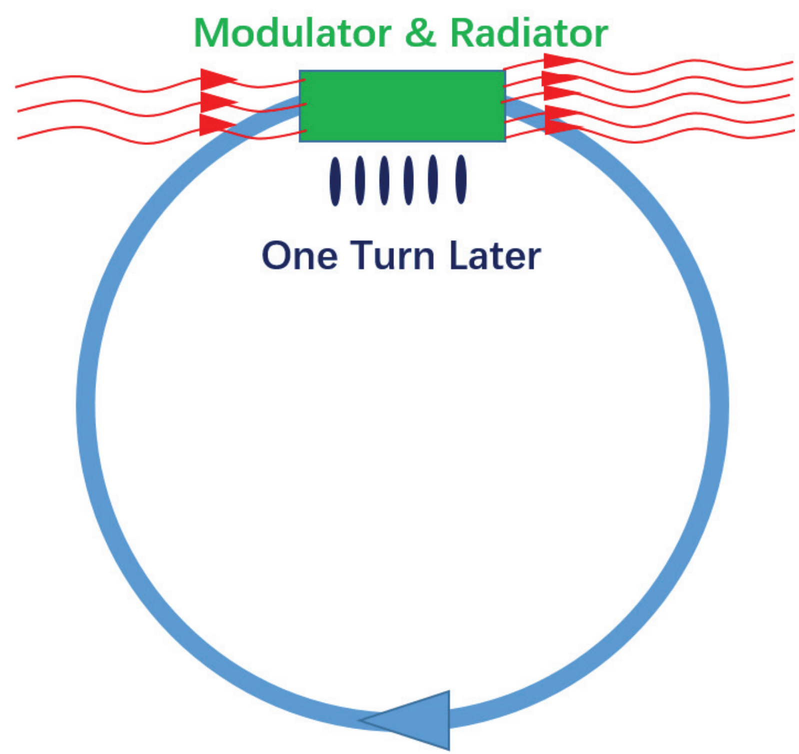


Feng, Chao, and Zhentang Zhao. Scientific Reports 7.1 (2017): 4724.

Proof-of-principle Experiment

- Realize EUV SSMB need careful dedicated work, the first step would be a single pass experiment to verify some basic ideas of SSMB and study related physics.

- Steps:
  - Let beam reach natural state;
  - Use a laser modulator to energy modulate the beam;
  - The microbunches formed one turn later will radiate coherently at the modulation wavelength.



Purpose of the proof-of-principle Experiment

- Verify microbunches can be formed and survive after traversing the whole ring;
- Realize amplification of the modulation laser power by the coherent radiation one turn later, proving the SSMB amplifier scenario;
- Study parameters and effects influencing the decay (smearing) rate of microstructures which would also be important for true SSMB;
- Since the test is to be performed using IR laser, its success would be readily applicable to an IR SSMB with applications of its own without having to push towards EUV.

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Example Experiment Parameters

Parameter	Value
Beam Energy	250 MeV
Momentum Compaction	2×10^{-5}
Modulation Laser Wavelength	800 nm
Modulation Laser Peak Power	500 kW
Undulator Parameter	2.05
800 nm Bunching Factor One Turn Later	0.25
Peak Current Needed For Amplification	48 A

- Peak current needed for amplification is beyond the present reach of MLS and methods to lower this requirement is under study.

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Summary

- An SSMB taskforce has been established in Tsinghua University.
  - Strong focusing and reversible seeding are the two schemes on which the team focuses and good progresses have been made;
  - Another main task now is the PoP experiment prepared to better understand physics related to SSMB.

- We have enlisted the technical challenges envisioned for the EUV SSMB, most of which comes from the short EUV wavelength. Challenging as it is, however, EUV SSMB offers an exciting area of research and the reward would be tremendous if realized.

The Collaboration Team