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Low-Alpha Storage Ring Design for Steady-State Microbunching to generate EUV radiation

On behalf of Tsinghua SSMB team

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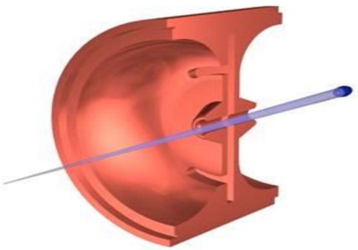

Accelerator Laboratory of Tsinghua University

FLS2023, Lucerne, Switzerland, Aug.27-Sep.2, 2023

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- Introduction
- Linear lattice design
- Nonlinear study
- Summary

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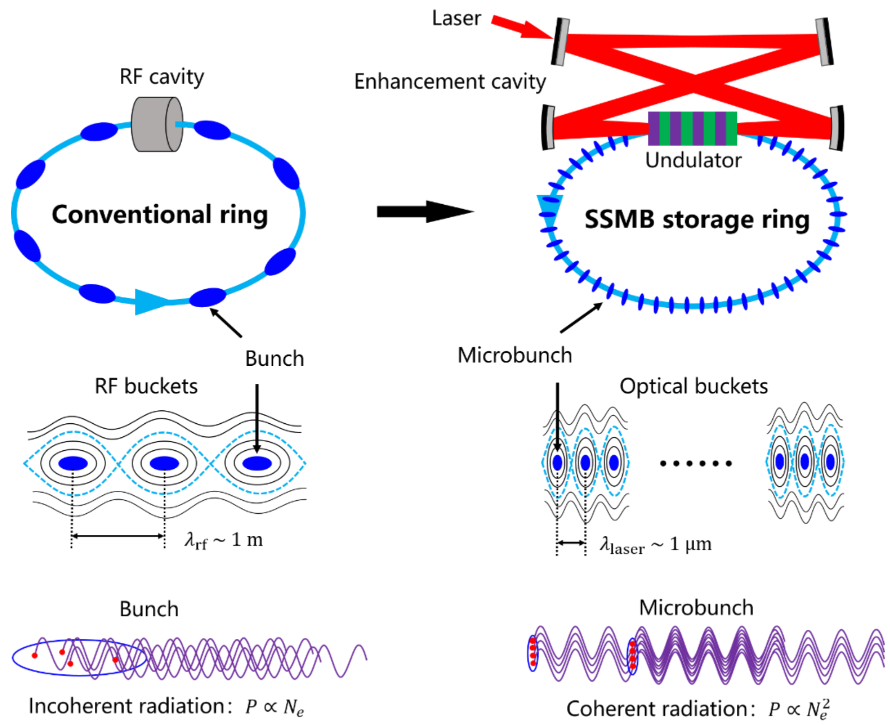
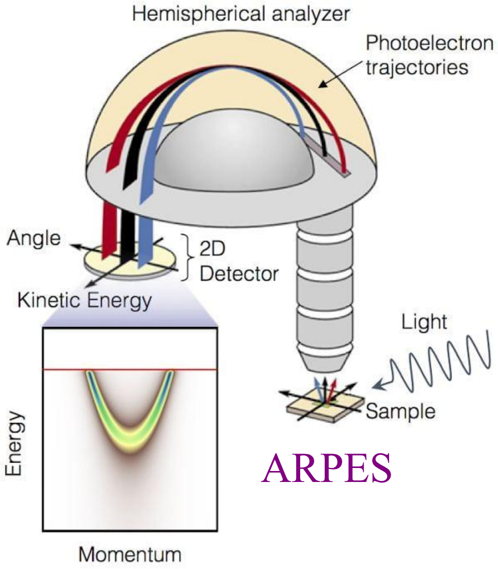
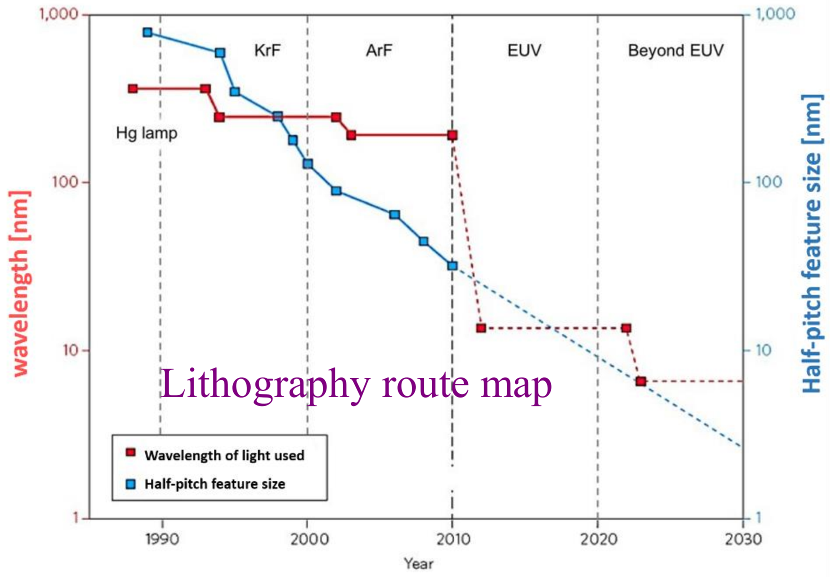
Steady-state microbunching (SSMB)*

6 orders of magnitude extrapolation





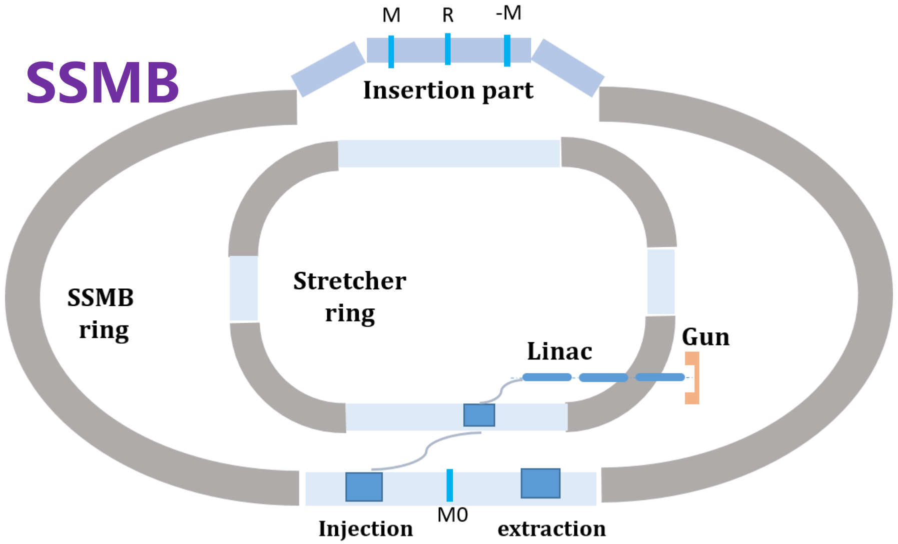


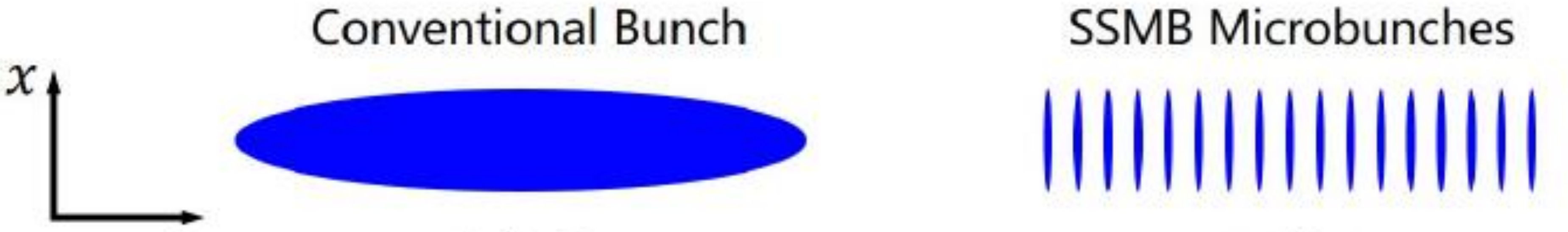
kW average power EUV radiation for lithography and high flux EUV for ARPES

- **Electron storage ring-based, longitudinal dynamics study needed**
- **Bunching system laser modulator, instead of RF cavity**
- **Two key points: Microbunching for strong coherent radiation; turn-by-turn steady state for high repetition rate**

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

DLSR and SSMB

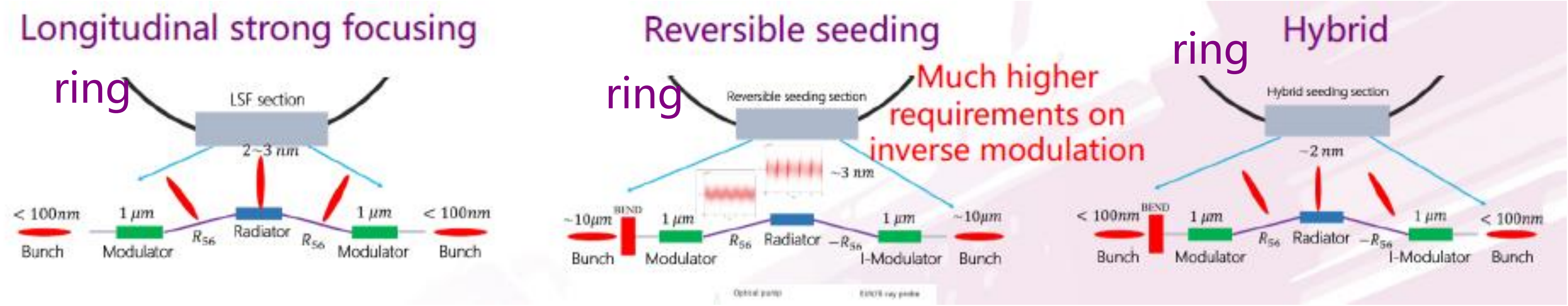




$\sigma_z > \sigma_x$ $\sigma_z \ll \sigma_x$

- DLSR: minimize transverse size to diffraction limitation
- SSMB: minimize longitudinal size for coherent radiation

SSMB schemes



- Low-alpha ring (~100 nm bunch) + LSF(~3nm)
- Required laser power: hundreds MW, pulsed, Duty rate: 1%
- Pulse power : several kW, average power : several tens W

- normal ring + ADM compress (~3nm)
- Required laser power: ~1 MW
- Low bunching factor, coasting beam (@10A)
- Average power : ~ kW

- Low-alpha ring (~100 nm bunch) + ADM compress (~3nm)
- Required laser power: ~1 MW
- high bunching factor
- Average power : ~ kW (@1A)

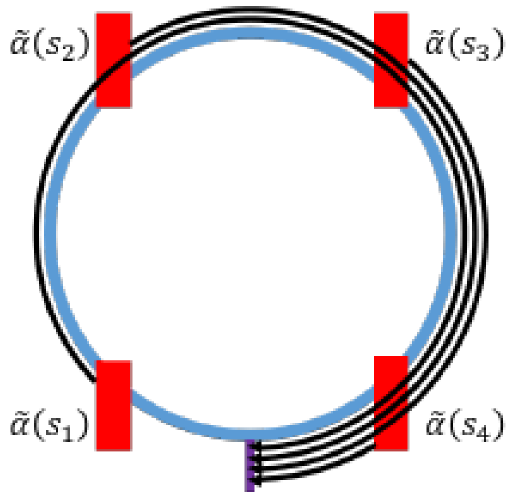
A low-alpha ring which is very different from normal ring is demanded by SSMB.

Low alpha storage ring

Existing low-alpha mode ring

- The bunch length in existing low-alpha mode ring:~1 ps
- There are two reasons why existing ring can' t meet SSMB requirements:
- Wavelength of bunching system
- Partial alpha effect or local R56

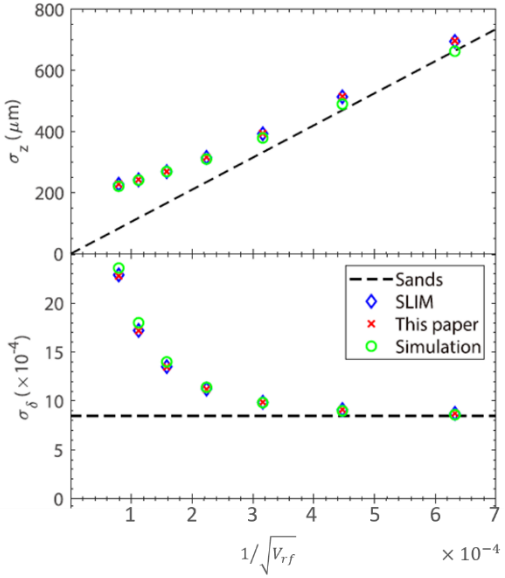
Facilities	Circumference[m]	Achieved alpha
Diamond light source	561.6	-6×10^{-5}
Metrology light source	48	$\sim1\times10^{-5}$
BESSY II	240	7.3×10^{-6}
SOLEIL	354	1.7×10^{-5}
TPS	518.4	-3×10^{-7}



$$\tilde{\alpha}(s_j)=\frac{1}{C_0}\int_{s_j}^{observation\ point}\frac{\eta(s)}{\rho(s)}ds \quad \sigma_\tau=\sigma_\delta\sqrt{(\alpha_c/\omega_s)^2+T_0^2 I_{\tilde{\alpha}}}$$

$I_{\tilde{\alpha}}$ the variance of $\tilde{\alpha}(s_j)$

- The scaling law $\sigma_z \propto \sqrt{|\eta|}$ breakdown when $\eta\to0$
- The key is to control $I_{\tilde{\alpha}}$ in low alpha ring



I.P.S Martin et al, THPF0371 IPAC'10,Kyoto, Japan
Wustefeld et al TU5RFP005 PAC09
N.P. Abreu et al WE5RFP010 PAC09

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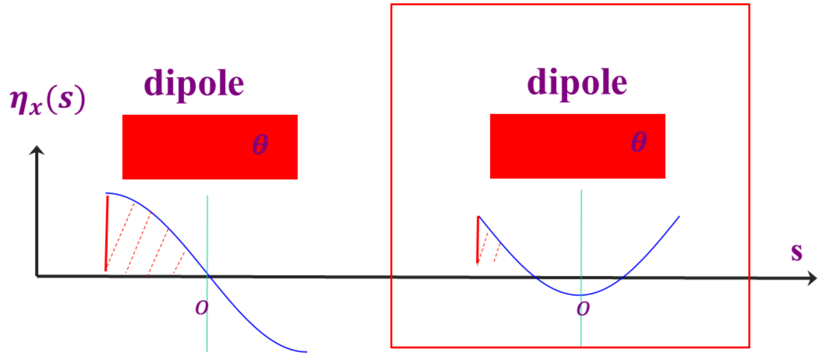
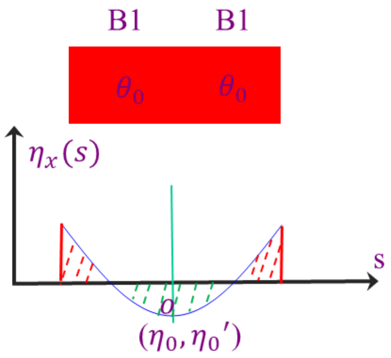
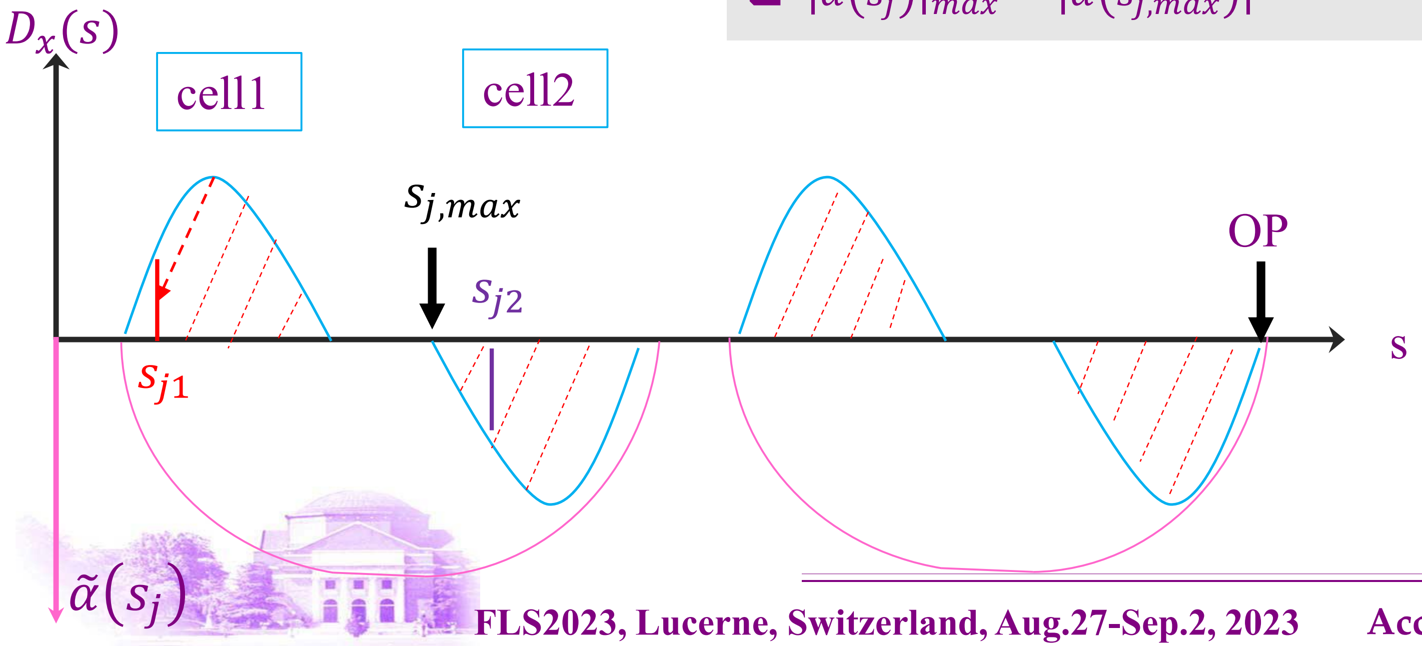
Partial alpha effects in low alpha ring

- $I_{\tilde{\alpha}} = \left\langle \left(\widetilde{\alpha_{s_j}} - \left\langle \widetilde{\alpha_{s_j}} \right\rangle \right)^2 \right\rangle = \left\langle \widetilde{\alpha_{s_j}}^2 \right\rangle - \left\langle 2\widetilde{\alpha_{s_j}} \right\rangle \left\langle \widetilde{\alpha_{s_j}} \right\rangle + \left\langle \widetilde{\alpha_{s_j}} \right\rangle^2 = \left\langle \widetilde{\alpha_{s_j}}^2 \right\rangle - \left\langle \widetilde{\alpha_{s_j}} \right\rangle^2$
- $\tilde{\alpha}(s_j) = \frac{1}{C_0} \int_{s_j}^{OP} \frac{D_x(s)}{\rho(s)} ds$
- **Control the max of dispersion**
- **The nature idea: make $\alpha_c \sim 0$ in each dipole**

- $R_{56,c} = R_{56,1} + R_{56,2} \sim 0$
- So $\tilde{\alpha}(s_j) < 0$ for all radiation points
- $|\tilde{\alpha}(s_j)|_{min} = 0$
- $|\tilde{\alpha}(s_j)|_{max} = |\tilde{\alpha}(s_{j,max})|$



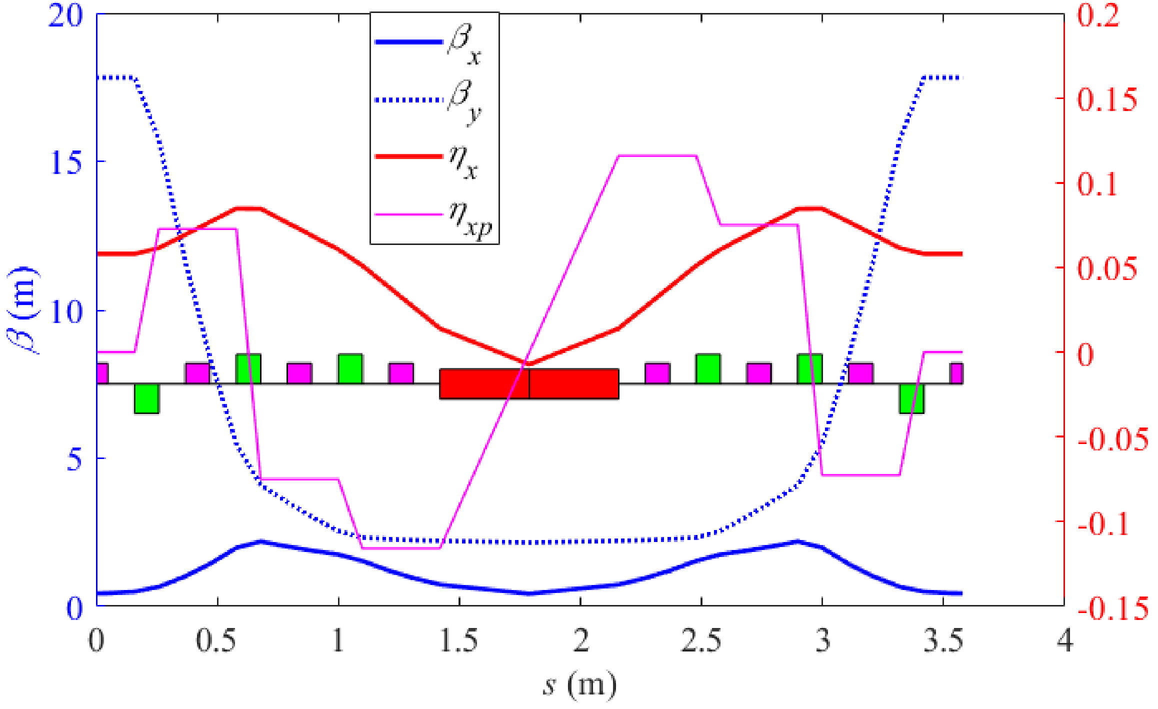




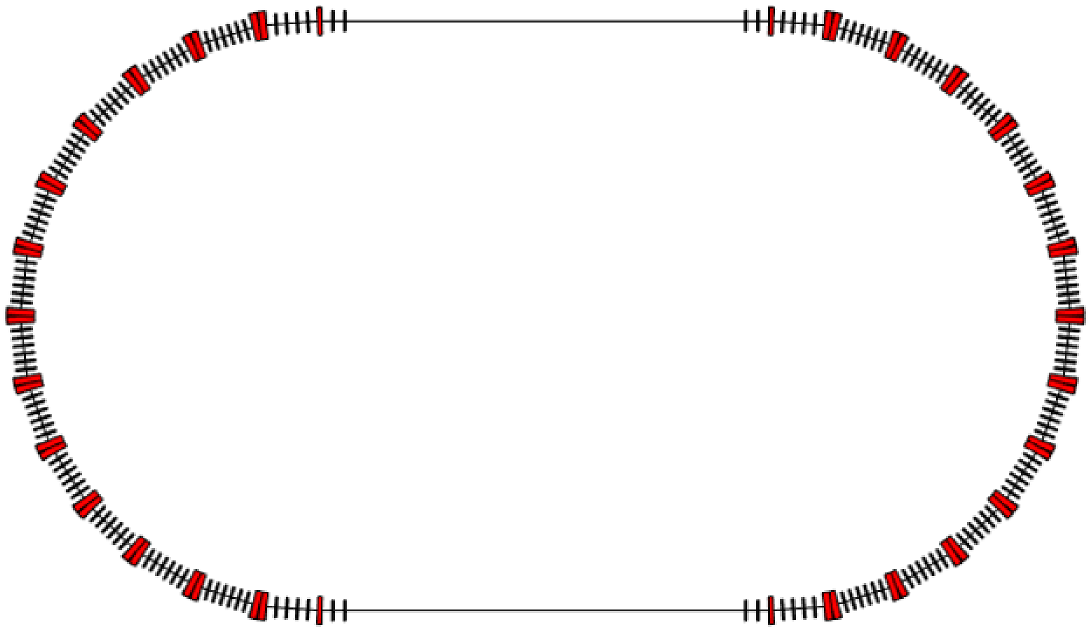
- Make the α_c in each dipole be 0
- η_0' at the middle of the dipole is 0
- We get $\eta_0 = \rho \frac{(\sin(\theta_0) - \theta_0)}{\sin(\theta_0)} \approx -\frac{1}{6} \rho \theta_0^2$,

and $\eta(\theta_0) = \frac{1}{3} \rho \theta_0^2$

Lattice design example



Main Cell



Ring layout

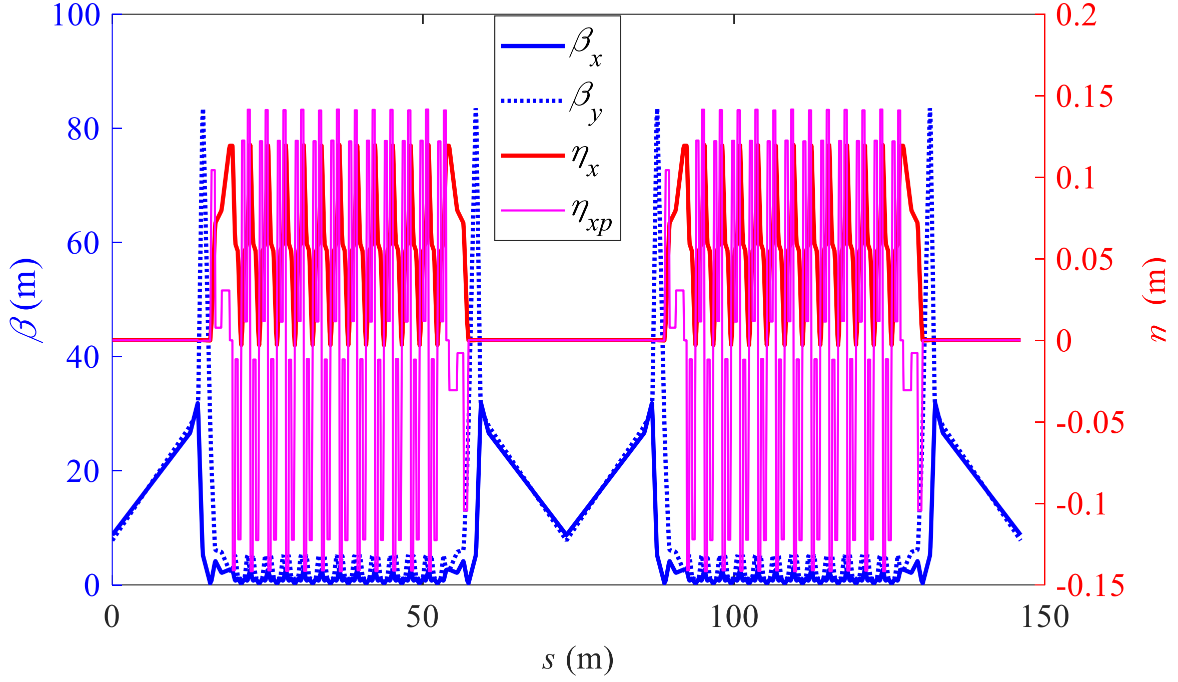
Tune: $\frac{i}{n}, \frac{j}{n}$, in this lattice n=12, tune $(\frac{7}{12}, \frac{3}{12})$

Dispersion in middle point: $-\frac{1}{6}\rho{\theta_0}^2$

Lattice parameters

Parameters	Value	Units
Circumference	143.78	m
Beam energy	400	MeV
Tunes x/y	18.58/7.11	/
Phase slippage factor	2.69e-6	/
2nd order phase slippage factor	1.23e-4	/
Natural emittance	281.7	pm
LM wavelength	1	μm
LM voltage	100	kV
Energy spread	2.23×10^{-4}	/
Bunch length at straight	91.4	nm
Damping times (x/y/z)	191.3/191.3/96.5	ms
Energy loss per turn	0.71	keV

$$\tilde{\alpha}(s_j) = \frac{1}{C_0}\int_{s_j}^{obser}\frac{D_x(s)}{\rho(s)}ds - \frac{1}{\gamma^2}\frac{C_0 - s_j}{C_0}$$



Twiss of ring

The bunch length at straight is less than 100 nm

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High order momentum compaction factor

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- Destroy RF bucket if too large

$$\alpha = \alpha_c + \alpha_2\delta + \cdots$$

$$\alpha_{c2} = \frac{1}{C}\int_0^C \left(\frac{\eta_2}{\rho} + \frac{{\eta_1'}^2}{2}\right) ds$$

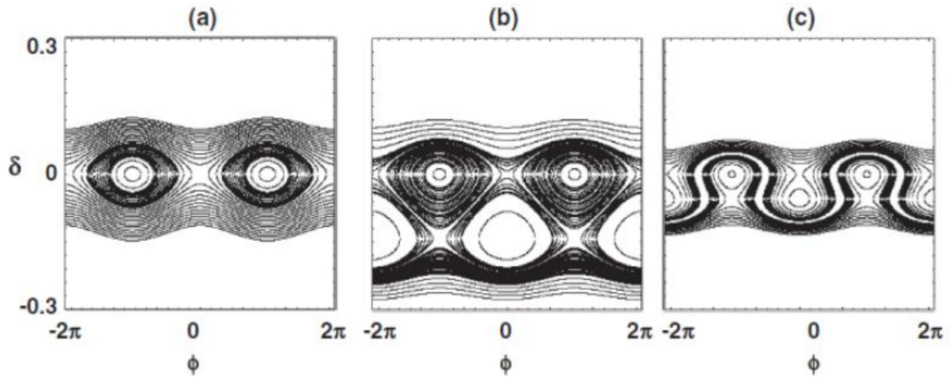


Fig. 8. Effect of second-order momentum compaction factor on longitudinal phase space in ring. The first-order momentum compaction factor in (a), (b), and (c) is 2.2×10^{-3}. The second-order momentum compaction factors in (a), (b), and (c) are 0.006, 0.02311, and 0.06, respectively.

when $|\alpha_2| > \alpha_{2Cr}$, the RF bucket will transmit to α-bucket, bucket area will shrink

$$\alpha_{2Cr} = \sqrt{\frac{E_0 h|\alpha_1|^3}{12eV_{rf}[-cos\varphi_s + \left(\frac{\pi}{2} - \varphi_s\right)\sin(\varphi_s)]}}$$

The sextupoles should be located at dispersive location to correct chromaticities for three directions， at least three families needed.

$$\eta_2(s) = -\eta_1(s) + \frac{1}{2\sin\pi Q_x} * \int_s^{s+C} \sqrt{\beta_x(s)\beta_x(\sigma)}\cos(\pi Q_x - \mu_{\sigma s}) *$$

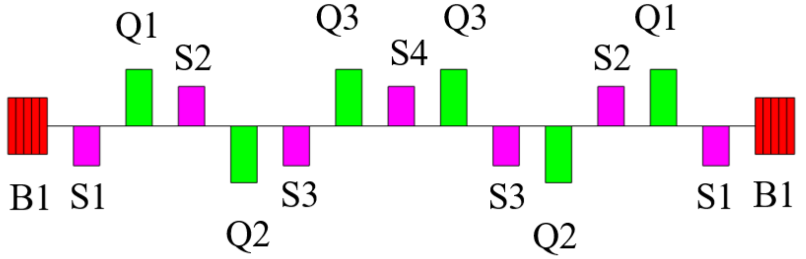
$$\left(K_1(\sigma)\eta_1(\sigma) - \frac{1}{2}K_2(\sigma)\eta_1^2(\sigma)\right)d\sigma$$

P.Gladkikh Design of laser-electron storage ring lattice dedicated to generation of intense X-rays under Compton scattering

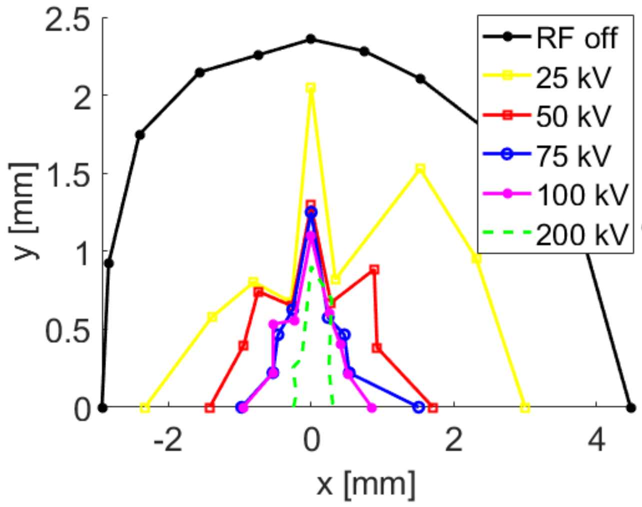
Eun-San Kim 2007 *Jpn. J. Appl. Phys.* 46 7952

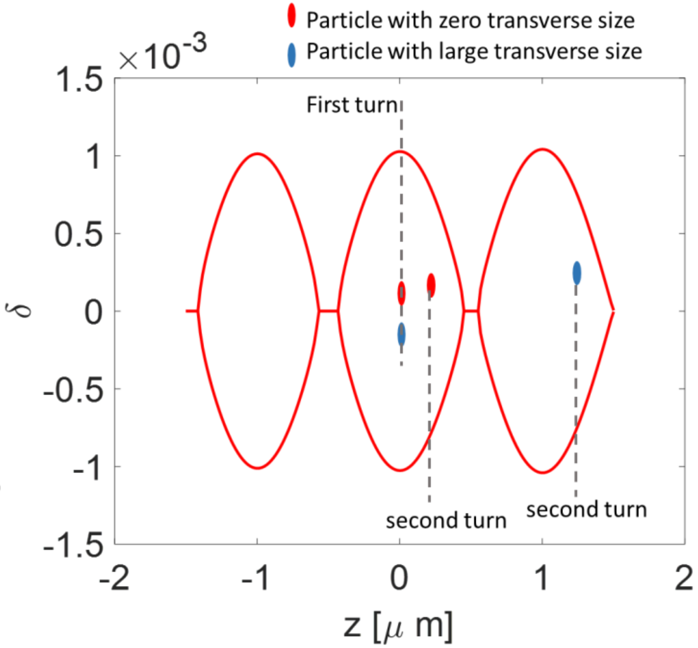
Nonlinear dynamics optimization

- Sextupoles are inserted in main cell for chromaticity and α2 correction



Main cell





- Bucket width will be 1 μm in SSMB ring
- The path length oscillation amplitude by transverse longitudinal coupling can be larger than 1 μm easily.
- Particles with large transverse size will jump in different buckets and make longitudinal motion become unstable

Nonlinear dynamics optimization

- **Define the Hamiltonian as (under 3rd order, omit longitudinal Hamiltonian)**

$$H(J_x,J_y,\delta)=\mu_x J_x+\mu_y J_y+h_{11001}J_x\delta+h_{00111}J_y\delta+|h_{20001}|J_x\delta e^{-2\phi_x j}+|h_{00201}|J_y\delta e^{-2\phi_y j}$$

- **So we can get path length deviation from T-L coupling (linear dispersion not discussed)**

$$\Delta z=\frac{\partial H}{\partial \delta}=h_{11001}J_x+h_{00111}J_y+|h_{20001}|J_x e^{-2\phi_x j}+|h_{00201}|J_y e^{-2\phi_y j}$$

- **From J. Bengtsson**

$$h_{11001}=\frac{1}{4}\sum_{i=1}^{N}[(b_2L)_i-2(b_3L)_i\eta_{xi}]\beta_{xi}$$

$$h_{00111}=-\frac{1}{4}\sum_{i=1}^{N}[(b_2L)_i-2(b_3L)_i\eta_{xi}]\beta_{yi}$$

$$h_{20001}=\frac{1}{8}\sum_{i=1}^{N}[(b_2L)_i-2(b_3L)_i\eta_{xi}]\beta_{xi}e^{j2\mu_{xi}}$$

$$h_{00201}=-\frac{1}{8}\sum_{i=1}^{N}[(b_2L)_i-2(b_3L)_i\eta_{xi}]\beta_{yi}e^{j2\mu_{yi}}$$

- **We can get more accurate expression as**

$$\Delta z_n=T_{511}x_n^2+T_{512}x_n x_n'+T_{522}x_n'^2 \qquad x_n=\sqrt{2\beta_x J_x}\cos(2\pi\nu_x n+\phi_0)$$

$$x_n'=-\sqrt{\frac{2J_x}{\beta_x}}(\alpha_x\cos(2\pi\nu_x n+\phi_0)+\sin(2\pi\nu_x n+\phi_0))$$

$$\Delta z=(\beta_x T_{511}-\alpha_x T_{512}+\gamma_x T_{522})J_x+A_x J_x\sin(4\pi\nu_x n+\psi_A)$$

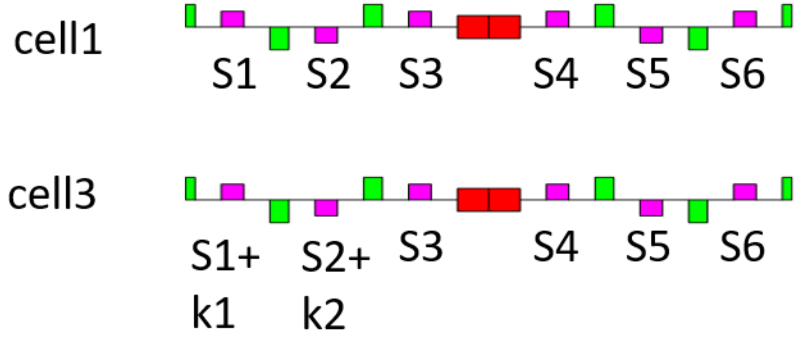
$$A_x^2=\beta_x^2T_{511}^2+\beta_x\gamma_x T_{512}^2+\gamma_x^2T_{522}^2-2\alpha_x(\beta_x T_{511}+\gamma_x T_{522})T_{512}+2(\alpha_x^2-1)T_{511}T_{522}$$

$$h_{11001}=2\pi\xi_x=\beta_x T_{511}-\alpha_x T_{512}+\gamma_x T_{522}$$

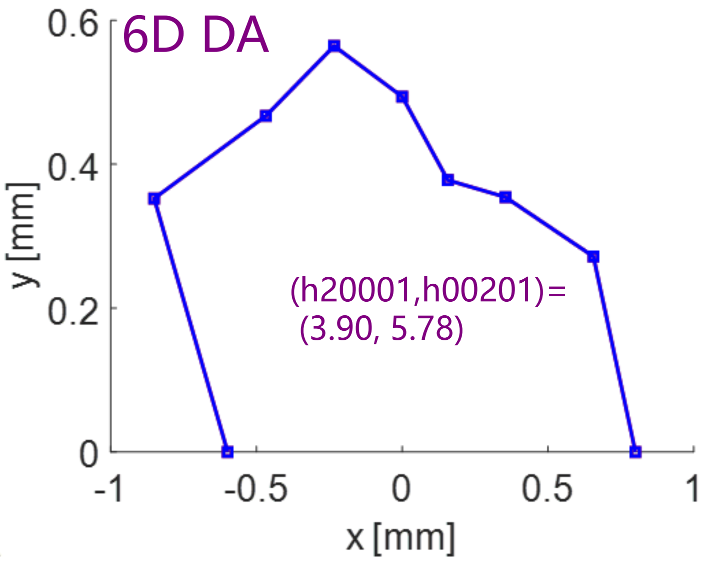
$$h_{20001}=\sqrt{\beta_x^2T_{511}^2+\beta_x\gamma_x T_{512}^2+\gamma_x^2T_{522}^2-2\alpha_x(\beta_x T_{511}+\gamma_x T_{522})T_{512}+2(\alpha_x^2-1)T_{511}T_{522}}.$$

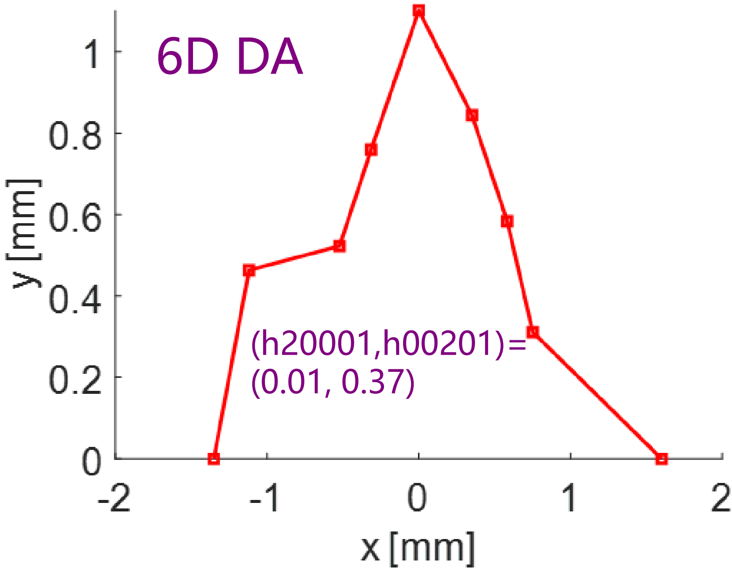
Nonlinear dynamics optimization

- **According to J. Bengtsson's formula, we have no knobs to control the h20001 and h00201 if sextupoles are all used periodically.**
- **We can break the period by the layout below**



By adjust k1 and k2, we can optimize (h20001,h00201) from (3.90, 5.78) to (0.01, 0.37)





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Summary

- We have done the analysis for partial alpha effects in low alpha ring, and proposed a method to minimize it.
- Based on the analysis, the linear lattice is designed, bunch length under 100 nm can be hold in the ring.
- We have done some preliminary studies on the nonlinear optimization for this kind of storage ring, the 6-D DA will be limited by T-L coupling, which has been optimized by specialized sextupole scheme.

Thanks for your attention!
Comments are appreciated!