中国科学院高能物理研究所
Institute of High Energy Physics
Chinese Academy of Sciences

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Intra-beam Scattering Study for Low Emittance of BAPS

S.K. Tian, J.Q. Wang, G. Xu, Y. Jiao (IHEP)

Outline

- Intra-beam scattering theory
- BAPS machine parameters(a temporary design lattice)
- Recent BAPS IBS calculations
- Conclusions

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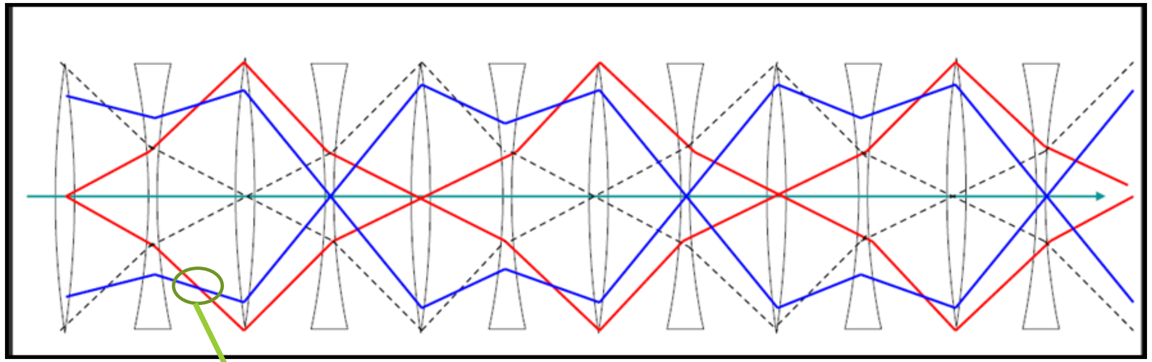
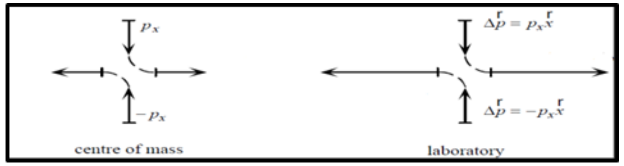
Intra-Beam Scattering

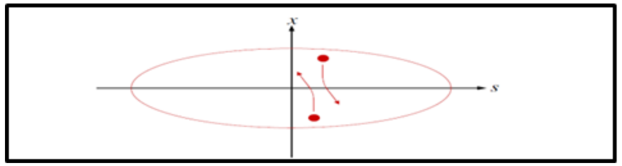
Particles in a circulating bunch execute transverse betatron oscillations, the transverse velocities are statistically distributed, these particles can be scattered by collisions so transferring transverse momenta into longitudinal momenta, In general, one should distinguish between:

Large-angle Single Scattering ---TOUSCHEK EFFECT---Lift Time

Multiple Small-Angle Scattering---INTRA-BEAM SCATTERING---Rise Time ☑







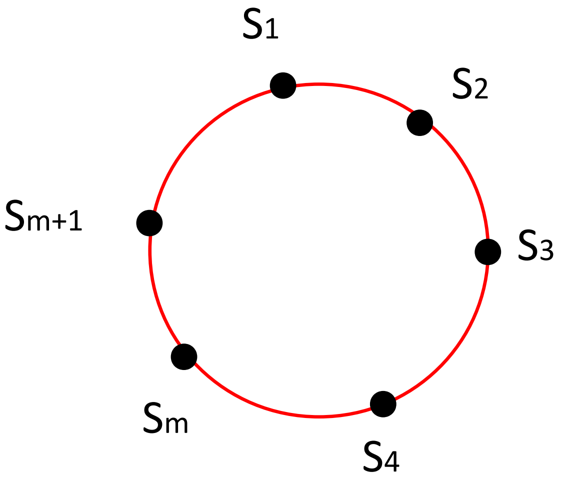
$$collision \Rightarrow \delta(x, xp, y, yp, z, \Delta p) \Rightarrow \delta\varepsilon_k(j) \Rightarrow \delta\tilde{\varepsilon}_k = \frac{1}{2N}\sum_{j=1}^{N}\delta\varepsilon_k(j)$$

Conventional Theory of IBS

Bjorken-Mtingwa derive T_i by the formula:

$$\frac{1}{T_p} \equiv \frac{1}{\sigma_p}\frac{d\sigma_p}{dt};\ \frac{1}{T_v} \equiv \frac{1}{\varepsilon_v^{1/2}}\frac{d\varepsilon_v^{1/2}}{dt};\ \frac{1}{T_h} \equiv \frac{1}{\varepsilon_h^{1/2}}\frac{d\varepsilon_h^{1/2}}{dt}$$

$$\frac{1}{T_i} = 4\pi A(\log)\left\langle \int_0^\infty d\lambda \frac{\lambda^{1/2}}{[\det(L+\lambda I)]^{1/2}} \times \left\{ TrL^i Tr\left(\frac{1}{L+\lambda I}\right) - 3Tr\left[L^i\left(\frac{1}{L+\lambda I}\right)\right]\right\}\right\rangle$$



$$\log = \ln\frac{b_{\min}}{b_{\max}} = \ln\frac{2}{\theta_{\min}}$$ Coulomb log factor

$$A = \frac{r_0^2 cN}{64\pi^2\beta^3\gamma^4\varepsilon_h\varepsilon_v\sigma_s\sigma_p}$$

$$\frac{1}{T_i} = \sum_{m=1}^{M}\frac{S_{m+1}-S_m}{C}\frac{1}{T_i^m};$$

$$S_{M+1} = C, S_1 = 0$$

$$S : elements(drift, quadrupole, bend - magnet...)$$

<……> indicates that the integral is to be averaged around the accelerator lattice

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Ultimate Storage Rings (USR)

Diffraction limited operation at 1 Å

$$\varepsilon < \frac{\lambda}{4\pi}$$

↓

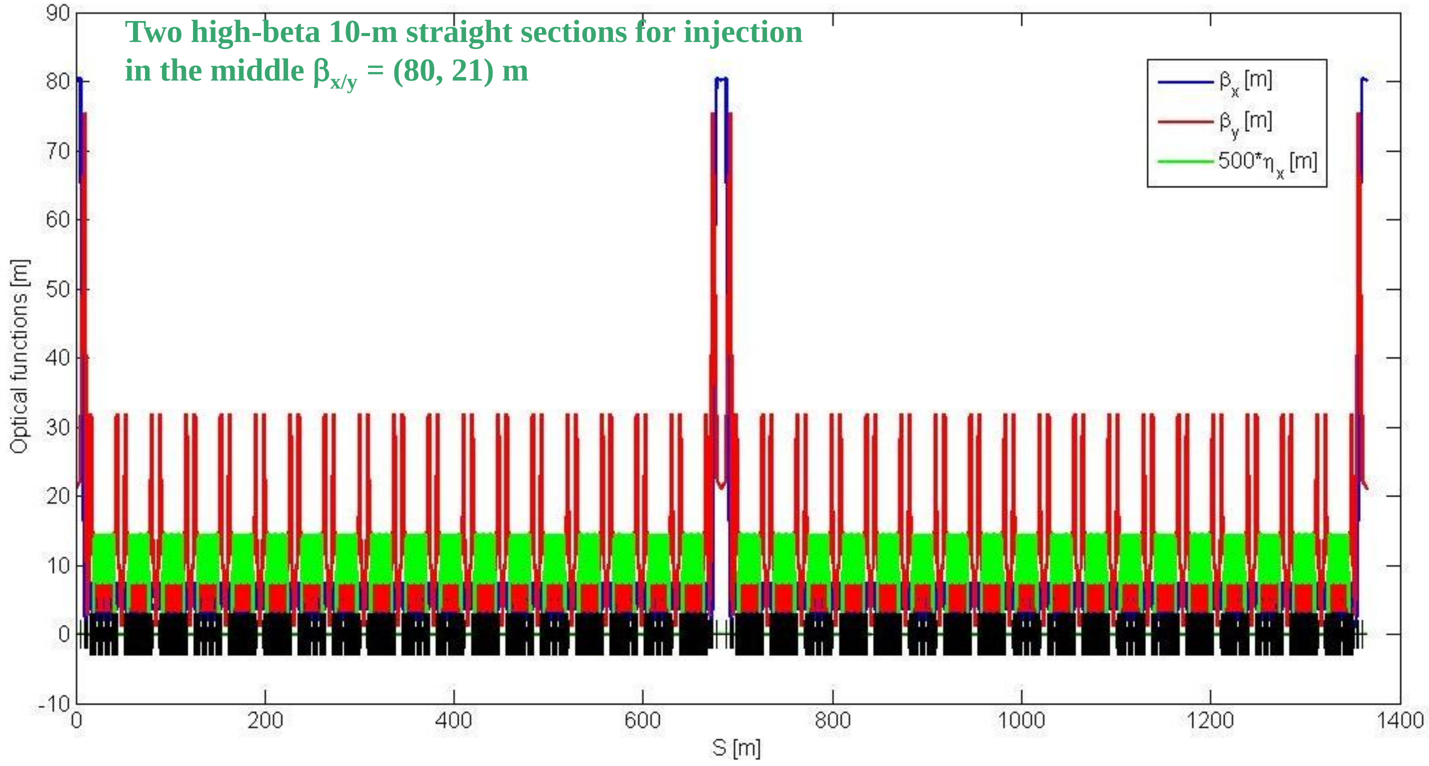
Both transverse planes emittance ~10 pm

For BAPS, we firstly obtain the total emittance about 20pm locally-round beam method→$\varepsilon_x = \varepsilon_y \approx 10pm$

Basic Parameters of BAPS (Bare Lattice)

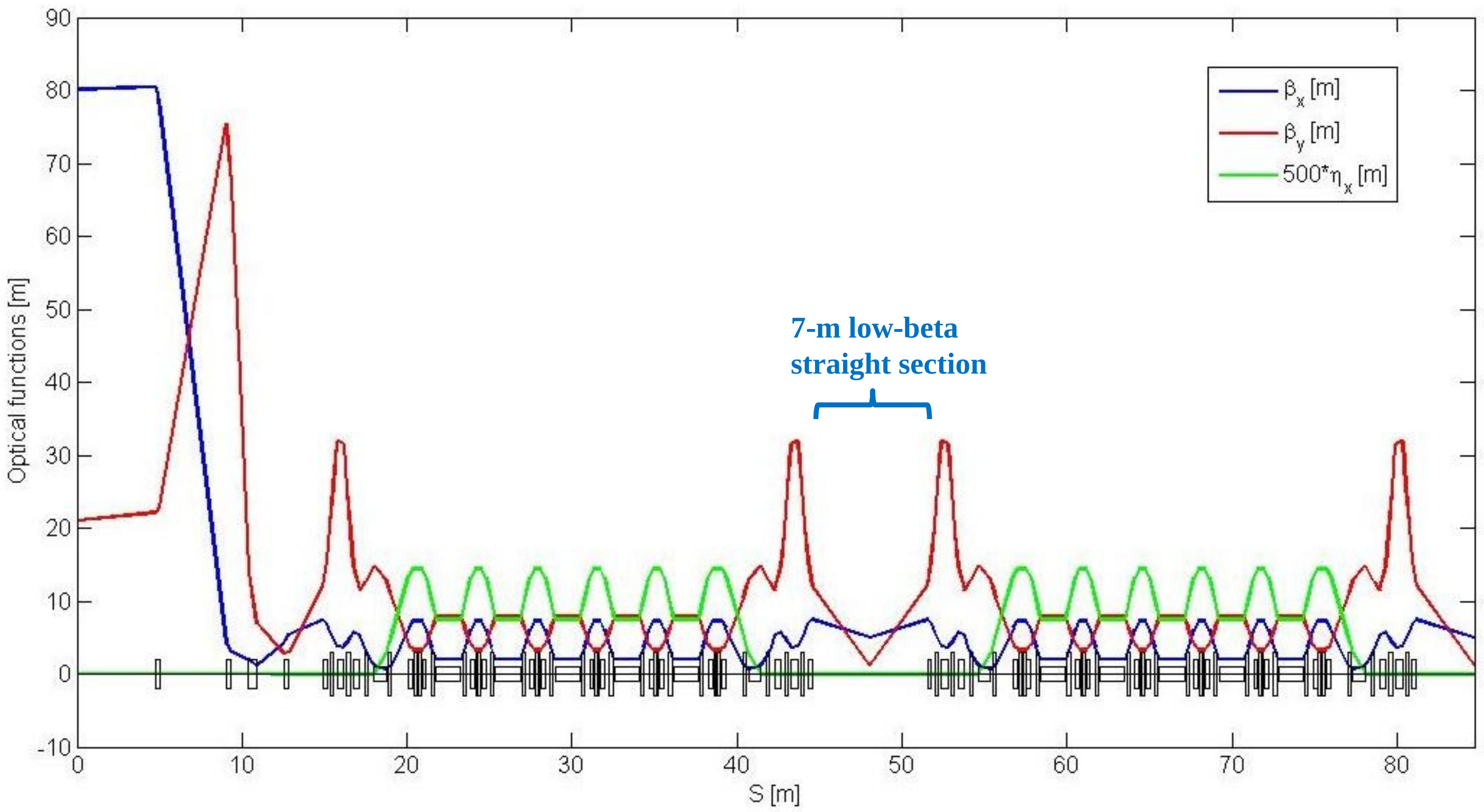
Parameter	Symbol, unit	Value
Energy	E，GeV	5
Circumference	C，m	1366.4
Current	I_0，mA	100
Bunch number	n_b	1836
Number of particles per bunch	N_b	1.55×10^{9}
Natural bunch length	σ_{l0}，mm	1.2
RF frequency	f_{rf}，MHz	500
RF voltage	V_{rf} MV	9
Harmonic number	h	2279
Natural energy spread	σ_{e0}	7×10^{-4}
Momentum Compaction	α_p	4×10^{-5}
Emittance of bare lattice	ε_x pm	51
Energy loss per turn	U_0，MeV	1.07

7BA*36 Linear Optics



Circumference: 1366.4 m, 2 superperiods, 36 supercells
Working point: 111.39, 39.30
Natural chromaticity: -184, -181
Natural emittance: 51 pm.rad --------------Y. Jiao

Lattice Layout in One Superperiod



High-beta 10-m Straight section , $\beta_{x/y}$ = (80, 21) m
Low-beta 7-m Straight section , $\beta_{x/y}$ = (5,1.11) m

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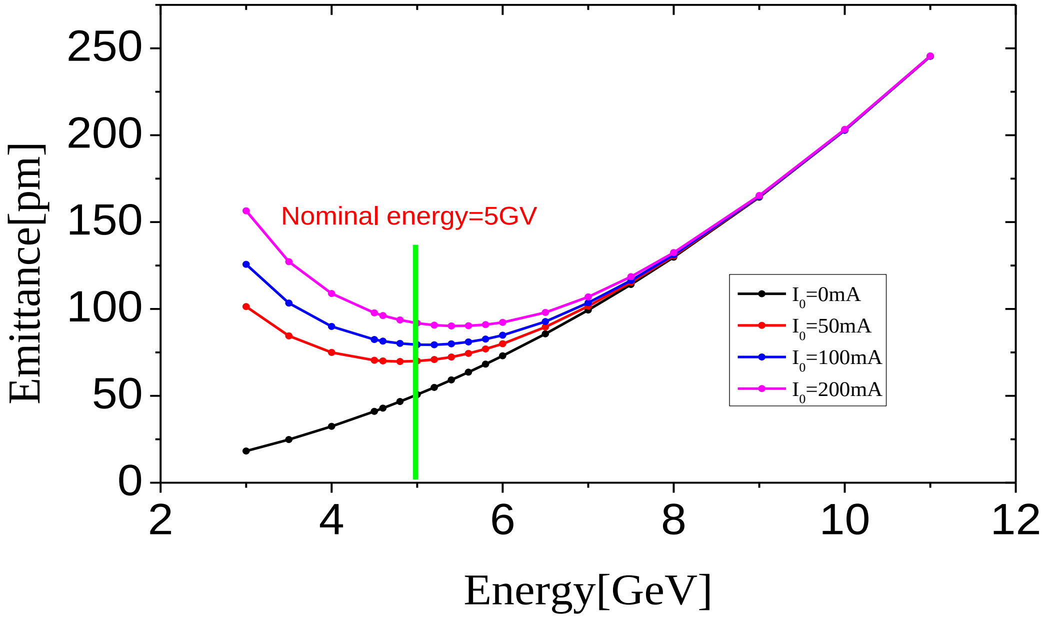
Impact of Energy

$$\varepsilon_{x0} = C_q \frac{\gamma^2 \langle H \rangle}{J_x \rho} \qquad \Rightarrow \gamma \uparrow \Rightarrow \varepsilon_o \uparrow$$

$$\frac{1}{T_i} \propto A = \frac{r_0^2 cN}{64\pi^2 \beta^3 \gamma^4 \varepsilon_h \varepsilon_v \sigma_s \sigma_p} \qquad \Rightarrow \gamma \uparrow \Rightarrow \frac{1}{T_i} \downarrow$$

the optimal energy for our lattice?



Emittance vs. energy for different currents

Conditions for calculation：
Bunch length=constant
Coupling factor=0.01

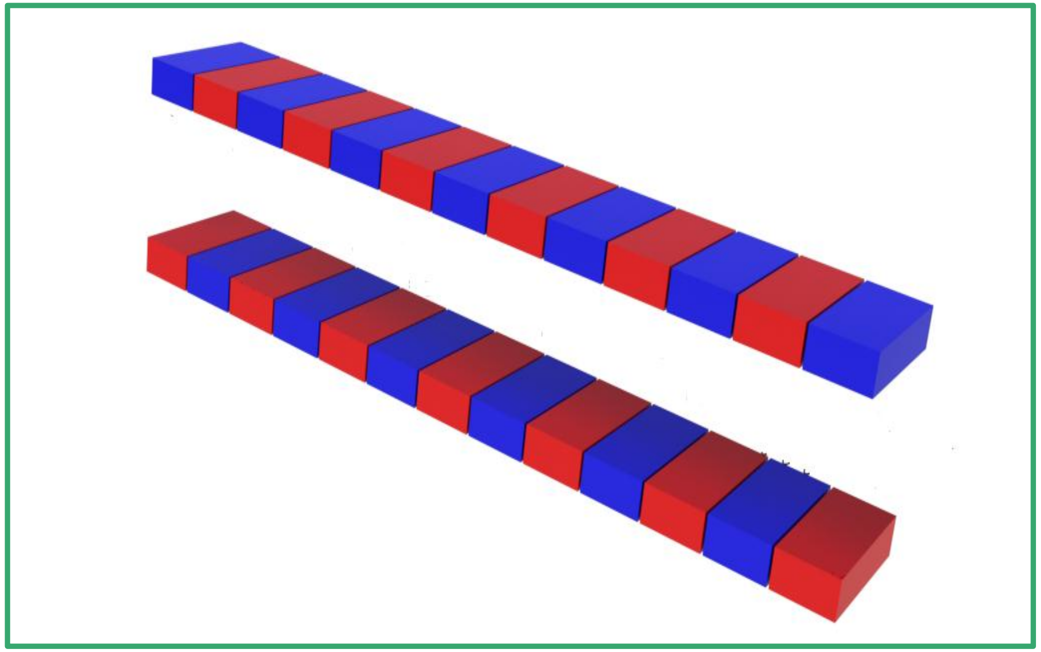
Other cases：
Over Voltage Factore V_{RF}/U_0=constant
RF voltage V_{RF}=constant

The emittance minimum is near the nominal energy in any case！

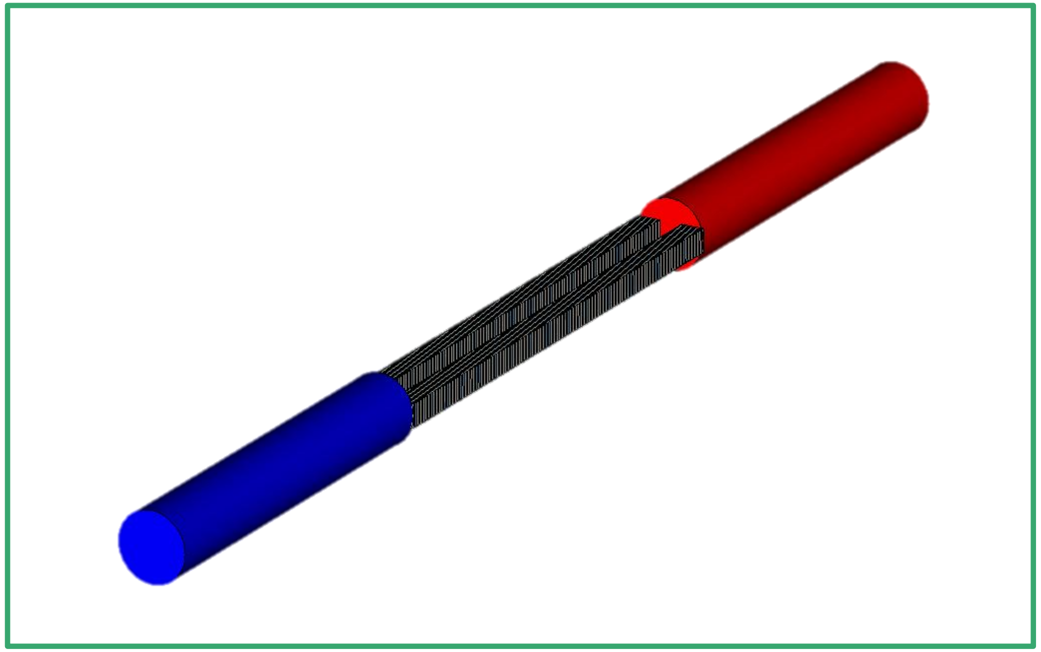
Impact of Initial (Input) Emittance

Optimized Radiation Integral → Decrease The Nature Emittance

Phase Space Manipulations →Change The Vertical and The Horizontal Emittance



Damping Wiggler



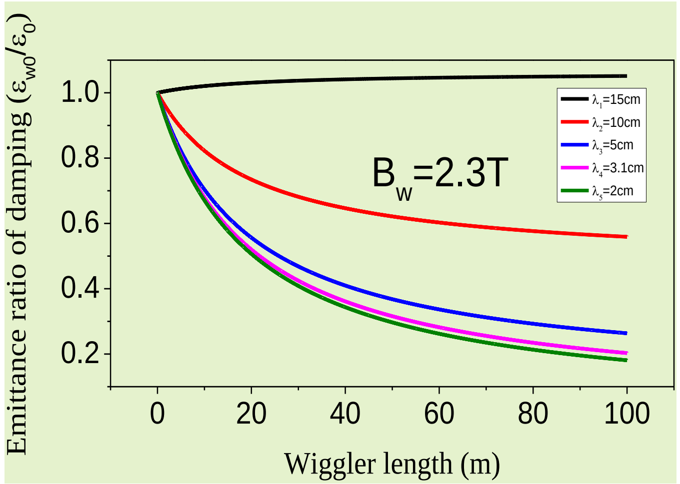
Round Beam with Solenoid Field (at Special Straights)

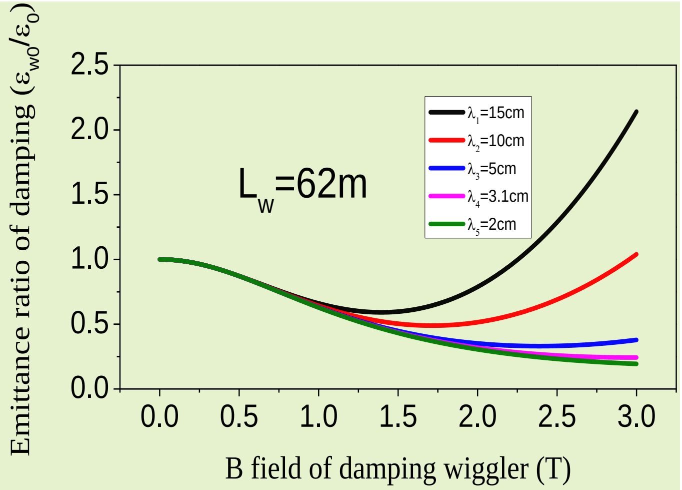
Damping Wiggler

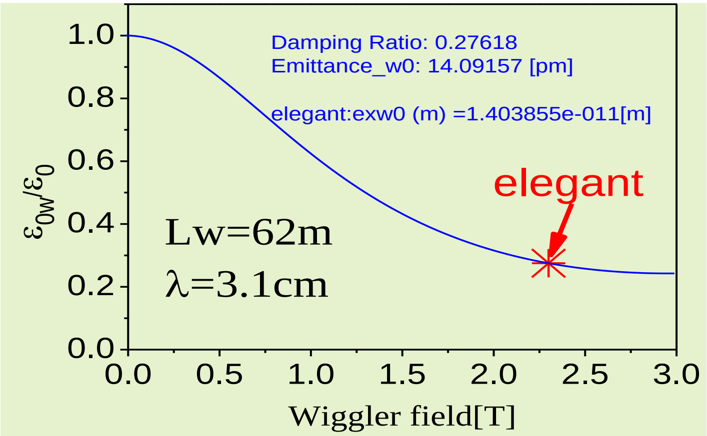
$$\frac{\varepsilon_{w0}}{\varepsilon_0} = \left(\frac{J_x}{J_{xw}}\right) \frac{1 + \frac{4C_q}{15\pi J_x} N_w \frac{\langle \beta_x \rangle}{\varepsilon_0 \rho_w} \gamma^2 \frac{\rho_0}{\rho_w} \theta_w^3}{1 + \frac{1}{2} N_w \frac{\rho_0}{\rho_w} \theta_w}$$

$$\theta_w = \lambda_w / 2\pi\rho_w$$
$$L_w = N_w \lambda_w$$

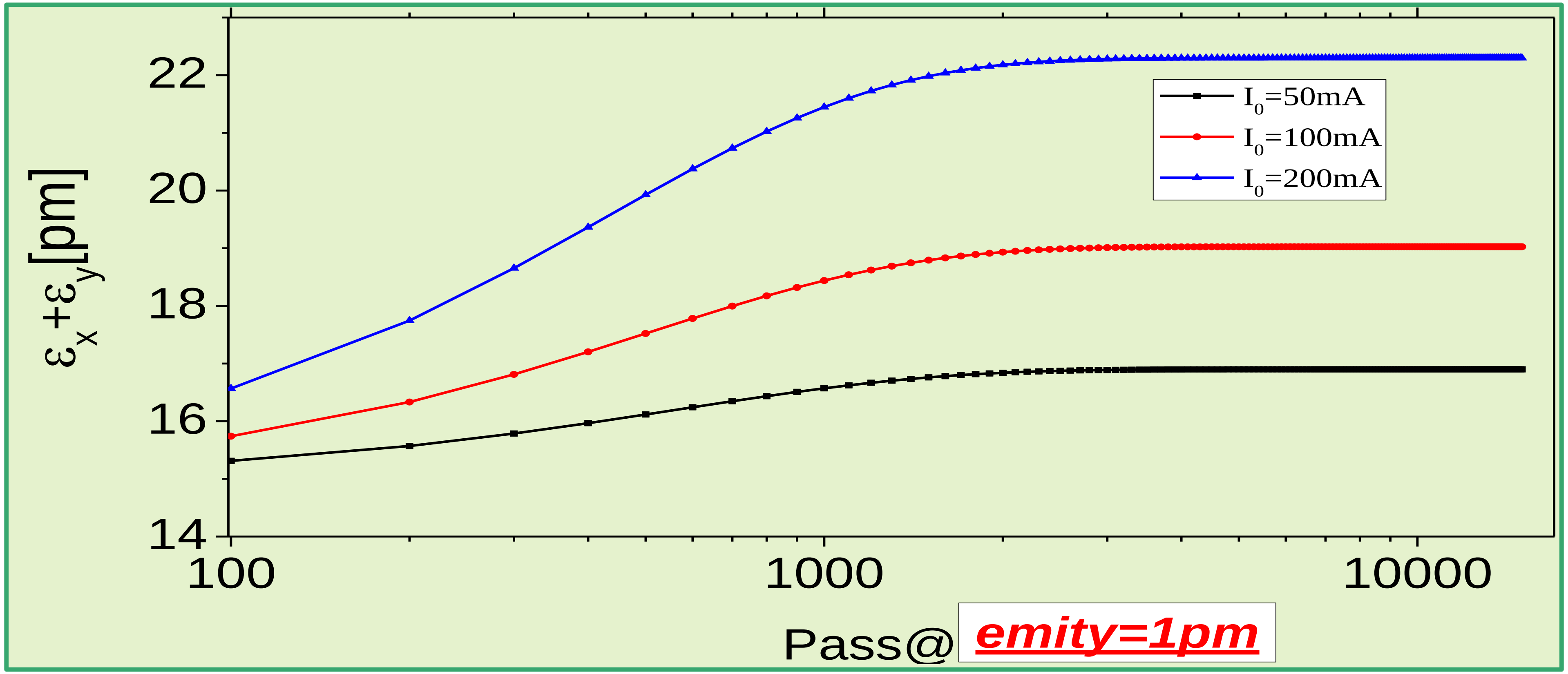
The emittance reduction depends on the wiggler period length, the wiggler peak field, and the total wiggler length.







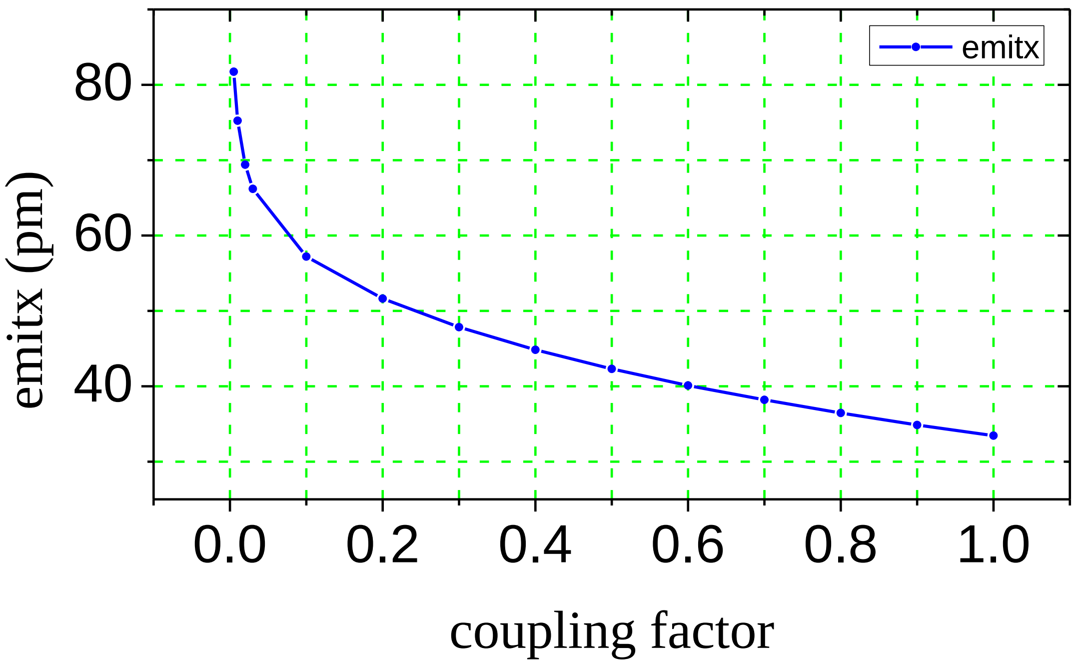
Relative emittance reduction vs. wiggler length (left) and vs. wiggler field (middle) for different wiggler period.



Steady-state emittances for different bunch current in BAPS with long damping wigglers

Damping wiggler parameters: $\mathbf{B_w}$=2.3T, $\boldsymbol{\lambda_w}$=3.1cm, $\mathbf{L_w}$=62m

Impact of Coupling Factor

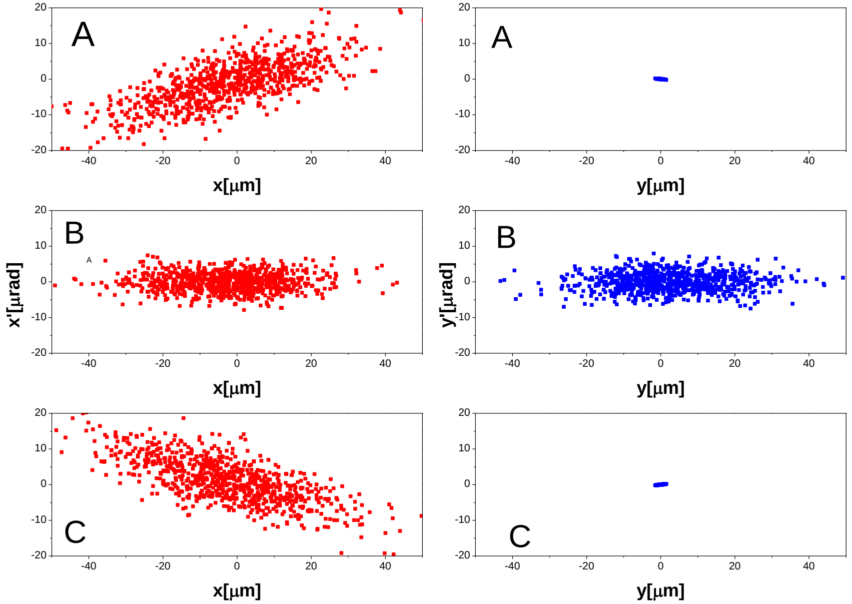


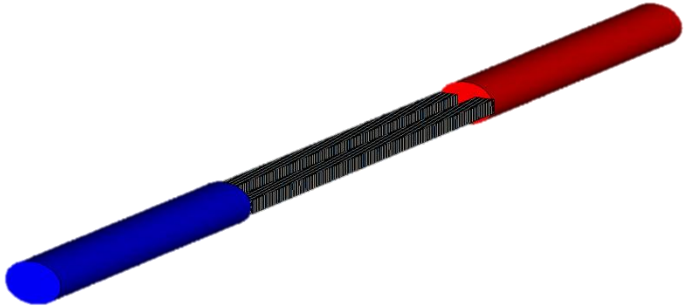
$$\frac{1}{T_i} \propto A = \frac{r_0^2 c N}{64\pi^2 \beta^3 \gamma^4 \varepsilon_h \varepsilon_v \sigma_s \sigma_p}$$

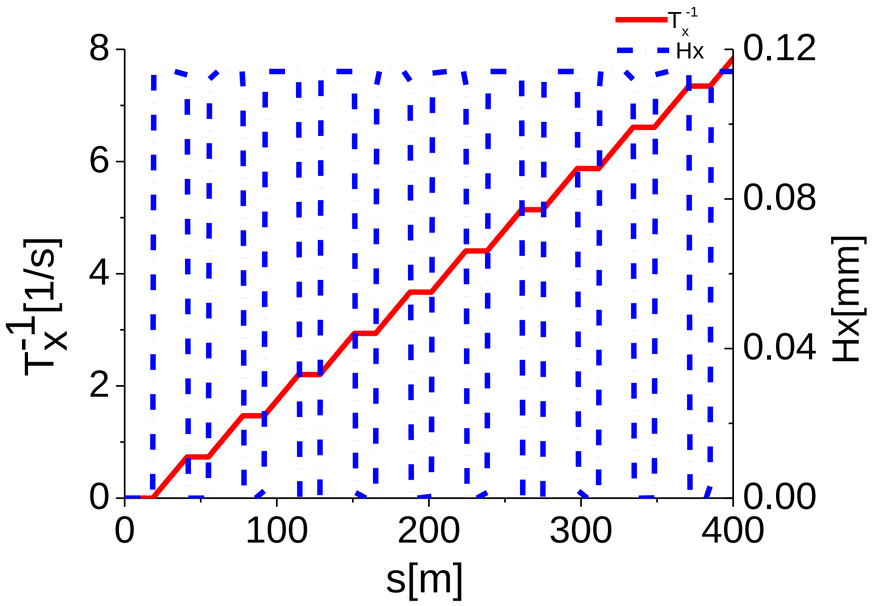
For simplicity and for the purpose of IBS calculations, we assume that the vertical emittance is primarily generated by the coupling, and the effects of the vertical dispersion can be ignored.

$$\kappa = \varepsilon_y / \varepsilon_x \qquad \varepsilon_{nat} = \varepsilon_x + \varepsilon_y$$

$$\varepsilon_x = \frac{1}{1+\kappa}\varepsilon_{nat} \quad \varepsilon_y = \frac{\kappa}{1+\kappa}\varepsilon_{nat}$$







By G. Xu, Y. Jiao

locally-round beam has no effect on control the IBS effect. The solenoid-ID-anti-solenoid section in a long straight section a dispersion-free region the dispersion invariant $\mathcal{H}$ is zero.

Impact of Bunch Length

$$A = \frac{r_0^2 c N}{64\pi^2 \beta^3 \gamma^4 \varepsilon_h \varepsilon_v \sigma_s \sigma_p}$$

Bunch Lengthening

↓

Decrease of Charge Density

↓

Decrease of Growth Rate

From storage ring longitudinal beam dynamics theory $\sigma * \Omega = \alpha_p * \sigma_p = constant$

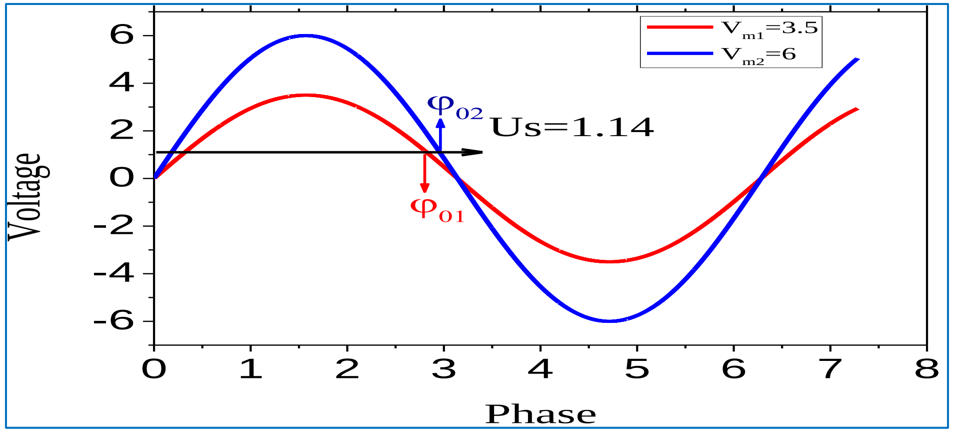
Where $\Omega^2 = \frac{\alpha e \dot{V}_0}{T_0 E_0}$ Synchrotron Frequency

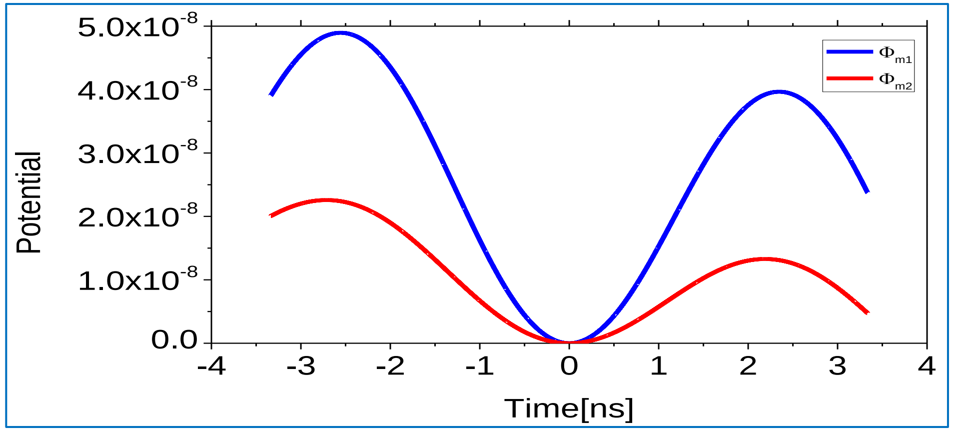
We can control on the longitudinal bunch size by changing the voltage slope seen by the bunch.

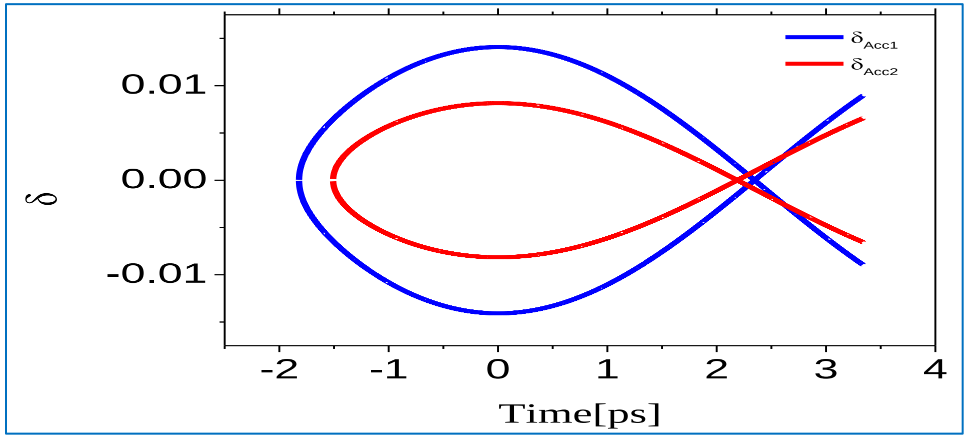
- Lowering the peak accelerating voltage
  reduce the bucket height
  decrease of beam lifetime

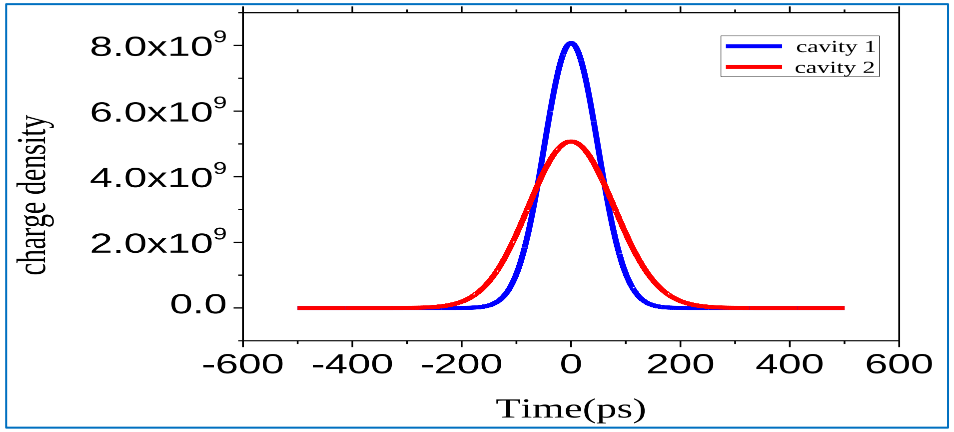
- Adding a harmonic cavity

Voltage and RF Acceptance









Double RF System(Landau Cavity)

$$V(t) = V_{RF}[\sin(\omega_{RF}t + \phi_s) + k\sin(n\omega_{RF}t + n\phi_h)]$$

$$V(0) = \frac{U_s}{e} = V_s$$

$$\frac{\partial V}{\partial t}\Big|_{t=0} = 0$$

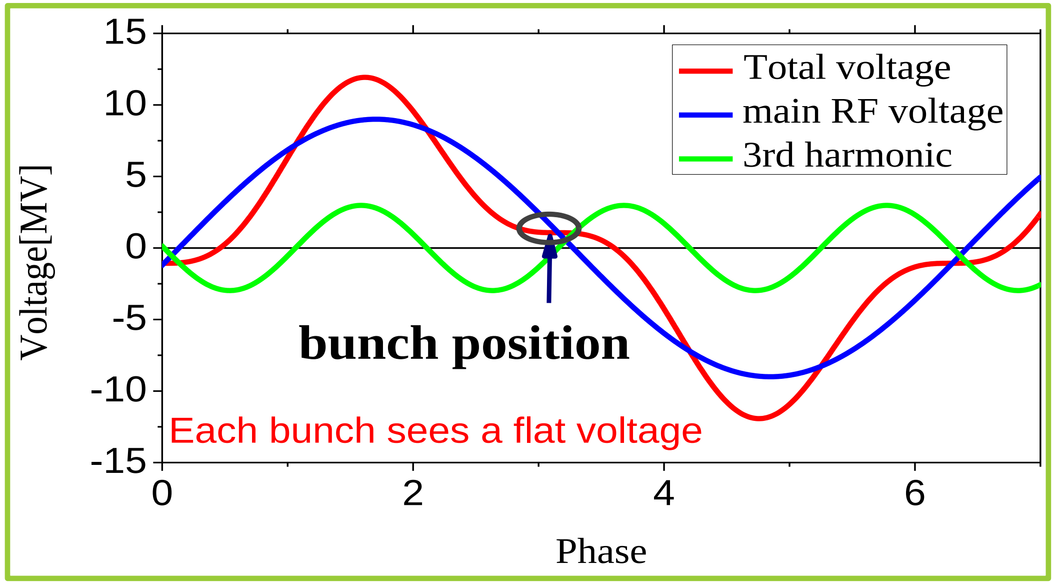
$$\frac{\partial^2 V}{\partial t^2}\Big|_{t=0} = 0$$

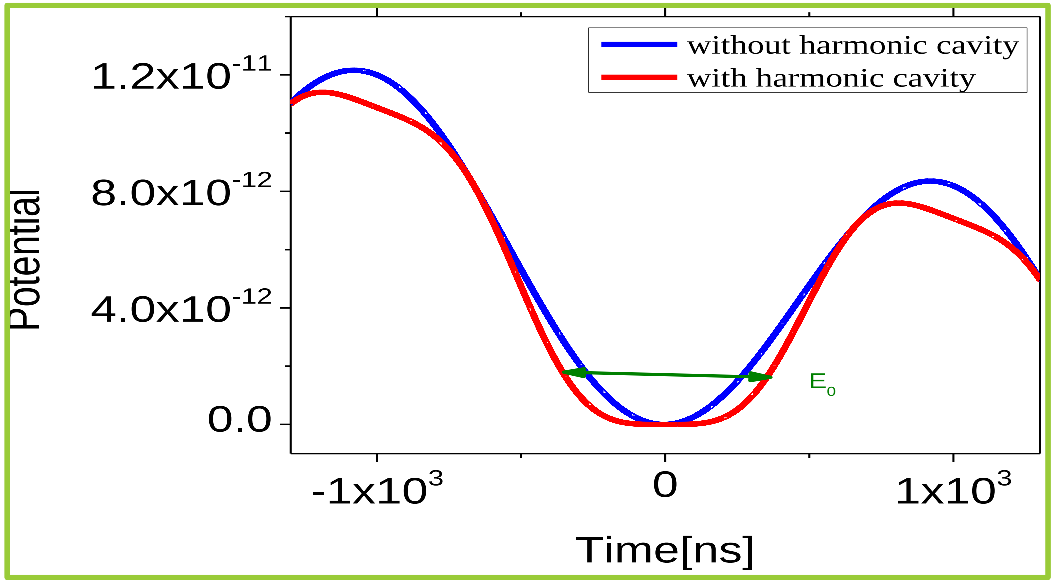
$$k = \sqrt{\frac{1}{n^2} - \frac{(U_0/V_{RF})}{n^2 - 1}}$$

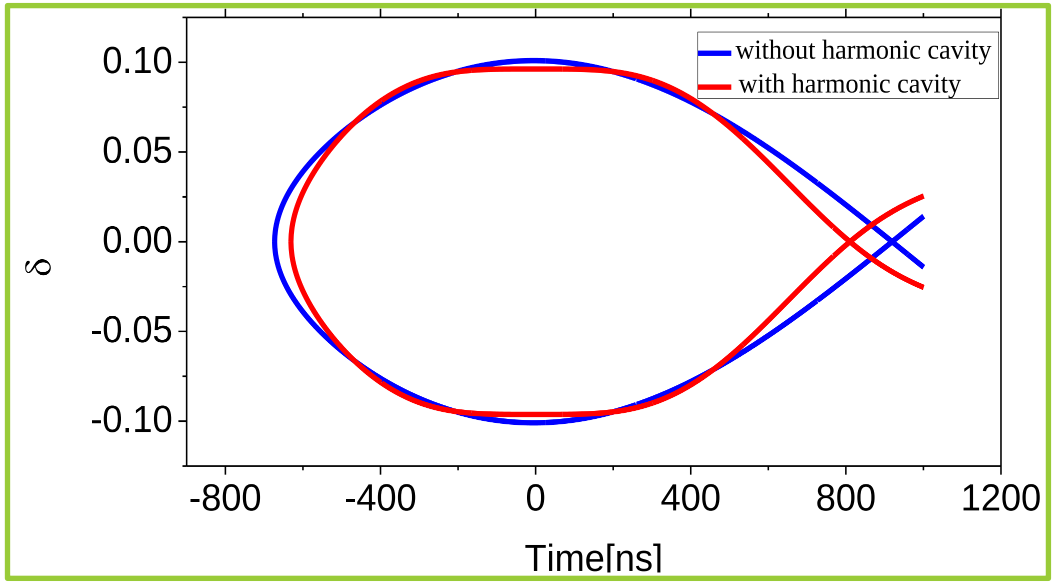
$$\phi_h = \frac{1}{n}\arctan(\frac{1}{n}\tan(\phi_s))$$

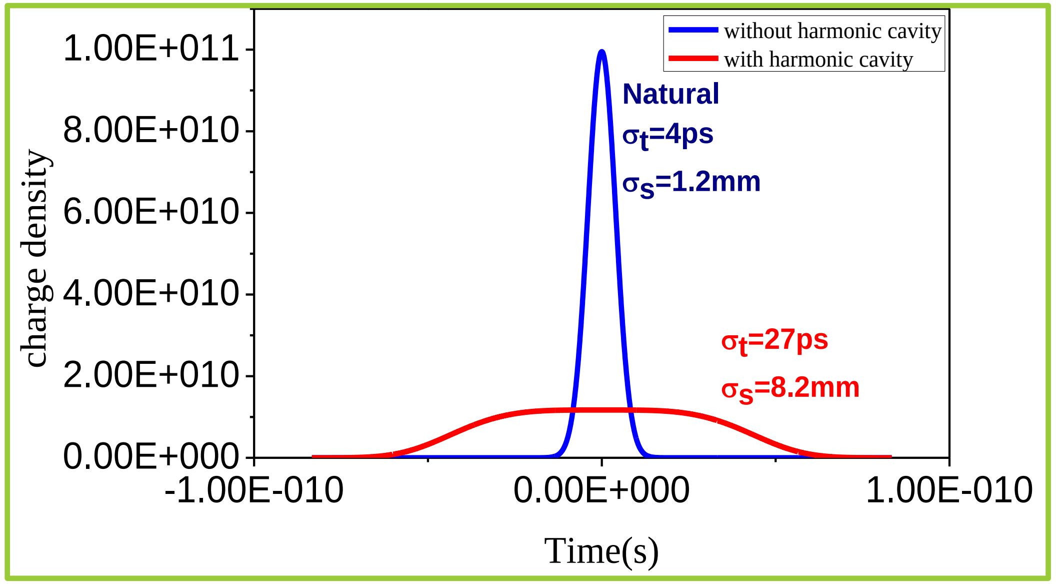
$$\sin\phi_s = \frac{n^2}{n^2 - 1}\frac{U_0}{V_{RF}}$$

- ◆The voltage gain per turn of the synchronous particle is equal to the total loss per turn
- ◆The first derivative of voltage should vanish at the center of the bunch
- ◆The second derivative of voltage should vanish in order to avoid having a second region of phase stability close by


Total voltage
main RF voltage
3rd harmonic
Voltage[MV]
15
10
5
0
-5
-10
-15
0
2
4
6
Phase
bunch position
Each bunch sees a flat voltage


without harmonic cavity
with harmonic cavity
Potential
$1.2x10^{-11}$
$8.0x10^{-12}$
$4.0x10^{-12}$
0.0
E_o
$-1x10^3$
0
$1x10^3$
Time[ns]

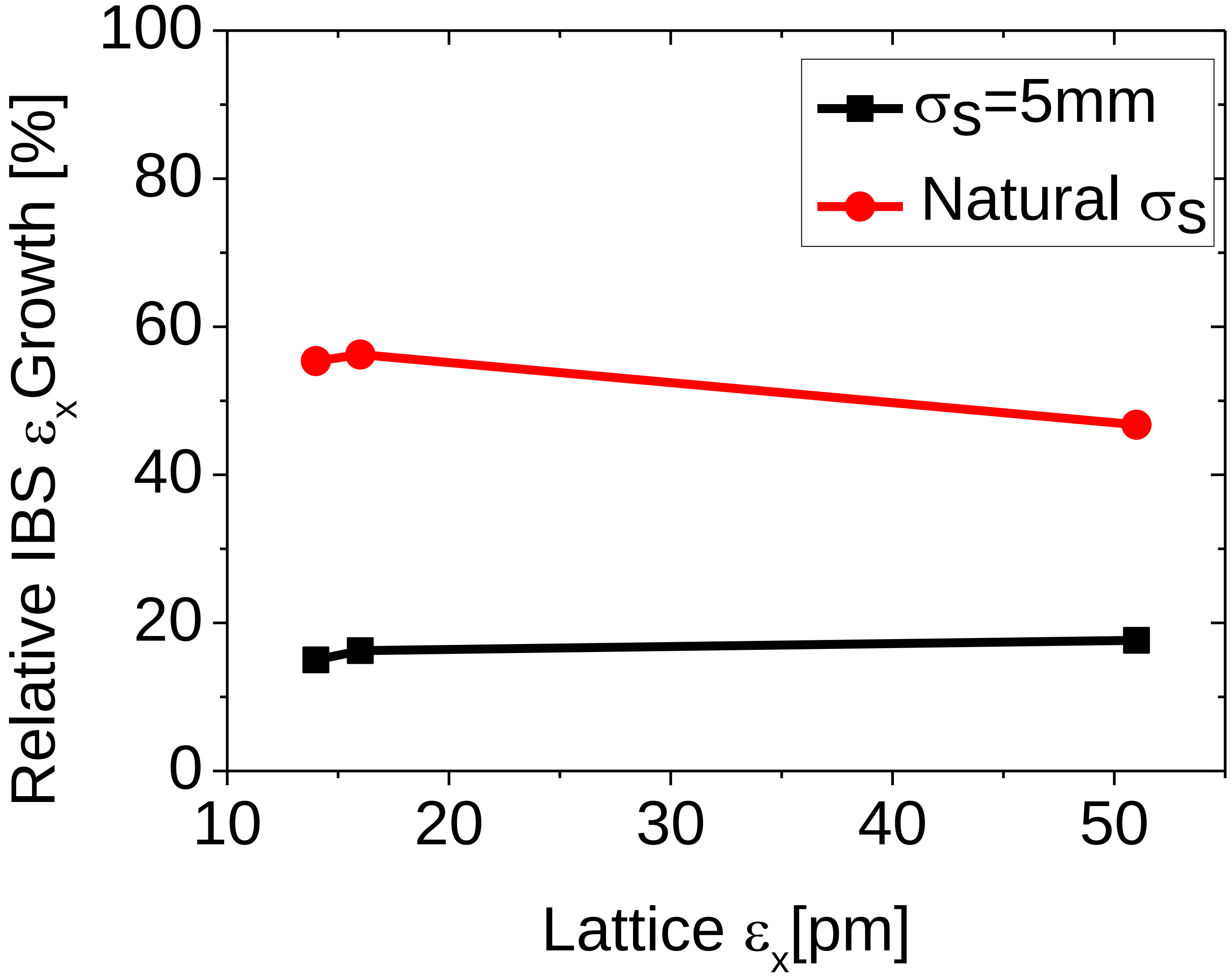

without harmonic cavity
with harmonic cavity
δ
0.10
0.05
0.00
-0.05
-0.10
-800
-400
0
400
800
1200
Time[ns]


without harmonic cavity
with harmonic cavity
charge density
1.00E+011
8.00E+010
6.00E+010
4.00E+010
2.00E+010
0.00E+000
Natural
σ_t=4ps
σ_s=1.2mm
σ_t=27ps
σ_s=8.2mm
-1.00E-010
0.00E+000
1.00E-010
Time(s)

Equilibrium Values for Emittance

	$\varepsilon_x + \varepsilon_y$	$\varepsilon_x + \varepsilon_y$
Bare Lattice	51+1	75+1.47
Bare Lattice with LC	51+1	60+1.18
Lattice with DW(62) and LC	14+1	16.1+1.14
Lattice with DW(49.6) and LC	16+1	18.6+1.15

Equilibrium values for the emittances calculated with (right) and without (left) IBS



Without bunch lengthening, emittance growth from IBS is significantly larger and becomes even stronger for ultra-low emittance configurations.

Conclusions

Intra-beam scattering is an effect which becomes important in future low emittance ring-base light sources and becomes a limiting factor for reaching ultimate storage ring.

Introduce Harmonic Cavity to lengthen the bunch to further reduce the effect of intra-beam scattering.

Round beams could help to control the IBS effect, we need new efficient and robust solutions to obtain round beams in electron storage rings

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Thank you！