INTRABEAM SCATTERING STUDIES FOR LOW EMITTANCE OF BAPS

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Abstract

In modern storage ring light sources, intra-beam scattering (IBS) is often thought of as a fundamental limitation to achieving ultra-low emittance and hence higher brightness. Beijing Advanced Photon Source (BAPS) is under designing dedicated to good coherence and high brightness at 5GeV, low emittance is required to reach the design request. Due to the low emittance, intra-beam scattering effect will be very strong. Accurately calculating to check if the design goal can be reached is necessary. In this paper we present the results of particle simulation study of intra-beam scattering effect on a temporary design lattice of BAPS

INTRODUCTION

Several example designs（PEP-X, Spring-8 upgrade）of ultimate storage rings (USR), with equal transverse emittances at diffraction limit for X-rays, have been done. One possible solution for Beijing Advanced Photon Source (BAPS) is designed to achieve the diffraction-limited emittances of 10 pm-rad in both horizontal and vertical planes, which is required by the ultimate storage ring. The total emittance, about 20pm, is firstly obtained, and thus round bean, ($\varepsilon_x = \varepsilon_y \approx 10pm$), can be given by the locally-round beam method [1].

Table 1: Main parameters for the BAPS storage ring

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

Intra-beam scattering which has implications on the smallest achievable emittances is one of the fundamental limitations in achieving ultrasmall emittances in storage rings. It leads to growth in emittance and energy spread in electron machines, its effect depends on the lattice and beam characteristics.

GENERAL IBS THEORY

Several theories and their approximations were developed over the years describing the effect, The Bjorken-Mtingwa formulation [2] is regarded as being the most general solution. For bunched beams, the growth rates for intra-beam scattering can be expressed as

$$\frac{1}{T_i} = 4\pi A(\log)\langle F\rangle \tag{1}$$

where T_i is the growth times, i represents p,h,v for the relative energy spread and horizontal and vertical emittances respectively, F is an integral expression .The angle brackets$< \cdots >$ indicates that the integral is to be averaged around the ring lattice, and

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

where N is the number of particles per bunch,r_0 is the classical radius of the charged particle,c is the speed of light in vacuum,β is the velocity divided by the speed of light,γ is the particle energy divided by the rest mass,$\varepsilon_{h,v}$is the emittance,$\sigma_s$is the rms bunch length, $\sigma_p$is the relative energy spread.

From the expression of A, it follows that the IBS effects depends on the beam energy, energy spread, bunch length and emittances, we can change these parameters to decrease its effect.

IBS DEPENDENCE ON BAPS PARAMETERS

Influence of Initial Emittance

All IBS models provide the same trend in the emittance evolution. In principle, any of them could be used to study the dependence of the output emittances on the different other beam parameters.

In low emittance machines such as BAPS, the IBS effect is determined by the initial emittance. In what follows, we will study the IBS dependence on zero current emittance.

Two ways of changing the emittance at zero current are considered: changing the coupling factor and adding damping wigglers.

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Coupling Factor

In general, there are four principal contributions to the vertical emittance of an electron beam in a storage ring [3]: a ''direct'' contribution, the vertical opening angle of the radiation, vertical dispersion, and betatron coupling. The direct contribution comes from the fact that two particles moving with zero transverse momentum, after collision, have some nonzero horizontal and vertical momentum. Thus transverse emittance growth will be increased, even where the horizontal and vertical dispersion are both exactly zero. The direct contribution is a small effect and we ignore it for now.

Also, the contribution from the vertical opening angle of the radiation is always small compared to the contributions from other sources for high energy beams.

The vertical dispersion in BAPS ideal design lattice is zero, but magnet misalignments will lead to vertical dispersion in real storage ring. For simplicity, we treat the vertical emittance as generated mainly by the transverse coupling, the contribution of vertical dispersion is ignored .Then the vertical emittance is proportional to the horizontal emittance, and it can be written as

$$\varepsilon_x = \frac{1}{1+\kappa}\varepsilon_{nat} \quad \varepsilon_y = \frac{\kappa}{1+\kappa}\varepsilon_{nat} \tag{3}$$

With κ being the coupling constant between 0 and 1 and $\varepsilon_{nau} = \varepsilon_x + \varepsilon_y$ being the nature emittance at zero current.

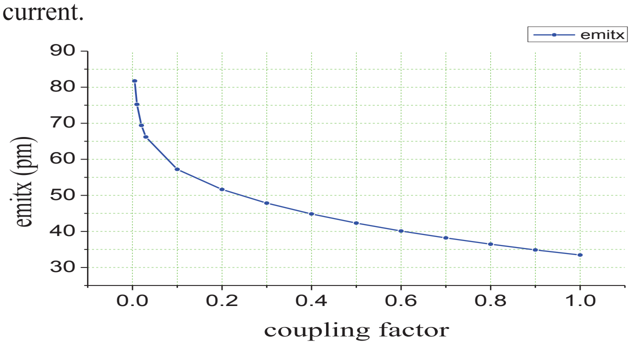

Figure 1: Steady-state horizontal emittance vs. coupling factor @I=100mA

From the picture we can see the steady-state emittance achieves the minimum value when coupling factor equal one, but we can't keep the coupling factor equal one in electron storage rings nowadays, we need new innovate solutions.

Damping Wiggler

For a modern light source design the damping wigglers play an important part in reducing the emittance. It is an efficient way comparing to the other method.

The relative reduction in natural emittance from ε_0 to ε_{0w} caused by a damping wiggler in the dispersion free straight can be estimated using an approximate analytical expression [4]

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

where C_q = 3.81×10−13m, J_{xw}, J_{xw} are damping partition numbers with and without wigglers, N_w is the number of wiggler periods, $<\beta_x>$ is the average horizontal beta function in the wiggler, ρ_w is the bending radius at peak wiggler field, $\theta_w = \lambda_w/2\pi\rho_w$ is the peak trajectory angle in the wiggler and λ_w is the wiggler period length, ρ_0 is the bending radius of the ring dipole.

Eq.4 shows the emittance reduction depends on the wiggler period length, the wiggler peak field, and the total wiggler length.

Fig.3 shows the ratio of $\varepsilon_{0w}/\varepsilon_0$ versus the wiggler peak field and the total wiggler length for various values of wiggler period length, where the wiggler is inserted in long straight sections with $<\beta_x>$=5.82.

From the figures, we can see that most of the damping ratio occurs within 70 m of the wiggler length, and that a wiggler period below 3.1cm does not significantly improve the damping ratio. Selecting a 62-m long wiggler with a 3.1-cm period, it follows that the optimal peak field is about 2.3 T.

For our IBS calculations, we assume the initial vertical emittance equal 1pm [5], the new vertical emittance record established in the storage ring of the Swiss Light Source (SLS).

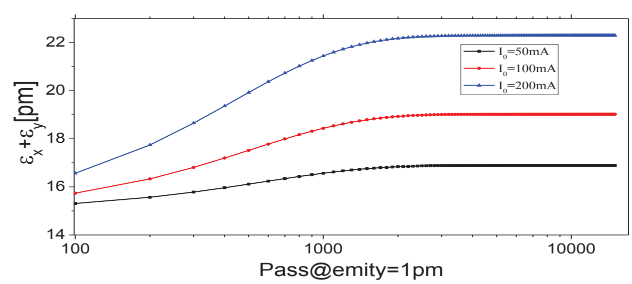

Figure 2: Steady-state emittances for different bunch current in BAPS with long damping wigglers

The resultant emittance with wigglers at zero current is 14pm. The steady-state total emittances have been calculated for different currents, it shows that we can achieve the goal when the current is about 100mA.

Influence of Bunch Length

From the formula (1) and (2), we can see the bunch length σ_s is inversely proportional to the IBS growth rate. In order to decrease the IBS growth rate, we can lengthen the electron bunches.

Bunch lengthening can be achieved by reducing the slope of the accelerating voltage in the vicinity of the electron bunch. Adding a harmonic cavity, sometime known as Landau cavity [6], is a good method.

Once the harmonic Landau cavities and damping wigglers are added, the influence of IBS becomes small.

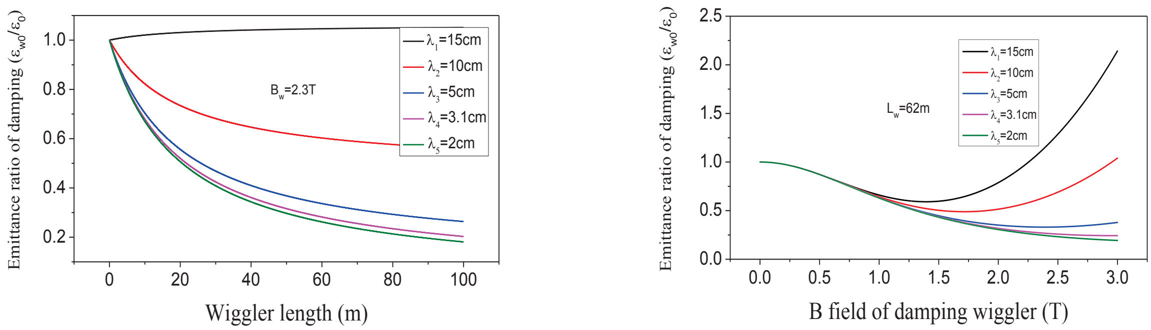

Figure 3: Relative emittance reduction vs. wiggler length (left) and vs. wiggler field (right) for different wiggler period.

In the case of a storage ring with damping wigglers (Lw =49.6m), and Landau cavities ($\sigma_s = 5mm$) the equilibrium emittance ($I_0 = 100mA$) including IBS remains well below

Table 2: Equilibrium values for the horizontal emittance calculated with (right) and without (left) IBS

	$\varepsilon_x + \varepsilon_y$(nm)	$\varepsilon_x + \varepsilon_y$(nm)
Bare Lattice	51+1	75+1.47
Lattice with DWs	16+1	25.5+1.5
Lattice with DWs and LC	16+1	18.6+1.15

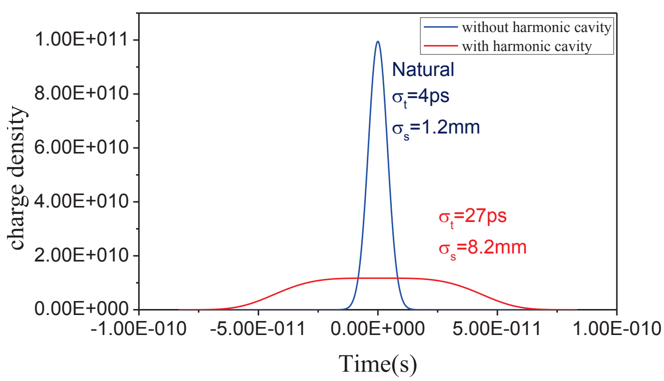

Figure 4: Longitudinal bunch distribution for single and third harmonic system at optimum condition

Influence of Beam Energy

As a result of the balance between quantum excitation and radiation damping, an electron beam in storage rings reaches an equilibrium distribution with horizontal emittance given by [7]:

$$\varepsilon_x = C_q \frac{\gamma^2}{J_x} \frac{I_5}{I_2} \quad (5)$$

$$C_q = \frac{55}{32\sqrt{3}} \frac{\hbar}{mc}, I_2 = \oint \frac{ds}{\rho^2}, I_5 = \oint \frac{\mathcal{H}_x}{\rho^3} \mathrm{ds} \quad (6)$$

J_x is the horizontal damping partition number, ρ is the bending radius, $\mathcal{H}_x$ is the horizontal dispersion invariant. For a given lattice that is scalable with energy, we want to know which energy is the optimal energy for it with the IBS effect. We performed IBS calculations for different energies.

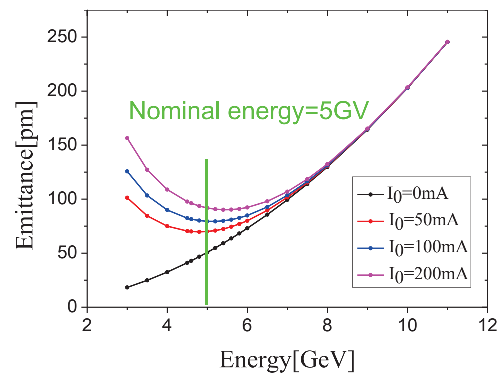

Figure 5: Emittance vs. energy for different currents

In Fig.5 we plot emittance vs. electron energy E, we note that the emittance minimum is near our nominal energy.

CONCLUSION

We calculated the emittance growth due to IBS effect in BAPS, the steady-state emittances including the IBS is much larger than the natural emittance of the bare lattice. We considered the application of damping wigglers and harmonic cavity to control the IBS effect. Using these devices our design goal of beam emittance can be achieved theoretically.

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