DESIGN OF AN ULTIMATE STORAGE RING FOR FUTURE LIGHT SOURCE*

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Abstract

An ultimate storage ring with natural emittance reaching the diffractive limit is capable of producing transversely coherent synchrotron radiation. This paper reports the progress of a 10 pico-meter storage ring design and study of microwave instability and IBS effects.

INTRODUCTION

Storage rings with natural emittance comparable to the diffractive limit can produce coherent light thus design of such storage rings is of great interest and several possible ring upgrades have been proposed on different projects recently [1, 2]. The design requires strong focusing magnets that can cause very large natural chromaticities. Thus families of sextupoles with strong gradient are required to correct the natural chromaticities. The resonance driving terms and tune shift with amplitude become very large and will significantly affect dynamic aperture and beam lifetime. Furthermore, a large circumference and the requirement of small emittance of these storage rings can produce a small momentum compaction factor that can lower the microwave instability (MI) threshold. MI effect introduces large energy spread thus deteriorates possible FEL performance. In this paper, we present a storage ring design with natural emittance less than 10 pico-meter and optimization of its dynamic aperture. In the end, we give a full analysis of intra-beam scattering effect and microwave instability effect.

LINEAR LATTICE

The emittance of a storage ring is scaled as $\epsilon \sim \gamma^2\theta^3$. We choose 11BA structure with 40 superperiods. The 11 BA structure is shown in Fig. 1, where 9 inner dipoles are 1.5 times the length of the 2 outer dipoles, the optical match is obtained by using quadrupole triplets. Each superperiod is separated by a 10 m straight section with zero dispersion. Quadrupole triplet is used to match the optics to achieve the theoretical minimum emittance (TME). Middle dipoles are 1.5 times longer than the 2 outer dipoles in order to match the H-function [3].

The total circumference of the ring is 2663m. Table. 1 shows the major parameters for our design. We choose nominal beam energy to be 5 GeV so that we can get hard X-ray FEL with 1 cm in vacuum undulator. When FEL is not implemented, the beam energy may be varied from 4 to 7 GeV according to their applications. The accelerator can also be made into a racetrack with two 100 m long straight sections.

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Table 1: Parameters for 10pm Storage Ring

Parameter	Value
Beam energy	5 GeV
Ring circumference	2663 m
Equilibrium energy spread $\Delta E/E$ (rms)	0.0378%
Natural emittance (rms)	9.1 nm-mrad
Natural horizontal chromaticity	-595.339
Natural vertical chromaticity	-148.741
Horizontal betatron tune	202.89
Vertical betatron tune	33.88
Momentum compaction factor	1.223e-5

The beam optics for one superperiod is shown in Fig. 1. Horizontal beta-function at the center of middle dipoles is matched to $\frac{L_{dip}}{\sqrt{15}}$ and horizontal dispersion matched to $\frac{L_{dip}\theta_{dipole}}{6}$ thus TME is achieved and the natural emittance is 9.1 pico-meters for this lattice. The betatron tunes are chosen to be $\nu_x = 202.89$ and $\nu_y = 33.88$ respectively so the zeroth order tunes stay relatively far away from most of lower order resonances. In order to move tunes to a safer location without changing optics and perturbing lattice properties, we vary the quadrupole triplet in the non-dispersive region. This does not affect the beta functions and dispersions in the central dipole regions thus change very slightly the emittance. Fig. 2 shows the tune space with up to 8th order resonance lines.

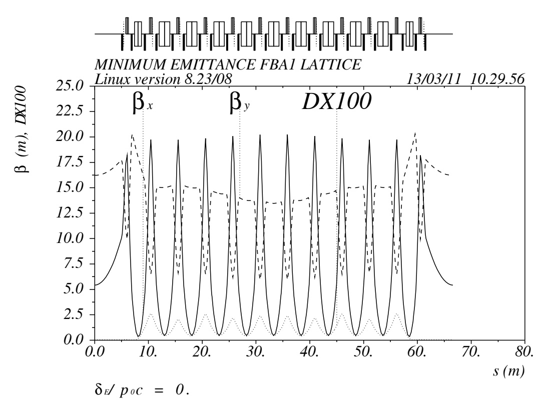

Figure 1: Plot of TWISS parameters. Horizontal dispersion is magnified by 100 times.

As we discussed before, huge natural chromaticities in-

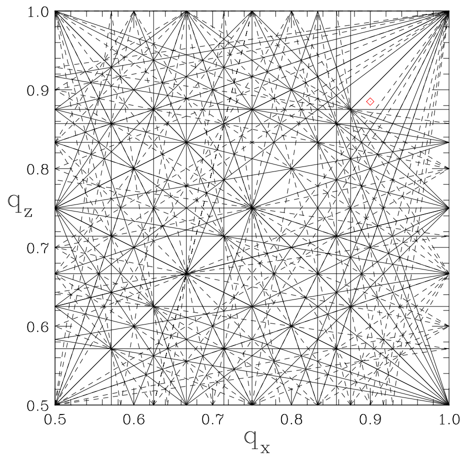

Figure 2: Plot of tune space with up to 8th order resonance lines. Red square is the location for 10 pm storage ring's tunes.

troduced by strong quadrupoles and small beta functions (in both x and y) need to be tackled with high gradient sextupoles to achieve a stable beam motion. Furthermore, a small momentum compaction factor induced by small dispersion function may also lower the microwave instability threshold. We will study the beam quality of the ultimate storage rings and give quantitative analysis on these topics in the following sections.

DYNAMIC APERTURE AND DRIVING TERMS

Modern storage rings require accumulation to achieve high beam current and intensity. It usually takes a few thousand turns of beam revolution to charge up to the desired current. Thus a beam life time of at least a few thousand turns is required. When beam is off the design orbit with an offset, it sees a different tune and may cross some strong resonances that causes beam loss. Strong sextupoles may also produce nonlinear resonance driving terms that also cause particle loss. We need to study dynamic aperture.

Using simulation code ELEGANT [4], we were able to calculate and optimize dynamic aperture using 8 families of sextupoles. We choose 4 families in the dispersive region to control chromaticities, and 4 families in the non-dispersive region mainly to control the driving terms. A single-particle tracking for 4000 turns shows an aperture of about 1.5 mm by 1.5 mm, as is shown in Fig. 3. The size of aperture is small but sufficient for beam to survive due to the tiny size of the beam(less than 30 μm). Beam accumulation is difficult but on-axix injection can be implemented.

The dynamic aperture is essentially determined by the nonlinear detuning generated by these sextupoles. A fully exploration of sextupole effects on dynamic aperture is one of our current efforts in accelerator physics research.

In order to better understand the mechanism of resonances, we track particles with different initial offsets in

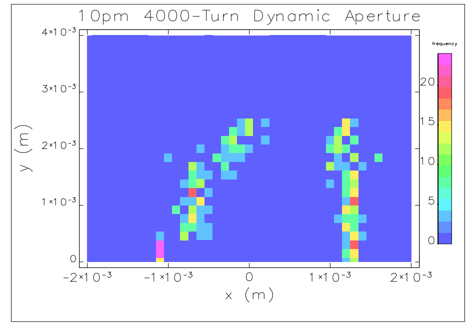

Figure 3: Dynamic aperture for 10 pm storage ring.

the DA and use the ICA method [5] to analyze the tracking data. Turn by turn tracking data is obtained by using simulation code MAD8 [6]. We observe chaotic phenomenon shown in Fig.4 due to the crossing of many resonances when the particle reaches the boundary of stable region. The chaos shows characteristic of noise spectrum.

These resonances come from two factors: one is the driving terms which drive certain order of resonances and the other one is the large tune shift with amplitude which is shown in Fig.5. These two effects can be changed by tuning sextupole families. Minimizing the tune shift with amplitudes seems to be a key condition to achieve a good DA. We are making efforts in this research.

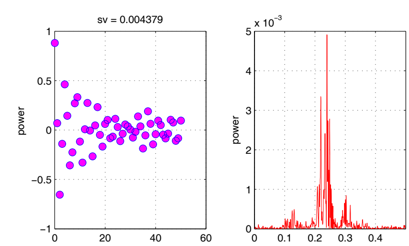

Figure 4: ICA analysis shows frequency spretrum with noisy peaks which indicates the particle experiences many different resonances at the boundary of DA. Temporal correlation of this mode has a characteristic property of noise pattern shown in the left plot. The frequency spectrum of the temporal wave function shows clearly overlapping resonances.

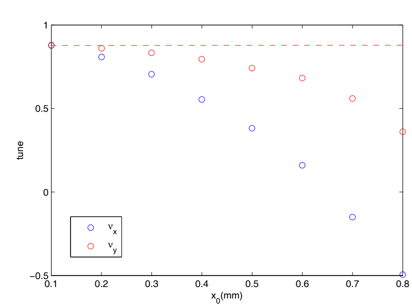

Figure 5: Quadratic tune amplitude dependence

MICROWAVE INSTABILITY AND INTRA-BEAM SCATTERING

The peak current of a beam in storage is largely limited by single bunch microwave instability. The operation threshold is given by Keil-Schnel equation:

$$\hat{I} = \frac{2\pi\beta^2(E/e)\sigma_\delta^2\,|\eta|}{\left|\frac{Z_{||}}{n}\right|} \tag{1}$$

where $\hat{I} = F_B I_0$ is the peak current of the beam, $F_B = \frac{\sqrt{2\pi}}{\sigma_\theta}$ is the bunching factor, and η the phase slip factor. For a typical 3rd generation light source, η is about the order of 10^{-3} while for ultimate storage rings η is only 10^{-5} due to the small dispersion function. This means we encounter the threshold much earlier. The energy spread growth is

$$\sigma_\delta = \left(\frac{I_b\left|\frac{Z_{||}}{n}\right|\nu_s}{\sqrt{2\pi}\beta^2(E/e)\eta^2}\right)^{\frac{1}{3}} \tag{2}$$

Fig. 6 shows the plot of calculated energy spread and FEL parameter with beam current for 10 pm storage ring. Although one can reach peak current in the order of kA, the FEL parameter is much smaller than the rms energy spread especially when we operate the machine at high beam current. A smoother vacuum chamber needs to be designed to alleviate microwave instability effect.

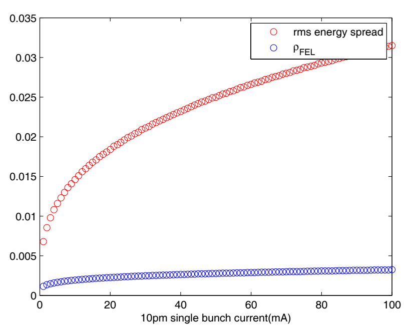

Figure 6: Calculated rms energy spread and FEL parameter versus the beam current with MI taken in account. $\frac{Z_{||}}{n}$ is assumed to be 0.5 ohms.

Since our calculated peak current can be very high, IBS effect also needs to be taken into account. Fig. 7 shows the equilibrium emittance with the consideration of IBS effect. The IBS effect is stronger when peak current is higher especially at a lower beam energy. Thus a low current operation is preferable for 10 pm storage ring when potential FEL process is considered.

Since both microwave instability and IBS deteriorate beam quality and induce larger energy spread, we compare these two effects. Our result shows that the microwave instability is much more important than the IBS as is shown in Fig. 8. The rms energy spread calculated from single bunch microwave instability is at least 3 times larger than IBS's result.

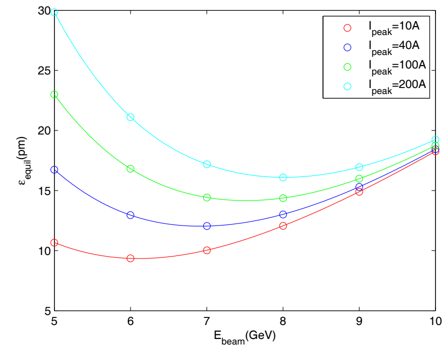

Figure 7: Equilibrium emittance when IBS effect is calculated under different I_{peak} and energy.

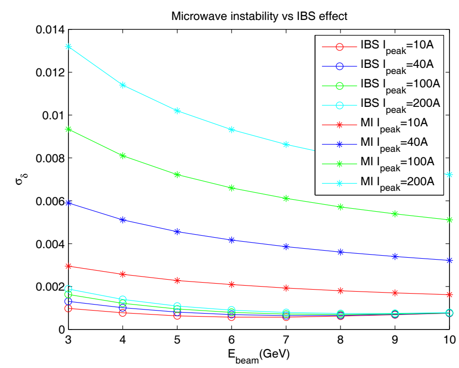

Figure 8: Comparison of IBS and MI effect on rms energy spread.

CONCLUSION

In this paper, we report the progress of designing an ultimate storage ring with a natural emittance less than 10 pico-meters. Linear optics are calculated and well matched to the theoretical minimum. A 1.5 mm by 1.5 mm dynamic aperture is obtained by optimizing the driving terms and tune shift with amplitude. Microwave instability and intra-beam scattering effects are found to be the bottleneck in preserving a good beam quality especially energy spread. FEL lasing is difficult with such a large energy spread. Further improvement of the storage ring DA is undergoing.

REFERENCES

[1] M. Borland, NIM A 557, 230C235 (2005).

[2] Y. Cai, SLAC report, LDRD-10-001 May (2009).

[3] S.Y. Lee, *Accelerator Physics*, (World Scientific Pub., 2005, Singapore).

[4] M. Borland, APS report, LS-287, September (2000).

[5] X. Pang, S.Y. Lee, ICA for beam measurements, Journal of Applied Physics, 106, 074902 (2009).

[6] H.Grote and F.C. Iselin, CERN/SL/90C13(AP) (Rev. 5)