DESIGN OF DAMPING RING FOR SuperKEKB

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Abstract

SuperKEKB, a plan upgrading the KEKB to higher luminosity of 5 $\times 10^{35}$ cm^{2}sec^{-1}, requires the beam currents of 9.4 A for the LER (3.5 GeV-electrons) and 4.1 A for the HER (8 GeV-positrons). In order to supply the HER with the positron beam, which is currently injected to the LER, the field gradient of the injector linac has to be increased. To meet this requirement, the S-band accelerating structures in the linac at the beam energy greater than 1 GeV, after the positron target, are replaced with C-band structures. A damping ring (DR) is indispensable since the aperture of the C-band structure is much smaller than the beam emittance. In this paper, we describe on the design of DR. We adopt a new cell structure for DR; FODO cell with alternating bends, where one of two bends in a cell is reversed. One of advantages of the proposed ring is that very small, even negative, momentum compaction factor is easily achieved by properly choosing the bend-angle ratio of the reverse bend to the main bend. Tracking simulation has shown that it has very large dynamic aperture in both transverse and longitudinal phase space, for very wide tune space.

INTRODUCTION

An asymmetric electron-positron collider SuperKEKB, an upgrading plan of the present KEKB, has been proposed[1], which aims at higher luminosity of 5 $\times 10^{35}$ cm^{2}sec^{-1}, with high beam currents up to 9.4 A for the LER (3.5 GeV-electrons) and 4.1 A for the HER (8 GeV-positrons). Currently the injector linac of KEKB accelerates, based on S-band technology, electrons up to 8-GeV and positrons up to 3.5 GeV. Positrons are generated from the target at 4-GeV location in the linac. In the SuperKEKB the lepton species is exchanged between the LER and the HER in order to reduce the electron-cloud instability. In order to supply the HER with the 8-GeV positron beam, the field gradient of the linac after the target has to be doubled. Adopted solution is to replace the S-band accelerating structures located downstream the target with high gradient C-band structures, realizing almost double the energy gain. In that case, we need a damping ring reducing the the emittance to fit the aperture of the C-band structures.

The positron beam, extracted at the end of Sector-2 from the injector linac where beam energy is 1 GeV, is compressed prior to injection through an energy compression system (ECS). Staying for 40 ms, which is two periods of the 50 Hz repetition rate, the damped beam is extracted and sent back to the linac.

BEAM PARAMETERS

Parameters of injected beam are summarized in Table 1. In order to maximize the beam charge per pulse we adopt the two-bunch scheme, where two bunches, 98 ns apart, are accelerated in a single Linac pulse. The energy spread and the bunch length were estimated using EGS4 code. We adopted ECS with compression factor of 1/3 to increase capture efficiency.

Table 1: Parameters of injected beam

		before /	after ECS
Energy	(GeV)	1.0	
Repetition frequency	(Hz)	50	
Emittance	(m)	1.225×10^{-6}	
Energy spread†	(%)	1.30	0.406
Bunch length†	(mm)	2.30	6.05
Number of bunches/pulse		2	
Bunch spacing	(ns)	98	
Bunch charge	(nC)	2.56	

†defined as extension that contains 95.5%divided by 4

FODO CELL WITH REVERSE BEND

The dynamic aperture is a crucial issue in the design of positron damping ring since the injected beam has large energy spread and large transverse emittance. It is well known that FODO cell has good feature of large dynamic aperture, where several percent is easily obtained in momentum aperture. One of drawbacks is, however, that the momentum compaction factor tends to be large, resulting higher accelerating voltage. To cure this we adopt a variant of FODO cell: FODO with alternating bend, that have a reverse bend for one of two bends, as shown in Fig. 1. The bend B2 is a reverse bend whose bending angle is $-r\theta$ $(-1 \leq r < 1)$, where θ is a bending angle of normal bend B1. When $r = -1$ it reduces to normal FODO lattice. We assume an identical bending radius for B1 and B2 to minimize the damping time. Since the bending angle is negative while the dispersion function is positive at B2, the momentum compaction factor is expected to be greatly reduced. This type of cell is expected to preserve the good feature of dynamic aperture and is attainable low, even negative, momentum compaction factor.

In a thin-lens model the momentum compaction factor α_p is written as

$$\alpha_p = G(r, \mu)\theta^2, \tag{1}$$

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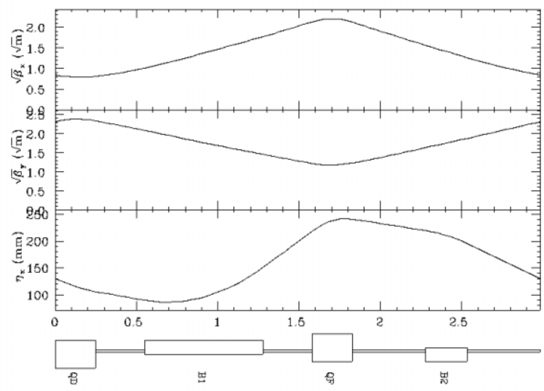

Figure 1: Optics functions of FODO cell with alternating bend. B2 is a reverse bend.

$$G(r,\mu) = \frac{(1+r^2)(3+\cos\mu) - 8r}{16\sin^2(\mu/2)}, \tag{2}$$

where μ is the phase advance per cell. An equal phase advance for horizontal and vertical plane was assumed. If r is greater than $2-\sqrt{3} = 0.268$ there exists a solution that satisfies α_p=0. In the Fig. 2(a), phase advance μ that satisfies $G(r,\mu) = 0$ is shown as a function of r. Remarkable feature is that for fixed r, by adjusting phase advance, low or even negative α_p can be achieved (Fig. 2(b)).

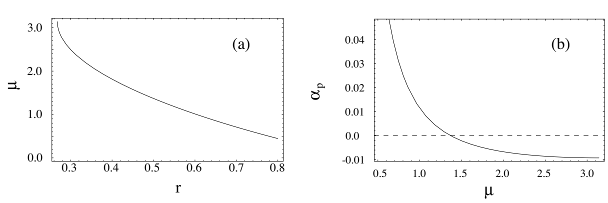

Figure 2: (a): Phase advance per cell that satisfies α_p=0 as a function of r. (b): α_p as function of phase advance for fixed r of 0.5 and $\theta = 0.314$.

The emittance is given as following expressions in the thin-lens model.

$$\varepsilon_0 = C_q \frac{\ell\theta^2}{\rho}\gamma^2 F(r,\mu), \tag{3}$$

$$\begin{aligned} F(r,\mu) = \big[&1 + 5|r| + r^2 + \\ &2(5 - 12r - 2|r| + 5r^2)\cos^2(\mu/2) + \\ &(1-|r|+r^2)\cos^2\mu\big] / (24\sin^2(\mu/2)\sin\mu) \end{aligned} \tag{4}$$

where ℓ is half cell-length, ρ bending radius, and $C_q = \frac{55}{32\sqrt{3}}\frac{\hbar}{mc}$. If we choose μ and r such that $\alpha_p \approx 0$, r being expressed by μ, Eq. (3) is rewritten in the form of

$$\varepsilon_0 = C_q \frac{\ell\theta^2}{\rho}\gamma^2 f(\mu). \tag{5}$$

The function $f(\mu)$ takes its minimum at $\mu = 2.1$, that corresponds to $r = 0.35$.

OPTIMIZING THE LATTICE PARAMETERS

We describe the optimization of parameters: damping time τ, phase advance μ, and number of cells n. Horizontal damping time is given by

$$\tau = \frac{2}{cJ_xC_\tau}\frac{\rho}{\gamma^3}\left[2\pi\rho + \frac{1-r}{1+|r|}(n\ell_1 + 2\ell_2)\right], \tag{6}$$

where, $C_\tau = \frac{4\pi}{3}r_e$, J_x the damping partition number, and c the speed of light. We assume $J_x = 1$. The length $2\ell_1$ and $2\ell_2$ are the cell-length subtracted by the length of two bends, and length of the long straight sections of the ring, respectively. The emittance at extraction ε_{ext} is given as

$$\varepsilon_{ext} = \varepsilon_0 + (\varepsilon_i - \varepsilon_0)\exp(-2T/\tau), \tag{7}$$

where, ε_i is the emittance at injection and T is the beam stay-time, for which we assume 40 ms, two times the repetition period of the Linac, that means two bunch-train is accommodated in the ring. Eliminating ρ and ε_0 from Eqs. (5)(6)(7), the emittance at extraction can be expressed as a function of τ, μ, and n. Note that $\theta = 2\pi/[(1-r)n]$, $2\ell = \ell_1 + (1+|r|)\rho\theta$ and $\alpha_p = 0$. The dependence of emittance at extraction on the parameters τ, μ, and n is shown in Fig. 3, where contour plot of emittance at extraction is given in (τ,μ) plane, for various number-of-cells n. It is

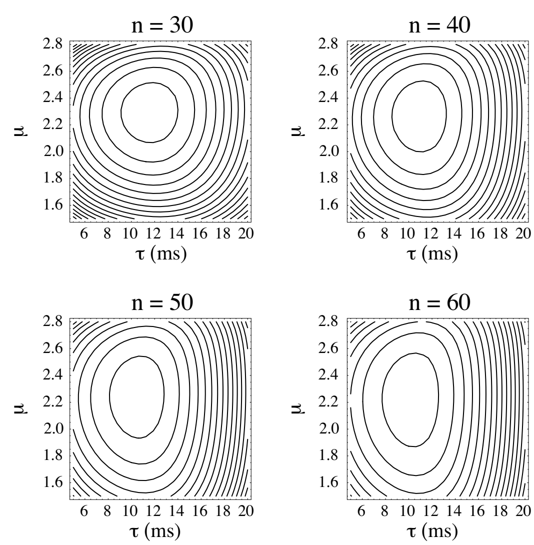

Figure 3: Contour plot of emittance at extraction in (τ,μ) plane, for various number-of-cells n.

found that for any n the region around (τ=12 ms, μ=2.3) gives minimum emittance. The minimum emittance itself depends on the number of cells. We must also take into account the field strength of the bend and the circumference. The parameters of DR is shown in Table 2. The emittance has a flat minimum for μ from 1.9 to 2.5. From dynamic aperture point of view smaller phase advance is preferable. We should avoid high-order resonance driven by sextupoles, which would be enhanced if μ is close to $2\pi/3 = 2.09$. As a compromise we chose 1.93. The cavity voltage of 0.261 MV is still within the specification of KEKB ARES cavity[2] that is 0.5 MV for a single cavity.

Table 2: Parameters of Damping Ring

Energy	1.0	GeV
Circumference	131.3	m
Repetition frequency	50	Hz
Beam stay-time	40	ms
Horizontal damping time	11.95	ms
Equilibrium emittance	12.2	nm
Emittance at extraction	13.7	nm
Energy spread	5.29×10^{-4}	
Bunch length	5.03	mm
Bend-angle ratio of reverse-bend	0.35	
Phase advance/cell	1.932	rad
Momentum compaction factor	0.0019	
Number of normal-cells	40	
Bend field	1.267	T
Length of straight sections	2×6	m
Length of main bend	0.7286	m
Rf voltage for 1.5% bucket-height	0.261	MV
RF frequency	509	MHz

In Fig. 1 shown are optics functions for the normal cell. Chromaticity correction was done using two-family of sextupoles, which are placed in both side of the reverse bend in the normal cells.

DYNAMIC APERTURE

We made a tracking simulation on the proposed ring and confirmed it has enough dynamic aperture, even for realistic machine errors. The results are shown in Fig. 4. Tunes are (ν_x, ν_y)=(12.24, 4.26). RF bucket height is 4%. Vertical axis is the amplitude (Courant-Snyder invariant) of the particle and the horizontal axis is the momentum deviation. Red lines show the largest initial amplitude of particles that survived after 4000 turns, for each of initial momentum deviation. The thick line is for the case of ideal machine while thin (red) lines are for the case with machine errors generated by 20 random seeds. The errors were assumed as: strength error of 3×10^{-4} and 5×10^{-4} for quads and sexts, respectively, and random misalignments of quads and sexts of 0.5 mm. Resultant orbit was corrected. The (green) rectangular shows the maximum amplitude of 4.9 μm and energy deviation of ±1.5% for injected beam.

The proposed ring has wide operational tune space. Left figure in Fig. 5 shows dependence of dynamic aperture on tunes for the case with no errors. The brighter region has the larger dynamic aperture. The highlighted area in the right figure of Fig. 5 shows the tune space where the dynamic aperture is larger than the extent of the injected beam. Strong third-order resonance exists in the horizontal

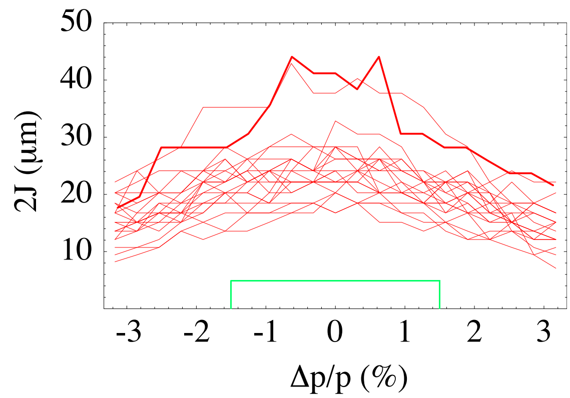

Figure 4: Dynamic aperture of the proposed ring. Thick (red) line is for the case of ideal machine, while thin (red) lines are for the case with machine errors. The (green) rectangular corresponds to the maximum amplitude and energy deviation of injected beam.

plane, driven by sextupoles with phase advance of 2.026 which is very close to $2\pi/3$=2.09.

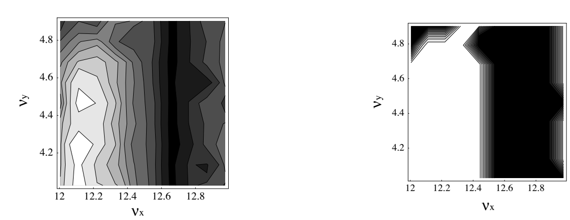

Figure 5: Tune survey results for the dynamic aperture. Left: the dynamic aperture for each tune. The brighter area designates the larger aperture. Right: highlighted area shows the tune space that has larger dynamic aperture than the injected beam

CONCLUSION

Design of positron damping ring has been presented. We adopted a new cell structure, FODO cell with alternating bends. The proposed ring has good features that very low momentum compaction factor can be achieved by properly changing the phase advance of normal cells. The RF voltage is 0.26 MV and can be supplied by a single ARES cavity. We have shown that the ring has very wide dynamic aperture in vast region of tune space, especially the momentum aperture is greater than 4%, which is limited only by RF bucket height.

REFERENCES

[1] K. Abe, "Letter of Intent for Super B Factory", KEK Report 2004-4.

[2] T. Kageyama et.al., "The ARES Cavity for KEKB", APAC'98, 1998