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BEAM DYNAMICS ISSUES IN THE JAPANESE HADRON PROJECT CIRCULAR ACCELERATORS

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Abstract

Beam dynamics issues in the JHP circular accelerators are described. The booster ring, which is a 3 GeV proton synchrotron, accelerates 5×10^{13} protons per pulse (ppp) and the main ring, which is a 50 GeV machine, accelerates 4×10^{14} ppp. Problems associated with high intensity beams are examined, especially space charge effects and dynamic aperture.

I. Introduction

The proposed accelerator complex of the Japanese Hadron Project (JHP) [1] consists of a 3 GeV fast cycling booster and a 50 GeV slow cycling main ring. In order to obtain high average beam current, which is 200 μA in the booster and 10 μA in the main ring, with technically feasible repetition rate, the number of protons per pulse becomes quite large. That is, 5×10^{13} for the 3 GeV booster and 4×10^{14} for the 50 GeV main ring. In terms of circulating current, they are 7 A and 14 A, respectively [2]. Obviously, beam loading effects in the longitudinal direction would be one of main beam dynamics issues in both machines.

Beam dynamics issues associated with the large number of protons per pulse exists in both longitudinal and transverse directions. One could easily imagine that space charge effects right after the injection until beams get accelerated up to sufficient energy may cause problems such as beam emittance growth and beam loss. The machines have quite little margin for those because the machine aperture is limited by size of each lattice components which are essentially determined by the total cost of the rings. Even a small fraction of beam loss, say 1%, is no more negligible because it is almost equal to the entire beam loss of the KEK PS, for example, and radio activation of the facility becomes serious problem.

In order to keep the space charge tune shift moderate magnitude, the beam emittance is taken relatively large from the beginning. At the same time, to squeeze the beam size small, a rather strong focusing lattice is adopted. Chromaticity correction by sextupoles, therefore, introduces strong nonlinearity and dynamic aperture becomes one of primary concerns.

In this paper, we will pick up some of those beam dynamics issues in the JHP synchrotrons and describe our present understanding. For those issues which are not studied yet, we will show our future direction of the study. As for the lattice design itself, a separate paper describes the detail [3].

II. Space Charge Effects

One of figures which describes space charge effects in a circular machine is Laslett tune shift.

$$\Delta\nu_y = -\frac{r_p \cdot n_t \cdot F}{\pi\beta^2\gamma^3\epsilon_y(1+\sqrt{\epsilon_y/\epsilon_x})B},$$

where $\Delta\nu_y$ is the vertical tune shift, r_p is the classical proton radius, n_t is the total number of protons, β and γ are Lorentz factors, ϵ_x and ϵ_y are unnormalized horizontal and vertical emittance, and B is the bunching factor. Laslett tune shift includes, not only direct electro-magnetic field in a free space, but the field due to image charge on vacuum chambers and magnets, which is represented by the form factor F. In fact, at the injection energy of the 3 GeV booster, namely 200 MeV, the tune shift mostly comes from a direct space charge field, but at that of the 50 GeV main ring, the field due to image charge accounts for not a small fraction of the total tune shift. In any case, we choose lattice parameters such that Laslett tune shift should be less than -0.25.

Since our design of machine acceptance is $320\pi\cdot mm\cdot mrad$ (unnormalized) for the 3 GeV booster and $54\pi\cdot mm\cdot mrad$ for the 50 GeV main ring, incoherent space charge limits are 5.6×10^{13} for the 3 GeV booster and 4.7×10^{14} for the 50 GeV main ring. Coherent space charge limit for the 50 GeV main ring is 4.2×10^{14}. Bunching factor is assumed to be 0.3 in all cases.

In addition to the fact that the space charge force shifts the transverse tune down, the space charge force itself creates resonances. Unless the beam distribution has a uniform shape, the space charge force has nonlinear dependence of its transverse coordinates. The Hamiltonian including space charge terms, therefore, becomes

$$H = \frac{1}{2}p_x^2 + \frac{1}{2}p_y^2 + \frac{1}{B\rho}[\frac{1}{2!}\frac{\partial B_y}{\partial x}(x^2-y^2)$$

$$+\frac{1}{3!}\frac{\partial^2 B_y}{\partial x^2}(x^3 - 3xy^2)$$
$$+\frac{1}{4!}\frac{\partial^3 B_y}{\partial x^3}(x^4 - 6x^2y^2 + y^4) + ...]$$
$$+\frac{r_p\lambda}{\beta^2\gamma^3 B}[-\frac{1}{\sigma_x(\sigma_x+\sigma_y)}x^2 - \frac{1}{\sigma_y(\sigma_x+\sigma_y)}y^2$$
$$+\frac{2\sigma_x+\sigma_y}{12\sigma_x^3(\sigma_x+\sigma_y)^2}x^4 + \frac{1}{2\sigma_x\sigma_y(\sigma_x+\sigma_y)^2}x^2y^2$$
$$+\frac{2\sigma_y+\sigma_x}{12\sigma_y^3(\sigma_x+\sigma_y)^2}y^4 + ...].$$

We assumed that the beam distribution is Gaussian and σ_x and σ_y are horizontal and vertical rms beam size, respectively, and λ is a line charge density. The first square bracket shows the magnetic force terms in lattice elements. They are essentially zero if the lattice is constructed in a perfect manner except a quadrupole term which provides focusing force and a sextupole one which is introduced intentionally to correct chromaticity. The second square bracket shows the space charge terms of both linear and nonlinear contributions. Those exist even if the lattice is perfectly constructed.

The driving term of one dimensional fourth integer resonance excited by space charge force ($4\nu_y = N$) is, for example,

$$\Delta e_s = \frac{2J_y}{4\pi}\int \beta_y^2 \frac{1}{\beta^2\gamma^3 B}\frac{2\sigma_y+\sigma_x}{12\sigma_y^3(\sigma_x+\sigma_y)^2}e^{-i\cdot 4\phi_y}ds,$$

where $2J_y$ is the Courant-Synder invariant, β_y is the vertical amplitude function and ϕ_y is the vertical phase of betatron oscillations. One can see that only harmonics which is integer times the number of superperiod ($N = integer \times n_s$) are non zero because the harmonics of rms beam size $\sigma_{x,y}$ follows lattice amplitude functions, $\beta_{x,y}$. In reality, there are small modulation in amplitude functions and harmonics other than the above number has small magnitude in driving term. Figure 1 shows the strength of driving terms of space charge induced fourth integer resonances in the KEK PS. Note that the KEK PS has fourfold symmetry ($n_s = 4$).

When the vertical tune is 7, the strength of the space charge induced resonance becomes maximum. This happens because the KEK PS has more or less a 28 normal FODO cell structure and therefore phase advance per cell becomes 90 degree. At the same time, the primary beam envelope modulation, namely space charge force, has 28 harmonic components. We name it space charge excited "super structure" resonance.

Since the 3 GeV booster has 24 FODO cells and the 50 GeV man ring has 88 FODO cells, the super structure resonance is located at the tune of 6 and 22, respectively. The operating point near that tune should be avoided.

III. Dynamic Aperture

Both rings are operated under transition energy with entire energy region. From collective instability point of view, such as zeroth mode of head-tail instability, beams are stable without chromaticity correction. In fact, natural

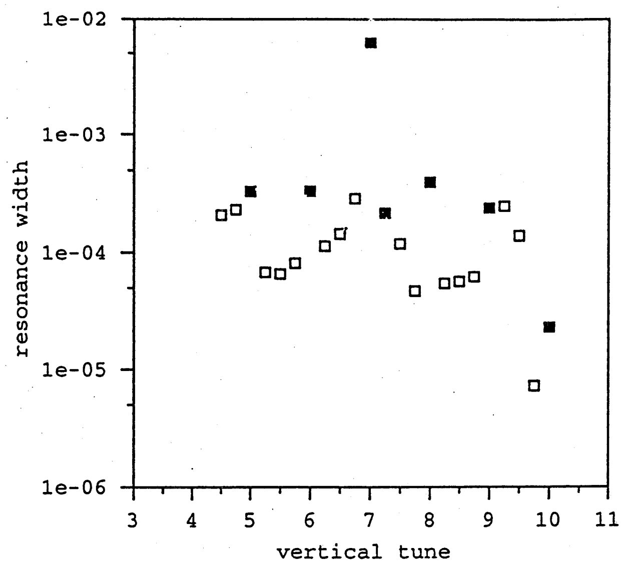

Figure. 1. Resonance width of space charge induced driving harmonics in the KEK PS. Because small amplitude function modulation is included, structure (filled box) as well as nonstructure resonance (empty box) is excited. Note that the KEK PS has fourfold symmetry. Horizontal tune is fixed to 7.12.

chromaticity of the 3 GeV booster ring is around -7 to -6 and we plan to start commissioning of the 3 GeV ring without chromaticity correction until it is required by some reasons.

On the other hand, the natural chromaticity of the 50 GeV ring is around -30. With momentum spread of $\pm 0.5\%$ in a beam, transverse tune oscillates $\pm 0.15\%$, that is not allowed. Chromaticity correction is essential in the 50 GeV ring.

Two families of sextupoles are installed in the missing bend regions, which are located one for every three FODO cells. Typical strength of the sextupoles to make the chromaticity zero is 29 T/m for focusing sextupoles and -59 T/m for defocusing ones. Those numbers include the sextupole length in it, that is 1 m. With those sextupoles excited, we investigated the dynamic aperture as follows.

A. Tune dependence

To obtain a rough idea of the dynamic aperture of the ring, we did tens of particle tracking runs taking transverse operating point as a parameter. The simulation code SAD [4] was used without synchrotron oscillations or momentum offset of a particle. Transverse tune area of $\pm$ 1 near the nominal operating point (24.25, 20.70) was searched. A dynamic aperture turns out 380 $\pi \cdot mm \cdot mrad$ at one point as shown in Figure 2, which is much larger than the physical aperture, that is 54 $\pi \cdot mm \cdot mrad$.

B. Momentum dependence

Momentum dependence of the dynamic aperture was studied using the simulation code Simpsons [5], which tracks particles in 6D phase space with synchrotron os-

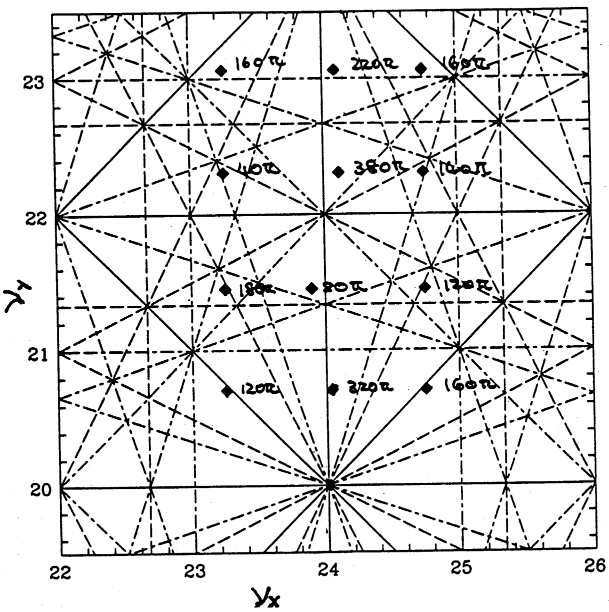

Figure. 2. Dynamic aperture of the 50 GeV ring at several operating points.

cillations. Operating point was chosen at (22.75, 22.65) and sextupoles are excited such that chromaticity becomes zero for both planes. The rf voltage of 200 kV was applied so that the rf bucket high is ± 0.43 % in the $\Delta p/p$ axis. The longitudinal tune at the injection energy is 0.004. As shown in Figure 3, no strong momentum dependence was

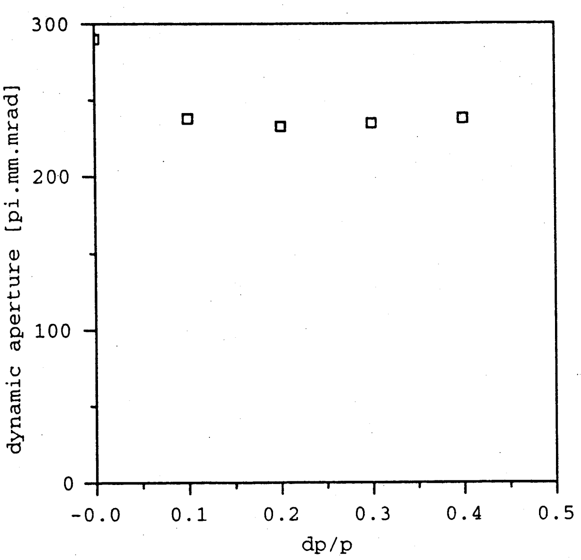

Figure. 3. Dynamic aperture of the 50 GeV ring with different momentum amplitude.

observed.

C. Chromaticity dependence

The last figure (Figure 4) shows the dynamic aperture of the 50 GeV ring with different chromaticity setting. The simulation code Simpsons [5] was used. Natural chromaticity is around -30. With a small correction of chromaticity (chromaticity = -25 and -20), still large tune oscillations

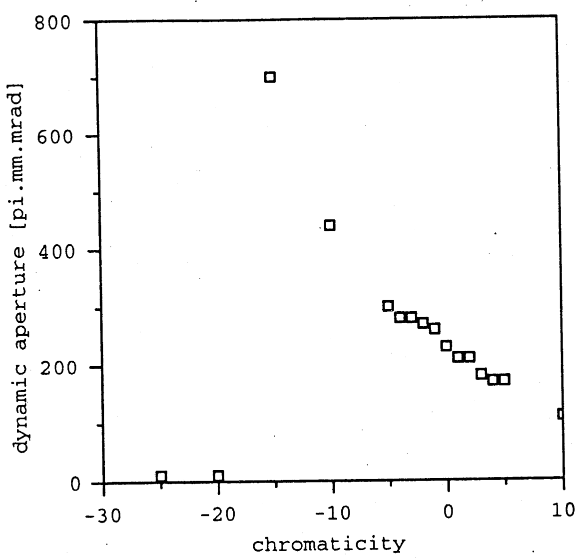

Figure. 4. Dynamic aperture of the 50 GeV ring with different chromaticity correction strength. Amplitude of beam momentum is fixed to 0.2 %.

exist and dynamic aperture is small. When stronger correction was applied, the dynamic aperture becomes large at one point (chromaticity = -15). The further increase of the strength of sextupoles, and therefore smaller chromaticity, reduces the dynamic aperture gradually.

At this moment, we are not sure if we should correct the chromaticity to zero or not.

IV. Summary

Based on the proposed lattice of the JHP circular accelerators, we studied space charge effects and dynamic aperture. In fact, combining those two effects is necessary, namely tracking study of dynamic aperture with space charge effects included. We plan to do it in near future.

References

[1] Y. Mori, *et al*, in this proceedings.
[2] C. Ohmori, *et al*, in this proceedings.
[3] Y. Ishi, *et al*, in this proceedings.
[4] SAD stands for "Strategic Accelerator Design" code. It is developed by K. Oide and colleagues at KEK.
[5] S. Machida, "The Simpsons Program", AIP Conference Proceedings 297, p.459, 1993.