Beam Optics and Dynamics of the JHF 50 GeV Main Ring

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Abstract

The 50 GeV main ring is characterized by high intensity and low beam loss. Several considerations have been taken into account in the lattice design to achieve those two primary goals. Although there are strict boundary conditions, such as the total circumference, which is limited because of the available site enclosed by the KEKB ring, a well-optimized lattice is obtained.

1 Overview of the Lattice

The dispersion function is adjusted so that the momentum compaction factor (MCF) becomes negative or, in other words, the transition energy becomes imaginary. Although many synchrotrons now under operation can conquer problems at the transition crossing, the best way to minimize beam loss during acceleration is not to have a transition energy.

In order to obtain a negative MCF, three FODO cells, starting from a defocusing quadrupole, are taken as the minimum unit of an arc. We refer to the unit as "module". In a module, four bending magnets are put in each half cell, except for two half cells on both sides of a focusing quadrupole magnet at the center. Due to those arrangements of the lattice, the dispersion function is modulated in a module and has a peak at the center. In the half cells at both ends, where the bending magnets are located, the dispersion function becomes negative. Therefore, the MCF, which can be obtained as the integral of the dispersion function through the finite curvature, becomes negative [1]. The beta functions in both the horizontal and vertical directions are not very much perturbed.

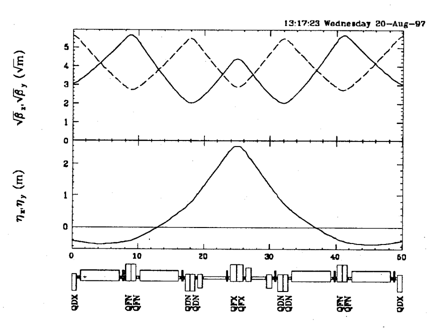

Figure 1: Lattice functions of "module" in the arc.

The lattice functions of the module are depicted in Fig. 1. The arc of the ring consists of six modules.

Between the arcs, four insertions are prepared: one for acceleration, one for fast extraction, one for slow extraction, and the last one for beam abort. The ring, therefore, has fourfold symmetry. Insertion has to be sufficiently long.

A long straight insertion consists of four FODO cells. Since the horizontal phase advance through the insertion is chosen to be 2π and the vertical is π, the beta and alpha functions in both directions and the dispersion function are all matched at both ends of the insertion. In other words, the insertion acts like a phase shifter without perturbing the lattice functions in the arc. In that way, a negative MCF is preserved to be somewhat independent of the configuration of the insertion.

An abort system is essential for a high intensity proton synchrotron. There are two abort channels: one for beams at the injection energy, and the other for higher energy beams, of around 30 to 50 GeV. For beams at the injection energy, about one third of the insertion space is dedicated to the fast kickers for the extraction of beams. Although the kicker strength is not sufficient to extract higher energy beams, the aperture of that abort channel is large enough to extract a beam filled in the vacuum chamber. For aborting higher energy beams, the fast extraction channel is used. Since the aperture of the fast extraction channel is designed based on the adiabatically damped beams, the lowest energy that the fast extraction channel can handle is limited. Still, the core part of the beam should be dumped into the fast extraction channel if it is necessary to abort rather low energy beams whose size is bigger than the aperture. The extracted beam eventually hits a target for neutrino production. The fast extraction channel should be ready whenever the machine is on.

Although the lattice is fourfold symmetry in shape, it has a higher symmetry as far as the phase advance is concerned. Namely, the phase advance of the insertion is 2π for the horizontal plane and π for the vertical. In such a way, insertion becomes transparent for a beam and the periodicity becomes higher. For example, the total phase advances of the sextupole resonance, $3\nu_x=h$ and $\nu_x+2\nu_y=h$ (h is an integer), in the insertion are 6π and 4π, respectively. Since the sextupole magnets are installed only in the arc, insertion is transparent for those resonances, and the periodicity becomes 24, which is the number of modules.

Since space charge effects are another concern, the phase advance of the lattice is carefully chosen. Although the beam emittance is quite large, 54 π mm-mrad at the injection (220 π mm-mrad, normalized), the tune spread, including image currents effects, may reach to slightly less than -0.1. A resonance free region in the tune space should be prepared, which can accommodate that magnitude of the tune spread. In addition, resonances excited by the space charge force, itself, must be taken into account. According to a recent study, a space charge induced resonance significantly appears when it couples to a local phase advance of 90 degrees [2].

2 Stability of the Linear Lattice

In order to assure stable operation and a search for good operating points, the stability of the linear lattice has been investigated. Since the upper limit is due to the hardware design, the strengths of the quadrupole magnets are adjusted so as to explore transverse tune space. The maximum values of the lattice functions in the arc and the insertion are moderate over a wide range of tune space.

The lattice functions are, then, examined as a function of the MCF. When the operating point is fixed at (21.85, 15.40), the MCF can be varied from -2.3×10^{-3} to 2.5×10^{-3}. In terms of the transition gamma, it corresponds to $20i$ to 20, respectively. As shown in Fig. 2, the horizontal and vertical beta functions are similar, and are around 31 m in the arc when the

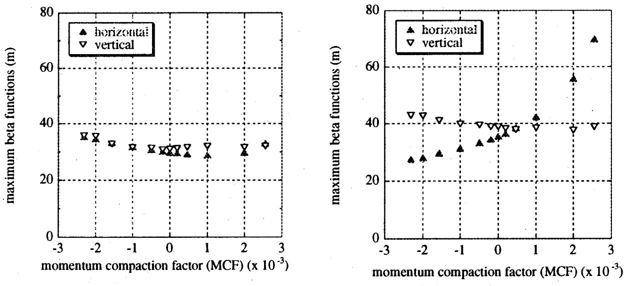

Figure 2: Maximum beta functions in the arc (left), and in the insertion (right) when the MCF is varied.

MCF is around zero. Those in the insertion also have a similar value of 38 m in both directions when the MCF is almost zero.

If one chooses a small magnitude for the MCF, the higher order effects of the MCF or the coefficient of the quadratic term of $\Delta p/p$ may become significant. The particle motion may be unstable if those higher terms are large, and different momentum particles see different rf bucket and transition energies. In order to examine those effects, often called the effects of α_1, α_2, and so on, the slippage factor η_s as a function of $\Delta p/p$ was calculated (Fig. 3). The momentum dependence within the range of +-1 % is sufficiently small and, even at the top energy, the variation of the slippage factor is small.

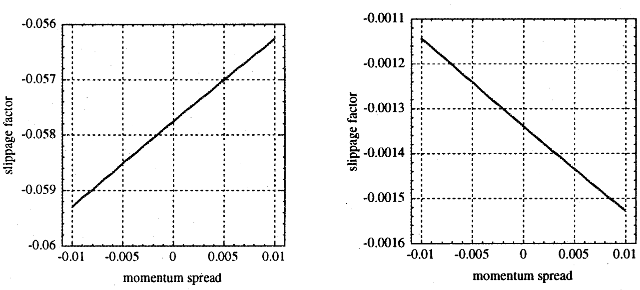

Figure 3: Slippage factor as a function of momentum spread at the injection energy (left) and the extraction energy (right).

3 Emittance and Acceptance

The beam emittance from the booster is expected to be less than 54 π mm-mrad (the normalized emittance is 220 π mm-mrad). The main ring acceptance has been determined to be 54 π mm-mrad also. It seems that no margin is reserved for additional emittance growth in the main ring.

At the moment, however, we assume that the margin is already included at booster injection. Since we do not inject a beam in a full acceptance of the booster, there may be only a tail of the beam near to the edge of the booster acceptance. If the emittance growth mainly occurs at injection, although the beam into the main ring may have a full emittance of 54 π mm-mrad, the core of the beam is still smaller. Thus, the question is what fraction of the beam is contained in the beam edge, which will be scraped by the main ring acceptance. We have no accurate idea. If it turns out not to be negligible, we will consider using a scraper and collector system either in the transport line between the booster and the main ring or in the main ring. An alternative way is to enlarge the acceptance. In that case the hardware design should be revised.

The necessary aperture of the magnets and other lattice components is determined by the sum of three parts: betatron amplitude, momentum spread with the dispersion function, and COD. Although the core size of the beam can be the square root of the quadratic sum of the first two, we define the full beam size as simply the arithmetic sum of those three.

The maximum betatron amplitude (or emittance, as discussed before) is 54 π mm-mrad. The COD can be less than 1 mm at the injection where the beam size is maximum. As for the momentum spread, +-1 % is assumed for injection with barrier buckets in future. As a result, the beam size becomes maximum at the middle of the module in the horizontal direction. In the vertical, one of the two defocusing magnets in insertion has the maximum beam size. In order to accommodate those maximum beam sizes, the beam pipe radius was determined to be 120 mm in all of the quadrupole magnets and 120 mm (hor.) x 100 mm (ver.) in all of the bending magnets.

4 Dynamic Aperture

According to the normal injection scheme, the first batch from the booster stays at an injection energy for 120 ms. The sextupole magnets for chromaticity correction will be a major source to limit the dynamic aperture. Other nonlinearities, such as the multipole components in the normal conducting lattice magnets, are negligible.

The strength of the sextupole magnets tends to be high compared with a normal FODO lattice for two reasons. One is that the number of sextupole magnets is less. The other is that the magnitude of horizontal and vertical beta functions is similar at the position of the focusing sextupole, even though the dispersion function is high there.

The dynamic apertures were estimated by particle tracking codes: SAD [3] and Simpsons [4]. It is defined in the following way in those codes. Several particles are launched with different amplitudes and tracked for 2,000 turns. Initially, each particle has equal horizontal and vertical amplitudes. We regard the beam as having been lost when its amplitude becomes more than 1 m. After tracking for 2,000 turns, the maximum initial amplitude among the surviving particles is defined as the dynamic aperture.

First of all, the dynamic apertures were surveyed over a rather wide transverse tune range using the code SAD. At interval of 0.05, tune is varied in 2D space, totally at 60 x 60 points. Since the momentum spread is assumed to be zero, the tracking is done in 4D phase space. The strength of the sextupole magnets is adjusted to make the chromaticity zero.

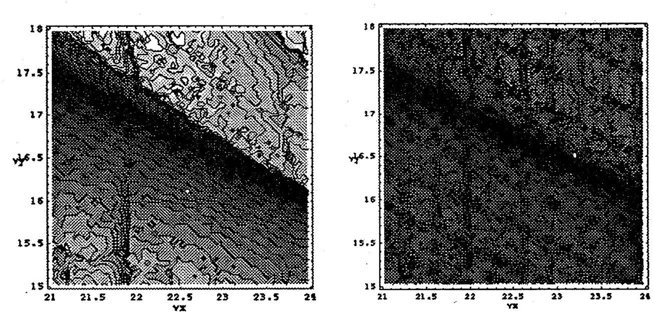

Figure 4: Dynamic aperture as a function of the transverse two dimensional tune. In the case of full number of sextupoles (left) and one missing one (right). The darkest grey means zero aperture and the lightest grey corresponds to four times as much as the physical aperture in size. A chromaticity correction sextupole is excited to make the chromaticity zero.

As shown in Fig. 4 (left), a fairly large dynamic aperture of around 200 π mm-mrad is obtained above and below the third integer resonance: $\nu_x+2\nu_y=56$. It is about twice as much as the size of the physical aperture and therefore four times that of the acceptance.

To the first order, the periodicity of the sextupole is 24 because the phase advance in the insertion is 2π and π for the horizontal and vertical planes, respectively. The insertion is transparent as far as the sextupole phase is concerned. The resonance, $\nu_x+2\nu_y=56$, actually has harmonics of 48 after subtracting the offset in the four insertions, which is an integer multiplied with a periodicity of 24. On the other hand, other third integer resonances having a periodicity of an integer multiple of the superperiodicity of 4 are relatively weak, or none in principle, because of the higher periodicity.

In reality, the symmetry of the sextupole magnets may be broken for various reasons. The phase advance in the insertion may, for example, differ from what we designed. Nevertheless, one expects that those perturbations are still small. The other source which one cannot treat as a perturbation is a missing sextupole at the injection section, we assume at the moment, where kicker and septa magnets are installed in place of the sextupole magnet. If we fix the design to inject beams in the middle of the arc, instead of taking them to the nearest insertion where sufficient space is available for injection without affecting other lattice elements, we must remove one sextupole and break periodicity.

The dynamic aperture in the same region as shown in Fig. 4 (right) is estimated with one missing focusing sextupole. Although the strengths of the sextupole magnets are similar to make the chromaticity zero, the dynamic aperture is considerably reduced. It is at most the same as the physical aperture. Because of the symmetry breakage of the sextupoles, the third integer resonances of all the harmonics appear. Still, the wide valley by $\nu_x+2\nu_y=56$ is quite noticeable.

Although we assume zero chromaticity until this point, and looked at the dynamic aperture, one may ask if it is really necessary to have zero chromaticity for the main ring. In fact, the chromaticity does not have to be zero, because it is operated under the "transition energy" all of the time. Moreover, a finite negative chromaticity is even preferable from the beam instability point of view.

Using the code Simpsons, the dynamic apertures are obtained as a function of the sextupole strength. The tune is fixed at (21.85, 15.40), which is given the lower-left corner of the previous figures. The synchrotron oscillations are included

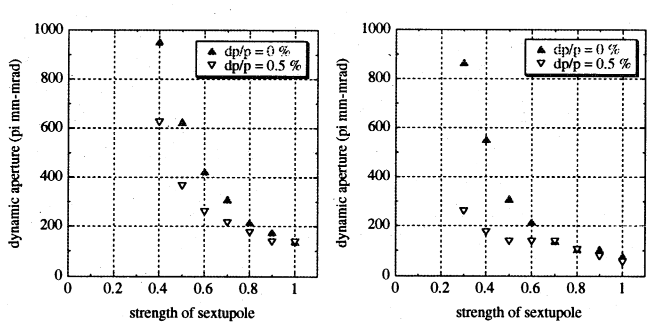

Figure 5: Dynamic apertures as a function of the sextupole strength. The sextupole strength of 1 makes the chromaticity zero. The left hand figure shows them in the high periodicity (24) lattice, and the right hand figure shows them in the one missing sextupole lattice. Synchrotron oscillations at the injection energy are included.

in that calculation. Two initial momentum spread, 0 and 0.5 % are compared. As shown in Fig. 5, the smaller is the strength of the sextupole magnets, the larger is the dynamic aperture obtained, as expected. Also, similar magnitude of the dynamic aperture in a high periodicity lattice is retrieved in the lattice with one missing sextupole if the sextupole strength is decreased to 70~60 %. A particle with a momentum spread of 0.5 % has the same tendency as a 0 % spread but is somewhat less sensitive to the strength.

5 Tune Shift

As another measure of the nonlinearity, we have looked at the tune shift as a function of the momentum spread and betatron oscillation amplitudes. The higher periodicity lattice is examined and the operating tune is fixed at (21.85, 15.40). The sextupole magnets are excited to make the chromaticity zero.

Since there are only two families of sextupole magnets to correct the chromaticity, no negligible higher order momentum dependence of the tune is observed. It is around 0.005 under nominal operation, where the maximum momentum spread is 0.5 %. If the number of sextupole families is increased, the higher order dependence is more suppressed. The defocusing sextupole magnets are divided into two families, and the vertical tune shift becomes much smaller. We adjusted the strength of the three families of sextupole so as to obtain the smallest tune shift in the momentum range of +-0.1 %. Increasing the number of sextupole families means an increase in the power supply units and more complex control. The advantage which we gain due to more sextupole families is marginal.

The transverse tune is a function of the betatron amplitude because of the higher order effects of the sextupole mag-

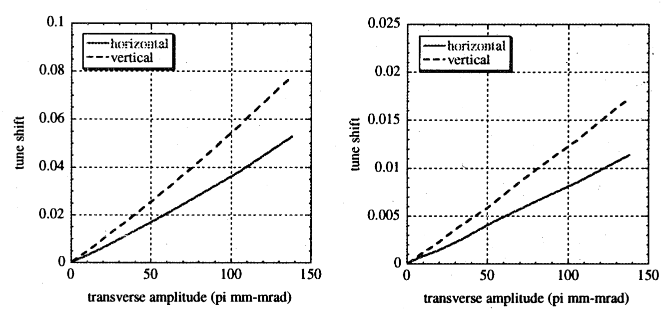

Figure 6: Amplitude dependence of the tune shift. With a full correction of the chromaticity (left) and half correction (right).

nets. When the sextupole is fully excited, the tune shift at an amplitude of 54 π mm-mrad, which is the physical aperture, becomes 0.02 in the horizontal and 0.03 in the vertical, as shown in Fig. 6 (left). The tune shift depends almost linearly on the amplitude, obviously due to the leading term of the octupole. The deviation from a linear relation at large amplitude, however, indicates that higher order effects than octupole are also noticeable. When the strength of the sextupoles is halved, the slope becomes almost one fourth. At the same time, higher order effects than octupole are reduced, as shown in Fig. 6 (right).

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