DESIGN AND BEAM DYNAMICS ISSUES OF THE JHF SYNCHROTRONS

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Abstract

The JHF synchrotrons, 50 GeV main ring and 3 GeV booster, aim to provide the beam intensity of 200 μA and 10 μA, respectively. Both will be the highest intensity proton synchrotrons among the ones with similar energies. In order to minimize beam loss, crucial beam optics and dynamics issues, such as an imaginary transition γ lattice for the main ring and space charge effects in the booster, are studied. We will discuss the present status of these studies.

1 INTRODUCTION

Japan Hadron Facility (JHF) is a multipurpose facility for elementary particle physics to biology. The accelerators accordingly provide two different types of beam; 3 GeV with 200 μA and 50 GeV with 10 μA. For any purpose, most of the proton beams are used for the production of secondary particles so that the key parameter of those synchrotrons is beam intensity.

It is inevitable that operation of high energy accelerator radio-activates machine components and tunnel. That has been on an allowable level until now since the beam intensity in the present running synchrotrons is not high. The key to success of high intensity synchrotrons, such as JHF ones, however, is the design to minimize beam loss and preparation of handling of beam loss if any.

There is always a question whether there is an optimized lattice structure for a high intensity machine. One says that the beta functions should be as uniform as possible. Another says that large dispersion function increases the beam size without increasing transverse emittance. Surely, those statements have their plausible reasons which we can understand to some extent. However, we adopted a more conservative approach. Our basic lattice structure is FODO.

In this paper, first we explain the lattice for the 50 GeV main ring. The imaginary transition energy lattice and its beam dynamics issues; dynamic aperture, are discussed. Secondly, after introducing the 3 GeV booster lattice briefly, space charge effects are analyzed. There we claim that the coherent tune shift should not cross a resonance condition. That is a new criterion which does not depend on incoherent tune shift or Laslett tune shift.

JHF Accelerator Design Study Report [1] has been recently compiled. Most of the study to be discussed in this paper are based on that report except the one on space charge effects, which have been further investigated by recent simulation study.

2 50-GEV MAIN RING

2.1 Imaginary transition energy lattice

The JHF 50 GeV main ring has a lattice with imaginary transition energy by missing bend module in the arc as shown in Fig. 1. Although the packing factor, defined as a ratio of the total bending magnet length to the total circumference, is not high compared with more conventional type of lattice, we are free from the beam loss inevitably at the transition energy. The transition energy of the lattice can be varied in wide range with minimum deviation of lattice functions [2].

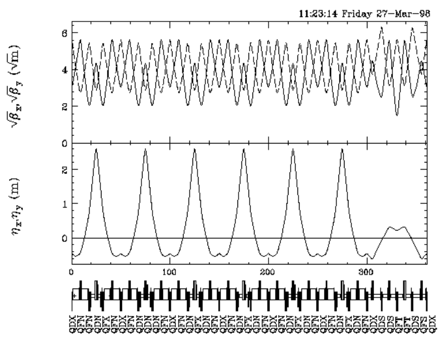

Figure: 1 Lattice functions of a quarter of the main ring.

There are four different types of quadrupoles in the arc and another four types of quadrupoles in the insertion. In the reference design, the phase advance in the insertion is chosen as 2π in the horizontal direction and π in the vertical one so that the insertion is transparent and the lattice functions in the arc are same as that without the insertion. On the other hands, some operations such as slow extraction and one with internal target require zero dispersion in the insertion. In order to satisfy those requirements, some variation of the reference lattice is also proposed.

may reduce dynamics aperture with chromaticity correction sextupoles. First, the number of sextupole is less and the strength of each sextupole tend to be high compared with normal FODO lattice. Because of small or negative dispersion around some quadrupole magnets, not all the place next to quadrupole is suitable for sextupole. Secondly, where the dispersion is high, the beta function of both planes are similar, so that sextupole focusing and defocusing effects tend to cancel each other.

By installing three sextupole families, we correct the chromaticity to zero and find out dynamic aperture. Figure 3 is the dynamics aperture surveyed in tune space near the nominal tune. First of all, the dynamic aperture is at least twice as much as physical aperture of 54 π mm mrad. It is large enough for the main ring. Secondly, there are only resonance line of $\nu x+2\nu y=56$, where 56=2x28 (# of cell), appears. That comes from the phase advance of the insertion. The choice of phase advance of 2π for horizontal and π for vertical in the insertion makes the insertion transparent for third or even higher order resonances.

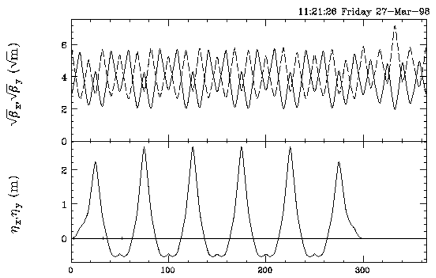

Figure: 2 Lattice functions with dispersion suppressor.

Figure 2 is the lattice with dispersion suppressor to make a dispersion in the insertion zero. The price we have to pay to have dispersion suppressor is the increased number of quadrupole family. Now, instead of four types of quadrupoles in the arc, we need ten families. Although the dispersion function is a little bit distorted by the dispersion suppressor, the requirement of negative momentum compaction factor is fulfilled.

2.2 Dynamic aperture

With the nominal tune of (21.8, 15.3), the chromaticity would be as high as -25. Since the momentum spread is assumed as +-0.5%, the tune shift due to chromaticity effects becomes +-0.1. That is the same order of space charge tune shift. The chromaticity correction with sextupoles is necessary.

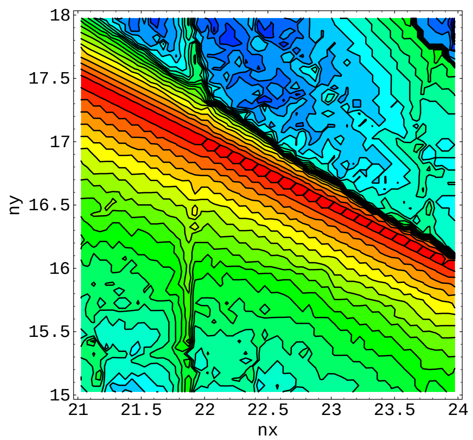

Figure: 3 Dynamic aperture surveyed in 2-D tune space. The darkest gray means zero aperture and the lightest one four times as much as the physical aperture in size.

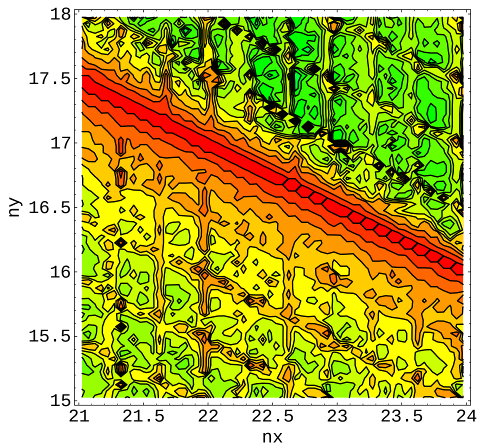

Figure: 4 Dynamic aperture with one missing sextupoles.

One of the issues on imaginary transition energy lattice is a dynamic aperture. There are two reasons that

Unfortunately, however, the high symmetry of sextupole location may be destroyed because of the injection channel. Since there is a strong demand that the injection line from 3 GeV to 50 GeV should be the minimum length, the beam injection takes place in the middle of one arc, where one sextupole have to be removed.

When one sextupole is removed and high symmetry of sextupole is broken, the dynamics aperture is considerably reduced as shown in Fig. 4. At the same time, all harmonic components appears as a resonance line. What we can do in that case is to adjust the chromaticity half way, say -10, and recover dynamic aperture. Of course, all harmonic components still exist, but become weaker accordingly.

3 3-GEV BOOSTER

3.1 Lattice overview

The reference design lattice for 3 GeV booster consists of 28 FODO cell structure [1], very similar to the present 12 GeV proton synchrotron, since the fitting to the existing tunnel is taken as a first priority. The better fitting results in more room for maintenance and also possible evacuation and reinstallation of one magnet without affecting the alignment of the other magnets. On the other hand, the normal FODO cell automatically determines transition energy as about the horizontal tune, which is above 3 GeV in the booster. Alternative lattice designs together with its pros and cons are described in another paper [2]. In order to study beam dynamics issues in the following, space charge effects for example, we assume the reference lattice as shown in Fig. 5 (you may find minor differences from the one in [1])

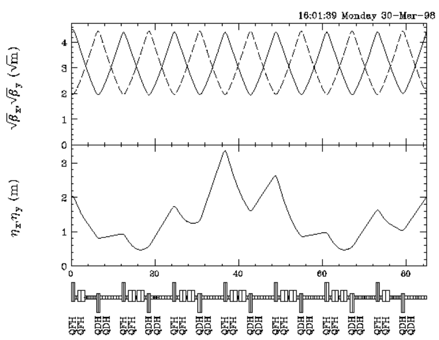

Figure: 5 Lattice functions of a quarter of the booster.

3.2 Space charge effects

If we plug in all necessary parameters to calculate incoherent space charge tune shift, it becomes -0.37. It is large taking into account third or fourth integer resonances.

In the course of simulation study to investigate emittance growth and beam loss, however, we found that the incoherent tune shift does not necessarily tells the resonance condition which deteriorates a beam. The coherent tune such as quadrupole, sextupole, and octupole modes and their resonances with lattice errors as well as a beam itself is the one that is directly related to the emittance growth and beam loss.

The tune shift of coherent mode was, in fact, first calculated by F. Sacherer for a beam with uniformly distributed particles in 2-D [3]. In that case, the coherent quadrupole tune shift is 5/8 times the incoherent tune shift. When the coherent shift shifted by space charge force hits the quadrupole resonance, a whole beam becomes unstable according to his study.

The following is the simulation results taking the JHF 3 GeV booster as a test lattice. We assume that the lattice has sextupole field errors. The bare tune is (6.85, 5.81) and the particle distribution is waterbag.

When the incoherent tune shift is around -0.25, the emittance growth occurs as shown in Fig. 6 (a). In the figure, only magnitude of tune shift is labeled. Since the distance between the bare tune and a resonance ($3\nu x=20$) is 0.18, the incoherent resonance condition is satisfied with much lower intensity. On the other hand, if one looks at the coherent mode frequency of sextupole, it becomes an integer of 20 when the emittance growth is observed as shown in Fig. 6 (b). In this case, the coherent tune shift is 0.7 times smaller than the incoherent tune shift.

When the strength of error fields is reduced, the emittance growth becomes less, but of course it occurs at the same tune shift. Similar explanation of the emittance growth by coherent mode shift are applicable to quadrupole and octupole mode, which is confirmed by simulations.

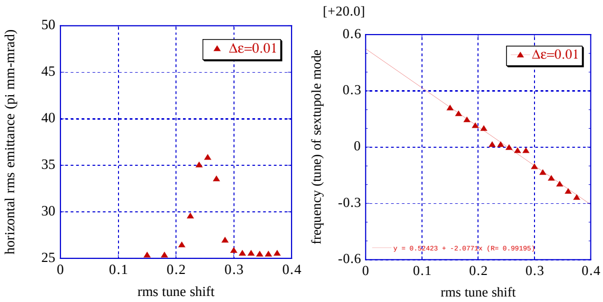

Figure: 6 (a) Emittance growth and (b) coherent tune of sextupole when the test lattice has sextupole field errors.

4 SUMMARY

The 50 GeV main ring and the 3 GeV booster are designed in order to accommodate the design intensity. In the main ring, beam loss at the transition energy is eliminated by adopting the imaginary transition energy lattice. Another issue is the dynamic aperture. As long as the high symmetry of sextupole configuration is kept, it is at least twice as much as the physical aperture. When the symmetry is broken, the half-way correction of chromaticity is also considered. In the booster, space charge effects is really a concern. We found that the coherent tune shift explains the emittance growth and beam loss much better than the incoherent tune shift. Further study of that coherent mode analysis is in progress.

5 REFERENCES

[1] `JHF Accelerator Design Study Report', KEK Report 97-16, March 1998.

[2] Y. Ishi, et. al., `Lattice design of the JHF synchrotrons', in these proceedings.

[3] F. Sacherer, `Transverse space-charge effects in circular accelerators', UCRL-18454, October 1968.