# HIGH BEAM CURRENT HANDLING IN THE JHF MAIN RING

S. Machida, Y. Mori, C. Ohmori, Y. Ishi, S. Shibuya, and M. Tomizawa
KEK-Tanashi, 3-2-1 Midori-cho, Tanashi-shi, Tokyo, 188 JAPAN

*Abstract*

The Japan Hadron Facility (JHF) synchrotrons are expected to store and accelerate ten times larger number of protons than that of the machines under operation ($2x10^{14}$ protons in the 50GeV main ring and $5x10^{13}$ protons in the 3GeV booster). A stable operation with a very small beam loss is essential. Beam dynamics not only of the beam core but of the tail and halo should be considered. More specifically, transverse space charge effects have to be taken into account from the design stage of the lattice. In that sense, a conventional way of the lattice optimization, such as maximizing dynamic aperture and minimizing smear, may not be applicable. We have started to simulate commissioning of a high intensity machine. As a first attempt, the tune survey with space charge effects is simulated. Beam loss and emittance growth are examined in the wide range of tune space. Those results are compared with dynamic aperture without space charge effects.

## 1 INTRODUCTION

The synchrotrons of the Japan Hadron Facility (JHF) are expected to deliver high energy and high intensity beams [1]. To obtain the average current of 10 μA in the 50 GeV main ring and 200 μA in the 3 GeV booster, the total number of particles in the rings becomes $2x10^{14}$ and $5x10^{13}$, respectively. That is more than ten times higher intensity than that of now available.

The total number of particles in a proton synchrotron is normaly limited by transverse space charge effects at the injection energy. Where the incoherent tune shift makes the tune of individual particle spread out in the large area of the tune space. The maximum allowable tune spread is around -0.2 to -0.7 depending on other machine parameters. For example, a slow cycling synchrotron such as the main ring, whose repetition rate is 0.3 Hz, forces the beams to stay at the injection energy for considerable time, say 1 s, and the allowable tune shift seems smaller than that of a fast cycling synchrotron such as the booster, whose repetition rate is 25 Hz.

Although one knows that space charge effects have to be taken into account to design a high intensity proton synchrotron, it is not clear how to incorporate the effects in designing a synchrotron. The best one can do is to calculate tune shift. A lattice and its operating point are determined almost independently of the effects.

Instead, one usually examine linear and nonlinear resonance structure in the tune space, and calculate dynamic aperture. Those procedures in most cases do not include space charge effects. One tries to find larger resonance free area in the tune space and enlarge dynamic aperture in a given lattice design by playing with phase advance of a unit cell, position of sextupole magnets, and so on. If it does not satisfy some requirements, one modifies the lattice or designs it from the scratch.

It is plausible that the optimized lattice and the best operating point without space charge effects should give reasonably stable operation even with strong space charge effects in reality. If necessary, further fine tuning can be done when the machine is constructed and commissioning is started. It is one of the reasons to leave a number of knobs available and makes the flexible lattice for the beam commissioning.

Recent progress of the beam tracking technique, however, makes it possible to simulate some of the commissioning procedures in a very realistic manner. Let us say ten years ago, most of them have been thought unrealistic even though not impossible. Nowadays, so called “dry run” of the machine has been tried extensitively everywhere a new machine is designed.

We study a possible way to visualize the commissioning of the JHF 50 GeV main ring and to incorporate the space charge effects from the design stage. We survery tune space and examine “dynamic aperture”, emittance growth, and beam loss with space charge effects included. Comparison of those results with conventional dynamic aperture survey without space charge effects is made.

## 2 JHF 50 GEV SYNCHROTRON

The main ring of the JHF is a 50 GeV synchrotron. In order to minimize beam loss, the lattice has been designed with imaginary transition energy. When we fixed the injection energy of 3 GeV and the extraction energy of 50 GeV, transition energy crossing during a ramping is inevitable unless the dispersion function is modulated and the momentum compaction factor is forced to be far from the nominal value. In our design, two missing bend magnets every three FODO cells introduce dispersion wave. The beta functions (βs) and dispersion function (η) of one quarter of the ring are depicted in Fig. 1. The whole ring makes four-fold symmetry.

The tune of the whole ring is adjusted in the following way. First, the arc of a superperiod is tuned to obtain a negative momentum compaction factor. Its nominal value is -0.001 and 31.6i in term of the Lorentz factor at the transition. At the same time, the phase

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advance of the arc is fixed to be 2π times [(total tune)/4-1] for the horizontal plane and 2π times [(total tune)/4-0.5] for the vertical. Secondly, the long straight insertion next to the arc is adjusted to connect βs, its derivative αs and η smoothly with the fixed phase advance of 2π for horizontal and π for vertical. In that way, lattice functions in the arc are not be altered by the long straight insertion. The momentum compaction factor is simply scaled with a ratio of the path length with and without the insertion.

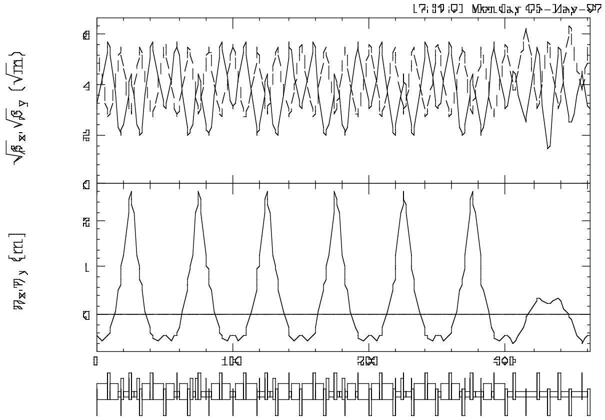

Figure 1: Lattice functions of one quarter of the 50 GeV main ring. Solid line on the top is the horizontal beta function and dashed line is the vertical one.

## 3 SPACE CHARGE MODELLING

Multi-particle tracking code has been employed to include space charge effects self-consistently. Based on the 3-D tracking code "Simpsons" [2], the algorism of the space charge calculation is simplified to gain the computational speed. It can be summarized as follows.

First, only 2-D transverse space charge effects are included. Beams are modelled as a cylindrical tube. The line density is fixed to the peak density of the actual bunched beam. The bunching factor is 0.3.

Secondly, in order to calculate the electric force, the particle distribution $n$ and the electric potential $\phi$ are decomposed in the azimuthal direction [3],

$$n = \sum_m n_m \exp(im\theta)$$

$$\phi = \sum_m \phi_m \exp(im\theta)$$

where $m$ is the mode number. The solution can be obtained from the equation,

$$\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial \phi_m}{\partial r}\right) - \frac{m^2}{r^2}\phi_m = -4\pi n_m$$

A test shows that simulation results does not change much if we take $m$ up to 2 (quadrupole mode). Another test shows that simulation results does not change much if we take more than $10^4$ macro particles.

Finally, space charge force is applied as a kick every 10 ns in the actual time scale. It corresponds to several kicks per a quadrupole focusing unit.

## 4 DYNAMIC APERTURE

Before simulating tune survey with space charge effects, we measure dynamic aperture in the same range of the transverse tune space without space charge effects. There is no misalignment errors or fabrication errors. Only nonlinearity comes from the chromaticity correction sextupoles. These sextupoles are excited to make the chromaticity zero in both planes. Twenty two circles in Fig. 2 indicate the tune points we measure the dynamic aperture. The fractional part of the tune is either 0.3 or 0.8 for the horizontal tune and 0.4 or 0.9 for the vertical one. All the circles together make a triangle area where the momentum compaction factor becomes negative with reasonable β maximum, around 35 m. Higher tunes in both horizontal and vertical can be obtained on paper with reasonable lattice functions. They are, however, not practical because of the strong quadrupole strength, more than 20 T/m, which is out of our specifications of the magnet.

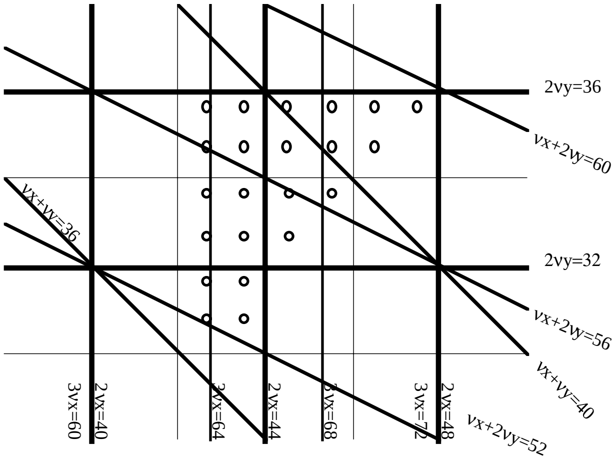

Figure 2: Tune space with the possible operating point of the 50 GeV main ring. Twenty two circles indicate the tune points we measure the dynamic aperture and survey emittance growth, beam loss, and "dynamic aperture" with space charge effects. Some systematic resonance lines are drawn with its order and harmonics.

Dynamic aperture is defined as the maximum amplitude of tracking particles survived for 1,000 turns. Table 1 lists it in the unit of a beam size whose emittance is 54 πmmmrad. Less than 1 means the dynamic aperture is smaller than the physical acceptance.

It is noticeable that the operating points along by the sextupole coupling resonance, νx+2νy=56, have small dynamic aperture, even smaller than the physical acceptance. On average, the dynamic aperture at the tune above the sextupole coupling resonance is larger than that below the resonance.

Table 1: Dynamic aperture at the tune points indicated in Fig. 2. The unit is a beam size whose emittance is 54 πmmmrad.

| | 21.30 | 21.80 | 22.30 | 22.80 | 23.30 | 23.80 (hor.) |
|---|---|---|---|---|---|---|
| 17.90 | 4.0 | 3.1 | 3.5 | 3.6 | 3.1 | 3.7 |
| 17.40 | 0.3 | 1.8 | 4.0 | 3.8 | 3.7 | |
| 16.90 | 1.2 | 0.6 | 0.4 | 3.9 | | |
| 16.40 | 1.9 | 1.7 | 1.4 | | | |
| 15.90 | 2.0 | 2.0 | | | | |
| 15.40 | 2.9 | 2.1 | | | | |
| (ver.) | | | | | | |

## 5 TUNE SURVEY WITH SPACE CHARGE

We track 10,000 macro-particles for 64 turns at the injection energy of the 50 GeV main ring at the same operating points above.

Table 2: Survival rate (%) at each operating point. Beam intensity is 6.9 A.

| | 21.30 | 21.80 | 22.30 | 22.80 | 23.30 | 23.80 (hor.) |
|---|---|---|---|---|---|---|
| 17.90 | 100. | 100. | 100. | 100. | 100. | 100. |
| 17.40 | 1. | 99. | 98. | 100. | 100. | |
| 16.90 | 95. | 100. | 2. | 92. | | |
| 16.40 | 100. | 100. | 94. | | | |
| 15.90 | 100. | 100. | | | | |
| 15.40 | 100. | 100. | | | | |
| (ver.) | | | | | | |

Table 3: Final rms emittance at each operating point. Beam intensity is 6.9 A.

| | 21.30 | 21.80 | 22.30 | 22.80 | 23.30 | 23.80 (hor.) |
|---|---|---|---|---|---|---|
| 17.90 | 14.0 | 14.2 | 13.3 | 13.9 | 13.9 | 14.5 |
| 17.40 | N/A | 24.7 | 13.1 | 15.5 | 13.8 | |
| 16.90 | 13.2 | 15.9 | 29.5 | 28.6 | | |
| 16.40 | 13.4 | 14.0 | 12.5 | | | |
| 15.90 | 13.3 | 14.1 | | | | |
| 15.40 | 13.3 | 13.8 | | | | |
| (ver.) | | | | | | |

The transverse particle distribution is gaussian. With the nominal intensity of 6.9 A and the initial rms emittance of 13.2 πmmmrad, the rms tune shift becomes -0.17. Table 2 and 3 show the survival rate in % and the final rms emittance in πmmmrad, respectively. We consider a particle is lost when its amplitude is more than 0.1 m. The final emittance is either horizontal or vertical whichever the larger one.

Both tables show that, in principle, where the dynamic aperture is small, beam loss occurs. The loss is accompanied by the emittance growth at the points above the sextupole coupling resonance, but that is not the case below the resonance. In addition, because of the space charge tune shift, an operating point with large dynamic aperture such as (22.80, 16.90) also suffers.

Table 4: Survival rate (%) when the intensity is doubled.

| | 21.30 | 21.80 | 22.30 | 22.80 | 23.30 | 23.80 (hor.) |
|---|---|---|---|---|---|---|
| 17.90 | 100. | 100. | 100. | 100. | 100. | 100. |
| 17.40 | 89. | 70. | 100. | 99. | 100. | |
| 16.90 | 100. | 96. | 94. | 60. | | |
| 16.40 | 100. | 100. | 100. | | | |
| 15.90 | 100. | 100. | | | | |
| 15.40 | 100. | 100. | | | | |
| (ver.) | | | | | | |

Table 5: Final emittance when the intensity is doubled.

| | 21.30 | 21.80 | 22.30 | 22.80 | 23.30 | 23.80 (hor.) |
|---|---|---|---|---|---|---|
| 17.90 | 20.8 | 16.0 | 16.2 | 14.0 | 17.8 | 15.2 |
| 17.40 | 15.0 | 51.0 | 18.5 | 19.2 | 18.9 | |
| 16.90 | 17.5 | 16.7 | 15.2 | 43.9 | | |
| 16.40 | 16.8 | 13.8 | 15.8 | | | |
| 15.90 | 16.1 | 16.1 | | | | |
| 15.40 | 15.7 | 14.0 | | | | |
| (ver.) | | | | | | |

Now the intensity is doubled and Table 4 and 5 show the results. Because of the tune spread, the beam loss is smoothed out. The emittance growth occurs at almost all the points. As far as the table shows, the operating point with the minimum emittance growth (21.80, 16.40) does not necessarily corresponds to the point with large dynamic aperture.

## REFERENCES

[1] Y. Mori, `Japan Hadron Facility', these proceedings.
[2] S. Machida, 'The Simpsons Program', AIP Conference Proceedings 297, p.459, 1993.
[3] M. L. Sloan, private communications.