SIMULATION CALCULATION OF LONGITUDINAL BEAM DISTRIBUTION IN J-PARC MAIN RING

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Abstract

The J-PARC accelerator complex consists of 3 accelerators, a linear accelerator, a rapid cycle synchrotron (RCS) and a Main Ring (MR) synchrotron. Simulation calculation of longitudinal beam distribution in J-PARC Main Ring has been performed. The effect that RF voltage pattern, space charge, and beam loading was examined.

INTRODUCTION

The J-PARC (Japan Proton Accelerator Research Complex) is an accelerator institution which supplies the high intensity proton beam. J-PARC has three proton accelerators: a 400 MeV linear accelerator (currently operating at 180 MeV), a 3 GeV rapid-cycling synchrotron (RCS) and a 50 GeV (currently 30 GeV) main ring (MR). Simulation calculation has been performed to longitudinal beam distribution in MR. Beam simulation calculation was roughly divided into two kinds.

(1) We compare tune shifts, which the space charge effect causes to, by five kinds of voltage patterns.

(2) When a charged particle passes through the cavity, the image current on the cavity wall induce beam loading voltage. We calculate effects of beam loading voltage to beam losses by four kinds of voltage patterns. And calculation results are compared with the actual beam loss.

SIMULATION CONDITIONS

Main parameters are shown in Table 1. To simulate the motion of particle, we used that derivative terms in synchrotron equation of motion

$$\frac{d}{dt}\left(\frac{\Delta E}{h\omega_{revs}}\right) = \frac{eV}{2\pi h}\left(\sin\phi - \sin\phi_s\right) \tag{1}$$

$$\frac{d\Delta\phi}{dt} = h\omega_{revs}\frac{\eta}{\beta^2}\left(\frac{\Delta E}{E_s}\right) \tag{2}$$

have a relation like following formula

$$\frac{d\Delta E}{dt} \simeq \frac{(\Delta E)_{turn}}{T_{revs}}. \tag{3}$$

Table 1: Main Parameters

Path of 50 GeV ring	1567.50 m
Injection Kinematic Energy	3 GeV
Extraction Kinematic Energy	30 GeV
Bending Radius	89.381 m
Momentum Compaction Factor	-0.001
Harmonic Number	9
Injection Time	0.04-0.12 s
Acceleration Time	0.5-1.9 s
parabolic:	0.1
linear:	0.3-1.7
parabolic:	0.1

CALCULATION RESULTS AND COMPARISON BY ACTUAL BEAM LOSS

Comparison of Different RF Voltage Patterns

Tune shift induced by the space charge force [1], [2] is given by

$$\Delta\nu_{sc} = \frac{N_B r_p}{2\pi\epsilon_y\beta^2\gamma^3}\frac{1}{B_f}, \tag{4}$$

where N_B is total charge, r_p is classical radius of proton, ϵ_y is transverse emittance and B_f is the bunching factor:

$$B_f = \frac{I_{average}}{I_{peak}}. \tag{5}$$

To estimate effects of RF voltage patterns we compare the value of $1/(\beta^2\gamma^3 B_f)$. Because the value of $1/(\beta^2\gamma^3 B_f)$ is purely related to the longitudinal component of the equation 4.

Parameters used in this section are shown in Table 2

Table 2: Selected Machine Parameters

RCS beam power	322 kW
RCS extraction fundamental RF voltage	150 kV
RCS extraction 2nd harmonics RF voltage	30 kV
MR injection fundamental RF voltage	80 kV
MR acceleration fundamental RF voltage	200 kV
MR 2nd harmonics RF voltage	0 kV
Injection Time	0.04 s
Acceleration Time	1.9 s
parabolic:	0.1
linear:	1.7
parabolic:	0.1

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Five RF voltage patterns compared in this section are shown in Figure 1. Only a voltage go up gradient is different, every patterns are same injection voltage and maximum acceleration voltage. For example, the value of $1/(\beta^2\gamma^3 B_f)$ vs time of pattern (I) is shown Figure 2. When voltage begins to go up, the value of $1/(\beta^2\gamma^3 B_f)$ is also go up. Because if voltage begins to go up, separatorix orbit will also go up along momentum axis, and this means that beam flatness decreases. If beam flatness decreases, the value of $1/(\beta^2\gamma^3 B_f)$ increases which can be understood by formula 4 and 5.

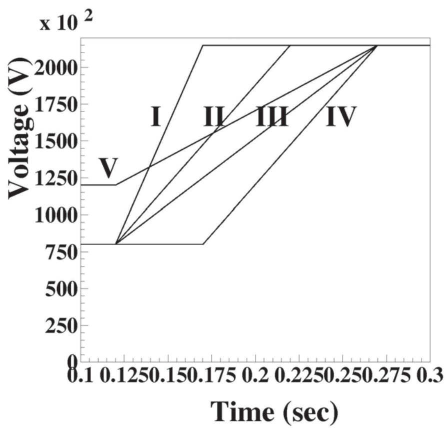

Figure 1: RF voltage pattern.

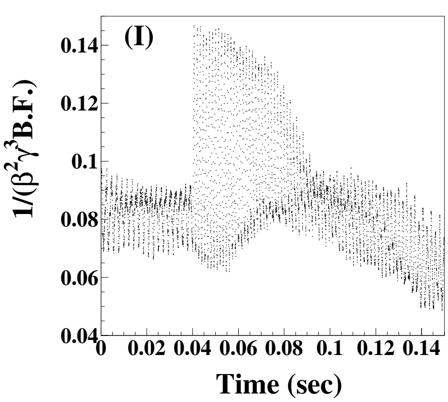

Figure 2: Calculation results of $1/(\beta^2\gamma^3 B_f)$ when beam are accelerates by the RF voltage pattern (I).

The maximum value of $1/(\beta^2\gamma^3 B_f)$ for every RF voltage pattern are shown in Table 3. It turns out that the maximum value of $1/(\beta^2\gamma^3 B_f)$ is also small that a voltage go up gradient is small.

Table 3: The Maximum $1/(\beta^2\gamma^3 B_f)$ Value for Various RF Voltage Patterns

RF voltage pattern	$1/(\beta^2\gamma^3 B_f)_{max}$
I	0.145
II	0.125
III	0.115
IV	0.11
V	0.105

Effects of Beam Loading to Beam Loss

The voltage seen by the beam is the sum of the voltage produced by the generator current and the beam induced current. In this section, the influence of the voltage which the beam itself induces to beam loss is examined.

To calculate beam loading voltage, firstly Fast Fourier Transform(FFT) of the beam is carried out. After that the voltage which a beam induced was calculated by taking the product of the frequency component of the beam and the impedance of cavity.

The parameter used for calculation of this section is shown in Table 4 also including the impedance characteristic of the cavity.

Table 4: Selected Machine Parameters

RCS beam power	300 kW
RCS extraction fundamental RF voltage	60 kV
RCS extraction 2nd harmonics RF volt.	30 kV
MR injection fundamental RF voltage	80-120 kV
MR acceleration fundamental RF volt.	215 kV
MR 2nd harmonics RF voltage	26.7 kV
The resonance frequency of cavity	1.7173 MHz
Impedance (Gap)	1113.57 Ω
Number of Gaps	17
The Q-factor	22.7
Injection Time	0.17 s
Acceleration Time	1.9 s
Number of macro particles	4680

Five RF voltage patterns compared in this section are shown in Figure 3. Only a voltage go up gradient is different, pattern (I)-(IV) are same injection voltage (80 kV) and maximum acceleration voltage (215 kV). Only the pattern (V) has high injection voltage (120 kV). Therefore pattern (V) has the smallest voltage go up gradient.

Calculation results are shown in Figure 4. There are smallest losses by the pattern (V). There are largest losses by the pattern (IV). Patterns (I), (II) and (III) are between two. Since the pattern (V) has higher injection voltage, influence of beam loading voltage is relatively small. Therefore losses of the pattern (V) is smallest. Influence of pattern (IV) which has longest low injection voltage span, is largest. From this we understand that operating on higher voltage can reduce the influence of beam loading.

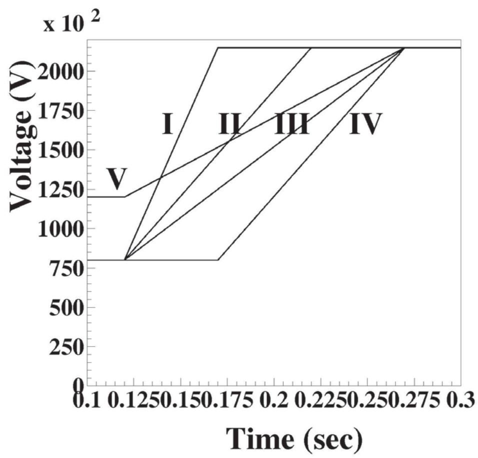

Figure 3: RF voltage pattern.

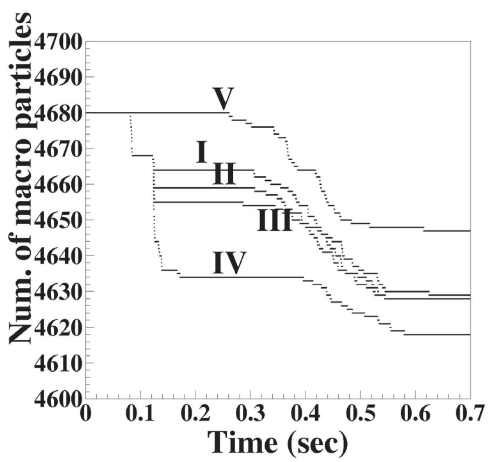

Figure 4: Beam losses for every RF voltage pattern.

However, as the previous section described, when voltage raised the fall of bunching factor will be caused and loss will be increased. Calculation results pertaining to this section are shown in Table 5.

Table 5: Calculation Results

RF voltage pattern	loss(%)	$1/(\beta^2\gamma^3 B_f)_{max}$
I	1.1	0.122
II	1.1	0.112
III	1.1	0.108
IV	1.3	0.097
V	0.7	0.111

The pattern (III) is the best when patterns (I), (II) and (III) are compared. When pattern (III) and (V) are compared, there small loss by the pattern (V) which has higher injection voltage, but $1/(\beta^2\gamma^3 B_f)$ become larger.

Beam losses of actual beam are shown in Figure 5 (only 1 batch injection). It looks there is the relation between the value of $1/(\beta^2\gamma^3 B_f)$ and a loss, when patterns (I), (II) and (III) are compared. There are smaller losses that the value of $1/(\beta^2\gamma^3 B_f)$ is low. The max values of $1/(\beta^2\gamma^3 B_f)$ are almost same between pattern (II) and (V), but there is larger loss by the pattern (V). While injection period the pattern (V) has a higher value of $1/(\beta^2\gamma^3 B_f)$ because injection voltage of pattern (V) is higher than others. Therefore the start of loss by pattern (V) become early and total loss is larger than pattern (II). It seems that there is small influence of beam loading at this intensity since loss by pattern (V) larger than pattern (II) and (III).

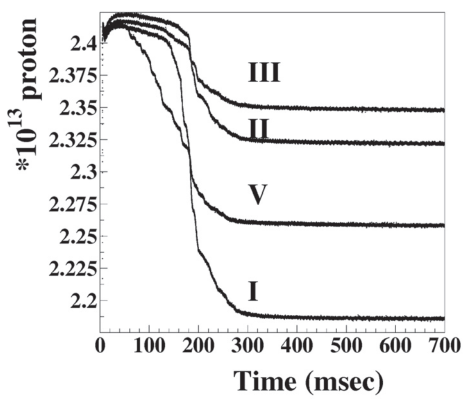

Figure 5: Beam losses measured by DCCT.

SUMMARY

Simulation calculation of longitudinal beam distribution in J-PARC Main Ring has been started. We will more comparison to an actual beam and include the more realistic effect.

REFERENCES

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