BEAM INJECTION AND LONGITUDINAL EMITTANCE CONTROL IN THE JKJ 50 GEV SYNCHROTRON

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Abstract

In high intensity proton synchrotrons such as those of the JAERI-KEK joint high intensity proton accelerator facility(JKJ), it is important to make peak space-charge density as low as possible. In the case of the 50 GeV synchrotron of the JKJ, it is required that the longitudinal emittance of an injected beam is enlarged more than 10 eVs with keeping the bunching factor more than 0.3. In this paper, the scheme of the longitudinal beam manipulation in the JKJ 50 GeV synchrotron is described with simulation studies.

1 INTRODUCTION

The accelerator of the JKJ project is composed of a 400MeV linac, 3GeV rapid-cycle synchrotron(RCS) and 50GeV main ring(MR) [1]. The number of circulating protons are 8.3×10^{13} in the RCS and 3.3×10^{14} in the MR, respectively. In such a high intensity machine undesired beam loss is one of the most serious problems.

In order to avoid beam loss, we have two requirements on the longitudinal beam distribution in the MR;

- We have to keep the bunching factor at the injection energy higher than 0.3, which corresponds to the betatron tune shift of 0.17.
- We have to enlarge the longitudinal emittance over 10eVs to avoid micro-wave instability at the flat-top energy.

Those conditions should be realized by employing suitable longitudinal manipulations, including precise voltage and phase programming of the rf system and an rf-phase modulation. About the second requirement, we have two choices; The emittance is enlarged at the injection energy, or during acceleration.

We have developed a one-dimensional multi-particle simulation-code to simulate the time-developments of the bunching factor in several operation conditions of the rf. This paper shows the simulation results at the injection energy to explain why dual-harmonic rf is necessary and how the requirements above are satisfied.

2 SIMULATION METHOD

The simulation-code simply integrates turn by turn the well-known coupled differential equations for rf-phase($\Delta\phi$) and momentum deviation(Δp);

$$\Delta\phi_{j,n+1} = \Delta\phi_{j,n} + 2\pi h\eta\frac{\Delta p_{j,n}}{p_s}, \qquad (1)$$

$$\Delta E_{j,n+1} = \Delta E_{j,n} + eV_{\rm rf}\sin(\Delta\phi_{j,n+1}), \qquad (2)$$

where ΔE is related to Δp by

$$p_s + \Delta p = \sqrt{(E_s/c + \Delta E/c)^2 - (mc)^2}. \qquad (3)$$

In the above equations, $j(\leq J)$ is the particle-ID, n is the turn number, h and η are the harmonic number and slippage factor, m is the proton mass, and E_s and p_s are the synchronous energy and momentum, respectively. Both pace-charge effect and wake-field are not included in the simulation. As an initial condition, a bucket is filled with macro-particles resulted from the simulation of the RCS [2]. The bunch length and the momentum spread of that beam are 44$^{\rm o}$ and 3.9MeV rms.

The bunching facotor($B_{\rm f}$) is defined by the average beam-intensity devided by the peak beam-intensity. In evaluating the peak intensity turn by turn, we make a histogram for $\Delta\phi$ with binning number $N_{\rm H}$, and smoothed it with four bins neighboring. In a normalization for beam-intensity, where the average one is $J/N_{\rm H}$, the peak beam-intensity is just the maximum incident of the histogram ($j_{\rm peak}$). Thus, the bunching factor is given by

$$B_{\rm f} = \frac{N_{\rm H}\, j_{\rm peak}}{J}. \qquad (4)$$

Smoothing the peak-height makes statistic error small, but, it is not reliable if the peak width is comparable to the bin size. Therefore, we will show the bunching factor with- and without smoothing, together.

3 INJECTION MATCHING

3.1 Single-Harmonic RF

First, we observed the time-development of the bunching factor with a fixed-amplitude sinusoidal(single-harmonic) rf. The rf-voltage is determined by the bunch length and momentum spread of the injected beam. From the view-point of suppressing the quadrupole mode synchrotron oscillation, the matching rf-voltage, which is calculated to be 21kV, is desirable. However, such a low rf-voltage is not acceptable, because the bucket-area is too narrow to capture the injected beam completely. Hence, we chose the rf-voltage of 40kV in the simulation, where momentum filling-factor(rms momentum spread devided by the bucket height) is 0.6. The other parameters are listed in Table 1.

The simulation result is shown in Fig. 1. In the bottom plot of the Fig. 1, a large-amplitude oscillation is observed with a periodicity of about twice synchrotron

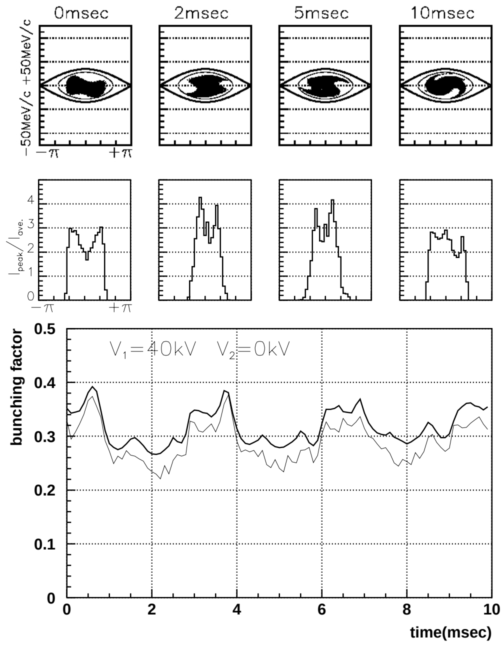

Figure 1: Simulation result with V_1=40kV. Phase-space distribution(top), bunch profile(middle) and bunching factor(bottom) with(thick) and without(thin) smoothing as functions of time.

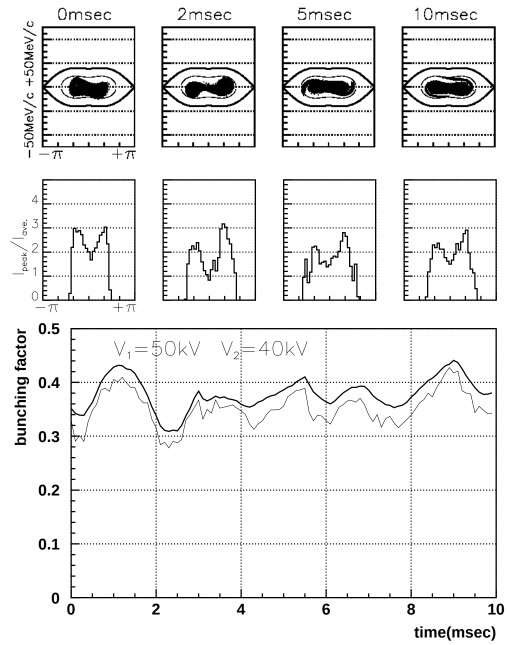

Figure 2: Simulation result with V_1=50kV and V_2=40kV. Phase-space distribution(top), bunch profile(middle) and bunching factor(bottom) are shown as functions of time.

frequency(2×175Hz); That is the quadrupole-mode synchrotron-oscillation caused by injection-mismatch. The bunching factor becomes below 0.3 due to the quadrupole osillation. Thus, our requirement can not be satisfied by a single-harmonic rf. It is important to suppress the quadrupole oscillation by minimizing the injection-mismatch; That will be accomplished by employing a dual-harmonic rf, which is described below.

3.2 Dual-Harmonic RF

We tried dual-harmonic rf, where the second-harmonic rf was added with the fundamental component. The purpose is to make the bucket shape flat around its peak and suppress the quadrupole oscillation. The rf voltages are 50kV for the fundamental and 40kV for the second-harmonic rf, respectively.

Figure 2 shows the result. The quadrupole oscillation became smaller compared to that without the second-harmonic rf(Fig. 1). The bunching factor was kept more than 0.3 in the simulated period of 10msec. With the help of the dual-harmonic rf, we could reduce the injection-mismatch to keep the bunching factor below 0.3. Thus, it is necessary to use a dual-harmonic rf in order to reduce the peak beam-intensity.

Table 1: Main parameters of the multi-particle simulation of the JKJ-MR at the injection energy.

parameter	value
mass of a particle	938.27231 MeV
charge of a particle	1 e
harmonic number	9
rf frequency	1.67 MHz
maximum rf voltage	280 kV
kinetic energy	3.0 GeV
slippage factor	0.0578
number of macro-particles	10687
histogram binning	40/rf-bucket

4 EMITTANCE CONTROL

Next subject is to enlarge the longitudinal emittance while keeping the high bunching factor. Though it is not necessary to be done before acceleration, we tried to enlarge the emittance at the injection energy,

4.1 Methods to Enlarge Emittance

There are at least two methods to enlarge the emittance. The first method is to apply some kind of noise or modulation on the rf, such as rf phase modulation, and high frequency amplitude modulation. The other is to change the rf voltage rapidly to excite a mismatch, which causes the filamentation. In this study, we adpated the phase-modulation and mismatch-excitation.

The phase of the rf was modulated in a sinusoidal function of time. Since the frequency of the modulation was chosen near the twice synchrotron frequency, a parametric

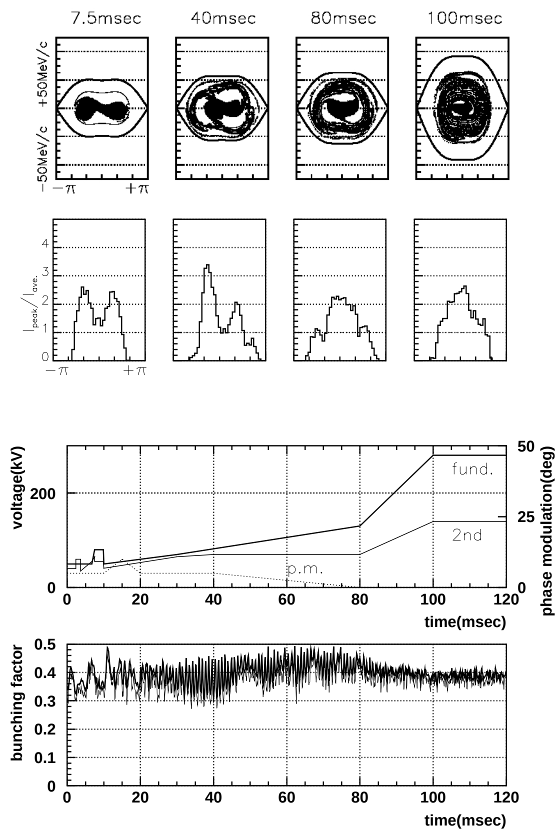

Figure 3: Simulation result for emittance blow-up. Mismatch excitation and phase modulation are used here. Phase-space distribution(top), program of the rf-voltages and phase modulation(middle), and bunching factor(bottom) are shown as functions of time.

resonance occurs to blow-up the emittance. The amplitude of the phase-modulation was $5^o \sim 10^o$.

The mismatch-excitation must be done very carefully, because the consequent quadrupole-oscillation may decrease the bunching factor at its minimum. The dual-harmonic rf system enables to enlarge the emittance without bunching factor reduction. We have two methods;

- rapidly increase (decrease) only the second-harmonic (fundamental) rf voltage when a quadrupole oscillation is in the phase where bunch is narrowest.
- rapidly decrease (increase) only the second-harmonic (fundamental) rf voltage when a quadrupole oscillation is in the phase where the bunch is widest.

4.2 Simulation Result

Figure 3 shows the best result in this moment. Phase-modulation and mismatch-excitation were applied in the regions 0∼80msec and 0∼10msec, respectively. The longitudinal full emittance is enlarged up to 14eVs in 80msec, while keeping the bunching factor higher than 0.3. At 100msec, the matching beam was obtained in the bucket with 280kV rf voltage, which is necessary in acceleration,

5 SUMMARY

We have studied the manipulation of the beam of the JKJ 50GeV main ring at the injection energy. Simulation studies showed that it is necessary to use dual-harmonic rf, otherwise the peak beam-intensity becomes high and space-charge instability may occur. Optimum capture voltages are 50kV for fundamental and 40kV for second-harmonic rf. A suitable rf-voltage programming just after the beam capturing was also studied. In the simulation, the longitudinal emittance could be enlarged up to 14eVs in 80msec while keeping the low peak intensity.

6 REFERENCES

[1] JKJ accelerator group, 'Accelerator Technical Design Report for High-Intensity Proton Accelerator Facility Project', to be published.

[2] M. Yamamoto, *et al.*, 'Longitudinal Emittance Control and Beam Loading Effects on Proton Synchrotron in JAERI-KEK Joint Project', PAC'2001, Chicago, 2001.