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The Simulation of the Bunch Compression in the JHP 1 GeV Compressor Ring

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Abstract The bunch compression process in the 1 GeV proton compressor/stretcher ring for the Japanese Hadron Project (JHP) has been simulated with a computer code including the longitudinal space charge effect.

INTRODUCTION

The production of a short bunch high intense proton beam is required at the Japanese Hadron Project [1]. The required bunch length is a few tens nano-second. To produce such a short bunch beam, a non-adiabatic bunch compression technique is employed. In this technique the rf-accelerating voltage is increased much faster than the synchrotron oscillation period. As a result, the bunch begins to rotate in the phase plane, and after rotating a quarter of a period of synchrotron motion, a short bunch will be obtained. The compression rate is proportional to the square root of the ratio of initial and final rf-voltages.The space charge field continuously acts on the traveling beam and the rf-accelerating field intermittently acts at each rf-accelerating gap. Below the transition energy, the effects of both fields on the beam are opposite to one another.

In a high intensity machine such as the JHP ring, analysis of the beam motion including the space charge effect is indispensable. By using a computer code we have estimated the effect of the space charge field on the beam. This computer code consists of two steps. The 1st step of the code simulates the stacking and storing processes. The 2nd step simulates the bunch compression process.

SIMULATION

The injected beam, which is chopped at the exit of the ion source, has a fine structure of 200 nsec pulse width at a frequency of 3 MHz. Since the harmonic number of the ring is 2, there are two bunches, one of which is used for compression. The designed peak current of the linac beam is 10 mA, i.e. the number of protons per bunch (ppb) is 1.25×10^{13}. For brevity in calculation, we used 2000 macro-particles substituted for 1.25×10^{13}, and also instead of 600 turns of multi-turn injection 200 macro-particles were stacked into the ring every 60 turns. The initial distribution of the linac beam is assumed to be uniform in the phase plane and the momentum spread $\Delta p/p$ to be ±0.13%. The tracking analysis during the stacking and storing periods were simulated assuming a constant rf-voltage (typically 7 kV). In order to compress the beam, the rf-voltage was increased from 7 kV to 200 kV in an interval of 50μsec, which is short enough in comparison with a synchrotron period. The maximum rf-voltage is restricted by the number of rf-cavities.

Energy gain and phase variation per turn

For simplicity of calculation, the many rf-cavities along the ring were replaced by a localized single cavity. We define the following variables;

E_n : kinetic energy of a particle at the n^{th} turn
ϕ_n : rf-phase of a particle at the n^{th} turn .

While a particle is traveling in the ring, both the rf-voltage V_{rf} and the potential V_s due to the space charge field act on it every turn. So we can write two difference equations with regard to the energy and the phase of each particle,

$$E_{n+1} = E_n + e\,[\, V_{rf} \sin(\phi_n) - V_s\,]$$

$$\phi_{n+1} = \phi_n + \frac{2\pi\eta\gamma h}{\gamma+1}\,\frac{dE_{n+1}}{E_0} ,$$

where E_o is the kinetic energy of the synchronous particle; $E_o = 1$ GeV, h is the harmonic number, γ and γ_t are the Lorentz factor of a particle and the transition energy, respectively, $\eta = 1/\gamma_t{}^2 - 1/\gamma^2$ and $dE_n = E_n - E_o$. Using these two equations we can easily track the behavior of the particles in the phase plane.

Estimation of the longitudinal space charge voltage

To estimate the longitudinal space charge voltage V_s acting on the beam, we assumed a round beam of radius **a** traveling in a circular beam duct of radius **b**. For a perfectly conducting smooth wall, the space charge voltage is written by the following equation [2];

$$V_s = -\frac{C e \gamma_0}{4\pi\varepsilon_0\gamma^2}\frac{d\lambda(s)}{ds},$$

where C is the circumference of the ring and $g_0 = 1+2\ln(\mathbf{b}/\mathbf{a})$. The g_0 value is supposed to be 2.5. In order to get a differential value $d\lambda(s)/ds$, the $\lambda(s)$ distribution was replaced by a discrete histogram in the phase plane. the bin width of the histogram was typically 10 degree.

RESULTS AND SUMMARY

The JHP ring will be operated during the stacking and storing processes with a harmonic number of h=2, and after ejecting the first bunch, the harmonic number of rf-system will be switched to unity for the compression. Since the stationary bucket length for the h=2 rf-system is ~333 nsec and the initial bunch length is 200 nsec, there is not enough marginal phase in the bucket area. Therefore, particles with a negative product of $\Delta p/p$ and $\Delta\phi$ do not stay long inside the bunch area. Figure-1 (A) shows the bunch shape at 1 msec from beam injection. Some particles have already spilled out of the bucket area. In this case the beam intensity was 1.25×10^{13} ppb.

For compression, the harmonic number is switched from h=2 to h=1 by means of changing the rf-frequency 3 MHz to 1.5 MHz. The reason is to have enough longitudinal bucket area so that the non-linear effect of synchrotron motion will be reduced. In Figure-1 (B) and (C), the phase space distributions of the bunch during the compression process are shown, where compression is started at 1.0 msec from beam injection. As seen in both figures, the filamentation is already observed at the beginning of compression. This filamentation caused by the diluted beam becomes conspicuous as the intensity exceeds 1×10^{13} ppb. As shown in Figure-2 (A), the results of our simulation are summarized. The solid line (a) in Figure-2 (A) shows that the filamentation arrested the bunch compression. When compression is started at 0.5 msec from beam injection, the dilution does not grow so much. Therefore, in spite of higher intensity, the bunch is successfully compressed (the dashed line (b) in Figure-2 (A)). Finally, in the case that the harmonic number of rf-system is switched before and after the compression, the bunch length of 200 nsec linac beam is compressed to ~50 nsec. Figure-2 (B) shows the results of the case that the linac beam is captured with the rf-bucket made by the harmonic number h = 1. In this case, especially, when the linac beam is chopped into 100 nsec pulses, a short bunch below 30 nsec is obtained.

In order to minimize the space charge effect, an optimized rf-voltage pattern during the stacking and storing processes is essential and is currently under developement.

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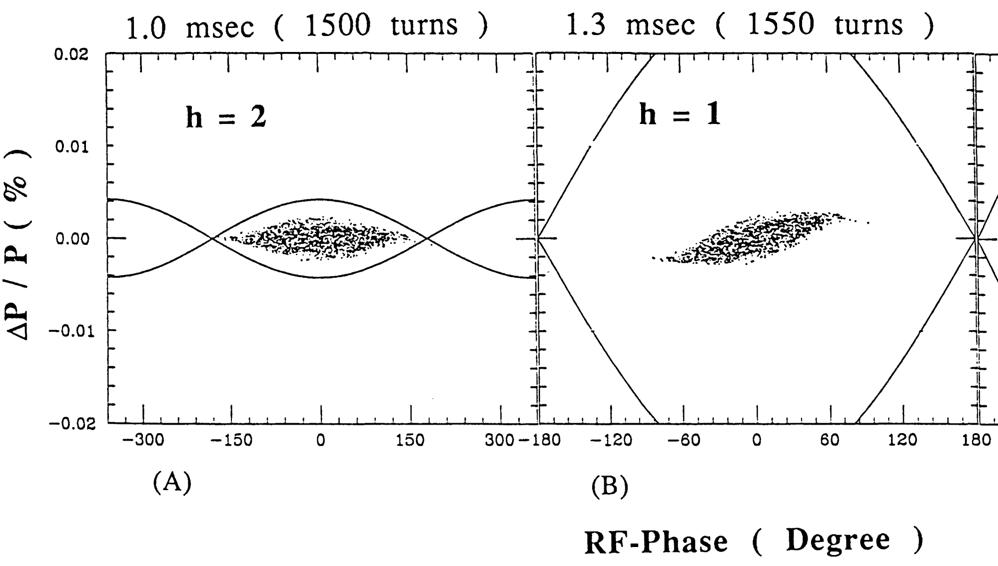

FIGURE-1. Simulation of bunch compression;
the initial length and the bunch intensity are 200 nsec and 1.25 × 10^{13}
(A) Bunch shape at 1 msec from beam injection (just before bunch co
(B)&(C) Bunch shapes during compression. The h=1 rf-system is us

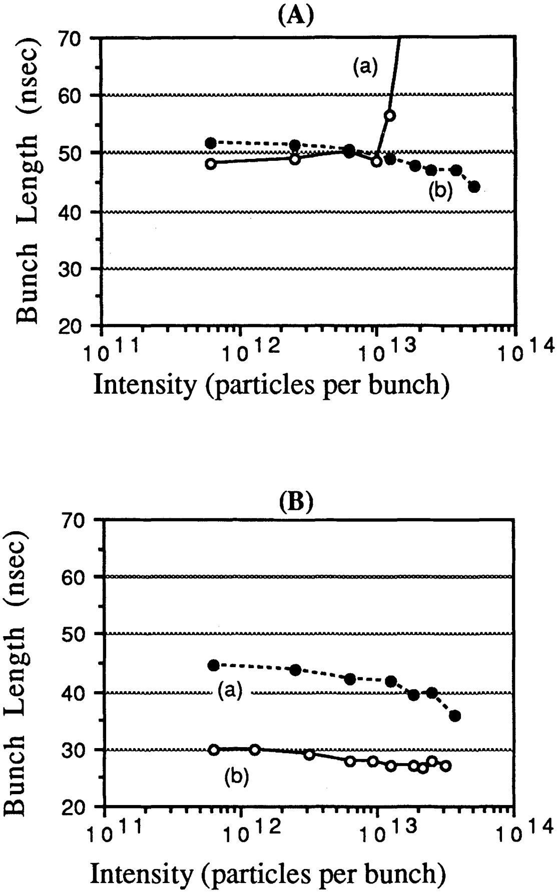

FIGURE-2. Obtained short bunch length vs beam intensity;

(A) The h=2 rf-system is switched to the h=1 rf-system at (a) 1 msec and (b) 0.5 msec from beam injection. The initial bunch length is 200 nsec.

(B) The h=1 rf-system is only used and the bunch compression starts at 0.5msec from beam injection. The initial bunch length is (a) 200nsec and (b) 100 nsec