LONGITUDINAL PAINTING STUDIES IN THE J-PARC RCS

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Abstract

In the J-PARC RCS, we employ the longitudinal painting methods combining the momentum offset injection and the second harmonic RF voltages, to increase the bunching factor so that the space-charge tune shift is reduced. By the dual-harmonic operation with wide-band MA loaded cavities, in which each single cavity is driven by a superposition of the fundamental and the second harmonic RF signals, we can generate a large amplitude second harmonic RF voltage without extra cavities for the second harmonic RF. We present the results of the beam tests for the longitudinal painting in the J-PARC RCS. Also, we present the beam behavior at very high beam power.

INTRODUCTION

For high current acceleration in the rapid cycling synchrotron (RCS) of the Japan Proton Accelerator Research Complex (J-PARC) [1, 2], it is essential to suppress the space-charge tune shift as low as possible. The longitudinal painting scheme during the injection period is employed in the RCS as well as the transverse painting. The longitudinal painting is carried out by adjusting the RF system parameters and programs.

By increasing the bunching factor (B_f), which is defined as the ratio, B_f = (average current)/(peak current), we can reduce the space-charge tune shift.

We combine the momentum offset method and the second harmonic RF for the longitudinal painting. We also employ the chopped beam injection to reduce the beam loss during the injection period. We apply the large amplitude of the second harmonic RF, 80 % to the fundamental RF, based on the particle tracking simulations. Also, to modify the bucket shape during the injection period, the "second harmonic phase sweep" method, which sweeps the relative phase of the second harmonic to the fundamental RF, is employed [3]. The simulation studies show that the bunching factor can reach 0.4 after the injection by combination of these methods.

The parameters of the RF system of the RCS are listed in Table 1 [4]. We employ wide-band ($Q = 2$) magnetic-alloy (MA) loaded cavities so that the dual-harmonic operation is fully supported. In the dual-harmonic operation, each single cavity is driven by a superposition of the RF signals, the fundamental accelerating RF ($h = 2$) and the second harmonic RF ($h = 4$). By the dual-harmonic operation, it is possible to generate large-amplitude second harmonic RF voltages without extra cavities for the second harmonic [5, 6]. We describe the results of the beam tests for the longitudinal painting in the J-PARC RCS. Also, we describe the beam behavior at very high beam power.

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Table 1: Parameters of the J-PARC RCS and its RF System

circumference	348.333 m
energy	0.181–3 GeV
accelerating frequency	0.938–1.671 MHz
harmonic number	2
maximum RF voltage	450 kV
repetition	25 Hz
duty (power)	30 %
No. of cavities	11
Q-value	2

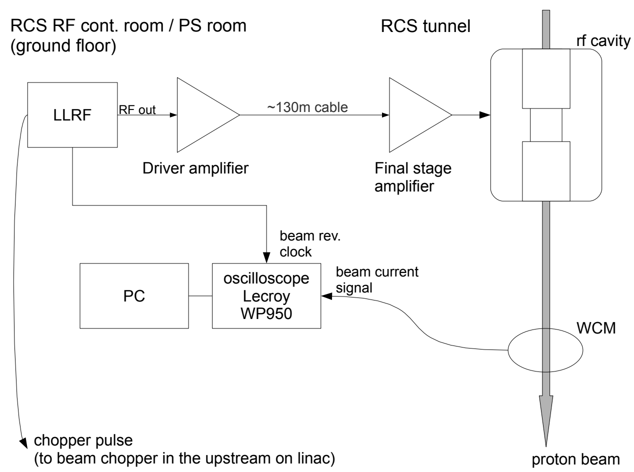

Figure 1: Beam test setup.

LONGITUDINAL PAINTING

The beam test setup is illustrated in Fig. 1. The beam current signal is picked up by a wall current monitor (WCM) and recorded by an oscilloscope (Lecroy WP950) at the sample rate of 200 Msamples/s. The recorded signals are analyzed with the beam revolution clock generated by the LLRF control system. The beam test conditions are listed in Table 2.

To realize the momentum offset injection, we apply a frequency offset df/f given as $df/f = \eta \times dp/p$, where η is the slippage, and dp/p the momentum offset. $\eta = -0.69$ in the RCS injection period.

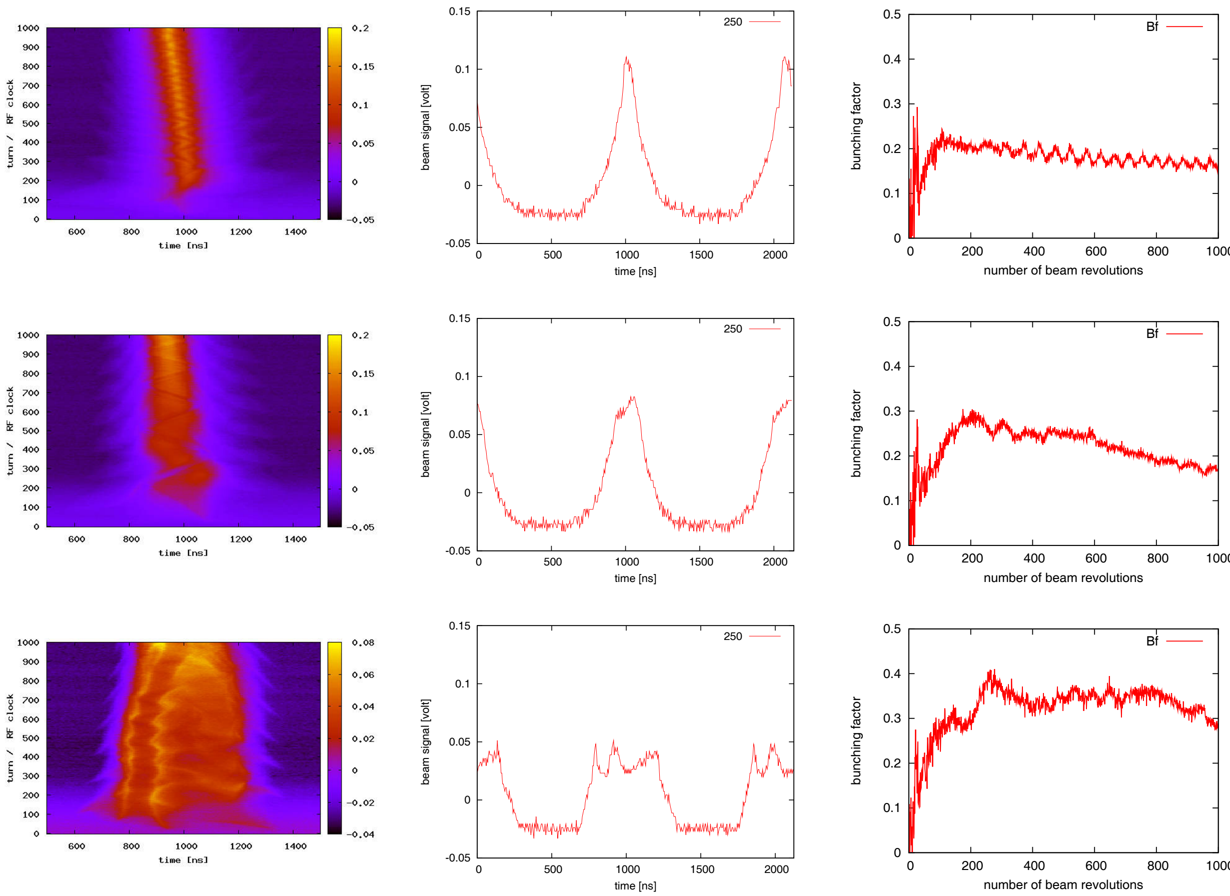

Figure 3: (Left) Mountain plots, (center) bunch shapes at 250-th turn, and (right) Bunching factor plots, in the cases of (upper) (i) fundamental RF only, (middle) (ii) with 50 % second harmonic, (lower) (iii) with 80 % second harmonic, momentum offset of -0.2% and phase sweep of 80 degrees.

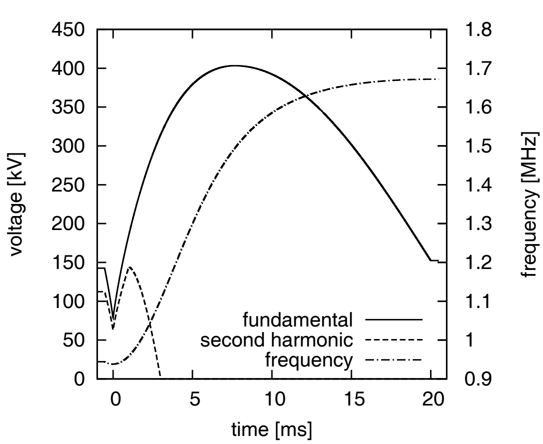

Figure 2: Accelerating voltage program with 80 % second harmonic and frequency program. $t = 0$ corresponds to B_{min}. The beam is injected from 117 turns before B_{min} to 117 turns after B_{min}.

Table 2: Beam Test Parameters

macro pulse width	500 μs
chopping width	560 ns
linac peak current	5 mA
number of filled buckets	2
number of accelerated protons	0.8×10^{13}
momentum spread of linac beam	± 0.05 %
RF frequency during injection	0.938–0.939 MHz
RF voltage during injection	78–111 kV
bucket height during injection	1.03–1.24 %
synchrotron freq. near injection	3370–4009 Hz
phase feedback	on

The typical accelerating voltage program is plotted in Fig. 2. The ratio of the second harmonic RF is at the maximum from the beginning of the injection to 1 ms after the minimum value of the bending magnet field (B_{min}), and the ratio is linearly reduced. At 3 ms after B_{min}, the amplitude of the second harmonic voltage goes to zero.

The macro pulse is from 117 turns before B_{min} to 117 turns after B_{min}. This is equivalent to 500 μs at the revolu-

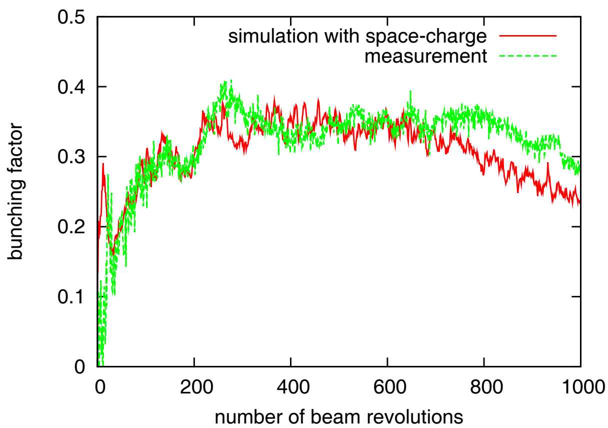

Figure 4: Comparison between the simulation and the measurement, with 80 % second harmonic, momentum offset of -0.2% and phase sweep of 80 degrees.

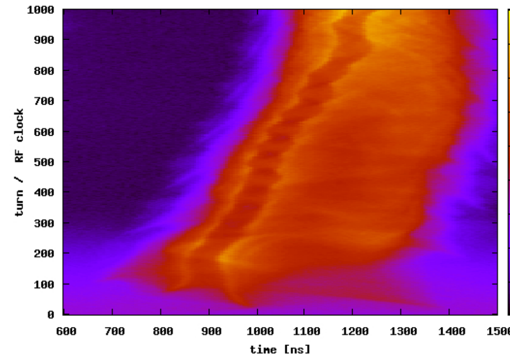

Figure 5: A mountain plot of the high current operation. 2.932×10^{13} protons, which correspond to 352 kW at 25 Hz operation, are successfully accelerated.

tion frequency of 469 kHz during the injection period.

In the "second harmonic phase sweep" method, the second harmonic phase relative to the fundamental was swept as $\phi_{(h=4)} = \frac{\phi_{\text{sweep}}}{T_{\text{inj}}}\left(t - \frac{T_{\text{inj}}}{2}\right) - 2\phi_s$ [deg], where $\phi_{(h=4)}$ is the second harmonic phase, ϕ_{sweep} the sweep range that was set to 80 degrees, T_{inj} the duration of the injection, and ϕ_s the synchronous phase of the beam.

The mountain plots and the bunching factor plots up to 1000-th turn, and the beam signal at 250-th turn, with the following cases are shown in Fig. 3: (i) fundamental RF only, (ii) with the 50 % second harmonic and no momentum offset, (iii) with the 80 % second harmonic, the momentum offset of -0.2 % and the second harmonic phase sweep of 80 degrees. In the mountain plot the color code corresponds to the charge density. With fundamental RF only, the beam density in the center of the bunch is high. The bunching factor is 0.2 just after injection (at 250-th turn). With 50 % second harmonic, the bunch is wider and the bunching factor is improved, 0.28 (at 250-th turn). It is clear that the bunch is very flat and the bunching factor is improved significantly with 80 % second harmonic, the momentum offset and the phase sweep. The bunching factor of about 0.38 (at 250-th turn) is achieved.

The bunching factor comparison between the measurement and the simulation is shown in Fig. 4. The simulation is carried out with longitudinal space-charge effects. The simulation and the measurement agree very well.

HIGH CURRENT OPERATION

We have performed the acceleration of high current beams. In Fig. 5 the mountain plot of 2.932×10^{13} protons, which correspond to 352 kW at 25 Hz operation, up to 1000-th turn is shown. In this case, the linac peak current was 15 mA, the chopping width was 700 ns and the macro pulse was 500 μs. At this level of the intensity, the longitudinal painting with the second harmonic RF is necessary to avoid beam losses. The transmission from the injection to the extraction is 0.961. For the 25 Hz operation, the acceptable beam loss is less than 3 %; so we must reduce the beam losses further.

SUMMARY

In the beam tests we have proven that the longitudinal painting with large amplitude second harmonic RF voltages improves the bunching factor significantly. Also we have demonstrated successfully the high current operation equivalent to 352 kW, while further reduction of the beam loss is necessary for the 25 Hz operation.

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