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NON-ADIABATIC LONGITUDINAL BUNCH MANIPULATION AT FLATTOP OF THE J-PARC MR

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Abstract

The J-PARC MR delivers the high intensity proton beams for the neutrino experiment. Eight bunches of high peak current are extracted by the extraction kickers, therefore the neutrino beam has the similar time structure. The new Intermediate Water Cherenkov Detector (IWCD) is a key detector for the future neutrino experiment and a low peak time structure is desired by the IWCD. Thus, we consider longitudinal manipulation at flattop of the MR for reducing the peak current. The manipulation requires the longer repetition period to extend the flattop. This reduces the output beam power. The manipulation should be quickly done to minimize the loss of the beam power, while the beam gap must be kept for the rise time of the extraction kicker. We propose a non-adiabatic bunch manipulation using the multiharmonic rf voltage. By using the neighbor harmonic of the accelerating harmonic, the first and eighth bunches can be decelerated and accelerated, respectively. After a certain period, the rf phase is flipped to π for debunching. Thanks to the initial deceleration and acceleration, the beam gap for the kickers can be maintained long enough. We present the concept and the longitudinal simulation result.

INTRODUCTION

The main ring (MR) of the Japan Proton Accelerator Research Complex (J-PARC) provides high intensity proton beams to the neutrino experiment. As of April 2021, the output beam power of the MR to the neutrino experiment is 510 kW. The parameters of the MR and its rf system is listed in Table 1. The harmonic number is 9 and eight rf buckets are filled. They are accumulated at 3 GeV and accelerated to 30 GeV. After the upgrade project of the magnet power supply, the repetition period will be shortened from 2.48 s to 1.16 s aiming at the higher output beam power. The bunches are ejected from the MR in a single turn by the fast extraction (FX) kickers. The generated neutrino beams have similar time structures to that of the proton bunches. At extraction, the bunch length is 50 ns and the gap between the bunches is 530 ns. The gap between the eighth and first bunches is 1110 ns and reserved for the risetime of the kicker.

The upgrade project of the neutrino experiment with Hyper-Kamiokande (Hyper-K) [1], which consists of an order of magnitude larger tank than that of the existing Super-Kamiokande, is underway. In the upgrade project, The new Intermediate Water Cherenkov Detector (IWCD) will be constructed for controlling the systematic errors on the oscillation measurements to maximize the precision of the measurements made by Hyper-K.

Table 1: Parameters of the J-PARC MR and Its RF System

circumference	1567.5 m
energy	3–30 GeV
γ_t	31.6i
beam intensity	(achieved) 2.6×10^{14} ppp
repetition period (FX)	(present) 2.48 s
	(upgraded) 1.16 s
accelerating frequency	1.67–1.72 MHz
harmonic number	9
number of bunches	8
maximum rf voltage ($h = 9$)	(present) 320 kV
	(upgraded) 600 kV
No. of cavities ($h = 9, 18$)	(present) 7, 2
	(upgraded) 11, 2
cavity resonant frequency	1.72 MHz
Slippage factor (η)	(3 GeV) -0.058
	(30 GeV) -0.0019
Q-value of rf cavity ($h = 9$)	22

The event pile-up in a bunch is one of the major concerns of the IWCD. The dead time fraction due to the pile-up with the short bunch length of 50 ns is estimated to be a large number. A longer time structure, i.e., fully or partially debunched beam, can improve the measurement efficiency. Therefore, we are investigating the longitudinal manipulation schemes. Since longitudinal manipulations are difficult during acceleration, it is to be performed at the flattop.

REQUIREMENTS AND POSSIBLE SCHEMES

The longitudinal manipulation is performed at flattop. In the normal fast extraction scheme, the beams are ejected just after reaching at the top energy of 30 GeV, i.e., the duration of the flattop is zero. The magnetic ramping pattern must be extended for the manipulation and the repetition period is increased as the extended flattop duration. To minimize the reduction of the output beam power, the manipulation should be completed as fast as possible. The repetition period of the MR must be an integer multiple of the RCS cycle, 40 ms. If the manipulation is done within 40 ms, the reduction of the output beam power is 3%.

The risetime of the extraction kicker is 1.1 µs, which is closed to the normal bunch gap between the eighth and first bunches. The gap must be kept also in case of the longitudinal manipulation to avoid beam losses caused by the kicker risetime.

There are several possible manipulation schemes. The naive scheme is simple debunching by turning off the rf

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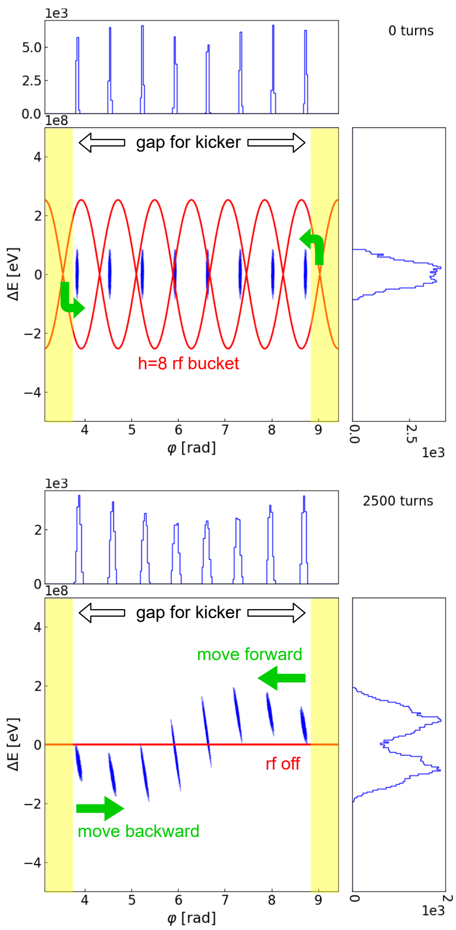

Figure 1: Operating principle.

voltages. This scheme is not suitable because the gap for the kicker cannot be kept. Debunching with barrier buckets [2] is promising scheme for keeping the bunch gap, while it requires the new development of the barrier rf system that can be operated under the heavy beam loading.

As shown in Table 1, the slippage factor is small as $\eta = -0.0019$ at 30 GeV. With this small η, adiabatic manipulations such as the batch compression [3] require very long time and the reduction of the output beam power will be significant and not to be acceptable for the experiment.

We propose a non-adiabatic bunch manipulation scheme using the multiharmonic rf voltage. The frequency response of the accelerating cavity in the MR covers the neighbor harmonics ($h = 8, 10$) as well as the main harmonic ($h = 9$), since the cavity has relatively low Q value of 22. The neighbor harmonic voltage can be generated for the manipulation without installing the additional cavities. The operating principle and the longitudinal simulation results are described in the following sections.

OPERATING PRINCIPLE

The simple debunching scheme cannot keep the bunch gap between the eighth and first bunches as described above. However, if the first and eighth bunches are decelerated and accelerated prior to the debunching, the first and eighth bunches will move backward and forward when turning off the voltage, respectively.

Such deceleration and acceleration can be realized by using the neighbor harmonic, $h = 8$, as shown the top of Fig. 1. At the flattop of the MR, the fundamental accelerating rf ($h = 9$) is turned off and the neighbor harmonic ($h = 8$) is applied. In the figure, the initial bunch distribution at the end of the acceleration, called the P3 timing, and the rf buckets generated by the ($h = 8$) rf voltage are plotted. The phase of the ($h = 8$) voltage is chosen so that the first and eighth bunches are decelerated and accelerated, respectively. Due to mismatch between the initial bunch spacing and the rf buckets, the bunches move differently.

After the first and eighth bunches are decelerated and accelerated enough, respectively, the rf can be turned off for debunching, as shown the bottom of Fig. 1. During debunching, the first and eighth bunches move backward and forward thanks to the momentum shift by the ($h = 8$) voltage. The bunch gap between the eighth and first bunches is kept during the debunching process.

The debunching speed with turning off the rf voltage is not fast enough to minimize the reduction of the output beam power. The full manipulation process takes 50 ms, which implies that the extension of the MR cycle is 80 ms and the reduction of the beam power is to be 6%.

The debunching can be faster by applying the rf voltage. The longitudinal simulation results are presented in the following section.

LONGITUDINAL BEAM SIMULATION

The longitudinal simulation is performed using the BLonD (Beam Longitudinal Dynamics) [4] code developed by CERN. The initial beam distribution at the P3 timing is obtained by the BLond code through the acceleration to 30 GeV without intensity effects, where the maximum momentum spread is 0.3% and the bunch length is 50 ns. The voltage of the neighbor harmonic ($h = 8$) is set to 50 kV, which can be generated by the existing rf systems. At 12 ms from the P3 timing, i.e., 2300 turns, the neighbor harmonic rf voltage is turned off and the superposition of the fundamental ($h = 9$) and second harmonic ($h = 18$) rf voltage is applied. The amplitude is 20 kV and 10 kV for the harmonics ($h = 9, 18$), respectively. The phase is chosen so that the bunches are located at the unstable fixed points.

The longitudinal distributions during the manipulation process are shown in Fig. 2. By the neighbor harmonic ($h = 8$) voltage, the first and eighth bunches are decelerated and accelerated. One can see that they are decelerated and accelerated enough at 2000 turns from the P3 timing. At 12 ms, the ($h = 9, 18$) voltages are applied. With the voltages, the debunching is faster than that of turning off the voltage, while additional momentum spread is introduced. The protons follow the contours outside of the rf buckets. At 6500 turns, i.e., 35 ms, the peak line density is low enough and the beams are ready to be ejected. The momentum

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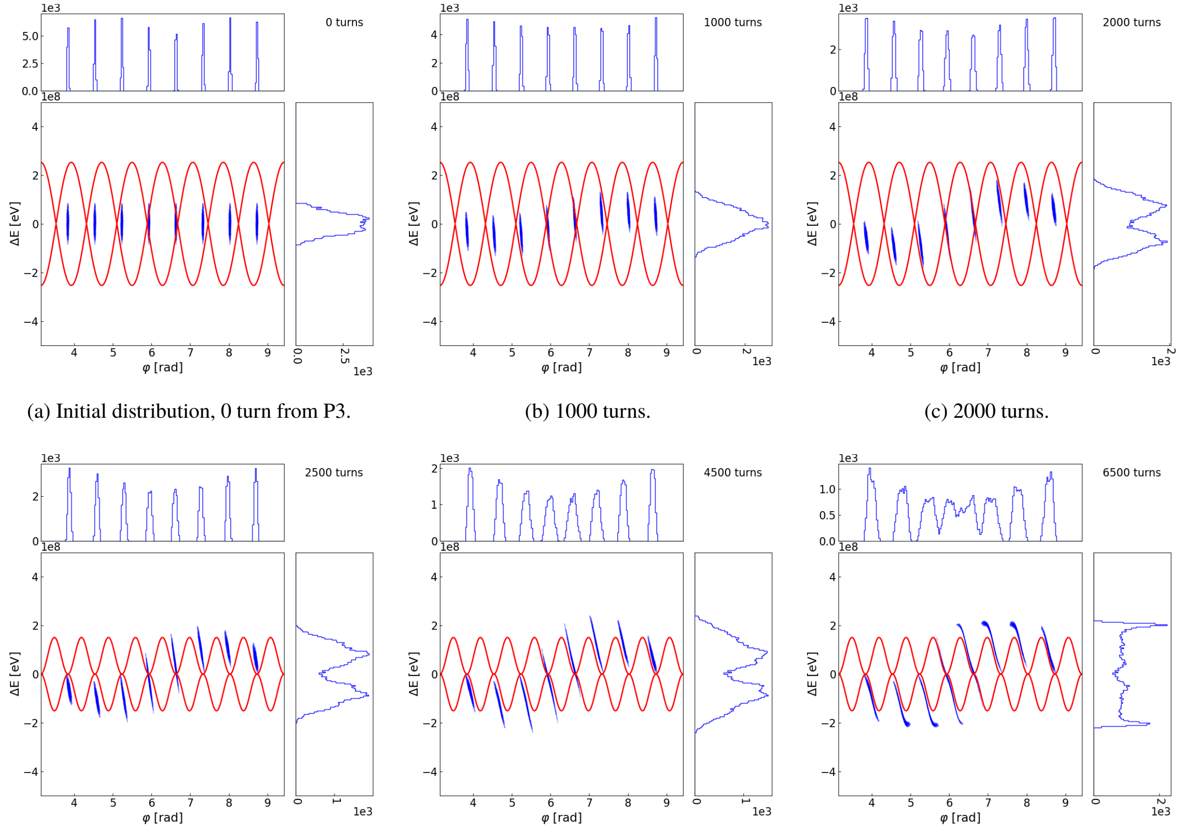

(a) Initial distribution, 0 turn from P3.

(b) 1000 turns.

(c) 2000 turns.

(d) 2500 turns.

(e) 4500 turns.

(f) Before extraction, 6500 turns.

Figure 2: Longitudinal distribution during the manipulation process.

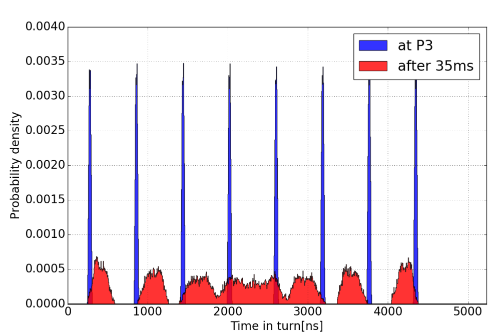

Figure 3: Comparison of the line densities at P3 and 35 ms.

spread is increased to 0.7%, which is still acceptable for the beam line to the neutrino experiment.

The line densities at the P3 timing and 35 ms are compared in Fig. 3. The peak density is reduced to 1/7. The gap between the eighth and first bunches is kept after manipulation.

SUMMARY AND DISCUSSION

A new non-adiabatic longitudinal manipulation scheme for the future neutrino experiment is presented. The peak line density is reduced down to 1/7. The scheme utilizes the neighbor harmonic ($h = 8$) so that the bunch gap for the extraction kicker is kept during debunching. By using the ($h = 9, 18$) harmonics, the debunching speed is increased. The manipulation process is fast enough to minimize the reduction of the output beam power down to 3%.

The intensity effects have not been included in the simulation. Instabilities during debunching for the slow extraction at the J-PARC MR are observed with much lower beam intensity than that of fast extraction as reported in [5]. The instability is a major concern for the high intensity operation. We are going to consider the effects of the various longitudinal impedance sources, such as the rf cavities and the extraction kickers.

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