BEAM STUDY WITH RF CHOPPERS IN THE MEBT OF THE J-PARC PROTON LINAC

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Abstract

A beam study of the RF fast chopper system in the MEBT of the J-PARC linac was successfully performed up to a beam current of 25 mA. The achieved rise/fall time of the chopped beam was about 10 ns. A beam signal during the chopper-on period, measured at the exit of the MEBT, was less than the noise level of the monitor systems. A flexible pattern of the chopped pulse train was achieved, which is useful for various kinds of operating pulse modes of the J-PARC accelerator.

INTRODUCTION

The J-PARC accelerator consists of three main parts: a 400-MeV proton linac, a 3-GeV rapid cycling synchrotron (RCS) and a 50-GeV synchrotron [1]. The linac accelerates a 50-mA beam of 500 μs in length at a repetition rate of 25 Hz. A fast chopper in the low-energy part of the linac was planned for reducing beam losses in the RCS. An RF chopper [2, 3] was adopted as a deflecting device in the medium-energy beam-transport line (MEBT) between the 3-MeV RFQ and the DTL [4]. In order to satisfy the purpose of the chopper system, it is important to minimize the transient rise/fall time of a chopped beam, since the beam behavior in the transient periods differs from that in the steady period, resulting in additional beam losses along the accelerator. A beam study up to the MEBT was performed [5]. The results of the chopped-beam study are described in this paper.

MEBT LAYOUT

The layout of the MEBT is shown in Fig.1. There are eight focusing magnets, two RF bunchers, two 324-MHz RF chopper cavities (RFD-A and RFD-B), five sets of steering magnets, a beam scraper for chopped beams and several kinds of beam diagnostics. The required time structure of the chopped beam is shown in Fig. 2. The chopping frequency is around 1 MHz in accordance with the RF frequency of the RCS.

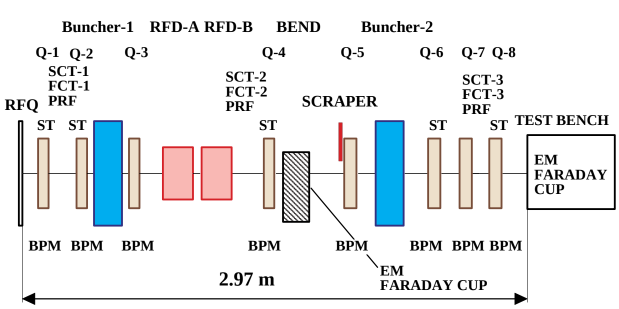

Figure 1: Layout of the MEBT.

RF CHOPPER (RFD) SYSTEM

An RFD is excited with a TE11-like mode. A loaded Q-value was tuned to be as low as about 11 by using two RF input/output couplers having large coupling coefficients. There are five methods to realize a faster transient rise/fall time of a chopped beam: (1) using a coupled RFD system [3] for obtaining a total deflecting-field strength as high as possible within a fixed RF power, (2) optimizing the loaded Q-value for obtaining the fastest rise time on the condition of a limited available RF power, (3) using the phase-reversal method [6] for achieving a faster fall time in the end part of the RF pulse, (4) using excess RF power in order to shorten the required time in which the deflecting field reaches the designed field level, and (5) using a power amplifier with a fast rise/fall time. In our system, two RFDs are connected with a waveguide, making a coupled cavity system and saving the cost of an RF power source. The optimum length of the coaxial waveguide between two RFDs was determined based on an HFSS simulation [7].

We constructed a 30-kW solid-state power amplifier. The amplifier consisted of thirty power modules, each of which produces an RF power of more than 1 kW, resulting in a maximum available power of 36 kW. The transient time of the power amplifier was about 15 ns. The incident wave for the power amplifier was modulated in amplitude by using a diode-switching circuit.

The required RF power of 22 kW for producing a deflecting field of 1.6 MV/m for the coupled RFD system was determined by a TRACE3D simulation under the condition that the chopped beam should be separated from the normal one by 4.4 mm. The deflecting field reached the designed value in nearly half the rise time if the driving power (P_{in}) was increased to 36 kW.

A beam scraper of tungsten was installed 70 cm downstream from the second RFD. The transverse

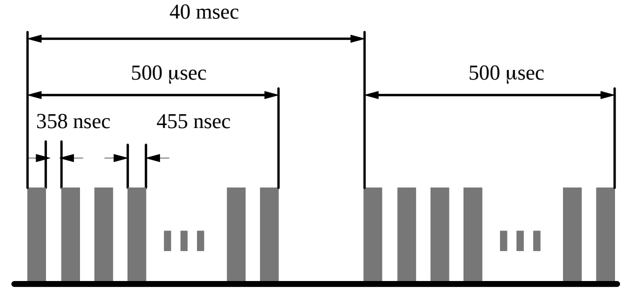

Figure 2: Required time structure of the linac beam pulse. A chopping ratio of 56% and a ring RF frequency of 1.23 MHz are assumed.

position of the scraper could be set with an accuracy of ±0.1 mm over a range of 50 mm. The beam current on the scraper could be measured.

METHOD OF CHOPPED-BEAM MEASUREMENTS

Two kinds of peak currents (5 and 25mA) were used. A low duty factor (repetition rate of 5 Hz and pulse duration of 50 μs) was selected, thus avoiding damage to the scraper surface in the beginning period of the experiment.

The chopped beam experiments consisted of three stages: (1) using a low-intensity beam and a single RFD for studying the fundamental characteristics of the RF chopper system, (2) using a low-intensity beam and a coupled RFD for studying the operation of the coupled RFD system, and (3) using a high-intensity beam and a coupled RFD for studying the characteristics of the total system under realistic conditions. A chopped beam was measured by using several kinds of beam monitors: slow current monitors (SCT), fast current monitors (FCT), beam position monitors (BPM) installed in each Q-magnet, a beam scraper and a Faraday cup. Each beam test consisted of the following steps: (1) eight focusing magnets and some steering magnets were tuned for obtaining both the highest transmission ratio through the MEBT and the allowable transverse emittance growth along the MEBT, (2) the RF amplitude of the first buncher was set to the design value, (3) the RF phase of the first buncher was set so that the average beam energy would be independent of the buncher operation, (4) the beam scraper position was set according to the results of a beam-size measurement, (5) the incident power of the RFD was increased gradually, and (6) the RF phase of the RFD was scanned for searching the optimum phase. Some iterations of the procedures mentioned above were required.

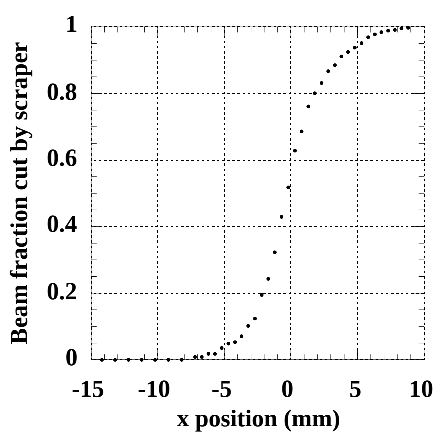

Figure 3: Measured beam fraction cut by the scraper as a function of the scraper position. The beam current was 5 mA. A symmetric transverse profile was assumed in data processing.

EXPERIMENTAL RESULTS

Beam Profile

The profile of a 5-mA beam at the scraper position was determined by measuring the third SCT current as a function of the scraper position (Fig. 3). The measured beam size was smaller than 10 mm, which roughly agrees with the calculated one with TRACE3D. Then, a scraper position of 10 mm away from the beam axis was selected for distinguishing the chopped beam from the normal one. The setting was effective throughout the study with a beam current of up to 25mA.

Deflecting Position

Figure 4 shows the deflecting scheme of a single RFD system. The deviation (Δx) of the chopped beam from the beam axis at the scraper position is expressed as

$$\Delta x = \theta_1 (L_1 + L_2)\left(1 + \frac{qB' L_q}{2mv}\frac{L_1 L_2}{(L_1 + L_2)}\right),$$

where, θ_1 is the deflecting angle in proportional to the deflecting electric field of an RFD, q the electric charge, B' the magnetic field gradient of the quadrupole magnet, m the rest mass of the protons, v the velocity and L_1&L_2 the distances. Figure 5 shows the measured deflecting beam position at the scraper as a function of the

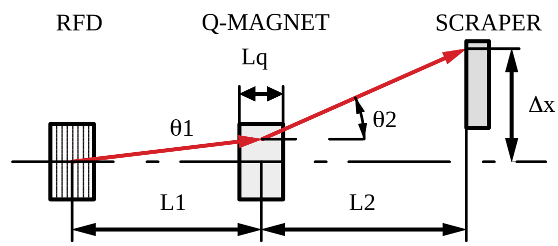

Figure 4: Deflecting scheme of a single RFD system.

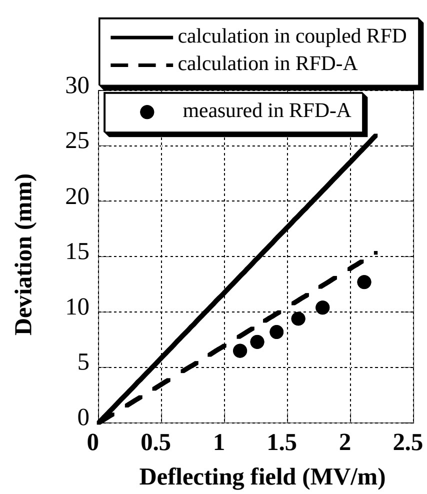

Figure 5: Measured deflecting beam position at the scraper in the single RFD-A system vs. deflecting field of the RFD. The calculated deviation for both the RFD-A and the coupled system are also plotted.

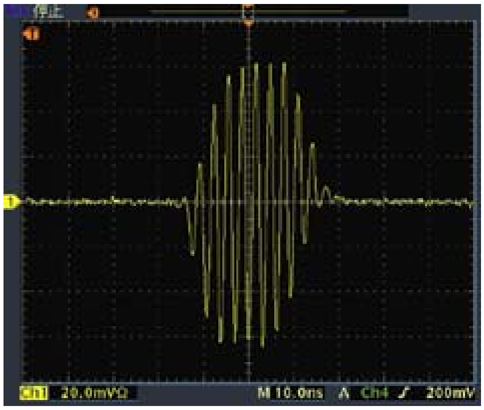

Figure 6: Signal of a chopped beam measured by the eighth BPM. The beam current was 24 mA. P_{in}=36 kW. The phase-reversal switch was turned on. 10 ns/div.

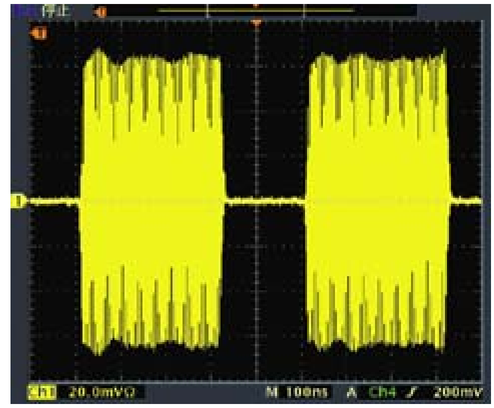

Figure 7: Signal of a chopped beam measured by the eighth BPM. The beam current is 24 mA. P_{in}=36 kW. The phase-reversal switch was turned on. 100 ns/div.

deflecting field of the single RFD-A system. The calculated results for both the RFD-A and the coupled RFD operation are also plotted. The agreement between the measured and calculated results is satisfactory.

Results of Coupled RFD Operation

A beam test with the coupled RFD system was successfully performed. Figure 6 shows a chopped beam pulse measured by the eighth BPM. A very short pulse was produced to clearly observe both transient parts. A transient time of about 10 ns for the rise/fall part was obtained. Figure 7 shows a typical chopped pulse train. The signal arising from the deflected beam, most of which was scraped by the scraper, was less than the noise level at the MEBT exit, indicating that the fraction of the beam at the exit of the MEBT during chopper-on time was negligibly small. The allowable separation between the deflected and normal beams of 23 mA was obtained when the driving power of the coupled RFD system was about 18 kW. However, the measured transient rise time of 15 ns was not so fast that a driving power of more than 18 kW was desirable from the viewpoint of the transient behavior. The tolerance of the allowable RF phase error of the RFD was sufficiently large; the coupled RFD system provided a separation between the chopped and normal beams over a driving RF full phase-range of 96/52 degrees for a driving RF power of 36/18 kW and a beam current of about 5 mA. The method for making any combination of the chopped beam of varied pulse durations or varied repetition rates was established. It was found that the RFD system is very stable in total performance. There were no problems in RFD high-power operation during the beam study period for over one month.

Phase-Reversal Operation

In Fig. 6, the input RF phase was reversed by 180 degrees as fast as possible at a timing of about 12 ns ahead of the RF pulse end. This increased the beam rise time by more than 3 ns.

CONCLUSION

It was proved by the beam study that the RFD chopper system operates very well up to a beam current of 25 mA, satisfying the fundamental requirements for a chopped beam. The achieved rise/fall time (10 ns) of the chopped beam was close to the limit of the RF chopper system, on the condition that a loaded Q-value of 11 and a limited available RF power of 36 kW were used. The beam signal during the chopper-on period measured at the exit of the MEBT was less than the noise level of the monitor systems. A flexible pattern of the chopped pulse train was achieved, which is useful for various kinds of operating pulse modes of the J-PARC accelerator.

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