BEAM TEST OF A NEW RFQ FOR THE J-PARC LINAC

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Abstract

We performed a beam test of a new 324-MHz 3-MeV H^- RFQ (RFQ III) for the beam-current upgrade of the J-PARC linac. RFQ III is the first RFQ developed to meet the requirement of the J-PARC linac. The peak beam current is 50mA, pulse length is 500 μs, and the repetition is 25 Hz. Prior to the installation to the accelerator tunnel in summer of 2014, we constructed a test stand for off line testing of the new ion source and RFQ. Basic performances of RFQ III such as transmission and emittances were measured. In this paper, the beam test results are presented.

INTRODUCTION

The Japan Proton Accelerator Research Complex (J-PARC) is a multi-purpose facility for particle physics, nuclear physics, materials and life science, and others. The J-PARC accelerator [1] consists of a 400-MeV linac, a 3-GeV rapid cycling synchrotron, and a 50-GeV main ring. The original design energy and peak beam current of the linac are 400 MeV and 50 mA, respectively. A four-vane-type radio frequency quadrupole (RFQ) built for the Japan Hadron Facility project was used for the initial phase linac, and the design peak beam current of this RFQ was 30 mA. To upgrade the beam current of the J-PARC linac to achieve the original design power of 1 MW (at the neutron target), a new RFQ with a design current of 50 mA has been developed [2]. This RFQ is called RFQ III, whereas the former 30-mA RFQ is called RFQ I [1]. Table 1 lists the design parameters of RFQ III.

Table 1: Design Parameters of J-PARC RFQ III.

Beam species	H^-
Resonant frequency	324 MHz
Injection energy	50 keV
Extraction energy	3 MeV
Peak beam current	50 mA
Vane length	3623 mm
Average bore radius (r_0)	3.49 mm
ρ_t/r_0 ratio	0.75 (ρ_t =2.62 mm)
Inter-vane voltage	81.0 kV
Maximum surface field	30.7 MV/m (1.72 Kilpatrick)
Nominal peak power	400 kW
Repetition rate	50 Hz
RF pulse length	600 μs
Duty	3%

RFQ III employs a conventional beam dynamics design. That is, the RFQ is divided into four sections: a radial matching section (RMS), a shaper (SP), a gentle buncher (GB), and an accelerator (ACC). Additionally, the inter-vane voltage V and the average bore radius r_0 are maintained constant except for the injection section. For the beam dynamics design of RFQ III, LINACSrfqDES [3] was used [2]. The feature that characterizes the beam dynamics in LINACSrfqDES is the equipartitioning condition, which is used to avoid the effect of parametric resonances in high current linacs [4]. This condition requires that the internal energies in the transverse and longitudinal phase spaces of the beam are same. When this condition is satisfied, there is no free energy to drive a resonance. However, the equipartitioning condition is not maintained with maintaining V constant as the particles are accelerated. Therefore, for RFQ III, we adopted equipartitioning in the GB, which is the most critical section of RFQs.

In accordance with the concepts described above, J-PARC RFQ III was designed and fabricated. Because the J-PARC linac provides a beam for user operation, the performance of RFQ III had to be confirmed by off line testing using a negative hydrogen (H^-) beam prior to replacing RFQ I. In this paper, the beam test results of J-PARC RFQ III are described.

EXPERIMENTAL APPARATUS

As mentioned in the previous section, RFQ III was tested off line prior to installation in the accelerator tunnel. To this end, an RFQ test stand (TS) was constructed on the ground floor of the J-PARC linac building. This TS allowed the use of a 50 mA beam with a duty factor of up to 25% of the nominal duty (500 μs, 25 Hz) for continuous operation, wherein the duty factor was limited by allowable radiation levels. Figure 1 shows a schematic drawing of the TS.

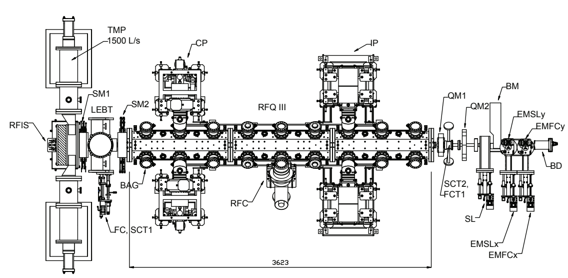

Figure 1: Schematic of the RFQ test stand (top view).

An RF driven ion source (RFIS) for the J-PARC linac upgrade [5] was employed for the RFQ testing. The plasma is driven by a pulsed 2-MHz RF power, and a 30-MHz con-

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[1] Because a sparking problem occurred in RFQ I, a spare RFQ was fabricated. We call this spare one RFQ II.

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tinuous wave RF is also used to ignite the plasma. A 60-kW solid-state amplifier system is used as the RF source. The typical RF power used under the standard 60-mA beam operation was 45 KW. The extraction energy is 50 keV. The low energy beam transport (LEBT) is equipped with two solenoid magnets (SM1 and SM2), and the space charge neutralization effect is also used to focus the beam. The beam current injected to the RFQ is measured using a movable Faraday cup (FC) or a slow current transformer (SCT1) located between the two SMs. The length of the LEBT is 580 mm.

Figure 2: Photograph of J-PARC RFQ III installed in the TS.

Figure 2 shows a photograph of J-PARC RFQ III. RFQ III consists of three longitudinally segmented unit cavities, and the vane lengths of the units are 1211.0 mm, 1226.0 mm, and 1186.1 mm, respectively. Each unit cavity consists of upper and lower major vanes and left and right minor vanes. The major and minor vanes were joined by vacuum brazing. The material of the cavity is oxygen free copper class 1 [6]. Three 1700-L/s (for N_2) CPs are attached to the second ports from the upstream direction, and four 400-L/s ion pumps (IPs) are attached to the eighth ports from the upstream direction. The pressure is measured with a Bayard-Alpert gauge attached to the most upstream port. Typical pressures were 6.0×10^{-6} Pa with the RF off, 1.0×10^{-5} Pa with the RF on, and 1.7×10^{-5} Pa under 50-mA beam operation. In the center port of the lower-left quadrant, a loop-type RF coupler (RFC) is inserted. The RF power was generated by a 324-MHz klystron (Toshiba E3740A).

The property of the extracted beam from the RFQ was measured with a bench (TB). The beam extracted from the RFQ was transported to the beam dump (BD) using two quadrupole magnets (QM1 and QM2). The extracted beam current form RFQ III was measured using SCT2. The beam energy was measured to be 3.00 MeV with the time of flight method using two fast current transformers (FCT1 and FCT2), separated by a distance of 1230 mm. FCT2 was located just upstream of the BD; however, it was removed after the beam energy was confirmed because it was a cause of neutron radiation due to beam loss. The energy spread was measured with an analyzer using a bending magnet (BM). The emittance monitor (EM) was a conventional double-slit-type emittance monitor to measure the transverse emittances of the RFQ. The slit of the EM was composed of W, which was water cooled via a copper (Cu) baking plate. The gap length of the slit was 0.1 mm, and the distance between the upstream slit (EMSL) and the downstream EMFC was 215 mm. The charges of the particles passing through the two slits were collected by the EMFC. Each slit was driven by stepping motors. Finally, the beam was directed to the BD. The BD consists of a Cu cylinder cut with an angle of 30 degrees and a 1-mm W plate attached to the cut surface of the cylinder by the HIP method. Because contamination by impurities such as nickel and Cu cause neutron radiation, a high purity W was used for the beam target.

BEAM TEST RESULTS

The beam test was performed from December 2013 to June 2014. In this section, the results of the 50-mA H^- beam experiment are presented and compared with those of the simulation. LINACSrfqSIM was employed for the RFQ simulation, and PARMILA [7] was employed for the TB simulation. For the input distribution into the RFQ, the generated distribution based on the measurement at the LEBT was used.

Figure 3 is the beam pulse of 54 mA beam and RF waveform of the RFQ.

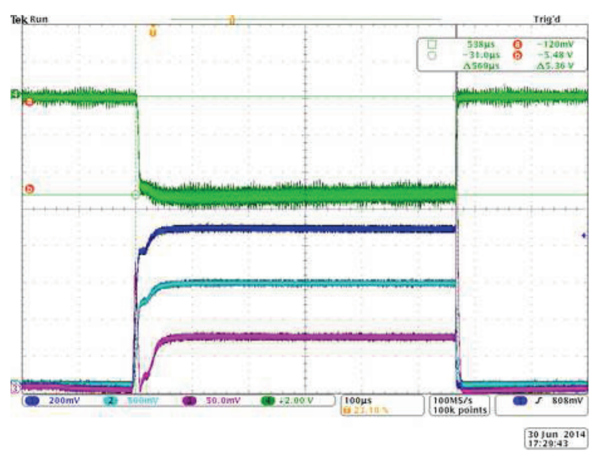

Figure 3: Beam pulse and RF waveform of RFQ III. Green: SCT2 signal. Blue: Forward RF to the RFQ. Cyan: RFQ tank level. Magenta: Reflected RF from the RFQ.

Figure 4 shows the inter-vane voltage dependence of the transmission through the RFQ. V_n denotes the inter-vane voltage of the RFQ normalized to the nominal voltage, and the vertical axis is the transmission. The solid and dashed lines represent the measured and simulated transmissions of the accelerated particles, respectively. The accelerated beam current was obtained by measuring the 324-MHz spectrum of the FCT2 signal using a Tektronix MDO4014B-3 mixed-domain oscilloscope. The measured beam current was normalized by the RFQ injection current measured with

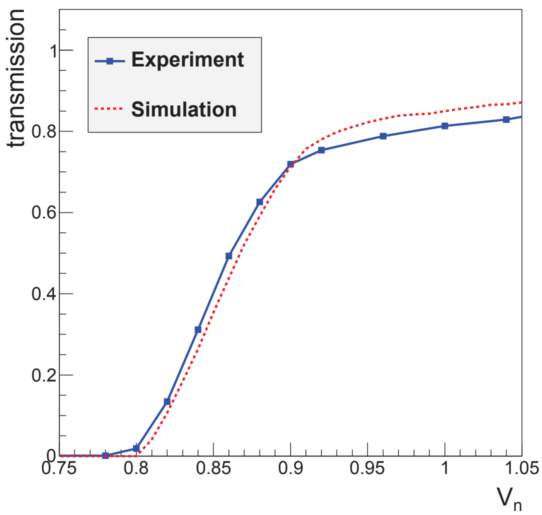

Figure 4: Measured and simulated transmissions of RFQ III as functions of the inter-vane voltage V_n.

the SCT1 of the LEBT. The measured and simulated transmissions agree with each other.

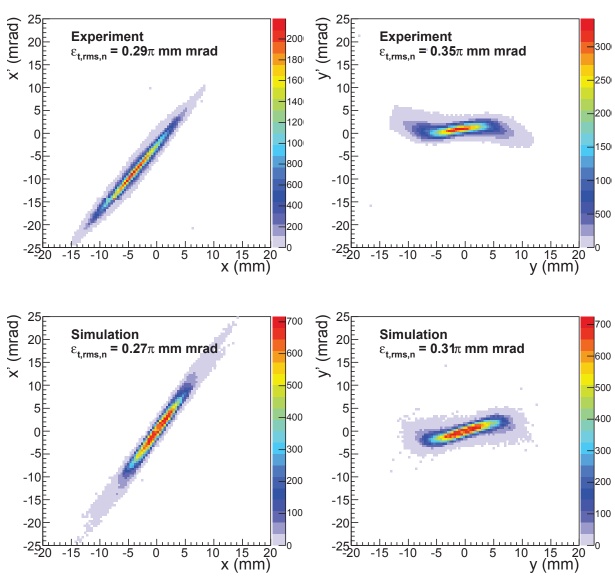

Figure 5: Measured (upper row) and simulated (lower row) transverse emittances of RFQ III.

The results of the transverse emittance measurements of the 50-mA beam are shown in Figure 5. To prevent melting of the edge of the slits, the emittances of the 50-mA beam were measured with a width of 100 μs and a repetition rate of 5 Hz. In Figure 5, the upper row shows the measurements and the lower row gives the simulation results. The measured values of the normalized rms transverse emittances in the horizontal and vertical planes were 0.29π mm mrad and 0.35π mm mrad, whereas the simulated emittances were 0.27π mm mrad and 0.31π mm mrad, respectively. The simulation well reproduces the measurements.

SUMMARY

A beam test of J-PARC RFQ III was successfully conducted. The equipartitioning condition was adopted in the GB, which is the most critical section. Before installing RFQ III into the accelerator tunnel, an off line beam test using a H^- beam was performed and the experimental data were compared with the simulation results. The experimental data and simulation results agreed very well.

RFQ III is installed in the accelerator tunnel by the middle of September 2014, and the operation will start subsequently. A 1MW equivalent high power test of the J-PARC accelerator is planned in October 2014. In this experiment, RFQ III will exhibit its full performance.

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