FIELD TUNING OF A RADIO-FREQUENCY QUADRUPOLE USING FULL 3D MODELING

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Abstract

The radio-frequency quadrupole (RFQ) is operating in the frontend of the J-PARC linac to accelerates 50-mA negative hydrogen beams from 0.05 MeV to 3 MeV. As a backup, the spare RFQ has been fabricated in 2018. The vane-voltage ramping is adopted to improve the acceleration efficiency so that the cross-sectional shape is adjusted longitudinally to produce the designed voltage distribution. Then, the three-dimensional cavity models including modulations and cutbacks were created in CST Micro-Wave Studio. The vane-base widths and cutback depths were optimized to produce the desired vane-voltage distribution. In the final tuning, the insertion depths of the stub turners were also determined based on the tuner responses obtained from the full 3D models.

INTRODUCTION

The J-PARC (Japan Proton Accelerator Research Complex) is a complex research facility consisting of high-intensity proton accelerators and experimental facilities. The accelerator comprises an injector linac, a 3-GeV Rapid-Cycling Synchrotron and a Main Ring. The front end of the linac consists of a negative hydrogen ion source and an RFQ with an output energy of 3 MeV. For the beam current upgrade, the new frontend (RF ion source, RFQ, chopping system) is installed in summer 2014. Since then, the beam current was increased to 30 mA, and to 40 mA from January 2016. We continued operation without major trouble, however, the spare RFQ was fabricated in 2018 in preparation for unexpected trouble. In this paper, the detailed design process of the cavity dimensions and the result of the low-power measurements are described.

RFQ PARAMETERS

The major parameters of the spare RFQ are shown in Table 1. The vane voltage distribution of the operating RFQ in J-PARC is taken to be uniform in the longitudinal direction [1], but in the new RFQ, the vane voltage distribution is designed to make the ramping on the downstream side

Table 1: Major Parameters

Frequency [MHz]	324
Cavity type	Four vane
Vane length [m]	3.1
Inter-vane voltage[kV]	$61.3 \sim 143$
Max. surface field [MV/m]	29.8(1.67 Kilpatrick)
Average bore radius [mm]	$2.6 \sim 6.2$
Vane-tip curvature [mm]	$0.75r_0$

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of the cavity to improve the acceleration efficiency. Figure 1 show the longitudinal variation of the vane voltage, the average bore radius, and the maximum surface field. The average bore radius increases smoothly toward the downstream so that the maximum surface field is almost constant. Figure 2 shows the test pieces of a vane tip. From left to right, the modulations for the longitudinally centre, entrance, and exit of the vane, respectively. Prior to the fabrication, the machining conditions of the vane-tip modulations using the ball-end mill were confirmed based on this prototype.
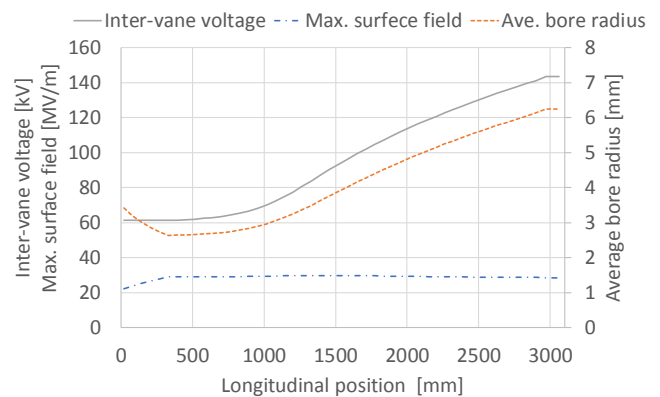

Figure 1: Longitudinal variation of the vane voltage and the average bore radius.
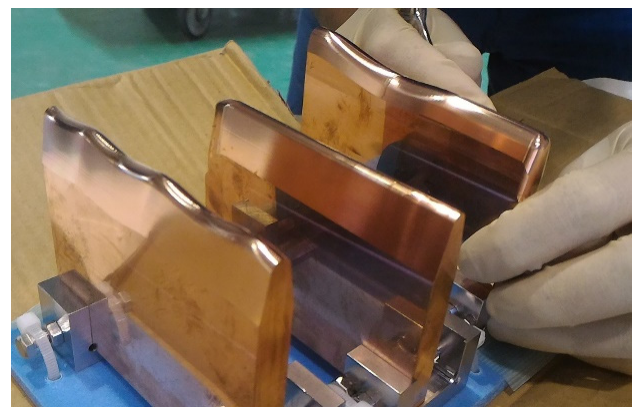

Figure 2: Test piece of the vane tip for checking the surface roughness with the machining conditions.

RF DESIGN

To make the vane-voltage distribution in the longitudinal direction, the vane-base width was adjusted. Cross sectional shape of the cavity is shown in Fig. 3.
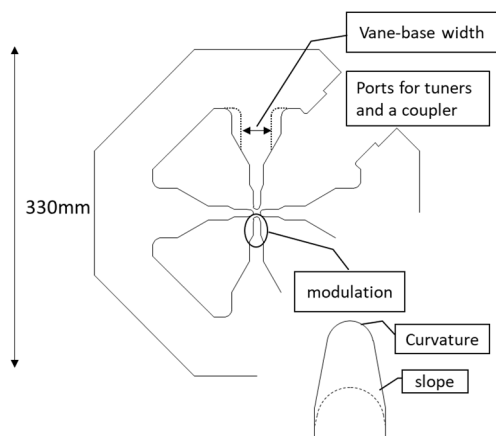
Figure 3: Cross-sectional shape of the RFQ cavity. The cavity radius is 110 mm.

The three-dimensional model for the RF simulation was created by the following procedure using SUPERFISH [2] and CST microwave studio [3].

- The cross-sectional shape of the cavity is determined using SUPERFISH.
- Initially, the vane-base width with the average radius is calculated using RFQFISH along the longitudinal position.
- Based on the obtained vane-base width and the average radius, a three-dimensional CAD model is constructed. Here, the vane-base widths are parameterized to connect with 18 faces in the longitudinal direction (Fig. 4). The end-cut depths are parameterized as well.
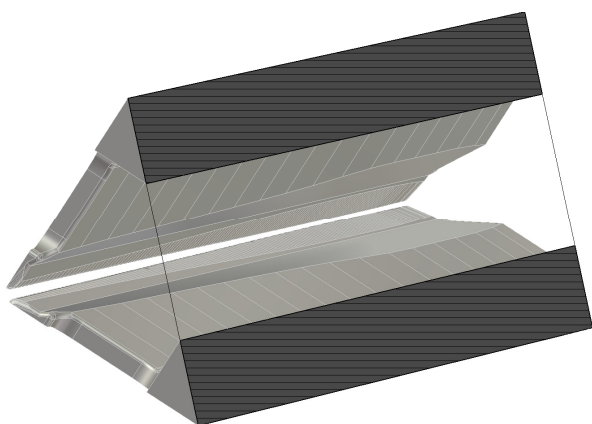

Figure 4: 1/4 model for tuning the vane-base widths and the depths for end cut.

From the three-dimensional simulation result for the electric field distribution, the voltage distribution at the vane tip is obtained by integrating the electric field. Although it is possible to fabricate a cavity with the dimensions calculated by RFQFISH and adjust the electromagnetic distribution using tuners, the voltage distribution was adjusted by optimizing the vane-base width to avoid increasing the stroke necessary for the tuners. Then, the tuners will adjust the errors for manufacturing and the RF calculations. Optimization of the above dimension parameters were carried out in the following procedure.

- The electromagnetic fields are calculated with changing the value of parameterized 19 points of vane-base width and end-cut depths by 1 mm, independently.
- To evaluate the variation of the vane-tip voltage distribution per unit length of these parameters, the vane-tip voltage is sampled at intervals of 20 mm, and created the matrix X with elements normalized by the average voltage for all parameters.
- The difference between the vane voltage for the case of the initial parameters and the designed voltage distribution is a column vector B.
- The correction for all parameters (vector A) is obtained by $A = (X^T X)^{-1} X^T B$,where $XA = B$.

If the three-dimensional model is complicated, the calculation time per case becomes long, therefore, the modulation was not implemented in the model for the matrix X calculation. The radial matching section and the fringe field section were connected with the average bore radius.
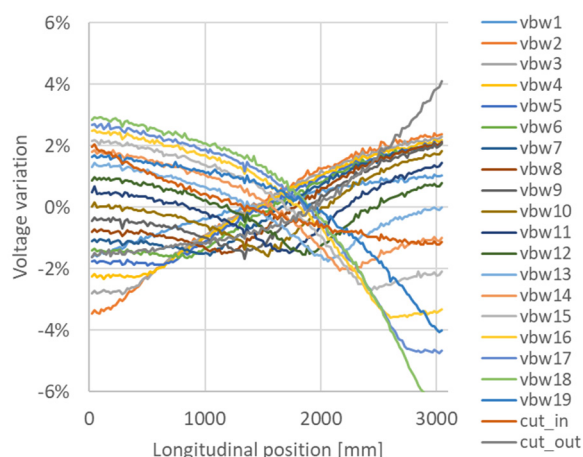

Figure 5: Voltage variations of the vane voltage for each cavity shape parameter.

The variation of the vane-tip voltage distribution per unit length (elements of the matrix X) of the parameters are shown in Fig 5. The curves are not smooth due to the roughness of the calculation mesh, but it is enough to adjust the voltage distribution within a certain (less than 1%) accuracy. After the designed voltage distribution is obtained with several iterations, the magnetic field distribution at the bead measurement position is calculated. Then, the modulations are implemented in the three-dimensional model and the optimization procedure carried out again to be equal to the target magnetic field distribution. At the low power measurement, this calculated magnetic field distribution is also a target value for tuner adjustment.

LOW-LEVEL TUNING

For the low-level tuning, the magnetic field distribution of each quadrant was measured using a bead-pull measurement method. The bead position is outside the dipole rod, where the magnetic field dominates. As shown in Fig. 6, the beads are passed through the hole outside the DSR. To

evaluate the magnetic field strength, the phase fluctuation is measured by a network analyzer.
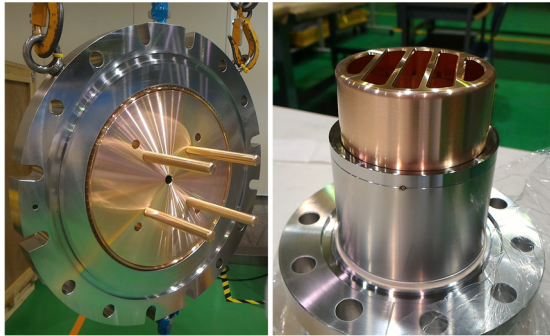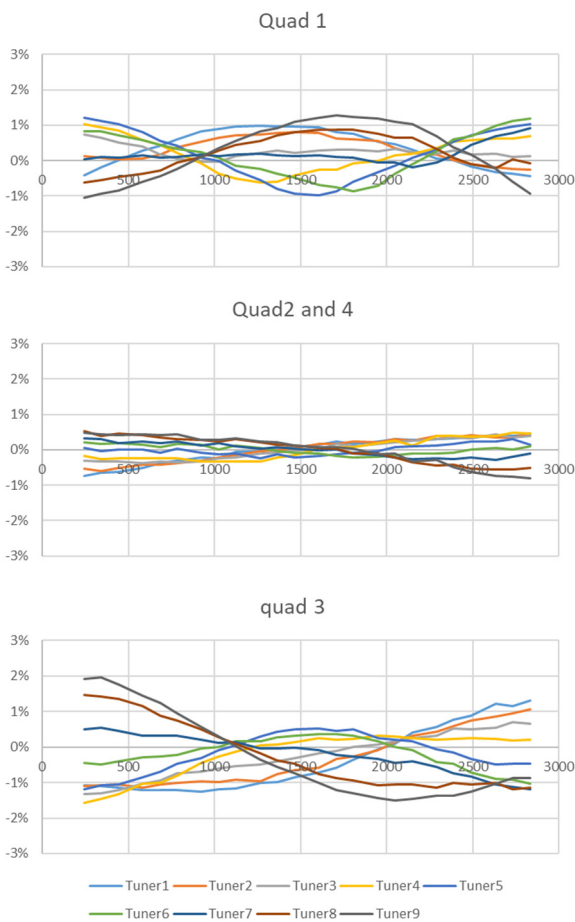

Figure 6: End plate and tuner.

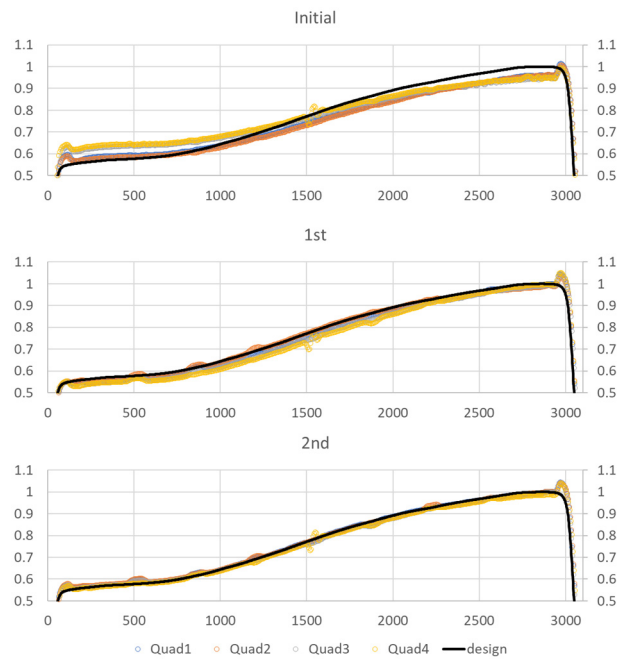Figure 7: Magnetic field variations with tuner insertion.

Figure 8: Bead-pull measurement result.

Although it is possible to create a response matrix by measuring the variation of the magnetic field distribution with changing the tuner insertion depth, to shorten the tuning period, the response matrix for the tuners is created by the RF simulation as the same procedure as the above-mentioned optimization for the dimension parameters. To evaluate the field variation by a tuner, it is necessary to use a full model including all quadrants. The calculated variation of the magnetic field distribution when inserting the tuners of the first quadrant by 1 mm is shown in Fig. 7. Only the tuner responses of the first quadrant was calculated, and all matrix elements were given by the quadrant symmetry. The insertion depths are given by summation of the inverse matrix results and the frequency offset length (all tuners equalized).

The bead measurement results before and after the tuning are shown in Fig. 8. After two iterations, the field error from the designed distribution was ± 1.5%. The local bumps in the first and second iterations are due to the disturbance by the tuner. Finally, the range of the insertion depth for all tuners were from -0.7 mm to +1.9 mm.

CONCLUSION

The RF design of the RFQ has been done based on the three-dimensional cavity models including modulations and cutbacks. The vane-base widths and cutback depths were optimized using the pseud-inverse matrix method to produce the desired vane-voltage distribution. In the low-level tuning, the insertion depths of the stub turners were also determined based on the tuner responses obtained from the full 3D model.

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