ACCELERATION PERFORMANCE OF A 50-MHZ SPLIT COAXIAL RFQ AND THE DESIGN OF A 25.5-MHZ PROTOTYPE

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Acceleration tests on a 50-MHz split coaxial RFQ have been conducted at INS. The 2-m long RFQ has accelerated protons from 2 to 60 keV. The experimental results concerning beam emittance and transmission efficiency agree with predictions of a computer simulation. Following this success, we are fabricating a 25.5-MHz prototype of 2-m long. The issues of the study are to establish a structure standing a high-power operation and to accelerate heavy ions with a charge-to-mass ratio larger than 1/30.

Introduction

The split coaxial RFQ (SCRFQ) has been developed at INS since 1984. The features of the SCRFQ structure at INS are as follows.[1] First, the RFQ is equipped with modulated vanes; the electric field generated by them is reliable as has been confirmed through experience with many four-vane RFQ's. Second, the whole cavity comprizes several module cavities, each of which corresponds to one split coaxial cavity (Müller at GSI demonstrated how the re-entrant cavity (the 2 × $\lambda/4$ cavity) excited in TEM mode is transformed to the split coaxial cavity[2]). As a result, the vanes running through the whole cavity are supported at several points. We have thereby solved the problem, peculiar to the SCRFQ, of how to align the inner electrode (the vanes in our case) accurately and firmly.

Our SCRFQ programme started with a cold model with flat vanes. Through the fabrication, we developed a cavity structure and an assembling method to attain precise alignment and good mechanical stability. Tests on rf characteristics verified that the cavity generates the required electric field distribution.[3,4] In parallel to the experimental work, an equivalent circuit analysis was made in order to explain the experimental results and to understand the rf properties of the complicated cavity.[5] Then the cold model was converted to a 50-MHz accelerating model (proton model) by replacing the flat vanes with modulated vanes.[6,7] Experimental results of acceleration tests using protons agree with predictions of a computer simulation (preliminary results were reported elsewhere[8]). Encouraged by the success, we decided to construct a 25.5-MHz prototype, which can be excited with high-power rf and can accelerate heavy ions with a charge-to-mass ratio (q/A) larger than 1/30. After completing studies with the prototype, we should be ready for a real machine for the Japanese Hadron Facility; the machine will accelerate ions of unstable nuclei with $q/A \gtrsim 1/60$. The cavity of the prototype is now being fabricated.

This paper describes the results of the acceleration tests of the 50-MHz proton model, particularly for beam emittances and transmission efficiencies, and the design of the 25.5-MHz prototype.

Acceleration Tests with the 50-MHz Proton Model

The structure of the 50-MHz proton model is shown in Fig. 1, and the main parameters are listed in Table 1. The whole cavity consists of four module cavities, 40 cm in diameter and 51 cm in length each. The material is brass except for the vanes and stems of aluminum alloy. The cavity is not cooled with water, because during acceleration tests it is supplied with an peak rf power of 270 W under a pulse operation with a duty factor of 10%: the repetition rate is 400 pps, and the pulse width is 0.25 ms.

Table 1. Main parameters of the 50-MHz proton model.

Frequency (f)	50 MHz
Charge-to-mass ratio (q/A)	$\gtrsim$ 1/7
Kinetic energy (T)	2.0 → 59.6 keV/n
Vane length (L)	205.2 cm
Number of cells (radial matcher)	168 (10)
Normalized emittance (ε_n)	0.3π mm·mrad
Intervane voltage (V_{proton})	2.9 kV
Mean bore radius (r_0)	0.541 cm
Minimum bore radius (a_{min})	0.294 cm
Margin of bore radius (a_{min}/a_{beam})	1.15
Transmission (0.0 mA protons)	85%
(0.1 mA protons)	76%
(0.2 mA protons)	62%

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The scheme of the acceleration test stand is shown in Fig. 2. The previously reported system[8] has been improved in a respect. New einzel lens was added for the final focusing onto the RFQ entrance and the location was intermediate between the RFQ entrance and the old one. This change improved remarkably the shaping of the emittance profiles of the input beam; as a result, it is now possible to match the beam emittance to the RFQ acceptance.

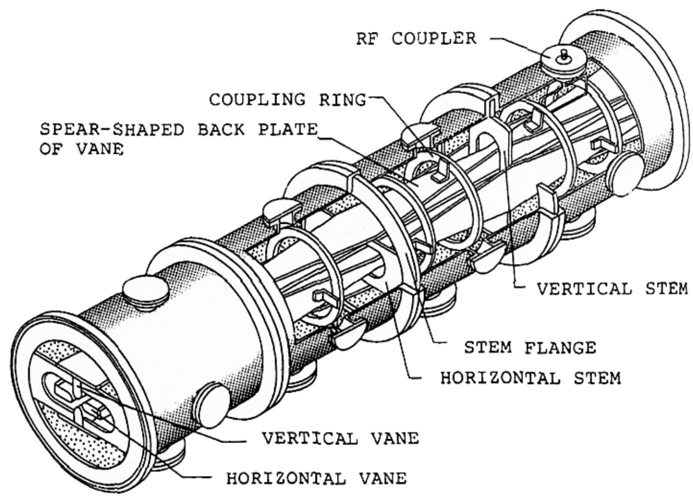

Fig. 1. Structure of the 50-MHz proton model. The tank diameter is 40 cm, and the overall length is about 205 cm.

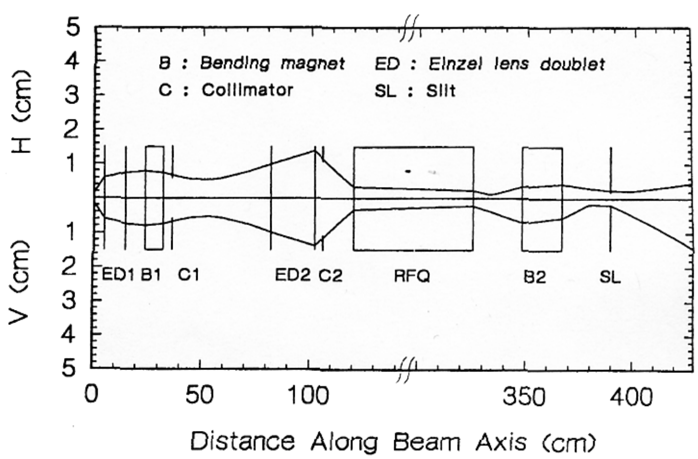

Fig. 2. Configuration of the acceleration test stand and the beam envelopes for a normalized emittance of 0.3π mm·mrad.

Protons were used during the acceleration tests. They were produced in an ECR ion source and extracted in pulses of 0.1 ms in width. The typical beam current was about 0.2 μA in average, ~5 μA in peak; the current is too low to examine the space-charge effect (see the bottom of Table 1).

Emittance Measurements

Figure 3 shows the measured emittance profiles of the input beam. The 90%–emittances (bars in the figure) are well matched to the RFQ acceptance (ellipses) of 145π mm·mrad (0.3π mm·mrad normalized). The emittance monitor has two pairs of slits: one pair for the horizontal plane (x–plane), and the other for the vertical plane (y–plane). The upstream and the downstream slits are separated by 6.8 cm, and the upstream ones are located at 12.0 cm from the RFQ entrance. The emittance profiles in Fig. 3 are the ones at this location.

The corresponding 90%–emittances of the output beam are shown in Fig. 4. The emittances are the ones at 7.51 cm down the vane end, where the upstream slits of the emittance monitor are located. The monitor is the same type as the one for the input beam, but the slit separation is 44.6 cm, since the beam divergence of the accelerated protons is smaller. The upstream slits and the downstream ones sandwich the analyzer magnet (B2 in Fig. 2). During emittance measurements, weak current is fed to the magnet so that the residual magnetization is suppressed; the beam is not bent in the magnet. These measurements verifies that the RFQ has the designed acceptance, and that no appreciable emittance growth occurs in the RFQ.

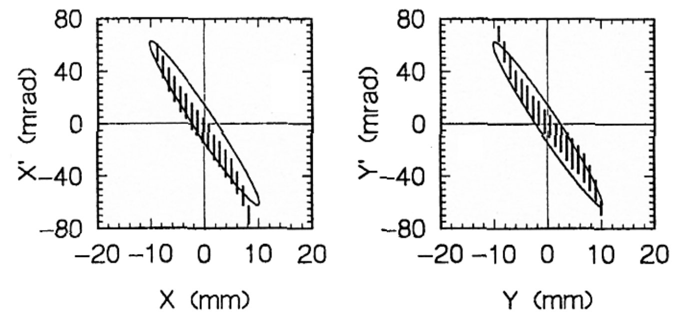

Fig. 3. Emittances of the input beam. The bars indicate measured profiles of 90%–emittance; the ellipses indicate the designed RFQ acceptances of 0.3π mm·mrad (normalized).

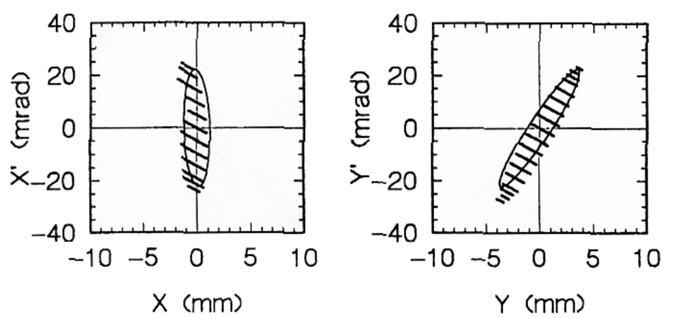

Fig. 4. Emittances of the output beam at a location 7.51 cm down the vane end.

Transmission Efficiency

The transmission efficiency was measured as a function of the intervane voltage. Two efficiencies were measured. One is for a beam comprizing both accelerated and unaccelerated protons, whose current is measured with a Faraday cup at the RFQ exit; the other is for a beam of accelerated protons only, whose current is measured with the one behind the analyzer magnet. The measured transmission efficiency for accelerated particles is indicated in Fig. 5 by dots. The result agrees well with the prediction (the dashed line in the figure) of a computer simulation using the PARMTEQ code. At the designed intervane voltage of 2.9 kV, the transmission is 85%.

As for the beam comprizing both accelerated and unaccelerated particles, the measured transmission is indicated by circles in Fig. 5, where the corresponding simulation result is given by a dash–dotted line. In contrast to the case of accelerated protons only, the discrepancy between the experimental result and the simulation one is large, particularly at intervane voltages from 1.7 kV through 2.6 kV. This discrepancy could not be attributed to some imperfection in the linac, but to some other mechanism, although the mechanism has not yet been revealed. One possibility is an effect of the fringe field at the RFQ exit between the cavity end wall and the vane edges. The effect has not been taken into account in the computer simulation because of difficulties in calculating the potential function of the electric field. The unaccelerated protons around 2 keV might be kicked so strongly that some of them could not reach the Faraday cup. Another possibility is that electrons created in the RFQ through some process, *e.g.* multipactoring, might be trapped by the unaccelerated protons and cancel the beam current. Analyses for the both possibilities are being attempted. Anyway a reduced transmission efficiency at a lower intervane voltage is not a severe problem in practice.

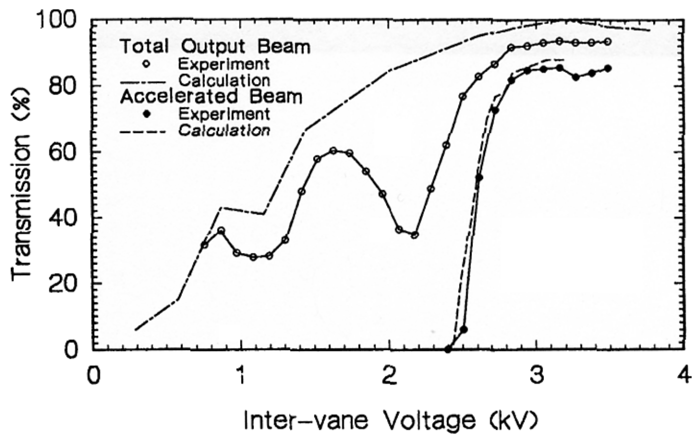

Fig. 5. Transmission efficiencies as a function of the intervane voltage.

Conclusion

Through acceleration tests it could be confirmed that the SCRFQ with modulated vanes works well and seems to be promising as long as the beam current is sufficiently low to neglect the space–charge effect. To examine the RFQ's performance for a high–current beam, we are preparing a new duoplasmatron ion source supplying protons of 100 ~ 200 μA in peak. With a test of a high–current beam acceleration, the study with the proton model will be terminated.

25.5–MHz Prototype

The success of the the proton model has enabled us to construct a prototype SCRFQ. The physical and mechanical design have been finished, and the cavity is now being fabricated. The issues to be studied using the prototype are to establish an inner structure standing high–power operation (the proton model is not cooled with water) and to accelerate heavy ions. Through studies with the prototype SCRFQ, we will obtain knowledge and experience necessary to construct a real machine for the Japanese Hadron Facility. Though the real machine will accelerate ions with a charge–to–mass ratio (q/A) larger than 1/60, the lower limit of q/A at the prototype is chosen to be 1/30 for the reasons described below. The optimized specification of the prototype is summarized in Table 2 in comparison with that of the real machine under design.

Table 2. Main parameters of the 25.5–MHz prototype in comparison with those of the real machine for the JHF.

	real machine	proto–type	
Frequency (f)	25.5	25.5	MHz
Charge–to–mass ratio (q/A)	≧ 1/60	≧ 1/30	
Input energy (T_{in})	1	1	keV/n
Output energy (T_{out})	170.2	45.4	keV/n
Normalized emittance (ε_n)	0.6π	0.6π	mm·mrad
Vane length (L)	22.3	2.135	m
Number of cells	537	136	
Kilpatrick factor (f_K)	2.2	2.2	
Intervane voltage (V)	109.3	109.3	kV
Mean bore radius (r_0)	0.946	0.946	cm
Minimum bore radius (a_{min})	0.618	0.521	cm
Margin of bore radius (a_{min}/a_{beam})	1.15	1.20	
Focusing strength (B)	3.0	6.0	

An ideal prototype would be the front part of the real machine.

The real machine of 25.5 MHz under design will accelerate heavy ions with a charge-to-mass ratio larger than 1/60 from 1 to 170 keV/n through a length of about 20 m. The length of the prototype is, however, financially limited to ~2 m. If the prototype is the same as a real machine truncated at 2 m, two problems can be foreseen concerning acceleration tests. First, the output energy is only 2.9 keV/n. Such a low output energy makes beam transport difficult, since the beam emittance is large. Second, the transmission efficiency will not be a good quantity for evaluating the RFQ's performance, as explained below. In an RFQ with modulated vanes, the bore radius, so called a-parameter, decreases with the distance along the beam axis, or beam energy, and stays constant after reaching its final value (slightly larger than the beam radius). In the real machine, however, the a-parameter at the truncation point does not reach its final value and is still 1.7-times larger than the beam radius. This means that, even if some imperfection brings about emittance growth, the beam with an enlarged emittance could pass through, *i.e.*, the imperfection might not be reflected in the transmission efficiency. Therefore this efficiency would not be useful for a crucial test of the prototype RFQ. To solve these problems we chose a q/A of 1/30 for the prototype instead of 1/60 for the real machine. As a result, the output energy is 45.4 keV/n, and the a-parameter at the RFQ exit is reaching its final value, 1.2 times larger than the beam radius.

At the beam dynamics design for q/A = 1/30, the mean bore radius r_0 and the intervane voltage were chosen to be the same as in the real machine, 9.46 mm and 109 kV, respectively. The rf characteristics of the cavity are thereby the same as those of the real machine, and the experimental results obtained with the prototype will be applicable to the real machine. Furthermore, when the prototype is lengthened in future by adding other module cavities, it could easily be converted to a real machine by replacing only the vanes with those for ions of q/A = 1/60.

The structure of the prototype is shown in Fig. 6. The material of the tank is mild steel plated with copper, and that of the inner electrode is oxygen-free copper except chrome-copper alloy for the vanes. Regarding the mechanical design, we conserved the basic principle at the 50-MHz proton model: the whole cavity (2.2 m in length and 0.9 m in inner diameter) is divided into three modules for easy assembling of the vanes at a high setting accuracy. For the convenience of assembling and water cooling we changed the stems in the proton model to stem-flanges (plates with two semilunar holes, as shown in Fig. 6). The flanges are connected by four rods so that the precise assembling of the inner electrode is accomplished completely outside the tanks. The flanges support the spear-shaped back-plates, to which the vanes are bolted. The cooling water flows through the four rods and along the stem-flanges and the back-plates. The flow rate is 150 l/min against an estimated rf power of 9 kW in average.

After the completion of the cavity a low power test is scheduled. In parallel to it, an acceleration test stand and an rf system for high-power operation will be designed and constructed.

Acknowledgments

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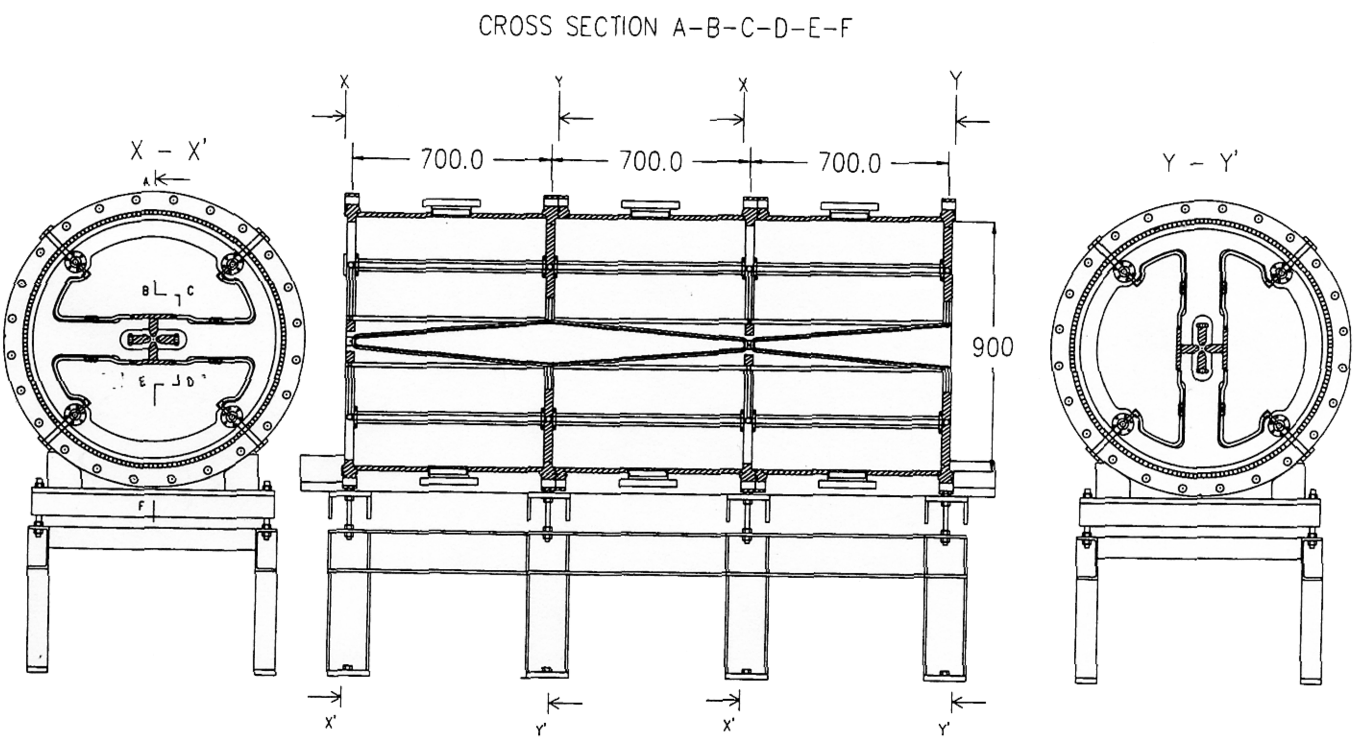

Fig. 6. Structure of the 25.5-MHz prototype SCRFQ under fabrication.