Performance Characteristics of the INS 25.5-MHz Split Coaxial RFQ

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Abstract

The performance of the INS 25.5-MHz split coaxial RFQ has been clarified through high-power and acceleration tests. The cavity operates stably at a duty factor of 20% and a peak power of 80 kW, generating an intervane voltage of 109.3 kV, the design value for ions with a charge-to-mass ratio of 1/30. Acceleration tests have been conducted to study the performance of the vanes machined by means of the two-dimensinally cutting technique. The results show that the A_{10} coefficient of the electric field will be close to the one calculated by Crandall, and that the field in the radial matching section might be different from the designed one.

1. INTRODUCTION

The INS 25.5-MHz split coaxial RFQ is a linac that accelerates ions with a charge-to-mass ratio (q/A) greater than 1/30 from 1 to 45.4 keV/u. The whole cavity, 2.1 m in length and 0.90 m in inner diameter, consists of three module-cavities and has modulated vanes, as shown in Fig. 1. This RFQ was constructed as a prototype of a longer machine accelerating unstable nuclei. The main issue concerning the rf was to operate the cavity at a duty factor greater than 10% and at a peak power 80 kW, generating an intervane voltage of 109.3 kV, the design value for $q/A = 1/30$ ions. The issue concerning the beam dynamics is to study the performance of the vanes machined by means of the two-dimensionally cutting technique. The transverse radius ρ_T at the vane tip is constant at the mean aperture radius $r_0 = 0.9458$ cm, and the correction for the A_{10} coefficient was not made [1]. Through tests we have found some problems in the cavity and the vane geometry. The problems will be easy to solve, and we have prospects of putting our RFQ to practical use by constructing a longer linac.

2. HIGH POWER OPERATION

2.1. Achieved Intervane Voltage

Through the initial conditioning of the cavity in 1990, we attained an intervane voltage of 114 kV under a pulse operation with a duty factor of 0.9% and a repetition rate of 50 Hz [2]. The cavity operates now at a higher intervane voltage and a duty factor, *e.g.*, 118 kV and 9% (150 Hz). We estimate the highest surface field to be 190 kV/cm (2.7 Kilpatrick) by using a field enhancement factor of 1.525, which is given by Crandall [1].

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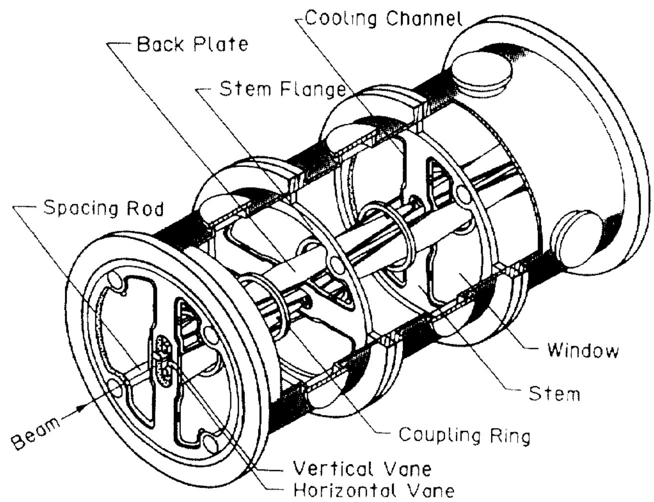

Figure 1: Structure of the 25.5-MHz split coaxial RFQ.

2.2. Frequency Shift

The shift of the resonant frequency was measured as a function of the average input power; the duty factor was 10% and the repetition rate was 100 Hz. The result is indicated with dots in Fig. 2. The resonant frequency, 25.480 MHz initially, increased to 25.608 MHz ($\Delta f = 128$ kHz) at a power of 8.5 kW and an intervane voltage of 112.7 kV. The observed frequency shift was unexpectedly large; this could be due to that some parts might have been locally heated, and consequently the intervane capacitance would have been decreased. We identified tentatively the coupling rings as the culprits, since they are not cooled directly by water (see Fig. 1). Being fixed to diametrically opposed back plates, the rings might have expanded and pulled apart the vanes.

To verify this hypothesis, we modified the coupling rings and re-measured the frequency shift. A coupling ring is composed of two arcs bolted together at places 90° apart from the rods connecting the arcs to the back plates. We removed the bolts and turned the arcs on the rods in opposite directions. The vanes are thereby free from the coupling rings. In the frequecny-shift measurement, the cavity was operated at a 10% duty (100 Hz) for average powers lower than 8 kW; for higher powers, the peak power

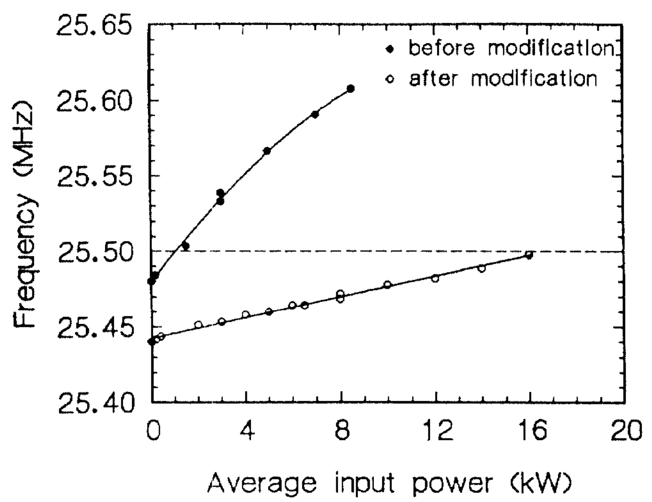

Figure 2: Shifts of resonant frequency *vs.* average input power, before and after the modification of the coupling rings.

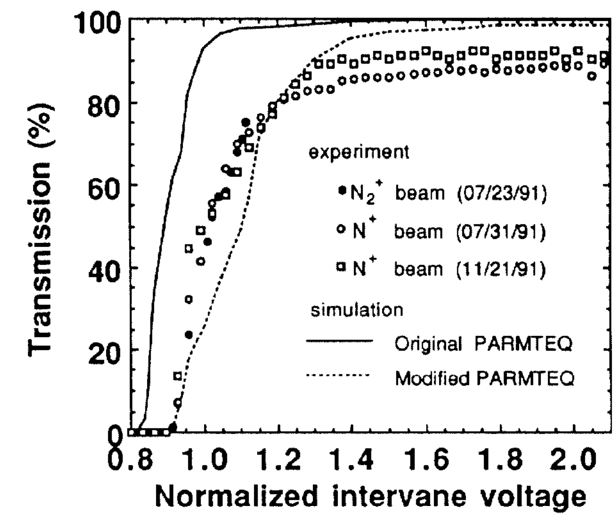

Figure 3: Transmission efficiencies *vs.* the normalized intervane voltage. Results of experiments and simulations are compared.

was kept at 80 kW (intervane voltage = 109.3 kV), and the repetition rate was increased up to a duty factor of 20%. The open circles in Fig. 2 are the frequency shifts after the ring modification; the frequency shift were suppressed appreciably. The initial frequency was 25.44 MHz, lower by 40 kHz than that before the ring modification. This frequency decrease is due to the increase of the capacitance between the back plates and the coupling rings. The resonant frequency was 25.47 MHz (Δf = 29 kHz) at an average power of 8 kW, and at 16 kW, 25.50 MHz (Δf = 56 kHz). These frequency shifts shall come under control with inductive tuners to be attached to the cavity soon. They are three piston tuners driven by pulse motors.

From the frequency-shift measurements, we found that the coupling rings are harmful. The purpose of the rings was to gain a better vane alignment. At the inspection of the vane alignment in the cavity construction, however, we found that the vanes could have been aligned well enough without the coupling rings. Moreover, at an acceleration test with the modified coupling rings, we obtained almost same beam performance as before. Therefore the coupling rings should be removed.

3. Acceleration Performance

3.1. Transmission Efficiency vs. Intervane Voltage

Figure 3 shows the transmission efficiency as a function of the normalized intervane voltage V_n, the voltage divided by the design value. Experimental data are compared with the results of two PARMTEQ simulations. At the original PARMTEQ, the electric field is derived from the two-term potential function [3]. At the modified PARMTEQ, the A_{10} coefficient that Crandall calculated for the $\rho_T = r_0$ vane is used in place of A, the A_{10} of the two-term potential function [1]. At our RFQ, the ratio A_{10}/A varies along the axial distance, starting with 0.654 and ending with 1.024 [4]. The original PARMTEQ predicts a steap increase of the transmission efficiency in the V_n range between 0.9 and 1.0, whereas the modified PARMTEQ predicts a slower increase. This is due to the small A_{10} in the beam-bunching process; the separatrix area is so narrow that the capture efficiency has gone worse. The experimental transmission efficiency increases slowly as the modified PARMTEQ predicts. Hence the A_{10} of the actual field will be close to the Crandall's A_{10}.

We have not yet obtained a good agreement between the experimental data and a simulation. The discrepancy could be attributed to the radial matching section, as is discussed below.

3.2. Radial Matching Section of the Split Coaxial RFQ

In the PARMTEQ simulation, we assume that the electric field in the radial matching section (RMS) is derived from a potential function:

$$U(x,y,z) = \frac{V}{2}\left[1 + \frac{x^2 - y^2}{a^2}\right]\frac{z}{L}\,, \tag{1}$$

where V is the intervane voltage, a the aperture radius at the exit of the RMS, and L the length. The ideal vanes should be shaped to the the equipotential surfaces obtained by equating the right-hand-side of Eq. 1 to 0 or V; at our RFQ, $U = 0$ on the horizontal vanes, fixed to the cavity end wall, and $U = V$ on the vertical ones. The resulting transverse radii of curvature at the vane tips are:

$$\rho_T = a \;\; (U = 0)\,, \quad a\left(\frac{2L}{z} - 1\right)^{1/2} \;\; (U = V)\,. \tag{2}$$

At the actual vanes, however, the vane tips are shaped to a circular arc with $\rho_T = a = r_0$, in the same manner for the modulated vanes. This shaping would be good for the $U = 0$ vanes, but worse for the $U = V$ vanes. Hence the electric field generated by the vanes with such a vane-tip geometry would be different from the one derived from the potential function given by Eq. 1.

3.3. Transmission Efficiency vs. Injection Energy

The potential distribution in the RMS of the split coaxial RFQ is different from that of the four-vane RFQ. At the latter RFQ, the potential on the beam axis is zero, but at the former, it increases from zero to $V/2$ along the axial distance. Since the longitudinal component of the electric field is not zero on the beam axis, the energy and phase modulation that the beam experiences in such an RMS is quite particular. For instance, if the input beam is a d.c. beam with the design energy W_{in}, ions move toward $\Delta\phi = \pm\pi$ ($\Delta\phi \equiv$ rf phase ϕ − synchronous phase ϕ_s). Consequently, at the exit of the RMS, the ion density is minimum at $\Delta\phi = 0$ and maximum at $\pm\pi$; whereas at the four-vane RFQ, the $\Delta\phi$-distribution is almost flat. Consequently, for the beam with $W = W_{in}$, the $\Delta\phi$-acceptance of the split coaxial RFQ is narrower than that of the four-vane RFQ.

The transmission efficiency as a function of the injection energy should reflect such an RMS performance. The modified PARMTEQ result is shown in Fig. 4 along with experimental data. The simulation result is remarkable for dips around $\Delta W_{in}/W_{in} = 0$. At the experimental data, however, the dips are much shallower and the transmission efficiencies are higher. This implies that the longitudinal field component E_z might be different from that derived from Eq. 1. We tried PARMTEQ runs by replacing the RMS with the one for the four-vane RFQ so that $E_z = 0$ on the beam axis [5]. The resulting transmission efficiency has no dips and agrees well with the experimental data in Fig. 3 in the range of $0.9 \leq V_n \leq 1.1$. We hence expect that the constant-ρ_T vanes in the RMS would have reduced the E_z-component.

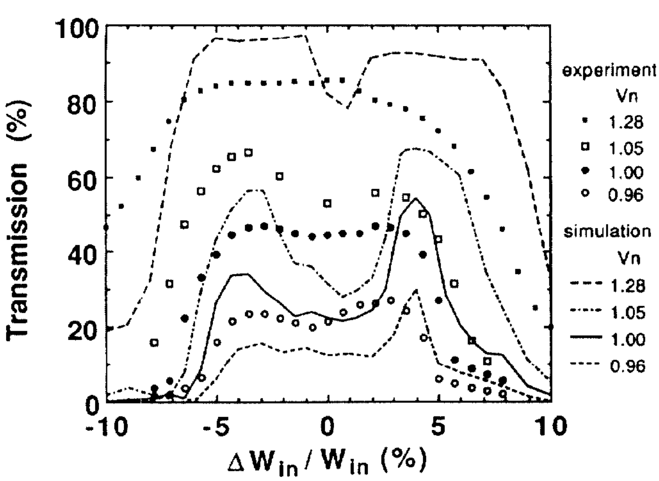

Figure 4: Transmission efficiency *vs.* injection energy for some values of the normalized intervane voltage V_n. The ions used in the experiments are N_2^+ ($V_n = 0.96, 1.00, 1.05$) and N^+ ($V_n = 1.28$).

4. Concluding Remarks

At INS we are about to build a facility delivering beams of exotic nuclei for nuclear physics experiments [6]. The present RFQ will be extended to an 8.5-m, 170-keV/u machine and used as the preaccelerator. We contemplate some improvements as follows. The coupling rings will be removed for easier operation at the frequency fixed at 25.5 MHz. The flow rate of cooling water, about 300 l/min now, will be increased for an operation at a duty factor of 30%. The variable-ρ_T geometry of the vane tip will be employed for the low-energy part, about 1-m long, and the $\rho_T = r_0$ geometry for the high-energy part. The new RFQ is being designed.

5. Acknowledgments

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6. References

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