RF CHARACTERISTICS OF THE 33.3 MHz 4-ROD RFQ

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Abstract

A full-scale 33.3 MHz 4-rod RFQ accelerator cavity has been constructed for the applications of ion implantation in commercial use [1,2]. The RFQ is operated in cw RF and in relatively low frequency to accelerate typical semiconductor-dopant ion beams with moderately large emittances. The RF characteristics of the accelerator cavity were measured in both low and high power RF with un-modulated RFQ electrodes. Low power measurements include Q-value, Q_O/R_O, electric-field distributions in both longitudinal and transverse directions. High power RF measurements were done to check the temperature rise of cavity cooling medium and over-all stability of the RFQ resonator in cw operation.

Introduction

The value of rf power, that requires to excite the RFQ cavity is, one of the most important parameters because our 4-rod RFQ is to be operated in cw operation. Cooling and vacuum engineering will be very difficult if the power efficiency of a cavity is too low. In that case, an accelerator could become very expensive and difficult to maintain. The electric-field distributions and the balance of the quadrupole strength are the other important properties of an RFQ. Measured rf characteristics of a full-scale 4-rod RFQ cavity with un-modulated electrodes are presented in this paper.

Table 1 Key parameters of 33.3 MHz 4-rod RFQ.

Frequency	33.3 MHz
Average bore radius	0.8 cm
Focusing strength	6.79
Inter-electrode voltage	54.9 kV
Charge to mass ratio	1/11 ~ 1/16
Injection energy	2.73 keV/u
Output energy	83.5 keV/u
Length of electrode	222 cm
Cavity diameter	60 cm

RFQ Electrode Assembly

Key parameters of our RFQ is given in table 1. Photo. 1 is a view of RFQ electrode assembly installed in the cavity. It consists of three major part : the RFQ electrodes, the electrode supporting posts, and the base plate. The material is all copper - aluminum version of the supporting posts are shown in photo. 1, however, which were made for low RF power testing purpose. The whole assembly is put together using alignment jigs outside the cavity. It was then installed in the cavity and securely fixed to the cavity with four M20 bolts. Assembling and disassembling of the RFQ electrode can be done relatively easily by just two people. The number of the post is six - this means a pair of RFQ electrodes is supported by three posts. The width and thickness of the post are 240 mm and 45 mm, respectively. The beam optics axis is 330 mm above the top surface of the base plate. The posts are evenly spaced by 405 mm from each other. RF contact between the tank and the base-plate of the RFQ assembly is made by commercially available " RF spiral shield ". Though not shown in photo. 1, there are three independent cooling-water channels allocated for the RFQ electrode assembly: two for the electrodes and one for the electrode-supporting post and base plate.

Measurements of R_O/Q_O and Q_O

One common way to determine RFQ's rf power requirement is to measure both R_O/Q_O and unloaded Q-value (Q_O) and then to estimate the shunt impedance (R_O) of the accelerator cavity.

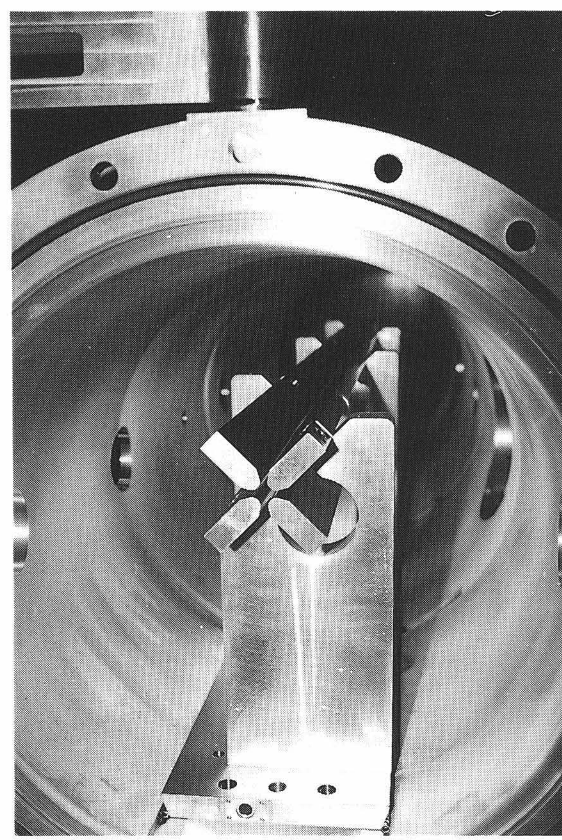

Photo. 1 Picture of 33.3 MHz 4-rod RFQ.

We have attempted determining R_O/Q_O by two different ways: bead-pull and so-called "capacity variation" (c.v.) method [3,4,5]. Q_O, perturbed resonant frequency (f), and unperturbed resonant frequency (f_O) are measured with a network analyzer. The measured value - by "transmission method" - of Q_0 is approximately 5000. This value of Q_0 is used throughout later calculations.

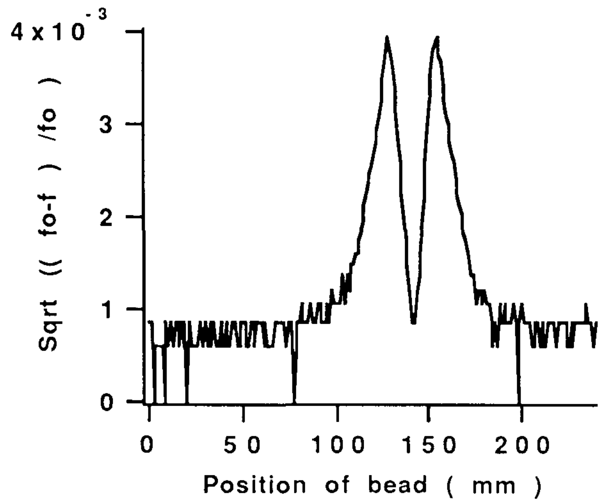

Fig. 1 Results of bead pull in transverse direction of 33.3 MHz 4-rod RFQ.

Bead pull - transverse direction

The result of bead-pull in transverse direction is shown in fig.1. The bead is a metallic sphere 3 mm in diameter. R_0/Q_0 is calculated as follows [4] :

$$\frac{R_0}{Q_0} = -\frac{2S^2}{k\omega\varepsilon f}\frac{\Delta f}{\Delta\tau} \quad (1)$$

,where S=separation distance of electrodes,
k=3,
$\omega=2\pi$ f, f is resonant frequency,
ε =permittivity of free space,
$\Delta f=f-f_0$,
$\Delta\tau$ =volume of perturber.

R_0/Q_0 is estimated to be 18.9 Ω when the measured unperturbed resonant frequency, f_0 is 33.024406 ±0.0000125 MHz and the lowest perturbed resonant frequency, 33.023910 ±0.0000125 MHz. The distance of the closest electrode separation, S is 7.0 mm. R_0 is then calculated to be 94.5 kΩ per cavity. The required power to excite the RFQ cavity at the design inter-electrode of 54.9 kV is estimated to be 15.9 kW.

Capacity variation method

This method is schematically depicted in fig.2. The idea is to perturb an inter-electode capacitance of one quadrant of the RFQ by putting a small ceramic capacitor. The net inter-electrode capacitance then increases and the resonant frequency shifts lower. R_0/Q_0 is determined as follows [5]:

$$\frac{R_0}{Q_0} = -\frac{2}{\omega_0^2}\frac{d\omega}{dc} \quad (2)$$

, where $\omega_0 = 2\pi f_0$,
$\omega = 2\pi$ f, f is perturbed resonant frequency,
c = perturbing capacitance.

At each quadrant, so called "local" characteristic impedance of the RFQ was measured by this method. The average value of R_0/Q_0 is used to estimate rf power requirement and the variation of R_0/Q_0 can be interpreted as representation of the quadrupole field balance.

Fig. 3 shows plots of resonant frequency vs. capacitance in each quadrant of the RFQ. Capacitors used are 1, 2, 3, 3.3, 5, 10 pF ,which are small compared with the effective inter-electrode capacitance - approximately 75 pF/quadrant

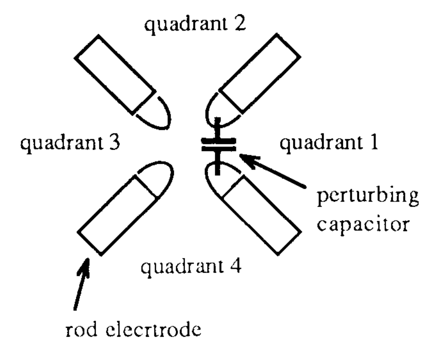

Fig.2 Schematic description of measuring R_0/Q_0 by capacity variation method.

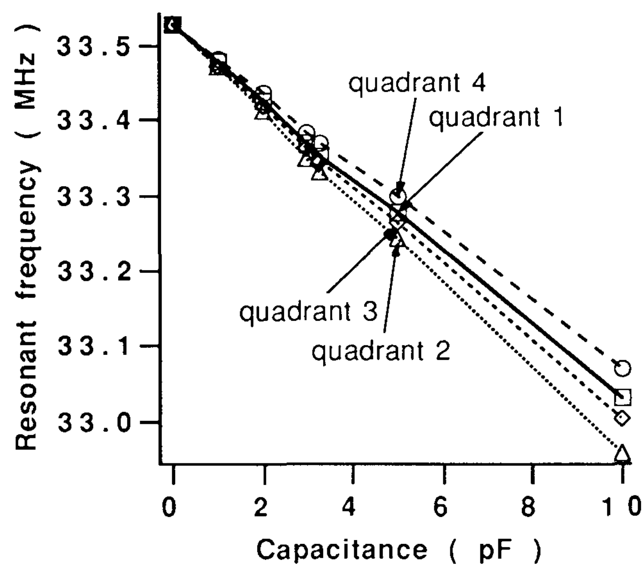

Fig. 3 Resonant frequency vs. capacitance by capacity variation method in the four quadrants of 33.3 MHz 4-rod RFQ.

from calculations using POISSON. The slopes of the curves, which correspond to $d\omega/dc$ are found by liner-fits. The average value of $d\omega/dc$ of quadrant 1 and 3 is 2π (- 0.0510) MHz/pF when f_0 is 33.5275 ±0.003 MHz. R_0/Q_0 is then calculated to be 14.4 Ω. This value is roughly comparable to the result obtained from the previously described transverse bead-pull measurements. Slight increase of the unperturbed resonant frequency, f_0 from the bead-pull measurement is due to installation of cooling pipes in the RFQ cavity. Quadrupole electric-field strength is roughly 6 % higher in quadrant 2 and 5 % lower in quadrant 4, compared with the average electric-field strength of quadrant 1 and 3. The results of this capacity variation method are later compared with that of measurements of longitudinal field distribution.

Bead pull - longitudinal direction

Because the RFQ cavity is rather long - over 2 m, a particular attention has to be given to the measurement setup of longitudinal bead pull : weight of perturber, perturbation due to the thread and the alignment of and tension in the thread. The bead is a plastic cylinder 8 mm in diameter and 11 mm in length. The diameter of a fishing thread is 0.22 mm. Unperturbed resonant frequency is measured for each setup of measurement when the perturber is pulled out of the cavity but the thread remains in the cavity. Fig. 4 shows the results of bead pull along the longitudinal axis in all four quadrants of the RFQ. The observation of fig.5 indicates that the quadrupole electric-field strength is flat within ±4 % in each quadrant and that the quadrupole electric-field strength is higher by roughly 6 % in quadrant 2 and lower by roughly 6 % in quadrant 4 compared with the average of quadrant 1 and 3. Those results agree with the results obtained by capacity variation method.

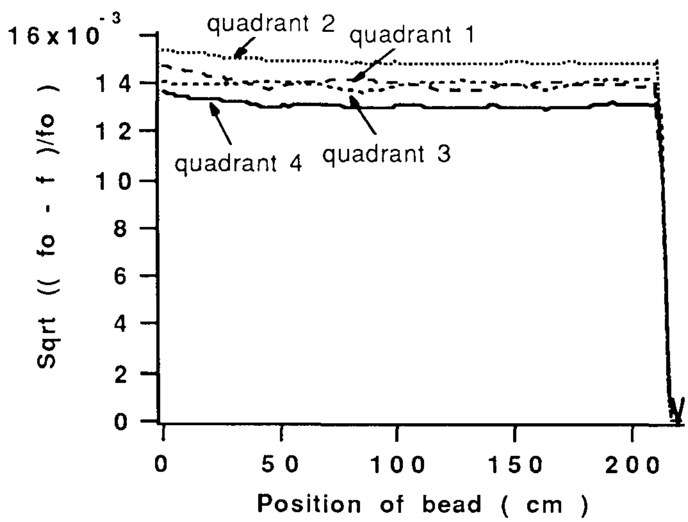

Fig. 4 The results of bead pull in the longitudinal direction in the four quadrant of 33.3 MHz 4-rod RFQ.

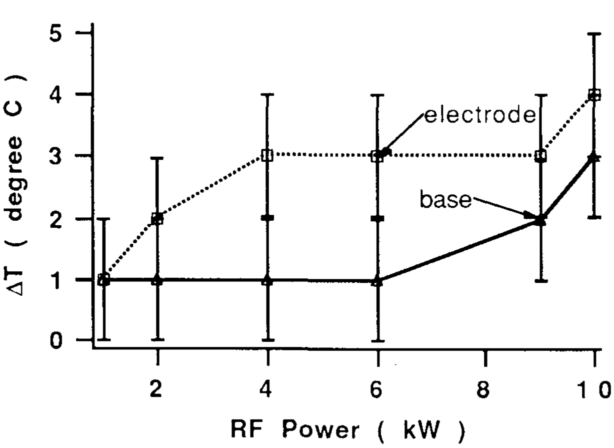

Fig. 5 Plots of temperature rises of cooling water in the components of 4-rod RFQ electrode assembly: the base and a pair of rod electrodes. Water flow rate are 20 and 18 liter/min. for the base and a pair of rod electrode, respectively.

High Power Tests

The high power tests of the 4-rod RFQ have been conducted in cw RF up to 10 kW. The results of temperature rise on cooling water are shown in fig. 5. As described in reference 2, almost half of rf power put into the cavity is spent by the RFQ electrode assembly, of which the rod electrodes contribute 50 %. In the experiments both forward and reflected power are monitored and a loop tuner is used to tune the cavity. Throughout the tests, reflected power is kept below 0.1 kW. Vacuum is about 1.4×10^{-6} torr at 10 kW input.

Summary

We can summarize the rf characteristics of the RFQ as in table 2.

Table 2 Summary of rf characteristics of 33.3 MHz 4-rod RFQ

	c.v. method	bead pull	network
Q_0	------	------	5000
R_0/Q_0 (Ω)	14.4	18.9	------
R_0 (Ω)	72	95	------
rf power (kW)	21	16	------
Field balance (%)	+6, -5	±6	------

There are some ambiguity left to be cleared before the results of the two methods are properly compared. One is that as mentioned earlier the cooling pipes were installed in the RFQ cavity between the two measurements. We didn't go back to recheck the transverse bead-pull measurements because we were only interested in finding the order of R_0 value and in roughly estimating the rf power requirement. On the other hand, a good agreement is obtained in the RFQ's electric field balance between the the results of the two measurements. The asymmetry of the electrode supporting structure is reflected in the balance of quadrupole field strength among the four quadrants by as much as 6 % [6]. This zeroth order error may be corrected in real application by offsetting the beam optics axis by corresponding proportion.

References

[1] H. Fujisawa, et al., "Design and Construction of a Heavy Ion RFQ Linac", *Proceedings of the 8th Symposium on Accelerator Science and Technology*, p.122-124 (1991).
[2] H. Fujisawa, et al., "Mechanical Design of 33.3 MHz 4-Rod Heavy Ion RFQ Cavity", *Bull. Inst. Chem. Res., Kyoto Univ.* Vol. 70, No. 1, p.28-36 (1992).
[3] R.H. Stokes, et al., "A Spiral-Resonator Radio-Frequency Quadrupole Accelerator Structure", IEEE Trans. Nucl. Sci. Vol. NS-30, No. 4, p.3530-3532 (1983).
[4] E.L. Ginzton, "*Microwave Measurements*", McGraw-Hill, New York, Sec. 10.4 (1975).
[5] Ibid., Sec. 10.2.
[6] R.M. Hutcheon, "A Modeling Study of The Four-Rod RFQ", *Proceedings of 1984 Linac Conference.*, p.94-96 (1984).