RFQ STRUCTURE FOR LOW FREQUENCY AND CW OPERATION

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Abstract

An unstable ion beams facility is proposed at TRIUMF since many years. The aim of such facility is to accelerate unstable ions provided by an isotopic separator on line (ISOL) to energies relevant to nuclear astrophysics. The front end of such an accelerator will be a radio frequency quadrupole (RFQ) that can accelerate ions with a charge to mass ratio greater than 1/60 operating in CW mode. Development of such RFQ had started at TRIUMF and a report on the cold model studies is given.

Introduction

The construction of a heavy ion linear accelerator complex for unstable nuclei (ISAC) has been under consideration at TRIUMF since 1985 [1]. The post accelerator of unstable ion beams must fulfill these main objectives:

1) since the nuclei of interest in the range of $6 \le A \le 60$ have velocities in the range of 0.01 c and very low q/A, it should be able to accelerate efficiently particles at such low velocity.

2) the losses of beam intensity should be small since the production process of these nuclei is very complex and the intensities are quite small. Typical intensities are in the range of 10^3 to 10^{11} p/s.

3) the final energy must be variable continuously in the range of 0.2 to 1.5 MeV/u.

4) The post-accelerator must be operated with 100% duty cycle in order to preserve the intensity of the unstable ion beams.

Accelerator design

Since the intensity of the unstable ion beams from the ISOL system are relatively low we must design an accelerator system which has high transmission in order to make the best use of the valuable beam as well as to keep the facility clean of radioactive contamination. The front end structure has a great influence on the transmission efficiency, especially when the ions with a very low charge to mass ratio such as (1/60) are injected at low velocity such as 2 keV/u. All these requirements call for a linear accelerator with a RFQ as a first stage. The RFQ accelerator has the merit that it can accelerate very low velocity ions with a good efficiency, $\geq 90\%$.

The key parameters of the ISAC RFQ are listed in table 1.

However, for accelerating ions with small charge to mass ratio as 1/60, the RFQ must be operated at low frequency, 10 to 30 MHz in order to have stable transverse behavior of the beam and reasonable acceptance. At low frequency the size of the conventional four vane RFQ tank becomes very large. To reduce the size of the cavity diameter for frequencies lowest than 200 MHz the four vane structures are replaced by the "0-mode RFQ structure" using four rods. Each pair of quadrupole electrodes consists of two copper

Table 1
ISAC RFQ parameters

Frequency (MHz)	25
Average bore radius (cm)	0.7
Focus Strength	2.99
Vane modulation	2.49
Inter Electrode Voltage (kV)	76
Charge to mass ratio	$q/A \geq 1/60$
Injection Energy	1 keV/u
Output Energy	60 keV/u
Synchronous Phase Deg.	-90 initial -30 final
Number of cells	308
Length of electrode (m)	7.6

rods connected to two stems forming an inductively loaded $\lambda/2$ oscillator, [2]. The accelerating mode, is the π-0-mode, the 0 means that the electrodes have the same phase along the structure. The split coaxial [3] or a spiral RFQ [4] are two candidates structures for operation at the required low frequency.

Few RFQ's have been built for 100% duty factor operation. The only one reported for heavy ions acceleration is the 33.3 MHz 4-rod of the Kyoto University [5] and [6]. A program was initiated at TRIUMF in order to find the best structure for low frequency and high duty cycle operation.

Low power measurements

One common way to determine the RFQ power requirements is to measure the shunt impedance. We have determined the shunt impedance by the measurement of the voltage, V on the rods and the input power, P_i, and by the so-called "capacity variation" method. For this method Q_0, the perturbed resonant frequency f, and the unperturbed resonant frequency f_0, are measured with a network analyzer.

P and V measurement method

We define the specific shunt impedance as follows:

$$Z = \frac{V_P^2}{(2P_i/l)}, \qquad 1)$$

where V_p is the peak inter-rod voltage,
P_i is the input power in the cavity,
and l the RFQ length.

The voltage and the phase on each rod is measured using four calibrated probes and a vector voltmeter. Figure 1 shows a schematic drawing of the arrangement used for power and voltage measurement.

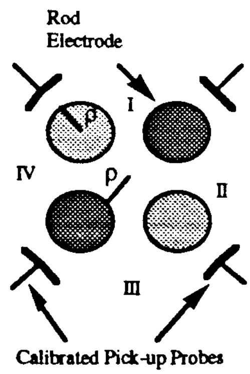

Fig. 1 Schematic description of the measuring Vp and phases on each rods.

Capacity Variation method

In this method the inter-electrode capacitance of one quadrant of the RFQ is perturbed by shunting two rods with a small capacitor. The inter-electrode capacitance then increases and the resonant frequency shifts lower. This method is schematically described in fig. 2. R_0/Q_0 is determined as follow;

$$\frac{R_0}{Q_0}=-\frac{\Delta f}{\pi f_0^2 \Delta C}, \qquad 2)$$

where f_0 is the unperturbed frequency,
f is the perturbed frequency,
Δf is the frequency shift and
ΔC is the perturbing capacitance.

The R_0/Q_0 value of each quadrant was measured. The average value of R_0/Q_0 is used to compute the shunt impedance. Typical values for the silver mica capacitors used ranged from 2.5-5.5 pF, which is more then one order of magnitude smaller than the inter rod capacitance.

Model measurements

Several scale models have been built to find the best RF structure suitable for cw operation. A modular assembly technique was adopted in order to make use of the same electrodes, frames and tank for all models. Parts were only bolted together, which accounts for the relatively low measured Q_0 values.

Scaling law

Before any further investigations we have verified the scaling law for the shunt impedance. The scaling law is expressed as follow:

$$Z(f)=Z(f_1)\left(f_1/f\right)^{3/2}, \qquad 3)$$

where $Z(f_1)$ is the shunt impedance measured at the frequency f_1 and Z(f) is the scale shunt impedance at the frequency f.

We have built two models of the same type, one a 3/4 scale of the other. The frequency and shunt impedance in the first case were 54.933 MHz and 79 ± 4 kΩm respectively. In the second case they were 72.356 MHz and 51.3 ± 2.5 kΩm respectively. Scaling according to equation 3 from case 2 to case 1 gives Z = 77 ± 4 kΩm which is in agreement with the measurement and confirm the scaling law.

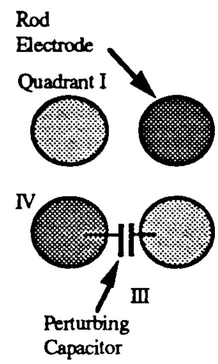

Fig. 2 Schematic description of the R_0/Q_0 measurement by the capacity variation method.

RFQ structures

The following structures have been investigated, split coaxial four rod, two stems four rod RFQ and what we called split ring four rod RFQ. Some structures like the split coaxial RFQ and the two stems show large voltage unbalanced at the end of the electrodes with respect to the external tank. The worst case is the split coaxial RFQ. In this case the voltage is V on one pair and 0 on the other one. This is also the case for the two stems four rod RFQ. Actually, at their end one pair is near the full potential V_p oscillating at the RF frequency, while the other pair remains near the ground potential. This voltage unbalance determines on the axis a potential difference $V_p/2$ between the end of the electrodes and the end plates. As a consequence, a longitudinal component E_z of the electric field appears, and such region behaves like a RF gap that modifies the velocity of the particles passing through it. In our case q time the E_z component will be of the same order as the particle energy entering the RFQ.

This voltage unbalance come from the fact that the pair of rods are not attached at the same longitudinal location. This was verified experimentally and with a theoretical analysis based on a transmission line model, [7].

We started looking for a structure having a small separation gap between the rod's supports. We finally arrived at a structure we called "split ring four rod RFQ", see fig. 3. In this type of structure the rod's support can have a very small separation. The dimension of the model are the following; ring radius R equal 8.8 cm, minor radius r equal 0.95 cm and the thickness 2.54 cm.

The shunt impedance of that structure can be written as follow;

$$Z_T=\frac{L}{R_S\left(\frac{5/4\,\pi R}{[2r+z]}+\frac{l_{cell}}{12\pi D_{rod}}\right)\left(C_T+C_0/l_{cell}\right)}, \qquad 4)$$

where;

$$R_S = \sqrt{\mu_0\ \omega/2\sigma}\ , \qquad (5)$$

R is the ring radius, r the minor ring radius, L_{cell} the cell length, L the inductance, z the ring thickness, C_T the rod capacitance per unit length, C_0 the intrinsic capacitance of the structure without rods, D_{rod} the diameter of the rod and σ is the conductivity.

Using the table for the inductance of a ring with rectangular cross section given in ref. [8] we can obtain the inductance of the structure by the following expression;

$$L = 0.9R\Big/\left(0.09[r/R]^{2/3} + 0.012\right). \qquad (6)$$

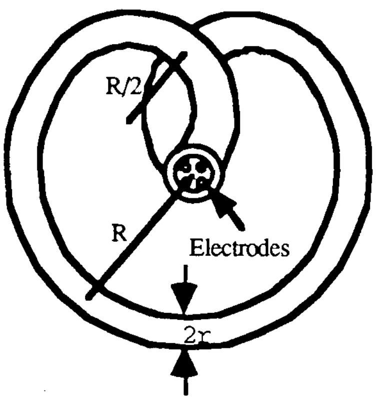

Fig. 3 Schematic drawing of the split ring RFQ.

We have built a 1/3 scale model composed of 5 cells of this split ring RFQ. The cell length was varied in order to find the maximum of the shunt impedance. Assuming that the capacitance of the four rod electrodes as described in fig. 1 is 92 pF/m and the measured Q value is 50% of the calculated Q, see dotted and dashed curves in fig. 5. Figure 4 shows the calculated shunt impedance and the frequency and the measured values using the expression 4. The full line in fig. 5 shows the shunt impedance scaled to 25 MHz for this split ring RFQ as a function of cell length. The specific shunt impedance is maximum for a cell length of 35 cm

Conclusion

We have investigated in our model studies different candidates for the front RFQ of the proposed unstable ion beams facility at TRIUMF. The so called "split ring RFQ" seems to be a good candidate for a low frequency and high duty cycle since the specific shunt impedance assuming only 50% of the Q can be as high as 265 kΩ m for a cell length of 35 cm.

A new model has been built. We have improved the mechanical alignment of the rods. It is composed of three individual cells connected together. New data points will be taken in order to go beyond the existing data point in order to test the calculated shunt impedance given by eq (4).

Assuming that we can acheive in the full scale RFQ 60% of the calculated Q a specific shunt impedance as high as 500 kΩ m at 25 MHz seems to be achievable if the ratio r/R is increase from 0.1 to .15 with a ring radius of 42 cm.

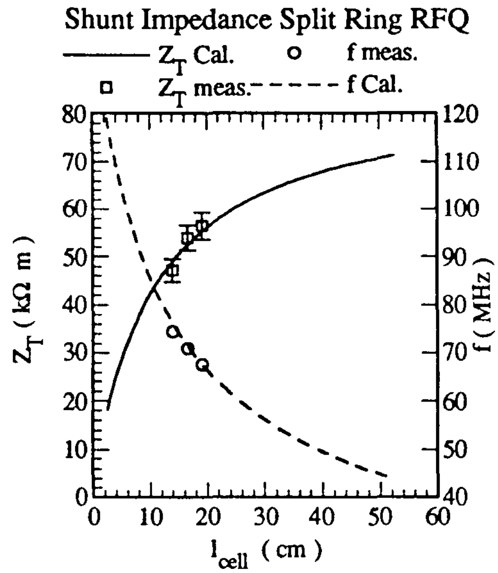

Fig. 4 Calculated shunt impedance as a function of the cell length and the measured values.

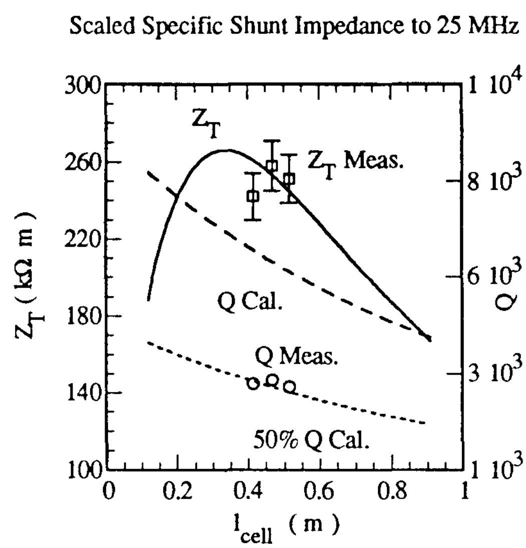

Fig. 5 Scaled shunt impedance as a function of the cell length. The dotted curve shows the calculated Q value.

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