A HEAVY ION RFQ WITH HIGH ACCELERATING GRADIENT

B.G. Chidley, R.M. Hutcheon and G.E. McMichael
Atomic Energy of Canada Limited, Research Company
Chalk River Nuclear Laboratories, Chalk River, Ontario, Canada K0J 1J0

Abstract

An RFQ accelerator that will accelerate ions of mass 6 to 60 amu with 1 keV/amu input energy to an output energy of 60 keV/amu has been proposed as part of an ISOL facility at TRIUMF. This RFQ has some novel features, including single turn lumped inductors, modular construction, and an aperture increase and longitudinal voltage tilt of 2.5 between input and output. Continuously increasing the aperture and intervane voltage of an RFQ as the particle velocity increases can significantly reduce its length while avoiding the complications of multiple tanks with step changes between them. Beam dynamics calculations showing the advantages and disadvantages of such tapered RFQ's are presented. From structure considerations, a 4-rod RFQ with the desired bore and voltage tilt seems inexpensive to build. A 1/5 scale cold model of the proposed TRIUMF RFQ was built, and preliminary measurements compared with computer code predictions.

Introduction

A conceptual design study* was undertaken to look at the feasibility and define some parameters of an accelerator to accept ions of mass 6 to 60 amu with an energy of 1 keV/amu, and accelerate them to an output energy that could be continuously varied over the range 0.2 to 1 MeV/amu. The accelerator proposed in this study included a 23 MHz 4-rod RFQ to accelerate the ions from 1 to 60 keV/amu[1]. Conventional design recipes[2] were used for this RFQ, and conservative upper limits were applied to the peak electric fields (1.5 * Kilpatrick[3]) and rod modulation (m=1.8 maximum) because of the requirement for 100% duty factor (cw) operation. The RFQ design obtained by this method was 15 m long, so ways were sought to shorten it. Keeping the same electric field and modulation, but increasing the bore and inter-rod voltage approximately proportional to β once bunching of the beam was completed, led to a decrease in length to 9.7 m. Further design calculations investigated the consequences of relaxing the original electric field and modulation limits, and determined over what region and to what extent the bore and intervane voltage could be tapered. Results are presented below.

Previous studies of the 4-rod RFQ rf properties were extended to develop better design equations for shunt impedance optimization. Also a low power 1/5 scale model of the 9.7 m tapered bore RFQ was built to confirm that the voltage tilts could be achieved and to study the rf properties of such a device.

Beam Dynamics Considerations

Following usual design recipes, an RFQ can be described as having 4 distinct longitudinal sections, which, starting from the input end, are called the radial matching, shaper, gentle buncher and accelerating sections. The transverse focusing is increased over the radial matching section by tapering the bore radius so that the focusing strength increases smoothly from essentially zero at the input to the value required for stable transverse oscillations at the output. Along the shaper, the modulation of the rods (or vanes) is gradually increased to begin bunching and accelerating the beam and moving it away from its input synchronous phase angle of $\phi_s = -90°$. The gentle buncher continues this process, gradually ramping the modulation up to a maximum, and shifting ϕ_s to about -30°. In most cases, this is done at a rate that keeps the physical length of the longitudinal separatrix constant, and the synchrotron oscillation frequency constant. Typically the beam energy increases by a factor of 6 to 10 over the first three sections.

Since total energy gains for RFQ's are usually a factor of 30 or more (60 in the case of the TRIUMF ISOL proposal), the bulk of the acceleration takes place in the last or accelerating section. Conventionally, synchronous phase, modulation, bore radius and inter-rod voltage are all held constant over this region. This causes the accelerating gradient to decrease from its peak value at the gentle buncher/accelerating section boundary, and the length of the accelerating section often accounts for 75% or more of the total length of the RFQ. Obviously, the accelerating section presents the greatest opportunity for significant length reduction.

The axial field in an RFQ for a particle with phase angle ϕ is

$$E_z = kAV \sin(kz) \sin(\omega t+\phi)$$

where $k = 2\pi/\beta\lambda$ and V is the inter-rod or inter-vane voltage. The energy gain depends on $\cos\phi$, but for the usual value of $\phi_s = -30°$, $\cos\phi_s = 0.87$. At most a 13% improvement is available and a reduction to $\phi_s = -17.5°$ gives a 10% improvement, but with a considerable reduction in longitudinal focusing. The accelerating factor "A" depends on the rod modulation "m" and the aperture "a" as follows:

$$A = \frac{m^2 - 1}{m^2 I_0(ka) + I_0(mka)}$$

where I_0 is a modified Bessel function. Problems arise with field enhancement and higher order modes as "m" is increased, making it difficult to use an "m" greater than about 2. This sets a practical limit for "A" of 0.6 for small values of (ka). For the 15 metre RFQ, A = 0.548 at the start of the accelerating section.

The most gain in accelerating field comes from increasing "V", but the peak electric field varies as V/r_0, where "r_0" is the mean bore radius, and cannot be increased without increasing the probability of sparking. One normally designs for as high a V/r_0 as possible based on sparking considerations, and therefore to increase "V", "r_0" must also increase. Therefore, the achievable length reduction is primarily determined by the initial bore radius and by how much the inter-rod or inter-vane voltage and bore radius can be jointly increased.

Constant bore RFQ's are usually designed by choosing values for r_0, m and V at the end of the gentle buncher section that will give equal transverse and longitudinal focusing with stable oscillations.

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To minimize the overall length, r_0, m and V should all be as large as possible. Higher order effects depend on the ratio of r_0 to $\beta\lambda$ so this often gives an r_0 that is somewhat too large at the input end, but the resulting emittance growth can usually be tolerated. In the accelerating section, because β is increasing, r_0 can increase at the same rate (i.e., by a factor of 3.1 for the TRIUMF case). Keeping V/r_0 constant will then keep E_z and A constant (to first order) over the accelerating section, and if the rod tip radius is varied over each cell to keep the voltage enhancement factor constant[4], sparking limits are also unaffected. Transverse focusing will decrease along the accelerating section, since the transverse field

$$E_r(r,\theta,z) = \frac{V}{r_0^2} r \cos(2\theta) - \frac{kaV}{2} I_1(kr) \cos(kz)$$

where I_1 is a modified Bessel function. However for the low current cases studied, the growth in beam envelope radius is acceptable. Figures 1(a) and 1(b) show the X-XP emittance plots for cases 3 and 4 of Table 2 below. X_{max} is larger in Fig. 1(b) but the emittances of the two beams are the same.

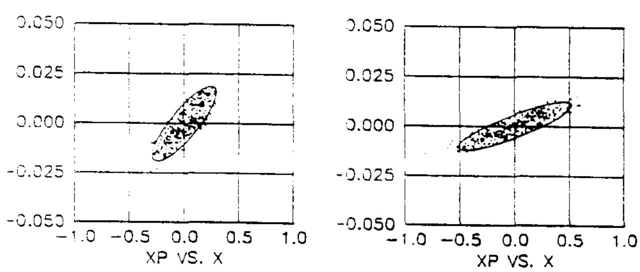

Fig. 1(a) Output emittance Case 3 (untapered).

(b) Output emittance Case 4 (tapered).

Effects of Operating Closer to the Sparking Limit and Tapering the Bore

Four RFQ designs were studied, and their parameters are given in Tables 1 and 2. Cases 1 and 3 are conventional untapered bore designs optimized for 1.5 and 2 * Kilpatrick fields respectively. Cases 2 and 4 are the same basic designs but with the bore, inter-rod voltage and for case 4, the synchronous phase, varied over the accelerating section. Cases 1 and 2 have conservative peak fields and modulations, 3 and 4 go slightly beyond that of currently operating accelerators, but are in line with values suggested by sparking tests and field enhancement calculations. The calculated power requirements are based on OFHC copper structures achieving 60% theoretical Q.

The Four Rod RFQ Structure and Tapered Vane Configurations

The four rod RFQ modular structure proposed previously[5,6] seems ideally suited to a low frequency cw application such as the TRIUMF ISOL. The rf efficiency is reasonable, construction and assembly should be relatively straightforward and cost should be minimal.

Each four rod module acts as an inductively centre loaded half wave transmission line resonator with no longitudinal currents at the rod ends. Also there is very little current flow between the inductor and the outer cylindrical tank. Therefore, even in cw system, a demountable mechanical joints (garter spring or "C"-seal) at the inductor base and between modules could be used to allow easy replacement and service. The configuration is automatically "strapped" by the inductors which connect opposite vanes via a very low inductance path. Thus the azimuthal electric field is well stabilized against asymmetries produced by thermal expansion. The maximum current density on the tank wall is at most only a few percent of that on the inductors. This means that only minimal (and possibly no) outer tank cooling is required, reducing tank construction costs. The dimensions of the tank have very little influence on the structure frequency, so that dimensional tolerances on the tank can be very coarse, again reducing cost. The tank does little more than provide a vacuum envelope.

For Case 2, the beam dynamics calculations determined that a 9.7 metre long, 23 MHz structure was required whose bore radius and vane-to-vane voltage increase from 5 mm and 38 kV at the input to 12.5 mm and 97 kV at the output. The first step in determining if a practical design with these properties was possible was to model the structure with the equivalent circuit code, RFQ3D[7]. It was found possible to produce the desired voltage tilt by monotonically changing the inductor values along the length of the structure (Fig. 2(b)). The code also calculates the positions of the nulls in longitudinal rod current (Fig. 2(a)), where one could divide the structure into individual modules.

The final requirement for suitability of the structure is that the rf power losses be acceptable. The shunt impedance per unit length of a structure of length ℓ_0 made up of N modules of the type shown in Fig. 3 was calculated, where the loss contributions from currents on both rods and inductors were included.

Table 2

Specific Parameters for the 4 Cases

	Case 1	Case 2	Case 3	Case 4
Peak Field (Kilpatrick Criteria)	1.5	1.5	2.0	2.0
Bore Taper (ratio)	1.0	2.5	1.0	3.1
Voltage Taper (ratio)	1.0	2.5	1.0	3.1
Length (m)	15.04	9.73	8.13	4.63
Number of Cells	421	331	230	170
Mean Bore Radius r_0 (cm)	0.498	0.498	0.615	0.615
Total RF Power Required (kW)	43	75	64	131
Transmission (%)	84	85	86	87
E_z Start Accel. Sect. (MV/m)	0.76	0.76	1.39	1.39
E_z End Accel. Sect. (MV/m)	0.27	0.66	0.51	1.41
Length Rad. Match. Sect. (cm)	5	5	5	5
Length Shaper Sect. (cm)	72	72	40	40
Length Gentle Bun. Sect. (cm)	157	157	85	85
Length Accel. Sect. (cm)	1270	739	684	334
Output Emittance (90%) (π mm mradians)	0.33	0.34	0.33	0.34

Table 1

Common Parameters for All Cases

Frequency (MHz)	23
Ion Mass (amu)	60
Charge State	1
Input Energy (keV)	60
Output Energy (MeV)	3.6
Input Emittance (100%) (π mm mradians)	0.5

$$Z = (2L_i/R_sC_t)/(R_0/r + \ell_0/[12N\ W_r])$$

where W_r is the length of the rod circumference that effectively carries longitudinal current, L_i is the inductance of an individual inductor ($L_i = R_0 * K(r,R_0)$ with K only weakly dependent on r and R_0), C_t is the total rod capacitance per unit length (≃ 110 μμf/m), and R_s is the "effective" surface resistance (≃ $1.24*10^{-3}$ ohms for copper at 23 MHz).

For the TRIUMF ISOL a convenient design would have five 1.9 metre long sections, each with two support inductors per section (N=10). To achieve 23 MHz, the individual inductors must have L_i ≃ 460 nH, which can be obtained with R_0 ≃ 0.20 m and r ≃ 0.03 m. The individual rods must be approximately oval in cross section to accommodate cooling and provide sufficient mechanical strength. Under these conditions, the current carrying portion of the circumference was estimated at W_r ≃ 0.10 m. This results in $Z_{inductor}$ ≃ 1 MΩ/m, Z_{rod} ≃ 8 MΩ/m and Z_{Total} ≃ 0.89 MΩ/m for pure copper. Assuming 60% of theoretical Q, a practical shunt impedance ̈ 0.5 MΩ/m should be achievable. Thus the structure power loss per unit length at 38 kV peak vane voltage is $P/\ell = V_p^2/Z_T$ = 3.0 kW/m. Assuming a linear variation of the voltage between 38 kV at input and 97 kV at output, the total power required for the 9.7 metre structure is P = 75 kW.

A 1/5 scale model with tapered vane bore (Fig. 4) was constructed to test the calculations. Preliminary results show agreement with the theoretical predictions.

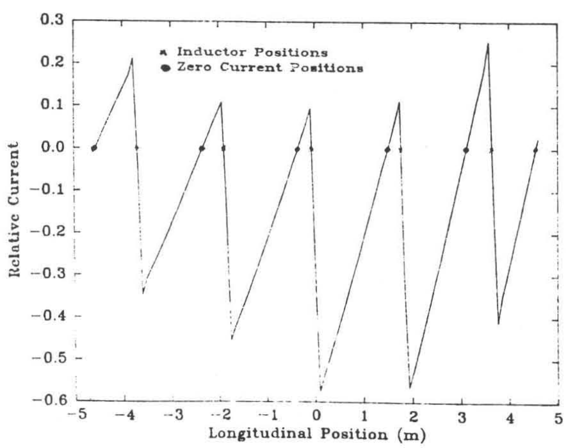

Fig. 2(a) Longitudinal rod current showing positions of nulls.

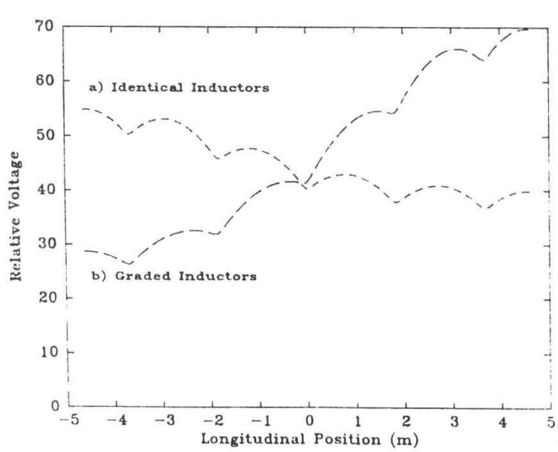

Fig. 2(b) Rod voltage showing field tilt

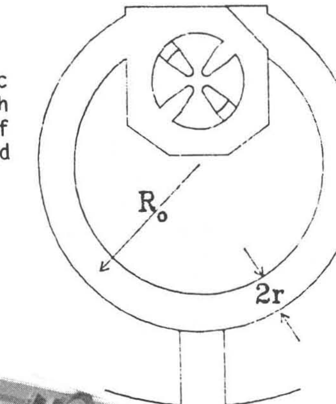

Fig. 3 A schematic cross-section through a support inductor of the proposed 4-rod RFQ module.

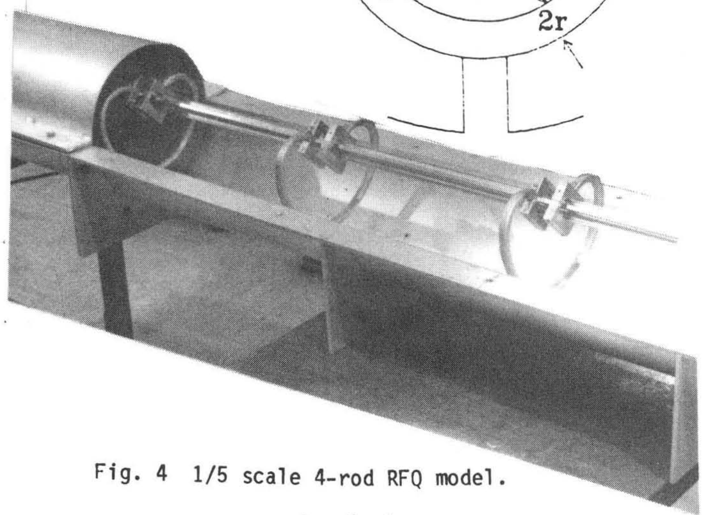

Fig. 4 1/5 scale 4-rod RFQ model.

Conclusions

The most effective way to reduce the length of a long RFQ is to operate with an electric field gradient as high as permitted by sparking considerations. Additional length reduction can be achieved by tapering the bore in the accelerating section while maintaining constant electric field gradient. This prescription does not reduce transmission or cause emittance growth, although it does increase the rf power required. The 4-rod design allows the tapered feature to be incorporated into the structure in a mechanically simple way leading to an inexpensive accelerator.

References

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