Summary

The rf design of a stabilized tunable high current RFQ was accomplished while remaining compatible with extreme pumping and cooling requirements. Several design innovations were introduced, including distributed pumping, compensated straps, and a tuner compensated drive loop. The code RFQ3D was demonstrated to be quantitatively useful for predicting design characteristics.

Introduction

A 75 mA, 600 keV cw proton accelerator, RFQ1, is being built at Chalk River. The accelerating structure (Fig. 1) is a 1.5 metre long 270 MHz 4-vane radiofrequency quadrupole (RFQ). It is designed to dissipate a total of 220 kilowatts of rf power with peak surface power density up to 11 watts/cm² while maintaining Q₀ = 10 000. The combination of large pumping holes distributed along the structure are needed to achieve such a pumping speed. The possibilities for thermal distortion, vane erosion and mechanical relaxation with temperature cycling dictate the use of vane shorting straps for azimuthal field stabilization. The large thermal transients at turn-on will cause significant frequency shifts, and thus dynamic tuning is necessary.

These requirements and characteristics necessitated answers to some very specific questions for the rf design:

1. How much would the vacuum pumping holes reduce the Q, lower the frequency, and change the longitudinal field distribution?
2. How much would the straps lower the frequency, change the longitudinal distribution and how well would they stabilize the azimuthal fields?
3. Could tuning plungers be used with sufficient tuning range, but with tolerable effects on field distributions?
4. Could the rf drive loop be critically coupled without introducing large shorting strap currents or, even worse, azimuthal tilts?

The following sections describe how, with the aid of cold model measurements and theoretical calculations using RFQ3D, these questions were answered.

RF Characteristics of Vacuum Pumping Ports

The usual solution to high pumping speed requirements is to use a few large pump ports with grills on them to reduce rf leakage into the pumps. This has two disadvantages for the present four-vane RFQ - (1) the individual quadrant cross section is small enough that, for the long structure, the system is conductance limited, (2) a large pumping port, even with a grill, can cause longitudinal field tilts. Thus a solution evolved with pumping manifolds and medium sized pumping holes distributed along the length of all four quadrants, to ensure unperturbed azimuthal and longitudinal field distributions. The influence of the individual port size and length-to-diameter ratio on the cavity frequency and Q was considered next.

A series of measurements was made of the rf magnetic fields in penetrations in cavity outer walls (i.e., regions of predominantly magnetic field). These indicated that for a hole diameter, D, small enough to be well below cutoff for the dominant mode, a hole length to diameter ratio (L/D) of 1.4 would give a magnetic field at the outer end of the hole of ~0.1% of the main cavity wall field. For a cavity with Q₀ = 10 000 this means that the rf radiation through such a hole is less than P₀, the power loss on an area of the cavity wall equal in cross section to that of the hole. The field penetration measurements were also used to estimate the contribution to the Q of the resistive losses on the walls of the penetration. These were found to be within ± 25% of P₀, and thus have only a small effect on overall cavity Q.

The same measurements also provided a method of estimating the frequency shift caused by a long outer wall penetration. This was found equal to the calculated frequency shift produced by a hole of length L = 0.19 ± 0.03 μm filled with cavity wall strength magnetic field.

The information gained from these first measurements was compared with the results of modifying a 350 MHz, 0.88 m long RFQ model (Q₀ = 3500) by adding 10 penetrations per quadrant, each 20 mm diameter and 25.4 mm long (L/D = 1.2). To within the experimental error of 7%, the Q was unchanged. The frequency shift (-1.3 MHz) corresponded to a wall effective hole depth of 0.16 ± 0.01, within error of the value 0.19 ± 0.03 quoted above. As a further check, a 0.30 m long, 0.26 m diameter DHRC copper cylindrical cavity, driven into the TE₁₁ mode (f = 1.7 GHz, Q₀ = 70 000) had 20 holes drilled in one 25.4 mm thick end plate. Within the measurement error of 3.5%, no reduction of the Q was noted for (L/D) = 1.33. The Q was reduced by approximately seven percent for (L/D) = 1.0.

The resultant vacuum pumping design for RFQ1 consists of 160 ports distributed along the four quadrants, each port of 32 mm diameter and with a very conservative value of (L/D) = 1.55. Since the holes account for less than a quarter of the high current carrying surface area, they should have, at most, a ±5% effect on the Q. The frequency shift produced by the ports was estimated to be -1.8 ± 0.2 MHz by direct scaling of the 350 MHz results. In fact, measurements on a 1:1 scale RFQ1 aluminum cold model (Fig. 2) yielded an extrapolated shift of -1.67 MHz.

Compensated Vane Shorting Straps

It is now understood that vane shorting straps, although providing excellent azimuthal field stabilization, do perturb the longitudinal field distribution because of the large local increase in effective vane-to-vane capacitance at the strap location. This "lumped" capacitive loading results in a substantial decrease in the RFQ frequency, together with a 'clothesline' or pinning effect in which the vane-to-vane voltage is a maximum at the strap locations and decreases between them. The explanation of this is that the portion of uniform quadrupole...
waveguide between the straps is operating below its cutoff frequency, \( f_c \), and the fields are attenuated (not absorbed but reflected back) between the straps.

The ideal solution to this longitudinal variation is to increase the local waveguide frequency in the strap region so that all parts of the resonator are operating at cutoff (theoretically uniform longitudinal vane voltage). This may be done by locally decreasing the inductance (i.e., area) of each quadrant in the region of the strap. For an RFQ with many straps this solution can be mechanically tedious, but in the present case, calculations with RFQ3D indicated that only two sets of straps were needed to achieve excellent stabilization. By locating the straps at the ends of the structure, the provisions for decreasing the inductance ('strap compensators') could simply be mounted on the endplates (Fig. 1).

The straps were made of 6.7 mm diameter copper tubing formed into approximate squares of 75 mm inside dimensions. The clearance hole through the vane was 17.3 mm diameter and 22.2 mm long. The straps were mounted in pairs with their centres separated longitudinally by 17.2 mm. Without compensators, the operating frequency of the 1:1 scale cold model went from 2.9 MHz above cutoff to 0.1 MHz below cutoff, a change of -11.9 MHz below cutoff. The field distributions were very concave (Fig. 3) indicating operation well below cutoff, as expected.

The code RFQ3D was used to calculate the theoretical frequency shift caused by the two strap pairs, needing only the local increase in vane-to-vane capacitance as additional input. The latter was calculated with the standard cylindrical capacitor formula, but with an effective sharp cutoff fringe field length of 1.05 times the difference between inner and outer conductor radii, as determined by Schneider from integration of exact static fields. The theoretical field distribution for operation at 11.9 MHz below cutoff is also shown in Fig. 3. The calculated frequency shift of -11.6 MHz agrees well with the cold model measurements.

The next step was to use RFQ3D to predict the size of the 'strap compensating' end plugs. This was done by decreasing the quadrant volume (i.e., inductance) at the structure ends until the resonant frequency returned to the original pre-strap value (with the expected longitudinal flat fields). A plug volume of \( 150 \text{ cm}^3 \) per quadrant was predicted, and cold model measurements yielded a value of \( 100 \pm 25 \text{ cm}^3 \). The vane voltage distribution for the compensated strap configuration is shown in Fig. 4, along with the measured 1:1 scale cold model distribution. The structure frequency may be adjusted by the same vane displacement on the 1:1 cold model was \( 4.6\% \).

The azimuthal stabilizing properties of the compensated strap system were estimated using RFQ3D. A 0.125 mm transverse displacement of one vane tip is calculated to introduce a maximum of 3.7% dipole field at the centre of the structure, tapering to zero at the straps. The measured dipole component introduced by the same vane displacement on the 1:1 cold model was \( 4.6\% \).

Calculations with RFQ3D predicted a frequency shift of \( 1.8 \text{ MHz} (53 \text{ kHz/mm}) \) for a 30 mm insertion of two 10 cm diameter tuning plungers. Measurements on the 1:1 scale model gave \( +1.12 \text{ MHz} \) for 20 mm insertion, or \( 56 \text{ kHz/mm} \). The measured change in field distribution caused by a 32 mm insertion is shown in Fig. 5. Beam dynamics calculations indicated the longitudinal field variation should be acceptable.

Compensating and Critically Coupling the RF Drive Loop

The RFQ structure is to be driven by a single magnetic loop inserted at the centre of one quadrant. The port through which the loop is inserted is limited by quadrant dimensions to a maximum diameter of 100 mm. The design of a suitable drive line with vacuum window and impedance matching characteristics is shown in Fig. 6. The drive port and loop assembly are usually significant perturbations on the drive quadrant although a method of totally compensating this by inserting material around the edges of the loop port has been demonstrated.

In the present case, exact compensation is done by locating a fixed (but initially adjustable) tuner in the quadrant just opposite the drive loop. The 1:1 scale cold model was used to develop this technique for achieving critical coupling while minimizing the strap currents. With straps in place (and thus ensuring azimuthally symmetric fields) the drive loop insertion was adjusted for critical coupling. The straps were then removed and the tuning plunger opposite the drive loop was adjusted until azimuthally symmetric fields were obtained. The straps, upon reinsertion, carry minimum current. In the present case, balanced fields were obtained with the tuning plunger inserted 1 ± 2 mm into the quadrant. This suggests that the increased port volume is compensated by the loss in field volume taken up by the actual loop material.

References

4. H.K. Schneider, TRIUMF, private communication.
Fig. 1 Isometric drawing of the RFQ1 end region, showing straps, end compensators, pumping manifold and distributed pumping holes.

Fig. 2 Full scale RFQ1 aluminum cold model before insertion of ports, vane endo and distributed pumping holes.

Fig. 3 The normalized longitudinal vane-to-vane voltage distribution squared, averaged over all quadrants, for operation varying amounts below cutoff. Examples of both measurement and theory are shown.

Fig. 4 The measured normalized longitudinal vane-to-vane voltage distribution squared for each quadrant, with straps, end compensators and drive loop in place.

Fig. 5 Measured change in normalized longitudinal average vane-to-vane voltage distribution squared, produced by a 32 mm movement of dual tuning plungers in opposite quadrants and located at the centre of the structure. The change was essentially identical in all four quadrants.

Fig. 6 An isometric view of the drive loop showing the cylindrical ceramic rf window and impedance transforming taper sections.