EXPLORING THE BEAM PARAMETER SPACE OF A CW RFQ PROTON ACCELERATOR*

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Abstract

RFQ1, a 100% duty factor radiofrequency quadrupole to accelerate 75 mA of protons to a final energy of 0.6 MeV, is a test bed for a wide range of high power RFQ experiments. First beam was accelerated in RFQ1 in July 1988 and an experimental program to investigate the beam parameter space of the machine was started. With the initial 3-beamlet ion source adjusted to deliver 5 mA to the RFQ, only 35% of the beam was captured and accelerated to design energy. Changing to a lower emittance single-beamlet source, transmission improved to almost 80% with over 6 mA cw accelerated. CW rf conditioning experience with the RFQ is described and results of the experiments compared with PARMTEQ and TRANSPORT calculations.

Introduction

The RFQ1 facility, its design, rf tuning and conditioning, and initial operation with a 3-beamlet source was described previously[1,2,3]. In the past six months, the RFQ vane-to-tank racetrack seals have been replaced after a cooling failure. During this time, the program emphasis has been on commissioning and beam experiments with a single-beamlet ion source, and the recalculation of the injector and RFQ beam dynamics.

RF Conditioning and CW Operation

The RFQ was recently returned to service after a two-month shutdown to replace the four racetrack seals. (The seals had failed when rf power was supplied to the tank after the tank cooling system main circulation pump had shut down). Prior to this, the RFQ was conditioned such that it operated almost spark-free at peak surface fields of 26 MV/m (≈ 1.6 Kilpatrick), and had accumulated over 100 hours of high power cw operation, much of it at powers exceeding 100 kW. Replacing the seals required the almost complete disassembly of the RFQ, including removal of all the vanes. The vane tips, which originally had been smooth and shiny, looked rough and weathered (like well-used electrical switch contacts). We tried to avoid touching the vane tips, but they were handled during the seal replacement and rubbed with feeler gauges and the alignment target during the alignment process. To determine how much of the previous rf conditioning could be retained, the vanes were reinstalled without any abrasive cleaning of the tips (cleaning was limited to vacuuming and washing with isopropyl alcohol). The tank wall and vane bodies (which were discoloured in places, probably from the breakdown under electron bombardment of diffusion pump oil vapour migrating from the injector vacuum system), received the same treatment. The time to rf condition, compared with the original conditioning when the RFQ was first assembled, is shown in Fig. 1. It was significantly harder to break through the multipactoring levels this time (the rf had to be pulsed for about 8 hours at low duty factor before it was possible to go to cw), but the cw conditioning after overcoming the multipactoring went much more rapidly.

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Vane-to-Tank "Racetrack" Seals

An OFHC copper racetrack-shaped gasket makes a deformable vacuum and rf seal between each vane and the tank in the RFQ, allowing the vanes to be moved for alignment or to study effects of vane displacements on rf fields and beam dynamics. Each vane is supported at three points (centre and 20 cm from each end) by a vane positioning mechanism which has screw adjustments to move the vane radially or rotate it about the long axis of the racetrack gasket. Figure 2 shows a section through a vane and segment of the tank at one of the vane positioning mechanisms. Locations of cooling channels in the vane, tank and gasket clamps are also shown. The racetrack gasket is 1.6 mm thick and is cooled by conduction to the tank, vane and clamps. The ends of the vane are rounded (radius 16 mm) and the vane cooling stops 6 mm before the rounded portion (21 mm from the end).

Although the beam dynamics design of the RFQ calls for an intervane voltage of 78 kV (peak surface field of 1.5 Kilpatrick), the thermal analysis and cooling were designed assuming the RFQ would be overdriven to 2 Kilpatrick (104 kV between the vane tips). Approximately 130 kW is dissipated in the RFQ when excited to 1.5 Kilpatrick (surface heat flux of 7 W/cm^2 on the tank wall), and 230 kW (12 W/cm^2) for 2 Kilpatrick. Calculated temperature isotherms on a section of the vane near the racetrack seal for a surface heat flux of 11 W/cm^2 are shown in Fig. 3. Gradients along the straight section are modest (< 10°C), but at the end, a maximum temperature of almost 120°C (80°C above the water temperature) is predicted. Gasket temperatures 20-30°C above that of the vane-base are predicted. We presently limit operation to just above the beam dynamics design rf fields, (tank power of ≈ 135 kW). At this power, a maximum vane base temperature of 85°C is predicted, and the racetrack gasket temperature should not exceed 120°C. Thermocouples installed during the reassembly confirm the vane-end temperature prediction, but show that the racetrack gasket reaches ≈ 220°C at the end, much hotter than expected. On the positive side, this shows that the racetrack seal can maintain vacuum and rf integrity for quite extensive temperature swings. But on the negative side, it shows that there are enhanced fields in the end region that need to be understood so that an accurate thermal analysis of this area of the RFQ is possible.

Vane-Coupling-Rings (VCR's)

VCR's, developed at LBL[4], are widely used on RFQ's of the 4-vane type to provide field stability and suppress the dipole modes. Two sets, (at either end of the vanes), are used on RFQ1 and are shown in Fig. 4. They are made from 6.3 mm OFHC copper tubes soft-soldered into spigots on the sides of the vanes, and form parallel cooling channels with the internal vane cooling. Estimated peak rf current in the VCR's is around 200 A, most of which is charging current for the ring-to-vane capacitance, not correction current for field imbalances. When the RFQ was opened to replace the racetrack seals, it was found that one of the solder joints had overheated (some globules of solder had splattered on the adjacent vane), but the joint tested leak tight. At the time, the overheating was assumed to have occurred during the time the cooling pump was off.

However, recently a VCR joint failed (developed a water-to-vacuum leak) and there is evidence on the tank walls and vanes of extensive vapour deposition of solder from 6 of the 16 joints. The remainder appear unchanged from when they were installed. Most of those that have been evaporating are at the high energy end (where fields are 10% higher than in the rest of the RFQ) on the rings closest to the end (which carry higher current due to the proximity to the end-flange tuners). In several cases, only one end of a half ring was affected, indicating that there is not a problem with the internal cooling (which is identical for each end), but with the joint itself or the exposed solder at the joints. To check this supposition, new VCR's, with a redesigned joint to lower the current density and minimize the amount of exposed solder, are being installed. From our operation to date, we do not see a fundamental problem with VCR's in a cw RFQ. However, there is something marginal in our specific design that must be identified and corrected.

RFQ and Injector Beam Dynamics

PARMTEQ transmission for RFQ1, for a properly matched 5 mA beam, is greater than 95%, dropping to about 80% at the design input current of 90 mA. To date, the maximum measured transmission is 80% with a single-beamlet ion source and 35-40% with a 3-beamlet source. Just over 6 mA cw has been accelerated (using the single-beamlet source, modified to limit the matched-output proton current to 8 mA). PARMTEQ predicts an acceptance for the RFQ of 0.075 (π•cm•mrad, normalized rms). Measured emittance of the single-beamlet source is 0.008 π•cm•mrad. The emittance for the 3-beamlet source is effectively determined by the rms divergence of the each of the 3 individual beamlets and the beamlet spacing at the extraction electrode. Calculated this way, the emittance of the 3 beamlet source is 0.05 π•cm•mrad rms.

The low 3-beamlet transmission prompted a recalculation of the RFQ1 injector[5] transport system, this time including measured properties of the bending magnet and solenoids. Through this analysis the following defects were found in the injector transport system:

- The fringing fields of the bending magnet were substantially larger than expected causing considerable astigmatism in the magnet. As a result, the beam height is approximately twice the width after the bending magnet instead of being circular.
- The first solenoid after the ion source steers the beam somewhat because the bending magnet fringe field extends in front of the solenoid.
- The required axial field in the second solenoid was underestimated when specifying its power supply, which limits at a solenoid field of about 0.3 T. This is almost the value required for maximum transmission but is too low to allow an adequate range about the optimum.
- There are some vertical and horizontal misalignments of the beam entering the RFQ. From measurements with a 4-quadrant beam current monitor at the entrance to the RFQ, it is estimated that the beam is approximately 5 mm off centre before the solenoid at the RFQ entrance.

The effect of some of the defects on the transmission through the RFQ were determined in the following way. The injector beam transport was modelled using TRANSPORT including the effects of the measured bend magnet fringe fields. All misalignments were approximated by a 5 mrad vertical deflection immediately after the bending magnet, giving about a 5 mm displacement of the beam entering the second solenoid. TRANSPORT was run for the single beamlet on axis and with 3 sets of offsets at the source to simulate the 3 beamlet beam. A reference single beamlet case without the vertical deflection was also run. Each set of cases was run for a range of fields in the RFQ entrance solenoid from 0.30 to 0.35 T. The beam characteristics calculated by TRANSPORT for each case were input to PARMTEQ to determine the RFQ transmission. The left graph in Fig. 5 shows the desired input transverse emittance for the RFQ. The right graph shows the input particle distribution from the 3 beamlet source as calculated by TRANSPORT with a 5 mrad vertical deflection after the bending magnet and 0.30 T on the solenoid. Under these circumstances, the total transmission for the 3 beamlet source is calculated to be 43% compared to 76% for the single beamlet case. This is similar to the transmissions actually measured indicating that most of the significant errors are being modelled.

If there is no vertical deflection, the single beamlet transmission is over 95%. PARMTEQ predicts that the 3 beamlet transmission would be over 90% with a solenoid field of 0.35 T, even with the vertical offset. Thus, the main contributor to the low transmission is probably the current limitation of the RFQ entrance solenoid. If the beam alignment into the RFQ is improved, the transmission should also improve. From these calculations, errors in the fringing fields of the bending magnet are not contributing significantly to the reduced transmission.

Misalignment of the beam entering the RFQ produces an additional effect. Under most circumstances, PARMTEQ predicts significant x-y correlations (tilted beams in x-y space) in the output beam if there are large positional or angular displacements of the beam entering the RFQ. To look for this effect, thin stainless steel foils, as used at Los Alamos to look at the FMIT output beam, were inserted into the exit beamline to look at the shape of hole melted in the foil by the beam. A magnetic-quadrupole singlet is built into the end-flange of the RFQ, 8 cm from the end of the vanes. Foils were inserted 28 cm after the quadrupole. Figure 6 shows the elliptic melt pattern as a function of quadrupole magnet current (the quadrupole is 2.54 cm long, field gradient 8.4 T/m per 100 A) and shows the expected x-y correlation.

Discussion and Conclusion

The realization of the replaceable component design of the RFQ, cw operation of VCR's, and the ability of the racetrack seals to maintain vacuum and rf integrity over large temperature gradients, were demonstrated. Design deficiencies in the injector that spoil the match to the RFQ have been identified and TRANSPORT and PARMTEQ used to examine corrective measures.

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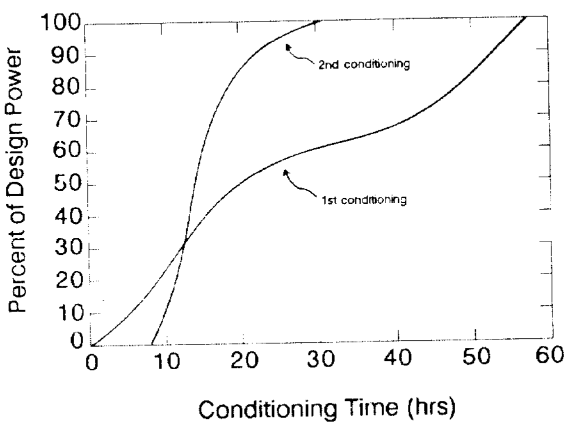

Fig. 1. RF conditioning of the RFQ. Curves show time-to-power for initial conditioning and after reassembly following racetrack seal replacement.

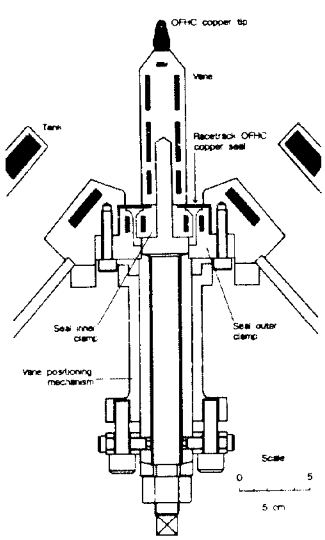

Fig. 2. Section through a vane and part of the tank showing location and details of the racetrack seal and the internal cooling channels.

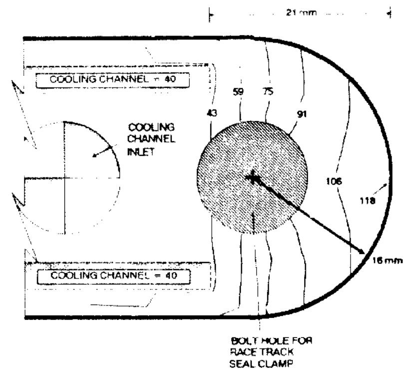

Fig. 3. Calculated temperature isotherms at the end of a vane in the base region near the racetrack seal.

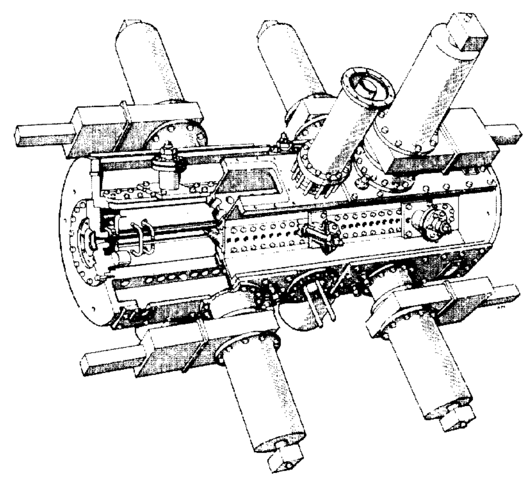

Fig. 4. Cutaway drawing of the RFQ showing position of VCR's and end-flange tuners.

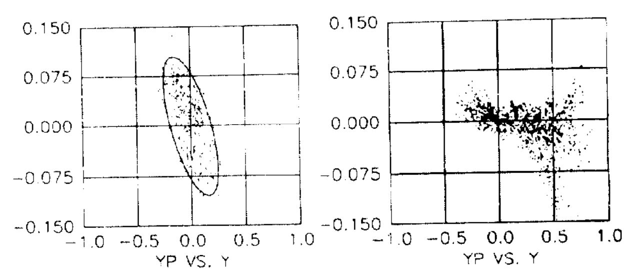

Fig. 5. Input transverse emittance for PARMTEQ calculations. Left graph is matched emittance from RFQUIK. Right is calculated output emittance of 50 keV injector for the 3-beamlet source using mapped fields for the dipole magnet and beamlet misalignments inferred beam spill measurements at the inlet to the RFQ.

Fig. 6. Melt pattern in 0.05 mm stainless-steel foils as current in end-flange quadrupole magnet is increased in 100 A steps to 400 A.