ENGINEERING DESIGN & FABRICATION OF A CW DEUTERIUM RFQ

John W. Rathke
Grumman Aerospace Corporation, M/S B29-25, 1111 Stewart Avenue, Bethpage, NY 11714

L.M.Young
Los Alamos National Laboratory, M/S H817, Los Alamos, NM 87545

Abstract

A 352 MHz CW Deuterium RFQ has been designed and fabricated for the Continuous Wave Deuterium Demonstrator (CWDD) Program. The RFQ is designed to operate at a peak metal temperature of 35 Kelvin with supercritical neon coolant at 26K. Analysis shows that the RFQ can also operate at room temperature with water cooling. The accelerator is 4 meters long (4.66λ) and fabricated in four one meter segments. Each of the segments is constructed from four vane/quadrant machinings which are made of tellurium copper (TeCu). The four machined parts are then assembled using a copper electroforming technique to yield a pseudo-monolithic structure. The RFQ has been fully constructed and is installed in the beamline at Argonne National Laboratory[1].

Introduction

The parameters of the RFQ (figure 1) are listed in table 1. Clearly the most challenging aspect of the design is continuous duty operation at cryogenic temperature. As such, the requirements for cooling of the cavity and all RF components becomes critical as does the overall construction and thermo-structural behavior of the cavity to survive the wide range of environments. The parameters of this machine are also very similar to current proposals for the next generation of high current, CW accelerators.

Due to the cryogenic operation, the RFQ is housed inside an MLI lined stainless steel vacuum vessel. RF power is provided from the single klystron through WR2300 waveguide which splits at a "magic tee" and feeds two waveguide to 3.125 in. dia. coax double transitions The four coaxial lines then feed through the vacuum wall and step down in size to 1.625 in. dia. drive loops located in opposite quadrants at two axial locations. The vacuum windows are in the 3.125 coax lines near the vacuum vessel feedthrough and 1λ away from the loop termination. For full power, 80 mA cryogenic operation, each drive loop will handle 70 kW.

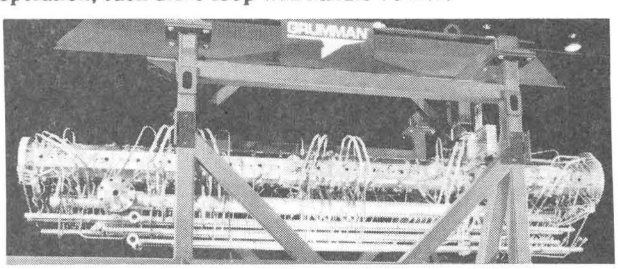

Figure 1
Completed RFQ with Cooling Lines Ready for Installation in Vacuum Vessel

Particle	D^-
Operating Frequency	352.2 MHz
Duty Factor	100% (CW)
Input / Output Energy	0.200 / 2.004 MeV
Input / Output Current	92.0 / 80.2 mA
Transmission	87.1%
In / Out Trans. Emitt.	0.075 / 0.099 π mm-mrad
Output Long. Emitt.	0.175 π mm-mrad
Intervane Voltage	87.7 kV (92.0 kV Final)
Peak Surface Field	33.7 MV/m (1.8 x Kp)
RF Power	544 kW (RT), 136 kW (35K)
RF Drive	1 MW Klystron, 4 Drive Loops
Coolant	Supercritical Neon @ 26K
Cavity Operating Temp.	<35K (Peak Metal Temp)
Coolant Pressure	450 psi
Cavity Length	3.96m (4.66 λ)
Cavity Material	Tellurium Copper
Cavity Construction	Electroformed

Table 1
RFQ Parameters

The supercritical neon coolant is fed to the RFQ through four separate, flow controlled circuits. The RFQ vanes are on a separate circuit from the cavity walls to allow dynamic flow balancing to achieve optimum transient performance. Each one meter RFQ segment has 12 parallel flow paths. The input and output ends of the paths are reversed from one segment to the next to equalize temperatures at the segment interfaces.

Engineering Analysis

Extensive analyses were performed for both the transient thermal response and the transient RF response of the RFQ. The RF loads were applied to an ANSYS[2] finite element model per the SUPERFISH analysis and were modified to account for the Q enhancement of the copper alloy cavity operating at cryogenic temperature[3]. The temperature dependence of both the material thermo-physical properties and the RF dissipation were accounted for in the transient thermal analysis. The deflection results of the thermal analyses were then used to determine the RF transient behavior using the $\Delta f/\Delta x$ and the $\Delta f/\Delta y$ sensitivities from the SUPERFISH output. Flow rates through the various coolant passages were adjusted to optimize the response. Results for the normal operating case showed a peak temperature of 35K at the cavity wall, a time to steady state of about 5 seconds and a maximum RF transient of -4.5 kHz. Figure 2 shows thermal results for the normal operating case near the exit of the one meter coolant passages. Figure 3 is the corresponding RF transient associated with the thermal results. Note that the RF results include the transient for the coolant entrance slice which differs noticeably from the exit slice. By averaging the entrance and exit results, a peak transient of about -2.3 kHz is expected. Further analyses were run to consider off-nominal conditions of Q enhancement and of beam loss. All results showed that the RFQ is very tolerant of these variations when operating at cryogenic temperature where the thermal conductivity of the material is very high and the thermal expansion coefficient is very low.

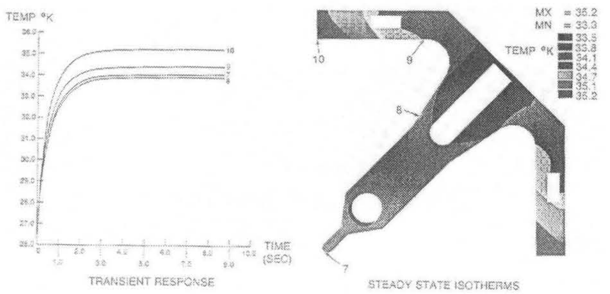

Figure 2
Thermal Response - Nominal Operating Condition Section at End of One Meter Flow Path

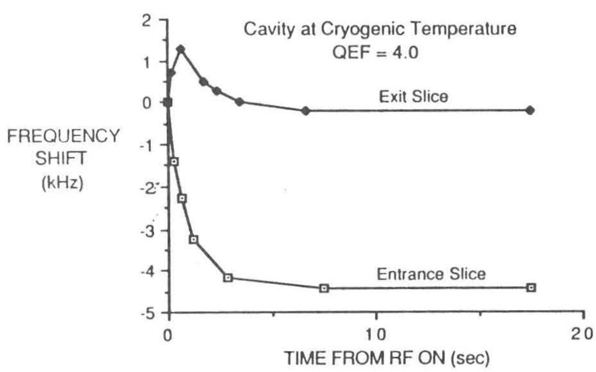

Figure 3
RF Transient Response Corresponding to Figure 2

Analyses were also conducted to show that the RFQ can run satisfactorily at room temperature with water cooling. This was a requirement of the design to allow full power, room temperature conditioning if required.

Cavity Construction

The RFQ is a fixed vane, slug tuned cavity which employs electroforming as the primary assembly technique. The cavity is constructed from four, one meter long, electroformed segments which are bolted together. The electroformed assembly technique for the segments is the same as that used for the Beam Experiment Aboard Rocket (BEAR) RFQ[4]. The vane material is TeCu rather than copper plated aluminum as used in BEAR. This is done to give the cavity stability over a wide range of temperatures as well as to eliminate the risk of a plating failure due to the significant differential thermal expansion between aluminum and copper. The TeCu alloy was chosen for its combination of high conductivity (90% IACS) and improved machining characteristics (80-90 on the free machining brass scale) relative to high purity copper (20). The finished assemblies exhibit spatially uniform and highly predictable behavior during thermal transients.

Each one meter RFQ segment comprises four machined vane sections. Each vane is nominally identical to the next except for the details of the vane tip modulations. Each vane detail includes one vane, one quadrant wall, and a quarter section of the circular flange at each end Each vane is machined from a 7 in. x 8 in. x 50 in. long TeCu extrusion. The initial machining process established the coolant passages. The passages consist of a single full length hole near the vane tip, a deep milled slot in the base of the vane, and a milled racetrack circuit in the quadrant wall. The full length hole was then used to establish the primary datums (theoretical beam axis) for all subsequent finish machining.

After rough machining, the vanes were electroformed to close the coolant passages. To do this the channels had a thin copper cover epoxied in place to prevent plating in the channel. A 0.100 in. thick layer of copper was then deposited over the entire external surface, bonding to the copper alloy surface. After electroforming, stainless steel fittings were soldered in place to complete the channels. All vanes were LN_2 cold shocked and proof pressure tested to 675 psi followed by vacuum leak test.

The final machining process finished all RF surfaces to final dimension including the modulated vane tip. Tolerances for this machining were ±0.001 in. on the profile of the tip over its full length. Tolerances for the other internal surfaces increase as they move further from the tip to a maximum of ±0.010 in. on the inside surface of the quadrant wall. This increase in tolerances is possible because the electroformed assembly process used for final cavity assembly requires no precision mating surfaces at the vane to vane joints. Final inspection results indicated worst case for all 16 vanes of +/-0.0007 in. on the vane tips increasing to +/-0.008 on the cavity walls.

The electroforming process was nominally identical to that used for the BEAR RFQ as documented in the reference. Differences included the use of special consumable copper anode bars and rods located close to the joint to accelerate the deposition and enhance the as-deposited thickness uniformity. This resulted in the units being able to stay in the plating bath longer (2-3 days) between intermediate grinding steps. This further allowed multiple segments (up to three) to be efficiently electroformed in parallel which significantly shortened the total process time.

After electroforming, the slug tuner ports, drive loop ports and vacuum pumping holes were machined through the cavity walls and all fastener holes were drilled and tapped. The final step was to finish the end flanges and bring the segments to final length. To establish segment to segment alignment, a precision drill fixture was aligned on the end flange using a coordinate measuring machine (CMM) and used to machine pin and bushing holes. This resulted in alignment accuracy's of +/-0.0005 in. between theoretical beam axes of the segments. Figure 4 shows a completed segment. Note the slug tuner ports, vacuum holes, and coolant fittings.

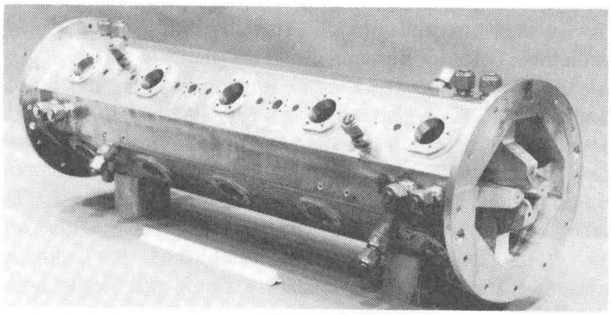

Figure 4
Completed One Meter Segment of the RFQ

Full cavity assembly was done in the vertical position in an assembly fixture. Each segment was sequentially lowered onto the previous segment and bolted in place. Support fittings and optical targets were also installed and positions were documented in the "zero-sag" condition for subsequent use in the installation on the beamline.

RF Tuning

The RFQ uses 76 fixed slug tuners distributed at 20 axial locations to achieve both the desired frequency and field balance (see figures 1 & 4). The tuners are machined from TeCu rod, have a one inch diameter vacuum pumping duct through the center and have a cooling tube soldered to the outer flange. The four tuners at each axial location are cooled in series. The adjustment range of the tuners is between 0.5 inch penetration and 0.25 inch retraction. With a nominal position of the tuners at 0.125 in. penetration this yields approximately a +/-2.35 MHz tuning range. The tuners are fixed (not adjustable) and were machined to size after initial tuning using sliding temporary slugs. This approach was considered to result in the most stable and robust design with no sliding seals that may fail under CW loads.

Tuning was completed in three days using the automated beadpull system developed by Los Alamos and the software program RFQTUNE[5]. The beadpull software, QUADPULL and QUADPLOT[6] generates a data file of the field profiles within the RFQ. RFQTUNE then uses the known geometry of the RFQ and perturbation theory to iterate the tuner positions to match the measured profiles and yield the desired resonant frequency. Five cycles through this process achieved final tune with the quadrupole within +/-0.5% and both dipoles less than +/-0.5%. Figure 5 shows the first QUADPLOT output for the RFQ with all tuners set to nominal position. Figure 6 shows the finished results.

After final tuning, the RFQ was packed and shipped by truck from New York to Chicago. Beadpulls performed after shipment showed no discernible difference from the pre-shipment results.

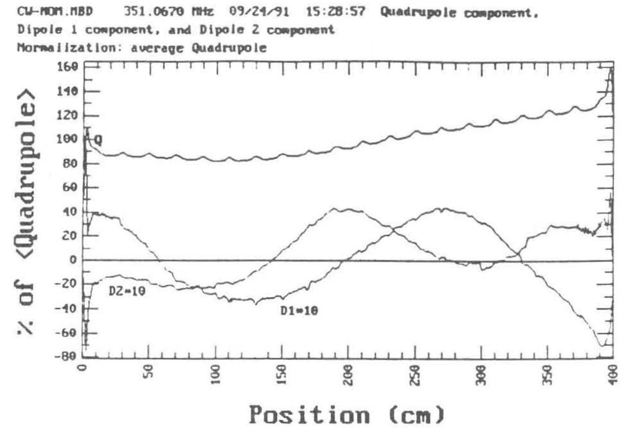

Figure 5
RFQ Field Profile Prior to Tuning

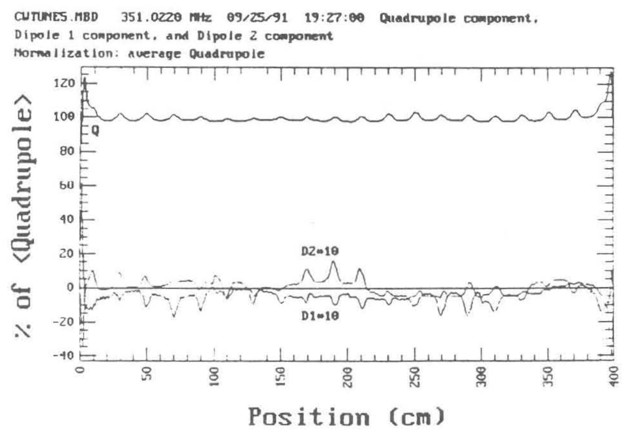

Figure 6
RFQ Field Profiles After Completion of Tuning

References

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