CW RFQ FABRICATION AND ENGINEERING *

D. Schrage, L. Young, P. Roybal, A. Naranjo, D. Baca, W. Clark, F. Martinez, H. Haagenstad, J. Mitchell, D. Montoya, A. Rendon, F. Krawczyk, T. Davis, D. Casillas, A. Gonzales, G. Gonzales, S. Hidalgo, E. Kettering, G. Leeches, B. Ormond, R. Reinert, O. Smith, & J. Tafoya
Los Alamos National Laboratory, Los Alamos, NM, 87545, USA

Abstract

The design and fabrication of a four-vane RFQ to deliver a 100 mA CW proton beam at 6.7 MeV is described. This linac is an Oxygen-Free Electrolytic (OFE) copper structure 8 m in length and was fabricated using hydrogen furnace brazing as the joining technology.

1 INTRODUCTION

The linear accelerator for the Accelerator Production of Tritium Project (APT) [1] will include a 6.7 MeV Radio Frequency Quadrupole (RFQ) linac. The first phase of this project, the Low Energy Demonstration Accelerator (LEDA) [2] consists of this RFQ plus a 20 MeV Cavity-Coupled Drift Tube Linac (CCDTL) [3]. The technical specifications for the APT/LEDA RFQ are given on Table 1.

Table 1: APT/LEDA RFQ Specifications

PARAMETER	VALUE
Frequency	350.00 MHz
Particle	H^+
Input Energy	75 keV
Input Current	105 mA
Input Emittance, trans./norm.	0.020 π-cm-mrad rms
Output Energy	6.7 MeV
Output Current	100 mA
Output Emittance, trans./norm. longitudinal	0.022 π-cm-mrad rms 0.174 deg-MeV
Transmission	95%
Duty Factor	100 %
Peak Surface Field	1.8 Kilpatrick
Average Structure Power	1.2 MW
Average Beam Power	0.7 MW
Average Total Power	1.9 MW
RF Feeds	12 Waveguide Irises
Average Heat Flux	11 W/cm^2
Maximum Local Heat Flux	65 W/cm^2
Resonant Segments	4 @ 2.0 m each
Brazed Sections	8 @ 1.0 m each
Slug Tuners	128 total
Length	8.0 m
Weight	5000 lb
Inlet Coolant Temperature	50°F
Operating Temperature	85°F

* Work supported by the US Department of Energy

These requirements presented significant challenges for the beam dynamics, cavity design, and thermal management. This was further exacerbated by the scarcity of similar devices which have been built and the limited operational experience. Indeed, none have been operated continuously for as long as one year. A comparison of CW RFQs is given in Table 2 on the following page. The CRNL1 RFQ, which has been moved to LANL and is now in operation as the CRITS (Chalk River Ion Source Test Stand), is the only device to have amassed significant operational time [4].

The original concept design for the APT RFQ was carried out in 1993 [5]. That concept incorporated a cavity that was segmented longitudinally as four resonantly-coupled cavities [6].

Because of the high output energy and current, there are some significant new features in the APT RFQ. Some of the issues and their resolution are:

- Long Electrical Length - This is possible through use of the segmented resonantly-coupled cavity [6]
- High Power - The use of a non-uniform vane-skirt width [7,8] reduces the peak and total cavity power.
- High Average Power Density - The average surface power of 11.4 W/cm^2 is a factor of four higher than CRNL1. Use of 24 longitudinal coolant passages in the cross section is required to dissipate the heat.

2 FABRICATION CONCEPT

The original fabrication concept [5] was based upon the electroformed joint which was developed by LANL, Northrop-Grumman, and GAR Electroformers for the BEAR RFQ [9] and later used for the CWDD [10] and SSC [11] RFQs. This method produces a monolithic cavity which has high structural efficiency and serves as an integral vacuum vessel. Electroforming is a room-temperature process and thus there is no concern regarding the maintenance of dimensional integrity. These advantages are largely offset by the high cost and long process duration.

Following completion of the conceptual-design study for the APT RFQ, LANL began an investigation of other manufacturing technologies in an attempt to reduce both cost and schedule. The primary focus was the joining technology. Welding, dip-brazing, plasma-spray, and hydrogen-furnace brazing were investigated. LANL has extensive experience in hydrogen-furnace brazing of linear accelerators. The brazed joining concept was tested on a 525-MHz, 0.48-meter-long engineering model [12].

The brazed RFQ linac concept has the advantages of using OFE copper for its high thermal and electrical conductivity while facilitating the attachment of high-strength copper (C15715 GLIDCOP [13]) for high-stress areas such as flanges.

The 8-meter long APT RFQ cavity was fabricated as eight one-meter long "sections." A cross section of the cavity of the APT RFQ is shown on Fig. 1 with a schematic of the entire 8-meter structure shown on Fig. 2. The cavity is a major/minor vane arrangement. Each vane is fabricated as a vane tip brazed onto a base. This allows coolant passages to be machined in and located very near the vane tips. Plugs are brazed over the coolant passages. The brazed-on vane tips are the only water-to-vacuum braze joints in the structure. An alternative would have been to deep-hole-drill the passages and plug the ends by brazing.

The manufacturing plan allowed for each one-meter-long section to be mechanically aligned and for the RF-field distribution and resonant frequency to be measured prior to brazing. The alloy used to form the longitudinal joints, Cusil (AWS BAg-8), flows freely over copper surfaces and these joints could be assembled metal to metal. The alloy was supplied from wire placed into grooves. Thus it was not necessary to compensate for the thickness of the alloy in the mechanical alignment and RF measurements. After brazing, it was determined that the mechanical alignment had not changed more than 0.001 in and the resonant frequency had changed less than 75 KHz.

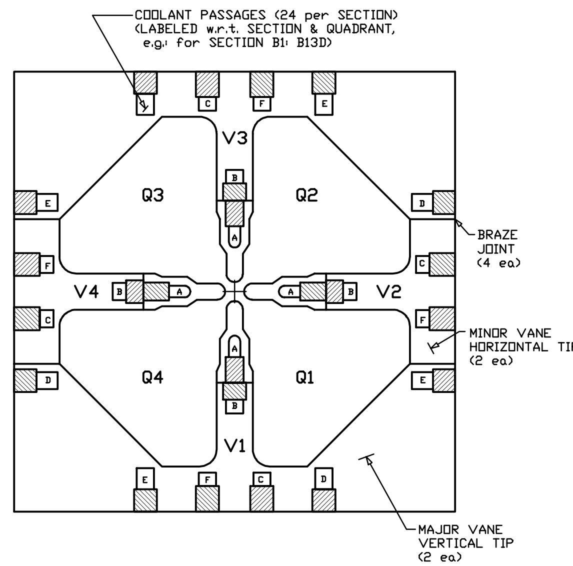

Figure 1: APT/LEDA RFQ Cross Section

Table 2: Comparison of CW RFQs

Parameter		**FMIT**	**CRNL**	**CRNL1 CRITS**	**CWDD**	**APT**
Particle		H_2+	H+	H+	D-	H+
Frequency	MHz	80	267	267	352	350
Injection Energy	MeV	0.075	0.050	0.050	0.200	0.075
Final Energy	MeV	2.000	0.600	1.270	2.000	6.700
Input Current	mA	105	90	86	92	110
Output Current	mA	100	75	75	80	100
Length	m	4.00	1.47	1.47	3.97	8.00
Wavelengths	λ	1.00	1.31	1.31	4.66	9.72
Intervane Voltage (Peak)	Kvolts	185.0	78.0	78.0	92.0	102.0
Peak Surf. Field	MV/m	27.2	25.0	28.8	33.7	33.6
Peak Surf. Field	Kilpatrick	1.00	1.50	1.75	1.80	1.80
Total Power	kW	600	133	254	304	1900
Beam Power	kW	193	50	105	144	700
Copper Power	kW	407	83	159	160*	1200
Avg. Cu Power/Length	kW/m	107	56	107	40	150
Avg. Cu Power/Area	W/cm^2	0.4	2.4	4.6	0.3*	11.4
Max Cu Power/Area	W/cm^2		8.7	16.7	2.7*	65.0
Operated		YES	YES	YES	NO	SOON
Reference		[14]	[15]	[4,16]	[10]	

* The CWDD RFQ was designed to operate at 35 K. The stated copper power includes the effect of enhanced surface electrical conductivity.

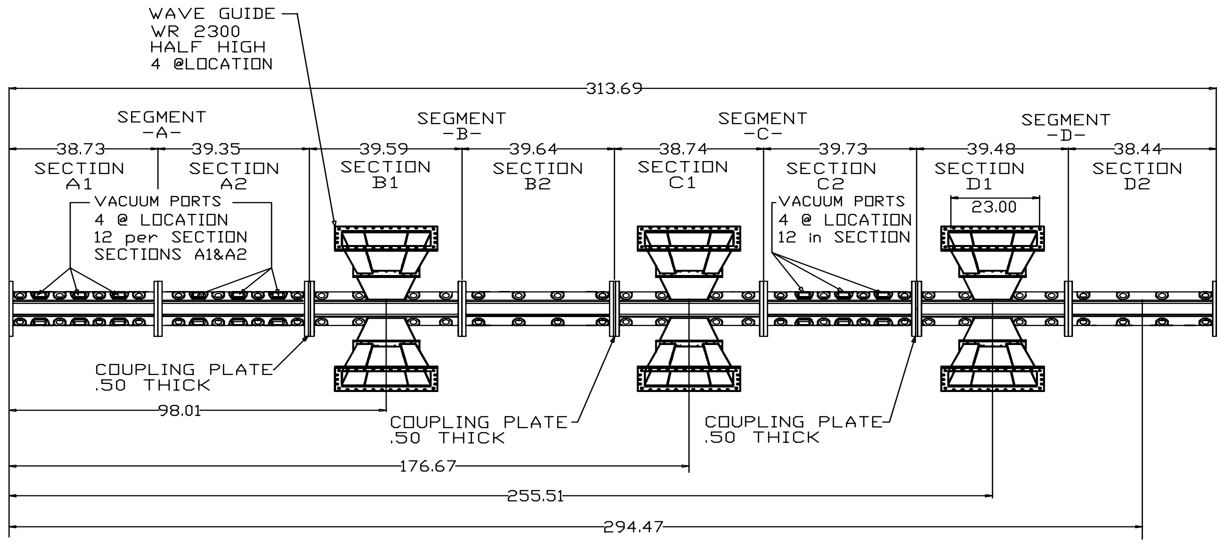

Figure 2: APT/LEDA RFQ Schematic

3 THERMAL MANAGEMENT

A total of 1.2 MW must be removed from the APT/LEDA RFQ cavity. With the average surface-power density being a factor of four higher than any earlier CW RFQ, thermal management was the major concern for the engineering analysis and design. The coolant passages were sized such that the bulk velocity did not exceed 15 ft/s to minimize flow erosion. The coolant passages were sized and located such that the heat gain per unit length in each passage was equal in the cross section. This was necessary in order to assure symmetric thermal distortion of the cavity.

A requirement that the longitudinal tilt of the local cavity frequency not exceed ±20 KHz in each one-meter long section established the number of cavity coolant passages (24 longitudinal passages in each section) and their locations. The “small” (350 MHz) cavity cross section did constrain the number, sizes, and locations of the coolant passages.

The RF field is ramped along the linac. The RF power in each of the four resonant segments is significantly different (A = 188, B = 318, C = 361, & D = 398 kW). In order to simplify manufacture, all segments have the same number and arrangement of coolant passages. The differences between the segment cooling requirements are addressed by having separate flow loops (including pumps and mixing valves) for each of the four resonant segments [17].

The resonance-control scheme provides coolant (360 GPM total) at a constant 50^{o}F into the tip passages (“A” & “B” as identified on Fig. 1) while the temperatures of the coolant (1160 GPM total flow) fed to the cavity wall passages (“C,” “D,” “E,” & “F”) are modulated to maintain the cavity on resonance. The inlet coolant temperatures to the cavity walls of each segment are predicted to be 71, 65, 63, and 61^{o}F respectively. Modulating only the cavity-wall-coolant temperature gives a positive derivative of the frequency with respect to the coolant temperature in the cavity-wall passages ($\partial f/\partial T = 1.7X10^{4}$ Hz/^{o}F).

Each slug tuner (128), vacuum pumping port (36), RF iris/waveguide unit (12), coupling plate (3), and both end-walls are also supplied with coolant. There are 424 coolant passages.

The 50^{o}F coolant temperature was selected in order to reduce the peak temperature of the cavity wall to about 100^{o}F. (The highest temperatures, ~150^{o}F, occur in the end undercut regions where the surface heat flux is 65 W/cm^{2}.) This serves to minimize longitudinal thermal expansion as well as cavity power which would have increased at higher surface temperatures. The 50^{o}F inlet temperature requires the coolant water to be refrigerated rather than supplied from a cooling tower. A cooling tower would provide 105^{o}F inlet water in the summer which would raise cavity-wall temperatures and power consumption significantly.

4 VACUUM SYSTEMS

The vacuum pumping system for the RFQ is designed to provide a cavity-vacuum level of better than $1X10^{-6}$ Torr. As much as 10 mA of the H^{+} input beam will not be captured. This will form $1.0X10^{-3}$ Torr-l/s of H_2 in the first resonant segment. There is an additional $0.5X10^{-3}$ Torr-l/s of other species (H^{+}, H_2^{+}, H_3^{+}, & O_2) from the injector that must also be removed. There are 36 vacuum pumping ports, 12 each in Sections A1, A2, and C2. Each pumping port has local heat fluxes up to 40 W/cm^{2} and therefore they must be actively cooled.

The vacuum-manifolding concept is based on that used for the SSC RFQ [11]. Five 8-in cryopumps are used. These are connected via manifolds to allow for operation during regeneration and to provide installed redundancy [18].

There are 12 RF windows [19] connected via ridged waveguide [20] to the quadrants of Segments B1, C1, and D1. Each window will transmit 250 kW thru a small (0.063 in wide by ~3.5 in long) iris. Because the vacuum conductance through these irises is very small (< 16 l/s) and the outgassing of the window and ridged waveguide assemblies is high (>$5X10^{-9}$ Torr-l/s), separate vacuum pumping units are required for each assembly. Direct-mounted non-evaporable getter (NEG) pumps will be used in these locations [21]. These have the advantages of being passive (no mechanical vibrations) and oil free. The selected units (SAES "CapaciTorr") have greater than 1000 l/s speed for H_2 and the predicted time between regenerations exceeds one year. There is no installed redundancy in the RF-window vacuum system.

5 STRUCTURAL SUPPORT

The cavity is a long, slender structure, sufficiently flexible that a statically-indeterminate support is required [22]. The cavity is suspended by five articulated links, one at the end of each resonant segment. This support meets the requirements that the gravitational deflection not exceed 0.0005 in and that the deflection due to predicted applied loads not exceed 0.005 in.

For assembly, the support structure was mounted in a vertical orientation on a pair of pyramidal towers (Fig. 3). The RFQ sections were stacked into the support structure. The entire assembly was then rotated to the horizontal and rolled into the linac tunnel. This concept was extrapolated from that used with the CWDD RFQ [10].

6 INSTALLATION STATUS

Fabrication of the cavity was completed in January of 1998, 28 months after commencement of the project. Preliminary RF tuning [23], vacuum testing, and assembly into the support structure was completed in the Spring of 1998. The unloaded Q of the cavity was measured at 8634, more than 80% of the value predicted by SUPERFISH. With the variable vane-skirt width, the Q calculated by SUPERFISH varies along the length of the RFQ so a length-weighted average value is quoted. Fig. 4 shows the complete 8-meter linac assembled for low power RF tuning.

The unit was installed in the linac tunnel in June of 1998. At the present time, the cavity vacuum system and cooling system are being installed. Fabrication of the ridged waveguide components [20] is underway at LANL and at AlliedSignal. Final testing of the RF-window vacuum systems is underway at LLNL [24]. High-power conditioning is scheduled to begin in the Fall of 1998.

7 SUMMARY

The detail design of the APT/LEDA RFQ cavity was scaled directly from the engineering-demonstration model [12]. The design, fabrication, and tuning tasks went smoothly were carried out at LANL and the original schedule was adhered to. The brazed-RFQ concept is robust and can be cost-effectively and predictably implemented at all duty factors up to CW and in the frequency range of about 200 to 800 MHz.

8 ACKNOWLEDGEMENTS

Other institutions participating in RFQ project include LLNL and TECH-SOURCE (vacuum system), AlliedSignal (resonance control cooling system), plus Northrop-Grumman (engineering support). Personnel from the Argonne National Laboratory (G. McMichael), the FERMILAB (M. May), General Atomics (C. Charman & L. Lommers), Northrop-Grumman (B. Abel & J. Rathke), TECH-SOURCE (P. Grande & N. Wilson), NOAO (E. Pearson), and LANL (T. Butler) served on the project's technical-review panels.

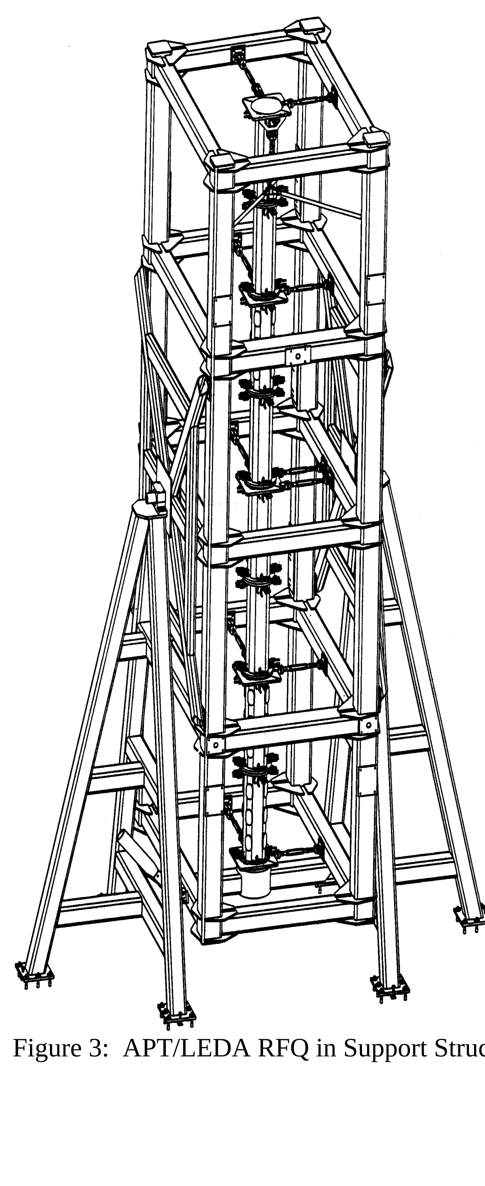

Figure 3: APT/LEDA RFQ in Support Structure

Figure 4: APT/LEDA RFQ Assembled for Pre-Installation RF Tuning

9 REFERENCES

[1] G. Lawrence, "High Power Proton Linac for APT; Status of Design and Development," these proceedings.

[2] H. V. Smith, "Status Update for the Low-Energy Demonstration Accelerator (LEDA)," these proceedings.

[3] R. Wood, et al, "Status of the Engineering Development of CCDTL for the Accelerator Production of Tritium," these proceedings.

[4] H. V. Smith, et al, "Comparison of Beam Simulations with Measurements for 1.25 MeV CW RFQ," these proceedings.

[5] D. Schrage, et al, "Conceptual Design of a 7-MeV RFQ Linac for the Accelerator Production of Tritium," LANL Report LA-UR-93-1790

[6] L. Young, "Segmented Resonantly-Coupled Radio-Frequency Quadrupole (RFQ)," Proceedings of the 1993 Particle Accelerator Conference," Washington, DC

[7] L. Young, "Simulations of the LEDA RFQ 6.7 MeV Accelerator," Proceedings of the 1997 Particle Accelerator Conference.

[8] D. Schrage, et al, "A 6.7 MeV CW RFQ Linac." Proceedings of the 1997 Particle Accelerator Conference.

[9] D. Schrage, et al, "A Flight-Qualified RFQ for the BEAR Project," Proceedings of LINAC88, Williamsburg, VA

[10] J. Rathke, et al, "Engineering Design of the Radio Frequency Quadrupole (RFQ) for the Continuous Wave Deuterium Demonstrator (CWDD)," Technical Symposium and Scientific Interchange on Neutral Particle Beam Technology, Monterey, CA, 1989

[11] D. Schrage, et al, Radio Frequency Quadrupole Linac for the Superconducting Super Collider," 12th Conference on the Application of Accelerators in Research & Industry, Denton, TX, 1992

[12] D. Schrage et al, "A New RFQ Fabrication Technique," Proceedings of LINAC94, Tsukuba, 1994

[13] GLIDCOP, OMG Americas, Triangle Park, NC

[14] W. Cornelius, "CW Operation of the FMIT RFQ Accelerator," Proceedings of the 1985 Particle Accelerator Conference, Vancouver, BC

[15] G. Arbique, et al, "CW Operation and Initial Beam Experiments with the RFQ1 Accelerator," Proceedings of the 1990 Linear Accelerator Conference, Albuquerque, NM

[16] G. Arbique, et al, "Beam Parameter Measurements on the CW RFQ1-1250 Accelerator," Proceedings of the 1992 Linear Accelerator Conference, Ottawa, ON

[17] R. Floersch, "Resonance Control Cooling System for the APT/LEDA RFQ," these proceedings.

[18] S. Shen, et al, "APT/LEDA RFQ Vacuum Pumping System, "Proceedings of the 1997 Particle Accelerator Conference," Vancouver, BC

[19] K. Cummings et al "Results and Lessons Learned from Conditioning 1 MW CW 350 MHz Coaxial Vacuum Windows," these proceedings

[20] R. Valdiviez et al, "The Mechanical Design & Fabrication of a Ridge-Loaded Waveguide for an RFQ," these proceedings

[21] S. Shen et al, "APT/LEDA RFQ RF Window Vacuum Pumping System - Conceptual Design Report," LLNL Report #APT/RFW-091797-001

[22] S. Ellis, "APT/LEDA RFQ and Support Frame Structural Analysis," LANL LA-UR #97-528

[23] L. Young, "Tuning of the LEDA RFQ 6.7 MeV Accelerator," these proceedings.

[24] K. Kishiyama et al, "Testing of Vacuum Pumps for the APT/LEDA RFQ," these proceedings