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DEVELOPMENT OF 400- TO 450-MHz RFQ RESONATOR-CAVITY MECHANICAL DESIGNS

by

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ABSTRACT

In the development of the radio-frequency quadrupole (RFQ) linac, the resonator cavity's mechanical design may be a challenge similar in magnitude to that of the development of the accelerator structure itself. Experience with the all-copper 425-MHz RFQ proof-of-principle linac has demonstrated that the resonator cavity must be structurally stiff and easily tunable. This experience has led to development of copper-plated steel structures having vanes that may be moved within a cylinder for tuning. Design of a flexible vane-to-cylinder radio-frequency (rf) joint, the vane, and the cylinder has many constraints dictated by the small-diameter cavities in the 400-MHz-frequency region. Two types of flexible, mechanical vane-to-cylinder rf joints are being developed at Los Alamos: the C-seal and the rf clamp-joint.

I. INTRODUCTION

The radio-frequency quadrupole (RFQ) linac is a revolutionary new focusing, bunching, and accelerating structure that promises to be an important part of any future proton, light ion, or heavy ion accelerator. The first RFQ structure outside the USSR was successfully tested in Los Alamos in February 1980. It eliminates the need for costly Cockcroft-Walton power supplies, complex multicavity buncher systems, and lengthy beam-transport systems previously necessary for injection into a drift-tube linac (DTL). The RFQ linac allows injection energies as low as 30 keV; it bunches and accelerates the continuous beam, that comes from ion sources, with less emittance growth than any other

known system. The general configuration of the RFQ linac is shown in Fig. 1. Mechanically, the device consists of four specially machined vanes mounted within a cavity. This RFQ resonator cavity is a mechanical support for the RFQ vanes and also is a radio-frequency (rf) resonant cavity.

Seven desirable criteria for an RFQ resonator cavity have been identified:

- (1) adequate structural stability,
- (2) low fabrication costs,
- (3) adequate cooling,
- (4) simple assembly techniques,
- (5) an acceptable cavity Q ,
- (6) ease of tuning and,
- (7) long-term stability.

In the design of the 400-MHz-region RFQ resonator cavities, the complete satisfaction of one criterion tends to result in violating another criterion. Therefore, RFQ resonator-cavity design is an optimization process, trading off relative advantages and disadvantages.

II. RESONATOR-CAVITY DESIGN REQUIREMENTS

The rf fields in an RFQ resonator cavity run axially between the vanes in each quadrant, circling the end of each vane to connect fields in the adjacent quadrants. These rf fields excite the cavity, causing rf currents to flow from vane to vane across the interior of the resonator cavity, as shown in Fig. 2.

Fig. 1.
General configuration of the RFQ linac.

Fig. 2.
The rf current flow within an RFQ resonator cavity.

The maximum current density on the resonator cavity wall is ~ 9 kA/m, or approximately six times the surface currents in a DTL. This same current density occurs from the vane end to the end of the resonator cavity. The electrical conductivity of surfaces exposed to rf must be high, and the current joints between components must be extremely good, to achieve an acceptably high rf-cavity Q.* The current-carrying surfaces should be copper; the rf joints may be made by a variety of methods: furnace brazing, copper plating, and plastic-deformation mechanical joints are the most common.

The rf fields between the vanes in each quadrant must be balanced and axially leveled for the RFQ linac to be properly tuned. The tuning requirements for frequencies in the 400-MHz range are

- magnetic field equal in each quadrant to $\pm 2\%$;
- longitudinal magnetic-field distribution flattened to within $\pm 5\%$; and
- frequency adjusted to the required frequency, corrected for the dielectric constant of air and the cavity's operating temperature.

The basic tuning approaches that may be used are

- machining inserts and/or moving tuners at the ends of each vane (varies the capacitance between the vanes and the cavity and adjusts the axial electric field distribution);
- radially moving of the vanes (primarily adjusts the frequency);
- circumferentially rocking the vanes (primarily alters the field distribution between quadrants);
- adjusting quadrant tuning slugs (tunes the frequency, balances the quadrant fields, and adjusts the longitudinal field distribution); and
- mechanically deforming the resonator cavity (simultaneously changes all tuning parameters).

Error analysis of the RFQ beam dynamics at 425 MHz indicates that the maximum allowable tolerance on the radial vane-tip position is $\sim \pm 0.005$ cm (± 0.002 in.).

*Q is the resonant-structure quality factor. It is a frequency-dependent ratio of the stored rf energy (W) to the rf energy dissipation rate (P). The quality factor can be written $Q = \omega W/P$, where ω is the cavity frequency. High Qs are desirable because the rf power required to drive a cavity of fixed stored energy at a fixed frequency is proportional to $1/Q$.

The maximum allowable longitudinal tolerance on the vane-tip position is about four times that of the radial tolerance.¹ Vane-tip displacement as small as 0.002 cm (0.0001 in.) can have a significant effect on the cavity tune. Most RFQ linac designs at 400 to 450 MHz require 1.8- to 2.5-m-long cavities, supported at only two points, as shown in Fig. 3. Therefore, the RFQ resonator cavity must be both sufficiently rigid and stable to maintain the tuning.

Surrounding the resonator cavity is the RFQ power manifold that supplies and distributes rf power to the RFQ linac,² either by directly driving the manifold with a klystron³ [as was done in the RFQ proof-of-principle (POP) test shown in Fig. 3], or by resonantly coupling the manifold to a DTL linac^{4,5} [as proposed for the Pion Generator for Medical Irradiations (PIGMI) accelerator⁶ shown in Fig. 4]. The rf power in the manifold drives the RFQ through diagonal rf coupling slots between the vanes in the RFQ resonator cavity. These slots are typically ~1.6 cm wide, inclined at an angle of 30° to 45° from the orthogonal plane, and should be as long as possible to enhance the rf coupling. The cavity-wall thickness at the slot is relatively unimportant, provided that the

Fig. 3.
RFQ POP linac schematic.

Fig. 4.
PIGMI injector, RFQ linac, and DTL.

slot width is at least equal to the wall thickness and less than $\sim 10\%$ of the slot length. Because the slots, interior, and most of the exterior of the RFQ resonator cavity are exposed to rf currents, these surfaces must be copper. The exterior surface of the resonator cavity should be fairly free of protrusions so that the rf fields in the power manifold are not unduly perturbed.

An alternative method of driving the RFQ is by rf loops in the quadrants. This obviates the need for coupling slots and a power manifold; however, because of the numerous holes required in the resonator cavity, an external vacuum enclosure is still required, and adequately distributing the rf power between the quadrants may be difficult. The rf coupling slots are also used to vacuum pump the resonator cavity; therefore, other provisions would have to be made to increase the vacuum conductance from the resonator cavity to the power manifold. The absence of rf power in this vacuum enclosure would greatly simplify the diagnostic access to the RFQ, but designs at Los Alamos will continue to use the RFQ power manifold approach, at least for the near term.

Vacuum within the resonator cavity must be adequate to achieve the required rf fields and surface electric fields. Surface electric fields are

customarily expressed in terms of a gap-independent field limit called the Kilpatrick Limit (KL). This is given by the formula⁷

$$\omega = 1.64 E^2 e^{-8.5/E},$$

where ω is the frequency in megahertz, below which sparking may occur for a peak electric field (E) in megavolts per meter. For pulsed room-temperature accelerators, reliable operation is possible at 1.8 KL, and structures have been operated at over 2.2 KL for short periods with no sparking. For continuous wave (cw) (100% duty factor) operation, the limit on peak surface fields for reliable operation is generally taken to be 1.5 KL.⁸ The performance of the RFQ linacs dramatically increases with higher surface fields; therefore, the vacuum required within the RFQ resonator cavity should be well into the 10^{-7} torr range to suppress sparking. The interior of the RFQ resonator cavity is primarily pumped through the rf coupling slots to the RFQ manifold; these slots are generally sufficiently large and numerous so that no special provisions need be made to increase the vacuum conductance.

A final design requirement for RFQ resonator cavities is the provision for cooling. RFQ linacs are capable of handling large beam currents and cw operation; however, most applications for RFQ linacs in the 400-MHz frequency range require low duty factors. For example, the PIGMI⁶ RFQ linac would operate with a 0.36% duty factor, and the cooling requirement is only ~1.4 kW for the 1.78-m-long structure (including the resonator cavity and power manifold). Schriber⁸ has developed a formula for the rf loss (which is manifested primarily as structure heating) per unit length for a four-vane RFQ linac.

$$P/\ell \approx 1.47 \times 10^{-18} V^2 \omega^{1.5} R_H^{-0.3},$$

where: P/ℓ = rf loss per unit length (W/m),

V = vane-tip voltage (v),

ω = rf frequency (Hz), and

R_H = average aperture (bore) radius (cm).

In the distribution of heating on the vane and cavity wall, the power loss (on a vane of uniform width) increases approximately with the square root of the radius from the center of the bore; that is, the heat deposited on the vane tip is relatively small, and the heat deposition (and the rf currents) reaches a maximum at the base of the vane and resonator-cavity wall. Schriber⁸ concludes that a thin vane is desirable to reduce the rf losses, and that a 50% increase

in the vane thickness increases the rf power loss by ~20%. Therefore, it is generally desirable to minimize the vane width and the resonator cavity's inside diameter consistent with the frequency and beam-dynamics requirements.

III. POSSIBLE RESONATOR-CAVITY CONFIGURATIONS

A prime function of the RFQ resonator cavity is to provide an rf current path from one vane to another. Figure 5 shows the three basic interior geometries of the four-vane resonator cavities that have been considered at Los Alamos. A cloverleaf geometry (shown in Fig. 6) was fabricated for cold-cavity (low-power) rf testing. It was initially thought to be significantly superior in rf power efficiency; however, computer analysis revealed that a square cavity, as a worst case, is only ~10% less efficient than the cloverleaf cavity.

In cold-test models, cooling and vacuum were not factors because the rf experiments are done at atmospheric pressure and low power. At low power, the quality of rf surfaces and rf contacts is relatively unimportant; however, these factors become of great importance in high-power tests if the cavity is to achieve an acceptable Q. The square resonator-cavity geometry was rejected for the high-power tests because it held no advantage (in the 400-MHz-frequency range) over the cloverleaf and circular geometries. Although the exact shape of the quadrant is relatively unimportant, it is desirable to approximate a cloverleaf cross section. A circular geometry (with flared vane bases) was selected for the first high-power test (the 425-MHz RFQ POP experiment) because fabrication appeared to be relatively straightforward.

Fig. 5.
Basic RFQ resonator-cavity interior geometry.

Fig. 6.
Cloverleaf RFQ resonator cold cavity.

IV. RFQ PROOF-OF-PRINCIPLE DESIGN

One application of the RFQ under development at Los Alamos is for the high-intensity 35-MeV, 80-MHz deuteron accelerator being designed for the Hanford Fusion Materials Irradiation Test (FMIT) Facility. An essential step in evaluation of the RFQ for this accelerator was a full-power test called the RFQ POP experiment. A 425-MHz size was chosen for the RFQ POP experiment so that an existing injector, power manifold, rf source, and high-energy beam-transport system in the PIGMI laboratory could be used.

The 425-MHz RFQ POP experiment² (illustrated in Fig. 3) accepted a nominal 50-mA beam of 100-kV protons and produced a focused, bunched, and accelerated 640-keV beam in 110.8 cm. Copper tubing, 6.125-in. (15.56-cm) o.d. with a 0.192-in. (0.49-cm) wall thickness was chosen as the main resonator-cavity structural element. Square copper ends were brazed (in a hydrogen brazing furnace) to the tube, then accurately faced to length. The square ends formed three mutually perpendicular planes, allowing the resonator cavity to be indexed and clamped so that dowel-pin and screw holes could be easily and accurately located and drilled.

The RFQ POP test cavity is shown in detail in Fig. 7. The vane bases were machined from solid OFHC copper with slots on the outside diameter for the 0.25-in. (0.63-cm) o.d. copper refrigerator tubing used for cooling. The vane bases, including the cooling tubing, were located in the cylinder by dowel pins

Fig. 7.
The RFQ POP test cavity.

and screws, and the entire assembly was then furnace brazed. Following brazing, a 2.250-in. (5.72-cm) -diam center hole was bored to produce a datum surface for subsequent machining operations. These operations included jig boring the dowel-pin holes and screw holes for locating the vane tips, machining the rf coupling slots, rounding the square ends, and finally turning the entire cavity to 6.095-in.(15.48-cm) o.d. It was ultrasonically cleaned before final assembly.

The specially machined and electropolished OFHC-copper RFQ vane tips (Fig. 8) were bolted into the resonator cavity using steel screws and dowel pins. Using an Excella numerically controlled (NC) mill, the machining tolerance was found to be ± 0.0043 cm (± 0.0017 in.).¹⁶ Each end of the resonator cavity was closed by a copper disk assembly containing four, small, movable copper end-tuners. The resulting cavity (Figs. 8, 9, and 10) was essentially composed of fully annealed copper. Following assembly of the entire cavity, it was found that the soft-copper structure was insufficiently rigid, and there were unacceptable dimensional deviations from designed values. The assembled cavity could not be tuned except by physically deforming the cavity. Fortunately, the soft-copper structure allowed deformations to be made without the application of very large forces. The RFQ POP resonator cavity was mounted inside a large steel frame equipped with suitable jacking screws. These screws were used to push and tug at the soft-copper structure until the vane tips were reasonably well aligned. Tuning was done electrically, with low-power rf and probes. This tuning procedure was very difficult and required a fair amount of "art" because when one component of the structure was moved, all other cavity components also shifted. When the deformation force was removed, the resonator cavity would relax into yet another configuration. Tuning required ~4 wk of intense work.

The RFQ POP resonator cavity was installed in the RFQ power manifold. The resonator cavity was suspended within the PIGLET (a modified, high-gradient-field test cavity located in the PIGMI laboratory) cavity by two solid-copper spools to form the RFQ power manifold, a coaxial line terminated at each end by an electrical short circuit. The spools were slid within the power manifold (and on the resonator cavity) to adjust the frequency of the power manifold. Whenever the spools were moved, the RFQ resonator cavity's support points were different, the soft copper deformed, and the RFQ tune changed slightly. Fortunately, the detuning was minor and the tests of the RFQ POP proceeded.

Fig. 8.
RFQ POP resonator-cavity assembly.

Fig. 9.
RFQ POP assembly, low-energy end.

Fig. 10.
RFQ POP assembly, high-energy end.

The 425-MHz RFQ POP experiment worked very well, operating reliably at rf fields 35% greater than the design value, and consistently accelerated more than 80% of a 38-mA proton beam, injected at 100 keV, to a final energy of 640 keV. Data analysis indicated that the emittance growth was less than 60%. However, the RFQ POP resonator cavity was structurally weak and extremely difficult to tune. It was obvious that future designs of RFQ resonator cavities must correct the difficulties encountered in the RFQ POP resonator cavity.

V. SECOND-GENERATION RFQ RESONATOR-CAVITY DESIGNS

Following the successful conclusion of the RFQ POP tests, several groups have adopted or proposed an RFQ linac for the front end of new or existing linacs. The frequencies included the 80-MHz FMIT RFQ linac; RFQ linacs in the 200-MHz region for European Organization for Nuclear Research (CERN), Centre d'Etudes Nucleaires, Saclay, France (LEN Saclay-LNS), Brookhaven National Laboratory, and Lawrence Berkeley Laboratory; 400-MHz-region RFQ linacs for PIGMI and a radioisotope production linac; and RFQ linacs in the 800- and 1300-MHz regions for various conceptual applications.

It was initially thought that a "standard" resonator-cavity design concept could be suitable for a variety of frequencies. Considerable debate occurred within the Accelerator Technology (AT) Division concerning the form of this standard configuration;^{11,12} however, interactions both within Los Alamos and with other accelerator groups (foreign and domestic) have revealed that, because of the physical size of the resonator cavities and vanes, each frequency creates unique structural and alignment problems. For example, a 200-MHz RFQ resonator cavity has an ~35-cm i.d.; this size is large enough for interior access into a quadrant by a hand or small tools. A 425-MHz RFQ resonator cavity has an ~16-cm i.d., too small for manual access to the cavity's interior; therefore, all adjustments and other mechanical operations must be accomplished through external access holes. Furthermore, although the weight of each 425-MHz vane is relatively modest, acceptable vane mechanical support (particularly for the cantilevered horizontal vanes) becomes an important consideration in the 200-MHz size, and a formidable design challenge in the 80-MHz application. Therefore, although RFQ linac mechanical design for each

frequency range has evolved away from a standard resonator-cavity design concept, there has been considerable exchange of ideas and innovations.

Some conceptual RFQ resonator-cavity configurations are illustrated in Fig. 11; the circular-cavity configuration has been selected for illustration simplicity. Configuration (a) is a one-piece cavity with no rf joints. It is structurally rigid but impossible to make using present vane-tip machining technology. Configuration (b) is a one-piece cavity with bolted-in vane tips; this is the configuration actually used for the RFQ POP resonator cavity. Because the vane tips cannot be easily moved, tuning is too difficult. The other cavity criteria can be achieved by proper design, and the vane-tip rf joint is in a region of relatively low currents (this is probably why the simple butt joint of the RFQ POP vane tip to vane base was successful). Configuration (c) is a development of Configuration (b). Rigidity of a one-piece vane

Fig. 11.
Conceptual RFQ resonator-cavity configurations.

aids the vane-tip machining. A flexible mechanical vane-to-cylinder rf joint allows the vane to be moved radially, and rocked, to ease tuning, but these joints are in the region of highest rf currents. Configuration (d) allows the resonator cavity to be machined in four similar pieces to ease fabrication difficulties. The two rf joints per vane are in the low-current region; this configuration lends itself to the efficient cloverleaf-shaped cavity (Fig. 6). However, Configuration (d) would not be easily tuned, and the structural rigidity is not as good as other configurations. Configuration (e) has rf joints in the same location as (c), but the cylinder is sectioned for ease of fabrication. For 400-MHz-region RFQs the structural rigidity is not as good as that of (c), but this may be an interesting configuration for higher frequency applications, particularly if the linac is driven by rf loops. Configuration (f) is of interest because it has only one rf joint per vane and may be opened up for ease of fabrication. Like (e) the structural stability is probably not as good as that of (c), but it may also be of interest for higher frequency RFQs. Configuration (g) has the major disadvantage of an rf joint in the highest current region, and the joint would be in the middle of the rf coupling slots. The structural stability of (g) is also surpassed by other configurations.

Table I is a qualitative evaluation of each of the configurations in Fig. 11. Configuration (c) appears to have the best combination of features, and variations of this configuration are being pursued at Los Alamos. Figure 12 represents a first attempt at a second-generation RFQ resonator-cavity design, as proposed in Ref. 6. The cylinder would be fabricated from stress-relieved mild steel, machined to the proper inside diameter. The rf coupling slots, the other necessary wall penetrations, and the cooling holes would be machined; then the cylinder would be copper plated using the leveling, bright-acid copper-plating process successfully used on other PIGMI accelerator components. The vane fabrication would be as follows. First, the OFHC-copper vane tips would be furnace brazed to a copper-plated mild-steel vane base. Next, the vane-tip geometry would be profile machined. The four completed vanes would be aligned in a jig so that the outside diameter of the four-vane assembly could be accurately machined to match the inside diameter of the plated resonator cavity. Last, the vanes would be rigidly mounted in the cylinder, and an rf joint would be made between the vane and the cylinder. Tuning would be done by means of the tuning buttons.

TABLE I

RELATIVE EVALUATION OF CONCEPTUAL RFQ CONFIGURATIONS

RFQ Configuration (as shown in Fig. 11)	RFQ Resonator-Cavity Criteria							Summary				
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	A	B	C	D	F
(a)	A	F	B	A	A	D	A	4	1	-	1	1
(b)	A	C	B	A	A	D	B	3	2	1	1	-
(c)	A	B	A	A	B	B	B	3	4	-	-	-
(d)	B	D	C	C	A	C	C	1	1	4	1	-
(e)	C	C	A	C	B	B	D	1	2	3	1	-
(f)	C	C	B	B	A	C	B	1	3	3	-	-
(g)	C	C	B	C	C	C	D	-	1	5	1	-
A = excellent				(1) = structural stability								
B = very good				(2) = fabrication cost								
C = acceptable				(3) = cooling								
D = marginal				(4) = assembly ease								
F = unsatisfactory				(5) = acceptable Q								
				(6) = tuning ease								
				(7) = long-term stability								

Several methods have been proposed to make the vane-to-cylinder rf joint. An electron-beam weld is difficult because of the length of the cylinder, and the small cross section. A laser weld cannot be done because copper is an efficient reflector of laser light in the wavelengths normally used for welding. A plasma-arc spray requires equipment that is probably too large to fit within the resonator cavity. A vacuum or hydrogen-furnace braze using a relatively low-temperature braze such as Braze BT (also known as Cusil--72% silver and 28% copper--with a braze temperature of 1450°F) would result in an acceptable rf joint, but braze runs may upset the tune of the cavity. There is also considerable reluctance to do a brazing operation as the last step in the fabrication of an expensive cavity.

A nonheat rf-joint technique would be to copper plate (either by solution plating or brush plating) over the boundary between the vane and the cylinder.

Fig. 12.
PIGMI RFQ resonator cavity.

Solution plating might result in copper-plate buildup in undesirable places, such as on the machined vane tip. Also, in such a complicated geometry, specially shaped electrodes may be necessary to ensure that a bright surface is maintained. Brush plating would be difficult in the confined space of the quadrant, and the nonbright brush-plated surface might be detrimental to attaining a high cavity Q . In each case, a gap between the vane and the cylinder might prevent the copper plate from forming the continuous surface necessary for a good rf joint. This gap could be closed before plating by

using a small amount of conducting epoxy, but this might cause vacuum problems from organic materials in the epoxy.

An rf joint formed by a compressed soft-metal wire or ring is a technique used in many accelerator applications. Metal wires (gold, silver, copper, indium, gold-plated copper, gold-plated silver, etc.) have been proposed for compression between the vane and the cylinder wall. There are three problems with this approach for a simple vane-to-cylinder rf joint: (1) good rf contact requires large compression forces, (2) surface irregularities might cause a nonuniform rf contact, and (3) the vane's radial position cannot be easily altered. As tuning experience has been acquired with RFQ linacs, it has become obvious that some method of moving the vanes during tuning is essential. Movable vanes disconnect the rigid electric tolerance requirements from the mechanical tolerance requirements; therefore, the cavity and vanes can be built to conventional machining tolerances. Recent efforts at Los Alamos in RFQ resonator-cavity development in the 400-MHz range have concentrated on the development of flexible rf joints between the vanes and the cylinder.

VI. RECENT 400-MHz-REGION RFQ RESONATOR-CAVITY DESIGNS

A major simplification in RFQ linac fabrication has been the adoption of copper-plated steel PFQ vanes, eliminating the separately machined OFHC-copper vane tips. Machining OFHC copper requires special machine tools, machining speeds are slow, and special care must be exercised because of the tendency of the copper to gall. The vane-tip profile machining may be done much more rapidly and easily with steel. Because of the greater mass and rigidity of the entire vane, the larger resistance to machining forces increases the machining accuracy. All vane-tip machining is now performed on a Mazak V-10 computer numerically controlled (CNC) mill. Copper plating with the leveling, bright-acid technique results in excellent surfaces for rf currents, and the deposition can be adequately controlled in the tip region to ensure an essentially uniform plating thickness.

All RFQ linac designs being developed at Los Alamos now incorporate copper-plated steel vanes with vane-movement capability and flexible rf contacts between the vanes and the cylinder. Several types of flexible rf contacts have been proposed that are compatible with the restricted space in 400-MHz-sized cavities. Figure 13 illustrates a very simple contact-finger flexible rf joint; however, this type of joint is not optimum for several reasons. The joint depends on a spring force to make the contact. A too-light spring force may be inadequate to compensate for surface irregularities down the cavity's length, and a too-heavy spring force may cause the contact point to dig into and ruin the copper-plated cavity surface during tuning movements. Acceptable flatness of the rf contact surface down the length of the vane may be difficult to achieve. The positioning screws are held in tension, and thread relaxation under stress would cause the vane to change position, detuning the cavity. Any vane rocking will cause the contact force on each side of the vane to vary. There is a relatively large surface over which the rf currents flow, and heating over a long period might also cause the contact finger to lose resilience, and the contact force would weaken. Minor sparking might occur, causing more heating, and rapid joint deterioration might occur. Finally, the extensions on the sides of the vanes reduce somewhat the circumferential length of the resonator-cavity wall available for the rf-coupling slot. The contact-finger rf joint is simple in principle, but it may not be reliable in practice.

Fig. 13.
RFQ with contact-finger rf joints.

Fig. 14.
RFQ with C-seal rf joints.

Two promising, flexible rf-joint design concepts are under development in AT Division for 400-MHz-sized RFQ resonator cavities: a C-seal joint and an rf clamp-joint. A cross section of the C-seal RFQ is shown in Fig. 14. It is a simple cylindrical cavity with each vane held in place by two rows of screws. The vane-to-cavity joint (Fig. 15) is by copper-plated linear C-seals. C-seals are commercially available in a variety of sizes and shapes. The C-seal for this application is made from Inconel X-750 with a 0.64-cm (0.250-in.) cross section, and it comes in 122-cm (48-in.) lengths. The C-seals were plated at Los Alamos with 0.005-cm (0.002 in.) copper, using the leveling, bright-acid process. The C-seal is captured in the vane groove and makes contact with the vane and the RFQ with a nominal 20% squeeze. This results in an $\sim 66.9\text{-kg/cm}$ (375-lb/in.) contact force. In theory, as the C-seal is squeezed, the contact points are forced outward from the vane causing highly localized contact force at the point where the rf currents must pass.

The C-seal represents a modification of the contact-finger joint shown in Fig. 13. It is more compact so that the rf coupling slots may be of adequate length. The relatively large radius at the contact point

lessens the probability that the copper-plated surfaces will be damaged. The small surface area for rf current flow implies that the potential for heat-caused changes in the contact force is lessened. The good contact force allows the C-seal to adjust to minor cavity-surface irregularities; also, the C-seal is very simple and inexpensive. However, the stressed positioning-screw threads may relax, causing the cavity to detune. The C-seal joint is the essence of simplicity, using commercially available hardware, but it must make two rf contacts per joint, doubling the probability of an eventual contact failure.

Fig. 15.
The C-seal rf joint.

The second type of flexible rf joint for 400-MHz-sized RFQ resonator cavities has become known as the rf clamp-joint,^{13,14} shown in Fig. 16. This rf joint is made by two compression bars, forced apart by compression bolts, clamping the soft-copper contact strips into contact with the copper-plated edge of the steel resonator-cavity cylinder. The compression force on the contact edge can be up to 357 kg/cm (2000 lbs/in.) --the normal design force on a wire vacuum seal. Figure 17 shows the resonator-cavity cross section with all the various components.

Fig. 16.
The rf clamp-joint.

Fabrication of the vanes begins with the machining of a mild-steel

Fig. 17.
The RFQ with rf clamp-joints.

vane blank, and welding necessary for the cooling passages. The 0.08-cm (0.30-in.) -thick copper contact strips are furnace brazed to the vane blank, the vane-tip profile is machined, and the vane is copper plated. The vanes are then ready for installation into the resonator cavity. Cavity fabrication begins with a stress-relieved, mild-steel cylinder that is machined to the proper inner and outer diameters. The cooling-tube grooves are cut, all necessary penetrations of the resonator cavity are machined (except for the rf coupling slots), and the dowel-pin sleeves are welded in

place. Mild-steel contact rods, held in place by dowel pins, are furnace brazed into the resonator cavity at the same time that the cooling tubes are attached. The cavity ends are faced, the rf-coupling slots and dowel-pin holes are machined, and the cavity is copper plated.

Assembly of the resonator cavity begins with installation of the compression bars, held together in the fully retracted position by the compression bolts, and attached to the resonator cavity by screws. The vanes are then inserted into the cylinder and held by the push and pull screws. The vane tips are placed in a nominally correct mechanical position in the cavity using alignment jigs that attach to each end of the vanes. The vanes are locked in place using the push and pull screws, and the compression bolts are used to make a light rf contact. Following the initial tuning operations, the compression bars are forced apart by the compression bolts to make the rf joints. The cavity Q can be measured to ensure that good joints are made; tightening the compression bolts continues until the Q is satisfactory. The vane-base end joint is made by pulling another copper contact strip against the cavity end cover. There will be a small gap between the copper contact strips at the corner of the vane base, but this is not seen as objectionable. Even at the design joint force, stresses in the bolts and cylinder can be less than 50% of

the yield stress. Final minor vane movements and tuning adjustments are made, with the copper strips deforming as necessary to compensate for the revised vane positions. The dowel-pin holes are then drilled and reamed in the vanes, using the holes in the dowel-pin sleeves as a guide, and the dowel pins are installed.

The rf clamp-joint has the advantage that the rf-joint contact force is independent of the vane positioning, and thread relaxation should not affect the cavity tune. For high duty-factor applications, the heat transfer with the rf clamp-joint copper strips may be an advantage over the copper-plated Inconel C-seals. The rf clamp-joint approach involves more machining than the C-seal, and it is certainly more expensive than the C-seal; however, the positive action of the rf clamp-joint may provide better long-term stability.

VII. CONCLUSIONS

The development of the RFQ linac in the prototypical form of the RFQ POP test required intense work and substantial development in beam dynamics and vane-tip machining technology. Development of RFQ resonator-cavity technology has lagged. Since design of the RFQ POP experiment began in the summer of 1979, much has been learned about the tuning and technology of RFQ linacs. The search for a tunable design that has long-term stability is still in progress, but the development of the C-seal and rf clamp-joint promises to be an important technological advance in 400-MHz-region RFQ resonator-cavity design.

ACKNOWLEDGMENTS

Many have contributed to the development of 400-MHz-region RFQ resonator cavities at Los Alamos. In particular, J. M. Potter and F. J. Humphrey have developed methods to evaluate and tune RFQ linacs, and their experience has greatly contributed to the development of practical pieces of hardware. The energetic and innovative ideas of D. A. Swenson had much to do with the conceptual development of resonator cavities. C. F. Fuller, M. D. Machalek, and S. J. Williams developed the RFQ POP resonator cavity and made it work, thereby providing the base from which all subsequent resonator-cavity designs spring.

J. L. Uher has done many useful experiments with wire seals for RFQ rf joints. N. G. Wilson, T. A. Hayward, and G. W. Lind developed the C-seal rf-joint approach, and the comments of M. T. Wilson were helpful in the development of the rf clamp-joint approach in RFQ resonator-cavity design.

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