MECHANICAL CONSIDERATIONS IN CW LINACS*

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Summary

An 80-MHz radio-frequency quadrupole (RFQ) linac has been designed, fabricated and operated at 100% duty factor (cw) for the Fusion Materials Irradiation Test (FMIT) project at Los Alamos.[1] This paper describes the design features, fabrication techniques, and operational problems of the device. The RFQ is an assembly of heavy steel, copper-plated weldments. It measures about 15 ft (4.5 m) long by 5 ft (1.5 m) in diameter and weighs over 12 t. Major components are two pair of diametrically orthogonal vanes mounted in a core cylinder. The core is assembled into a manifold cylinder that couples rf power into the vane quadrants. The design features discussed include assembly of hollow wall, flood-cooled components; high-conductivity rf seals; removable and adjustable vanes; and tuning devices. Fabrication challenges such as close-tolerance weldments, vane-tip-contour machining and large-component plating requirements are covered.

Introduction

This paper describes the design, fabrication, assembly and development of the 80-MHz cw RFQ prototype for the FMIT program. This device (which is a type of linear accelerator that captures, bunches, and accelerates an ion beam) was constructed and installed in early 1983 by the Systems Integration Group in the Accelerator Technology (AT) Division at Los Alamos. The effort was a cooperative one, involving physicists, engineers, designers, laboratory technicians, machinists, and fabricators--both in the Laboratory and in private industry. Theoretical design determined the shape and size of components. Engineering of thermal, structural, vacuum, rf drive, and tuning mechanisms developed the configuration. Mechanical designers worked out assembly schemes, joint and seal techniques, system interfaces, and fabrication plans. Major components were contracted to outside vendors for fabrication, which required procurement procedures and acceptance inspections. Assembly and check-out was performed at Los Alamos. Parts were cleaned, fitted, aligned, and leak checked. Major prerun activities were tuning, titanium-nitride coating, and rf conditioning. Installation in the accelerator system involved systems integration of water cooling, vacuum control, rf power system, instrument/controls, and beam diagnostics.

The RFQ and associated systems have operated over 40 h at cw with 20-mA, 2-MeV beam output. Operation was begun with pulsed rf conditioning and progressed to cw power input. Beam was introduced first in the pulsed mode and the duty factor was progressively increased. During this process, several areas of localized overheating were discovered. Modest design changes were required.

The main features of the FMIT prototype RFQ are shown in cutaway illustrations, Figs. 1 and 2. The RFQ has two pair of diametrically opposed and orthogonal vanes that are contoured at the tips to produce the required field configuration. Vane positioning is accomplished through adjustable mounting to a core cylinder that is sized to resonate at 80 MHz. A manifold cylinder is coaxially mounted around the core cylinder. The manifold supports rf drive loops, vacuum pumps, and slug tuners. Ring capacitors between the core and manifold compensate for the difference between electrical and physical lengths of the cavity. Angular slots pass rf currents into the vane quadrants. The vanes, core cylinder, and manifold cylinder are hollow walled for flood cooling. All of the cavity parts that must conduct rf power are copper plated for maximum conductivity. Tuning is accomplished by vane adjustment in the core and capacitor sizing and slug tuner displacement in the manifold.

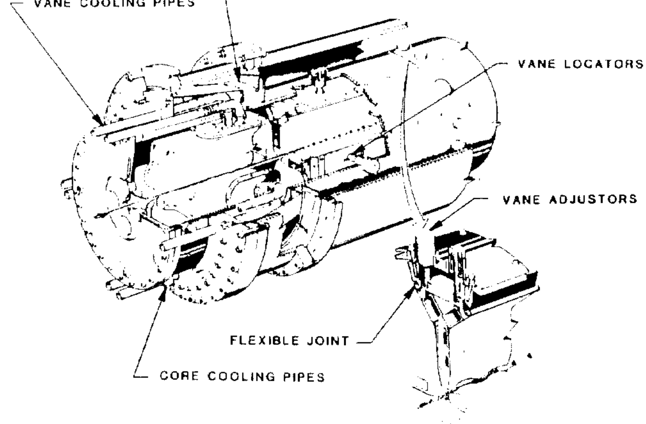

Fig. 1. RFQ core assembly.

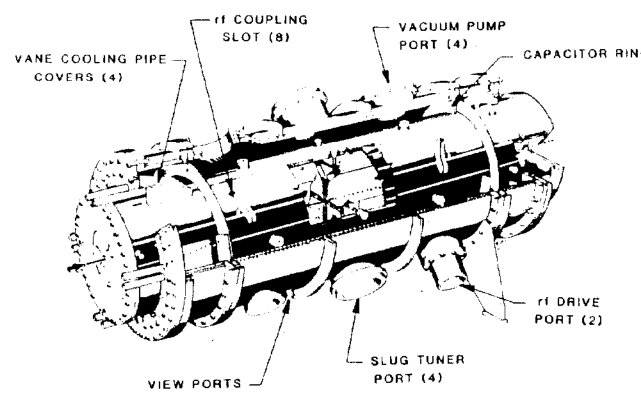

Fig. 2. RFQ assembly.

The vanes were constructed in several stages. Weldments (called blanks) were fabricated by contract with a vendor. Another vendor performed the tip machining. Finally, a third vendor applied copper plating. Each vane measured 16 x 168 in. and weighed 1400 lb.

Vane blanks were constructed from mild steel bars, plates, and structural, rectangular tubing. Because of its high rigidity and flat sides, the tubing was used for the central "Y" shape. The tubing was also convenient to fabricate. The interior of the tubing made excellent cooling-water passages. Welding of the blanks was risky because of the straightness requirement of 0.1 in. in 160 in. Special welding techniques were used, such as using two welders simultaneously on opposing sides of a part to equalize

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shrinkage stresses. Each weldment was heat treated to relieve stresses several times during fabrication. A system of tack welding a pair of blanks together to form a symmetrical shape for heat treatment helped maintain straightness.

A base structure contoured to fit the inside of the core cylinder was welded to the blank with a thin, stainless steel tube in between. The slotted tube formed a single convolution bellows and allowed the tip to be moved into correct position with adjustment screws at assembly. During cw operation, the stainless steel tube overheated in the relatively short section around the vane ends and had to be replaced with copper. The adjustment screws originally were a differential thread type, but later were replaced by heavier, opposing thread bolts. Figure 1 shows the details.

The RFQ vane tips were machined using a computer-controlled, three-axis, vertical milling machine. Because most machines can handle complex path motion in only one plane at a time, the three-dimensional tips were machined in repeated passes or steps over the vane, using a ball-end cutter of a radius smaller than the minimum tip-valley curvature. Surface-finish requirements dictated a maximum step size of 0.04 in. The typical cross section of the tip was a straight slope at a constant 28° up one side, a circular arc over the tip, and reciprocal slope down the other side. At 4200 cutter passes per vane, the machining process was very time-consuming. Programming for the tip machining has been an ongoing program in AT Division since the proof-of-principal (POP) RFQ was built in 1979. A new cutter system based on a stagger-toothed form cutter is currently in development.

The core and manifold cylinders are coaxial cavities that are electrically compensated by a pair of capacitor rings. Vacuum pumps, rf drive loops, and slug tuners are mounted in ports in the outer manifold. The vanes are supported by the inner core. Both cylinders are double walled with flood-cooling passages inside.

Core construction was begun with an inner wall of rolled and welded steel plates. Longitudinal ribs welded to the outside form risers for the outer-shell plates. The ribs also serve as water-channel dividers. Every other rib is open at the downstream end to allow the water to cross and return flow. The resulting cooling pattern is four pair of counter-flow channels. Each pair has its own inlet and outlet at the upstream end of the core. In operation, the channels are connected in parallel. The purpose of this kind of arrangement is to minimize uneven thermal expansion in the cavity.

Numerous holes were required in the core design. There are 192 vane bolt holes, 24 adjuster holes, 8 rf coupling slots, 8 vane locator holes, and 8 vacuum-conductance holes. Because all penetrations were through the water passages, they were sleeved so that the welds would be accessible for repair if they did not test leak tight. Many leaks were found and repaired during final inspection, but the core has not leaked during operation.

The capacitive loading of the manifold permits the manifold to be shorter than the core by a few inches at the ends, allowing the core-cooling connections to be made outside the cavity. Cooling connections for the vanes could not conveniently reach the exposed ends; therefore, they were routed through the core wall inside the cavity and were turned parallel to the beam axis to exit through the upstream support flange. To prevent rf arcing around the pipes, conductive covers were installed. The original cover design proved inadequate during the progress to cw and they overheated. They were replaced with lower profile, water-cooled models.

Manifold and core construction (Fig. 2) is similar in that they are formed from rolled and welded plates. Penetrations are larger and in the form of ports for vacuum pumps, slug tuners, and drive loops. Both the core and manifold have a number of glass view ports that proved useful in locating rf arcing when it occurred. Cooling passages carry water back and forth around the manifold instead of along its length.

The capacitor rings initially were circular parallel plates that overlapped in the space between the core and manifold. The inner plates were brazed to the core. The outer ones were sandwiched between segments of the manifold. Assembly was difficult and cooling was an unresolved problem. It was suspected that the plates had a mechanical vibration problem as well. A superior cylindrical design was developed that used the wall of the manifold as half of the capacitor. The inner half still was brazed to the core but was made thick enough to contain imbedded cooling tubes. The sections of manifold were brazed together, eliminating several seals and rf joints.

The vanes, core, and manifold all required copper plating. A major problem with plating the components was their bulk. Very few vendors have tanks large enough handle 5-t weldments; however, one in Seattle had tanks that could be modified to fit the need. The plating process was completely audited by Los Alamos personnel. (A detailed account of the procedure has published.[2]) Some problems with adhesion and thickness uniformity were found in the finished product. These were superficially repaired. The recommendation for future such jobs is to build full-sized mockups to be test plated. Proper anode design and circulation methods are a complex process that can best be accomplished by testing.

Tuning devices for the RFQ required significant development effort. The original core-tuning scheme was to shape the vane-end pieces and use adjustable slugs at the upstream vane-tip ends. When initial tuning was attempted, it was found that the devices were inadequate. Considerably more material had to be added in the base area of the vane ends. Copper straps and blocks were fabricated and brazed in place. The adjustable end tuners were discarded. The tuning straps worked until conditioning reached 150 kW average power and then overheating melted one and damaged the other. The alternative to end tuning was to attempt to use the vane adjusters for precision positioning. The vane adjustors had to be modified, but core tuning finally was accomplished without the use of additional devices.

Core-to-manifold tuning originally was accomplished by bending segments of the capacitor plates (through holes in the support flanges). When the circular capacitors were changed to cylindrical design, the spacing could no longer be adjusted by bending. Capacitance was adjusted by trial and modification of the width of the rings. Fortunately, the capacitors needed to be adjusted only into the range of the four large slug tuners.

The slug tuners were designed by scaling up from the LAMPF devices, which are used at low duty. They proved inadequate for cw operation. The space behind the slug was designed so that it would not be resonant, but sufficient current was conducted to overheat the stainless steel bellows around the actuator. A number of modifications[3] were tried, such as shorting across the bellows with copper straps and air cooling the interior of the bellows. The most successful change was direct shorting of the slug to the manifold port wall with spring fingers.

The rf joint design for this 80-MHz cw linac required considerable development work. Some Q-cavity testing was performed during the design phase, but full-power tests could not be done because the power amplifiers were not available until later. The basic method chosen was crushed 0.06-in.-diam wire, and annealed copper was found to be the best choice--being the best conductor. The Q-cavity testing demonstrated that copper would make a very low resistance joint only if the copper were oxide free. Because assembly of large components was time-consuming, it was impossible to keep the copper from oxidizing. The solution was to brush plate the wire with gold. The gold-plated copper wire currently is used between the vane bases and the core wall. The wire had a tendency to creep out of the joint under heating conditions, but this was corrected by using short lengths of wire with ends inserted into retaining holes.

Copper wire did not work as well for the core and manifold flanges because small deflections in the series of four joints caused a mismatch in the components. More ductile gold wire was used instead. The gold wire had an even greater tendency to creep out of joints when heated, but this was not altogether undesirable because it pinpointed problem areas to be corrected.

The rf joints were not used as vacuum seals. They were backed up by Viton O-rings wherever a vacuum barrier was required.

Conclusions

Engineering considerations in cw linacs are largely a matter of refining thermal design. Surface heating by rf power establishes high gradients in poor thermal conductors like steel. Aluminum or some similar material probably will replace steel in large devices. Airborne and space applications also will demand lighter materials. At this time, thin flexible members are usually stainless steel, chosen for its toughness; however, for future applications we will require optimized designs or will replace these members with new innovations. The rf joint seal design will need more development work. One interesting idea is to use oval tubes pressurized with gas or liquid. Certainly, the application of better analysis codes will help optimize designs for better performance.

Acknowledgments

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