

Design and Operation of the LBL Heavy Ion RFQ Linac

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Summary

LBL has designed and tested a heavy ion RFQ Linac for ions in the mass range of 1 to 40. Designed as part of a preinjector package for synchrotron applications, it is a low duty factor device, operating at 200 MHz with maximum surface fields as high as 28 MV/meter. It is a loop-driven, four vane structure employing several innovative design concepts. These include an exit matcher section, to ensure efficient capture by a following Alvarez linac; advanced mechanical design features, to ensure accurate positioning of the vane pole-tips; and vane coupling rings, to ensure field stabilization and balance. This RFQ has been used on a test bench to accelerate a variety of ions as heavy as silicon, with charge to mass ratios as low as 1/7. Results of the initial operation show that the structure meets all of the design performance criteria, and that it holds promise for a long lifetime of simple and reliable service. This RFQ linac will soon be incorporated into the Bevatron operations program as part of the 200 MHz injector upgrade. A further application of this same RFQ design is in the dedicated Heavy Ion Medical Accelerator presently under study at LBL. Details of the design, construction and testing of the RFQ linac are given.

Introduction

The RFQ described here was designed, built and tested as part of an upgrade of the Bevatron 200 MHz (local) injector¹. This effort addresses the need at the Bevatron for a source of ions in the mass range of 4 to 40 which is independent of its other injector, the SuperHILAC, where the primary demand is for the heavier mass ions up through uranium. Ions below mass 40 are needed primarily for biomedical research which includes a program of human cancer radiotherapy with heavy ions. This RFQ also serves as a prototype design for the preinjector of a dedicated hospital-based medical accelerator now under design at LBL². A further application of the RFQ technology developed here is a second production unit, the LBL contribution to a collaborative project to inject light ions into the CERN PS complex³.

The general requirements were for a compact design with simple, reliable operation in the charge to mass range of 0.5 to 0.14. Certain constraints were placed on the project by the need to match into a following Alvarez linac which operates at 200 MHz and a duty factor of 0.001.

The technical approach adopted was to use a four vane, loop-driven structure. Like other heavy ion RFQ designs, the Bevatron RFQ is characterized by a small aperture with tight tolerance requirements on the placement of the pole tips, and it was recognized early that the mechanical design and the tuning of the structure were areas that needed to be addressed very carefully. Many of the features ultimately incorporated into final design were developed with the aid of a modest R and D effort that included the construction of a scale model.

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Design Features

Table 1: Summary of Bevatron RFQ Parameters

Design ion	28Si ⁴⁺
Frequency	200 MHz
Input energy	8.4 keV/amu
Output energy	200 keV/amu
Normalized acceptance	0.5 π mm mrad
Theor. transmission	86%
B (Focusing)	2.7
Vane length	2.24 m
Average bore radius (r ₀)	2.54 mm
Maximum surface field	27 MV/m
Peak RF power	150 kW
Duty factor	0.002
Stored energy	0.6 J

The parameters of the Bevatron RFQ are summarized in Table 1. Because of the extremely high capacitive loading associated with the pole tip geometry, it appeared that each of the vane tips would have to be placed and maintained within a 0.005 mm tolerance over their entire length if acceptable field distributions were to be achieved without the development and use of special tuners. The strategy developed to overcome this difficulty was first, to develop a design which allowed for the best achievable and dimensionally stable mechanical alignment⁴; and second, to provide azimuthal field stabilization by periodically shorting together diametrically opposed vanes near the tip⁵. The resulting configuration is shown schematically in Figure 1.

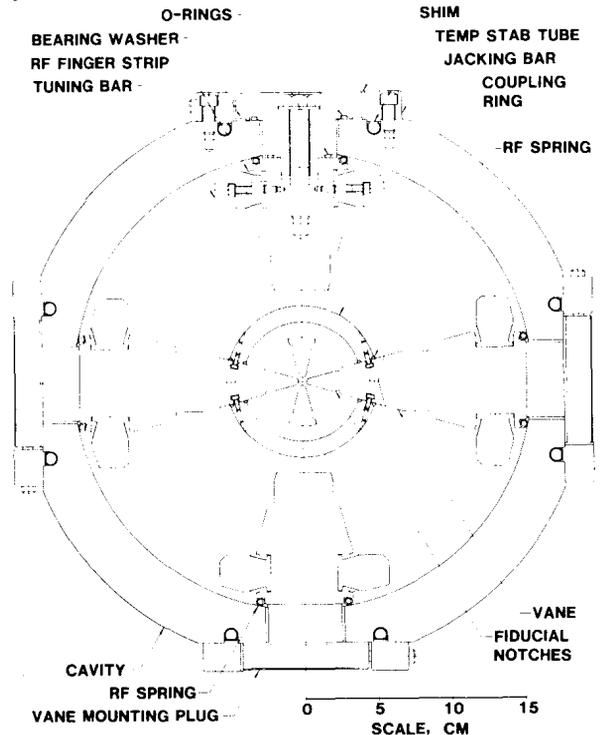


Fig. 1: Typical Section of Bevatron RFQ

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The primary reference surfaces for the structure are the flats which are accurately ground onto four sides of a cylindrical, thick-walled, copper-plated steel cavity. Each vane is mounted by means of six equally-spaced cylindrical plugs which mate to both the precision flat on the cavity and to holes bored into the base of the vane. Adjusting the distance between these two mating surfaces on the plug determines the radial position of the pole tip relative to the cavity. Transverse vane placement is determined by the thickness of the shims located between the flats on the vane mounting plug and one of the jacking bars. These bars run down the length of the structure, and are keyed into the cavity. (They also serve to capture the tubes through which temperature stabilized water flows.) During assembly and alignment, the vanes can be readily removed from and reinstalled into the cavity in a reproducible manner. Individual mounting plugs can be removed to permit small local adjustments of the radial and transverse position of the vane without removing the entire vane.

The vane geometry itself incorporates many features which facilitate verification of the alignment, simplify machining procedures, and ensure dimensional stability⁶. They are made of mild steel, copper plated to a thickness of 50 microns using an acid process everywhere except in the area of the vane tips. There, the 5 micron copper strike, which underlies the acid copper plate, is the only finish given to the surface. A numerically-controlled mill with a 2.44 m bed was used to produce the modulated surface on the tips of the vanes. During the same set up, the fiducial notches shown in Figure 1 were machined, providing an accurate surface from which to reference the location of the complex pole tip surface. Near the base of each vane is attached a pair of bars used for coarse frequency adjustment. They can be readily removed and reinstalled without disturbing the alignment of the vanes. A canted helical spring is used for the main RF joint between the vanes and the cavity. They were made from precipitation-hardened, beryllium-copper which was silver plated.

The vane coupling rings (VCR's), used to provide azimuthal field stability, are also seen in Figure 1. They form a low impedance connection between diametrically opposite vanes, providing a strong coupling between the quadrants, and tend to equalize the quadrant field amplitudes locally. Because the connections are between vanes nominally at equal potentials in the TE(210) mode, the field distributions and resonant frequency are not greatly perturbed. For the dipole modes, however, the rings introduce a short circuit between vanes that would normally have opposite polarities. Axial field distributions and the resonant frequency are in this case both significantly changed. The resulting stabilization of the TE(210) field amplitudes substantially eases the mechanical tolerances associated with positioning the vane tips, and greatly simplifies the tuning procedures. There are three pairs of VCR's used on the Bevatron RFQ - one set at each end, and one set at the center.

Because of the field stabilization provided by the VCR's, a single dynamic tuner can be used for frequency tracking. This consists of a simple, rotating loop located diametrically opposite the drive loop. It penetrates the cavity wall near the longitudinal center using a ferrofluidic seal. Six monitoring loops per quadrant provide sampling of the H-field near the cavity wall. Each quadrant is pumped through a radial port using commercially available cryopumps.

Assembly

The RFQ was assembled on a test stand which had roller supports permitting the cavity to be easily

rotated about its axis of symmetry. Each vane was first installed at the bottom of the cavity one at a time, and its radial, transverse and longitudinal position were accurately established relative to the cavity. The measurement of transverse position was made from the precision flats on the outside of the cavity, through the mounting holes for the adjacent vanes, to the fiducial surfaces near the tip of the vane. These measurements determined the thickness of the alignment shims, which could be accurately ground to ± 0.002 mm. The radial position was determined at six points along the length by a measurement from the opposite cavity flat through the mounting holes for the opposing vane to a crest of the modulated vane tip. Any necessary local radial adjustments were made by removing the vane mounting plug and altering the distance between its two critical mating surfaces. This adjustment could be made to about ± 0.01 mm. Once the proper positioning of a vane was established, it was removed to permit the installation and alignment of the next vane. A reinstalled vane would assume the original position to within 0.01 mm, which was near the repeatability limit of the measuring apparatus.

As a final check after assembly of all four vanes, a 152 cm long Diatest bore measuring instrument with a special modified probe tip was used to confirm the aperture between opposing vane tips. A 25 cm long Diatest bore instrument was inserted through the monitor ports to confirm the vane spacing between adjacent vanes. After one iteration, the vanes had been placed to within about 0.04 mm of their design coordinates. The total time required for the assembly and alignment of the vanes was about one month.

Tuning

Bead pulling apparatus was built to permit perturbation measurements of both the E-field near the pole tip, and H-field near the cavity wall. Additional H-field information could be obtained from the 6 monitoring ports uniformly spaced along the cavity.

The first field measurements were performed immediately following the mechanical assembly and alignment described above - prior to installation of the VCR's and the frequency adjusting bars, and prior to any attempt at optimizing the end geometry. The TE(210) quadrupole mode was observed at 192.083 MHz, and the nearest dipole modes, the two degenerate TE(110) modes were seen at 189.4 and 189.9 MHz. H-field perturbation measurements near the cavity wall revealed axial field variations of $\pm 40\%$, and $\pm 30\%$ field variations between quadrants. Three pairs of VCR's were then installed (in about 1 hour) and the azimuthal field variation was reduced to $\pm 2.5\%$. The frequency of the TE(210) mode was lowered about 7 MHz, while the TE(110) modes were shifted to higher frequencies by approximately 40 MHz.

The proper end geometry was established by attaching small wedge-shaped pieces to the ends of each vane and empirically adjusting the position of the end wall. For this purpose, special end walls with circumferential spring fingers were built, so their position relative to the ends of the vanes could be easily adjusted.

The bar tuners, located near the base of the vanes, were installed to raise the frequency to approximately 200 MHz. They were tapered in the exit matcher section to compensate the reduced vane to vane capacitance associated with the increasing radius parameter, r_0 .

The drive and tuner loops are located near the center VCR pair, but in diametrically opposite quadrants. The drive loop can be rotated to give drive impedances from near zero to 125 ohms. The tuner consists of a shorted copper loop 67 mm in

diameter which can be rotated by a motor to keep the RFQ tuned at the proper frequency. It has a range of ± 90 kHz. Throughout this tuning range, the field changes observed were less than $\pm 1\%$.

The complete tune-up procedure was completed in one month. This included the manufacture of the end walls, fixed wedge tuners, and the bead pull apparatus. The final azimuthal field variation was $\pm 2.5\%$ and the final axial variations were within $\pm 6\%$. A modified PARMTEQ code was used to confirm that there were no transmission losses associated with the measured axial field distribution.

Test Results

The RFQ was delivered to the Bevatron on April 28, 1982, for installation at the test site. After installation and alignment, the four cryopumps were mounted on the cavity. Within 1 1/2 days of delivery, the unit was under vacuum. High power RF tests began and within 8 1/2 hours, 75% of full gradient had been achieved. No changes were observed in the field amplitudes as determined by the monitoring loops. Operation at full gradient required another day of conditioning. Once at full gradient, the conditioning could be maintained overnight; some reconditioning was required after a quiescent period of a few days. Maximum field was held at the required repetition rate of 2 Hz and duty factor of 0.002 with a few sparks per minute. (Subsequent inspection inside the cavity revealed that all of the sparking was occurring near the pole tips, at the location of highest surface fields.) The Q-value, measured after some RF cycling, was 5950, and the base vacuum was $3-4 \times 10^{-7}$ Torr. During full warm-up of the RFQ, the resonant frequency of the cavity was observed to decrease by ~ 70 kHz, in good agreement with estimates of power dissipation.

Analyzed beams of several ions from helium to silicon were introduced to the RFQ in the test setup which made use of the existing Bevatron PIG source, and an existing magnet to analyze the output beam. Measurements were made of transmission, output energy and momentum spread, emittance growth, and the effect of varying the injection energy. Performance in all of these areas was in good agreement with expectation⁷. The tests indicated that the RFQ holds promise for a long period of reliable, trouble-free operation. The total time from the beginning of construction to the conclusion of the testing period was approximately 1 year.

Project Status

After a brief testing period, it was necessary to dismantle the RFQ test bench to allow for the removal of the Cockcroft Walton and the modifications to the Alvarez linac to proceed. The new PIG source installation on a 60 kV platform has been completed and is operational. The remaining work on the project is scheduled for completion later this year, at which time the RFQ will be reinstalled for online service in support of the Bevatron user program.

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