A Compact Proton RFQ Injector for the Bevalac†

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Abstract

A compact 800 keV 410 MHz RFQ using new construction techniques has been fabricated at LBL. It comprises four integrated vane-cavity sections, with end caps and vane coupling rings. The RFQ will inject protons into the present heavy-ion linac by drifting the protons through a heavy ion RFQ into the two $2\beta\lambda$ Alvarez tanks which will be operated in the $\beta\lambda$ mode, producing 20 MeV protons. Along with a new third ion source, the Bevatron injector systems will comprise two RFQ's and two Alvarez tanks, offering rapid particle selection from 20 MeV protons to 5 MeV/n argon. The mechanical characteristics of the RFQ and the drift-through process in the second RFQ will be emphasized.

Background

The LBL Bevatron complex, used since 1971 to accelerate heavy ions, has two injector systems, the SuperHILAC and the Local Injector (LI). The SuperHILAC is used to inject ions to mass 238. The LI, used to provide 5 MeV/n ions up to mass 40, consists of a $q/A \geq 1/7$ RFQ followed by two $2\beta\lambda$ Alvarez tanks, all operating at 200 MHz[1]. A duoplasmatron provides He^{1+} ions and a sputter PIG provides both gas and metallic ions through Ar^{6+}.

Unlike the original configuration of the LI, this arrangement is unable to provide 20 MeV protons for injection into the Bevatron. Because of uncorrectable closed orbit error at low fields, 5 MeV protons cannot be accepted. The Alvarez tanks can be run in the $\beta\lambda$ mode, but then must be injected with 800 keV protons, which the present heavy ion RFQ cannot provide. Additionally, the heavy ion RFQ is located immediately upstream of the first Alvarez tank to simplify matching into the DTL with no space for an inflection magnet to introduce an 800 keV proton beam.

New RFQ Injector

The problem of providing 20 MeV protons to the Bevatron can be solved by providing a source of 800 keV protons with a new RFQ and drifting the protons through the present heavy ion RFQ which functions as a transport channel. The proposed configuration is shown in Figure 1. It has been experimentally established that a 400 keV proton beam with β = 0.029 is efficiently transported through the heavy ion RFQ[1], which has a synchronous velocity range from input to output of $\beta = 0.0043$ to $\beta = 0.021$. The proton beam is not synchronous with the accelerating wave in the heavy ion RFQ, which provides only transverse focusing throughout its length. The transverse matching of the proton beam into the DTL will be the same as is presently used for heavy ions, with a slight decrease in the r.f. defocusing strength. The energy spread of the proton beam is slightly increased, and will be discussed quantitatively below.

Proton RFQ Characteristics

LBL has produced three 200 MHz RFQ's operating at LBL[1], CERN[2] and BNL[3]. The new 800 keV proton RFQ, shown in Figure 2, is a departure from the previous 200 MHz technology; it is a lightweight, compact copper plated aluminum structure which operates at 410 MHz. This structure incorporates new concepts in mechanical design, vacuum practice and assembly techniques. The beam dynamics design is derived from the proton RFQ made for BNL[3] and from the BEAR[4] design and makes use of a relatively long shaper section and a shorter gentle buncher. This configuration results in a shorter structure with a smaller longitudinal output emittance but with the characteristic that the output energy spread tends to increase with decreasing input current. The RFQ parameters are tabulated below.

Ion	proton	
Frequency	410	MHz
Input Energy	40	keV
Output Energy	800	keV
Vane Length	101.7	cm
Vane Voltage	72	kV
Measured Q	6300	
Cavity Power	135	kW
Choke Current	108	mA
Foc Parameter B	4.77	
Surface field	1.9	Kilpatrick
r_0	0.303	cm
Final ϕ_s	-32°	
Acceptance	0.05π	cm-mrad, normalized
No. of cells	160	
No. of RM cells	8	

The shaper section is 31 cm long, accelerating the beam from 40 to 80.7 keV with a final ϕ_s of -60°. The gentle buncher is 17.5 cm long, accelerating to 195 keV with a final ϕ_s of -40° with a constant Δ_{gap} of -0.12. The accelerator section is 50.9 cm long, with ϕ_s tapering to -32°.

A constant $\rho_\perp = 0.75 r_0 = 0.227$ cm design is used with a minimum value of $\rho_{||min} = 0.48$cm. This small $\rho_{||min}$ requires a tight cutter design, described below.

Parmteq simulations show a 91% transmission of a 30 mA input beam with a 38% transverse emittance increase and a longitudinal emittance of ± 16 keV $\times \pm$ 29° at the 90% contour.

This structure was originally to be a mechanical and vacuum test model, and the 1 meter length was arbitrarily chosen. Later when this use was discovered for this structure, the specific beam dynamics design was constrained by the 1 meter length. A satisfactory solution was found.

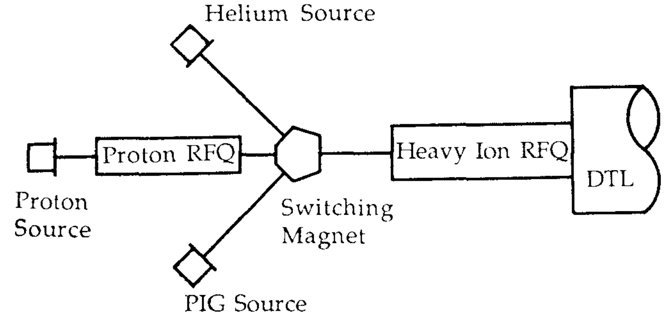

Figure 1
Injector configuration with existing PIG heavy ion source and duoplasmatron helium source, and new duoplasmatron proton source and 410 MHz RFQ.

Mechanical Design

The mechanical design of this RFQ departs significantly from the previous RFQ's designed and built at LBL. The goal was to produce an economical, lightweight and compact structure that is easily assembled without precision tooling or highly skilled person-

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nel. The techniques developed are applicable to large scale production of RFQ structures. Patent proceedings are presently underway regarding the mechanical design.

The structure consists of even and odd vane pieces, as shown in Figure 2, which bolt together to form a strong and integral assembly. The mating surfaces serve as fiducials for the machining of the vane tips, so no adjustments are necessary at assembly. Measurements verifying the intervane spacings after assembly indicate that the ±0.5 mil (0.0005 inch = 13 microns) accuracy is readily achieved. The average machining error of the vane tip before plating was 0.3, 0.2, 0.5 and 0.2 mils from specification for each of the four vanes.

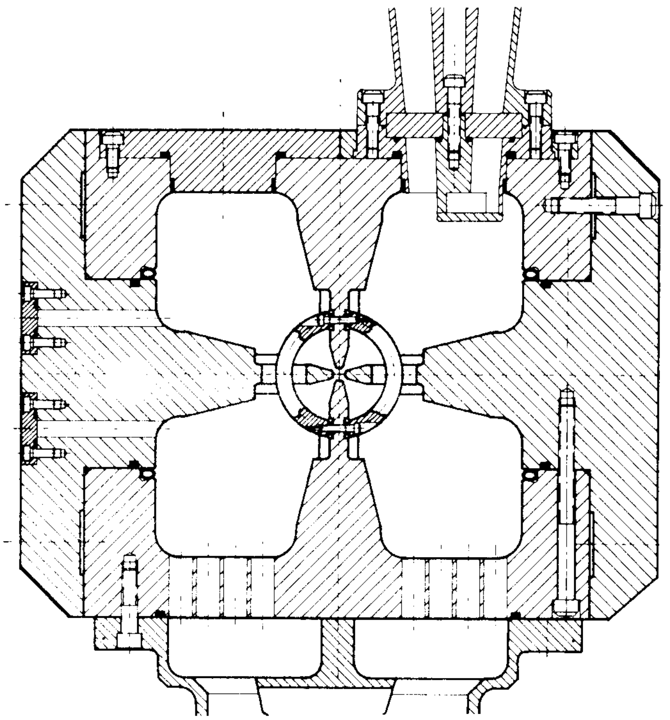

Figure 2
Cross section of RFQ showing both drive loop (top) and pump port (bottom), actually existing at differing longitudinal locations. The outside cavity dimensions are 9.8 by 7.5 inches.

As the precise frequency of the structure is not important in this case, no provision for tuning is included; however, tuning is readily added. In addition, as the duty factor is less than 0.2% and the thermal resistance from the vanes to the outside of the structure is very low, only ambient cooling is used. Cooling channels, if needed for other applications, are bolted onto the outside of the structure. The r.f. surface current crosses only four joints, rather than up to 24 as in previous designs.

A single tool steel cutter was used to machine all four vane tips. The cutter consists of a single plate with the proper shape, rotated along its axis as shown in Figure 3. As $\rho_{||min}$ = 0.48 cm the distance from the axis of rotation to the cutter is 0.158 inches = 0.40 cm.

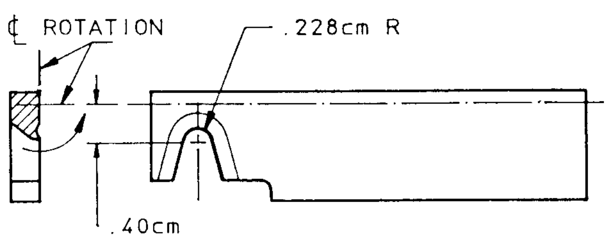

Figure 3
Tool used to cut the vane tip modulation. The small value of $\rho_{||min}$ of 0.48 cm requires the axis of rotation to be near the upper edge of the cutting surface.

The cavity sections were copper plated in the LBL shop. Three treatments were applied to the sections: cyanide and acid copper on the r.f. surfaces, and black anodizing on the exterior surfaces for hardness. No treatment was given to the fiducial (mating) and vacuum sealing surfaces. Three different masking operations were required, one each for the cyanide and the acid copper plating, and one for the anodizing. Several auxiliary electrodes surrounded the structure during the plating process to insure even thickness.

The copper plate consists of 0.3 mil thick cyanide strike on all r.f. surfaces, followed by 2 mil acid copper away from the vane tips. The aluminum surface is first prepared by a caustic etch followed by a hydrofluoric acid etch and a zincate surface preparation. The thickness of copper plate over aluminum cannot be measured by standard magnetic thickness gauges. The thickness away from the vane tips is not critical, and the thin cyanide strike on the tips is well controlled during the plating process.

R.F. Characteristics

Two pairs of vane coupling rings, each near the end of the vane, and one drive loop in the physical center of the cavity are used. The measured Q is 6300, 65% of the pure copper Q. With 30 mA of beam loading, 160 kW of r.f. power is required. The measured quadrant unbalance is <2% at the rings, and about 10% in the center where the drive loop is located. The quadrupole field component varies no more than ±4% along the structure. The only electrical adjustment required after assembly is the positioning of the end walls. Temporary movable end walls were fitted during bead perturbation tests. The final end walls are then machined of 6061-T6 aluminum which is copper plated.

The high power tests were carried out by AccSys Technologies, Inc., under contract to LBL. The structure conditioned to over the 1.9 kilpatrick design gradient in 5 hours, producing X-ray emission which was stopped by an eighth inch lead shield. The r.f. amplifier uses multiple planar triodes and was designed and built by AccSys for the Boeing Aerospace cryogenic RFQ accelerator development program.

Vacuum

Each quadrant of the RFQ is provided with a vacuum port of hexagonally packed 0.375 inch diameter holes with a center spacing of 0.435 inches in wall material 0.9 inches thick. Only one pump is fitted, directly evacuating two adjacent quadrants and pumping the two opposing quadrants through the gap and end regions. The opposing pump port is blanked off, and all four quadrants contain the same inductive perturbation at the port. An 8 inch cryopump is used for the initial test. After r.f. conditioning the base pressure is less than 10^{-7} Torr with the r.f. off.

The O-ring has a cubical topology which extends around the ends of the structure with segments connecting the ends extending along the mating surfaces of the vanes, as shown in Figure 4. The longitudinal segments join the end segments in "T" sections with glued joints. The assembly of the structure with the O-ring in place is straightforward and no failures have occurred over many assemblies. Using an integral O-ring, rather than enclosing the RFQ in a tank, results in a small, light and accessible structure. The outside surfaces of the RFQ provide a direct reference to the beam axis.

Integration into Local Injector System

The RFQ will be located upstream of the switching magnet in the LEBT for the present heavy ion RFQ, sharing the LEBT with two other ion sources, as shown in Figure 1. The proton beam from a duoplasmatron source will be accelerated to 800 keV by the 410 MHz RFQ and then will be drifted through the heavy ion RFQ into the DTL tank operated in the $\beta\lambda$ mode.

During the commissioning of the heavy ion RFQ in 1983, a 400 keV proton beam was drifted through with vane voltages of 4, 12.9 and 38.1 kV, corresponding to focusing parameter B values of 1.5, 4.8 and 14.1[5]. The output energy spectrum is a bimodal distribution with peaks separated by about 17 keV for $B = 14.1$. Beam transmission was typically 50% with no great effort at optimizing the input match.

To model the drift through beam dynamics a simple simulation program was written which integrates an ensemble of particles of arbitrary input energy along the axial field of the RFQ. (Parmteq cannot be used as the equations of motion assume near synchronous energy in each cell.) Transverse motion is ignored which is acceptable as the gap defocusing term averages to zero.

Simulations with a 400 keV d.c. beam agree fairly well with the distributions measured during commissioning of the heavy ion RFQ. In the case of the 800 keV beam drifting through the heavy ion RFQ with $B = 2.7$, the same value presently used for heavy ions, the output energy spread is ±0.2%, well within the longitudinal acceptance of the DTL.

The proton beam leaving the 410 MHz RFQ will debunch in about 1.5 meters, less than the distance to the entrance to the DTL. Any 410 MHz bunch structure is irrelevant anyway, as it is not synchronous with the second harmonic of the 200 MHz DTL. The ±0.2% energy spread introduced by the heavy ion RFQ will not cause appreciable rebunching of the beam at the DTL frequency, so the DTL acceptance is expected to be about 25%, with the overall acceptance about 10% from the ion source. This is completely adequate for our application.

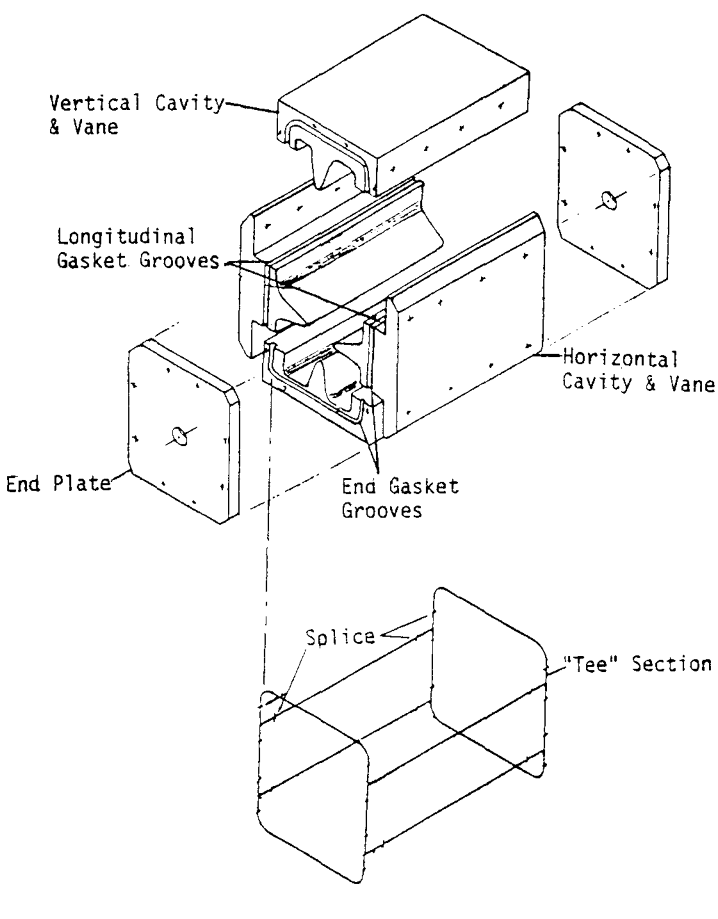

Figure 4
Exploded view of the the RFQ showing the even and odd vane pieces, the end caps and the O-ring configuration.

Costs

The cost of producing this RFQ in aluminum are less than half the cost of a steel 4-vane RFQ using individual vanes in a cylindrical cavity. These savings are due to the simplicity and reduced number of parts, the reduced machining time, and the substantially reduced time required for assembly and alignment. Because of the self-aligning features of the basic mechanical design, the alignment tolerances are attained on the first assembly with no shimming required, and the time and effort required for this assembly is reduced by over a factor of 4. The total time required to produce an RFQ with this design is about one-half that required for a steel 4-vane structures. Furthermore, the fabrication techniques are particularly advantageous for multiple units or for large-scale production.

Acknowledgements

Al Harcourt and Peter Sanchez did the outstanding plating job on the cavity.

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