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SUBMITTED TO To be published in the proceedings of the 9th Int. Conf. on Cyclotrons and Their Applications, Caen, France, September 7-10, 1981

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USE OF THE RADIO-FREQUENCY QUADRUPOLE STRUCTURE AS A CYCLOTRON AXIAL BUNCHER SYSTEM*

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Abstract.- The radio-frequency quadrupole (RFQ) is a new linear accelerating structure being developed as a low-velocity linac. In this structure rf electric fields are used to simultaneously focus, bunch, and accelerate ions. The slow introduction of the accelerating field results in the adiabatic bunching of a dc ion beam with a large capture efficiency. Realistic computer simulations have shown that this new structure could also be used as a buncher in the axial injection system of a cyclotron. A description of the RFQ geometry and its general properties is given. A preliminary design is presented for a variable frequency RFQ to be used as a buncher in the axial injection system of a variable energy cyclotron. The operating parameters for this RFQ are discussed.

1. **Introduction.**- Axial injection systems are presently used on many cyclotrons because the space limitation for internal ion sources prohibits the use of large sources such as those for polarized ions. With external ion sources the vacuum in the cyclotron is better because there is no gas load from the ion source, and the ion sources have easy access during operation and maintenance because they can be placed outside the cyclotron vault. However, the use of external ion sources and axial injection has disadvantages: the ions must be transported at low energy for long distances and must be inflected into the cyclotron correctly for acceleration. Also, an rf bunching system must be used to enhance capture of the injected dc beam into the phase acceptance of the cyclotron accelerating system.

In addition to the buncher, the transport system for an axial injection beamline usually contains several electrostatic or magnetic lenses and steering elements. The transported ion beam is bent into the median plane of the cyclotron by a gridded electrostatic mirror or an electrostatic channel. The main objective of these elements is to provide a good match from the ion source into the cyclotron. The matching constraints are that the beam optics should provide minimum divergence of the beam at the inflector with maximum transmission, the beam energy and inflection should provide a centered first orbit, and the beam should be bunched into the phase acceptance of the cyclotron.

The optics of an axial injection system can be designed to provide the necessary transport matching. The orbit-matching constraint can be satisfied by scaling the ion injection energy with the cyclotron output energy (which is proportional to the frequency squared). Such scaling of the injection energy and matching into the cyclotron has been reported for the variable energy cyclotron at Lawrence Berkeley Labo-

ratory.¹⁾ This scaling of the energy is limited in practice by the variability of the ion extraction energy and by the maximum inflector and accelerating voltage, because the inflector voltage must be $\sqrt{2}$ times the injection energy to inflect the ions into the median plane and the dee voltage must be ~ 5 times the injection energy for a centered first orbit.

Most axial injection systems presently employ a sine-wave rf buncher to provide the bunching of the dc beam extracted from the ion source. This type of buncher usually increases the beam accepted into the cyclotron by a factor of 3 to 5 over an unbunched beam.²⁾ But this bunching process can introduce a large energy spread in the bunched beam and requires a large drift space.

Described in this paper is an alternate axial injection buncher that employs the radio-frequency quadrupole (RFQ) accelerating structure, a structure presently being developed at the Los Alamos National Laboratory and at other laboratories as a high-transmission, low-velocity linear accelerator. In this structure rf electric fields simultaneously focus, bunch, and accelerate an ion beam. Hence, the RFQ can replace the buncher and some of the optics elements in the axial injection system of a cyclotron. When operated in the axial injection system of a variable frequency cyclotron, the RFQ ion output energy scales with the frequency so that the injected ions have a constant first-orbit radius. A description and the general properties of the RFQ will be presented along with a discussion of this application of the structure. Finally, the parameters for a preliminary design of an RFQ for the axial injection system of the variable energy cyclotron at Texas A&M University are presented, as an example, along with the calculated performance.

2. **Description of the RFQ.**- In the RFQ, the electric fields are generated by four poles arranged symmetrically around the beam axis, as seen in Fig. 1. In this structure, first proposed by Kapchinskii and

*Work supported by the US Department of Energy.

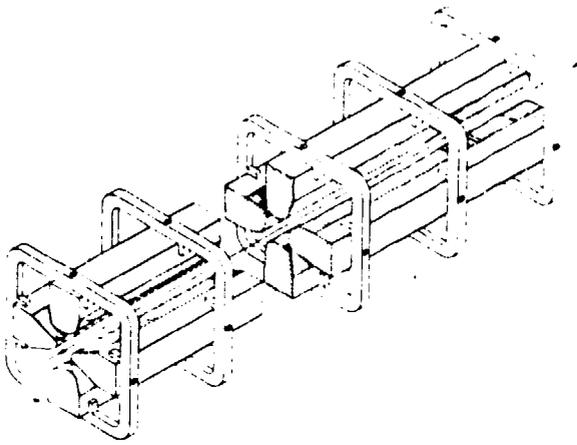


Fig. 1: Drawing of the four pole RFQ.

Teplyakov,³⁾ these poles are excited with rf power so that, at any given time, adjacent poles have equal voltages of opposite sign. If the pole tips are at a constant radius from the beam axis (designated the Z-axis) then only a transverse electric field (mostly quadrupole) is present. This electric field is focusing in each plane during one-half of the rf period and defocusing during the other half, giving this structure the properties of an alternating-gradient focusing system with a strength independent of the particle velocity. To generate a longitudinal accelerating field, the pole-tip radii are periodically varied, as seen in Fig. 1, with the pole tips in one plane at a minimum radius when the pole tips in the orthogonal plane are at a maximum radius. Figure 2 is a cut through one plane of the poles and shows the mirror symmetry of the opposite poles. The radius parameter a , the radius modulation parameter m , and the unit cell $\beta\lambda/2$ (where $\beta = v/c$ and λ is the wavelength of the rf excitation) are defined. The longitudinal electric field is generated within this cell between the pole-tip minima in the two orthogonal

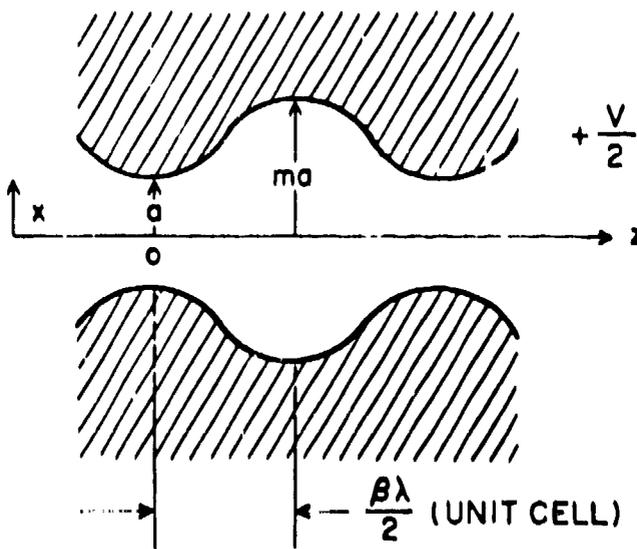


Fig. 2: RFQ pole-tip geometry.

planes, so the unit cell corresponds to an acceleration gap. At any given time, adjacent unit cells have oppositely directed axial fields; therefore, only every other cell contains a particle bunch. It is the gradual introduction of this axial electric field that allows adiabatic bunching of the dc ion beam with a very high capture efficiency.

3. Beam-Dynamics Design Procedures for RFQ Systems.- The method for generating an RFQ system to meet specific objectives has been described previously.⁴⁾ The electric field distribution for the RFQ is obtained from the lowest order potential function.³⁾ These electric fields are used to construct transformations for the beam-dynamics simulation program PARMTEQ.⁴⁾ This program, which includes space-charge effects, analyzes specific RFQ designs to obtain the transmission efficiency, radial emittance growth, and radial and longitudinal characteristics of the output beam.

The shape of the hyperbola-like pole tips is obtained from the potential function as an equipotential surface in the electrostatic solution for the structure. This isopotential surface gives the radial variation of the pole tips and the variation of the radius of curvature in the transverse plane both as a function of Z . The pole tips are then constructed by generating a data file on paper tape that is used as input to a computer-controlled vertical milling machine.

An essential step in the development of the RFQ was the design, construction, and testing of a full-scale experimental accelerator. A test of a 425-MHz RFQ for accelerating protons from 100 keV to 640 keV was completed in 1980 at Los Alamos; the experimental results have been described and compared⁵⁾ with the earlier beam-dynamics design and calculated performance.⁴⁾ The success of this test has led to a variety of RFQ applications in Los Alamos⁶⁾ and in other Laboratories.^{7,8)}

4. Application of the RFQ as an Axial Injector System.- The RFQ can simultaneously accelerate, focus, and bunch an ion beam with a very high transmission efficiency; therefore, such a structure can possibly replace most of a conventional axial injector beamline for a cyclotron. Also, because the $\beta\lambda$ profile within the RFQ is fixed for a given design, the output energy of the RFQ is proportional to the resonant frequency squared. In addition, because the focusing force is also constant for a given design, the scaling laws for operating a fixed RFQ structure with different frequencies and ion species are given by:

$$\frac{q}{m} \frac{V}{f^2} = k_1, \quad \text{and} \quad \frac{W_f}{mf^2} = k_2, \quad (1)$$

where W_f is the final energy from the RFQ, f is the frequency, q and m are the charge and mass of the accelerated ions, V is the intervane voltage, and k_1 and k_2 are fixed by the design. However, due to the adiabatic nature of the phase bunching used in the RFQ, a large energy gain is required for high capture and good bunching. Because of the upper limit to the injection energy in a cyclotron created

by inflection and first-orbit constraints, very low, variable energy injection into the RFQ is required. The difficulty this creates in terms of the ion source extraction-voltage requirements can be overcome by the use of an accel-decel extraction system.

To better convey the advantages of such an axial injection RFQ, a preliminary design was calculated for use with the axial injection system of the Texas A&M variable energy cyclotron polarized-ion facility.⁹⁾ This facility presently consists of a commercially available atomic-beam polarized-ion source for D^+ and H^+ ions and an optically pumped source for polarized He^3 ions. The present axial injection system uses electrostatic quadrupole triplets and steerers for transporting the ion beam and a gridded-gap sine-wave buncher for bunching the ion beam. The beam is inflected into the cyclotron median plane with an electrostatic mirror, and a movable puller electrode is used in connection with the dee voltage for centering the first orbit. The transport distance from the ion source to the injector is $>5m$.

The RFQ parameters calculated for this application are given in Table I. The performance of this RFQ was optimized for injecting 100 μA of D^+ ions into the cyclotron at 11 MHz. A length was chosen that would occupy most of the distance between the

Table I

Parameters of the Axial Injection RFQ Example

Ions	H^+ , D^+ , and He^3
Frequencies (MHz)	5.5 - 16.0
Output Energies (keV/amu)	2.7 - 22.7
Intervane Voltage (kV)	1.9 - 7.0
Final Radius, a_f (cm)	0.75
Average Radius, r_0 (cm)	1.5
Vane Length (m)	3.32
No. of Cells	163
Final Synchronous angle, θ_s (deg)	-18
Energy Gain, W_f/W_i	25

ion sources and the cyclotron median plane, and the transmission efficiency within a 30° phase width was optimized while keeping the energy spread to a minimum. The scaling constants for the final design were chosen so that the structure would yield a 30-keV D^+ ion beam at 13 MHz, because of the dee and inflector voltage limitations in this system. The energy gain chosen for this design was 25; therefore, the input energy is 4% of the output energy. The axial pole-tip profile for this RFQ in one plane is shown in Fig 3. Note that the transverse scale has been expanded relative to the longitudinal scale. This computer-generated plot is labeled to show the functional sections⁴⁾ in this RFQ.

For this design the beam dynamics of 100 μA of D^+ ions accelerated at 11.00 MHz was calculated with PARMTEQ; Fig. 4 shows the beam characteristics

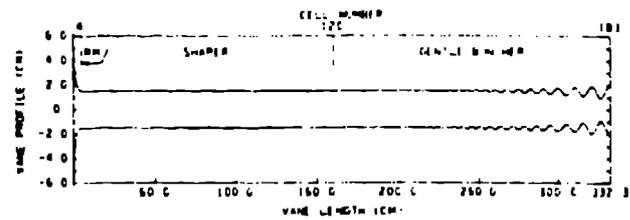


Fig. 3: Axial injection RFQ pole-tip shape.

plotted versus cell number. At the top of the figure, the radial position in the x-z plane of 360 particles is plotted at the point in each cell where the beam is circular. The upper and lower dotted lines give the bore dimensions. The middle plot shows the bunching of 360 particles, initially distributed uniformly in phase (unbunched), with the phase of each particle relative to the synchronous phase being plotted. In the lower plot, the energy of each particle is plotted relative to the energy of the synchronous particle. In the phase and energy plots,

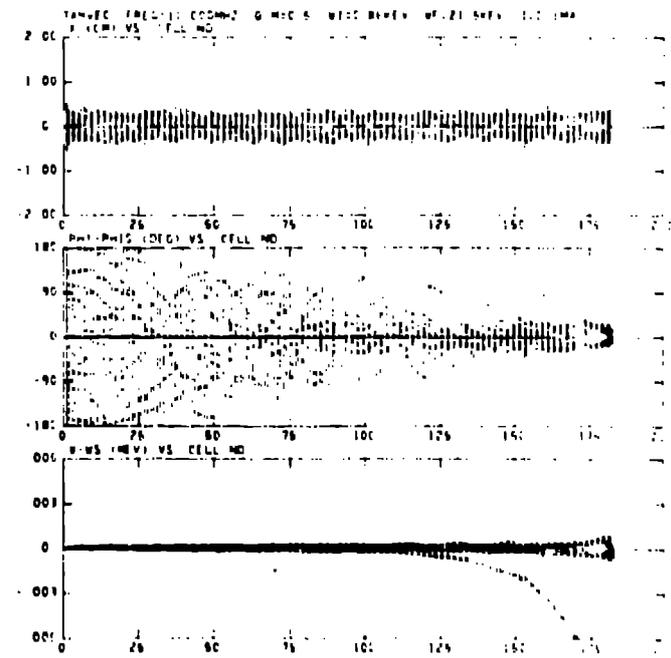


Fig. 4: Axial injection RFQ beam dynamics.

the dotted lines give the location of the zero space-charge separatrix. At this optimized frequency, this design has a total beam transmission of 90%. As seen in Fig. 5, where the final beam properties are given, the FWHM energy spread of the 21.5-keV deuteron beam is 0.5 keV, which gives $\Delta w/w = 0.023$. The FWHM phase spread of this beam is only 20° , and 86% of the input beam is within $\pm 15^\circ$ of the synchronous phase.

The scaling parameters for operating this RFQ axial injection system are given in Fig. 6, and the performance parameters calculated with PARMTEQ at several operating points along this curve are given in Table II for input currents of 10 and 100 μA . The transmission of the input beam into a 30° phase width at the output energy is listed as $T(\pm 15^\circ)$. Calculations

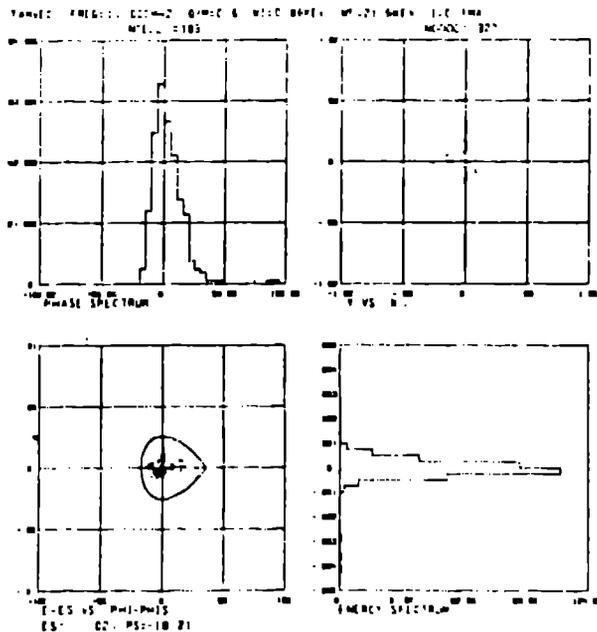


Fig. 5: Calculated output beam properties of the axial injection RFQ example for 100 μ A of D^+ ions at 11.00 MHz.

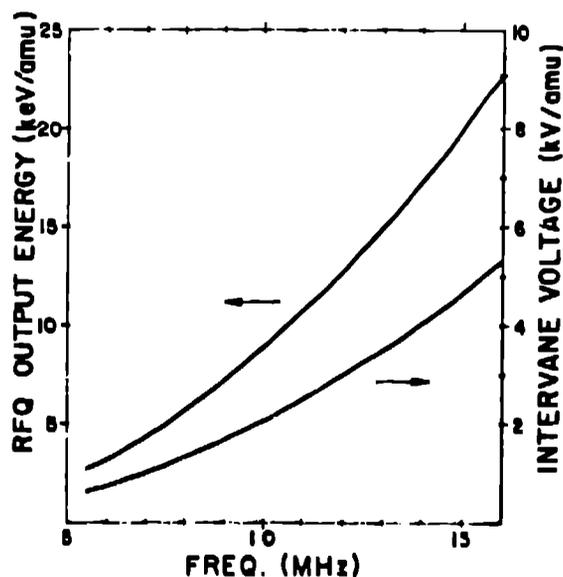


Fig. 6: Scaling parameters for the axial injection RFQ example (D^+ acceleration is only up to 13 MHz and He_3^+ acceleration is only up to 8 MHz.)

lations with 10 μ A of input current always gave more than 5% total transmission with a phase width of $<30^\circ$ FWHM. However, as seen in Fig. 7, the total transmission at higher currents is reduced at a given frequency as one approaches the current limit of the structure. Also, the transmission at a given current decreases as the frequency is lowered because the current limit decreases.

Table 1:

Calculated Performance of the Axial Injection RFQ Example

Particle	f (MHz)	w_f (keV)	I_{in} (μ A)	γ_{25} (%)	$\sigma_{1\mu m}^{(D^+)}$	$\frac{\sigma}{L}$ (1/m)
H^+	10.6145	10.00	10	88.1	25	0.010
H^+	13.0000	15.00	10	89.7	20	0.017
H^+	15.9177	22.50	10	89.7	25	0.025
H^+	10.6145	10.00	100	56.9	30	0.025
H^+	13.0000	15.00	100	72.2	20	0.033
H^+	15.9177	22.50	100	84.7	20	0.022
D^+	8.3915	13.50	10	85.3	30	0.040
D^+	10.6144	20.00	10	85.8	20	0.050
D^+	11.0000	21.48	10	85.6	20	0.041
D^+	13.0000	30.00	10	88.1	20	0.033
D^+	8.3915	12.50	100	53.1	25	0.040
D^+	10.6144	20.00	100	74.7	30	0.025
D^+	11.0000	21.48	100	78.1	20	0.023
D^+	13.0000	30.00	100	64.4	20	0.033
He_3^+	6.1264	10.00	10	76.7	25	0.030
He_3^+	7.5033	15.00	10	84.2	25	0.030

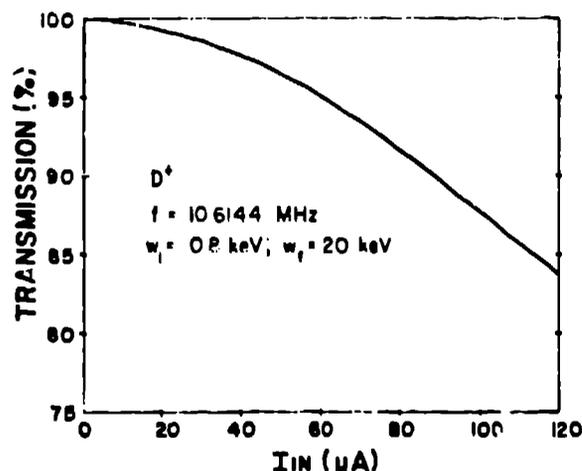


Fig. 7: Calculated transmission for the axial injection RFQ example.

5. Operational Properties.- A diagram of how this RFQ would fit into the Texas A & M Cyclotron Institute's axial injection system is given in Fig. 8. The RFQ electrodes would be mounted inside a vacuum housing in the place of the present buncher and electrostatic optics system. An accel-decel extraction system on the ion sources and an einzel lens in front of the RFQ would allow matching of the beams from the ion sources into the RFQ at the required energies. The RFQ would then bunch, focus, and accelerate the ions through most of the distance from the ion sources to the cyclotron. The bunched beam from the RFQ would then be matched by an electrostatic quadrupole into the cyclotron. The distance from the RFQ exit to the inflector should be minimized because of the debunching of the beam in a drift space. At the 10- μ A current level this debunching is about 0.4 to 0.6 deg/cm for the ions and output energies in this example; but because this debunching combines in quadrature with the final phase spread from the RFQ, the phase width would grow typically from 20° FWHM to about 35° FWHM for a 60-cm drift distance. If a larger drift

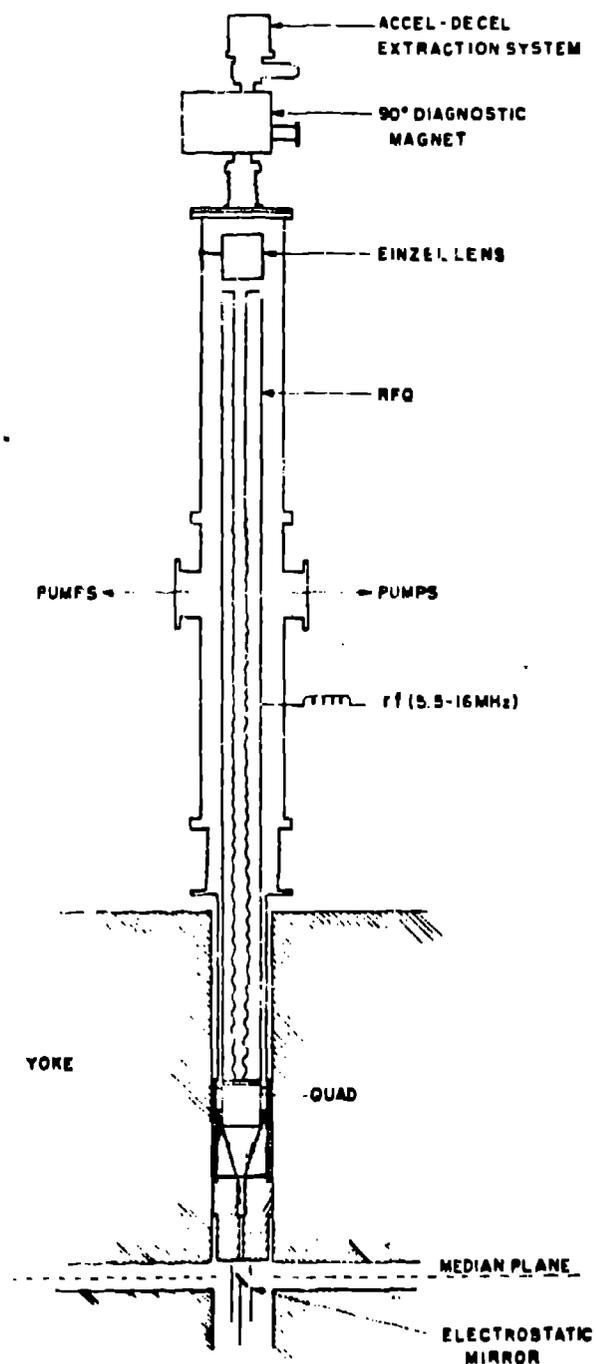


Fig. 8: Schematic drawing of the RFQ in an axial injection system.

distance is necessary, a single-gap sine-wave buncher could maintain the phase width from the RFQ to the inflector. No additional energy spread in the ion beam would be produced because the buncher could operate in a linear region of the voltage wave form.

As indicated in Fig. 8, the RFQ would be driven as a capacitive load at its midpoint from an externally tunable resonant circuit with a triaxial feed-through. The interspace capacitance for this structure would be ~ 100 pF/meter, and because the structure length is much less than the wavelength, the voltage variation along the pole tips would be

minimal. The electrode voltage with respect to ground is < 4 kV and the rf current on the electrodes is not high; therefore, the poles possibly could be constructed of aluminum.

Calculations of a tunable coaxial resonator to drive this structure have shown that < 1 kW of rf power dissipation in the coaxial line would be required to resonate this capacitive load at the design excitation level. For a coaxial resonator with a characteristic impedance of 50Ω , the length would be ~ 2 m, at 13 MHz.* Hence, the rf source to power this RFQ should pose no difficult technical problems and could be constructed easily.

6. Conclusions.— The RFQ structure, because of its ability to focus, bunch, and accelerate a low-velocity dc ion beam, is a possible candidate for use as a variable frequency buncher and accelerator in a cyclotron axial injection system. The RFQ could not only replace the buncher, but most of the beam-optics elements. Because the output energy scales with the operating frequency, the RFQ can be designed for a constant first-orbit radius in the cyclotron, as seen in the design example presented. In addition, the construction of an RFQ for this application appears to be simple and the operation appears practical. The performance of such a device, as given by the design example, should improve the performance of the axial injection system by increasing the beam current into the cyclotron as compared with a conventional axial injection system.

Acknowledgments.— We thank R. C. Rogers of Texas A&M University, D. J. Clark of Lawrence Berkeley Laboratory, and G. H. Hendrie of The Cyclotron Corporation for their advice and discussions on the requirements for axial injection into cyclotrons.

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*The use of a coaxial resonator to drive this RFQ was suggested by R. C. Rogers of Texas A&M University.