RFQ LENS FOR LOW ENERGY ION BEAM FOCUSING*

D. A. Swenson, D. D. Gillings, W. J. Hoffert, S. R. Schmidt
Science Applications International Corporation
4161 Campus Point Court, San Diego, CA 92121

Abstract

A new application for RFQ focusing has been identified, namely that of preparing low energy charged particle beams for injection into RFQ linacs. The relatively large-diameter, short-focal-length requirement of this application has proven difficult to satisfy with conventional, static, electric or magnetic, quadrupole or solenoid, lens elements. The RFQ lens offer some unique capabilities for this application: 1) being electric in nature, the RFQ lens is particularly effective for low energy ion beams, 2) being rf in nature, the RFQ lens can have arbitrarily short periods in the focal structure, which can produce near-symmetrical action on the beam in both transverse planes, and 3) being primarily two-dimensional in nature, the RFQ lens offers less aberrations to the beam than a highly three-dimensional array of quadrupole lenses. The RFQ lens, used as suggested here, may represent an important new element for low energy beam transport systems. The lens exhibits a net focusing in both transverse planes, maintains a near circular beam throughout the lens, has no frequency or phase constraint to subsequent linac structures, has acceptable surface field strengths, and is tunable, simultaneously in both transverse planes, by rf amplitude. A 10-inch-diameter, 3.5-inch-long, 300-MHz RFQ lens unit, complete with a 20-kW, close-coupled, rf power system has been designed, fabricated and tested. Features of the design, fabrication, tuning and excitation will be presented. Results of the preliminary beam tests will be described.

RFQ Lens Background

The success of RFQ linacs presents us with lower energy beams in low energy beam transport (LEBT) systems and the need for more strongly convergent beams at the entrance to linacs. Achieving the required focusing with quadrupole or solenoid lens systems has become a problem. The lower beam energies give added impetus to the use of electric, as opposed to magnetic lenses in these regions.

The RFQ lens is an electric quadrupole lens with the added advantages that no insulators are required to support the resonant electric fields in the structure and the required "alternating gradient" feature is provided by the temporal alternation in the polarity of the fields.

RFQ lenses are inherently simpler than RFQ linacs. They have been around longer than their linac counterpart, finding application in atomic physics, plasma physics, and mass spectroscopy. Prior to this initiative, however, they were thought to be too weak in focusing strength to serve the demanding application of matching low-energy ion beams into modern RFQ linacs.

A key observation, made by one of the authors (DAS), is that there are some configurations of RFQ lenses whose effect on the beam is independent of the phase of the rf excitation at the time that the particle enters the lens. This, in turn, suggests that these configurations do not have to be synchronized with the linac phase or frequency to have a useful focusing effect on the beam. In particular, it suggests that RFQ lenses could be designed to operate at a lower frequency than the linac where their strength would be substantially stronger.

Properties Of RFQ Lenses

The focusing strength for RFQ devices is proportional to $B=E\lambda^2/((m/q)r)$, where E is the surface electric field on the tip of the electrode, λ is the rf wavelength, m/q is the mass-to-charge ratio of the beam particles, and r is the radial aperture of the electrodes. If E is expressed in units of MV/m, λ in meters, m in MeV, q in multiples of the proton charge, and r in meters, the quantity B, which we will call the "B-value" or focusing strength of the RFQ, is unitless. For example, an RFQ lens with E=11.2 MV/m, λ=1.0 m, m=938 MeV, q=1, and r=0.01 m, has a B-value of 1.2.

For a given beam particle and electric surface field limit, the maximum achievable focusing strength of an RFQ lens is proportional to λ^2/r. Hence, for small apertures, small wavelengths (high frequencies) are acceptable; for large apertures, large wavelengths (low frequencies) are required.

The optimization of RFQ linacs for focusing and acceleration of small diameter particle beams essentially precluded the use of RFQ lenses, operating at the linac frequency, on the larger diameter beams in LEBTs, because of inadequate lens strength. The key observation, presented here, is that there are some configurations of RFQ lenses that do not have to be at the linac frequency in order to effect a useful transformation on the beam and, in particular,

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may operate at a lower frequency where their strengths can be substantially higher.

The basic components and performance of an RFQ lens for LEBT applications are shown in Fig. 1. The lens comprises three sections, namely, the input matching section, the center section, and the output matching section. It is the proper configuration of the two matching sections that gives the all-important phase independence of the focusing action. The RFQ field strength in the two matching sections must increase smoothly from zero to full strength, or vise versa, over some minimum distance to allow the beam to adapt to the time-varying rf fields within the lens.

The beam profiles through the basic RFQ lens, as displayed by the TRACE program, are shown in the lower part of Fig. 1. The horizontal profiles are shown above the center line and the vertical profiles are shown below. The four different trajectories, seen in each profile near the center of the lens, correspond to four different phasings of the beam relative to the lens excitation.

Figure 2 shows the transverse phase spaces (the six boxes at the top of the figure) and the beam profiles (the large box at the bottom of the figure) for four beams, separated by 90° in phase, at the beginning (left), middle, and end of an RFQ lens. The phase spaces display the transverse dimensions of the beam versus the angular divergence of the beam. The beams are considered to occupy the elliptical regions in the transverse phase spaces. The A and B values in each box correspond to the α and β twiss parameters respectively for the four beams.

The phase space and profiles of the four beams are chosen to be identical at the input side of the figure. In the middle of the lens, the

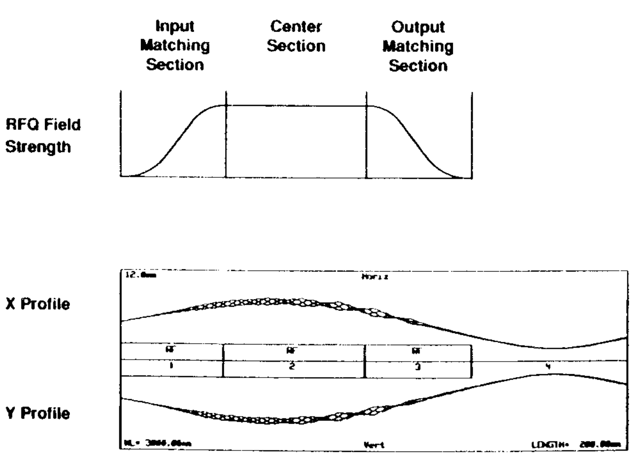

Fig. 1. Basic Components and Performance of an RFQ Lens.

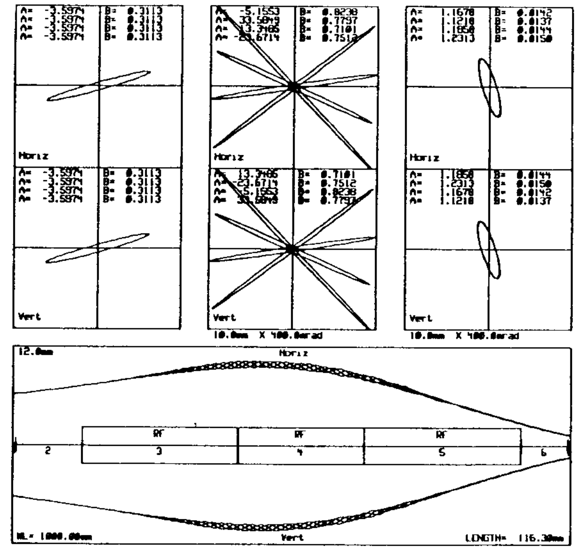

Fig. 2. Phase Space at Beginning, Middle and End of RFQ Lens.

phase spaces occupied by the four beams are dramatically different. The fact that these phase spaces and profiles coalesce at the end of the lens demonstrates that the lens action is independent of phase.

Consider a beam in a LEBT that is ten times the diameter of the beam in a 425-MHz RFQ linac. Because the radial aperture of the lens electrode must be ten times larger than that of the linac in order to accommodate the beam, the achievable RFQ lens strength in the LEBT, at the frequency of the RFQ linac, is down on order of magnitude from that in the linac. Since the focusing strength is proportional to the square of the rf wavelength, the possibility of using a 100-MHz lens, instead of a 425-MHz lens, regains that order of magnitude in strength.

A unique feature of the RFQ lens is its ability to achieve short focal lengths for large diameter beams, utilizing quadrupole focusing, while maintaining nearly circular cross-sections for the beams. This requires focal periodicities that are short relative to the diameter of the beam. This can be shown to be impractical for electrostatic or magnetostatic quadrupole lens systems and practical for the RFQ lens. In the static cases, the field limitations are longitudinal and the field pattern is highly three dimensional. In the rf case, the field limitations are transverse and the field patterns are primarily two dimensional, which may in turn reduce beam aberrations. In these geometries, the transverse field limitations are much higher than the longitudinal limits, leading to higher focusing strengths and shorter focal lengths for the RFQ lens.

A wide variety of match conditions are possible with the RFQ lens. The output of the RFQ lens has azimuthal symmetry as required by the input to RFQ linacs. Consequently, matching a beam to an RFQ linac with an RFQ lens may require only two adjustable parameters compared to the four adjustable parameters required by static quadrupole systems. The two adjustable parameters could be lens excitation and lens position. Another approach would be to have two RFQ lenses in tandem to provide the two adjustable parameters.

The RFQ lens differs from an electrostatic quadrupole lens because of the time-dependent nature of its electric fields. Unlike an electrostatic lens, it can discriminate between different ions species in a particle beam. The RFQ lens is similar to a magnetic lens in that it focuses lighter particles more strongly than heavier particles of the same charge and energy.

The choice of the optimum length and frequency for a specific application of the RFQ lens is complicated by the interplay between two competing phenomenon. The focusing effect of an RFQ lens is a complex function of its length, aperture, excitation, and resonant frequency. Longer lenses require less electric field gradient, which implies lower surface electric fields and less rf power. Larger aperture lenses require the same electric field gradient, which implies higher surface electric fields and more rf power. For systems involving highly divergent or convergent beams, longer lenses, with their lower electric field gradient will allow larger beam excursions, which, in turn, will require larger lens apertures and more rf power. This puts an upper bound on the lens lengths for some lens applications.

The input and output radial matching sections of the lens add to the total length of the lens. In these sections, the electric field gradient must increase smoothly from zero to full strength, or vice versa, to allow the beam to adapt to the time varying nature of the rf fields within the lens. Design experience tells us that these sections should each be about three particle wavelengths in length: shorter sections result in significant beam emittance growth. In some cases, lower frequencies, with their longer matching sections, will allow larger beam excursions, which, in turn, will require larger lens apertures and more rf power. This puts a lower bound on the frequencies for some lens applications.

The RFQ lens, as described here, represents an important element for low-energy beam transport systems. It offers exceptional strength for low-energy ion beams. It exhibits a net focusing in each transverse plane, maintains a near circular beam throughout the lens, may be exceptionally low in aberrations, has no frequency or phase constraint to subsequent linac structures, has acceptable surface field strengths, and is tunable, simultaneously in both transverse planes, by rf amplitude.

Design, Fabrication, and Test

An RFQ lens was designed, fabricated and tested. The goal was to focus a slightly divergent, 20-mA beam of 20-keV protons into a modern RFQ linac. Beam dynamic studies (using TRACE2D) suggested suitable parameters for this system to include a resonant frequency of 300 MHz, a lens length of 10 cm, a radial aperture of 1 cm, and a focusing strength of 1.2.

A decision was made to fabricate this RFQ lens as a very short, large-diameter, four-vane RFQ structure. The initial estimates of the transverse dimensions of the lens cavity and its rf power requirements were based on two-dimensional rf cavity calculations (SUPERFISH). These estimates suggested a cavity diameter of 25 cm, a vane-to-vane voltage of 112 kV, vane-tip electric field of 11.2 MV/m, a maximum surface electric field of 13.9 MV/m, and a peak rf power of 7.1 kW.

The outer part of the lens cavity was constructed as a heavy-walled cylinder, 10 inches in diameter and 3.5 inches long. Four vane assemblies are mounted inside this enclosure, attached to the heavy cylindrical wall by two concentric push/pull screw assemblies. Electrical contact between the vane bases and the cavity walls is based on flexed fins at the edge of the vane bases, which are designed to produce a substantial force against the wall. The vacuum requirement for the RFQ lens is simplified by surrounding the entire lens assembly with a vacuum housing that bolts directly to an RFQ linac.

The rf power is supplied by a close-coupler rf power system base on an Eimac Planar Triode, Y-690, which provides a peak rf power pulse of 26 kW at a 1% duty factor.

In the preliminary test of this RFQ lens system, no focusing action was observed. During the test, it was determined that we were low in lens strength, by a factor of 4, due to an abnormally low cavity Q value and insufficient rf power. Neither of these limitations are fundamental and further tests are planned. The RFQ lens concept still seems sound and its realization still seem practical.