APPLICATION OF ELECTROSTATIC LEBT TO HIGH ENERGY ACCELERATORS

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We discuss the principles and performance of a new type of high-current injector for RFQs. Our injector uses electrostatic focusing everywhere, avoiding gas neutralization entirely, so that its performance is independent of pulse length. It was originally developed for cw H^- beams but is equally useful for heavy ions or for handling the microsecond pulses needed for high energy accelerators and storage rings.

Introduction

This paper describes the design and operation of a versatile injector for radio frequency quadrupoles (RFQs). The system tested consists of a volume production ion source [1], a 100-keV electrostatic preaccelerator [2], and a new electrostatic transport and matching system. The injector has been tested with up to 45 mA of H^- and with the equivalent of 130 mA of H^- using positive helium ions.

As discussed previously [2], the H^- volume source operates at a pressure of more than 10 mTorr. To minimize stripping of the H^- beam, we use an open accelerator and transport structure with high conductance to pumps. Electrons from the source are removed by an electron trap mounted on the extractor grid [2].

We use electrostatic quadrupole (ESQ) focusing for our low energy beam transport (LEBT) and an axisymmetric lens for matching into the RFQ. The ESQ LEBT (Fig. 1a) provides sufficient length for effective pumping while preventing the accumulation of charge and the formation of plasma in the transport channel. Some applications, such as injectors with very short pulses and low duty factors, may not require much pumping. In such cases, it might be possible to operate without the ESQ transport section (using only the axisymmetric lens for the final match) as shown in Fig. 1b.

The prototype LEBT that we tested uses ESQ accelerator technology [3] which was developed for the DOE magnetic fusion energy program [4] and adapted for the present application.

Electrostatic Quadrupole LEBT

Some of the features of our plasma-free LEBT are: (1) The open structure gives good gas pumping capability. (2) Gas pressure can be arbitrarily low in the LEBT; gas independence improves reproducibility. (3) Gas independence permits either dc operation or pulsed beams with arbitrarily short pulse lengths. (4) Electrostatic tuning provides excellent flexibility. (5) Emittance growth from plasma noise is eliminated. (6) Also eliminated is emittance growth from sheath transitions into and out of gas neutralized regions. (7) Our approach avoids the hard-to-locate final de-neutralization transition zone where space charge suddenly becomes very large. This occurs near the RFQ match point in gas neutralized designs.

Electrostatic vs Magnetic, Gas-neutralized, Focusing

Electrostatic quadrupole focusing

The quadrupole pole face electric field E_Q required to transport a specified beam current I with normalized emittance ϵ_N at beam energy qV is given by [5]

$$\frac{L^2}{a_Q^2}E_Q^2 = C_1\frac{I}{A_0^2}V^{1/2} + C_2\frac{\epsilon_N^2}{A_0^4}V \qquad (1)$$

for a matched beam; L is the quad cell length, a_Q is the quad aperture radius, and A_0 is the mean beam radius. The constants C_1 and C_2 depend on the particle charge and mass and the electrode occupancy factor; C_2 also includes a correction for beam ripple which is usually negligible at higher energies where the ϵ_N term becomes significant [5].

The E_Q^2 external force term on the left of Eq. (1) balances the space charge and emittance pressure terms on the right. In a typical high current LEBT, $E_Q \approx 10$ kV/cm. For a bright beam transported at low energy, the emittance term is usually negligible, and

$$E_Q \propto V^{1/4}. \qquad (1')$$

We routinely use Eq. (1) or (1') when designing ESQ accelerators and LEBTs. The required electric field is not very sensitive to beam energy, so one could easily design a standard electrostatic LEBT which would handle almost any RFQ requirement.

Magnetic, gas neutralized, focusing

If the electrostatic quadrupoles are replaced by magnetic quadrupoles, then

$$E_Q^2 \longrightarrow C_3 V B_Q^2 .$$

For a 100 keV D^- beam, 10 kV/cm is approximately equivalent to

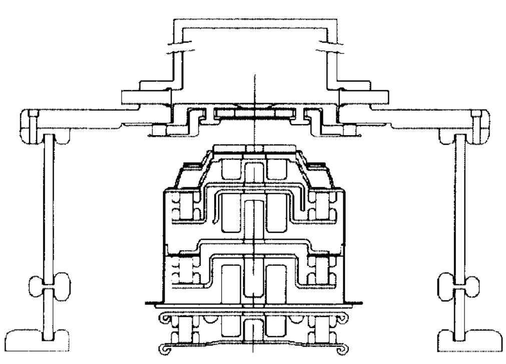

Fig. 1a. Preaccelerator and quadruplet ESQ LEBT; ring lens not shown.

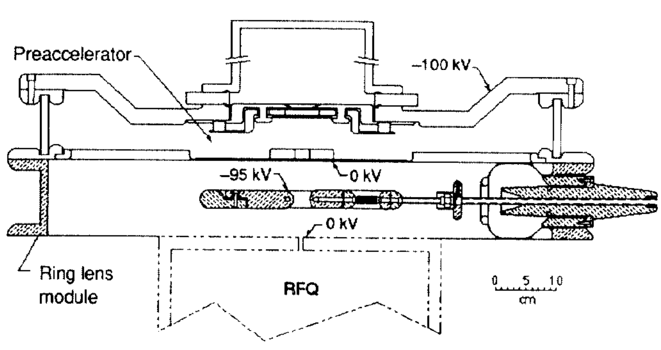

Fig. 1b. Preaccelerator with ring lens only.

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3 kG. However, in the absence of external electrostatic fields, a neutralizing plasma develops. We define the neutralization coefficient K_n, where typically $K_n \approx 0.99$, and get

$$C_3 \frac{L^2}{a_Q^2} B_Q^2 = C_1 (1 - K_n) \frac{I}{A_0^2} V^{-1/2} + C_2 \frac{\epsilon_N^2}{A_0^4} \qquad (2)$$

In Eq. (2), the factor $(1 - K_n)$ is very sensitive to the degree of neutralization; for example, it doubles if K_n changes from 0.99 to 0.98. This is the reason that gas neutralized LEBTs are unsuitable for pulsed systems where the plasma buildup time is comparable to or longer than the pulse length.

Beam Simulations for Quadruplet LEBT

Fig. 2 shows an envelope simulation for a quadruplet LEBT. Corresponding to a particular experimental run, the preaccelerator was assumed to inject 45 mA of H^- in a round beam of 0.9 cm radius into the LEBT. The normalized emittance is 0.160 π mrad-cm. The ESQ voltages were adjusted to produce a round beam at the exit. (The voltages were in the order of ±2.5 kV for Fig. 2; a 100 mA case required about ±4 kV.) The voltage variation across the beam is small because no attempt is made to use the ESQ voltages for matching into the RFQ. That function is reserved for the aperture-lens module.

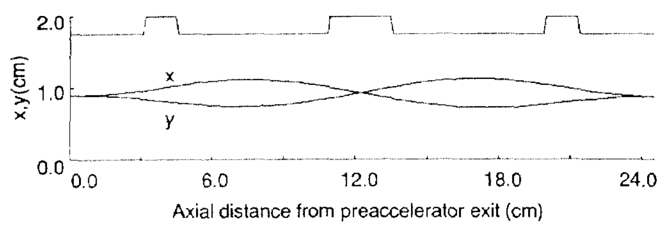
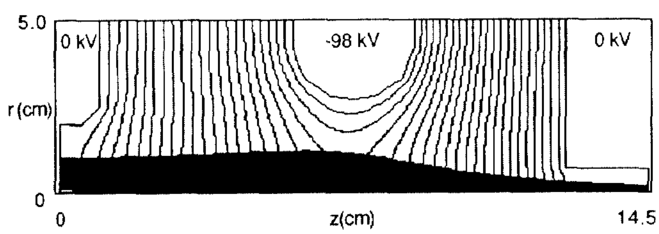


Fig. 2. Beam envelopes for the quadruplet LEBT of Fig. 1; see text.



Particle	H^-
Energy (keV)	100
Current (mA)	100
ϵ_N (π cm-mrad)	0.014
Entrance radius (cm)	1.00
Entrance angle (mrad)	0
Exit radius (cm)	0.299
Exit angle (mrad)	-71

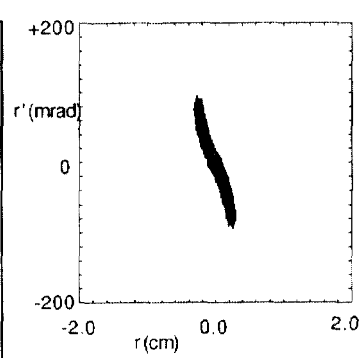


Fig. 3. Sample particle simulation of the axisymmetric lens for RFQ matching, showing the beamlet trajectories and the phase plot at 12.6 cm, the location of the simulated RFQ entrance. The beam radius is 3 mm at this point and decreases toward the RFQ match point.

Axisymmetric Aperture-lens Matching Module

A difficult problem in designing injectors for RFQs is that a small beam diameter and large convergence angle are required at the match point just inside the RFQ entrance. We found that producing a steeply converging round beam, using only ESQs, requires large focusing voltages which produce excessive aberrations. We chose the alternative of axisymmetric focusing between the LEBT and RFQ. This produces less chromatic aberration; furthermore, the design can be optimized with the help of exact 2-D round-beam particle codes, which run much faster than 3-D particle codes.

Self Consistent Particle Simulation of Ring Lens

Fig. 3 shows a sample particle simulation for the ring lens system of Fig. 1b (or Fig. 4) obtained with the self-consistent WOLF particle code [8]. Parameters are given in the figure; the current is larger than for Fig. 2, so this case is more stringent. The equipotentials show that the beam is decelerated from 100 keV to about 15 keV and reaccelerated to 100 keV at the RFQ input. The potential variation across the beam radius is small—about 10%—at the worst point (the center of the ring lens) and is generally negligible elsewhere in Fig. 3. Therefore, chromatic aberrations are small: the calculated rms emittance growth is only 2.9%.

Construction of Ring Lens

Fig. 4 shows the ring lens module that we built and tested, along with two ESQ modules that had been constructed for another purpose [3,6,7] and were adapted for this LEBT application. One sees that our axisymmetric lens is not a conventional einzel lens; by definition, einzel lenses have field-free drift regions, which we wish to avoid, since plasma can accumulate in such regions. On the other hand, we do not use a classical thin-plate aperture lens because we wish to avoid electric field concentrations. Our compromise design looks like a ring (near the beam), and we simply call it a ring lens. The major and minor radii of the ring were adjusted to minimize beam aberrations.

The figure shows one of three insulators which support the ring. These insulators also serve as vacuum feed-throughs, providing both

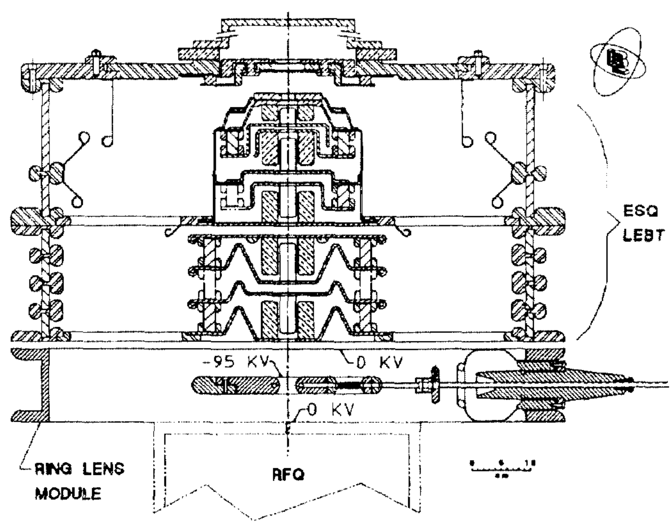


Fig. 4. Prototype LEBT shown with ring lens, as tested. The ring is supported by three feed through insulators, one of which is seen here (see text). The hypothetical RFQ entrance region shown schematically with dotted lines is replaced experimentally by the exit electrode described in the text.

electrical current and cooling water for the ring lens electrode. This electrode is a two piece assembly with the outer ring serving as a support for an inner ring which can be shimmed and translated to accurately align the electrode bore with the beam axis. Not shown is a movable, grounded, exit electrode containing a small aperture simulating the entrance of the RFQ. The exit electrode is positioned by a remotely controlled actuator that replaces the small aperture by a large one during tune up of the ESQ portion of the LEBT.

Depending on requirements, a voltage in the range of -95 to -98 kV (with respect to ground) is applied to the ring during operation. Note that the ring is actually energized by a small 2–5 kV floating power supply connected to the -100 kV H^- ion source potential.

Experimental Results

Preliminary test results are shown in Fig. 5. These were obtained using our 20-cm diameter H^- volume source [9]. For the run shown, the beam-forming aperture diameter was reduced to 1.4 cm in order to improve the current density. In this particular run, the source produced a rather asymmetric beam with a lump on one edge, as seen in Fig. 5a. The lump grows as it is transported through the LEBT (Fig. 5b) and appears to be somewhat disconnected at the ring lens focus (Fig. 5c). The important point, however, is that after passing through the LEBT and after passing through the ring lens, the bulk of the emittance area is essentially straight and free of aberration .

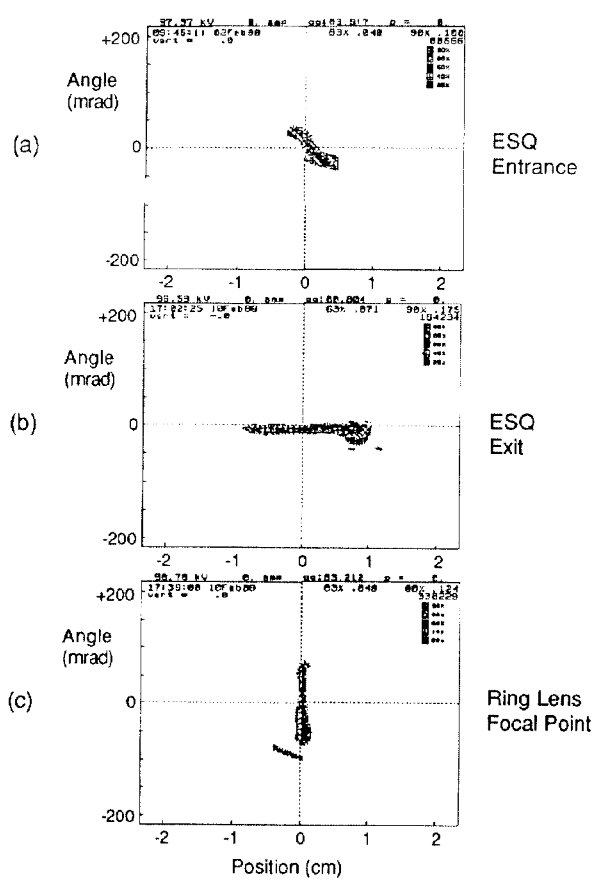


Fig. 5. Emittance scans projected back to: (a) the ESQ entrance; (b) the ESQ exit; and (c) the ring lens focal point. The larger phase space area seen in (b) is probably an instrumental effect. In (a) and (c) the normalized emittance is about 0.025 π mrad-cm.

In this run, the LEBT operated at 100 kV. The transported H^- current was 30 mA, primarily limited by the plasma generator. The beam loss in the LEBT, if any, was too small to measure. The beam exiting the LEBT at 10 mm radius was focused by the ring lens to a radius of 1 mm; the convergence angle was 70 mrad at the focal point.

We also rigorously tested our LEBT with a much brighter beam of He^+ ions. The transverse beam temperature was about five times lower than with H^-, and the equivalent H^- current density was more than four times higher. Once again, we found no significant emittance growth in transport or in final matching.

By adjusting the ring voltage, the matching module can handle a wide range of beam currents and can produce a wide range of convergence angles, up to 100 mrad. (In extreme cases it may be necessary to adjust the electrode spacings on each side of the ring.) Both the ESQ module and the ring lens module are flexible and capable of handling beam energies in the range 30-100 keV for various beam currents or particle species.

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