INJECTOR FOR RFQ USING ELECTROSTATICALLY FOCUSED TRANSPORT AND MATCHING

O.A. Anderson, L. Soroka, J.W. Kwan, and R.P. Wells*

Accelerator and Fusion Research Division

Lawrence Berkeley Laboratory

University of California

1 Cyclotron Road, Berkeley, CA 94720

ABSTRACT

We discuss the principles and performance of a new type of high-current H^- injector for RFQs. The distinguishing feature of our injector is that we replace the conventional gas-neutralized transport and matching units by electrostatic focusing units. Our system prevents plasma formation along the beam instead of utilizing it. Some advantages of this approach are discussed.

1. INTRODUCTION

This paper describes the design and preliminary operation of a dc H^- injector for a radio frequency quadrupole (RFQ). 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^- , but simulations show that it is capable of handling beams with several times higher current. To allow for dc operation, all components are water cooled.

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, described in Section 2, provides sufficient length for effective pumping while prevent-

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ing the accumulation of charge and the formation of plasma in the transport channel. The final match is obtained with an axisymmetric electrostatic lens rather than with ESQ focusing, as discussed in Section 3. Experimental results are given in Section 4.

2. ELECTROSTATIC QUADRUPOLE LEBT

Our new approach for transport of intense H^+ beams uses ESQ focusing instead of the usual combination of magnets and gas neutralization [3,4]. 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) The de-neutralization transition near the match point in the RFQ, a tricky issue in conventional designs, is avoided.

Our LEBT uses ESQ technology [5] which was developed and tested for the DOE magnetic fusion energy program [6] and adapted for the present application.

2.1 Field Strength Compared with Magnetic (Gas Neutralized) Case

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 [7]

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

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 [7].

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 LEBT, $E_Q \approx 10$ kV/cm. For a bright

beam transported at low energy, the emittance term is usually negligible, and

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

We routinely use Eq. (1) or (1') when designing ESQ accelerators and LEBTs.

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 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

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

In Eq. (2), note that 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. We also note that K_n is a poorly known function of position and time in a magnetic LEBT, so that Eq. (2) is not useful for design purposes unless the emittance term is large enough to dominate. Thus, the design of magnetic LEBTs must be largely empirical.

2.2 Mechanical Configuration of Experimental LEBT

The electrostatic LEBT which we tested is shown in Fig. 1. The hardware is the same as used for the 200 kV Constant Current Variable Voltage (CCVV) prototype accelerator tested and described previously [5,8,9]. Two ESQ modules containing a total of five sets of quadrupoles are shown in the figure. In the accelerator prototype application, the first module is for matching and the second is for acceleration. The initial quadrupole in the matching module has been shortened to facilitate the transition from an initially round beam to a beam matched for transport or acceleration. The second module is the first of an eventual series of identical acceleration modules [9].

and therefore does not have a shortened exit quadrupole.

Even though the hardware shown in Fig. 1 was not designed for LEBT applications, it proved to be perfectly adequate as a demonstration LEBT capable of handling parameters of interest in all known RFQ injector applications. Naturally, a dedicated electrostatic LEBT would be designed differently, with fewer elements and shorter overall length.

The CCVV accelerator that we adapted for our LEBT experiment was developed for applications that require constant beam current over a wide energy range. Flexibility in energy results from the use of transverse field ESQ focusing in the main accelerator rather than the use of longitudinal field focusing as in conventional Pierce columns. Therefore it is easy to reduce the output beam energy from the nominal 200 keV CCVV level to the 100 keV level used in the LEBT mode. In fact, much lower energies can be reached without loss of beam current, because the preaccelerator voltage, which determines the beam current, is always kept at the same value [5].

Operation in the LEBT mode requires not only reduction in the output energy as just mentioned, but also adjustment of the beam shape. In the CCVV accelerator mode, the exit beam is elliptical in cross section, whereas the RFQ LEBT needs to produce a round beam. This adjustment can also be made, as shown in the next section.

Fig. 1. ESQ system used for testing 100 keV electrostatic LEBT principle. Running in its accelerator mode, this system is the 200 keV prototype for a MeV dc accelerator with fusion energy applications.

2.3 Beam Simulations for Experimental LEBT

Fig. 2 shows an envelope simulation for the hardware of Fig. 1 running in the LEBT mode. Corresponding to a particular experimental run, the preaccelerator was assumed to inject 45 mA of H^- in a round beam of 0.8 cm radius into the LEBT. The normalized emittance is 0.160π mrad-cm. The ESQ voltages were adjusted to produce a round beam at the exit with a diverging envelope (about 24 mrad) as required for the aperture lens module described in the next section. 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 discussed in Section 3.

We have also recently started running self consistent 3-D particle simulations for the ESQ structure of Fig. 1, using a version of the ARGUS code [10] especially developed for our purposes by SAIC [11]. Fig. 3 shows preliminary results from a test run by SAIC for the acceleration mode. In the near future we will be able to do 3-D LEBT mode simulations at LBL which will allow exact predictions for emittance growth.

3. AXISYMMETRIC APERTURE-LENS MATCHING MODULE

A difficult problem in designing RFQ injectors is in the beam matching: a small beam diameter and large convergence angle are required at the match point just inside the RFQ entrance. We found that producing a round beam of this sort, using only ESQ

Fig. 2. Beam envelope simulation for the system of Fig. 1, running in LEBT mode. Parameters are given in the text.

units, requires relatively large focusing voltages which could produce excessive aberrations. Since low emittance growth is one of our goals, we chose the alternative of axisymmetric focusing between the LEBT and RFQ. Although axisymmetry *per se* does not guarantee improvement, a big advantage is that the design can be optimized with exact 2-D round-beam particle codes, which run much faster than 3-D particle codes. We used the self-consistent 2-D WOLF code [12] to model our matching module.

Fig. 3. Beam trajectories for the device of Fig. 1, running in accelerator mode with 200 mA of H^+ . The trajectories are shown projected in the x and y directions.

3.1 Construction of Ring Lens

Fig. 4 shows a third module added to the two ESQ modules of Fig. 1; this module is our axisymmetric lens. One sees that it 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 figure shows one of three insulators which support the ring. These insulators

also serve as vacuum feed-throughs, providing both 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.

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

3.2 Self Consistent Particle Simulation of Ring Lens

Fig. 5 shows a sample particle simulation for the ring lens system of Fig. 4, obtained with the self-consistent WOLF particle code [12]. 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. Aberrations are small, and the emittance growth is only 2.9%.

It would be interesting to compare the aberrations for the ring lens and the ESQ focusing options for RFQ entrance matching. This will be possible in the near future using the ARGUS code [10, 11] for the ESQ option.

Fig. 5. 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.

4. EXPERIMENTAL RESULTS

Preliminary test results are shown in Fig. 6. These were obtained using our large aperture H^- volume source [13]. For the run shown, the extraction grid 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. 6a.

Fig. 6. 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 0.05π mrad-cm.

The lump grows as it is transported through the LEBT (Fig. 6b) and appears to be somewhat disconnected at the ring lens focus (Fig. 6c). The important point, however, is that the bulk of the phase plots are essentially straight and free of aberration after passing through the LEBT and after passing through the ring lens.

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, 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.

By adjusting the ring voltage and the electrode spacings on each side of the ring, the matching module can handle a wide range of beam currents and can produce a wide range of convergence angles, up to 100 mrad.

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