ILSE-ESQ Injector Scaled Experiment*

E. Henestroza, S. Eylon, and S. Yu
Lawrence Berkeley Laboratory,
University of California
Berkeley, California 94720

D. Grote
Lawrence Livermore National Laboratory,
University of California
Livermore, California 94550

Abstract

A 2 MeV, 800 mA, K^+ injector for the Heavy Ion Fusion Induction Linac Systems Experiments (ISLE) is under development at LBL. It consists of a 500keV-1MeV diode pre-injector followed by an electrostatic quadrupole accelerator (ESQ). One of the key issues for the ESQ centers around the control of beam aberrations due to the "energy effect": in a strong electrostatic quadrupole field, ions at beam edge will have energies very different from those on the axis. The resulting kinematic distortions lead to S-shaped phase spaces, which, if uncorrected, will lead eventually to emittance growth. These beam aberrations can be minimized by increasing the injection energy and/or strengthening the beam focusing. It may also be possible to compensate for the "energy effect" by proper shaping of the quadrupoles electrodes. In order to check the physics of the "energy effect" of the ESQ design a scaled experiment has been designed that will accommodate the parameters of the source, as well as the voltage limitations, of the Single Beam Transport Experiment (SBTE). Since the 500 KeV pre-injector delivers a 4 cm converging beam, a quarter-scale experiment will fit the 1 cm converging beam of the SBTE source. Also, a 10 mA beam in SBTE, and the requirement of equal perveance in both systems, forces all the voltages to scale down by a factor 0.054. Results from this experiment and corresponding 3D PIC simulations will be presented.

I. INTRODUCTION

The US Heavy-Ion Fusion Accelerator Research (HIFAR) Program at Lawrence Berkeley Laboratory has proposed a sequence of experiments that collectively are called the Induction Linac Systems Experiments, or ILSE. A principal design criterion was that the beams in ILSE should be at the same line charge density expected in a full-scale heavy-ion driver. A key element in the ILSE project is the ion injector that will provide 0.8A of 2-MeV K^+ ions, equivalent to a line charge density of 0.25 μC/m; it is further specified that the beams must have a low normalized-emittance ($\approx 1\ \pi$ mm-mr). Two main options that could meet the requirements were considered, namely the Electrostatic Aperture Column (ESAC) and the Electrostatic Quadrupole Injector (ESQ). The ESAC option consists of a number of axisymmetric electrodes arranged in a conventional Pierce electrode geometry. The key issue for this option is high-voltage breakdown and beam emittance. The ESQ option consists of an axisymmetric front end (which could be a diode or a multiple aperture column) followed by a sequence of quadrupoles arranged to focus and accelerate the beam at the same time. The key issue for this option is the beam aberration produced by the "energy effect". Based on reliability, driver scaleability, and beam specifications the ESQ option was selected for the ILSE injector.

*Work supported by the Director, Office of Energy Research, Office of Fusion Energy, of the U.S. Department of Energy under Contract DE-AC03-76SF00098.

III. THE ILSE-ESQ INJECTOR

The ESQ concept was first proposed by Abramyan *et al.* in the late 1960's . More recently, the Magnetic Fusion Energy program at LBL has worked towards the construction of a MeV-class ESQ injector. As compared to the ESAC, the ESQ is generally a longer machine with correspondingly lower gradients. The secondary electrons are swept out by the large transverse fields, which reduces significantly the breakdown risks. In addition, the sources in an ESQ are generally smaller, so their intrinsic emittance is reduced. The ESQ is also attractive from the standpoint of driver scaling; it has the potential advantage of operating at energies much higher than 2MeV, since the critical issues in an ESQ tend to center in the transition from preinjector into the first accelerating quadrupoles. The ILSE-ESQ injector was designed to provide four beams of K^+ at driver line charge densities. It is followed by a matching section that shapes the beams to the proper radius and "squeezes" them together for insertion into the electrostatically focused induction linac.

III. THE "ENERGY EFFECT"

One of the key issues for the ESQ centers around the control of beam aberrations due to the "energy effect": in a strong electrostatic quadrupole field, ions at beam edge will have energies very different from those on the axis. This effect can be analyzed by a perturbation treatment of the particle orbits to leading order. Expanding the single-particle equations of motion to fourth order in the external electrostatic potential ϕ we obtain:

$$v_x = v_{x0} + v_{x1}$$

$$\phi = V_{00} + \left[V_{20} + V_{22}\cos 2\theta\right]\left(\frac{r}{R}\right)^2 + \left[V_{40} + V_{42}\cos 2\theta + V_{44}\cos 4\theta\right]\left(\frac{r}{R}\right)^4$$

$$\frac{dv_{x1}}{dz} = \frac{v_{z0}}{2}\left\{\begin{array}{l} \left[\frac{1}{8}\left(\frac{eV_{22}}{T_0}\right)^2 + \frac{eV_{44}}{T_0}\right]\left[-\frac{\partial}{\partial x}\left(\frac{r}{R}\right)^4 \cos 4\theta\right] + \\ \left[\frac{1}{2}\left(\frac{eV_{22}}{T_0}\right)\left(\frac{eV_{20}}{T_0}\right) + \frac{eV_{42}}{T_0}\right]\left[-\frac{\partial}{\partial x}\left(\frac{r}{R}\right)^4 \cos 2\theta\right] + \\ \left[\frac{1}{8}\left(\frac{eV_{22}}{T_0}\right)^2 + \frac{1}{4}\left(\frac{eV_{20}}{T_0}\right)^2 + \frac{eV_{40}}{T_0}\right]\left[-\frac{\partial}{\partial x}\left(\frac{r}{R}\right)^4\right] \end{array}\right\}$$

The second order terms in the potential give rise to the "energy effect". The fourth order terms (octupoles) are due to the "inter-digital" structure of the quadrupoles. The resulting kinematic distortions lead to S-shaped phase spaces, which, if uncorrected, will lead eventually to emittance growth. These beam aberrations can be minimized by increasing the injection energy and/or strengthening the beam focusing. It may also be possible to compensate for the "energy effect" by proper shaping of the quadrupoles electrodes to include octupole corrections.

IV. NUMERICAL SIMULATIONS

The dynamics of the beam in the ESQ was simulated by the 3-D particle-in-cell codes WARP3D[1] and ARGUS[2]. A full 3D simulation code was required to incorporate the beam space charge field as well as the self-consistent fields from the accelerating quadrupoles, including their "inter-digital" structure. Large normalized-emittance growth (≈ 2 π mm-mr) was obtained for the case of a 500keV beam injected into the ESQ. A smaller normalized-emittance growth (≈ 0.6 π mm-mr) was obtained for the case of a 1MV injected beam. The initial normalized-emittance in both cases was 0.4 π mm-mr.

V. SCALED EXPERIMENT

We are presently building a one-beam prototype of the ILSE-ESQ Injector. The prototype consists of a 500keV-1MeV diode followed by an ESQ that will focus and accelerate the beam to 2MeV. In order to check the physics of the "energy effect" of this design a scaled experiment has been designed that will accommodate the parameters of the source, as well as the voltage limitations, of the Single Beam Transport Experiment (SBTE). Since the 500 KeV pre-injector delivers a 4 cm converging beam, a quarter-scale experiment will fit the 1 cm converging beam of the SBTE source. Also, a 10 mA beam in SBTE, and the requirement of equal perveance in both systems, forces all the voltages to scale down by a factor 0.054. The SBTE source normalized-emittance was measured to be 0.06 π mm-mr. A schematic of the scaled experiment is shown in Fig. 1. Two set of measuremts were taken corresponding to scaled versions of a 570keV,787mA (36keV,12.6mA) and a 1MeV,787mA (30keV,4.1mA) beams. Fig. 2 and Fig 3. shows the experimental results as well as the WARP3D numerical simulations. Further measurements taken by scanning the injection energy for a given quadrupole voltage setting shows a consistent agreement between experimental results and 3D numerical calculations (Figs. 4a and 4b).

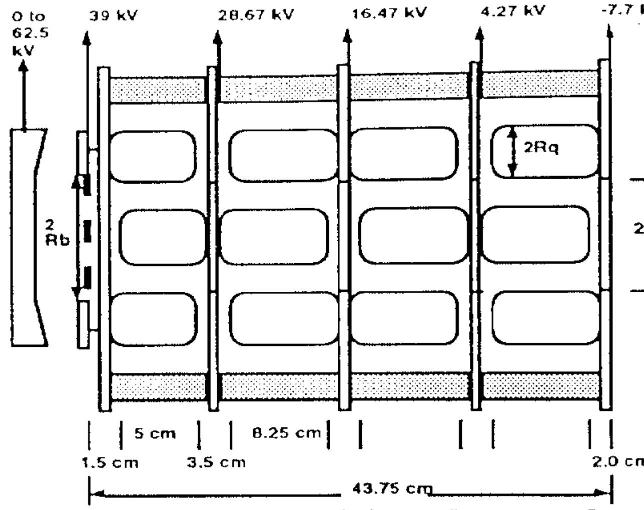

Fig. 1 Schematics of the ESQ-Scaled Experiment. Cross-sectional view.

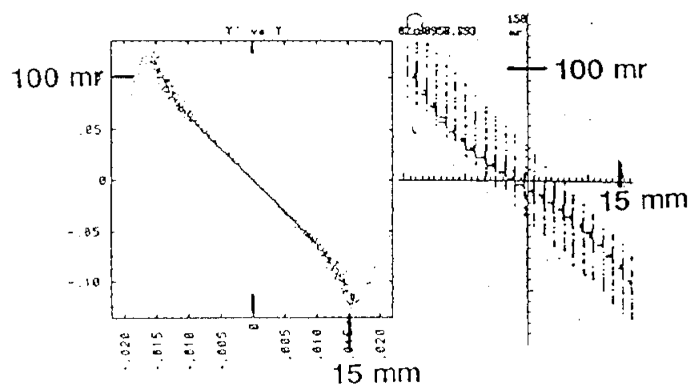

Fig. 2 WARP3D simulation and measured phase-space distributions. Scaled version of a 570keV,787mA (36keV,12.6mA) beam.

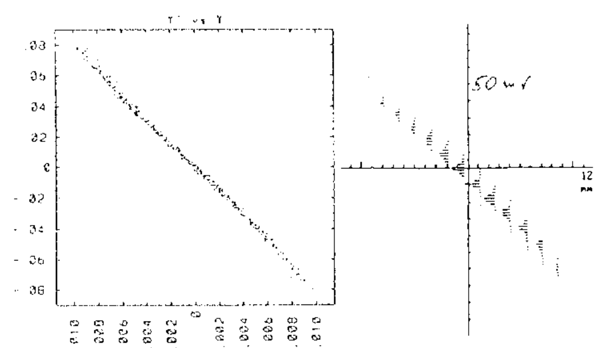

Fig. 3 WARP3D simulation and measured phase-space distributions. Scaled version of a 1MeV,787mA (30keV,4.1mA) beam.

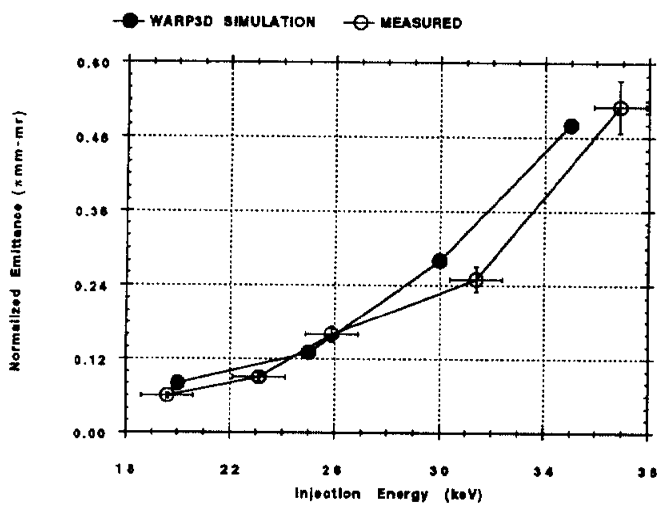

Fig. 4a Scan of the normalized emittance versus the injection energy for the quadrupole voltage setting corresponding to the scaled version of a 570keV,787mA (36keV,12.6mA) beam.

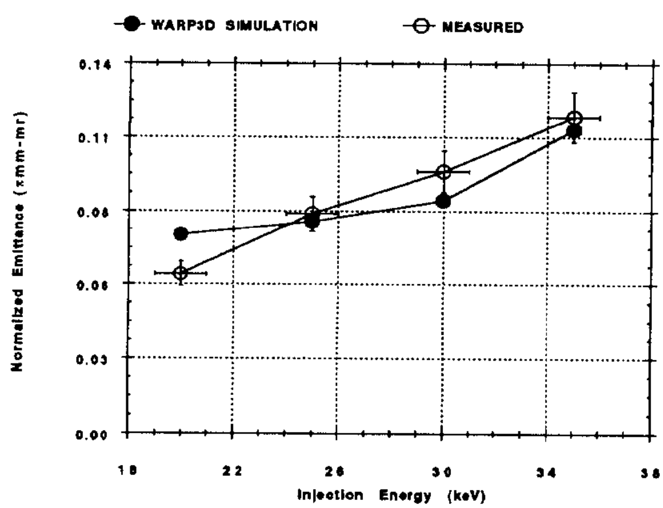

Fig. 4b Scan of the normalized emittance versus the injection energy for the quadrupole voltage setting corresponding to the scaled version of a 1MeV,787mA (30keV,4.1mA) beam.

V. CONCLUSIONS

Phase space distortions predicted by simulations have been observed in the 570keV scaled experiment leading to a factor of 8 growth in the beam normalized emittance. A growth of less than a factor of 2 in the beam emittance observed in the 1MeV scaled experiment is in agreement with the numerical simulation and the expected decrease in emittance growth by an increase in injection energy. We found consistent agreement between 3D numerical simulations and experimental results.

ACKNOWLEDGEMENTS

We thank D. Vanecek for mechanical design.

REFERENCES

[1] A. Friedman, D. Grote, and I. Haber, "Three-dimensional particle simulation of heavy-ion fusion beams", *Phys. Fluids* B4,2203(1992).

[3] C.L. Chang, D. Chernin, A. Drobot, K. Ko, M. Kress, A. Mankofsky, A. Mondelli, and J. Petillo, "Three-Dimensional Modeling of Accelerators", *Proc. Conf. on Computer Codes and the Linear Accelerator Community* (Los Alamos National Laboratory, January 22-25, 1990, **LA-11857-C**), pp. 27-56.