BEAM DYNAMICS STUDIES OF THE HEAVY ION FUSION ACCELERATOR INJECTOR*

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

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

ABSTRACT

A driver-scale injector for the Heavy Ion Fusion Accelerator project has been built at LBL. This machine has exceeded the design goals of high voltage (> 2 MV), high current (> 0.8 A of K^+) and low normalized emittance (< 1 π mm-mr). The injector consists of a 750 keV diode pre-injector followed by an electrostatic quadrupole accelerator (ESQ) which provides strong (alternating gradient) focusing for the space-charge dominated beam and simultaneously accelerates the ions to 2 MeV. The fully 3-D PIC code WARP together with EGUN and POISSON were used to design the machine and analyze measurements of voltage, current and phase space distributions. A comparison between beam dynamics characteristics as measured for the injector and corresponding computer calculations will be presented.

I. INTRODUCTION

The Fusion Energy Research Program at Lawrence Berkeley Laboratory has built a driver-scale injector for heavy ion fusion research. The principal design criterion was that the beam delivered should be at the same line charge density as expected in a full-scale heavy-ion driver. The injector will provide 0.8 Amperes 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 (≈ 1 π mm-mr), repetition rate of 1 Hz and pulse length of 1μs.

On the basis of reliability, driver scalability, and beam specifications an ESQ design was selected for the injector. The ESQ accelerator consists of a diode followed by a sequence of quadrupoles arranged to focus and accelerate the beam at the same time. The ESQ concept was first proposed by Abramyan and Gaponov [1]. The ESQ is generally a long machine with correspondingly low 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 2 MeV, since the critical issues in an ESQ tend to center in the transition from the pre-injector to the first accelerating quadrupoles.

The key issue for this design is the control of beam aberration produced by the energy effect — in a strong electrostatic quadrupole field, ions at beam edge will have energies very different from those on the axis. The "inter-digital" structure of the electrostatic quadrupoles could enhance the aberrations. The resulting kinematic distortions lead to S-shaped phase spaces, which, if not corrected, 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.

A schematic of the one-beam injector is shown in Fig. 1. The components of the injector are a large hot alumino-silicate source, a diode column in which the beam is extracted and accelerated, and electrostatic quadrupoles that accelerate the beam to 2 MeV.

II. THE PRE-INJECTOR

For a 0.8 A K^+ beam to be accelerated to 2 MeV, numerical calculations showed large normalized emittance growth (≈ 2 π mm-mr) for the case of a 500 keV beam injected into a representative ESQ. A smaller normalized emittance growth (≈ 0.6 π mm-mr) was obtained for the case of a 1 MeV injected beam. The ini-

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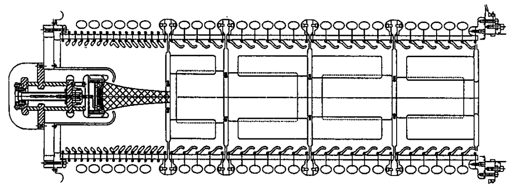

Figure 1: Schematic of the ESQ injector showing the diode column and the electrostatic quadrupoles.

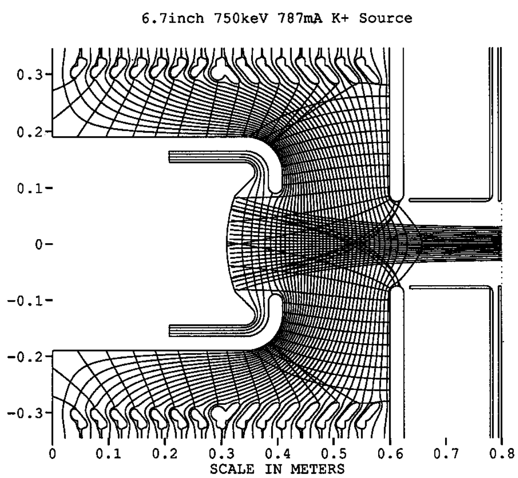

Figure 2: EGUN output showing the geometry of the axisymmetric injector diode, ion and electron trajectories, and field equipotential surfaces.

tial normalized emittance in both cases was 0.4 π mm-mr. To check the physics of the energy effect of the ESQ a scaled experiment was designed to accommodate the parameters of the source, as well as the voltage limitations, of the Single Beam Transport Experiment (SBTE) apparatus. Phase space distortions predicted by simulations have been observed in the 570 keV 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 1 MeV scaled experiment agrees with the expected decrease in emittance growth by an increase in injection energy. Therefore a major effort was launched to design a high energy diode that would deliver a high current (0.8 A) and low normalized emittance ($\approx 1\ \pi$ mm-mr) K^+ beam. A diode designed to hold up to 1 MV, with minimal breakdown risks, consists of a hot alumino-silicate source with a large curved emitting surface surrounded

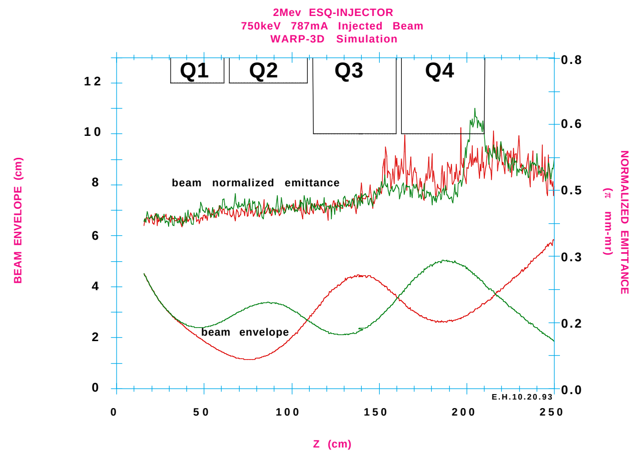

Figure 3: WARP3D simulation of the beam in the ESQ.

by a thick "extraction electrode." An extraction pulser switches the source from -80 kV to +80 kV relative to the extraction electrode during beam turn-on. The geometry of the diode, beam envelope and field equipotential surfaces as calculated by the EGUN [2] code are shown in Fig. 2. A cross-check of the design was obtained by running an *rz* particle-in-cell calculation using the GYMNOS code [3].

III. THE INJECTOR

The design of the ESQ Injector was based on the three-dimensional PIC (particle-in-cell) codes WARP3D [4] and ARGUS [5] running in a steady state mode. A full 3-D PIC 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. The parameters of this design represent optimal choices to have a proper balance between breakdown risks and emittance growth. Fig. 3 shows the beam envelope and normalized emittance along the ESQ column as calculated by WARP3D, showing a small emittance degradation.

The construction of the 2 MeV Injector has been completed. The actual operation of the injector has exceeded the design parameters.

IV. NUMERICAL SIMULATIONS

Measurements of the transverse phase spaace distribution has shown excellent agreement with WARP3D calculations. Fig. 4 shows a comparison of measured and calculated phase space distribution in the horizontal plane.

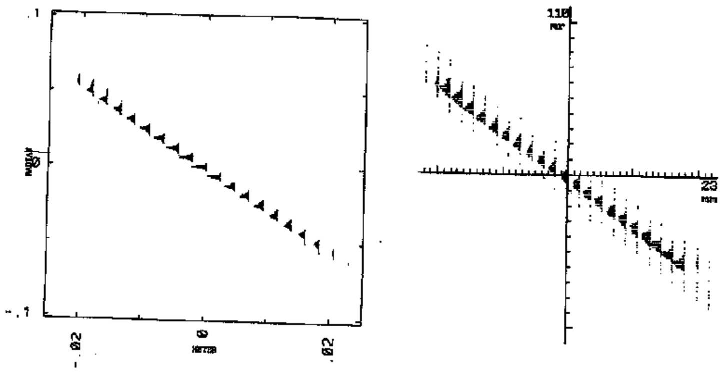

Figure 4: Horizontal phase space at the end of the injector as calculated and as measured.

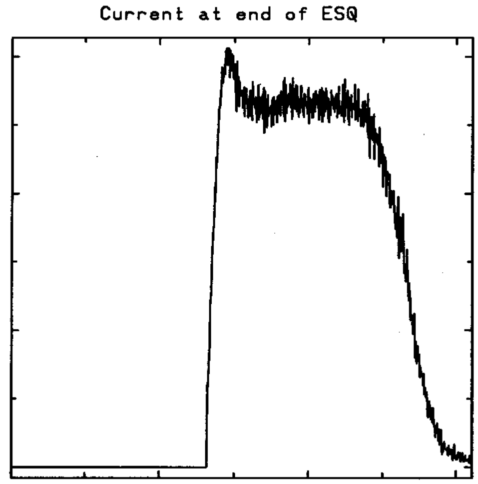

Figure 5: Current waveform at the end of the ESQ as calculated by WARP3D.

The transient longitudinal dynamics of the beam in the ESQ was simulated by running GYMNOS and WARP3D in a time dependent mode.

During beam turn-on the voltage at the source is biased from a negative potential, enough to reverse the electric field on the emitting surface and avoid emission, to a positive potential to start extracting the beam; it stays constant for about 1 µs, and is reversed to turn-off the emission. Since the Marx voltage applied on the accelerating quadrupoles and the main pre-injector gap is a long, constant pulse (several µs), the transient behavior is dominated by the extraction pulser voltage time profile. The extraction pulser voltage profile has, in general, a 0.5 µs rise time, a 1 µs flat top and a 0.5 µs falloff. The pulser rise used in the simulations followed the Lampel-Tiefenback functional dependence on time which eliminates current transients in a one-dimensional diode [6].

The results of both simulations codes showed a significant spike in current and energy at the head of the beam. A similar spike appeared in the experimental results. Fig. 5 shows the current profile at the end of the ESQ as calculated by WARP3D. The current waveform from the experiment shows a similar profile. The extraction voltage pulser shapes used in the simulations does not exactly match the experimental pulser shape.

The height of the initial spike is dependent on the rise time of the pulser. Simulations of the pre-injector with varying rise time showed that the minimal spike height was obtained with a 500 ns rise time. In an ideal, one-dimensional injector, with a rise time equal to the transit time, the Lampel-Tiefenback relation would result in no spike being formed.

Another feature seen in the simulations is the shortening of the current rise time with respect to the pulser rise time. With the pulser rise time of 500 ns, the current rise time produced is 200 ns; significantly shorter. This is in agreement with the experiment which showed the same behavior. After the initial rise and spike, a stable flat top was maintained for a time comparable to the flat top of the pulser voltage. The tail of the current waveform showed a long falloff as expected.

V. CONCLUSION

The 2 MeV ESQ Injector was designed using three-dimensional particle-in-cell calculations. Measurements of the beam parameters at the end of the injector have shown excellent agreement with computer simulations.

VI. REFERENCES

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