# 2 MV, 0.8A, $K^+$ INJECTOR FOR HEAVY ION FUSION

S. Eylon, E. Henestroza, S. Yu, and D. Grote†
Lawrence Berkeley National Laboratory, Berkeley, CA 94720, USA
† Lawrence Livermore National Laboratory, Livermore, CA 94550, USA

### Abstract

A driver-scale injector for the Heavy Ion Fusion Accelerator program has been built at LBNL. The injector has exceeded the design goals of high voltage ( > 2 MV), high current ( > 0.8 A of potassium ions) and low normalized edge emittance ( < 1 π mm-mr). The injector consists of a 750 keV pre-injector diode 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 ESQ is followed by a six-quadrupole section to match the beam into the main accelerator. 3-D PIC simulations, confirmed by comparing with scaled experiments, were used to generate a physics design with minimal emittance growth. Detailed measurements of ion current, emittance, and beam energy, and comparison with code predictions are reported.

### Introduction

The driver accelerator required in a Heavy Ion Fusion power plant scenario [1] must deliver several megajoules of heavy ions with particle energy of a few GeV, onto a target of 2 to 3 mm radius in 10-15 nanoseconds. The linear induction accelerator approach to the fusion driver consists of multiple beams, each confined to a quadrupole focusing channel, which is electrostatic at the low energies, and magnetic at high energies, and sharing a common induction acceleration core. A driver-scale one-beam heavy ion injector was constructed and operates at Lawrence Berkeley National Laboratory. The injector has as design goals a particle energy of 2 MeV, line charge density of 0.25 µC/m (800 mA of singly charged potassium) and a normalized edge emittance of less than 1 π mm-mr. These design parameters are the same as in the front end of a full-scale driver. The low emittance is essential for final focusing onto a small target. The line charge density corresponds to the optimal transportable charge in a full-scale electrostatic quadrupole channel, and the high injector energy has a significant cost advantage in a fusion-driver.

The design of the injector was based on calculations using the three-dimensional PIC (Particle-in-cell) codes WARP3d [2] and ARGUS [3] running in steady state mode. A full 3D PIC simulation code was required to incorporate the beam space-charge-field as well as the self consistent fields from the accelerating quadrupoles. The parameters of the design represent optimal choices to have a proper balance between breakdown risks and emittance growth.

### The Injector System

The injector is based on an electrostatic quadrupole (ESQ) configuration [4]. Fig. 1 shows the layout of the injector system. The ion beam, after extraction from an axisymmetric diode, is injected into a set of electrostatic quadrupoles arranged to provide simultaneous acceleration and strong focusing. The ESQ configuration was chosen over the more conventional electrostatic aperture column primarily because of high voltage breakdown considerations. The accelerating gradient of an ESQ can be made quite low, and the strong transverse fields sweep out secondary electrons, features which may avoid the initiation of breakdown processes. However, the ESQ configuration must be carefully controlled to minimize emittance degradation. The injector is composed of 5 ceramic columns. The first column consists of a brazed structure with 16 alumina rings, each 1.5" in width, and separated by thin niobium rings enclosing the alumino silicate source and the 750 kV diode front end. The subsequent 4 columns consist of similarly brazed structures with 3" alumina rings, each containing a set of 4 electrodes arranged in a quadrupolar configuration designed to provide strong beam focusing and acceleration from 750 keV to 2 MeV. The quadrupole electrodes are shaped to minimize surface fields without introducing unwanted higher order multipoles. The ceramic column is contained in a pressure vessel under 80 psig of $SF_6$ gas. Water resistors around the column provide graded voltages to the diode and each of the 4 quadrupoles.

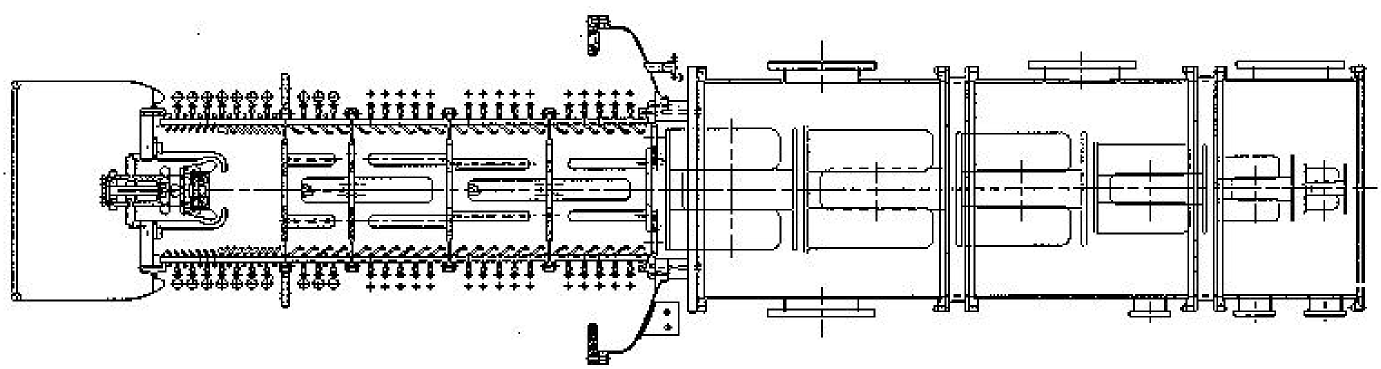

Fig. 1. The Injector System layout showing from left to right the source, the four-quadrupole ESQ accelerator, and the six-quadrupole matching section assemblies.

The source is a 6.7" diameter curved hot alumino-silicate source emitting potassium ions. These sources have been shown to produce beams with temperature-limited emittances, and have long life-time and high reliability [5]. The source assembly is coupled to an extraction pulser which is at -80 kV relative to the high voltage dome at all times except during beam extraction when the pulser is switched to +80 kV in about 500 nanoseconds. This extraction pulser configuration allows ion extraction without the need for grids which tend to be unreliable and beam-quality degrading.

The injector is powered by a 2 MV Marx [6] which consists of 38 trays with parallel LC and RC networks to produce a 4 μs flat-top pulse to accommodate the entire ion beam plus the transit time across the injector.

A 3 meter long, six-quadrupole matching section is being constructed and tested in stages at the end of the injector ESQ section. The matching section performs a dual function of focusing and steering of the ion beam. In a multiple beam accelerator design, the matching section is needed to focus beams which are 4 cm in radius at injector exit to 1 cm in radius into the electrostatic channels in close proximity.

## Injector performance

On the first day of operation (November 92) a $K^+$ beam in excess of the design parameters of 2 MeV and 800 mA was produced (Fig. 2).

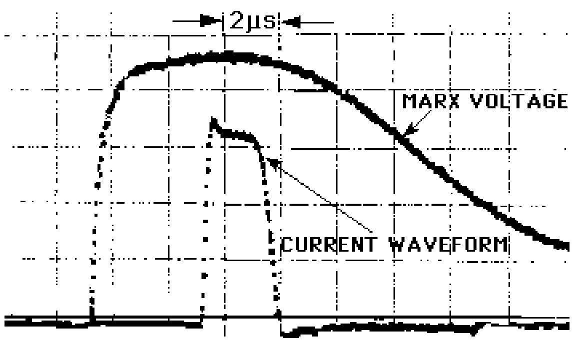


Fig. 2. Measured Marx voltage waveform (2 MV at flat top) and beam current waveform (800 mA at flat top).

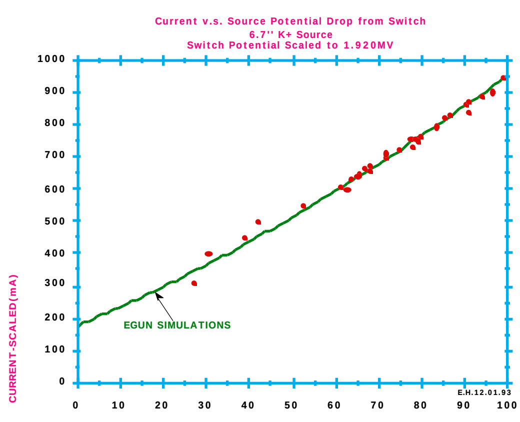


Fig. 3. Current measurements on the ESQ-Injector in excellent agreement with computer simulations.

The measurement of the current was made with a Faraday cup and a Rogowski loop at the exit of the injector. The current was measured for a range of Marx and source gate pulser voltages, and the agreement with code predictions was excellent (Fig. 3). The highest energy and current achieved thus far is 2.3 MeV and 950 mA of potassium, 15% above the design goals.

The emittance was measured with a double slit scanner in both the horizontal and vertical directions. Over a broad range of parameters the measured normalized edge emittance was less than the required 1 π mm-mr. The measured emittance, beam radius, divergence, and beam centroid displacement were found to be reasonably constant over the entire pulse.

Precision measurement of the beam energy from head-to-tail, were performed using a modified 1 MeV electrostatic spectrometer. The spectrometer energy range was extended to above 5 MeV by placing a gas stripper in front of the 1 MeV spectrometer thus changing the singly ionized potassium ions to multiply charged ions up to the charge state 5. With this sensitive energy measuring device we were able to fine tune the extraction pulser to the point were the beam is flat to less then 0.2% over a 1 μs pulse length.

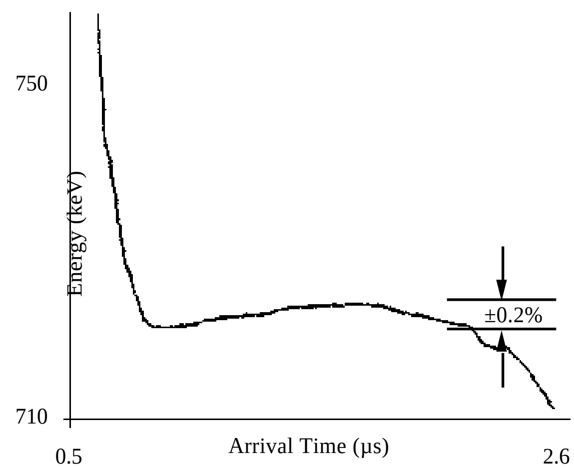


Fig. 4. Time profile of measured head-to-tail beam energy.

The transport of the injector ion beam through the matching section is being studied in stages. Displacements of a single quad by 1.5 cm in a 3-quadrupole experiment led to the bending of the beam by nearly 2 cm, in very good agreement with simulation predictions. Preliminary beam profile measurements resulted in profile variations along the matching section that can be connected to the beam profile measured at the injector exit. Further investigations, experimental as well as theoretical, will continue.

## Numerical simulations

Measurements of the transverse phase space distribution has shown excellent agreement with WARP3d calculations[7]. Fig. 5 shows a comparison of measured and calculated phase space distribution in the horizontal plane.

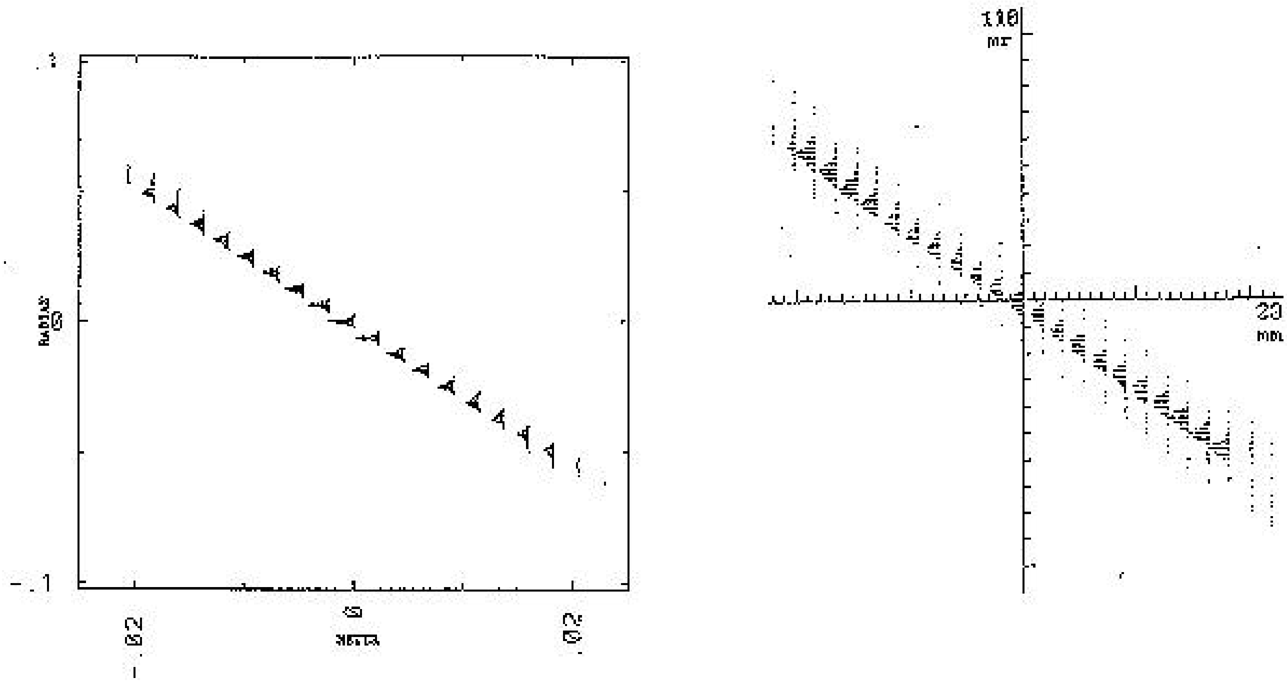


Fig. 5. Horizontal phase space at the end of the injector as calculated and as measured.

The transient longitudinal dynamics of the beam in the ESQ was simulated by running 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 fall-off.

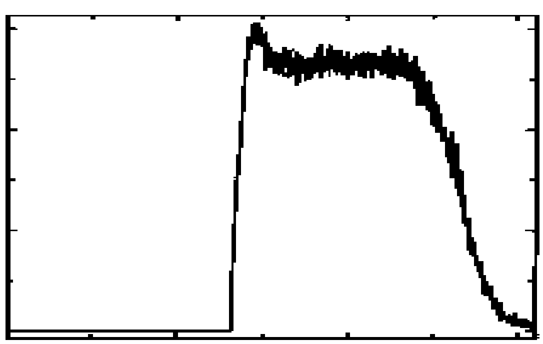

Figure 6: Current waveform at the end of the ESQ as calculated by WARP3d. Compare with Fig. 2. Horizontal scale at 1µs per division.

The results of the simulations showed a significant spike in current and energy at the head of the beam. A similar spike appeared in the experimental results. Fig. 6 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 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 [8]. 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, which agrees with the experiment. 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 fall-off as expected.

## Acknowledgements

Work supported by the U.S. Department of Energy under Contract DE-AC03-76SF00098.

## References

[1] Hogan, W.J., et al., "Energy from Inertial Fusion", Physics Today **42**, p. 9, 1992.
[2] Friedman, A., Grote, D., and Haber, I., "Three-dimensional particle simulation of heavy-ion fusion beams", Phys. Fluids **B4**, p. 2203, 1992..
3] Chang, C.L., et al., "Three-Dimensional Modeling of Accelerators", LA-11857-C, 1990.
[4] Abramyan, E.A., and Gaponov, V.A., Atomnaya Energiya **20**, p. 385, 1966.
[5] Eylon S., et al., Proceedings of the 1993 Particle Accelerator Conference, p. 3199, 1993.
[6] Abraham, W., et al., "Design and testing of the 2 MV Heavy Ion Injector for Fusion Energy Research Program", Proceedings of the 1995 Particle Accelerator Conference, p. 902, 1995.
[7] Henestroza E., et al., "Beam Dynamics Studies of the Heavy Ion Fusion Accelerator Injector", Proceedings of the 1995 Particle Accelerator Conference, p. 916, 1995.
[8] Henestroza E., and Grote, D., "Transient Beam Dynamics in the LBL 2 MV Injector", Fusion Engineering and Design **32-33**, 1996.