# HEAVY ION FUSION 2 MV INJECTOR*

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## ABSTRACT

A heavy-ion-fusion driver-scale injector has been constructed and operated at Lawrence Berkeley Laboratory. The injector has produced 2.3 MV and 950 mA of $K^+$, 15% above original design goals in energy and current. Normalized edge emittance of less than 1 $\pi$ mm-mr was measured over a broad range of parameters. The head-to-tail energy flatness is less than ±0.2% over the 1 μs pulse.*

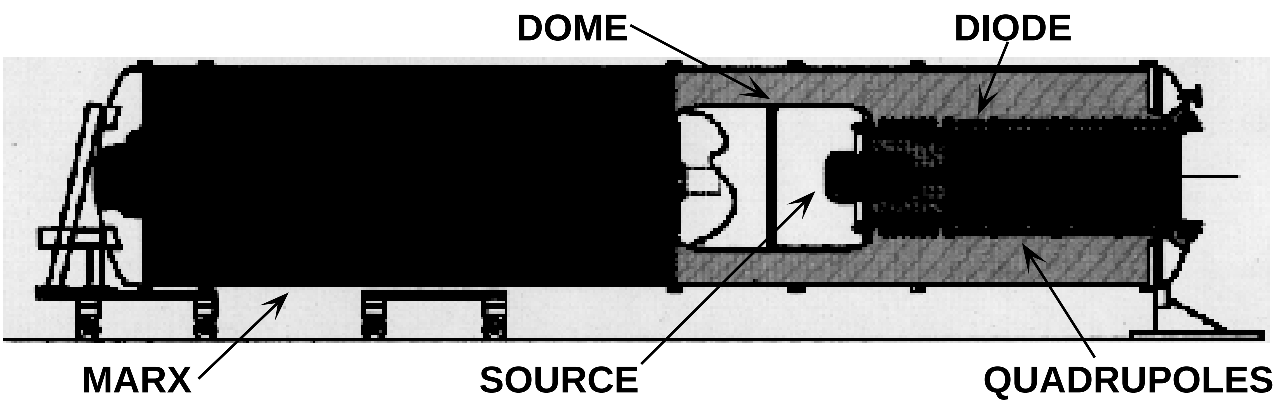


Fig.1

## INTRODUCTION

The accelerator required for Heavy Ion Fusion[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 the high energies, and sharing a common induction acceleration core. A variant of the induction linac approach, which recirculates the heavy ions through quadrupole focusing channels and induction cores in a circular configuration is also being studied as a potentially low cost driver option.[2] The ILSE (Induction Linac Systems Experiments) project has been proposed to study all the key beam dynamics issues in a driver-scale accelerator, and the first half of this machine , the electrostatic focusing section has been approved as the 'Elise" project. As a prerequisite to the ILSE/Elise project, a driver-scale, one-beam heavy ion injector has been constructed and operated at Lawrence Berkeley Laboratory

The new injector has as its design goals, the particle energy of 2 MV, line charge density of 0.25 μC/m (800 mA of $K^+$) and a normalized edge emittance of less than 1 $\pi$ mm-mr. These design parameters are the same as in a full-scale driver. The low emittance is essential for final focusing onto a small target. The line density corresponds to the optimal transportable charge in a full-scale electrostatic quadrupole channel, and the high injector energy has significant cost advantages in a fusion-driver. The ultimate injector for a fusion accelerator is conceptually a replicate of this one-beam injector to many beams, with an extended pulse length of many microseconds, instead of the one to two microseconds (budget-determined) in the ILSE/Elise injector. While the particle energy and particle current has been achieved separately in previously built injectors, the unique combination of energy, current, and emittance requirements pose a new technical challenge for the Elise injector. Furthermore, the required beam parameters must stay constant over the entire microsecond long pulse, and the machine must run reliably.

The new injector is based on an electrostatic quadrupole (ESQ) configuration.[4,5] The ion beam, after extraction from an axisymmetric diode, is injected into a set

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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 which may initiate breakdown processes. However, the ESQ configuration has an inherent beam aberration mechanism, which must be carefully controlled to minimize emittance degradation. The key design issues center around the control of high voltage breakdown and deleterious phase-space distortions.

## HIGH VOLTAGE ENGINEERING

A schematic of the full injector is shown in Figure 1. The Elise injector column consists of a diode followed by four electrostatic quadrupole sections. The ceramic column has an inner diameter of 26” and a total length of about 100”. The diode section is brazed from 16 1-1/2” alumina rings separated by thin Niobium plates. The quadrupole sections are composed of 3” rings. The segmented structure prevents continuous plasma avalanching along the ceramic walls, and reduces insulator breakdown risks. The inner surface of the insulator column is further protected with 1 cm thick stainless steel and copper shields carefully shaped to block beam-generated secondary electrons and X-rays. Detailed computer designs were performed to minimize surface field stress to less than 60 kV/cm at all points on the metal surfaces and to very low fields at the “triple points” (interface between insulator, metal, and vacuum). Quadrupole electrodes were also computer-designed to minimize field stress without enhancing higher order multipoles which could distort the phase-space of the beam. The ceramic column is contained in a pressure vessel under 80 psig of $SF_6$. The outside of the insulator column is further protected with guard rings and metal-oxide-varisters. Water resistors around the column provide graded voltages to the diode and each of the four quadrupoles. The full-size quads were tested to hold voltage of up to 700 kV without beam. The design quad voltages for the full injector were set at less than 400 kV. The diode was tested to up to 1 MV with beam, and the design diode voltage is less than 700 kV.

The source is a 6.7” diameter curved hot alumino-silicate source emitting $K^+$ ions. These sources have been shown to produce beams with temperature-limited emittances, and have long life-time and high reliability[6]. 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 ns. 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[7] which consists of 38 trays, with parallel LC and RC circuits arranged to produce a 4 μs flat-top (to accommodate the entire ion beam plus transit time across the injector column). The 6 kΩ system is sufficiently stiff to render beam loading transient effects negligible.

## BEAM DYNAMICS

A low energy ion beam in a strong electrostatic focusing channel experiences a third-order aberration which we call the “energy effect.” The cause of this effect is that ions at a given axial location within the quadrupole channel can have variable energies, depending on their relative proximity to the negative and/or positive electrodes. Variations in beam energy lead in turn to a spread in betatron motion, which results in a kinematic aberration of the beam. The mechanism could be understood if we start with the equation of motion in a focusing channel:

$$\frac{d^2x}{dz^2} = \frac{1}{{v_z}^2}\left(\frac{eE_\perp}{m}\right)$$

Noting that ${v_z}^2$ is proportional to the potential in a quadrupolar field

$$\frac{1}{2}m{v_z}^2 = e\Phi = e\left(\Phi_0 + \Phi_q r^2 \cos 2\Theta\right)$$

where $\Phi_0$ is the potential on axis and corresponds to the energy of an on-axis particle, and $\Phi_q$ is the quadrupole component. Assuming that $\Phi_q << \Phi_0$, we obtain at once, to leading order

$$\frac{d^2x}{dz^2} = -{k_\beta}^2 x\left(1 - \frac{\Phi_q}{\Phi_0} r^2 \cos 2\Theta\right)$$

It is evident that the resulting aberration is third order in the field. It is also clear that the magnitude of the aberration is proportional to the ratio of the quadrupole field to the beam energy, and the effect is most serious when the beam energy is low and quadrupole field is strong.

The beam dynamics of the ESQ is further complicated by the facts that the interdigital geometry of the electrode package is fundamentally 3-dimensional, and the beam is space-charge dominated. Detailed theoretical predictions require 3-D PIC simulations. Substantial code developments were invested to make WARP3D our “design tool.”[8] Realizing that the beam dynamics is sufficiently complicated, a 1/4 scale experiment was designed and conducted using an existing 100 kV $K^+$ beam at the Single-Beam Transport Experiment facility at LBL, and detailed phase-space measurements were performed over a broad range of parameters. The agreement with WARP3D predictions was excellent.

WARP3D was used to determine the voltages of the diode and the quads that would yield minimal emittance growth. The final quad and diode voltages were determined on the basis of beam dynamics simulations and high voltage breakdown considerations.

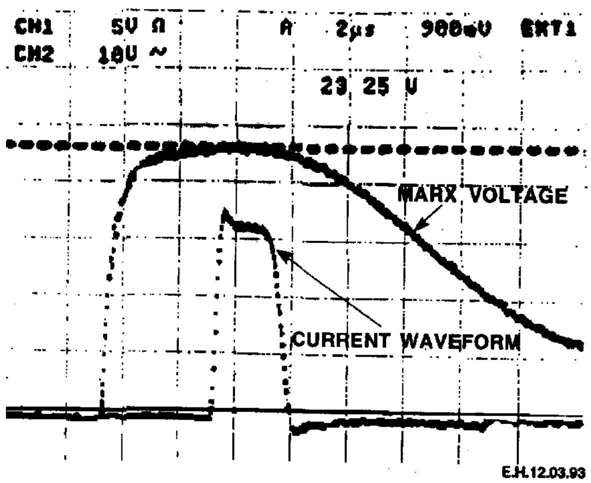



Fig.2

## INJECTOR PERFORMANCE

Engineering design and construction of the ESQ injector commenced in November 1992, and the project was completed in October 1993. On the first day of operation, a $K^+$ beam in excess of the design parameters of 2 MV and 800 mA was produced. (See Figure 2.) The measurement of current was made with a Faraday cup and a ragowski located at the exit of the injector. The current was measured for a range of Marx voltage and pulser voltages, and the agreement with code predictions was excellent. (See Figure 3.)

The highest energy and current achieved thus far is 2.3 MV and 950 mA of $K^+$, or 15% above design goals, and we have not yet attempted to push the injector to its limit of performance.

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 1 $\pi$ mm-mr. (See Figure 4.) As the current is increased (at fixed MARX voltage), phase-space distortions are enhanced, as predicted by theory and simulations. Simulations have successfully predicted details of measured phase-space, subject to an observed sensitivity of code results to the beam extraction conditions near the source, which is not fully understood.

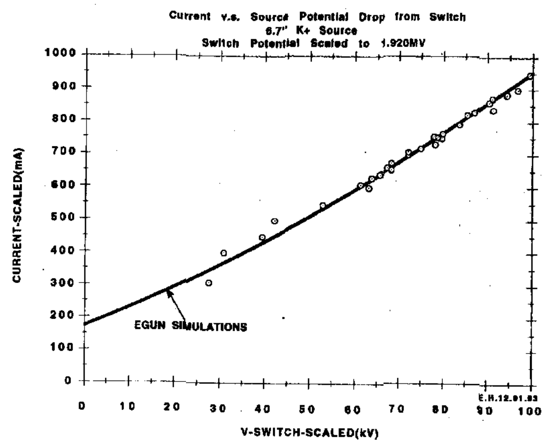
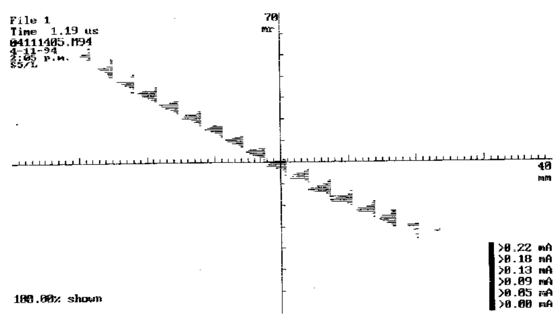



Fig.3

The measured emittance, beam radius, divergence, and beam centroid displacement are reasonably constant over the entire pulse from our measurements. (See Figure 5.)




0.65 $\pi$ mm-mr

Fig. 4

To provide a high precision measurement of the beam energy from head-to-tail, we have constructed a new energy spectrometer by placing a gas stripper in front of a previously constructed electrostatic spectrometer with a maximum energy measuring capability of less than 1 MV. (See Figure 6.) The gas stripper changes the incoming singly ionized potassium ions to multiply ionized species, and the dynamic range for the $K^{+n}$ is increased up to n =5, (See Figure 7.) We have measured ions to n=5, allowing this same device to measure ions of the full Elise 5 MeV beams.

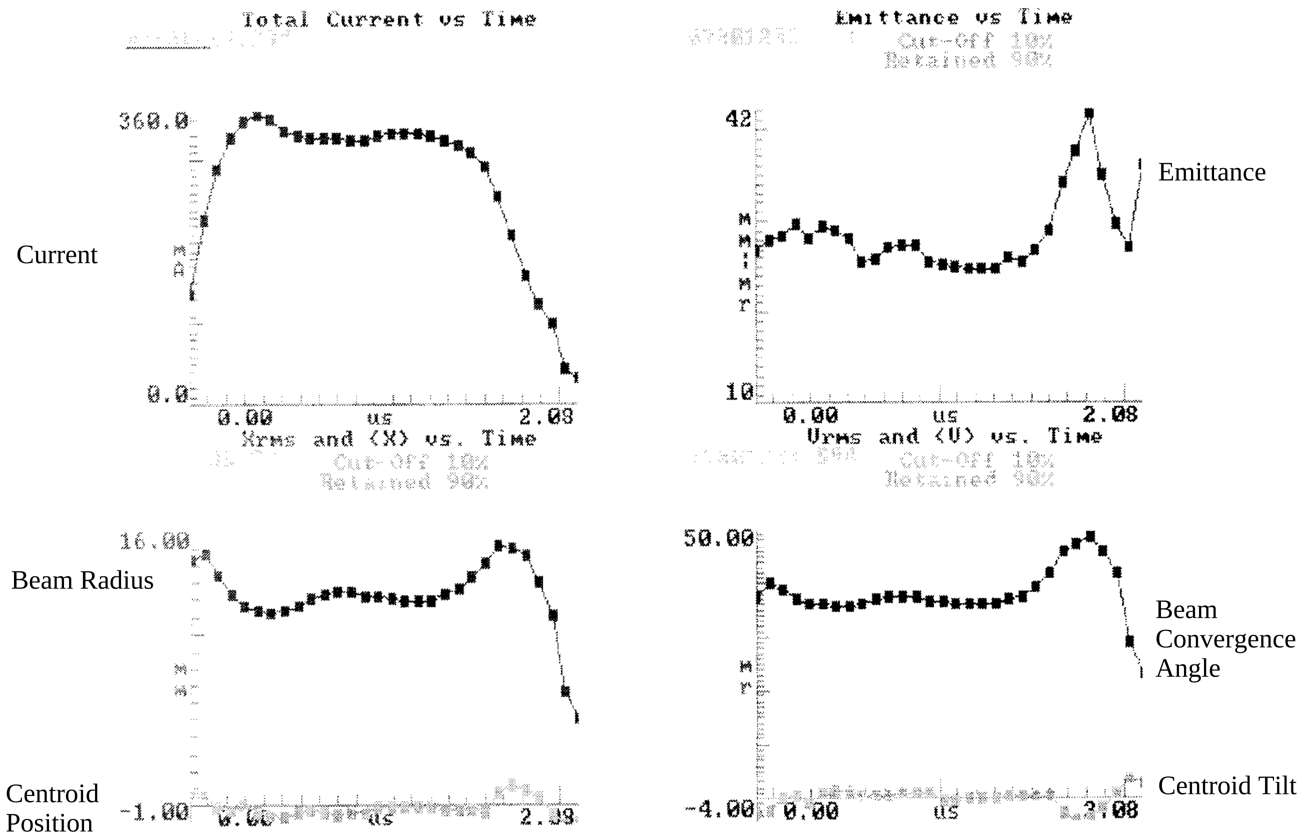



Fig.5

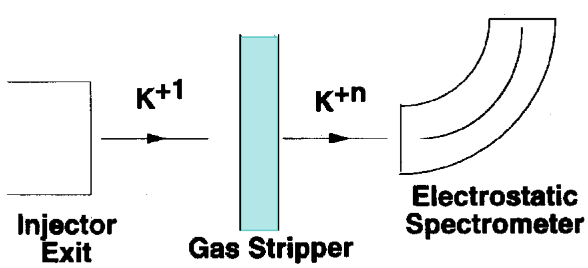



Fig. 6

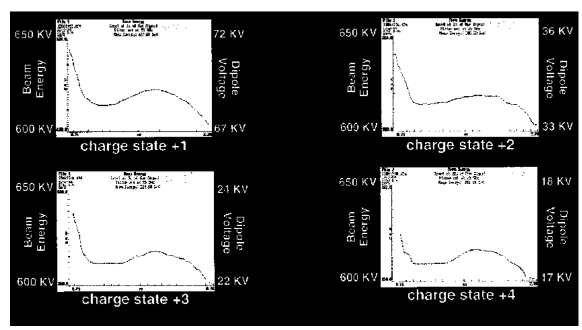



Fig.7

With this sensitive energy measuring device, we were able to “fine-tune” the extraction pulser to the point where the exiting beam is flat to less then ±0.2% over 1 µs. (Figure 8) The variations of beam emittance and envelope over the pulse for the “flat” beam is expected to be further reduced from our first double-slit scanner measurements. Detailed comparisons of the transient features observed in the experiments with WARP3D are ongoing. The goal is to deliver the entire pulse through a 3-m long matching section presently under construction, into the 2.3 cm radius Elise focusing channel.

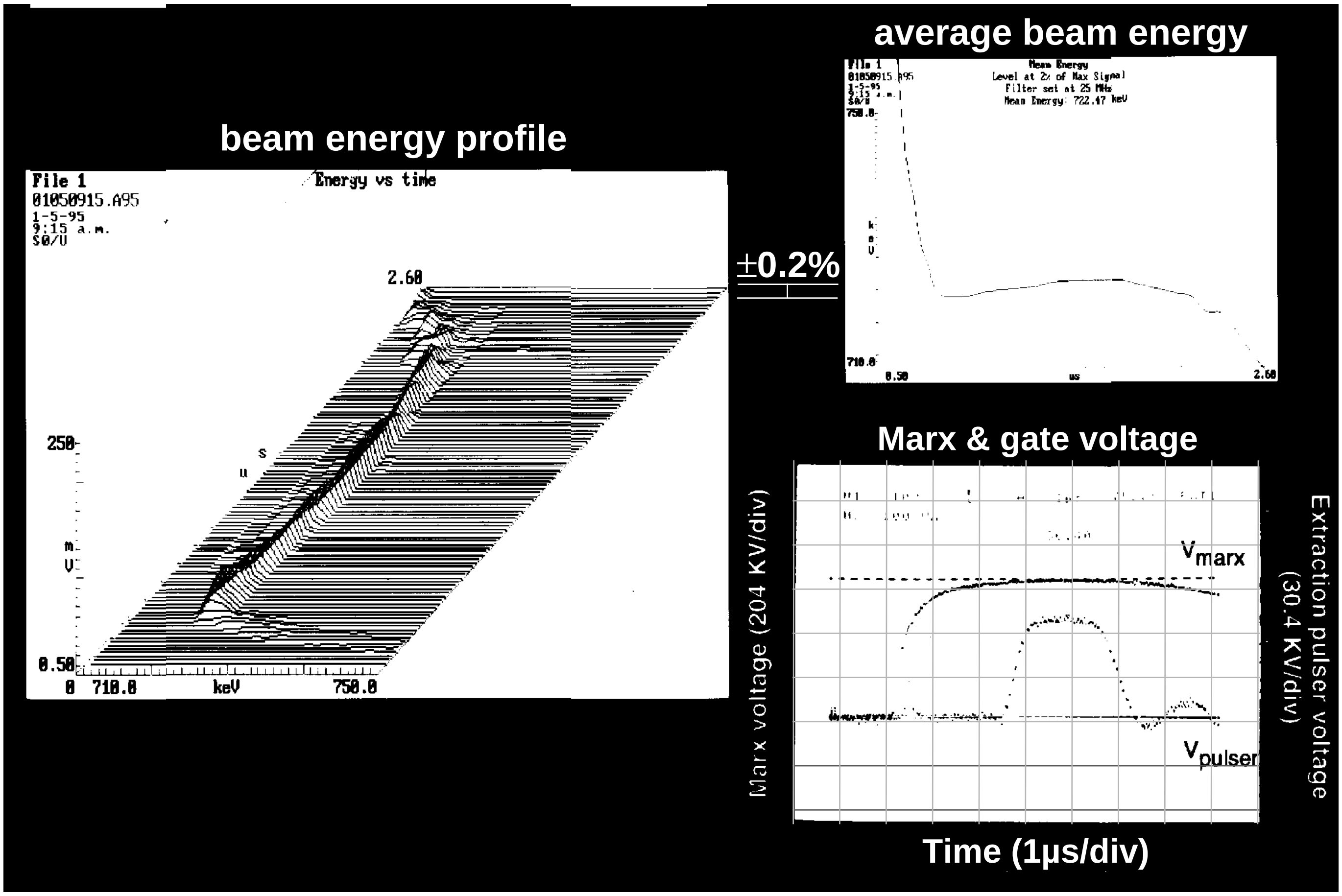



Fig. 8

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