High-Current Injector for Heavy-Ion Fusion (*).

S. YU (1), S. EYLON (1), W. W. CHUPP (1), A. FALTENS (1), T. FESSENDEN (1)
E. HENESTROZA (1), R. HIPPLE (1), D. JUDD (1), C. PETERS (1), L. REGINATO (1)
H. RUTKOWSKI (1), J. STOKER (1), D. VANECEK (1), J. BARNARD (2), G. CAPORASO (2)
Y.-J. CHEN (2), F. DEADRICK (2), A. FRIEDMAN (2), D. GROTE (2) and D. HEWETT (2)

(1) *Lawrence Berkeley Laboratory - 1 Cyclotron Road, Berkeley, CA 94720, USA*
(2) *Lawrence Livermore National Laboratory - Livermore, CA 94550, USA*

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Summary. — A 2 MV, 800 mA, K^+ injector for heavy-ion fusion studies is under construction. This new injector is a one-beam version of the proposed 4-beam ILSE injector. A new 36-module MARX is being built to achieve a 5 μs flat top. The high-voltage generator is stiff ($< 5\,\mathrm{k\Omega}$) to minimize effects of beam-induced transients. A large ($\approx 7''$ diameters) curved hot alumino-silicate source emits a 1 μs long beam pulse through a gridless extraction electrode, and the ions are accelerated to 1 MV in a diode configuration. Acceleration to 2 MV takes place in a set of electrostatic quadrupole (ESQ) units, arranged to simultaneously focus and accelerate the ion beam. Heavy shields and other protection devices have been built in to minimize risks of high-voltage breakdown. Beam aberration effects through the ESQ have been studied extensively with theory, simulations, and scaled experiments. The design, simulations, experiments, and engineering of the ESQ injector will be presented.

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The Heavy Ion Fusion Accelerator Research group at LBL has built and studied several ion injectors over the years, all of which used a conventional Pierce column configuration. Although considerable progress was made toward a 2 MV, 16-beam injector, the reliability of the system proved less than acceptable; moreover, the beam parameters were not suitable for ILSE. A study conducted in March-

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September 1992 by a joint LBL-LLNL group has led to a different approach based on the ESQ (electrostatic quadrupole) concept, and we are presently building a one-beam version at ILSE/driver scale. The rationale for choosing the ESQ was based on three major considerations:

1) *Reliability*. The goal of the ILSE project is to test driver physics issues. If the series of proposed experiments is to be executed in a timely manner, a reliable injector is an absolute necessity.

2) ILSE *specifications*. The proposed physics experiments impose requirements upon the beam's energy, current-profile flatness, and emittance. While the requirements for various experiments may be different, the ILSE injector must deliver beams of sufficient quality to meet the overall ILSE physics needs.

These design parameters were chosen for the ILSE injector:

– Beams: 4.

– Output energy: ~ 2 MeV.

– Charge/length/beam: 0.25 μC/m, equivalent to 0.79 A of K^+. (Operation with Cs^+ is also planned in order to increase experience with a candidate driver ion.)

– Pulse length: 1 μs.

– Repetition rate: 1 Hz.

3) *Driver scalability*. One of the ILSE goals is to produce the line charge density required for the full driver. However, practical considerations (primarily cost) have led to ILSE parameter values, such as ion mass, pulse length, and number of beams, which are quite different from those of a driver. It is very important that the injector technology be scalable to a full-sized driver. There must be room for upgrades in beam energy, pulse length, and compactness. The technology must, of course, be scalable to heavier ions as well.

The two main options that could potentially meet the ILSE injector requirements are 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 column geometry. It is the conventional approach to injectors, and there is a large data base of operational experience, although the ILSE requirements for total voltage (2 MV) and current (≤ 1 A) place the ESAC injector somewhat beyond the parameter space of operating machines. The key issue is high-voltage breakdown.

Our main task here is to determine the level of confidence for extrapolation to the ILSE regime. In principle, the design of the ESAC injector could be made as conservative as desired by reducing the voltage gradient. The price, however, would be an increase an injector size and, correspondingly, the size of the source, which in turn would increase beam emittance. In the ILSE injector, the window of simultaneously acceptable emittance and voltage gradient is somewhat limited.

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 to accelerate the beam at the same time. The concept was piloted by Abramyan *et al.* [1] in Russia in the late 1960's. More recently, the Magnetic Fusion Energy program at LBL has worked towards the construction of a MV-class ESQ injector [2].

Electrostatic quadrupole transport has, of course, been studied in great detail within our group, both experimentally and theoretically. These experiences notwithstanding, it would be fair to say that much less is known about the ESQ than the ESAC.

In spite of the lack of operational experience, the ESQ option offers some significant potential advantages for HIF applications. The ESQ is generally a longer machine with correspondingly lower gradients. The secondary electrons are quickly swept out by the large transverse fields, decreasing the energy and flux of electrons and X-rays striking the insulators and other critical injector components, which in turn 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 MV, since the critical physics issues in a ESQ tend to center around the low-energy portion, in the transition from preaccelerator into the first few matching quadrupoles. This is in distinct contrast to an ESAC, in which the level of difficulty rises steeply with operating voltage. Finally, since the breakdown risks for an ESQ are much lower in general, there is potentially more room for design improvements to reduce the overall size, so the large number of beams in the final driver could be packaged within reasonable space.

The most critical issue for ESQs is related to beam aberrations (the «energy effect») which, if uncorrected, may lead to unacceptable growth in emittance. Significant effort has been devoted to the theory, simulation and experiments on this topic [3]. Our studies of various issues—most importantly breakdown and protection, beam aberrations, transient beam behavior, and source size and emittance—have led us to select the ESQ for the ILSE injector. The present injector design consists of 4

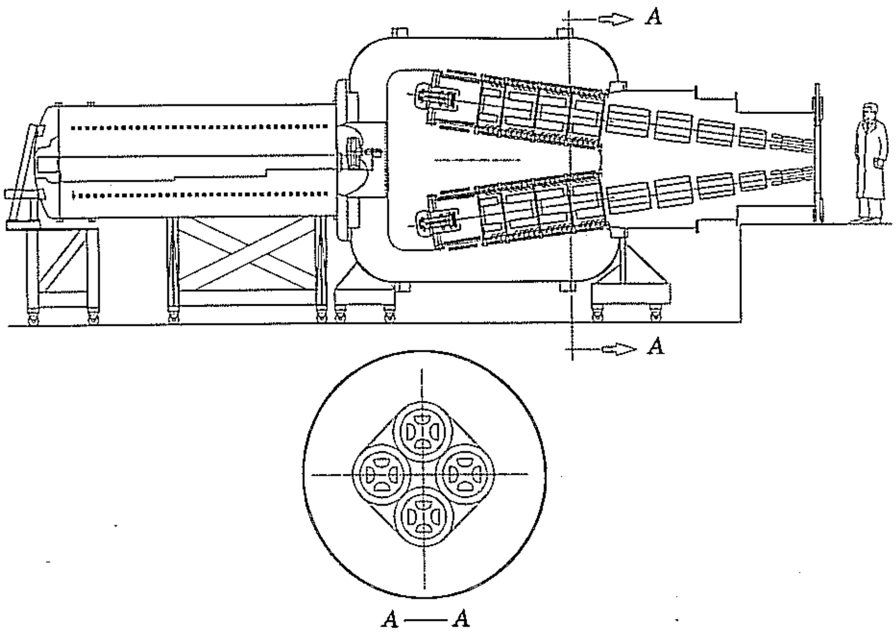

Fig. 1. – The ILSE injector consisting of a high-voltage MARX generator, four independent ESQ columns, and a pre-electrostatic accelerator matching section.

beamlines arranged as shown in fig. 1. Each beamline consists of two major sections: a 1 MV diode and a 4-unit electrostatic quadrupole section to accelerate the beam to 2 MV.

A one-beam version of the 4-beam injector is under construction at LBL. Since the 4 columns in the ILSE injector are essentially independent, the one-beam version addresses most of the key issues for the 4-beam injector. The new injector is powered by a single MARX generator at 2 MV. The pulse duration is 4–5 μs to accommodate the transit of the beams through the columns and settling of associated transients. The power supply is designed to be «stiff» ($< 5\,\mathrm{k}\Omega$), minimizing voltage variations due to beam-loading effects.

The diode consists of a 6.7-inch diameter curved alumino silicate source emitting 0.79 A of K^+ [4]. The geometry of the diode, as calculated by the EGUN code, is shown in fig. 2. The normalized emittance at the exit of the diode is calculated to be less than $0.4\,\pi$ mm mrad.

The diode column is 24 inches long with an inner diameter of 26 inches. A 6.7 inch diameter source with associated heater elements is located midway in the column. The curved source, together with its Pierce electrode, is surrounded by a thick copper electrode, which is maintained at the same potential as the dome at all times. The source is at -80 kV relative to the extraction electrode before beam extraction and is rapidly switched to $+80$ kV for beam production. The extraction voltage wave form has a flat top of over 1 μs and has a rise time of a few hundred nanoseconds. Voltage standoff good to ± 100 kV is provided by small insulator columns at the base of the source-heater assembly. The 24 inch long diode column is subdivided into 16 rings, which are brazed together. At each joint, a shield is appropriately shaped to provide protection at the triple point as well as maximal line-of-sight blockage from

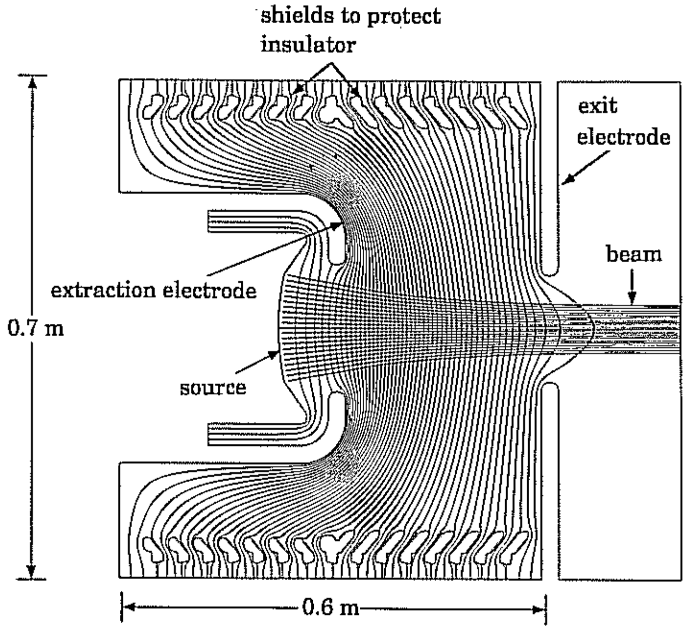

Fig. 2. – EGUN output showing the geometry of the axisymmetric injector diode, the beam envelope, and field equipotential surfaces.

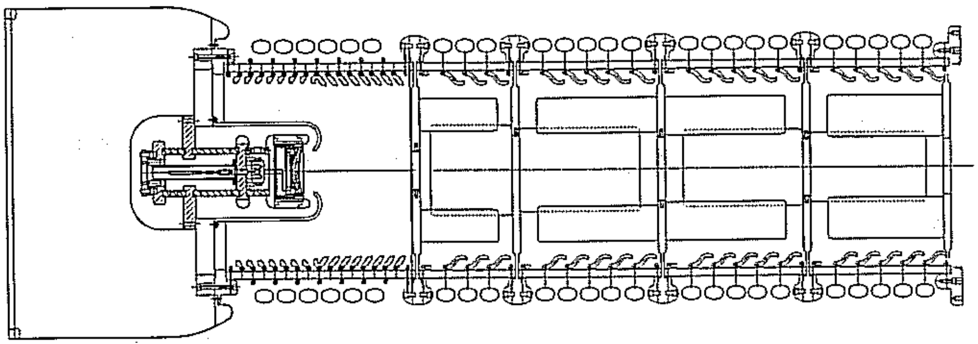

Fig. 3. – Cross-section of the diode and electrostatic quadrupole accelerator column.

TABLE I. – *Parameters of the 4 quadrupole units in the* ESQ *section.*

	Unit 1	Unit 2	Unit3	Unit 4
length (cm)	30	46	46	46
quadrupole aperture radius (cm)	12	10.5	10.5	10.5
quadrupole voltage (kV)	206	259	308	281

X-rays and secondary electrons emitted from the source region. The shields are made from stainless steel in a complicated shape that in most places afford more than 1/2 inch of effective thickness; this helps block energetic X-rays.

The 1 MV ion beam exits from the diode and enters into 4 quadrupole units arranged as shown in fig. 3. The ESQ section consists of 4 quadrupoles with representative parameters given in table I. The special arrangement of electrodes provides the required *A-G* focusing as well as acceleration to 2 MV. The first quadrupole unit is 12 inches long, whereas the succeeding three quadrupoles are each 18 inches long. Each quadrupole sections consists of 3-inch-long porcelain cylinders clamped together with lucite rods external to the column. The shields

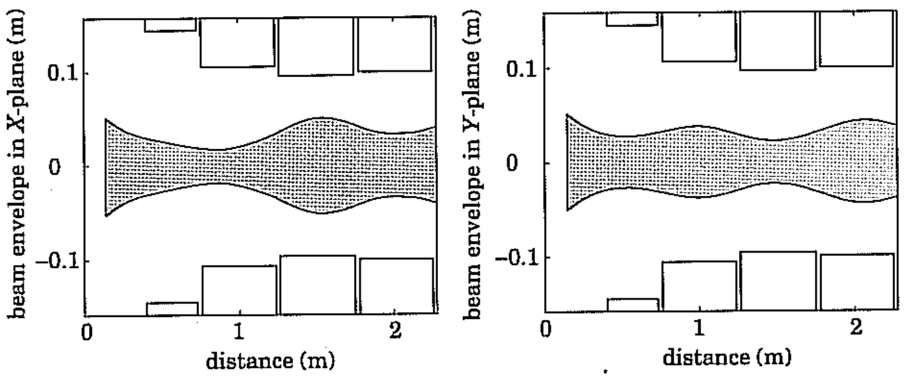

Fig. 4. – WARP3D calculations of the beam envelopes in the injector.

around the column provide triple-point protection, line-of-sight blockage, and shielding against X-rays.

The beam envelopes as calculated by the 3D particle-in-cell code WARP3D [5] are shown in fig. 4. The normalized emittance at the exit is predicted to be less than 0.7 π mm mrad.

In addition to WARP3D, a number of simulation codes have been used in the design of the injector. The diode was designed using EGUN and POISSON. The transient effects have been studied with a 2-1/2-D PIC simulation GYMNOS and the 1-1/2-D simulation with self-consistent circuit modeling HINJ. The beam dynamics effects in ESQ have been studied analytically, with single-slice particle codes, as well as with ARGUS at earlier stages of our program. These simulations, together with the experiments on ESQ beam dynamics, ESQ breakdown, as well as on ESAC beam dynamics [3], have enhanced our confidence in the present design. Checkout of the front section of the ESQ injector is now in progress.

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