Heavy Ion Fusion Injector Program*

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Abstract

A program is underway to construct a 2 MV, 800 mA, K^+ injector for heavy ion fusion. The Electrostatic Quadrupole (ESQ) injector configuration consists of a zeolite source, a diode of up to 1 MV, together with several electrostatic quadrupole units to simultaneously focus and accelerate the beam to 2 MV. The key issues of source technology, high voltage breakdown, beam aberrations, and transient effects will be discussed. Results from ongoing experiments and simulations will be presented.

I. INTRODUCTION

A new high current ion injector for heavy ion fusion is under construction at Lawrence Berkeley Laboratory . The objective is to build a one-beam version of the 4-beam injector needed for the Induction Linac System Experiments (ILSE). As such, the machine must have high reliability, and the technology must be scalable to the ultimate full-scale fusion driver. The design goals for the K^+ ion beam are driver-scale line charge density (0.25 μC/m A), driver scale particle energy (2 MV), very low emittance (normalized emittance of less than 1π mm-mr) repetition rate of 1 Hz, and pulse length of 1 μs. While all previous injectors in the Heavy Ion Fusion Accelerator Research (HIFAR) group at LBL have been based on electrostatic aperture column (ESAC) designs, a six-month study at LBL and LLNL from March to September 1992 has led to the choice of the electrostatic quadrupole (ESQ) injector as the most suitable for the long term need of induction linac-based heavy ion fusion research work. The ESQ is a concept which uses a set of electrostatic quadrupoles to simultaneously focus and accelerate an ion beam. The front end of the ESQ is an axisymmetric diode containing a large source (of up to 7" in diameter according to present designs). The concept originated with Abramyan [1] and has been studied extensively by the Magnetic Fusion Energy group at LBL for a number of years [2]. As a high energy , high current injector, the ESQ concept has the distinct advantage of reduced voltage breakdown risks (as compared to ESAC), resulting from the intrinsically lower accelerating gradient and the presence of large transverse fields to sweep out deleterious secondary electrons.

II. INJECTOR DESIGN

A schematic of the one-beam injector is shown in Figure 1. The key components of the injector are a 2 MV MARX generator, a large hot alumino-silicate source (of ≤ 7" diameter), a diode column in which the ion beam is accelerated to ~ 1 MV after extraction, and a number of electrostatic quadrupoles to bring the ion beam to 2 MV. Furthermore, external to the accelerating columns, protection devices (metal oxide varisters and guard rings) are built in to prevent irreversible damage in the case of major breakdowns.

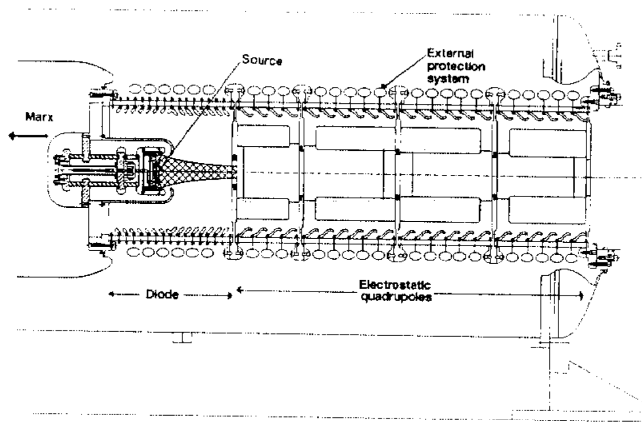

Fig. 1. Schematic of the one-beam injector.

The new MARX is a 36-stage pulse-forming network designed to produce a 2 MV pulse with 1 μs rise and 5 μs voltage flat top. This flat top can maintain constant voltage for the 1 - 2 μs long ion pulse during its transit through the length of the injector (~ 2 μs transit time). To minimize beam-induced transients, the electrical system as designed is quite stiff. The total resistance is 5 kΩ.

Source development is reported in a separate paper in this conference [3]. Tests with a small 1" hot alumino-silicate source over the past year has produced very encouraging results. The measured current density of 20 mA/cm^2, the temperature and emission uniformity, as well as life time have been shown to exceed ILSE requirements under normal operating conditions. A 4" source and a 6" source have been fabricated and initial tests have yielded similar emission characteristics.

The key design constraint for an ESQ injector arises from a distortion of the particle phase space which may lead to an unacceptable increase in beam emittance. This effect arises from a large spread in particle energy with varying radial position when a low energy beam traverses a strong electrostatic quadrupole structure. The phase space distortion resulting from this "energy effect" is further enhanced by the higher order multipole fields intrinsic in an interdigital electrostatic quadrupole structure. Earlier designs with a low energy diode (500 keV) show unacceptable growth in

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emittance. 3D simulations of these effects have been confirmed quantitatively in a scaled experiment [4].

Three design paths have been identified for the reduction of these deleterious beam dynamics effects. First of all, if the diode energy is increased to 1 MV, the emittance growth through an ESQ is shown to be significantly reduced. Secondly, increased quad voltages lead to a reduced beam envelope with corresponding reduction of nonlinear effects. Thirdly, simulations have shown that the distortions are entirely attributable to fourth order single particle effects. Hence, external correction schemes are straightforward in principle, although the actual implementation may be somewhat involved.

The most cost-effective way to design a ESQ with acceptable emittance is to increase diode energy as well as quad voltage. Both of these measures would enhance breakdown risks. Hence, the choice of the optimal ESQ parameters involves a proper balance between breakdown risks and emittance growth.

To determine the quad breakdown voltage for our ESQ designs, we constructed a full-size quad unit with electrodes as well as X-ray shields, and tested the voltage holding capabilities in the absence of beam (Figure 2). The pulsed voltage from an existing MARX generator has a 30 μs rise, and ~10 μs flat-top (Figure 3). For two electrode to end-plate gap spacings of 5.5 cm and 7.6 cm, the breakdown voltages were determined to be 550 kV and 700 kV, respectively. On the basis of these data, we have designed our ESQ quads for voltages of up to 350 kV (7 cm gap spacing).

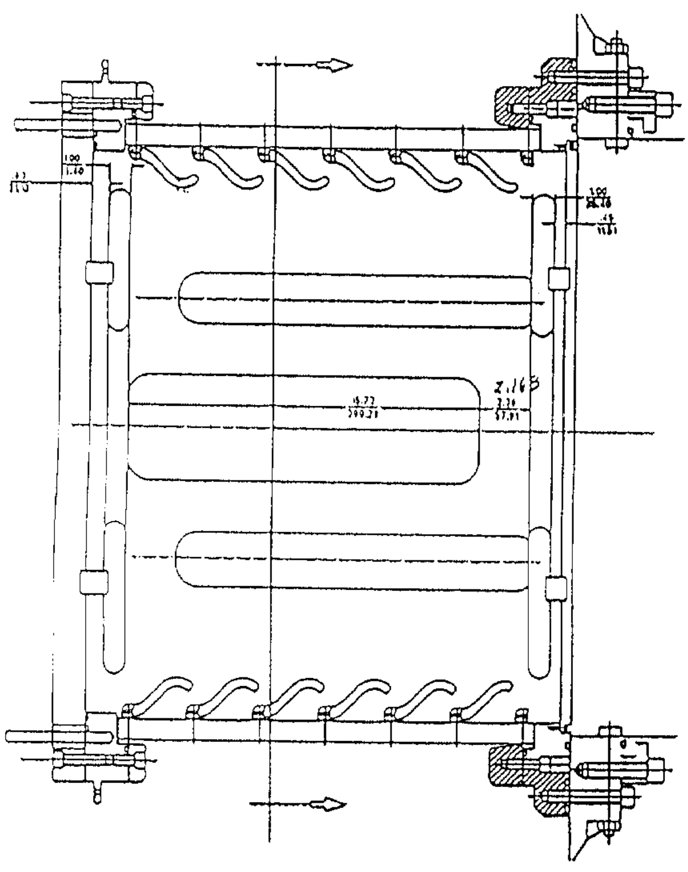

Figure 2. Schematic of the full-size quad breakdown test.

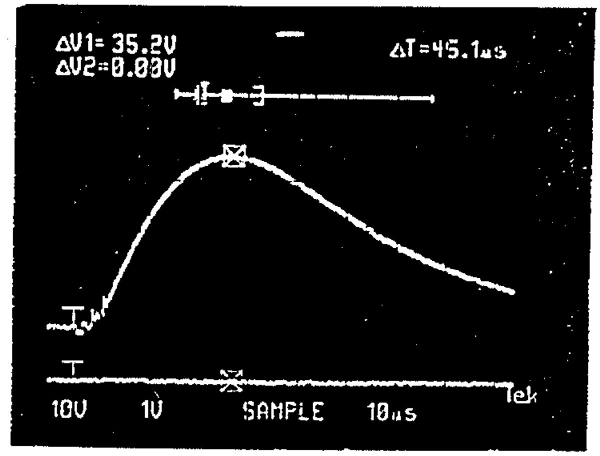

Figure 3. Voltage waveform for quad breakdown test. Peak voltage = 700 kV, pulse length = 80 μs

The diode is designed to hold up to 1 MV. A hot alumino-silicate source with a large (< 7") curved surface is surrounded by a thick copper "extraction electrode." An extraction pulser switches the source from -80 kV to +80 kV relative to the extraction electrode during beam turn-on. The waveform for a low voltage bench test of the extraction pulser is shown in Figure 4. The insulator column is a brazed 16-ring ceramic unit (1.5" per ring) with 1 cm thick stainless steel shields to protect against secondary electrons and X-rays produced by the beam.

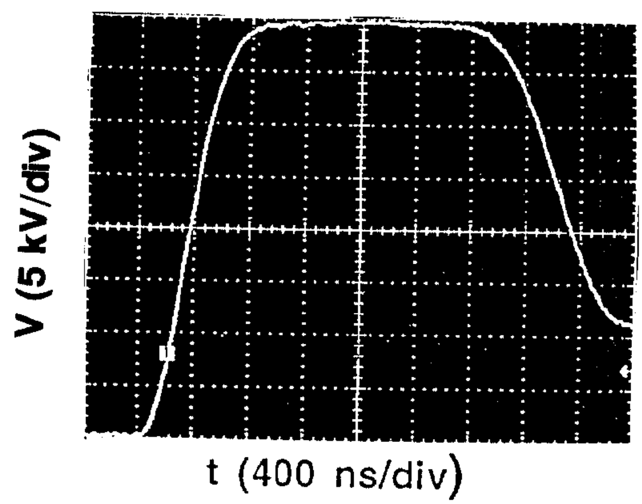

Figure 4. Beam extractor waveform.

The geometry of the diode, as calculated by the EGUN code, is shown in Figure 5. At 1 MV operation, the highest surface field (at the extraction electrode) is about 85 kV/cm, whereas the peak field at the shields is about 65 kV/cm. The average field along the insulator is about 15 kV/cm. The normalized emittance at the exit of the diode is calculated to be less than 0.4π mm-mr.

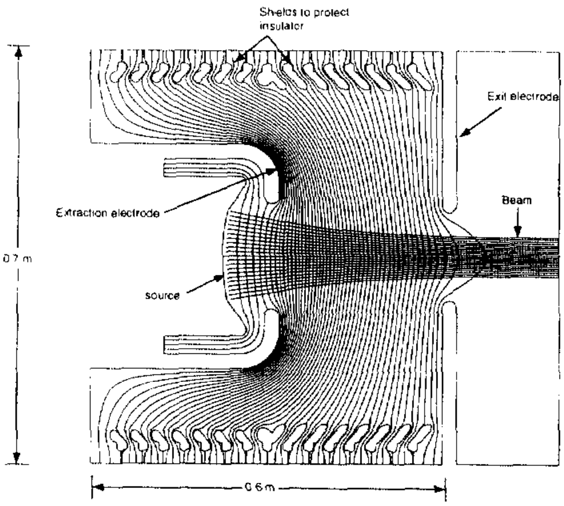

Figure 5. EGUN output showing the geometry of the axisymmetric injector diode, the beam envelope, and field equipotential surfaces.

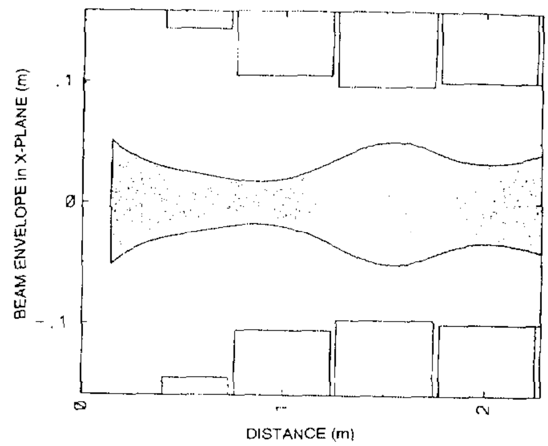

Figure 6. WARP3D calculations of the beam envelopes in the injector.

The ESQ section consists of 4 quadrupoles with representative parameters given in Table 1. The beam envelopes as calculated by the 3-D particle-in-cell code WARP3D are shown in Figure 6. The normalized emittance at the exit is predicted to be less than 0.7π mm-mrad.

	Unit 1	Unit 2	Unit 3	Unit 4
Length, cm	30	46	46	46
Quad aperture radius, cm	12	10.5	10.5	10.5
Quad voltage, kV	206	259	308	281

Table 1. Parameters of the 4 quadrupole units in the ESQ section.

III. REFERENCES

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