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THE BERKELEY INJECTOR†

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The injector being developed at Lawrence Berkeley Laboratory is a sixteen beam device which is to provide 500-mA C^+beams at 2 MeV. The first half of the accelerating column has been tested at full operating voltage and beam experiments are underway. Information on column performance and source development is included.

1 INTRODUCTION

The injector portion of any heavy ion fusion driver is very important because the beam quality available from the machine is no better than that available from the injector. The injector being built at Berkeley is intended for the front end of the ILSE machine[1] but it also serves as a test bed for different approaches to HIF injector problems. In order to meet the ILSE requirements, the machine has to provide the following:

1) Beam energy: 2 MeV
2) Sixteen beams, 340-mA C^+ ions in each beam
3) Normalized emittance per beam: $5 \times 10^{-7}\ \pi$ m-rad
4) Pulse length: 1 μsec
5) Pulse flatness ± 0.1%

The current and energy given above translate into a charge per unit length in the beam of 0.06 μC/m, which is less than the 0.25 μC/m that one might expect in a driver. The technical challenges of building the injector are threefold. First, there is a compact gas-insulated high-voltage generator that provides a long, critically damped pulse to the accelerator column. Second, there is a vacuum

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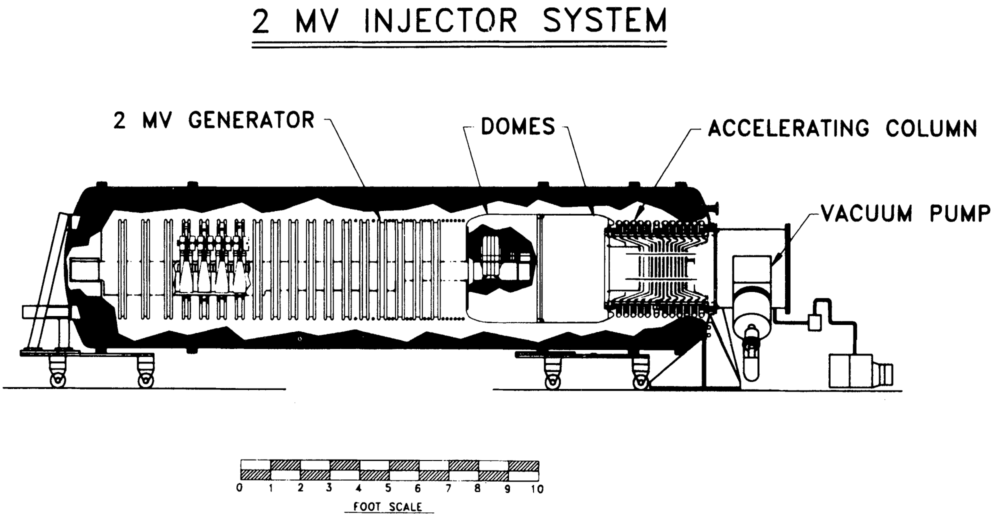

FIGURE 1 The injector system for full 2 MeV operation.

carbon-arc ion source which operates in conjunction with an electrostatic plasma switch that defines the ion emission surface throughout the extraction pulse. Third, there is an electrostatic acceleration column, suitable for sixteen beams, which uses aperture lenses to focus the beam to its exit from the injector. All three of these major components are developmental in nature and press the limits of technology in each area. A picture of the full injector design is shown in Figure 1. At the present time the full generator has been constructed but only the first half of the accelerator column has been constructed. Single beam experiments at the 1 MeV level are being carried out. We will now discuss the three main components in detail.

2 HIGH VOLTAGE GENERATOR

The high-voltage generator consists of a Marx circuit with inductors inserted into the circuit at every other stage (spark gap-capacitor combination). These inductors are large coils 97 cm. in diameter with 100 turns per coil resulting in a self-inductance of 18 mH. The purpose of this unusual inductive loading in the circuit is to slow the rise time to $\sim 30\,\mu s$ without applying the total system voltage to a single inductor. This keeps voltages from overshooting on the accelerator column inter-electrode gaps during pulse turn-on. (Voltage overshoot would occur if a fast pulse were applied to the column because of stray capacitances in the column.) The Marx circuit itself consists of 36 stages composed of 60-nF. 100-kV capacitors in all stages except the ends, which have 120-nF capacitors. The circuit is charged symmetrically using two power supplies with a virtual ground. The entire system is mounted on plastic trays with two stages per tray and with the trays themselves mounted on plastic-impregnated wooden beams, cantilevered from the end of the pressure vessel. Resistive grading of the column electrodes is provided by conductive water resistors. This resistance provides a load to the generator which must be adjusted to give the proper waveform to the acceleration voltage pulse. Once set, the load is kept constant by a commercial conductivity-control system. The interior of the pressure vessel is filled with 80 psig of SF_6 for insulation. The use of a gas insulator is important so that shock-wave-induced fractures of the column insulator do not result in oil contamination of the vacuum system.

The high-voltage generator was used in a twelve-tray version to drive an open circuit rather than the column resistor, thus allowing the circuit to be rung up to higher than its critically damped output. This version tested the suitability of the dome-vessel sizing for use at 2 MV. Since then the twelve-tray version has been used for 1-MV experiments with beam and for column high-voltage conditioning. Lifetime tests run on the capacitors indicate that a life of more than 2 million shots is expected. Tests on the spark gaps indicate comparable life, but only with strict control of air quality. The normal repetition rate for the generator is 5 shots per minute.

3 ION SOURCE

The ion source is a vacuum carbon arc. The arc is a lightweight source which does not require large amounts of power as a hot-plate source would. The cylindrical carbon cathode sits on the end of a ceramic rod which contains two tantalum trigger wires. A flashover on the end of the ceramic rod between the wires generates a trigger plasma that shorts the gap between the carbon cathode and the stainless steel anode

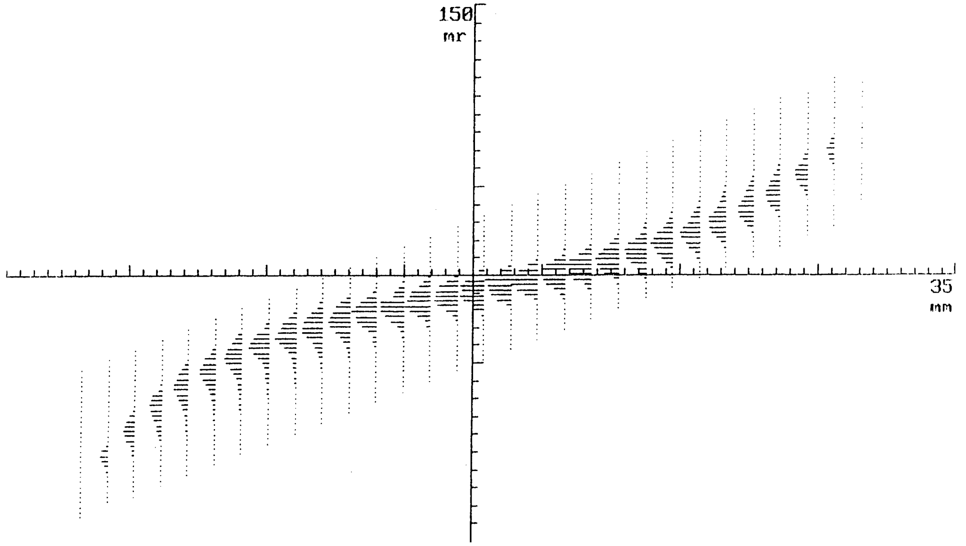

FIGURE 2 Carbon arc source emittance scan for a 2 inch aperture beam using double slit method.

0.032 inch away. An L-C pulse forming network is discharged across the gap and the resulting plasma drifts through the anode hole and down a tube, which is 10 cm long, to the plasma switch. The plasma switch consists of two grids, one of which is on the end of the plasma drift tube and the other of which is biased at -45 to -75 V with respect to the first. This grid, described elsewhere,[2] defines the emission surface for ions injected into the column. The use of the plasma switch eliminates optical variation due to transient effects in a plasma meniscus during pulsed extraction.

Carbon is being used because ILSE is a scaled experiment using comparatively light ions to perform transport experiments that simulate the transport of heavy ions. The vacuum source was selected because the cathode material is solid and thus the gas load created in the column when the source is fired is transient. Continuously fed gas sources would create unacceptably high background pressure in the acceleration column, resulting in beam loss due to charge exchange.

The main features of interest as far as the source is concerned are current density, emittance, and lifetime. The first two quantities can be combined into brightness. The current density required for the ILSE application is 25 mA/cm^2, and 32 mA/cm^2 has been achieved. Normalized emittance for the carbon arc source in test stand experiments has been 2.0–2.5 $\times$ 10^{-6} π m-rad. The emittance is measured by a two slit method using one shot for each point in phase space. A typical scan is shown in Figure 2. The normalized emittance for this run of 900 shots was 2.33 $\times$ 10^{-6} m-rad. The curling in the plot is due to planar optics aberration in the test gun. The quoted emittance is the value after subtraction of that aberration. An earlier version of the source using three small carbon rods as cathodes achieved 1.6 $\times$ 10^{-6} π m-rad. In this version the pulse-forming network (PFN) energy was split among three simultaneous discharges. The small diameter rods were quickly eroded, however, and the change to a single large cathode was made. The grid in the plasma switch has a large effect on the output emittance because the ions passing through the grid see transverse electric fields near the wires. This effect has been simulated and is described in another paper at this Symposium.[3] Experiments are underway to see if it is possible to reduce the emittance by dropping the plasma switch potential, coincident with extraction. In the experiments done so far dropping from $\sim$55 V to 15 V had no observable effect on the emittance plot. The switch voltage was dropped on a time scale comparable to the rise time of the test stand extraction pulse. New electronics have been developed to force the voltage lower than the plasma floating potential. If the emittance cannot be reduced, some other way of dealing with transient extraction will have to be used because the beam-combining scheme in ILSE requires low initial emittance.

The lifetime of the source is another very important issue, especially when one considers HIF drivers that must last for years. The present lifetime limit of the arcs we have tested is 20 000–30 000 shots. The limiting factor seems to be carbon coating of the flashover trigger. Eventually enough carbon builds up to prevent the trigger from igniting. No long-term remotely applied cure for this has been found; eventually the source must be removed from the system and cleaned. One possible improvement is to reduce the arc pulse length from 100 μs at present down to 20 or 30 μsec. This may only improve the lifetime by a factor of three or so. A lifetime of 100 000 shots would be fine for a beam physics experiment but not for a driver. The source is presently being used with a 250-A arc current in the interests of long life, but the electronics are capable of 350 A. Because of the emittance and life problems, a gas source that is puff-filled may be a better solution, but since the plasma switch is the root of the emittance problem some other way of controlling the optics in a short pulse would have to be found. For the present, the carbon source will be used to study the behavior of the acceleration column.

4 ACCELERATION COLUMN

The high-voltage acceleration column is a high-gradient aperture-lens structure designed with the EGUN[4] computer code. In addition to providing beam for experiments, the column is a test of what can be achieved with relatively high field stresses in a structure that has very high beam currents flowing in it. Figure 3 shows the structure of the first half full column. The actual full design voltage of the structure is 944 kV. The system is designed to have a 1 μs current pulse of 500 mA C^+ ions injected into it after the full acceleration potential has been applied to the column (30 μs). The flat top ($\pm 0.1\%$) top of the voltage pulse is 2.5 μs wide. Injection is accomplished with a current valve, which is a 9.75-mm gap immediately to the right of the plasma switch. Ions are extracted with a 13.6 kV pulse from a PFN at the plasma switch grid. The ions exit through a 90% transmitting electro-deposited nickel grid whose openings are 0.036 cm square.

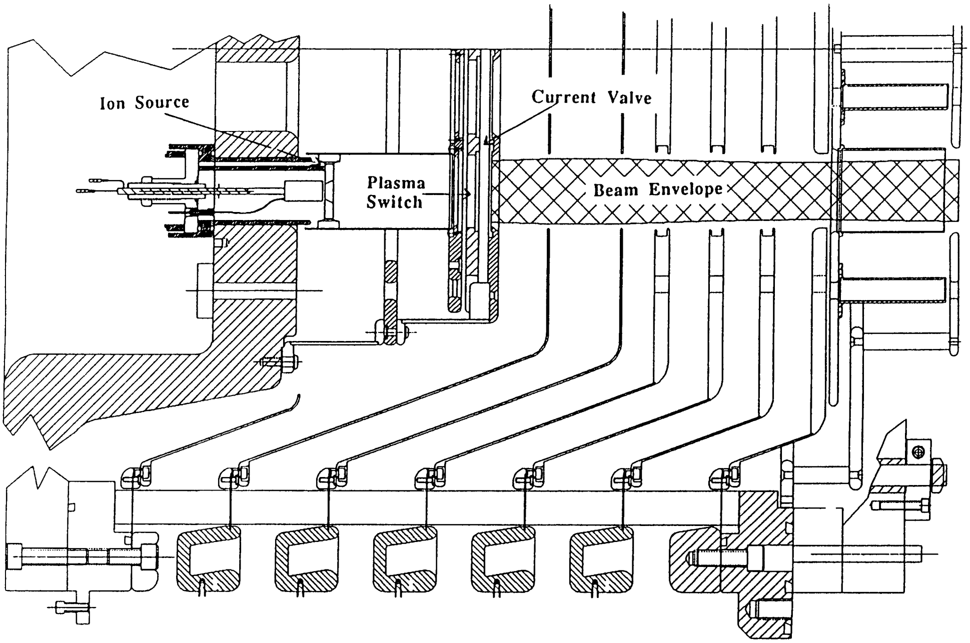

FIGURE 3 The first half of the acceleration column suitable for 944 KeV use showing ion source, plasma switch, current valve, and acceleration electrodes.

The current valve has been set up on a test stand to see how it operates in the presence of fields from the main accelerating voltage. The first gap after the current valve was re-created and the design voltage of 69.4 kV was applied to it. The electric field from this gap penetrates back through the nickel mesh to the plasma switch grid, and ions are extracted for the duration of the extraction pulse while no voltage is applied to the current valve. The level of current appears to be about 20 mA over the full 20-cm^2 aperture. This low level of leakage can hopefully be tolerated in the machine downstream of the injector. Attempts were made to keep the electric field from penetrating by using multiple grids of the same type that is used for the current valve grid. The grids were separated by 0.157 cm in the case of two grids and 0.785 cm in the case of three grids. The concept was to simulate an array of tubes whose length was several times their diameter. Some reduction of leakage current attenuation was seen, but the reduction could be accounted for by the additional geometric attenuation of the additional grids. The current valve pulser was also fired at full voltage with the source in operation and the voltage pulse applied was monitored. No distortion of the desired voltage pulse was seen though there is high-frequency structure on the current pulse. Therefore if the low leakage current can be lost in a non-destructive manner, the current valve is ready for use.

The column itself is constructed from 6 Al 4V titanium alloy. This material was chosen because of its superiority to stainless steel in the production of secondary electrons. Each electrode was custom-built to the contours of the EGUN design in two pieces. The inner flat portion containing the sixteen beam holes was laser welded to an outer conical section. Special holes are provided in the flat section for alignment rods used in assembly. The column was assembled in a temporary clean room, and precautions were taken to protect it from debris during installation on the injector itself. After the column was installed it was dc conditioned up to the normal single-section voltage of 175 kV. The conditioning proceeded section by section. In some cases 1 to 1.5 h was needed before conditioning was achieved. After two or three days of this, voltage from the generator was applied to the column and full design voltage was achieved in less than one hour. The column was taken to 110% of design voltage.

The beam experiments done so far have been without the current valve. The plasma switch grid was temporarily placed at the normal location of the current valve grid. With extraction using the full acceleration voltage waveform directly from the plasma switch grid, the EGUN code predicts a 300 mA peak current at 944 kV. The current from the column was measured using a 30-cm-deep Faraday cup with a 10-cm aperture. Peak currents of 220 mA were observed. The measured current from the cup did not depend strongly on the bias voltages in the cup, which has a 12.7-cm long cylindrical electron suppressor upstream from the 12.7-cm deep cup. The column was able to produce long pulse currents at full voltage at the design rate of 5 shots/min. After the current measurements, the system was set up for automated emittance scanning, which uses the double slit method and one shot for each data point. Normally in these tests 900 shots are consumed to get one emittance plot. A full scan was complete though the source started to have a high misfire rate toward the end. Enough data was present to compare the output beam with the

EGUN predictions. Agreement was reasonable. It must be emphasized, however, that the column did perform very satisfactorily at full design voltage and a high beam current in rep-rate usage. After full characterization of the column in this mode the current valve will be installed and full beam current will be injected.

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