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TITLE: A HIGH-CURRENT FOUR-BEAM XENON ION SOURCE FOR HEAVY-ION FUSION

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ABSTRACT

The growing interest in inertial confinement fusion using heavy ions has elicited from the Los Alamos Scientific Laboratory a proposal[1] to use a multi-channel radio-frequency quadrupole (RFQ) structure for the initial stage of the heavy-ion accelerator. The RFQ would have 4 channels in each module and each channel would accelerate 25 mA of Xe^{+1}. Based on experiments with xenon beam production with a high current duoPIGatron source at Chalk River Nuclear Laboratories[2], a 245 keV 4-beam xenon injector has been designed for this 4-channel RFQ. The injector is of modular design with 4 small independent plasma sources mounted in a 10 cm square array on a common combined extraction and acceleration column. The electrodes have 4 separate sets of apertures and each channel produces a 29 mA beam for injection into its corresponding RFQ channel. This paper presents a conceptual design for the injector, code calculations for the column electrode design and results of a preliminary test carried out to verify the feasibility of the concept.

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Introduction

At the present time one of the most promising approaches to inertial confinement fusion is the use of high energy (1-10 GeV), high power (∿ 100 TW) beams of heavy ions to implode and ignite a pellet. To achieve this power a 100 μs, 1 A beam is compressed to a 1 ns, 10 kA pulse before striking the pellet. The radiofrequency linac provides an efficient accelerator for such beams at high energy. At the low energy end of the accelerator, where space charge forces are very high, the radiofrequency quadrupole (RFQ) accelerator currently being developed at the Los Alamos National Scientific Laboratory appears promising, especially if a funneling technique is used. Eight 4-beam RFQ accelerators would be used to feed a system of electrostatically and magnetically focused linear accelerators to give a 0.8 A, 3 GeV beam.

The RFQ has two advantages that greatly ease injector design. Firstly it requires a relatively low injection energy - approximately 250 keV for Xe^{+1}. Secondly it has a capture efficiency of 97%[3] so the injector need provide only 26 mA of Xe^{+1}. The four beams must be in a 10 cm square array to match the RFQ channel spacing. Each beam should be slightly converging and less than 3.5 cm diameter where it enters the RFQ matching section. Normalized emittance for 90% of the beam should be less than 0.07 π mm•mrad. A source that provides a high ($\sim$ 90%) fraction of Xe^{+1} would make magnetic separation unnecessary and permit a close coupled design which would greatly ease beam transport. High source gas efficiency is required to reduce charge exchange losses and reduce the gas load in the system. High arc efficiency would ease the requirements for cooling and for power delivery to the high voltage dome (at 245 kV). A high-current heavy-ion duoPIGatron source developed at the Chalk River Nuclear Laboratories[2] provides an ideal plasma generator for this injector. This source has produced xenon beams of up to 100 mA with current densities of over 70 mA/cm^2. At this current, total power consumption (arc, filament, and coil) is less than 500 W and the gas flow is approximately 1.4 atm cc/min.

Injector Description

The injector uses four plasma sources or a 10 cm square array because a single source that would provide the desired current density over a large area would require an extremely high arc power. The four sources are mounted on a common extraction and acceleration column that uses an Einzel lens to provide the required focusing. High-voltage column design techniques developed at Chalk River[4] are used to ensure reliable operation. To provide consistent beam characteristics with different pulse lengths and duty cycles, the plasma sources operate continuously and an extraction electrode is pulsed to give the desired pulse length and duty cycle.

The plasma sources are essentially a duplicate of those developed at Chalk River, with minor mechanical modifications to suit the rather cramped quarters. As the required current is much below the rated current of these sources, and low current operation enhances the Xe^{+1} fraction, the design current density is chosen to be 58 mA/cm^2, well below the normal operating value of 70 mA/cm^2. A single 8 mm diameter plasma aperture is used to give 29 mA of mixed beam which, at 88% single charged fraction, gives the required Xe^{+1} current. For this current each arc supply must provide 10 A at 25 V (250 W) with approximately 50 V required for starting. Each coil requires 0.8 A at 40 V (32 W) and each filament requires 40 A at 3 V (120 W). Gas flow per source is approximately 1.2 atm/cc/minute.

One problem encountered in the development of this design was interference between the fields of adjacent sources. Since the PIG region of the source operates in the fringing field from the intermediate electrode and fields at the extraction apertures are small (less than 15 gauss), relatively small perturbations can strongly affect source operation. This was in fact the case. When a second coil with an intermediate electrode inserted was energized near an operating source the extracted beam current dropped to approximately 25% of its original value. Magnet shimming experiments carried out on a two-module mockup (with beam extracted from only one module) showed that the field perturbation could be overcome by judicious placement of thin ($\sim$ 1 mm) sheets of iron and that normal source operation could be restored. Positions of the magnetic shims as determined from the two-module test are shown in the illustration of the source (Fig. 1). The simple geometry of these shims should make shimming of the four-module source relatively straightforward.

Figure 1 shows one quarter of the extraction and acceleration column and one plasma source module. The first column electrode holds the molybdenum plasma aperture plate with a 8 mm diameter shaped aperture. For convenience the potential of this plate will be defined as zero volts. The next electrode is the extraction electrode which is held at +30 V between pulses to prevent plasma flow into the column. During a pulse it is at -45 kV to extract the beam. The next electrode is part of the Einzel lens and is at -10 kV. The following electrodes are at -45, -145 and -245 kV with respect to the plasma aperture plate. The bottom electrode incorporates a magnetic electron-suppression element to prevent damage from backstreaming electrons during the pulse. As is shown, the vanes of the RFQ penetrate into the bottom of the column. The ceramics are convoluted to reduce surface tracking and are well shielded to reduce photo-electron production by bremsstrahlung radiation from backstreaming electrons. The active regions of all electrodes are of molybdenum to reduce beam-induced sparking. The outside of the column is insulated with low pressure SF_6.

The extraction, focusing and acceleration optics were designed using BEAM, an ion beam extraction and acceleration modeling code being developed at Chalk River by the authors and R.A. Judd. Figure 2 shows the configuration of the central region of the electrodes and the calculated ion trajectories for a 29 mA beam. At the entrance to the RFQ, the beam is 1.3 cm diameter and slightly convergent. The extraction voltage and the voltage on the lens electrode can be varied to change the beam size and divergence as required by the final design of the RFQ.

Initial plans were to measure the beam emittance from an accel-decel mockup of the first stage since this stage, and especially the plasma surface, has the strongest effect on emittance. However the low energy and high current of the beam made it impossible to design an accel-decel column with sufficient electron suppression with the available power supplies. An estimate of the emittance can be made by extrapolation from the values measured on a 13 mA, 32 keV beam from a 5 mm diameter plasma aperture (ε_n = 0.037 π mm·mrad for 96% of the beam). Constant brightness scaling would give a normalized emittance of 0.055 π mm·mrad for 96% of the beam while a scaling with the emittance proportional to the aperture diameter gives 0.059 π mm·mrad. Both of these are well within the desired value of 0.07 π mm·mrad for 90% of the beam.

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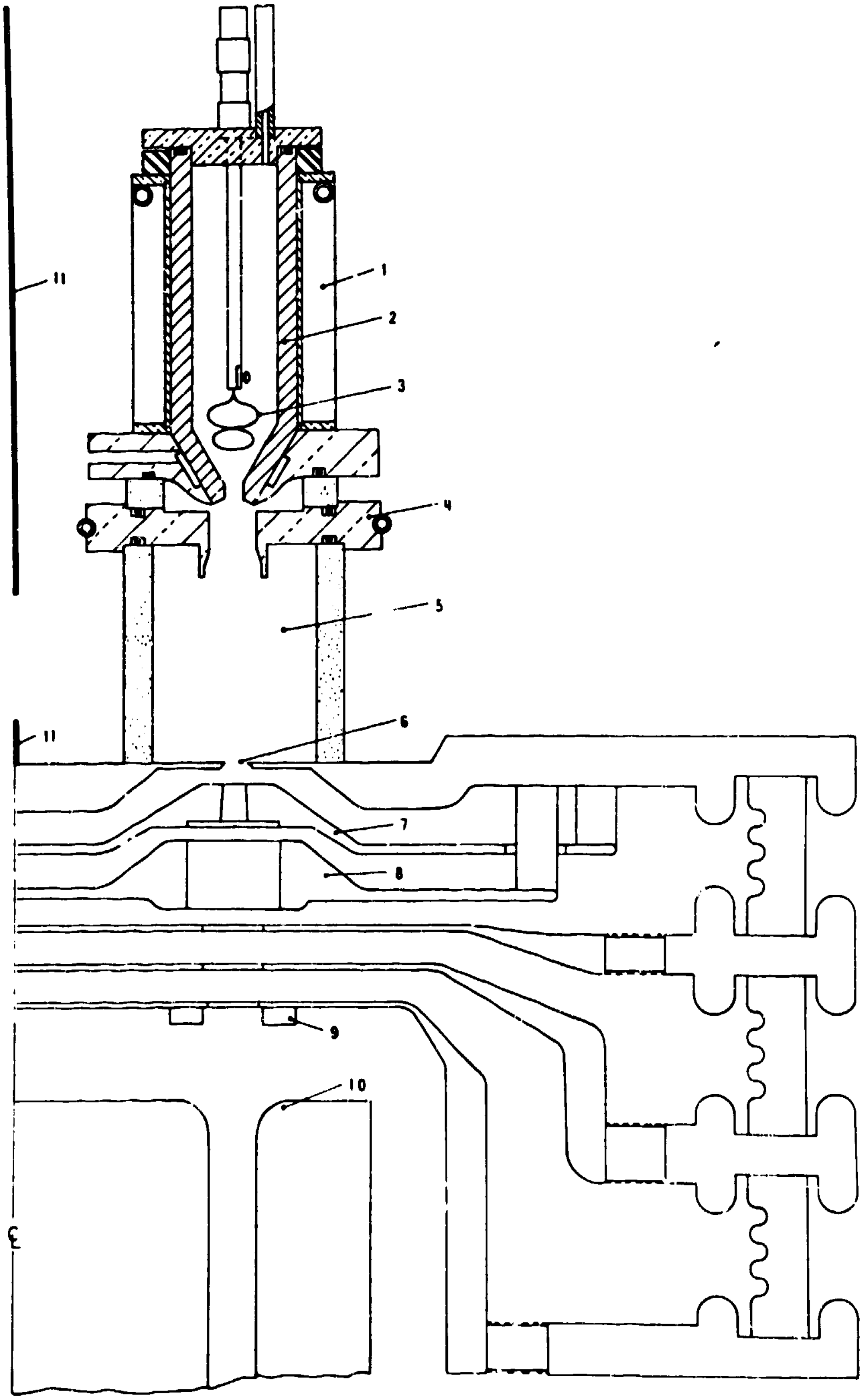
Figure Captions

Figure 1. One quadrant of the injector showing:

(1) compressor coil
(2) iron intermediate electrode
(3) cathode
(4) anode
(5) PIG region
(6) extraction aperture
(7) extraction electrode
(8) lens electrode
(9) suppression magnet
(10) RFQ vanes
(11) magnetic shielding.

Figure 2. Computer simulation of ion beam optics in the injector.



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