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HIGH CURRENT DENSITY BEAMLETS FROM AN RF ARGON SOURCE FOR HEAVY ION FUSION APPLICATIONS

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Abstract

In a new approach to develop high current beams for heavy ion fusion, beam current at about 0.5 ampere per channel can be obtained by merging an array of high current density beamlets of 5 mA each. We have done computer simulations to study the transport of high current density beamlets and the emittance growth due to this merging process. In our RF multicusp source experiment, we have produced a cluster of 61 beamlets using minimum gas flow. The current density from a 0.25 cm diameter aperture reached 100 mA/cm^2. The normalized emittance of 0.02 π-mm-mrad corresponds to an equivalent ion temperature of 2.4 eV. These results showed that the RF argon plasma source is suitable for producing high current density beamlets that can be merged to form a high current high brightness beam for HIF application.

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1 INTRODUCTION

The induction linac's approach to heavy ion driven inertial fusion (HIF) will use high current ion beams that have > 0.5 ampere per channel from their ion sources. An HIF driver system may have an array of N≈100 parallel ion beams with a final beam energy in the multi-GeV range. A general description of the ion source and injector requirements along with various options can be found in our previous papers [1, 2].

High current heavy ion beams have significant space-charge effects. Based on space charge limited flow, when producing high current from a single contiguous beam, the current density decreases as the beam current increases. Thus the traditional way for HIF is to use low current density, large aperture, contact ionization sources [3]. Unfortunately, the large source diameter limits the beam brightness, and results in an injector (and matching section) that is very large in size.

More recent HIF target designs favor slightly lower ion mass (atomic mass < 100) with lower final beam voltage and higher beam current. Our goal is to develop an alternate HIF ion source and injector approach that can be extended to higher current (e.g. several amperes) but not large in size. Nowadays, the systems that have similar demand in beam current are the deuterium neutral beam injectors used in tokamak (a magnetic fusion device) and the xenon ion propulsion systems used in spacecraft. In both cases, a plasma ion source is fitted with an extraction grid containing multiple small apertures to form a large number of beamlets. Since the beamlets are small size, the current density of each individual beamlet can be high. The beamlets are designed to merge into a single beam upon leaving the accelerator. Ultimately, the figures of merit in comparing different systems are the final average current density and emittance of the merged beam as well as the system size and complexity.

In our studies we found that a high current beam with sufficiently high brightness can be obtained by merging a large number of high current density beamlets. The average current density was improved in comparison to the traditional method of using large diameter contact ionization sources resulting in nearly a factor of six reduction in size for the injector system. In this paper we report recent results obtained in the simulation of merging 91 beamlets that shows an emittance growth and also results obtained from testing an RF argon plasma source that produced 61 beamlets with current density exceeding 100 mA/cm^2.

2 SIMULATION STUDY OF MERGING BEAMLETS

In merging multiple beamlets, the high current density beamlets (each beamlet has only a few mA of current) are kept separated from each other by the acceleration grids in order to overcome the space charge expansion. After they have gained sufficient kinetic energy (e.g. > 1.2 MeV), the beamlets will be allowed to merge together to form a high current beam (e.g. > 0.5 A). Figure 1 shows a schematic diagram of an injector based on this concept. In order to obtain high average beam brightness, the preaccelerator makes use of an Einzel lens system designed to accelerate 2 mm diameter K^+ ion beamlets to 1.2 MeV kinetic energy with current density up to 100 mA/cm^2.

The main physics issues for merging beamlets are envelope matching and emittance growth in the merging process. The front end of an HIF induction linac uses electrostatic quadrupoles (ESQ) for beam transport. An innovative way to produce a matched beam into an ESQ channel is to aim the beamlets differently in the two transverse planes such that, when merged, the beam spot at the entrance to the ESQ channel is an ellipse with a matched envelope divergence. The injector system is therefore purposely designed to be astigmatic using different x and y focal planes. The result as shown in figure 2 is a very short matching section and the beam envelope excursion is minimized.

Theoretically, the emittance growth (normalized to a constant beam current) is minimized when the beamlet energy is high, the number of beamlets is large, and the beamlets are close to each others [4]. Recent computer simulations by Grote [5] further showed that the final emittance also depended on the initial beamlet convergent angle (best at around –2 to –4 mrads) and the ion temperature. Nevertheless the ion temperature dependence was weak, thus ion sources with high ion temperature can be used as long as the average current density remains high. Figure 3 shows the evolution of 91 beamlets in configuration space and phase space. The x and y rms emittance was found to initially rise to different values because of the elliptical shape but later came to an equilibrium value (average between x and y emittance) after a few undepressed betatron periods (in about 10 m distance). The beam halo produced was about 1%.

3 EXPERIMENTAL SET UP

Figure 4a shows a cut-out view of the multicusp source that has the dimension of 26 cm ID x 25 cm deep. The chamber, made of stainless steel, is surrounded by 38 rows of permanent magnets. The RF antenna has a loop diameter of 10 cm with a quartz tubing surrounding the conductor. The antenna is driven by a 13 MHz RF oscillator capable of delivering up to 18 kW of RF power (measured at the oscillator output) with a pulse length > 1 ms. Since the custom-built RF oscillator is small, it can be placed inside a "hot box" at ion source potential without needing a RF isolation transformer.

Figure 4b is a photograph of the extraction grid on top of the beam-forming electrode. The one shown here has 61 apertures, but there was another one that has only a single aperture (on axis) for studying the current and emittance of an individual beamlet. Typically, the plasma is started at least 500 μs before turning on the high voltage extraction pulse. The maximum available extraction voltage is 100 kV and the beam pulse length is typically around 20 μs.

The beam current was measured by a Faraday cup. By locating a Faraday cup at about 2 meters from the source, time of flight measurement allowed separation of different charge states. Measurement of projectional emittance was done by using a double-slit scanner. The gas pressure referred to that inside the source chamber during a steady flow.

4 EXPERIMENTAL RESULTS

In a previous experiment, we have demonstrated the production of a heavy ion beamlet with current density exceeding 100 mA/cm^2 by using a 10-cm diameter rf-driven multicusp gas source with a 3-mm aperture [6]. However, the source gas pressure, at > 20 mTorr, was considered too high for HIF application. With the new 26-cm diameter source, we found that the gas efficiency was improved such that the optimum gas pressure was around 2 mTorr. The data shown in figure 5 was taken from a single 2.5-mm diameter beamlet at the center with the source pressure set at 2 mTorr. Current density reached 100 mA/cm^2 at the highest RF drive. For lower extraction voltages, the curves peaked at Child Langmuir space charge limits.

Figure 6 shows the data from time of flight measurement. The Ar^{2+} and Ar^{3+} fractions increased with RF power; at the power level of interest to us the singly charge fraction is near 90%. The emittance is minimized when the source current density (controlled by RF power) matched the space charge limit (controlled by the extraction voltage). A typical emittance diagram is shown in Fig. 7. The normalized emittance of 0.02 □-mm-mrad has an equivalent ion temperature of about 2.4 eV. The uniformity of current density over a large extraction area was demonstrated by imaging the array of 61 beamlets on a kapton film as shown in Fig. 8. The data confirmed that current variation was within +/- a few percents.

5 CONCLUSION AND ACKNOWLEDGEMENT

Our simulation results confirmed that a high current and high brightness heavy ion beam could be obtained by merging high current density beamlets. This method significantly reduces the size of the injector and matching section. Experimental results also showed that the RF argon plasma source is suitable for producing the high current density beamlets required for HIF application. At present, we are designing curved electrodes that will allow us to merge the beamlets and study the emittance growth.

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Figure Captions:

Figure 1. A conceptual injector design based on merging an array of high current density beamlets.

Figure 2a. An elliptical arrangement of beamlets.

Figure 2b. x and y beam envelopes matched into an ESQ channel.

Figure 3. Merging 91 beamlets in configuration space and phase space.

Figure 4a. A 26-cm ID multicusp source for producing high current beams.

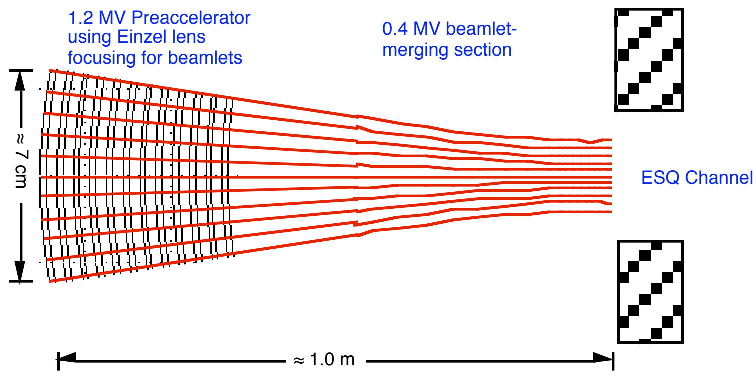
Figure 4b. A 61-aperture extraction grid.

Figure 5. Extracted current from a single beamlet at 2 mT source pressure and at various extraction potentials.

Figure 6. Argon ion charge state fractions vs. RF power.

Figure 7. Ar+ Emittance diagram for the 26-cm multicusp source.

Figure 8. Image of 61 beamlets on a Kapton sheet. The fine lines on the beam spots are due the presence of a mesh in front of the Kapton to neutralize the deposited beam charge.



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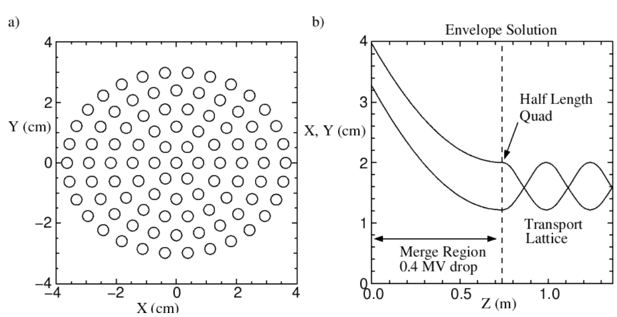

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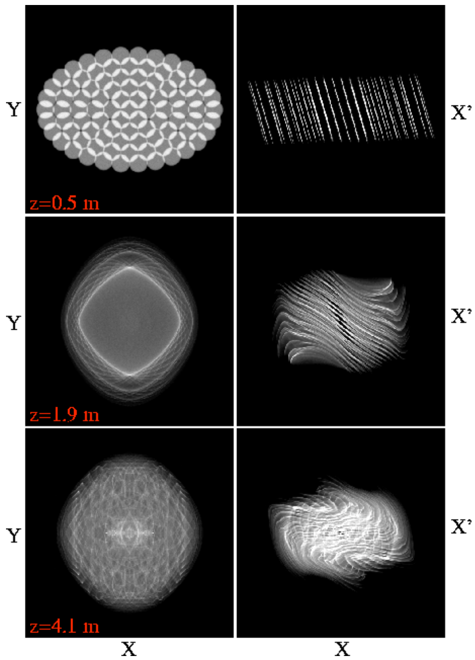

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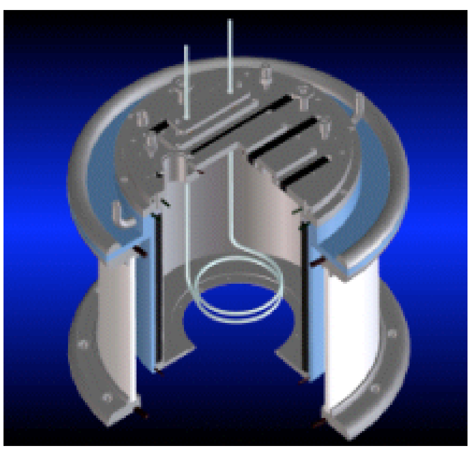

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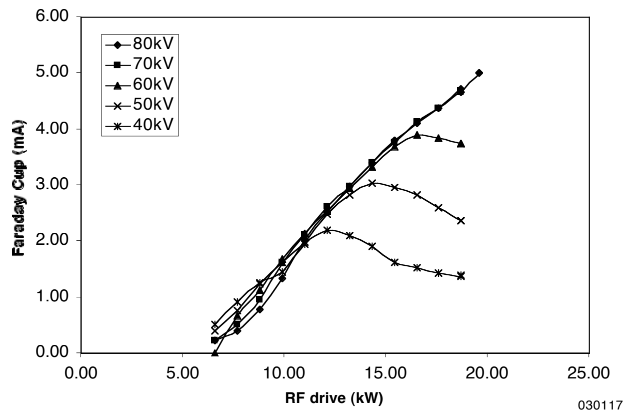

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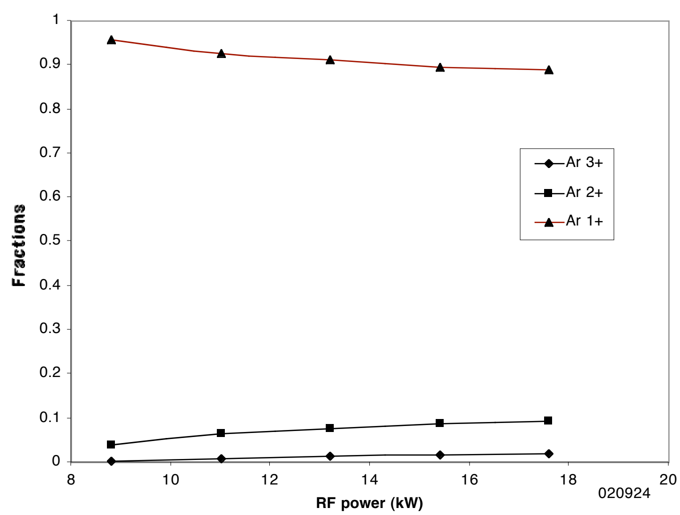

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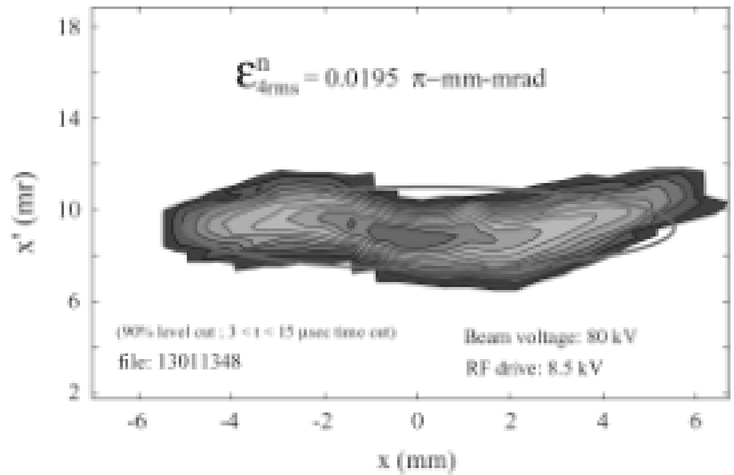

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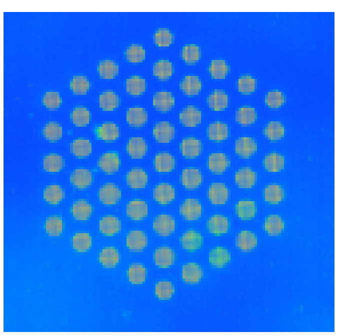

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