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COMPACT HIGH-CURRENT HEAVY-ION INJECTOR*

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Abstract

To provide a compact high-brightness heavy-ion beam source for Heavy Ion Fusion (HIF), we have been experimenting with merging multi-beamlets in an injector which uses an RF plasma source. An array of converging beamlets was use to produce a beam with the envelope radius, convergence, and ellipticity matched to an electrostatic quadrupole (ESQ) channel. Experimental results were in good quantitative agreement with simulation and have demonstrated the feasibility of this concept. The size of a driver-scale injector system using this approach will be several times smaller than one designed using traditional single large-aperture beams. The success of this experiment has possible significant economical and technical impacts on the architecture of HIF drivers.

BACKGROUND

Following a proposal that the usual limits on brightness for compact ion-beam sources used in Heavy Ion Fusion can be circumvented by using a multi-beamlet injector[1], we performed experiments to examine practical issues. The final source envisioned will start with 200 5-mA beamlets across a 100-kV gap. The beamlets will be focused by Einzel Lens while their energy is increased to about 1.2 MeV. The beamlets are then merged to produce a 1-A beam with a normalized 4*rms emittance of about 1 π-mm-mrad at 1.6 MeV. For the envisioned source we need a low-temperature source that can provide ion emission densities of ~100 mA/cm^2, and would like to use electrical fields with strength on the order of 100 kV/cm. The main beam transport issues involved in the multi-beamlet approach are emittance growth and envelope matching in the merging process.

INDIVIDUAL BEAMLETS

We used an rf plasma source to produce the argon ion beamlets. The plasma chamber had a 26-cm inner diameter with multicusp permanent magnets to confine plasma. RF power (13 MHz) was applied to the source via a 2-turn, 11-cm diameter antenna inside the chamber. The RF power was typically applied for about 400 μs while the accelerating gap voltage was typically applied on for 20 μs. We have shown that we could extract 100 mA/cm^2 from the chamber. Optimum performance at 80 kV was achieved with ~2 mTorr gas in the plasma chamber using 22 kW of rf drive power. The lowest emittance (optics) was achieved when the beamlet current was slightly below the peak current value. Current density was found to increase with RF power as long as there was sufficient extraction voltage. At 80 kV, we have reached our goal of producing 100 mA/cm^2 of Ar$^+$ ions (i.e. 4.9 mA per beamlet). For operation with 10 kW of drive powers we estimated that less than 5% of the extracted ions were in the Ar^{++} state. The thermal temperature of the ions was below 1 eV. Additional details about the rf plasma source have been published [2,3,4].

GRADIENT EXPERIMENTS

The Full Gradient Experiment was designed to test the electrical gradient limit in the working environment of the RF Plasma source. The dimensions and electric fields are typical of what we would like to use in a driver scale injector. Since we were limited to about 400-kV of pulsed voltage, only the first 5 gaps of a full system could be tested (See Fig. 1). To reduce the cost we did not use curved plates. The highest vacuum electric field gradient occurred between the 2nd plate and the 3th plate, and was 100 kV/cm on axis for a 1.2 cm gap. Fields at the edge of the holes were expected to be about 120 kV/cm for this experiment. For these experiments we tested a 61-beamlet extraction array using a series of Einzel lens[4]. The source apertures were 2.2 mm in diameter while all the other electrodes had 4.0 mm diameter holes. The current per beamlet was 3.8 mA at an extraction current density of 100 mA/cm^2. There were 61 beamlets for a total current of 232 mA.

One of our goals was to test the high gradient insulators which were used to assemble the electrode plates. When tested individually, each would hold 80 kV DC without beam. The insulators were either 4.27 cm or 2.13 cm in length. A conservative working voltage is about 30 kV/cm for a 20-μsec pulse in the gap environment. Achieving these gradients required conditioning of the surfaces.

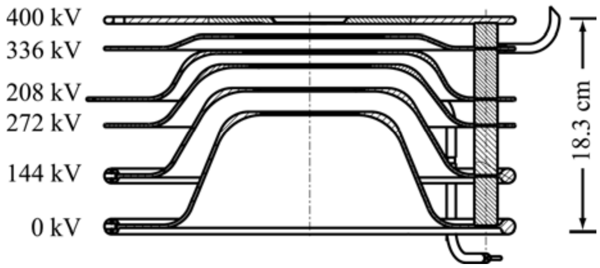

Figure 1. Side view of the electrodes used in the Full Gradient Experiment. Electric Field between the 2nd and 3th cup was 100 kV/cm.

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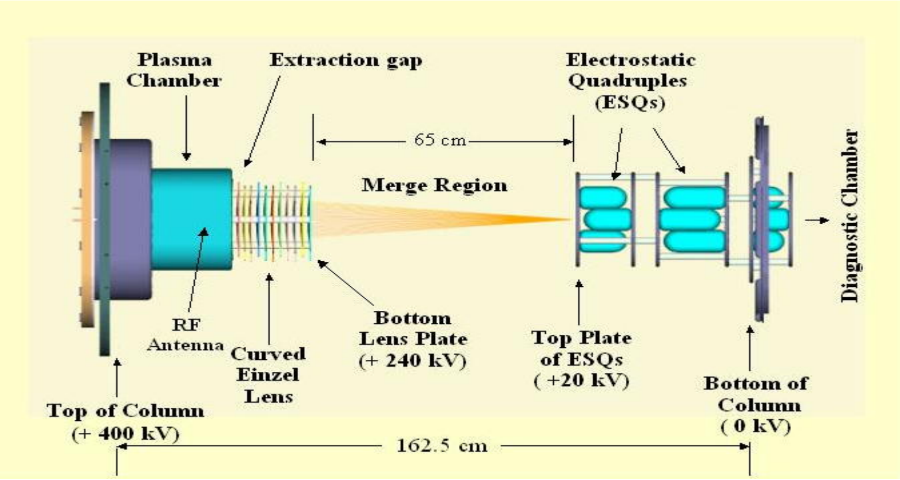

Figure 2. Layout of Merging Experiment.

MERGING BEAMLETS

We performed experiments where 119 multi-beamlet were merged into a beam. Although the source has the same optics as a full 1.6 MV injector system, these test were carried out at 400 kV due to the test stand's high voltage limit. We measured the beam's emittance after the beamlets were merged and passed through an electrostatic quadrupole (ESQ). Our goal was to confirm the emittance growth and to demonstrate the technical feasibility of building a driver-scale HIF injector.

Since all the voltages in this electrostatic system are reduced by the same factor, and the current density is scaled according to the "3/2" space charge limited condition, the beam optics of merging remains unchanged. A layout is shown in Fig. 2. There was an extraction plate plus 10 lens plates in the experiment. Figure 3 shows the lens assembly mounted in the column. Because the voltages between plates was reduced by a factor of four, we did not need reentrant cups, as in the Full-Gradient Experiment. We used HGI directly between the plates to hold the assemble together and provide alignment.

The emittance growth (normalized to a constant beam current) is minimized when the beamlet energy is high (at the time of merging), the number of beamlets is large, and the beamlets are close to each others. The final emittance depends on the initial beamlet convergent angle and weakly on the ion temperature[1]. Figure 4 shows the evolution of beamlets in x-z configuration 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) in about 10 m distance.

Figure 5 shows an emittance diagram (constructed from optical images produced by the ions passing through a slit) at 10 cm beyond the end of the ESQs. Figure 6 shows a comparison of predicted emittance and the measured emittances. Signal noise made it difficult to find the edge

Figure 3. Einzel Lens Assemble for the Merging Experiment installed in the top of the column (without the field shield installed).

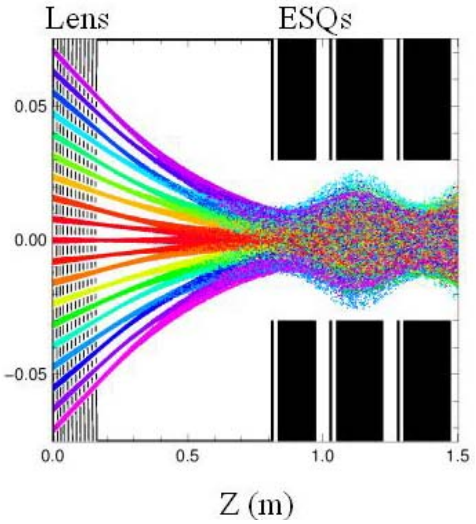

Figure 4 .Particle trajectories in x-z space. The quadrupole fields in the experiment were different that what was used to generate the figure.

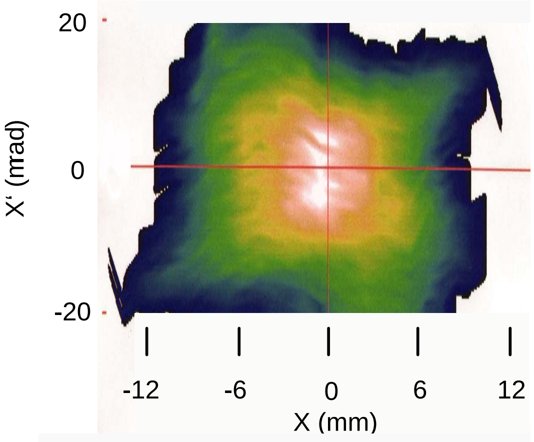

Figure 5. Optical measurement of x-x' phase space at 10 cm below the last quadrupole.

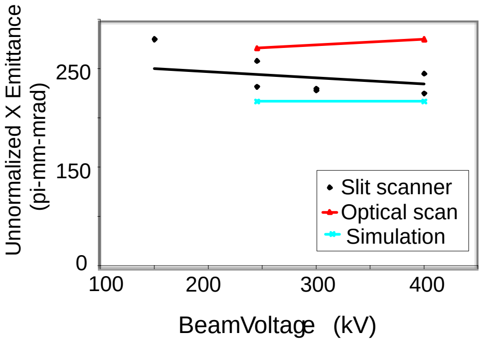

Figure 6: Comparison of the measured unnormalized x emittance and the same emittance predicted by simulation.

of the phase space in the experiments. The optical emittance scans used a 90% amplitude cutoff. The slit scanner emittances fit the emittance vs. cutoff curve, and projected back to 100% level. The simulations line is the 4*rms emittance taken for 90% of the ions.

The unnormalized emittance does not depend on the injector voltage if the perveance is held constant and the focusing fields are scaled to the beam voltage. The main contribution to the phase area was the "trapped" area when the beamlets were merged.

Figure 7 shows the beam current into the Faraday cup as a function of the beam voltage. The simulation beam current assumes a flat emitting meniscus. Higher current can be obtained at the expense of interior beam optics if the ion-emitting surface are allowed to bulge into the extraction gap by overdriving the RF plasma. At near 400 kV we believe that we were losing current from gas collision near the Faraday Cup. Obtaining good transport required that we operated near the correct perveance. At 400 kV we measured 70 mA into the Faraday Cup.

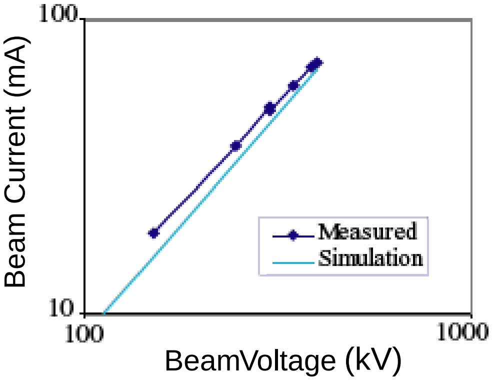

Figure 7. Beam current into Faraday Cup located after the ESQs.

ACKNOWLEDGEMENTS

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REFERENCES

[1] D.P. Grote, E. Henestroza, J.W. Kwan, PRST Accelerators and Beams 6, 014202 (2003).

[2] J.W. Kwan, D.P. Grote and G.A. Westenskow, "High Current Density Beamlets from a RF Argon Source for Heavy Ion Fusion Applications", Rev. Sci. Instrum., **75**, p1838, (2004).

[3] G.A. Westenskow, et al., "High Current Ion Source Development for Heavy Ion Fusion", Proceedings of The Third International Conference on Inertial Fusion Sciences and Applications (IFSA2003), Monterey, California, September 7-12, 2003, p. 703.

[4] G.A. Westenskow, et al., "RF Plasma Source for a Heavy Ion Fusion Injector", Heavy Ion Fusion Symposium, Princeton, NJ, June 2004.