LBNL-57435 and HIFAN 1151.

A COMPACT MULTI-BEAMLETS HIGH CURRENT INJECTOR FOR HIF DRIVERS*

J. W. Kwan, F.M. Bieniosek, Lawrence Berkeley National Laboratory;
D. P. Grote, G. A. Westenskow, Lawrence Livermore National Laboratory

Abstract

Using curved electrodes in the injector, an array of converging beamlets can 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 the one designed using traditional single large-aperture beams, so the success of this experiment has significant economical and technical impacts on the architecture of heavy ion fusion (HIF) drivers.

INTRODUCTION

The commonly proposed method of using heavy ion beams to drive inertial fusion requires 50 - 100 A of beam current arranged in multiple beam channels. The injector energy will be about 1.6 MV with beam current per channel at ~ 0.5 A. In order to overcome the space-charge limit, an effective way to produce these high-current beams is by merging a large number of high-current-density beamlets. The size of an injector system using this approach can be several times smaller than the traditional design using the large-aperture surface ionization source method [1]. Thus the success of this experiment would have a significant economical and technical impact on IFE drivers.

Previously we have published results from simulation studies of merging beamlets [ref] and from testing an RF-driven multicusp source to produce high current density argon beams [ref]. In this experiment, we inject 119 beamlets into an ESQ channel to study the emittance growth of beam merging. At 400 kV (1/4 full voltage) the beam current obtained was 70 mA, which scaled to 0.56 A at 1.6 MV. In testing multi-beamlet extraction at the full voltage gradient condition, we obtained argon current density > 100 mA/cm^2.

SIMULATIONS AND DESIGNS

The main physics issues for merging beamlets are envelope matching and emittance growth in the merging process. Since the front end of an HIF induction linac uses electrostatic quadrupoles (ESQ) for beam transport, it is desirable to produce an elliptically shaped beam spot at the ESQ channel entrance to eliminate the conventional ESQ matching section. We have considered two different ways to do the matching: (1) starts with a circular array of beamlets using astigmatic electrodes, or (2) starts with an elliptical array of beamlets using axi-symmetic electrodes. Although the first way was preferred because it produced a slightly smaller final emittance, we found that electrodes curved differently in the two planes were too expensive to make so we used the second method instead.

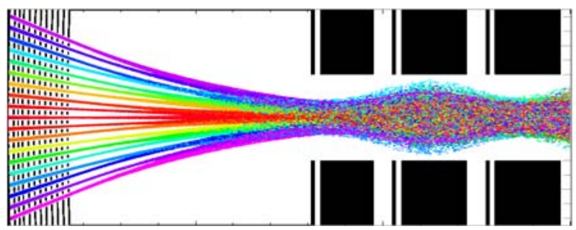

Fig. 1. Computer simulation of beamlet trajectories.

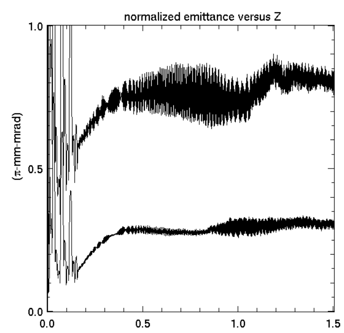

Fig. 2. Emittance growth during merging of beamlets

In order to prevent space charge blow-up, the beamlets must be kept separated and focused while at low energy. At sufficiently high energy (e.g. > 1.2 MeV in our case), the line charge density will be low enough for merging to form a single high current beam. Figure 1 shows the beamlet trajectories at the mid-plane of the array as obtained from computer simulation. The pre-accelerator made use of Einzel lens focusing, and high voltage gradient, to handle the high current density beamlets. In the experiment, 119 beamlets were extracted from an RF-driven Ar^+ plasma source with current density up to 100 mA/cm^2 and the aperture diameter was 2.2 mm each.

Computer simulation, as shown in Fig. 2, indicates that the x and y rms emittances initially rise to different values because of the beamlet's elliptical arrangement, but gradually came to an equilibrium averaged value after traveling many ESQ lattice periods (a few 10's m

* This work is supported by the Office of Fusion Energy Science, US DOE under contract No. DE-AC03-76SF00098 (LBNL) and W-7405-ENG-48 (LLNL).

distance). Our aim is to study the beam properties after the initial emittance growth, at about 1.5 m from the ion source.

EXPERIMENTAL SETUP

A schematic diagram of the apparatus is depicted in Fig. 3. The high voltage column was 1.6 m tall, operating in atmosphere at a full voltage of 400 kV. At the top was a RF-driven multicusp ion source. Below that was the merging module that had 12 electrodes, and were glued together using high gradient insulators. These electrodes were curved with a common focal point just below the first ESQ entrance. Voltages were tapped from the grading rings of the high voltage column. A high current (~ 1 kA) water resistor was used as a voltage divider driven by a 20 μs HV pulser. Figure 4 shows photographs of the Merging module and the ESQ module.

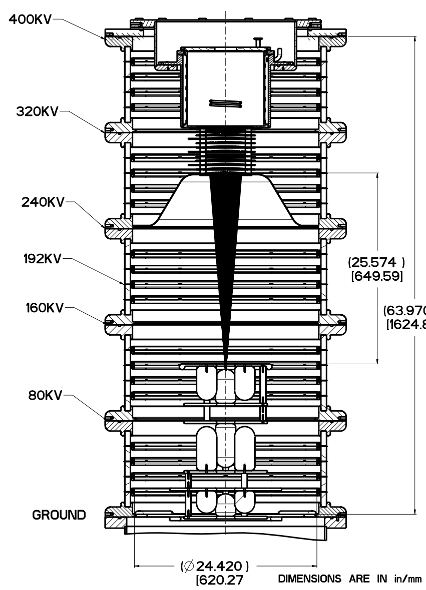

Fig. 3. Schematic of the 119 beamlet experiment.

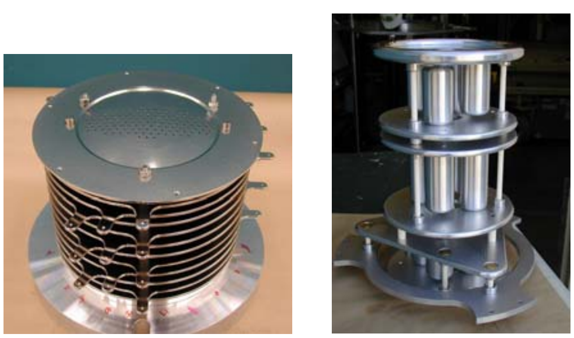

Fig. 4. Photos of the Merging module and ESQ module.

At 400 kV, this is a 1/4 scale voltage experiment to demonstrate the physics of a 1.6 MV heavy ion fusion driver-scale injector. According to the Child-Langmuir electrostatic scaling law ($I \sim V^{3/2}$), the beam current will be reduced to 1/8. However, the important point is that there is no change in the ion trajectories and therefore the beam physics is still valid.

In order to demonstrate the technical feasibility of producing and transporting high current density beamlets using high voltage gradient, we also ran a separate experiment using 61 beamlets and accelerated the ions under electric field similar to that in a 1.6 MV injector. In this experiment, the beam current density is the same as that found in a driver-scale HIF injector. Figure 5 shows the "full-gradient" acceleration schematic diagram and a photograph of the last electrode. For compact construction, we used "high-gradient" insulators (made of multi-layer discs) designed for 35 kV/cm.

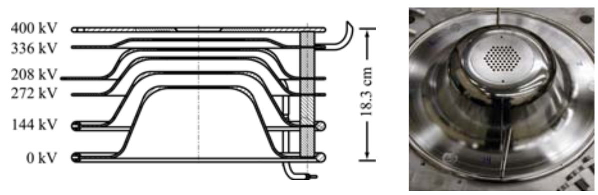

Fig. 5. The full-gradient acceleration module.

EXPERIMENTAL RESULTS

Results from Merging Beamlets Experiment

In merging the 119 beamlets, at 400 kV, we measured 70 mA into the faraday cup. This result was in good agreement with predictions from simulation. Higher beam current, e.g. 80 mA, can be obtained by overdriving the RF plasma in the ion source but at the expense of higher beam emittance due to mismatched beam optics ("over-perveance") at the extraction gap. Scaling this result up to the full voltage of 1.6 MV for a driver-scale injector, the full beam current would be 8 x 70 mA = 560 mA.

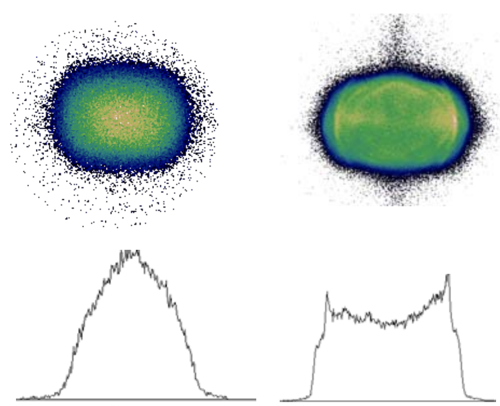

Fig. 6. Images of the merged beam at two different z positions.

Using alumina scintillators, we produced optical images of the beam's cross-section at two different locations: first at the beginning of the second ESQ, and then at 10 cm after the exit of the ESQ channel. These images are shown in Fig. 6. The first image was taken without applying ESQ voltages in order to observe the beam condition right after merging but before ESQ focusing. The second image showed the beam condition after going through the ESQ transport channel. These data confirmed that the 119 beamlets had merged to form an elliptically-shaped beam. Fine structures in the current density were caused by the original discrete beamlets and should dissipate to form a homogenously uniform beam as the beam propagates further downstream.

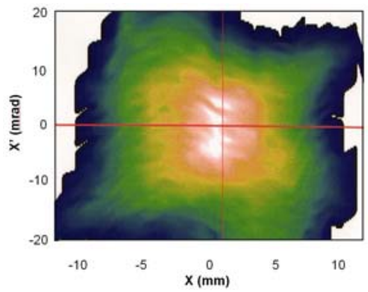

Fig. 7a. Emittance diagrams from experimental

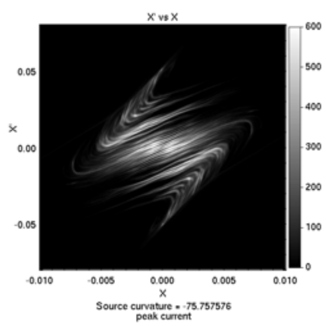

Fig. 7b. Emittance diagrams from simulation

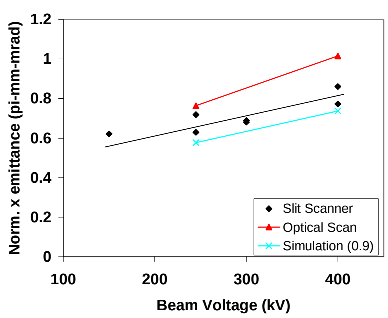

Fig. 8. Normalized emittance of the merged beam.

Fig. 7 shows typical x-x' emittance diagrams measured at 10 cm after the ESQ channel exit. The scan was done using an "optical scanner" that had a front slit with a scintillator imager at the back. Although the beamlets are merged together into a large beam, the fine features in the diagram reveal the reminiscence of original beamlets. Also shown in Fig. 7 is an emittance diagram from simulation. The normalized emittance as a function of beam voltage is plotted in Fig. 8. Data from the optical scanner and from conventional double-slit scanner were both agreeing with that from simulation. We also had good agreement between the double-slit scanner y-y' emittance data and simulation (but not the optical scanner in this direction which had poor resolution).

Results from Full-Gradient Experiment

The full-gradient experiment demonstrated the acceleration of 61 beamlets with current density up to 100 mA/cm^2 and a maximum voltage gradient of 100 kV/cm. Figure 9 shows the measured beam images at z = 15 cm downstream of the module and the corresponding simulation prediction. Here the beamlets have not been fully merged and therefore showed that all the beamlets had comparable current.

In trying to reach 400 kV with this module, we encountered a voltage breakdown problem at the last gap. Since, this gap has a lower design voltage gradient than the second gap which held voltage, we concluded that the problem was most likely due to a defective insulator. The highest operating voltage gradient for the insulators was shown to be 30 kV/cm.

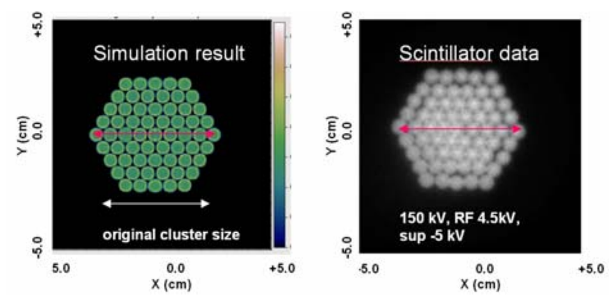

Fig. 9. Simulation and measured beamlets at z=15cm.

SUMMARY AND ACKNOWLEDGEMENT

We have demonstrated 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. Using computer simulation, the merging module was designed to minimize emittance growth and effectively matched the merged beam into an ESQ channel. Our experiment had also demonstrated the feasibility of producing an uniform array of beamlets at > 100 mA/cm^2 with an accelerating field of 100 kV/cm.

The authors would like to thank Bob Hall, Erni Halaxa, Gary Freeze, and Will Waldron for their technical support, and also Grant Logan, Alex Friedman and Christine Celata for their constant encouragement.

REFERENCES

[1] J. W. Kwan, in "*The Physics and Technology of Ion Sources*", edited by I.G. Brown, (Wiley-VCH, Weinheim, 2004), p. 311-340.

[2] D.P. Grote, E. Henestroza, J.W. Kwan, Phy. Rev. Special Topics-Accel. & Beams, 6, (2003), 014202

[3] J. W. Kwan, D. P. Grote, and G. A. Westenskow, Rev. of Sci. Instrum., 75, (2004), p1838.