

## U.S. Heavy Ion Beam Science towards Inertial Fusion Energy

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**Abstract.** Significant experimental and theoretical progress in the U.S heavy-ion fusion (HIF) program is reported in modeling and measurements of intense space-charge-dominated heavy ion and electron beams. Measurements of the transport of a well-matched and aligned high current (0.2A) 1.0 MeV potassium ion beam through 10 electric quadrupoles, with a fill factor of 60%, shows no emittance growth within experimental measurement uncertainty, as expected from the simulations. Another experiment shows that passing a beam through an aperture can reduce emittance to near the theoretical limits, and that plasma neutralization of the beam's space-charge can greatly reduce the focal spot radius. Measurements of intense beamlet current density, emittance, charge-state purity, and energy spread from a new, high-brightness, Argon plasma source for HIF experiments are described. New theory and simulations of neutralization of intense beam space charge with plasma in various focusing chamber configurations indicate that near-emittance-limited beam focal spot sizes can be obtained even with beam perveance an order of magnitude higher than in earlier HIF focusing experiments.

### 1. Introduction

This article reports results from the last two years of experiments and simulations with space-charge-dominated heavy ion and electron beams relevant to understanding the behavior of the high-brightness heavy ion beams ultimately required to drive high-gain inertial fusion targets. The success of inertial fusion energy (IFE) with heavy ions will require high-brightness and peak power accelerators [1], high-gain target designs [2], methods to produce, and inject such targets at 5 Hz pulse rates and targets that can be mass produced at low cost [3], and long-lasting, low-activation chambers that can protect the walls and focusing magnets from repeated fusion energy bursts [3]. Heavy ion beam research is carried out under the auspices of the Heavy-Ion Fusion Virtual National Laboratory (HIF-VNL) by Lawrence Berkeley National Laboratory, Lawrence Livermore National Laboratory, and Princeton Plasma Physics Laboratory, and other HIF beam science research is performed by the University of Maryland, the Naval Research Laboratory, Mission Research Corporation, and the University of Missouri.

Heavy Ion Fusion is attractive for Inertial Fusion Energy because high energy accelerators of MJ range beam energies potentially have the required efficiencies, pulse rates, and durability, and because clear-bore magnets used to focus heavy ions can avoid line-of-sight target debris and radiation. Transporting and focusing space-charge dominated beams with 0.1 to 10  $\mu\text{C}/\text{m}$  suitable for Inertial Fusion Energy is the main new challenge. Particle-in-cell simulations are in good agreement with the results of past low current (mA level) beam experiments in transport, merging, acceleration and final focus, in which the dimensionless beam perveances (space-charge potential/ion kinetic energy) had driver-scale values. Here, we report initial results on three new experiments at high currents ( $>10\times$  larger) and large tune depressions, where kV-level space-charge potentials can attract and sometimes trap stray electrons and therefore affect transport: the High Current Experiment (HCX), which studies transport of such beams and interaction with gas and electrons (Sec. 2); beam production by high brightness plasma sources (Sec. 3); and ballistic focusing with plasma neutralization in the Neutralized Transport Experiment (NTX) (Sec. 4). The University of Maryland also performs experiments and simulations with electron beams with perveances relevant to heavy ion fusion (Sec. 5). Supporting theory/simulation for the HIF-VNL is described in Sec. 6. Finally, a brief summary of future plans is given in Sec. 7.

## 2. The High Current Experiment (HCX)

The High Current Experiment (HCX), located at Lawrence Berkeley National Laboratory and carried out by the HIF-VNL, is designed to explore the physics of intense beams with line-charge density of about 0.2  $\mu\text{C}/\text{m}$  and pulse duration  $4 < \tau < 10 \mu\text{s}$ , close to the values of interest for a fusion driver [4]. Experiments are performed near driver injection energy (1-1.8 MeV). HCX beam transport is at present based mainly on electrostatic quadrupole focusing, which provides the most efficient option at low energy and provides clearing fields to remove unwanted electrons. However, magnetic transport experiments will also be performed to explore limitations associated with magnetic focusing, in particular, the onset of transport-limiting effects due to electrons trapped in the space-charge potential of the ion beam. The principal initial effort on the HCX (see FIG.1. below) has been experiments carried out with a matched and well-aligned  $\text{K}^+$  ion beam transported through 10 electrostatic quadrupoles. The main scientific results to date are:

- There is no emittance growth ( $\varepsilon_n = 0.6(\pm 20\%) \text{mm} - \text{mrad}$ ) within diagnostic sensitivity, and little beam loss ( $< 2\%$  in the middle of the beam pulse), as expected from initial particle simulations. See FIG. 2 below showing the beam envelope (x and y vs z) through the 10 quad transport region between QD1 and the end diagnostic station (D-end) in FIG. 1 below. The beam centroid is aligned to  $< 0.5 \text{ mm}$  and 2 mr of the central axis of the channel, with envelope mismatch amplitude  $\approx \pm 1.0 \text{ mm}$ .
- A long-life, alumino-silicate source of improved surface uniformity has replaced a contact-ionization source, eliminating depletion-induced experimental uncertainties.
- Significant differences between the experimental data and early theoretical calculations of the beam envelope propagating through the electrostatic quadrupoles were encountered. More detailed envelope models and simulations have resolved most of the discrepancy, and achievable limits on envelope predictability and control are being probed.

- The experimental current density distribution,  $J(x,y)$ , and phase-space data are being used to initialize high-resolution simulations to enable realistic modeling and detailed comparisons with experiment. New methods have been derived for projecting the full 4-D phase space from experimental measurements, and the resulting distributions are being used in high-resolution PIC simulations of the experiment.
- Considerable progress has been made in the development of new time-resolved phase-space diagnostics, which will speed up data acquisition in this and other upcoming beam experiments in the HIF-VNL.
- A new Gas and Electron Source Diagnostic (GESD) has made preliminary measurements of the secondary electron coefficient. The secondary emission yield varies as  $\cos^{-1}(\theta)$ , as predicted theoretically (see FIG. 3. below). Data from the GESD will be relevant to upcoming experiments on gas, particle loss and electron effects in a magnetic quadrupole lattice.

A beam line of four pulsed magnetic quadrupoles, instrumented with diagnostics to measure the production and energy of trapped electrons, secondary atoms and ions is being installed downstream of the 10 electrostatic quads [5].

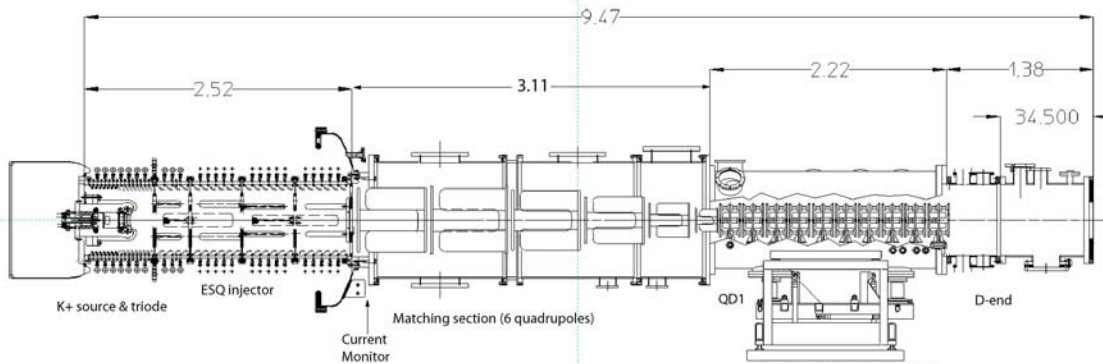


FIG. 1. Initial experimental configuration of HCX. A secondary electron, ion and gas diagnostic was installed downstream of the end station (D-end) diagnostic.

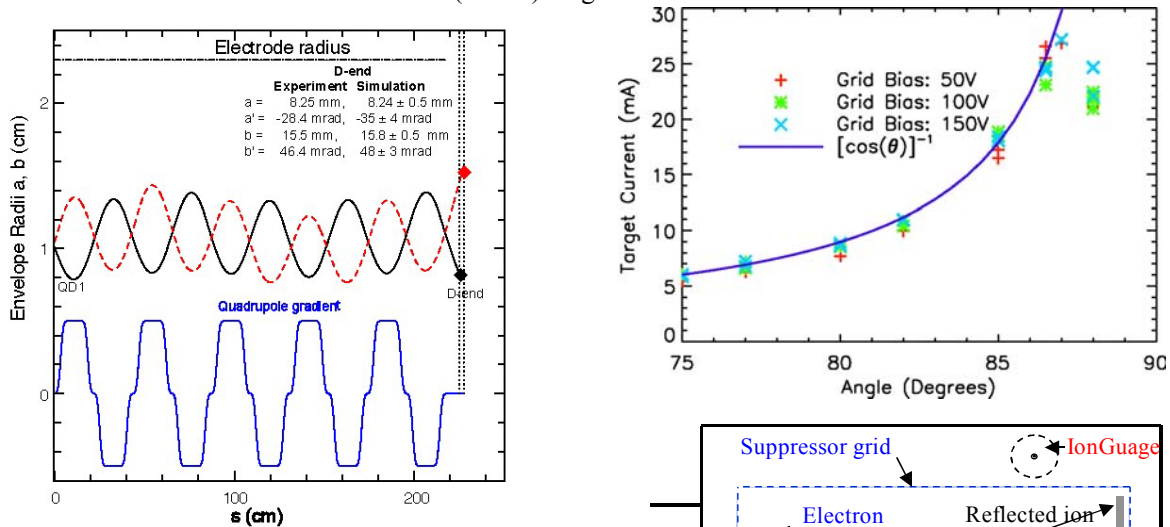


FIG. 2. Predicted HCX beam envelopes (red and black curves) are initialized with  $I$ ,  $\epsilon$ ,  $a'$ ,  $a$ ,  $b$ ,  $b'$  measured at QD1, and projected to the diagnostic station at D-end. The tabulated envelope uncertainty at D-end is  $1\sigma$  of a Monte Carlo set, from uniformly distributed ( $\pm 0.5\text{mm}$ ,  $\pm 1.0\text{mrad}$ ) measurement uncertainty at QD1.

FIG. 3. Gas and Electron Source Diagnostic and initial data on secondary yield versus angle.

Construction of an optimized prototype superconducting quadrupole and a cryostat for two magnets has begun, with significant improvements in integrated gradient, field quality, coil mechanical support and cost with respect to the first prototype series [6].

In the area of longitudinal beam dynamics and control, an induction module is being built by First Point Scientific [7] under the auspices of a DOE Small Business Innovative Research Phase II grant. The module will apply agile control of the acceleration waveforms to correct for space-charge field effects on the head/tail of the beam. The apparatus includes a complete system of induction cores and modulators for installation in the HCX lattice between the matching section and the first transport quadrupole. “Ear” waveforms ( $\approx 200\text{kV}$ , actively regulated to  $\approx 3\%$ ) will prevent the bunch ends from eroding due to the longitudinal self-field of the beam. This module will also regulate  $20\text{kV}$  variations during the flattop (to  $\approx 0.1\%V_{\text{injector}}$ ) to study the consequences of pulse energy variations and correct waveform imperfections.

### **3. Multi-beamlet injector and plasma ion source research on the STS-100 facility.**

High-voltage breakdown and Child-Langmuir space-charge current density constraints combine to require very large area ion sources for large currents with a single beam. In addition, long matching sections are usually required to compress the beam size and transform a round beam into the elliptical beam shape for matched transport in a quadrupole-focused transport lattice. We are investigating a novel compact merging-beamlet injector concept for HIF to avoid these limitations. In this new system, about 100 mini-beamlets (of 5 mA each) are produced from a high-current-density ion source. The beamlets are kept separated from each other within a set of acceleration grids in order to control the space charge expansion. Simulations [8] indicate that, after gaining sufficient kinetic energy ( $> 1.2\text{ MeV}$ ), the mini-beamlets can be merged to form a high-current beam ( $\approx 0.5\text{A}$ ) with only a small increase in emittance ( $\Delta\varepsilon_n < 1.0\pi\text{ mm-mr}$ ). The beamlets can be arranged to fill an elliptical pattern, and aimed differently in the two transverse planes in such a way that the merged beam spot is already an ellipse matching the entrance requirements of an electrostatic quadrupole (ESQ) channel. The combination of high current density and lack of need for extensive further matching, results in a dramatic reduction of the injector size (a factor of 6 compared with the large single beam approach). For success of this concept, we need high current density beamlets ( $> 100\text{ mA/cm}^2$ ), low emittance (equivalent effective ion temperature  $< \text{a few eV}$ ), nearly-pure charge state ( $> 90\%$  in a single state), low energy dispersion (momentum spread  $\Delta p/p_0 < 0.5\%$  at the end of the injector), and fast rise time ( $< 1.0\ \mu\text{s}$  for a driver and even shorter for near-term experiments). The following recent results (see FIGS. 4, 5, 6, and 7 below) using a single beamlet from an RF-driven Argon plasma source at the STS-100 test stand at LLNL [9] indicate that each of these goals are achievable.

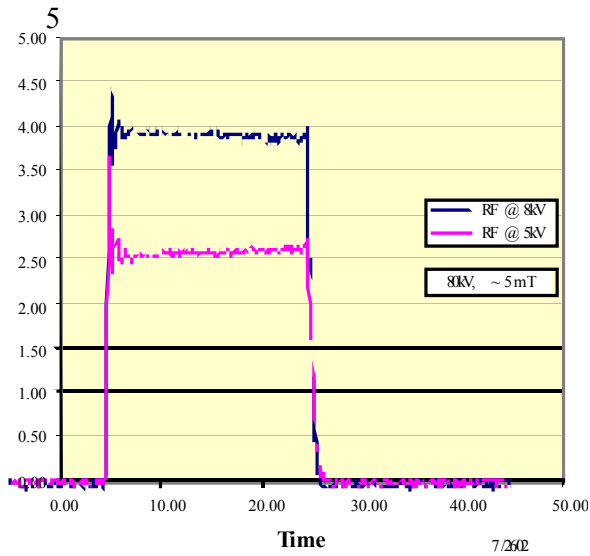


FIG. 4. Beamlet current versus time measured with a Faraday cup for two RF power levels at 10 MHz (for 17.6 kW @ 8kV plate voltage and for 11 kW @ 5 kV plate voltage, with 80 kV extraction gap voltage, and 5 mT source gas fill. The Argon plasma source @ 17.6 kW has produced 3.9 mA beamlets @ 80 mA/cm<sup>2</sup> current density (80% of the goal). The goal may be reached with a small increase in RF power or plasma chamber confinement.

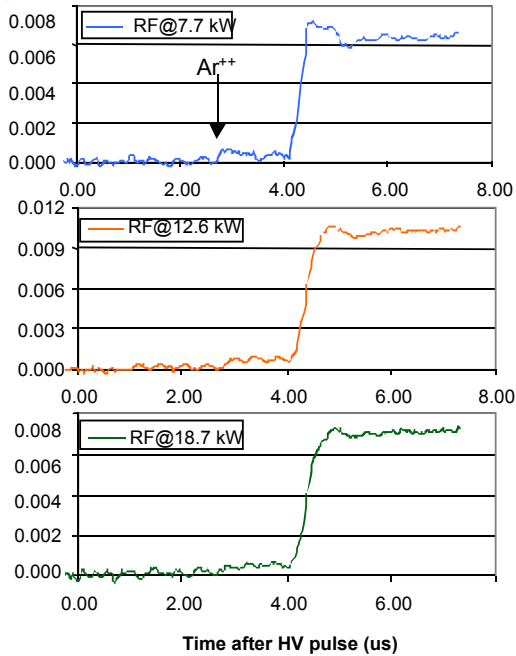


FIG. 6. The time of flight of argon ions measured with a pair of Faraday Cups 1.9 m apart, for three different powers. The dominate species Ar<sup>+1</sup> arrives at the far Faraday cups at approximately 4.1  $\mu$ s. The smaller pedestal signals beginning at 2.9  $\mu$ s indicates a small (7%) Ar<sup>+2</sup> ion current.

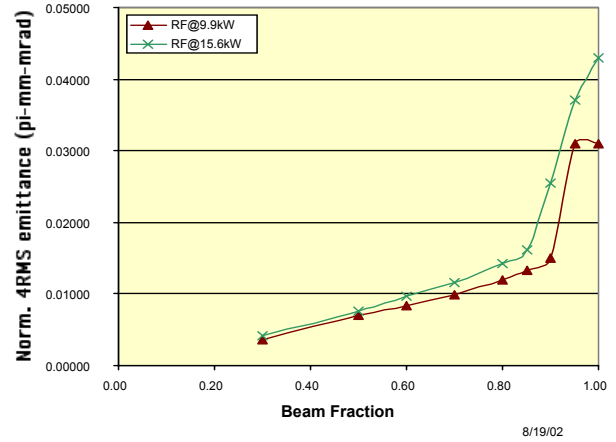


FIG. 5. Normalized RMS beamlet emittance measured with a slit scanner diagnostic as a function of the fraction of beam included in the phase-space measurement, for 9.9 and 15.6 kW RF power levels. Emittance is measured just to the left of the “knees” to subtract out spurious noise. The normalized emittance of 0.018  $\pi$  mm-mr at the knee corresponds to an effective ion temperature of 2 eV, which is adequate for use in future merging of many beamlets.

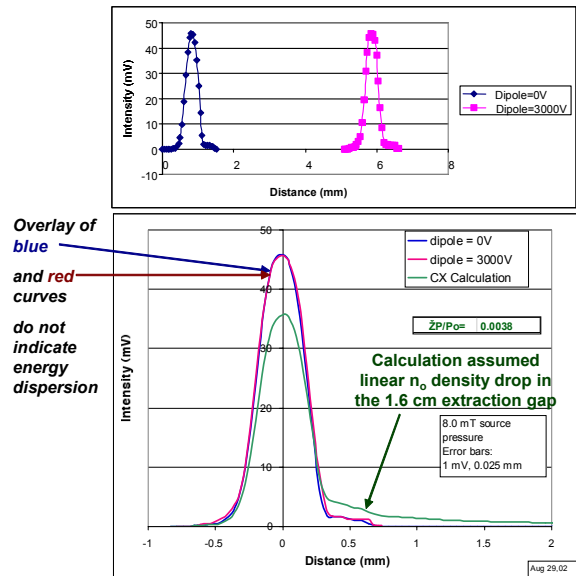


FIG. 7. Upper traces are the current versus transverse distance of a beamlet undeflected (blue-dipole off) and deflected with a 3000V dipole voltage applied. The overlay of the two curves as shown in the lower graph does not indicate any dispersion due to energy spread. A simple calculation (green curve) predicts energy dispersion due to beam ions charge-exchanging with gas within the extraction gap depending on gas density.

A measurement of energy spread of the beam produced by the plasma source seems to indicate negligible charge exchange on gas from the source. One possible explanation of this welcome result is that the gas density drops much faster with distance than expected.

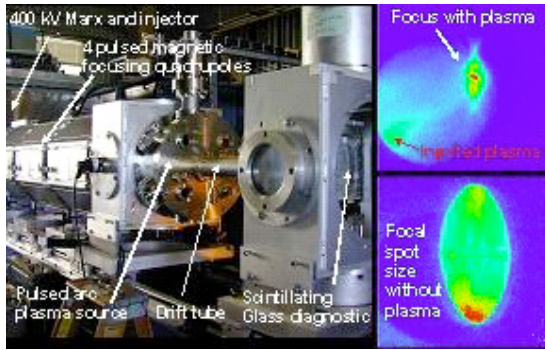
The HCX experiment is now operating with a 10-cm diameter alumino-silicate potassium ion source. That ion source appears to be adequate for the HCX near-term experiments because duty factor and lifetime are not critical issues there. For the next experiment planned, the Integrated Beam Experiment (IBX), a source with a few hundred-ns or less rise-time is required. Further work is needed to determine whether the plasma meniscus formation time for good beamlet optics is fast enough. If current experiments with the RF plasma source provide high quality beamlets that can be merged into a single beam with good emittance and sufficiently fast rise time, this approach could be used in the IBX.

#### **4. The Neutralized Transport Experiment (NTX)**

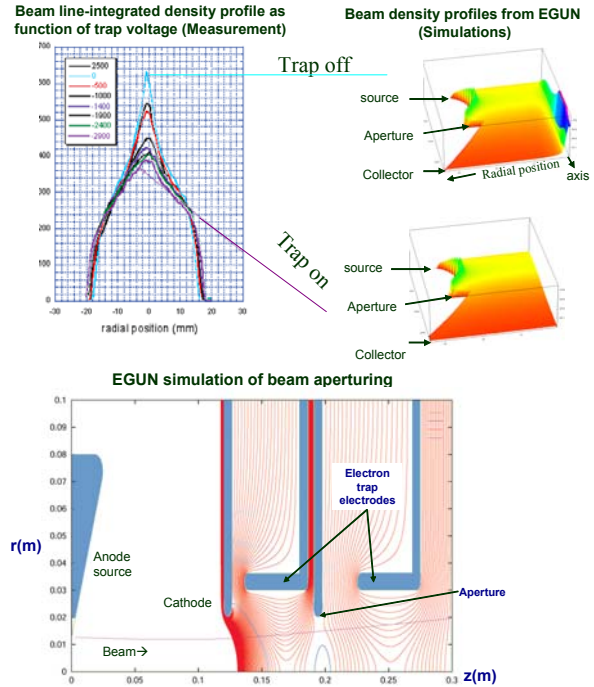
NTX is an experiment (see FIG. 8. below) to test the physics of final focusing in a heavy ion fusion driver. The key components are a neutralized drift section and the preceding magnetic final focus lattice. The objective is to quantitatively study magnetic nonlinearities and emittance growth due to incomplete charge neutralization. The first phase of the NTX has been completed, producing a beam with a variable perveance (a key dimensionless parameter for emittance growth) up to  $2 \times 10^{-3}$ , and with a sufficiently low emittance ( $<0.2 \pi$  mm-mr) so that variations in the focal spot radius will be dominated by magnetic nonlinearities and plasma effects.

Initial operation yielded the predicted 80 mA at 400 keV of  $K^{+1}$  ions, and the voltage-current dependence followed the Child-Langmuir relation. The peak current density was  $16 \text{ mA/cm}^2$ . Initial measurement of the emittance at 80 mA gave  $0.1 \pi$  mm-mr.

A beam aperturing experiment was performed on NTX to improve the emittance and to vary the beam perveance. A 2-cm diameter aperture was placed downstream of the exit cathode. This aperture intercepted one half (predicted and measured) of the beam current. Secondary electrons produced at the aperture were successfully confined by means of two adjacent cylinders with negatively biased potentials. FIG. 9. below shows that electrons neutralized the central portion of the ion beam, leading to enhancements of the density on axis and significant distortions of the phase space. The measured profiles and phase space were qualitatively consistent with calculations from LSP, a particle-in-cell simulation code, and also with a version of EGUN adapted to include electron effects. Beam size and the divergence angle agreed with EGUN predictions. When the electron trap was turned on, a uniform profile and phase space were measured, and the emittance was then  $0.05 \pi$  mm-mr (see FIG. 10 below).



**FIG. 8.** The Neutralized Transport Experiment beginning operation (September 2002, picture on the left). The lower right picture shows a large focal spot size due to space-charge blow-up of a high perveance ( $5 \times 10^{-4}$ ) beam of 300 kV, 25 mA  $K^{+1}$  ions. The upper right picture shows a dramatically smaller focal spot when a pulsed “plug” of plasma is injected between the focusing magnets and the focal plane diagnostic. Theory and particle-in cell simulations (in progress for this experiment) have also shown much reduced focal spots with plasma neutralization of beams, and without deleterious beam-plasma instabilities.



**FIG. 9:** The NTX beam is apertured both to control the beam current and perveance, and to improve the downstream beam quality for focusing experiments. This figure shows that effects of secondary electron clouds from the beam aperture can be mitigated with proper bias on the trapping electrodes.

The second phase of NTX (in progress) consists of the design, construction and testing of a system of four pulsed quadrupoles used to focus the ion beam. The first completed magnet was tested for 10,000 pulses at a current of 8 kA (20% above present operating parameters). The fields were measured with magnetic field probes, which measured  $B_x$ ,  $B_y$ , and  $B_z$  with an accuracy of a fraction of a percent. The measured axial profile of the quadrupole field agreed well with ANSYS calculations. Measurements were also made with the inclusion of a vacuum aperture tube. A reduction of fields by 6% due to eddy currents in the tube was measured and is consistent with code predictions. A potassium beam, apertured to 25mA at 300keV, was first transported to the end of the quadrupole system on August 8, 2002.

Construction is complete for a neutralized drift at the downstream end of the pulsed quadrupoles, with two plasma sources: a local “plug” plasma region just after the focusing magnets, and a volumetric plasma source (an ECR source developed at PPPL for NTX) filling the region near the focal spot. The first neutralized drift experiment deploying the pulsed plasma plug (vacuum arc source) began on Sept. 6, 2002, and initial results are encouraging, with the injection of a pulsed plug plasma reducing the focal spot size (included in FIG. 8. above).



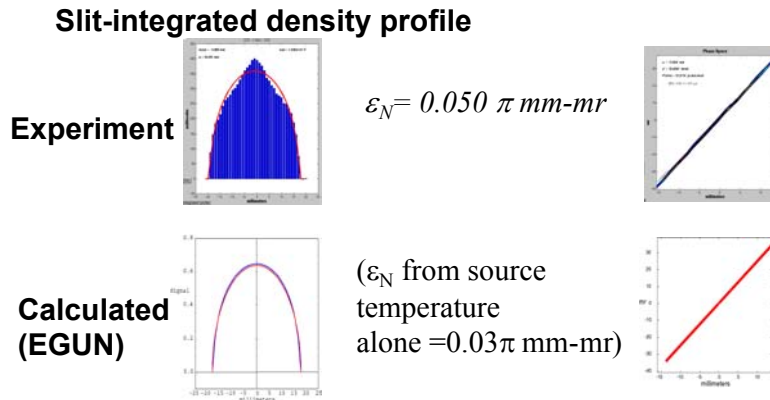


FIG. 10. A high brightness aperture beam (300kV, 25mA)

## 5. Experiments with electron beams relevant to heavy ion fusion at the University of Maryland

Non-relativistic electron beams at 10 keV and  $\sim 100$  mA can be used to experimentally simulate the space-charge dominated beam dynamics of heavy-ion beams that might be used in a future heavy-ion powerplant. The University of Maryland Electron Ring (UMER) [10] is designed as a low-energy recirculator using induction modules and with its parameters scaled to match Heavy Ion Fusion drivers (see FIG. 11. below). Scheduled to come on-line by mid-2003, UMER will provide a low-cost platform to study long-path issues over many hundreds of focusing lattice periods, and will also be useful in benchmarking computer codes used in machine design, such as WARP [11] (see FIG. 12. below). The issues addressed by UMER include transverse and longitudinal temperature equipartition, mixing and dissipation of perturbations and instabilities, and emittance and halo growth. Since UMER is designed to be a research machine, it is fitted with a large number diagnostics having high temporal and spatial resolution, such as current monitors, pepper-pot and double-slit phase space monitors, BPMs, and phosphor screens. An ultra-high resolution retarding energy analyzer is currently under development for monitoring longitudinal phase space [12].

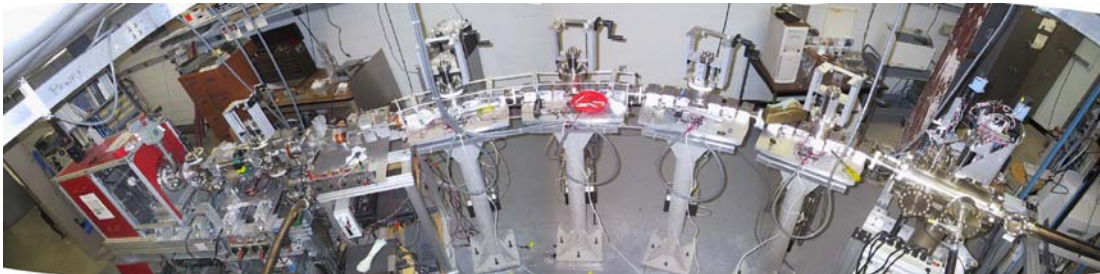


FIG. 11. A recent photograph of UMER under construction.



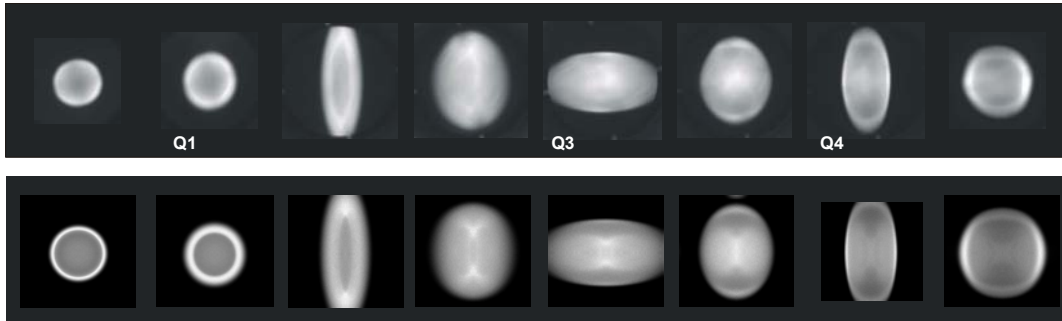


FIG. 12. Experimental measurements of beam profiles at various positions along the UMER injector using a phosphor screen (top) compared with WARP simulations (bottom). The simulation results are sensitive to the details of the initial distribution. Only when the input distribution is constructed to fit the initial distribution in the experiment can such agreement be obtained.

## 6. Theory and simulations in the Virtual National Laboratory

Analytical and simulation studies are addressing the injection, acceleration, transport and compression of the intense ion beams in the driver, and their transport and focusing in the target chamber. A large part of this effort supports the HCX, advanced injector, and NTX experimental programs described above. Other research is providing an understanding of fundamental nonlinear and collective beam dynamics, and is developing physics understanding and design concepts for the next-step Integrated Beam Experiment (IBX), an Integrated Research Experiment (IRE), and a fusion driver. Three dimensional (3D) particle-in-cell (PIC) simulations of the HCX clarified the influence of an overly-long injector voltage pulse rise time and motivated an injector triode retrofit for reduced aberrations; transverse-plane 2D PIC simulations are guiding the experimental determination of limits on the beam-pipe fill-factor (a significant determinant of driver cost). Tomographic syntheses of the 4D transverse particle distribution function from a small number of 2D phase-space measurements have been developed and are being used to initialize HCX simulations [13]. Analyses and simulations of the final drift compression process have also been carried out. Initial studies of the generation and trapping of stray electrons in the ion beam self-fields have been performed. Nonlinear perturbative simulations in 3D have clarified the detailed behavior of collective instabilities driven by beam temperature anisotropy [14] and by interactions with unwanted background electrons [15]. Analyses and simulations [16, 17, 18] are clarifying the influence of charge and current neutralization on beam focusing in NTX and in a fusion chamber. This work is providing the basis for a benchmarked source-to-target modeling capability that will greatly aid the planning of future experiments. Here, we present three selected topics: simulation studies of the HCX injector and matching section, of the two-stream collective instability, and of beam propagation in fusion-chamber plasmas.

### *Simulation of beams through the HCX injector and matching section*

Extensive 3D and 2D WARP PIC simulations of the injector and matching section have helped explain the observed phase space structure of the beam. Simulations and theory have shown that the relaxation of collective modes launched by phase space distortions arising from an imperfect injector leads to only modest emittance growth [19]. Continuing 2D and 3D simulations support the experimental program by determining the expected beam properties, aiding in machine tuning and diagnostic interpretation, suggesting additional diagnostics, offering guidance on required diagnostic resolution, and guiding further improvements in the machine. Here, we present an example of an “integrated” calculation

that gives a comprehensive view of the beam. The calculation begins by using WARP in its 3D time-dependent mode on a  $64 \times 64 \times 640$  grid, computing space-charge limited emission from the source as the injector voltages ramp up. FIG. 13(a). below shows a frame from a movie of this calculation. The beam head is mismatched transversely (leading to less than 0.1% particle loss) because its line charge density differs from the nominal, a result of the overly-slow 800 ns rise time of the injector gate voltage. Simulations using a 400-ns rise time show no loss (the actual rise time in HCX is slightly less than 800 ns). The particle data at the injector exit plane is saved over the flat-top of the pulse. It is then used to initiate a WARPxy “slice” calculation (in a steady-flow 2D approximation on a finer  $512 \times 512$  grid) of the mid-pulse behavior through the matching section and ten electrostatic quadrupole lenses of the transport line. A view of this later stage is shown in FIG. 13(b). below. Detailed agreement of such “end-to-end” simulations with HCX results, complicated by incomplete characterization of machine imperfections, remains a goal; simulations initialized “tomographically” from experimental data, which complement fully integrated runs, have been initiated. Integrated simulations (with ensembles of random machine errors within projected tolerances) will be important to the planning of the IBX and other future experiments.

#### *Two-stream collective instabilities*

In the absence of background electrons, the Beam Equilibrium Stability and Transport (BEST) code has demonstrated quiescent (stable) beam propagation over thousands of equivalent lattice periods [20]. In the presence of a large population of background electrons, however, a strong two-stream instability is observed. FIG. 14 below shows that this instability leads to a dipole ( $m = 1$ ) transverse displacement of the beam ions and background electrons. Detailed properties of the mode have been determined as functions of beam intensity and axial momentum spread [21, 22]. The code has also been used to model an observed instability in the Proton Storage Ring (PSR) at Los Alamos.

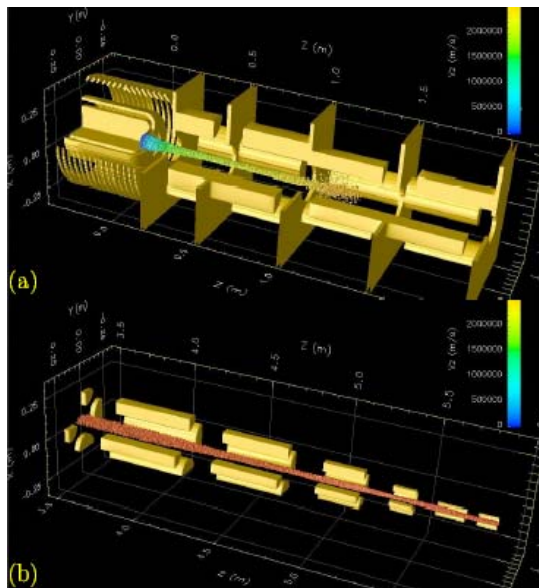


FIG. 13. WARP simulation of HCX: (a) beam head in injector; (b) mid-pulse in matching section and transport line.

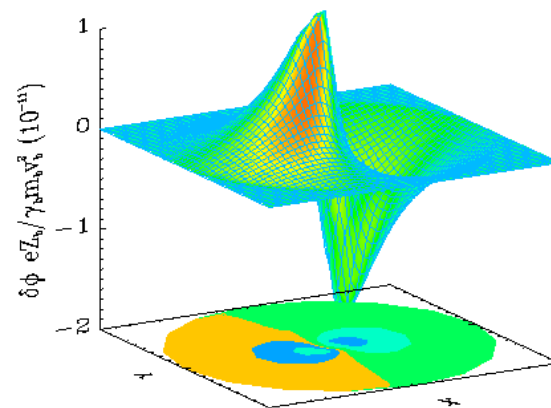


FIG. 14. BEST simulation of two-stream instability with electron density 10% that of the beam, showing perturbed potential.

*Studies of beam propagation in fusion-chamber plasmas*

In a heavy ion driver the energy is delivered to the target in a time-shaped pulse consisting of lower energy "foot pulse" beams that arrive first, followed by the main pulse beams. The 3D PIC code LSP [18], which offers an implicit particle/fluid hybrid model, has been used to make "realistic" simulations of driver-like foot and main pulses in a target chamber. In these calculations, the beam enters the chamber through a conical three-meter beam port with layers of hydrogen plasma near each end to pre-neutralize the beam, then drifts three more meters through low-density BeF<sub>2</sub> vapor to a 5-mm radius target. In these simulations the main pulses have 2.8 kA of 2.5 GeV Xe<sup>+1</sup> ions, and the foot pulses have 947 A of 1.9 GeV ions. These runs allow Child-Langmuir electron emission from conducting walls, and several also include time-dependent photo-stripping of the beam and photoionization of the background gas by X-rays from the heated target. Although these processes have major effects on the beam charge state and on the density of free electrons near the target, their overall effect in the cases examined to date is a modest reduction in the beam spot size [23]. Results from a typical main-pulse simulation are shown in FIG. 15 below, where the beam density and electron densities from several sources are shown after 80 ns of transport. At this time, electrons from the plasma layers and from the beam-pipe walls provide the largest share of beam neutralization, although neutralization by photoionization electrons becomes dominant when the beam pulse is within 50 cm of the target. An important finding of this and similar simulations is that the beam waist for either type of pulse is close to values required by current distributed-radiator targets [24].

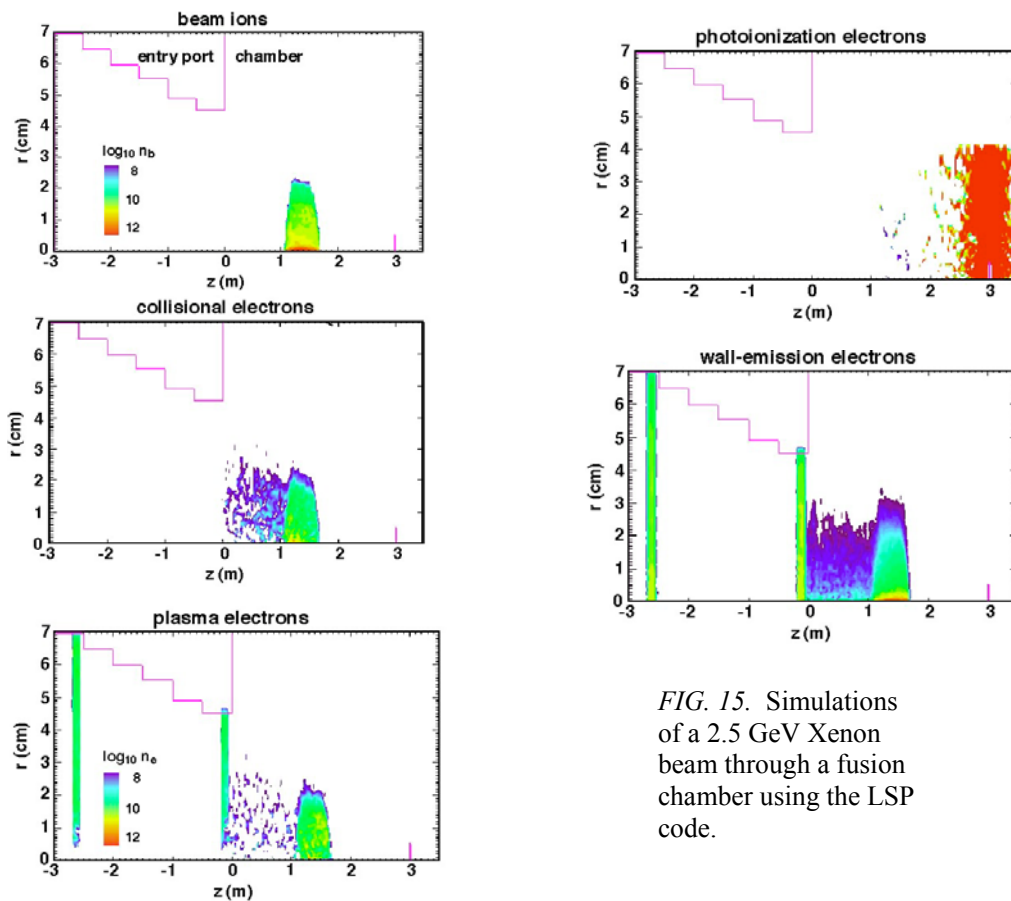


FIG. 15. Simulations of a 2.5 GeV Xenon beam through a fusion chamber using the LSP code.

## 7. Future plans

After the experiments described in earlier sections are completed, the next step in the Heavy Ion Fusion program will be to study transverse and longitudinal emittance growth through injection, acceleration, longitudinal beam compression, and final focus in an Integrated Beam Experiment (IBX), a 5-20 MeV, 500 mA beam experiment which is a candidate proof-of-principle experiment for Heavy Ion Fusion in the U.S. Fusion Energy Sciences Program [25]. A well-diagnosed IBX, together with well-benchmarked integrated models, should improve focal spot predictive capability for future high-energy-density ion-target interaction experiments.

Heavy Ion Fusion has significant potential for lower cost experiments through innovative technology: higher current density merging-beamlet injectors; high-field, compact superconducting quadrupoles, agile-waveform induction modules; and high-gradient insulators. Experiments on neutralizing beam space charge in the chamber may lead to lower voltage and lower cost drivers. Innovative target designs may increase allowed beam spot size, and fast ignition may reduce peak ion beam power, lengthen pulse durations, and allow larger focal spot size.

## Acknowledgements

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## Keyword Index

heavy ion driven inertial fusion