FOCUSING AND NEUTRALIZATION OF INTENSE BEAMS

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Abstract

In heavy ion inertial confinement fusion systems, intense beams of ions must be transported from the exit of the final focus magnet system through the target chamber to hit millimeter spot sizes on the target. Effective plasma neutralization of intense ion beams through the target chamber is essential for the viability of an economically competitive heavy ion fusion power plant. The physics of neutralized drift has been studied extensively with PIC simulations. To provide quantitative comparisons of theoretical predictions with experiment, the Heavy Ion Fusion Virtual National Laboratory has completed the construction and has begun experimentation with the NTX (Neutralized Transport Experiment) as shown in Figure 1. The experiment consists of 3 phases, each with physics issues of its own. Phase 1 is designed to generate a very high brightness potassium beam with variable perveance, using a beam aperturing technique. Phase 2 consists of magnetic transport through four pulsed quadrupoles. Here, beam tuning as well as the effects of phase space dilution through higher order nonlinear fields must be understood. In Phase 3, a converging ion beam at the exit of the magnetic section is transported through a drift section with plasma sources for beam neutralization, and the final spot size is measured under various conditions of neutralization. In this paper, we present first results from all 3 phases of the experiment.

INTRODUCTION

In the quest for heavy ion fusion (HIF) the desire for compact cost-effective driver has led us to consider beams with low kinetic energy and high current. [1] The final focusing of the beams with strong space-change self-forces is particularly challenging. The target and chamber requirements are such that after the last focusing magnet, each beam must drift through several meters of target chamber and chamber-magnet interface regions to converge on a millimeter-sized spot. [2] Space-change blowup of the beam can be avoided if a plasma could be introduced into the drift region to neutralize the repulsive self-forces. The mainline HIF chamber with thick liquid walls has an equilibrium vapor of a millitorr. Heavy ion impact ionization of the background is a natural source of plasma. Once the target gets hot (~100eV), photons are emitted and the region around the target will be populated
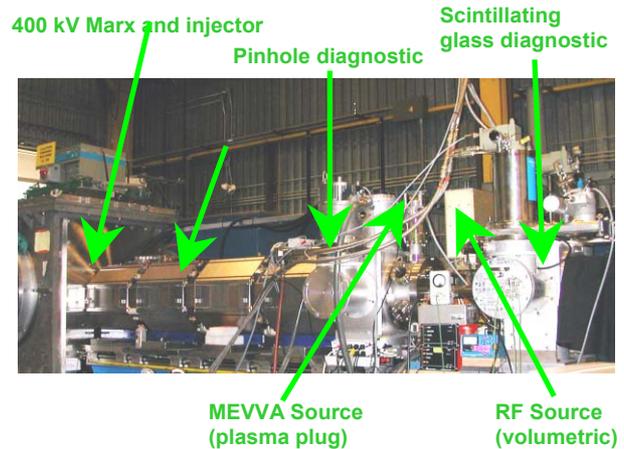
Figure 1: Neutralized Transport Experiment (NTX).

with a volume plasma from photo-ionization of the background gas. While the introduction of plasma into the interior of the chamber is difficult, it is straightforward to inject a "plasma plug" at the entrance to the chamber. [3] The plasma plug provides a reservoir from which electrons are dragged along as the ion beam leaves the plug and enters the chamber. The mechanisms of neutralization with beam-initiated ionization of background gas, volume plasma, and plasma plug are quite different. Simulations with the 3-D electromagnetic code LSP show that the cumulative effect of all 3 sources of plasma will provide enough neutralization of the ion beams to meet the mm spot size requirement. [4]

Even if the neutralization is 100% effective, the beam will not be able to hit the small spot unless the emittance after the magnetic final focusing system is sufficiently small. Indeed there are higher order nonlinearities in the final focusing system, which are known to cause emittance growth. Chromatic and geometric aberrations for highly space-charge dominated beams are areas of active ongoing research [5].

In this paper we report on an experiment to study the neutralization physics and emittance growth in the magnet final focus system. The Neutralized Transport Experiment (NTX) uses singly charged potassium ions of up to 400kV and 80mA. The relevance of a low energy low current experiment is determined by a key parameter, the beam perveance Q, defined as

$$Q = \frac{e\lambda}{4\pi\varepsilon_0 T}$$

where λ is the line charge density, and

$$T = \frac{1}{2} M v^2$$

is the kinetic energy of the heavy ion. From simulations and theory, it has been shown that the essential physics of the magnetic aberrations as well as much of the neutralization processes are determined by the perveance. [6] Since the perveance is the ratio of the potential energy to the kinetic energy of the beam, we can access driver-relevant physics with low energy beams as long as the experimental perveance values are driver-relevant. NTX addresses final focus physics in the $Q \sim 10^{-3}$ range in contrast to previous experiments in the $Q \sim 10^{-5}$ range [7].

INJECTOR

The NTX injector [8] is required to have variable perveance in order to study final transport and neutralization dynamics when perveance is changed. The injector must have low emittance $(\varepsilon_N \leq 0.1 \pi mm - mr)$ in order to provide a sensitive probe of magnetic high-order aberrations, and residual fields from incomplete neutralization. Beam aperturing is a technique we deployed to achieve the dual purpose of variable perveance and low emittance.
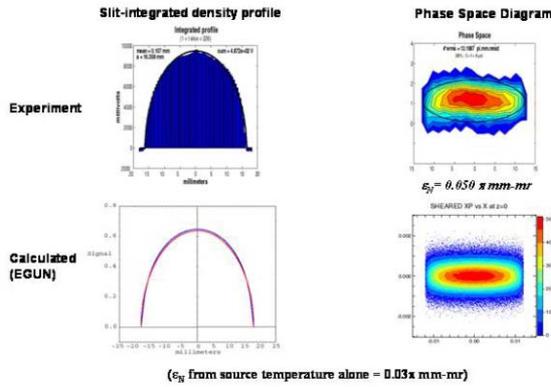

Figure 2: A High brightness apertured beam (300kV, 25 mA, 2 cm aperture).

In the NTX gun, a 1" hot alumina silicate source produces up to 80 mA of singly charged potassium ions at 400 keV from a conventional 12 cm diode with Pierce electrodes at the source. Immediately downstream of the diode is an aperture plate with a variable hole size sandwiched axially between 2 cylinders, which can hold several kV of negative potential (bias). The purpose of the cylinders is to serve as an electron trap, which confines electrons produced at the aperture plate locally, and to inhibit unwanted beam neutralization away from the aperture. In the ion source characterization phase of the experiment, a diagnostic station downstream of the aperture assembly measures the current with a Faraday cup and measures the line-integrated beam profile and emittance at injection with a slit/slit-cup set up. When the bias potential is turned off, electron neutralization leads to enhanced current density on-axis and highly non-uniform beam profile. However, when a bias potential of 2 to 3kV is turned on, a uniform beam profile is obtained. The unapertured beam current follows a Child-Langmuir Law reaching 80mA at 400kV. With a 2cm diameter aperture; the current is reduced by approximately one half. A 1cm diameter aperture reduces the current to 1/4 of the 2cm aperture value.

Most of the detailed experiments were performed with the 2cm aperture where the current is 25mA at 300kV. The line-integrated beam profile is parabolic, indicative of a uniform beam profile, and the normalized edge emittance is measured to be 0.05 π-mm-mr, which is less than a factor of 2 above the source temperature imposed value. The beam size, density, and emittance are in good agreement with EGUN predictions as shown in Figure 2. [8]

MAGNETIC LATTICE

The second phase of NTX consists of magnetic transport with 4 pulsed quadrupoles [9] enclosing a thin-wall stainless steel tube approximately 26 cm in diameter. The half-lattice period is 60 cm. Figure 3 shows the beam going through large excursions of up to 10 cm in the magnetic lattice to reach an exit condition of 2 cm radius and 20 mr convergence in both the x and y planes. This is the desired entrance condition for the final neutralized drift experiment.
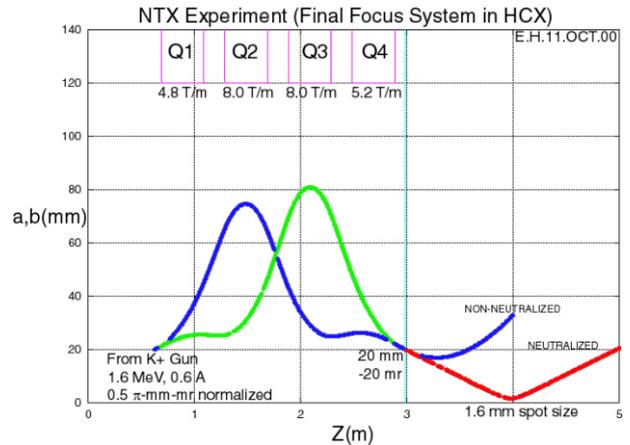

Figure 3: Final focus lattice for neutralized drift.

The pulsed magnets [10] were fabricated in-house, and the conductors were arranged to minimize unwanted higher order multipoles. Fields were measured with accurate 3-way B dot probes, and the agreement with ANSYS code calculations was excellent as shown in Figure 4.

Axial profile (measurement vs. ANSYS)

Three-way B probes
(B_x, B_y and B_z)
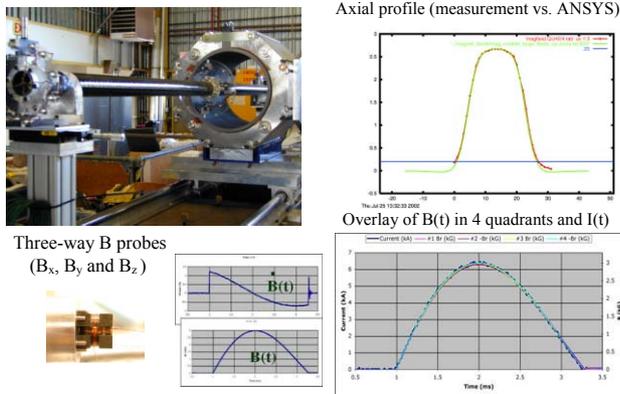
Overlay of B(t) in 4 quadrants and I(t)

Figure 4: Magnetic field measurement.

The beam size and angle at lattice exit were quite sensitive to small changes in quad fields and/or beam energy. These changes were measured optically, and found to be in excellent agreement with predictions of WARP3D, a 3-D particle-in-cell code for space charge dominated beam transport. [9] In Figure 5 we show the variations with beam energy (in steps of 3%) of the measured beam image (bottom row) against WARP3D simulations (top row).
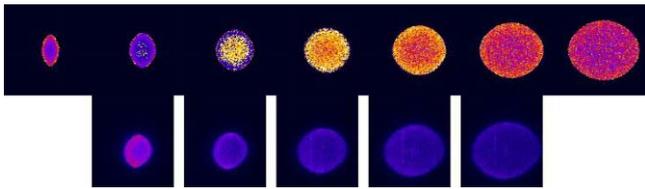

Figure 5: Numerical results and camera images of beam profiles as function of energy.

NEUTRALIZED DRIFT

The neutralized drift experiment [11], the third phase of NTX, is performed in a one-meter long pipe installed at the exit of the four-pulsed-quadrupole section. Two sources of plasma were injected at the upstream and downstream end of the 3" diameter pipe.

The upstream source is a MEVVA source [12] consisting of two metal vapor arcs that provide plasma pulses of $\sim 10^{10} / cm^3$ injected from two opposite holes on the side of the 3" beam pipe. The plasma is not expected to be spatially uniform, and has a pulse-to-pulse jitter of 10%. This source serves as a plasma plug from which the ion beam would extract electrons for neutralized drift downstream. Theory predicts that as long as the plasma density is much higher that the beam density (which is the case in our experiment), beam neutralization is insensitive to spatial inhomogeneities or small pulse-to-pulse variations. [3]

In the downstream end of the drift section is an RF plasma source [13], which produces a comparable plasma density of up to $10^{10} / cm^3$. The RF plasma source is very stable from pulse-to-pulse. It is operated in a pulsed mode where short puffs of Argon gas are injected into the beam region where ionization by the RF source takes place. By varying the duration and timing of the gas puff, and by varying the power of the RF source, both the plasma density as well as the gas density can be independently controlled. The evolution of the gas and plasma densities was well characterized prior to installation into the NTX beamline.

The Langmuir probe measurements of plasma density profile were also extended to the MEVVA source. The purpose of the RF source downstream is to simulate the volume plasma from photo-ionization in a target chamber, as well as the gas effects in a vapor-filled thick-liquid-wall chamber. The MEVVA source and the RF source parameters are varied during the course of the neutralization drift experiments.

The first drift experiment was conducted with both plasma sources turned off. A large 2cm radius beam was measured at the exit of the 1-meter drift, consistent with the predicted vacuum solution. It should be noted that this solution was obtained only after measures to minimize wall emission of electrons were implemented. With the MEVVA source turned on, the spot size was significantly reduced. The spot size continued to decrease as we tuned on the RF source and gas effects respectively. It should be pointed out that the interpretation of these results were somewhat complicated by electrons emitted from the target scintillator plate, and by an associated upstream bias potential which was independently controlled. See Figure 6.
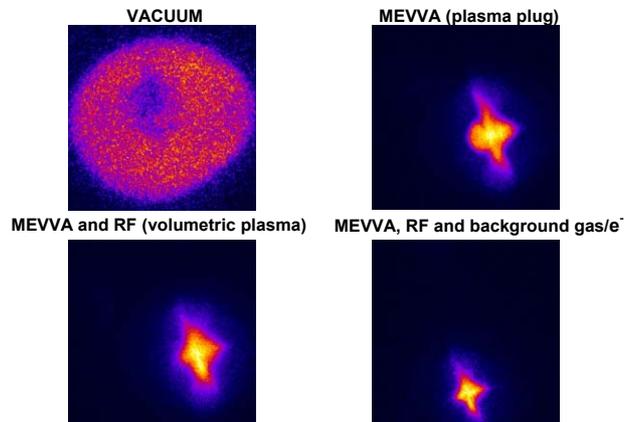

VACUUM MEVVA (plasma plug)

MEVVA and RF (volumetric plasma) MEVVA, RF and background gas/e⁻

Figure 6: Spot size dependence on neutralization mechanism. Image box size is 4cm × 4 cm squares.

While the first results are qualitatively consistent with theoretical expectations, quantitative comparisons with simulation results require much more work.

The first step toward quantitative comparison is a much better characterization of the 4-D phase space of the incoming ion beam. The final spot size at target is very

sensitive to beam emittance and details of the beam phase space. We measured the transverse 4-D phase space with a movable pinhole inserted at the entry plane to the drift section, i.e., at the exit of the magnetic lattice. The image from the pinhole was measured at the focal point. If the beam had zero emittance such a measurement would yield an identical spot at the same location as the pinhole is moved around to sample different parts of the entering beam. In reality, we measure large aberrations, particularly at the beam edge, consistent with the prediction of geometric aberrations through the magnetic lattice. Superposition of all these images provides a measurement of the purely ballistic beam. At the same time, they provide information of the full 4-D phase space at entrance. [11]

CONCLUSIONS

In the future, we expect to continue detailed comparisons of LSP simulations with measurements. In this regard, a new diagnostic under development, a non-intercepting electron-beam diagnostic [14] to measure the beam electric field profile with and without plasma), will provide much more detailed information of the neutralization dynamics throughout the path of the converging ion beam. While the experimental investigation of the final focusing of high perveance ion beams is still ongoing, the results, both theoretical and experimental have given us a much better understanding of both magnetic final transport as well as neutralized drift. In the process of these investigations, we have developed diagnostics and made measurements to a level of detail hitherto unattained, and the comparisons between theory and experiments are quite encouraging.

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