A FAST FARADAY CUP FOR THE NEUTRALIZED DRIFT COMPRESSION EXPERIMENT*

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Abstract

Heavy ion drivers for high energy density physics applications and inertial fusion energy use space-charge-dominated beams which require longitudinal bunch compression in order to achieve sufficiently high beam intensity at the target. The Neutralized Drift Compression Experiment-1A (NDCX-1A) at Lawrence Berkeley National Laboratory (LBNL) is used to determine the effective limits of neutralized drift compression. NDCX-1A investigates the physics of longitudinal drift compression of an intense ion beam, achieved by imposing an initial velocity tilt on the drifting beam and neutralizing the beam's space-charge with background plasma. Accurately measuring the longitudinal compression of the beam pulse with high resolution is critical for NDCX-1A, and an understanding of the accessible parameter space is modeled using the LSP particle-in-cell (PIC) code. The design and preliminary experimental results for an ion beam probe which measures the total beam current at the focal plane as a function of time are summarized.

INTRODUCTION

One of the most significant challenges in developing heavy ion drivers for high energy density physics applications and inertial fusion energy is in the final transport section. In a heavy ion driver, intense beams of ions are transported from a final-focus magnet system through the target chamber, where they focus on the target with a spot size of a few mm. After the intense beams of ions leave the final-focus magnet system, the ions drift about 6 m without further external focusing to the center of the target chamber. In addition, when the ion beams reach the center of the target chamber, the current of each beam must be on the order of tens of kAs with a pulse length of less than 10 ns.

In order to focus an intense ion beam to the small spot size required, the majority of the ion beam's space-charge must be neutralized during the final transport stage. A low-density plasma positioned between the final-focus magnets and the target chamber provides electrons which neutralize the beam's space-charge and allow the intense beams to be focused beyond the space-charge limit.

The Heavy Ion Fusion Virtual National Laboratory constructed the Neutralized Transport Experiment (NTX) at the Lawrence Berkeley National Laboratory to study, on a reduced scale, the physics of the final-focus and neutralized transport of space-charge-dominated beams [1]. The 400 keV injector generated a low-emittance, variable-perveance K^+ beam, which passed through a magnetic-focusing section in order to study the magnet tuning physics and its effects on the phase-space evolution of the beam. The beam was given a convergent angle and allowed to drift through a region containing background plasma. The plasma electrons provided sufficient neutralization of the beam space-charge that a final transverse spot radius of < 2 mm was achieved at the focal plane. The neutralization physics, description of the beamline system, and other experimental results obtained on NTX were recently published [1, 2, 3].

Transverse focusing of an ion beam is only part of the challenge. In order to achieve < 10 ns pulse lengths, each ion beam pulse must also be compressed along the direction of propagation. In order to achieve high current densities on target, there is a need to determine the physical and technological limits of longitudinal focusing, achieved by applying a time-dependent head-to-tail velocity tilt to the beam and allowing it to drift through a background plasma. The concept is called neutralized drift compression, and the upgrade of the NTX facility is called the Neutralized Drift Compression Experiment-1A (NDCX-1A).

In NDCX-1A, the primary addition to NTX is the induction module, which is a linear induction accelerator [4] with one acceleration gap that applies a voltage pulse to the beam to create the required axial velocity tilt. The beam pulse then drifts through the background plasma until a focal plane in current density is reached. The two main goals of NDCX-1A are to determine the limits of how high the current density can be compressed and how accurately the compression factor can be measured. Simulations using the LSP particle-in-cell (PIC) code [5] predict a pulse width of a few ns with up to about one A/cm^2 of current density at peak compression. Therefore, fast diagnostics have been incorporated into NDCX-1A and are being tested.

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FAST FARADAY CUP SIMULATIONS

The NDCX-1A requires accurate measurements of the compressed ion beam current, $I_b(t)$, current density, $J_b(x, y, z, t)$, and pulse width at the longitudinal focal plane near the end of the plasma region. Several probe designs, based on PIC simulations, are being tested to measure these parameters. The use of the LSP code [5] is one method for simulating an ion beam pulse propagating through a background plasma. The LSP code is an electromagnetic PIC code designed for large-scale plasma simulations and supports multiple coordinate systems and geometries. The LSP code has been utilized in order to realistically predict the accuracy of the probe designs.

The ion beam probes designed for NDCX-1A are modified Faraday cups. Generically, a Faraday cup consists of a negatively-biased repelling ring located "upstream" of a positively-biased collector cup enclosed in a grounded housing such that plasma particles and secondary electrons in the system are controlled. A design that admits the entire compressed ion beam is inadequate for the purposes of NDCX-1A because of the complex plasma and secondary electron behavior within the probe. In order to accurately measure $I_b(t)$ or $J_b(x, y, z, t)$ in NDCX-1A: (1) plasma ions and beam ions must not shield the negatively-biased repelling ring; (2) co-moving plasma electrons must be completely rejected from the probe; (3) beam ions must not be allowed to strike the repelling ring and create secondary electrons; (4) secondary electrons created by ion bombardment on the collecting surface must be trapped; and (5) beam current densities up to an A/cm^2 must be measured at the collector with sub-nanosecond time resolution.

The LSP simulations predict that the regular Faraday cup design should be modified such that it includes a grounded frontplate with Debye-length-size holes, replaces the repelling-ring with a repelling-plate with slightly larger holes, and replaces the collector cup with a collector plate. The aligned holes of the frontplate and repelling-plate (or the backplate) lend some geometric shadow to the probe by allowing only a fraction of the compressed beam pulse to enter the diagnostic, thereby simplifying the control of the five important processes listed above.

The design used in the initial experiments consists of a frontplate with hole radii approximately a Debye length in size ($n_p \sim 10^{10}$ cm^{-3}, $kT_p \sim 3$ eV), followed 1 mm "downstream" by a backplate with larger hole radii, and a collector plate 1 mm "downstream" of the backplate. Table 1 shows the hole radius, the horizontal hole-to-hole separation, and the applied bias for each of the plates. The vertical hole-to-hole separation is $\sqrt{3}/2$ times the horizontal separation, and each row of holes is staggered with respect to the adjacent rows, giving an hexagonal arrangement. The frontplate and backplate are each 102μm thick ($< 2r_{hole}$), made of stainless steel, and contain 2,146 holes.

Table 1: "Pinhole" Faraday cup specifications

Plate	r_{hole}	Hole-to-hole	Bias
Front	114 μm	1016 μm	*grounded*
Back	241 μm	1016 μm	$-150V$
Collector	N/A	N/A	$+50V$

The LSP simulations predict that plasma ion densities two orders-of-magnitude lower ($\sim 10^8$ cm^{-3}) than the bulk plasma densities will be accelerated by the electric field between the frontplate and the backplate, but will be repelled from the collector due to the stronger, reversed electric field between the backplate and collector. Plasma ions that strike the backplate are expected to create negligible amounts of secondary electron current ($< 10\mu$A). The frontplate is grounded so as to minimize the perturbation to the surrounding plasma environment. Neither the plasma ions nor the beam ions are expected to significantly shield the backplate's potential, due to the close 1 mm spacings. Co-moving plasma electrons are completely rejected from the probe by the electric field between the frontplate and the backplate, and the secondary electrons created by ion bombardment on the collecting surface are trapped by the electric field between the backplate and the collector. If all co-moving electrons were not rejected, then $I_b(t)$ would be under-estimated; if all secondary electrons were not trapped on the collector, then $I_b(t)$ would be over-estimated. The holes in the backplate are designed to allow diverging beam ions (< 125 mr) to pass without striking the backplate and creating large secondary currents. The 1 mm gaps were chosen to reduce space-charge effects and to minimize induced image current effects at the collector. Therefore, the entire beam (less the 5% transmission factor) will be admitted into the $d = 5$ cm probe and the collector will measure the total beam current, $I_b(t)$, before the beam has sufficient time to decompress due to space-charge forces. Figure 1 shows (a) the probe measuring $I_b(t)$ in the LSP simulation, and (b) a photograph of the probe.

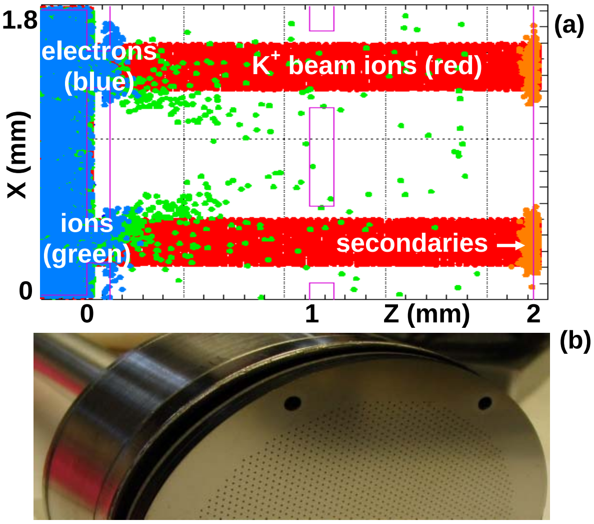

Figure 1: $I_b(t)$ probe: (a) particle-plot from LSP simulation (aspect ratio 1:1), and (b) photograph before installation.

INITIAL EXPERIMENTAL RESULTS

Initial measurements taken with the "pinhole" Faraday cup show that, when only plasma is present, the collector plate draws no current and the backplate draws about 0.2 mA of plasma ion current, in agreement with LSP simulations with plasma density $n_p \sim 10^{10}$ cm^{-3}. The probe biases were chosen such that the diagnostic would operate properly under the harshest conditions expected at the focal plane ($n_p = 10^{11}$ cm^{-3}, $n_{beam}^{peak} = 10^{10}$ cm^{-3}). The injector produces a 6μs-long, 299 keV K^+ beam of approximately 2 cm radius which is transported in the $+\hat{z}$ direction through the magnetic-focusing and plasma drift sections. Its current is then measured by the probe in the presence of plasma. The voltage swing across the acceleration gap is set to create an electric field whose direction is initially in the $-\hat{z}$ direction and changes to point in the $+\hat{z}$ direction later in time, so that the head of the beam is slowed and the tail is accelerated, causing a focal plane in current density to be created about 1 m "downstream". The induction module's timing and voltage act on the middle 2 μs section of the beam such that the longitudinal focal plane coincides with the plane of the collector plate.

Figure 2 shows the current $I_b(t)$ recorded by the collector plate. The negative dip in the data is believed to be an electronic artifact (reflection from a coupling box). Figure 3 is the same data, but normalized to the initial beam current (without an applied tilt) and expanded around the location of peak compression to show error bars (of the nine-shot average) as well as comparison to LSP simulations.

The initial results of the fast $I_b(t)$ diagnostic in NDCX-1A are encouraging. The observation of over $50\times$ longitudinal compression in the presence of plasma has been verified by optical measurements and agrees well with LSP simulations using realistic experimental parameters, including the applied velocity tilt. Without the neutralizing plasma present, a factor of approximately $20\times$ compression was measured, also in agreement with LSP simulations.

Future research will include four key areas. First, there are small pulse-width (full-width, half-maximum) discrepancies between the "pinhole" Faraday cup (5 ns), optical measurements (2 ns), and LSP simulations (3.25 ns). Induced image current signals in the backplate of the probe suggest pulse widths between 3 and 4 ns. Thus, electronic modifications for faster temporal response need to be investigated. Second, noise and sampling issues need to be addressed. Larger, more closely-spaced holes would reduce the signal noise and increase the statistical sampling of the beam, at the cost of using higher biases in the probe to control the plasma and secondary behavior as well as degraded structural integrity of the frontplate and backplate. Currently, sub-mm-scale fluctuations in current are lost to the frontplate and averaged over. Further calibration tests are required to verify the beam current magnitude. Third, the role of desorbed gas from the frontplate and collector plate needs to be considered, although its effect on the measurement appears to be small. Fourth, the current density diagnostic will be similar to the $I_b(t)$ probe except it will be smaller and moveable. It will map out $J_b(x, y, z, t)$ at the focal plane and provide key insights into the physical and technological limitations of neutralized drift compression.

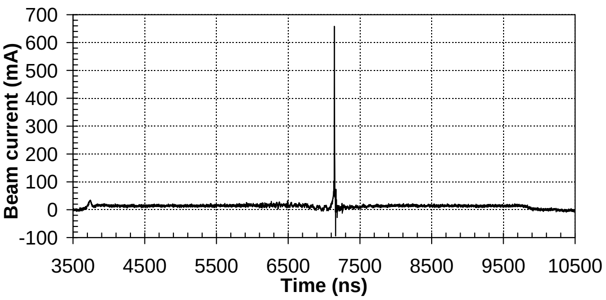

Figure 2: $I_b(t)$: Average of nine shots near focal plane.

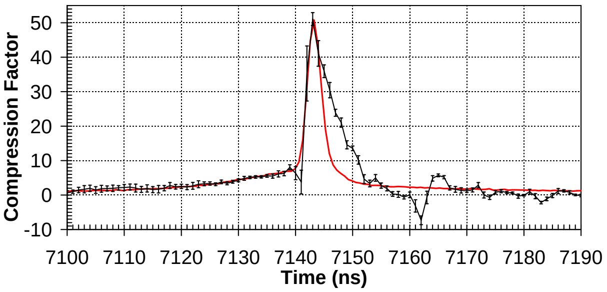

Figure 3: Initial measurement of longitudinal compression: (Black) Experiment, (Red) LSP simulation.

Neutralized drift compression offers the potential of compressing heavy ion beams to very high current densities and, therefore, shorter accelerators could be used as heavy ion drivers for high energy density physics and fusion applications, making them more compact and cost-effective than previously envisioned.

REFERENCES

[1] E. Henestroza, S. Eylon, P. K. Roy, S. S. Yu, A. Anders, F. M. Bieniosek, W. G. Greenway, B. G. Logan, R. A. MacGill, D. B. Shuman, D. L. Vanecek, W. L. Waldron, W. M. Sharp, T. L. Houck, R. C. Davidson, P. C. Efthimion, E. P. Gilson, A. B. Sefkow, D. R. Welch, D. V. Rose, and C. L. Olson, Phys. Rev. ST Accel. Beams **7**, 083501 (2004).

[2] P. K. Roy, S. S. Yu, S. Eylon, E. Henestroza, A. Anders, F. M. Bieniosek, W. G. Greenway, B. G. Logan, W. L. Waldron, D. L. Vanecek, D. R. Welch, D. V. Rose, R. C. Davidson, P. C. Efthimion, E. P. Gilson, A. B. Sefkow, and W. M. Sharp, Phys. Plasmas **11**, 2890 (2004).

[3] C. Thoma, D. R. Welch, S. S. Yu, E. Henestroza, P. K. Roy, S. Eylon, E. P. Gilson, Phys. Plasmas **12**, 043102 (2005).

[4] N. Christofilos, R. Hester, W. Lamb, D. Reagan, W. Sherwood, R. Wright, Rev. Sci. Instrum. **35**, 886 (1964).

[5] LSP is a software product of ATK Mission Research, Albuquerque, NM 87110.

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