A SOLENOID FINAL FOCUSING SYSTEM WITH PLASMA NEUTRALIZATION FOR TARGET HEATING EXPERIMENTS *

P. K. Roy[1], P. A. Seidl[1], J.J. Barnard[2], F.M. Bieniosek[1], J. E. Coleman[1,5], R. C. Davidson[3], J. A. Duersch[5], P. Efthimion[3], E. P. Gilson[3], J. Y. Jung[1], M. Leitner[1], B. G. Logan[1], D. Ogata[5], A. Molvik[2], A. B. Sefkow[3], W. L. Waldron[1], D. R. Welch[4]

[1]LBNL, [2]LLNL, [3]PPPL, [4]Voss Scientific, and [5]UCB, USA

Abstract

Intense bunches of low-energy heavy ions have been suggested as means to heat targets to the warm dense matter regime (Temperature ~ 0.1 to 10 eV, solid density ~1% to 100%). In order to achieve the required intensity on target, a beam spot radius of approximately 0.5 mm, and pulse duration of 2 ns is required with an energy deposition of approximately 1 J/cm^2. This translates to a peak beam current of 8A for 0.4 MeV K^+ ions. To increase the beam intensity on target, a plasma-filled high-field solenoid is being studied as a means to reduce the beam spot size from several mm to the sub-mm range. A prototype experiment to demonstrate the required beam dynamics has been built at Lawrence Berkeley National Laboratory. The operating magnetic field of the pulsed solenoid is 8 T. Challenges include suitable injection of the plasma into the solenoid so that the plasma density near the focus is sufficiently high to maintain space-charge neutralization of the ion beam pulse. Initial experimental results are presented.

INTRODUCTION

Intense ion beams of low kinetic energy offer an attractive approach to heating dense matter uniformly to extreme conditions, because their energy deposition is nearly classical, shock-free, and have ability to heat all target materials (conductors, insulators, foams, powders), and have opportunity of high repetition rates (≥0.1Hz). High energy density physics and ion-driven inertial fusion require the simultaneous transverse and longitudinal compression of an ion beam to achieve high intensities. A beam of ~200 A (23 MeV Na^+) with a 1-mm focal spot radius and pulse length of ~1 ns would be suitable as a driver for Warm Dense Matter experiments. These beam spot sizes and pulse lengths are achievable with beam neutralization [1-3] and longitudinal compression [4-11] in a background plasma.

In beam neutralization, electrons from a plasma or external source are entrained by the beam and neutralize the space charge sufficiently that the pulse focuses on the target in a nearly ballistic manner to a small spot, limited only by longitudinal and transverse emittance. This plasma neutralization is provided by co-moving electrons in the drift section filled with plasma, referred to here as the plasma channel. Typically, $n_p/Zn_b>1$, where n_p is the plasma density, and n_b and Z are the ion beam density and charge state, respectively.

*Work supported by US DOE for HIF-VNL

#PKRoy@LBL.GOV

In neutralized drift compression (NDCX), the beam is longitudinally compressed by imposing a linear head-to-tail velocity tilt, by an induction-bunching module (IBM) that produces a linear velocity ramp of ±15% for 0.2μs. Longitudinal compression of space-charge-dominated beams has been studied extensively in theory, simulations and experiments [4-11].

Longitudinal space-charge forces limit the beam compression ratio, the ratio of the initial to final current, to about 20. This depends very much on beam parameters and space charge. Theoretical models and simulations predicted that much Higher compression ratios (of order 100) can be achieved if the beam compression takes place in a plasma-filled drift region in which the space-charge forces of the ion beam are neutralized [7, 8]. We reported achieving 50-fold compression [9] in experiments with a high perveance heavy ion beam. But the neutralized longitudinal compressed ion beam spot size was larger (>6 mm FWHM) at the point of maximum axial compression. This feature was due to a time-dependent defocusing effect. Recently this has been compensated for and a sub-millimeter beam spot size along with higher ratio beam bunching [10-13] has been observed. In a recent simulation [12] the compressed beam pulse reaches 10^{12} cm^{-3} peak density vs. a beam density of ~2x10^8 cm^{-3} entering the IBM gap. The longitudinal compression ratio peaks at 120 with a transverse spot a_s = 1.3 mm (edge radius) is expected. Thus, a target placed at the focus would receive peak deposition energy of ≥ 0.035 J/cm^2 for a 300 keV 26 mA beam. Limitations of beam dynamics (emittance, chromatic aberration) and achieving a sufficiently high plasma electron number density near the focal plane are the key issues. The ferroelectric plasma source (FEPS) [14] radially ejects plasma in the order of 10^{10} cm^{-3} along a length of a meter; and a combination of two filtered cathodic arc plasma sources (FCAPS) [15-16], has yielded similar results.

In order to establish a strong focusing field near the target plane, a new final focus solenoid is located 18 cm upstream of the FCAPS and the target plane to provide strong beam focusing near the target, and its fringe field concentrates the FCAPS plasma density on axis near the target plane. Though a peak beam density of ~10^{14} cm^{-3} is required for some WDM experiments, the measured peak density for these initial scoping experiments is in the range 10^{12}-10^{13} cm^3. This of beam density is presently limited by the available density from the plasma source. Demonstration of the final focus solenoid with plasma neutralization is presented.

1-4244-0917-9/07/$25.00

FINAL FOCUSING SOLENOID

Figure 1(a) shows a sketch of the prototype final focus solenoid (FFS). To reach 8 Tesla magnetic field the magnet has to be pulsed. In order to limit eddy currents, the solenoid winding consists of Litz wire wound on a non-conductive G-10 tube. For the same reason, the winding pack was inserted into an electrically insulating, but thermally conducting Polypropylene (Cool-Poly© D1202) housing and potted with highly viscous epoxy (to be able to wick the single strands of the Litz wire). The magnet is forced-air cooled through cooling channels. Figure 1(b) shows a field profile taken during initial tests. Table 1 represents summarized main magnet parameters.

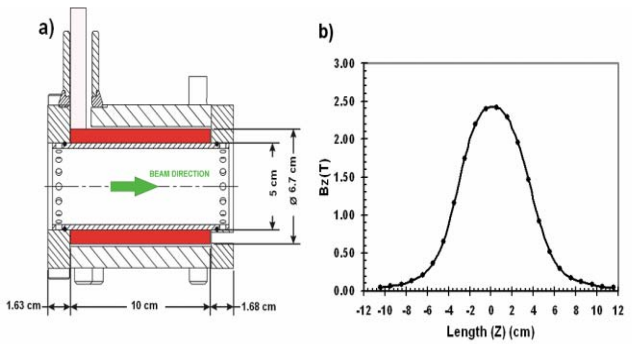

Figure 1. (a) A sketch of final focus solenoid and (b) characteristic magnetic field profile.

TABLE 1. Parameters of the final focus solenoid (FFS).

Parameter	Value
Maximum Solenoid field:	8T
Effective field length:	10.15 cm
Winding pack ID and OD	5.1 cm and 6.7 cm
Wire specification:	24 strand gauge 20 AWG, heavy build insulation MW80-155 Deg., profiled to 1cm x 0.16 cm, wrapped in Nomex paper
Number of turns:	32 (8 turns/layer)
Coil resistance:	$7.75 \times 10^{-3} \Omega$, coil
Inductance:	2.80×10^{-5} H.
Epoxy specification:	CTD-101K
Stored energy:	5.9 kJ
Max. voltage across magnet:	2.4kV
Max. current:	21.3 kA
Pulse length :	784 μs

PLASMA DENSITY MEASUREMENT

The FFS was installed with a new beam target chamber. Initially the target would be a thin self-supporting gold or aluminum metallic foil, mounted on a glass or sapphire substrate. The ion beam would be passed through and heat the target foil, exiting through a hole in the substrate to be measured with diagnostics [17]. We measured plasma density before installing the target foil. The FFS was installed in the target chamber along with the two FCAP sources and a Langmuir probe to measure plasma density in the solenoid, between the solenoid and the target plane, where the beam density would be highest. The FCAP was formed by two pulsed aluminum cathodic arc sources. Each source was equipped with a 30^0 macroparticle filter towards the FFS providing a flow of fully ionized aluminum plasma. The distances between the target plane (here FCAP source filter apertures) and the downstream-end and the center of the FFS were 11.7 cm and 18.27 cm, respectively.

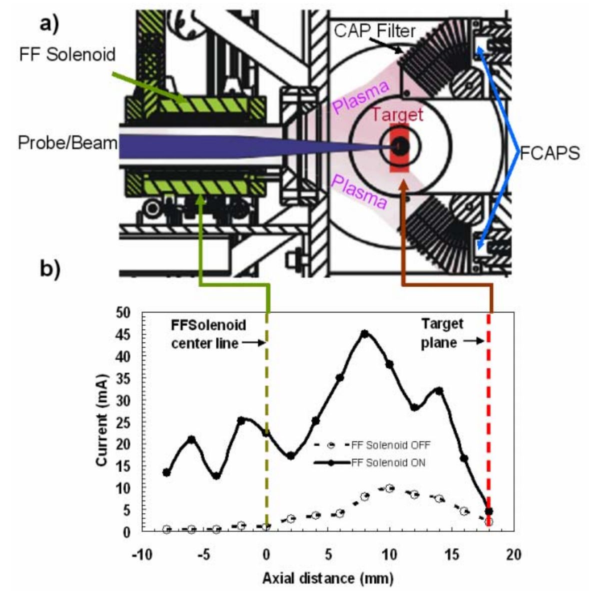

Figure 2. (a) A sketch of FCAP filters and the FFS in the target chamber, (b) measured plasma current (FCAPS: 1 kV discharge) with (for 4T) and without FFS powered.

Figure 2(b) shows the measured ion saturated plasma current (FCAP discharge voltage 1 kV) using the on axis Langmuir probe with and without the FFS powered. Plasma was channeled on to the beam axis by the solenoid fringe field. The maximum peak plasma current of 9.9 mA was measured between the gap of the target plane and the FFS, when the FFS was not powered. Measured current was as high as 45 mA when the FFS was powered for 4T field. This data were plotted as a plasma density distribution, which depends on the mean velocity distribution, as shown in Fig.3 for two cases of initialized velocities. In principle, plasma density is expressed as the ratio of measured current to the product of the probe area, plasma ion velocity, and charge. Plasma velocity was varied roughly between the range of 1.4 to 6 cm/μs as measured using the time of flight (TOF) method (velocity=distance/time). It seems that the jitter was on the order of 5 μs, and over a 10 cm TOF span corresponds to 2 cm/μs uncertainty. A plasma velocity in the presence of the solenoid was obtained using LSP simulations [10] using initial velocities of 1.5 cm/μs and 6cm/μs. Maximum plasma density of 2.8×10^{12} cm^{-3} was achieved between the gap of the FFS and the target plan, where the particles velocity was lower due to the FFS field. This density was reduced to 1.3x10^{11} cm^{-3} at the same plane when the FFS was not powered. Data also shows that density decreased as velocity increased at the upstream end of the FFS, but density was higher (~2.5x10^{11} cm^{-3}) than the density without FFS field (~10^{10} cm^{-3}). Density at the FCAP did not vary significantly with variation of the FFS field (4 to 5T).

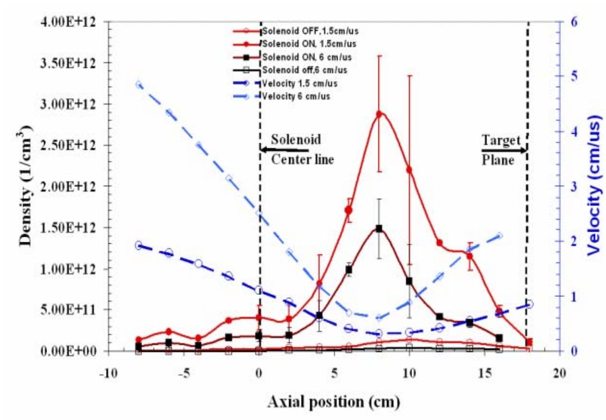

Figure 3: Inferred experimental axial plasma density distributions with and without magnetic field, for two initialized velocities in simulation. The dotted lines (blue in color) represent calculated velocities, initialized at 1.5 cm/μs and 6 cm/μs.

INTEGRATION OF THE FFS AND FCAPS WITH THE NDCX BEAM EXPERIMENT

Figure 4 shows integration of the final focus solenoid assembly with the NDCX K^+ beam line to measure simultaneous transverse and longitudinal beam focusing at the target plane.

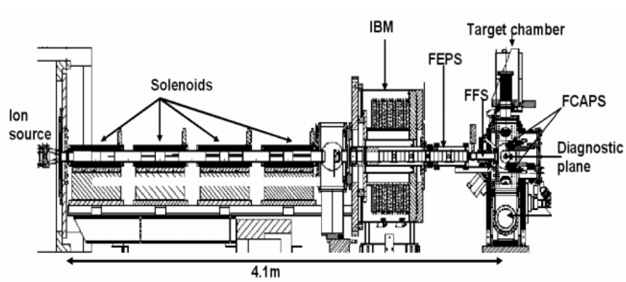

Figure 4: Sketch of the final focus solenoid (FFS) assembly integration with a K^+ NDCX beamline.

A K^+ beam of 315 keV, 28-mA was focused by four pulsed solenoid magnets [18] to control the beam envelope (beam radius and convergence angle). These were followed by an IBM for beam bunching and compressed the beam as 89 times, and a 85 cm long FEPS (9kV operating voltage) for primary beam neutralization. These are integrated with the FFS system (5T or off) including the FCAPS (1kV discharge voltage). The beam diagnostics were a multiple-pinhole Faraday cup, and a scintillator, the signal of which was detected using a gated camera through a quartz glass window (>90% transmission wavelength between 300 to 1000 nm). A time-gated camera was also used to measure the beam optical profile and intensity. Figure 5 shows the initial resulting beam profile for the FFS system with plasma neutralization. FWHMs of 2.2 mm and 3.0 mm were measured when the FFS was powered with 5T field and without powered, respectively, as shown in Fig. 5(c).

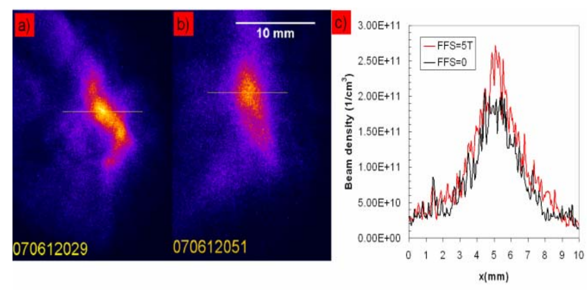

Figure 5: NDCX plasma neutralized beam profiles for axial compression (IBM: 25 kV, FCAPS 1 kV, FEP: 9 kV) with the final focus solenoid (a) powered, and (b) without powered; (c) profiles of the two images.

SUMMARY

A pulsed final focus solenoid (FFS) magnet was designed, developed and tested in neutralized beam focusing and bunching experiments. The plasma density measurements qualitatively confirm the model prediction of enhanced density within the FFS, and a peak density in the gap between the FFS and the focal plane. The beam results show an enhancement of intensity at the target from the FFS.

REFERENCES

[1] P. K. Roy et al., Phys. of Plasmas **11**, 2890 (2004).
[2] B. G. Logan et al., Nucl. Fusion **45**, 131 (2005).
[3] C. Thoma et al., Phys. of Plasmas **12**, 043102 (2005)
[4] R. C. Davidson et al., PRST A&B, **8**, 064201 (2005)
[5] W. M. Sharp et al., NIM A **544**, 398 (2005).
[6] W. M. Fawley et al., Phys. Plasmas **4**, 880 (1997).
[7] D. R. Welch et al., NIM A **544**, 236 (2005).
[8] C. Thoma et al., in *Proc. of the PAC05*, p.4006.
[9] P. K. Roy et al., PRL, **95**, (2005), pp. 234801.
[10] A. B. Sefkow et al., NIM A**577**, 289 (2007), and to be published in PAC07 proc.
[11] P. A. Seidl et al., NIM A **577**, 215 (2007).
[12] D. Welch et al., NIM A**577**, 231 (2007), and to be published in PAC07 proc.
[13] J.E. Coleman et al., to be published in PAC07 proc.
[14] P.C. Efthimion et al., NIM A**577**, 203 (2007)
[15] A. Anders et al., J. Appl. Phys. **91**, 4824 (2002).
[16] A. Anders and R. A. MacGill, Surf. Coat. Technol. **133-134**, 96 (2000).
[17] F. M. Bieniosek, to be published in PAC07 proc.
[18] J.E. Coleman et al., "Matching and transporting an intense ion beam through a solenoid focusing channel", to be submitted in PRST A&B, 2007.

1-4244-0917-9/07/$25.00