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Neutralized drift compression experiments with a high-intensity ion beam

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Abstract

To create high-energy density matter and fusion conditions, high-power drivers, such as lasers, ion beams, and X-ray drivers, may be employed to heat targets with short pulses compared to hydro-motion. Both high-energy density physics and ion-driven inertial fusion require the simultaneous transverse and longitudinal compression of an ion beam to achieve high intensities. We have previously studied the effects of plasma neutralization for transverse beam compression. The scaled experiment, the Neutralized Transport Experiment (NTX), demonstrated that an initially un-neutralized beam can be compressed transversely to $\sim$1 mm radius when charge neutralization by background plasma electrons is provided. Here, we report longitudinal compression of a velocity-tailored, intense, neutralized 25 mA K^+ beam at 300 keV. The compression takes place in a 1–2 m drift section filled with plasma to provide space-charge neutralization. An induction cell produces a head-to-tail velocity ramp that longitudinally compresses the neutralized beam, enhances the beam peak current by a factor of 50 and produces a pulse duration of about 3 ns. The physics of longitudinal compression, experimental procedure, and the results of the compression experiments are presented.

Keywords: Beam; Ion; Longitudinal compression; Plasma; Neutralization; Diagnostics; Induction cell

1. Introduction

Intense ion beams of moderate energy offer an attractive approach to heating dense matter uniformly to extreme conditions, because their energy deposition is nearly classical and shock free. 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 $\sim$200 A (23 MeV Na^+) with a 1 mm focal spot radius and pulse length of $\sim$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 and longitudinal compression 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. Several numerical and experimental articles on beam neutralization and transverse compression have been published elsewhere [1–6]. In neutralized drift compression, the beam is longitudinally compressed by imposing a linear head-to-tail velocity tilt that produces a pulse duration of a few ns. Longitudinal compression of space-charge-dominated beams has been studied extensively in theory and simulations [7–12]. Longitudinal space-charge forces limit the beam compression

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ratio, the ratio of the initial to final current, to about 10 in most applications. An experiment with five-fold compression has been reported [13]. Recent 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 [14,15]. We report here achieving 50-fold compression [16] in experiments with a high perveance heavy ion beam. The physics and technical issues, fast diagnostics, experimental results of longitudinal beam compression are presented in this article.

2. Physics and technical issues

2.1. Velocity-tailored voltage ramp and compression

Fig. 1 shows a concept of longitudinal beam compression. A 300 keV beam with 25 mA current of 10 μs pulse length (Fig. 1(a)), enters a neutralized drift section, where an induction bunching module applies a velocity ramp to roughly 300 ns, Fig. 1(b), of the 10 μs pulse and compresses that portion of the beam to a few nanoseconds (Fig. 1(c)). A brief description of the cell is presented in Section 3.2. The tilt core applies a head-to-tail velocity tilt on the beam pulse segment and increases the current by decreasing the pulse duration. The longitudinal envelope equation for a beam with a parabolic profile without space charge can be expressed as [17]

$$\frac{d^2L}{dS^2}=\frac{16\varepsilon_z^2}{L^3} \tag{1.1}$$

where L is the bunch length, S is the axial distance and ε_z is five times the rms longitudinal emittance. The velocity tilt required to compress the beam to a "stagnation" point

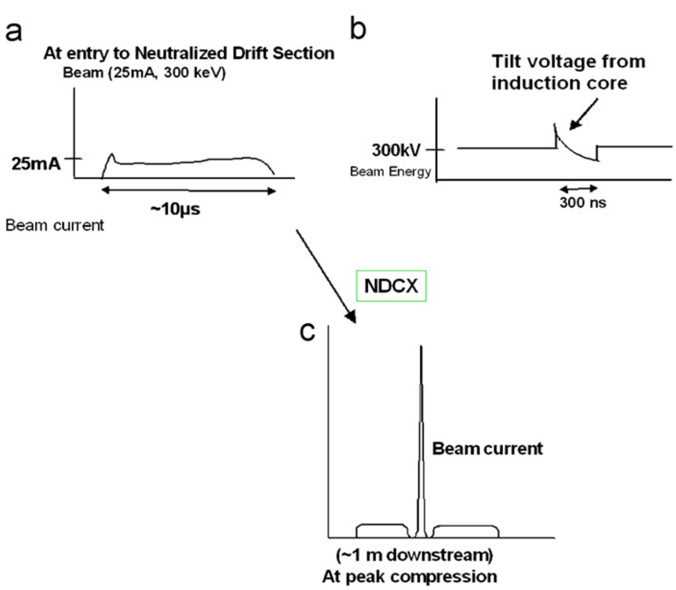

Fig. 1. A sketch of the longitudinal current compression concept: (a) beam pulse before compression, (b) tilt core voltage waveform applied to uncompressed beam pulse and (c) compressed beam current.

(where $dL/ds = 0$) is given by

$$\frac{\Delta V^2}{V^2}=\frac{16\varepsilon_z^2}{L_0^2}\left[C^2-1\right]\simeq\frac{C^2}{\eta^2}\left\langle\frac{\delta p^2}{p^2}\right\rangle \tag{1.2}$$

where ΔV is the velocity difference between the tail and head of the beam, C is the ratio of initial bunch length, L_0, to final bunch length L_f, $\langle(\delta p^2/p^2)\rangle$ is the fractional mean square in the momentum spread, and η is the conversion factor from a tilt to an rms quantity ($\eta = 0.29$ for a beam with constant line charge). The voltage ramp ΔV required to produce a velocity tilt satisfies $\Delta V/V = 2(\Delta v/v)$, where v is the axial velocity obtained from the relation $qV = 1/2\,mv^2$. Here $qV =$ ion energy and q is the ion charge.

If the compressed pulse length is dominated by the longitudinal beam temperature T_l, the compressed pulse length is approximately given by

$$L_f=\frac{d}{v_l^2}\sqrt{\frac{2kT_l}{M}} \tag{1.3}$$

where v_l, d, M and k are the mean longitudinal beam velocity, drift length, ion mass and Boltzmann constant, respectively. Here, T_l is an effective temperature including the effects of errors in the tilt waveform.

2.2. Plasma neutralization

The compressed beam bunch has higher space-charge density than the uncompressed beam bunch section. This higher space charge can limit the peak bunch density. To overcome this limitation, the compressed beam is neutralized with electrons from a plasma. 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. This plasma neutralization is provided by co-moving electrons in the drift section filled with plasma, referred to here as the plasma column.

3. Experiment setup and diagnostics

The Neutralized Drift Compression Experiment (NDCX) consists of four major sections: a K^+ ion source and injector pulsed by a 400 kV Marx, a four-quadrupole matching and transport section, a velocity-tailored voltage tilt cell, and a meter long plasma column with plasma plug, and beam diagnostics. Fig. 2(a) shows a sketch of the NDCX layout, and Fig. 2(b) shows a photograph of the NDCX beamline. Major sections of the NDCX device are described in the following sub-sections.

3.1. Ion source, marx and quadrupoles

The K^+ beam is produced by an alumino-silicate coated hot-plate source, with the perveance being determined by a current limiting aperture with a diameter smaller than the extracted beam diameter at the exit of the diode. The NDCX experiment uses the same front end as the earlier Neutralized Transport Experiments (NTX) [1–6].

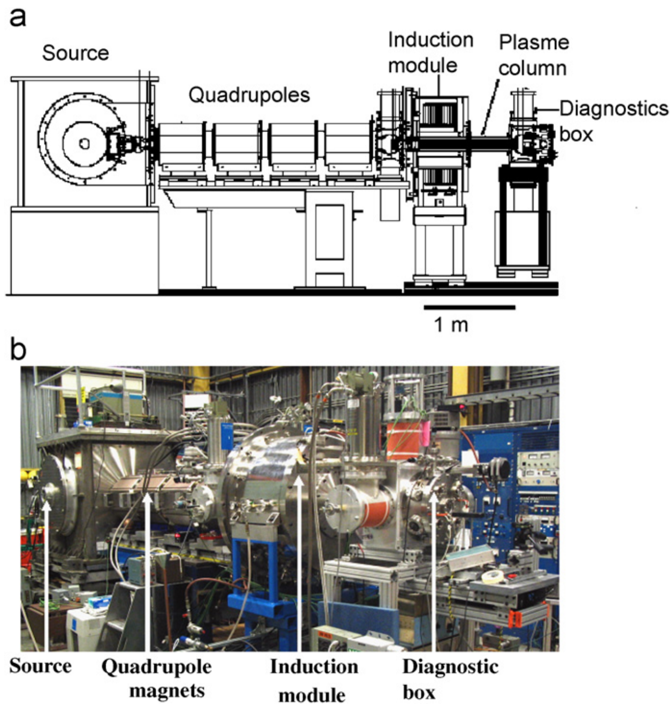

Fig. 2. (a) A sketch of the NDCX beamline and (b) photograph of the NDCX experimental setup.

It consists of a 300 keV, 25 mA K^+ beam. The four pulsed quadrupoles magnets used in NTX to control the beam envelope (beam radius and convergence angle) are retained for the present experiments on NDCX.

3.2. Tilt cell

The induction module consists of 14 independently driven ferromagnetic cores in a pressurized gas (SF_6) region that is separated from the vacuum by a high voltage insulator. The basic concept of the induction cell is shown in Fig. 3. A pulsed voltage generates a changing magnetic field inside a ferromagnetic core. This change in magnetic flux inside the core induces an electric field along its axis, according to Faraday's law. The voltage pulse is timed so that the field is present when beam particles pass through the core. The waveforms applied to the 14 cores inductively add at the acceleration gap. Each core is driven by a thyratron-switched modulator. Because the modulator for each core can produce different waveforms and can be triggered independently, a variety of waveforms can be produced at the acceleration gap using the 14 discrete building blocks.

3.3. Plasma source and plasma column

Fig. 4 shows a sketch of the plasma source and meter long plasma column with the induction module (tilt core). In this experiment, the plasma column is formed by two pulsed aluminum cathodic arc sources located at the downstream end. Each source is equipped with a 45° open-architecture macroparticle filter providing a flow of fully ionized aluminum plasma [18]. The two plasma flows are pointed at an angle of 45° towards the solenoidal column (~1 kG, 7.6 cm diameter, and 1 m long). A significant fraction of the plasma enters the solenoid, and drifts practically unattenuated through the entire column (the rest of the aluminum plasma condenses at the wall and is thereby removed from the system). In most of the operating regimes, the plasma density ($>5\times10^{10}\,\mathrm{cm}^{-3}$) is at least a factor of 10 higher than the beam density and is maintained throughout the channel. Fig. 5 shows the axial plasma density along the length of the plasma column for a plasma source (gun) [19]. A plasma density of 3×10^{11}–$5\times10^{11}\,\mathrm{cm}^{-3}$ is measured experimentally for two plasma guns and used in the experiment. At the upstream end of the column, we have introduced a plasma stopper consisting of two opposing magnetic dipoles of ~1 kG each, which inhibit the motion of plasma upstream into the induction gap and the quadrupole focusing sections. A second plasma column consisting of a meter-long ferroelectric plasma source that does not require solenoidal confinement has been constructed and will be tested in upcoming drift compression experiments.

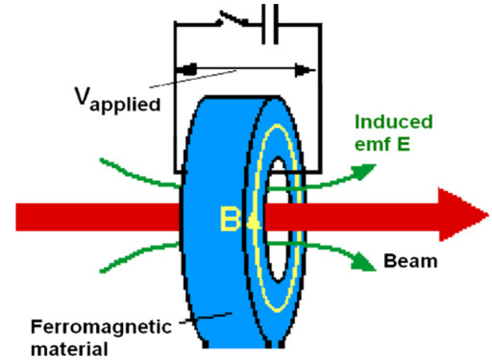

Fig. 3. Schematic of an induction accelerator module.

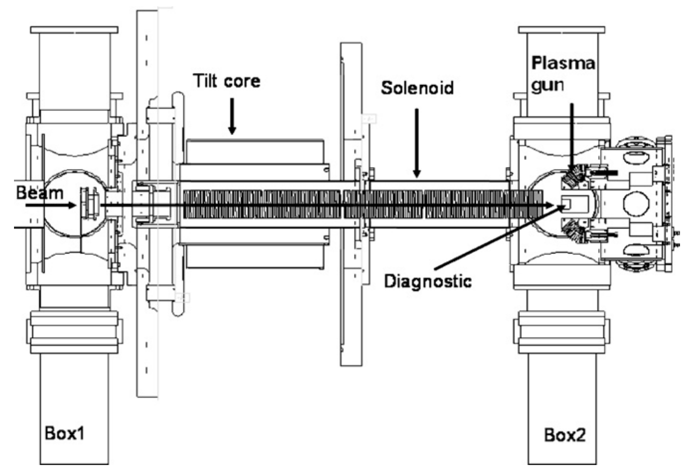

Fig. 4. A sketch of compression and neutralization section.

3.4. Diagnostics

Fig. 6 shows the diagnostics that are used in the experiment. The diagnostics are a multiple-pinhole Faraday

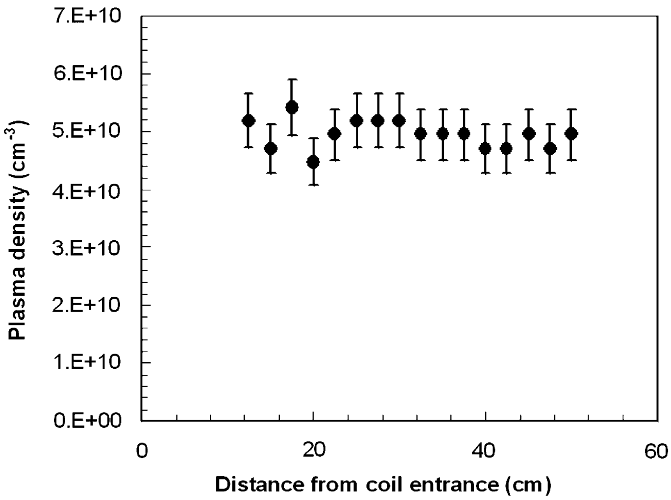

Fig. 5. Variation of plasma density along the *z*-axis into the plasma channel for one plasma source (gun). Experimentally, we have used two plasma guns.

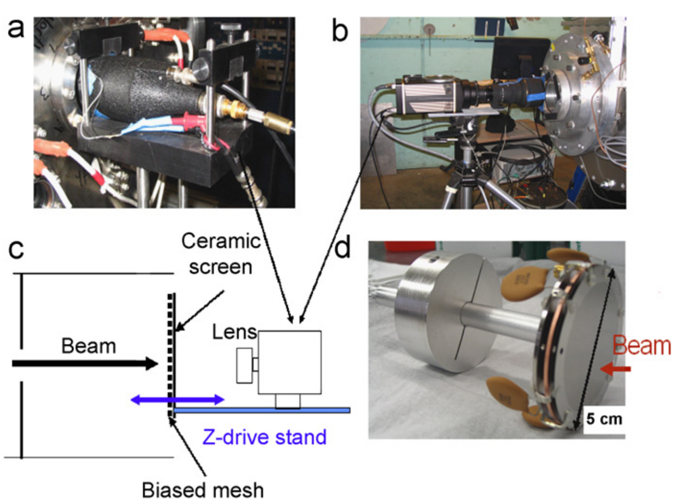

Fig. 6. NDCX diagnostics: (a) a phototube, (b) a gated camera, (c) an assembly of the scintillator for the phototube and the camera, and (d) pinhole Faraday cup.

cup, and a scintillator, the signal of which is detected using a gated camera or a phototube through a quartz glass window (>90% transmission wavelength between 300 and 1000 nm). A brief description of each of these diagnostics is presented below.

3.4.1. Phototube diagnostic

A phototube diagnostic [20], Fig. 6(a), is used to measure beam pulse compression with and without neutralization. The optical system is based on a Hamamatsu phototube with sub-nanosecond response and readout via a 500 MHz oscilloscope. The beam pulse is measured by using the phototube to collect the optical photon flux from an aluminum oxide scintillator placed in the path of the beam, Fig. 6(c). The time response of the scintillator is fast enough to make measurements on a nanosecond time scale. Small amounts of stray light emitted by the plasma over long periods of time (100 s of μs) can drain the bias charge in the phototube's internal power supply, and thus reduce the gain of the phototube during the beam pulse. This background plasma light is blocked from entering the phototube by an electro-optic gated shutter (Displaytech) that opens just before the beam pulse arrives at the scintillator. The scintillator itself is not sensitive to low-energy plasma electrons. As a result, we have been able to obtain beam pulse compression data with minimal interference from the neutralizing plasma. Scintillator degradation over many beam pulses limits useful scintillator lifetime that has required vigilance.

A time-gated camera is also used to measure the beam optical profile and intensity. It has a time resolution of about 1 ns.

3.4.2. Faraday cup

A beam diagnostic probe (a Faraday cup) is used for measurements of the current. The Faraday cup is specially designed to function in a plasma environment. It consists of hole plates with hole sizes comparable to the Debye length, in order to prevent plasma from entering into the cup. The cup geometry and external circuitry are optimized to assure a fast time response (<3 ns). A particle-in-cell code has been used to model the propagation of the intense ion beam and to design the diagnostic probe. The characteristics of the cup have been published elsewhere [21].

4. Beam compression experiment

4.1. Instrumental pulse timing

The longitudinal beam compression experiment depends on the simultaneous pulsing of Marx, quadrupoles, tilt core, plasma channel and plasma guns waveforms. All triggers for the system are generated from multiple DG-535 trigger generators that share a common terminal or referring time, T_0.

To align the peak of the plasma channel solenoid current with the peak in the magnet currents, the trigger delay is adjusted to allow the plasma to be on for about 200 μs before the Marx is triggered.

The Marx is then fired at the peak of the plasma channel solenoid current ($t =$ at 2.149 ms in Fig. 7), the peak of the magnet currents, and after the cathodic are plasma has been on for 200 μs. The crowbar is triggered at 2.16 ms to produce pulse from the Marx. This delay is dependent on the diagnostic used. The tilt core modulators M1–M6 are triggered together at 2.156 ms near the middle of the Marx voltage to produce the negative part of the tilt waveform. Individual modulator delay times and waveform accuracy have been considered. The tilt core modulators M7–M12 are triggered to produce the positive part of the tilt waveform. The reset circuits for the tilt core modulators are all triggered at T_0, so that the cores are reset before the modulators are triggered.

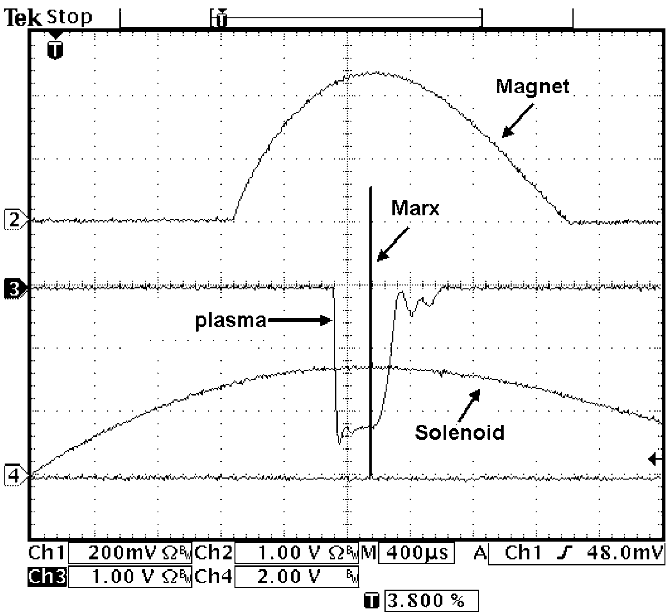

Fig. 7. Operational timing of the NDCX system including the pulse of the Marx, plasma plug, solenoid current for the plasma column, and quadrupoles.

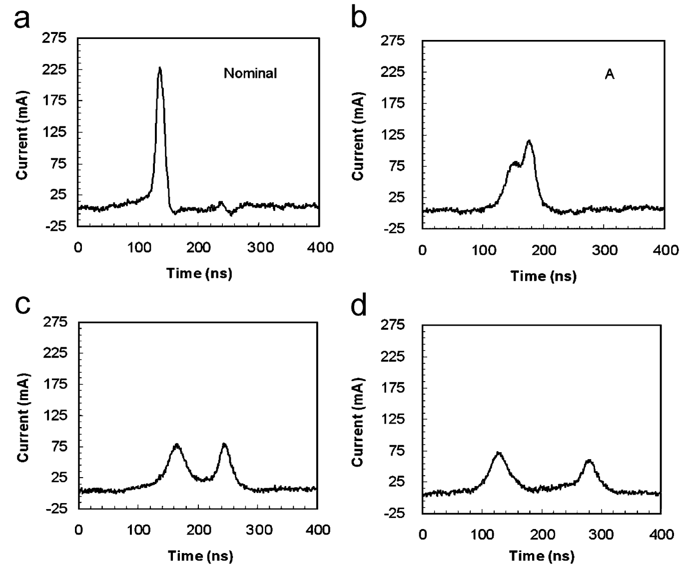

Fig. 8. Neutralized drift-compressed beam current with the voltage waveforms in Fig. 9.

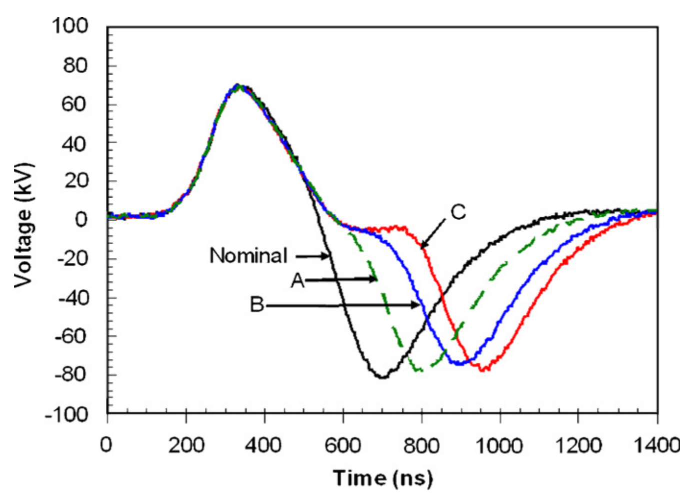

Fig. 9. Bunching module voltage waveforms produced by varying the timing of the modulators.

4.2. Tilt cell waveform optimization

When the tilt voltage waveform was turned on, beam bunching was observed in the downstream diagnostic box. The degree of bunching, as well as the pulse shape, shown in Fig. 8, was clearly correlated with the voltage waveform, shown in Fig. 9. Theory specifies the ideal voltage waveform is required to produce an exactly linear (versus z) velocity ramp [5,14]. The induction module voltage waveform was optimized to obtain a rather close approximation to the ideal waveform as shown in Fig. 10 by adjusting the timing of the individual cores. For 20 beam pulses using the waveform with 23 kV charge and 80 V reset, measurements showed that the tilt core had a jitter of 2 ns (± 1 ns).

4.3. Beam energy optimization

For a given voltage waveform, the position of maximal compression varies with the beam energy. A scan in beam energy demonstrates this behavior and is shown in Fig. 11.

4.4. Effective plasma density

The strong effects of neutralization are evident by comparing the compression ratio with the plasma turned on and off. Fig. 12 shows that the peak current is significantly reduced when the plasma is turned off. The particle-in-cell code LSP [22] show qualitatively similar results. Note that the simulated beam energy and observing station do not exactly match those of the experiment, which is responsible for the different peak locations between the simulations and the experiment.

4.5. Maximum beam compression

The maximum compression is observed by fine tuning the beam energy to match the voltage waveform and precisely position the longitudinal focal point at the diagnostic location. This case is shown in Fig. 13. The compression ratio of about 50, seen in Fig. 13(b), is obtained by taking the ratio of the signal with velocity tilt on (with compression) to the signal with tilt voltage off (without compression) (see Fig. 13(a)). A similar result is measured with the Faraday cup, see Fig. 13(c). LSP simulations under these experimental conditions predicted a peak compression ratio of 60 (Fig. 13(d)).

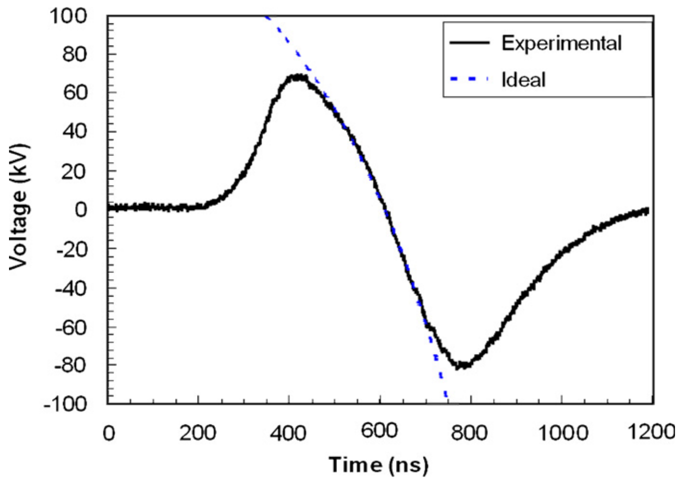

Fig. 10. Experimentally optimized and ideal induction module voltage waveforms.

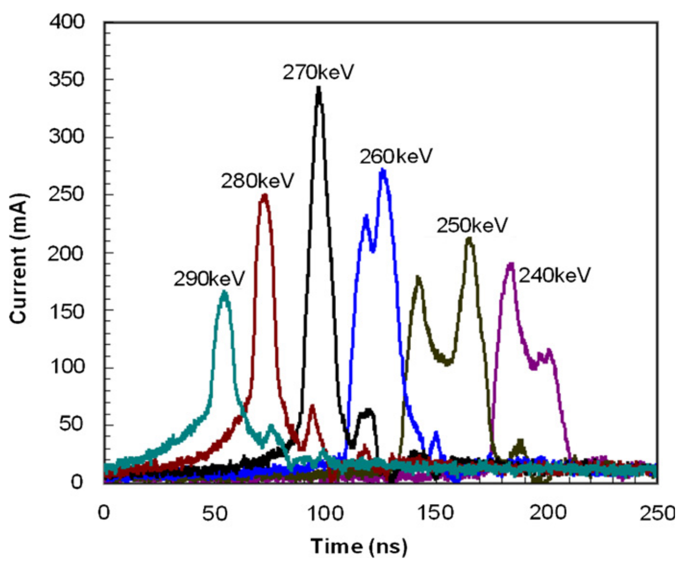

Fig. 11. Compressed beam current pulses using a nominal tilt core voltage waveform as the beam energy is varied.

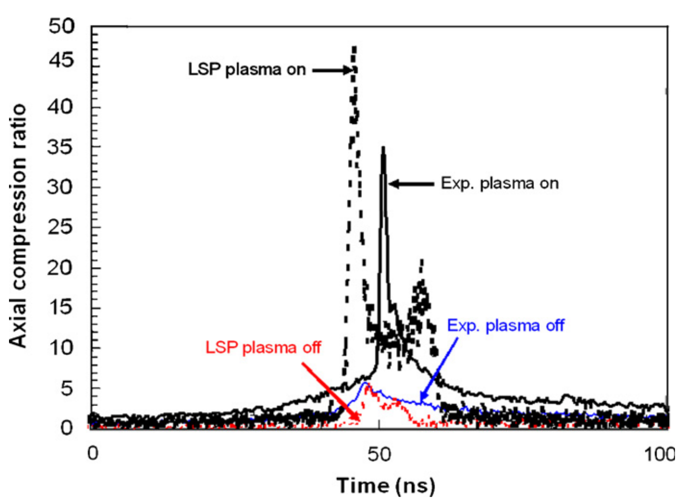

Fig. 12. Experimental data and LSP simulation of beam compression with neutralization (plasma source on) and without neutralization (plasma source off).

In NDCX, optical imaging diagnostics measured the transverse beam size as a function of time during longitudinal compression. We were able to measure the images with a 1 ns time resolution. The measured spots in Fig. 14 for the 1 m beam focusing angle (15 mm–13.5 mr) had roughly a 6 mm radius; while the simulation yields a 5 mm radius for a 13.5 m rad angle. It was interesting to observe that the transverse spot size was larger at the point of maximal compression, as shown in Figs. 14(a) and (b). This feature was due to time-dependent defocusing effects occurring at the induction gap, and was also seen in LSP simulations, as shown in Fig. 15.

4.6. Effect of drift length on compression

Theory predicts that the nature of the beam compression is strongly dependent on the drift length [14]. As the length is increased, the compression is more sensitive to the degree of neutralization. It is also more sensitive to the intrinsic longitudinal temperature of the ion beam. Finally, if there are any instabilities, e.g. two-stream, they may become evident with longer drift lengths. Although theory predicts two-stream effects to be benign, an experimental confirmation was deemed desirable.

For the above reasons, we have performed additional experiments with the plasma-filled drift length extended to 2 m. We are able to recover the 50-fold compression in the 2 m experiment as shown in Fig. 16. The corresponding LSP simulation is also shown.

On the basis of this 2 m experiment, we conclude that: (1) the degree of charge neutralization is sufficient to achieve 50-fold longitudinal compression while avoiding

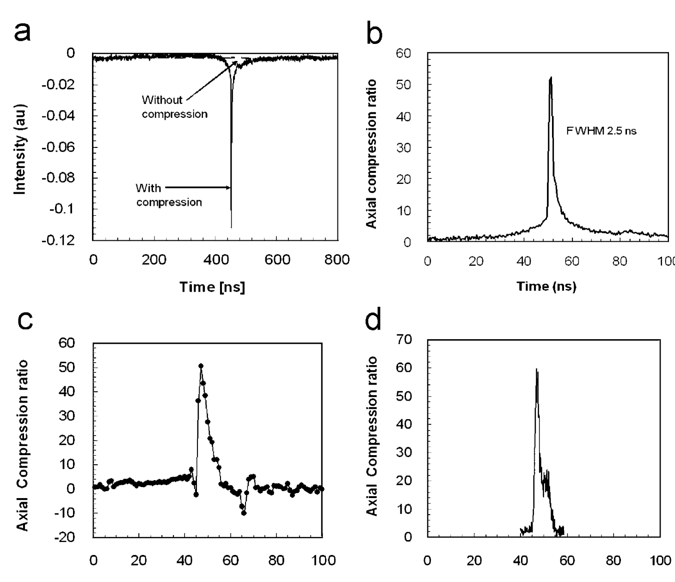

Fig. 13. (a) Measurements of beam signal using the phototube diagnostic for neutralized non-compressed, and neutralized compressed beams, (b) compression ratio obtained from the measurements using the phototube, (c) compression ratio obtained from measurements using the Faraday cup and (d) LSP simulation for axial compression ratio under the experimental conditions.

space-charge blow-up of the beam for the experimental configuration investigated, (2) the intrinsic longitudinal temperature is less than 1 eV, and (3) no collective instabilities have been observed.

5. Conclusion

Transverse as well as longitudinal compression is required to achieve the high intensity required for high-energy density physics and fusion applications, as mentioned earlier. Simulations indicate that the small spot sizes required for a fusion target [23,24] could be achieved with plasma neutralization [22,25]. We have previously studied the effects of plasma neutralization [1–6] and are preparing for experimentally exploring simultaneous transverse and longitudinal compression [26].

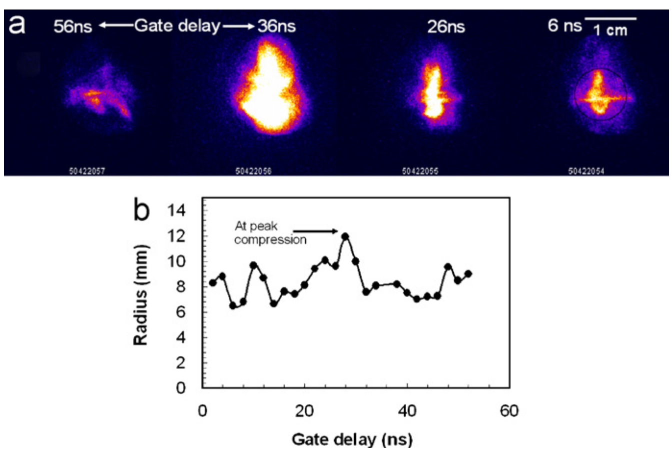

Fig. 14. Transverse images of neutralized longitudinal compressed beam: (a) optical profile and (b) beam radius.

Acknowledgments

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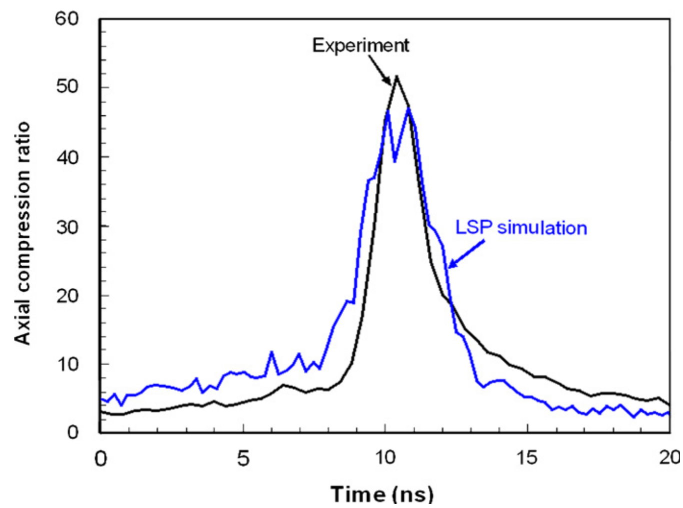

Fig. 16. Comparison of beam compression between experiment and LSP simulation for the 2 m long plasma column.

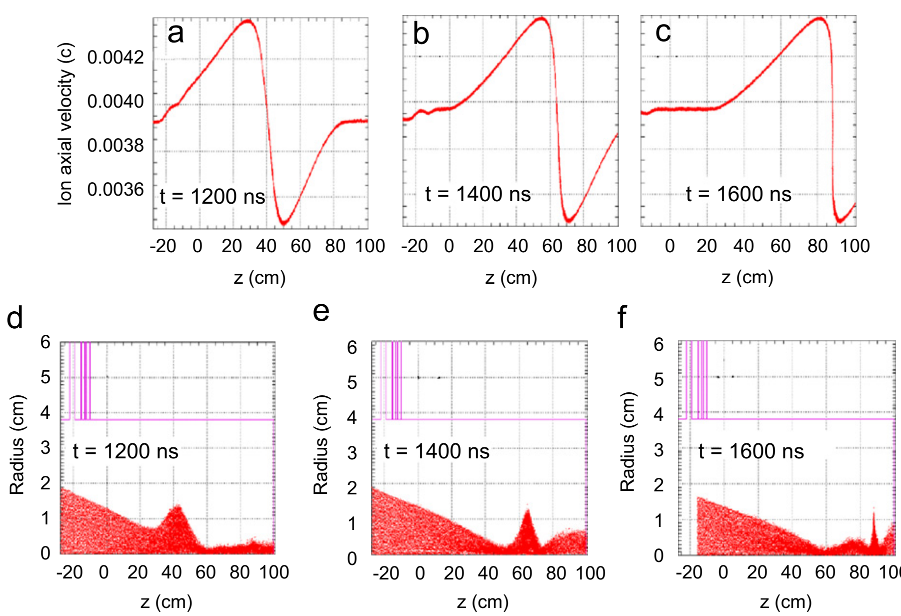

Fig. 15. The ion beam axial phase space (a)–(c) and configuration space (d), (e) at 1200, 1400, and 1600 ns obtained from an Lsp simulation. The neutralizing plasma extends for $z > -5$ cm.

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