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INITIAL RESULTS ON NEUTRALIZED DRIFT COMPRESSION EXPERIMENTS (NDCX-IA) FOR HIGH INTENSITY ION BEAM

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Abstract

Ion beam neutralization and compression experiments are designed to determine the feasibility of using compressed high intensity ion beams for high energy density physics (HEDP) experiments and for inertial fusion power. To quantitatively ascertain the various mechanisms and methods for beam compression, the Neutralized Drift Compression Experiment (NDCX) facility is being constructed at Lawrence Berkeley National Laboratory (LBNL). In the first neutralized drift compression experiment, a 280 KeV, 25 mA, K^+ ion beam is longitudinally 50-fold compressed using an induction core to produce a velocity tilt. This compression ratio is measured using various diagnostics.

INTRODUCTION

Heavy ion fusion (HIF) and ion-driven high energy density physics (HEDP) require the acceleration, compression, and transverse focusing of an intense ion beam [1]. Neutralized drift compression of an ion beam makes use of a temporal velocity tilt and neutralizing plasma to achieve small pulse lengths [2]. Here, we consider the neutralized drift compression experiment (NDCX) in which a 280 keV, 25-milliamp K^+ ion beam is given a head to tail energy variation using a 'tilt core' induction cell. The tilt core applied a roughly 150 kV energy ramp to 500 ns of the beam. Pulse compression and focusing are achieved in the presence of a neutralizing plasma provide by a Al arc or MEVVA source. Given adequate neutralization of the beam charge and current, the compression ratio is limited only by the accuracy of the applied velocity tilt and longitudinal temperature of the beam. The time-dependent velocity function at a particular plane that produces a perfect beam longitudinal compression at a downstream distance L is given by,

$$v(t) = \frac{v(0)}{1 - \frac{v(0)t}{L}}, \quad (1)$$

where v(0) is the velocity of the pulse at t = 0. The characteristic thermal velocity or error Δv limits the pulse length achievable to $t_{min}=L\Delta v/\langle v\rangle^2$, where <v> is the mean beam velocity. In the NDCX, the beam ion velocities deviate somewhat from an ideal curve with simulations predicting a compression ratio of roughly 60. The simulations of drift compression and focusing were performed with the 3D parallel LSP [3,4] particle-in-cell code using a fully kinetic energy-conserving algorithm.

Experimental results on beam compression including ideal and experimental tilt core wave form, compressed beam profile with and without neutralization and diagnostics performance are presented.

EXPERIMENTAL SETUP

Figure 1 shows a photograph of the NDCX-Ia beam line, consists of (1) an ion beam injector, (2) 4 quadrupole magnets, (3) 1.3 m-long neutralized drift compression section equipped with velocity tilt core induction cell, plasma source, solenoid tube for plasma channel and diagnostics such as gated camera, phototube, Faraday cup.

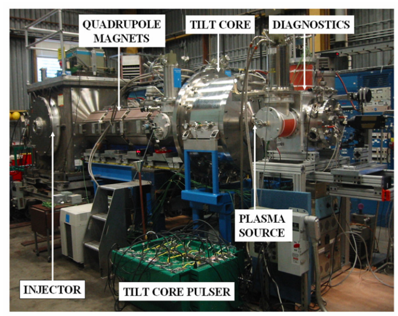

Figure 1: A viewgraph of NDCX-Ia beam line.

Injector & beam focusing.

The K^+ beam is produced by a standard hot-plate source, pulsed power is provided by a Marx generator. The beam size, density, and emittance are in good agreement with simulation and experiments [5-6]. The quadrupole fields are chosen to obtain a beam with a large excursion of up to 10 cm in the magnetic lattice to reach an exit condition where the tilt core and MEVVA plasma plug is located. The MEVVA plasma source is located at the downstream end of the beamline and plasma is drifted upstream to the tilt core through a solenoid tube called a plasma channel.

Velocity tilt core cell

The tilt core is an induction accelerator cell which applies the required velocity tilt to the beam to produce longitudinal compression. This induction cell consists of 14 independently driven magnetic cores in a pressurized gas region which is separated from the vacuum by a conventional high voltage insulator. 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 be designed to 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. Figure 2 shows an ideal and experimental wave form of the tilt core.

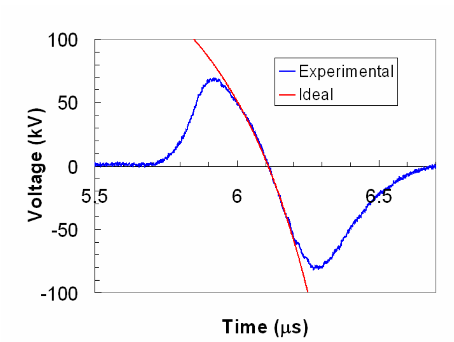

Figure 2: Ideal and experimental tilt core wave form.

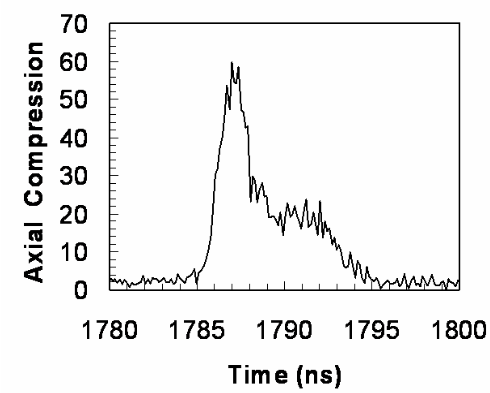

Figure 3: Simulation of neutralized drift compression.

Plasma Channel

Metal plasma is generated at cathode spots in a metal-vapor vacuum arc (MEVVA). It expands rapidly from the spot, with ions attaining supersonic velocity of about 1.5 x 10^4 m/s. The measurements show that the plasma density along the axis is peaked, 10^{11} cm^{-3}, at the location of the pair of entry ports where the plasma enters the beam line. Characterization of beam neutralization using this MEVVA plasma plug has been well defined [7].

Time Delay of the NDCX-Ia system

To align the peak of the MEVVA solenoid current with the peak in the magnet currents, the four magnets were triggered at 1.28 ms. This delay did not include the delay for the magnetic field to penetrate the beam pipe and was therefore not the peak of the magnetic field. The MEVVA plasma source was then triggered at 1.92 ms. This delay allowed the plasma to be on about 200 µs before the Marx was triggered. The Marx was then fired at 2.149 ms at the peak of the MEVVA solenoid current, the peak of the magnet currents, and after the MEVVA plasma had been on for 200 µs. The Crowbar was triggered at 2.16 ms to produce an 11µs wide pulse from the Marx. Tilt core modulators M1-M6 were triggered together at 2.156 ms near the middle of the Marx voltage to produce the positive part of the tilt waveform. Individual modulator delay times and waveform accuracy had been considered. Tilt core modulators M7-M12 were triggered to produce the negative part of the tilt waveform. Individual modulator delay times and waveform accuracy had been considered. The Reset circuits for the tilt core modulators were all triggered at T_0, so that the 12 cores were reset before the modulators were triggered.

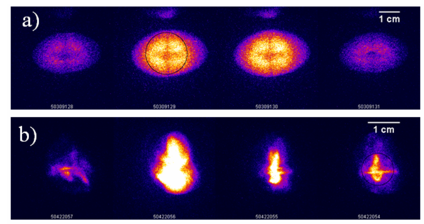

Figure 4: Beam compression optics (a) non-neutralized (b) neutralized.

BEAM COMPRESSION MEASUREMENT

We have developed and implemented three diagnostic systems: (1) the photo-tube optical system, (2) the new Faraday cup system [8] with multiple pinholes, for the measurement of total current and current density, and (3) the optical gated camera system for beam profile. All three systems are capable of measuring the compressed ion beam with nanosecond time-scales.

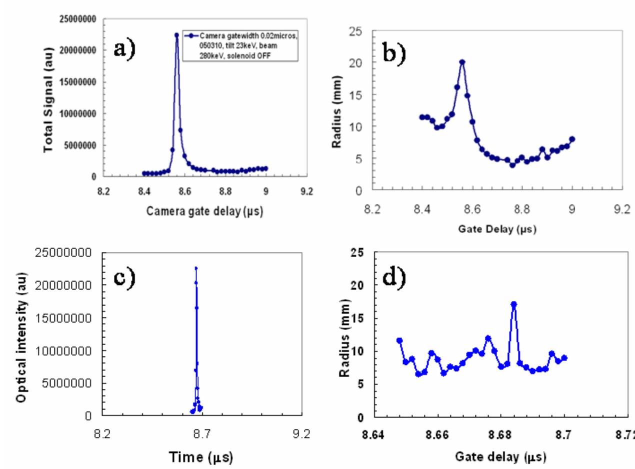

Figure 5: (a) Non-neutralized compressed beam optical signal, (b) non-neutralized compressed beam radius, (c) neutralized compressed beam optical signal (5 ns at FWHM) and (d) neutralized beam radius.

Measurement using gated camera system

Non-neutralized and neutralized compressed beam optical profiles were captured on an aluminum oxide scintillator using a fast gated camera. Initially, the beam was compressed by the velocity tilt core without the MEVVA plasma. The ion beam radius in each increment of delay (20 ns) is shown in Fig 4(a). The same experiments were repeated for a small window of 2 ns width with fine tuning in 2 ns steps. In this case, a signal peak width of 4 ns at FWHM and 2.2 cm beam radius were measured during non-neutralized compression. Higher signal (Fig. 5a) and relatively larger beam size (Fig. 5b) were measured during this non-neutralized compression. The same experiment was performed for a small window of 1 ns width with very fine tuning of 1 ns steps. In this case, a 2.25 cm beam size was measured which indicated that detecting a beam with fine resolution leads to enhanced accuracy of beam size and signal intensity measurements. We then captured a neutralized compressed beam using the same system with 1 ns width and 1 ns delay step. Figure 5(c) and 5(d) show measured intensity and beam size. Though plasma neutralized the beam and reduced beam size, incremental damage to the scintillator due to beam bombardment prevented absolute intensity measurement during the neutralized beam compression experimental run. Despite the damage, this diagnostic remained useful for beam profile measurements.

Measurement using Phototube system

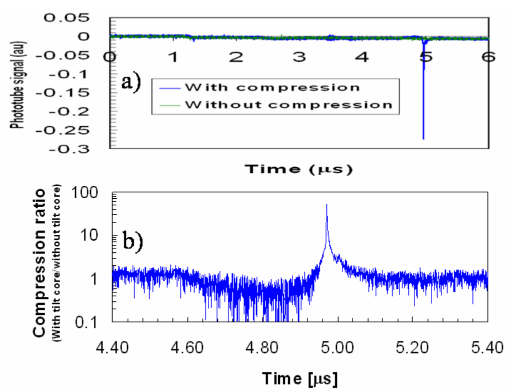

Figure 6: (a) Direct measurement of phototube signal for neutralized (blue) and non-neutralized (red) compressed beam and (b) compression ratio (neutralized compressed beam and neutralized non-compressed beam).

We have implemented an optical Phototube diagnostic system that has provided the first measurements of beam pulse compression with and without neutralization. The optical system was based on a Hamamatsu phototube with fast (sub-ns) response and coupled with a 500-MHz oscilloscope; we have resolved compressed beam pulses with FWHM as small as 1.6 ns. The beam pulse has been measured by using the phototube to collect the optical photon flux from an aluminum oxide scintillator placed in the path of the beam. The time response of the scintillator is fast enough to make measurements on a nanosecond time scale. The gain of the phototube is more than adequate to detect the optical pulse response of the scintillator to the beam. Optical coupling also greatly simplifies the electrical circuit, eliminating potential problems with pulse reflections at the vacuum wall and bias boxes. Small amounts of stray light emitted by the plasma over long periods of time (100s of microseconds) can drain the bias charge in the phototube's internal power supply, and thus spoil 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 take beam pulse compression data with minimal interference from the neutralizing plasma. We define compression ratio as the ratio of the two signals with and without compression. The compression ratio as detected by the phototube is shown in Fig 6(b). The phototube, which has sub-nanosecond response, has measured a compression factor of 50. The compressed pulse has a FWHM of about 3 ns.

Measurement using Pinhole Faraday cup system

In order to verify the photo tube data, a new Faraday cup useful in a plasma environment has been designed [8] to measure longitudinal neutralized beam compression. According to the initial data, we found a 52-fold beam compression with a time response of 5ns at Full Width Half Maximum of the compressed beam peak. This result corroborates our earlier measurements using the phototube-scintillator diagnostic. Thus, the compression ratio of 50 observed with the two diagnostics is in good agreement with simulation.

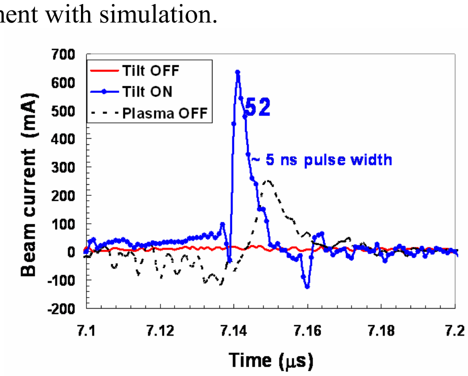

Figure 7: 52 fold neutralized compressed beam (blue line), non-neutralized compressed beam (dotted line) and non compressed beam current (red line) measured using pinhole Faraday cup.

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