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Nuclear Instruments and Methods in Physics Research A 577 (2007) 223–230
NUCLEAR INSTRUMENTS & METHODS IN PHYSICS RESEARCH Section A
www.elsevier.com/locate/nima

Neutralized drift compression experiments with a high-intensity ion beam

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Available online 22 February 2007

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 ~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 ~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 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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0168-9002/$ - see front matter
doi:10.1016/j.nima.2007.02.056

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]

$$\frac{d^2L}{dS^2} = \frac{16\varepsilon_z^2}{L^3} \quad (1.1)$$

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

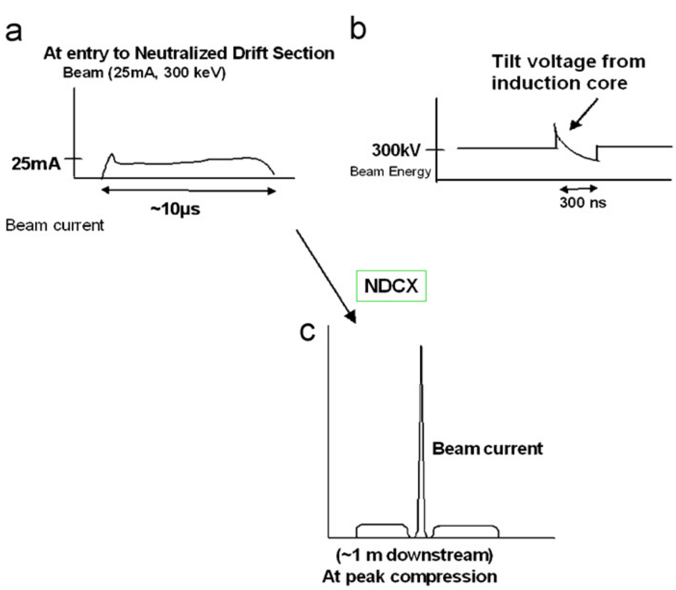

Fig. 1. A sketch of the longitudinal current compression concept: (a) beam pulse before compression, (b) tilt core voltage waveform applied to uncompressed beam pulse and (c) compressed beam current.

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

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

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

$$L_f = \frac{d}{v_l^2}\sqrt{\frac{2kT_l}{M}} \quad (1.3)$$

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].