Lsp SIMULATIONS OF THE NEUTRALIZED DRIFT COMPRESSION EXPERIMENT*

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Abstract

The Neutralized Drift Compression Experiment (NDCX) at Lawrence Berkeley National Laboratory involves the longitudinal compression of a singly-stripped K ion beam with a mean energy of 280 keV in a meter long plasma. We present simulation results of compression of the NDCX beam using the PIC code Lsp. The NDCX beam encounters an acceleration gap with a time-dependent voltage that decelerates the head and accelerates the tail of a 500 ns pulse which is to be compressed 130 cm downstream. Results show good longitudinal compression without significant emittance growth, but a time-dependent focal length limits the beam radius. An explanation is given for the sizable defocusing effect of the voltage gap. An envelope calculation including the time-dependent focusing effect is in good agreement with the Lsp simulations.

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. Neutralized drift compression of an ion beam makes use of a temporal velocity tilt and a neutralizing plasma to achieve small pulse lengths[1]. Here, we consider the neutralized drift compression experiment (NDCX) in which a 285 keV, 26-milliamp K^+ ion beam is given a head to tail energy variation using a tilt core induction cell. The tilt core applies a roughly 150 kV energy ramp to 500 ns of the 5 μs beam. Pulse compression and focusing are achieved in the presence of a neutralizing plasma provided by an 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. Simulations of drift compression and focusing are performed with the 3D parallel Lsp [2] particle-in-cell code using a fully kinetic energy-conserving algorithm. The goal of these calculations is to elucidate the basic physics issues of the plasma-neutralized beam in the context of HIF and HEDP research.

We now examine the physics of a beam that has already acquired a head-to-tail velocity tilt for longitudinal time-of-flight compression. The time-dependent velocity function at a particular plane that produces a perfect beam longitudinal compression at a downstream distance L is given by,

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

where $v(0)$ is the axial 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 $\langle v \rangle$ is the mean beam velocity. In the NDCX, the beam ion velocities deviate somewhat from the above ideal curve with simulations predicting a compression ratio of roughly 60. The critical new physics involves the neutralization of the compressing beam space charge by a plasma over 1.3 meters. From a simple 1D analysis, if stipulated that the beam impulse due to space charge (resulting in electric field E) over the neutralized drift, $EL/\langle v \rangle$, must be less than the applied tilt, the neutralization fraction must be

$$f > 1 - \frac{a^2}{2L^2 ZK(0)} \tag{2}$$

where $K(0)$ is the initial beam perveance (0.0007 for NDCX) defined as $K = 2I_b/I_A\beta^2$ with Alfven current $I_A = m_i c^3/eZ$. Here, I_b, a, βc, γ, m_i and Z are the beam current, radius, velocity, relativistic factor, mass, and charge state, respectively. For NDCX parameters, f must be > 0.9. The presence of a high density plasma ($n_p >> n_b$) has been shown to provide this excellent charge neutralization in Lsp simulations. The plasma density condition requires increasingly higher plasma density as the beam compresses. A second obstacle to beam compression is caused by the relative velocity of the beam ions and background plasma electrons. The electrostatic beam-plasma electron two-stream or Buneman instability results in longitudinal emittance growth that ultimately limits compression. One dimensional LSP simulations, in which the longitudinal cell size of 0.03 cm was required to resolve the instability wavelength (for a 10^9 cm^{-3} density plasma), show the impact of the instability to be a small effect with compression ratios close to those of the 2D simulations with coarse longitudinal zoning.

Another key issue concerning NDCX involves the transverse focusing of the beam. Practically, the beam emittance ultimately limits the maximum tolerable focal length. However, the varying voltage at the accelerating gap gives a time-dependent focal length to the beam. Simulations show this effect limits the beam minimum radius to roughly 1 cm at the longitudinal focal position. This transverse focusing effect is considered at length below.

Lsp SIMULATION OF NDCX

The neutralization and compression of the NDCX beam are simulated in a 2-D cylindrical Lsp simulation. A 285 keV, 26 mA K^+ beam is injected into a 3.8 cm radius pipe. Figure 1 shows the simulation space. The 1500 ns ion pulse is injected at $z = -27$ cm with a radius of 1.9 cm and an angle of -22 mrad. This initial angle provides adequate transverse focusing in the absence of the applied voltage. The beam temperature is 0.21 eV. A pre-filled carbon plasma (not shown in Fig. 1) with density $n_p = 10^{11}$ cm^{-3} is positioned initially in the region $z > -5$ cm to provide neutralization. The plasma is confined downstream by a
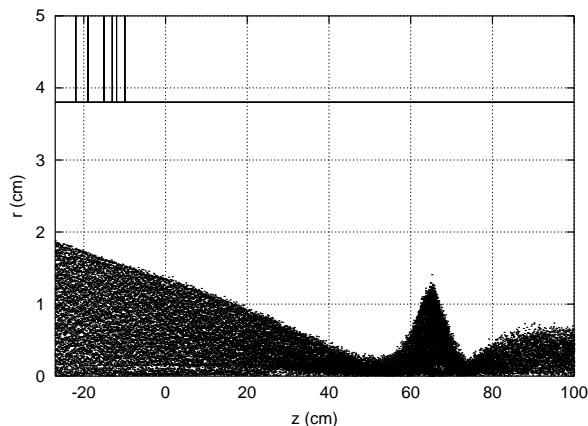

Figure 1: Simulation space of Lsp simulation of NDCX. Ion particles are shown at $t = 1400$ ns. The neutralizing plasma ($z > -5$ cm) is not shown.

radial electrostatic trap centered at z = -12 cm. A time-dependent voltage waveform, shown in Fig. 2, is applied at the tilt-core gap which is centered at $z = -20.5$ cm and has a width of 3 cm. The waveform applies a head-to-tail velocity tilt to about a 400 ns section in the middle of the pulse. Also shown in Fig. 2 is a fit to an ideal voltage waveform which will generate a perfect velocity time-dependence of the form of Eq. 1. Since the waveform is non-ideal the longitudinal compression is limited to a factor of about 60.

The longitudinal focus occurs at about 1700 ns at $z \sim 95$ cm. Figure 1 shows the position of the ion pulse macroparticles at 1400 ns. The most striking feature is the prominent peak in beam radius at $z \sim 65$ cm. The peak also occurs at the instantaneous position of maximum longitudinal compression. So the axial velocity tilt applied by the time-dependent voltage gap also apparently has the effect of disrupting the transverse focusing of the compressed pulse.

EXPLANATION OF TIME-DEPENDENT TRANSVERSE FOCUSING IN NDCX

The gap at which the voltage waveform is applied is a simple bipotential lens, in which the radial component of the electric field is anti-symmetric about the center of the
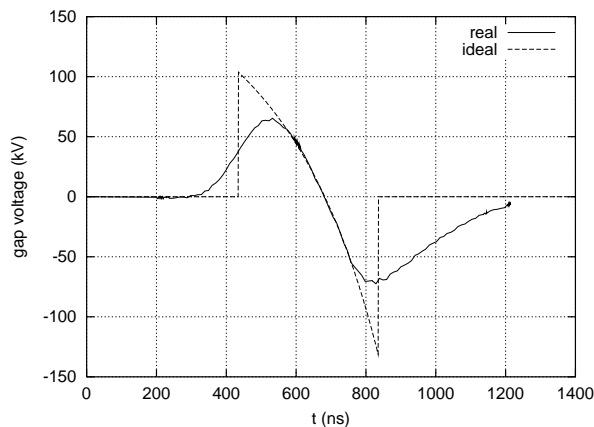

Figure 2: Gap voltage as a function of time for NDCX simulation. The real waveform is shown as well as a fit to an ideal waveform.

gap. In the paraxial approximation E_r is also proportional to r. The beam receives a net radial kick up on the upstream side of the gap (assuming a positive voltage difference ΔV across the gap) and net radial kick downward on the downstream side of the gap. For a constant voltage the slight change in the radius of particles as they traverse the gap results in incomplete cancellation of the upward and downward radial forces and leads to a small net focusing effect. For NDCX however the ion beam is relatively slow moving and the gap voltage can change significantly during the ion transit time through the lens. Since E_r is proportional to the time-dependent voltage, the net radial forces upstream and downstream of the center of the gap do not cancel. With a simple thin-lens model, in which the radial forces are modelled by delta function impulses separated by the width of the gap, the time-dependent change in radial velocity of a non-relativistic singly-stripped ion going through the gap can be approximated by the formula

$$\frac{\Delta v_r(t)}{r} = -\frac{e\Delta\dot{V}(t)}{2m_i v_{z0}^2}, \qquad (3)$$

where v_{z0} is the axial velocity of the ion upstream of the gap and r is the radius of the ion going through the gap. The change of the axial velocity of the ion as it is accelerated across the gap is neglected in deriving Eq. 3, as is the change in radius. So a large and negative ΔV, which is required for longitudinal focusing, also has a net transverse defocusing effect. Of course, the axial velocity is altered by the gap as well. The change in axial velocity is given by

$$\frac{\Delta v_z(t)}{v_{z0}} = 1 - \sqrt{1 - \frac{2e\Delta V(t)}{m_i v_{z0}^2}}. \qquad (4)$$

This gives a spread in axial velocity of about $\pm 10\%$ for a 285 keV beam and the real NDCX voltage waveform shown in Fig. 2.

For a bipotential lens of radius b and width d, the on-axis potential can be approximated by [3]

$$V(z,t) = \Delta V(t) \ln \frac{\cosh \alpha z}{\cosh \alpha(z-d)}, \qquad (5)$$

where $\alpha = 1.318/b$. In the paraxial approximation the electric fields are calculated from the on-axis potential as $E_z = -\partial V/\partial z$ and $E_r = 1/2 \partial^2 V/\partial z^2 r$. Using Eq. 5 ion test particles can be numerically integrated through the gap allowing Δv_r and Δv_z to be calculated more rigorously. Using the NDCX voltage waveform the results were in good agreement with Eqs. 3 and 4.

To qualitatively assess the effect of the time-dependent voltage on the downstream transverse focusing of the compressed pulse, a simple model was used in which the pulse is treated as a sequence of rigid disks which pass through the voltage gap. The disks are treated as independent (since plasma neutralization should cancel the longitudinal space-charge forces) and are allowed to overlap one another due to the velocity tilt. The edge radius of the disks is obtained by solving a simple envelope equation. On the downstream side of the voltage gap each disk is given the initial angle

$$a_0' = \frac{v_{r0} + \frac{\Delta v_r(t)}{r} a_0}{v_{z0} + \Delta v_z(t)}, \qquad (6)$$

where a_0 is the disk edge radius at the gap and v_{r0} is the radial velocity of the disk edge just upstream of the gap.

This envelope analysis was carried out for the same parameters as the LSP simulation. Perfect neutralization was assumed in the plasma region ($z > -5$ cm), for which the beam perveance was set to zero in the envelope equation. The velocity changes $\Delta v_r(t)/r$ and $\Delta v_z(t)$ were calculated by integrating ion trajectories using Eq. 5 with the NDCX voltage waveform. The results of this analysis are shown in Fig. 3, where the disk radii are plotted as a function of z at $t = 1400$ ns. As can be seen in Eq. 6, the transverse focus is perturbed by both time-dependent changes in axial and radial velocity. It is the change in radial velocity which causes the pronounced peak in radius. The change in axial velocity alone adds only a gentle sweeping of the transverse focus. Comparison with Fig. 1 shows that all of the major features of the transverse focusing have been captured by this simple envelope model.

CONCLUSIONS

We have demonstrated good longitudinal compression using the real NDCX voltage waveform in LSP simulations. But the transverse focusing of the compressed pulse is also adversely affected by the time-dependence of the voltage. We have explained the mechanism for this effect and shown qualitative agreement between LSP and an envelope model. Ideally the NDCX pulse should have good longitudinal and transverse focusing. In future work more attention needs to be given to a magnetic focusing scheme which can mitigate the defocusing effect of the time-dependent voltage.
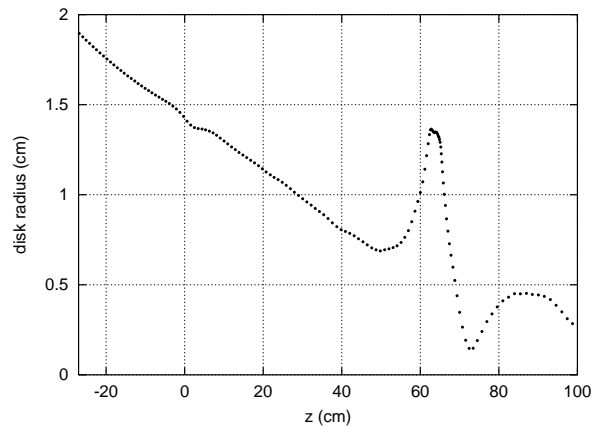

Figure 3: Disk radii of NDCX ion pulse at t = 1400 ns. From an envelope model using time-dependent focusing at voltage gap.

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