END-TO-END SIMULATIONS OF AN ACCELERATOR FOR HEAVY ION BEAM BUNCHING *

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Abstract

Longitudinal bunching factors in excess of 70 of a 300-keV, 27-mA K+ ion beam have been demonstrated in the Neutralized Drift Compression Experiment in rough agreement with particle-in-cell end-to-end simulations. These simulations include the ion source temperature, experimental diode voltage and induction bunching module voltage waveforms in order to determine the initial beam longitudinal phase space critical to longitudinal compression. To maximize simultaneous longitudinal and transverse compression, we designed a solenoidal focusing system that compensated for the impact of the applied velocity tilt on the transverse phase space of the beam. Here, pre-formed plasma provides beam neutralization in the last one meter drift region where the beam perveance becomes large. We compare simulation results with the experimental measurements and discuss the contributions to longitudinal and transverse emittance that limit compression.

INTRODUCTION

Heavy ion fusion (HIF) and ion-driven warm dense matter (WDM) physics require the acceleration, compression, and transverse focusing of an intense ion beam. In both HIF and WDM scenarios, to achieve the desired isochoric heating, the ion beam energy must be transported to the target and deposited in a small spot before hydrodynamic disassembly. Longitudinal neutralized drift compression (NDC) is initiated by imposing a linear head-to-tail velocity tilt to a drifting beam. In the presence of a perfectly neutralizing plasma, the compression is only limited by the accuracy of the applied velocity tilt and the ion beam longitudinal temperature.[1] Thus, this technique has demonstrated 50-fold compression on the Neutralized Drift Compression Experiment (NDCX).[2,3]

Here, we make use of an integrated numerical simulation capability with the flexibility to model ion acceleration, magnetic transport, NDC and focusing in a dense plasma. It should be noted that this investigation does not include a final focus solenoid within the plasma transport section, which is the subject of future work. In these simulations, the enabling algorithms available in the particle-in-cell (PIC) code LSP simulation code[4] include fast implicit electromagnetic solver and energy-conserving particle advance that preserves the cool experimental plasma temperature. With these algorithms we can efficiently explore the tightly coupled physics of ion acceleration, compression and focusing of both recent and planned experiments on the Solenoidal Transport Experiment (STX) (layout shown in Fig. 1).

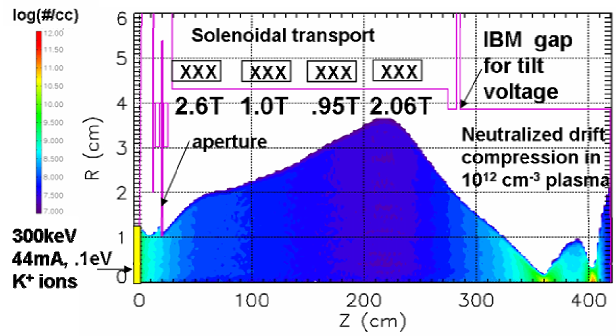

Figure 1: The STX simulation geometry is shown with the beam density near the time of peak simultaneous focus. From left to right are the ion source, diode, magnetic transport, IBM gap and plasma regions.

We first present a reasonably optimized 2D simulation using the experimentally measured diode voltage (average of 5 shots) and induction bunching module (IBM) waveform. The IBM waveform [Fig. 2(a)] is relatively short in duration, compressing only a 100--200 ns segment out of the >6 μs beam pulse. The complete beam envelop is shown in Fig. 1 which actually plots the beam density at 3.2 μs near peak simultaneous (longitudinal and transverse) focus at the z = 415 cm plane. The thermionic 0.1-eV K^+ ion source, at far left, provides a 9.7 mA/cm^2 ion flux out to 1.2-cm radius giving an initial 44-mA ion current in the diode at 300 keV. A 1-cm aperture at z = 20 cm scrapes off the beam edge including any unwanted beam halo exiting the diode leaving 27 mA in the apertured beam. This beam has a calculated 0.01-eV longitudinal temperature and 0.08-π-mm-mrad transverse emittance. The maximum fields in the four 44-cm-long 5.8-cm radius solenoids (B_z = 2.6, 1, 0.95, 2.06 T) are designed to provide a roughly 2-cm, -30-mrad beam envelop at z = 275 cm before entering the IBM gap without losing ions to the outer transport wall. The IBM waveform is chosen to optimize the head-to-tail energy ramp that maximizes the axial compression ratio $R = I_{max} / I_0$, where I_{max} and I_0 are the maximum current at the z = 415-cm plane and initial beam current. The large incoming beam angle counteracts the defocusing produced by the IBM waveform and the beam focuses transversely also at the 415-cm plane. At z = 310 cm, the beam space charge is neutralized in a 3-eV, 10^{12} cm^{-3} density plasma. In this initial simulation, a fast plasma model (sigma model) is assumed in which the plasma currents are described as a tensor conductivity; *J*=

*Work supported by DOE through PPPL and the HIFS_VNL.
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$\sigma(E+v_p\mathrm{x}B)$, where v_p is the plasma electron velocity. The sensitivity of the beam compression to plasma density is discussed later. The compressing beam pulse reaches 10^{12} cm^{-3} peak density or a total density compression of 10000 when compared with beam density entering the IBM gap. The longitudinal compression peaks at R=120 with a transverse spot a_s=1.3 mm (edge radius). A target placed at the focus would receive peak deposited energy of 0.046 J/cm^2.

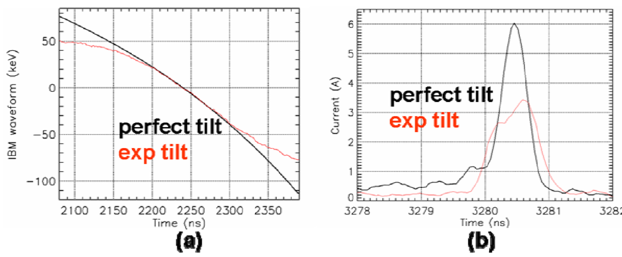

Figure 2: In (a), the experimental and perfect IBM voltage waveform are plotted. The resulting beam currents (27 mA initial) at z = 415 cm are shown in (b).

PHYSICS OF AXIAL COMPRESSION

We now examine the limiting physics for axial compression of an ion beam of energy E_i given a head-to-tail velocity tilt. The time-dependent velocity function at a particular plane that produces a perfect beam longitudinal compression at a downstream distance L is given by $v(t) = v(0)/(1-v(0)t/L)$, where $v(0)$ is the velocity of the pulse at t = 0. For ion mass m_i, the voltage producing this ideal tilt, $V(t) = \frac{1}{2}m_i v(t)^2 - E_i$. As seen in Fig. 2, the experimental waveform only follows the ideal for 100 ns.

Due to ion source and accumulated errors, the beam will have some characteristic thermal longitudinal velocity $v_{||} = (kT_{||}/m_i)^{1/2}$ that limits the pulse length (FWHM) achievable to roughly $t_{pmin} = v_{||}L/v(0)^2$. The beam frame temperature $T_{||}$ translates into the laboratory frame coordinates as energy variation $\Delta E = (2E_iT_{||})^{1/2}$. Previous measurements of t_{pmin} have been 2--4 ns on NDCX with 300 keV K^+ ion and L = 130 cm.[2,3] This pulse width implies a total $T_{||}$ = 1 eV or ΔE ~ 1 keV and energy variation $\Delta E/E_i$ ~ 0.003 for STX. Several factors influence $T_{||}$ and limit t_{pmin} (and R) which we now address.

Beam Longitudinal Cooling in the Diode

The thermionic ion source used on STX has roughly 0.1-eV temperature.[2] The calculated STX beam parameters just upstream of the IBM has $T_{||}$~0.01 eV with a 0.08-π-mm-mrad normalized emittance ($T_\perp$~0.2 eV). The cold temperature is a result of the conservation of longitudinal emittance in the diode (with voltage V) that in the 1D limit reduces the beam temperature from that of the anode source T_s as described by $kT_{||}=(kT_s)^2/(2eV)$.[5] The integrated simulation calculates $T_{||}$ ~0.01 eV or ΔE = 100 eV at the entrance to the IBM gap that would translate into t_{pmin}=0.3 ns which is consistent with the simulation given an ideal IBM waveform [see Fig 2(b)].

Beam Space Charge Depression

A physical limitation on ΔE is the result of the beam space charge depression. In a long drift tube of radius R_w, $\varphi_{sc}(r)=[1-(r/a)^2+2\ln(R_w/a)]\,\nu/\beta\ m_ec^2$, where ν and β are Budker number (beam current normalized by 17 kA) and beam velocity normalized by the speed of light c, respectively. Integrating over the beam envelop, the mean space charge depression $\Delta E_{sc}=12^{-1/2}\nu/\beta m_ec^2$. Ion transverse phase mixing while a is changing can increase ΔE to some fraction of ΔE_{sc} (58 eV or $T_{||}$=0.006 eV for the 27 mA beam). This is roughly the minimum value calculated in the integrated simulation and corresponds to t_{pmin} = 0.22 ns with an ideal IBM waveform.

Velocity Spread Due to Focusing Angle

After passing through the IBM gap, the beam is left with the proper focusing angle to coincide with the longitudinal focus. This angle adds an effective $T_{||}$ to the beam. This spread is easily calculated assuming a small angle θ at $r = a$ given by $T_{||foc} = 24^{-1}\, m_i\, c^2\beta^2\theta^4$. For a 15-mrad angle corresponding to L=130 cm and a = 2 cm, the temperature is quite small, $T_{||foc}$ =0.0006 eV. For larger θ, the effect can quickly become significant.

Voltage Oscillations in Diode

As stated earlier, the effective energy variation of the beam just after the tilt voltage waveform is applied is of order 0.3%. The measured voltage produced in the Marx, however, has variations of order 1%. An ion bunch accelerated in the diode voltage with fluctuation periods t_f such that $t_a < t_f < t_{p0}$ will experience the most damage to the beam longitudinal emittance and limit longitudinal compression. High frequency fluctuations are averaged out during acceleration and low frequency fluctuations add only a small velocity tilt to the beam. If significant this tilt can affect the plane of longitudinal focus and add shot-to-shot variation to R.

Beam Plasma Two-Stream

The electrostatic beam-plasma electron two-stream instability results in longitudinal emittance (or $T_{||}$) growth that could limit compression. A series of highly spatially-resolved 1D LSP simulations show that significant growth in $T_{||}$ can only occur for very small beam and plasma initial temperatures. For a beam with $T_{||}$ = 0.02 eV and 3-eV plasma temperature, the beam longitudinal emittance increased only 25%---too small to have a significant impact on compression in STX experiment.

Beam Temperature Anisotropy Instability

Startsev, Davidson and Qin[6] have analyzed and simulated the stability properties of intense non-neutral charged particle beams with large temperature anisotropy. They show that an electrostatic Harris-like instability[7] can develop in such beams and is a potential source of deterioration of beam quality (growth of $T_{||}$ and longitudinal beam emittance). The theory, as well as LSP integrated simulations, predicts no growth in the beam $T_{\parallel}$ for STX due to the short 3-m transport length.

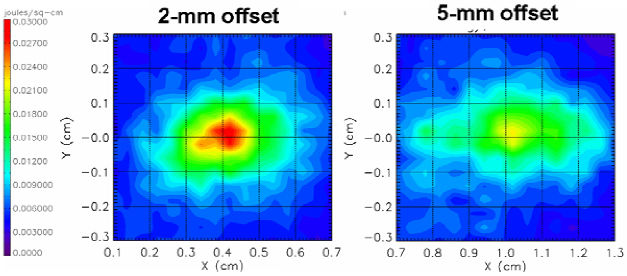

Figure 3: The energy deposition (J/cm^2) from the compressed beam pulse is plotted for beam offset (a) 2 mm and (b) 5 m.

Deviation in Tilt Waveform From Ideal

The IBM voltage waveform constructed for the STX experiment is only a very good approximation to the ideal waveform for roughly 100 ns. Using the ideal waveform (see Fig. 2), *R* increases 84% from that using the experimental waveform. This increase for the ideal waveform is consistent with an effectively longer IBM pulse and more gathered beam charge.

PHYSICS OF TRANSVERSE FOCUSING

Compression or focusing of the STX beam in the transverse plane is complicated by the longitudinal physics and is now addressed.

Aberrations From IBM Waveform

The gap through which the IBM voltage waveform is applied acts as a simple bipotential lens, in which the radial component of the electric field is anti-symmetric about the center of the gap. The net radial forces upstream and downstream of the center of the gap do not cancel since E_r is proportional to the increasing IBM voltage and the beam defocuses. The gap aberration is worse for a larger radius beam. For a given beam emittance ε_n, a larger initial beam radius a_0 with shorter L leads to a smaller spot on target $a_s=\varepsilon_n L/a_0\gamma\beta$. In a series of idealized simulations, we find that the ratio of the energy deposition on target of the tilted beam to that of an untilted beam increases with a_0, indicating that the gap aberration is becoming increasingly important. If the time-dependent aberration is corrected, a factor 4 higher energy deposition on target could be achieved.

Beam Misalignments Entering IBM Gap

Misalignments of the ion source and solenoid axis lead to offsets in the beam centroid or a dipole beam motion which are magnified by the IBM gap. In 3D simulations with 2 and 5-mm beam offsets entering the IBM gap (see Fig. 3), we find the offsets are doubled at the target with loss of beam intensity. Keeping beam offsets at the IBM gap to <1 mm should be tolerable for STX.

Sensitivity of Focus to Plasma Density

For a purely transversely focusing beam, ion beam space charge can effectively be neutralized (>99%) in the presence of a high density plasma $n_p >> n_b$.[8] In fully kinetic plasma simulation, $n_p=10^{11}$ cm^{-3} yields the same compression as the sigma plasma model (3.3 A and 1.3 mm radius). An $n_p=10^{10}$-cm^{-3} simulation indicates a slight degradation in current at focus, but the minimum radius increased to 1.7 mm. The $n_p=10^9$-cm^{-3} simulation gave a 33% smaller current and a 3.5-mm spot. These results suggest that the rapidly changing beam density to $>10^{12}$ cm^{-3} due to the strong longitudinal compression allows for significantly smaller plasma density than beam density for the shallow 7-mrad focusing angle.

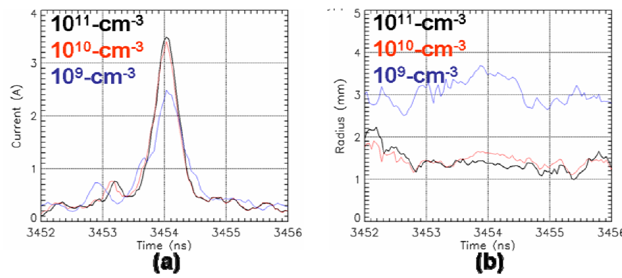

Figure 4: In a series of kinetic plasma simulations, the (a) compressed beam current and (b) edge radius at simultaneous compression are shown for the three plasma densities.

SUMMARY

A numerical investigation using the electromagnetic LSP code into the limiting physics of simultaneous beam focus on the STX experiment has shown an overall ion beam density compression from the IBM gap to target of 10000. These results are currently being compared in detail to experiment with preliminary comparison encouraging.

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