White Paper for *Frontiers of Plasma Science Panel*

Date of Submission:	***June 19, 2015***

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Title:	The Plasma Physics of Neutralized and Non-neutral Intense Ion Beams
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(Limit text to 3-pages including this form. Font Times Roman size 11.
1 page of references and 1 page of figures may also be included. *Submit in PDF format*.)

Research frontier and the importance of the scientific challenge

How can heavy ion beams be compressed to the high intensities required to create high energy density matter and fusion conditions? How are intense charged-particle beams transported in and how does their energy couple to high energy density plasmas? These research topics are closely related to the FES strategic goals (#3, 4) on high energy density plasma science and the fundamental understanding of the full range of basic plasma science, including non-neutral plasmas.

New drivers and probes are being developed and directed toward the field of warm dense matter (WDM, with $T \approx 1$ to a few eV, $P > 0.1$ Mbar), a sub-area of high energy density science. Precisely controlled ion beams are a relatively unique complement to the laser and x-ray probes that are making great strides [Sc15]. The novel beam conditions – unusually high current and brightness with > MeV beams entering and exiting neutral and relatively cool plasmas – provide a venue to explore collective effects in high intensity particle beams. These beams are exciting tools for the study of WDM and they are themselves an exciting platform for exploration. For example, the formation and manipulation of these beams rely on collective effects with high intensity particle beams propagating in background plasma in the presence of an applied magnetic field. These effects are relevant to the formation of collisionless shocks in astrophysical systems [De06].

This research will provide new insight to the underlying plasma physics, and will provide techniques to push the present-day limits of compression and focusing of energetic beam pulses. This naturally leads to the enhancement of beam drivers for warm dense matter, and to novel approaches to achieve the high intensities required to create HEDP and fusion conditions.

We present three examples of topics that can be explored with presently available extreme space-charge beams or with beam anticipated in the near future:

1. The two-stream instability of an ion beam propagating in background plasma has been predicted from theoretical work [Ke71, Qi03]. It has been observed in electron and proton storage rings, where methods to control the two-stream instability have been developed. In accelerator two-stream or electron cloud effects appear due to stray electron from the walls or volumetric ionization of contaminant gases, and efforts to mitigate the electron cloud effects center on reducing the number density. However, new high intensity ion beams in linear accelerators include neutral plasmas interacting with the beam in focusing or transport regions. The plasma effectively cancels the beam space-charge forces, and so enhances focusing of the ion beam beyond the space-charge limit. Though the concern that streaming instabilities would prevent the desired focal properties was put to rest -- with suppression due to the velocity spread of the beam bunch -- the experiments are flexible enough to create special conditions below and through the onset of the predicted instability [To15].

2. Strong collective focusing of an ion beam in an under-dense plasma and a weak magnetic field can occur due to a self-pinching effect, which becomes most pronounced when the beam radius is small compared to the collisionless plasma electron skin depth. A collective focusing scheme was proposed and experimentally tested by Robertson [Ro82]. Recently, the original theory was extended with an eye toward using the effect to great advantage in high intensity ion beams [Do12]. For example, for a given focal length of the focusing system, the magnetic field for the collective focusing scheme can be reduced by a factor $(m_e/m_i)^{1/2}$ to achieve the same ion beam radius on a target, or from several Tesla to only a few hundred Gauss. This would greatly reduce the stray magnetic field near the target plane in a short focal-length system, simplifying the diagnosis of, e.g., back-scattered or ejected charged particles due to the intense beam-target interaction.

3. With higher intensity, collective effects in the ion beam bunch become increasingly important. For example, the dynamics of the isolated bunch (or to leading order the beam envelope and phase space volume) is mainly determined by the initial bunching velocity ramp of particles, the repulsive space charge force and the applied electromagnetic fields. A cold beam with high space charge is highly collisionless, essentially a Vlasov system, subject to the rich wave dynamics that can be initiated by perturbations [Da01]. The longitudinal compression of a high intensity beam pulse enables >10x current amplification by increasing the effective line charge density of the ion bunch [Se15]. The amplification is limited by the stagnation of the bunch length due to its own space charge but at this stage, the beam should have very little velocity spread, attractive for downstream focusing. (In the absence of space charge, the bunch would compress further to a length limited by the phase space volume occupied by the beam, but it would have a significant velocity spread with consequences for chromatic aberrations in focusing.) Understanding the interplay of applied fields and self-generated fields can be carried out with available diagnostics.

Approach, required research tools and capabilities

The Neutralized Drift Compression Experiment-II at Lawrence Berkeley National Laboratory is now generating beam spots size with radius $r < 1$ mm within 2 ns FWHM and approximately 10^{10} ions/pulse [Se15]. Higher intensity experiments are being prepared, and research topics are described in [Sc15] and [Ba15]. The accelerator beam is characterized by high perveance and low emittance, which lends itself to studies of the beam physics questions raised here. It accelerates and rapidly compresses the beam pulses by adjusting the slope and amplitude of the voltage waveforms in each of twelve gaps of the 8-meter long accelerator.

1. Create a high intensity ion pulse via drift compression. By tailoring the longitudinal energy distribution and aperturing the beam radially, conditions can be established that will manifest the streaming instability. Diagnostics are available that will permit direct comparison to advanced particle in cell simulations, as shown in Fig. 1. The defocusing of the beam can be measured directly and time resolve to observe the self-bunching of the beam due to the streaming instability.
2. To demonstrate strong collective focusing with a weak magnetic field, an underdense plasma in the presence of a weak magnetic field, plasma electrons from a larger volume provides are dragged into the magnetic field region. These co-moving electrons are predicted to be effective at allowing the self-pinching effect to manifest. Experimentally one challenge will be to diagnose the transverse compression without introducing back-streaming electrons from the diagnostics into the magnetized plasma. The results may be directly compared to advanced particle in cell simulations as shown in Figure 2.
3. Tune the bunch compression so that a space-charge limited stagnation point occurs at the measurement plane of a high resolution spectrometer. This provides a detailed map of the beam longitudinal phase space (ΔE, Δt) in the axial direction. The measurements will be sensitive to space charge waves initialized by non-ideal features of the bunching waveforms or other sources. The results may be compared to advanced particle in cell simulations. In related work, other researchers have studied longitudinal compression using electron beams with lower space charge as surrogates for ion beams [Be11, Sa14].

Impact on plasma science and related disciplines and any potential for societal benefit

Controlling ion beams formed in advanced induction and RF accelerators as well as ion pules from laser-plasma acceleration in novel intensity and space charge regimes will create probes of warm dense matter, for applications in materials science, and the development of fusion materials.

Longitudinal bunch compression has been used at lower intensities to increase current in a number of large ion accelerators (such as at GSI, Germany or KEK, Japan). Any application requiring high peak current will benefit from these studies.

Beam-plasma interactions are important to understand both for beams passing through plasmas in an IFE reactor target chamber and for driver designs where plasmas are used for neutralized drift compression.

Astrophysical phenomena are studied in the context of collisionless shocks and streaming instabilities. Though the experiments described above will not create collisionless shocks, the ability to study the interaction between the charged ion beam and the neutral plasma in an accessible experimental and diagnostic setting and should be of synergistic interest. The plasma density can be monitored and the influence of the plasma and magnetic field on the beam can be both be tracked experimentally.

These will also test our understanding and contribute to precise control of beam conditions using future laser-plasma ion acceleration facilities, such as BELLA-i [Le15].

References (Maximum 1 page)

[Sc15] T. Schenkel, et al., *Extreme chemistry and the properties of warm dense matter*, White Paper for *Frontiers of Plasma Science Panel,* (2015).

[De06] M.E. Dieckmann, et al., Plasma Phys. Control. Fusion 48, B303 (2006)

[Ke71] E. Keil and B. Zotter, Tech. Rep. Cern-isr-th 0 71-58, Genève: CERN (1971)

[Qi03] H. Qin, et al., *Laser and Particle Beams 21*, 21 (2003) and references therein.

[To15] E. Tokluoglu and I.D. Kaganovich, Phys. Plasmas 22, 040701 (2015)

[Ro82] S. Robertson, Phys. Rev. Lett. 48, 149 (1982) and J. Appl. Phys. 59, 1765 (1986)

[Da01] Ronald C. Davidson, *The Physics of Non-Neutral Plasmas,* World Scientific, ISBN-1-86094-302 (2001)

[Do12] M. Dorf, et al., *Enhanced collective focusing of intense neutralized ion beam pulses in the presence of weak solenoidal magnetic fields,* Phys. Plasmas 19, 056704 (2012)

[Se15] P.A. Seidl et al., *Short Intense Ion Pulses for Materials and Warm Dense Matter Research,* (2015*)* http://arxiv.org/

[Ba15] J.J. Barnard, et al., *Warm Dense Matter Science Using Intense Ion Beams*, White Paper for *Frontiers of Plasma Science Panel,* (2015).

[Be11] B. Beaudoin, et al., Physics of Plasmas 18, 013104 (2011)

[Sa14] Y Sakai et al., Nucl. Inst. Methods A 733 70 (2014)

[Le15] W. Leemans, et al., *BELLA-i PW laser facility for intense laser-matter interactions,* White Paper for *Frontiers of Plasma Science Panel,* (2015).

Figures (maximum 1 page

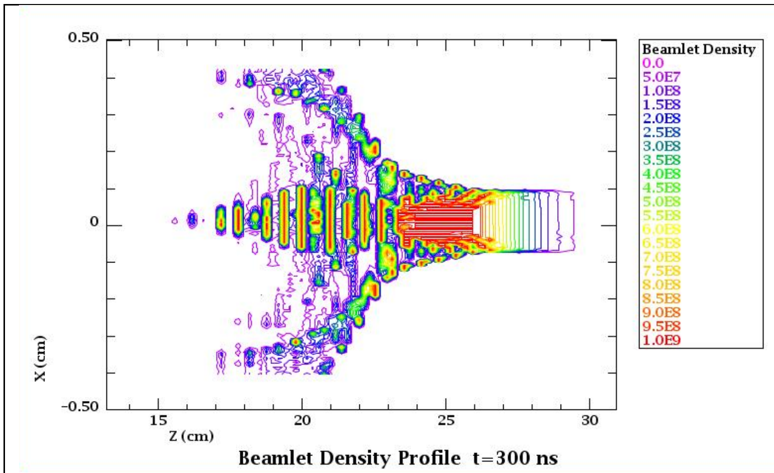

Figure 1: The beam density profile for an apertured beam in a background plasma, 300 ns after entering the plasma [To15].

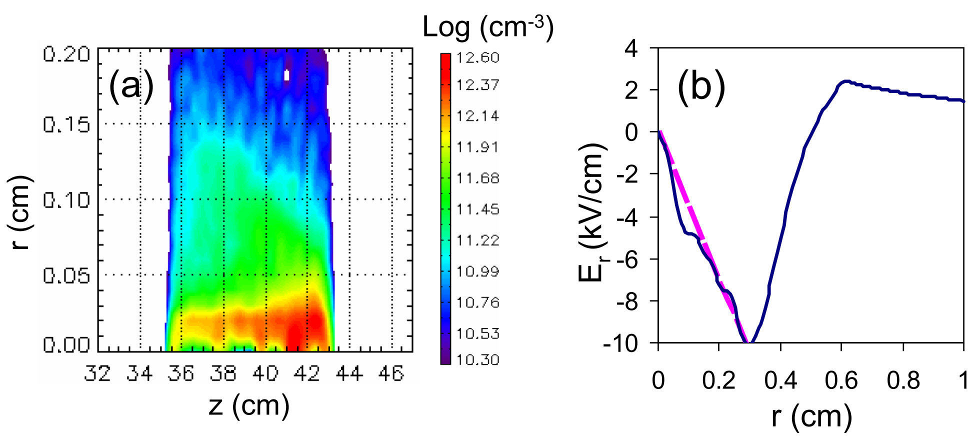

Figure 2: Particle-in-cell (LSP) simulation of the NDCX-II experiment [Do12] using the collective focusing effect to focus the high intensity beam using a weak magnetic field and a plasma.