The Plasma Physics of Neutralized and Non-neutral Intense Ion Beams

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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?

Creating a high energy and high intensity ion pulse:
Source of ions → acceleration, compression and focusing → target sample

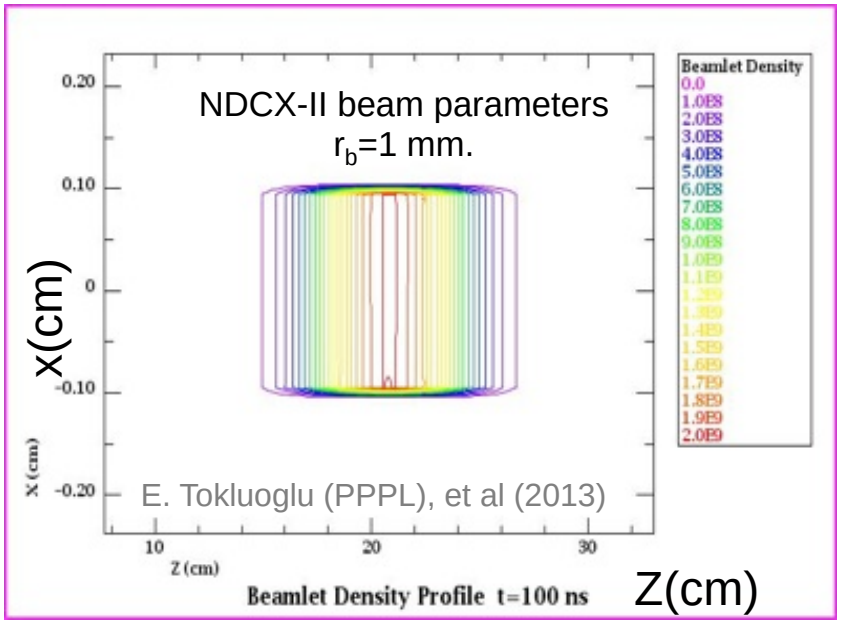
Leads to interesting non-neutral and neutral plasma physics questions.
E.g.:

1. Two-stream instability of an ion beam propagating in background plasma
2. Strong collective focusing of an ion beam in a plasma and a weak magnetic field
3. Explore the limits of the longitudinal compression of a high intensity beam pulse with and without neutralization

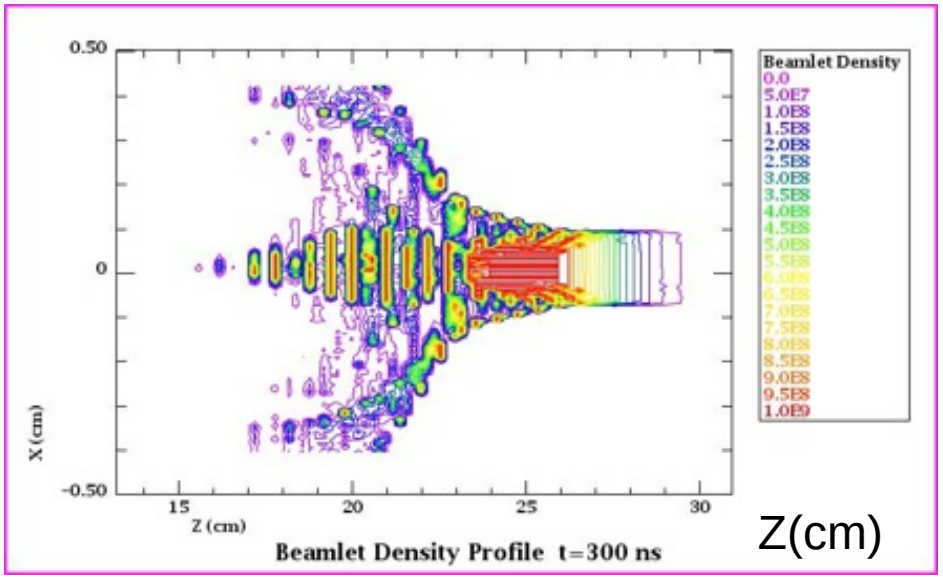
Reproducibility, repetition rate, sensitive diagnostics

1. Two-stream instability of an ion beam propagating in background plasma predicted

- In high energy accelerators: two-stream or electron cloud effects arise from stray (unwanted) electrons. → Reduce/eliminate!
- For new high-intensity ion beam systems, plasma is introduced to cancel the defocusing space charge force.



Beam density contour at t = 100 ns (1 m of propagation).



Beam density contour at t = 300 ns (3 m of propagation).

Defocusing when Δv/v is small.

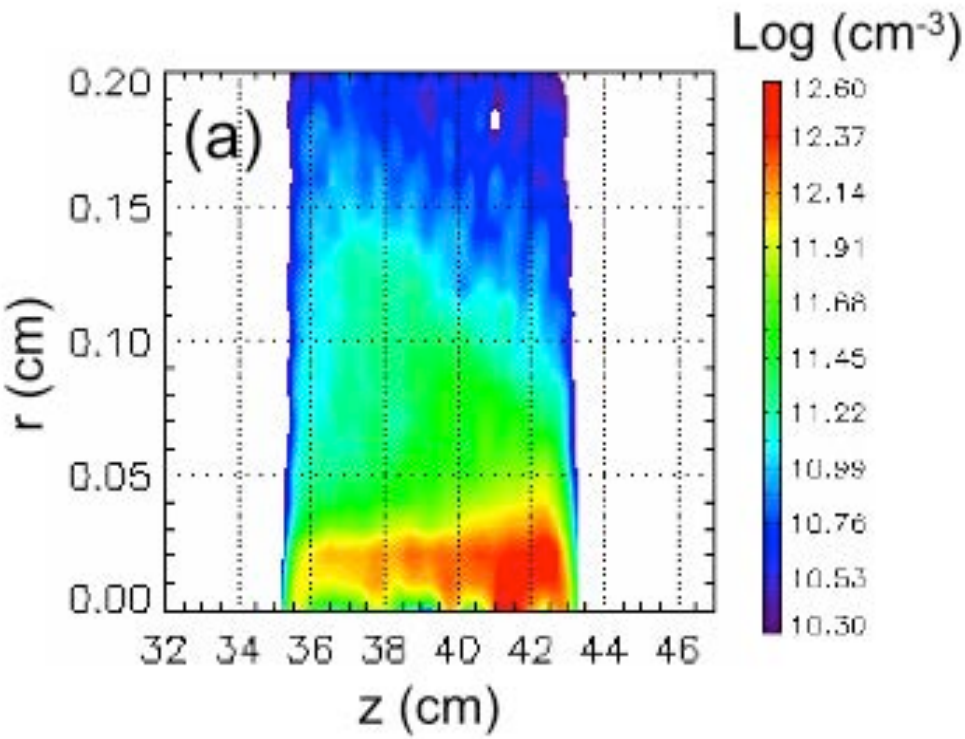
Goal: observe transverse defocusing and longitudinal self-bunching of beam

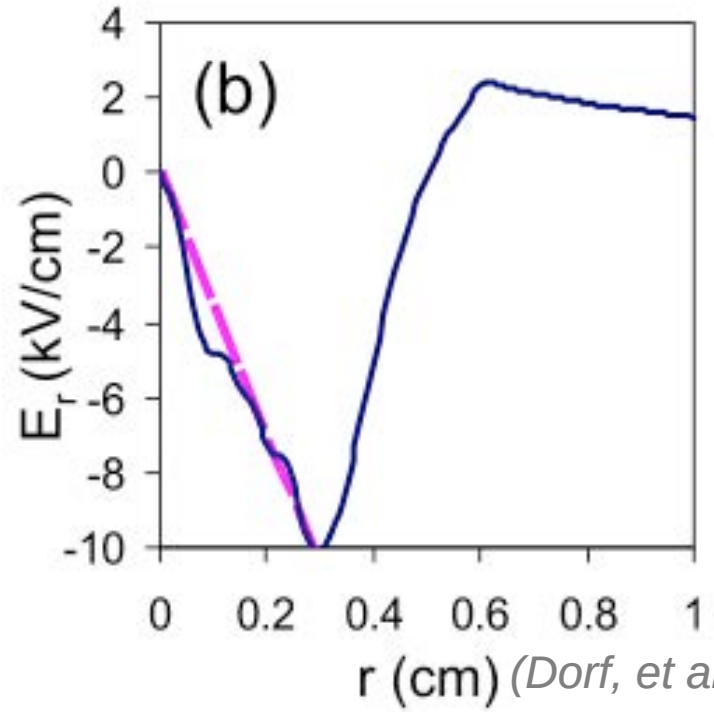
2. Strong collective focusing of an ion beam in a plasma and a *weak* magnetic field

Most pronounced when the beam radius is small compared to the collisionless plasma electron skin depth $r_b < c/\omega_{pe}$

Applied **B** can be reduced by a factor $(m_e/m_i)^{1/2}$ ~10 Tesla→ ~10^2 Gauss

Can this be used to great advantage in high intensity ion beams?





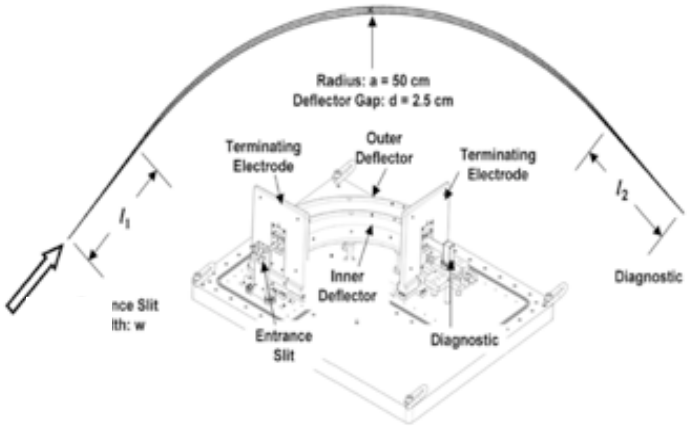
(Dorf, et al, 2012).

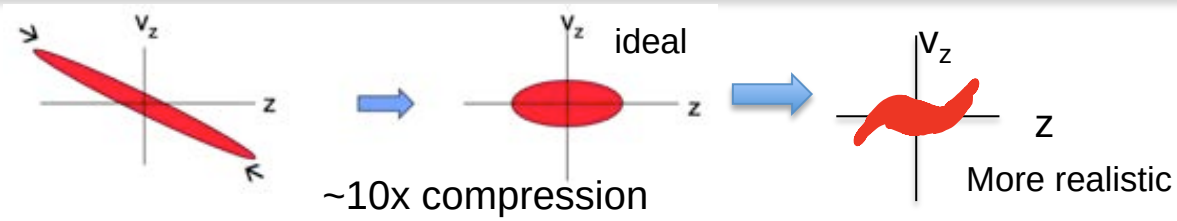
Particle-in-cell (LSP) simulation of the NDCX-II experiment using the collective focusing effect to focus the high intensity beam using a weak magnetic field and a plasma.

Non-neutral compression of a long pulse can create a high current bunch with very little energy spread

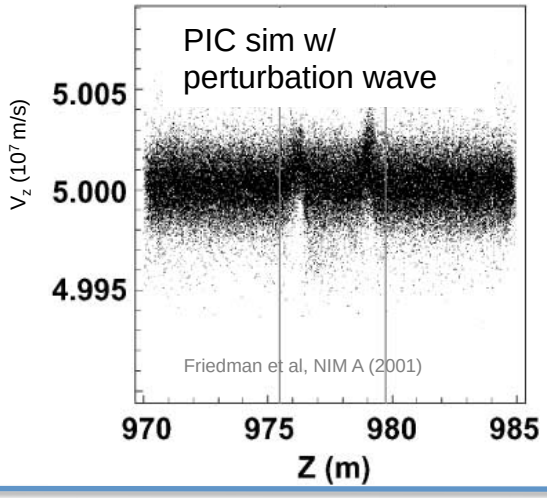
Focusing with low chromatic aberrations

Diagnostic: E.g.: energy analyzer

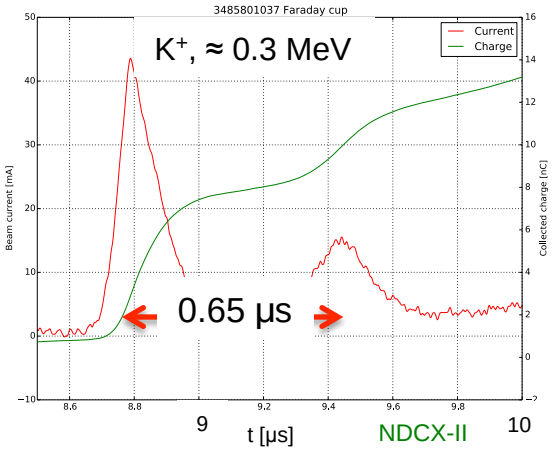




Waveform errors can launch space charge waves, and degrade the final energy spread and may cause particle loss. Detailed initial conditions must be included in simulations.



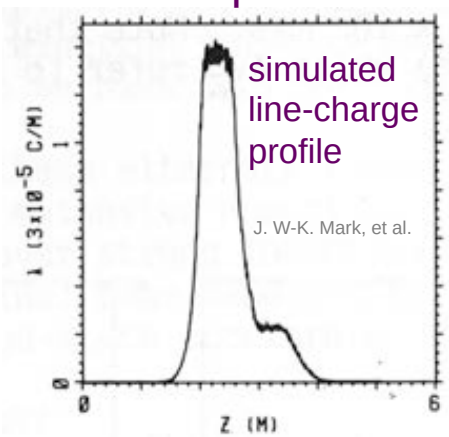
enables pulse shaping, double bunches

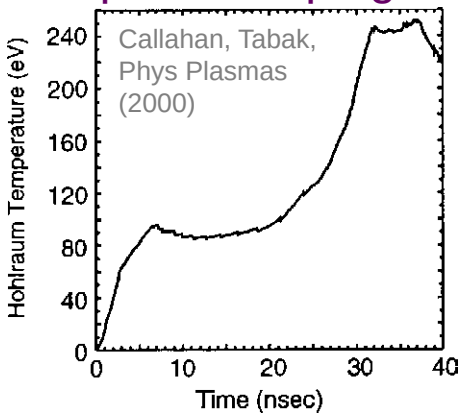


pump-probe for materials studies

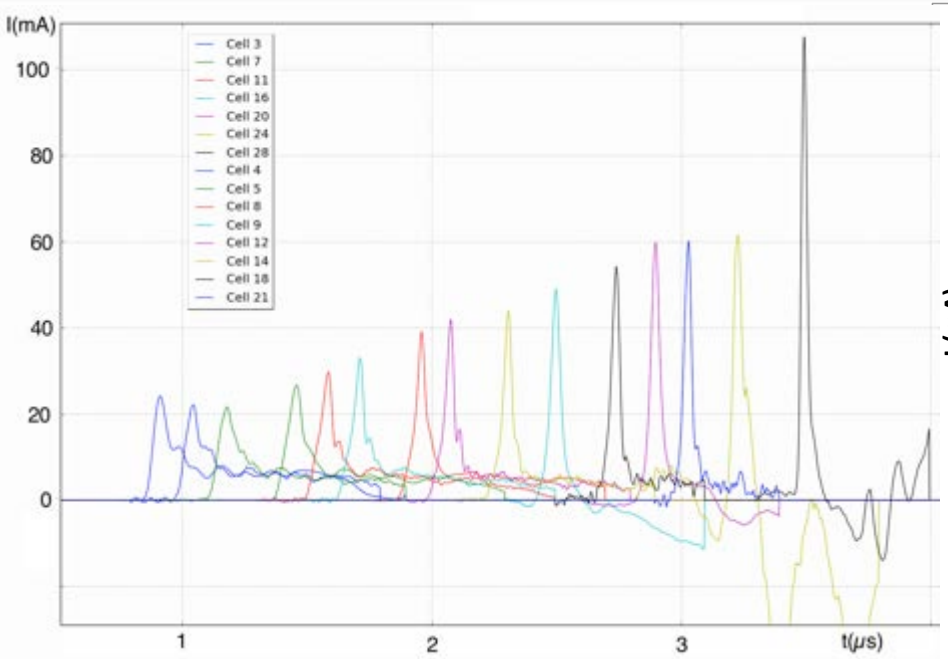
Double pulsing

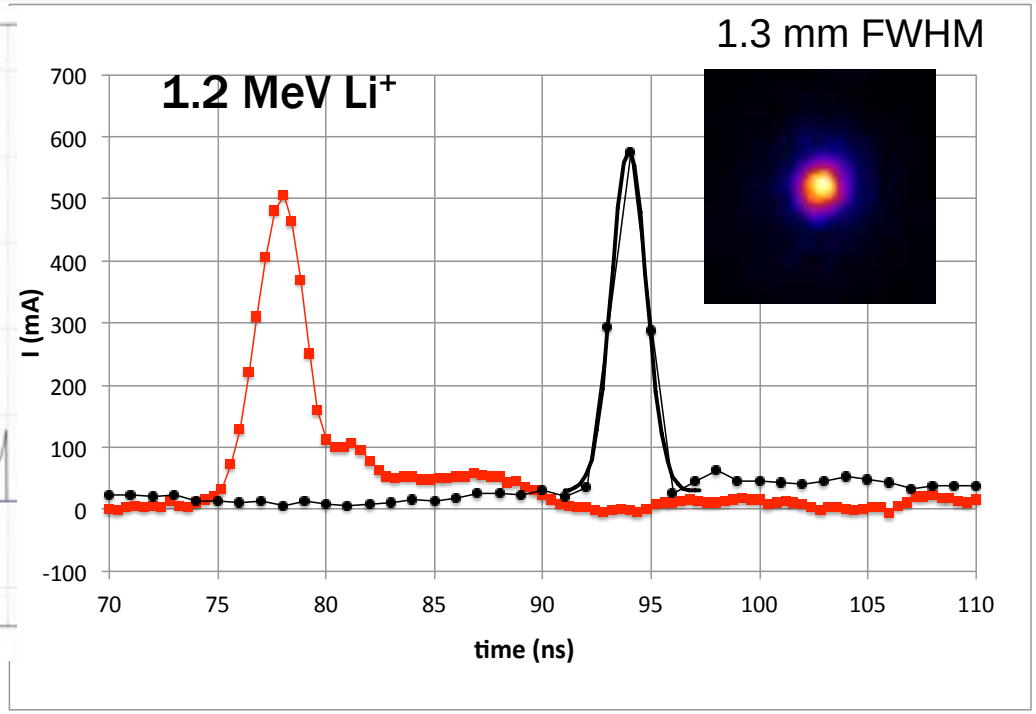
Explore driver final pulse shaping





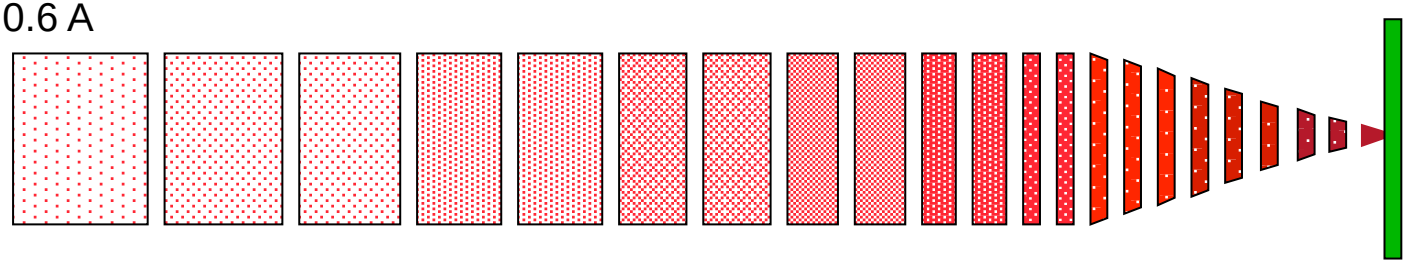
Approaches: Neutralized drift compression (NDCX-II), electron beams (Umd), Paul traps (PPPL, HU), FAIR (Germany).





NDCX-II

- beam spots size with radius r < 1 mm within 2 ns FWHM and approximately 10^{10} ions/pulse.
- 0.02 A → 0.1 mA → 0.6 A



Ion source and injector, 500ns

Linac custom waveforms for rapid beam compression

Neutralized drift compression and final focus

Target

Z=10 m

Other approaches: High intensity beam physics in unexplored regimes using scaled devices

Can an extreme space charge beam be transported and accelerated over long distances?

– UMER

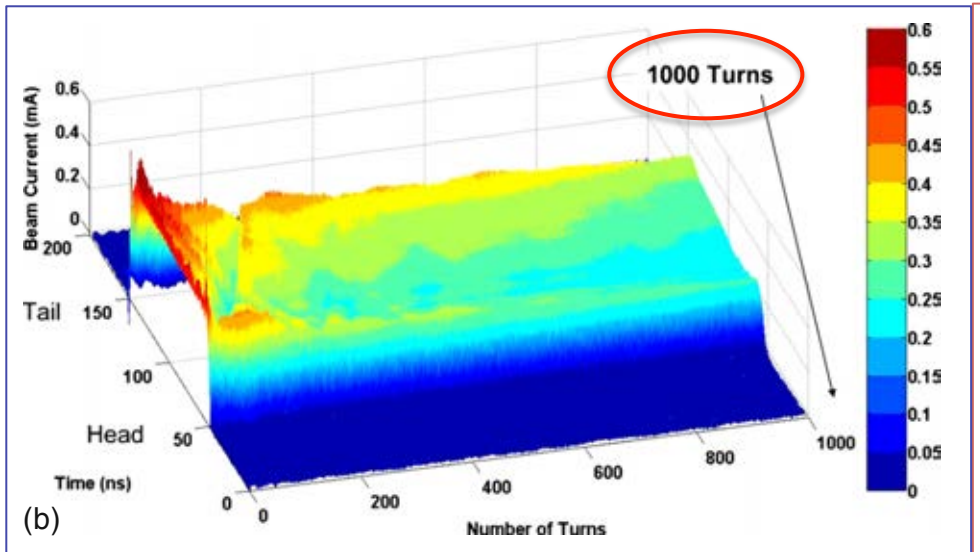
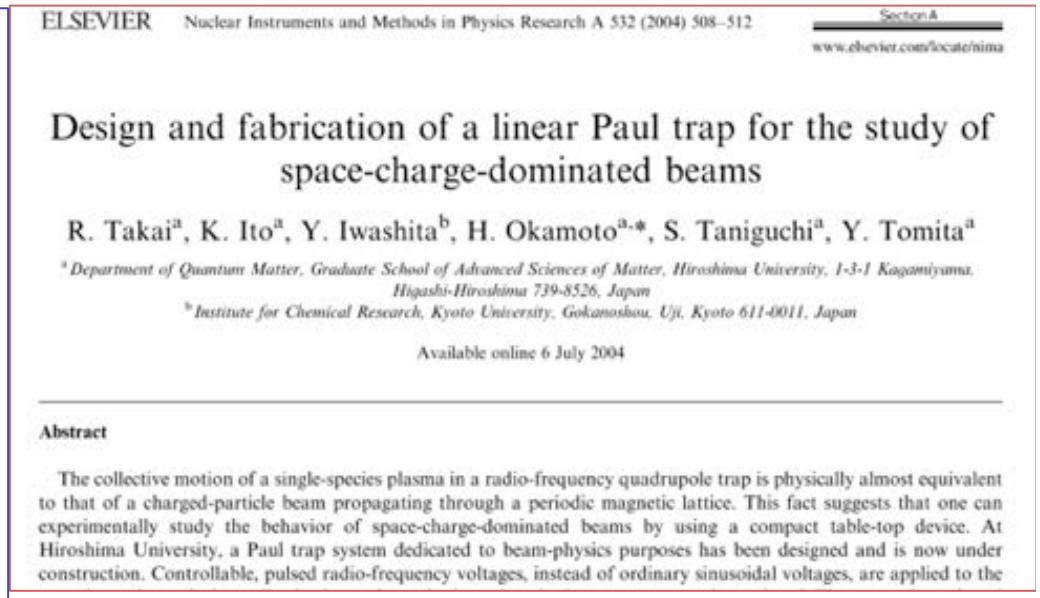


FIG. 8. (Color online) Three-dimensional view of the measured beam current at RC10 as a function of turns.

Longitudinal confinement and matching of an intense electron beam, Beaudoin, et al., UMd., Phys. Plasmas 18, 013104 (2011)

– Paul traps



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Design and fabrication of a linear Paul trap for the study of space-charge-dominated beams

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Abstract

The collective motion of a single-species plasma in a radio-frequency quadrupole trap is physically almost equivalent to that of a charged-particle beam propagating through a periodic magnetic lattice. This fact suggests that one can experimentally study the behavior of space-charge-dominated beams by using a compact table-top device. At Hiroshima University, a Paul trap system dedicated to beam-physics purposes has been designed and is now under construction. Controllable, pulsed radio-frequency voltages, instead of ordinary sinusoidal voltages, are applied to the

Also, at PPPL: *Paul Trap Simulator Experiment to Model Intense-Beam Propagation in Alternating-Gradient Transport Systems*, Gilson, et al, Phys. Rev. Lett. 92, 155002 (2004).

Impact on plasma science and related disciplines

Understand and control ion beams in novel intensity and space charge regimes

- advanced induction, RF and laser-plasma accelerators
- probes of warm dense matter, for applications in materials science, and the development of fusion materials.

Understand the limits of bunch compression

- has been used at lower intensities to increase current in a number of large ion accelerators (e.g.,GSI, KEK). Any application requiring high peak current will benefit from these studies.
- Beams passing through plasmas for, e.g.:
  - beam focusing toward an inertial fusion target and
  - bunch compression of an intense beam

Astrophysical phenomena, collisionless shocks and streaming instabilities

- Experiments described above will not create collisionless shocks,
- ability to study the interaction between the charged ion beam and the neutral plasma in an accessible experimental and diagnostic setting
  - The plasma density can be monitored and the influence of the plasma and magnetic field on the beam can be both be tracked experimentally.

Contribute to precise control of beam conditions using future laser-plasma ion acceleration facilities, e.g., BELLA-i.

Questions asked by the Panel on July 31

Can all of the proposed research be carried out with existing facilities?

Yes, with minor modifications and in some cases minor fabrication costs. The three examples given may be carried out on the Neutralized Drift Compression Experiment at LBNL in very close to its present configuration. Diagnostics either exist or may be readily assembled. By themselves the experiments would be significant and yield new results comparable to advanced simulations for which the computational tools (e.g., LSP, Warp) already exist. Furthermore the results would be enhanced by complementary and independent experiments at other facilities (eg, University of Maryland Electron Ring, Paul Traps at, e.g., PPPL and Hiroshima University).

Summary of the significance to plasma physics

Significance: How are intense charged-particle beams transported in and how does their energy couple to high energy density plasmas? This is tightly coupled to the FES strategic goals on high energy density plasma science and the fundamental understanding of a wide range of basic plasma science, including non-neutral plasmas. While creating new opportunities to study WDM, the beams are themselves an exciting platform for fundamental research.

This interplay between neutral plasmas and the high intensity (non-neutral) beams is, for example, subject to rich wave dynamics in unexplored parameter ranges. The unusually high current and brightness with MeV-and-above ion bunches entering and exiting neutral and relatively cool plasmas provide a venue to explore and control collective effects for new applications.

Approach: All of the proposed research may be carried out with existing facilities with minor modifications. The relevant advanced simulation tools are in hand. For example, exploration of the two-stream instability, collective focusing and pushing the limits of longitudinal compression of an ion bunch may be carried out on the Neutralized Drift Compression Experiment at LBNL in very close to its present configuration. Valuable complementary research, for example, using electrons to mimic ions (UMd) should also be supported.