Ion Beam Compression in Space and Time for HEDP Applications*


Presented on behalf of the

Heavy Ion Fusion Science - Virtual National Laboratory
LBNL, LLNL and PPPL

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The HIFS-VNL concentrates on the beam science common to both High Energy Density Physics (HEDP) and fusion

→ We address a top-level scientific question central to both HEDP and fusion:

*How can heavy ion beams be compressed to the high intensities required for creating high energy density matter and fusion?*

Principal science thrust areas & Outline of this talk:
- High brightness beam transport (*my area*)
- Focusing onto targets
- Longitudinal beam compression
- Advanced theory and simulation tools
- Beam-target interaction (*growing effort*)
Significant progress towards HEDP and Fusion!

Unique world class capability in electron cloud physics – flooding with electrons yields:

Beam phase space distortion

Electron drift oscillations

IBET – Ion Beam Electron Trap:
• Ion beam potential (+2 kV) provides radial confinement
• Negatively biased rings at both ends provide axial confinement
• Here, downstream ring off – floods with elec. from end wall
Significant progress towards HEDP and Fusion!

Unique neutralized final focus:
Success from embracing, rather than avoiding plasmas

Non-neutralized
FWHM: 2.71 cm
Neutralized
FWHM: 2.14 mm

Unique ion pulse compression in plasma: From concept to simulation to 50X compression data in 12 months
Developed new approach to ion-driven HEDP with much shorter ion pulses (< few ns versus a few $\mu$s)

Ion energy loss rate in targets

Maximum $dE/dx$ and uniform heating at Bragg peak require short (< few ns) pulses to minimize hydro motion. [L. R. Grisham, PoP, (2004)].

$Te > 10 \text{ eV} @ 20J, 20 \text{ MeV}$

(Future US accelerator for HEDP)

GSI: 40 GeV heavy ions $\rightarrow$ thick targets $\rightarrow$ Te $\sim$ 1 eV per kJ

Dense, strongly coupled plasmas $10^{-2}$ to $10^{-1}$ below solid density are potentially productive areas to test EOS models (Numbers are % disagreement in EOS models where there is little or no data)

(Courtesy of Dick Lee, LLNL)
LSP-PIC simulations demonstrate the possibility of dramatically larger compression and focusing of charge neutralized ion beams inside a plasma column

Snapshots of a beam ion bunch at different times shown superimposed

Background plasma @ 10x beam density (not shown)

• Velocity chirp amplifies beam power analogous to frequency chirp in CPA lasers.
• Solenoids and/or adiabatic plasma lens (Z-pinch) can focus compressed bunches in plasma.
• Instabilities may be controlled with $n_p >> n_b$, and $B_z$ field [Welch, Rose (MRC); Kaganovich (PPPL)].

Existing 3.9T solenoid focuses beam

$\leftarrow$ Ramped 220-390 keV K$^+$ ion beam injected into a 1.4-m-long plasma column:

• Axial compression 120 X.
• Radial compression to 1/e focal spot radius < 1 mm.
• Beam intensity on target increases by 50,000 X.

(Welch et al., 2004)
Neutralized Transport Experiment (NTX)

300 keV K+ ions @ 25 mA

Neutralized

FWHM: 2.14 mm

Non-neutralized

FWHM: 2.71 cm

400 kV Marx generator

pinhole diagnostic

injector

four magnetic quadrupoles

MEVVA source (Plasma plug)

RF source (Target-region plasma)

Measurement

Normalized fluence

R (mm)

Zero Space-charge

MEVVA and RF

MEVVA ONLY

Theory

100% neutralized

MEVVA and RF

MEVVA ONLY

Normalized fluence

R (mm)
Measurements on the Neutralized Transport Experiment (NTX) demonstrate achievement of smaller transverse spot size using target-region plasma.

Neither plasma plug nor target-region plasma.  
Plasma plug.  
Plasma plug and target-region plasma.

Neutralized drift compression experiment (NDCX)  
- 300 keV K+ ions @ 25 mA
50 Fold Beam Compression achieved in neutralized drift compression experiment

The $\rho - T$ regime accessible by beam-driven experiments is similar to the interiors of giant planets and low-mass stars.

Figure adapted from “Frontiers in HEDP: the X-Games of Contemporary Science:”

Accessible region using Intense beams (this decade)

Region is part of Warm Dense Matter (WDM) regime

WDM lies at crossroads of: degenerate/classical and strongly Coupled/weakly coupled
HYDRA simulations confirm temperature uniformity of targets at 0.1 and 0.01 times solid density of aluminum (20 MeV Ne+ ions @ 330 A)

Δz = 48 µ

Axis of symmetry

r = 1 mm

0.1 solid Al

Δz = 480 µ

0.01 solid Al (at t=2 ns)
Conclusions

- There have been many exciting scientific advances and discoveries during the past two years:
  - Demonstration of compression and focusing of ultra-short ion pulses in neutralizing plasma background.
  - These enable unique contributions to High Energy Density Physics (HEDP).
  - Contributions to cross-cutting areas of accelerator physics and technology, e.g., electron cloud effects, diagnostics.

- Heavy ion research is of fundamental importance to both HEDP in the near (and long) term and to fusion in the longer term.

- Experiments heavily leverage existing equipment and are modest in cost.

- Theory and modeling play a key role in guiding and interpreting experiments.