High-Intensity Ion Beam Neutralization and Drift Compression Experiments

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(with S. S. Yu, P.A. Seidl, and B.G. Logan et al., HIFS-VNL Collaboration)
Outline

1. Applications and techniques of ion beam focusing
   - Ion beam applications
   - Techniques of ion beam focusing
   - Beam space charge neutralization for radial compression
   - Drift compression of an ion beam

2. NTX and NDCX-1 experiments
   - Beam neutralization results
   - Drift compression results

3. Simultaneous beam compression
   - Plasma channel with a final focus solenoid
   - Axial plasma density
   - Fabrication of a new plasma source
   - Design and fabrication of a radial plasma probe
   - Outcome of initial beam compression experiments

4. Summary
Ion beam applications

Intense ion beams of low kinetic energy offer an attractive approach to heat dense matter uniformly to extreme conditions.

1. Ion beam energy deposition \( \left( \frac{dE}{dx} \right) \) is nearly classical and shock-free.

2. Ion beams have the ability to heat target materials
   - conductors
   - insulators
   - foams, and powder
   with **high repetition** rates.
High energy density physics and heavy-ion-driven inertial fusion require the simultaneous transverse and longitudinal beam compression of an ion beam to achieve high intensities.
Small beam spot sizes and short pulse lengths are achievable with beam neutralization and longitudinal compression.

The beam travels along the $z$ axis with velocity $v_z$. Both types of compression are critical for achieving high intensities on target, since power per unit area is $\sim \frac{1}{r_b^2}$ and $\sim \frac{1}{t_p}$.
In neutralization experiment, defocusing nature of the electric self-fields of space-charge-dominated ion beams is reduced by space-charge neutralizing using plasma.

Electrons from a plasma are entrained by the beam and neutralize the space charge such that the pulse focuses on the target in a nearly ballistic manner to a small spot, limited only by longitudinal and transverse emittance. Typically,

\[ \frac{n_p}{Z n_b} \geq 1 \]
Beam space charge neutralization for radial compression

Neutralization and beam transport in plasma

1. Key scaling parameter for beam transport is the perveance (ratio of the beam space charge to kinetic energy).

\[ k = \frac{2l_b}{l_A B_i^2}, \quad l_A = \frac{\beta_i \gamma_i m_i c^3}{eZ}, \]

where, \( l_A \): Alfven current and \( l_B \): Beam current

2. Provided \( \frac{km_i}{km_e} \geq 1 \), electrons from this plasma can accelerate in the beam space-charge potential to the beam velocity. This condition limits the minimum residual space charge potential to \( \frac{1}{2} m_e v_i^2 \)
Drift compression of an ion beam

Concept of longitudinal beam compression

The axial compression is achieved with an induction bunching module (IBM)

Compressed beam bunch has higher space charge density than uncompressed beam bunch section. This higher space charge can contribute to beam blow-up before reaching the target or diagnostic location. Therefore, the compressed beam must be neutralized with an appropriate plasma density.
IBM produces a head-to-tail velocity ramp that longitudinally compress the beam for a short pulse length.

If the compressed pulse length is dominated by the longitudinal beam temperature $T_L$, the compressed pulse length is

$$t_f = \frac{d_L}{v_z^2} \sqrt{\frac{2kT_L}{m_i}}$$

where, $v_z$, $d_L$, $m_i$ and $k$ are the mean longitudinal beam velocity, drift length, ion mass, and Boltzmann constant, respectively. $T_L$ is an effective temperature including the effects of errors in the tilt waveform.
Beam neutralization results

Sketch of Neutralized Transport Experiment (NTX) to demonstrate radial compression of a beam
Neutralized transport experiment (NTX)

NTX used a higher current (∼25 mA) and higher energy (250-350 keV) K⁺ beam. The beam perveance (∼10⁻³) was effectively neutralized with RF and cathodic-arc plasma sources.
Applications and techniques of ion beam focusing
NTX and NDCX-1 experiments
Simultaneous beam compression
Summary

Beam neutralization results

Typical NTX Ion Beam Characterization

K\(^+\) source

Optimization of source profile

\[ \varepsilon_n = 0.050 \, \text{π-mm-mr (measured)} \]
from source temperature alone \( \varepsilon_n = 0.030 \, \text{π-mm-mr} \)

254 keV, 24 mA
Beam neutralization results

**Beam current density increased** \( > 100 \times \) for radial beam compression (NTX alone)

**Results**

254 keV, 24 mA, \( K = 6 \times 10^{-4} \)

Vacuum transport beam diameter: 4.5 cm

Neutralized beam diameter: 2.2 mm

Sensitivity Study of Neutralization

100% Current Transmission Through Neutralized Drift Section (24 mA Beam)

Beam head to tail variation
Uniform at the flat top

Neutralized drift compression experiment (NDCX-1)

NDCX uses many components of the former NTX. The axial compression is achieved with an induction-bunching module (IBM) inserted after the matching section.

Plasma column consists of a 1m long solenoid (~1kG & 7.6 cm diameter).

Plasma density ~ $5 \times 10^{10}$ cm$^{-3}$

2 pulsed Al cathodic arc sources are equipped with a 45° open-architecture
Drift compression results

Three Fast (ns) diagnostic systems deployed for NDCX

- Phototube (<1 ns)
- Faraday Cup (~3 ns)
- Optical imaging (1 ns)
Drift compression results

Beam bunching observed as induction bunching module (IBM) turned on.

The degree of bunching, as well as the pulse shape, is correlated with the voltage waveform.

Induction module voltage waveforms produced by varying the timing of the modulators.
Drift compression results

**First time $\geq 50$ times longitudinal beam compression measured**

IBM operated at $\pm 80$ kV, a $\pm 12.5\%$ velocity ramp is imparted to 150–200 ns subset of the several $\mu$s beam pulse.

Initial NTX and NDCX-1 experiments demonstrated that sufficient plasma is essential for radial and longitudinal compression.

1. The beam intensity, immediately after the longitudinal compression, is significantly higher than the uncompressed beam, illustrating that a higher plasma density is required to maintain a small beam spot size.

2. Also to focus the intense beam to a target, a final focus solenoid is suggested.
A space charge neutralizing plasma channel for simultaneous beam drift compression

1. FEPS injects plasma in the radial direction.
2. CAPS provides in axis plasma.
3. A FFS provides beam focusing field near the target.
A strong final focus magnet increases beam density near the target plane.

- 8T FFS magnet with 837-µs pulses and a peak current of 21.7 kA.
- 1.5 kJ/pulse, which necessitates active cooling.
Axial plasma density

Measurement of axial plasma density using single Langmuir probe
Axial plasma density

The two-FCAPS provides a plasma density of $\leq 10^{12}\text{cm}^{-3}$ when the FFS was powered.

Maximum plasma density $\leq 2.8 \times 10^{12}$ cm$^{-3}$ between the gap of the FFS and the target plane, where the plasma electron density was lower due to the FFS field and Filter field.
A higher plasma density may further decrease the beam spot size.

Expected Beam peak density:
- Compressed: $\sim 1.5 \times 10^{12} \text{cm}^{-3}$
- Non-compressed: $\sim 1.8 \times 10^{8} \text{cm}^{-3}$

Expected beam deposition energy $\geq 18 \text{mJ/cm}^2$ (60 fold and 1.3 mm edge radius, with 300 keV, 26 mA, 15mm edge radius input beam)
FCAPS system with bent filter replaced by a CAPS system with straight filter for axial higher density plasma
The new four-CAP provides $\sim 30$ times greater plasma than the two-FCAPS with bent filters.

- The calculated average velocities were considered for the FFS on or off, and for various axial locations. These calculated velocities were well matched with some measured velocities, measured using TOF.
### Design and fabrication of a radial plasma probe

**An array of 37 collectors to measure radial and axial plasma distribution**

<table>
<thead>
<tr>
<th>Name</th>
<th>Number</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of collector</td>
<td>37</td>
</tr>
<tr>
<td>Collector material</td>
<td>Copper</td>
</tr>
<tr>
<td>Collector wire size</td>
<td>24 Gauge</td>
</tr>
<tr>
<td></td>
<td>(1.6mm diameter)</td>
</tr>
<tr>
<td>A collector area</td>
<td>2.01 mm²</td>
</tr>
<tr>
<td>Collector shielding</td>
<td>Alumina tube</td>
</tr>
<tr>
<td>Alumina tube (each)</td>
<td></td>
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<tr>
<td>Outer diameter</td>
<td>2.46 mm</td>
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<tr>
<td>Inner diameter</td>
<td>1.64 mm</td>
</tr>
<tr>
<td>Length</td>
<td>38.1 mm</td>
</tr>
<tr>
<td>Distance between wires</td>
<td>2.46 mm (Center to center)</td>
</tr>
<tr>
<td>Total diameter of the probe (37 collectors)</td>
<td>1.73 cm</td>
</tr>
<tr>
<td>Total probe area</td>
<td>2.35 cm²</td>
</tr>
</tbody>
</table>

- Copper wire
- Alumina tube
- 1.73 cm
The precise 23.5 cm z-motion position was established using a fine position monitor.

Circuit diagram for one collector, biased to 70 V for operation in the ion saturation mode.
Plasma forms a thin column of diameter $\sim 5$ mm along the 8T solenoid axis.

- Particles entering the FFS with minimum angles passed through the axis to the downstream end of the FFS with their axial velocity, $v_{0\parallel} = v_0 \cos \theta_0$.
- Those particles with higher incident angles ($v_{0\parallel} = v_0 \cos \theta_0$) to the beam axis, reflected back from where the adjacent field lines were dense and developed a magnetic mirror.
Design and fabrication of a radial plasma probe

Transverse and axial plasma distribution (surface plot) using the 37 collectors

The electrons mobility enhances the plasma diffusion.

3-D electrostatic PIC simulation shows qualitative agreement with experiment

1. With velocity of 3 cm/μs, temperature of 7 eV.
2. The density rapidly falls off, off-axis inside the solenoid.
3. The peak density is ~10x smaller than experiment is due to a smaller injected plasma density out of the FCAPS.
The four-CAPS provides axial plasma of $\geq 10^{13}$ cm$^{-3}$ when the FFS was powered.

- The plasma (electrons and ions) drift into the bore using the diffusive $B$ magnetic field map and the CAPS $B$ field.
Design and fabrication of a radial plasma probe

Integration of the plasma channel with beam drift compression experiments
A profile of $\leq 2.5$ mm (at FWHM) was measured as operated for simultaneous radial and longitudinal compression.
Physics results presented in this talk have established a basic background for an ongoing 11M$ NDCX II ARRA project for target heating experiment at LBNL.
Outcome of initial beam compression experiments

An artistic view of target heating

LITHIUM ION BEAM BUNCH

Final Beam Energy:  > 3 MeV
Final Spot diameter :  ~ 1 mm
Final bunch length :  ~ 1 cm or ~ 1 ns
Total Charge Delivered:  > 20 nC

μm foil or foam TARGET

30 J/cm² isochoric heating will raise aluminum temperature to ~ 1 eV

Exiting beam available for dE/dx measurement
Summary

1. Successfully accomplished > 100x radial compression.
2. Successfully accomplished >50x longitudinal compression.
3. Developed a radial plasma diagnostic in parallel of three other diagnostics.
4. Simultaneous radial and longitudinal compression system is being exploring the warm dense matter phenomenon at present.
5. The presented experimental results established confidence on many high intense beam experiments as NDCX-II ARRA project.