Extreme Compression of Heavy-Ion Beam Pulses: Experiments and Modeling

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...and the rest of the HIFS-VNL Team...
Outline

0) MOTIVATION AND ISSUES
   a) Overview
   b) Plasma neutralization-assisted focusing of space-charge-dominated beams

1) LONGITUDINAL COMPRESSION: ACCELERATION GAP EFFECTS
   a) Finite-size gap and voltage waveform
   b) Non-zero initial beam temperature (emittance)
   c) Initial pulse length $t_p$, intended fractional tilt $f$, and initial beam energy
   d) Comparison: theoretical models, particle-in-cell simulation, and experiment

2) TIME-DEPENDENT TRANSVERSE DEFOCUSING EFFECT OF THE ACCELERATION GAP
   a) Description of the effect
   b) The “over-focusing” technique for simultaneous transverse and longitudinal compression

3) SIMULTANEOUS FOCUSING USING A STRONG FINAL-FOCUS SOLENOID
   a) Focal plane aberration due to static magnetic field and beam velocity tilt
   b) Supersonic cathodic-arc plasma injection into the high-field region from the low-field end
   c) Collective excitations during the beam-plasma interaction for $n_b > n_p$
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Overview of a driver for Heavy Ion Fusion and High-Energy-Density Physics

Relevant research for many areas:

- Nonneutral plasma physics
  - Theoretical techniques, space-charge effects
- High-energy and nuclear physics
  - Accelerator physics and technology
- High-energy-density plasma physics
  - Warm-dense-matter studies
- Magnetic fusion plasma physics
  - Beam-plasma interaction, diagnostics
- Advanced nonlinear dynamics
  - Chaos, collective processes
- Advanced computing
  - PIC/hybrid approaches, parallel computation

Example parameters at target:

- 4 GeV beam energy, ~16 beams
- LONGITUDINAL COMPRESSION: ~10 kA / beam, 10 ns pulses
- TRANSVERSE COMPRESSION: few mm radius
Key scientific issues

- Development of high-current, compact ion sources and injectors
- Accelerate beams to large energies (HIF: GeV) at high intensities and currents (tens of kAs)
- **Transport intense beams and transversely focus to small spot size** (\(< 2\) mm)
- **Longitudinally focus (compress in time) to short pulse widths** (\(< 10\) ns)
- Optimize targets robust to beam aiming errors
- Develop attractive chamber concepts
HIF and HEDP: Many issues benefit from active research

Key scientific issues

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Key physics issues affecting high-intensity ion beam propagation

- Quality of injected beam
- Emittance growth
- Beam-plasma instabilities
- **Transport and focusing (transverse and longitudinal)**, and associated aberration
- **Beam charge and current neutralization effects**
- Ionization of beam and background gas
- Stray electron behavior
- Multiple beam effects
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Transverse focusing of intense ion beams via neutralization*

Neutralized Transport Experiment (NTX) at LBNL

**Externally injected plasma**

**Converging ion beam**

**Low pressure chamber**

**Target**

**Final focus magnet**

**RF Source: Volume plasma**

Transverse ion beam compression was a success on NTX

Source range:
- $E_0 \sim 250-400$ keV
- $I_0 \sim 10-80$ mA
- $r_b \sim 1-2$ cm
- $T_b \sim 0.2$ eV

Ion species: $K^+$

Background neutralizing plasma required to allow quiescent intense ion beam focusing above the space-charge limit
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Experiment

The upgrade of NTX is the Neutralized Drift Compression Experiment (NDCX).

**Issues to study:** fundamental limits of longitudinal compression, understand non-ideal experimental aspects, provide theory and simulation

**Primary component addition:**

**Single-gap** linear induction accelerator induces pulsed $E(t)$ along axis of beam to impose a head-to-tail axial *velocity tilt* on the passing ion beam

**Particle-in-cell simulations (LSP code):**
Used to model downstream end
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**Particle-in-cell simulations (LSP code):**
Used to model downstream end

**Figures of merit at the focal plane:**
Current compression ratio $I_b^{\text{max}}/I_0$
Full-width, half-maximum pulse length $t_{\text{fwhm}}$
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Voltage waveform and finite-size gap for longitudinal compression

Ideal waveform \((dV/dt < 0)\) depends on:

- Initial beam energy: \(E_0 = 400\) keV
- Initial pulse length: \(t_p = 300\) ns
- Intended fractional tilt: \(f = 0.5 = \Delta v/v_0\)

Resulting drift length: \(L_d = 78.7\) cm

Generally, excess beam used \((t_p > 300\) ns\)
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The actual \(\Delta z = 3\) cm acceleration gap on NDCX

**Effective** \(\Delta z_{\text{gap}} = 10\) cm

The transit time of a 400 keV K\(^+\) particle across the “3 cm” gap is about 75 ns.

In this coordinate system:
\[z = \{-30\ \text{cm}, +100\ \text{to} +250\ \text{cm}\}\]
Voltage waveform and finite-size gap for longitudinal compression

The Heavy Ion Fusion Science Virtual National Laboratory

Generally, excess beam used ($t_p > 300$ ns)

Particles sample too much of the $V(t)$ during their transit time across the gap. The integrated force over the gap is less than the intended amount to achieve the desired $f = 0.5$.

**Ideal waveform** (dV/dt < 0) depends on:

- Initial beam energy: $E_0 = 400$ keV
- Initial pulse length: $t_p = 300$ ns
- Intended fractional tilt: $f = 0.5 = \Delta v / v_0$

Resulting drift length: $L_d = 78.7$ cm

The actual $\Delta z = 3$ cm acceleration gap on NDCX

- Effective $\Delta z_{gap} \approx 10$ cm
- The transit time of a 400 keV $K^+$ particle across the “3 cm” gap is about 75 ns.

The extra voltage in the “realistic” waveform across the finite-size gap re-populates some of the head and tail of the velocity tilt with the excess beam.
Finite-size gap imparts velocity spread akin to temperature to beam.

Transverse and longitudinal phase space coupling effect within the gap: transit time and $V(t)$ cause an $+E_r(r,z,t)$ imbalance, and radial movement within gap implies the dependence of integrated $E_z$ on particle radius entering the gap.
Finite-size gap imparts velocity spread akin to temperature to beam

The initial $T_b = 0$ eV beam gains effective longitudinal temperature from the gap, which sets a finite upper bound to the compression due to associated chromatic aberration.

Transverse and longitudinal phase space coupling effect within the gap: transit time and $V(t)$ cause an $+E_r(r,z,t)$ imbalance, and radial movement within gap implies the dependence of integrated $E_z$ on particle radius entering the gap.
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Longitudinal compression demonstrates $\sqrt{T_b}$ dependence

Compression at focal plane for various initial $T_b$

- $T_b = 0.1$ eV
- $T_b = 0.2$ eV
- $T_b = 0.4$ eV
- $T_b = 0.8$ eV
- $T_b = 1.6$ eV

(e.g. $T_b = 0.2$ eV $\Rightarrow \varepsilon_n^{4\text{rms}} = 9.3 \times 10^{-3}$ cm-mrad)

Table 4.1: Longitudinal compression dependence on initial emittance for $E_0 = 400$ keV, $t_p = 300$ ns, and $f = 0.5$. The $T_b = 0$ eV case is included for reference.

<table>
<thead>
<tr>
<th>$T_b$ (PIC)</th>
<th>$I_{b\text{max}}/I_0$ (PIC)</th>
<th>$t_{\text{fwhm}}$ (PIC)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 eV</td>
<td>2650</td>
<td>0.035 ns</td>
</tr>
<tr>
<td>0.1 eV</td>
<td>430</td>
<td>0.51 ns</td>
</tr>
<tr>
<td>0.2 eV</td>
<td>320</td>
<td>0.70 ns</td>
</tr>
<tr>
<td>0.4 eV</td>
<td>230</td>
<td>1.01 ns</td>
</tr>
<tr>
<td>0.8 eV</td>
<td>160</td>
<td>1.40 ns</td>
</tr>
<tr>
<td>1.6 eV</td>
<td>115</td>
<td>2.05 ns</td>
</tr>
</tbody>
</table>

Reminder:
- $E_0 = 400$ keV
- $t_p = 300$ ns
- $f = 0.5$
- $L_d = 78.7$ cm
Longitudinal compression demonstrates \( \sqrt{T_b} \) dependence

Compression at focal plane for various initial \( T_b \)

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\( T_b = 1.6 \text{ eV} \)

(e.g. \( T_b = 0.2 \text{ eV} \) \( \rightarrow \varepsilon_{\text{rms}} = 9.3 \times 10^{-3} \text{ cm-mrad} \))

<table>
<thead>
<tr>
<th>( T_b ) (PIC)</th>
<th>( f^* ) ( T_b ) (PIC)</th>
<th>( f_{\text{shape}} ) (PIC)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 eV</td>
<td>2650</td>
<td>0.035 ns</td>
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Reminder:
\( E_0 = 400 \text{ keV} \)
\( t_p = 300 \text{ ns} \)
\( f = 0.5 \)
\( L_d = 78.7 \text{ cm} \)

Comparison: infinitely thin gap and 3 cm gap

The gap and “realistic” waveform add an effective \( \sim 45\% \) \( T_b \) increase to the initial \( T_b \) of the beam pulse, \textit{for these parameters}, due to the reduction of the achieved \( f^* \) from the intended value \( f \).

The geometrical constant [accounting for the acceleration gap and \( V(t) \) effects] depends on the gap geometry and \( V(t) \) compared to the pulse length and energy of the beam (as well as other beam parameters).
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Voltage waveform parameter variation in $t_p$ with fixed $f$ and $E_0$
Voltage waveform parameter variation in $t_p$ with fixed $f$ and $E_0$

The compression ratios level off for larger $t_p$ with growing $t_{\text{fwhm}}$ due to increasing aberration from the longer drift lengths.

Color-coded results (initial $T_b = 0.2$ eV) at longitudinal focus

The leveling-off effect grows linearly for $t_p \geq 300$ ns.

<table>
<thead>
<tr>
<th>$t_p$ (ns)</th>
<th>$I/I_0$</th>
<th>$t_{\text{fwhm}}$ (ns)</th>
<th>$L_d$ (cm)</th>
<th>$t_{\text{in}}$ (PIC)</th>
<th>$z_{\text{in}}$ (PIC)</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>0.5</td>
<td>26.2</td>
<td>468.3</td>
<td>+8.4</td>
<td></td>
</tr>
<tr>
<td>200</td>
<td>0.6</td>
<td>52.5</td>
<td>710.5</td>
<td>+33.5</td>
<td></td>
</tr>
<tr>
<td>300</td>
<td>0.7</td>
<td>78.7</td>
<td>959.0</td>
<td>+59.5</td>
<td></td>
</tr>
<tr>
<td>400</td>
<td>0.9</td>
<td>104.9</td>
<td>1208.5</td>
<td>+85.6</td>
<td></td>
</tr>
<tr>
<td>500</td>
<td>1.2</td>
<td>131.2</td>
<td>1457.5</td>
<td>+111.7</td>
<td></td>
</tr>
</tbody>
</table>
Voltage waveform parameter variation in $f$ with fixed $t_p$ and $E_0$

Larger tilts are generally desired for better compression, but are limited by the desired drift length to the focal plane, as well as voltage hold-off and transverse focusing aberration considerations.
Voltage waveform parameter variation in $f$ with fixed $t_p$ and $E_0$

Larger tilts are generally desired for better compression, but are limited by the desired drift length to the focal plane, as well as voltage hold-off and transverse focusing aberration considerations.

Table 4.3: Longitudinal compression dependence on intended fractional tilt $f$ for $E_0 = 400$ keV, $T_b = 0.2$ eV, and $t_p = 300$ ns.

<table>
<thead>
<tr>
<th>$f$</th>
<th>$l_{\text{max}}/l_0$</th>
<th>$t_{\text{focal}}$</th>
<th>$L_d$ [Eq. (4.20)]</th>
<th>$t^{l_{\infty}}$ (PIC)</th>
<th>$z^{l_{\infty}}$ (PIC)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.3</td>
<td>210</td>
<td>1.4 ns</td>
<td>136.8 cm</td>
<td>1359.8 ns</td>
<td>+117.3 cm</td>
</tr>
<tr>
<td>0.4</td>
<td>260</td>
<td>1.0 ns</td>
<td>100.7 cm</td>
<td>1109.0 ns</td>
<td>+81.5 cm</td>
</tr>
<tr>
<td>0.5</td>
<td>320</td>
<td>0.7 ns</td>
<td>78.7 cm</td>
<td>959.0 ns</td>
<td>+59.5 cm</td>
</tr>
<tr>
<td>0.6</td>
<td>360</td>
<td>0.6 ns</td>
<td>63.7 cm</td>
<td>859.1 ns</td>
<td>+44.5 cm</td>
</tr>
<tr>
<td>0.7</td>
<td>380</td>
<td>0.5 ns</td>
<td>52.6 cm</td>
<td>787.8 ns</td>
<td>+33.5 cm</td>
</tr>
</tbody>
</table>

$\sim f^{-0.82}$ for $f \leq 0.5$, $\sim f^{-1.23}$

$\sim f^{-0.51}$ for $f \geq 0.5$
Small (± 2.5 - 5%) constant \( E_0 \) shifts cause optimal focal plane degradation.

Beam energy accuracy in laboratory known to be approximately \( \leq \pm 5\% \).
Small (± 2.5 - 5%) constant E₀ shifts cause optimal focal plane degradation. The slope of the V(t) is only ideal for one particular E₀, and results in optimum compression only at one particular axial location. Color-coded results at the respective focal planes.

Scan in E₀ with fixed V(t) and fixed diagnostic does not unambiguously determine optimum compression for a given V(t). Beam energy accuracy in laboratory known to be approximately ≤ ±5%.

<table>
<thead>
<tr>
<th>E₀</th>
<th>I₀nom/I₀</th>
<th>t_center</th>
<th>z_center (PIC)</th>
</tr>
</thead>
<tbody>
<tr>
<td>380 keV</td>
<td>180</td>
<td>0.9 ns</td>
<td>930.9 ns</td>
</tr>
<tr>
<td>390 keV</td>
<td>250</td>
<td>0.8 ns</td>
<td>944.1 ns</td>
</tr>
<tr>
<td>400 keV</td>
<td>320</td>
<td>0.7 ns</td>
<td>959.0 ns</td>
</tr>
<tr>
<td>410 keV</td>
<td>260</td>
<td>0.7 ns</td>
<td>971.8 ns</td>
</tr>
<tr>
<td>420 keV</td>
<td>230</td>
<td>0.6 ns</td>
<td>983.7 ns</td>
</tr>
</tbody>
</table>

20-40% decrease from optimal.
Small (± 2%) temporal $E_0(t)$ linear drifts cause optimal focal plane degradation

Longitudinal compression at respective focal planes

$E_0 = 400$ keV
$E_0(t) = 400-408$ keV (+2%)
$E_0(t) = 400-392$ keV (-2%)

$E_0$ may drift by ±1-2% over $t_p = 300$ ns window in experiments

Unintentional experimental beam energy inaccuracies, whether constant in time or not, will not reach the optimum compression compared to the desired $E_0$ for the specific $V(t)$ under consideration.

Table 4.5: Longitudinal compression dependence on initial linear increase or decrease in $E_0(t)$ by ±2% with $T_b = 0.2$ eV for $E_0 = 400$ keV, $t_p = 300$ ns, and $f = 0.5$.

<table>
<thead>
<tr>
<th>$E_0$</th>
<th>$I_{p,\text{max}}/I_0$</th>
<th>$t_{f,\text{ehmm}}/\text{ns}$</th>
<th>$t_{f,\text{cc}}/\text{(PIC)}$</th>
<th>$z_{f,\text{cc}}/\text{(PIC)}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>400 – 392 keV</td>
<td>250</td>
<td>0.8 ns</td>
<td>961.5 ns</td>
<td>+59.3 cm</td>
</tr>
<tr>
<td>400 keV</td>
<td>320</td>
<td>0.7 ns</td>
<td>959.0 ns</td>
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22% decrease from optimal
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Excellent comparison to neutralized drift compression experiments

Initial $I_0 \sim 20$ mA, $r_b \sim 2$ cm, $T_b \sim 0.2$ eV

~2.4-m drift length for $E_0 = 320$ keV, with $f^*_{\text{exp}} \sim 0.15$
Excellent comparison to neutralized drift compression experiments

Initial $I_0 \sim 20$ mA, $r_b \sim 2$ cm, $T_b \sim 0.2$ eV

$\sim 2.4$-m drift length for $E_0 = 320$ keV, with $t_{\text{fwhm}} \sim 0.15$

Experiment (fast Faraday cup) *
LSP (PIC) Simulation *
Kinetic model (no gap effects) **
Hybrid fluid-Vlasov model***

$t_{\text{fwhm}} \sim 4.5$ ns

The new goal is to simultaneously focus such an axially compressed pulse to a coincident focal plane with a sub-mm radius for warm-dense-matter experiments.

Initial \( I_0 \sim 20 \text{ mA}, r_b \sim 2 \text{ cm}, T_b \sim 0.2 \text{ eV} \)

\[ \sim 2.4\text{-m drift length for } E_0 = 320 \text{ keV}, \text{ with } f_*^{\text{exp}} \sim 0.15 \]

Experiment (fast Faraday cup) *  
LSP (PIC) Simulation *  
Kinetic model (no gap effects) **  
Hybrid fluid-Vlasov model***

\[ t_{\text{fwhm}} \sim 4.5 \text{ ns} \]

However, \( r_b^{\text{foc}} \sim 1 \text{ cm} \)  
(reason explained next)  
\[ J_z^{\text{foc}}/J_{z0} \sim 240 \times \]

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   a) Overview
   b) Plasma neutralization-assisted focusing of space-charge-dominated beams

1) LONGITUDINAL COMPRESSION: ACCELERATION GAP EFFECTS
   a) Finite-size gap and voltage waveform
   b) Non-zero initial beam temperature (emittance)
   c) Initial pulse length $t_p$, intended fractional tilt $f$, and initial beam energy
   d) Comparison: theoretical models, particle-in-cell simulation, and experiment

2) TIME-DEPENDENT TRANSVERSE DEFOCUSING EFFECT OF THE ACCELERATION GAP
   a) Description of the effect
   b) The “over-focusing” technique for simultaneous transverse and longitudinal compression

3) SIMULTANEOUS FOCUSING USING A STRONG FINAL-FOCUS SOLENOID
   a) Focal plane aberration due to static magnetic field and beam velocity tilt
   b) Supersonic cathodic-arc plasma injection into the high-field region from the low-field end
   c) Collective excitations during the beam-plasma interaction for $n_b > n_p$
The acceleration gap causes a time-dependent transverse defocusing effect. The defocusing effect occurs during the longitudinally compressing \([dV(t)/dt < 0]\) portion of the waveform.

All particles participating in the axial velocity tilt receive a net divergence to their trajectories.
Transverse defocusing effect witnessed in simulations and experiments

Simulation

Initial parameters:
- \( E_0 = 300 \text{ keV K}^+ \)
- \( r_b = 2 \text{ cm} \)
- \( I_0 = 18 \text{ mA} \)
- \( T_b = 0.2 \text{ eV} \)
- \( \Delta \theta_r = -15.4 \text{ mrad} \)
- \( t_p = 700 \text{ ns} \)

Axial compression:
- \( f^*_{\text{exp}} \sim 0.1 \)
- \( I_b^{\text{max}}/I_0 \sim 67 \times \)
- \( t_{fwhm} \sim 1.7 \text{ ns} \)
- \( r_b^{\text{foc}} \sim 2 \text{ cm (flat-top)} \)
- \( z^{\text{foc}} = +95 \text{ cm (L_d} \sim 1.15 \text{ m)} \)

Phase space plots at \( t = 1000 \text{ ns} \):
- \( \{z, r\} \)
- \( \{z, v_r\} \)
- \( \{z, v_z\} \)
Transverse defocusing effect witnessed in simulations and experiments

Simulation

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- \( z^{\text{foc}} = +95 \text{ cm (} L_d \approx 1.15 \text{ m)} \)

Large spot sizes unusable for target heating experiments since \( J_z \approx r_b(t)^{-2} \)

Experiment

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   c) Collective excitations during the beam-plasma interaction for $n_b > n_p$
The simplest compensation method is to transversely “over-focus” the beam.

Simulation
Beam density isocontours

Regular focus case:
\[ n_b^{\text{foc}} \sim 1.4 \times 10^9 \text{ cm}^{-3}, \ r_b^{\text{foc}} \sim 2 \text{ cm} \]

Over-focused case:
\[ n_b^{\text{foc}} \sim 2.3 \times 10^{11} \text{ cm}^{-3}, \ r_b^{\text{foc}} \sim 0.125 \text{ cm} \]

Over-focusing required to recover sufficient main pulse contrast and achieve desired \( r_b^{\text{foc}(t)} \)
The simplest compensation method is to transversely “over-focus” the beam.

\[ \Delta \theta_r = -15.4 \text{ mrad} \]
\[ \Delta \theta_r = -32.3 \text{ mrad} \]

**Simulation**

Beam density isocontours

**Regular focus case:**
- \( n_b^{\text{foc}} \sim 1.4 \times 10^9 \text{ cm}^{-3} \), \( r_b^{\text{foc}} \sim 2 \text{ cm} \)

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**Experiment**

Poster tomorrow: J. E. Coleman [ THPAS004 ]

2 rms radius
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A strong final-focus solenoid can achieve better simultaneous focusing. A final-focus solenoid transversely re-focuses the longitudinally compressing beam, controls the transverse focal length, and reduces the amount of $n_p$ needed upstream.

Here, $B_z = 150 \text{ kG} (~140 \text{ kG at focus}), l_{\text{sol}} = 20 \text{ cm}, r_{\text{sol}} = 3.8 \text{ cm}$

Amount of transverse compression sensitively depends on strength and positioning of solenoid.
A strong final-focus solenoid can achieve better simultaneous focusing

A final-focus solenoid transversely re-focuses the longitudinally compressing beam, controls the transverse focal length, and reduces the amount of \( n_p \) needed upstream.

Here, \( B_z = 150 \) kG (~140 kG at focus), \( l_{sol} = 20 \) cm, \( r_{sol} = 3.8 \) cm

Amount of transverse compression sensitively depends on strength and positioning of solenoid

An axial velocity tilt contributes to focusing aberration within a final-focus solenoid

Lower-energy head nominally focuses earlier in space and time
Higher-energy tail nominally focuses later in space and time

Aberration depends on radius:
beam particles entering the solenoid with same \( z \) (and \( E \)) but larger \( r \) acquire more \(-v_\theta\) and will not focus at same location

\[-F_\theta = +q \left[(+v_z) \times (-B_r[r,z])\right] = -m_i \left(\frac{dv}{dt}\right)_\theta\]
\[-F_r = +q \left[(-v_\theta) \times (+B_z[r,z])\right] = -m_i \left(\frac{dv}{dt}\right)_r\]
Aberration at simultaneous focal plane depends on beam velocity distribution

Ideal longitudinal compression across an infinitely thin gap

Consider three cases of $J_z(t)$ and $r_b(t)$ entering the chosen static final-focus solenoid

1. $r_b$ and $J_z$ constant (for $r_b = 1 \& 2$ cm)

2. $r_b(t)$ linear increase from $r_b = 0.1$ to 1 & 2 cm over $t_p$, with $J_z(t) \sim r_b(t)^{-2}$ to maintain $I_0 = 80$ mA constant

3. $r_b(t)$ linear increase from $r_b = 0.1$ to 1 & 2 cm over $1^{st} t_p/2$, and linear decrease from $r_b = 1 \& 2$ to 0.1 cm over $2^{nd} t_p/2$, with $J_z(t) \sim r_b(t)^{-2}$ to maintain $I_0 = 80$ mA constant

Case #3: The most “realistic” scenario, due to transverse defocusing effect

Beam parameters:
- $E_0 = 400$ keV
- $t_p = 300$ ns
- $f = 0.5$
- $L_d = 78.7$ cm
- $I_0 = 80$ mA
- $T_b = 0.2$ eV
- $\Delta \theta_r = 0$ mrad
- Intended:
  - $I_{b\text{max}}/I_0 = 400$
  - $t_{\text{fwhm}} = 0.6$ ns
  - $z_{\text{foc}} = +58.25$ cm
Aberration at simultaneous focal plane depends on beam velocity distribution

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3. $r_b(t)$ linear increase from $r_b = 0.1$ to 1 & 2 cm over $1^{st} t_p/2$ and linear decrease from $r_b = 1$ & 2 to 0.1 cm over $2^{nd} t_p/2$, with $J_z(t) \sim r_b(t)^2$ to maintain $I_0 = 80$ mA constant

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Intended:
- $I_b^{\text{max}}/I_0 = 400$
- $t_{\text{fwhm}} = 0.6$ ns
- $z^{\text{foc}} = +58.25$ cm

Can reduce aberration by allowing faster particles (arriving later) to have larger $r_b$ entering the solenoid

Slower head particles: desire weaker $-B_r$ to focus later $t$ / longer $z$
Faster tail particles: desire stronger $-B_r$ to focus earlier $t$ / shorter $z$

Rationale for Case #2: (expecting it to minimize aberration)

$-B_r(r) \sim r^1$ for most $r < r^{\text{sol}}$ and $v_z$ tilt approx. linear

↑ yes
Focusing improved by factors of 2 to 5 compared to constant $r_b$ cases

The defocusing effect provides a beneficial* $r_b(t)$ for simultaneous focusing using final-focus solenoids relative to constant $r_b$ cases.

Nominal longitudinal compression recovered.
~ 8 GW cm$^{-2}$ on-axis peak, and total $J_z$ compression > $10^6$

Table 6.2: Compression dependence on initial $r_b(t)$ profile using a 150 kG solenoid.

<table>
<thead>
<tr>
<th>Initial $r_b(t)$</th>
<th>$I_b^{max}/I_0$</th>
<th>$t_{fwhm}$</th>
<th>$E_{peak}$</th>
<th>$r_b^{loc} (1/e)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>2 cm, constant</td>
<td>100</td>
<td>2.7 ns</td>
<td>1.1 J cm$^{-2}$</td>
<td>0.011 cm</td>
</tr>
<tr>
<td>1 cm, constant</td>
<td>310</td>
<td>0.8 ns</td>
<td>2.3 J cm$^{-2}$</td>
<td>0.011 cm</td>
</tr>
<tr>
<td>2 cm, triangular</td>
<td>275</td>
<td>0.8 ns</td>
<td>3.8 J cm$^{-2}$</td>
<td>0.010 cm</td>
</tr>
<tr>
<td>1 cm, triangular</td>
<td>375</td>
<td>0.7 ns</td>
<td>5.3 J cm$^{-2}$</td>
<td>0.010 cm</td>
</tr>
<tr>
<td>2 cm, linear increase</td>
<td>290</td>
<td>1.0 ns</td>
<td>5.0 J cm$^{-2}$</td>
<td>0.010 cm</td>
</tr>
<tr>
<td>1 cm, linear increase</td>
<td>400</td>
<td>0.6 ns</td>
<td>7.7 J cm$^{-2}$</td>
<td>0.008 cm</td>
</tr>
</tbody>
</table>

* indicates: Cumulative energy deposition profiles
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Can supersonic cathodic-arc $Al^+$ plasma be injected into the high-field region?

**Variable solenoid strength:**

- $B_y \sim 2$ kG (guide field for creating plasma column)
- $B_y \sim 30-150$ kG for transverse final-focus

Does the magnetic mirroring effect prevent the plasma flow?
Can supersonic cathodic-arc $A^+\text{I}$ plasma be injected into the high-field region?

Variable solenoid strength:
$B_y \sim 2 \text{ kG}$ (guide field for creating plasma column)

$B_y \sim 30-150 \text{ kG}$ for transverse final-focus

Does the magnetic mirroring effect prevent the plasma flow?
Separation distance (magnetic topology) affects plasma-fill dynamics

Injection into **53 kG** final-focus solenoid with filter coils operating at 0.45 kG.

- \( v_y^i \sim 1.44 \text{ cm/µs} \)  
  \[ \sim 29 \text{ eV, measured} \]

- \( T_i \sim 3 \text{ eV and } T_e \sim 10 \text{ eV} \)  
  is an ion mach speed \( M_i \sim 1.7 \)

\( J_{p0} \sim 2 \text{ A cm}^{-2} \) in each 
filter coil \( \sim 10^{13} \text{ cm}^{-3} \) peak

Plasma density \( \{y,z\} \) isocontours through \( x = 0 \) slices
2D supersonic plasma injection into a 40 kG final-focus solenoid

Plasma injection occurs at z~18 cm in upstream (-z) direction

Assumption (from reduced dimensionality):
\[ J_z^i \sim 0.3, 0.6, 1.2, 2.4 \text{ A cm}^{-2} \text{ with constant} \]
\[ n_p \sim 10^{12} \text{ cm}^{-3} \text{ at injection plane} \]

4 cases:
\[ v_z^i = -1.5, -3, -6, -12 \text{ cm/µs} \]
\[ T_i \sim 1 \text{ eV and } T_e \sim 5 \text{ eV} \]
\[ (M_i \sim 2.7, 5.5, 11, 22) \]

Coordinate switched back: -y direction now +z direction, again
2D supersonic plasma injection into a 40 kG final-focus solenoid

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Plasma density isocontours

Counter-propagating streams: magnetic mirroring!
Measured: high-density plasma penetration into $B_z = 40-50$ kG solenoids

Compression of plasma measured
Measured: high-density plasma penetration into $B_z = 40-50$ kG solenoids

Poster tomorrow: P. K. Roy [THPAS006]

Compression of plasma measured

Preliminary experiment and simulation comparison
Measured: high-density plasma penetration into $B_z = 40-50$ kG solenoids

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Compression of plasma measured

Preliminary experiment and simulation comparison

$n_p$ isocontours in presence of final-focus solenoid
Measured: high-density plasma penetration into $B_z = 40-50$ kG solenoids

Poster tomorrow: P. K. Roy [THPAS006]

Preliminary experiment and simulation comparison

Simulation, in presence of simulated “realistic” plasma profiles (left)

Experiment ($B_z \sim 50$ kG)

Preliminary simultaneous compression comparison

$n_p$ isocontours in presence of final-focus solenoid

FEPS electron density

(main drift length plasma)

CAPS electron density

(supersonic plasma injection for focal plane)
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Peak energy deposition depends on plasma density (esp. near focal plane)

PIC simulations show the beam-plasma interaction during simultaneous compression in cases with $n_b < n_p$ and $n_b > n_p$ in a 150 kG solenoid.
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Higher \( n_p \)'s are required in the presence of a strong \( \mathbf{B} \) field \( (c/\omega_{pe} > \rho_{Le}) \). The \( L_b \) can decrease to \( O(r_b) \) at focus [and \( O(c/\omega_{pe}) \)] so that charge neutralization is harder to provide for a given amount of plasma.
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Cumulative energy deposition profiles through the intended simultaneous focal plane
Charge and current quasi-neutrality lost when $n_b > n_p$

The $n_b$ can approach the $n_p$, especially near the focal plane, and the assumption of charge and current neutralization may become invalid, leading to large perturbations in the plasma and field properties.

Strong final-focus solenoid present here, cold background carbon plasma modeled.
Charge and current quasi-neutrality lost when $n_b > n_p$

The $n_b$ can approach the $n_p$, especially near the focal plane, and the assumption of charge and current neutralization may become invalid, leading to large perturbations in the plasma and field properties.

Strong final-focus solenoid present here, cold background carbon plasma modeled

As the beam tries to focus with $n_b > n_p$,
(1) LEFT: the $\rho$ and $J$ will become increasingly unneutralized,
(2) BOTTOM: the defocusing self-fields of the beam will grow, and
(3) RIGHT: the plasma will locally heat.
Plasma responds to beam’s self-fields with collective excitations*

Once the beam stagnates, the plasma supports strong electrostatic and electromagnetic excitations, due to large perturbations created during stagnation of the ion beam.

Plasma responds to beam’s self-fields with collective excitations

Once the beam stagnates, the plasma supports strong electrostatic and electromagnetic excitations, due to large perturbations created during stagnation of the ion beam.

**Observed frequency:** $\omega \sim 8 \times 10^8$ rad s$^{-1}$

Range: $[\Omega_{ci} < \omega_{pi} < \omega << \omega_{pe} < \Omega_{ce}]$

Carbon plasma: $m_e / m_i \sim 4.5 \times 10^{-5}$

$k \perp B_{sol}$ with $k_\perp \sim 6.3 \times 10^3$ m$^{-1}$, with a small component satisfying $k_\parallel / k_\perp \sim 4 \times 10^{-3}$.

**Electrostatic lower hybrid oscillation:**

$$\omega^2 \sim \frac{1}{2}(\omega_{pe}^2 + \Omega_{ce}^2) - \frac{1}{2}[(\omega_{pe}^2 + \Omega_{ce}^2)^2 - 4\omega_{pe}^2 \Omega_{ce}^2 \cos^2 \theta]^{1/2}$$

**Plasma densities t = +33 ns after stagnation**

$(n_{p0} \sim 10^{12}$ cm$^{-3}$)

**Snapsots at t = +55 ns after stagnation**

- **Electric energy near focus**

---

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Summary and conclusions

1. In order to achieve high intensities on target with space-charge-dominated beams, plasma neutralization-assisted focusing is required.

2. Longitudinal bunch compression in the laboratory is constrained by acceleration gap size, voltage waveform shape and accuracy, beam temperature, initial pulse length, intended fractional tilt, and energy accuracy for the specified waveform. Excellent agreement is found between theory, simulations, and recent experimental measurements.
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3. The “over-focusing” technique may be used to recover mm spot sizes by offsetting the time-dependent transverse defocusing effect, which is an inherent side-effect of the longitudinal focusing process.

4. Simulations show current density compression by factors from $10^3$ to over $10^6$, depending on the strength and focal length of the focusing elements. Final-focus solenoids can be used for extreme simultaneous compression, and high-density supersonic plasma has been simulated and measured to partially penetrate strong solenoids for beam neutralization purposes.
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5. Beam-plasma interaction simulations near the simultaneous focal plane illustrate compression stagnation for $n_{\text{beam}} > n_{\text{plasma}}$ and that the plasma supports collective excitations in the background plasma with an external $B$ field.
The **physics foundation** of simultaneous transverse and longitudinal focusing of intense charge bunches in the *Neutralized Drift Compression eXperiment (NDCX)* will provide key insights for the next-step heavy ion beam experiments. The ultimate goal is the development of heavy ion drivers for warm-dense-matter, high-energy-density, and heavy ion fusion applications.