Manipulating Ion Beams for High Energy Density Physics Studies

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Not pictured:
Introduction

• High Energy Density (HED) and Warm Dense Matter (WDM)
• Why Ion Beams?
• Manipulating Ion Beams for HEDP
  – Stage 1: Neutralized transport and focus (NTX)
  – Stage 2: Neutralized drift compression (NDCX-I)
  – Stage 3: Add acceleration schedule (NDCX-II)
  – Stage 4: Pulse shaping and shock timing (IB-HEDPX)
Interesting phenomena at

\[ 0.01 \, \rho_{\text{solid}} < \rho < 1.0 \, \rho_{\text{solid}} \]

and

\[ 0.1 \, \text{eV} < kT < 10 \, \text{eV} \]

**Unknown properties:**

- EOS \((p(\rho,T), U(\rho,T))\),
- Liquid-vapor boundary,
- Latent heat of vaporization,
- Evaporation rate,
- Surface tension,
- Work function,
- Electrical conductivity,
- \(dE/dx\) for hot targets

**Phenomena:**

- Metal-insulator transitions,
- Phase transitions,
- Plasma composition (ion-ion plasmas)
What’s so interesting about ions?

- Foils heated by hard x-rays
  - XFEL heating -> small energy/volumes (~1µm radius, ~0.1µm thickness)
  - May limit diagnostic accuracy. Poor coupling to lower Z.

- Supersonically heated foams or low Z material (thermal x-rays)
  - MJ of soft x-rays available on Z machine but limited number of shots.

- Shock compressed and heated thin foils
  - Lasers absorb at $\rho_{\text{critical}} \ll \rho_{\text{solid}}$
  - -> large density/pressure gradients

- Tailored Bragg-peak ion beams heating thin foils
  - Fast heating of a solid with penetrating ions
  - -> more volume/lower gradients
  - -> more accurate EOS
Ion Beams on Solids

Range matched to energy and species,
For < 1 MeV, can use lighter ions, e.g. He+,
For > 10 MeV, can use heavier ions, e.g. C+
Ion beam source limitations

• Multicusp Plasma, Pulsed ECR
  – High residual gas pressure – results in resonance charge exchange processes that increase energy spread
  – High ion temp (~2eV), high current density (100 mA/cm²)

• Contact Ionization/Aluminosilicate
  – Produces alkali metal ions (with low ionization potential) from a solid surface with high work function (e.g. tungsten) at high temperature.
  – Ion temperature \( \leq 0.3 \) eV; \( J \leq 20 \) mA/cm².
  – It had been used widely for ion thrusters in the early space-rocket program.

• Metal Vapor Vacuum Arc (MEVVA) sources
  – \( J \sim 10 \)’s mA/cm²
  – Low pressure, no residual gas
  – Mixed ion charge states
High current / High brightness beams

\[ B \equiv \left( \frac{2}{\pi^2} \right) \frac{I}{\varepsilon^2} \]

At the ion source:

\[ \varepsilon \equiv 2r \sqrt{\frac{kT_i}{mc^2}} \quad \text{thus} \quad B \propto \frac{J}{T} \]

• High brightness means either low emittance, or high current, or both.

• At the ion source, high brightness is obtained by either high current density, or low ion temperature, or both.

• Achieving both high current and high brightness together is difficult at the ion source.

• Typical ions are (K, Li, Na,) Bi, Pb, Hg, Cs, Xe, Rb, K, Ar, and Ne.
Neutralization boosts final intensity

• Achieving mm to sub-mm spot sizes with high perveance, high brightness beams requires
  – Excessively large stored energy in final focus solenoids, or
  – Removing repulsive space charge forces and using reasonably sized focusing magnets

• Neutralized plasma requirements
  – $Z_b N_e > N_b$
  – Denser electron plasma densities closer to target plane
Plasma Technology

- Ferroelectric plasma source (FEPS)
  - \( N_e \sim 10^{10} \text{/cm}^3 \)
- RF sources
  - \( N_e \sim 10^{11} \text{/cm}^3 \)
- Cathodic Arc plasma source (CAPS)
  - \( N_e \sim 10^{14} \text{/cm}^3 \)
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NTX: Neutralized Transport Experiment

NTX Parameters:
- 300kV, 25mA, 10µsec K+ beam
- 4 transport magnetic quadrupoles
- 2 MEVVA density $\sim 10^{10}-10^{11}$ cm$^{-3}$
- RF plasma density $\sim 10^{11}-10^{12}$ cm$^{-3}$

Introduce neutralizing plasmas in final focus beamline
Neutralized Transport Results

No neutralization  MEVVA only  MEVVA + RF plasma

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NDCX-I

Beam species  K$^+$
Beam current  25 - 40 mA
Beam energy  270 - 350 kV
Beam power  ~7-14 kW
Energy spread  ~0.2 keV
Pulse length  ~3-20 µsec

Injector solenoids  ~3T peak field
Final focus solenoid  8T peak field
Neutralizing plasmas
   FEPS  2 – 8 $10^{10}$ /cm$^3$
   4 MEVVA/FCAPS  0.9 - 6 $10^{13}$ /cm$^3$
Compressing Voltage Swing  ~150 keV / 500 nsec
Envelop Dynamics

Uncompressed Beam

Beam compresses ballistically in the drift compression stage.

Compressed pulse fluence at target plane

~200mJ/cm²

1.66mJ / 5ns

WARP
Drift Compression

- Simple ballistic compression of non-relativistic beams.
- Use a programmable pulser to impart time-dependent velocity ramp.
- Neutralize beam space charge to improve compression factor.
- Trade some volt-seconds to add acceleration.
NDCX-I Emittance limits

• Transverse \((\beta_z \sim 0.004)\)
  – Gun exit: \(4\varepsilon_{\text{nrms}} = 0.088 \pi \text{ mm mrad} \sim 2 (2\pi r_{\text{emitter}} v_{Tx})\)
  – IBM entrance: \(4\varepsilon_{\text{nrms}} = 0.088 \pi \text{ mm mrad}\)

• Longitudinal
  – \(T_z = (2.4 \pm 1.6) \times 10^{-2} \text{ eV} \text{ K+ beam itself}\)
  – \(T_z = (4.7 \pm 2.8) \times 10^{-2} \text{ eV} \text{ K+ beam after neutralization}\)

• Final Focus Optics
  \(~25\text{mrad convergence angle} – r_{\text{spot}} \sim 0.9\text{mm}\)

• Longitudinal Compression
  \(~100-200\text{ps for NDCX-I} \quad (L_{\text{drift}} \sim 1.5 – 3 \text{ m})\)
Target Chamber Beam Diagnostics

- Fast Faraday Cup \(\sim 1\text{ns} \) response time (ion transit time)

- Alumina scintillator with intensified, gated MCP camera
  – 10ns resolution, \(\sim 30\text{ns}\) minimum gate
Compressed Current

Peak current ~2.8A
Uncompressed ~30mA

FWHM ~3ns

Compression Ratio >90
Beam Intensity and Fluence

284kV beam energy, 25mA current, ~7kW beam power

Uncompressed

Beam intensity (kW/cm²)

Compressed

Beam fluence (J/m²)

~ 4 mJ
High Intensity Beam Profiling

Solid state scintillators incur damage and lose sensitivity with every shot – nonlinear in intensity

Gas phase Beam Intensity Monitor
Observe beam excited gas lines, correlate to beam distribution

Tungsten foil calorimeter –
3µm thick foil responds to beam peak intensity –
radiated intensity $\sim \sigma T^{4+}$
Calibrating the calorimeter

Merging of beam and target diagnostics

Temperature-dependent density and specific heat capacity

Melting Point

Temperature (K), Beam Flux (kW/cm²)

BEAM PROFILE

Time (us)

EH21JAN2010
Time-dependent gap defocusing is correlated to slice energy through the impressed IBM energy modulation.

This effect compounds chromatic aberrations in the final focus section.

\[ \Delta v_r \approx -\frac{qr}{2mv^2_{z0}} \frac{dV_{gap}(t)}{dt} \]
Measurement of chromatic variations

Beam intensity (kW/cm²)
- 50% radius 0.93mm
- 50% radius 2.4mm

Beam fluence (J/m²)
- 50% radius 0.93mm
- 50% radius 2.4mm

51.5ns gate

Uncompressed: ~33mJ/cm² compared with ~200mJ/cm²
Compressed
Fast Corrector

Time-dependent geometric and chromatic aberrations can in principal be corrected.

Transit-time effects complicate matters.
Longitudinal slippage with unipolar IBM waveform

\[ \Delta t_{\text{slip}}(\Delta z) = \left( \frac{1}{\langle v \rangle} - \frac{1}{v_0} \right) \Delta z \]

\[ \langle v \rangle = \frac{L_{\text{Drift}}}{\tau_p} \ln \left( \left[ 1 - (v_0 + \delta v) \frac{\tau_p}{L_{\text{Drift}}} \right]^{-1} \right) \]

\[ \delta v = v_{\text{head}} - v_0 \]

**IBM and Drift Design**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ion Energy</td>
<td>300000 eV</td>
</tr>
<tr>
<td>Initial Axial Velocity</td>
<td>1216819 m/s</td>
</tr>
<tr>
<td>Initial Pulse duration</td>
<td>4.00E-07 s</td>
</tr>
<tr>
<td>Pulse length</td>
<td>48.7 cm</td>
</tr>
<tr>
<td>Drift length</td>
<td>2.88 m</td>
</tr>
<tr>
<td>Avg. Voltage gain</td>
<td>95000 eV</td>
</tr>
<tr>
<td>Average beam voltage</td>
<td>395000 eV</td>
</tr>
<tr>
<td>Beam head velocity</td>
<td>1267417 m/s</td>
</tr>
<tr>
<td>Beam tail velocity</td>
<td>1538184 m/s</td>
</tr>
<tr>
<td>Average pulse velocity</td>
<td>1396252 m/s</td>
</tr>
<tr>
<td>Slippage rate, 1/&lt;v&gt; - 1/v0</td>
<td>-106 ns/m</td>
</tr>
<tr>
<td>Pulse slippage, Ld(1/&lt;v&gt; - 1/v0)</td>
<td>-304 nsec</td>
</tr>
<tr>
<td>Volt-seconds in pulse</td>
<td>37.97 kV-sec</td>
</tr>
<tr>
<td>Average voltage across gap</td>
<td>94.9 kV</td>
</tr>
</tbody>
</table>
Longitudinal compression vs. group delay

Compressed pulse arrives before uncompressed beam
A collective focusing scheme has been suggested by colleagues at PPPL.

Requires a final focus magnet field of ~100-300G rather than 8T!

Electrostatic focusing by trapped electron population.

The moving ion beam polarizes the magnetized plasma background, creating a strong radial self-electric field, which provides the enhanced self-focusing.
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NDCX-II (15 cells, 2.0MeV)
Accel/Decel Injector

Pervenance ‘multiplier’: Shortens pulse length to economize on induction module volt-seconds.
Compression and Acceleration

250 kV “flat-top” (measured waveform from test stand)

200 kV “ramp” (measured waveform from test stand)

“shaped” (to impose velocity tilt for initial compression)

“shaped” (to equalize beam energy after injection)

36 cell case
“Let It Bounce”™

Final bunch lengths can be obtained with minimum emittance growth by allowing the longitudinal phase space to evolve, with guidance.

- time for entire beam to cross a plane at fixed z
- time for entire beam to cross the finite-length gap
- time for a single particle at mean energy to cross the finite-length gap

36 cell case
# NDCX-II vs. NDCX-I

<table>
<thead>
<tr>
<th></th>
<th>NDCX-I (typical bunched beam)</th>
<th>NDCX-II 15-cell (r,z simulation)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ion species</td>
<td>K$^+$ (A=39)</td>
<td>Li$^+$ (A=7)</td>
</tr>
<tr>
<td>Total charge</td>
<td>15 nC</td>
<td>55 nC</td>
</tr>
<tr>
<td>Ion kinetic energy</td>
<td>0.3 MeV</td>
<td>2.0 MeV</td>
</tr>
<tr>
<td>Focal radius (containing 50% of beam)</td>
<td>1 mm</td>
<td>0.7 mm</td>
</tr>
<tr>
<td>Bunch duration (FWHM)</td>
<td>2 ns</td>
<td>0.45 ns</td>
</tr>
<tr>
<td>Peak current</td>
<td>3 A</td>
<td>17 A</td>
</tr>
<tr>
<td>Peak fluence (time integrated)</td>
<td>0.03 J/cm$^2$</td>
<td>17 J/cm$^2$</td>
</tr>
<tr>
<td>Fluence within a 0.1 mm diameter spot</td>
<td>0.03 J/cm$^2$ (50 ns window)</td>
<td>9.5 J/cm$^2$ (1 ns window)</td>
</tr>
<tr>
<td>Fluence within 50% focal radius and FWHM duration (k.e. x I x t / area)</td>
<td>0.014 J/cm$^2$</td>
<td>1.0 J/cm$^2$</td>
</tr>
</tbody>
</table>

NDCX-II estimates are from (r,z) Warp runs (no misalignments), and assume no timing or voltage jitter in acceleration pulses, no jitter in solenoid excitation, perfect neutralization, and a uniform non-depleted source; they also assume no fine energy correction (e.g., tuning the final tilt waveforms).
NDCX-II, The Movie
Project Path

N.1.6 Solenoid & Steering Coil Design
First-Article Solenoid
Solenoid Fabrication

N.4.3 Magnet Measurement Facility Design
Magnet Measurem. Facility Construction

N.1.3 Accelerator Cell Design
First-Article Cell Fabrication & Testing
Accelerator Cell Refurbishment

N.1.5 Diagnostic Cell Design
First Article Diagnostic Cell
Diagnostic Cells Fabrication

N.3 Drift Compression

N.1.2 Injector Design
Injector Fabrication
Injector Assembly

N.10.3 Cell Block Installation

Schedule Contingency

FY 09 FY 10 FY 11 FY 12

July 2009

First-Article Solenoid Package Built

First-Article Induction Cell Complete

Accelerator Block 1 Installed

Accelerator Installed

Project Complete
Prototype hardware components are tested for QA

- Thyratron switch chassis
- Blumlein
- Spark Gap
- Charging transformer
- Charging supplies and trigger generators
- Cell
- Oil-filled transmission line
- Shaping network
- Test stand in bldg 58
• Conceptual device to attain $\sim 10\text{eV}/1\text{Mbar}$ conditions in planar heated targets.
• Extend NDCX-II to 50 ATA cells, $\sim 10$ MeV acceleration
• Short pulses (100-200ps)
• Pulse shaping and shock timing
  – Can study hydrodynamic coupling and shock physics.
Summary

• Beam manipulations are crucial elements in ion beam drivers for HEDP studies.
• These manipulations are only possible due to access to high density, large volume, cool \((T_e \sim \text{eV's})\) plasma sources.
• NDCX-II will significantly expand our reach into WDM and HEDP studies.
• Complex beam dynamics will play an ever increasing role in providing usable beam fluence.
Back up slides
Beam intensity requirements

• Source brightness (space charge limited)
  – Aluminasilicate sources,
    \[ K^+, Na^+ \sim 0.5 \text{A/}(\text{mm mrad})^2 \quad (J \sim 10 \text{ mA/cm}^2) \]
    \[ \text{Li}^+ \sim 0.005 \text{A/}(\text{mm mrad})^2 \quad (J \sim 2 \text{ mA/cm}^2) \]
  – Normalized emittance \( \sim <1 \text{ to few } \pi \text{ mm mrad} \)

• Required target plane peak intensity
  \[ T \sim 0.5 \text{eV} \ (15nC \ K^+, 300\text{keV}) \quad 0.2\text{J/cm}^2 \ , \sim 200\text{A/cm}^2 \]
  \[ T \sim 1-2 \text{eV} \ (30nC \ \text{Li}^+, 3\text{MeV}) \quad 30\text{J/cm}^2 \ , \sim 8\text{kA/cm}^2 \]
  \[ T \sim 10 \text{eV} \ (30nC \ Na^+, 10\text{MeV}) \quad 200\text{J/cm}^2 \ , \sim 1\text{MA/cm}^2 \]
NDCX-I in Bldg 58

Source Tank
Marx
Solenoids and dipoles
Induction Bunching Module
Neutralized drift section
8T Final Focus Solenoid
Target Chamber
Target Diagnostics

Fast Optical Pyrometer

Fast Current Transformer

Absolutely-calibrated streak-spectrometer

Challenges and requirements:
- Ultra fast response (sub-ns)
- Higher sensitivity (>=1500 K)
- Different, more efficient beam splitting mechanism
- No published paper

Technical issues:
- Need low noise amplified photo receiver with flat gain from DC to 4GHz and big active surface.
- Fiber coupling limits the efficiency
- Picoseconds time scale means:
  - Modal (temporal) dispersion in MM fiber, careful cabling, impedance match and termination of detectors

Channel #1: 750 nm +/- 75 nm, 76 ps rise/fall time
detect: ~ level ~500 K (blackbody)
Channel #2: 1000 nm +/- 75 nm, 72 ps rise/fall time
detectable level ~1500 K (blackbody)
Channel #3: 1400 nm +/- 75 nm, 70 ps rise/fall time
detectable level ~2000 K (blackbody)

- Records continuous spectrum from 500 nm to 850 nm
- Temporal resolution down to 5 ps
- Linear response

- When calibrated with tungsten lamp, can be used for true temperature determination and spectral emissivity
- Can discriminate useful signal from NDCX plasma radiation
- No published paper
A module is one or more induction cells plus an “Intercell” for beam steering and diagnostics.

Exterior solenoid flux lines have been redirected to prevent loss of induction core volt-seconds.