Status of Heavy Ion Fusion Science Program*

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Status: the US HIFS-VNL has made large advances over the last year to the beam science common to both High Energy Density Physics (HEDP) and fusion

→The program concentrates on ion beam experiments, theory and simulations to 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?*

Topics to be addressed:
- New approach to accelerator driven HEDP and IFE
- Experimental and theoretical advances
- A new Pulse-Line Ion Accelerator
- Warm dense matter studies
- Future plans
Creating warm dense matter and fusion ignition conditions requires **longitudinal** as well as **transverse** beam compression.

Induction acceleration is most efficient at $\tau_{\text{pulse}} \sim 100$ to 200 ns.

Near term High Energy Density targets require $\sim 1$ ns pulses; Fusion requires $\sim 10$ ns.

Bunch tail has a few percent higher velocity than the head (tilt) to allow compression in a drift line.

**Scientific issues under study:**
1. Electron cloud effects (wherever the beam transports in vacuum).
2. Beam-plasma instabilities during compression.
4. Focal spot (chromatic effects) vs minimum pulse-width trade off with tilt.

**New direction:** neutralize the beam space charge both in longitudinal drift compression as well as in final focus.
Neutralized beam compression and focusing: unique approach to ion-driven HEDP needed for shorter ion pulses (< few ns versus a few μs)

Ion energy loss rate in targets

Maximum dE/dx \textit{and} uniform heating at Bragg peak require short (< few ns) pulses to minimize hydro motion. [L. R. Grisham, PoP, (2004)]. \(\rightarrow Te > 10 \text{ eV} @ 20\text{J}, 20 \text{MeV}\) (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)
Plasma neutralization of beam space charge *upstream* of final focus is needed for HEDP targets driven by medium mass ions at peak of dE/dx.

<table>
<thead>
<tr>
<th>Beam ion</th>
<th>1.5xEnergy (MeV) @ peak dE/dx (cold aluminum)</th>
<th>Range (microns) (10% solid Al)</th>
<th>Target Δz (microns) for &lt;5% T variation</th>
<th>Beam energy (J)/mm² for 10 eV 10%po Al</th>
<th>τhydro= Δz/(2Cs) (@10eV) (ns)</th>
<th>Beam power GW per mm²</th>
<th>Beam current (A) for 1 mm dia. spot</th>
<th>Beam perveance (@ final focus)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Li</td>
<td>2.4</td>
<td>30</td>
<td>22</td>
<td>3.3</td>
<td>0.6</td>
<td>6.1</td>
<td>1990</td>
<td>0.93</td>
</tr>
<tr>
<td>Na</td>
<td>24</td>
<td>60</td>
<td>54</td>
<td>8.0</td>
<td>1.3</td>
<td>6.1</td>
<td>200</td>
<td>5.4x10⁻³</td>
</tr>
<tr>
<td>K</td>
<td>68</td>
<td>140</td>
<td>91</td>
<td>13.6</td>
<td>2.2</td>
<td>6.1</td>
<td>70</td>
<td>5.1x10⁻⁴</td>
</tr>
<tr>
<td>Rb</td>
<td>237</td>
<td>250</td>
<td>150</td>
<td>22.4</td>
<td>3.7</td>
<td>6.1</td>
<td>20</td>
<td>3.3x10⁻⁵</td>
</tr>
<tr>
<td>Cs</td>
<td>456</td>
<td>400</td>
<td>190</td>
<td>28.5</td>
<td>4.7</td>
<td>6.1</td>
<td>11</td>
<td>8.5x10⁻⁶</td>
</tr>
</tbody>
</table>

These perveances are likely too high for vacuum compression, even with plasma neutralization in the target chamber → must extend plasma neutralization upstream of final focus → use plasma-filled solenoids, plasma lens, or assisted-pinches for final focus

Likely too expensive for US budgets
Neutralized drift compression and focusing is also key to enable a new modular driver development path to IFE

Key Enabling Advances:
- Neutralized drift compression and focusing
- Time dependent correction for achromatic focusing
- Multi-pulse longitudinal merging and pulse shaping
- Fast agile optically-driven solid state switching

Concept for a modular multi-pulse heavy ion IFE driver (induction or PLIA)
Neutralized Transport Experiment (NTX-2004) encouraged use of plasma neutralization for radial compression.
The neutralized drift compression experiment (NDCX) began operation Dec. 2004 to explore neutralized longitudinal compression.
50 Fold Beam Compression has been achieved in the neutralized drift compression experiment.

Corroborating data from Faraday cup and LSP simulation.

Phototube intensity and time data:

- With compression
- Without compression

Optical data:

- Compression ratio
- Time (ns)

LSP simulation:

- Axial compression
- Time (ns)

Corroborating data from Faraday cup:

- Beam current (mA)
- Time (ns)
- ~ 5 ns pulse width

52 x

The Heavy Ion Fusion Virtual National Laboratory
Rate of progress in heavy ion beam compression in plasma points towards a revolution in high peak power ion beams

Simulation of concept
Mar 11, 2004

NDCX-1A Constructed, first data

40 ns FWHM
Dec. 9, 2005

20 ns FWHM
Feb 27, 2005

4 ns FWHM
May 2005
NDCX-II vision: a short pulse high gradient accelerator for ion-driven HEDP and IFE is being evaluated.

1 eV target heating
>0.1 $\mu$C of Na$^+$ @ 24 MeV heating @ Bragg peak dE/dx
NDCX-1C + $5$M hardware
LSP simulation by Dale Welch for future 24 MeV Na\(^+\) NDCX-II exp. shows compression to 100 ps with 500 micron central peak focus beam radius (cm x1000). Smaller spot can be achieved by more aggressive focusing scheme.

Spot limited in simple solenoidal focusing (4T) by energy tilt (\(\Delta E/E\)):

\[
\frac{a_f}{a_0} \approx \frac{\pi \Delta E}{8E}
\]

Time-Integrated Energy Deposition for NDCX2:

- 500 micron HWHM

Beam density approaches \(10^{13}\) cm\(^{-3}\)
The High Current Experiment (HCX) is exploring beam transport limits.

K⁺ Beam Parameters
I = 0.2 (- 0.5) Amp
1 (- 1.7) MeV, 4.5 µs
Comparison: Clearing electrodes and e-suppressor on/off

- Beam ions
- Electrons from ions hitting surface
- Secondary electrons

Comparison suggests semi-quantitative agreement.
Completed merging beamlet injector experiments on STS-500 validated the concept of this compact, high current source (Kwan, Westenskow)

Monolithic solid sources suffer from poor scaling vs. size at high currents
This new concept circumvents the problem via use of many small, low-current sources

From scaled merging experiment:
• Obtained emittances comparable to simulation
• Effects of “dirty” physics (electrons, charge exchange) were minimal
• Scales to 0.5 A, 1.6 MeV, ~1 π-mm-mrad, 13 mA/cm²

From a full-gradient (parallel-beamlet) experiment

Simulation

Experiment

-0.05 x (m) 0.05 -0.05 x (m) 0.05

The Heavy Ion Fusion Virtual National Laboratory
New Pulse Line Ion Accelerator (PLIA)* concept is being explored w/ accelerating fields traveling in a “distributed transmission line”

NDCX-II Accelerator Cell

Helical winding

Solenoid & cryostat

Compact transformer coupling (5:1 step-up)


\[ \nu_{ph} = \frac{1}{\sqrt{LC}} \]
For low beta, high perveance, short ion bunches, the PLIA might reduce costs per volt by 100 X compared to induction linacs

Induction Module for the Dual-Axis Radiographic Hydrotest Facility (DARHT):
  0.4 V·s (200kV×2μs)
  ~10,000 kg, 1 M$
(without pulser or transport magnet)

PLIA test module results (LBNL Dec 04):
  0.4 V·s (2MV×0.2μs)
  ~40 kg, 10 K$
(without pulser or transport magnet)
Hydra simulations confirm temperature uniformity of targets at 0.1 and 0.01 times solid density of aluminum (NDCX-II parameters)

0.1 solid Al

0.01 solid Al (at t=2 ns)
New theoretical EOS work meshes very well with the experimental capabilities we will be creating.

R. More: Large uncertainties in WDM region arise in the two phase (liquid-vapor) region.

Accurate results in two-phase regime essential for WDM.

R. More has recently developed new high-quality EOS for Sn.

Interesting behavior in the T~1.0 eV regime.

Critical point unknown for many metals, such as Sn.

Critical point

EOS tools for this temperature and density range are just now being developed.
**Grand technical challenges in ten years**

**Challenge 1:** Understand limits to compression of neutralized beams

**Challenge 2:** Integrated compression, acceleration and focusing sufficient to reach 1 eV in targets:

\[ 0.1\mu C \text{ NDCX1C +PLIA +5M$=NDCXII} \]

**Challenge 3:** Affordable (<50M$) high shot rate (>10 Hz) accelerator, laser, & targets for (a) HEDP user facility (<5% EOS uncertainty), and for (b) prototype IFE driver module

Add acceleration

Add chambers, targets, HEDP diagnostics

1 eV target heating

\[ >0.1 \mu C \text{ of Na}^+ @ 24 \text{ MeV heating @ Bragg peak dE/dx} \]

NDCX 1C + $5M hardware
Adding accelerator ion beam R&D to exploratory fast ignition research portfolio → prudent risk management

Unstable electron beams may not deposit where laser is pointing.

Petawatts of photons are available for FI experiments

Focusing paraboloid not IFE durable

Petawatts of ions await development for FI experiments

Focusing magnets IFE durable

Magnetic pinch region near target may be needed

Ion beams dE/dx along straight lines to the Bragg peak
Conclusions

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

- Heavy ion research is of fundamental importance to both HEDP in the near 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.