Warm Dense Matter Science Using Intense Ion Beams

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Frontiers in Plasma Physics Town Hall Meeting
Bethesda, Maryland
June 30 – July 1, 2015

LLNL-PRES-673751

* This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Security, LLC, Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344, by LBNL under Contract DE-AC02-05CH11231, and by PPPL under Contract DE-AC02-76CH03073.
Several current and future facilities will use intense ion beams to explore warm dense matter science.

Examples of accelerator-based ion beam facilities:

- **HIAF** (China, ~2022)
- **Bella-i** (US, ~2018?) (see Esarey, Schenkel, Geddes talks)
- **NDCX-II** (US, 2015)
- **JLF** (US, present day)
- **Trident** (US, present day)

Examples of laser-based ion beam facilities:

- **FAIR** (Germany, ~2018)
- **Trident** (US, present day) + ...
Accelerator driven ion beams have unique characteristics for WDM experiments

Large sample sizes compared to diagnostic resolution volumes (~ 1's to 10's µ thick by spot sizes ~ 1 mm diameter)

Uniformity of energy deposition

A benign environment for diagnostics (low debris and radiation background)

High shot rates (~2/minute) to facilitate calibration and experimental setup

Precise control of energy deposition (and ability to do energy accounting by measuring transmitted beam)

Small shot-to-shot energy variation in energy and intensity

Ability to heat all target materials (conductors and insulators, foams, powders, ...)

Pulse long enough to achieve local thermodynamic equilibrium (T_e = T_i)

Very small beam induced magnetic fields (no high energy electrons generated)

High availability for experiments

Facility can be a training ground for limited availability experiments on facilities such as LCLS, Rochester, NIF

X-ray heating, direct laser heating, laser-produced ion heating, pulsed power heating, accelerator based ion heating each have non-ideal aspects. Multiple approaches are needed for validation.
Neutralized Drift Compression Experiment II (NDCX-II) has recently been commissioned (2015).

**NDCX-II beam:**
- 1.2 MeV, \( \sim 70 \text{ nC} \)
- \( (5 \times 10^{11} \text{ ions}), \sim 1\text{ns} \)
- \( \sim 1 \text{ mm spot diameter} \)

**Targets:**
- solids or foams; conductor or insulators;
- For foam targets:
  - pore size: \( \sim \text{nm to } \mu\text{m} \)
  - density: 1 to 100% solid

**Diagnostics:**
- Optical pyrometry, streak cameras, VISAR, energy analyzer ...
Maximize uniformity and efficiency by placing center of foil at or near Bragg peak

In simplest example, target is a foil of solid or “foam” metal

Example: Ne

Fractional energy loss can be high and uniformity also high if operate at Bragg peak (L. R. Grisham, Physics of Plasmas, 11, 5727 (2004)).

\[
\frac{1}{Z^2} \frac{dE}{dX}
\]

\((\text{MeV/mg cm}^2)\)

\(\Delta dE/dX \propto \Delta T\)

(dEdX figure from L.C Northcliffe and R.F.Schilling, Nuclear Data Tables, A7, 233 (1970))
Ion beams can explore a variety of topics in WDM science

Areas of investigation (in context of NDCX-II accelerator) include:

- Equation of state
- Ion stopping power
- Electrical and thermal conductivity
- Ion driven shock dynamics
Measurements of electron temperature, density and hydrodynamic expansion velocity allow distinction between EOS models.

Pyrometry: Upper set: LEOS without Maxwell construction
Lower set: QEOS without Maxwell construction
(Magenta: T_max; Blue: 150 nm; Green: 450 nm; Red: 1500 nm)

HYDRA$^1$ simulations:

VISAR: Upper set: LEOS without Maxwell construction
Lower set: QEOS without Maxwell construction
(Magenta: $dz/dt$ of outermost zone; Blue: 150 nm; Green: 450 nm; Red: 1500 nm)

Multi-frequency (upper left) and multi-angle pyrometry measurements, together with multi-frequency Visar measurements (upper right) can distinguish between EOS candidates.

X-ray imaging of density profile (lower, shown at 10 different snapshots) can distinguish between EOS

Density

(1.2 MeV, 12 J/cm², 1 ns Li⁺ ion beam on Al target)

Ion stopping rates (dE/dX) in heated matter can be measured using NDCX-II both directly and indirectly. An electrostatic energy analyzer (EEA) or other direct energy diagnostic may be used to measure energy of transmitted ion beam.

Indirect method: measure neutron production on deuterated carbon (plastic CD$_2$) target or (better) targets with known fraction of D and T.

He$^+$ + D $\rightarrow$ "knock-on" D (~100 kV) + D $\rightarrow$ n + charged particles

Number of created neutrons proportional to $1/(dE/dX|_{\text{He}}) \times 1/(dE/dX|_{\text{D}})$ since the lower the dE/dX the greater chance a knock-on collision will occur and the greater chance a neutron producing reaction can occur.
Thermal conductivity in heated matter is another area of investigation.

Thermal conductivity can be measured by determining time for heat to reach various depths in foils thicker than range of ions.

This experiment will be carried out at low ion intensities, so that the material is below the vaporization temperature.

Ion beam heats tamper and rest of target nearly uniformly. Thermal wave from higher temperature tamped region "breaks out" at various times depending on depth of grooves and heated material conductivity.
Electrical conductivity can be measured using magnetic diffusion time.

A voltage is rapidly pulsed across the fine wires. Ion beam heats foil and magnetic field diffuses through foil, depending on resistivity of heated foil. Magnetic field is measured using Faraday effect through the optical fiber.
Hydrodynamics of shocks formed with volumetric energy deposition is another area investigation

Example: Tamper shock (that can be used in HI direct drive targets) can create additional shocks that can merge with the primary

Experimental scenario:

- **Solid** ~ 1 µ
- Foam (~10 – 75% solid) ~ 5 to 20 µ

"Tamper" shock at density interface

"End of range shock"

"Tamper shock" can catch up with "end of range shock"

Tamper absorbs energy that is not necessarily converted to mass flow.

What is the optimal combination of tamper thickness, density for efficient conversion to flow kinetic energy?
Other areas of interest to investigators of WDM and fusion science that may be explored using intense ion beams

1. **Phase transitions**: in particular **liquid-vapor phase transition** and the complete boundary between the regions, and critical points. (Critical point is poorly known for many of the refractory metals). (Solid-liquid and solid-solid phase transitions are also of interest for some material.)

2. Phase transitions from metal to insulator and insulator to metal.

3. Transition between transparent and opaque, as in transient darkening.

4. **Unusual plasma configurations**, such as positive/negative plasmas (with low concentrations of electrons) as in halogens and some metals such as gold and platinum at temperatures above 0.4 eV.

5. **Fragmentation/fracture mechanics** of materials under extreme conditions (e.g. carbon, silicon)

6. **Droplet formation** and the role of surface tension in rapidly expanding heated metals

7. **Plasma physics of neutralized and unneutralized intense ion beams** (see Peter Seidl poster and Erik Gilson talk, this meeting).
Conclusions

Warm dense matter science using intense ions is an area rich in plasma physics.

Ion beams can support a wide range of experimental investigations:
• **Equation of state** in the WDM regime
• **Ion dE/dX** in heated materials
• **Conductivity** in heated matter
• **Hydrodynamic coupling** of ion beams using volumetric energy deposition
• Other areas include: **phase transitions** (solid-solid, solid-liquid, and liquid-vapor); metal to insulator and **insulator to metal transitions**; **opacity transitions** (such as from transparent to opaque); **fragmentation/fracture mechanics** for materials under extreme conditions; droplet formation and **surface tension**; unusual plasma configurations; and intense **beam dynamics** (non-neutral as well as neutralized).

NDCX-II offers a different approach to produce WDM states in the Laboratory (beyond lasers, laser-produced ions, X-rays, etc.) **Multiple approaches are needed for validation.** Other WDM facilities such as LCLS MEC, FAIR, Bella-i, etc. will be complementary.