Hydrodynamic Simulations Using HYDRA*

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Outline of talk

1. Comparison of the isochoric ion beam target heating concepts at GSI (HEDgeHOB) and the HIFS VNL (NDCX II)

2. Simulations of the LAPLAS experiment using HYDRA, and comparison with GSI simulations

3. Simulations of HIFS VNL planar targets
   -- Foams
   -- Solids
   -- Exploration of two-phase regime
     Existence of temperature/density “plateau”
     Maxwell construction
   -- Parameter studies of more realistic targets

4. Simulations of Rayleigh Taylor Instability
Ion-driven isochoric heating experiments are planned using ions in two different regimes

*High Energy Density Matter Generated by Heavy Ion Beams (HEDgeHOB)*

- **NDCX (at HIFS VNL)**
  - Ion energy: < 1 MeV/u
  - Current: ~ 100 A
  - Pulse duration: < 1 ns
  - Foil thickness: 3 µ (solid) - 300 µ (foam)

- **Laboratory Planetary Science (LAPLAS) (at GSI)**
  - Ion energy: ~ 2 GeV/u
  - Ion current: ~ 2 A
  - Pulse duration: ~ 50 ns
  - Characteristic radial dimension: ~ 1 mm (solid)

*Heavy Ion Heating and Expansion (HIHEX) (at GSI)*

Metals, insulators...

Metals, insulators, etc..

**Metals, insulators...**

(Liscohric = constant volume)
GSI experiment will heat a central core of hydrogen by ion deposition in an outer case of high Z material (such as gold).

**LAPLAS Experiment:**

- **Inner region:** Cylinder of frozen hydrogen ($\rho = 0.0884 \text{ g/cm}^3$)
  - Radius: 0.4 mm

- **Outer region:** Cylinder of frozen gold ($\rho = 19.3 \text{ g/cm}^3$)
  - Radius: 0.4 to 4.0 mm

- **Beam:** Uranium, 2 GeV/u
  - Bunch length: 50 ns
  - Power profile: parabolic between 0.6 and 1.6 mm
  - Number of particles: $1 \text{ to } 5 \times 10^{11}$
Ion deposition is in a cylindrical ring outside of the hydrogen core, with a parabolic intensity profile.

Assumed beam current profile

50 ns FWHM

Beam radial intensity profile

Hydra stopping model

Hydra stopping model

Uranium dE/dX

Hydrogen

Gold

Hydrogen

Uranium range

Gold
Evolution of density ($N_p=1 \times 10^{11}$ particles/bunch)

- 0 ns
- 73 ns: End of heating pulse
- 104 ns
- 200 ns
- 300 ns
- 376 ns

$g/cm^3$

73 ns: End of heating pulse
Evolution of temperature ($N_p = 1 \times 10^{11}$ particles/bunch)

- 73 ns: End of heat pulse and maximum temperature reached
Evolution of pressure ($N_p=1 \times 10^{11}$ particles/bunch)

- 0 ns
- 73 ns
- 104 ns
- 200 ns
- 300 ns
- 376 ns

70 ns: End of heating pulse

~300 ns: Maximum central pressure (3.7 Mbar)
Evolution of pressure ($N_p=5 \times 10^{11}$ particles/bunch)

73 ns: End of heating pulse
HYDRA ion intensity was altered to match HEDgeHOB pressure profile at 50 ns.

Simulations are qualitatively and sometimes quantitatively similar, but also show significant differences.
At time of maximum central pressure (170 ns), there is broad hydrodynamic agreement between HYDRA and HEDgeHOB simulations. Detailed comparison of central temperature and density show marked differences possibly due to different EOS assumptions.
HIFS VNL Strategy: maximize uniformity and the efficient use of beam energy by placing center of foil at Bragg peak

In simplest example, target is a foil of solid or metallic foam

\[ \frac{1}{Z^2} \frac{dE}{dX} \text{ (MeV/mg cm}^2) \]

\[ \Delta dE/dX \propto \Delta T \]

Example: Neon beam
\[ E_{\text{entrance}} = 1.0 \text{ MeV/amu} \]
\[ E_{\text{peak}} = 0.6 \text{ MeV/amu} \]
\[ E_{\text{exit}} = 0.4 \text{ MeV/amu} \]
\[ \frac{\Delta dE/dX}{(dE/dX)} \approx 0.05 \]

(dEdX figure from L.C Northcliffe and R.F.Schilling, Nuclear Data Tables, A7, 233 (1970))
Initial Hydra simulations confirm temperature uniformity of targets at 0.1 and 0.01 times solid density of Aluminum

(simulations are for 0.3 \( \mu \)C, 20 MeV Ne beam -- possible NDCX II parameters).
Metallic foams were expected to ease the requirement on pulse duration

With foams easier to satisfy

$$\Delta t_{\text{pulse}} \ll t_{\text{hydro}} = \Delta z/c_s$$

But foams locally non-uniform. Timescale to become homogeneous

$$t_{\text{homogeneity}} \sim n \frac{r_{\text{pore}}}{c_s}$$

where $n$ is a number of order 3 - 5, $r_{\text{pore}}$ is the pore size and $c_s$ is the sound speed.

Thus, for $n=4$, $r_{\text{pore}}=100$ nm, $\Delta z = 40$ micron (for a 10% aluminum foam foil):

$$t_{\text{hydro}}/t_{\text{homogeneity}} \sim 100$$

However, R. More has suggested that sound wave reflections and escape may determine ultimate uniformity evolving over longer time scale.
We have begun to simulate foams as multiple layers (solid density interspersed with low density voids)

density vs position
average density = 0.33 solid density
VNL has been using two simulation codes to investigate hydrodynamics questions

In this work 2 codes were used:

DPC: 1D
EOS based on tabulated energy levels, Saha equation, melt point, latent heat
Tailored to Warm Dense Matter regime
Maxwell construction, QEOS

HYDRA: 1, 2, or 3D
EOS based on:
  QEOS: Thomas-Fermi average atom e-, Cowan model ions and Non-maxwell construction
  LEOS: numerical tables from SESAME
Maxwell or non-maxwell construction options
When initial temperature places expanding foil into two-phase regime, plateaus in $\rho$ and $T$ have been numerically observed$^{1,2}$

Example shown here is initialized at $T=0.5$ or 1.0 eV and shown at 0.5 ns after “heating.”

HYDRA simulations show both similarities to and differences with More, Kato, Yoneda simulation of 0.5 and 1.0 eV Sn at 0.5 ns

(oscillations at phase transition at 1 eV are physical/numerical problems, triggered by the different EOS physics of matter in the two-phase regime)

Density

\(T_0 = 0.5 \text{ eV}\)

Temperature

\(T_0 = 0.5 \text{ eV}\)

Density

\(T_0 = 1 \text{ eV}\)

Temperature

\(T_0 = 1 \text{ eV}\)

Propagation distance of sharp interface is in approximate agreement

Uses QEOS with no Maxwell construction

Density oscillation likely caused by \(\partial P/\partial \rho\) instabilities, (bubbles and droplets forming?)
Maxwell construction reduces instability in numerical calculations

LEOS without Maxwell const
Density vs. z at 3 ns

LEOS with Maxwell const
Density vs. z at 3 ns

LEOS without Maxwell const
Temperature vs. z at 3 ns

LEOS with Maxwell const
Temperature vs. z at 3 ns

All four plots: HYDRA, 3.5 µ foil, 1 ns, 11 kJ/g deposition in Al target
Expansion of foil is expected to first produce bubbles then droplets

Example of evolution of foil in \( \rho \) and \( T \)

- The foil will melt then enter 2-phase conditions.
- First, bubble forms (B), then the continuous liquid fragments into droplets (D)

Maximum size of a droplet in a diverging flow

Locally, \( \frac{dv}{dx} = \text{const} \) (Hubble flow)

\[
dF/dx = \mu \ v(x)
\]

\( \sigma \) Steady-state droplet

- Equilibrium between stretching viscous force and restoring surface tension

**Capillary number** \( Ca = \text{viscous/surface} \approx \int \mu \ \frac{dv}{dx} \ x \ dx / (\sigma \ x) \approx (\mu \ \frac{dv}{dx} \ x^2) / (\sigma \ x) \approx 1 \)

\[ x_{\text{max}} \sim 0.20 \ \mu m \]

Kinetic gas: \( \mu = \frac{1}{3} m \ v^* n l \)

mean free path: \( l = \frac{1}{\sqrt{2}} n \sigma_0 \)

\[ x = \sigma / (\mu \ \frac{dv}{dx}) \]

\( \mu = \frac{m \ v}{3 \ \sqrt{2} \ \sigma_0} \)

\[ x_{\text{max}} \sim 0.20 \ \mu m \]

- AND/OR: Equilibrium between disruptive dynamic pressure and restoring surface tension: **Weber number** \( We = \text{inertial/surface} \sim (\rho \ v^2 A) / \sigma \ x \sim \rho \ (dv/dx)^2 \ x^4 / \sigma \ x \sim 1 \)

\[ x_{\text{max}} \sim 0.05 \ \mu m \]

\[ x = (\sigma / \rho \ (dv/dx)^2)^{1/3} \]

We have begun using Hydra to explore accelerator requirements to study beam driven Rayleigh Taylor instability.

23 MeV Ne, 0.1 μC, 1 ns pulse (NDCX II) impinges on 100 μ thick solid H, T=0.0012eV, ρ =0.088 g/cm³; No density ripple on surface, blowoff accelerates slab.
When initial surface ripple is applied, evidence for Rayleigh Taylor instability is suggestive.
When initial surface ripple is applied, evidence for Rayleigh Taylor instability is suggestive (continued)

\[ v_z \] 
\[ t=0.4 \text{ ns} \]
\[ v_z \] 
\[ t=1 \text{ ns} \]
\[ v_z \] 
\[ t=3.5 \text{ ns} \]
\[ v_z \] 
\[ t=5 \text{ ns} \]
\[ v_z \] 
\[ t=7.5 \text{ ns} \]
\[ v_z \] 
\[ t=10 \text{ ns} \]

Scale for above figures \((v_z)\): cm/µs

Scales from previous page \((\rho \text{ and } T)\):

g/cm³
eV
Parametric studies

Case study: possible option for NDCX II
2.8 MeV Lithium$^+$ beam
Deposition 20 kJ/g
1 ns pulse length
3.5 micron solid Aluminum target

Varied: foil thickness
finite pulse duration
beam intensity
EOS/code

Purpose: gain insight into future experiments
Variations in foil thickness and energy deposition

DPC results

Compare 3 foils (2.5, 3.5 and 4.5 microns)

Peak pressure in foil

1 nsec ion pulse

4.5 micron foil →

3.5 micron foil →

← 2.5 micron foil

Pressure (Mbar)

Deposition (kJ/g)

HYDRA results using QEOS

Compare 3 foils (2.5, 3.5 and 4.5 microns)

Peak pressure in foil

1 nsec ion pulse

4.5 micron foil →

3.5 micron foil →

← 2.5 micron foil

Pressure (Mbar)

Deposition (kJ/g)

Deposition (kJ/g)

Temperature (eV)

Deposition (kJ/g)

Temperature (eV)
Expansion velocity is closely correlated with energy deposition but also depends on EOS.

Using simple instantaneous heating/perfect gas model (see e.g. Landau & Lifshitz):

\[ \varepsilon_0 = \frac{c_{s0}^2}{\gamma(\gamma - 1)} \]

\[ v = \frac{-2c_{s0}}{\gamma - 1} \quad \Rightarrow \quad v = \sqrt{\frac{4\gamma}{\gamma - 1} \varepsilon_0^{1/2}} \]

In instantaneous heating/perfect gas model outward expansion velocity depends only on \( \varepsilon_0 \) and \( \gamma \)
Conclusion

We have carried out hydrodynamic simulations to evaluate and predict target behavior concerning a number of topics including:

-- implosion dynamics for the LAPLAS experiments

-- the hydrodynamics of foams (and the homogenization process)

-- the dynamics in the two-phase regime including droplet formation

-- Rayleigh - Taylor instability in ion-driven targets

-- parametric studies of expansion velocities, maximum pressure and temperature in solid foils, as function of pulse duration, energy deposition, and foil thickness