Numerical modeling of HED states in matter, induced by intense ion beams

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Shock-Wave Generators

High explosives & guns
- plain gun, 8 km/s
- sphere, 14 km/s (Fe)
- light gas gun, 8 km/s

Pulsed power
- railgun, 10 km/s
- 20 MA, 40 km/s (Al), 300 TW x-ray
- 6 MA, 12 km/s, 5 TW

Nuclear
- 4 Gbar
- 1000 km/s
- 21 kJ (10 kJ@350 nm)x192 lasers = 4 MJ (500 TW)

Z, Sandia
Angara-5
NIF, Livermore
Investigated Pressure Scale of Elements

- Nuclear explosions, Russia
- Laser shocks
- Nuclear explosions, USA
- Shock waves
- DAC
- Laser-driven shocks by PHELIX: 6 kJ
- 1 kJ
Shock-Wave Data for Al

Shock Hugoniots

Release isentropes

Shock compression:
0.3 < ρ/ρ_0 < 6
P < 400 TPa (4 Gbar)

Release expansion:
10^{-3} < ρ/ρ_0 < 3
10^{-2} GPa < P < 1 TPa (10 Mbar)

Pressure-density and pressure-mass velocity plots for Al according to I.V. Lomonosov,
Ion beams: FAIR & LHC

- FAIR (GSI) & LHC (Cern) – greatest engineering construction in XXI
- HED states: hundred \( \kappa J/g \), 1 Mbar, 300-400*10^3 K
  - # non-ideal plasmas
  - # CP, metal-insulator
  - # ion fusion
- Safety problems
- Target’s functioning&design
**FAIR : HIHEX & LAPLAS**

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

- uniform quasi-isochoric heating of large-volume solid target
- isentropic expansion in 1D plane or axial setup

Different high-energy-density states of matter:
EOS & transport properties of strongly coupled plasmas, domains of WDM and critical point
Extreme states in Pb (FAIR)

Квази-изохорический нагрев и расширение

Extreme states in Cu (LHC)

Experiments: Al 3D P-V-T

- **ICE:** \( P(V, S = \text{const}) \)
- **DAC:** \( P(V, T = \text{const}) \)
- **IEX:** \( E, V, T, H, \text{Cs (}P = \text{const}) \)
- **Hugoniots** \( H_1, H_p: U_s - U_p \ (P, V, E) \)
- **S** = const: \( P - U_P (P_S, V_S, E_S) \)
- **EPI:** \( P, E \ (V = \text{const}) \)
- **HIHEX:** \( P, E, T \ (t) \ SIS18 \ & SYS100 \)
FPIC3D – parallel code for numerical modeling of high-energy-density processes

- Parallel gas dynamic code: finite-size particles in cells method
  - ALE
  - Merging & splitting of particles
  - Data decomposing
  - Linear acceleration (SKIF-MSU, 2008)
- Multi-phase EOS (30 metals), caloric EOS (150 materials)
- Models of elastic-plastic deformation & failure
- Parallel solving of heat conductivity equation
- Parallel ion’s energy deposition (FAIR)
- Parallel proton’s energy deposition (LHC)


3D Ion Beam

Ions Paths Ensemble:

\( \{ \vec{r}_0, \vec{r}, E_0 \}_N \)
Ion Beam Energy Deposition

\[ E_s = \left[ \frac{\partial E}{\partial (\rho x)} (E_{\text{ion}}) \right] \cdot n \cdot \rho_{ij} \cdot L_{ij} \]

* M.M.Basko, N.A.Borisenko, A.A.Golubev et al.
Modeling: HED Experiments & FAIR

FPIC3D, 2D Godunov:
- energy deposition (SRIM)
- EOS
- elastic-plastic fracture

3D energy deposition

U beam on Pb foil

trajectories of target expansion:
- good uniform 1D expansion
3D Results:  

_Influence of the Aperture on the Beam Geometry_

- Exp#1 - FWHM w/o Ta
- Exp#1 - FWHM with Ta
- Exp#1 - linear fit
- Exp#2 - FWHM w/o Ta
- Exp#2 - FWHM with Ta
- Calc#1_FWHM_intT
- Calc#1_FWHM_ions
- Calc#2_FWHM_ions
- Bragg peak 2.44 mm
- beam after aperture
- Ta aperture 0.128 mm
- X=\tan(0.0353 \text{ rad}) \cdot Z

X, mm

-6 -5 -4 -3 -2 -1 0 1 2 3 4 5

Z, mm

-0.3 -0.2 -0.1 0.0 0.1 0.2 0.3

1.22 mm
$^{238}\text{U}^{73+}$ in Pb

Influence of the Aperture on the Beam Geometry
3D Results:

Acceleration of Iron Foil

HHT August 2006, shot#39
3D Ion Radiography

(Energy loss Dynamics)

SIS 18
1.5 GeV, Carbon
FWHM=5 mm

SIS 100
$2 \times 10^{12}$, 238 GeV, Uranium
$t=50$ ns
3D Results:

Ion Radiography in LAPLAS Experiment

The results of 2D high-resolution calculations (BIG-2) of the LAPLAS experiment were used in 3D ion radiography setup (PIC3D)

3D Density field section combined with resulting radiogram at 200 ns
Ion Radiography

Results of numerical Modeling

40 ns  80 ns  120 ns

160 ns  200 ns  220 ns
Anti-proton Target (FAIR)
Goal: development of theoretical drops radiation model

Tasks:
- 1-D gasdynamic code for multi-phase equations of state and drop kinetics singularity;
- development of effective calculation method for solution of drop kinetics equation;
- selection models and their numerical realization for calculations of drop absorption sections and complex index of reflection;
- preliminary computations of effective temperature.
THERMAL RADIATION TRANSFER

$T, \text{ kK}$

$Q=1\text{kJ/g (300ns)}$

$T_{\text{in}}$

$m_{\text{liq}}$

$T_{\text{eff}}$

$T_{\text{out}}$

$t, \text{ ns}$
THERMAL RADIATION TRANSFER

\[ Q = 2 \text{kJ/g (300ns)} \]

\[ T_{\text{in}}, T_{\text{out}}, T_{\text{eff}}, m_{\text{liq}}, t, \text{ns} \]
VAPOR-DROP REGIONS

Graph showing temperature (T, kK) on the y-axis and density (ρ, g/sm²) on the x-axis. The graph includes curves for different values of Q:

- Q = 2 kJ/g
- Q = 1.5 kJ/g
- Q = 1.3 kJ/g
- Q = 1.1 kJ/g
- Q = 1.05 kJ/g

A peak labeled \( \tau = 300 \text{ns} \) is observed.
Conclusions

- realistic 3D modeling – only parallel computations
- 3D code with realistic physical models & 3D energy deposition developed
- Performance (16 processors, 200x200x800 grid) ~30 GFlops, 10-20 hours, today ~ 2-3 TFlops
- 3D energy deposition by protons
- Realistic anti-proton target design
Conclusions

(40 papers since 2002)


