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

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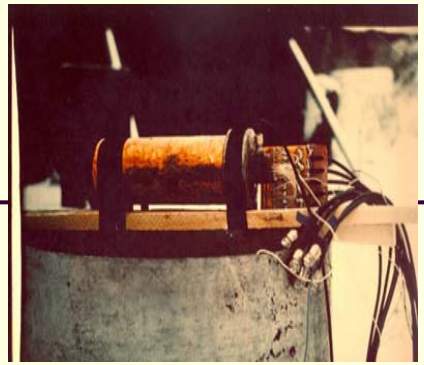
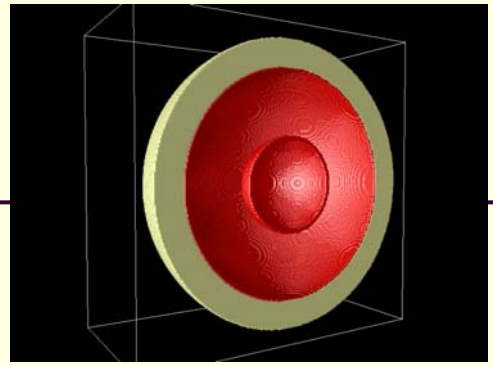
IPCP – GSI&TU Darmstadt collaboration (DFG 436 RUS 113/816/0-2 – RFBR 06-016-04011, 08-02-92882)

Shock-Wave Generators

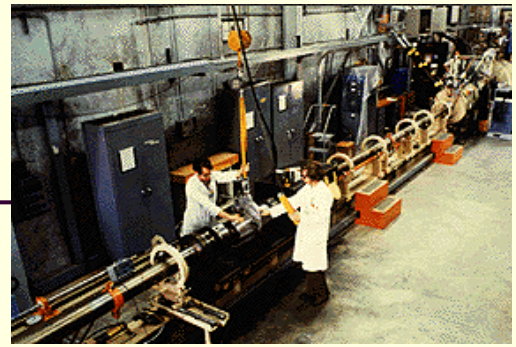
High explosives & guns



plain gun, 8 km/s

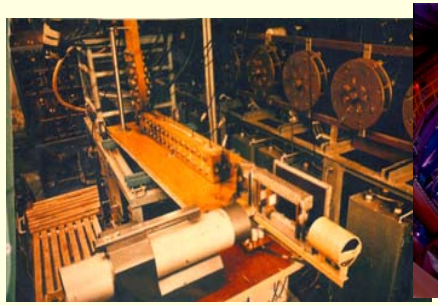


sphere, 14 km/s (Fe)



light gas gun, 8 km/s

Pulsed power



railgun, 10 km/s

Z, Sandia

20 MA, 40 km/s (Al), 300 TW x-ray

Angara-5

6 MA, 12 km/s, 5 TW

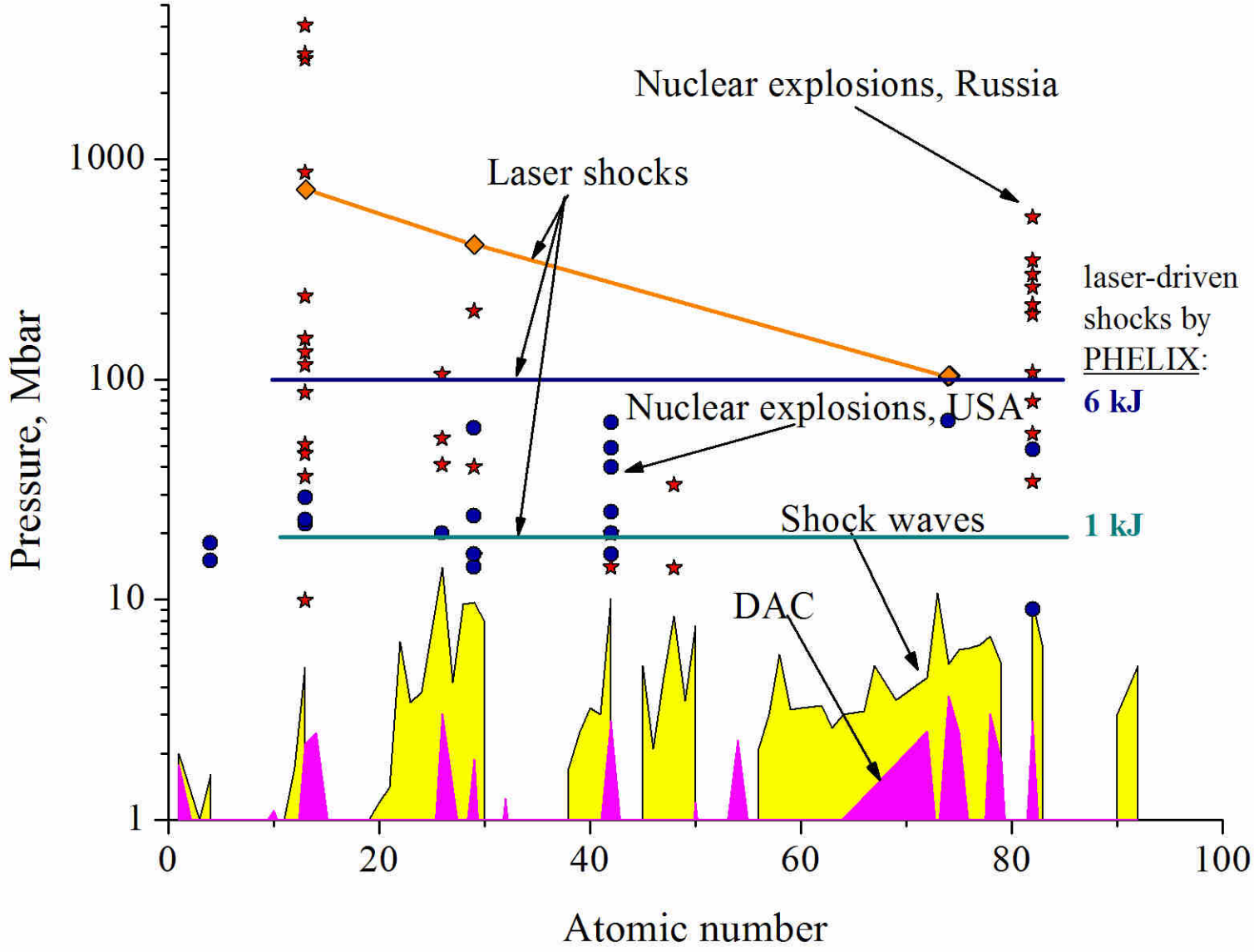
Nuclear

4 Gbar
1000 km/s

NIF, Livermore

21 kJ (10 κJ@350 nm)x192 lasers = 4 MJ (500 TW)

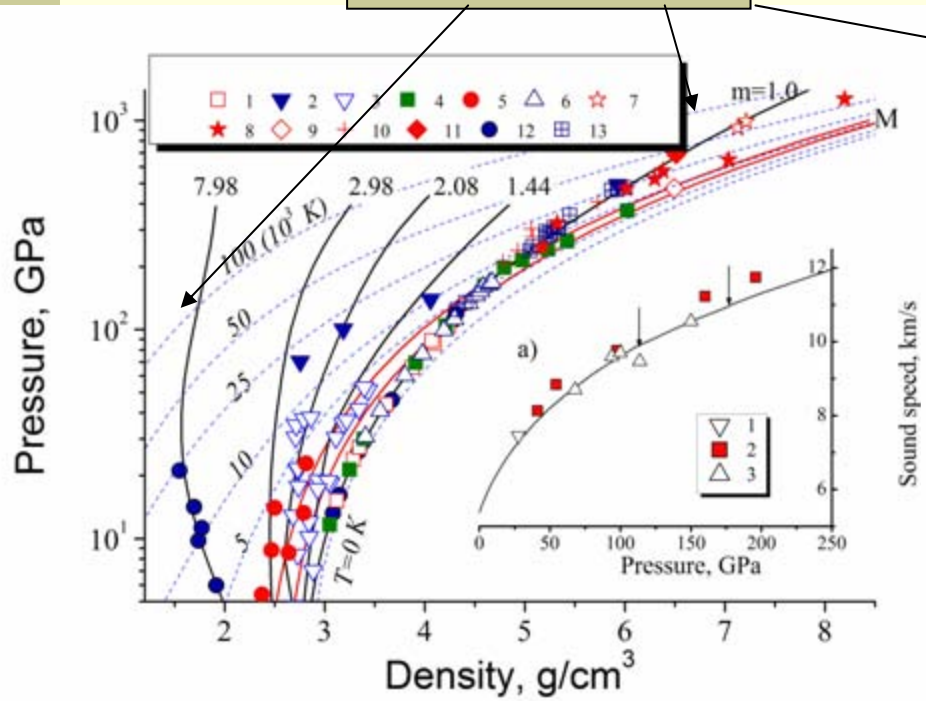
Investigated Pressure Scale of Elements

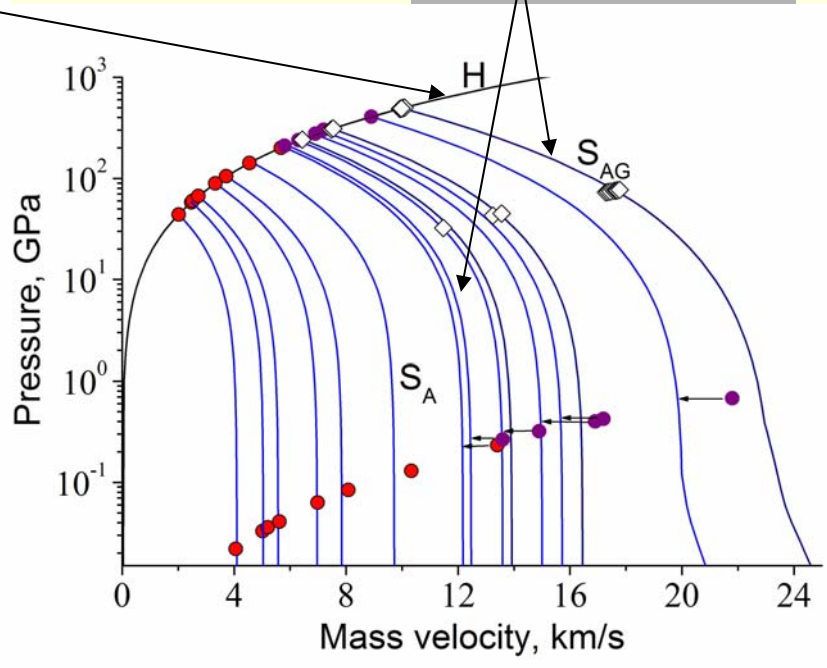


Shock-Wave Data for Al

Shock Hugoniots

Release isentropes





Shock compression:

$0.3 < \rho/\rho_0 < 6$

P < 400 TPa (4 Gbar)

Release expansion:

$10^{-3} < \rho/\rho_0 < 3$

10^{-2} GPa < P < 1TPa (10 Mbar)

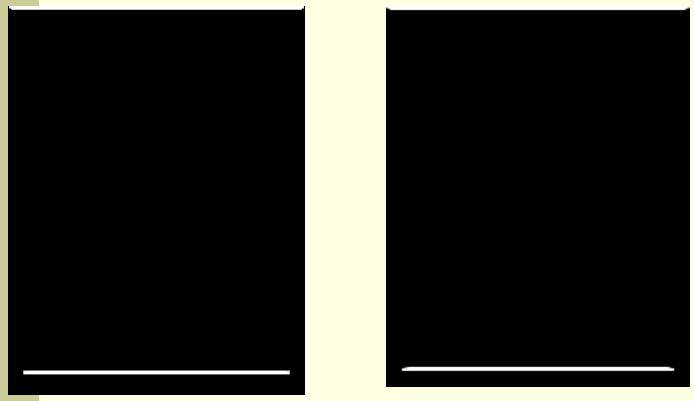
Pressure-density and pressure-mass velocity plots for Al according to I.V.Lomonosov, Laser & Part. Beams, 25, 567 (2007)

Ion beams: FAIR & LHC

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

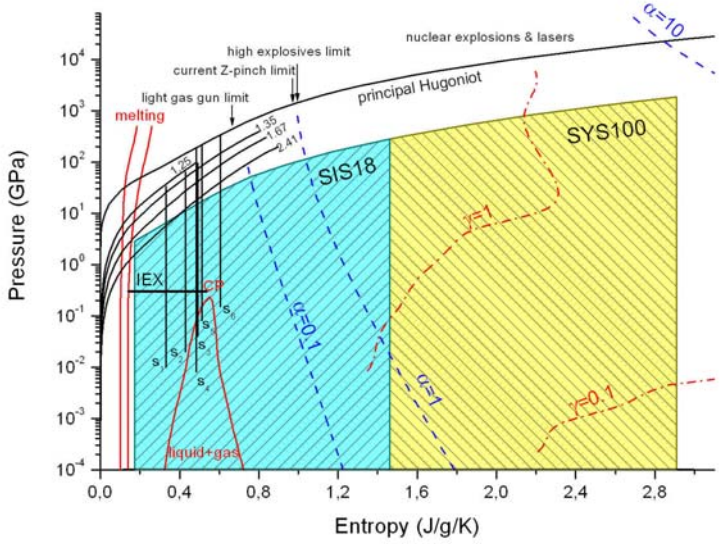
FAIR : HIHEX & LAPLAS

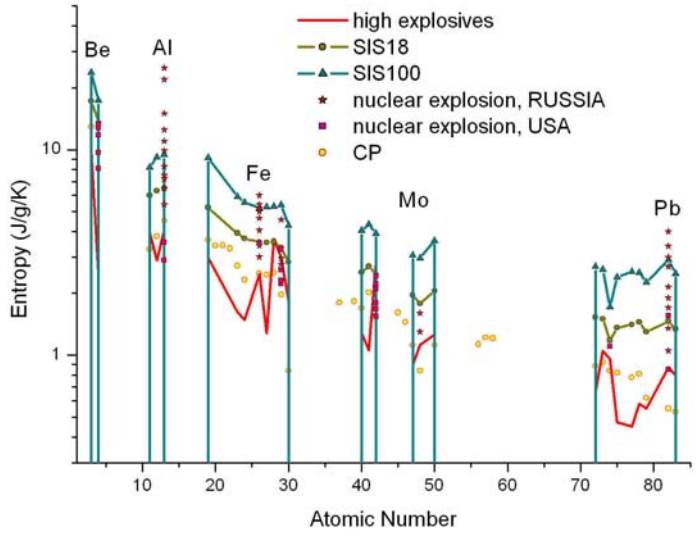
HIHEX (Heavy Ion Heating and Expansion)



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

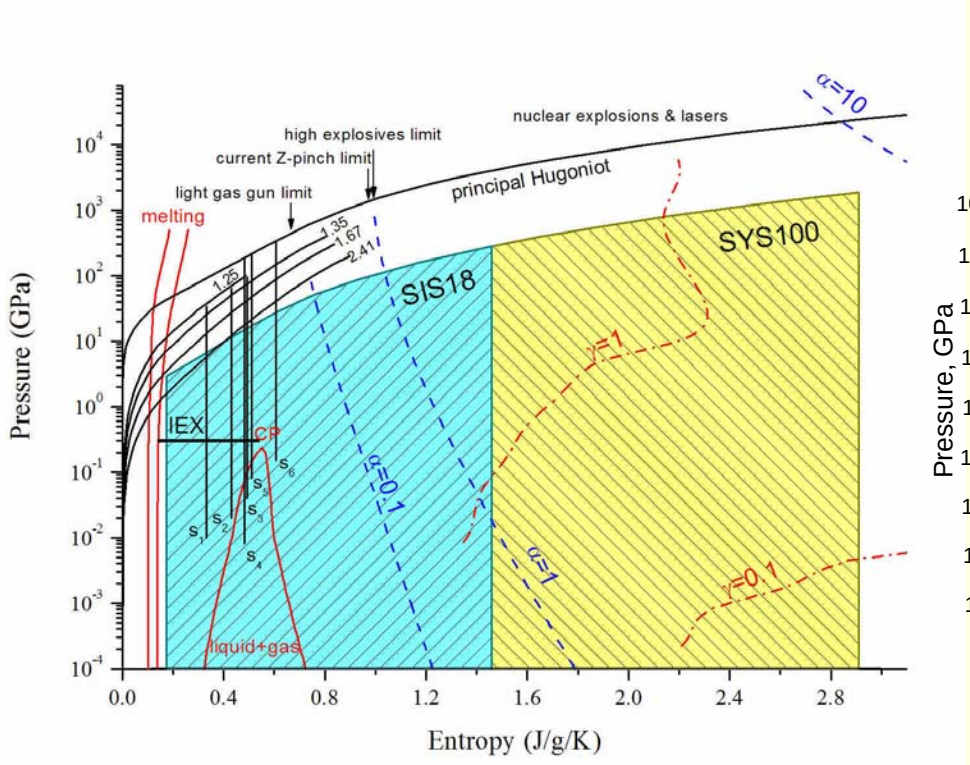
- Different high-energy-density states of matter:
  EOS & transport properties of strongly coupled plasmas, domains of WDM and critical point

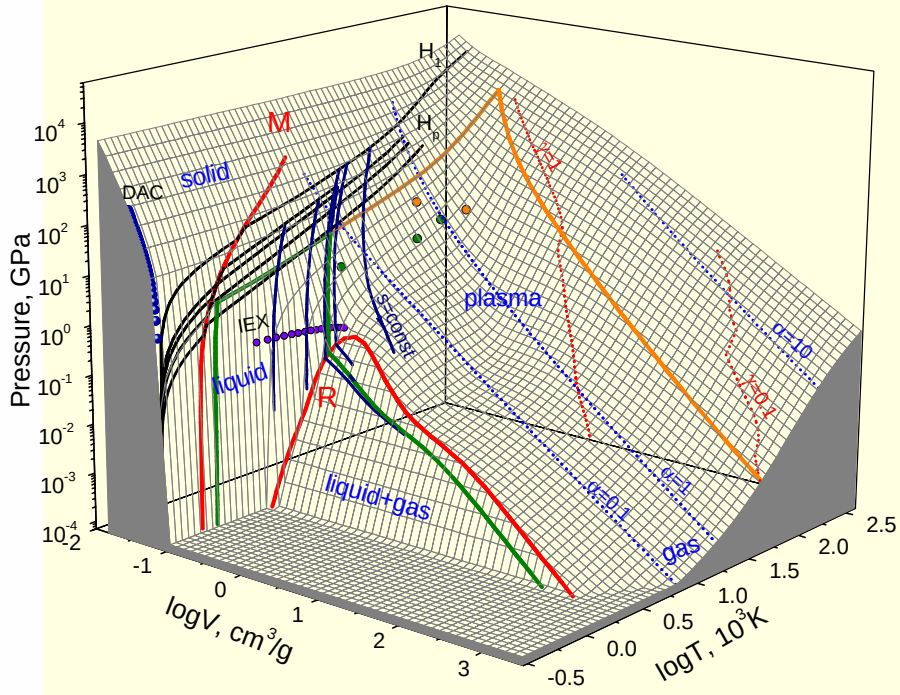




Extreme states in Pb (FAIR)

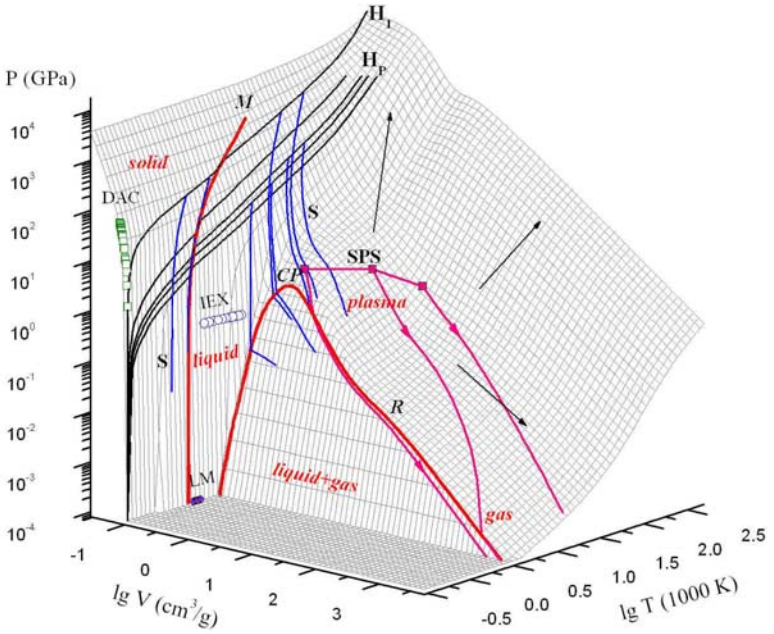
Квази-изохорический нагрев и расширение

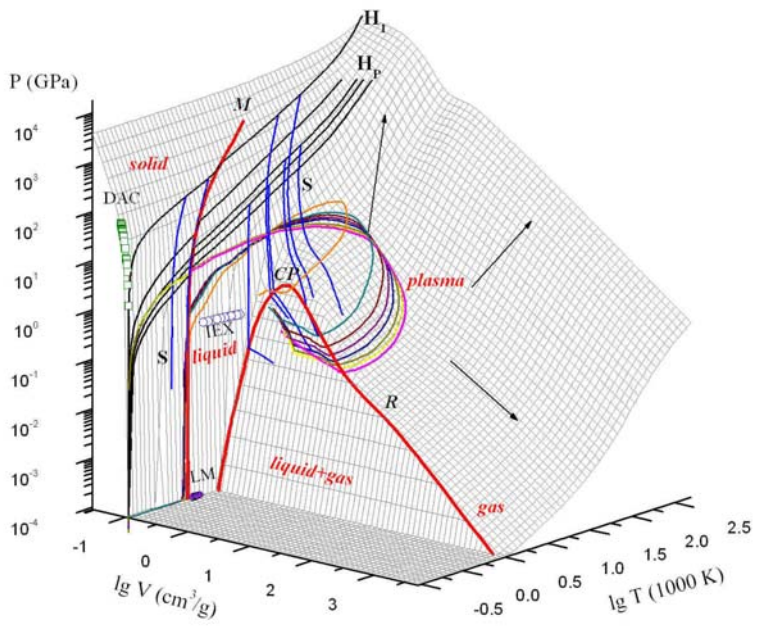




Hoffmann D.H.H., Fortov V.E., Lomonosov I.V., Mintsev V, Tahir N.A., Varentsov D., Wieser J. Phys. Plasmas. 2002. V. 9 P. 3651-3655
N. A. Tahir,C. Deutsch, D. H. H. Hoffmann, M. Kulish, I.V. Lomonosov et al. Phys. Rev. Lett., V.95, p.035001, 2005

Extreme states in Cu (LHC)





N.A. Tahir,C. Deutsch, D.H.H. Hoffmann, I.V. Lomonosov, A.V. Shutov et al. Phys. Rev. Lett., V.94, p.135004, 2005
N.A. Tahir, R. Schmidt, M. Brugger, I.V. Lomonosov, A. Shutov, et al. Laser and Particle Beams, v. 25, 2007, pp. 639-647
N.A.Tahir, R.Schmidt, M.Brugger, R.Assmann, A.V.Shutov, I.V.Lomonosov, V.E.Fortov, et al. New Journal of Physics, 10, 073028 (2008)

Experiments: Al 3D P-V-T

Hugoniots H_1, H_p: U_s-U_p (P,V,E)

ICE: P(V,S=const)

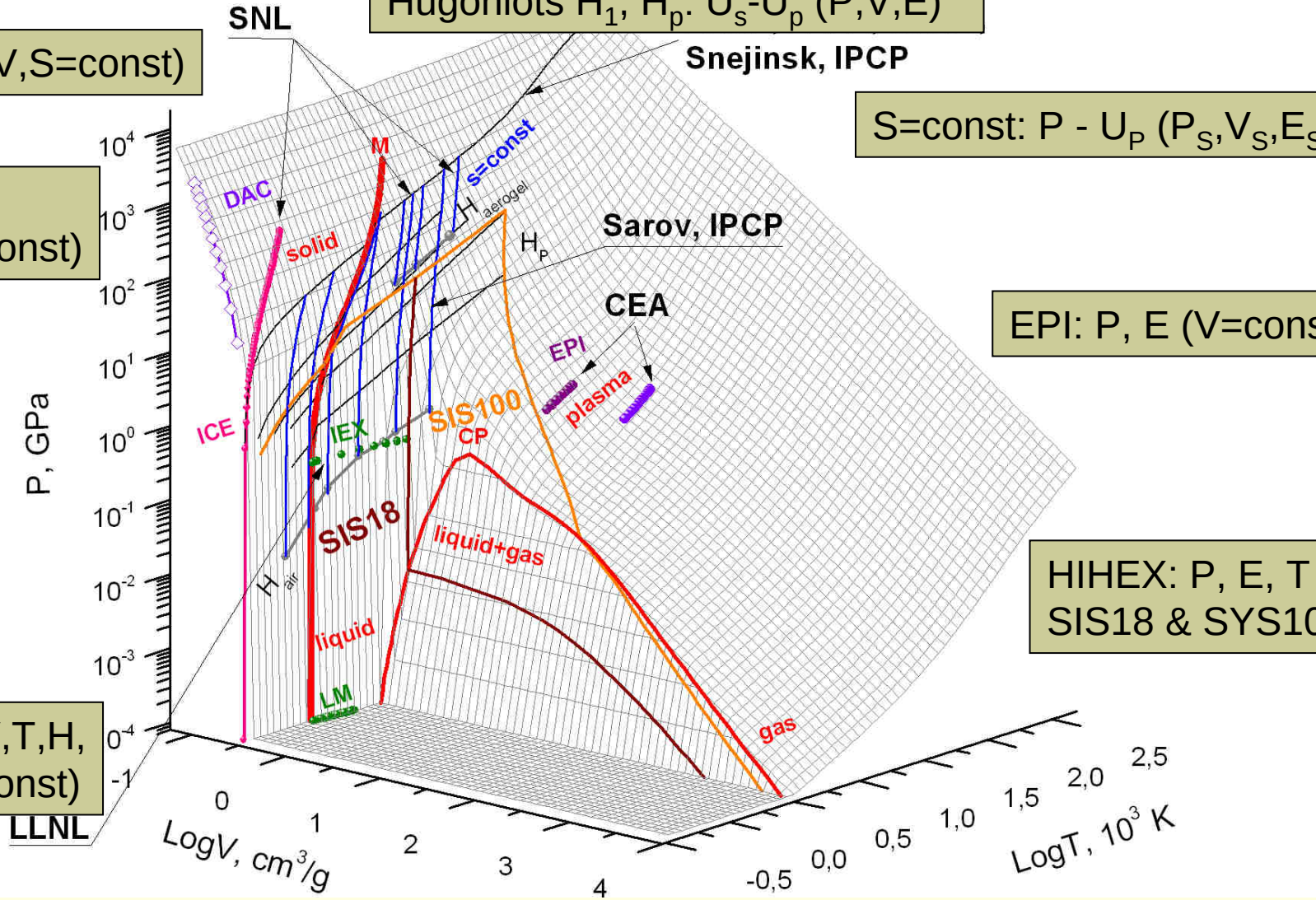
S=const: P - U_P (P_S,V_S,E_S)

DAC: P(V,T=const)

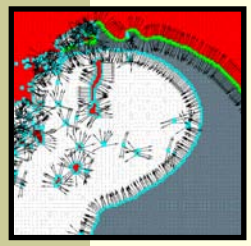
EPI: P, E (V=const)

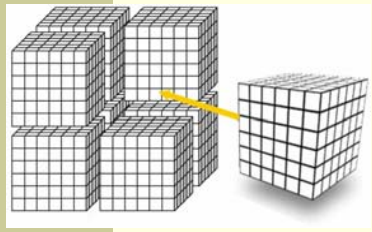
HIHEX: P, E, T (t) SIS18 & SYS100

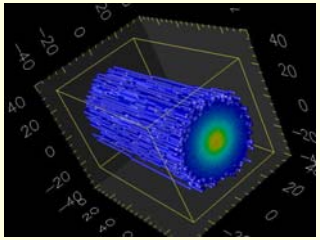
IEX: E,V,T,H, Cs (P=const)



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)

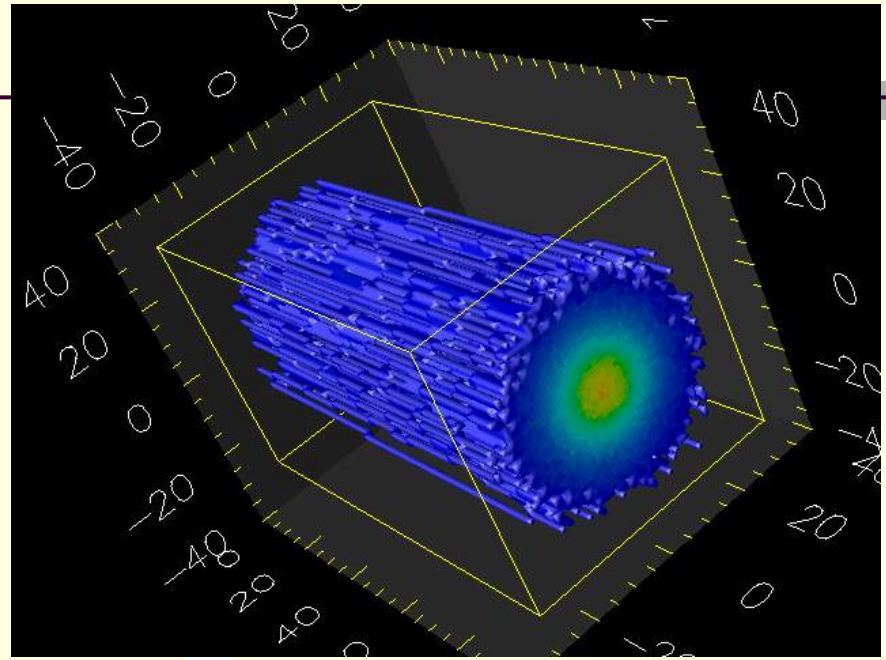
V. E. Fortov, V. V. Kim, I. V. Lomonosov, A. V. Matveichev, A. V. Ostrik. Numerical modeling of hypervelocity impacts, Intern J Impact Engeneering V.33. P.244-253 (2006).

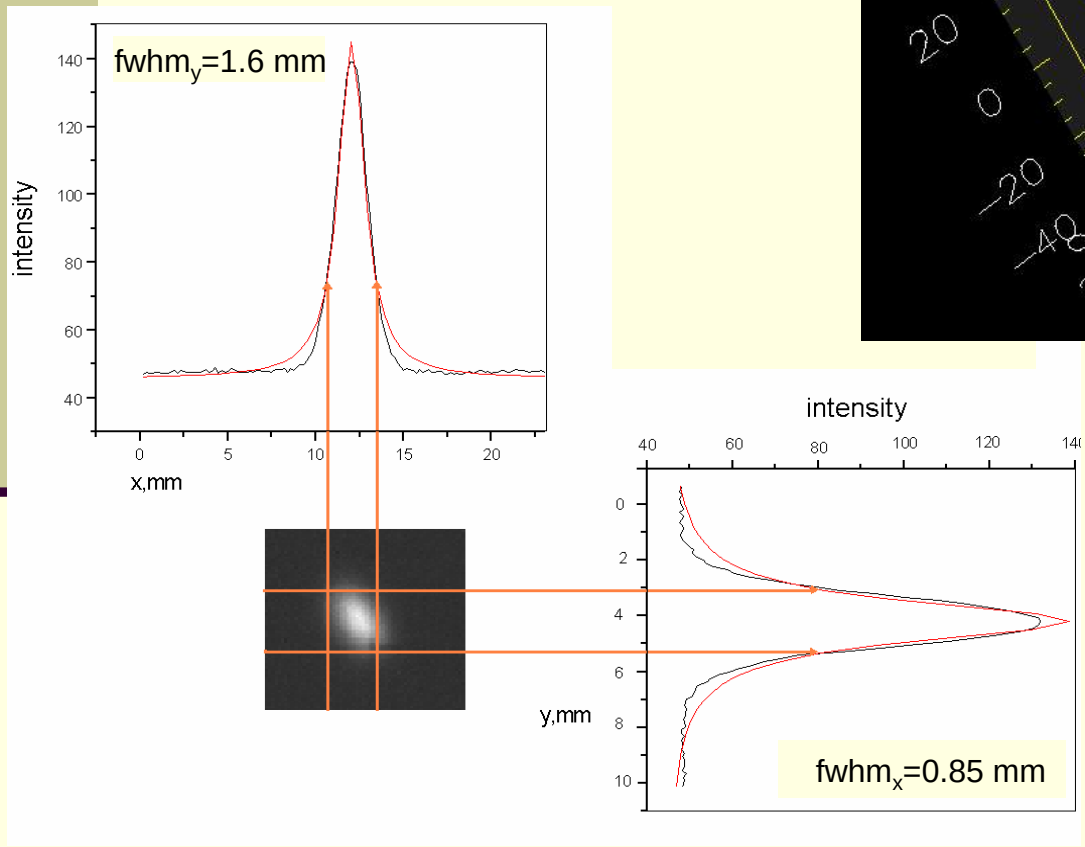
V.V.Kim, I.V.Lomonosov, A.V.Ostrik, V.E.Fortov. Finite-size particle in cell method for numerical modeling of high-energy-density loadings on matter. Mathem. Modeling, 18(8), 5-11 (2006) [in Russian]

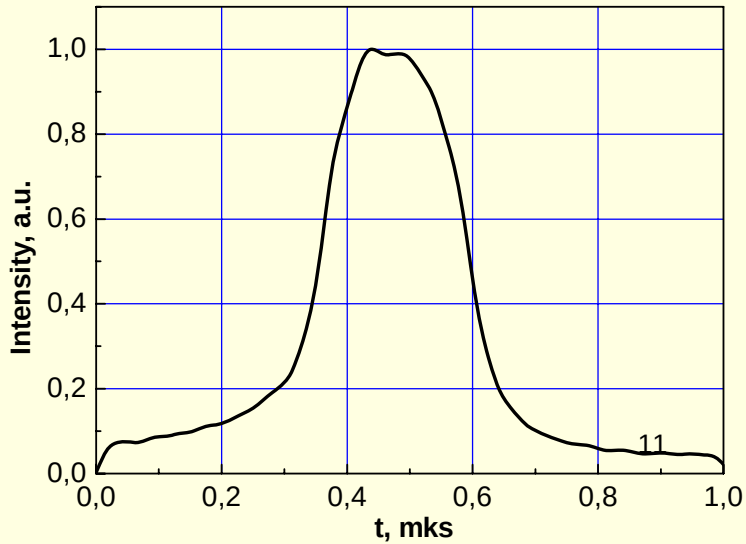
3D Ion Beam

Ions Paths Ensemble:

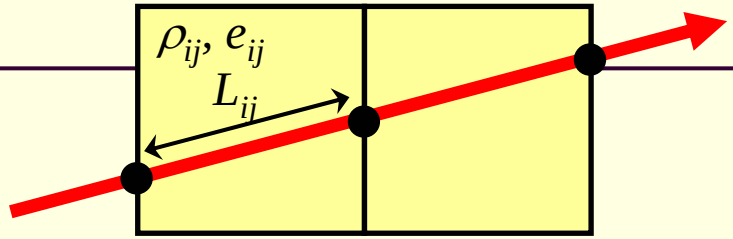
$$\{\vec{r}_0, \vec{r}, E_0\}_N$$



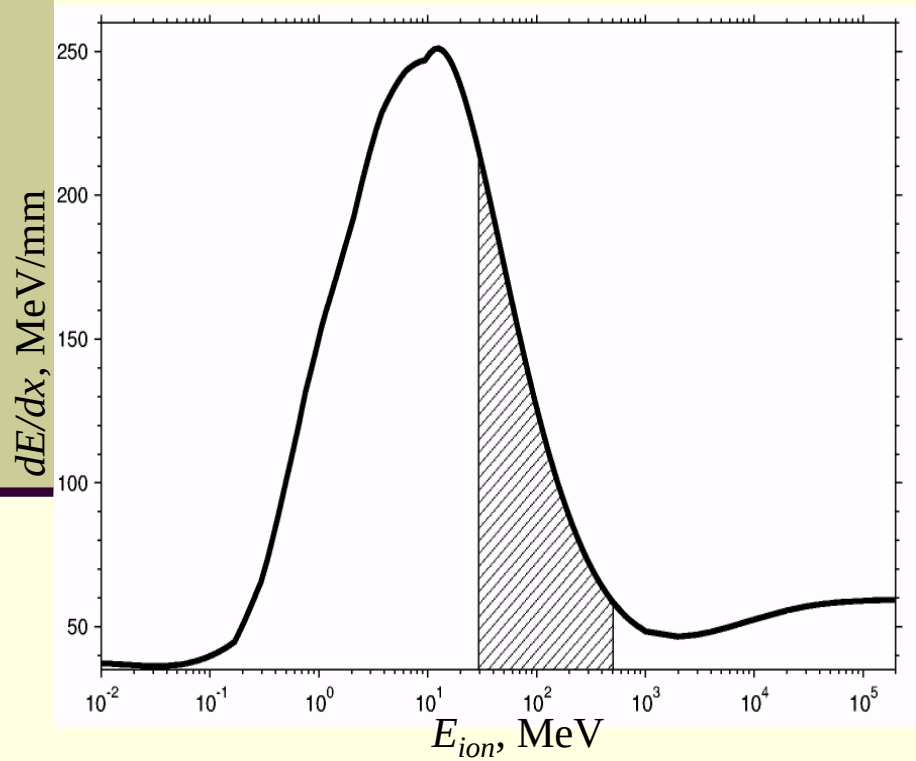


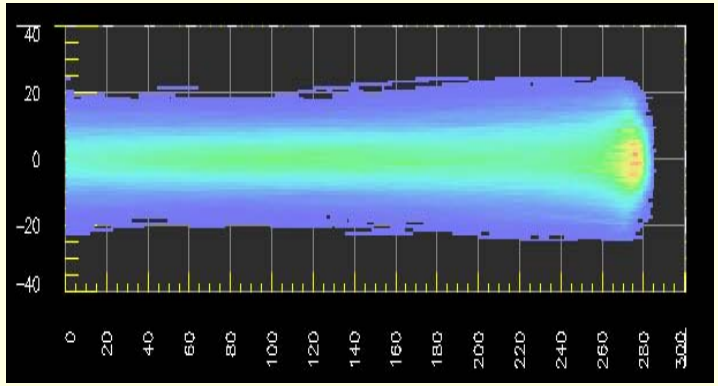


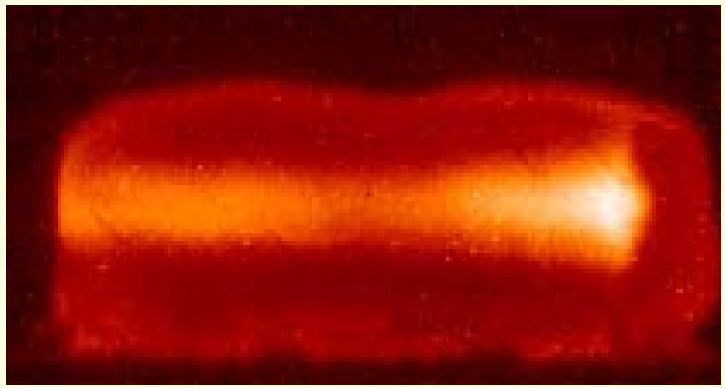
Ion Beam Energy Deposition



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







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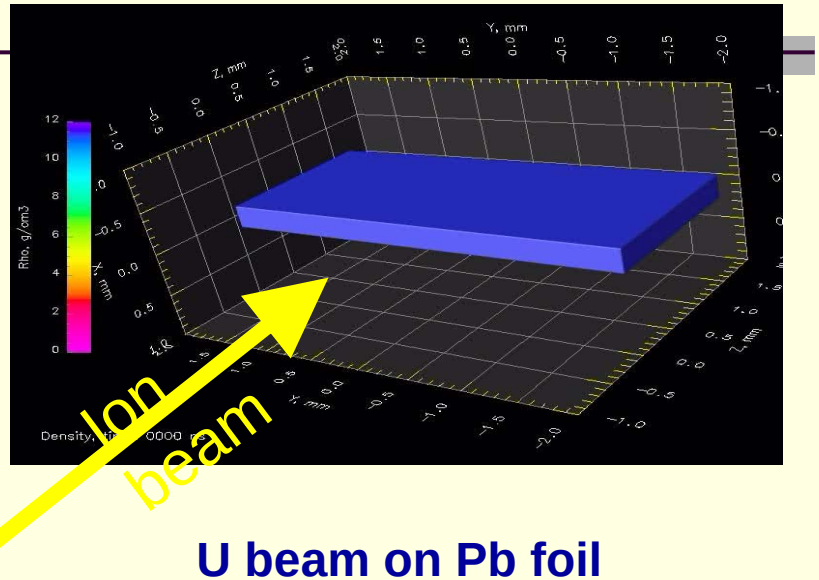
** M.M.Basko, N.A.Borisenko, A.A.Golubev et al. Report on International Conference «Equation of State of Matter», Elbrus, 2004*

Modeling: HED Experiments & FAIR

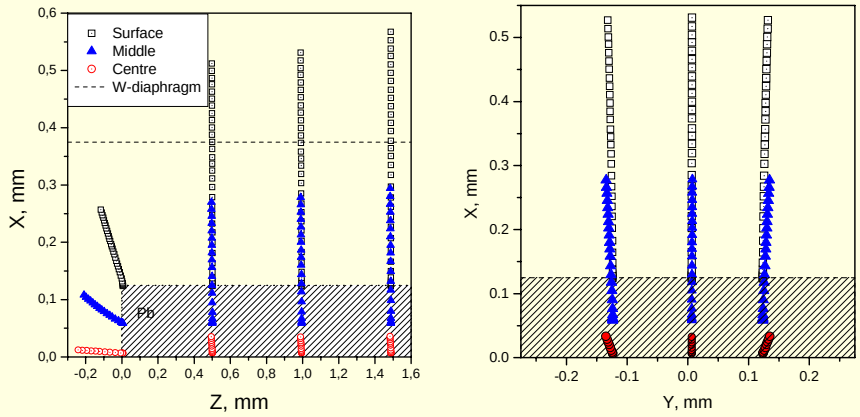
FPIC3D, 2D Godunov:

energy deposition (SRIM)
EOS
elastic-plastic
fracture

3D energy deposition



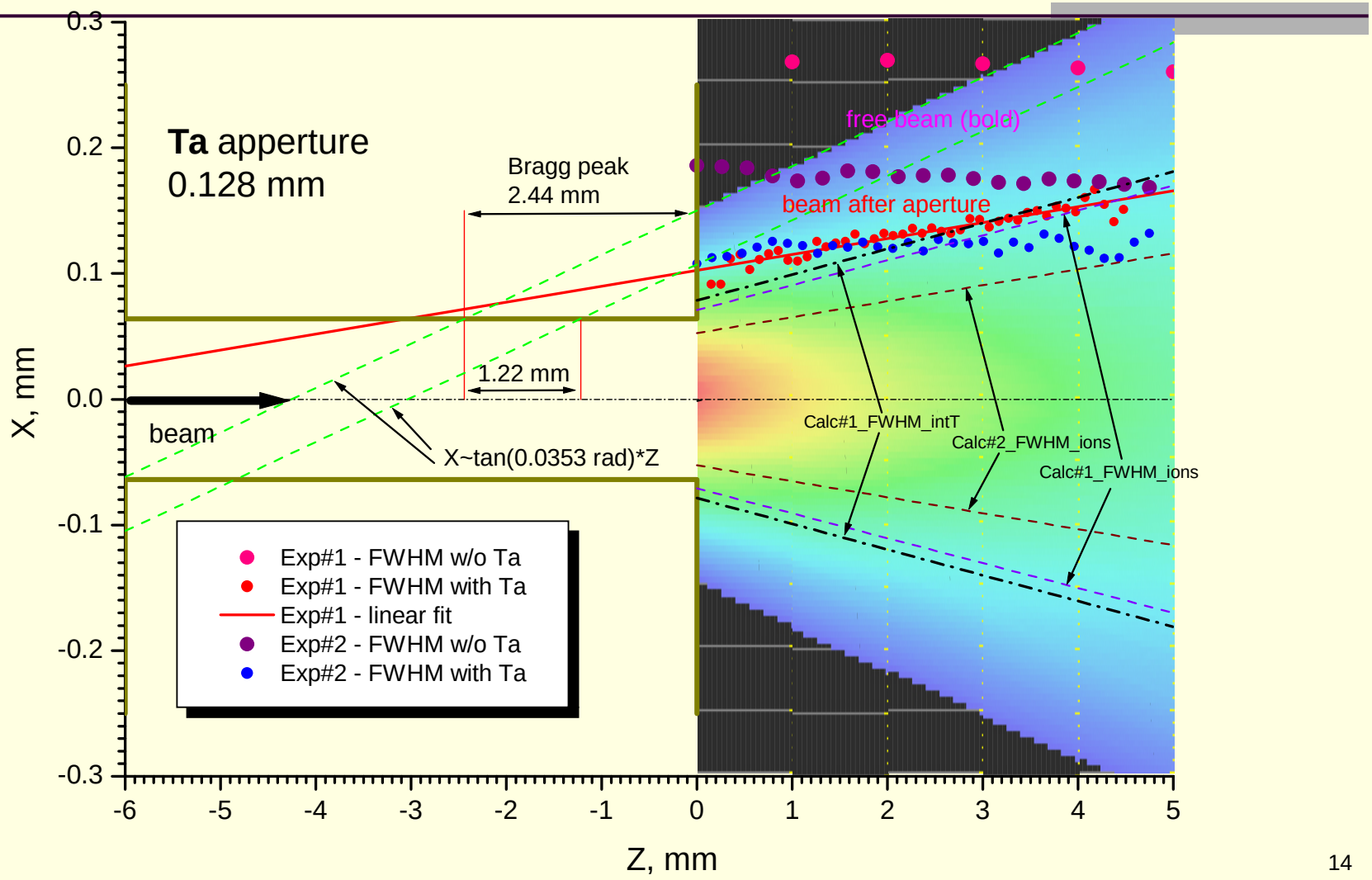
U beam on Pb foil



trajectories of target expansion: good uniform 1D expansion

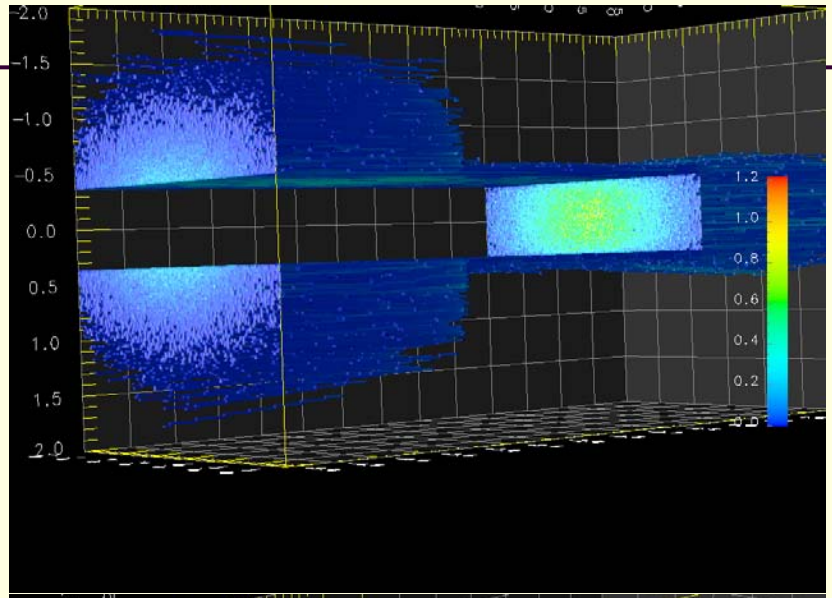
3D Results:

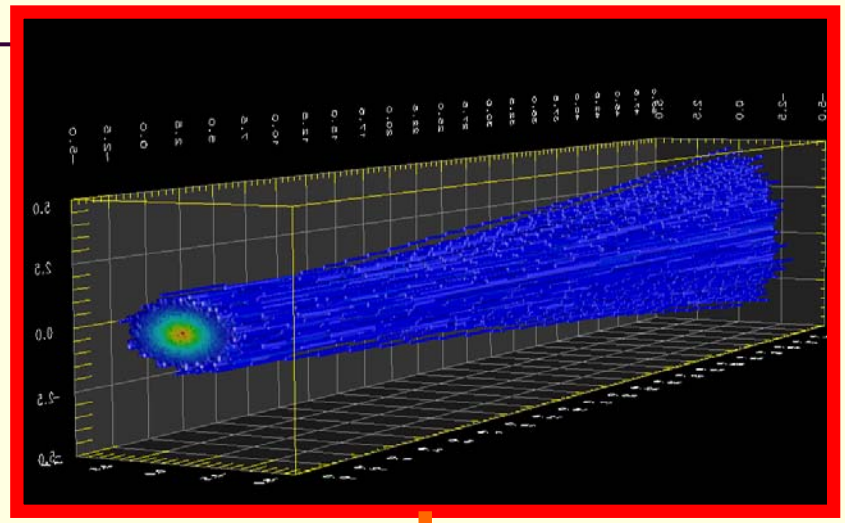
Influence of the Aperture on the Beam Geometry

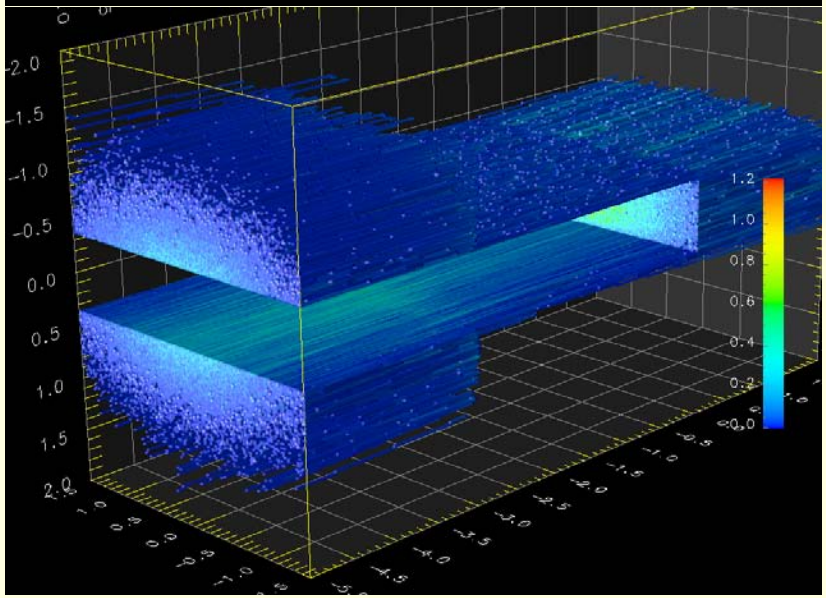


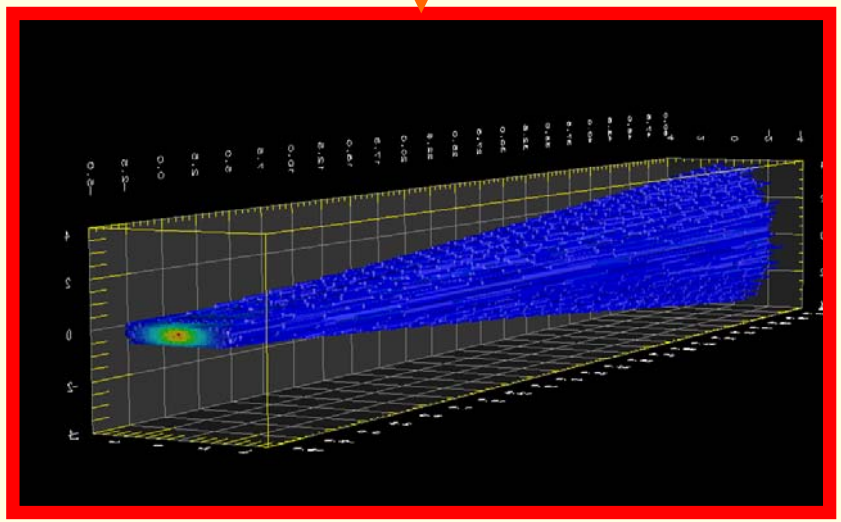
$^{238}U^{73+}$ in Pb

Influence of the Aperture on the Beam Geometry



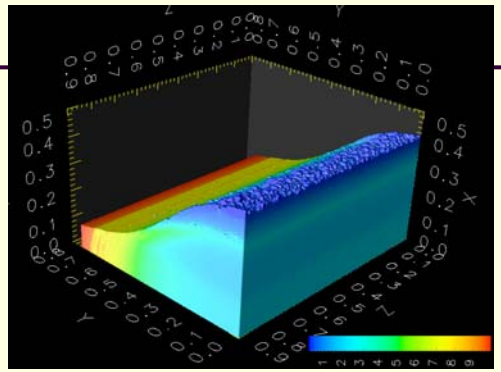


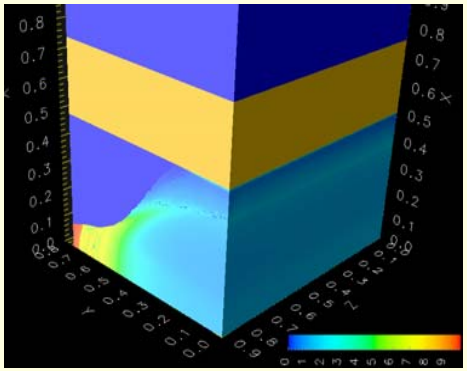


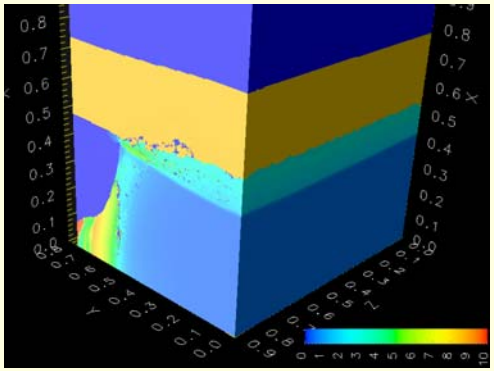


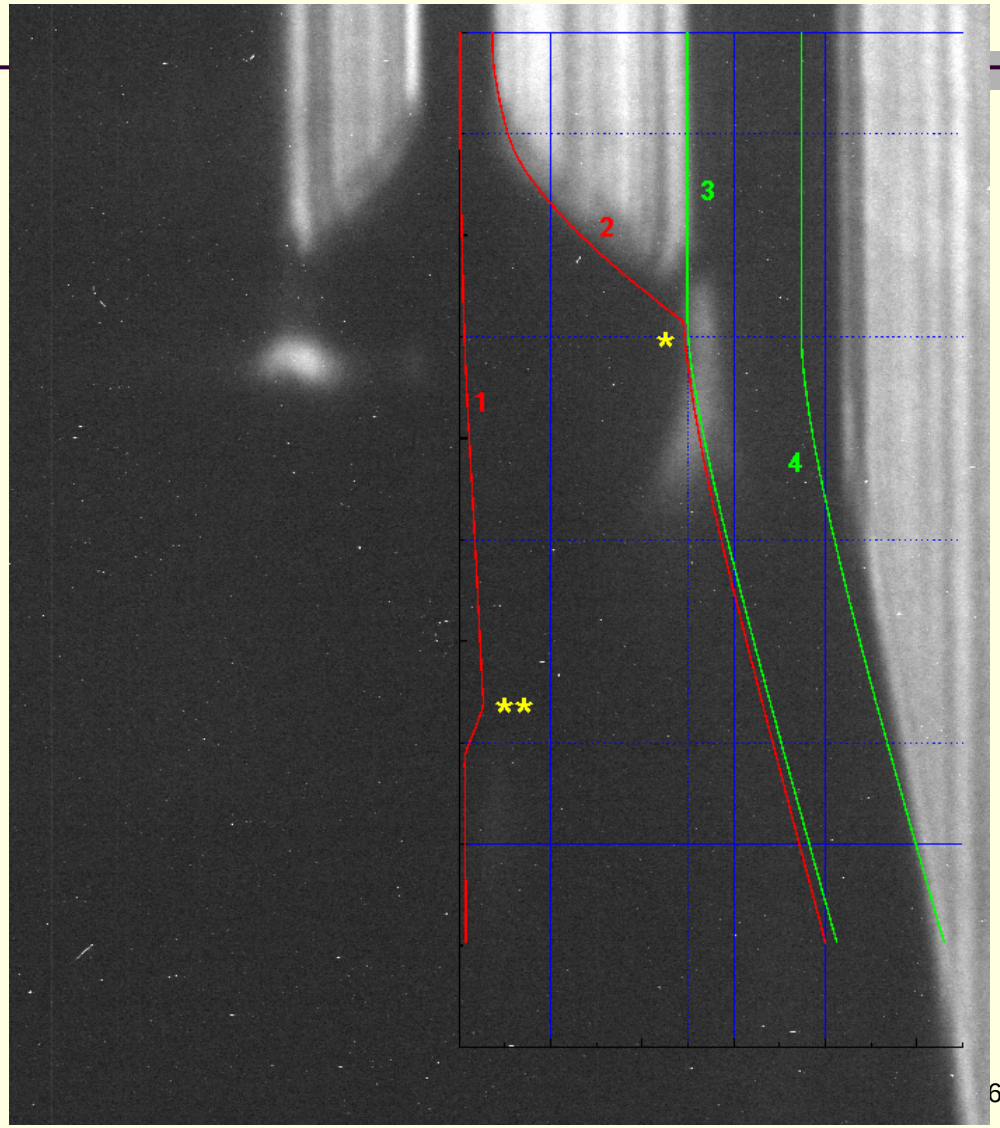
3D Results:

Acceleration of Iron Foil



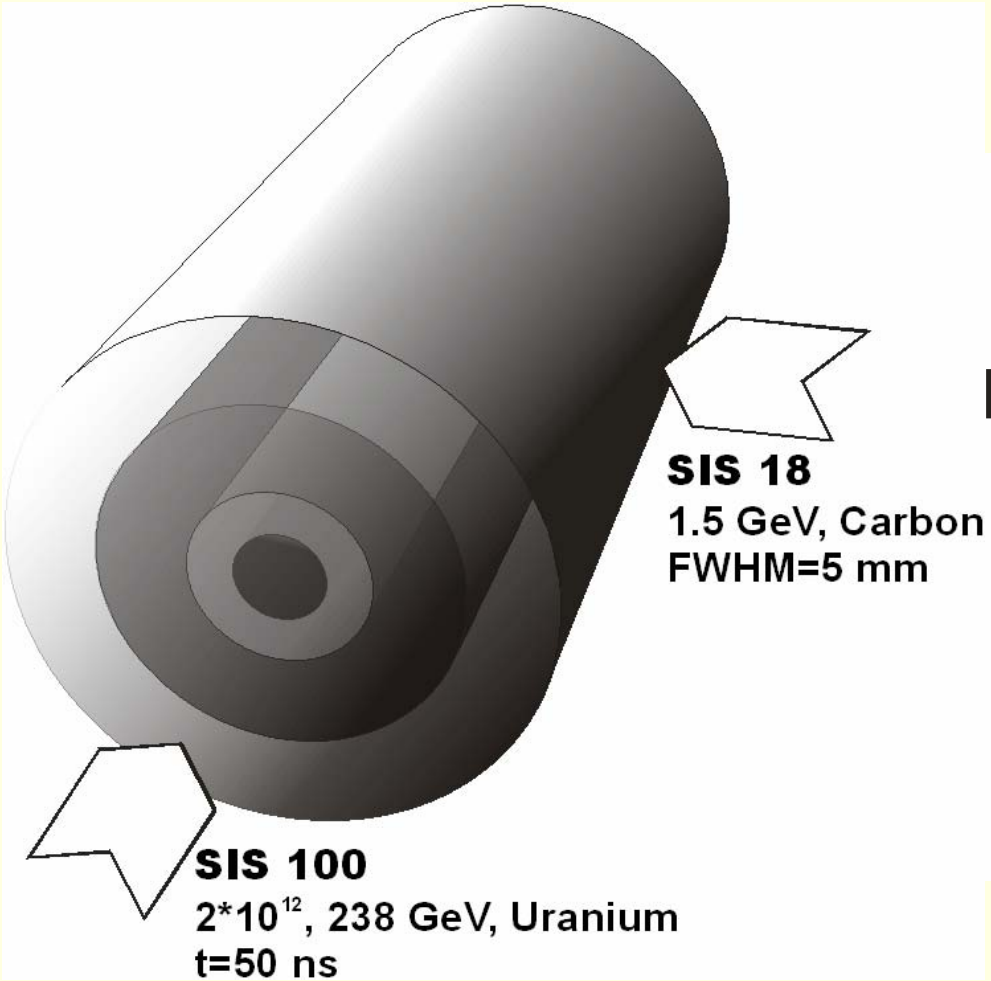


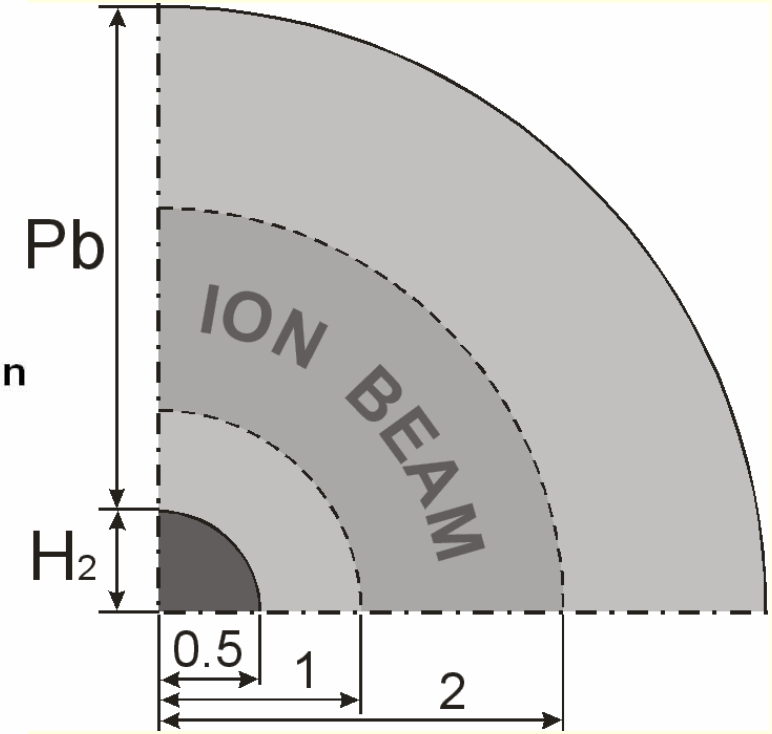




HHT August 2006, shot#39

3D Ion Radiography
(Energy loss Dynamics)

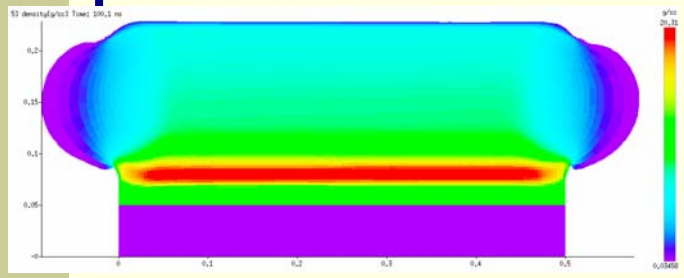




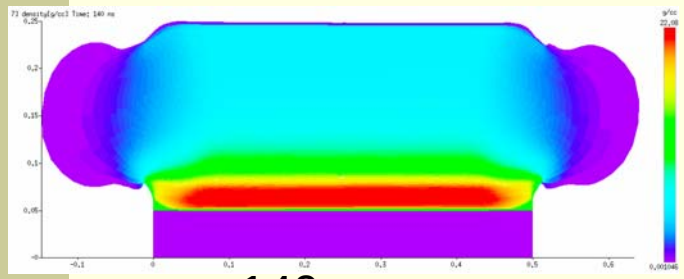
3D Results:

Ion Radiography in LAPLAS Experiment

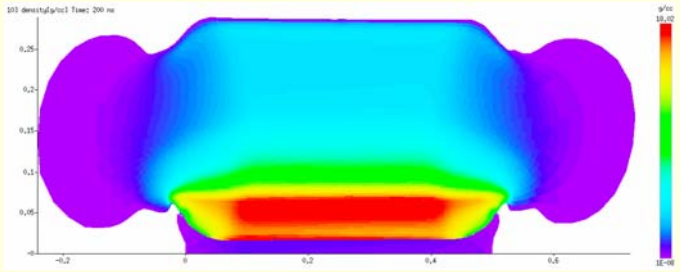
The results of 2D high-resolution calculations (BIG-2) of the LAPLAS experiment were used in 3D ion radiography setup (PIC3D)



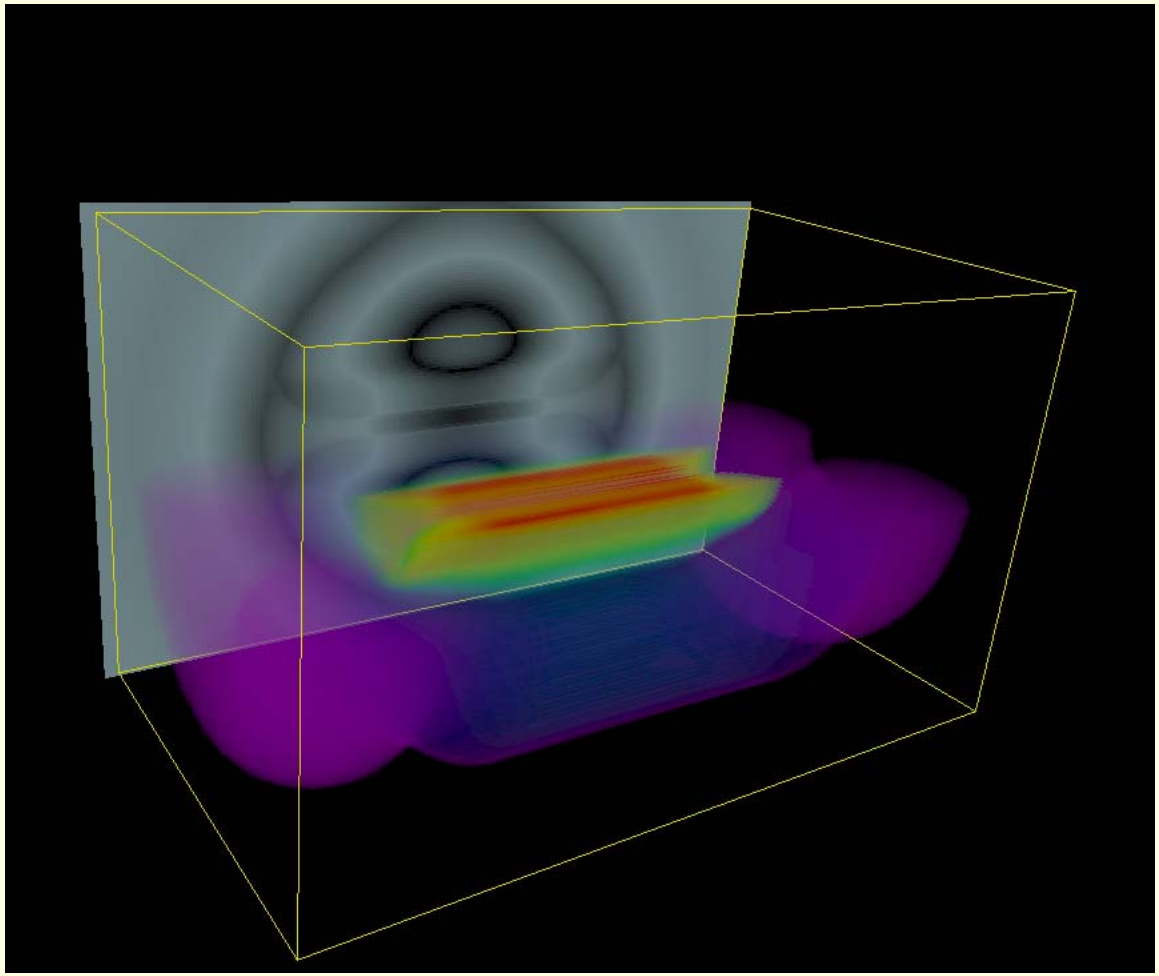
100 ns



140 ns



200 ns

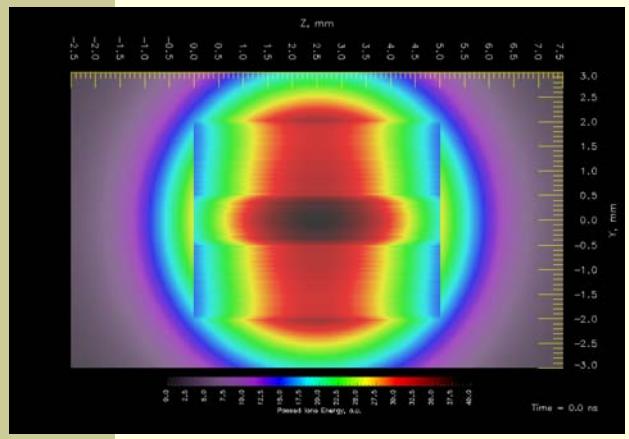


3D Density field section combined with resulting radiogram at 200 ns

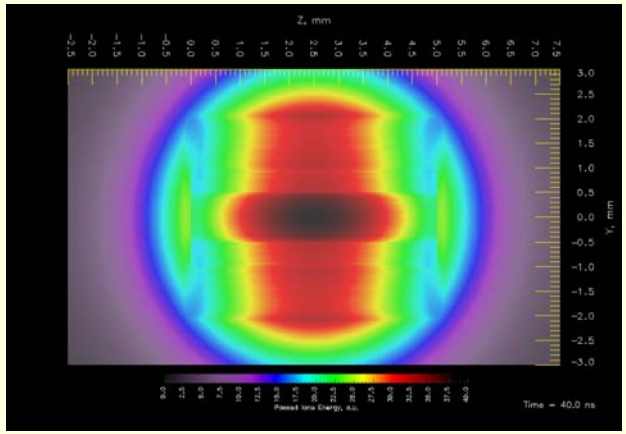
Ion Radiography

Results of numerical Modeling

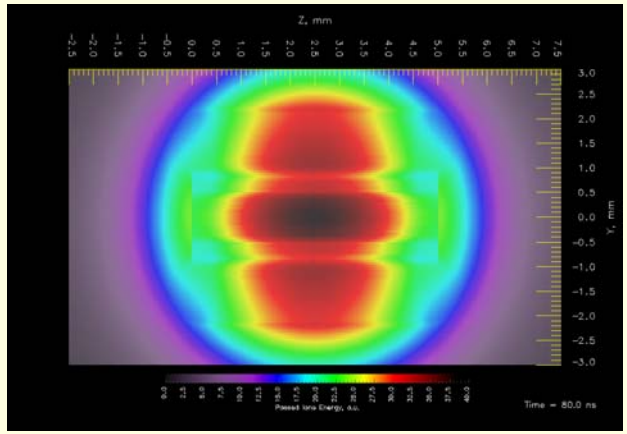
40 ns



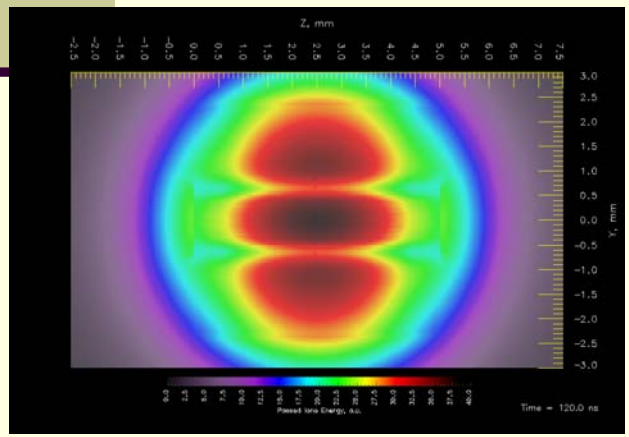
80 ns



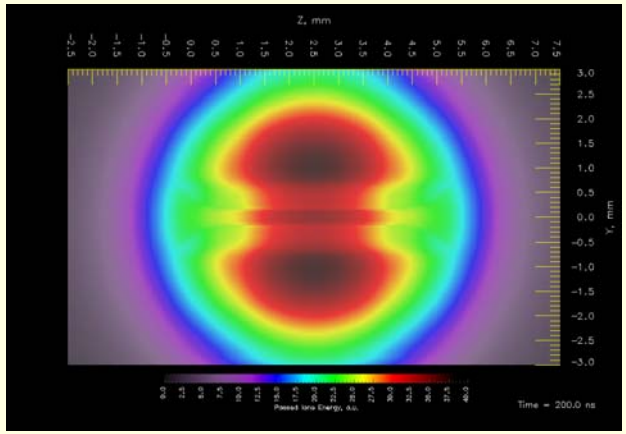
120 ns



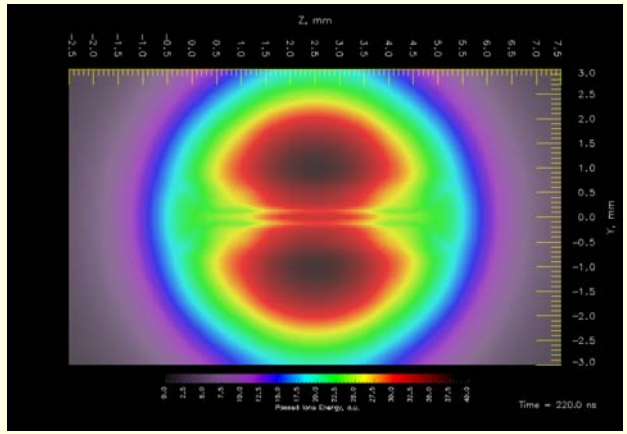
160 ns



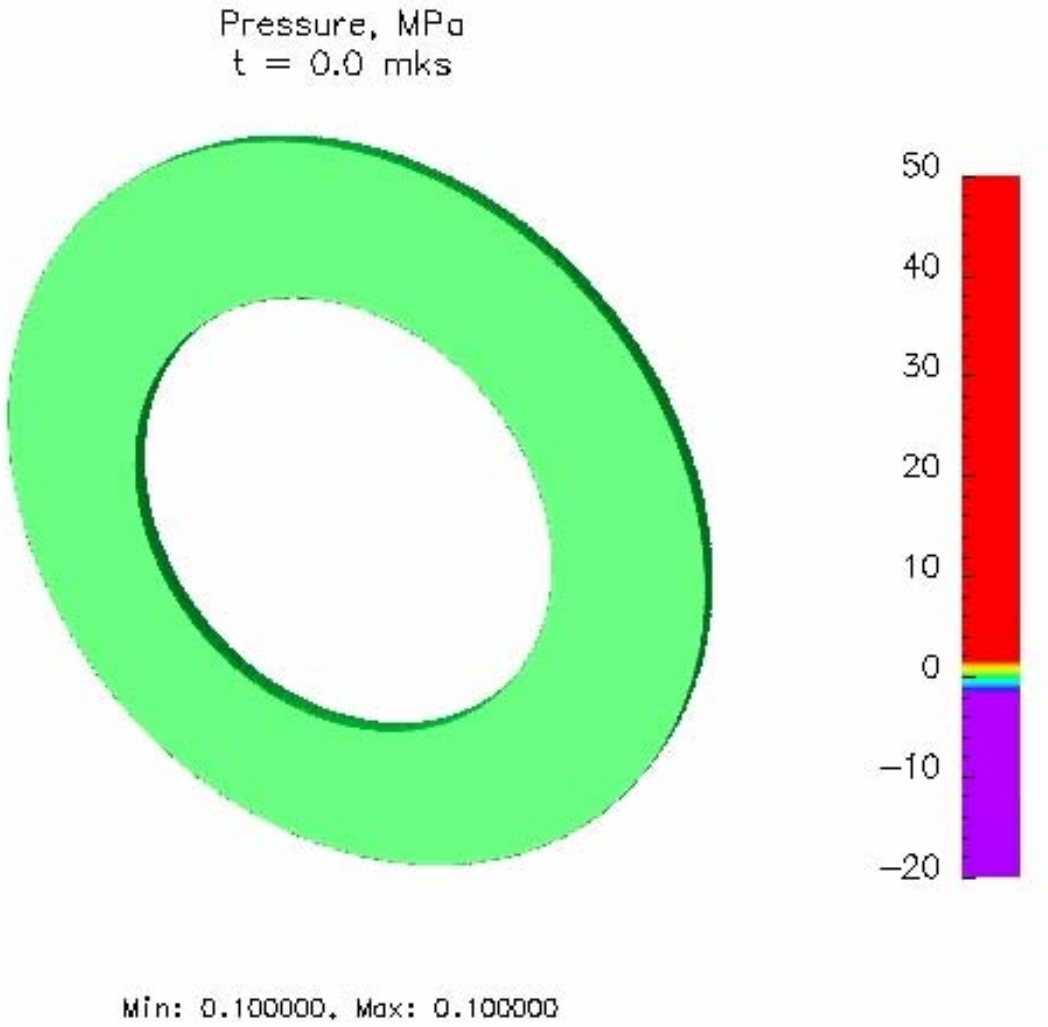
200 ns



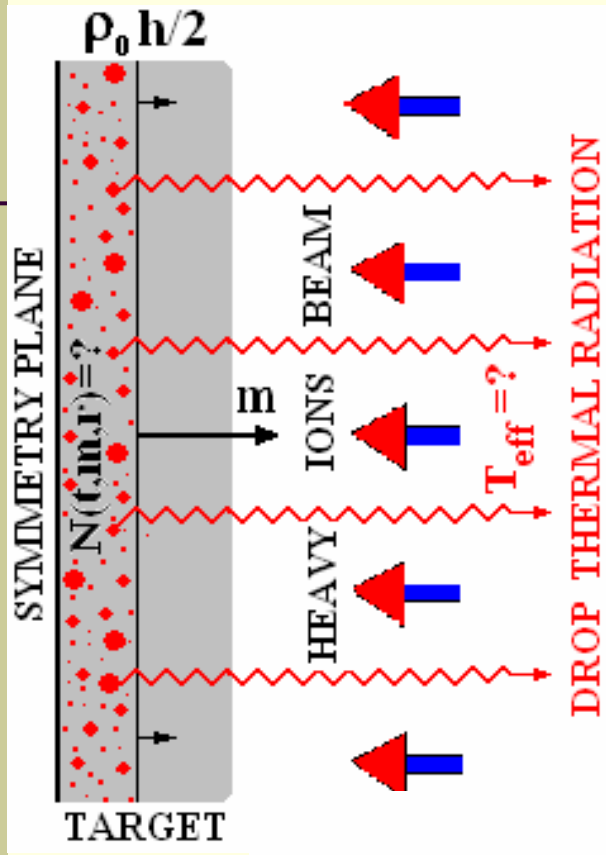
220 ns



Anti-proton Target (FAIR)



THERMAL RADIATION: FORMULATION

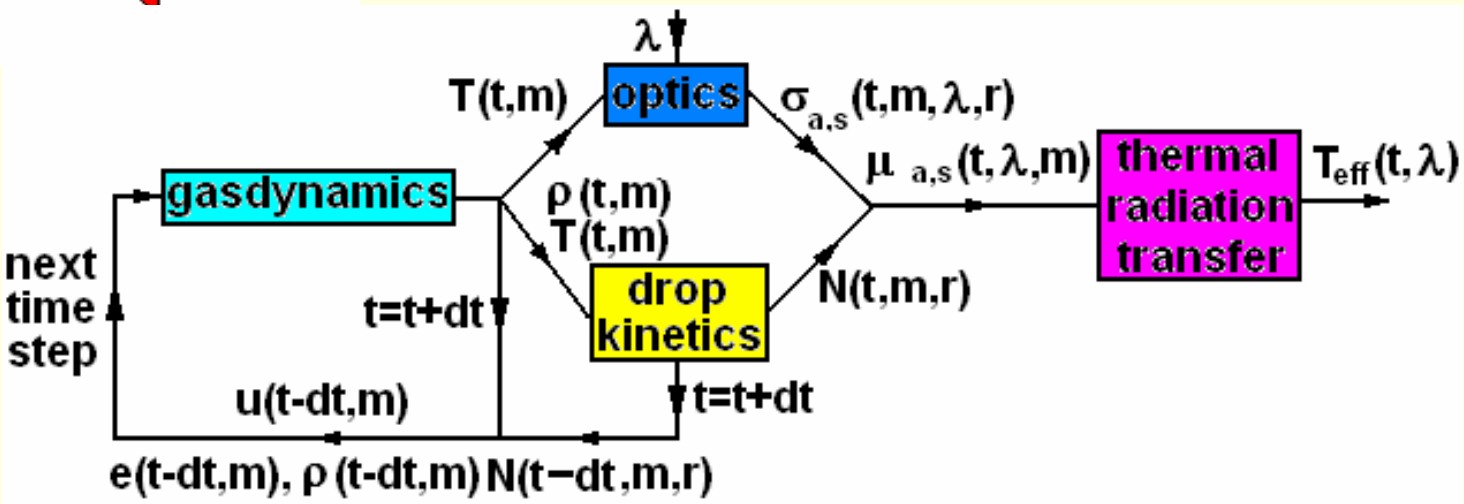


Goal: development of theoretical drops radiation model

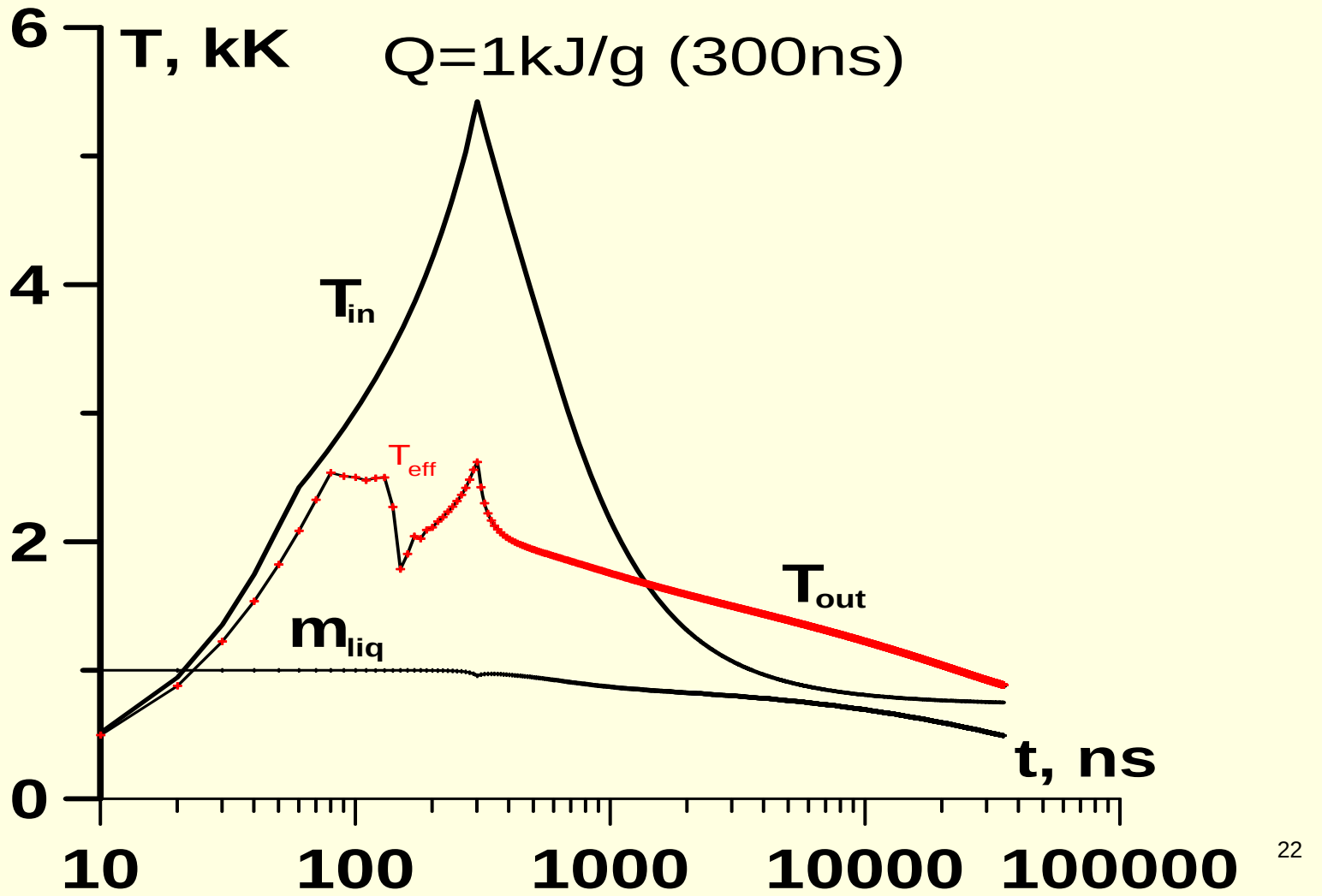
Tasks :

- 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;
- selections models and their numerical realization for calculations of drop absorption sections and complex index of reflection;
- preliminary computations of effective temperature

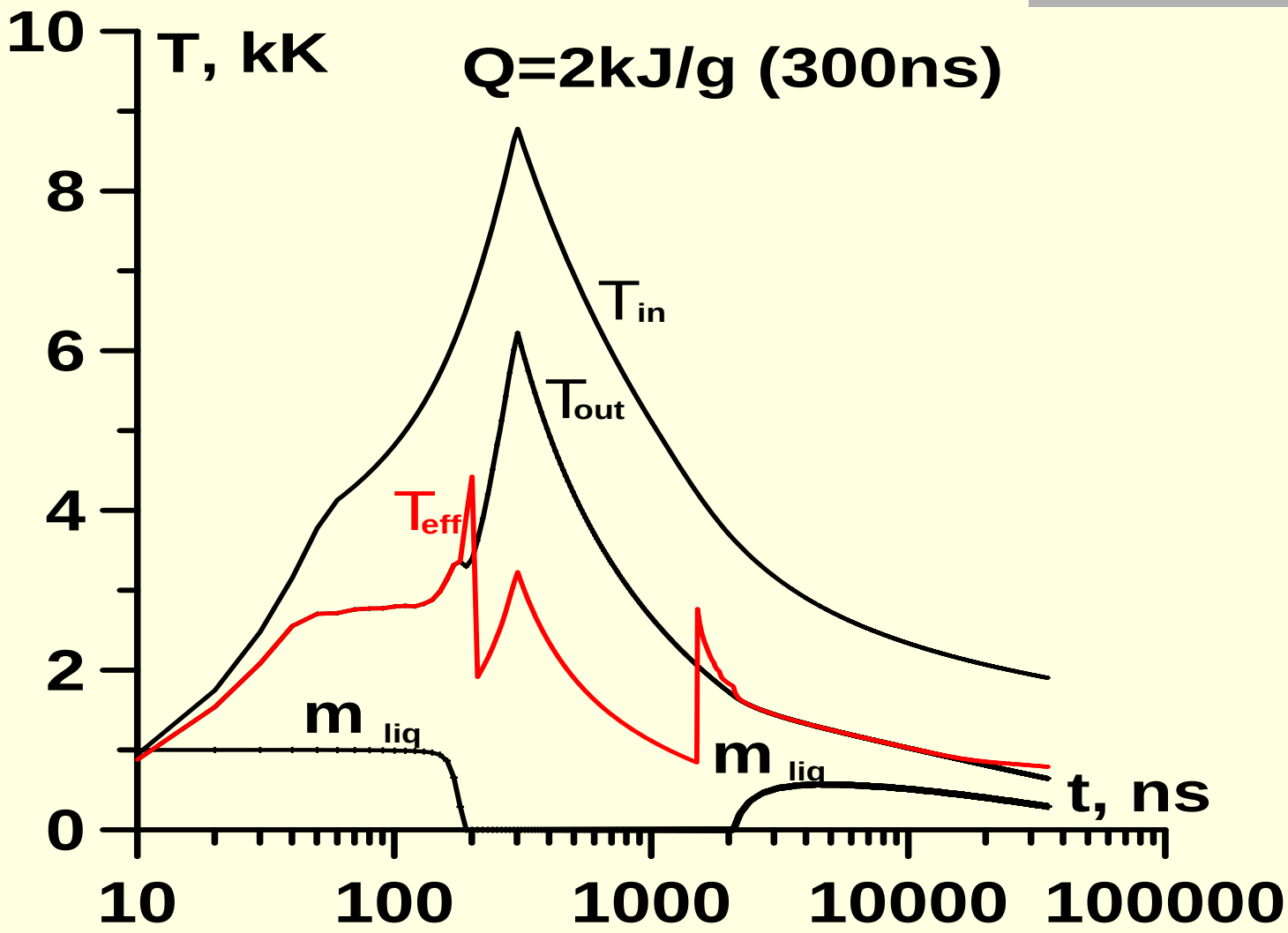
T_{eff}=? --- >



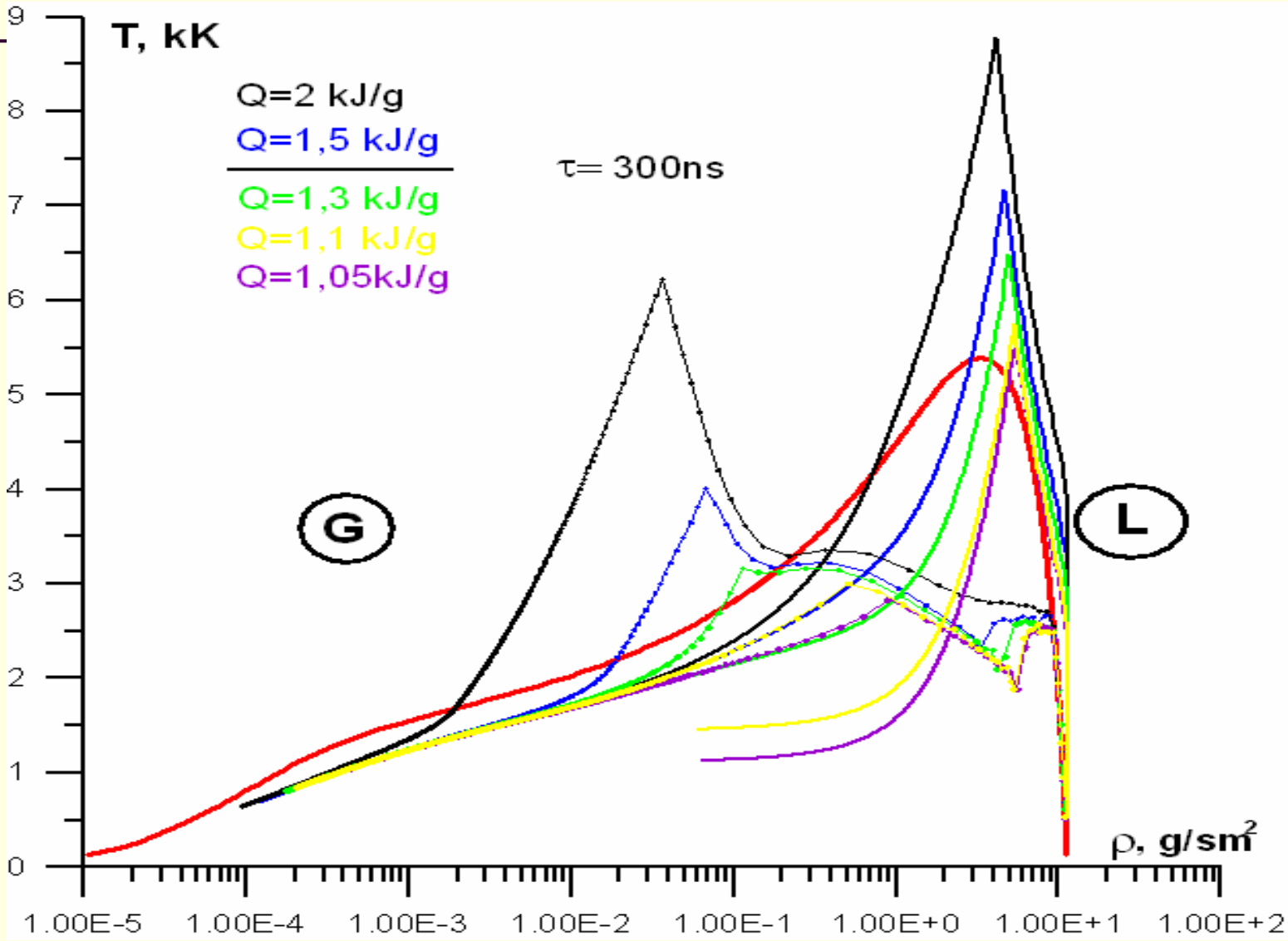
THERMAL RADIATION TRANSFER



THERMAL RADIATION TRANSFER

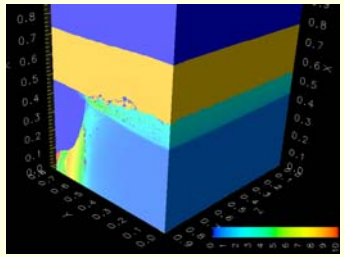


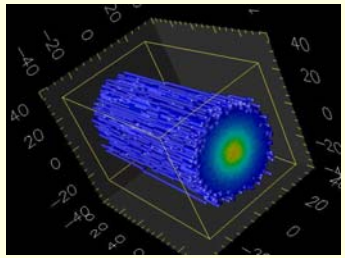
VAPOR-DROP REGIONS

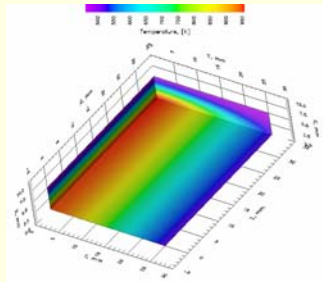


Conclusions

- 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)

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