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)

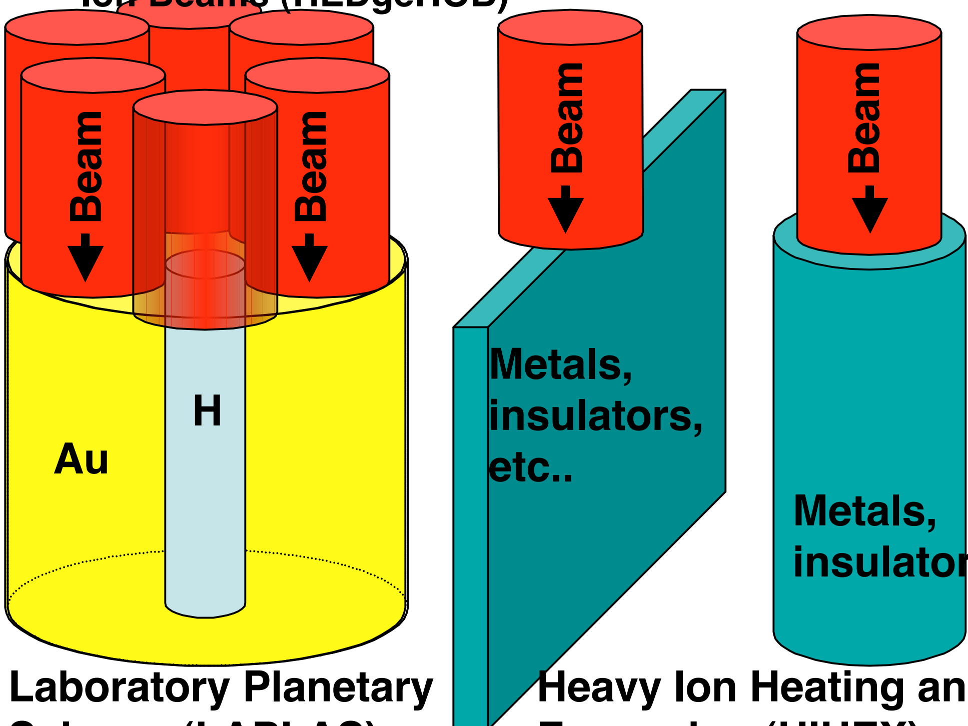
2. Simulations of the LAPLAS experiment using HYDRA, and comparison with GSI simulations

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)

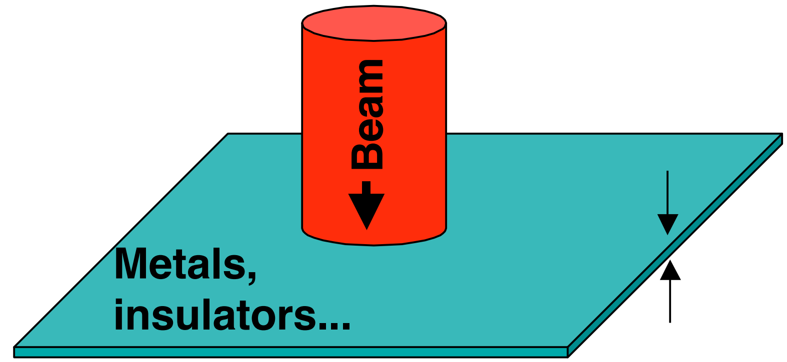


Laboratory Planetary Science (LAPLAS) (at GSI)

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

Ion energy: ~ 2 GeV/u
Ion current: ~ 2 A
Pulse duration: ~ 50 ns
Characteristic radial dimension: ~ 1 mm (solid)

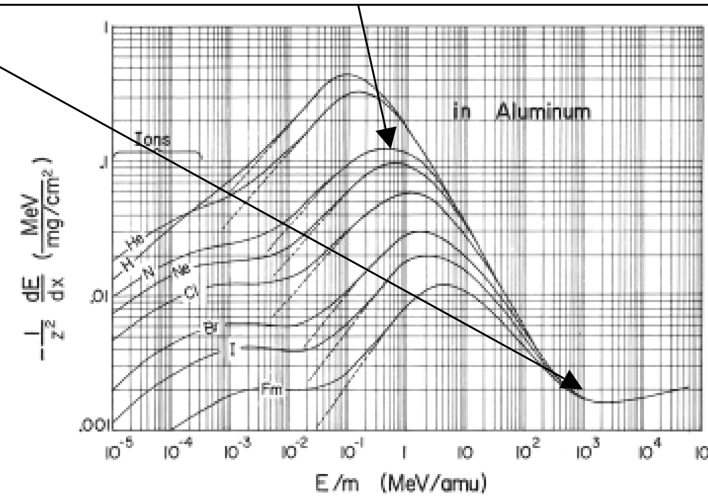
(Isochoric = constant volume)



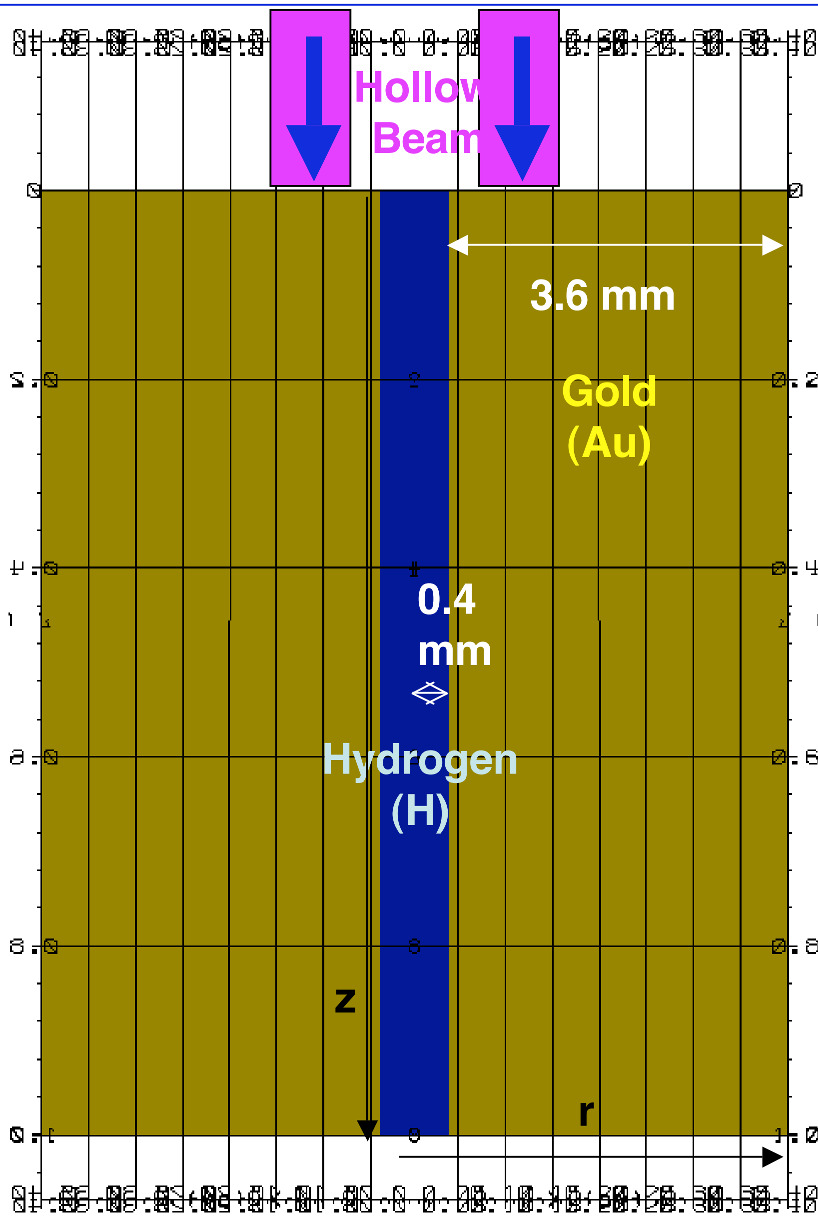
NDCX (at HIFS VNL)

Ion energy: < 1 MeV/u
Current: ~ 100 A
Pulse duration: < 1ns

Foil thickness:
3 μ (solid) -
300 μ (foam)



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



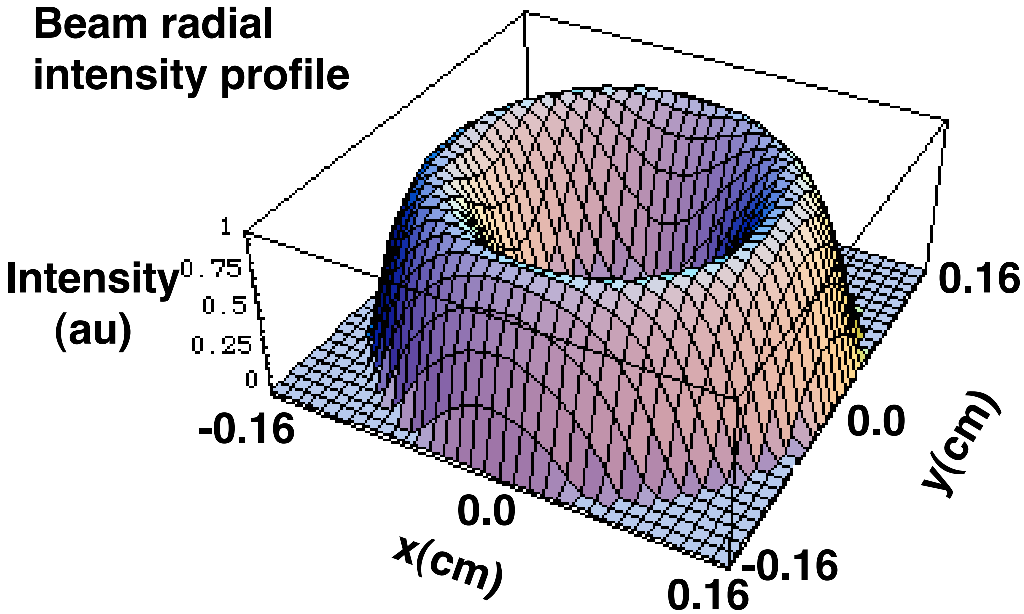
LAPLAS Experiment:

Inner region:
Cylinder of frozen hydrogen
(ρ=0.0884 g/cm^3)
Radius: 0.4 mm

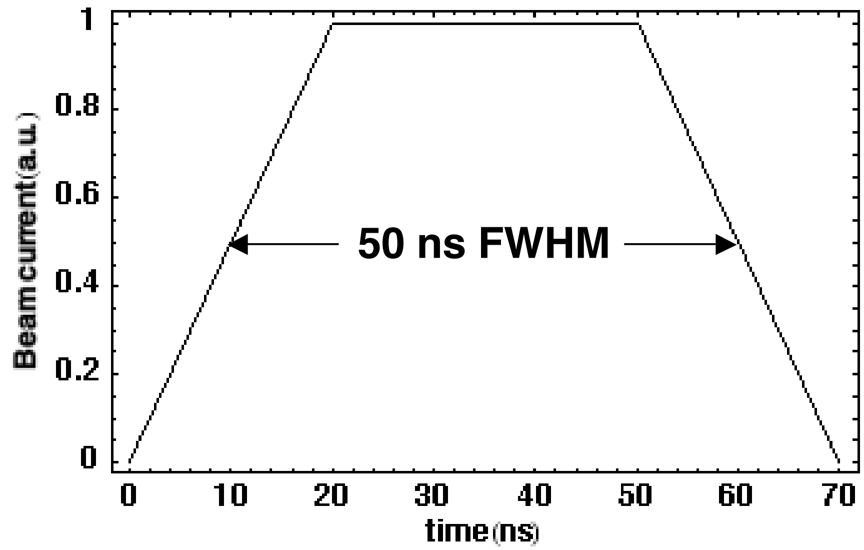
Outer region:
Cylinder of frozen gold
(ρ=19.3 g/cm^3)
Radius: 0.4 to 4.0 mm

Beam:
Uranium, 2 GeV/u
Bunch length: 50 ns
Power profile: parabolic between 0.6 and 1.6 mm
Number of particles: 1 to 5 x 10^{11}

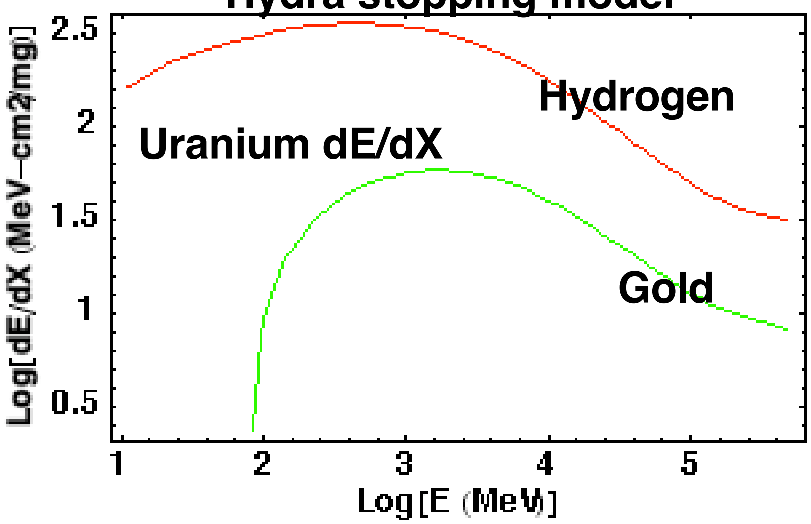
Ion deposition is in a cylindrical ring outside of the hydrogen core, with a parabolic intensity profile



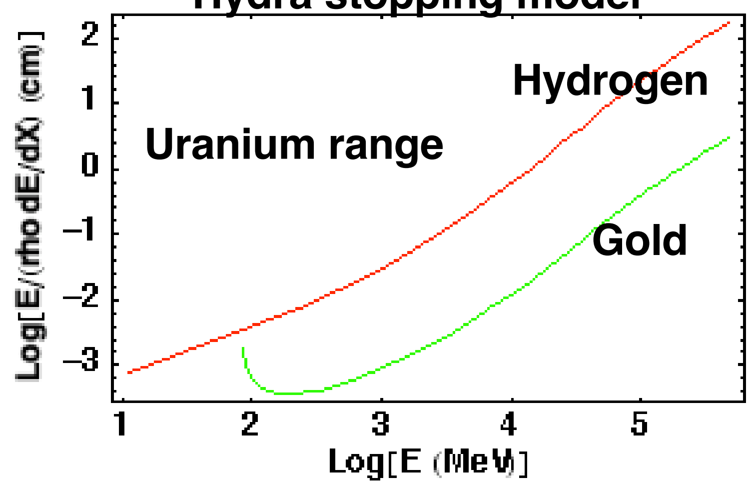
Assumed beam current profile



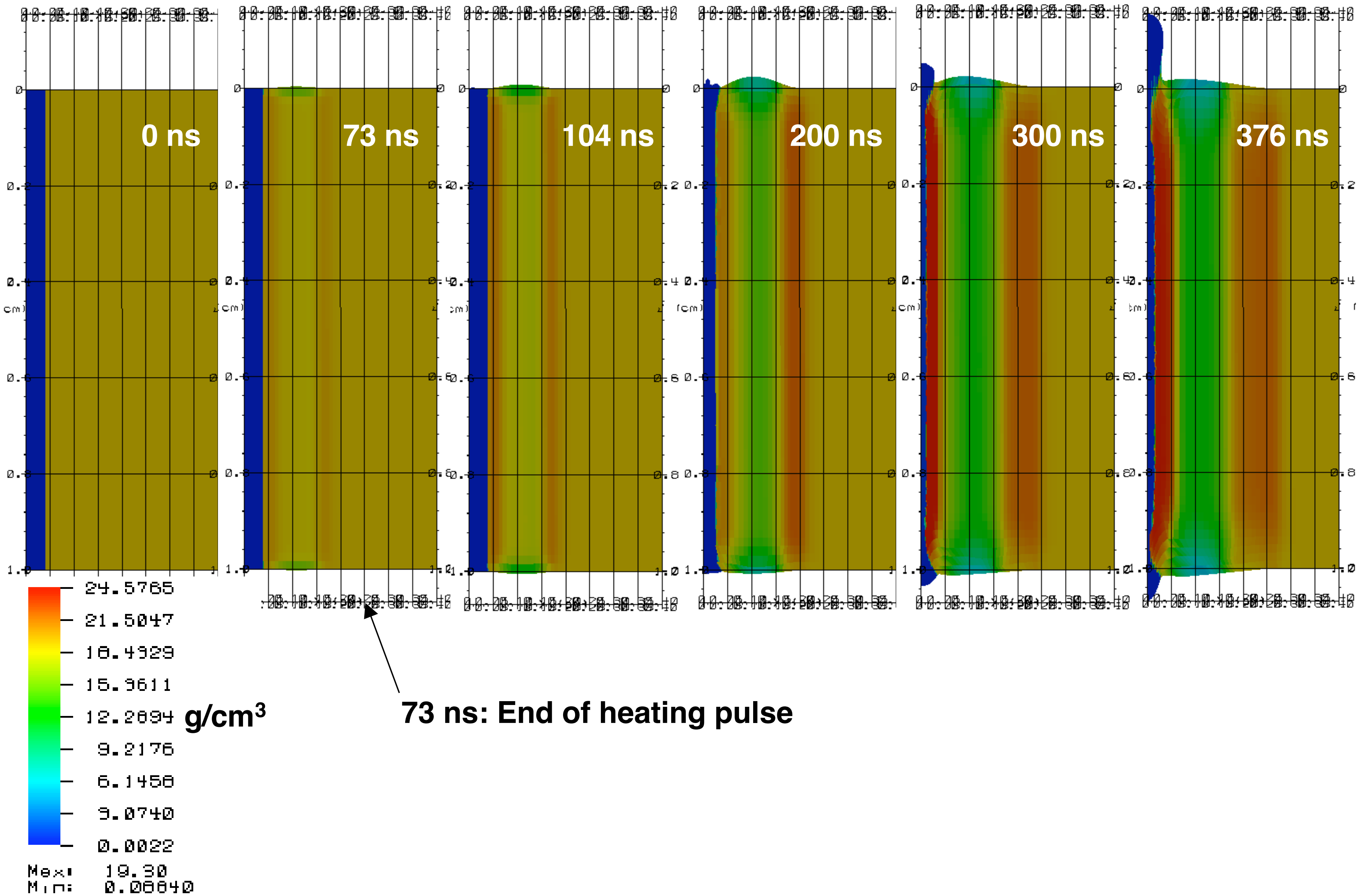
Hydra stopping model



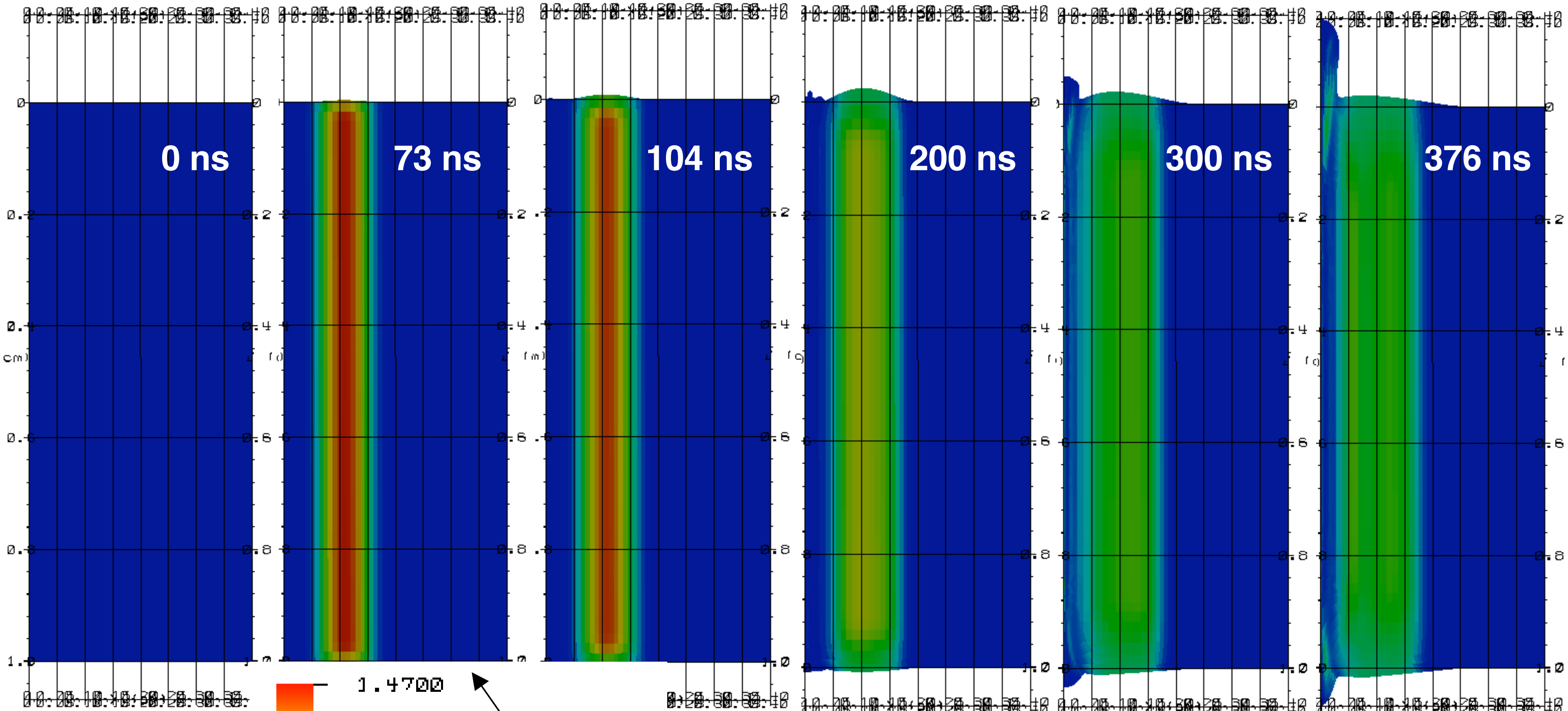
Hydra stopping model

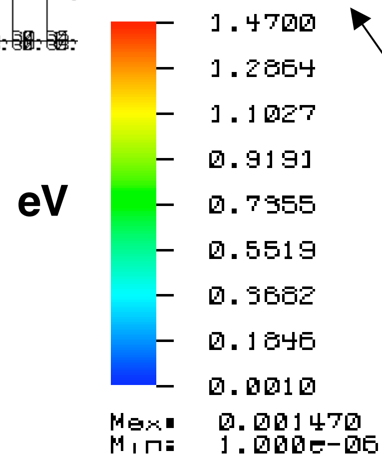


Evolution of density (N_p=1 x 10^{11} particles/bunch)



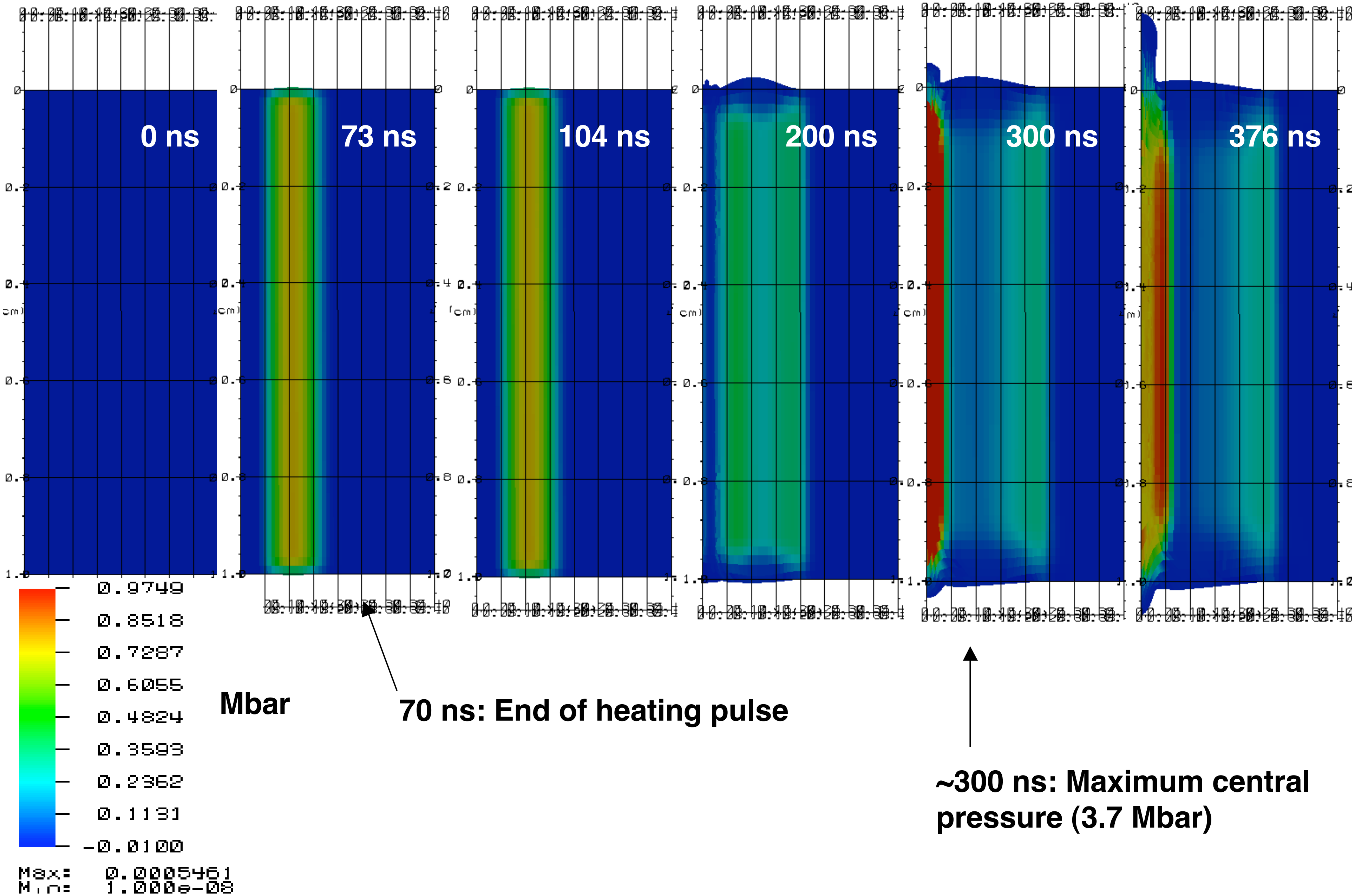
Evolution of temperature (N_p=1 x 10^{11} particles/bunch)



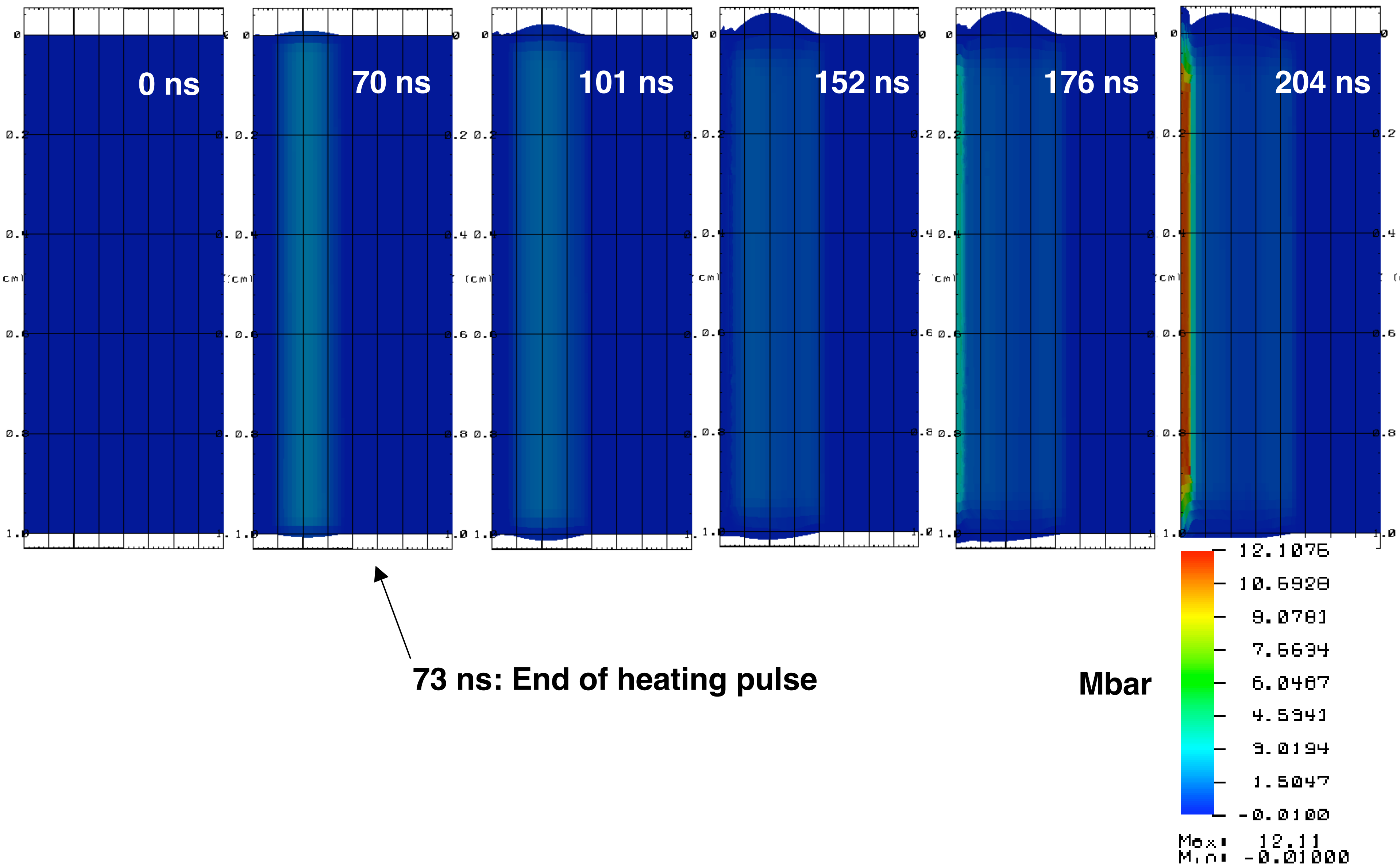


73 ns: End of heat pulse and maximum temperature reached

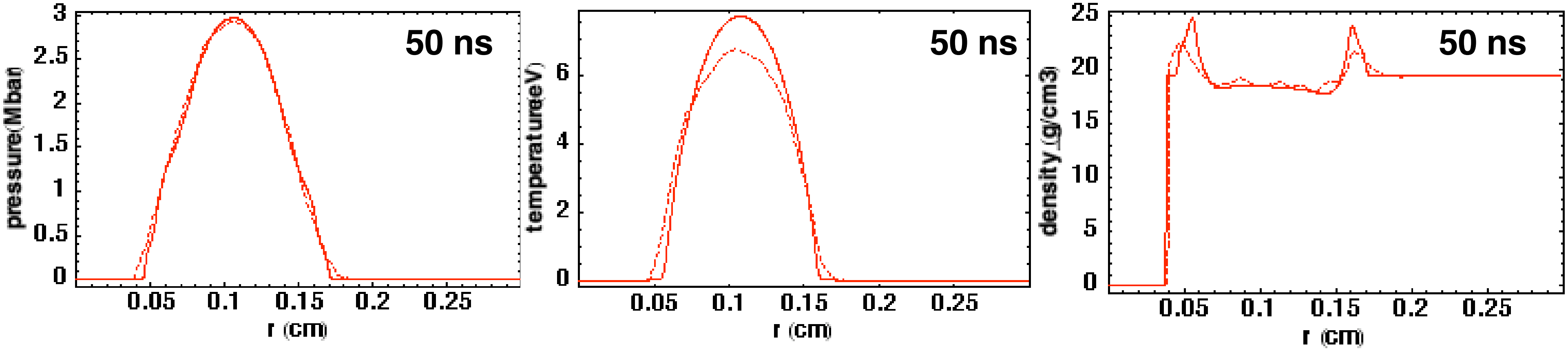
Evolution of pressure (N_p=1 x 10^{11} particles/bunch)



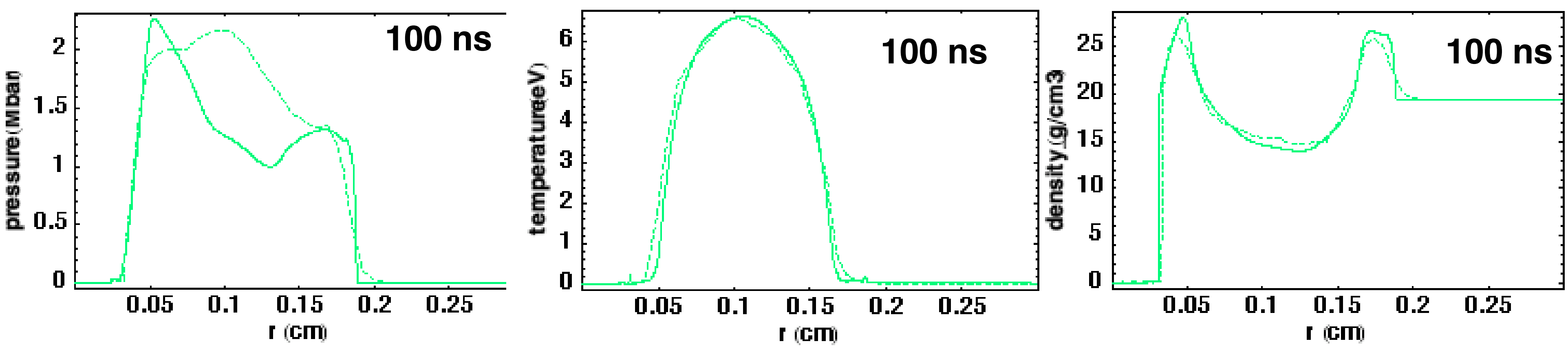
Evolution of pressure (N_p=5 x 10^{11} particles/bunch)



Comparison of HEDgeHOB simulations (solid curves) with HYDRA simulations (dashed curves)

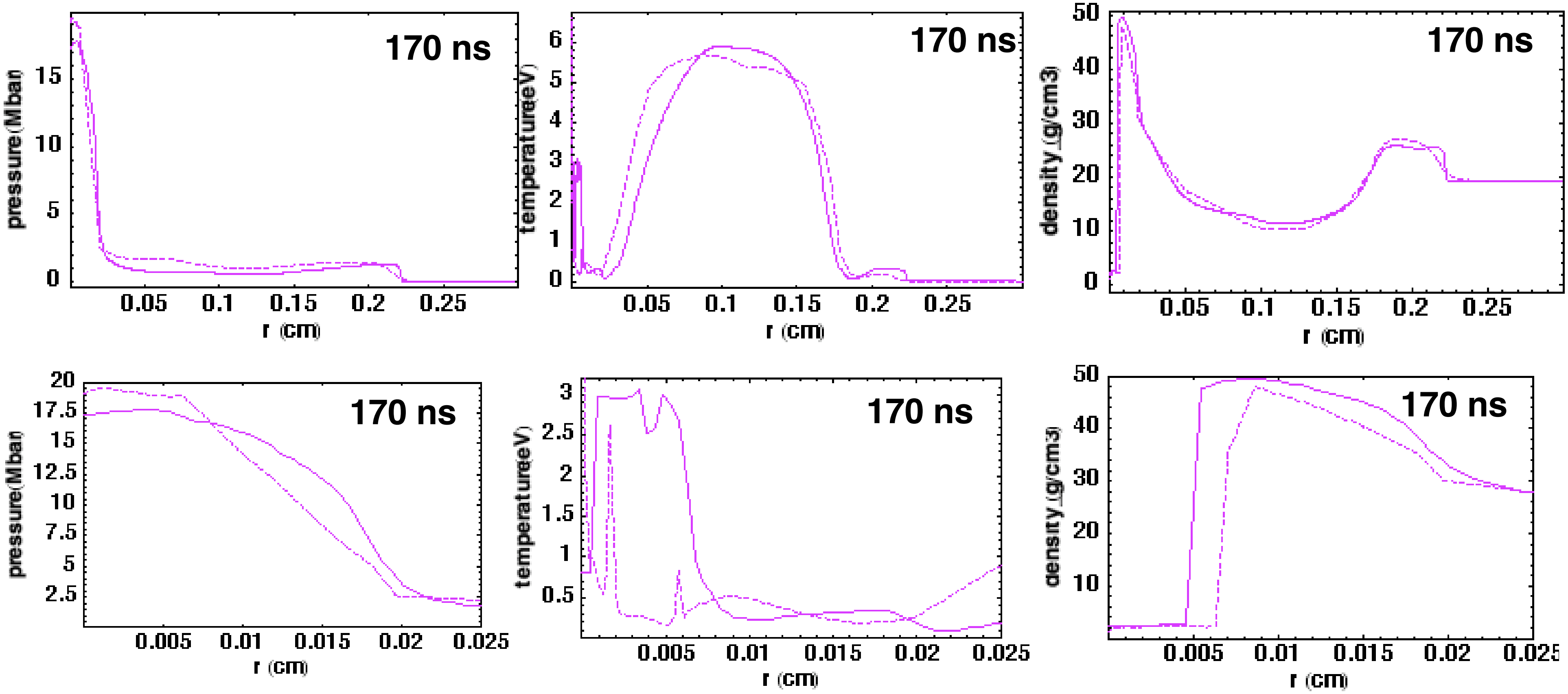


HYDRA ion intensity was altered to match HEDgeHOB pressure profile at 50 ns.



Simulations are qualitatively and sometimes quantitatively similar, but also show significant differences

Comparison of HEDgeHOB simulations (solid curves) with HYDRA simulations (dashed curves) --- continued



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

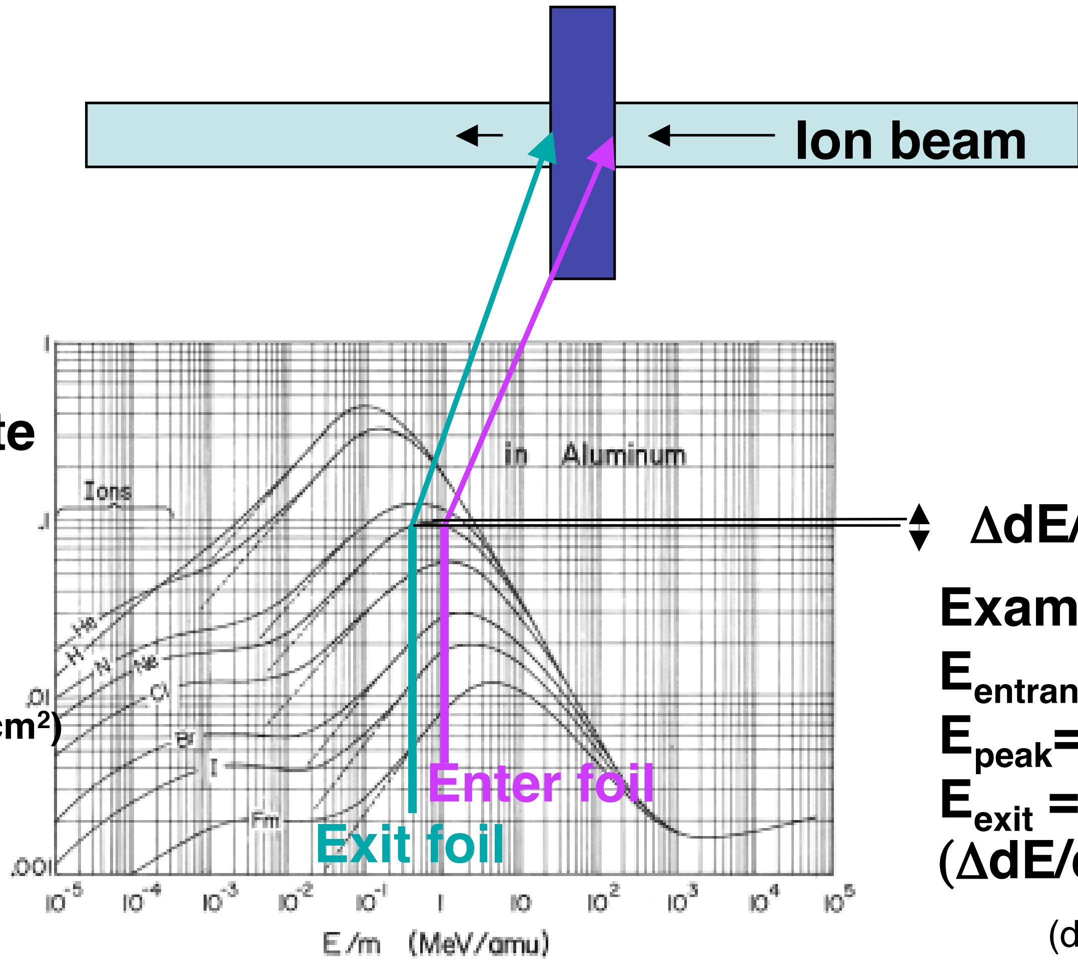
In simplest example, target is a foil of solid or metallic foam

uniformity and fractional energy loss can be high if operate at Bragg peak (Larry Grisham, PPPL)

Energy loss rate

$$-\frac{1}{Z^2}\frac{dE}{dX}$$

(MeV/mg cm²)



Energy/Ion mass **(MeV/amu)**

$\Delta dE/dX \propto \Delta T$

Example: Neon beam

$E_{entrance}$=1.0 MeV/amu

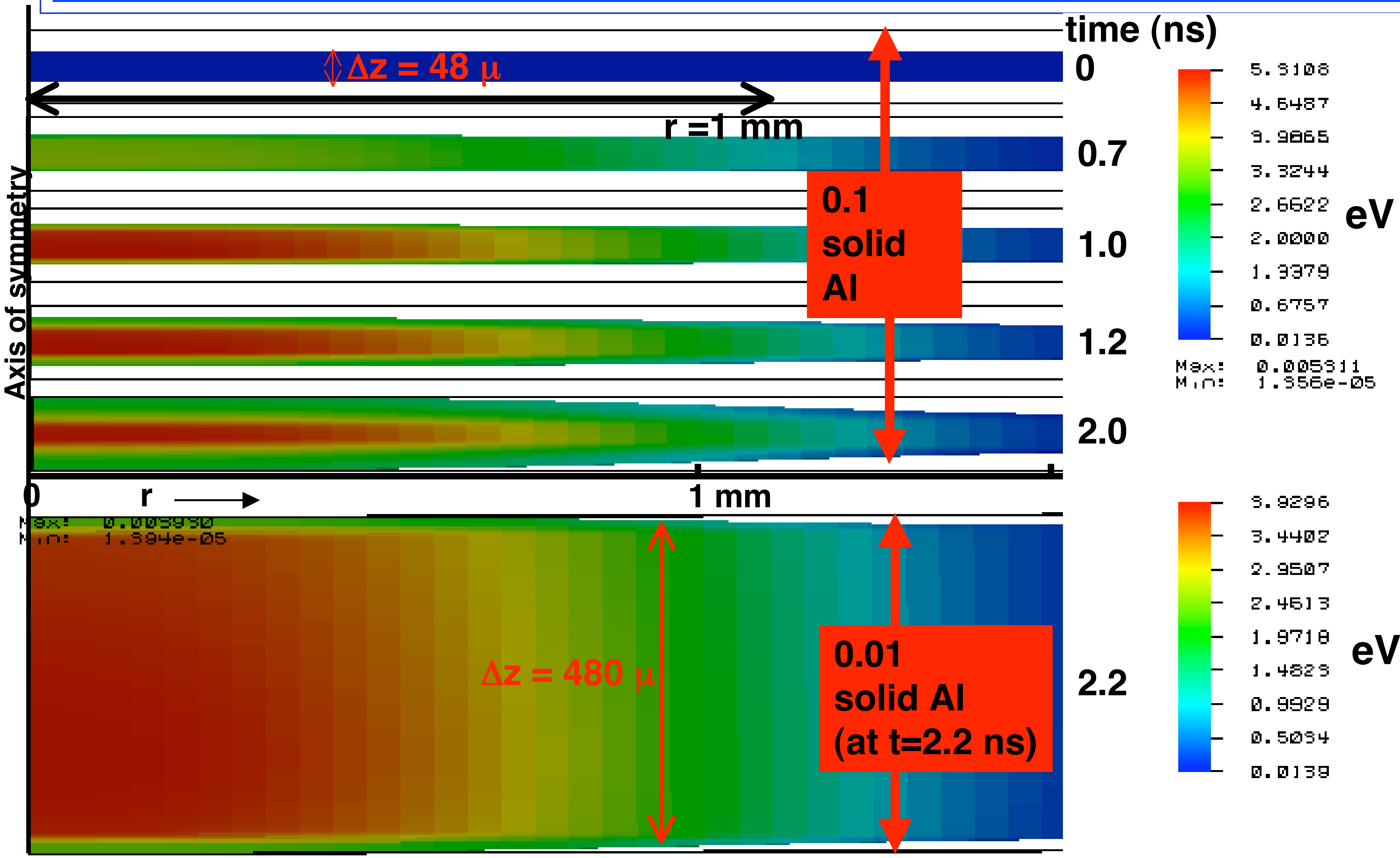
E_{peak}= 0.6 MeV/amu

E_{exit} = 0.4 MeV/amu

$(\Delta dE/dX)/(dE/dX) \approx 0.05$

(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 μC, 20 MeV Ne beam -- possible NDCX II parameters).

Metallic foams were expected to ease the requirement on pulse duration

With foams easier to satisfy

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

But foams locally non-uniform. Timescale to become homogeneous

$$t_{homogeneity} \sim n\, r_{\mathrm{pore}}/c_s$$

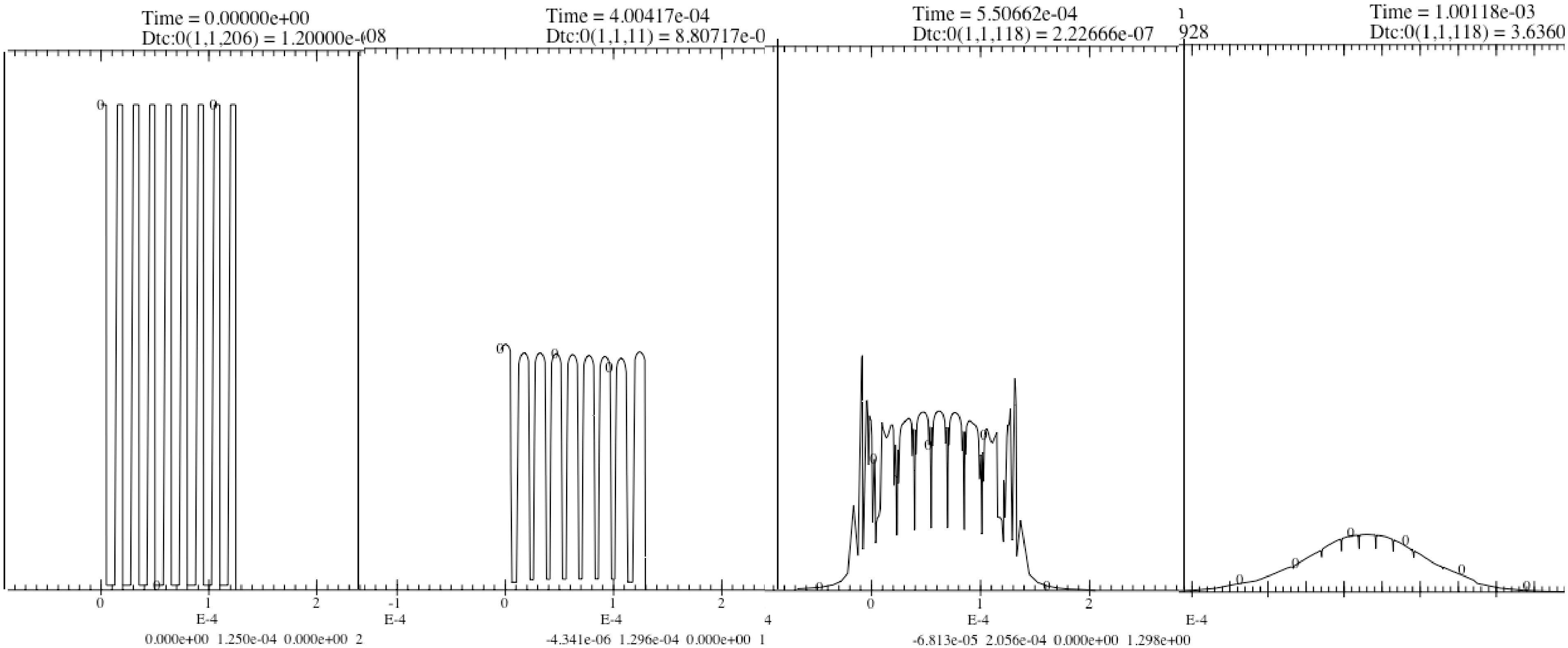
where n is a number of order 3 - 5, r_{pore} is the pore size and c_s is the sound speed.

Thus, for n=4, r_{pore}=100 nm, Δz =40 micron (for a 10% aluminum foam foil):

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

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**
- **Ref: R. More, H. Yoneda and H. Morikami, JQSRT 99, 409 (2006).**

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**
  - **Ref: M. M. Marinak, G. D. Kerbel, N. A. Gentile, O. Jones, D. Munro, S. Pollaine, T. R. Dittrich, and S. W. Haan, Phys. Plasmas 8, 2275 (2001).**

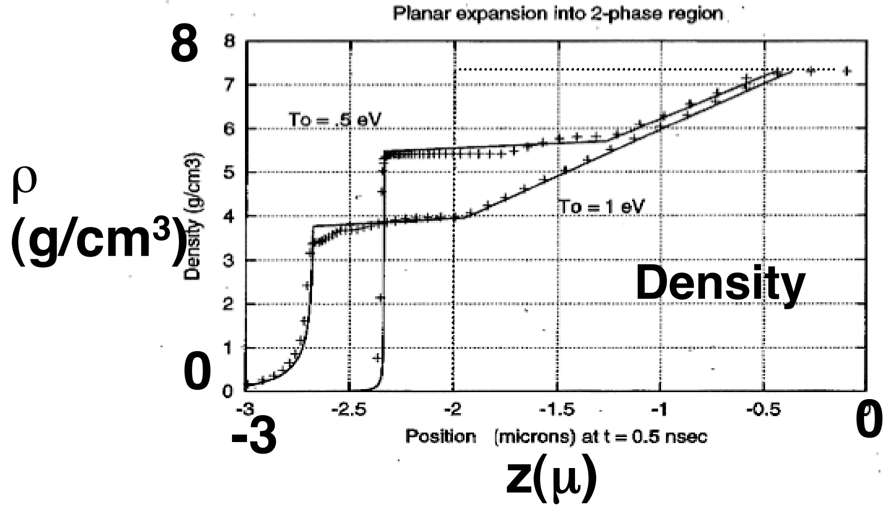
When initial temperature places expanding foil into two-phase regime, plateaus in ρ and T have been numerically observed[1,2]

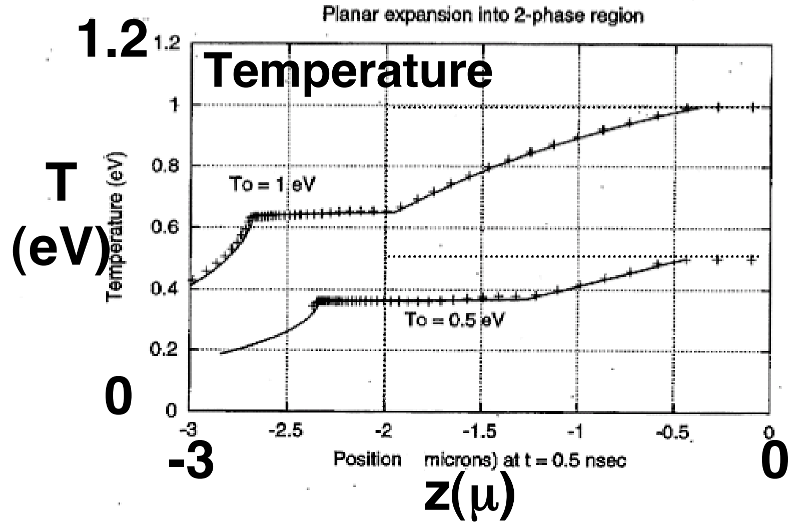
.... Initial distribution

———— Exact analytic hydro (using numerical EOS)

+++++++++ Numerical hydro

DPC code results:



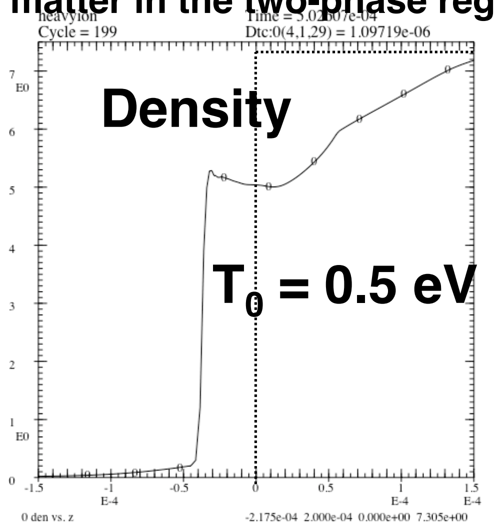


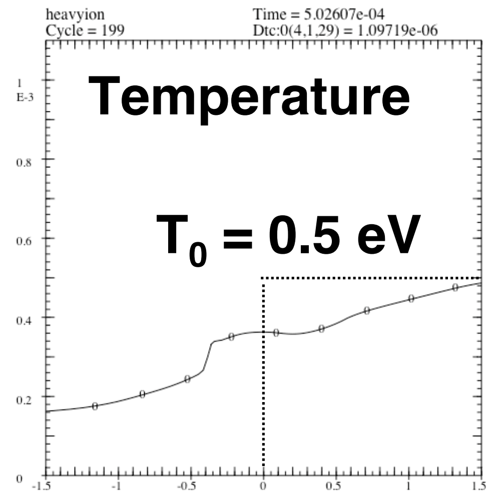
Example shown here is initialized at T=0.5 or 1.0 eV and shown at 0.5 ns after "heating."

[1]More, Kato, Yoneda, 2005, preprint. [2]Sokolowski-Tinten et al, PRL 81, 224 (1998)

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

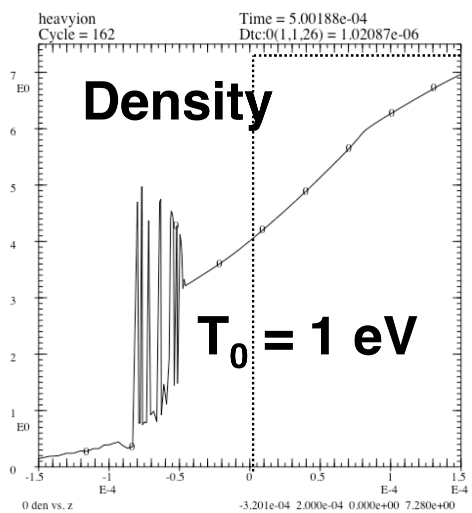
(oscillations at phase transition at 1 eV are physical/numerical problems, triggered by the different EOS physics of matter in the two-phase regime)

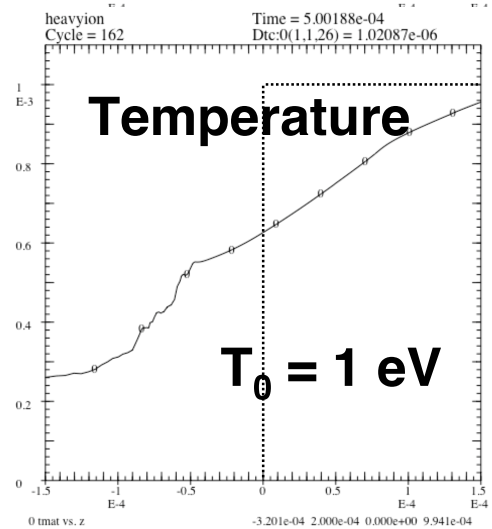




Propagation distance of sharp interface is in approximate agreement

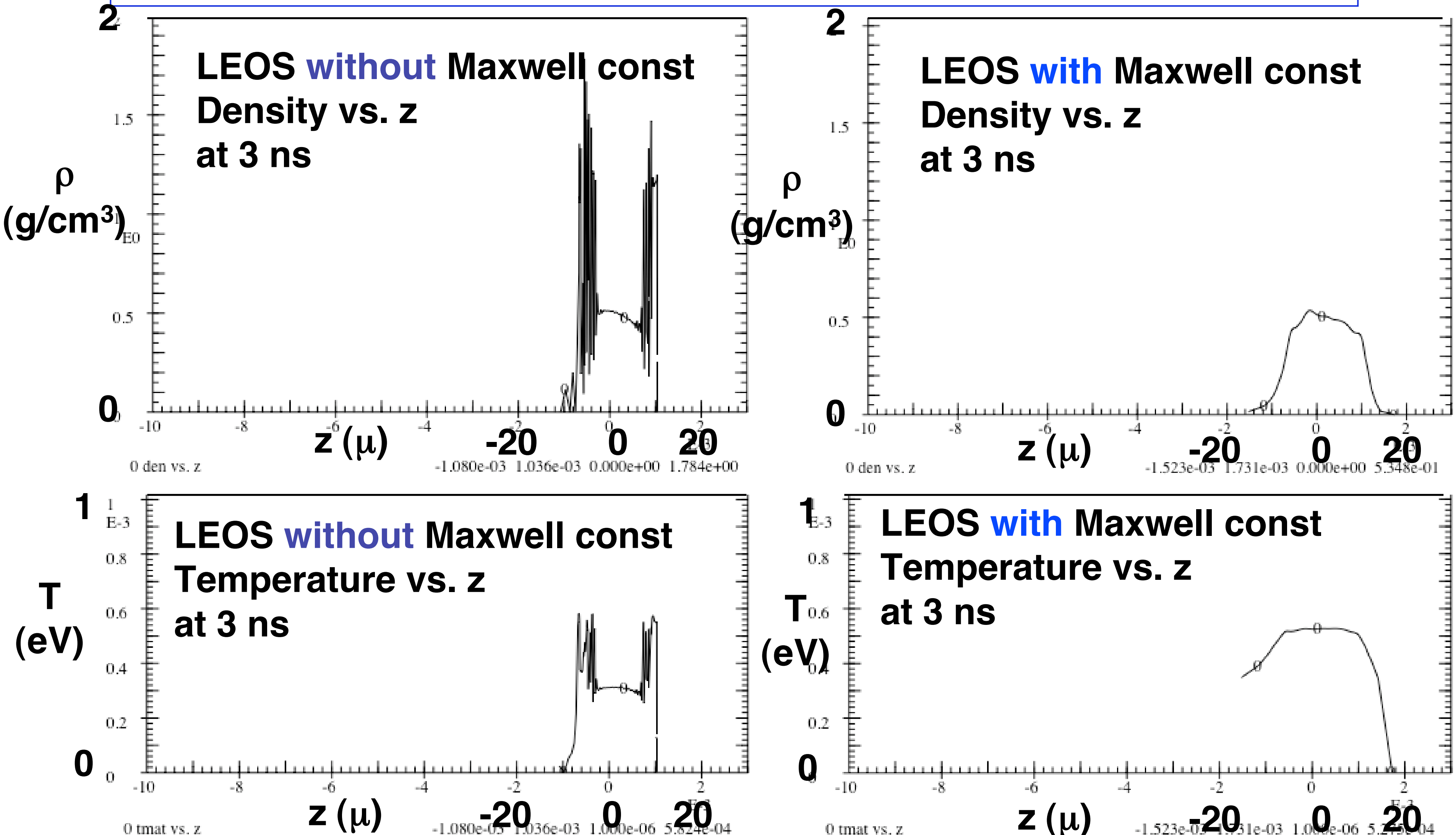
Density oscillation likely caused by ∂P/∂ρ instabilities, (bubbles and droplets forming?)





Uses QEOS with no Maxwell construction

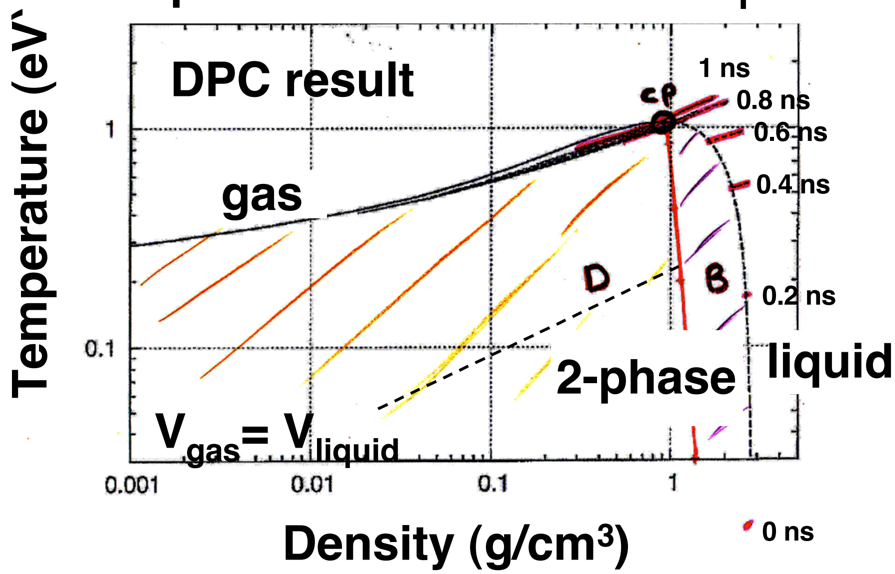
Maxwell construction reduces instability in numerical calculations

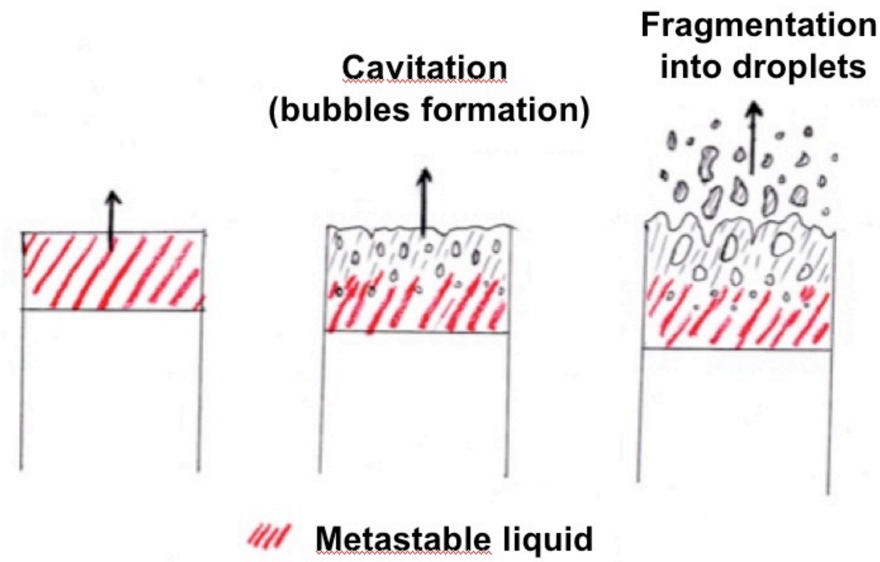


All four plots: HYDRA, 3.5 μ foil, 1 ns, 11 kJ/g deposition in Al target

Expansion of foil is expected to first produce bubbles then droplets

Example of evolution of foil in ρ and T

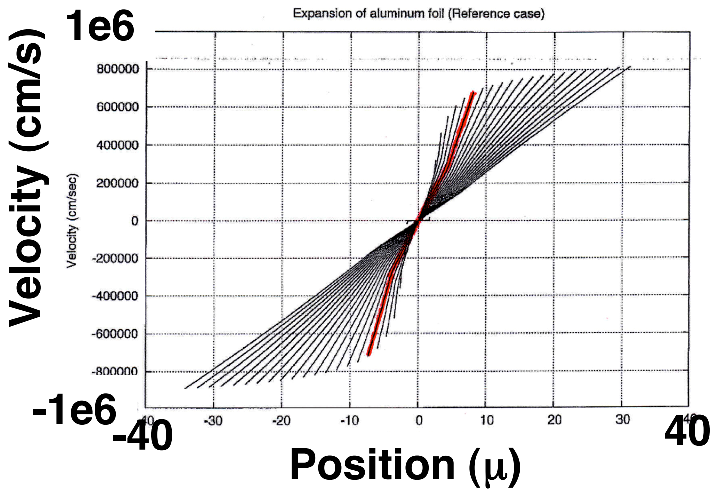




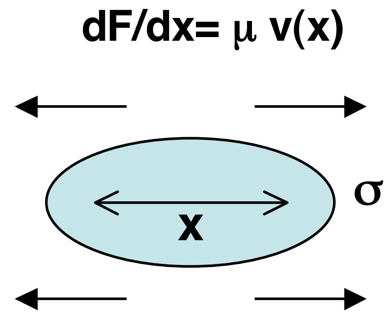
- The foil will melt then enter 2-phase conditions.
- First, bubble forms (B), then the continuous liquid fragments into droplets (D)

Ref: J. Armijo, master's internship report, ENS, Paris, 2006. Also, Armijo, Barnard, and More, 2006, DPP APS meeting 2006, Philadelphia, PA.

Maximum size of a droplet in a diverging flow



Locally, dv/dx = const (Hubble flow)



Steady-state droplet

- **Equilibrium between stretching viscous force and restoring surface tension**

Capillary number Ca= viscous/surface ~ $\int \mu\, dv/dx\, x\, dx / (\sigma x) \sim (\mu\, dv/dx\, x^2) / (\sigma x) \sim 1$

→ **Maximum size :** $x = \sigma / (\mu\, dv/dx)$

Kinetic gas: $\mu = 1/3\, m\, v^*\, n\, l$ **mean free path :** $l = 1/ \sqrt{2}\, n\, \sigma_0$

→ $\mu = m\, v / 3 \sqrt{2}\, \sigma_0$

→ **Estimate :** $x_{max} \sim 0.20\ \mu m$

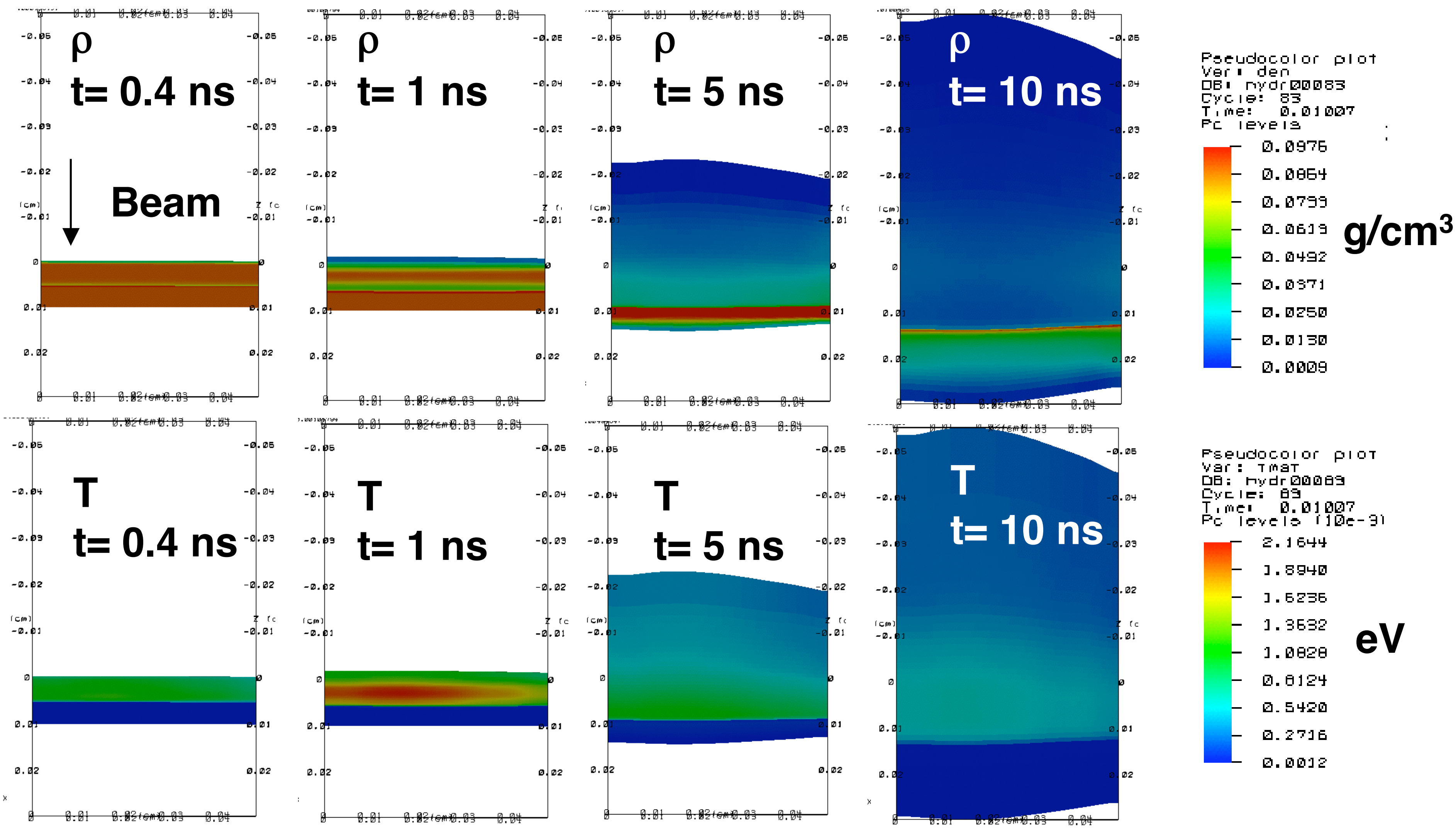
- **AND/OR: Equilibrium between disruptive dynamic pressure and restoring surface tension: Weber number We= inertial/surface ~ $(\rho v^2 A)/\sigma x \sim \rho (dv/dx)^2 x^4 / \sigma x \sim 1$**

→ **Maximum size :** $x = (\sigma / \rho\, (dv/dx)^2)^{1/3}$

→ **Estimate :** $x_{max} \sim 0.05\ \mu m$

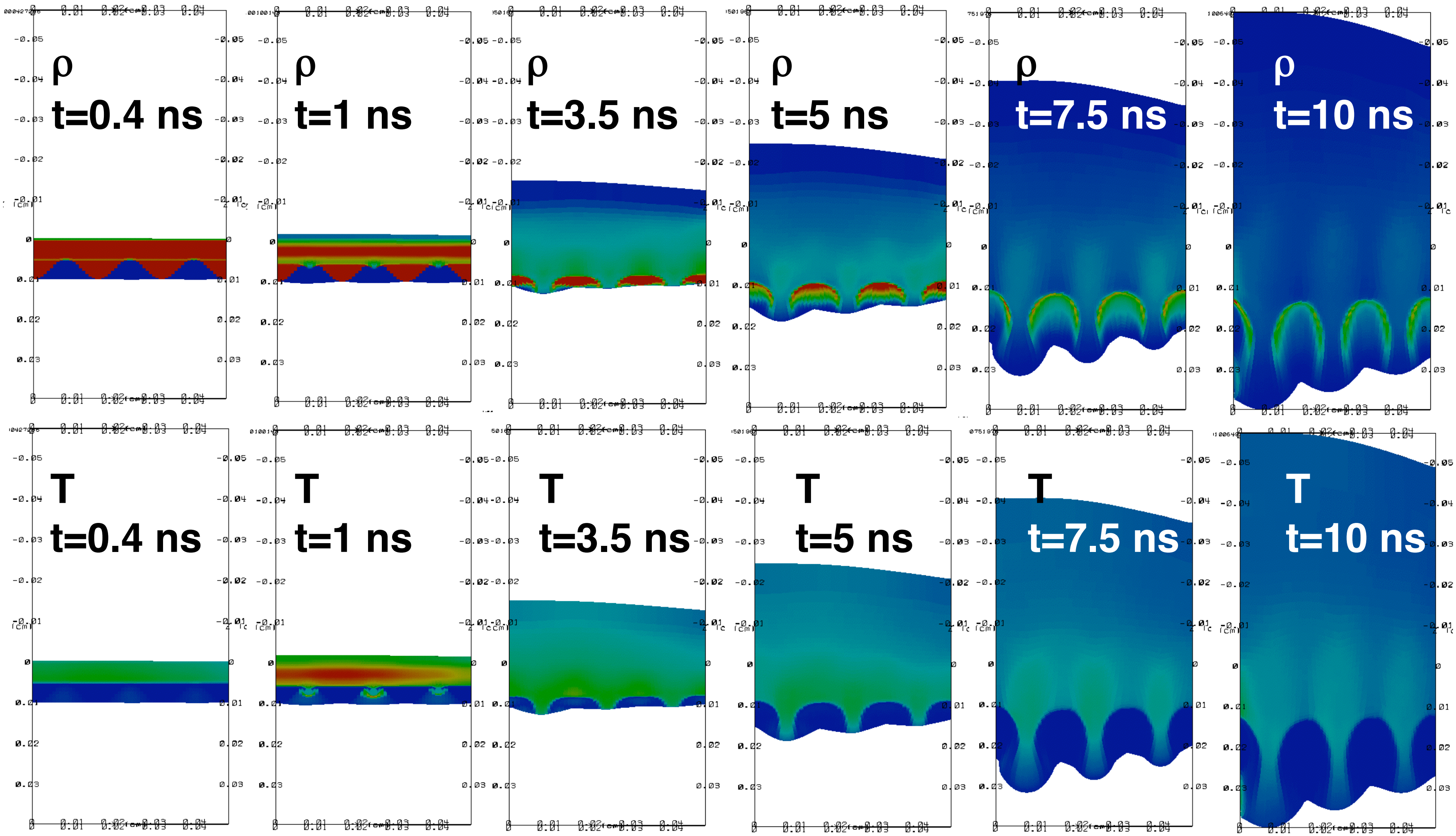
(See J. Armijo, master's internship report, ENS, Paris, 2006, and Armijo, J., Barnard, J.J., and More, R.M., Bulletin of the APS, 2006)

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

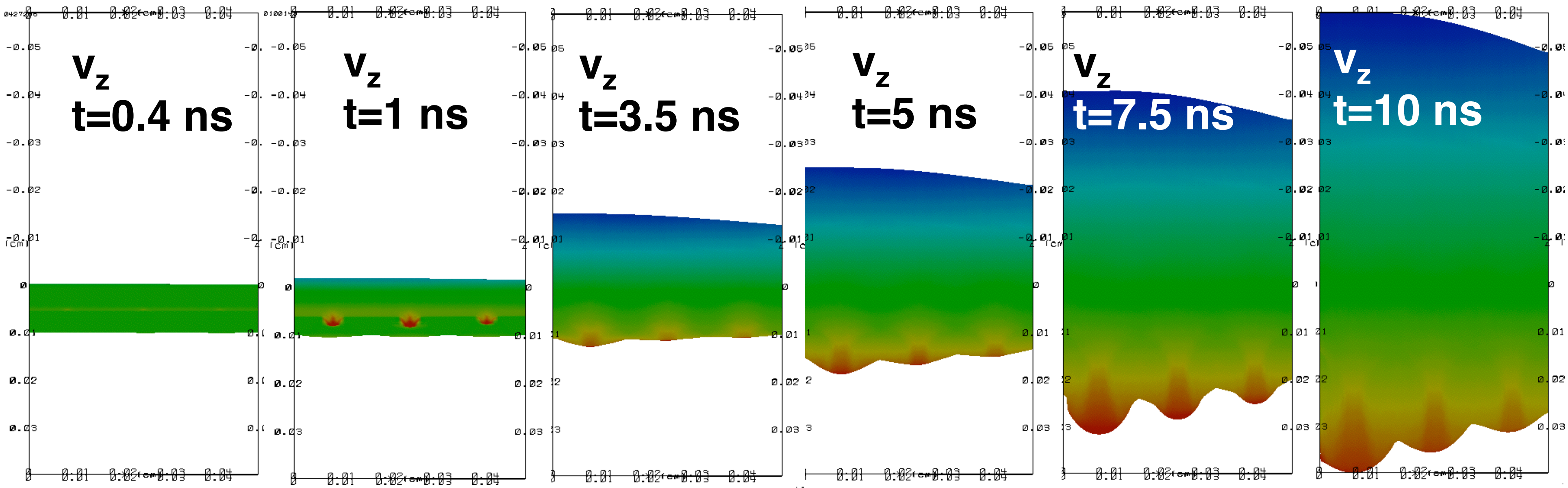


23 MeV Ne, 0.1 μC, 1 ns pulse (NDCX II) impinges on 100 μ thick solid H, T=0.0012eV, ρ =0.088 g/cm3; No density ripple on surface, blowoff accelerates slab

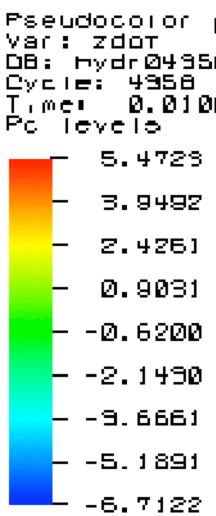
When initial surface ripple is applied, evidence for Rayleigh Taylor instability is suggestive



When initial surface ripple is applied, evidence for Rayleigh Taylor instability is suggestive (-- continued)

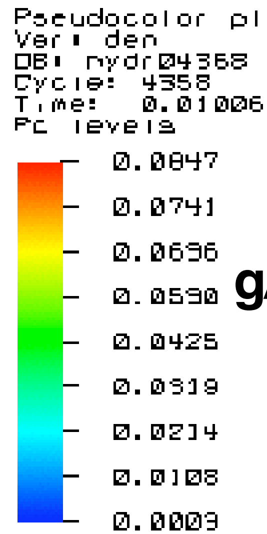


Scale for above figures (v_z):

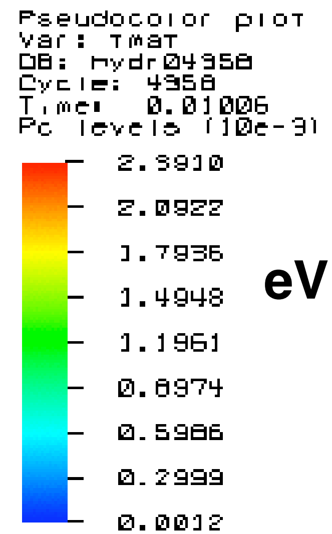


cm/μs

Scales from previous page (ρ 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

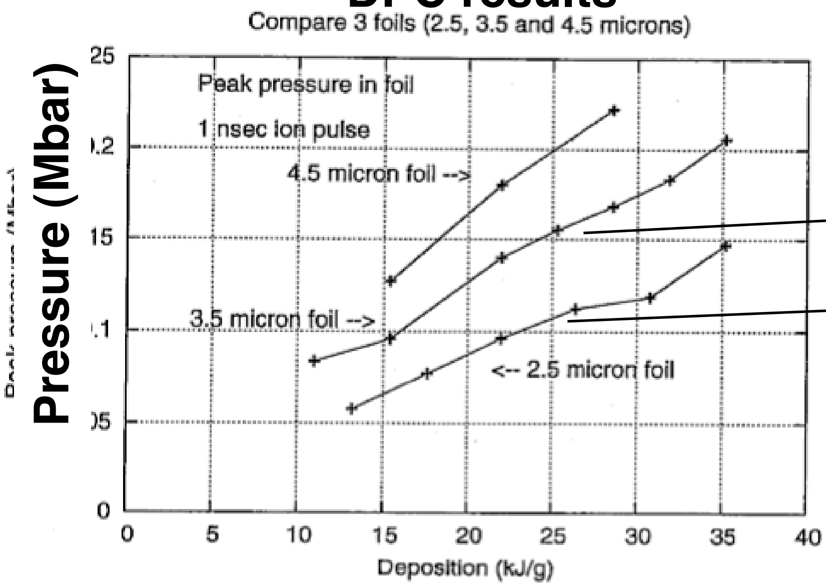
beam intensity

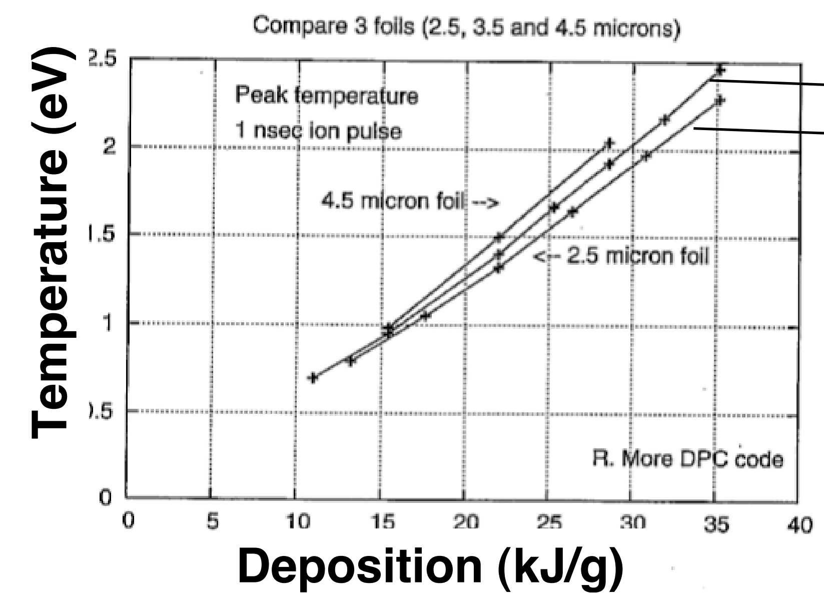
EOS/code

Purpose: gain insight into future experiments

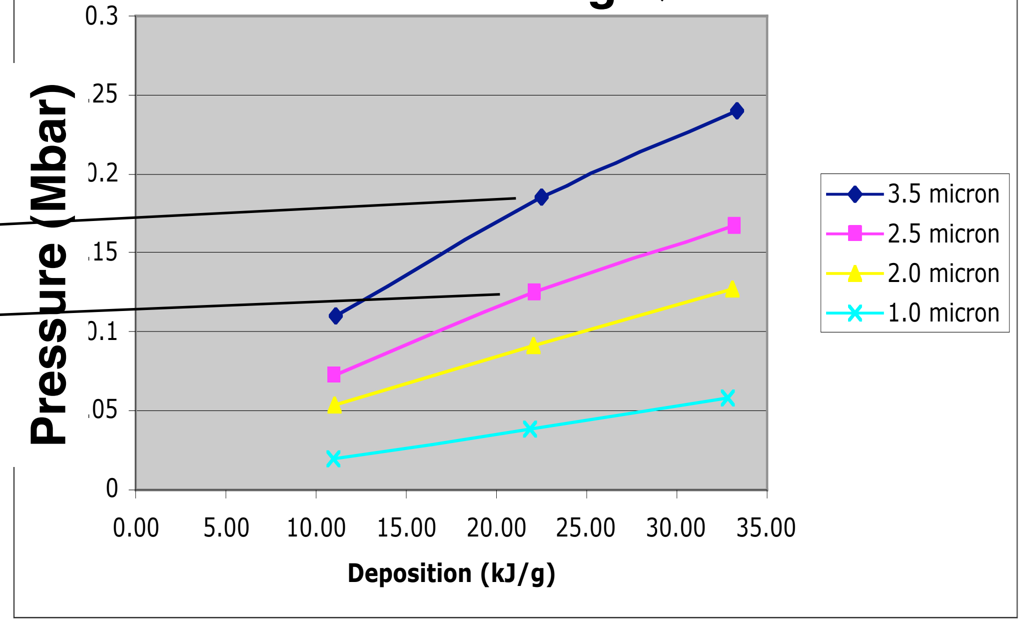
Variations in foil thickness and energy deposition

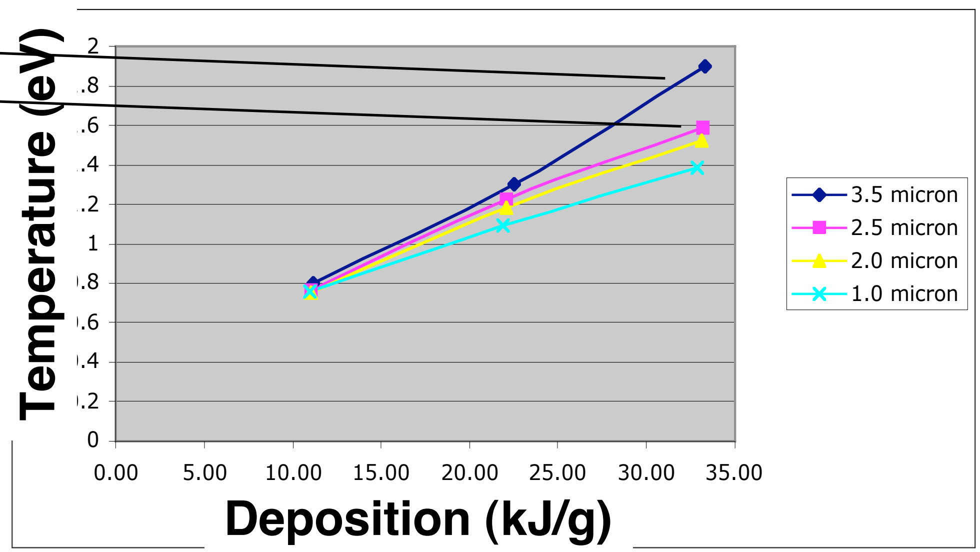
DPC results



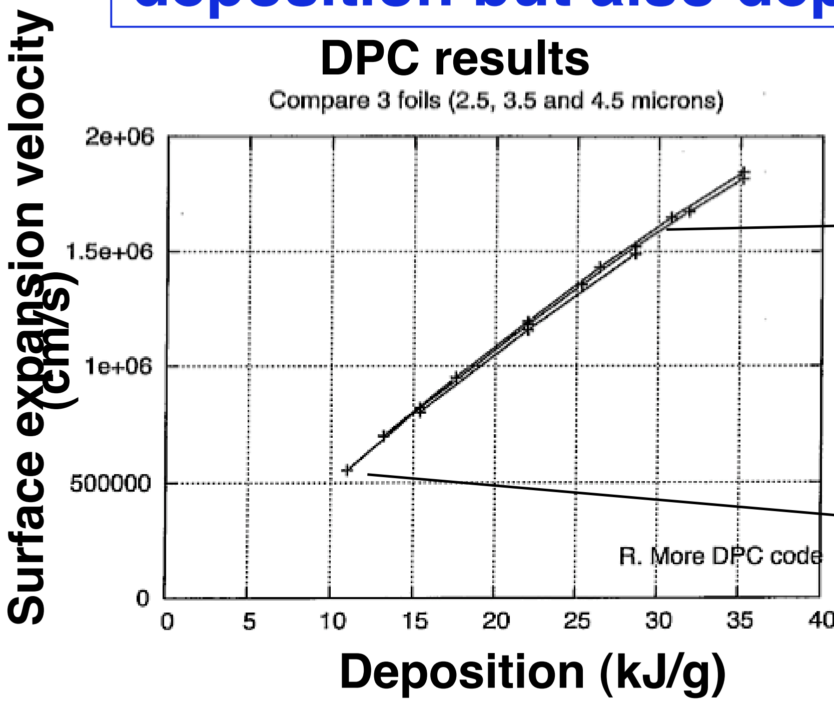


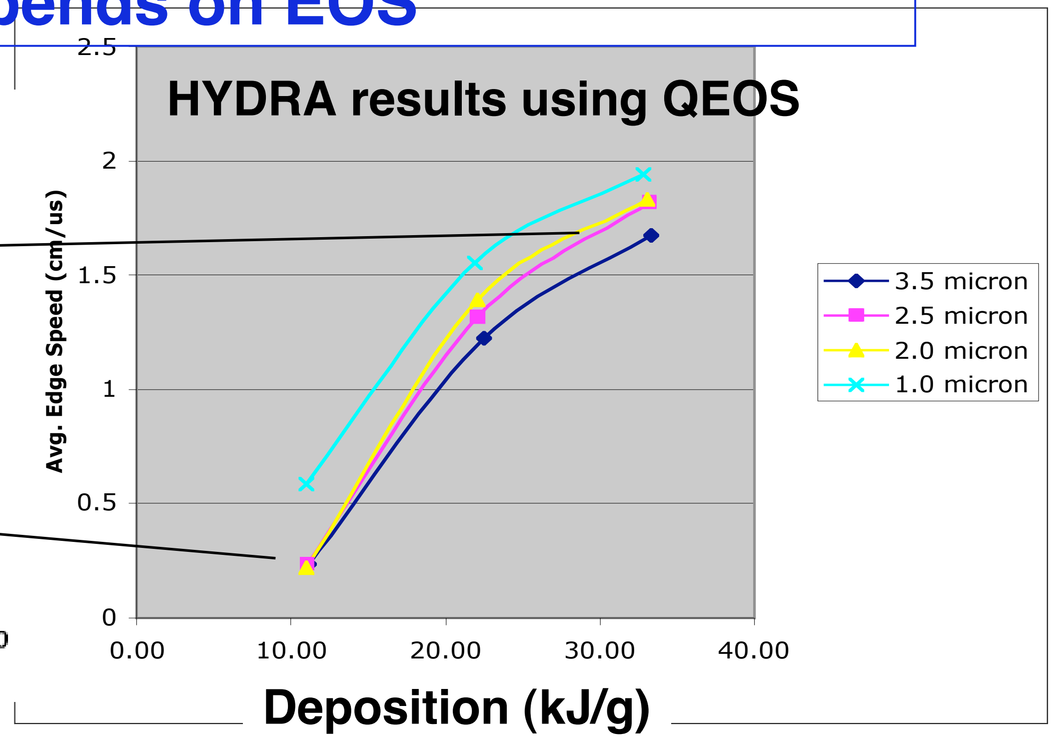
HYDRA results using QEOS





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):

$$\varepsilon_0 = \frac{c_{s0}^2}{\gamma(\gamma-1)} \qquad v = \frac{-2c_{s0}}{\gamma-1} \qquad \Longrightarrow \qquad v = \sqrt{\frac{4\gamma}{\gamma-1}\varepsilon_0^{1/2}}$$

In instanteneous heating/perfect gas model outward expansion velocity depends only on ε_0 and γ

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**