Using Ion Beams for High Energy Density Physics and Warm Dense Matter: Concepts and Calculations

John Barnard (LLNL) on behalf of

The Heavy Ion Fusion Science Virtual National Laboratory

Symposium on Recent Advances in Plasma Physics ---
In Celebration of Ronald C. Davidson's 40 Years of Plasma Physics Research and Graduate Education

Princeton Plasma Physics Laboratory, Princeton University

Princeton, NJ

June 10-12, 2007

This work was performed under the auspices of the U.S. Department of Energy by the University of California, LBNL and LLNL under Contract Numbers DE-AC02-05CH1123 and W-7405-Eng-48 and PPPL under contract DEFG0295ER40919 .

HIFS VNL collaborators on HEDP and WDM

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The Heavy Ion Fusion Science Virtual National Laboratory engages in three broad HEDP related activities

Heavy Ion Fusion Science experiments:

The physics of compressing beams in space and time

-- Drift compression and final focus

-- High brightness beam preservation

-- Electron cloud/halo/ and non-linear processes

Warm Dense Matter (WDM) experiments

-- Equation of state

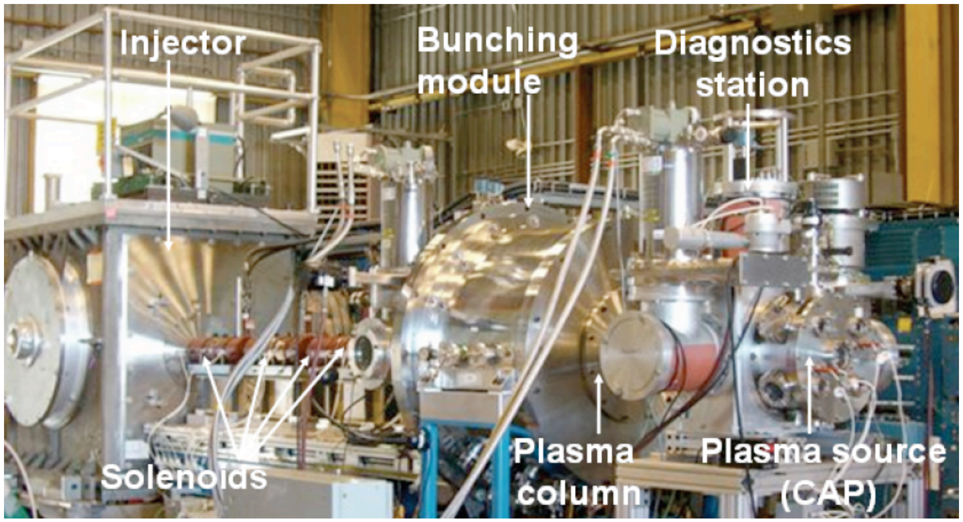
-- Two-phase regime and droplet formation

-- Insulator and metals at WDM conditions

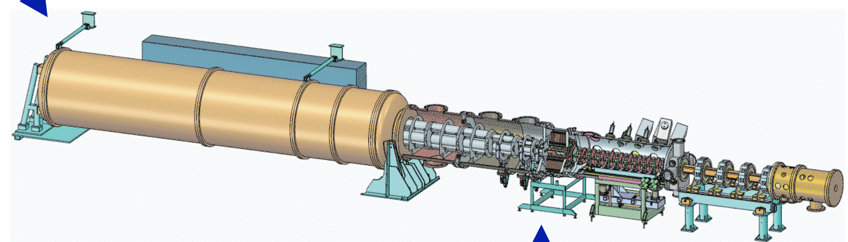
Hydrodynamics experiments relevant to HIF targets

-- Hydro stability, volumetric ion deposition and Rayleigh Taylor mitigation techniques

The HIFS VNL has developed a plan for using present and future accelerators for WDM and HIF experiments



Today:



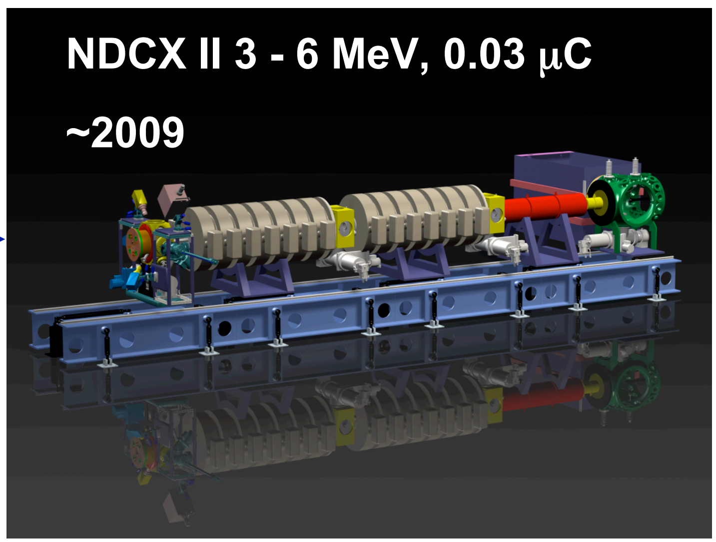
HCX

1.7 MeV, ~0.025 μC

NDCX I

0.4 MeV, 0.003 μC

Soon



Future

IB-HEDPX (with CD0)
5 - 15 year goal
20 - 40 MeV, 0.3 - 1.0 μC
WDM User facility

10 kJ Machine for HIF
10 - 20 year goal
Target implosion physics

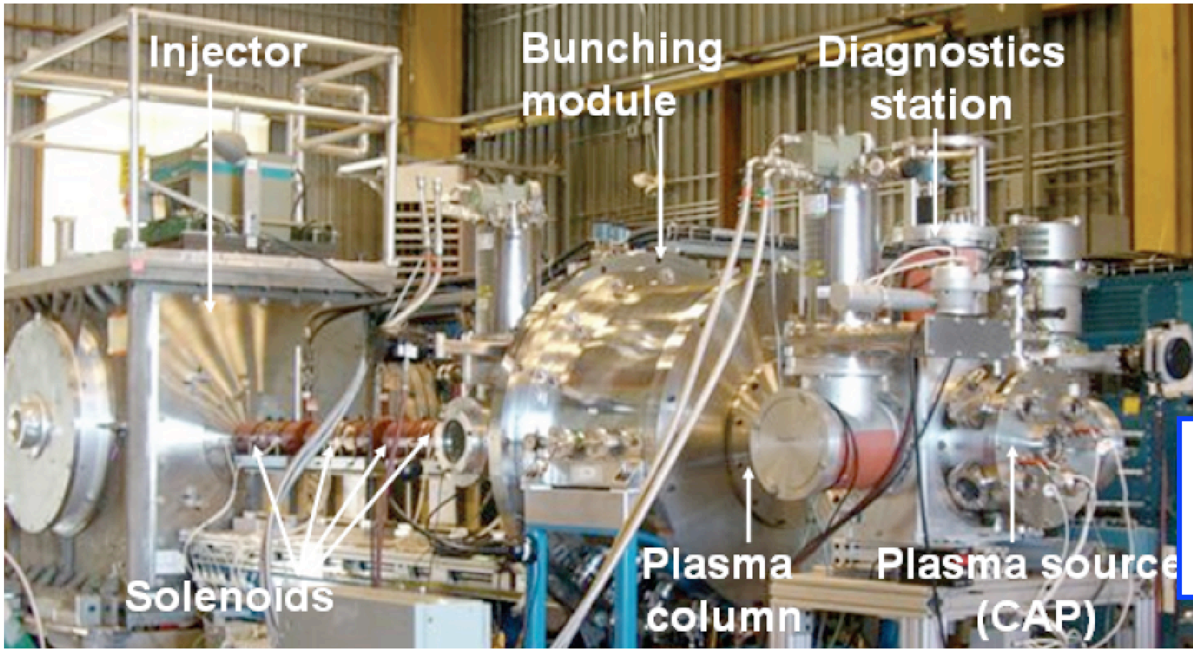
HIF/WDM beam science: neutralized focusing and drift compression are now being tested for use in WDM and HIF

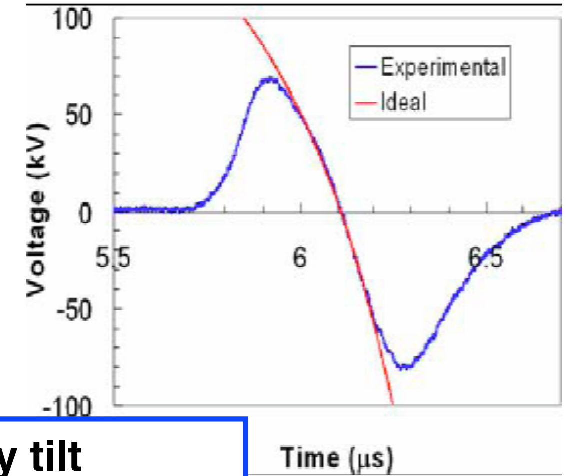
Both techniques virtually eliminate the repulsive effects of space charge on transverse and longitudinal compression

Transverse compression (= focusing the beam to a small spot, raising the watts/cm^2): Recent VNL experiments, eg. scaled final focus experiment, (MacLaren et al 2002), NTX (Roy et al 2004), and current NDCX-1 have demonstrated benefits of neutralization by plasmas, also required for HIF.

Longitudinal compression (= raising the watts): WDM experiments require very short, intense pulses (<~ 1 ns) (shorter than needed for HIF). Neutralization allows high current/high power beams. Modular HIF concept also pushes limit of high current.

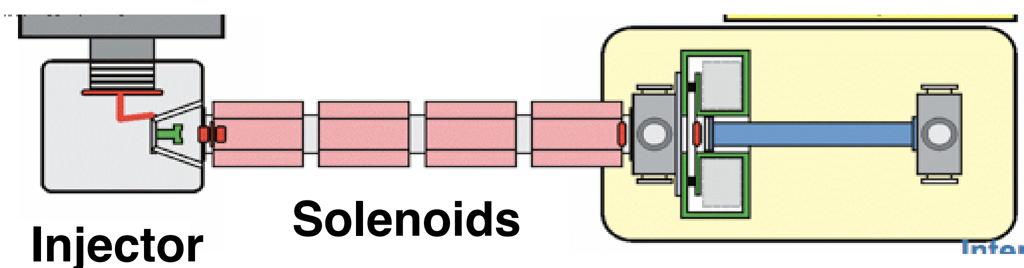
NDCX-1 has demonstrated > factor 70 pulse compression, and kinematically limited spot radius



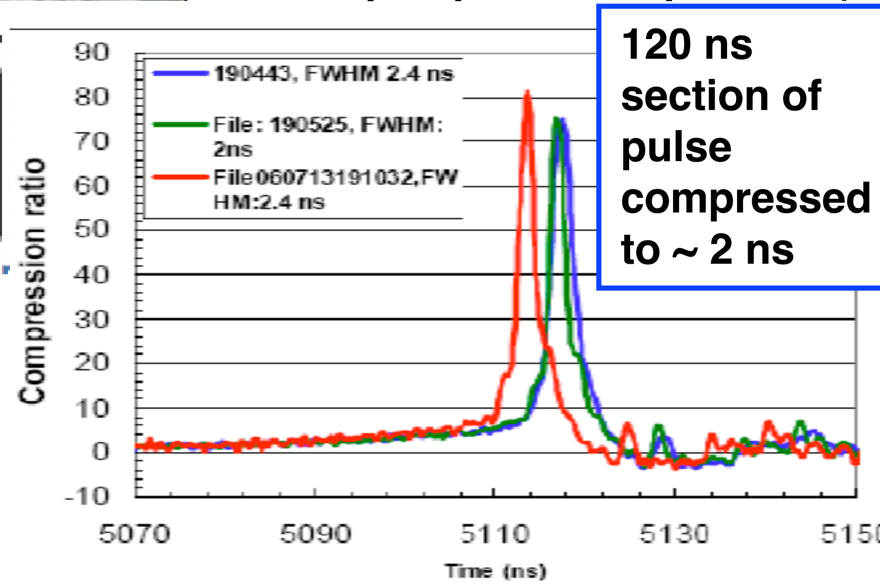


Velocity tilt accelerates tail, decelerates head

(Like chirped pulse compression)



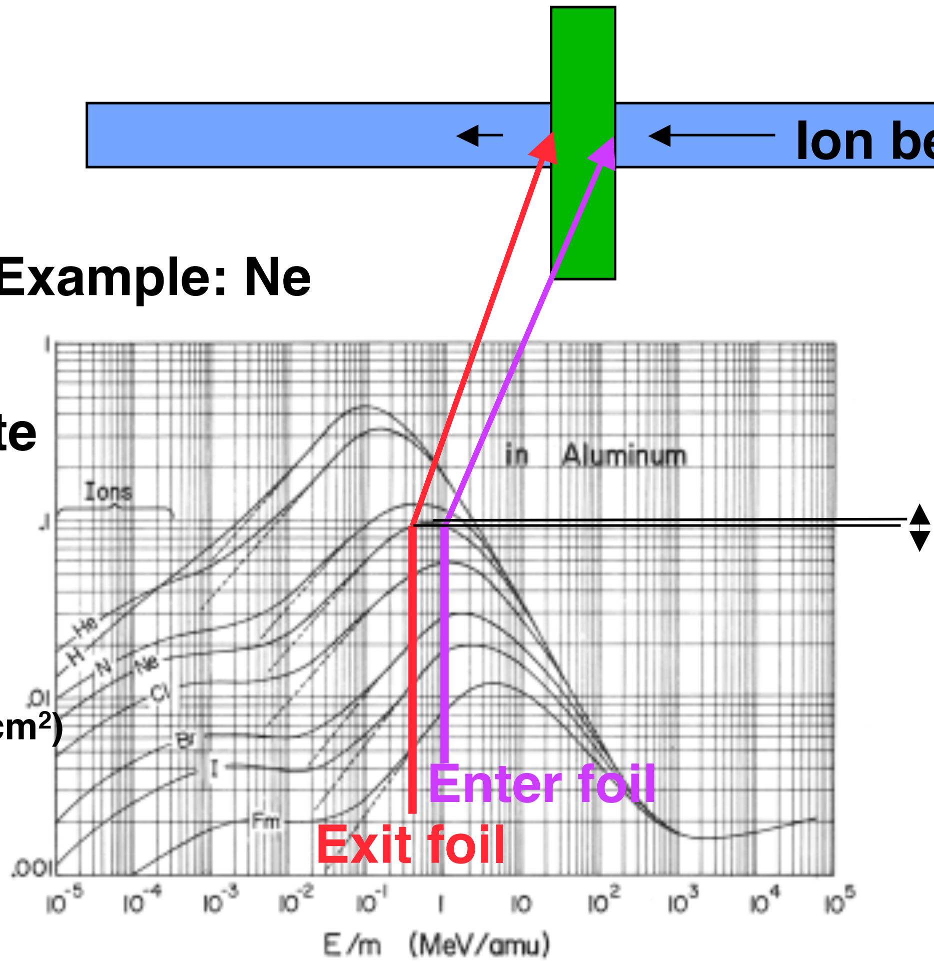
Plasma column/ Neutralized drift section (2 m)



120 ns section of pulse compressed to ~ 2 ns

WDM 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 "foam" metal



Example: Ne

Energy loss rate

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

(MeV/mg cm^2)

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

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

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

In example,
$E_{entrance}$=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))

A user facility for ion beam driven HEDP/WDM will have unique characteristics

Precise control of energy deposition

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

Uniformity of energy deposition (<~ 5%)

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

Pulse long enough to achieve local thermodynamic equilibrium

A benign environment for diagnostics

High shot rates (10/hour to 1/second)

Potential for multiple beamlines/target chambers

We have identified a series of warm dense matter experiments that can begin on NDCX-I at Temperature < 1 eV

	Target temp.	NDCX-1 or HCX	NDCX-2
Transient darkening emission and absorption experiment to investigate previous observations in the WDM regime	**Low (0-0.4 eV)**	√	
Measure target temperature using a beam compressed both radially and longitudinally	**Low**	√	
Thin target dE/dx, energy distribution, charge state, and scattering in a heated target	**Low**	√	
Positive - negative halogen ion plasma experiment	**>0.4 eV**	√	√
Two-phase liquid-vapor metal experiments	**0.5-1.0**	√	√
Critical point measurements	**>1.0**	**?**	√

time

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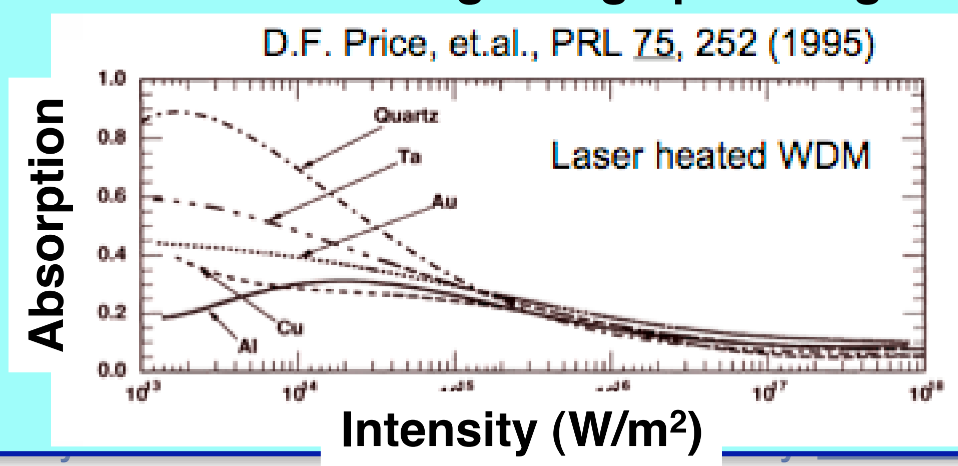
Transient darkening emission and absorption experiment to investigate previous observations in the WDM regime	**Low (0-0.4 eV)**	√	

time

What is the physical mechanism for changes in the optical properties of glass, as matter approaches the WDM regime? Can these optical changes be induced from excitation by ion beams? What information is obtained from the emission? How does the darkening differ in crystalline and amorphous materials (e.g. glass vs. quartz)? Can the darkening be used for fast switching of high power light beams?



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	Target temp.	NDCX-1 or HCX	NDCX-2
Measure target temperature using a beam compressed both radially and longitudinally	**Low**	√	

Can we measure the thermodynamic properties of matter heated by ion beams compressed in space and time? How uniform must the target temperature be for useful equation of state measurements? What are the differences between foams and solids at low T? Can we go beyond specific heat and expansion measurements to obtain liquid-vapor phase diagram, evaporation rates and EOS?

time ↓

We have identified a unique series of warm dense matter experiments that can begin on NDCX-I at Temperature < 1 eV

	Target temp.	NDCX-1 or HCX	NDCX-2
Thin target dE/dx, energy distribution, charge state, and scattering in a heated target	**Low**	√	

time

Can an ion beam (*after* it heats and exits a target) be used as a unique target probe for WDM exploration? How do the differences in charge state and energy loss differ between an ion beam propagating through a foam and a beam propagating through a solid of the same column density? Our ions have precisely determined E, so ion dE/dX can be accurately measured.

We have identified a unique series of warm dense matter experiments that can begin on NDCX-I at Temperature < 1 eV

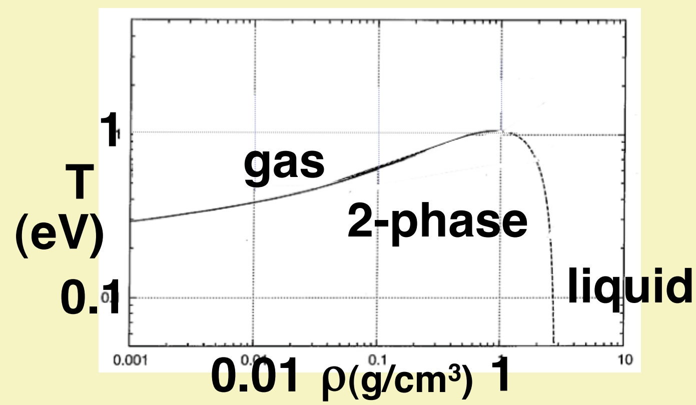
	Target temp.	NDCX-1 or HCX	NDCX-2
Positive - negative halogen ion plasma experiment	**>0.4 eV**	√	√

Can unique states of matter be created with nearly equal quantities of positive and negative ions (and few electrons)? What are the physical properties of such a state? **Is there a phase transition from low conductivity to a semiconductor? (Negative ions are like "donors" and positive ions like "acceptor" impurities.) Is there an emission (annihilation) line signature of this plasma? What are the photoconduction and junction non-linearities for these plasmas? Can these plasmas handle large current densities?**

time

We have identified a unique series of warm dense matter experiments that can begin on NDCX-I at Temperature < 1 eV

What is the temperature-density boundary between the liquid, liquid-vapor, and vapor regime for strong (refractory) metals? What is the equation of state (pressure as a function of temperature and density)? In the two-phase regime, what is the best way to make predictive simulations of the dynamics including the effects of droplets? (Are theory models for evaporation kinetics correct?) What determines the spectrum of droplet sizes?



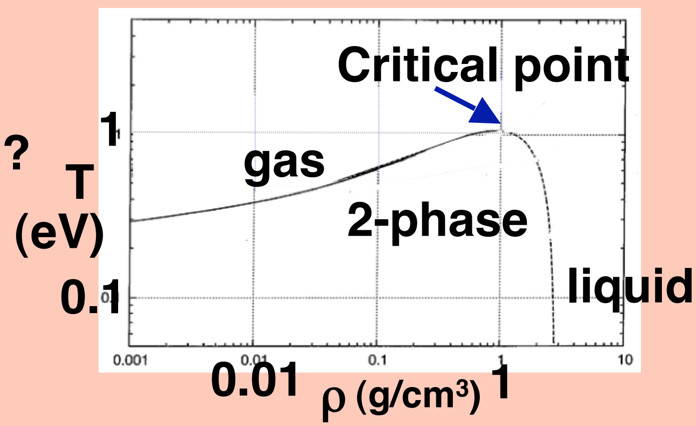
	Target temp.	NDCX-1 or HCX	NDCX-2
Two-phase liquid-vapor metal experiments	0.5-1.0	√	√

time

We have identified a unique series of warm dense matter experiments that can begin on NDCX-I at Temperature < 1 eV

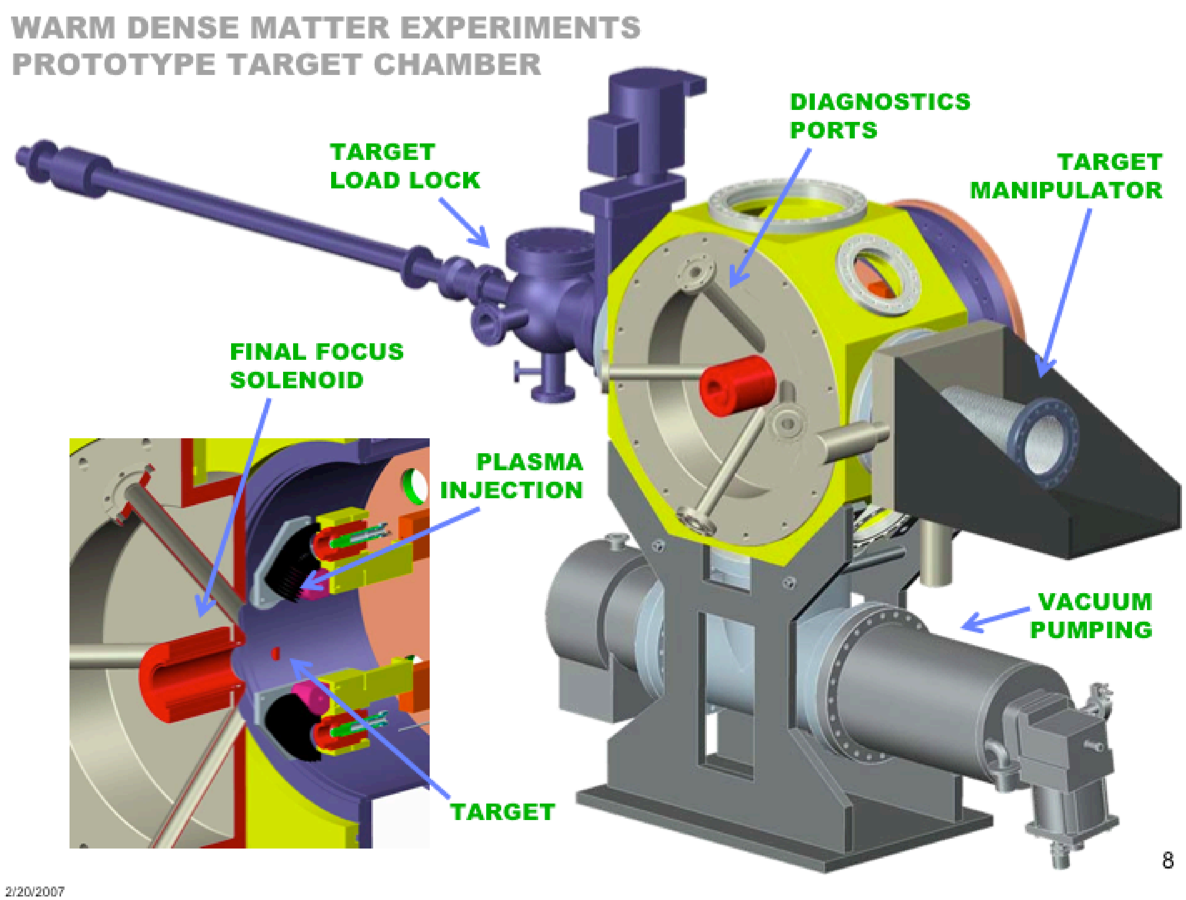
	Target temp.	NDCX-1 or HCX	NDCX-2
Critical point measurements	>1.0	?	√

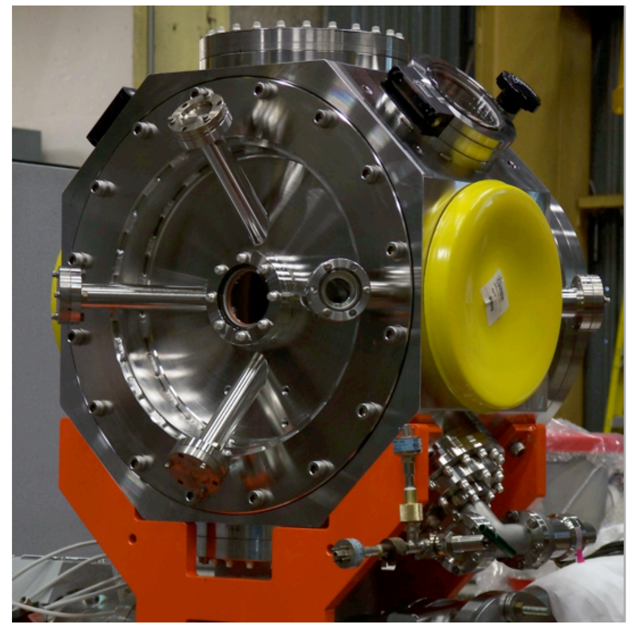
What is the temperature (for each element) above which, there is no distinction between liquid and vapor, and what is the density at this point (i.e. what is the critical point)? What are the material properties (pressure, thermal and electrical conductivity, opacity, viscosity, etc) at this point? As material cools from above the critical point, how fast do droplets form? What happens when ionization occurs at critical point for some materials?



time

WDM target chamber is designed and being fabricated



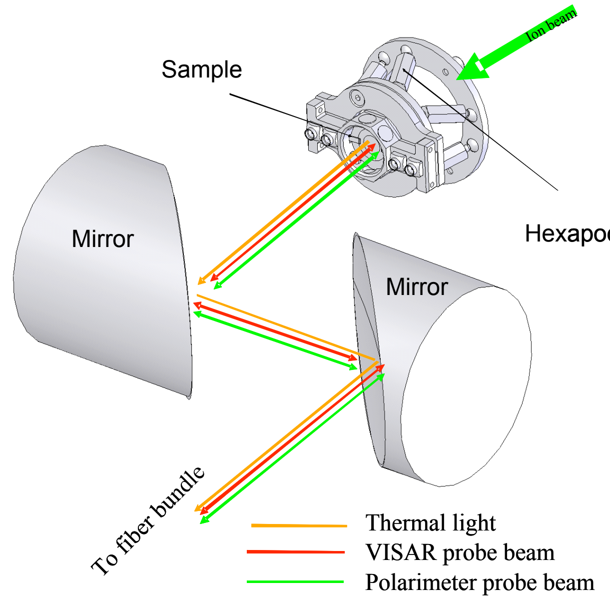


Target chamber as of April 19, 2007

We are developing target diagnostics for first target experiments on NDCX-I

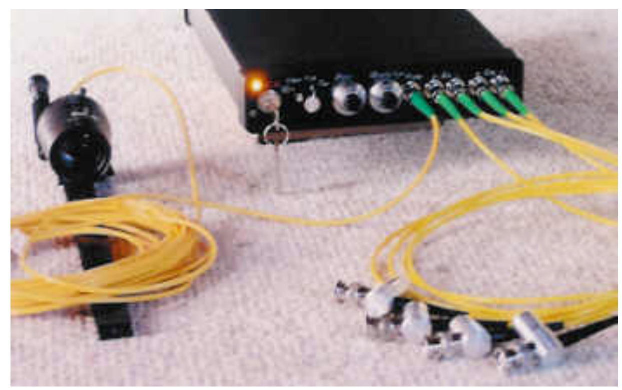
Fast optical pyrometer

- New design by P. Ni for fast response (~150 ps) and high sensitivity
- Temperature accuracy 5% for T>1000 K
- Spatial resolution about 10 micron at 1 eV
- *Now being assembled*



Fiber-coupled VISAR system – *now under test*

- ps resolution
- 1% accuracy

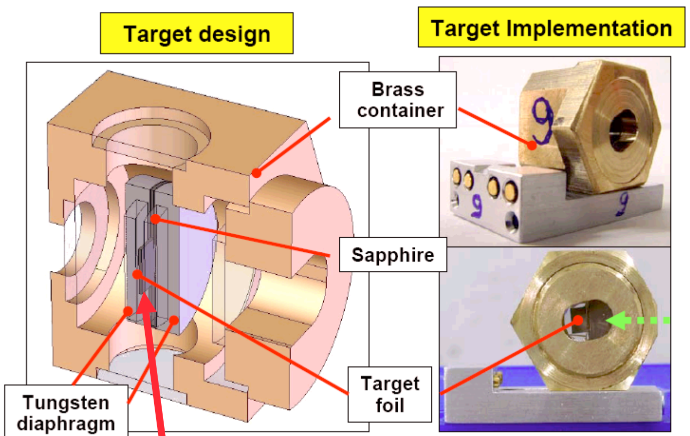


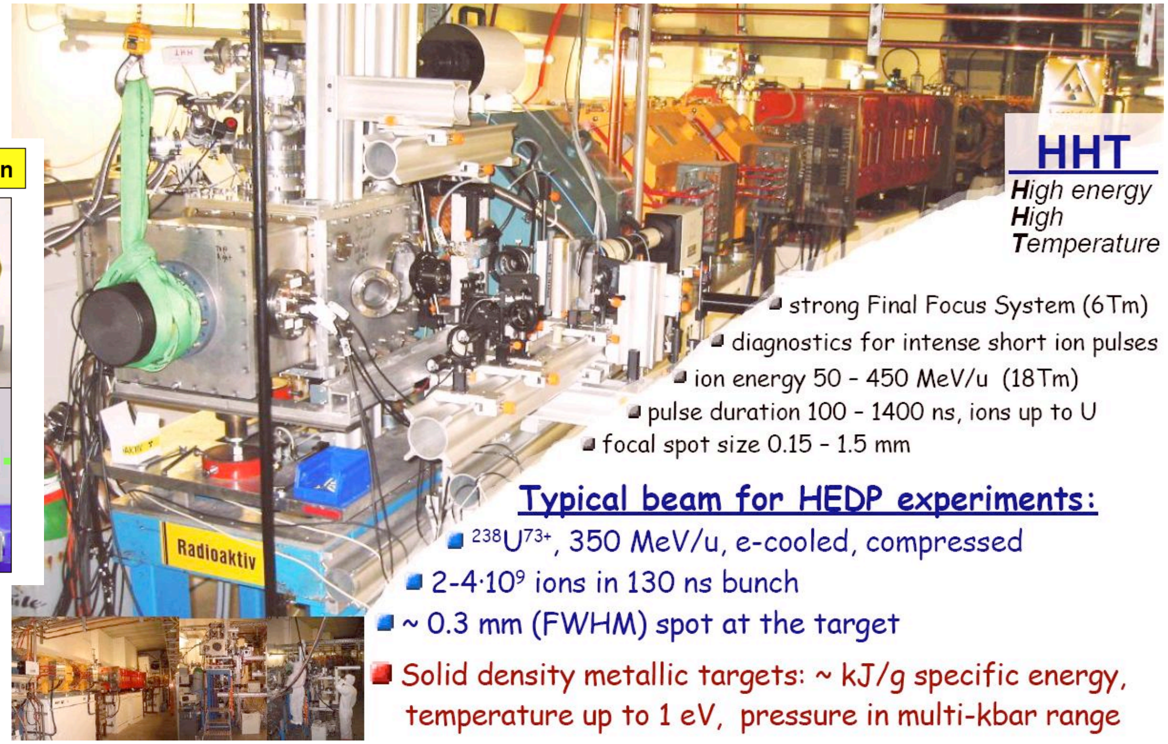
Hamamatsu visible streak camera with image intensifier

- ps resolution
- *arrived Feb. 2007*

All ready by end of summer

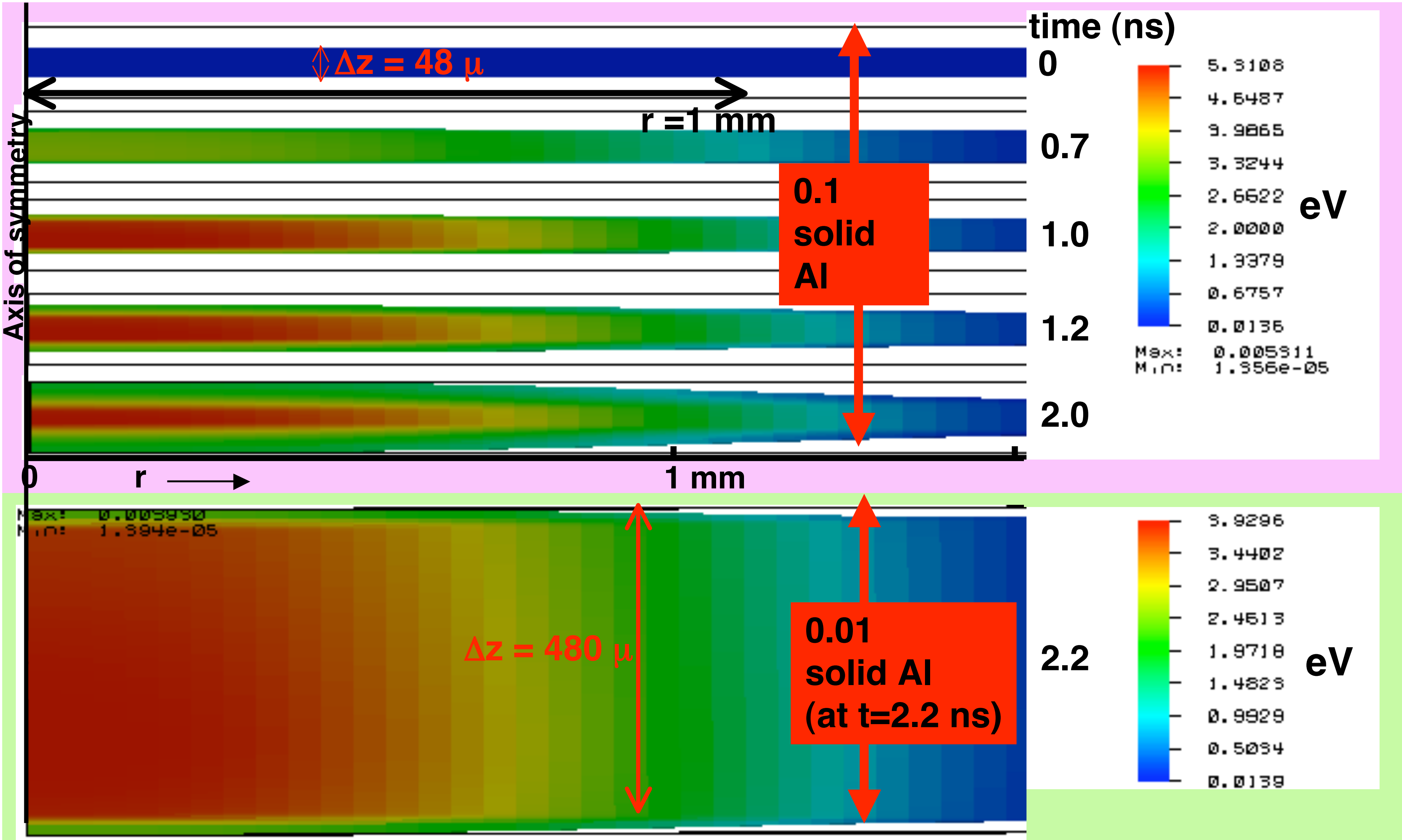
VNL porous target experiments at GSI have already begun





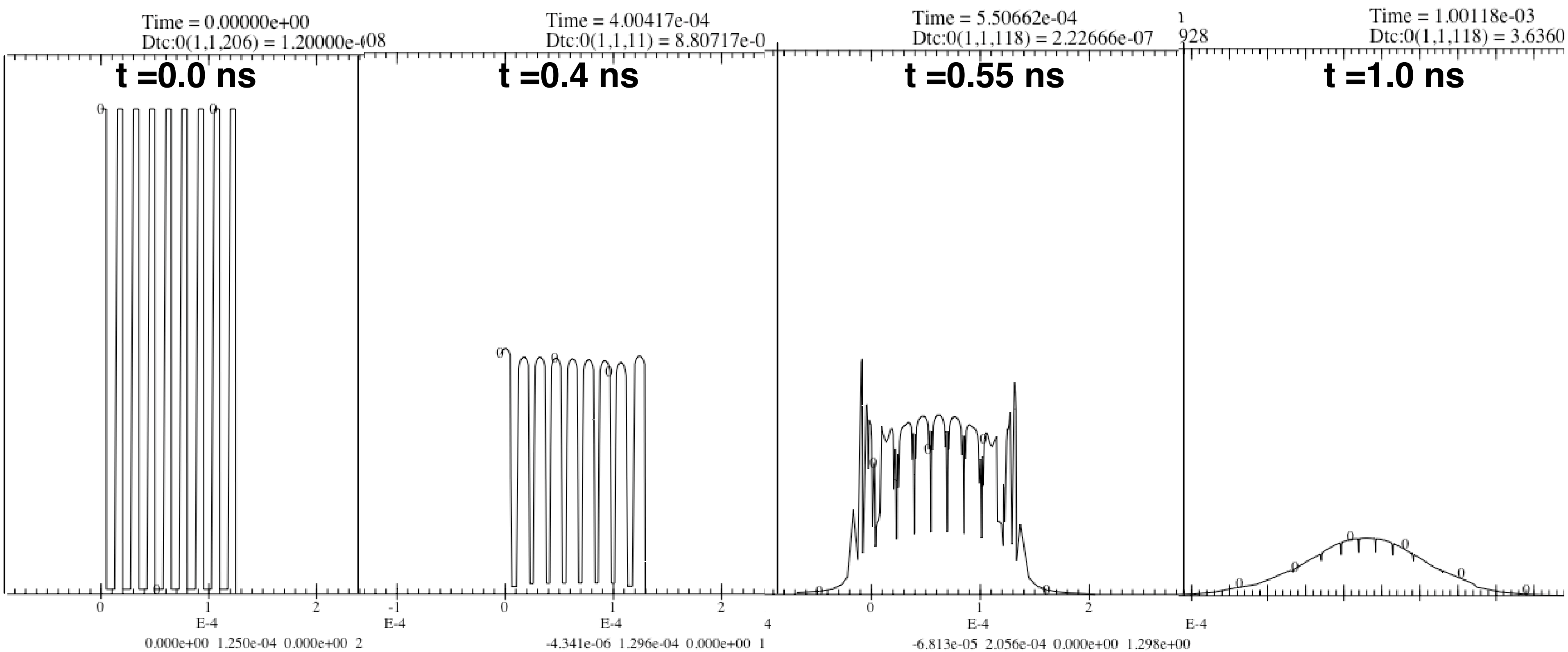
- Replace target foil with porous material.
- Study effect of pore size on target behavior using existing diagnostics.
- Sample targets: LLNL (Au, 50 nm), Mitsubishi (Cu, 50 micron).

HYDRA beam-heating simulations validate temperature uniformity



(simulations for 0.3 μC, 20 MeV Ne beam -- possible NDCX II / IB HEDPX parameters).

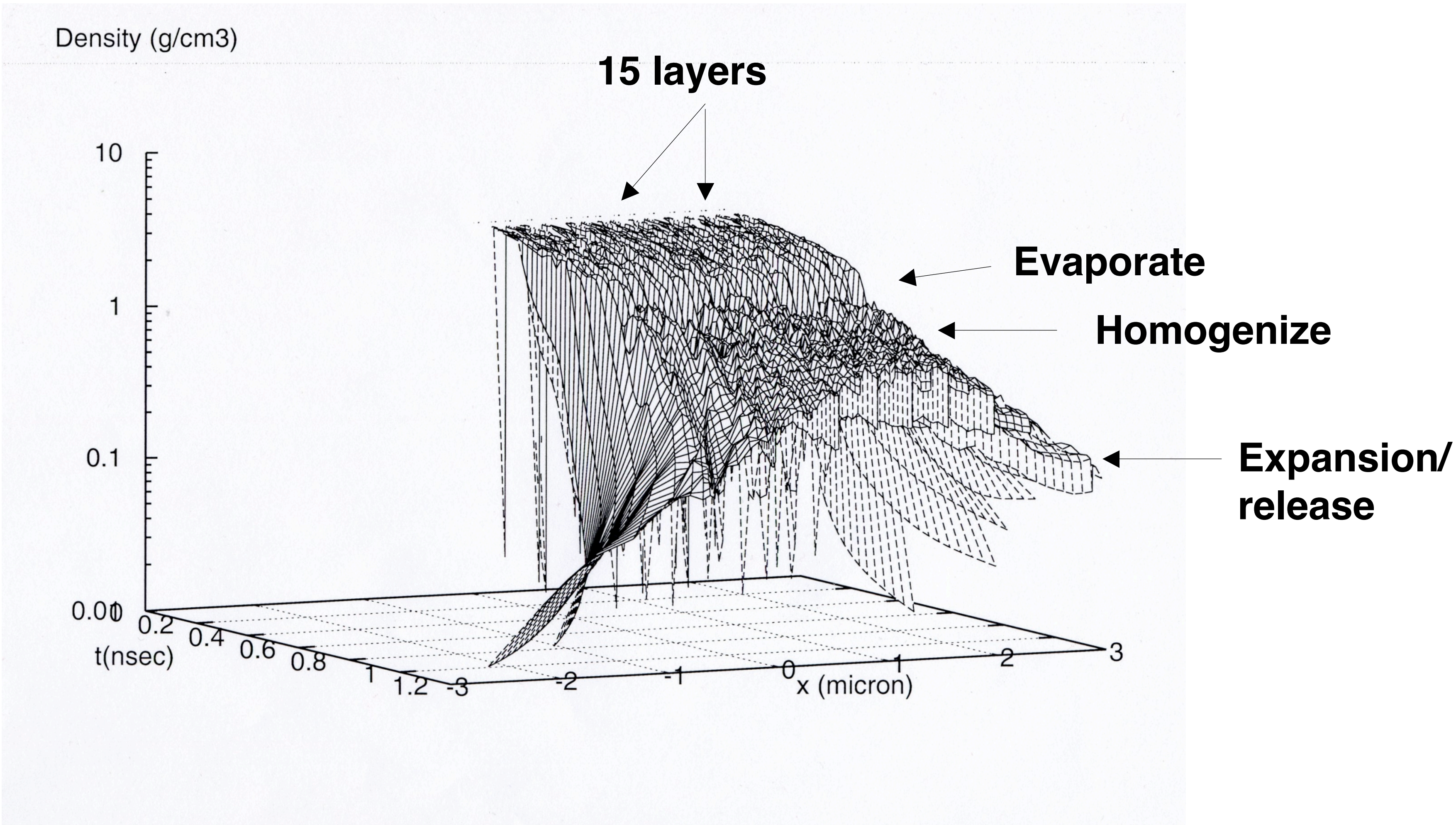
We simulate foams as multiple layers (solid density interspersed with low density voids)



density vs position
average density = 0.33 solid density

Studies being carried out using both HYDRA and DPC (R. More).

Using DPC with different EOS, qualitatively similar results are obtained



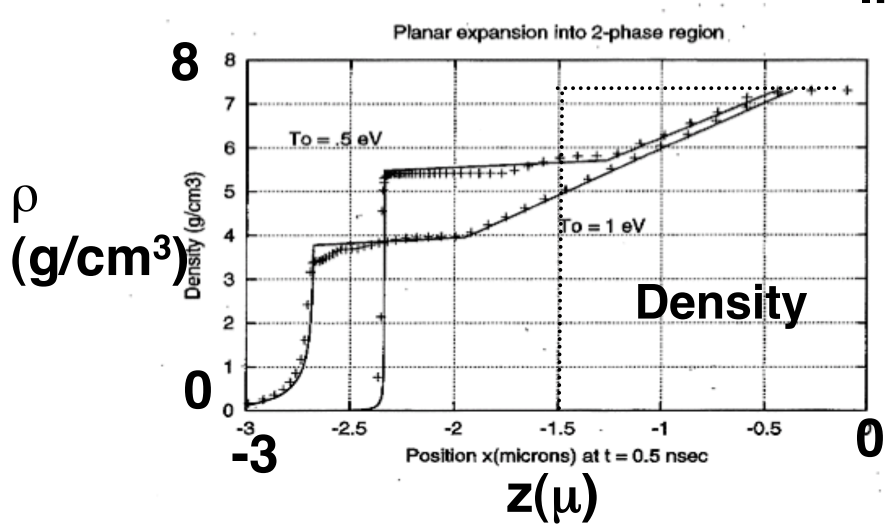
New EOS predicts a sharp density cliff which may facilitate detection and help determine critical points

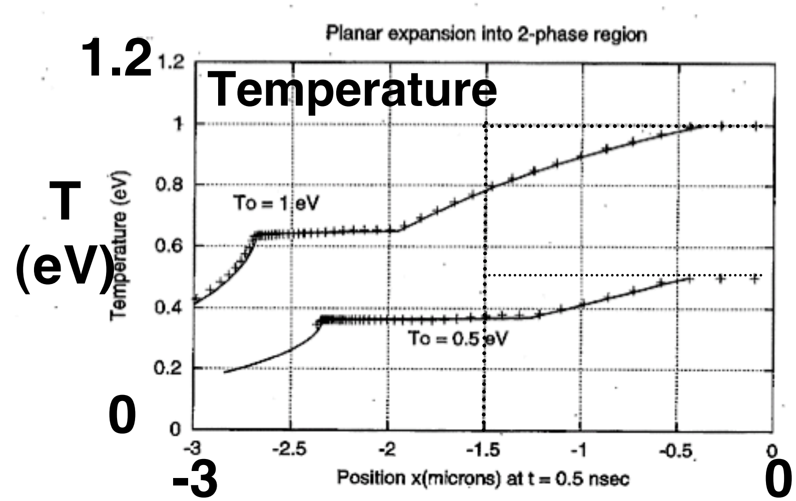
1D hydro calculations using DPC (R. More).

New EOS based on Saha equation with known energy levels (in contrast to QEOS, which uses “average” (Thomas Fermi) atom model)

Two phase medium results in temperature and density plateaus with sharp interfaces

Initial distribution

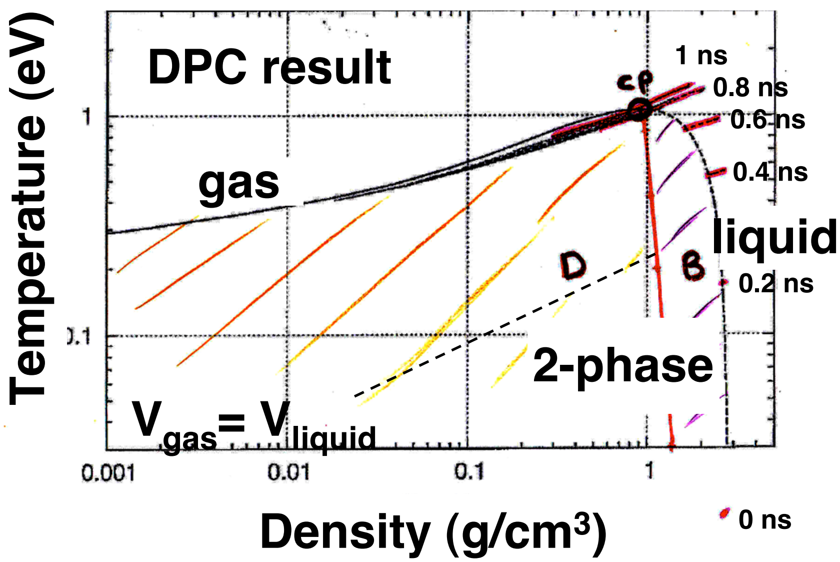




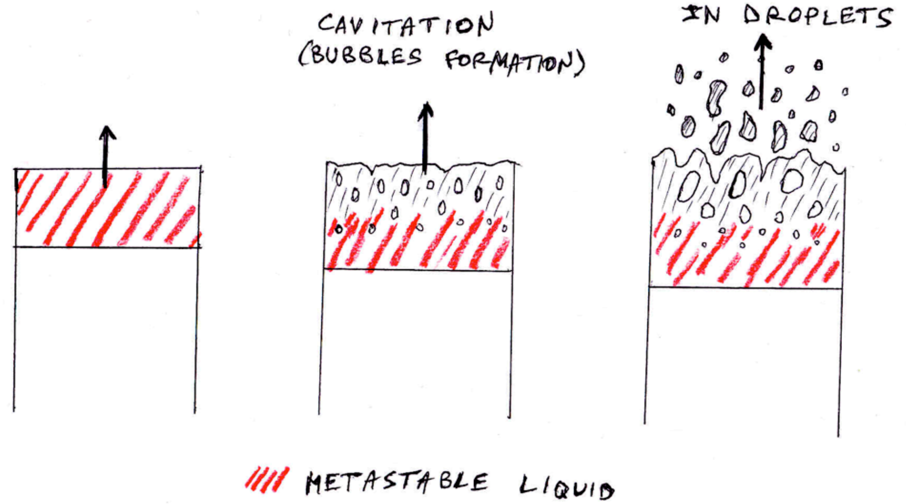
Example, shown here is initialized at T=0.5 or 1.0 eV and shown at 0.5 ns after instantaneous “heating.”

Formation of droplets during expansion of foil is being investigated

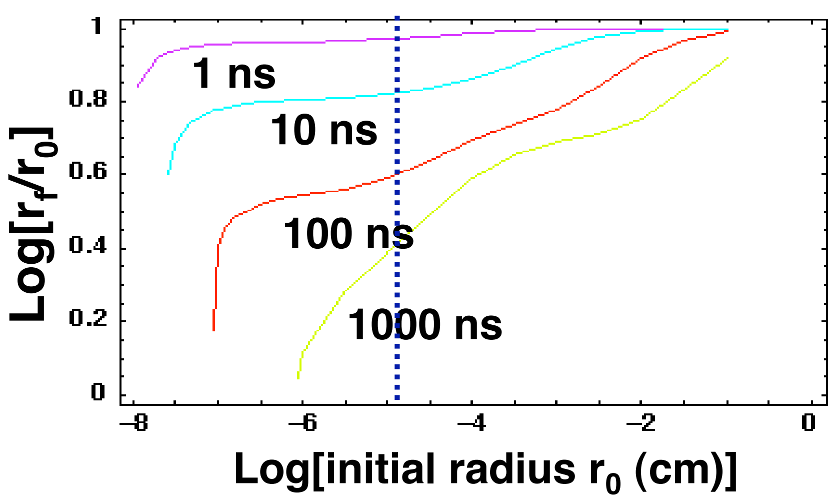
Example of evolution of foil in ρ and T



Foil is first entirely liquid then enters two phase regime.



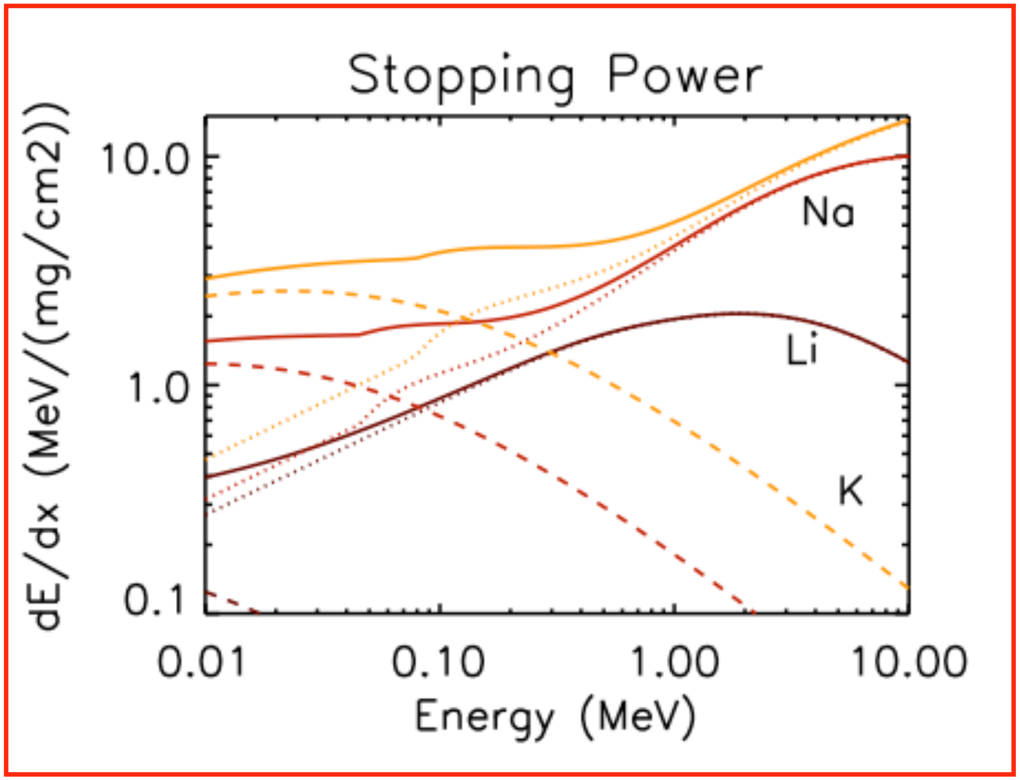
Ref: J. Armijo, master's internship report, ENS, Paris, 2006.



Evolution of droplet radius, (Armijo et al, APS DPP 2006, and in prep).

C. Debonnel and A. Zeballos are incorporating a model for surface effects into hydrodynamics code Tsunami

Extended and improved ion deposition algorithms for low energy ions are being developed for hydro codes



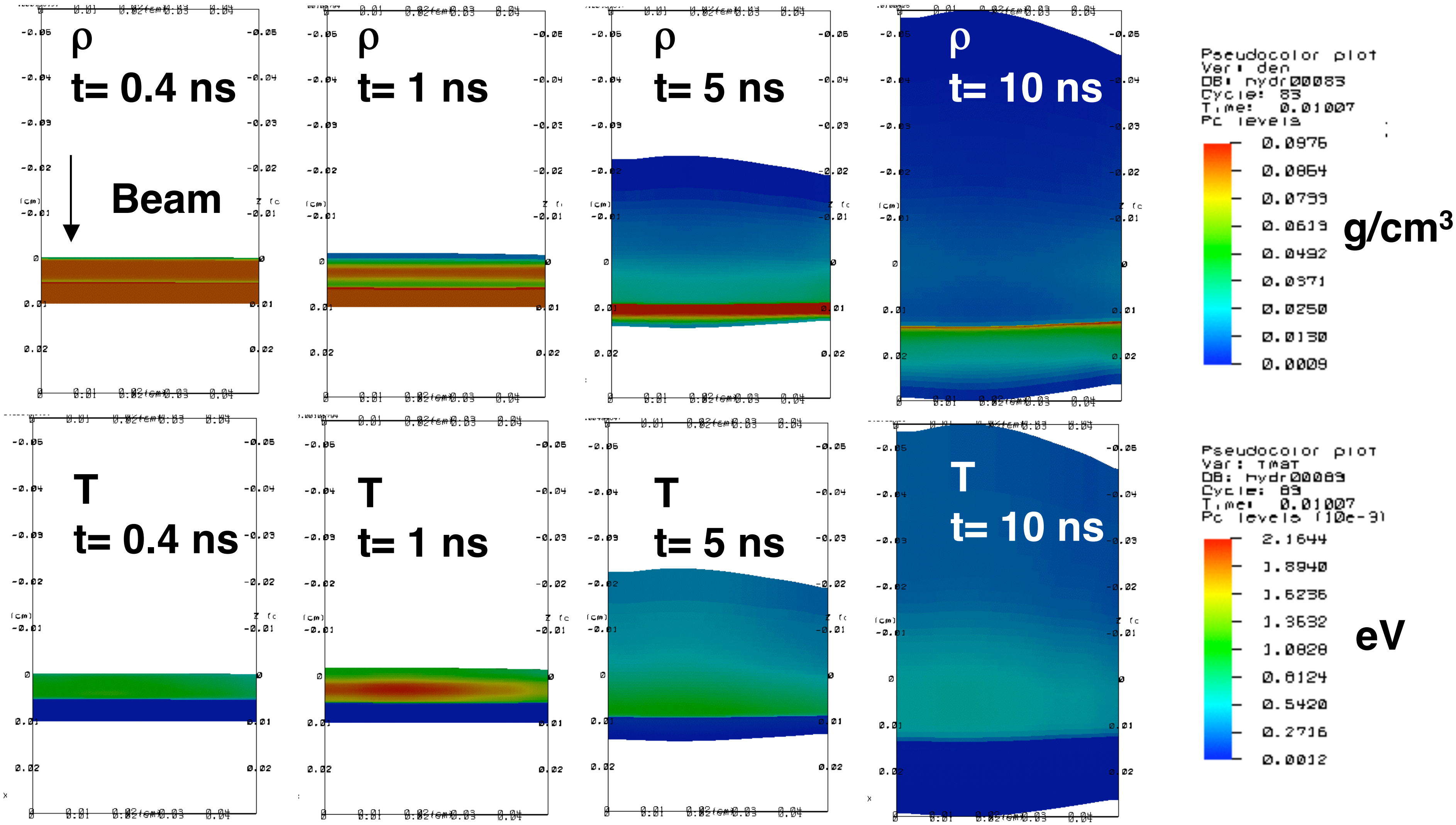
Tech-X Corp. stopping algorithm reproduces SRIM (industry standard code) results in the cold target limit, over a large range of beam energies, but extends results to finite T

Nuclear stopping important at lower energies (eg. 400 keV K^+ beams)

(Tech-X package Txphysics results at left.
Dashed: nuclear stopping;
Dotted: bound electronic;
Solid: total)

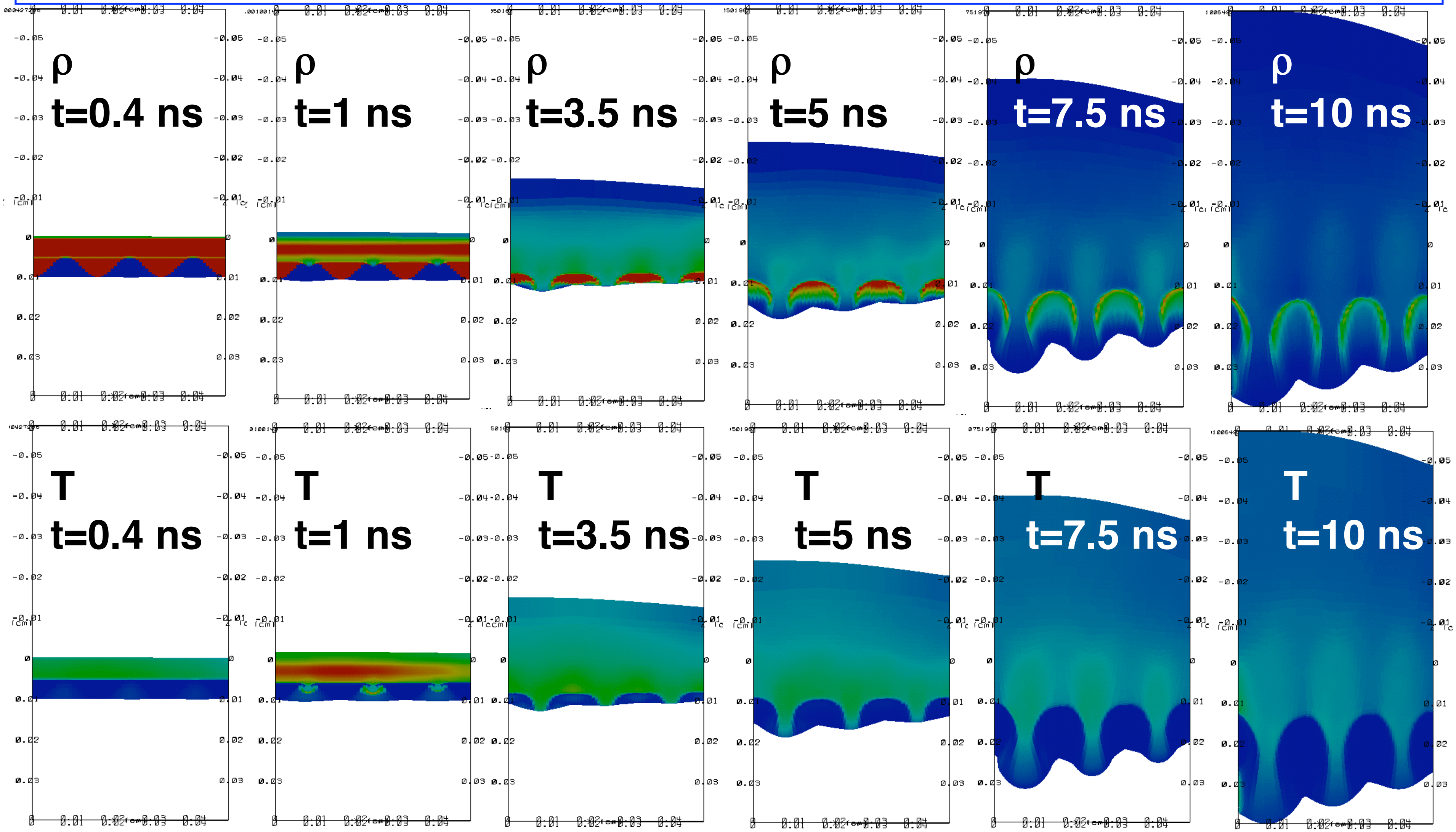
S. Veitzer, P. Stoltz (Tech-X) working with M. Marinak (LLNL) to modify HYDRA code.

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/IB-HEDPX) impinges on 100 μ thick solid H, T=0.0012eV, ρ =0.088 g/cm3; No density ripple on surface, blowoff accelerates slab

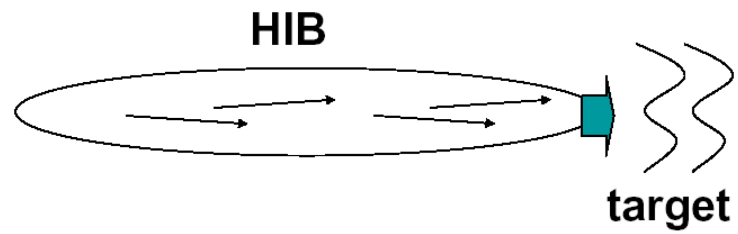
When a density ripple imposed, evidence of Rayleigh Taylor instability is observed in the simulations



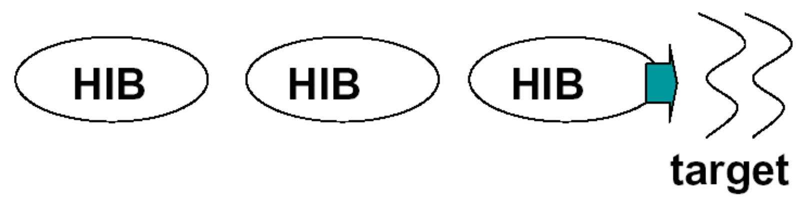
→How does ion-driven RT differ from laser driven RT?

S. Kawata (Utsunomiya U.) has proposed several techniques to reduce RT growth in ion-beam-driven direct drive

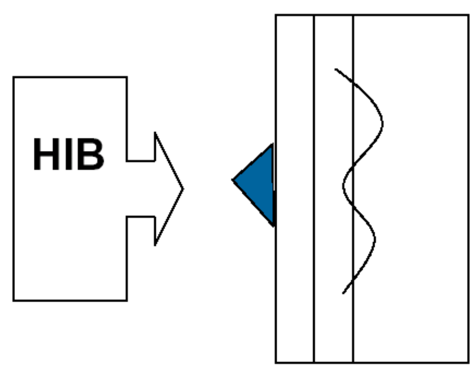
HIB axis rotation or swing
-> reduce the R-T growth!



Successive HIBs induce a dynamically Oscillating *g*!
-> reduce the R-T growth!



Large-scale HIB-energy deposition profile
-> Large-scale density gradient
-> Reduce the R-T growth!



δg(x), induced by an shaped Ablator, controls R-T phase & growth

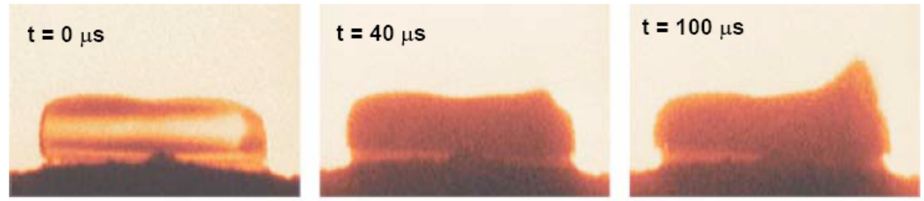
L&PB, 11(1993)757

Shaped target with an Ablator for R-T phase control

→These techniques can be explored on NDCX-II or IB-HEDPX

Ion-driven hydrodynamic studies on cryogenic hydrogen could be carried out on NDCX II or IB-HEDPX scale facilities

- ***GSI first practiced ion-driven target hydrodynamics with cryogenic Xenon targets at beam intensities well below those required for full target ionization:***

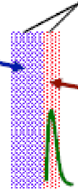


- **Direct drive hydrodynamics/RT physics can benefit from "pump-probe" double pulses:**

Solid D_2 "payload"

Payload and ablator D_2 layers are doped with different impurities to diagnose optical depth modulations

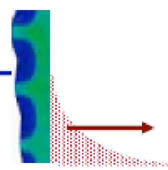
Time just before first pulse



Ablator D_2 layer ~ > than initial ion range

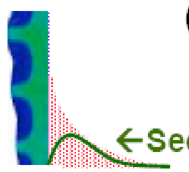
← First ns ion beam pulse dE/dx (beam enters from the right)

Time ~ 10 ns later before second pulse arrives



RT "bubbles & spikes" grow measurable amplitudes.
(1) Can upstream beam GHz RF modulation reduce RT?
(2) Do RT non-uniformities in ablation plasma smooth out with time and distance (any "ablative stabilization")?

Second ion pulse arrives, and stops *mostly within ablation blow-off* (in 1-D approx.)!

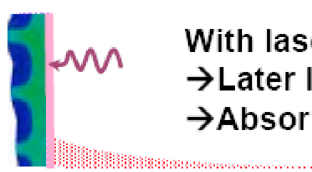


(1) "Rocket science": what ion range/ablator thickness maximizes hydro implosion efficiency with later ion pulses re-pressurizing same ablation layer mass?

←Second ns ion beam pulse dE/dx

(2) How is RT growth affected (any "cloudy day" effect?)

With laser direct drive, later pulse ablates at fresh critical density layer further left



With laser direct drive, ablation plasma << critical density,
→Later laser light transmits through ablation plasma.
→Absorption in inverse bremsstrahlung layer moves left as ablator layer erodes

← Unique physics with ion drive using NDCX-II

The HIFS VNL plan is to create accelerator facilities that are relevant to both WDM and HIF

The physics of ion driven volumetric energy deposition is significantly different than energy deposition by lasers, so that exploring this hydrodynamics will yield new science results, beyond the original WDM mission

Hydrodynamic studies of the acceleration and stability of solid target foils can yield insight into the physics of ion-driven direct drive targets.

Recent innovations to enable ion-driven HEDP also enable direct drive modular drivers for HIF or target hydro experiments

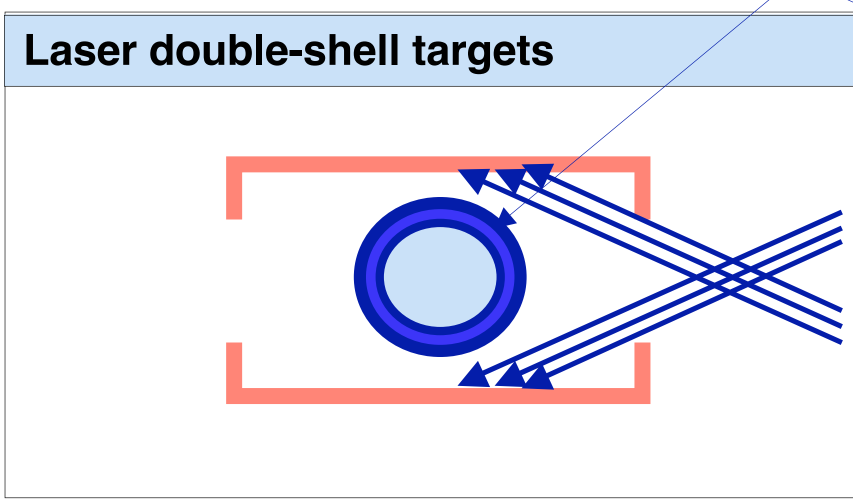
Minimum pulse energy for studying implosion physics has been estimated by G. Logan to be ~ 10 kJ. Direct drive experiments with such ion beams might supplement NIF laser target data.

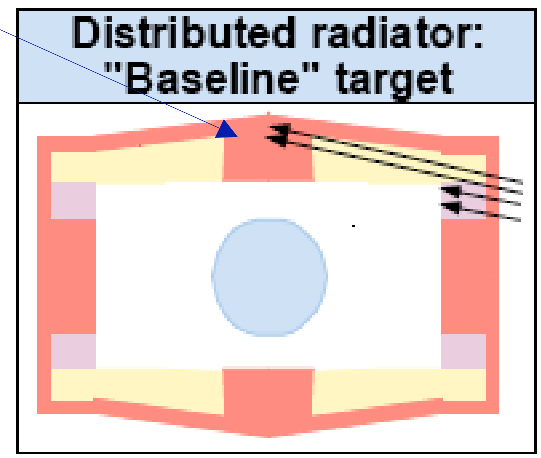
WDM and hydro studies have direct impact on IFE

- Effects of preheat
- Early-time hohlraum hydro
- Target debris physics
- Performance of foams

Two examples:

Foams





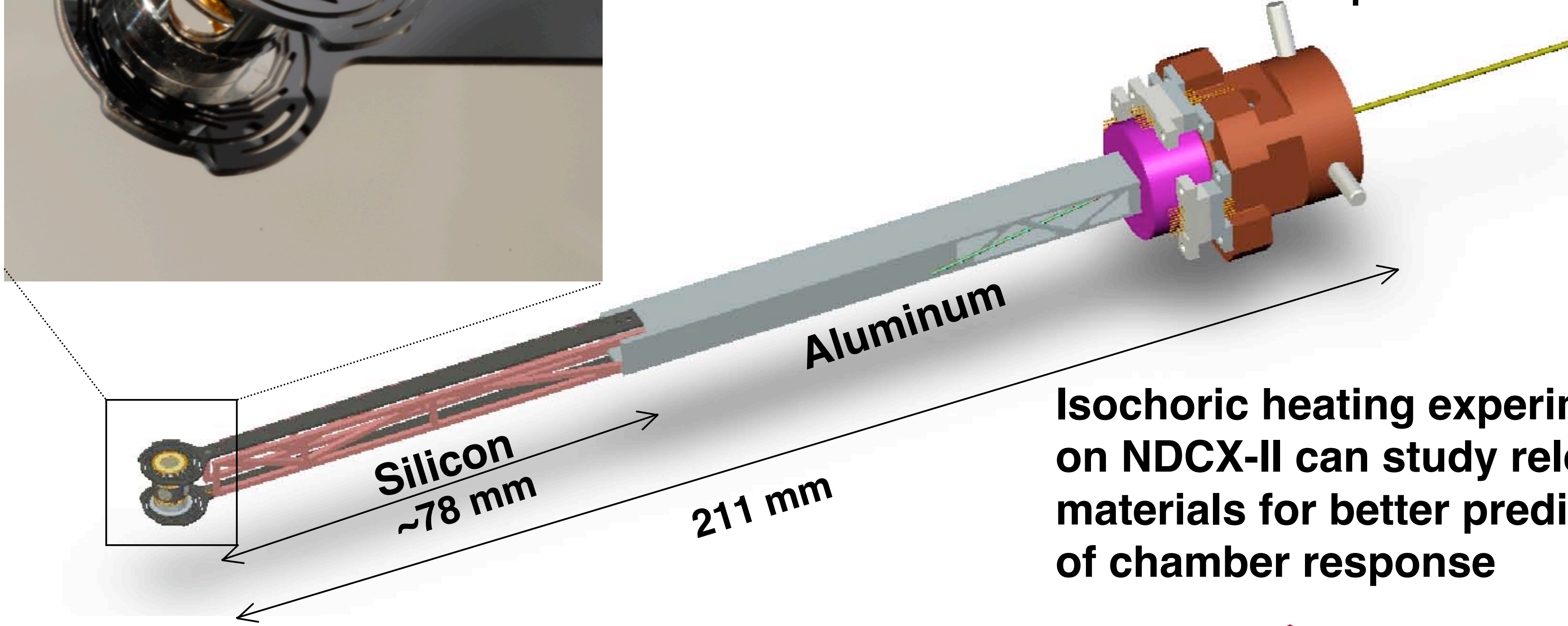
- Ion deposition, acceleration, and stability

Isochoric heating by ion beams can simulate neutronic isochoric heating near NIF target

Exposure: 10^{17} - 10^{19} neutrons per shot

$kT \sim 4\ eV\ (1\ cm/r)^2\ (N_n/10^{19})(\sigma/10^{-24}\ cm^2)$

Near target, material is vaporized, but some material a few cm away is volumetrically preheated by neutrons to melting point or lower, changing material properties, before hohraum shock wave reaches preheated material



Isochoric heating experiments on NDCX-II can study relevant materials for better predictions of chamber response

Conclusion

Heavy Ion Fusion Science experiments on NDCX I are making outstanding progress in neutralized compression.

Warm Dense Matter experiments are beginning

-- Transient darkening experiments on HCX

-- Metallic foam studies at GSI

-- Target heating experiments (~.2 - .5 eV) to begin this year on NDCX I

-- 1 eV experiments on NDCX II by 2009 (assuming 1.5 M$ funding increase)

Hydrodynamics experiments for stability and ion physics deposition studies can be carried out on NDCX II and/or IB-HEDPX. Simulations being carried out.