Ion Beam Driven HEDP

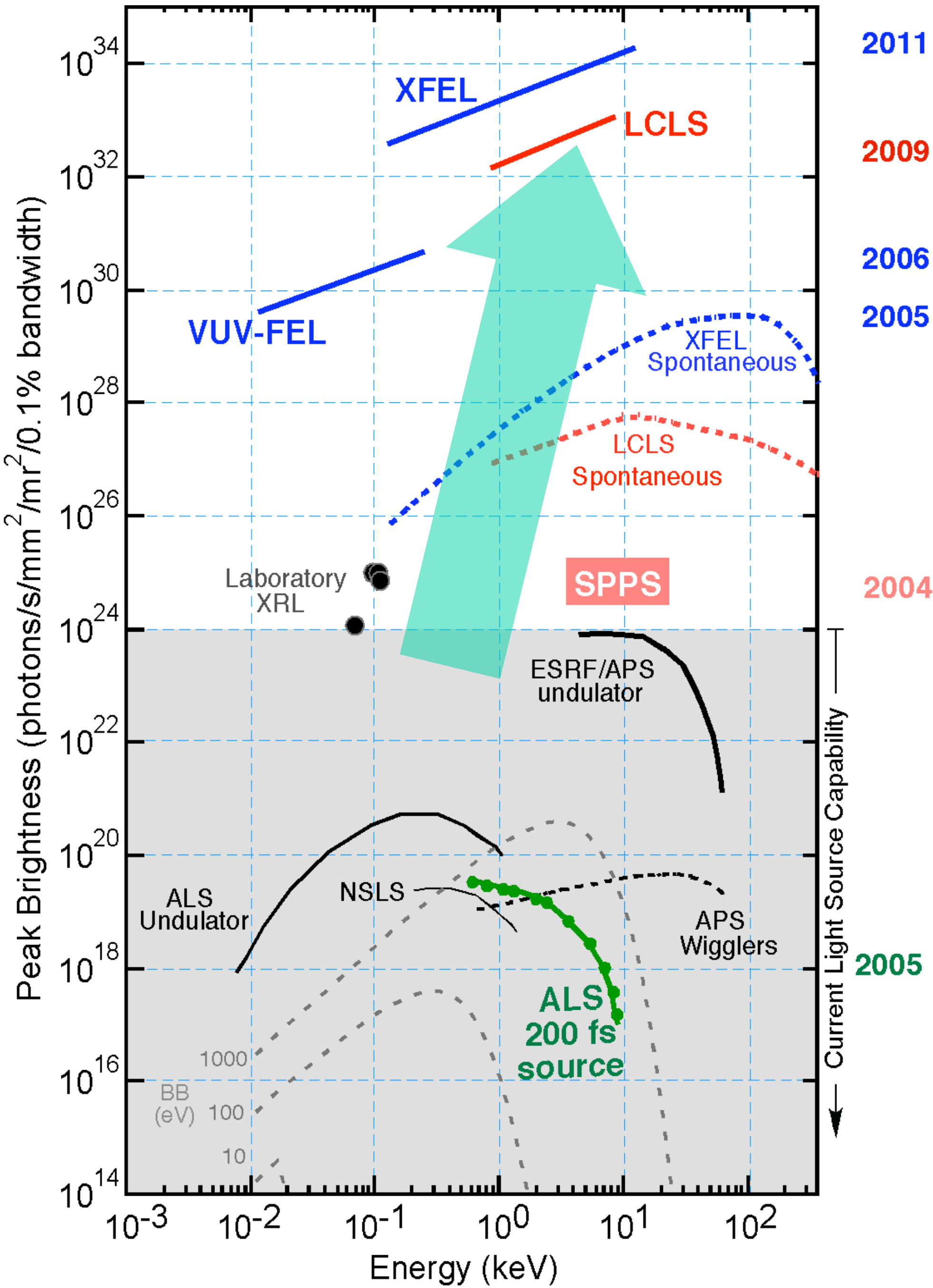
- **WDM at the LCLS and MEC endstation**
  - **LCLS Parameters**
  - **MEC endstation – Matter at Extreme Conditions = High Energy Density**
- **WDM at LCLS/MEC**
  - **Long pulse optical laser created high pressure states & LCLS probes**
  - **LCLS creates high pressure states & LCLS probes**
  - **Short pulse laser, protons… create WDM & LCLS probes**

R. W. Lee, J. S. Wark, H.-J. Lee, B. Nagler, J. B. Hastings, H. Scott, S. Moon, R. Shepherd, M. Fajardo, P. Audebert, D. Fritz, S. Boutet, H.-K. Chung, A. Nelson, H. Chapman, S.Bajt, S. Toleikis, T. Tschentscher, R. Faustlin,T. Whitcher, S. Vinko, D. Riley, T.Dzelzainis, M. Kozlova, L.Juha, P.Mercere, P. Heimann, R. Sobierajski, J. Krzywinski, J. Chalupsky, J. Cihelka, M. Jurek, V. Hajkova, K. Seksl, U. Zastrau, C. Fortmann, T. Döppner S.H. Glenzer, G. Gregori, R. Redmer…

LCLS is the first x-ray FEL providing more than 10^{10} increase in peak x-ray brightness

FEL Specifications

- Short bunch duration (~10 - 100 fs)
- Full transverse coherence
- High repetition rate (~120 Hz)
- Tunable from 600 to 8500 eV
- High # of photons per bunch > 10^{12}



- *Possibilities for HED studies*

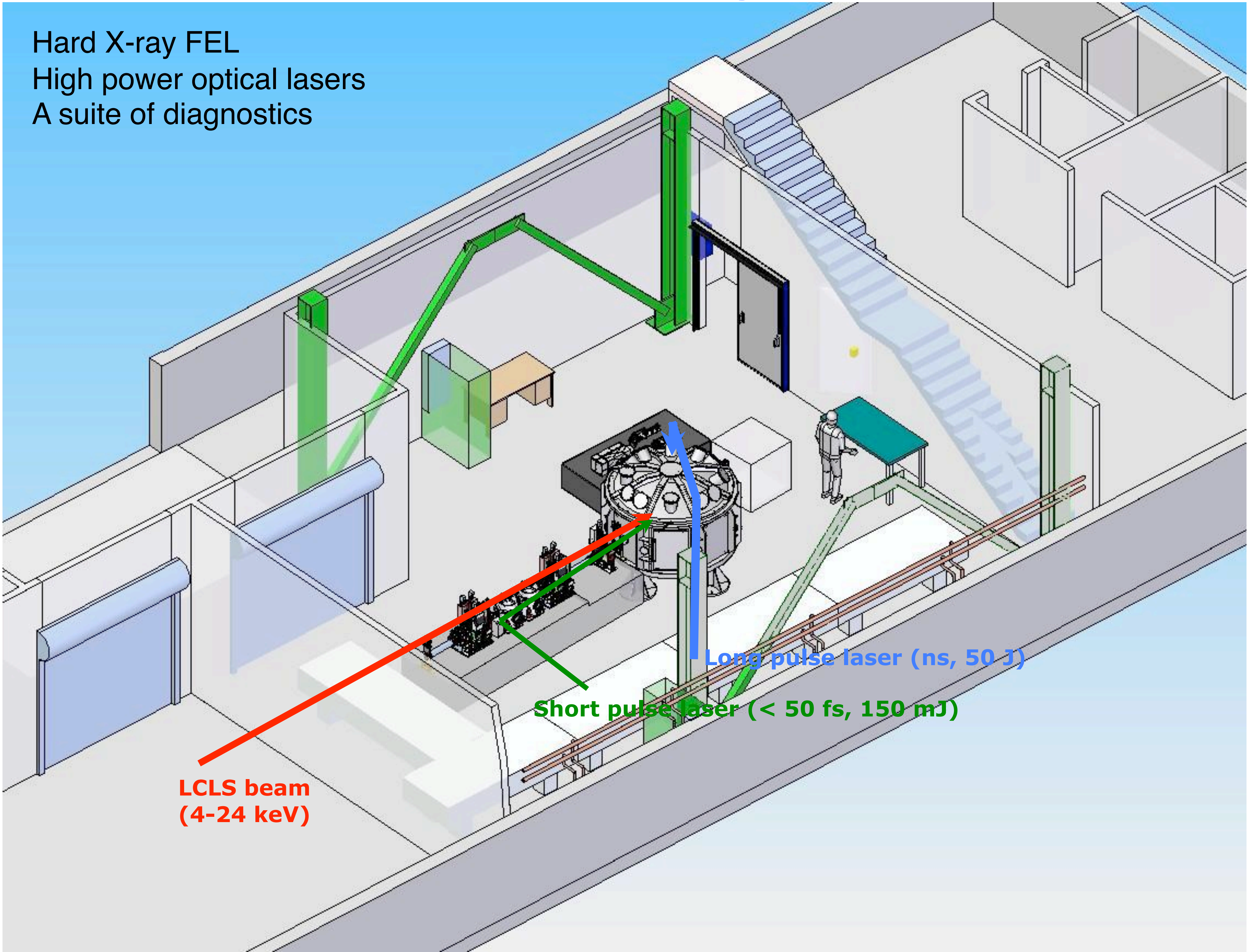
Materials under Extreme Conditions (MEC)

- Arbitrary definition of high energy density physics is energy density > 10^{11} J/m^3.
  - Solids compressed more than a factor of 2
    - Pressure typically a few Mbar – few 10^{11}N/m^2, therefore PV work per unit volume is in the 10^{11}J/m^3
  - A solid heated to a few eV - even naively assuming ideal gas
    - $E_{internal}$~NkT, for solid density need ~ 10eV.

- *How* we create the lower end of the HED phase space, which is warm dense matter, is important

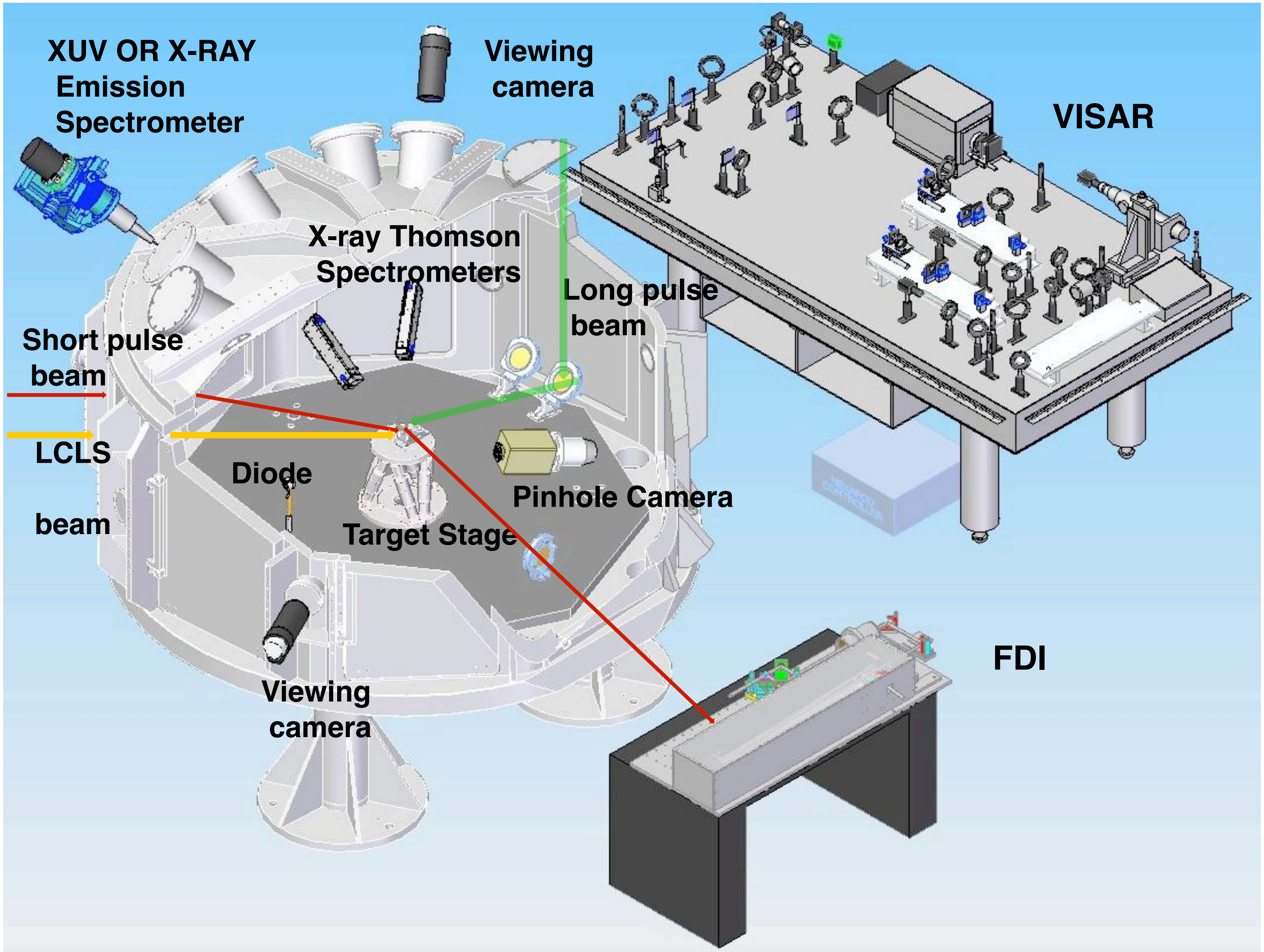
- The MEC endstation at LCLS provides a few alternatives.

MEC instrument layout



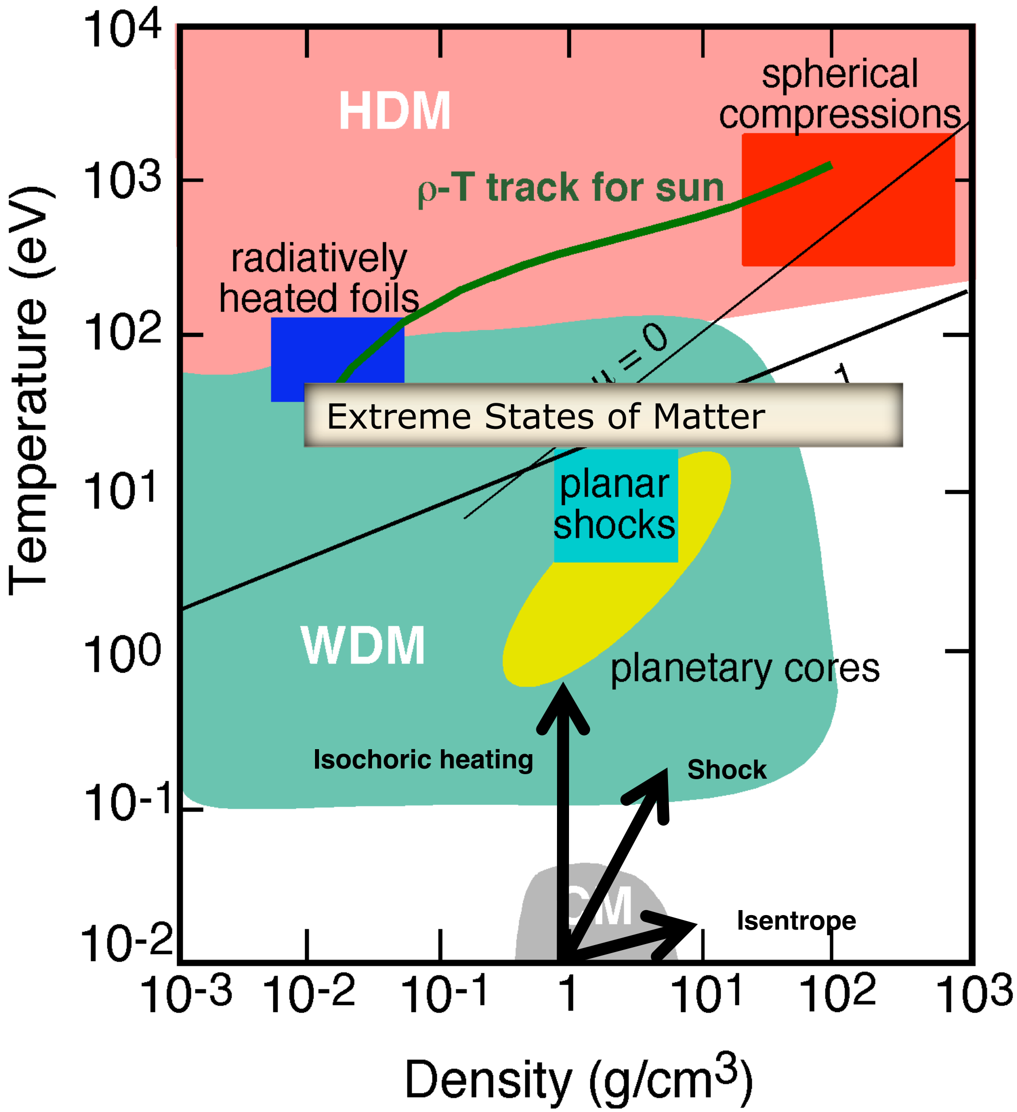
Target diagnostics with target chamber: provides a full suite of instruments

- Fourier Domain Interferometer (FDI)
- VISAR system
- Thomson Scattering spectrometers
- XUV and X-ray spectrometers
- X-ray Streak camera
- Sample stage
- X-ray beam diagnostics and focusing
- Alignment system
- Transmitted beam diagnostics



- **Concept is to encourage single investigators to participate in the HED research**

Scientific program at the MEC endstation



Warm Dense Matter Physics

High Pressure Research

High Energy Density Physics

Equation of state
Material properties of WDM/HDM
Electron-ion equilibrium
Transport phenomena

MEC diagnostics capability will address these scientific issue by measuring conditions of extreme states of matter

MEC long pulse laser can create high pressures (1)

- MEC long-pulse laser will contain of order 50 J of energy in a pulse length of between 1 and 10 ns
- Use the FEL spot size (~300 μm), or focus smaller (~10μm)
- For a few ns the irradiance, I, can be of order

$$I = \frac{50}{10^{-9}\pi(50 \times 10^{-4})^2}\,\mathrm{Wcm^{-2}} = 6 \times 10^{14}\,\mathrm{Wcm^{-2}}$$

- High irradiance causes pressure via ablation
- Note, typical sound (compression) velocity in a metal is 5km/s, which is 5μm/ns – over 1 ns good match to scattering lengths

MEC long pulse laser can create significant pressures via shocks (2)

- Simple model assumes most of the energy deposition flows from the critical density surface toward the lower temperature ablation layer

$$P_a \approx 2.8x10^{-9}\lambda_L^{-2/3}I^{2/3} \text{ Mbar}$$

where λ_L is the laser wavelength in μm and I is the laser intensity in W/cm^2

- Get pressures of 6 Mbar for 1μm at 10^{14} W/cm^2 and 30 Mbar at 0.5μm at $6x10^{14}$ W/cm^2

- Temperature reached at n_{cr} using $P_{cr} = n_{cr}k_bT_{cr}$ is

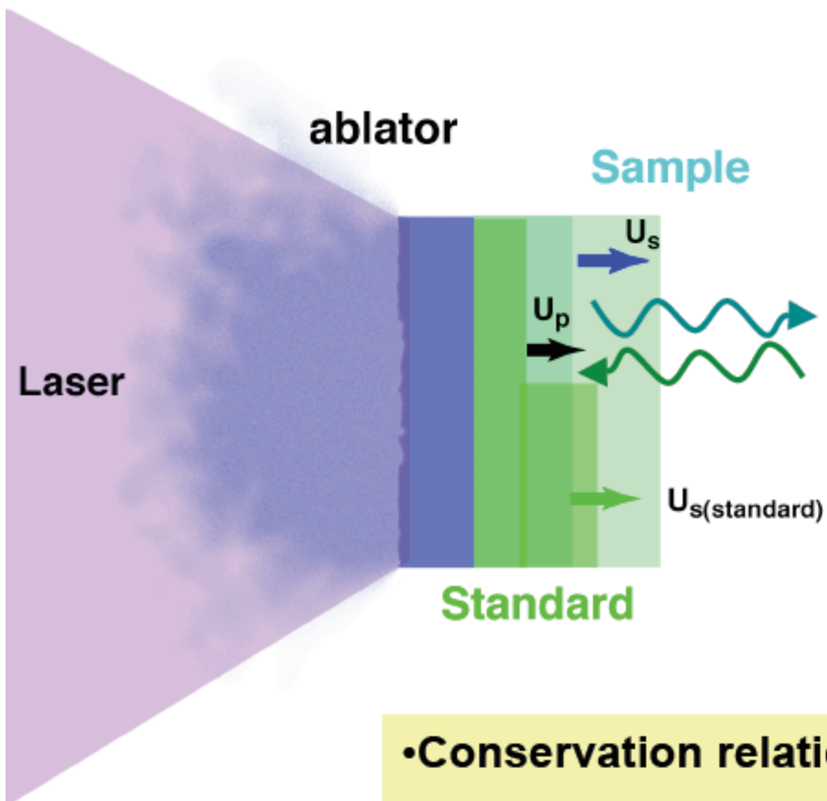
$$T_c \approx 70\lambda^{4/3}\left(\frac{I}{10^{16}}\right)^{2/3} eV$$

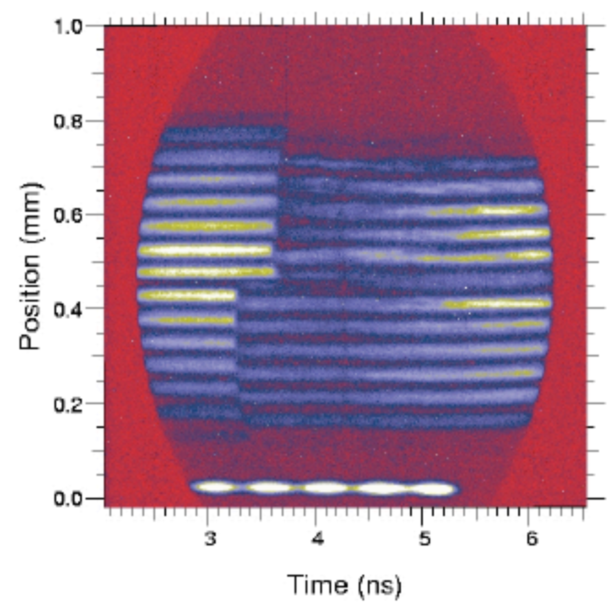
- Giving a few 100 eV for a 1μm laser at 10^{14} W/cm^2

- Thus, the MEC can create the high pressure shocks

MEC is instrumented for single researchers to do WDM experiments

- Laser irradiates an ablator and launches shock
- VISAR measures the velocities of particles, shock and standard from a stepped sample





•Conservation relations => $P = \rho_0 U_s U_p$

$\rho/\rho_o = 1/(1-U_p/U_s)$

•Temperature needs to be measured separately

MEC endstation can address problems in shock physics

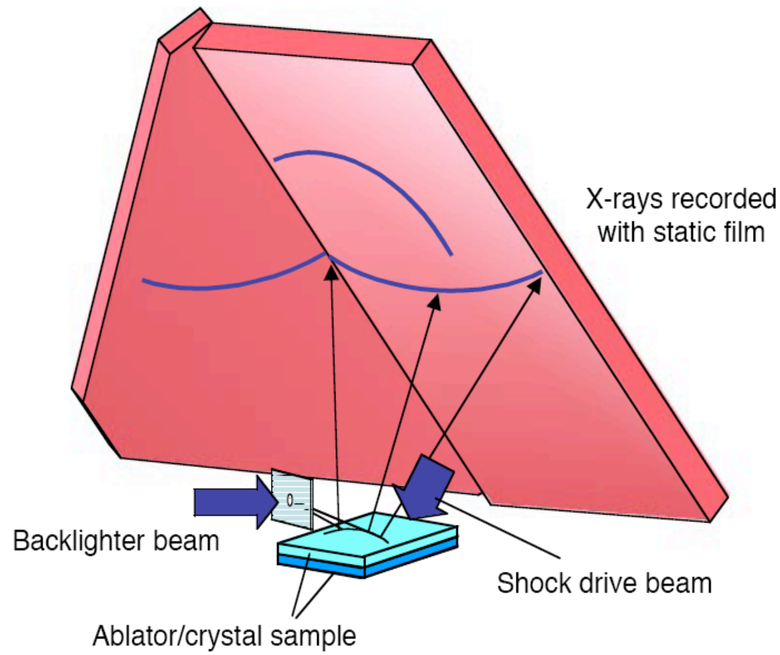
- Major issues in shock physics (J. Wark):
  - How do solid materials ‘flow’ like a liquid (hydrostatic compression)?
  - Where do the defects come from (and where do they go)?
  - What is the interplay between defects/twinning and other deformation mechanisms?
  - How quickly can various phase transitions take place?
  - How well do we understand the equation of state at ultra-high pressures?

- All of these issues necessitate, or greatly benefit from, a knowledge of what is happening at the lattice level.

- Indicates that ultrashort-pulse X-ray probing during the laser-driven shock is of importance

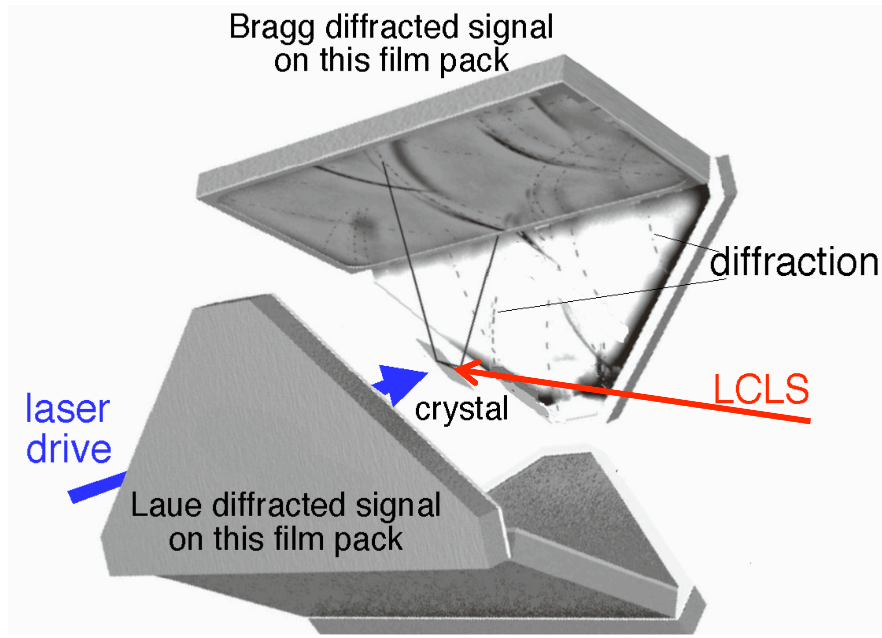
Lasers provide high divergence probe, while LCLS provides low divergence probe

- **Schematic of ns-laser shock, ns -laser probe experiment**



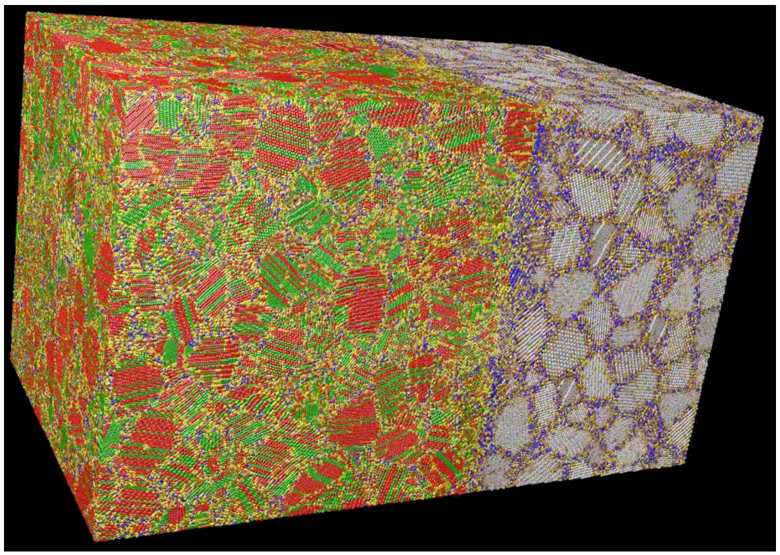
- Laser creates a shock in a single-crystal sample
- Delayed beams create ns-scale highly divergent x-ray source
- Angular spread of the x-ray source samples many crystal planes
- **Technique provides critical data on dynamics at high pressure**

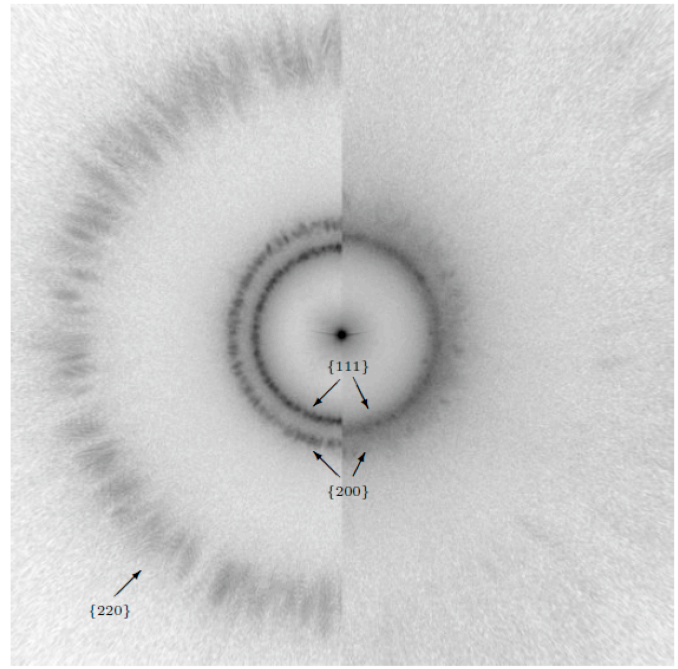
- **Schematic of ns-laser shock, LCLS probe experiment**



- Laser creates a shock in a polycrystalline sample
- XFEL creates fs-scale non-divergent monochromatic source
- Grains in the polycrystal diffract the beam
- **Low Divergence ⇒ *nm-scale fs diffraction of real solids***

1st LCLS Shock experiment will use polycrystalline material (LLNL/Oxford)





Unshocked Shocked

- Collimated, monochromatic X-ray beam
- Polycrystalline target

High pressure work at LCLS has benefits

- LCLS has high photon fluxes ~ 10^{12}
  - Laser-Plasma sources have limited x-ray fluxes

- LCLS has sufficient photons in 100 fs to freeze motion

- LCLS photon fluxes in 2^{nd} & 3^{rd} harmonic sufficient at higher photon energies to study higher Z materials

- LCLS divergence is small
  - Laser-produced sources must collimate
  - To maintain signal can not collimate enough
  - Result is poor resolution

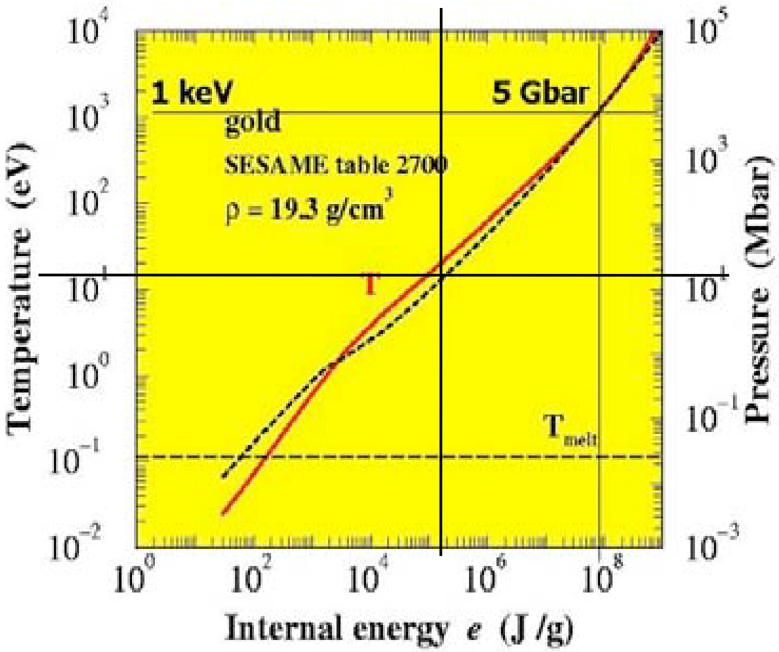
- LCLS is tunable can, e.g., scan just below a K-edge

LCLS creates high pressure states

LCLS X-ray laser can create high pressures without generating a shock

- Phase-Space Plot*

Temperature and Pressure
Versus Internal Energy

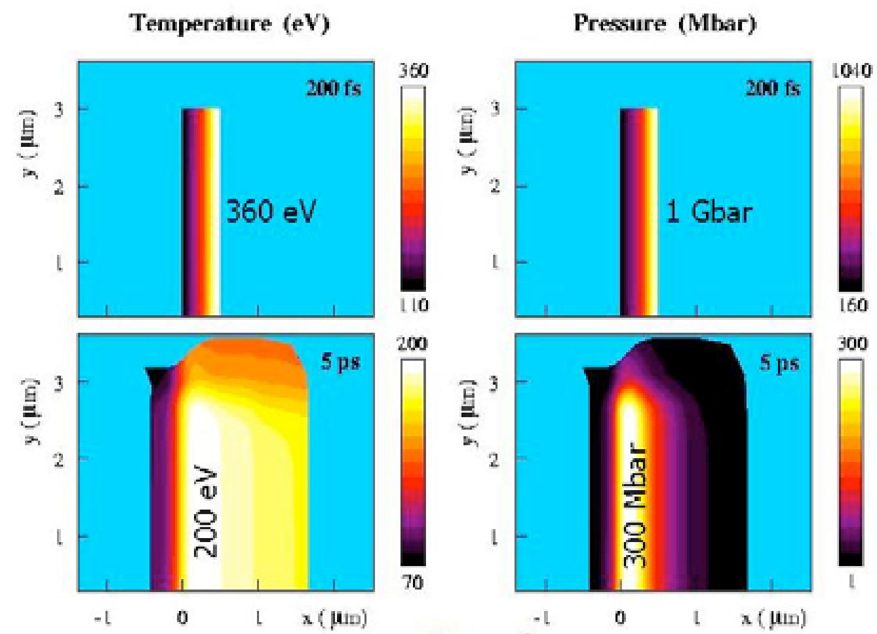


- Temperature (—), Pressure (····) vs J/g
- (– –) melting T reached with ~100 J/g
- Solid horizontal line corresponds to 10^8 J/g deposition, generating solid plasma of 1 keV, 5 Gbar

* Sesame / LANL

- Simulations*

Temperature and Pressure
Versus Time and Space

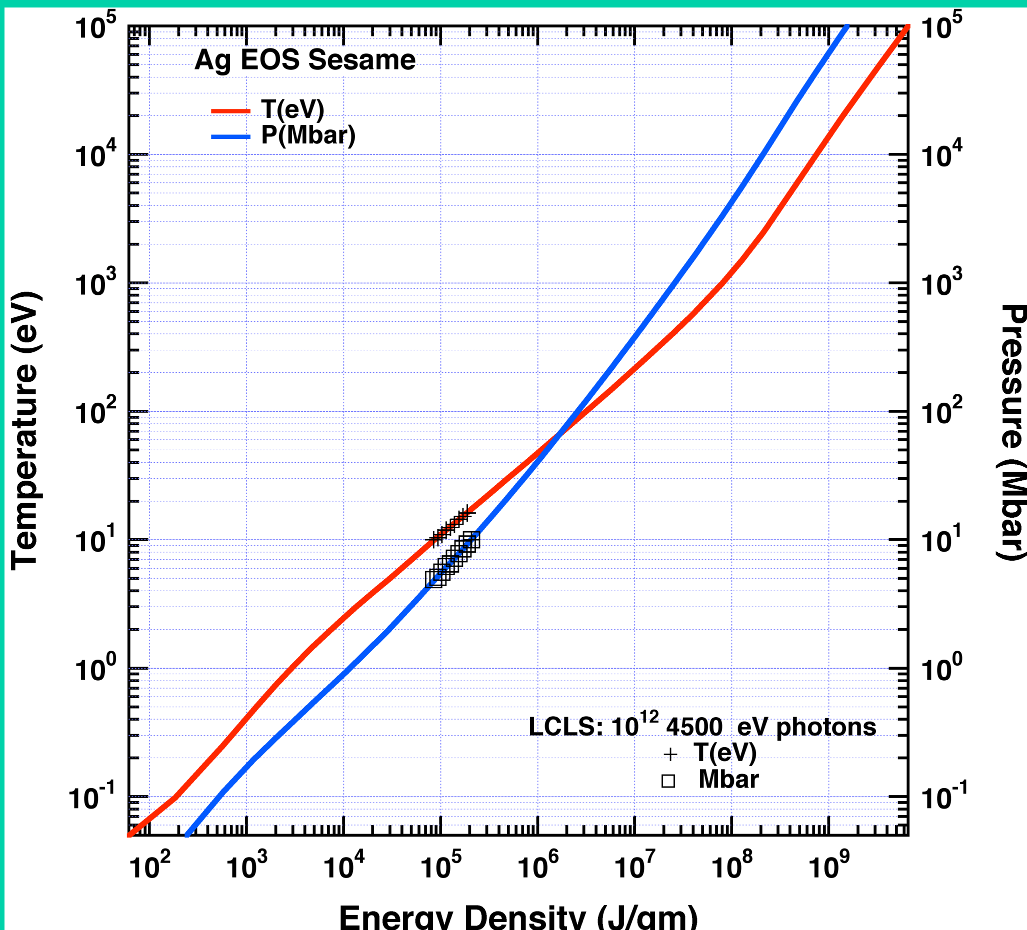


- Simulation: 0.5 μm Au
- Thickness is two absorption lengths
- XFEL: 100 fs, 10^{17} W/cm^2 pulse, 3.1 keV comes from right

* 2-D Multi-code / MPI

Before one looks at Gbar shocks over 6μm spots study x-ray energy deposition

- LCLS can be focused to 6 μm Au case ***but*** to provide a diagnosable surface one needs to verify sample response



Further the locus of points for the heating of 1μm of Ag is indicated for each 0.1μm section by + and □ symbols for the temperature in eV and the pressure in Mbar, respectively, where the highest temperature and pressure are at the irradiated surface.

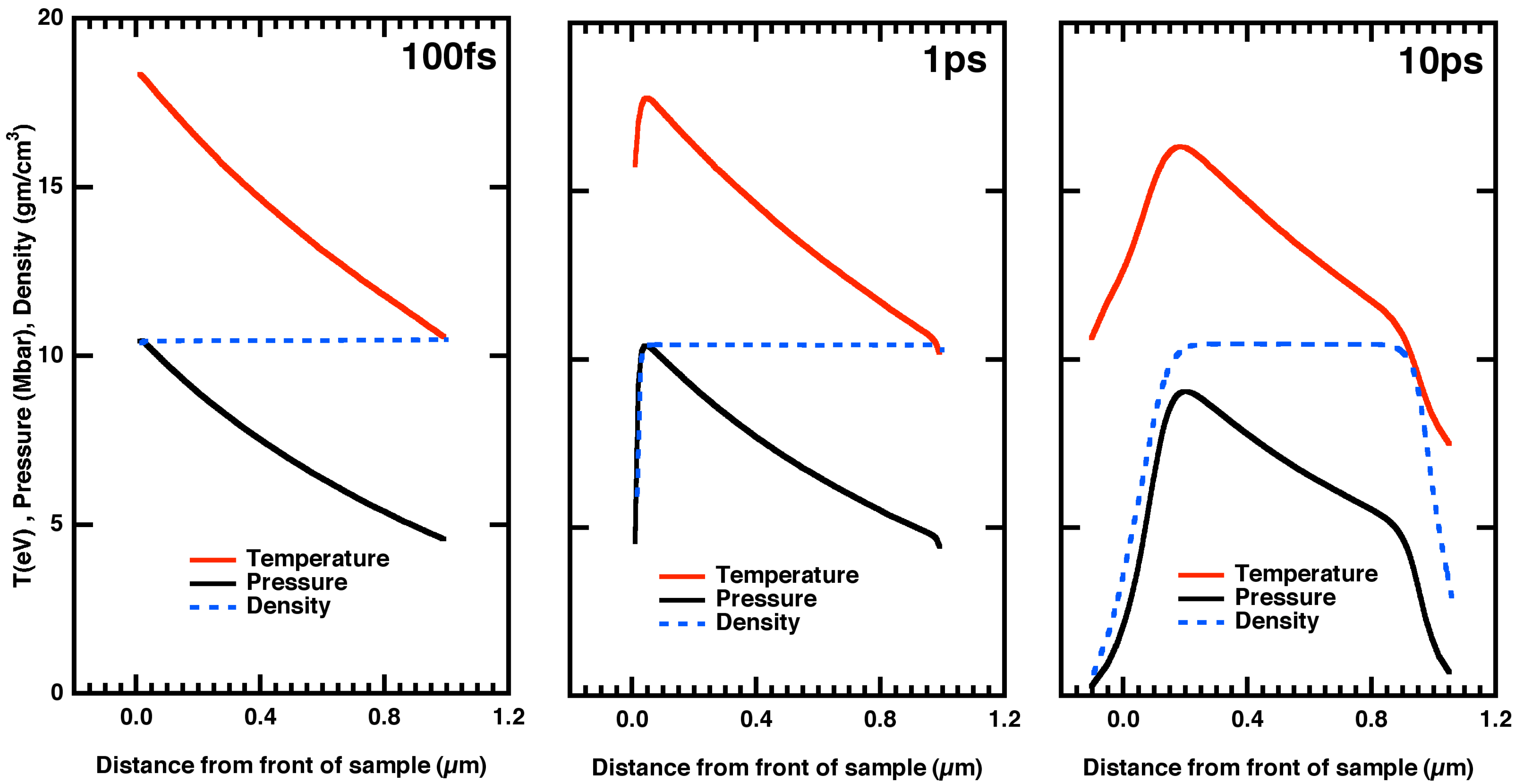
- The time scale for the deposition is 100fs so there is effectively no hydrodynamic motion during deposition
- As long as the LCLS does not saturate the absorption the energy density deposited can be calculated by using:

$$E_D = n_{photons} E_{photon} (1 - e^{-l/\tau})$$

E_D is the energy density of volume of width l and cross-sectional area of the beam, and τ is the absorption length.

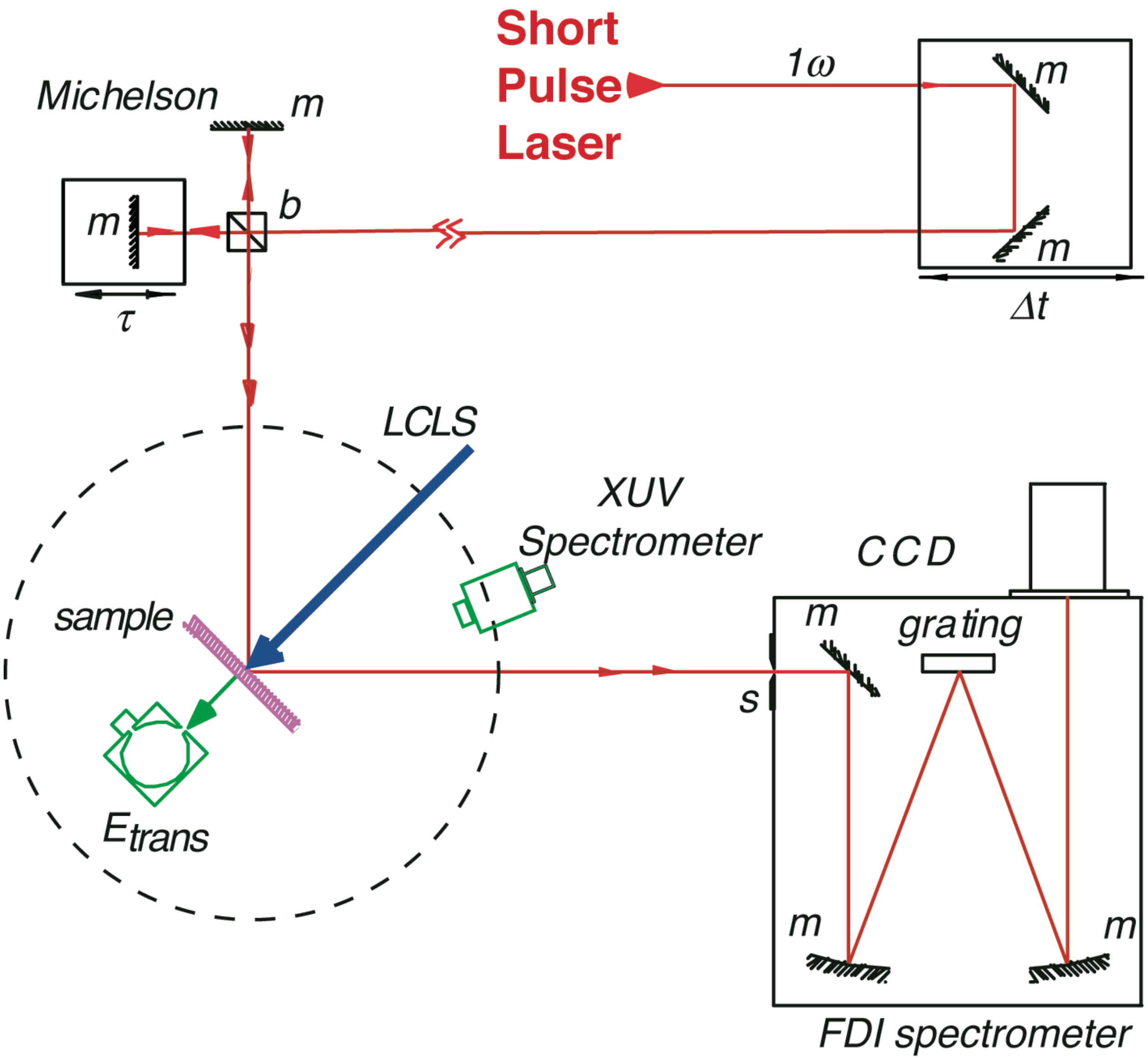
- Assuming the system is approximately described by the equilibrium equation of state one can use EOS table to look up the temperature and

With an initial condition the simulation predicts the 'long' time behavior



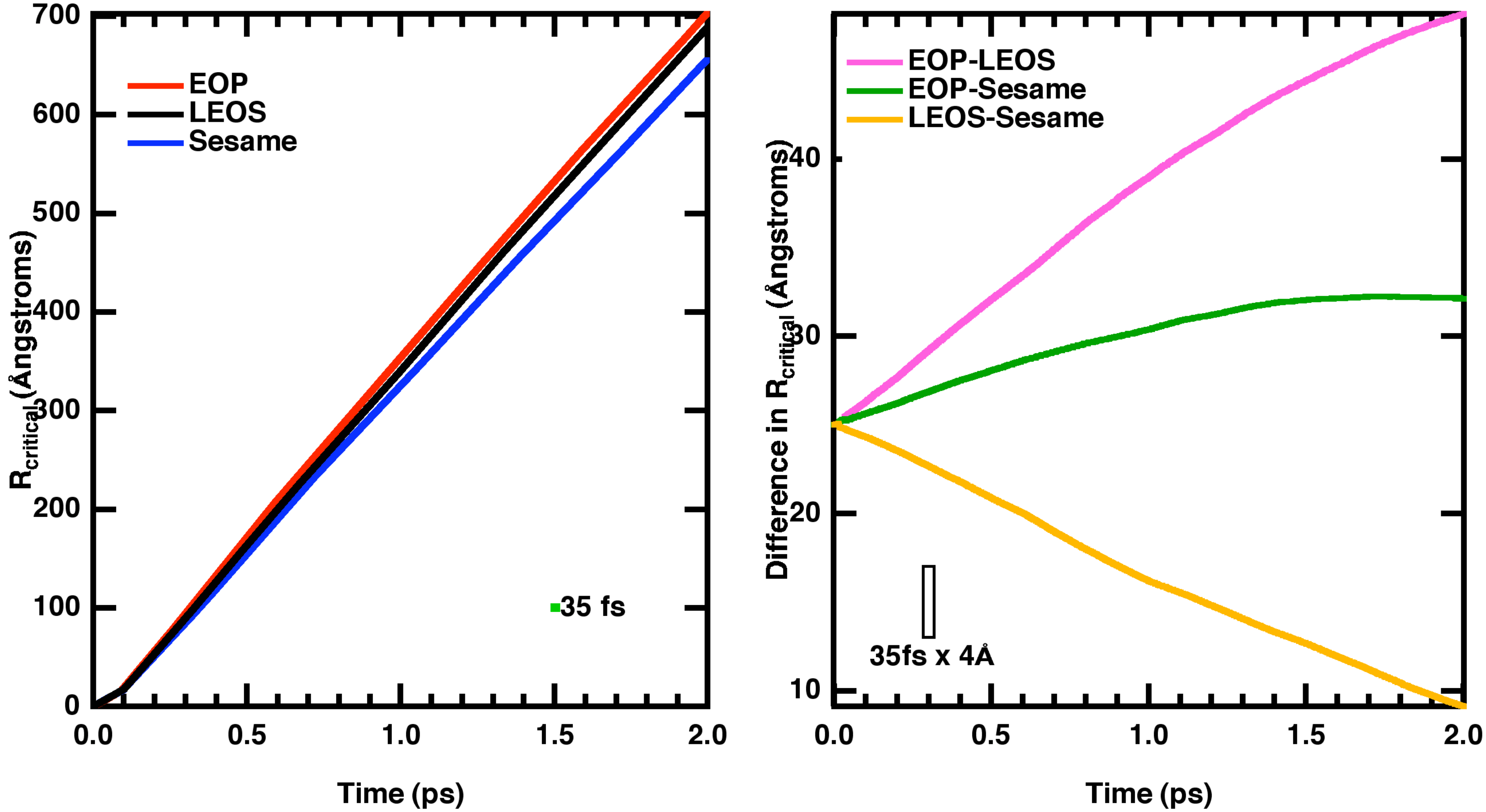
- Simulations indicate that the gradient leads to a distinct expansion on front and rear surfaces.
- Heating is isochoric but *not* isothermal so the system is NLTE
- Important to measure the expansion to determine if we understand global front/rear differences.

Experiment will monitor the expansion on sub-ps time scales using FDI



- Experiment will measure incident/transmitted energy
- Front and rear surface expansion using FDI (*only front is shown*)
- XUV emission from the 10eV front surface
- Resolution in time is ~35fs
- Resolution in space is ~4Å
- Data is sufficient to test various EOS models

Diagnosis of Ag sample may differentiate EOS models off the principle Hugoniot



- The simulations require the EOS's which are in question
- The FDI data front and rear will be sufficient to provide information on the validity of the modeling
- The FDI front versus back will indicate if the degree of thermalization is consistent with simulations.

1st experiments on WDM at LCLS will probe shocks and create WDM

- ***Next set will use extended capability***

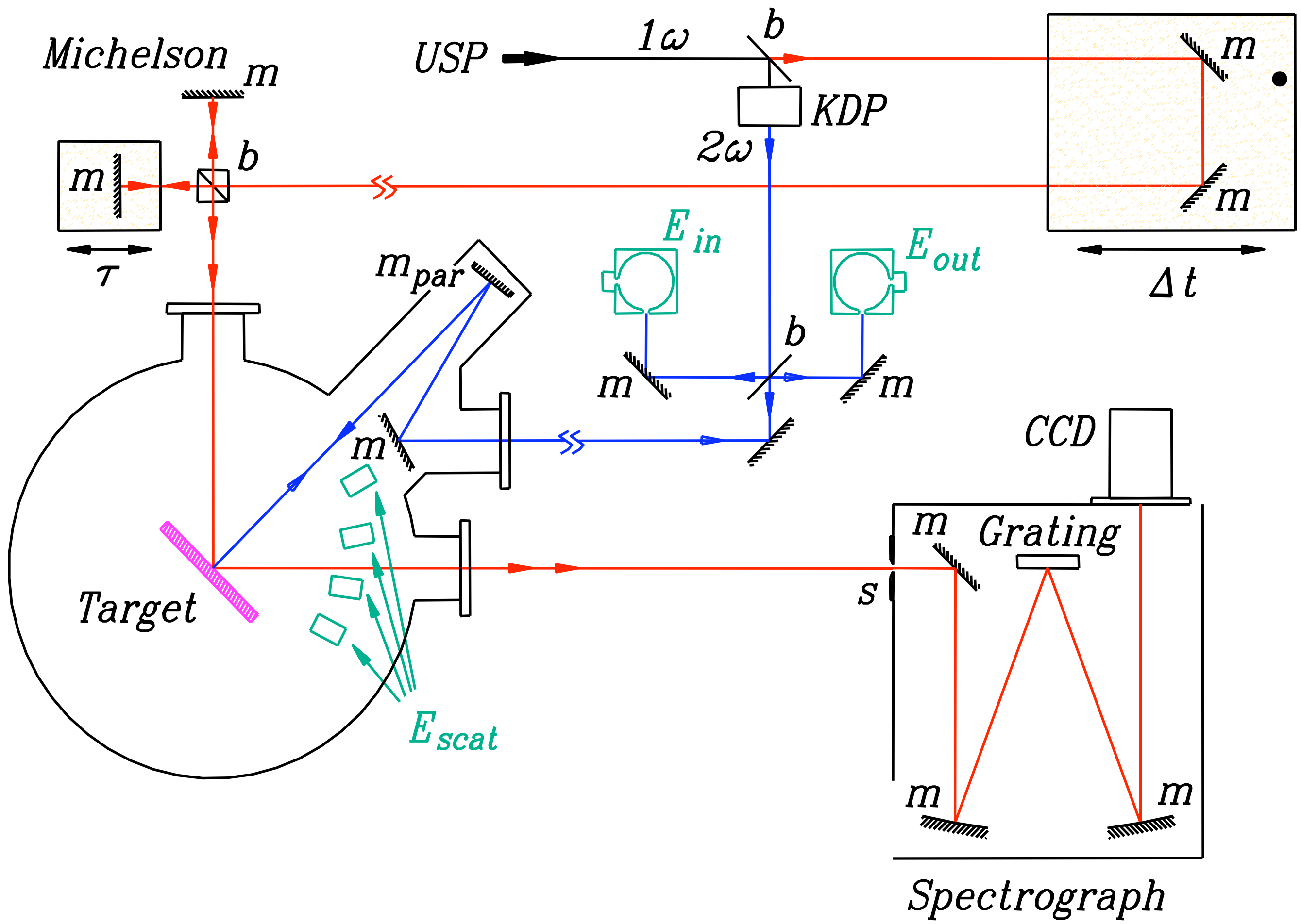
  - Use LCLS to create WDM and probe using two-color LCLS beam providing sub-ps diffractive imaging

  - Use the LCLS to provide sub-ps probing of WDM created by other sources
    - Can LCLS provide test of differences in the various methods to generate WDM on a single platform

  - Use the split and delay capability to heat both surfaces equally, to create isochoric and isothermal samples
    - Samples will still be NLTE to start but the heat flow can be removed

  - Can one perform WDM experiments at the MEC endstation that can access the same part of phase-space as a heavy ion beam WDM experiment

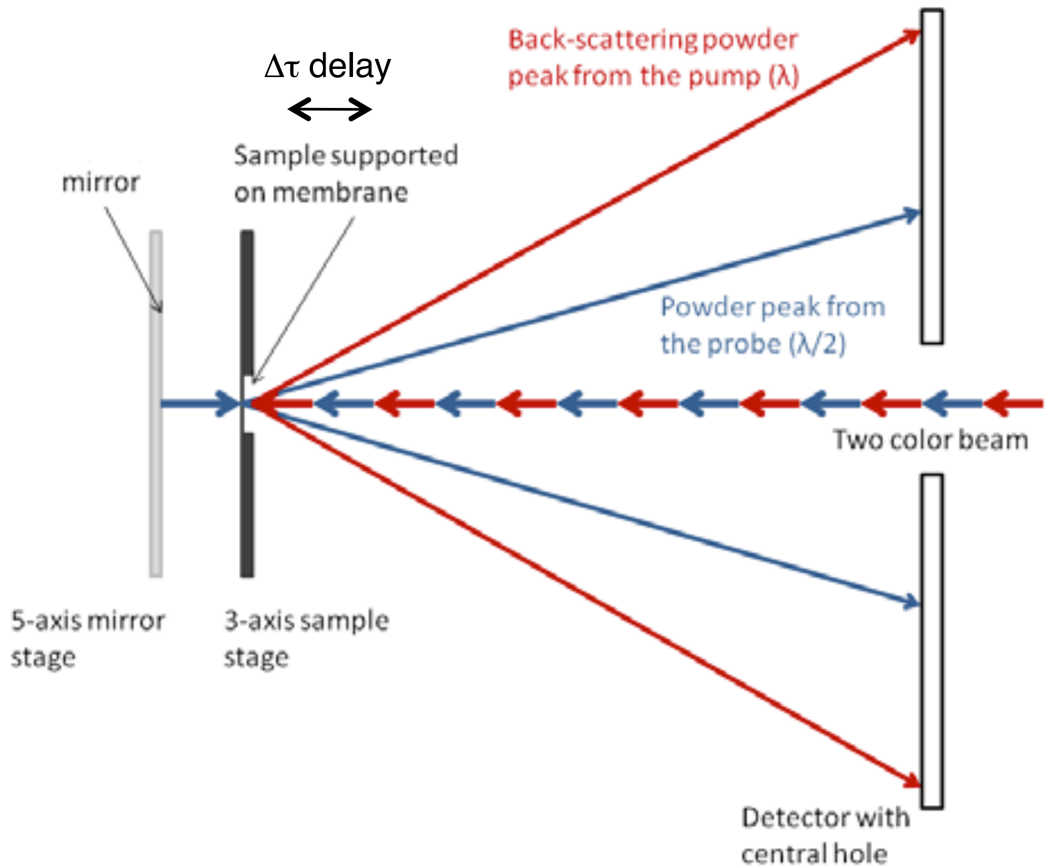
Future (1): other source creates WDM and use LCLS as a probe to measure



- Energy balance and FDI measurements provide *insight* into the EOS through hydrodynamic simulations

- LCLS can measure the diffuse scattering on a 10-100fs time scale with high efficiency
- Diffuse scattering will provide information on the pair correlation function as function of delay after the heating pulse
- Delay set within 200fs with more precision available post mortem

Future (2): LCLS can propagate 1st and 2nd harmonic with intensity ratio of 10 to 1



- Δτ varies from 5fs to 10ps
- Δτ jitter is of order 3 fs

- Two-color beam passes through 2D detector before hitting sample
- 2nd harmonic (λ/2) is reflected back onto sample
- 2D detector allows measurement of:
  - back-scattered λ powder ring from the pump pulse and
  - λ/2 powder ring from the probe pulse time delay of Δτ

The End

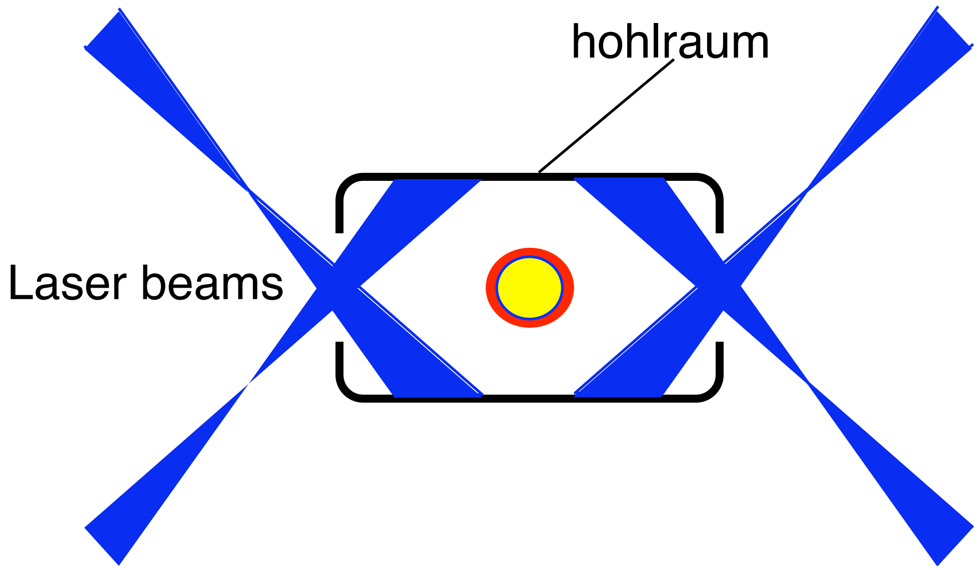
Heavy ion beams could uniquely create matter at extreme conditions

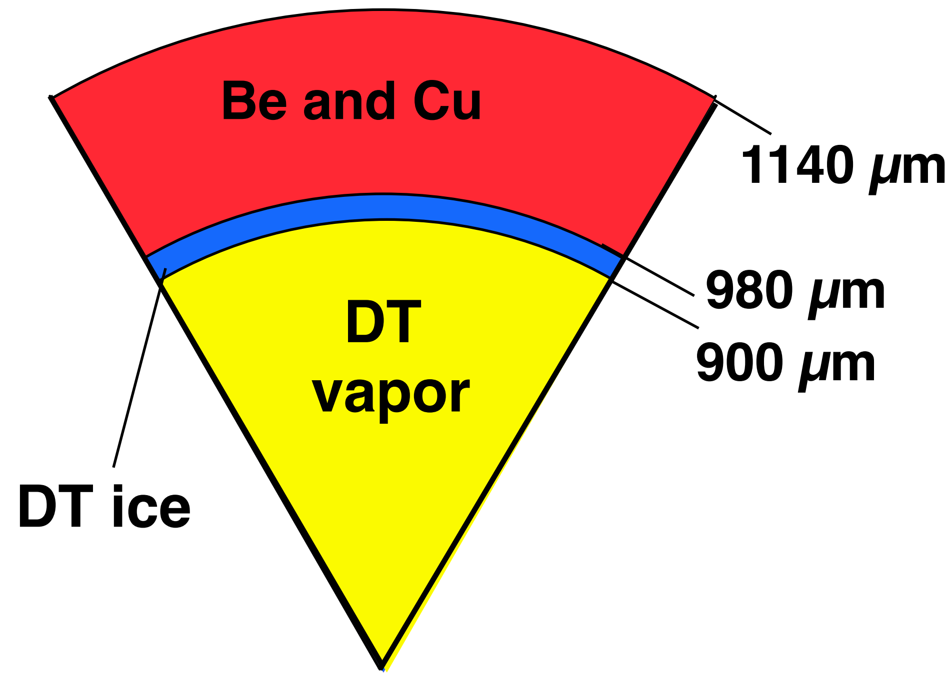
- Emphasize the WDM part of HED regime
- Heavy ion beams have a decided advantage:
  - Relatively large sample sizes (mm^3)
  - More uniform conditions
  - Achieve high entropy at high density
  - Extreme conditions persist for long times
  - Repetition rates can be high
- In contrast, optical laser-based experiments in WDM regime have:
  - smaller volumes, larger gradients, shorter lifetimes, and lower repetition rates

Development of a Heavy Ion Beam user capability would timely

- Heavy ion beams provide a unique method to study HED matter
  - The creation of high pressure in a shockless manner
  - The long time scales and larger volumes obtainable are unique for the WDM regime
  - The heating can be achieved by deposition at the Bragg range or shorter distances
- Repetition rate of 1 Hz coupled to a dedicated user facility would provide an important research tool
  - PW laser coupled to the system could provide:
    - Backlighting
    - Sample preionization for dense plasma related studies
- Five year plan makes heavy ion beams an aggressive competitor with other planned facilities

WDM is created in ICF experiments

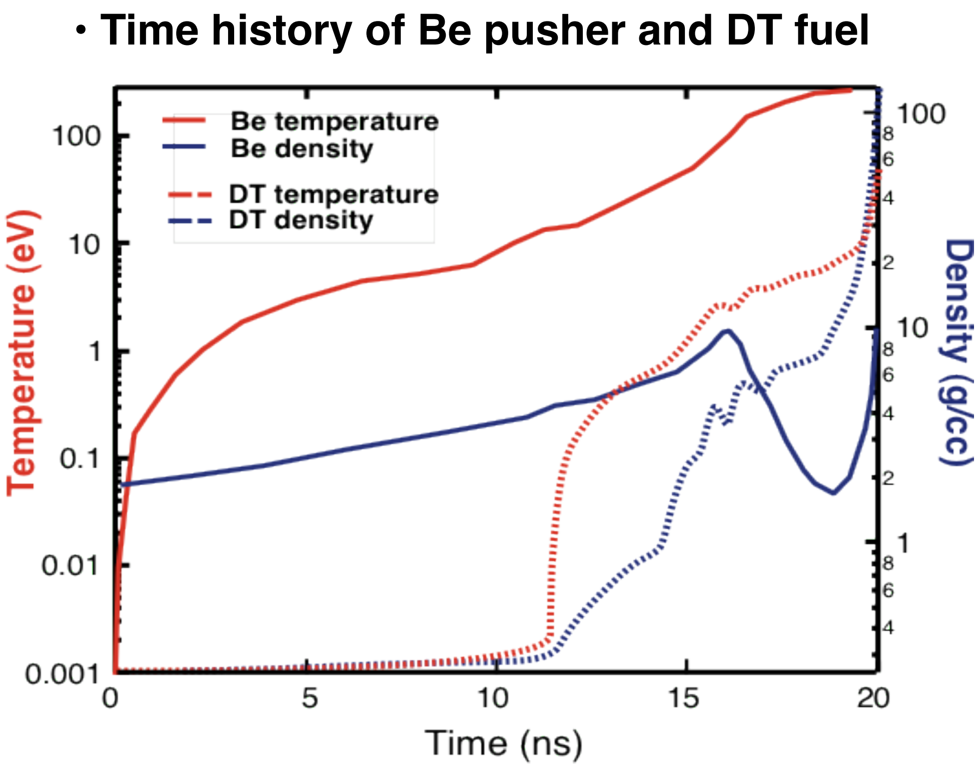


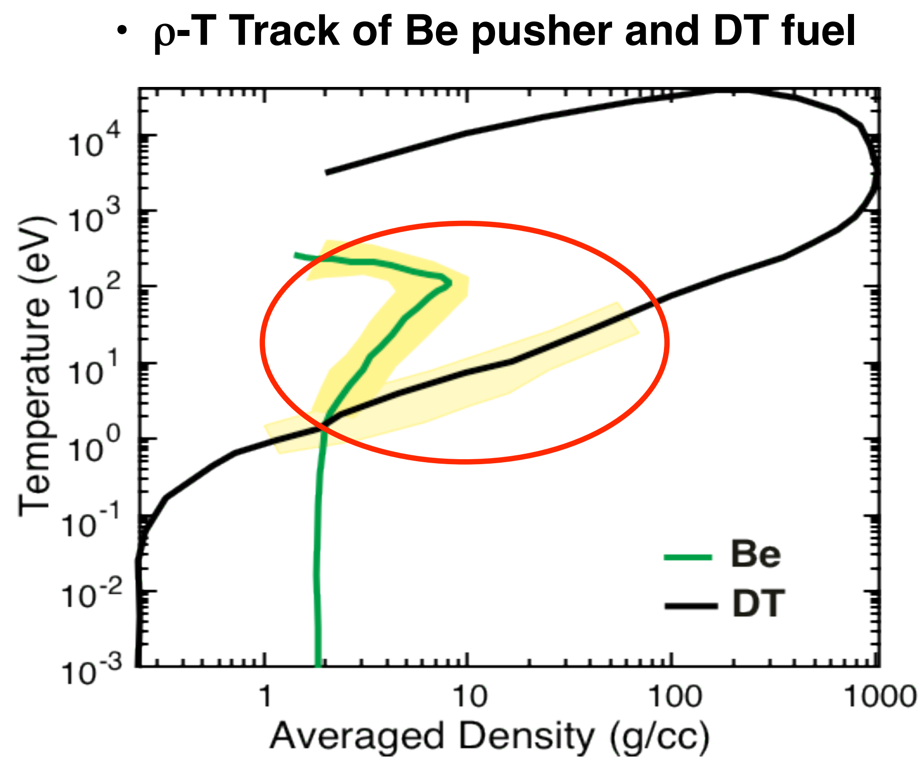


- Laser is focused through hole in holhraum
- Laser impinges on wall creating a plasma
- Wall plasma radiates x-rays
- X-ray are absorbed in the pusher part of sphere
- Heated material drives a shock

Designs cause "gentle" compression ⇒ WDM regime is sampled

- The ρ-T paths for Be and DT traverse the WDM regime





- **DT** EOS may be modified by WDM effects: dissociation, pressure ionization
    - Changes detailed performance of NIF ignition capsules

- It is also clear that **Be** will have WDM effects: ionization

WDM created by isochoric heating then isentropic expansion samples phase space

- Ion beam isochoric heating / isentropic expansion
- Principal (H_1) and porous (H_p) Hugoniots shock compression experiments
- Studied release isentropes (S)
- Iisobaric expansion (IEX)
- Ionization degree (α) and non-ideality parameter (γ) are shown

Pb phase diagram