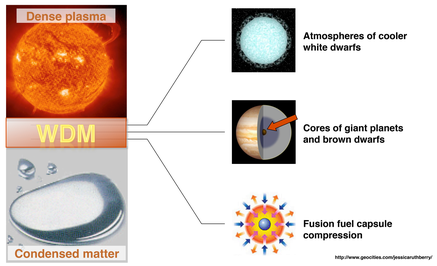
Ultrafast proton heating for equation of state studies of warm dense matter

Ronnie Shepherd, Hui Chen, Yuan Ping, Klaus Widmann, Jim Bonellie, Lee Elberson
Jupiter Laser Facility, Lawrence Livermore National Laboratory

Gilliss Dyer, Byoung-ick Cho, Aaron Bernstein, Alan Dalton, Will Grigsby, and Todd Ditmire
Texas Center for High Intensity Laser Science, The University of Texas at Austin

Patrick Rambo, Jens Schwarz, Matthias Geissel, Erik Brambrink, Briggs Atherton, Aaron Edens
Z-Beamlet facility, Sandia National Laboratory

Warm dense matter describes states of matter at the shared frontier of plasma and condensed matter physics

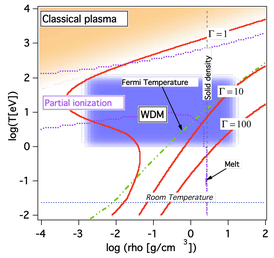


Atmospheres of cooler white dwarfs

Cores of giant planets and brown dwarfs

Fusion fuel capsule compression

http://www.geocities.com/jessicaruthberry/



Megabarr pressures

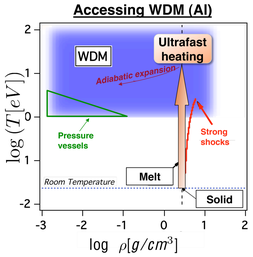
Partial ionization

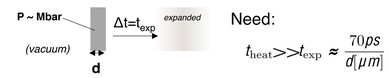
$kT \gtrsim E_{fermi}$

$\Gamma \gtrsim 1$

Warm dense matter can be achieved through isochoric heating of a solid by laser-accelerated MeV protons

Accessing WDM (Al)

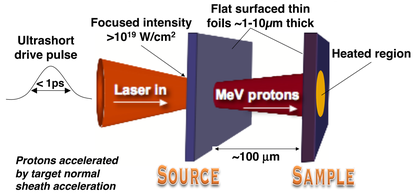




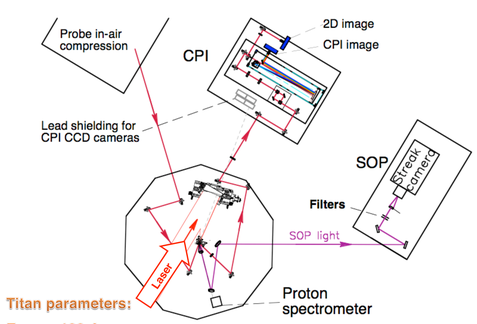
Need:

$$t_{heat} >> t_{exp} \approx \frac{70ps}{d[\mu m]}$$

Basic proton heating concept



We performed our experiments on the Titan laser at LLNL, firing at 150TW



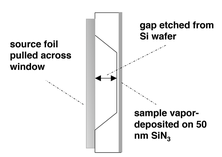
Titan parameters:

E_{pulse} = 100 J

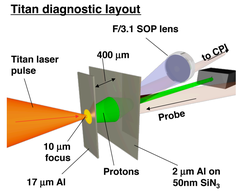
Dt_{pulse} = 600-700 fs

l_{center} = 1.054 mm

Titan target design

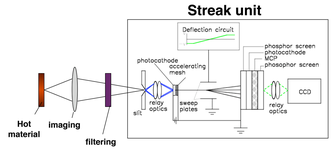


Titan diagnostic layout



We used an absolutely calibrated streaked optical pyrometer (SOP) to measure thermal emission from the heated Al sample

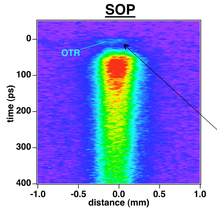
Streak unit



Hamamatsu C7700

- 2.5ps resolution
- High dynamic range

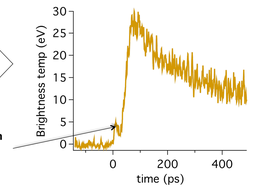
SOP



Brightness temperature + OTR

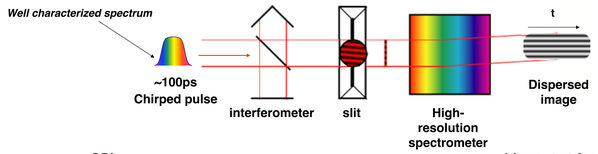
Initial fast signal rise is optical transition radiation from fastest particles, for an automatic t= 0 fiducial

Lineout at hottest region

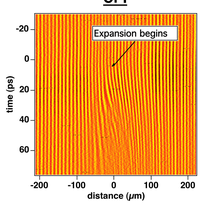


SOP first used with proton heating by Patel, et al. Phys. Rev. Lett. 91, 1250004

Simultaneously, we measured the free expansion of the heated Al sample using a chirped pulse interferometer (CPI)



CPI



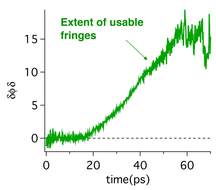
Phase reconstruction

Partially accounts for doppler shifting effect on phase, for:

$$\Delta t_{resolution} \approx \Delta t_{compressed}$$

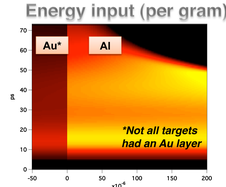
J. P. Geindre, P. Audebert, S. Rebibo, and J. C. Gauthier. Optics Letters, 2001.

Lineout at fastest expansion



In HYADES, we modeled the conditions of the experiment, scaling proton input to reproduce the SOP signal

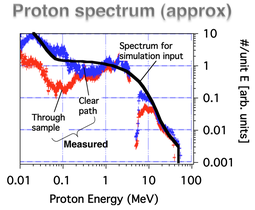
Energy input (per gram)



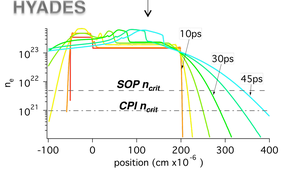
NIST pStar proton stopping powers

(approximate)

Proton spectrum (approx)



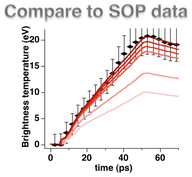
HYADES



proton number

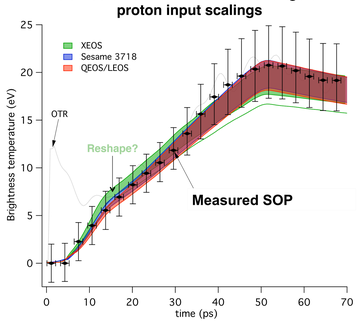
Simulated SOP

Compare to SOP data

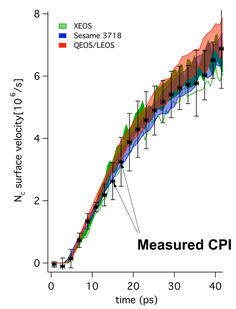


SESAME 3718 was found to better fit our data than LEOS, but neither could be categorically rejected within error

SOP data vs. simulations for a range of proton input scalings



CPI: same shot, same simulations



Find proton input scalings that give fit within SOP error bars

Accuracy of EOS models confirmed within ~ 20%

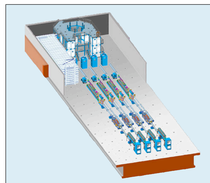
Future experiments will enable studying WDM in greater detail by refining and expanding upon these techniques

General improvements, e.g.:

- Reduce uncertainty in SOP and CPI calibration
- Faster heating, from a smaller gap and/or thicker sample
- More detailed accounting of proton spectrum and total number
- Probing at shorter wavelengths (e.g. probe harmonics)

Proton heating on other lasers

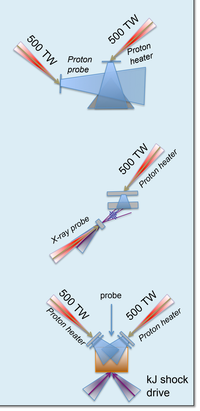
- Sandia 100 TW CPI of expanding WDM recently obtained
- Texas PW: a major research thrust
- Several other groups pursuing & expanding on these techniques



Proton heated WDM experiments on OMEGA EP

What could we do with two petawatt-class beams, and more?

- Expect excellent proton source (recall Nova petawatt, Vulcan)
  - Several percent conversion efficiency; peak energy >10 MeV
  - Achieve higher temperatures or heat larger area
  - Block low-energy protons for faster heating window
- A second petawatt beam unlocks many possibilities
  - Increased, more uniform heating
  - High-quality x-ray probes for opacity or scattering
  - Proton probe for potential stopping power experiments
  - Possible applications of proton focusing[1]
- The two high-energy beamlines could also be used
  - Shock pre-compressed targets access higher densities
  - Long-pulse x-ray probe, streaked



[1]*Hegelich et al. Focusing and spectral control of laser-driven, picosecond ion beams. American Physical Society (2006) pp. 2005*