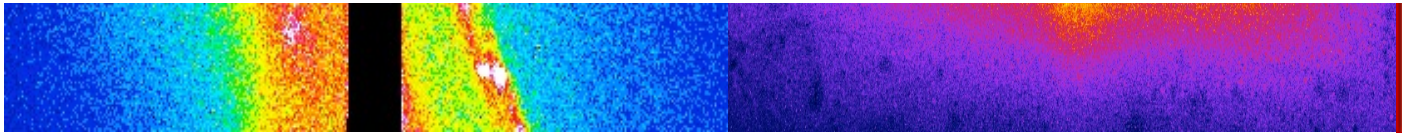


Generation and characterisation of warm dense matter in the laboratory

D Riley

Centre for Plasma Physics

Queen's University Belfast

IUPAP Regional E-conference on physics Jan 18th -21st 2022

What is warm and dense?

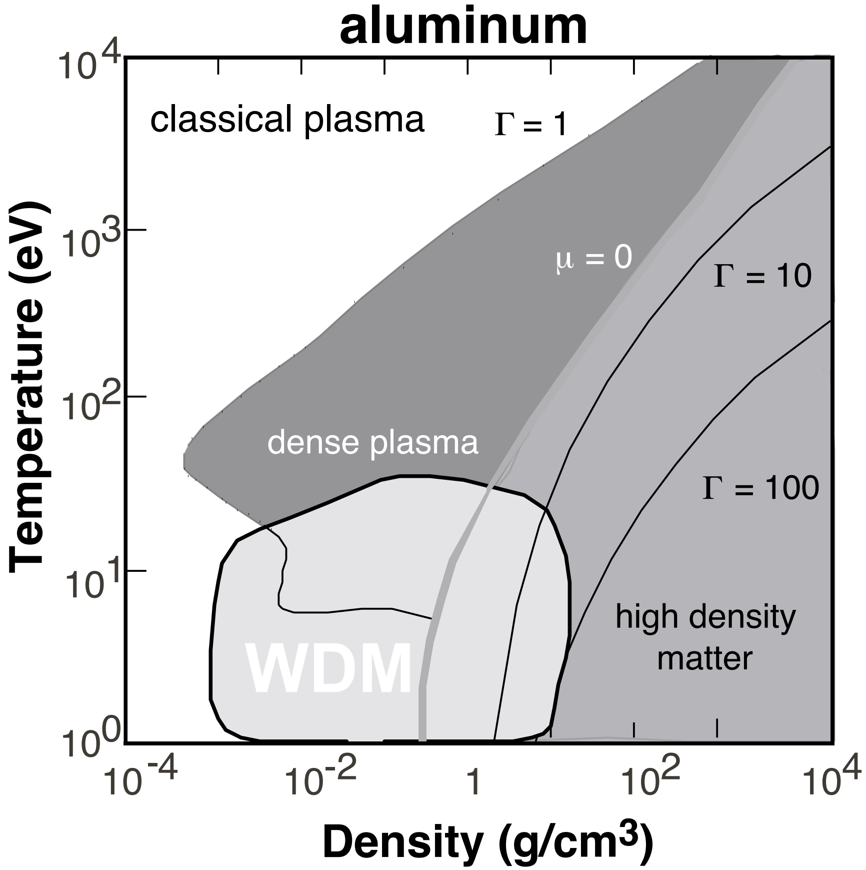
- Strong coupling between particles

$$\Gamma_{ii} = \frac{(Ze)^2}{ak_bT_i} > 1$$

- Partial degeneracy $\mu/kT \sim 0.1\text{-}10$

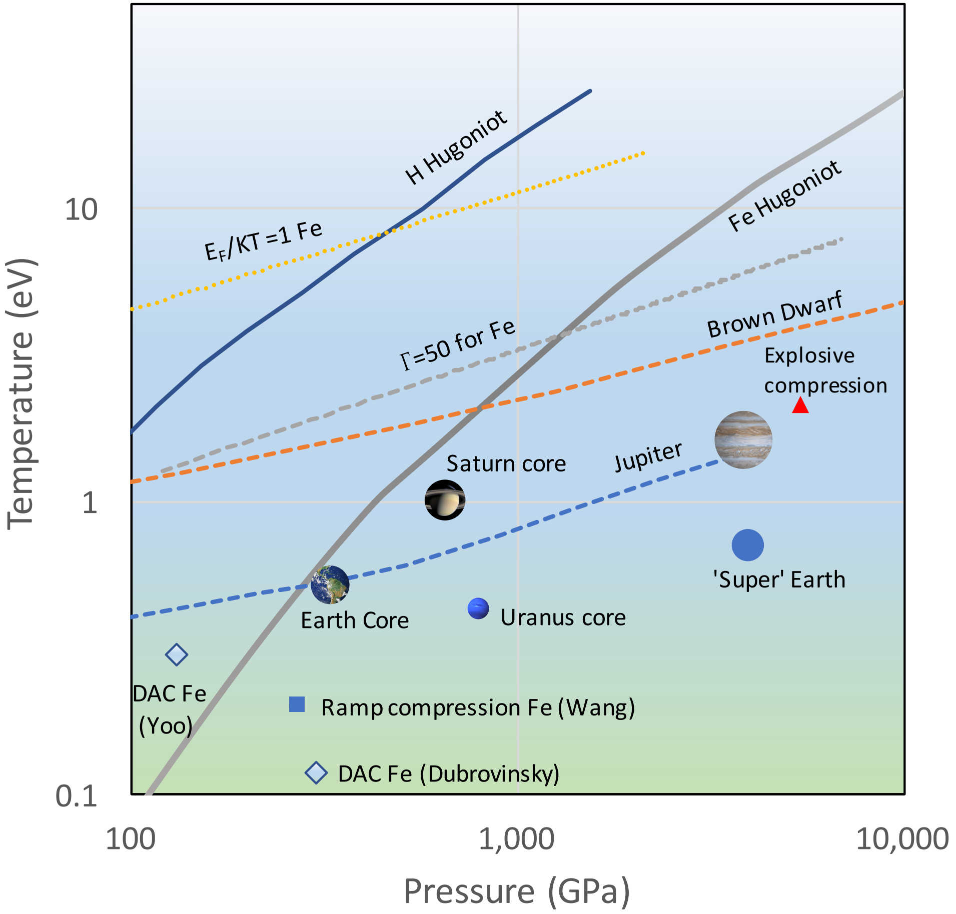
- Partially ionized.

RW Lee *et al* JOSA B **20** 770, 2003



Warm dense matter occurs in planets

- Diamond layers in Uranus and Neptune? –(Ross, Nature **292** 435 1981)
- Metallic water and the magnetic field in Uranus and Neptune? (Stevenson, Rep. Prog. Phys. **46**, 555, 1983)
- Equation of state of H for Jupiter, how does it separate from He? (Nettelman *et al* Astrophys. J **683** 1217, 2008)
- The melting curve for Fe?



Experimental challenges in WDM

- Samples should be uniform- optical lasers intrinsically at a disadvantage.
- Scale-length long enough to be probed with spatial resolution helps.
- mm scale sample helps. If c_s is 10^4 m/s then 1mm scale suggests decompression in 100ns timescale- needs energy
- Timescale for evolution suited to being probed.
- Timescale also important for equilibration, melting etc.
- Access to sample for probing. Too cold and dense for emission spectroscopy or optical probing.

Generating warm dense matter

- Shock/ramp compression
  - Laser driven shocks >10Mbar[1]
  - Z-pinches >5 Mbar[2]
  - Explosives[3] (1-2Mbar typical but 100Mbar done) and gas guns >5Mbar[4]
- Volumetric heating
  - Radiation from laser plasmas- solid density 50eV[5]
  - Particle beams (e.g. laser-plasma protons)[6]
  - X-ray and XUV lasers[7]

[1] L. Veeser and J. Solem, PRL **40**, 1390

[2] M. R. Martin *et* al, Phys. Plasmas **19**, 056310

[3] VE Fortov and VB Mintsev, PPCF **47** A65–A72

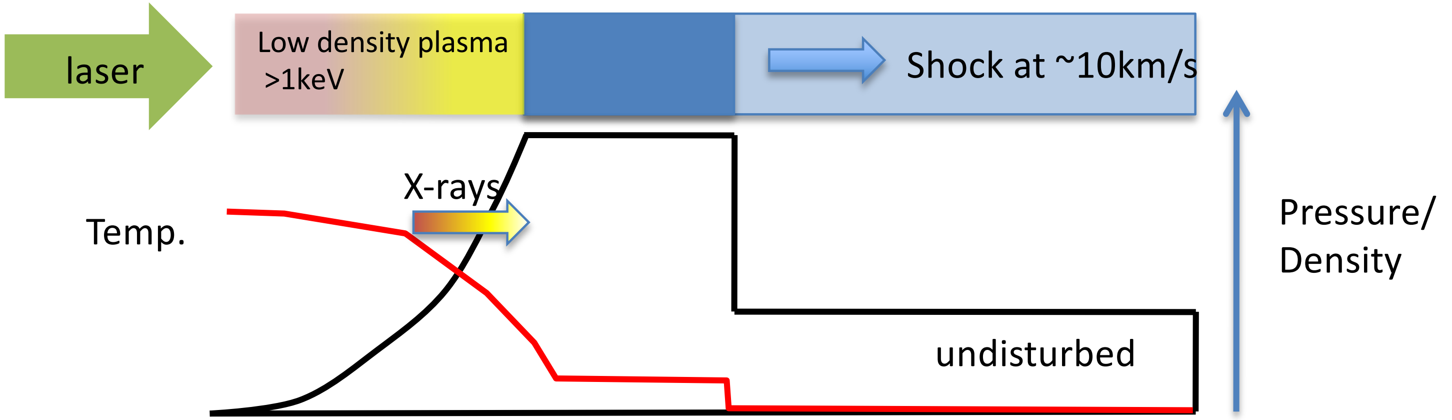
[4] e.g. JM Brown *et al* J. Appl. Phys. **88** 5496

[5] SH Glenzer *et al,* PRL **90** 175002

[6] P.K. Patel, et al., Phys. Rev. Lett. **91** 125004.

[7] B Nagler *et al* Nat. Phys. **5** 693, 2009

Driving intense shocks can be done with lasers



Rankine-Hugoniot

$$\rho_0 v_0 = \rho v_1$$

$$P_0 + \rho_0 v_0^2 = P + \rho v_1^2$$

$$E_0 + \frac{P_0}{\rho_0} + \frac{v_0^2}{2} = E_{int} + \frac{P}{\rho} + \frac{v_1^2}{2}$$

Pressure generated typical scaling;

$$P(Mbar) = 8 I_{14}^{3/4} \lambda^{-1/2}$$

10^{14} Wcm^{-2} at 0.527nm means 11Mbar (1100GPa)

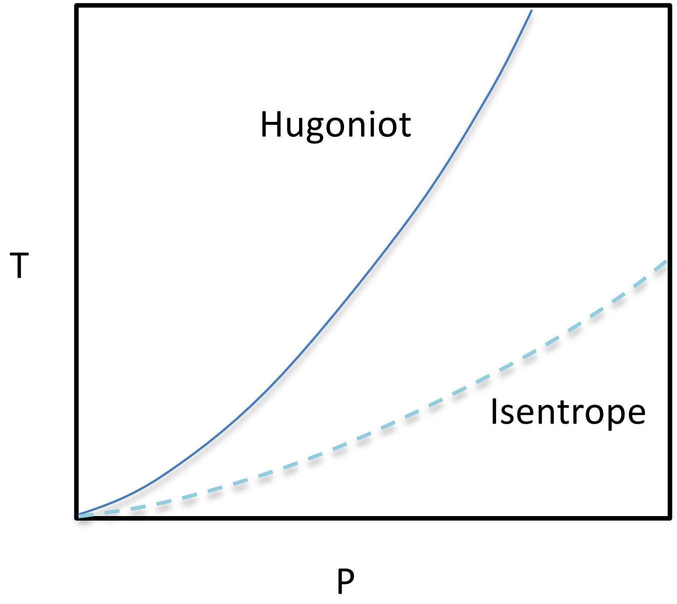
For 1ns drive 10Km/s suggests 10mm targets

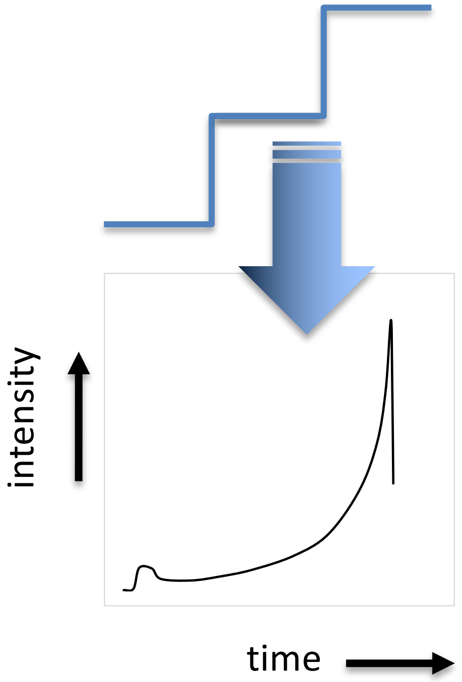
Ramp compression can lead to lower temperature

Entropy generated in a shock

$$S_1 - S_0 = C_V \ln\left(\frac{P_1 {V_1}^{\gamma}}{P_0 {V_0}^{\gamma}}\right)$$

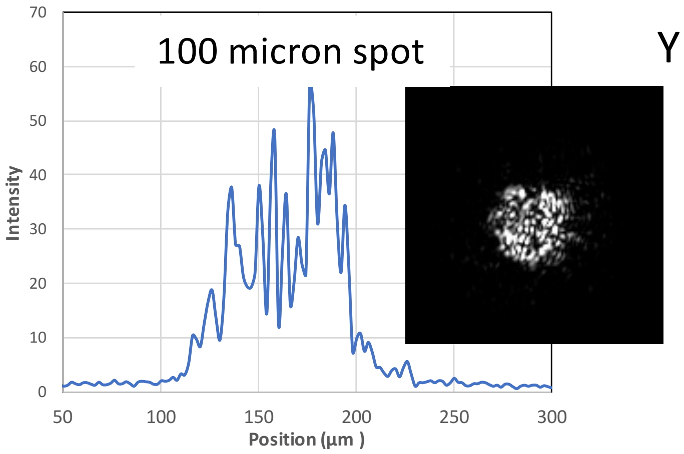
This means that for a given final pressure, the entropy is lower if we achieve it in steps



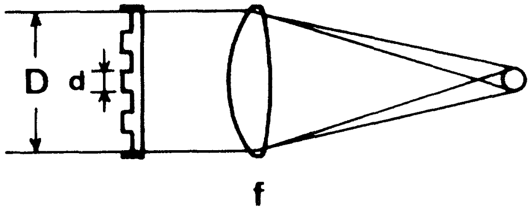


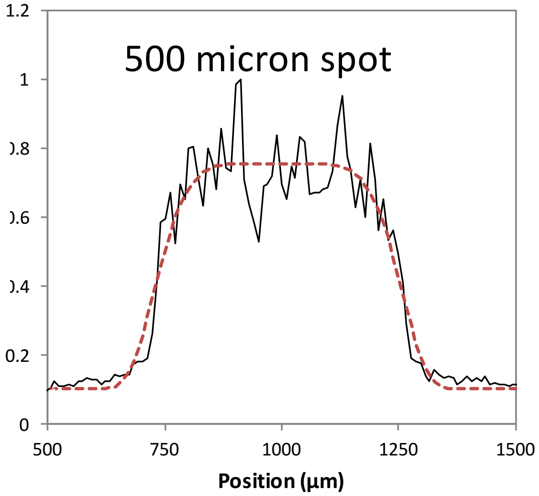
Pulse shaping is now routine

The focal spot issue for laser-driven shocks



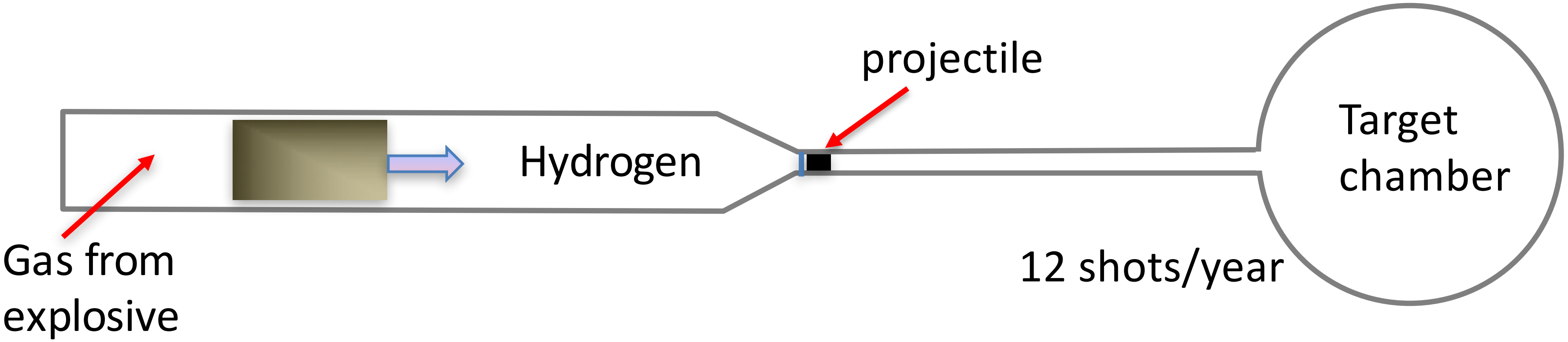
Y Kato et al PRL **53**, 1057, 1984





- 100 mm can be driven at 10^{14} wcm^{-2} for 1ns with 10J, from 5 cm diameter beam
- For 100 mm spot need 5mm elements for 1m focus- only ~75 elements in 5 cm beam
- For 500 mm spot need 1mm elements for 1m focus- 2500 elements.

Flyer plates are an option



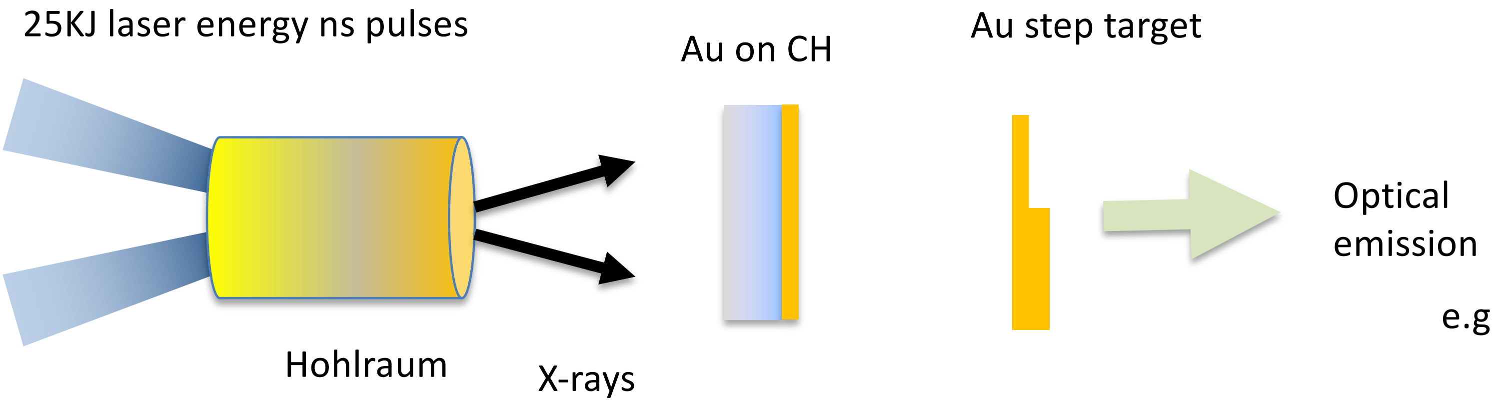
projectile

Hydrogen

Target chamber

Gas from explosive

12 shots/year



25KJ laser energy ns pulses

Au on CH

Au step target

Optical emission

Hohlraum

X-rays

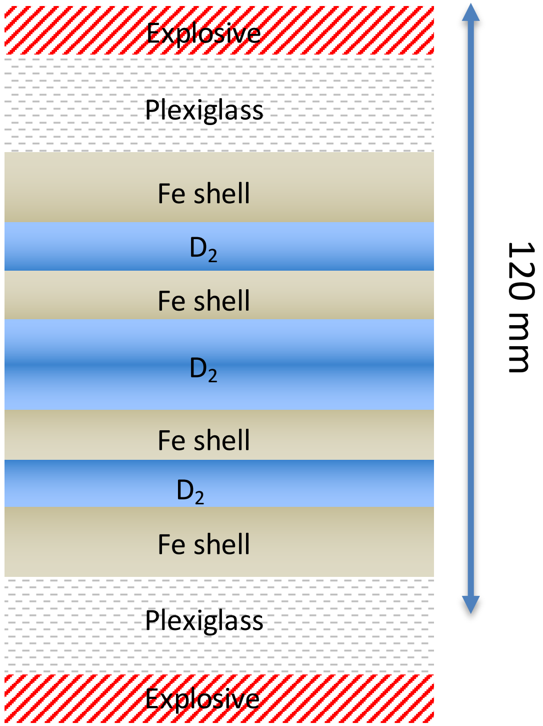
Flyer plate gives
~1Gbar for 30ps based
on shock speed

e.g. Cauble *et al* PRL **70** 2102, 1993

A key issue is hydrodynamic stability- does the plate hit “flat” on?
This is an issue for gas guns as well

Explosives can be used to compress-SKIP

For example, Mochalov *et al* JETP **124**, 505, 2017

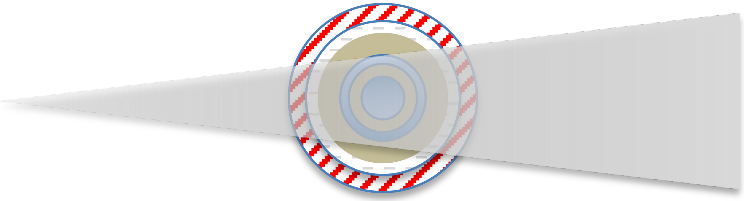


Initial pressure >250 bar

Cut-away of cylindrical compression of D_2, hard X-ray radiography through the shells was used. In spherical compressions 55Mbar at ~2eV was achieved.

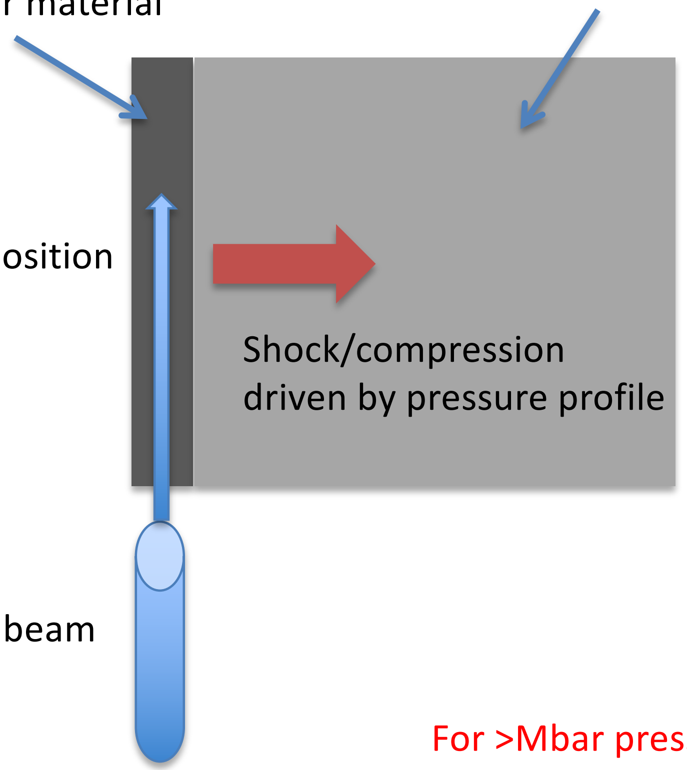
Shocks driven reverberate in the shells to generate a quasi-isentropic compression.

Issues of course include how to probe with other diagnostics, practical issues for most labs in using explosive.



Radiography follows the compression

Using ion beams is possible



Absorber material

Test material

Energy deposition
$>10^5$ J/g

Shock/compression
driven by pressure profile

'elliptical' ion beam

10^5 J/g for Pb is
$\sim 10^{12}$ Jm^{-3} ~ 10Mbar
Temp ~15eV

See: PA Ni *et al* LPB **26** 583 (2008)
For experiments on W.

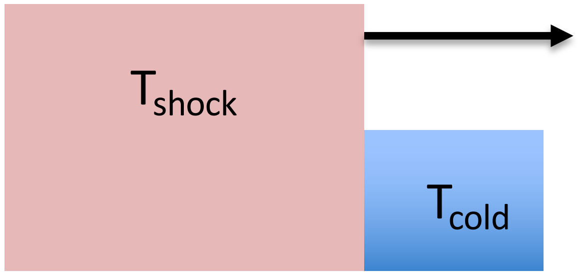
Grinenko *et al* LPB **27** 595 (2009)
for conceptual study of ramp
wave Loading

Dewald *et al* IEEE Tran. Plasma
Sci. **31** 221 (2003) had
200MeV/u U beams depositing
1.5kJ/g in Pb reaching 0.2eV.

For >Mbar pressures we do not have to create
A keV plasma with ion beams. Timescale >10ns

Diagnostics for shocked WDM- Optical Pyrometry

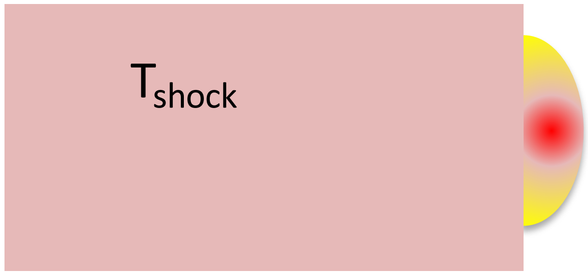
Shock front



T_{shock}

T_{cold}

Shock break-out

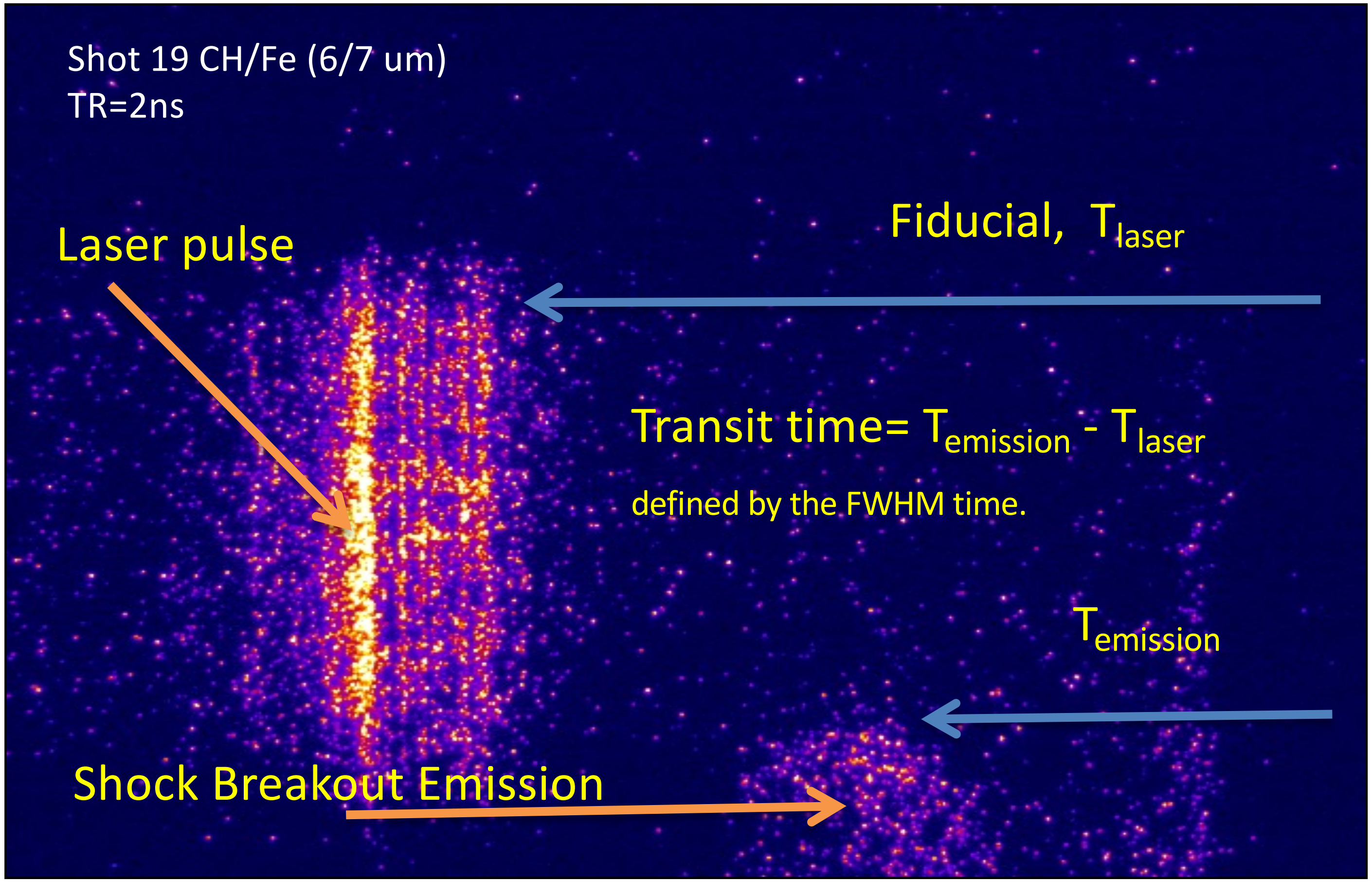


T_{shock}

Plasma
glows

For T ~1eV should have strong optical emission. At high density close to BB shape but rapid decompression makes this problematical. A tranparent window can be used shock condition depend on impedence match as optical properties under extreme conditions need to be known.

An example from Fe at 4 Mbar shock- weak glow

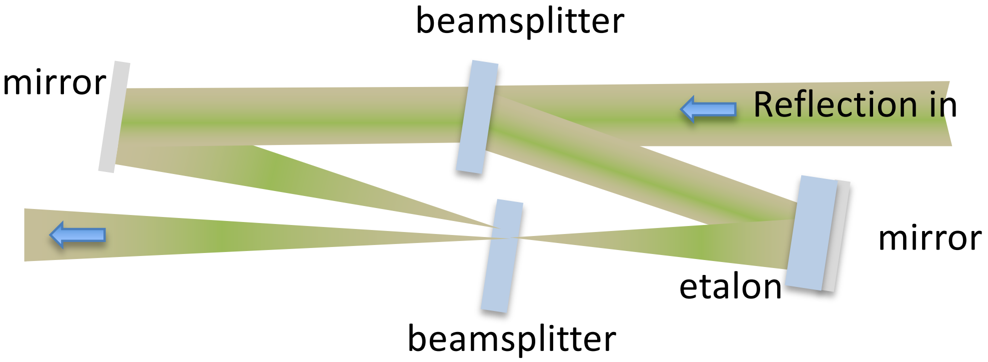


Shot 19 CH/Fe (6/7 um)
TR=2ns

Transit time= $T_{emission}$ - T_{laser}

defined by the FWHM time.

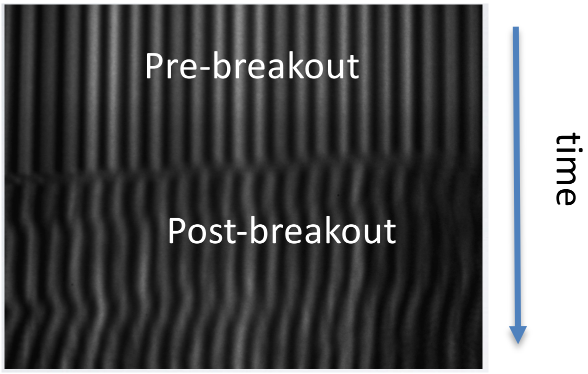
Shocked target diagnostics-VISAR



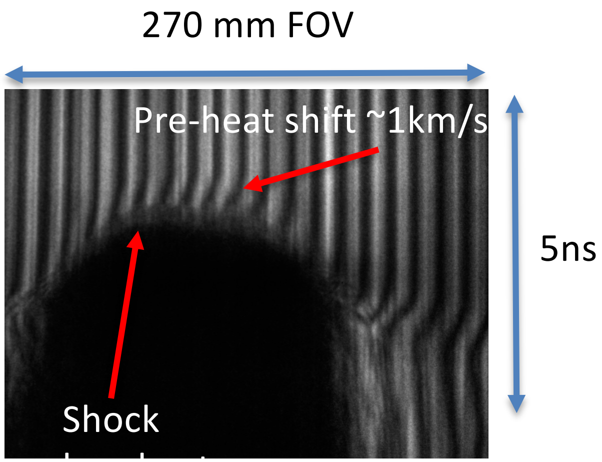
VISAR: interferometric method
e.g. Celliers *et al* RSI **75,** 4916**,** 2004

$$U_r = \int_{\rho_0}^{\rho} \frac{c_s d\rho}{\rho} = \int_{V(P_H)}^{V(P=0)} \left(-\frac{dP_S}{dV}\right)^{1/2} dV$$

U_r ~$2U_p$ for ~Mbar regime



Rear of windowed target



Rear of Fe target 4Mbar shock
On exit ~7×10^{13} Wcm^{-2}

Shocked target diagnostics- X-ray scattering

$$I(k,\omega) = I_T(k)\left[\left|f_i(k)+q(k)\right|^2 S_{ii}(k,\omega) + Z_b\int S^c(k,\omega-\omega')S_i(k,\omega')d\omega' + Z_f S_{ee}(k,\omega)\right]$$

Thomson
Cross-section

Ionic form factor

Electron-ion
correlation

**Ion-ion
structure factor**

Incoherent
Scatter from
bound electrons

**Free electron
structure factor**

$$\rho_e = \frac{m^2}{12\pi^3\hbar^3 e^2 n}\int_0^{2q_F} dq\, q^3 \left|V_{ei}(q)\right|^2 S_{ii}(q)$$

Resistivity

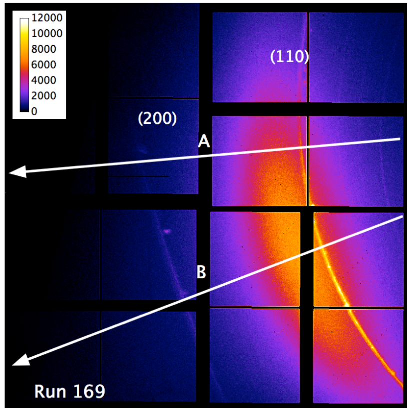
$$\frac{U}{Nk_BT} = \frac{3}{2} + \int d\mathbf{q}\,\frac{(Ze)^2}{q^2}\left[S(q)-1\right]$$

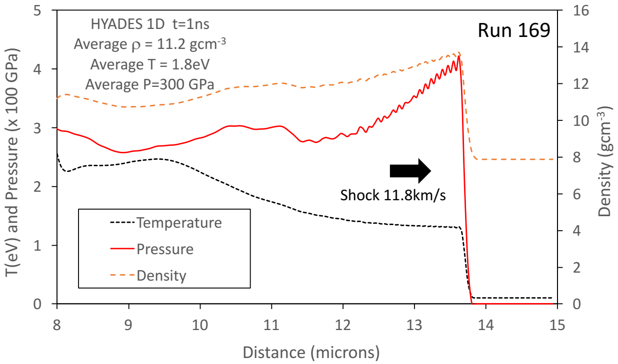
Internal energy

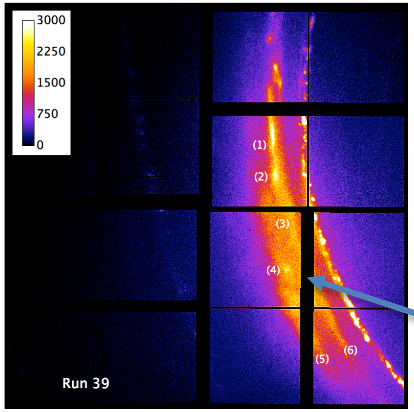
J. Chihara J. Phys F **17** p295, 1987
E Nardi, Phys. Rev. A **43** p1977, 1991

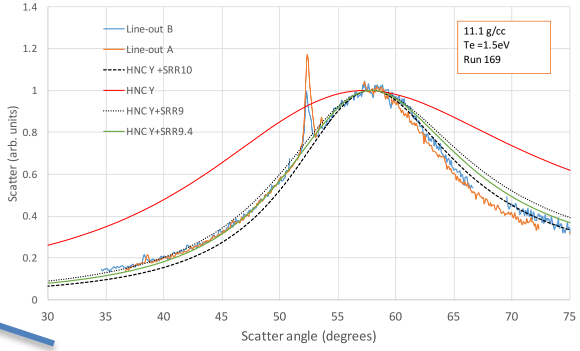
Glenzer and Redmer RMP, **81**, 1625, 2009

An example – timescale plays a role







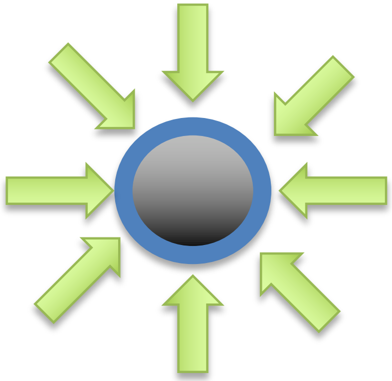


hcp features
~11g/cc

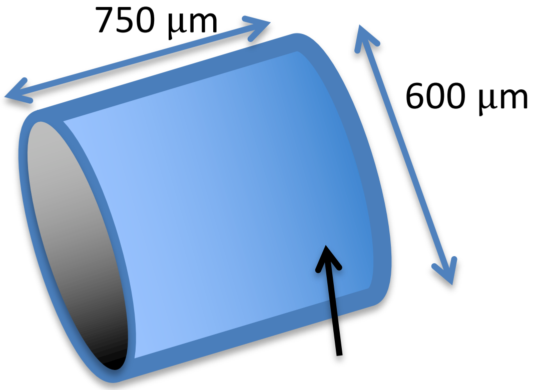
- Heating to above the equilibrium melt temperature is possible.
- Analysis by Luo and Ahrens suggests can be ~25% above equilibrium melt for Fe
- Depends on heating rate weakly. We are at about 10^{13} K/s
- Requires homogeneous nucleation
- Similar seen at 14g/cc

Sheng-Nian Luo *et al*, Phys. Rev. B **68**, 134206, 2003

Radiative heating with laser-plasmas- mm scale possible

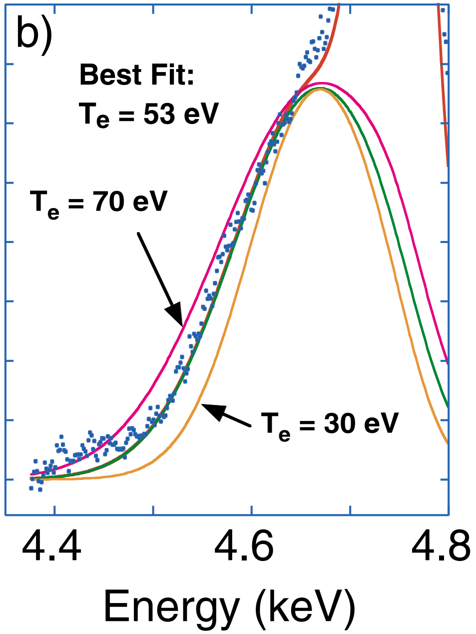


Be cylinder



Rhodium coating
L-shell emission 2.7-3.4keV

X-ray Thomson Scatter

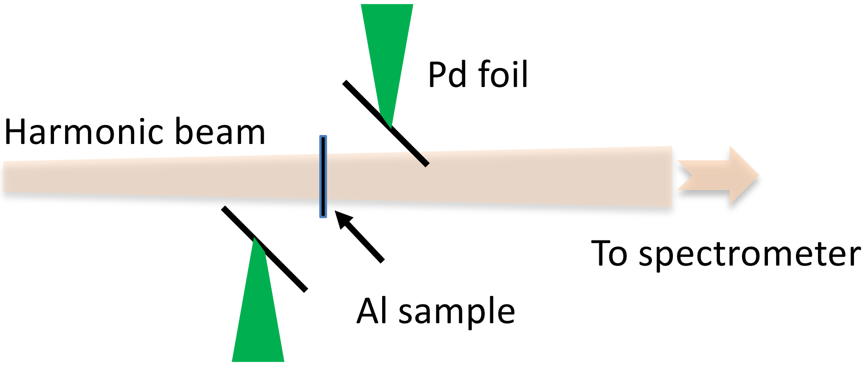


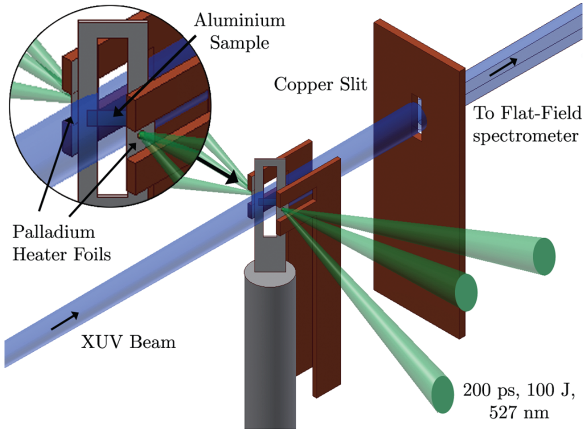
- Uniform heating to 50eV at solid density but depends on low opacity of target to allow this.
- Hot outer plasma at high Z may obstruct diagnostics

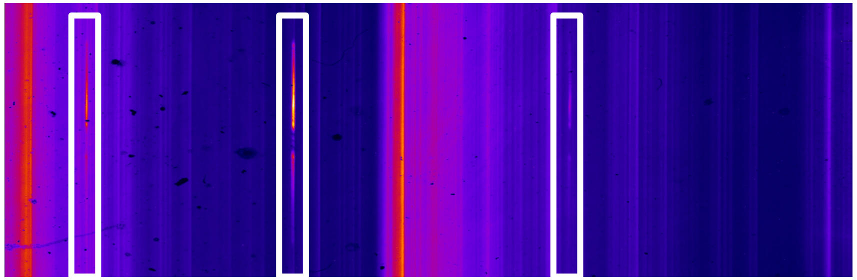
Omega laser 351nm **15KJ**
30 beams

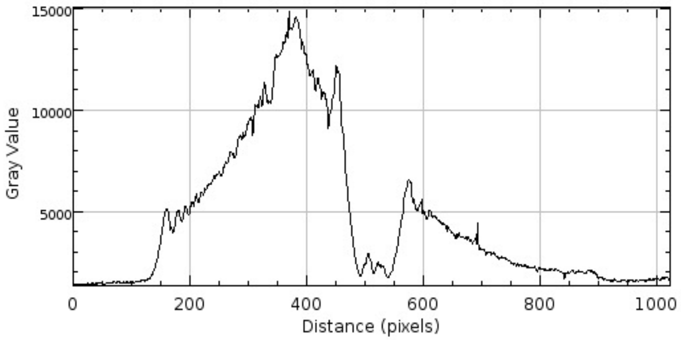
See: Glenzer *et al* PRL **90** 175002 2003 Also AB Zylstra *et al* J of Phys: Conf. Series717 (2016) 012118

Radiative heating with laser-plasmas- thin target possible







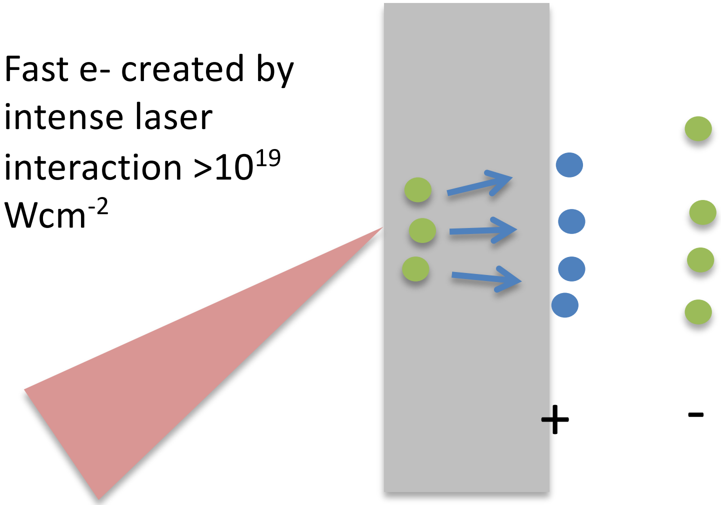


Key point: Expansion time for 400nm foil ~50ps: probe <1ps

Laser produced protons-limitations exist

MeV electrons escape and pull protons from contaminants on rear surface. Conversion <10% into <50MeV protons.

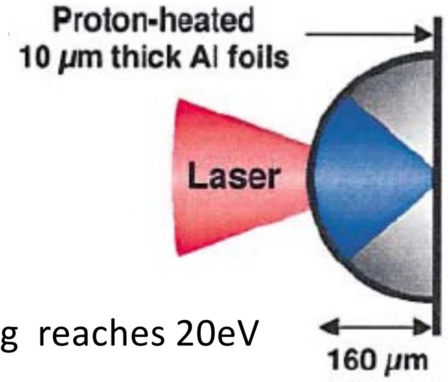
Fast e- created by intense laser interaction $>10^{19}$ Wcm^{-2}



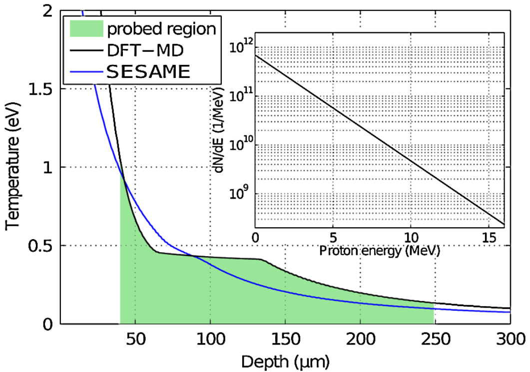
Very hot plasma with hard X-rays generated.

Beam of protons diverges rapidly.

Beam diverges with 0.5 radian. Has been used to create WDM. Patel *et al* PRL **91** 125004 2003

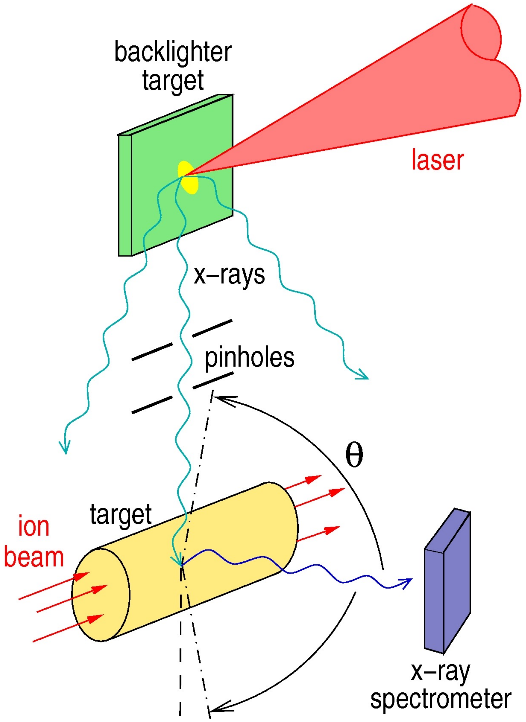


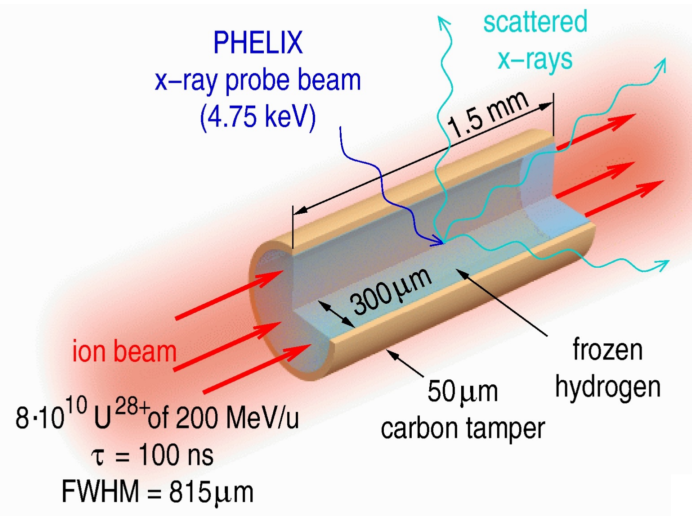
10^5 J/g reaches 20eV

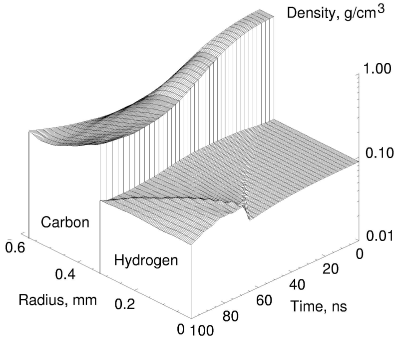


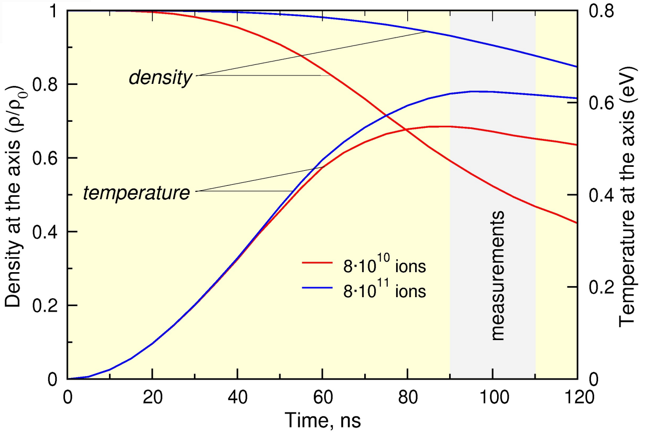
A Pelka *et al* PRL **105** 265701

Ion beams can have advantages in volumetric heating









No hot outer high Z plasma. X-ray probe

A. Kozyreva, M. Basko, F. Rosmej, T. Schlegel, A. Tauschwitz, D. Hofffmann, PRE **68**, 056406 (2003)

Some facilities for mm sized WDM samples

- NIF (1.8MJ energy at 351nm)
- Omega laser at Rochester LLE (30KJ at 351nm)
- GEKKO laser FIREX II   (50KJ 527nm)
- Orion (5kJ at 351nm)
- Z Sandia (>20MA)
- Magpie Z-pinch (>1MA)
- FAIR (40kJ) assuming 10^{12} U ions at 1Gev/u

Conclusions

- Several methods exist for WDM creation

- Diagnostics based on bulk and microscopic properties are complementary

- Challenges in measuring temperature

- Large ion beam facilities offer some advantages in both shock drive and volumetric heating

    - Reduction of radiative pre-heat at strong shocks
    - Volume heating of mid-higher Z materials

Why WDM and what are the problems?--SKIP

- Why is WDM important?
- What are challenges?
- Discuss experiments and diagnostics together
- Facilities and future facilities
- Conclusions

Characteristics of WDM-SKIP

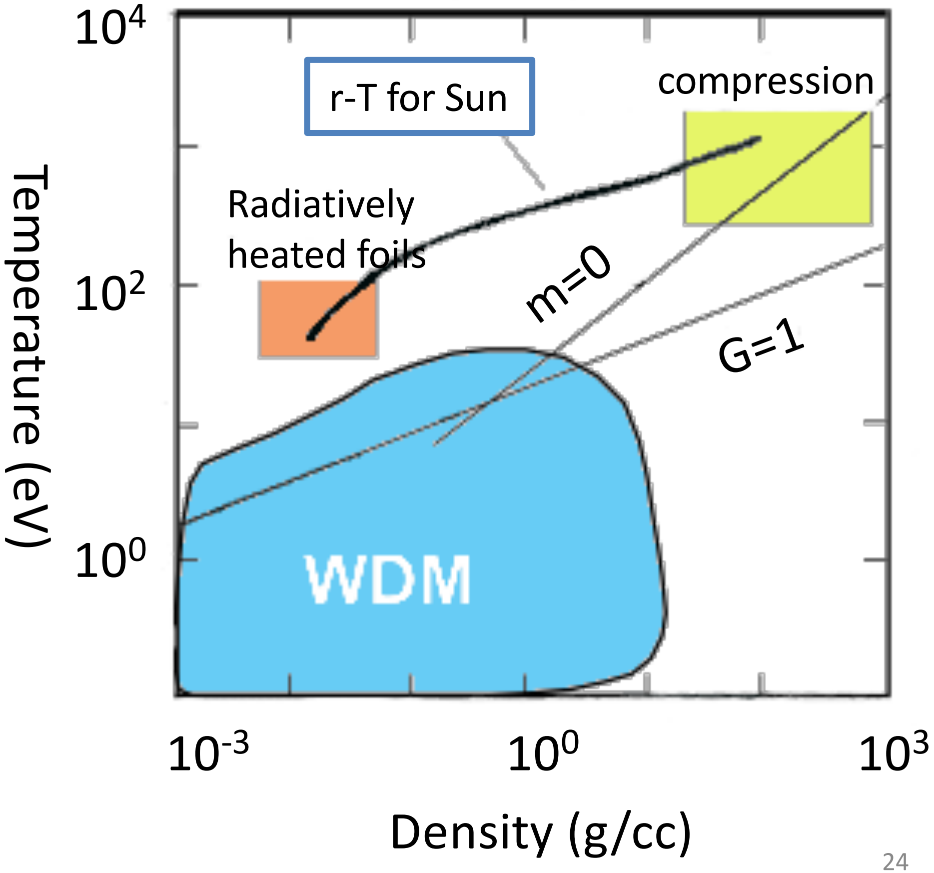
- Strong coupling between particles

$$\Gamma_{ii} = \frac{(Ze)^2}{ak_bT_i} > 1$$

- Partial degeneracy $E_F/kT \sim 1$

- Partially ionised

RW Lee *et al* JOSA B **20** 770, 2003



The challenge of diagnostics- SKIP

- Optical emission does not come from core only surface
- Peak black-body emission would be ~30eV for 10eV.
- Soft X-ray regime hard to work in.
- Optical probing not useful.
- Small spatial and short temporal scales.
- Temperature is a particular issue.