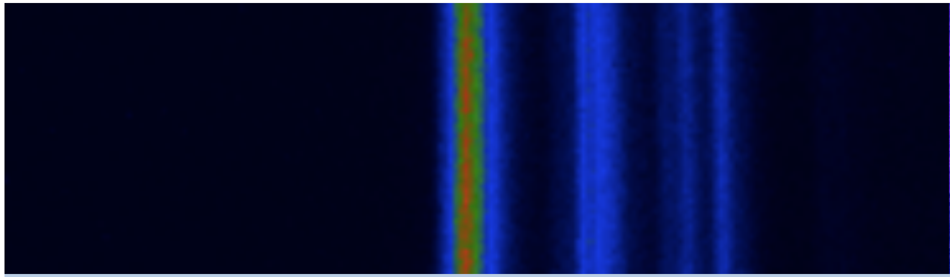

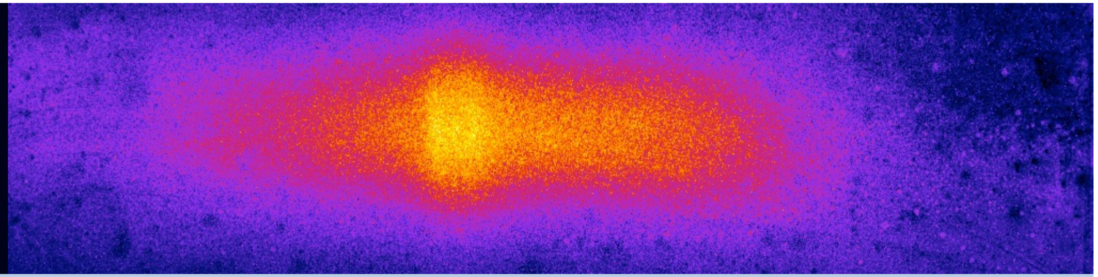

Warm Dense Matter Experiments

D. Riley

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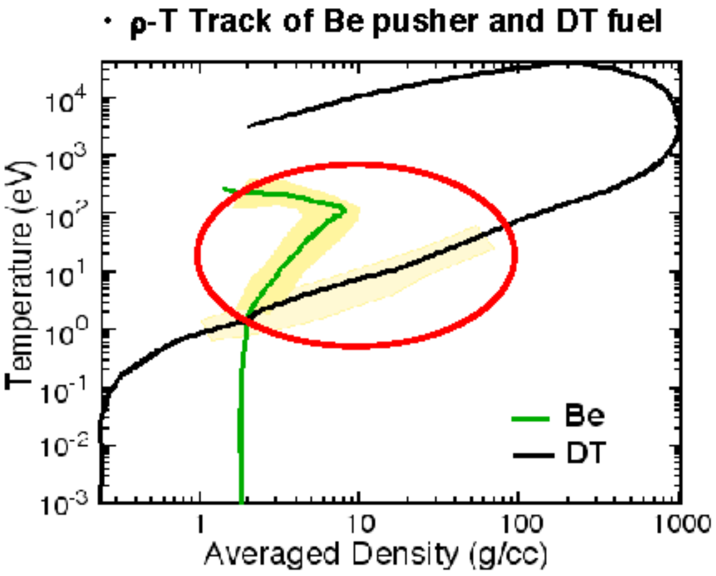
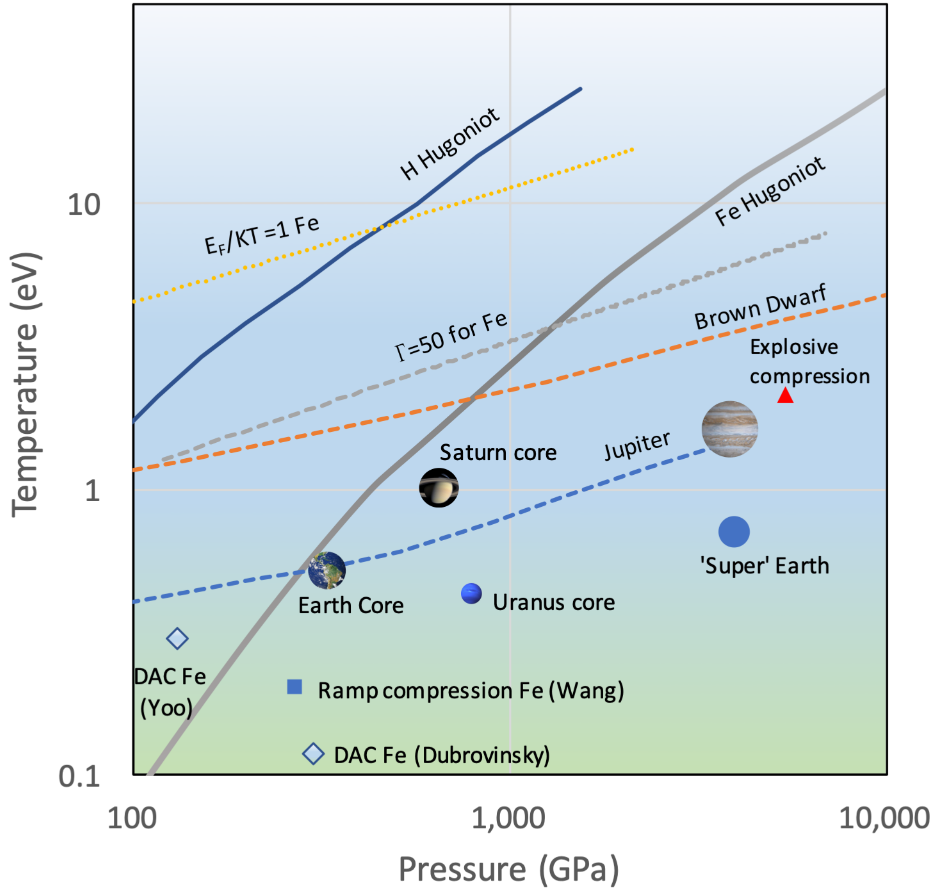
Context of WDM

- Theoretical challenge of strong coupling, partial degeneracy, partial ionisation.
- Occurs in laser-fusion, astrophysics and planetary sciences
- Typically, energy density > 10^{11} J/m^3



See RW Lee *et al* Laser Part. Beams **20** p527 2002



$$\Gamma = \frac{(Ze)^2}{a k_B T}$$

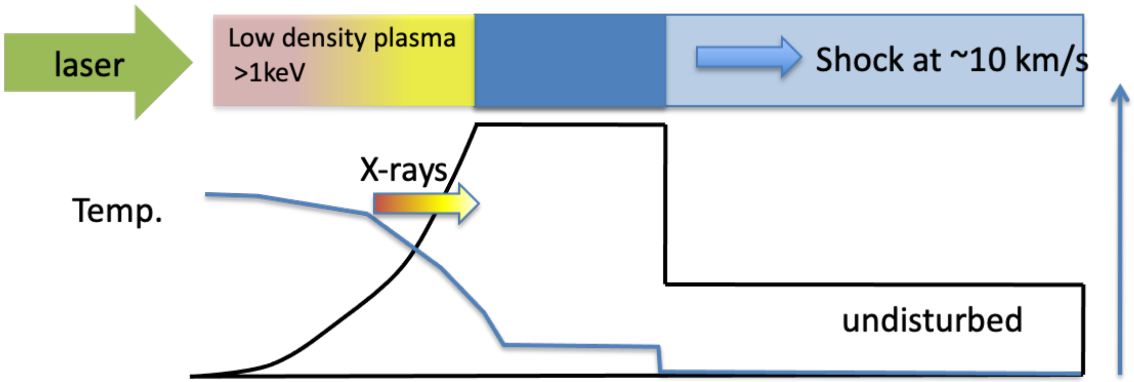
a = ion-sphere radius

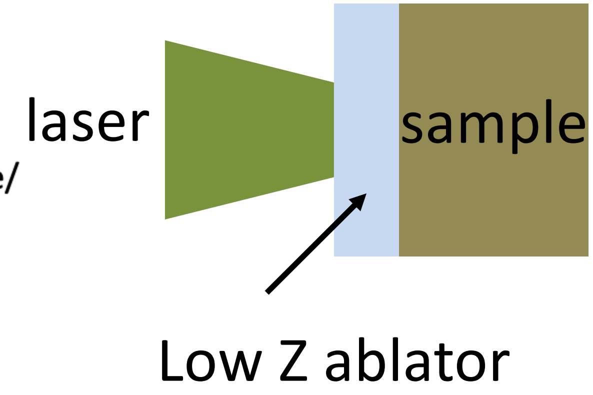
There are different approaches to WDM production

- Shock/ramp compression
  - Laser driven shocks   >1000 GPa[1]
  - Z-pinches   >500 GPa[2]
  - Explosives[3] (>100 GPa) and gas guns >500 GPa[4]
- Volumetric heating
  - Radiation from laser plasmas[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] e.g. 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

Example: Driving intense shocks

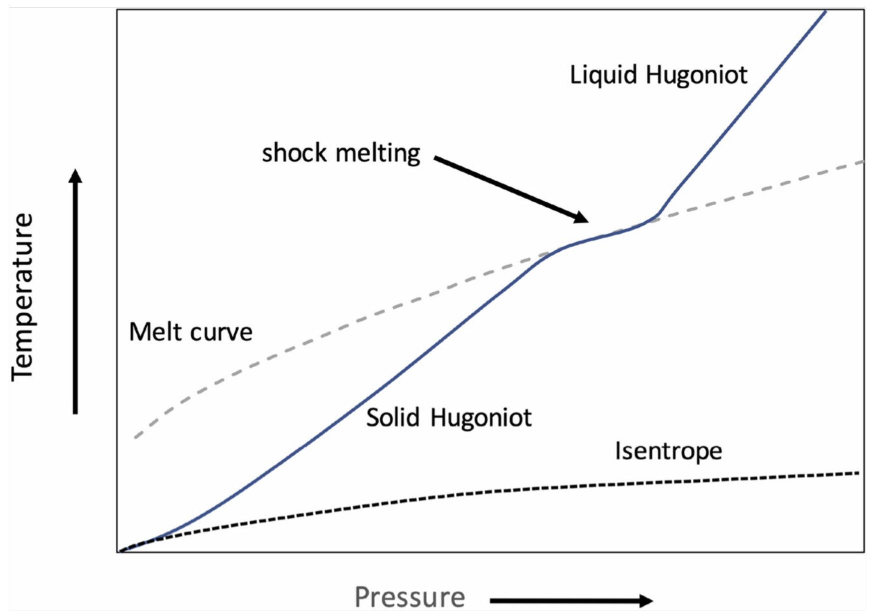




1 KJ in 1 ns over ~ 1mm^2 gives ~10^{14} Wcm^{-2} and a pressure of in excess of 1 TPa.

$$P(GPa) = 800 I_{14}^{3/4} \lambda^{-1/2}$$

[1]PC Thompson *et al*, J. Phys. D **14**, 1215, 1981



Rankine-Hugoniot equations.

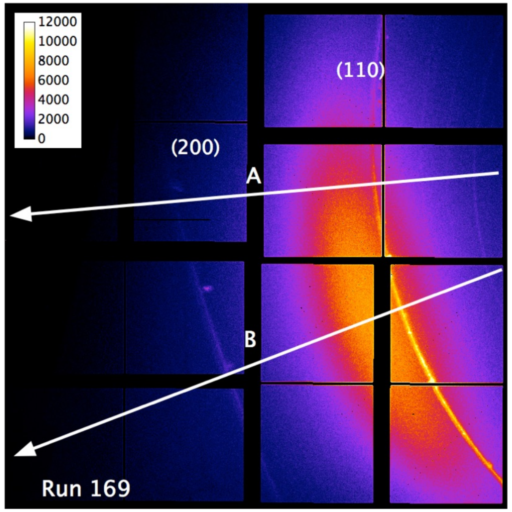
$$\rho_0 v_0 = \rho v_1$$

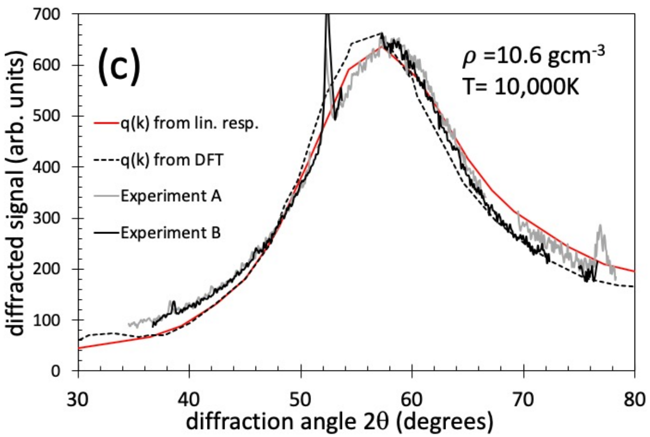
$$P_0 + \rho_0 v_0^2 = P + \rho v_1^2$$

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

Shock diagnostics include:

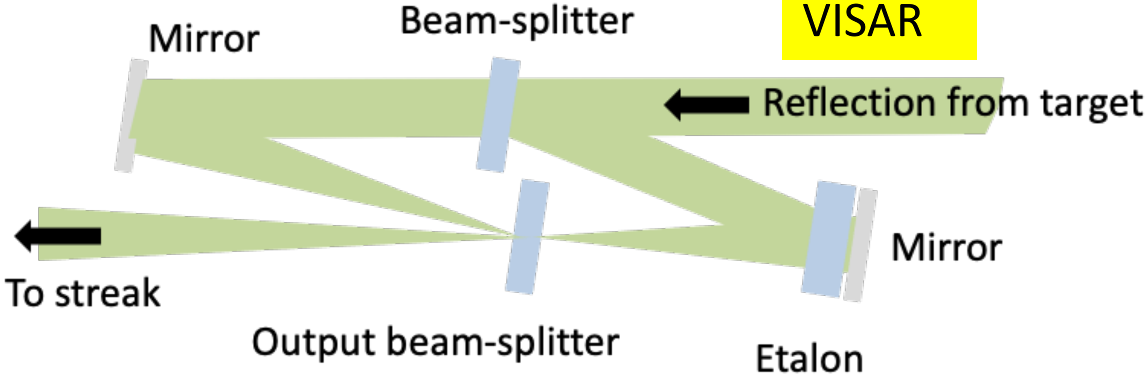
XRD

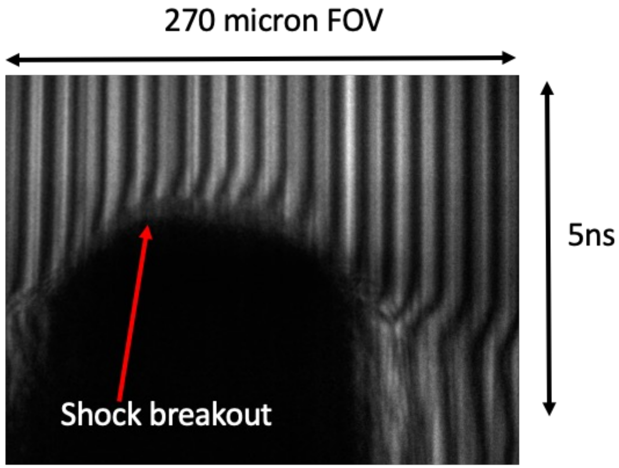




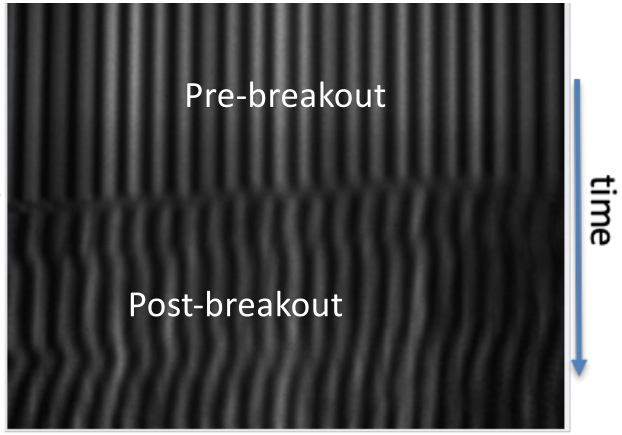
Density and Temperature

VISAR





Rear of Fe target 400 GPa shock
On exit ~7×10^{13} Wcm^{-2}



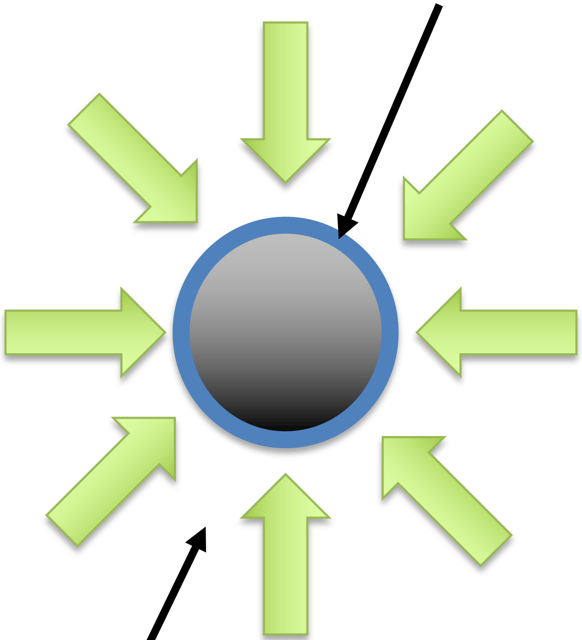
Rear of windowed target

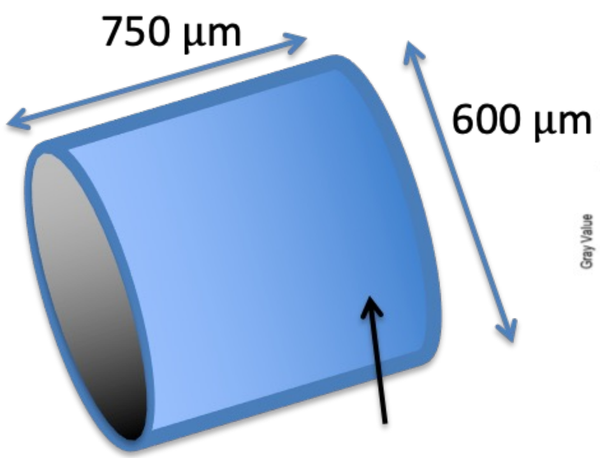
Celliers *et al* RSI **75,** 4916, 2004

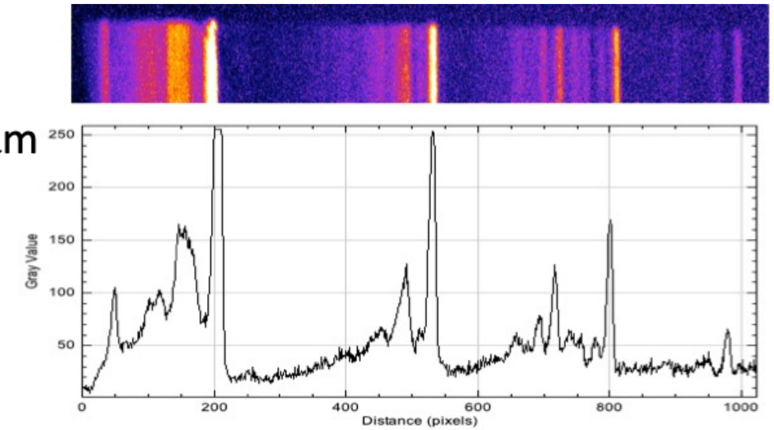
Shock speed and particle speed

Example: Radiative heating with X-rays

0.6 mm diameter Be, coated by 1 μm Rh(Z=45)







Rh L-shell emission 2.7-3.4 keV 5-10 % conversion.

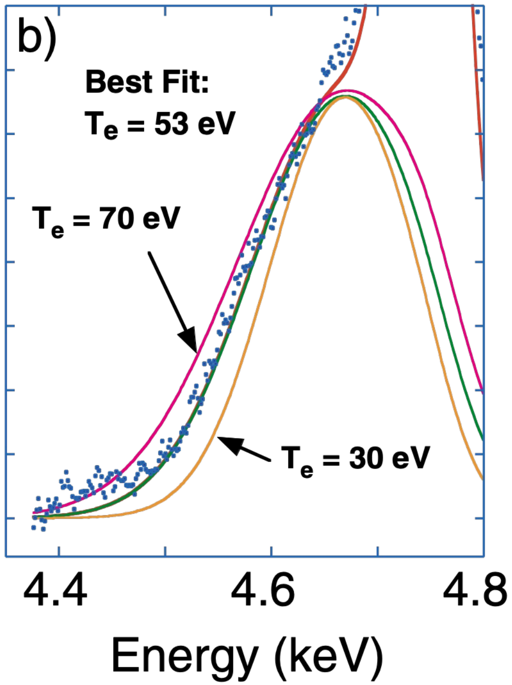
L-shell photons have 100s μm mfp in Be

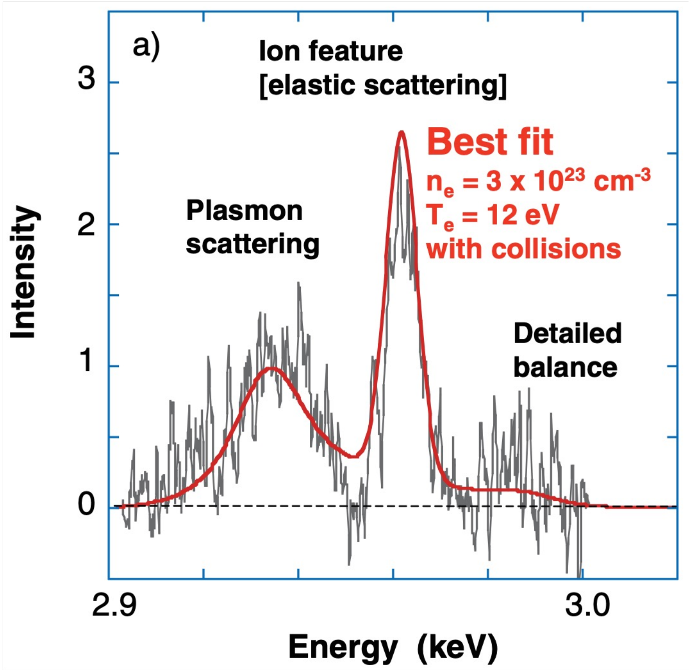
Omega laser 351nm 15KJ 30 beams.

Uniform heating to ~50 eV at ~ 1.2 gcm^{-3} density. P~ 2.8 TPa: Timescale ~ 10 ns with ~ 1ns duration x-rays. Possible due to low opacity of Be to x-rays.

Glenzer *et al* PRL **90** 175002 2003

The diagnostic was XRTS





Glenzer, S. H. et al. Phys. Rev. Lett. **98**, 065002 (2007)

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

Thomson Cross-section

Ionic form factor

Electron-ion correlation

Ion-ion structure factor

Bound-free electrons

Free electron structure factor

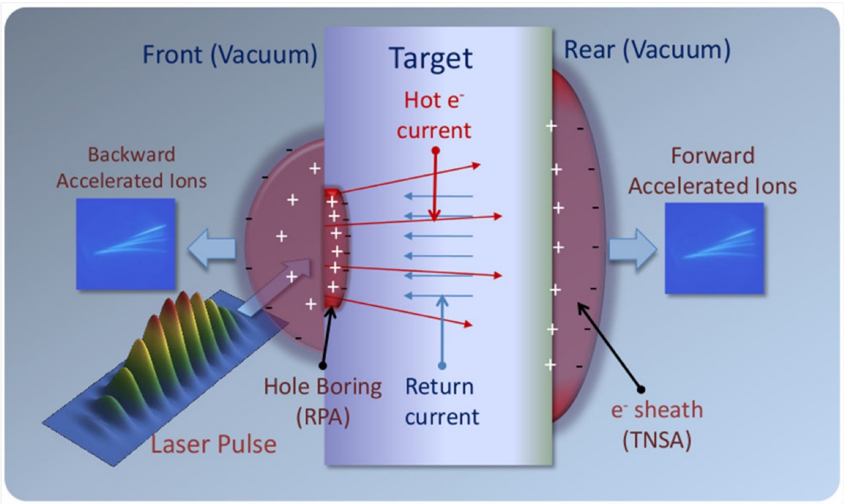
[1]J. Chihara J. Phys F **17** p295, 1987

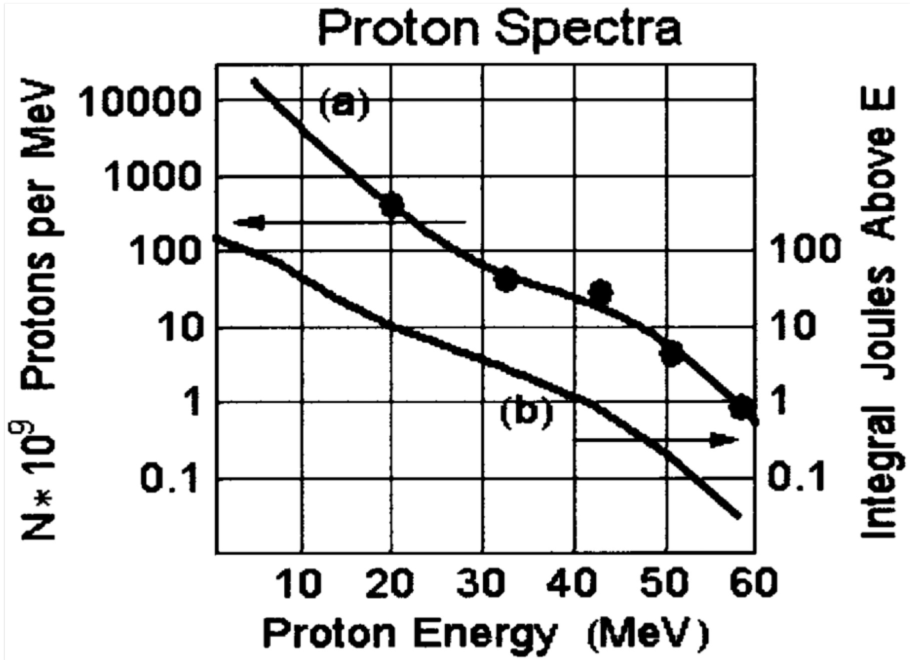
[2]E Nardi, Phys. Rev. A **43** p1977, 1991

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

Proton heating approach

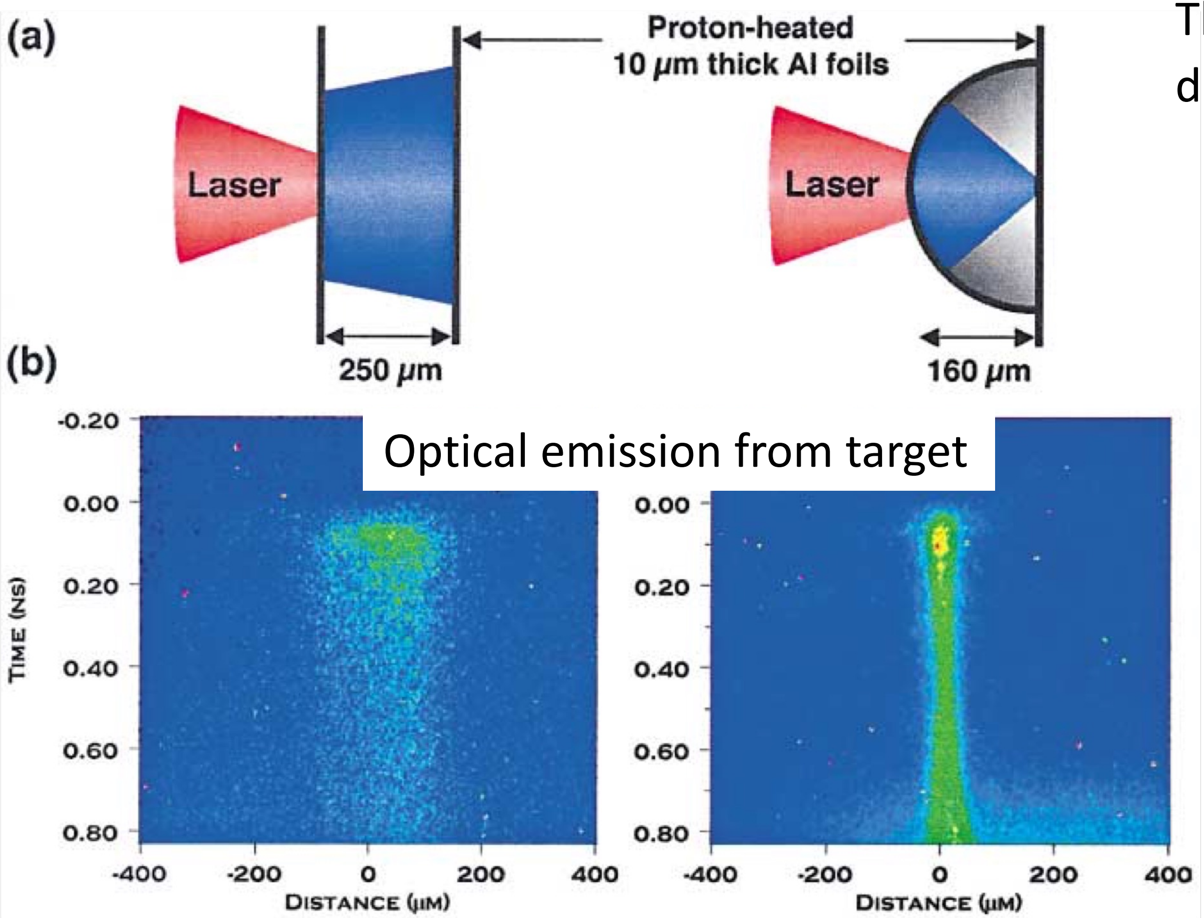
The laser generates fast protons by mechanisms such as TNSA (Snavely et al PRL **85** 2945, 2000, Clark et al PRL **84** 670, 2000. Energies can be in a spectrum ranging from MeV to 100 MeV with a conversion efficiency up to 10%.





A Macchi, M Borghesi, and M Passoni, Rev. Mod. Phys. **85** 751-793, 2013

Proton heated WDM has been created

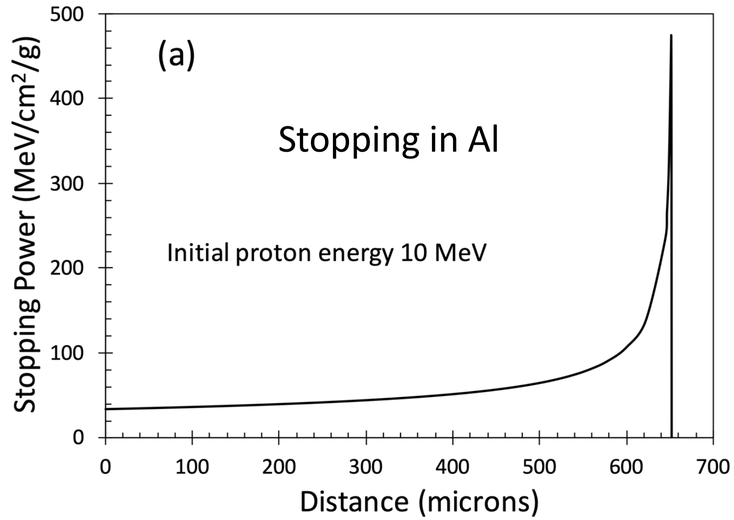


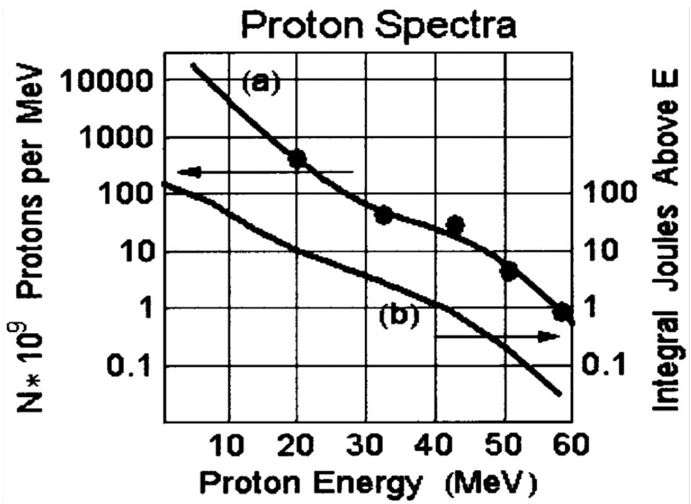
T~ 20 eV for focussed, 4 eV unfocussed

Patel et al, PRL **91** 125004, 2003

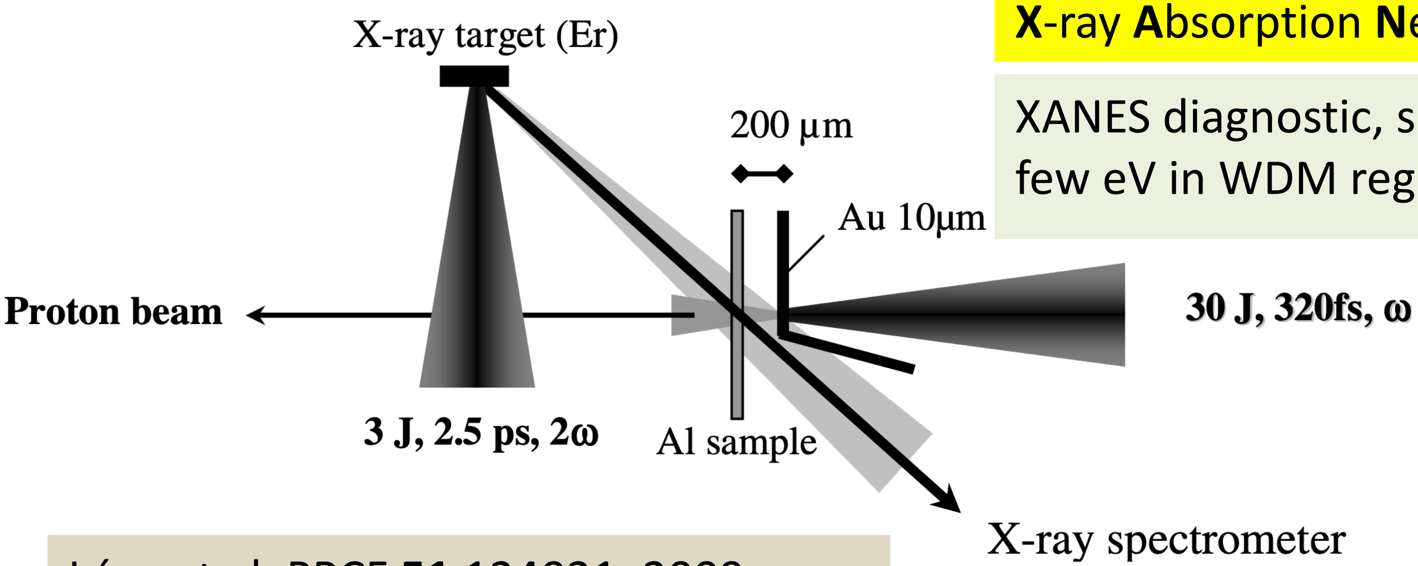
Streaked Optical Pyrometry. (SOP)

The protons stop with a Bragg peak depending on energy and material





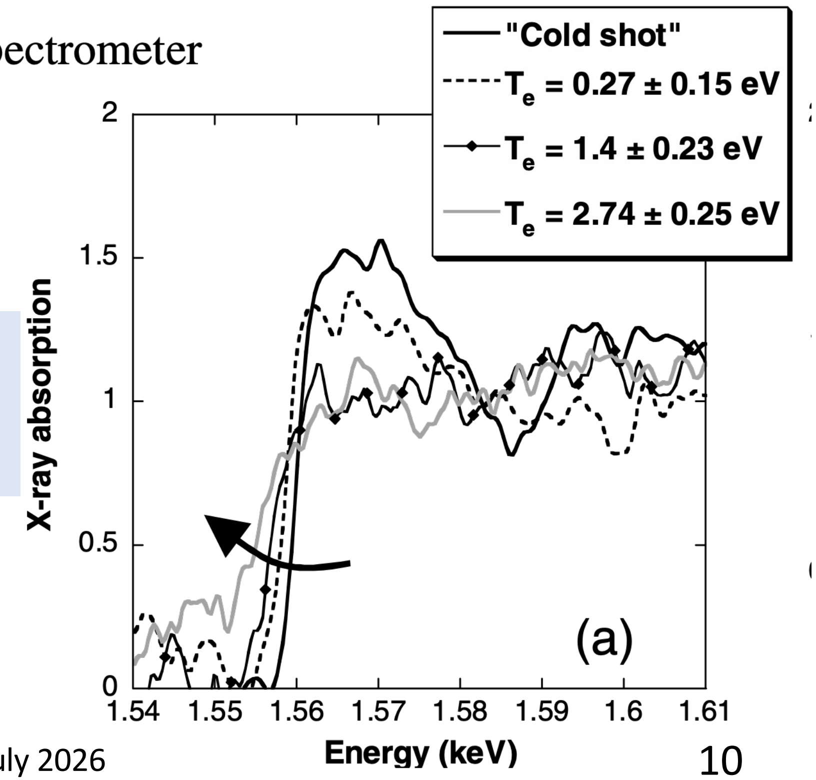
Probing is not trivial but possible



X-ray **A**bsorption **N**ear **E**dge **S**pectroscopy

XANES diagnostic, solid densities and a few eV in WDM regime

Lévy et al, PPCF **51** 124021, 2009



see also

L Lecherbourg et al, *Phil. Trans. R. Soc. A* **381**: 20220214 (2023)
F. Dorchies et al Struct. Dyn. **10**, 054301 (2023)
A. McKelvey et al Scientific reports **7,** 7015 (2017)

Challenges- some specific issues for laser-plasmas

- Fast protons use TNSA and this means fast electrons with hard-x-ray bremsstrahlung. Highly divergent proton beams (~0.5 radians).
- Laser-driven shocks can involve x-ray pre-heating.
- X-ray heating OK for lower Z but higher Z can be an issue for heating and probing.
- Timescale for evolution may make time-averaging effects significant.
- Access to sample for probing can be an issue- see Lévy experiment.

Some examples of where FAIR can be competitive

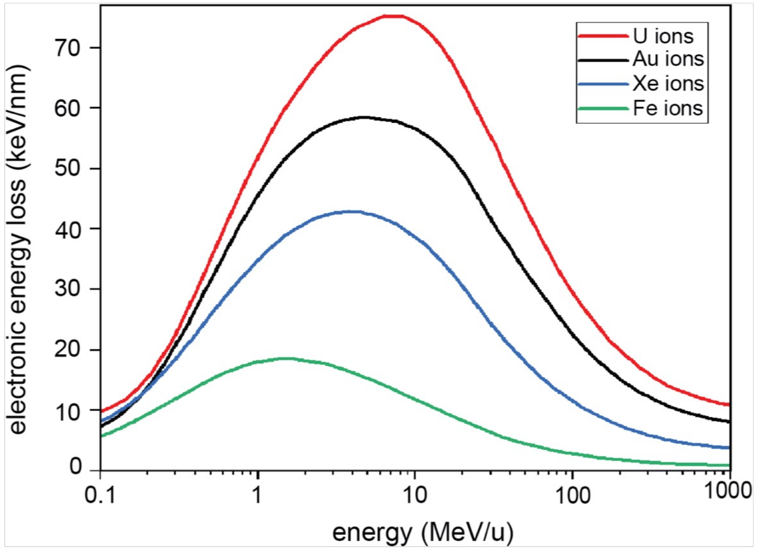
- Creation of a large volume WDM sample with low temporal and spatial gradients and using higher Z.

- Shock or high-pressure compression without x-ray preheat.

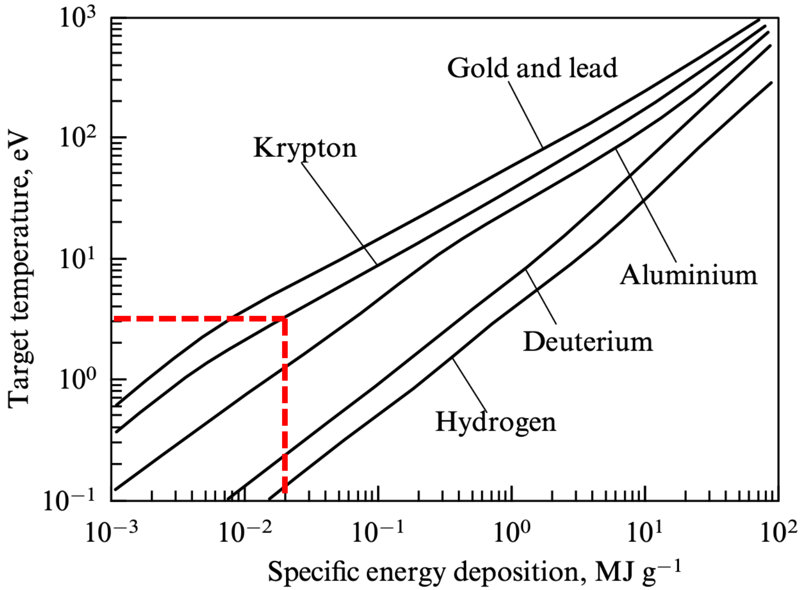
- Timescale for heating is ~ 100ns but decompression times can also be large.

- Ion source separated from sample for easier probing.

SIS-100 beams can produce WDM



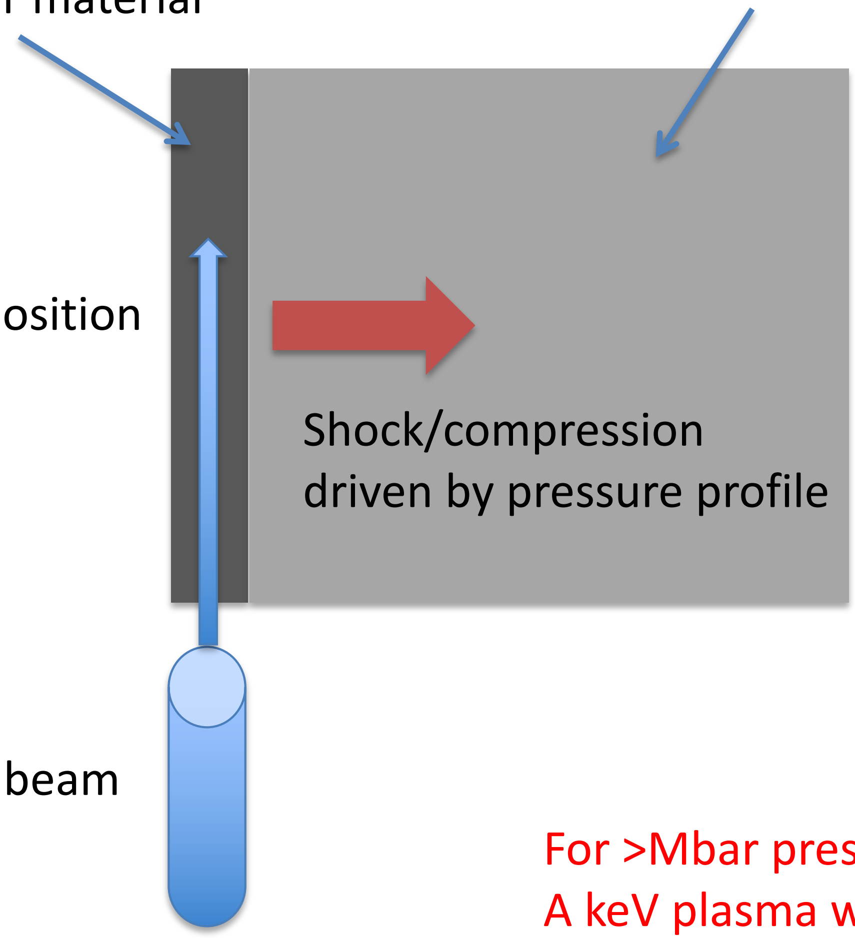
From Tzifas et al Phys. Rev. Res **8** 023054 (2026)



V E Fortov, D H H Hoffmann, B Yu Sharkov
Physics Uspekhi **51** (2) 109 -131 (2008)

1 GeV/u U^{+28} ions loss rate of about 10 keV/nm in Steel (Fe). Range ~ 10 g/cm^2 which is about 13 mm in Fe. Over a mm dimension sample, we would have uniform heating to $2x10^7$ J/kg with 10^{11} ions in a ~ 1mm area focal spot. This should lead to ~ 3eV.

Ion beam shocks have been proposed



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 1.5 kJ/g in Pb, 0.2
eV and 15 kbar shocks

10^5 J/g for Pb is ~10^{12}Jm^{-3} ~ 10Mbar

For >Mbar pressures we do not have to create
A keV plasma with ion beams. Unlike laser
driven shocks

Hydrodynamic evolution vs size

If we imagine a sample at a pressure of ~ 100 GPa with density ~ 1gcm^{-3}, which is typical of WDM then we can estimate a sound speed given by

$$c_s = \sqrt{\frac{\gamma P}{\rho}} \sim 10^4 m s^{-1}$$

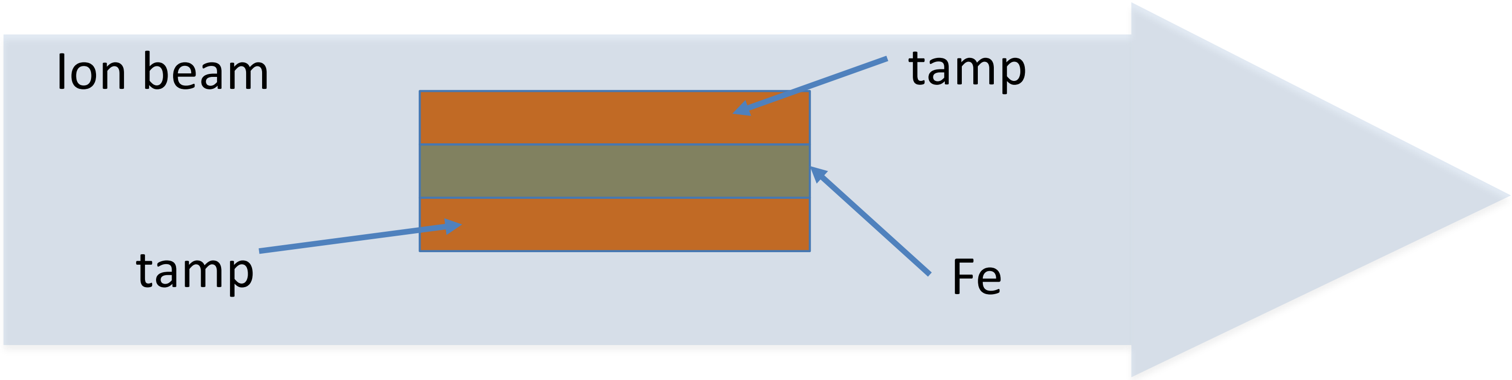
Estimate a hydrodynamic decompression time, based on sample size, d

$$t = d/c_s$$

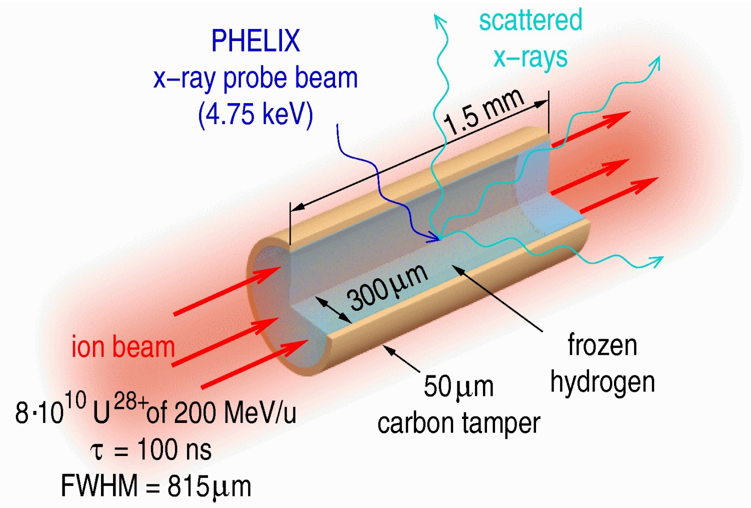
For a mm-sized target this gives 100 ns. For laser-plasma drive x-ray probes we can get typically 1ns with quite good conversion. Thus, volumetric heating over a large volume has some key advantage. For the Lévy experiment the thickness was of order 1 micron and sound speed estimated at 5 km/s. So, timescale ~200ps compared to heating time of ~ 10ps.

Experimental issues remain e.g. probing higher Z

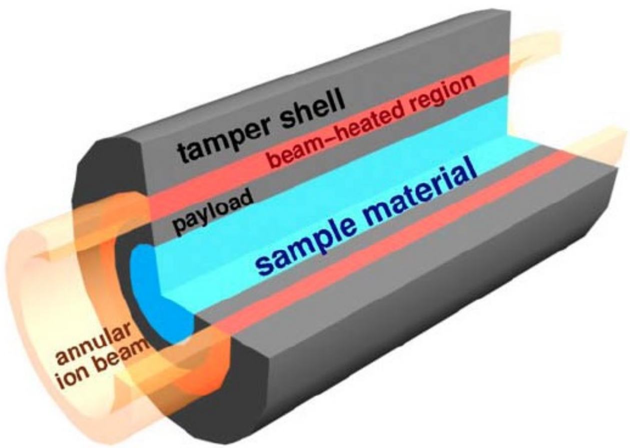
- For $2x10^7$ J/kg for Fe the pressure should be about 160 GPa.
- This means a sound speed at solid density of about 5 km/s.
- For XANES 1-1.5 mfp for the K-edge region is about 3-5 μm. Decompression time is then ~ 1ns.
- For probing with XRTS etc we may wish to restrict the thickness to about 20 μm, as this is a mean-free path for ~ 6-7 keV photons just below edge. The decompression time would then be ~ 4 ns. **Maybe tamped targets needed**.



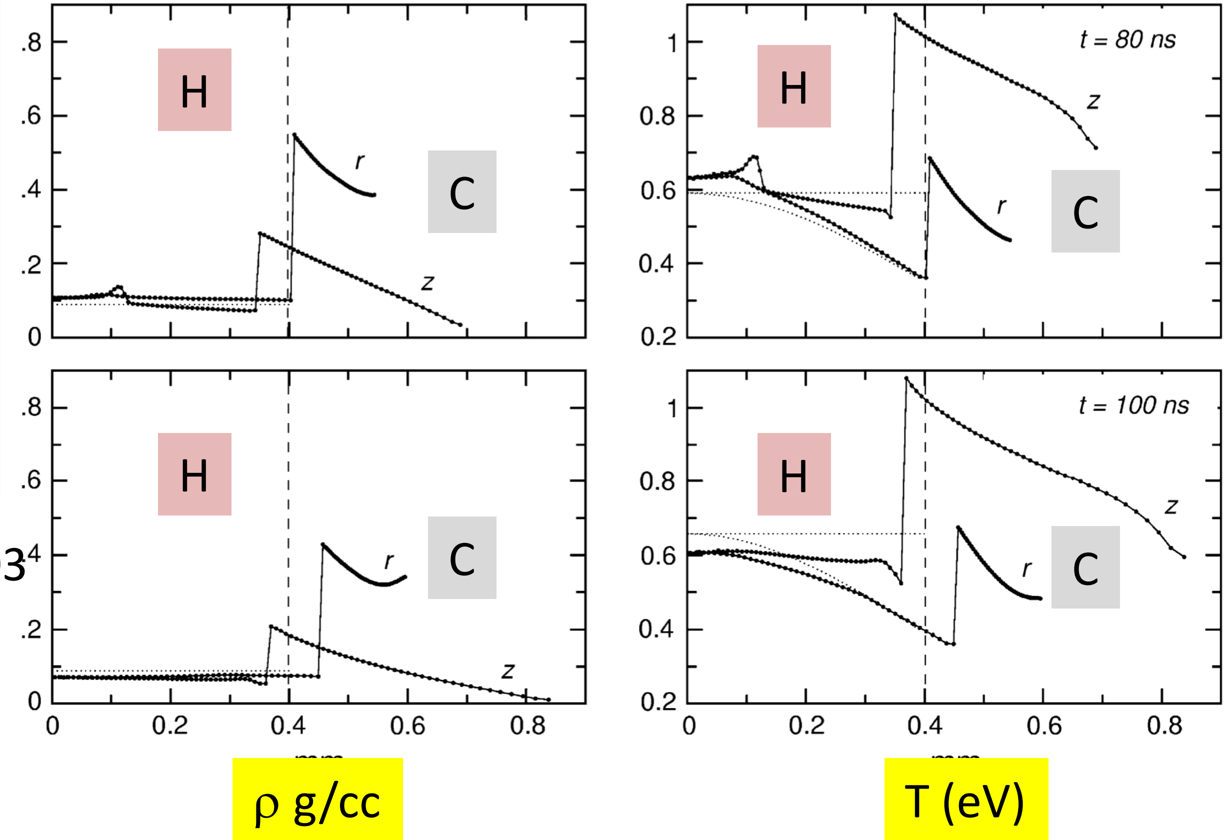
Tamping proposed previously



Kozyreva, et al PRE **68**, 056406 (2003



Weinwurm *et al* Phys. Plasma. **20**, 092701 (2013)

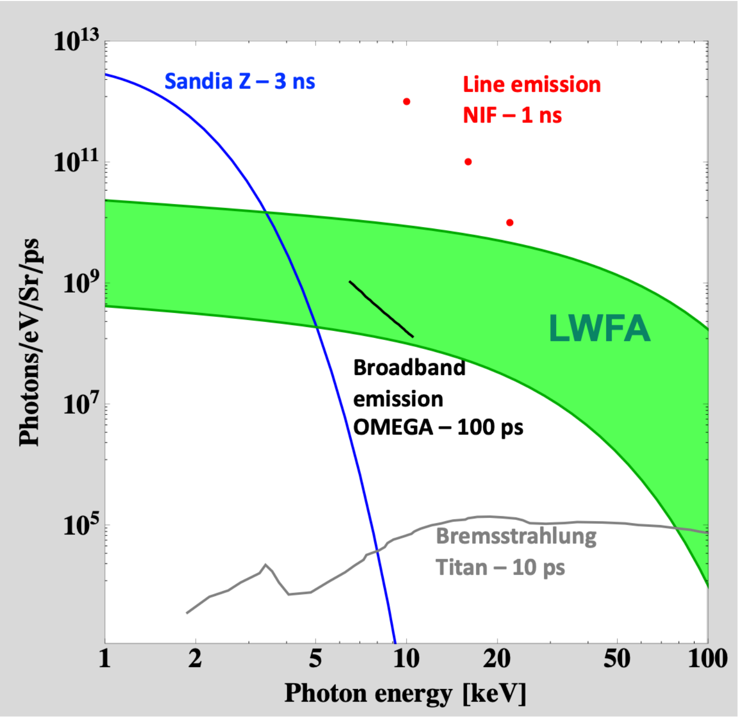


Tauschwitz *et al* HEDP **3** 371 (2007)

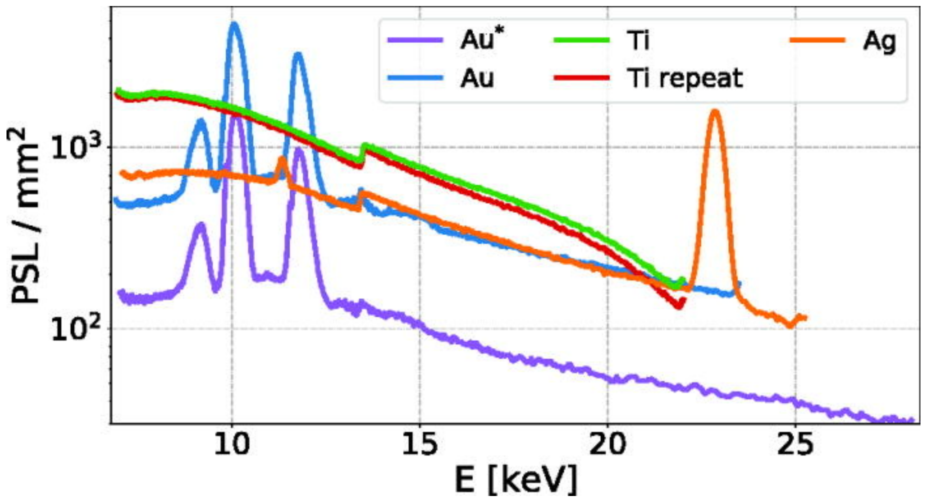
8 x 10^{10} U^{+28} ions : 200 MeV/u

815 µm FWHM beam : 100 ns pulse

Experimental issues remain e.g. probing higher Z



Betatron radiation



2ns pulses 351 nm

Krygier et al Appl. Phys. Lett. **117**, 251106 (2020)

Irradiate solid targets directly.

Albert et al, PRL 118, 134801 (2017)

Complex set-up

Noise issues due to fast electrons

- Energy transfer of ions mainly to electrons in the target.
- Simple consideration of momentum suggests transfer of energy is given by mass ratio m_e/m_{ion}. For uranium-238 mass ratio is ~ 4.4×10^5.
- For 200 MeV/u this means ~ 100 keV electrons. These can generate bremsstrahlung radiation that causes background noise and damage in instruments.

Summary

FAIR/SIS-100 can compete well in several key areas:

Volumetric heating possible for wide range of sample materials

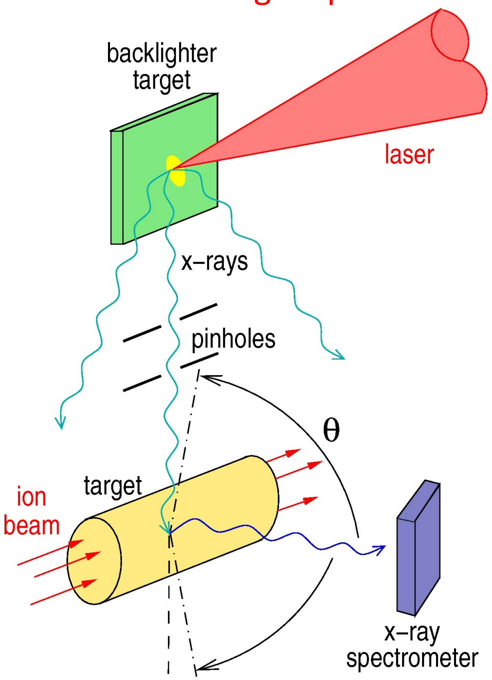
Ion heating can be far more controlled and flexible than laser drive proton source experiments.

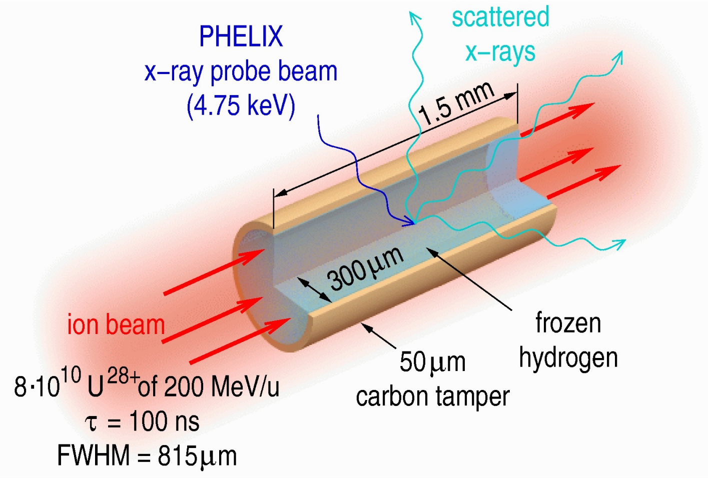
There are still experimental challenges e.g. trade off between hydrodynamic decompression times and having samples that can be probed.

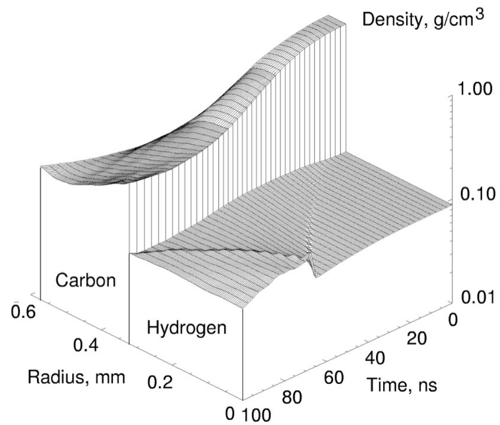
Fast electrons still can be an issue due to collisional transfer from ions.

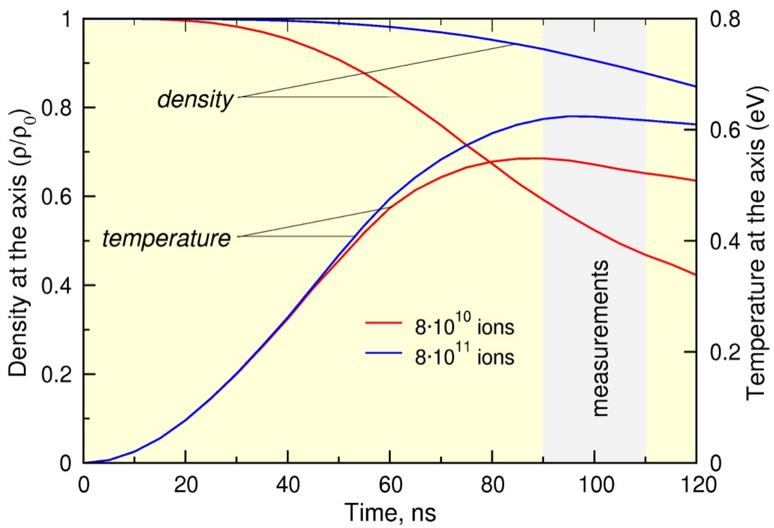
Tamping has been discussed previously

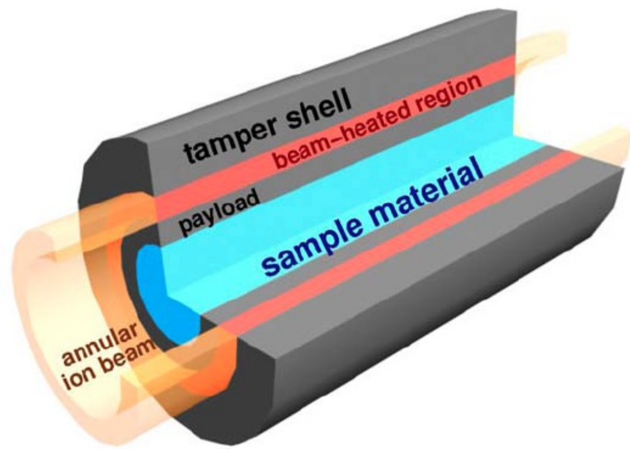
No hot outer high Z plasma. X-ray probe











Kozyreva, et al PRE **68**, 056406 (2003

Rosmej et al, Journal of Physics: Conference Series **72** (2007) 012007

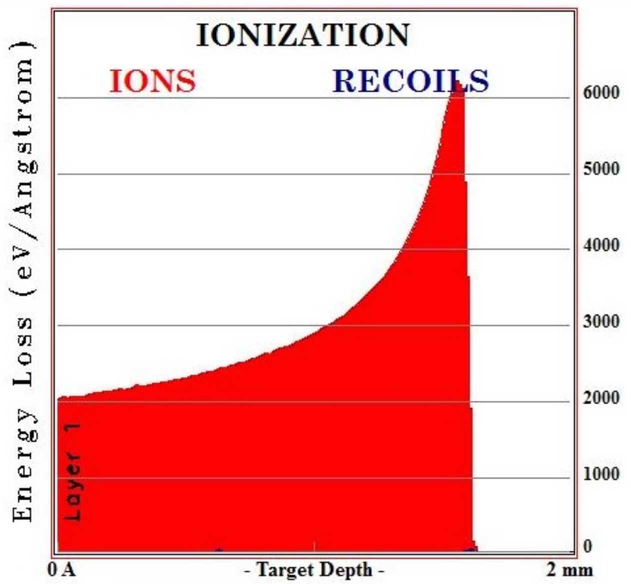
Weinwurm *et al* Phys. Plasma. **20**, 092701 (2013)

Diagnostics- a variety are available

- **Emission spectroscopy:** Requires low opacity to be effective? WDM is low temperature and high density. Probes surface? SOP can give shock temperature.
- **Absorption spectroscopy:** Smooth background spectra useful for EXAFS/XANES. Opacity of higher Z targets may require thin targets (decompression time short) or higher energy photons.
- **X-ray diffraction:** Can give microscopic structure of ions. Interpret in terms of density and temperature.
- **X-ray Thomson scattering:** Dynamic structure factor- temperature and electron density/average ionization.
- For x-rays we probe the bulk of a sample, but opacity can be an issue.

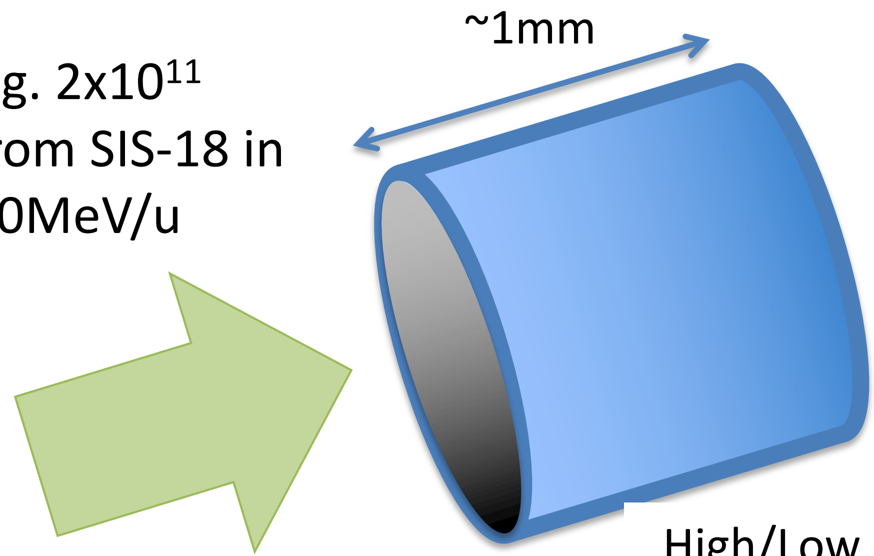
Ion beams can have advantages

Uniform heating depends location of Bragg peak of ions. Major benefit is ability to heat higher Z materials



2mm Pb target   200MeV/u U ions

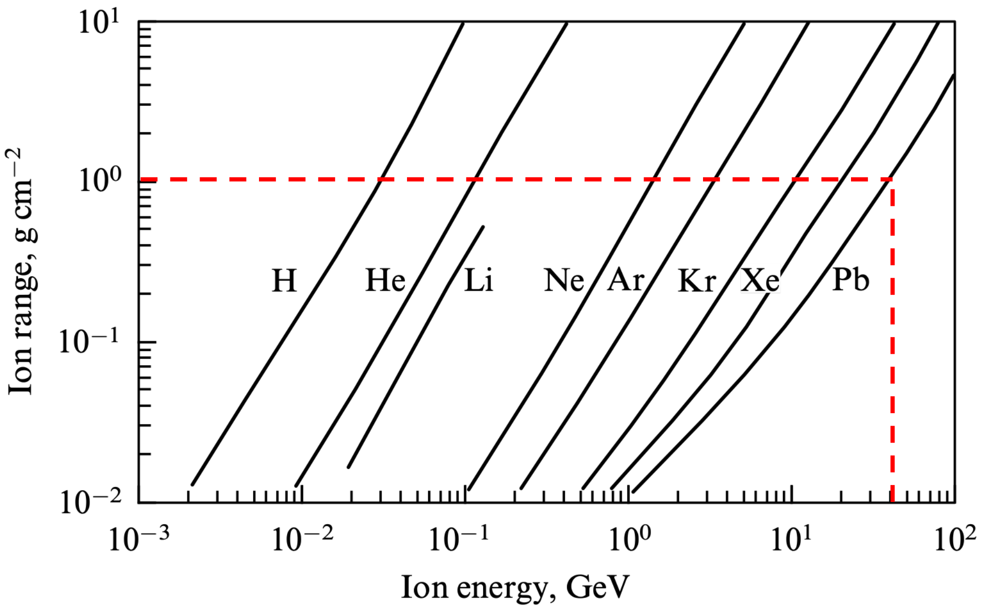
ion beam e.g. $2x10^{11}$ ions, U^{28+} from SIS-18 in 100ns at 200MeV/u



High/Low Z cylinder

For SIS-100 $2x10^{12}$ ions. Range of 1 GeV/u U ions in Pb is ~15mm.

Ion beams can do this well



For Pb ions at 200 MeV/u (e.g. SIS-18) we have range of about 1 gcm^{-2}. This is >3 mm in Al. For SIS-100 with 1 GeV/u we would get > 3cm.

Can heat high Z but probing needs higher Z source?

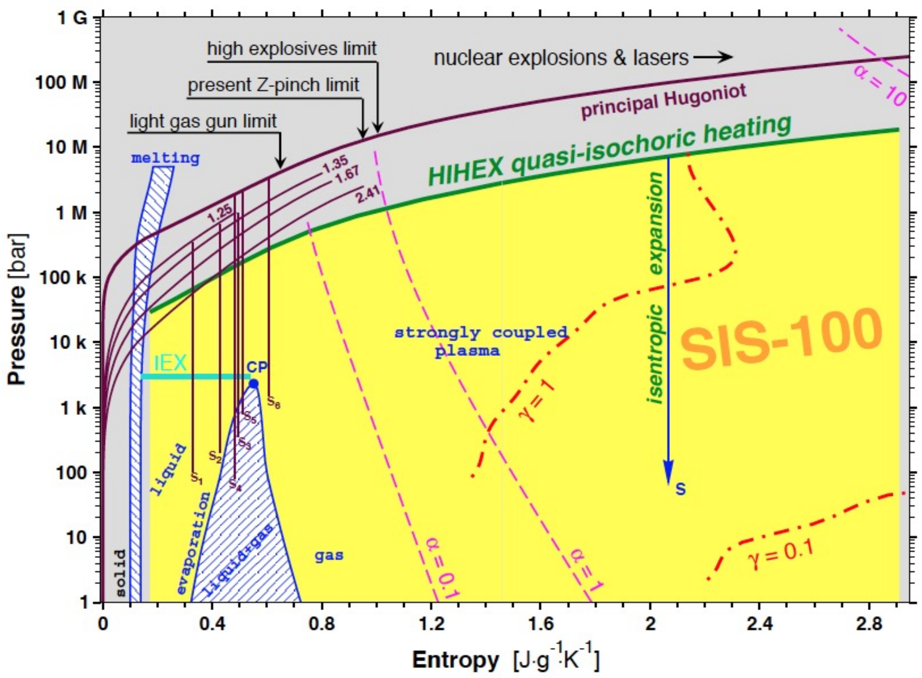
Challenges

- Samples should be as uniform as possible
- Spatial scale-length ideally long enough to be probed with spatial resolution.
- Timescale for evolution affects physics- equilibration within and between species may be affected.
- Timescale for evolution may make time-averaging effects significant.
- Access to sample for probing is important.

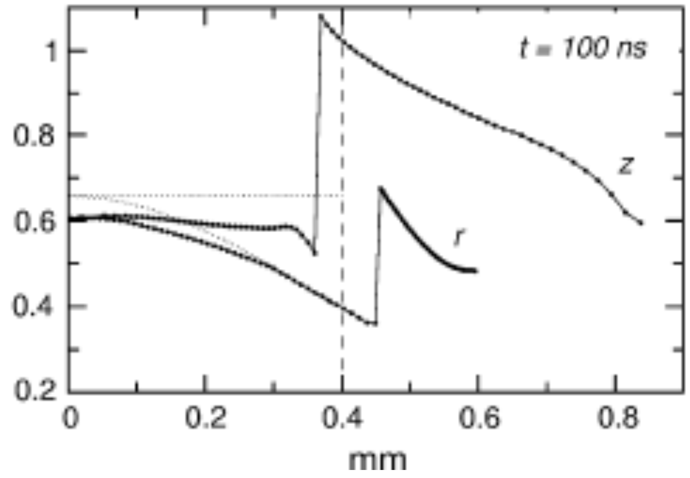
Facilities for WDM production

- Large Laser-Facilities: Shocks are a key method, but also fast electrons, X-ray volumetric heating and proton beam heating.
- Z-pinches: Flyer plate driver as well as X-rays, pinch compression.
- Gas Guns: Shocks principally.
- X-FEL facilities: Volumetric X-ray heating.
- Ion Beam Facilities: Principally volumetric ion beam heating.

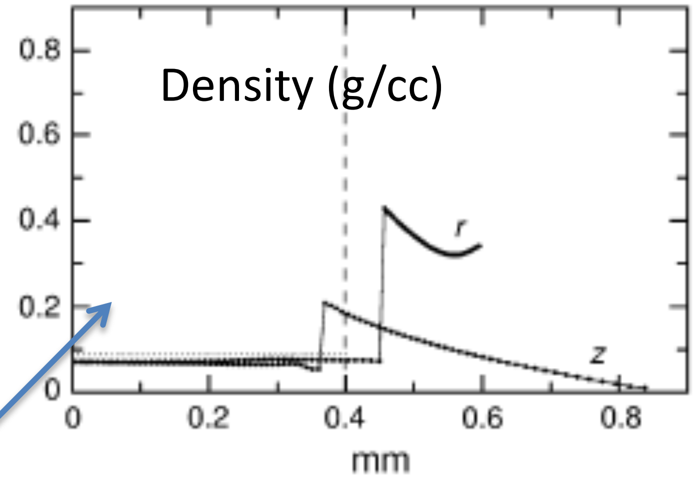
SIS-100 accesses WDM states of H to Pb



Pb accessible regime from HEDgeHOB report 2005.



T(eV)



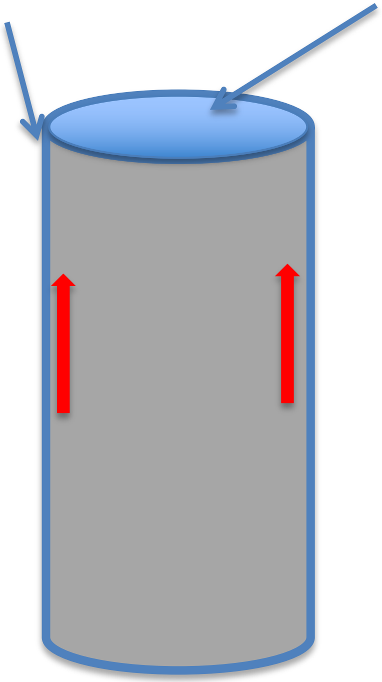
Density (g/cc)

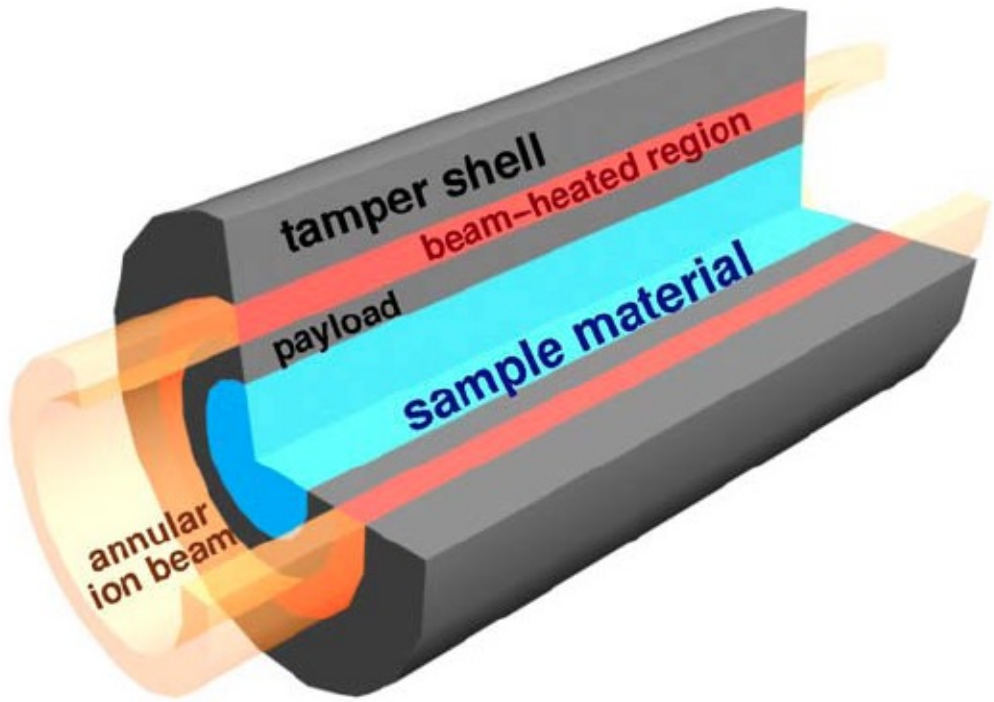
Dynamically confined H- Tauschwitz *et al* HEDP **3** 371 (2007)

Example (b) : Compare to Z-pinch

Be liner

Frozen H/D core



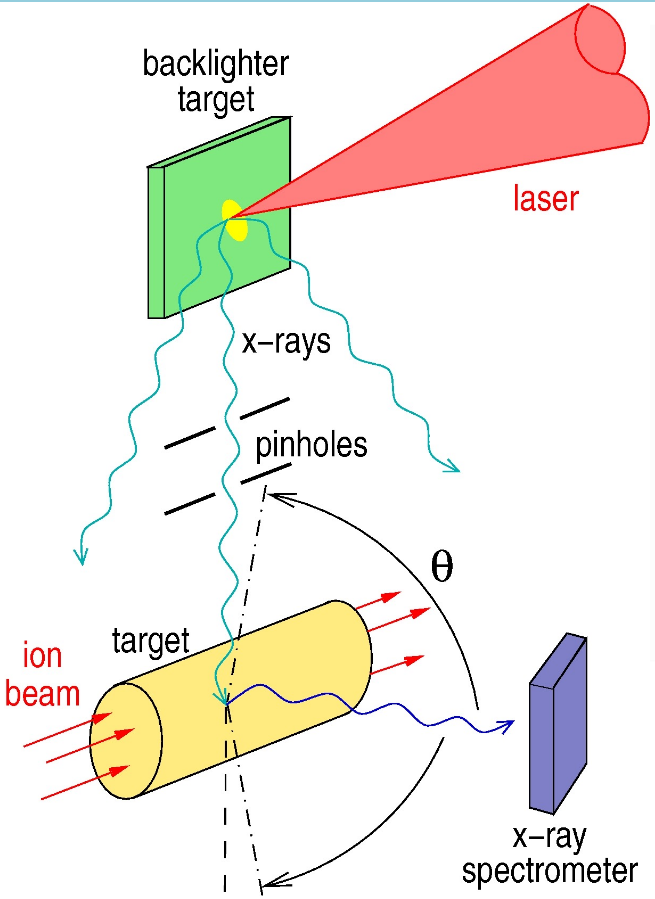


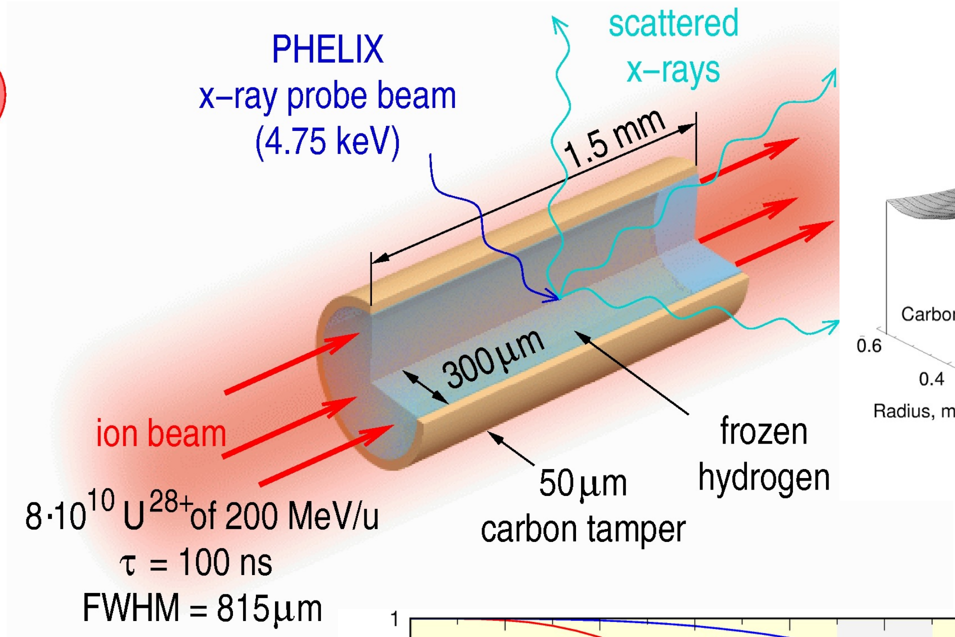
Shaped current rise over several 100ns leads to quasi-isentropic compression.

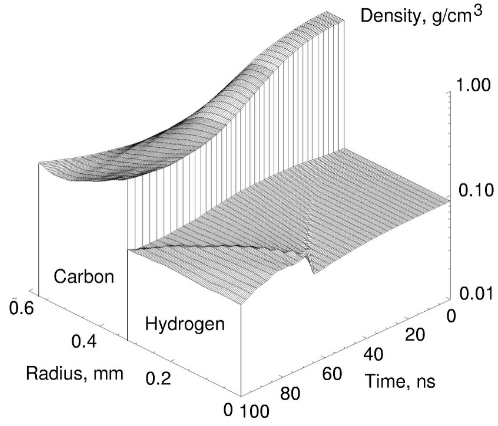
HEDgeHOB LAPLAS collaboration.

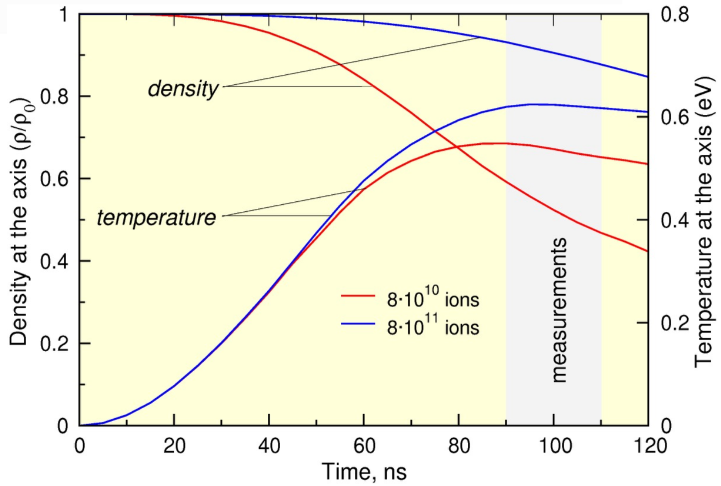
Weinwurm *et al* Phys. Plasma. **20**, 092701 (2013)

Ion beams at FAIR can have advantages









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)