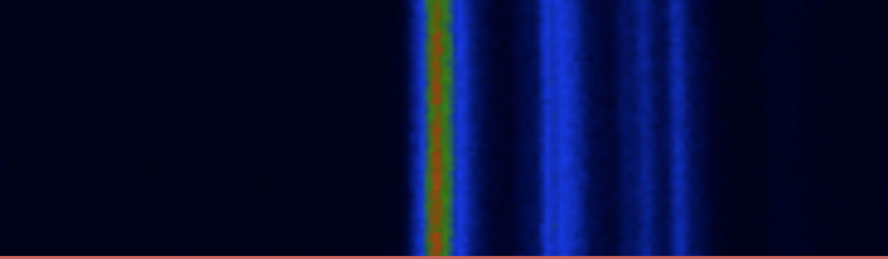
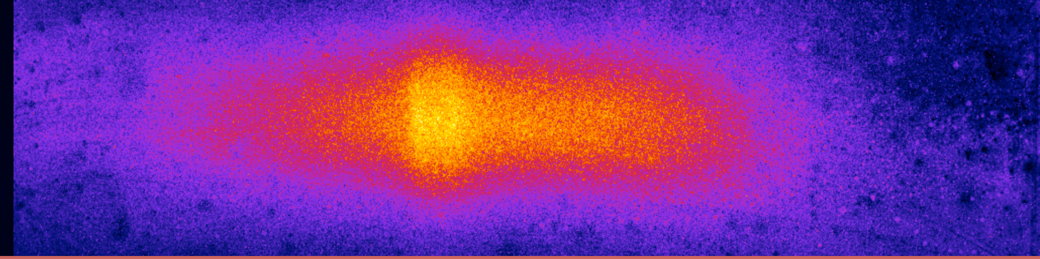

Plasma physics at FAIR-International context

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FAIR competes with:

- Large Laser-Facilities: Fusion, new particle and radiation sources, **shock generation, warm dense matter (WDM), compressed matter**
- Z-pinches: Fusion, radiation sources, **WDM, shocks, compressed matter**
- Gas Guns**: Shocks, WDM**

<u>Not just classical plasmas but WDM and equations of state at high pressure are areas FAIR competes in.</u>

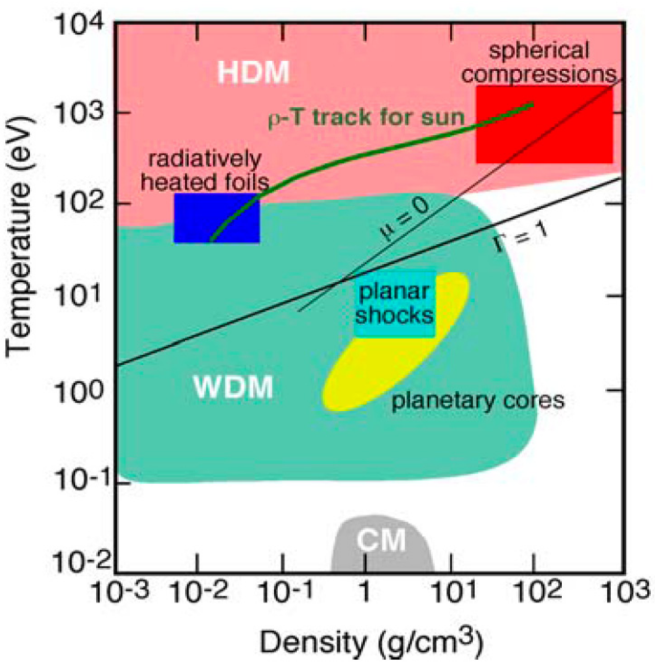
We are particularly interested in "Warm Dense Matter"

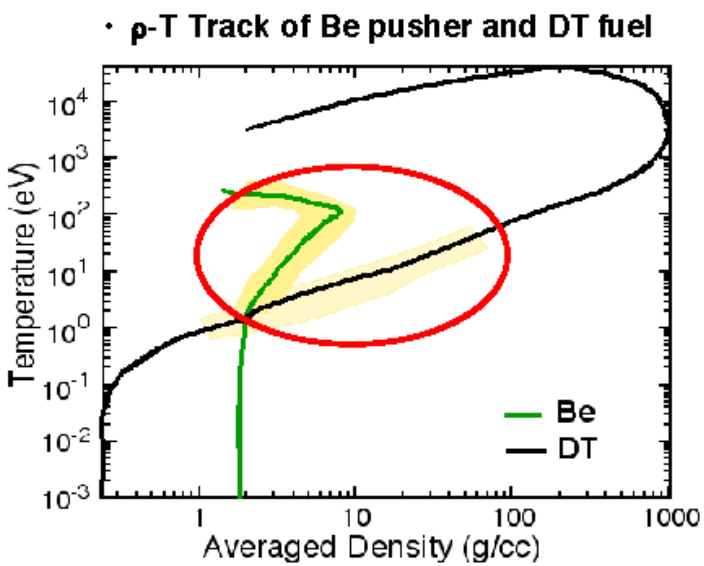
- Represents a major theoretical challenge: classical plasma physics or condensed matter physics will not do.
- Occurs in laser-fusion, astronomy, planetary sciences
- Laboratory experiments can serve as analogues for planetary matter exploring relevant physics areas.

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

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

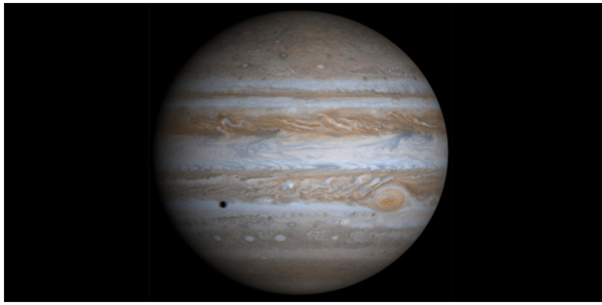
$$\frac{4}{3}\pi a^3 = \frac{1}{n_i}$$

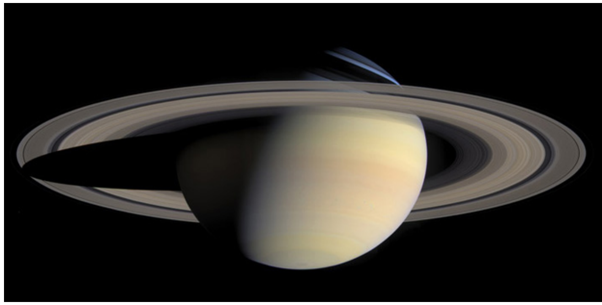


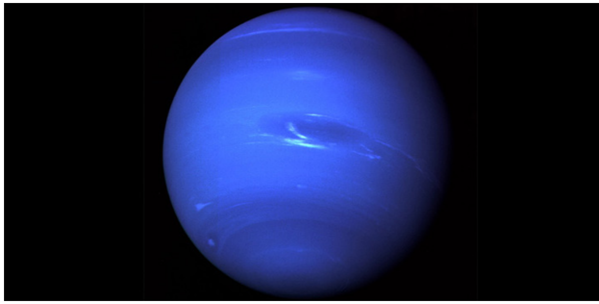


Warm dense matter in planets- some questions

- Are there diamond layers in Uranus and Neptune? – (Ross, Nature **292** 435 1981)
- Does high density metallic state of water contribute to sustaining magnetic field in Uranus and Neptune? (Stevenson, Rep. Prog. Phys. **46**, 555, 1983)
- What is equation of state of H across range of conditions for Jupiter, how does it separate from He? (Nettelman *et al* Astrophys. J **683** 1217, 2008)
- What is exact melting curve for Fe?
- Much experimental work using shock physics (e.g. Knudson *et al*, Science **322**, 1822, 2008, Eggert *et al*, Nature Physics, **6**, 40, 2010 on Carbon/ diamond)







Photos from JPL

Generating warm dense matter

- Shock compression
  - Laser driven shocks >10Mbar[1]
  - Z-pinches >5 Mbar[2]
  - Explosives[3] (1-2Mbar) and gas guns >5Mbar[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

Challenges

- Samples should be uniform
- Spatial scale-length long enough to be probed with spatial resolution helps.
- Timescale for evolution suited to being probed with time average effects being important.
- Access to sample for probing.

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)

Some examples of where FAIR has a competitive edge

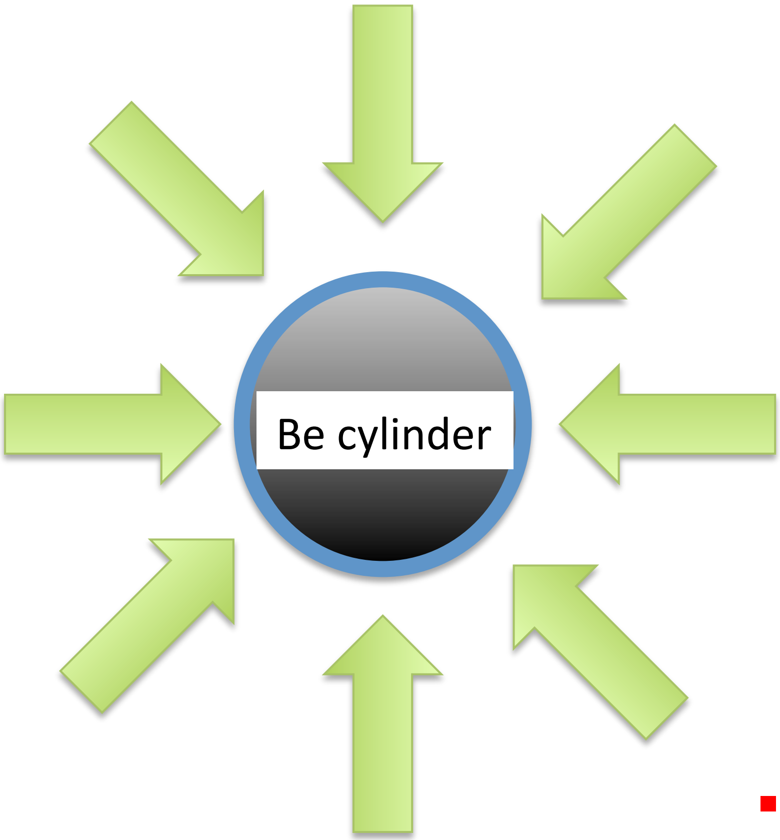
a. Creation of a large volume WDM sample with low temporal and spatial gradients

b. Shock/high pressure compression

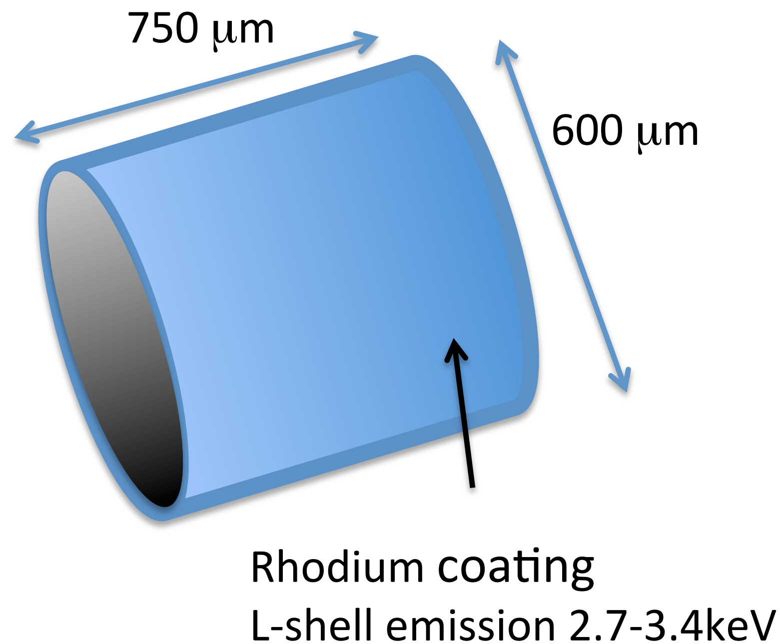
c. Ion beam heated WDM

In the next few slides I will outline the problem and how it is approached by other types of facility and how FAIR can compete.

Example (a) : The competition: Radiative heating with laser-plasmas



Omega laser 351nm 15KJ
30 beams



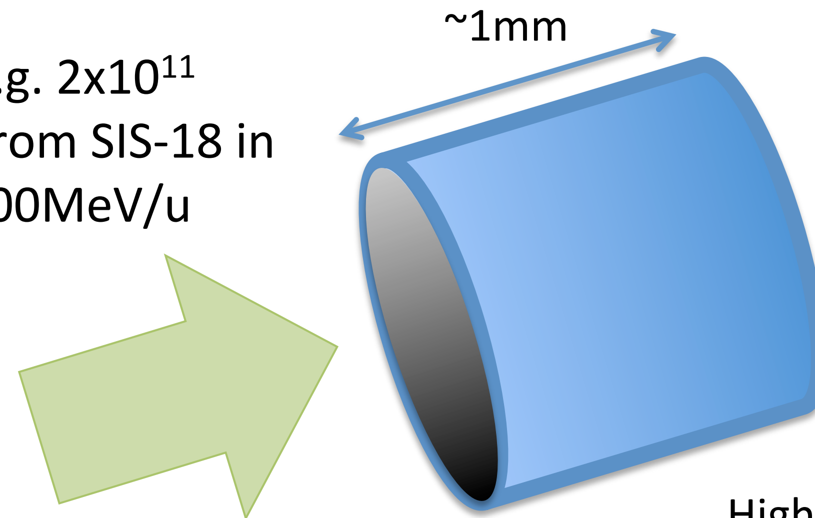
- Uniform heating to 50eV at solid density but depends on low opacity of target to allow this.
- Only a handful of facilities available for this

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

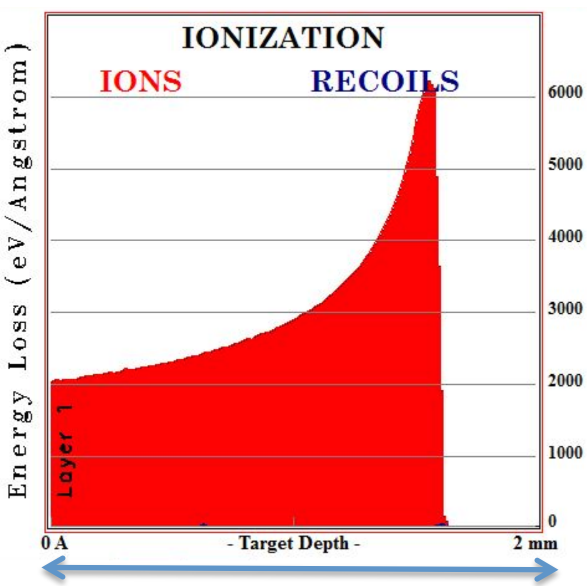
Example (a) FAIR approach: ion beams can have advantages

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

ion beam e.g. 2×10^{11} ions, U^{28+} from SIS-18 in 100ns at 200MeV/u



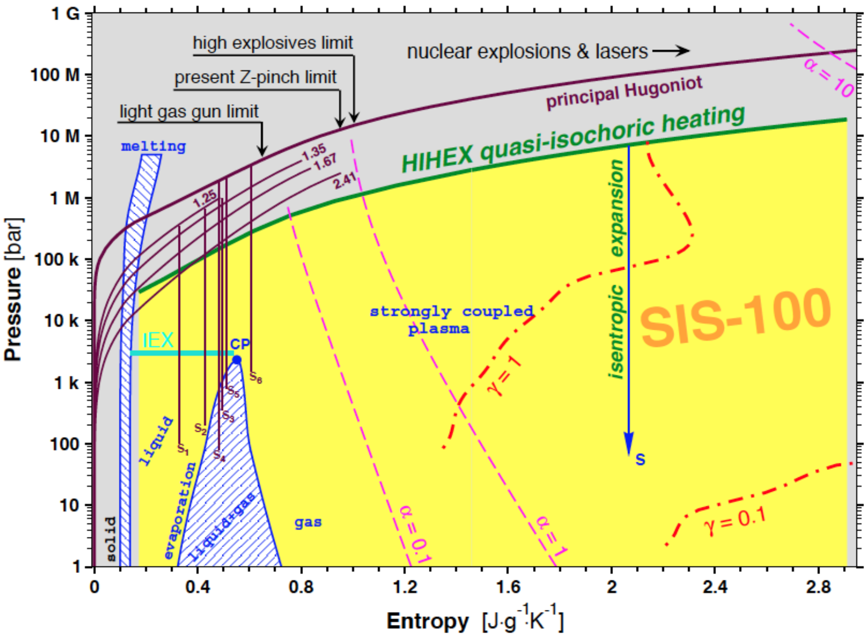
High/
Low Z
cylinder



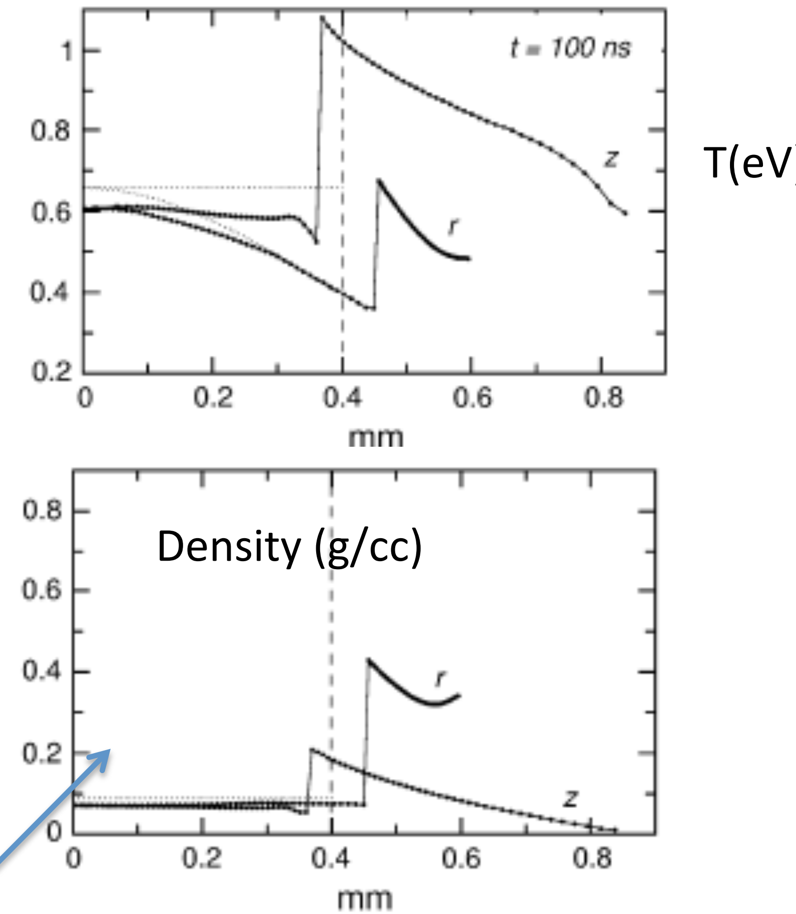
For SIS-100 2×10^{12} ions. Range of 1 GeV/u U ions in Pb is ~15mm.

2mm Pb target 200MeV/u U ions

SIS-100 accesses WDM states of H to Pb

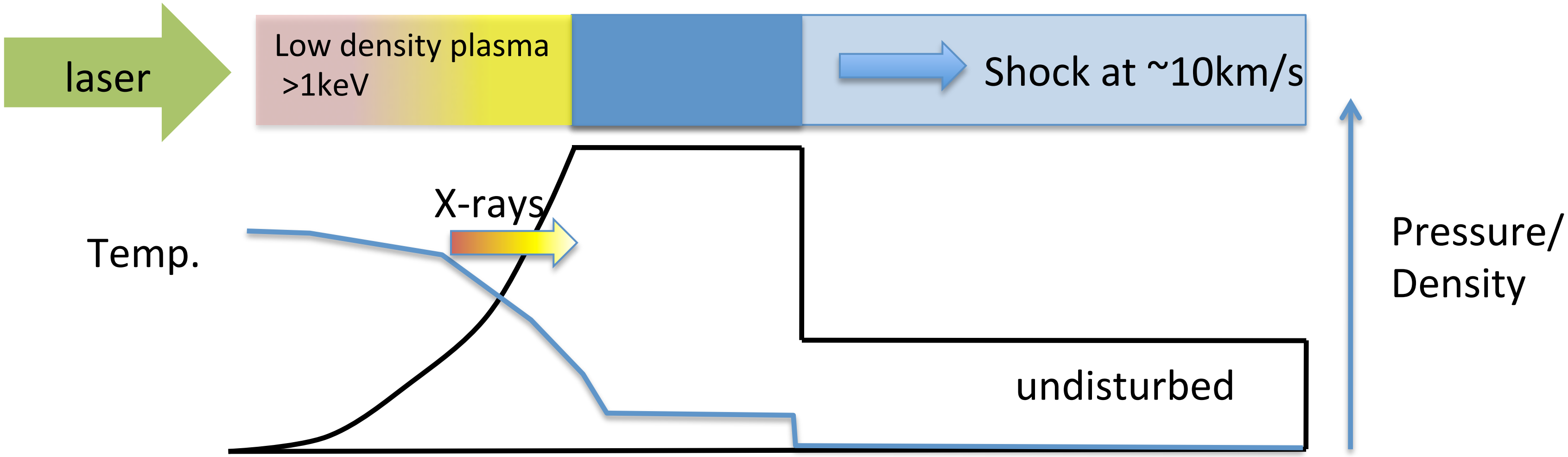


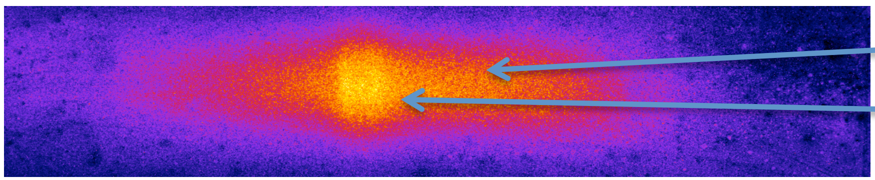
Pb accessible regime from HEDgeHOB report 2005.



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

Example (b) : Driving intense shocks





With 1KJ in 1ns over area of 1mm^2 we can have intensity 10^{14} Wcm^{-2} and a pressure of in excess of 10Mbar.

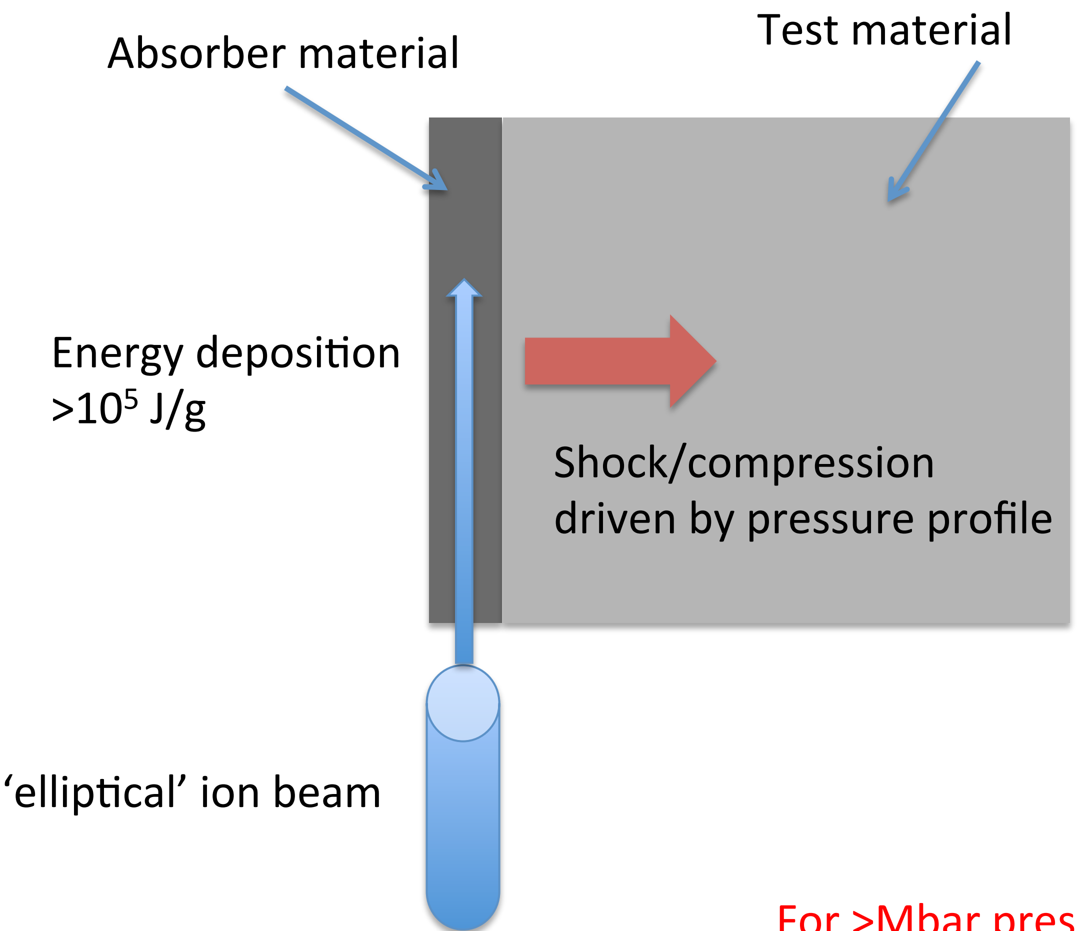
$$\rho_0 v_0 = \rho v_1$$

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

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

Rankine-Hugoniot equations help
To determine the EOS but **ONLY** if we know the initial conditions. Radiation shield can help but problem still needs careful consideration.

Example (b) : HEDgeHOB ideas



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

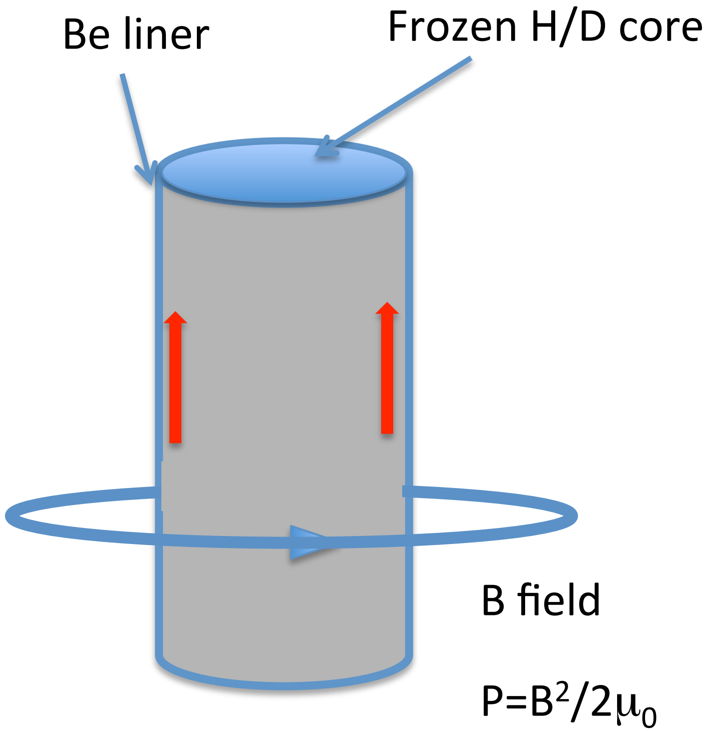
Grinenko *et al* LPB **27** 595 (2009)
for conceptual study of Ramp Wave Loading

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

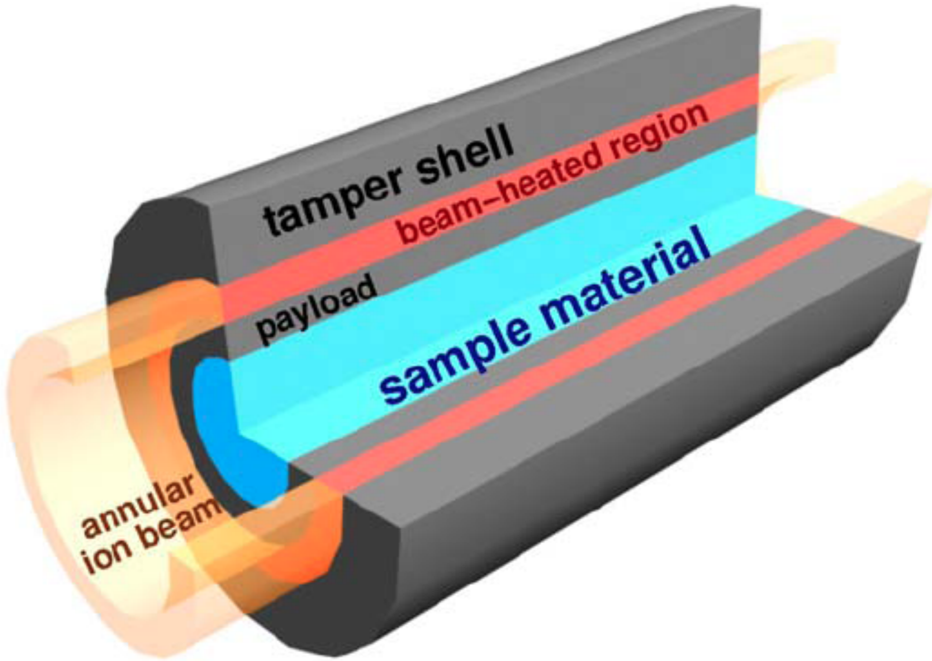
10^5 J/g for Pb is ~10^{12}Jm^{-3} ~ 10Mbar

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

Example (b) : Compare to Z-pinch



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



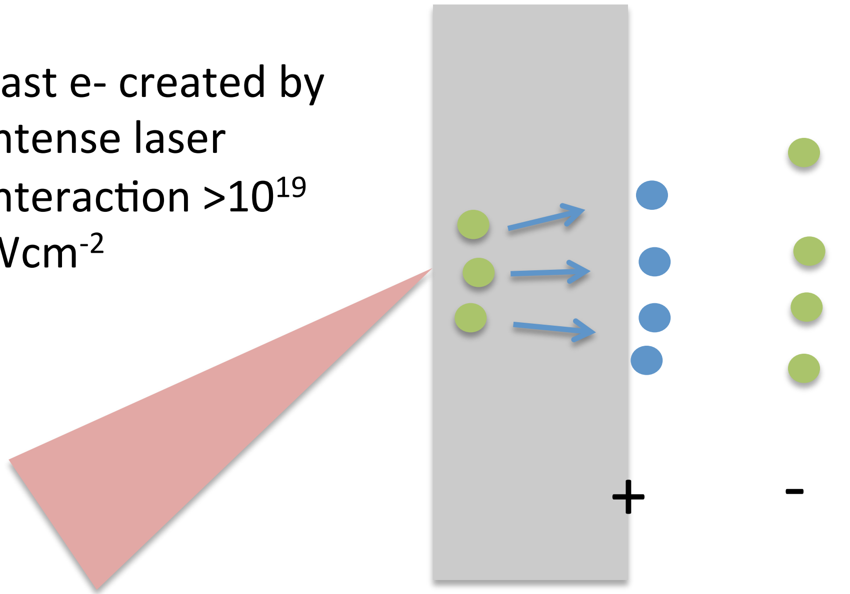
HEDgeHOB LAPLAS collaboration.

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

Example (c) : 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}

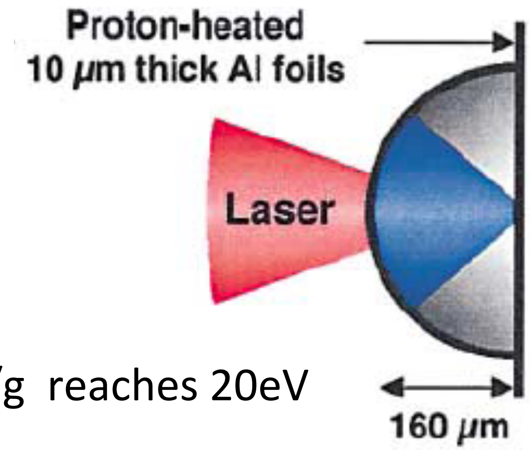


Very hot plasma with hard X-rays generated.

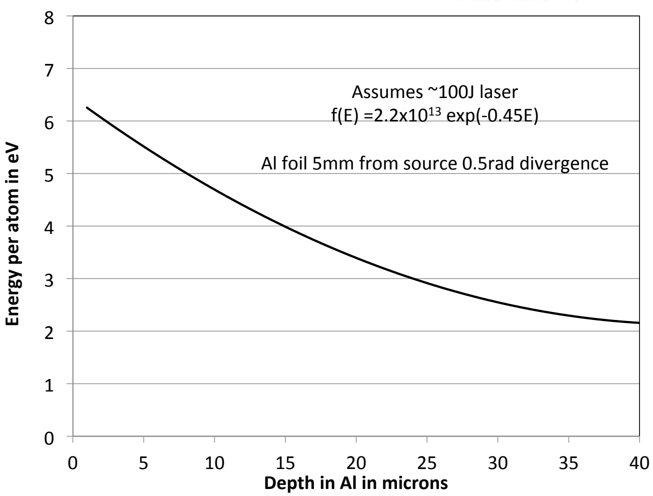
Beam of protons diverges rapidly.

PHELIX can do this and use it as a probe.

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



Summary

FAIR can compete well in several key areas:

Both shock compression and low entropy compression possible without hot source of keV photons interfering.

Volumetric heating possible for wide range of sample materials

Ion heating can be far more controlled and flexible than laser drive proton source experiments. Short pulse of laser drive protons can be used with PHELIX