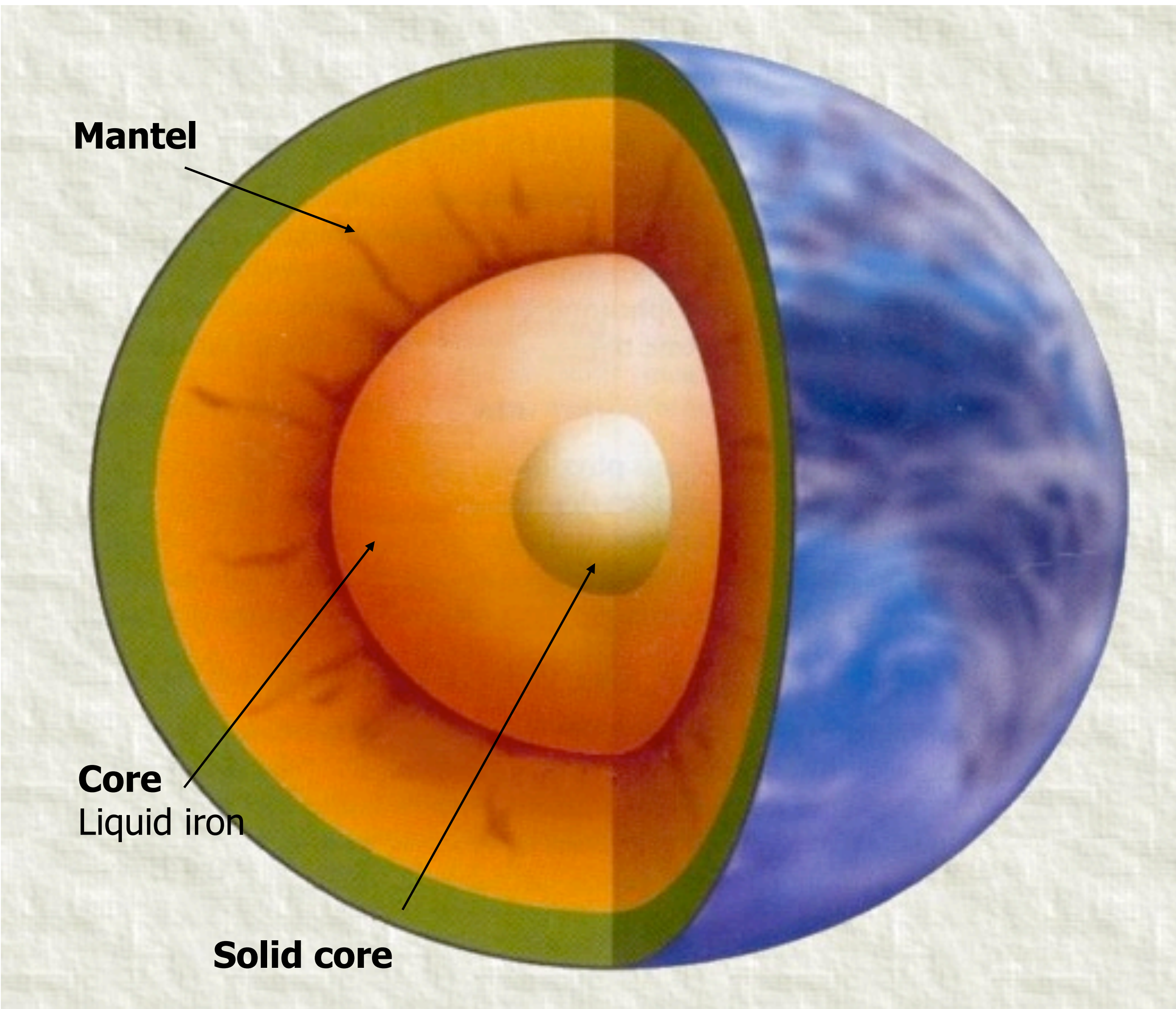
Experimental and Numerical Study of Isentropic Compression by Laser Irradiation

Erik Brambrink
PNP13

Outline

- The relevance of iron for geophysics
- Isentropic compression with lasers
- Experimental implementation and results
- X-ray based diagnostic development
- Study of phase transition effects with molecular dynamics

Relation to geophysics



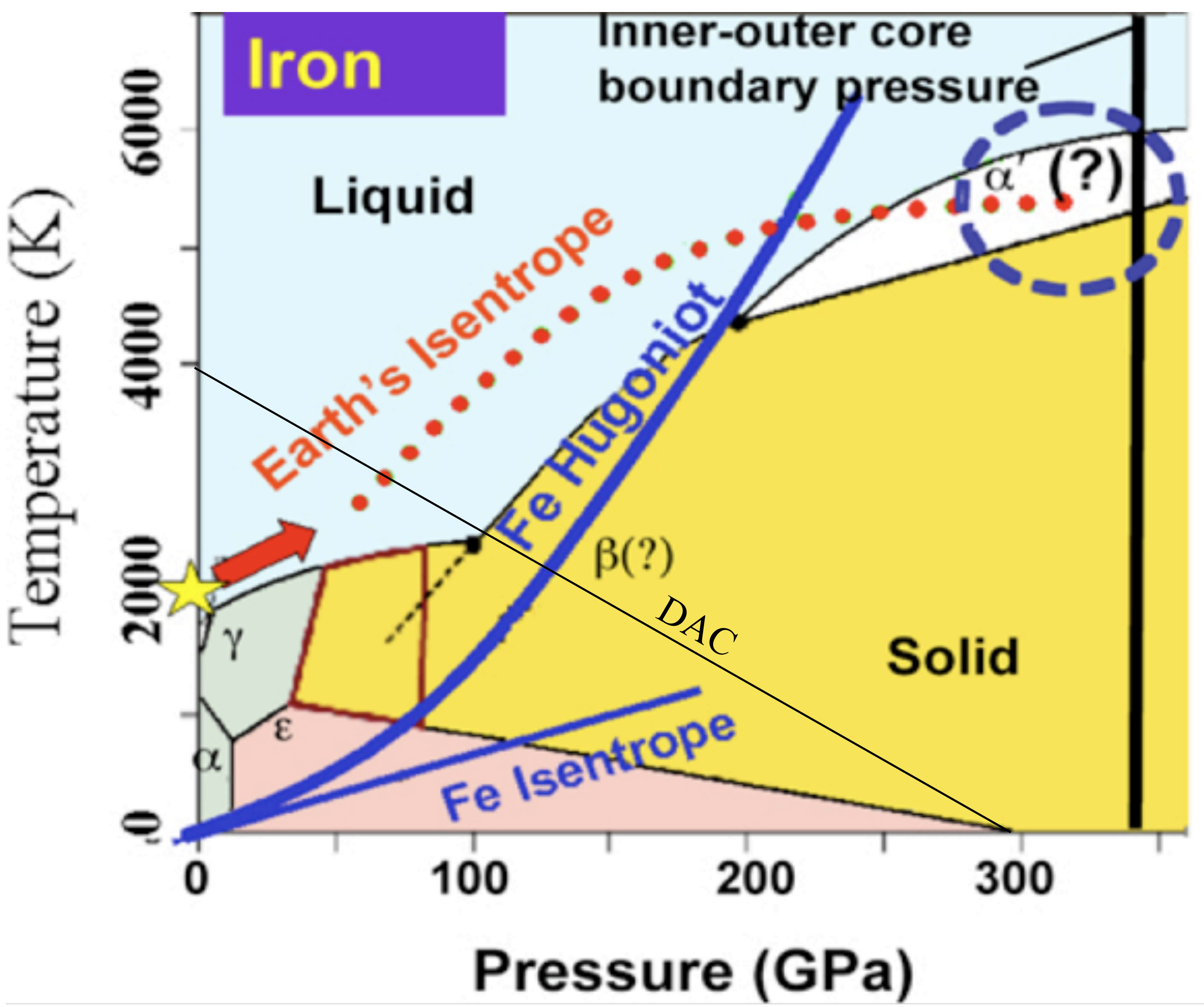
Solid-liquid transition of iron plays important role for energy balance of the earth core

Core emits 1-4 TW, how much contributes latent solidification energy?

Temperature profile of the earth core influences core dynamic

Explore iron melting curve P(T)

How to reach earth core conditions?



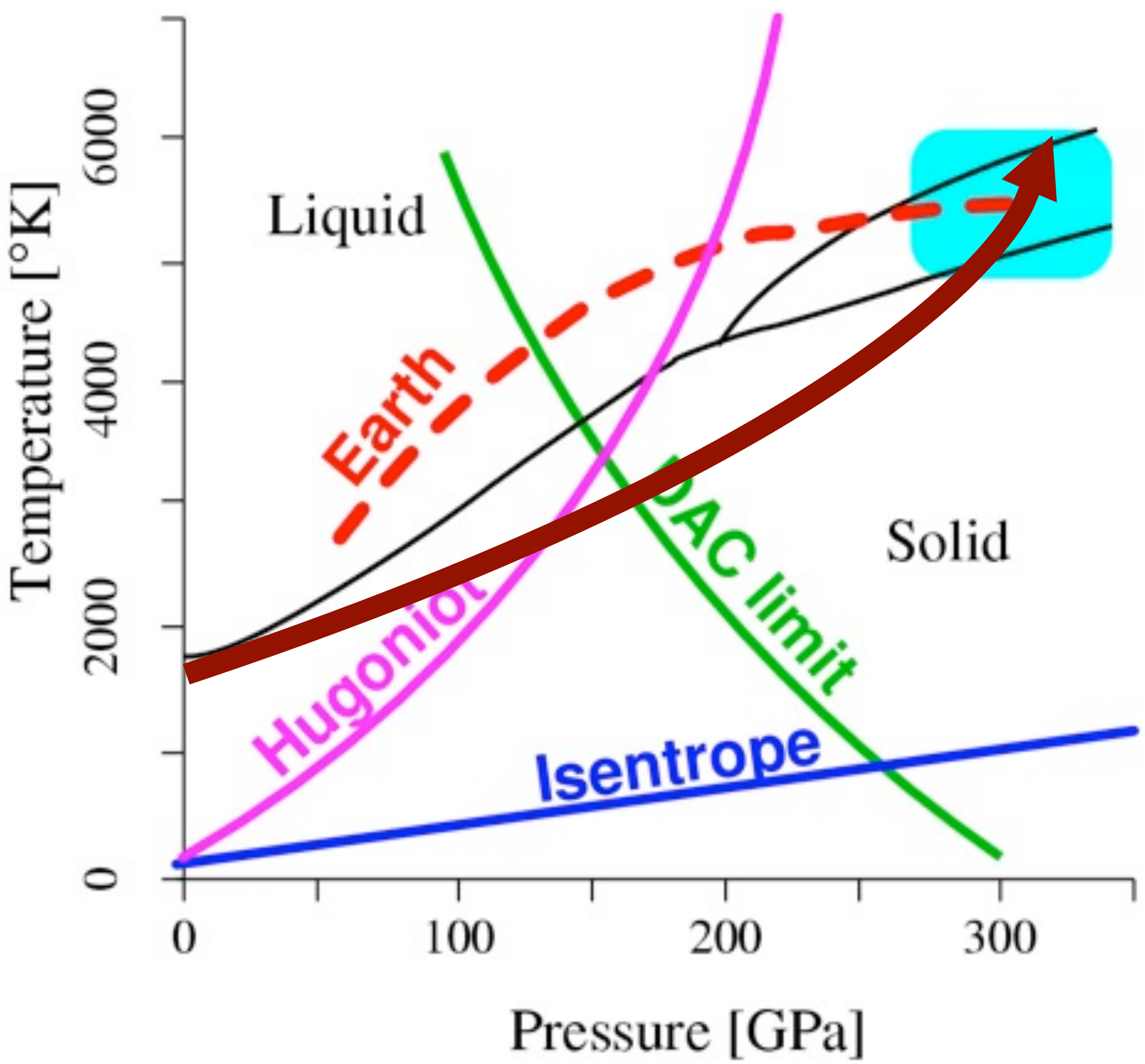
Static compression cannot reach necessary pressure and temperature

Shocks have not sufficient compression

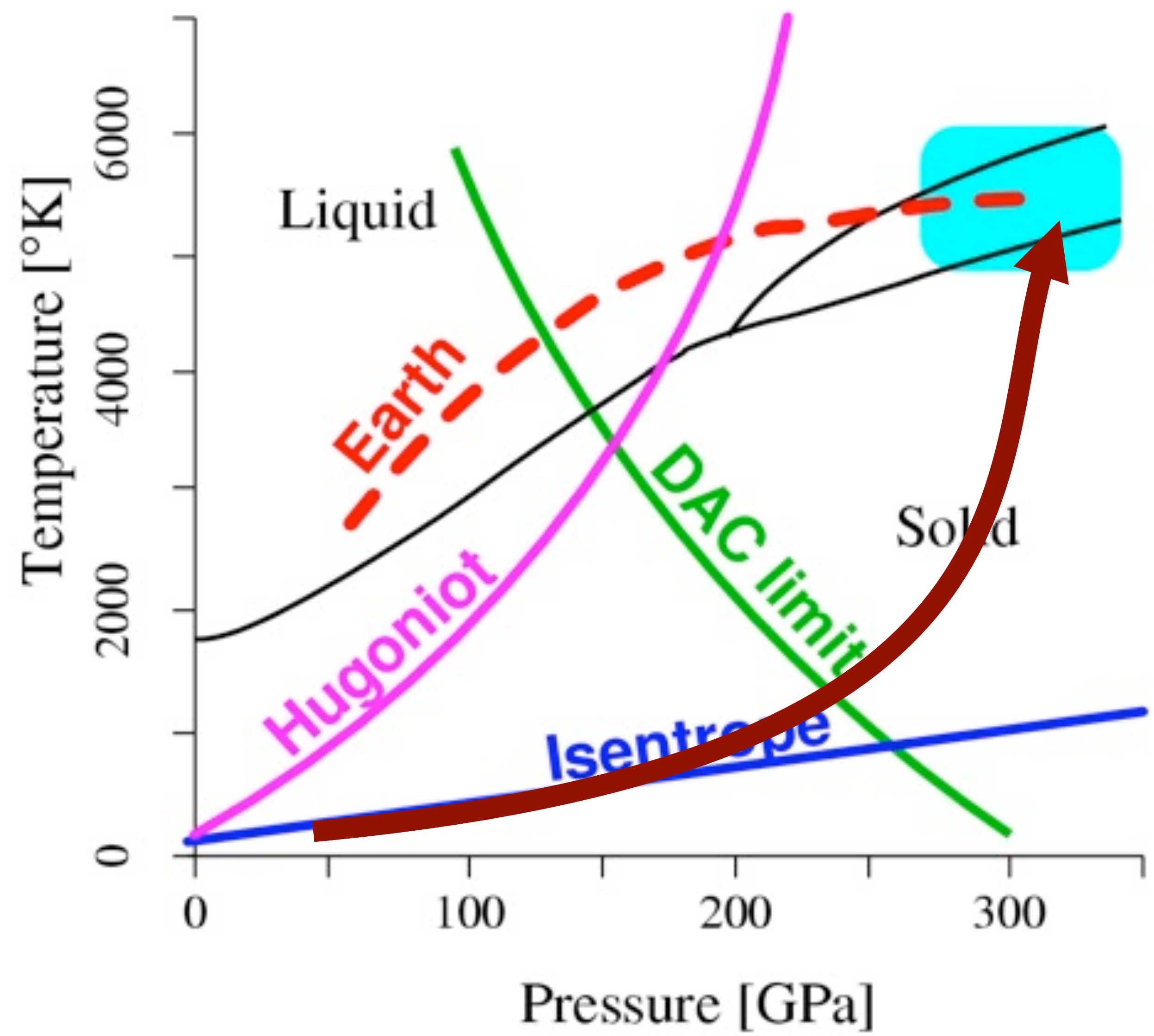
Isentropic compression reaches density, but not temperature

→ Alternative compression scheme necessary

How to reach earth core conditions?



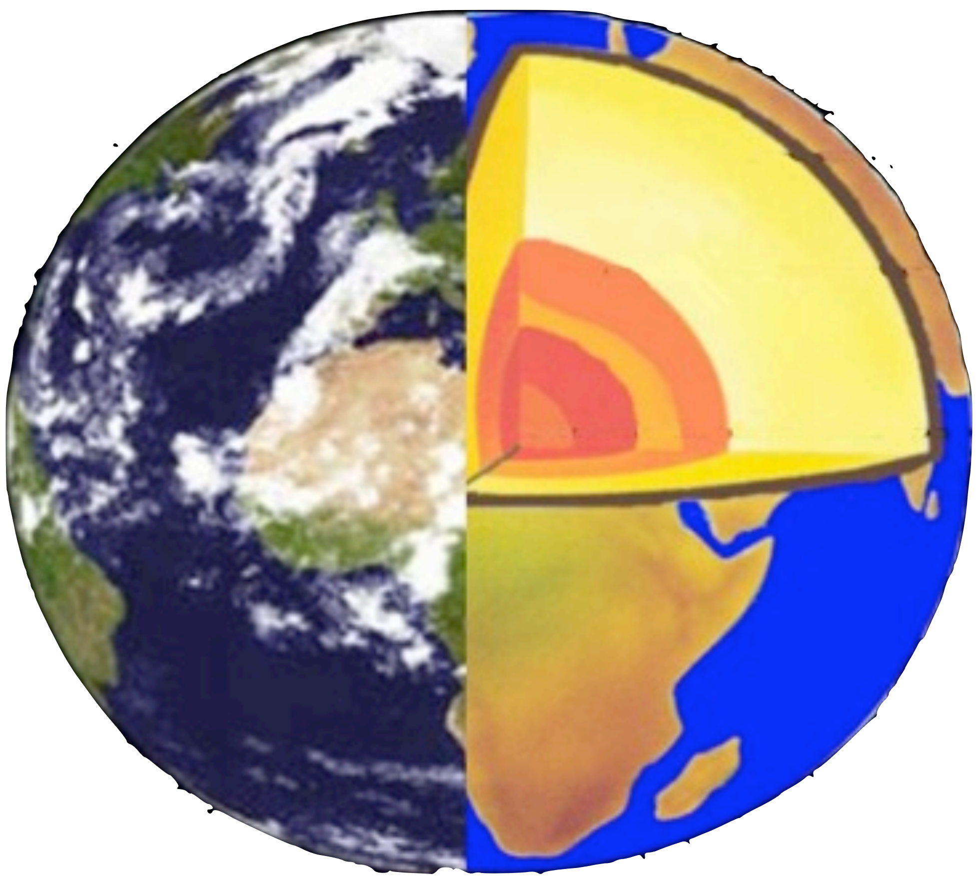
Isentropic compression from preheated state



Isentropic compression with subsequent shot

ANR SECHEL

A three year program has been funded by the French reasearch council



- Development of off-Hugoniont compression techniques
- Study of x-ray based diagnostics (density, melting)
- Multiscale modeling capabilities (MD, hydro)

4 laboratories are involved: LULI, CEA, LCD, IMPCM

WORKPLAN

	2008	2009	2010	2011

ICE

Reservoir

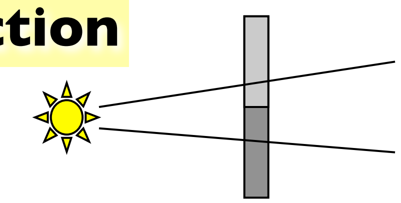
Pulse shaping & Heating cell

integrated

LIL

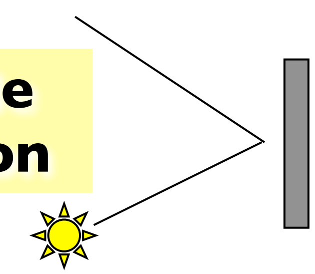
X-ray > 40 keV

Radiography & Transverse diffraction



X-ray ≈ 8 keV

Rear side diffraction



Hydro & MD & QMD & Data analysis

Targets design
1D simulations
+ MD EOS

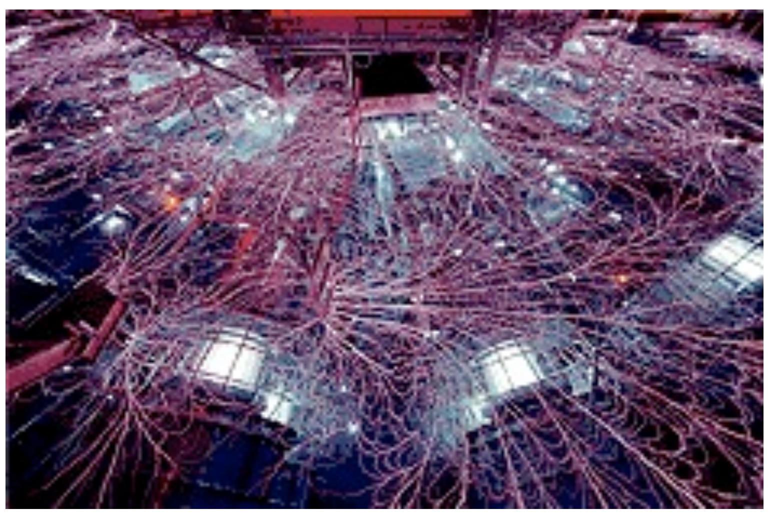
ICE data analysis
waveform

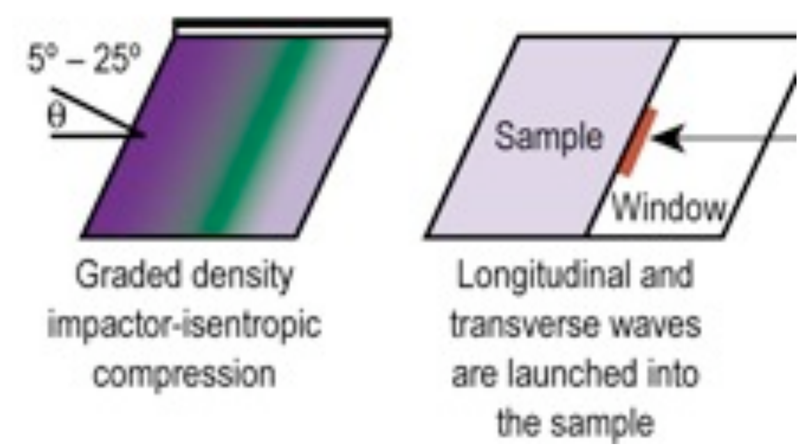
design
1D simulations
+ MD EOS
+ QMD
+diffraction analysis

Isentropic compression

Isentropic compression

Smoothly raising pressure without creating a shock





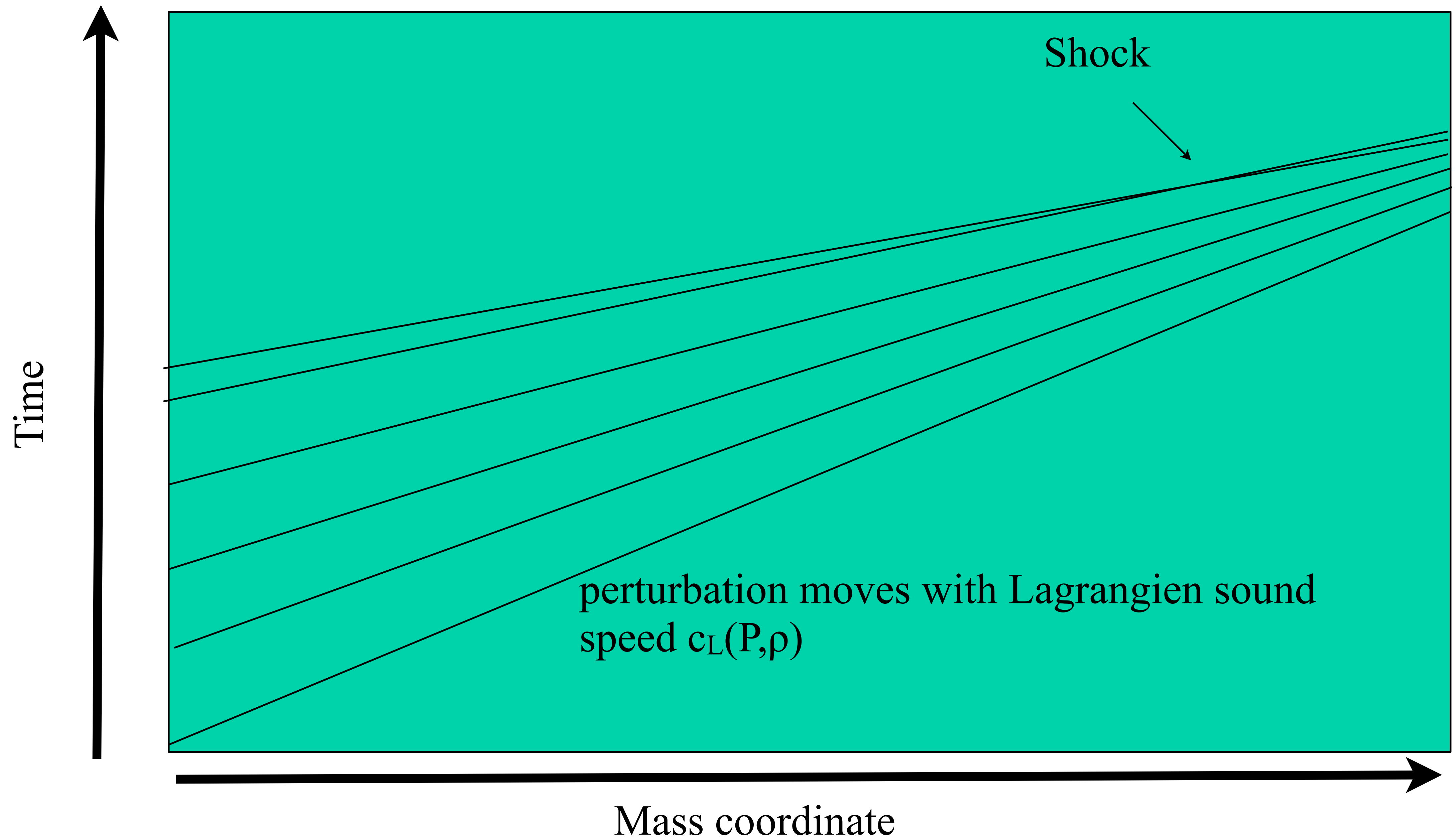
EOS calculated from sound and particle speed measurement

$$P(u_p) = \int_0^{u_p} \rho_0 C_L(u_p) du_p \qquad V(u_p) = V_0 - V_0 \int_0^{u_p} \frac{du_p}{C_L}$$

$\rightarrow$ $P(\rho)$ on the isentrope

Characteristics

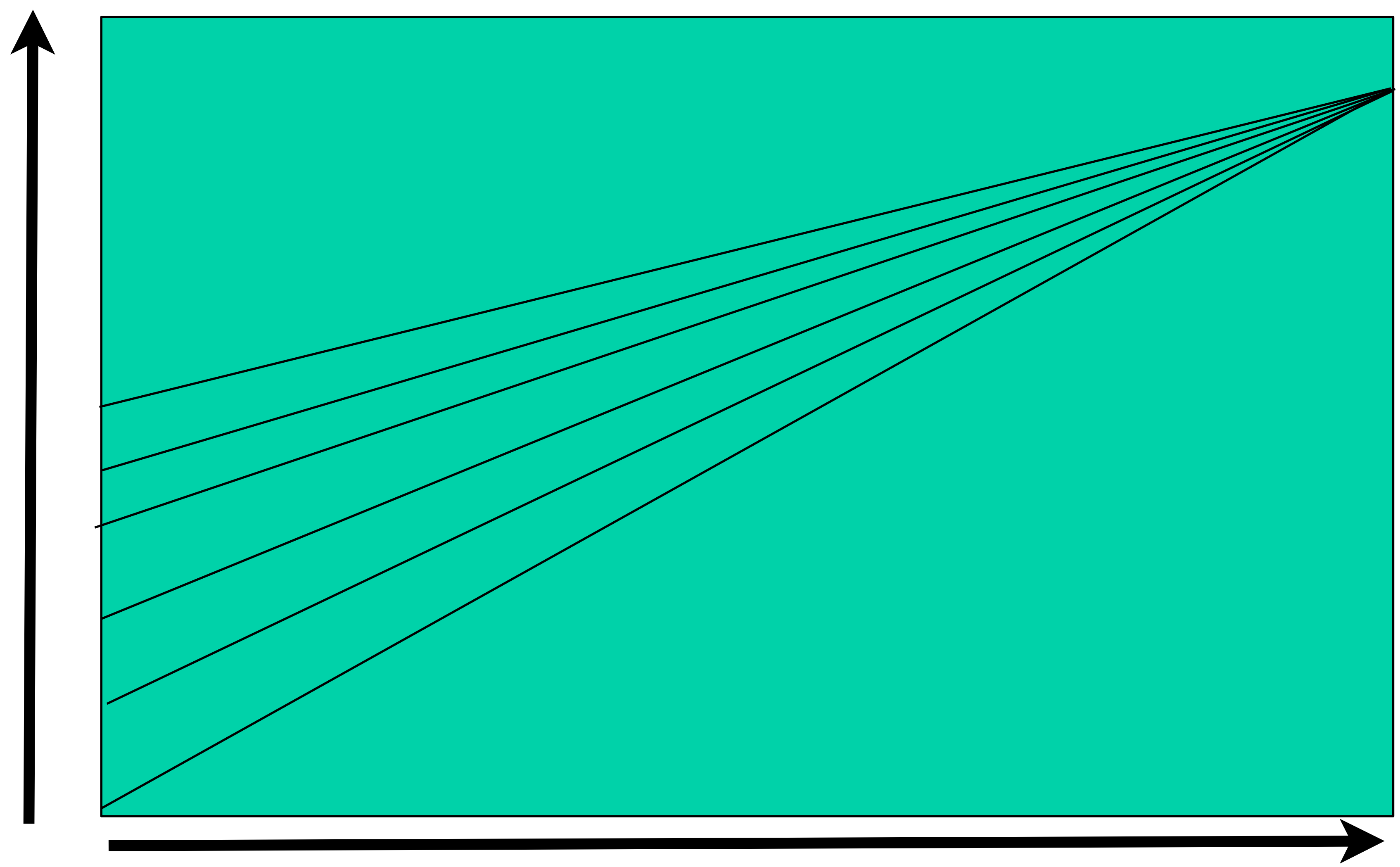
Propagation of perturbation (e.g. pressure) in Lagrangien coordinates



Compression is shock free, if characteristics never cross

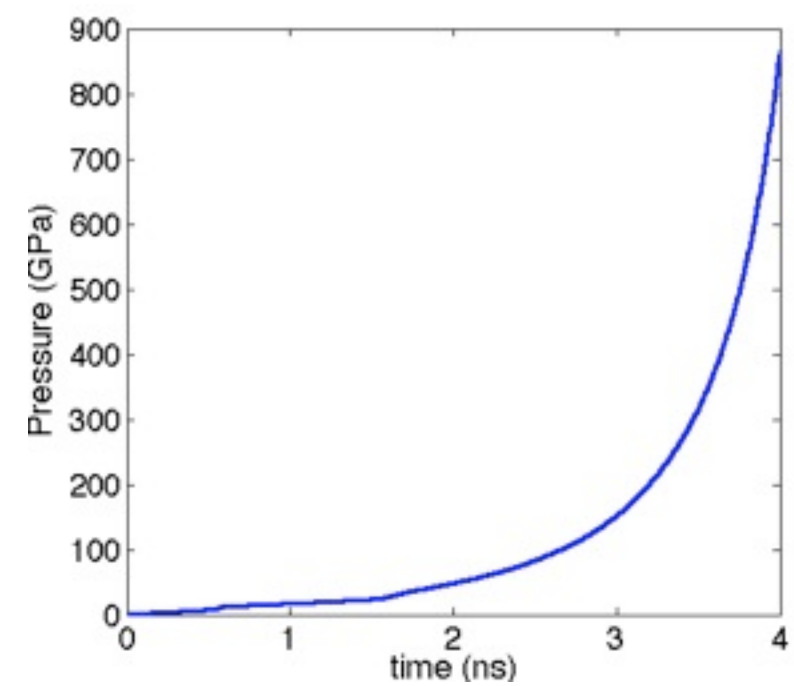
The ideal ramp

Highest pressure without shock is reached, when transit time through the target is equal for all sound waves



$$\frac{dP}{dt} = \frac{C_L^2}{d}\left(\frac{dC_L}{dP}\right)^{-1}$$

Swift et al., PRE 2008



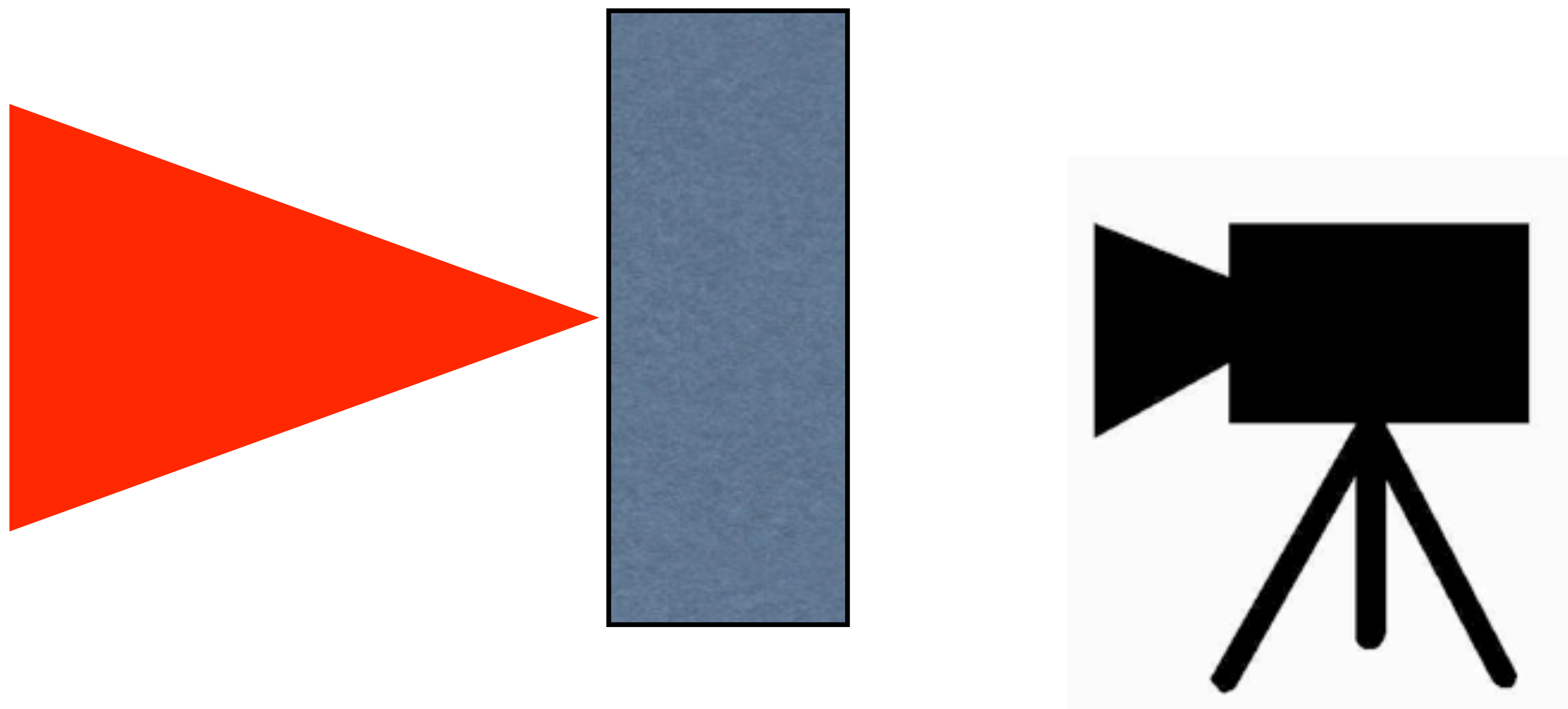
Fe, 20 µm, 4 ns,

Ideal ramp can lead to infinite pressure, if laser pulse duration $t_L > d/C_L$

Limitations due to laser and diagnostic have to be taken into account

A more realistic ramp

Ramp is limited by laser performance and detector resolution

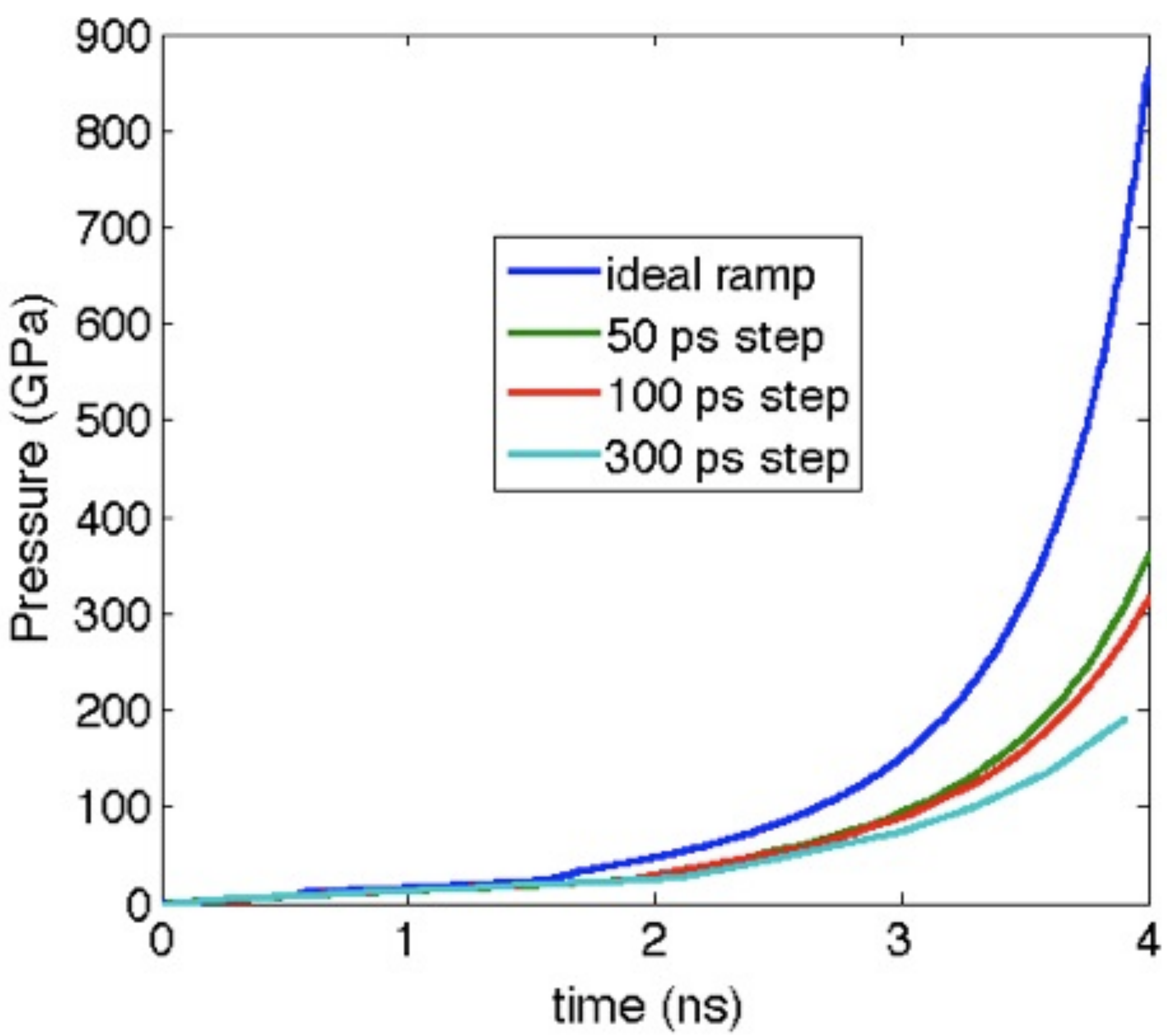


Laser profiler has limited temporal resolution

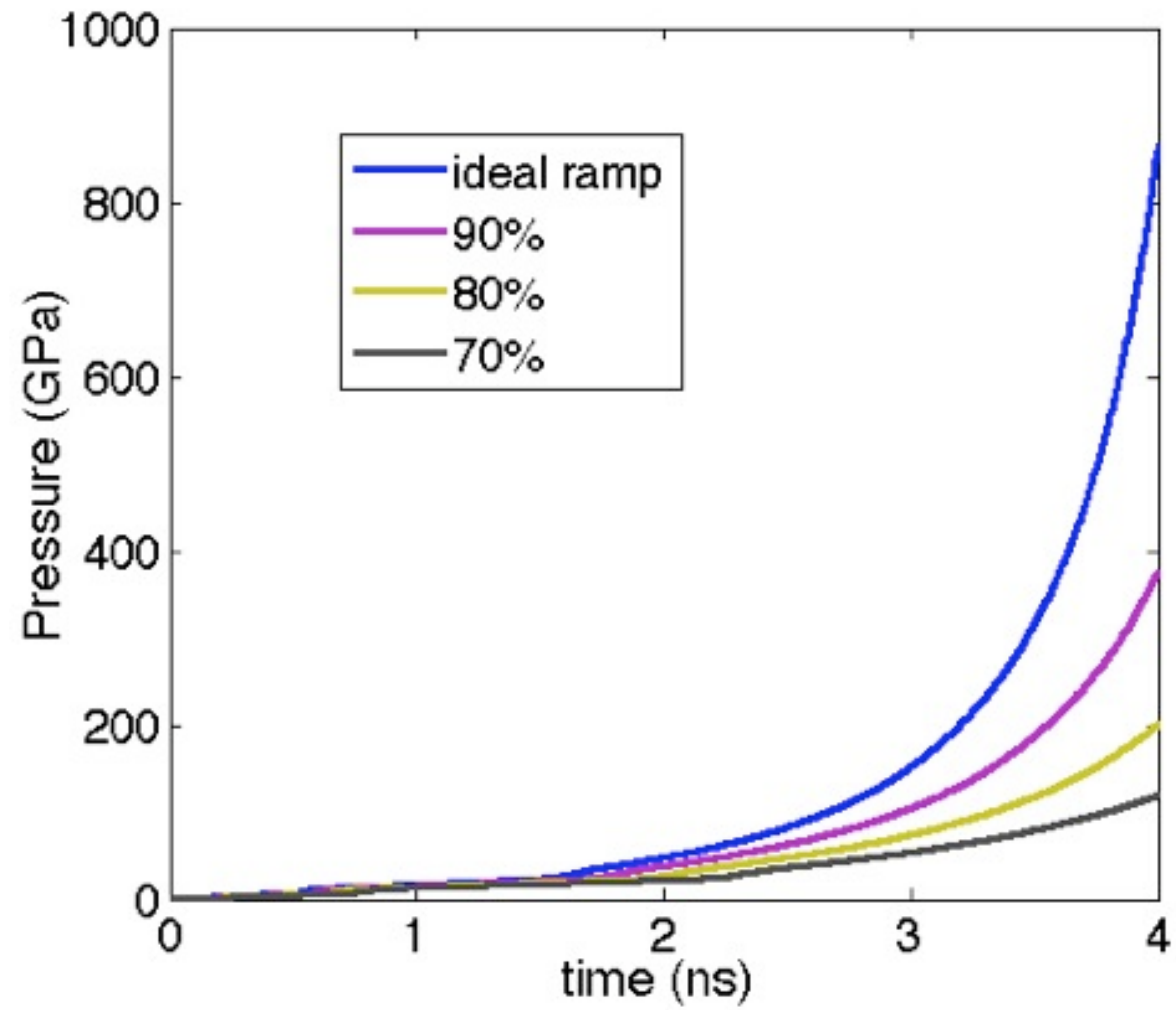
Laser fluctuations require margin

Measured speed must not change too much within temporal resolution

Limitations of the Laser



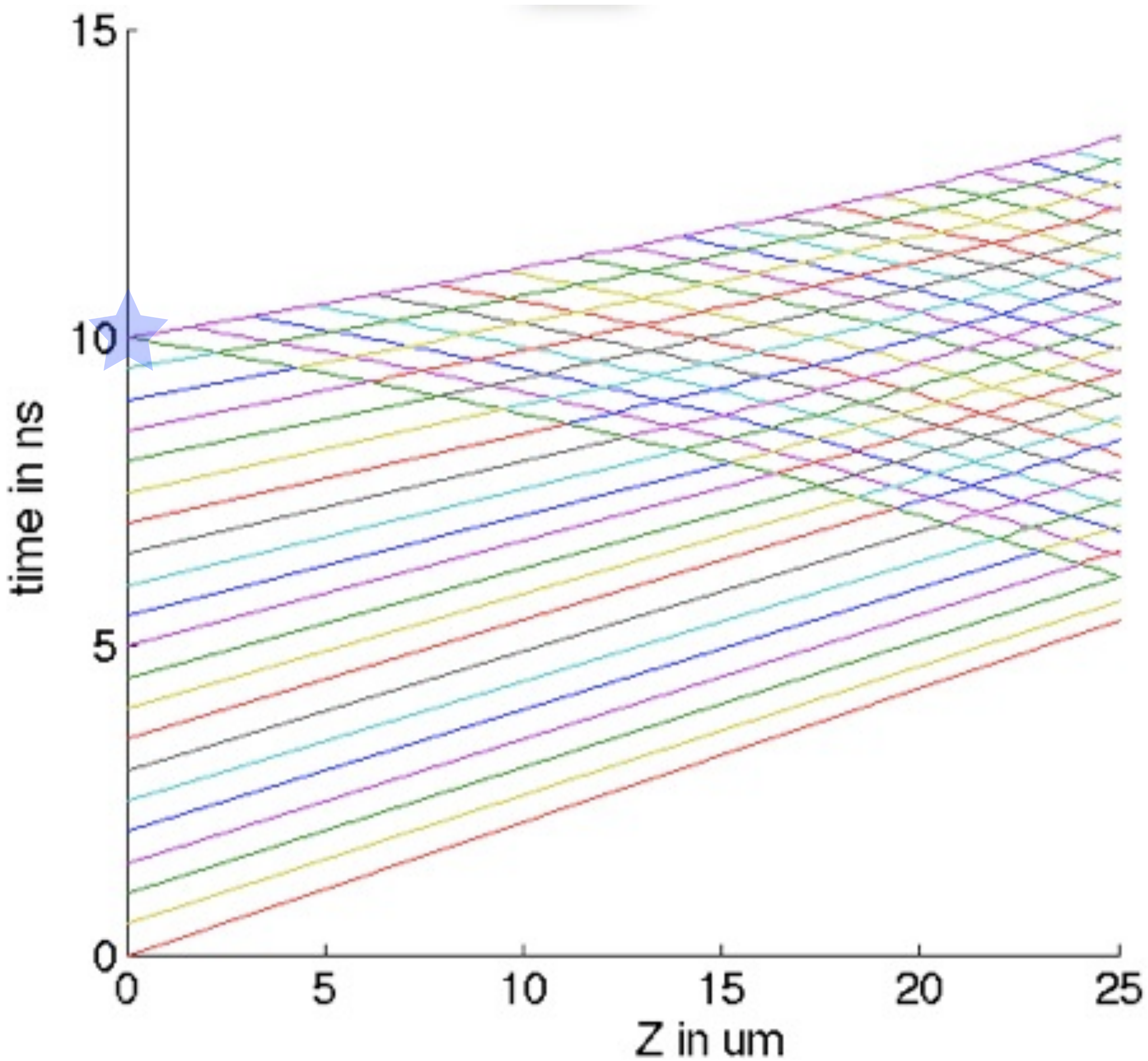
time step of profiler



contingency for laser fluctuations

→ Stability of the laser is very important

Effect of reflection



Reflection of the wave on the rear surface changes propagation

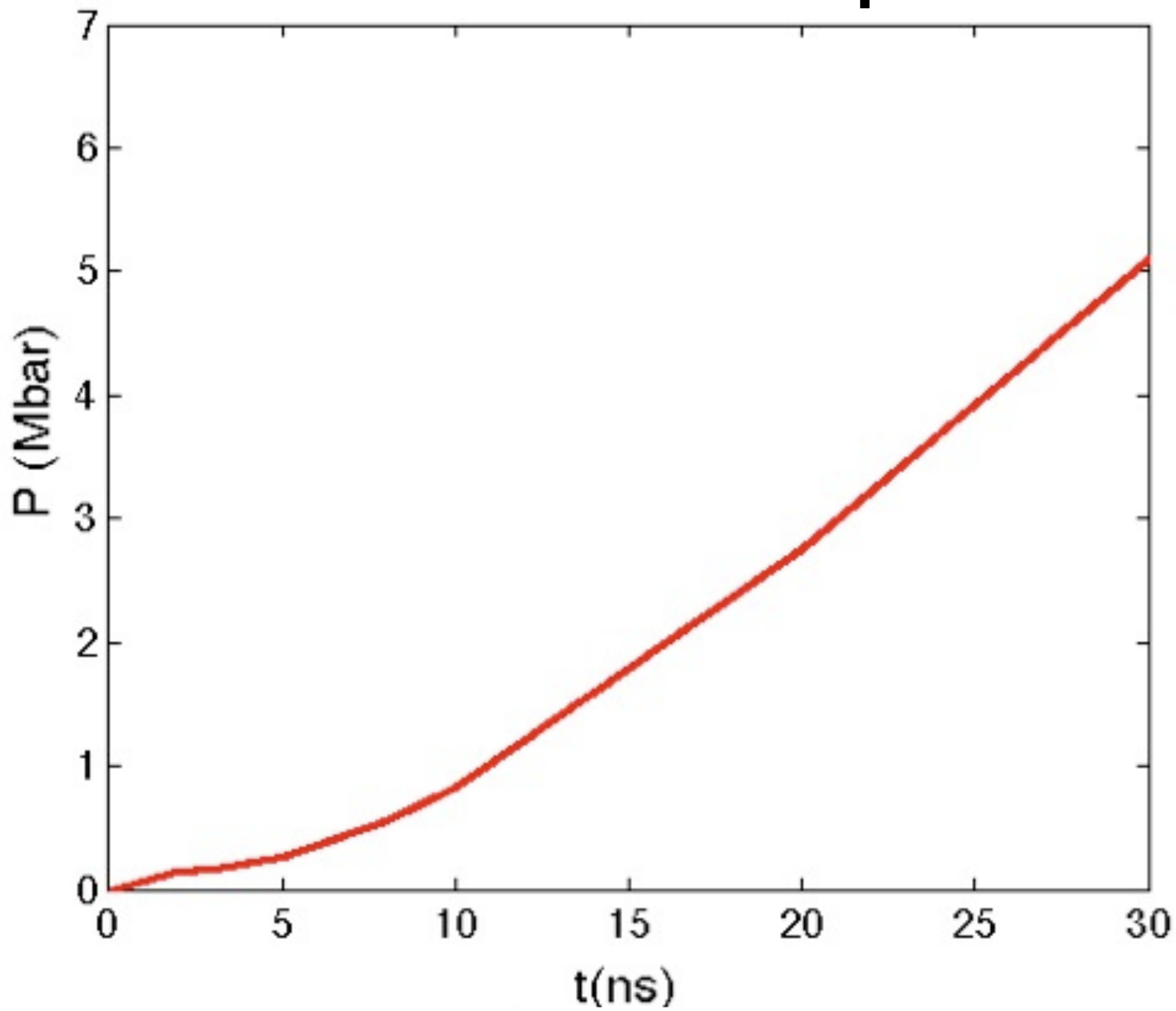
No analysis possible, after frist reflection reaches front surface

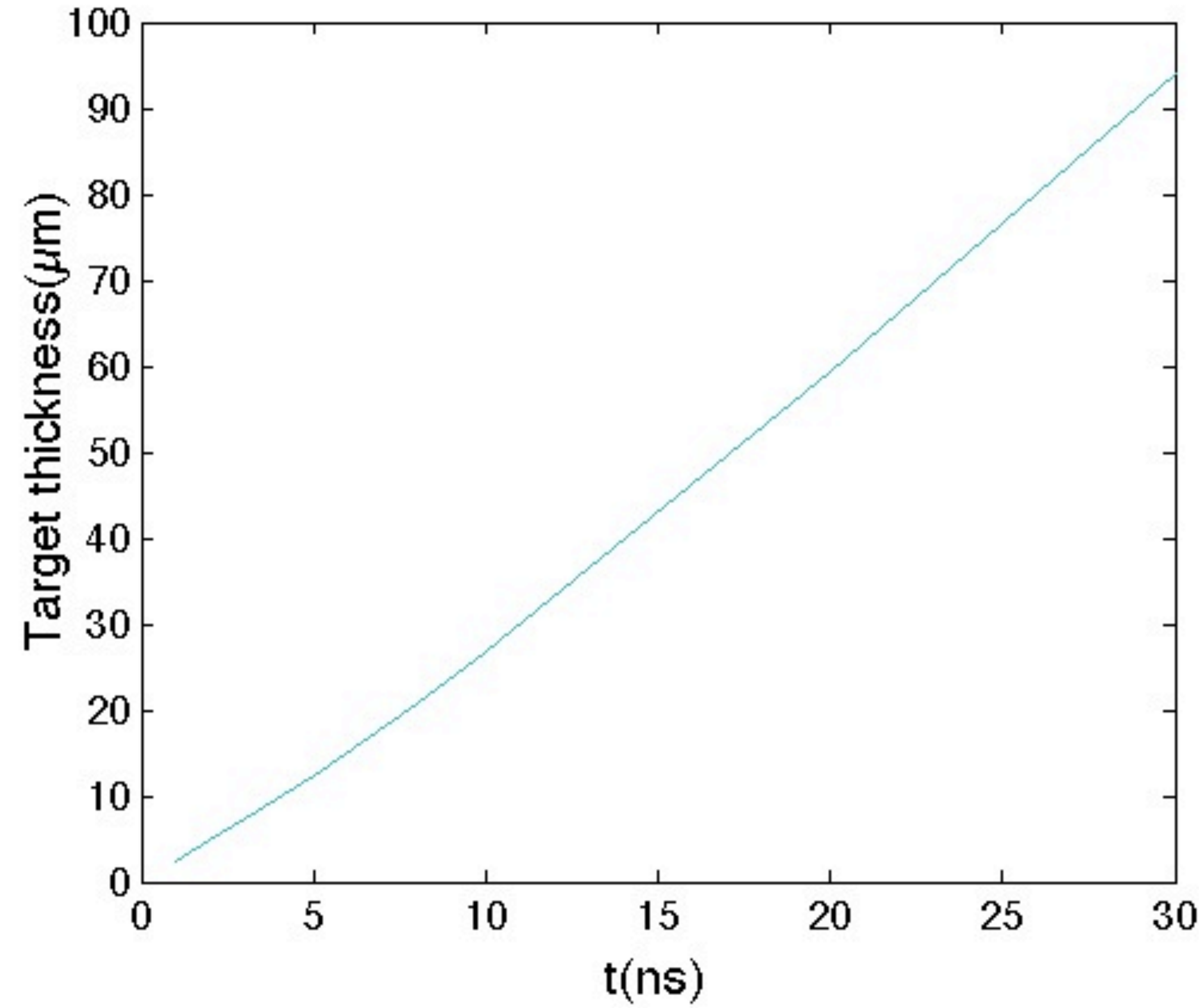
Ideally, compression time matches reflection time

→ For a given compression time, there is an optimal target thickness, which leads to highest pressures

Maximum pressure

Taking into account all limitations, optimal thickness and maximum pressure for a given pulse length



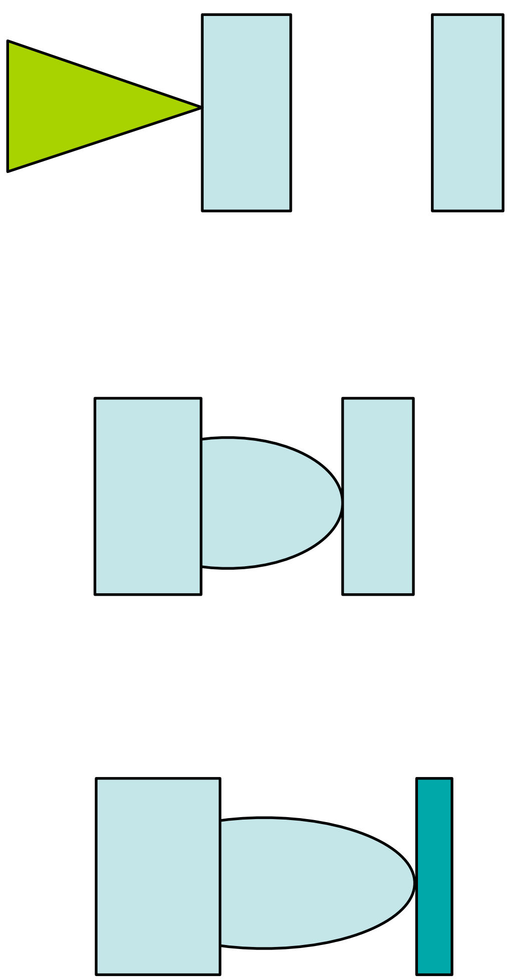


100 ps steps for laser power, 20 ps diagnostic temporal resolution, 1% precision of velocity, 20% contingency

Laser driven isentropic compression

Laser driven ICE

Reservoir compression



First foil is exploded by laser impact

Foil is expanding towards the sample

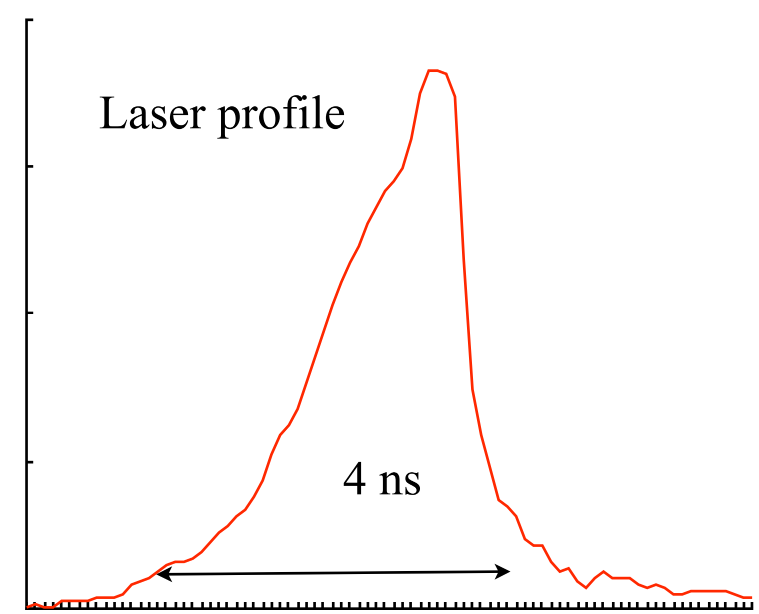
Main target is compressed due to the piling up

Smith, Phys. Plasmas **14**, 057105 (2007)

Slower ramp, no laser profiling necesary

Laser pulse shaping

Continously increasing laser intensity produces increasing ablation pressure leading to ramp compression

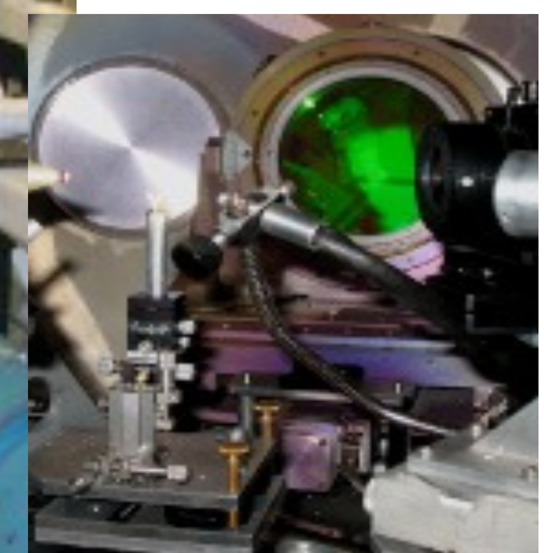


Better efficiency, profile can be chosen

LULI laser installation



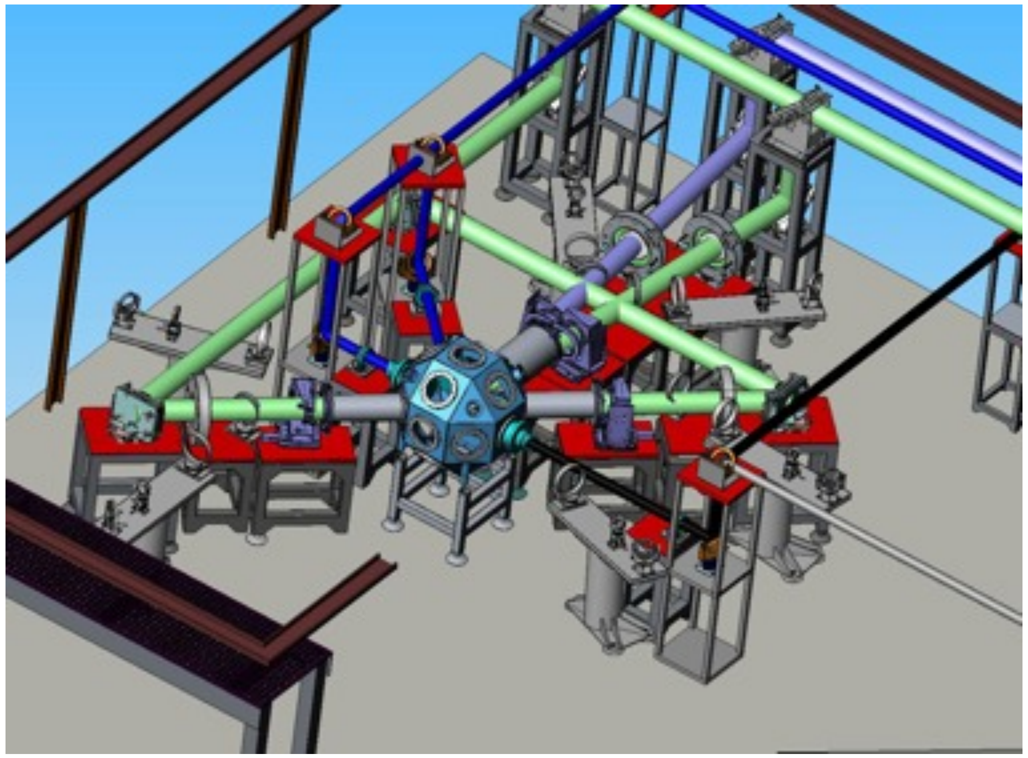




kJ ns beam combined with ps high energy beam

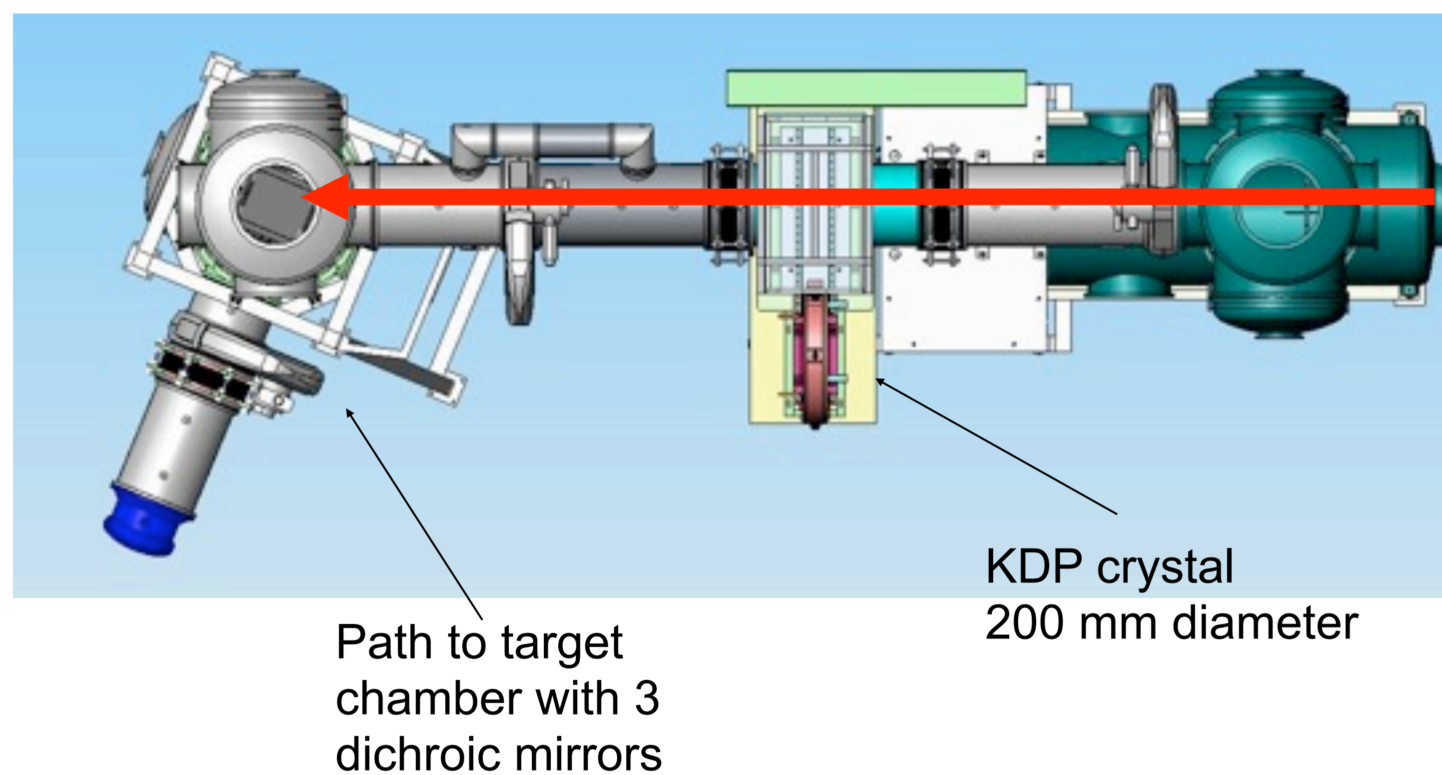
1 shot/2 hours, 30 weeks of operation per year
User facility, call for proposals 14th july each year

Recent upgrades

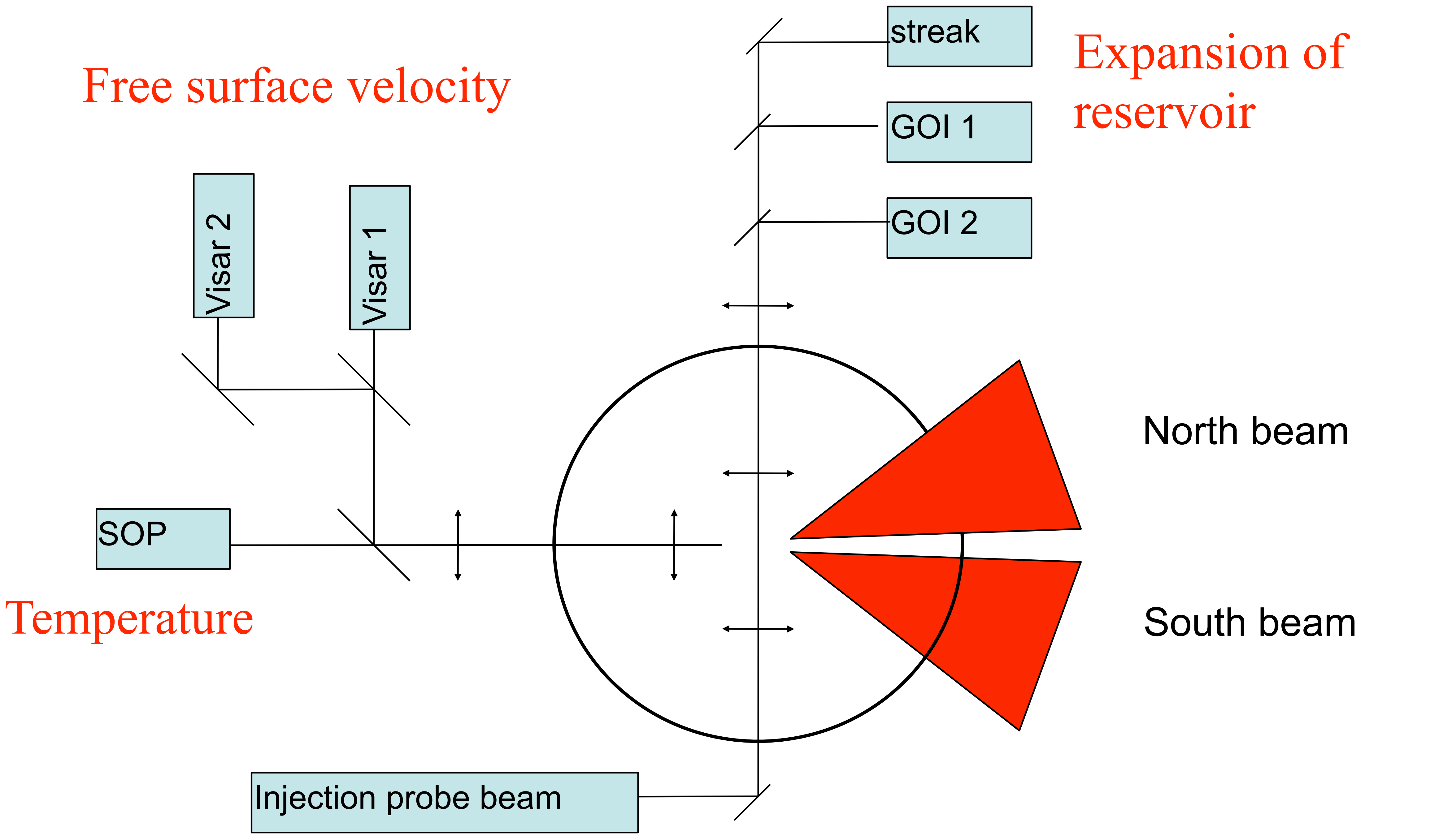


New target area
Dedicated to long pulse operation: 2 x 1kJ

Frequency doubling for short pulse beam

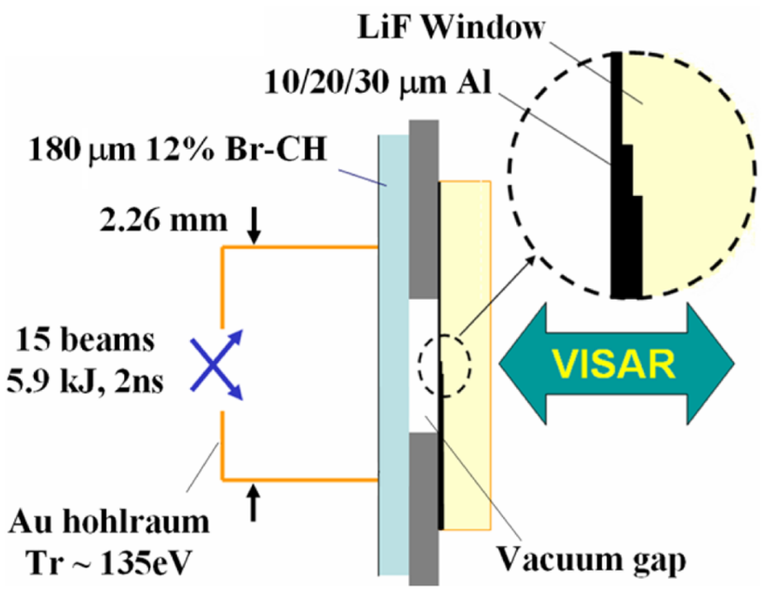


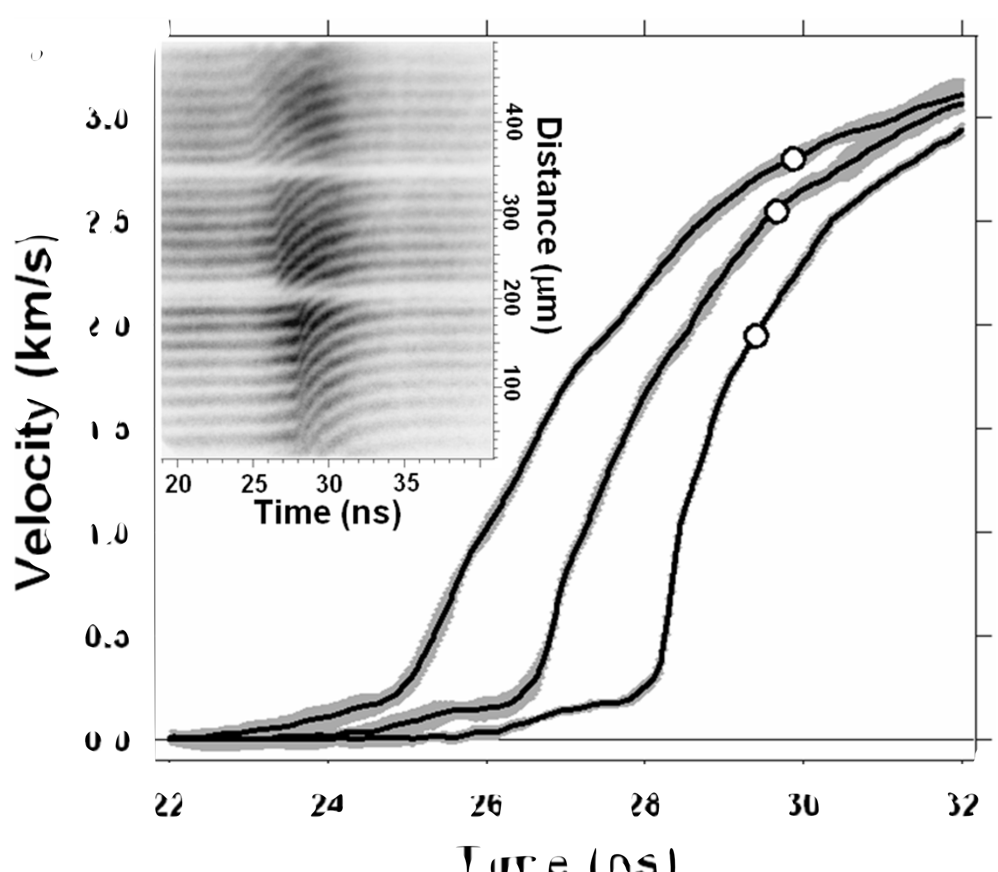
Experimental setup

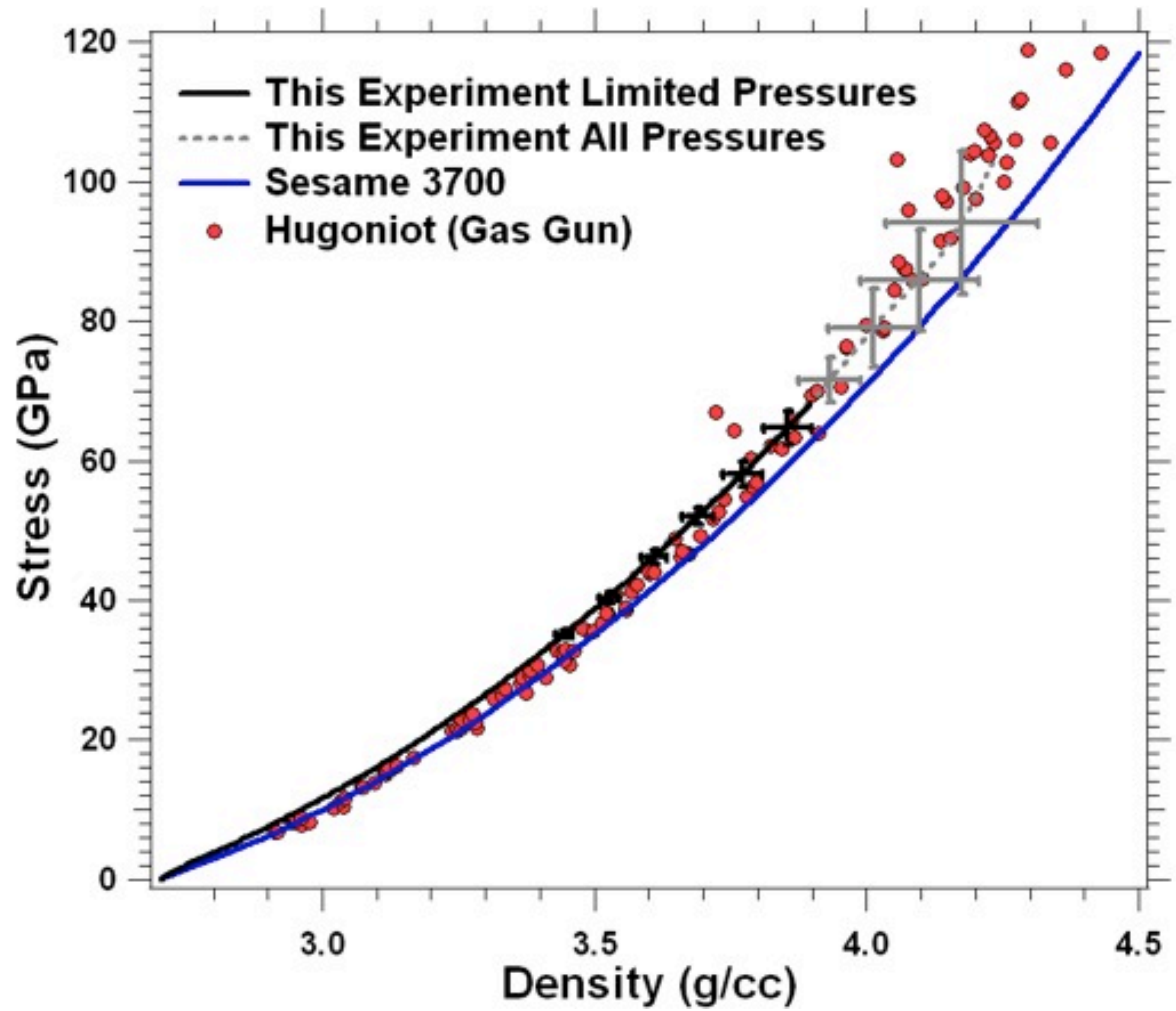


Sound speed is measured by comparing different target thicknesses

Reservoir compression of Al





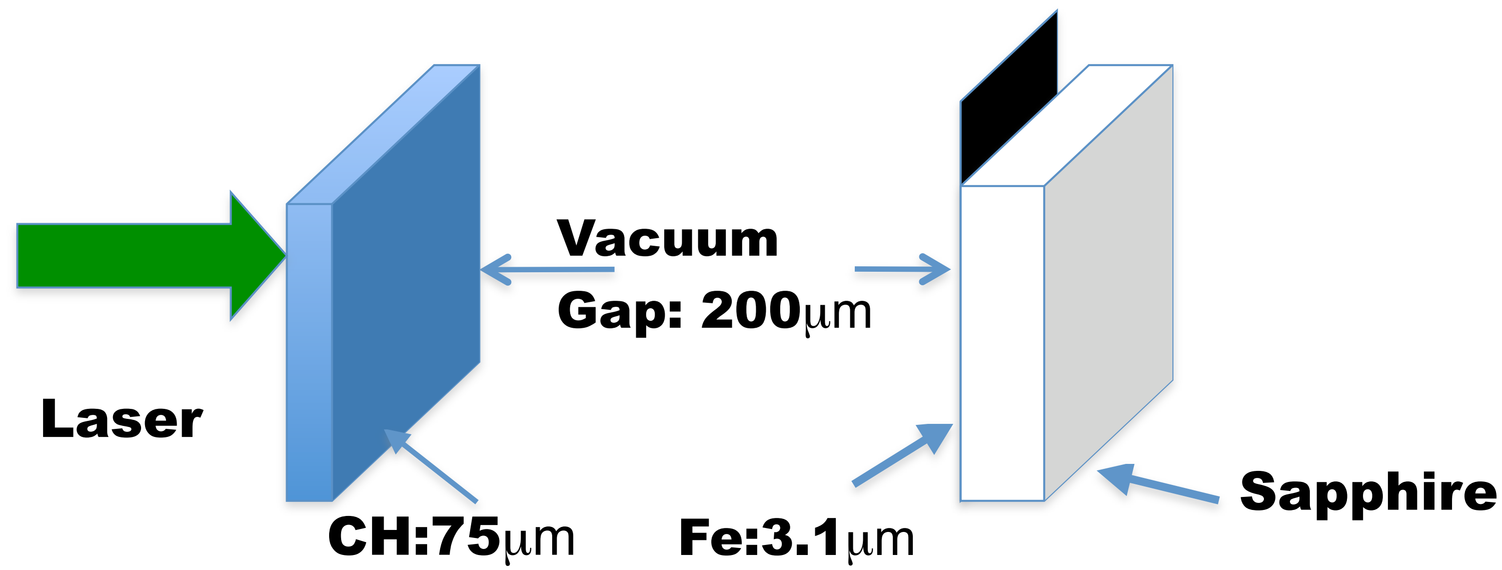


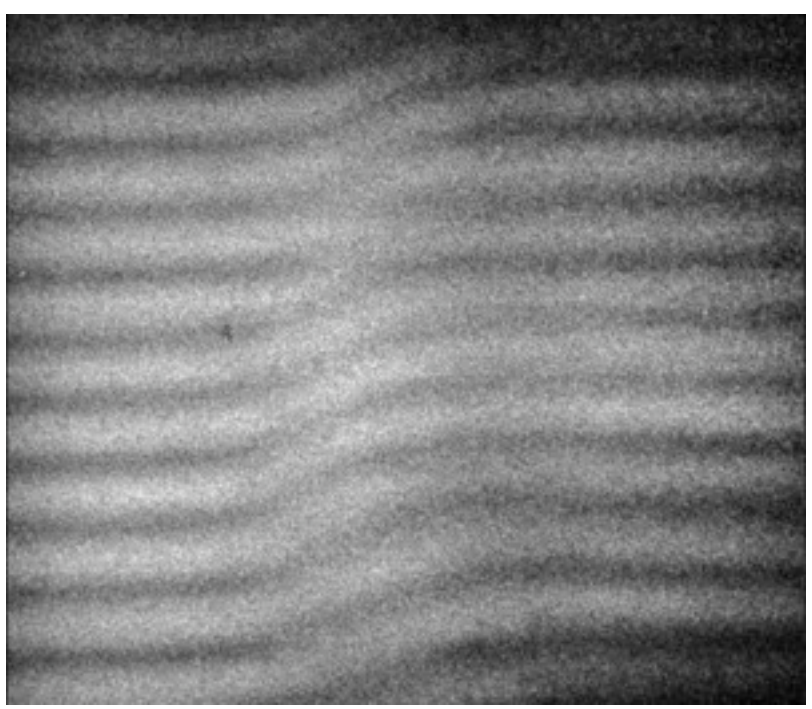
Enhanced stiffness due to high strain rates observed

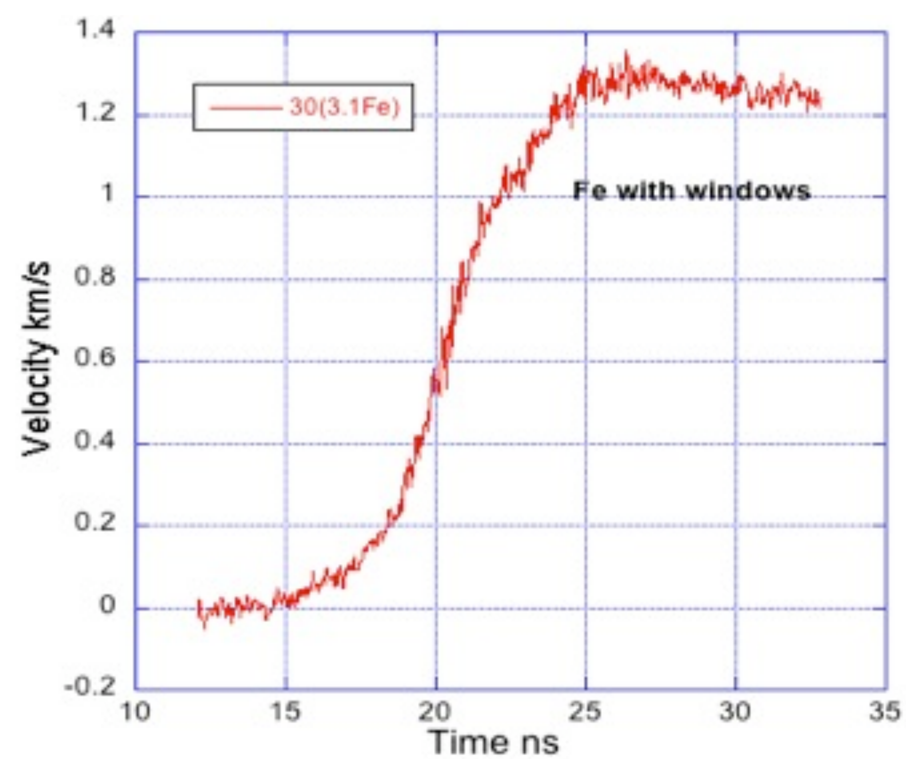
Smith et al., PRL (2007)

Reservoir compression

LULI experiment
Dec 2008



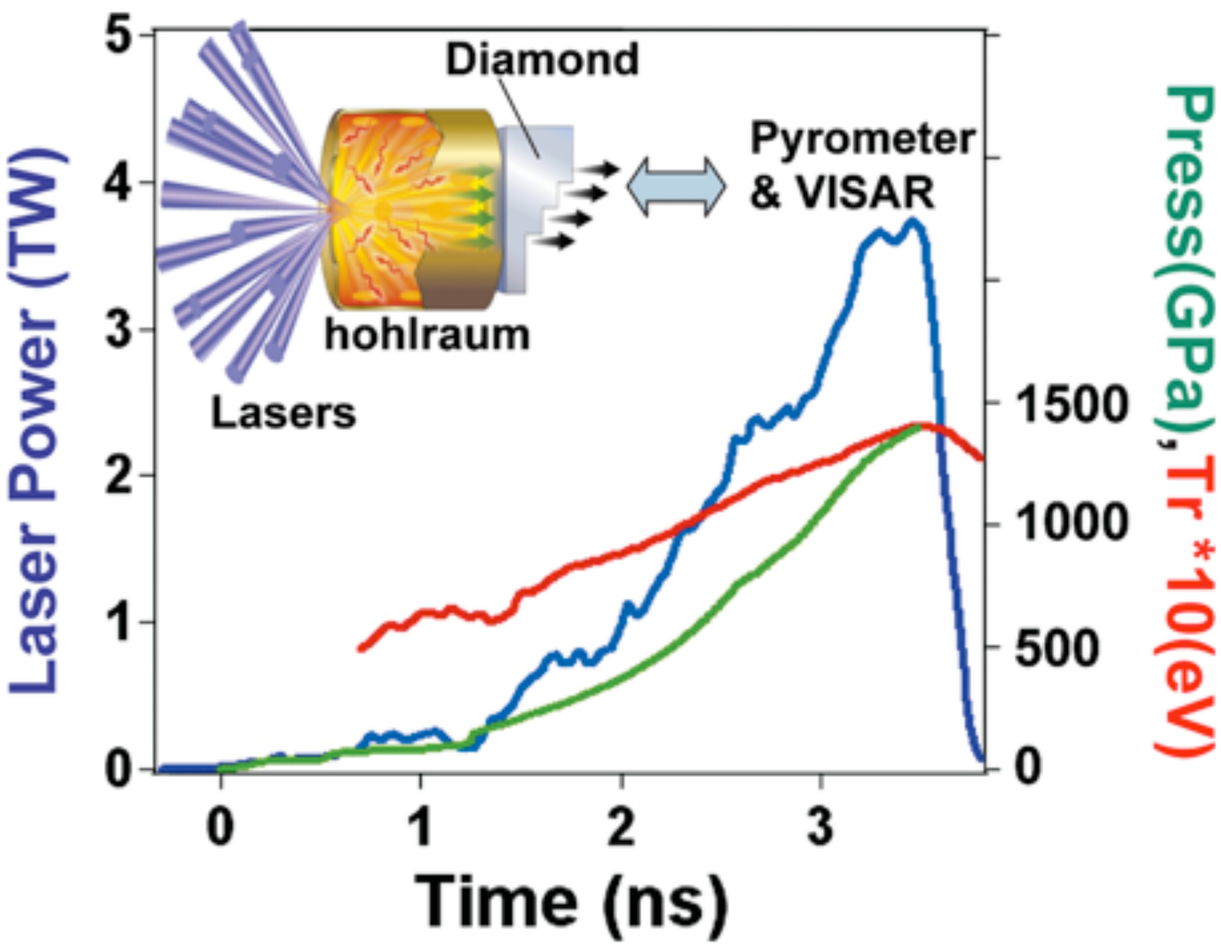


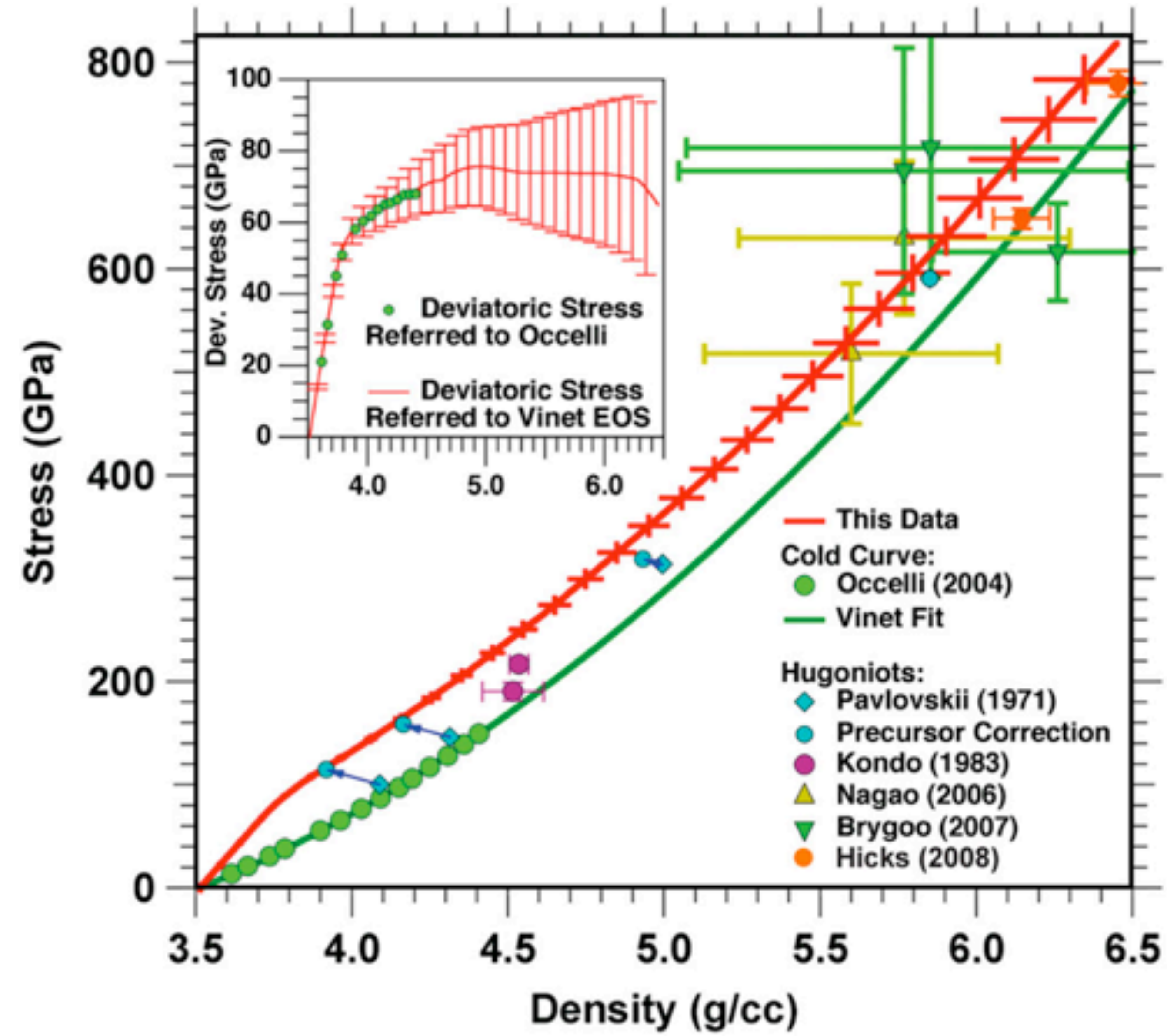


Maximum pressure 50 GPa

Direct compression of diamond

Increasing laser ramp over 4 ns
Conversion using a hohlraum
Soft x-rays drive ablation and compress smoothly

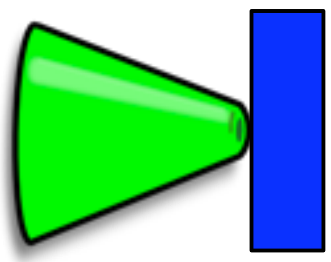


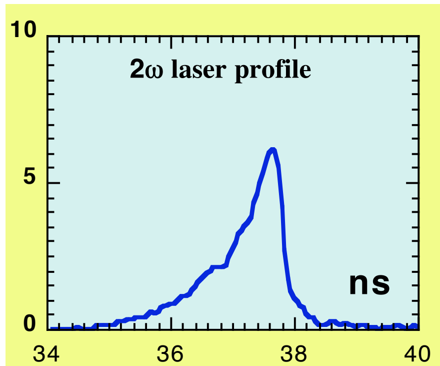


Diamond phase maintained up to 8 Mbar

Bradley et al., PRL 2009

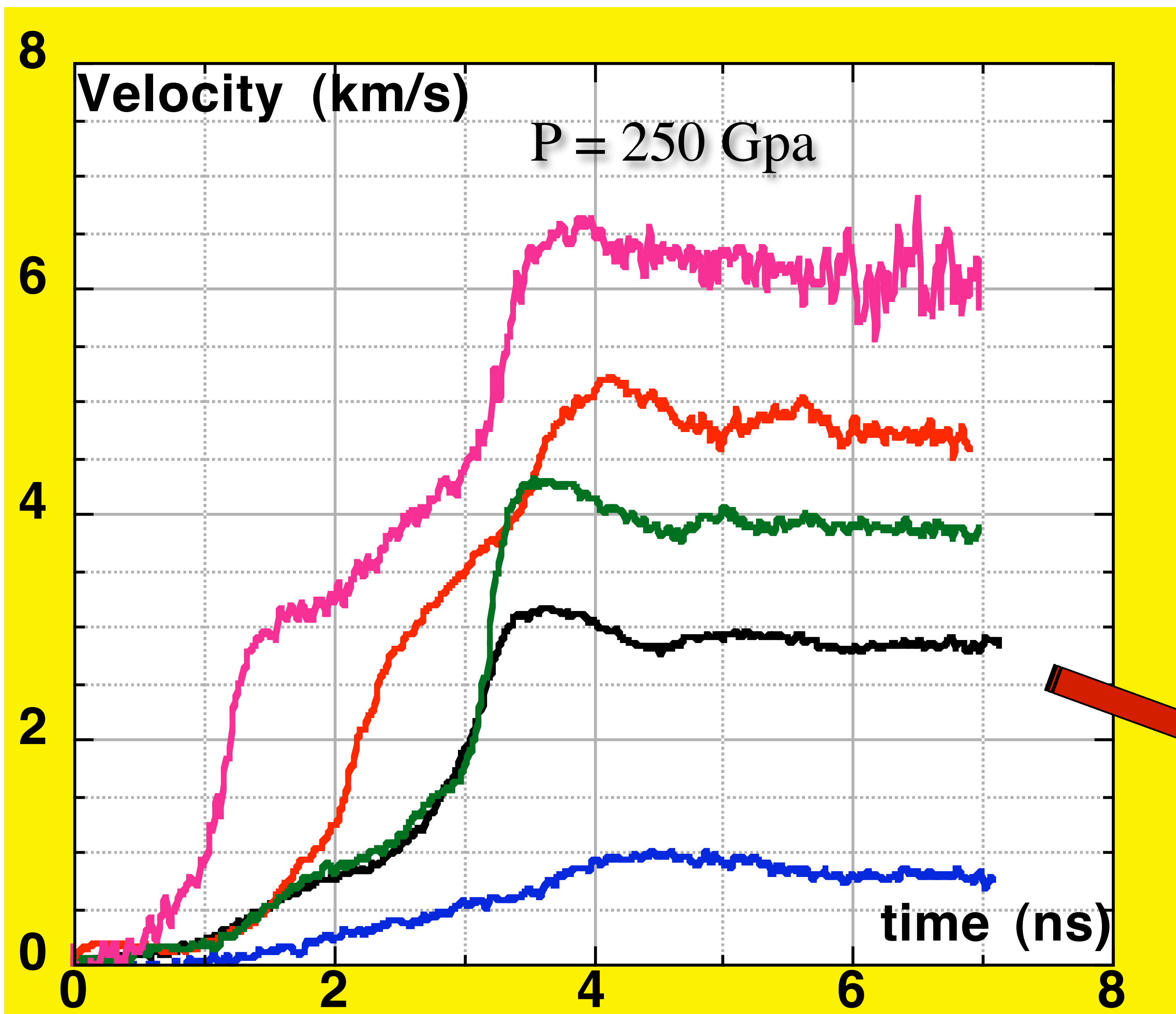
Direct laser ramp compression

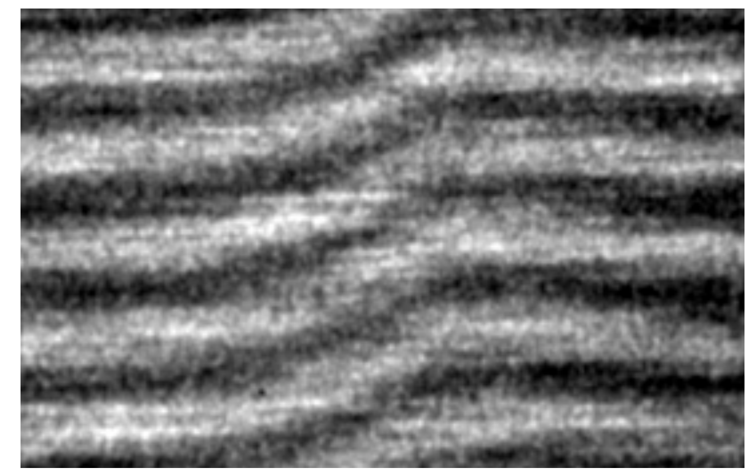


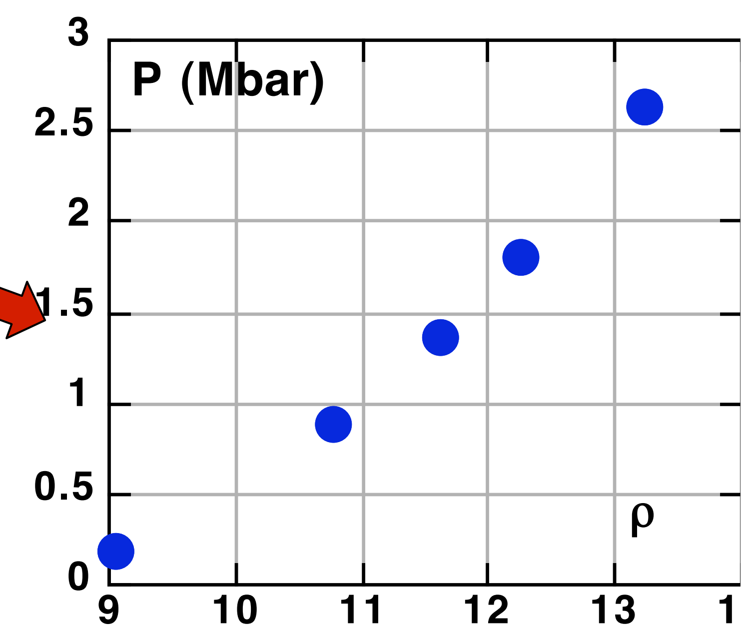


Energy scan (100- 900 J at ω)
We kept same target thickness (10 μm)

Alpha-epsilon transition at V~0.8 km/s

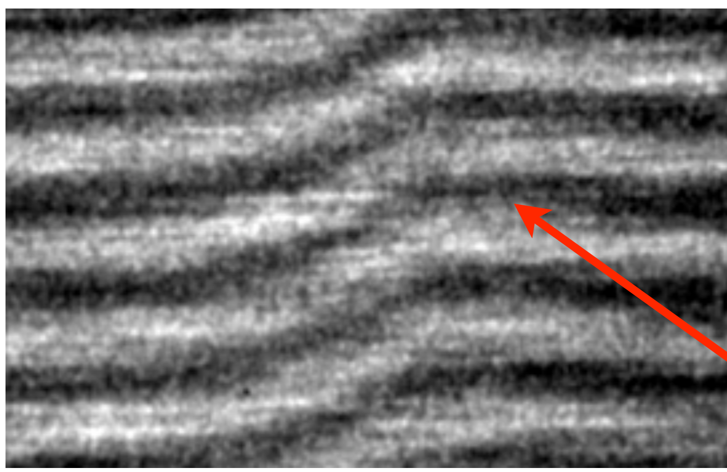




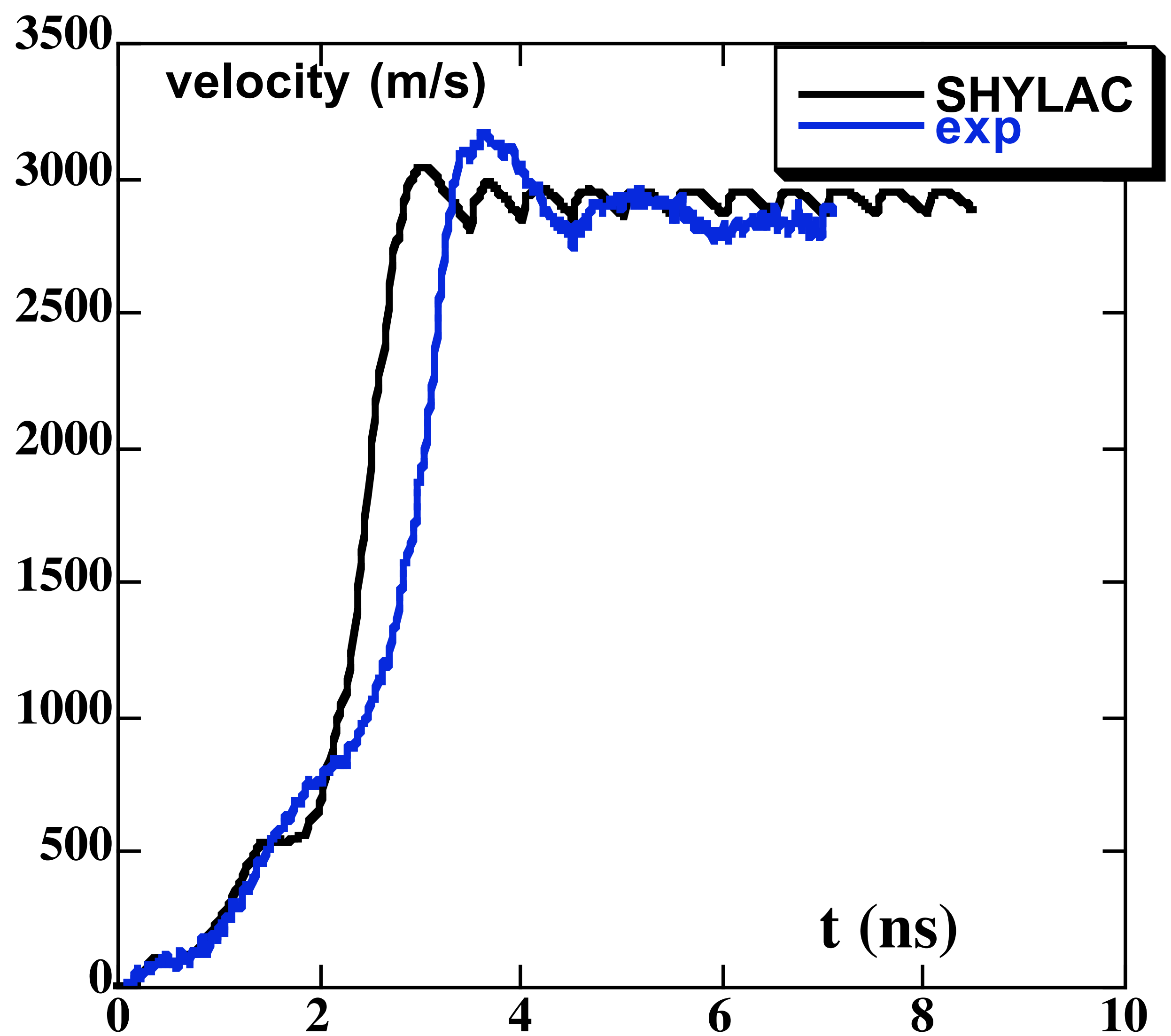


Spallation observed

As we are in the solid phase, we do expect spallation effect



Velocity decreases



Comparison with SHYLAC code developped in Poitiers

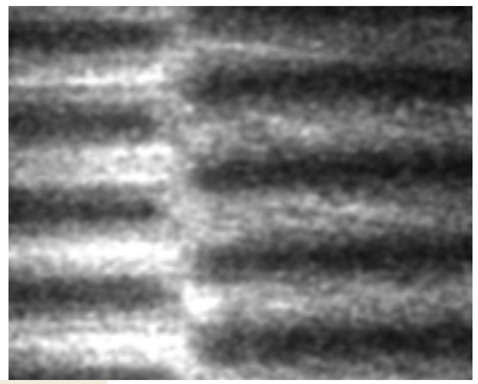
Multi-phase EOS

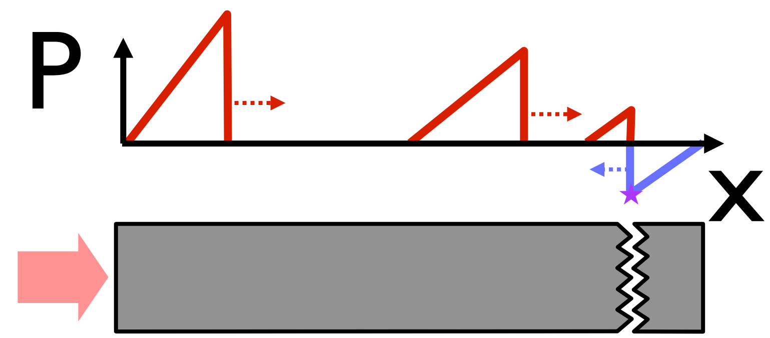
See *de Rességuier & Hallouin, JAP 2001, PRB 2008*

Observed spall strength of 7 GPa

Preheated samples

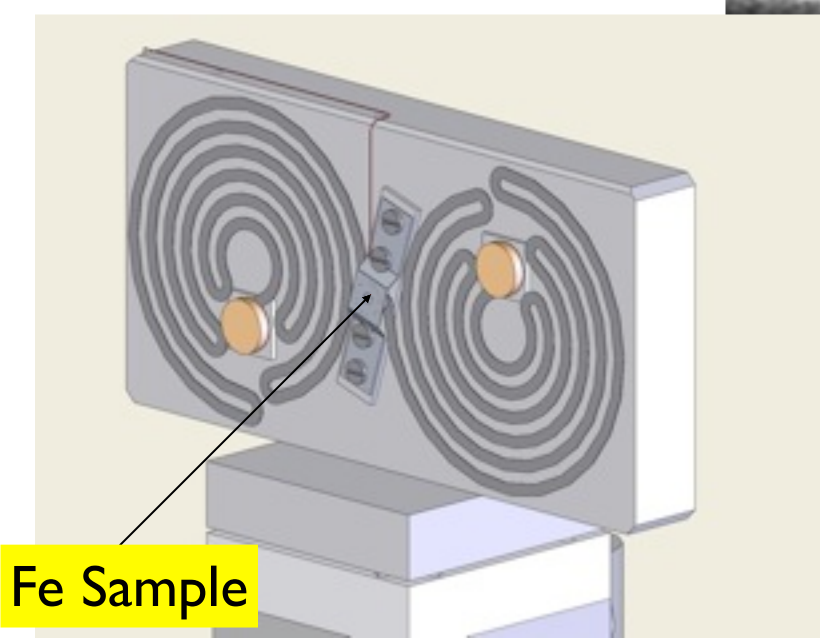
To preheat the sample, a dedicated heating cell was designed
Decaying shock in a 100 μm foil was performed



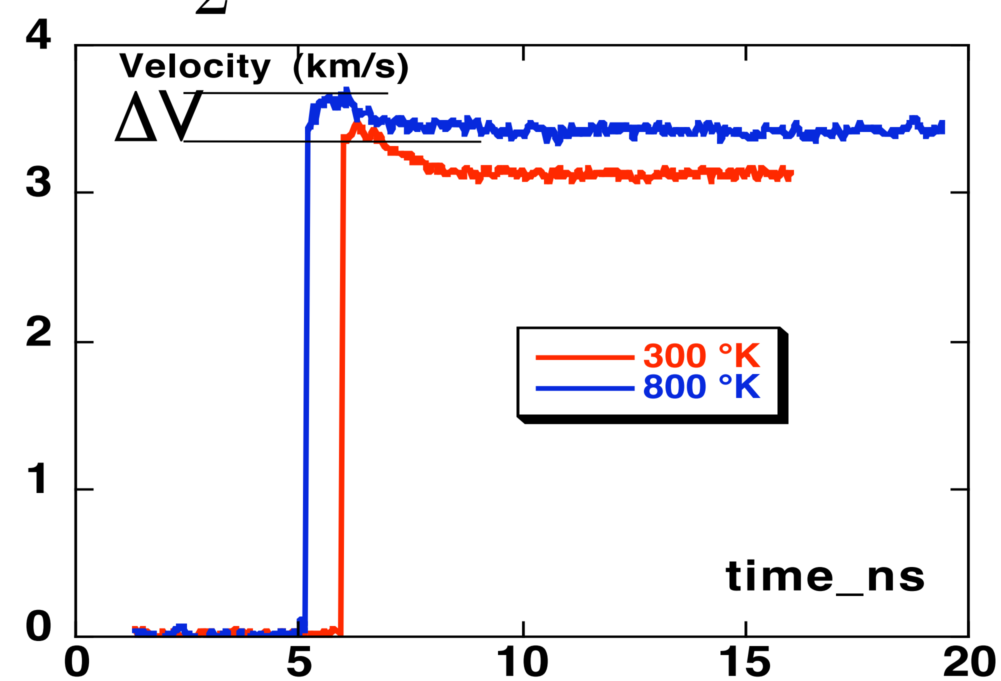


Spall strength

$$\sigma_R \approx \frac{1}{2}\rho_0 C \Delta v \approx few\ GPa$$



F. Occeli (CEA)

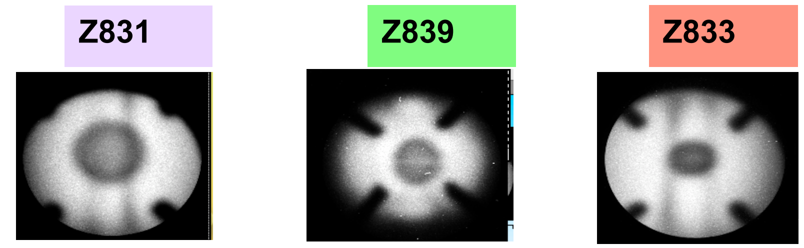


The "hot" sample presents a smaller spall strength as expected

σ_R(800 °K)≈3.5 Gpa, σ_R(300 °K)≈6.7 Gpa

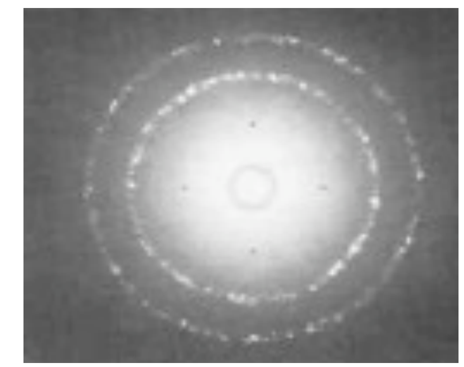
X-ray diagnostic development

x-ray diagnostics



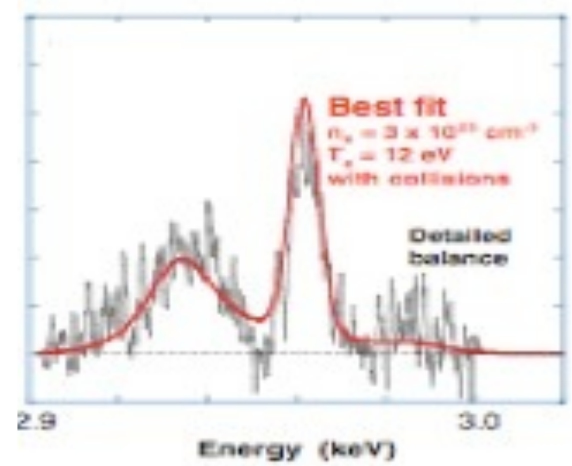
X-ray radiography

Absorption by bound electrons
→ ion density, shape



X-ray diffraction

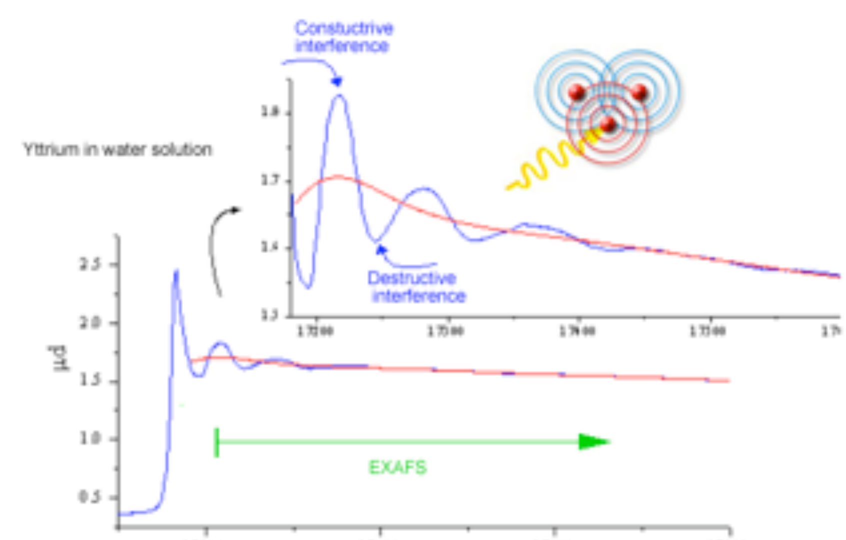
Coherent elastic scattering
→ lattice/ion structure



Glenzer et al. PRL 98,065002

X-ray Thomson scattering

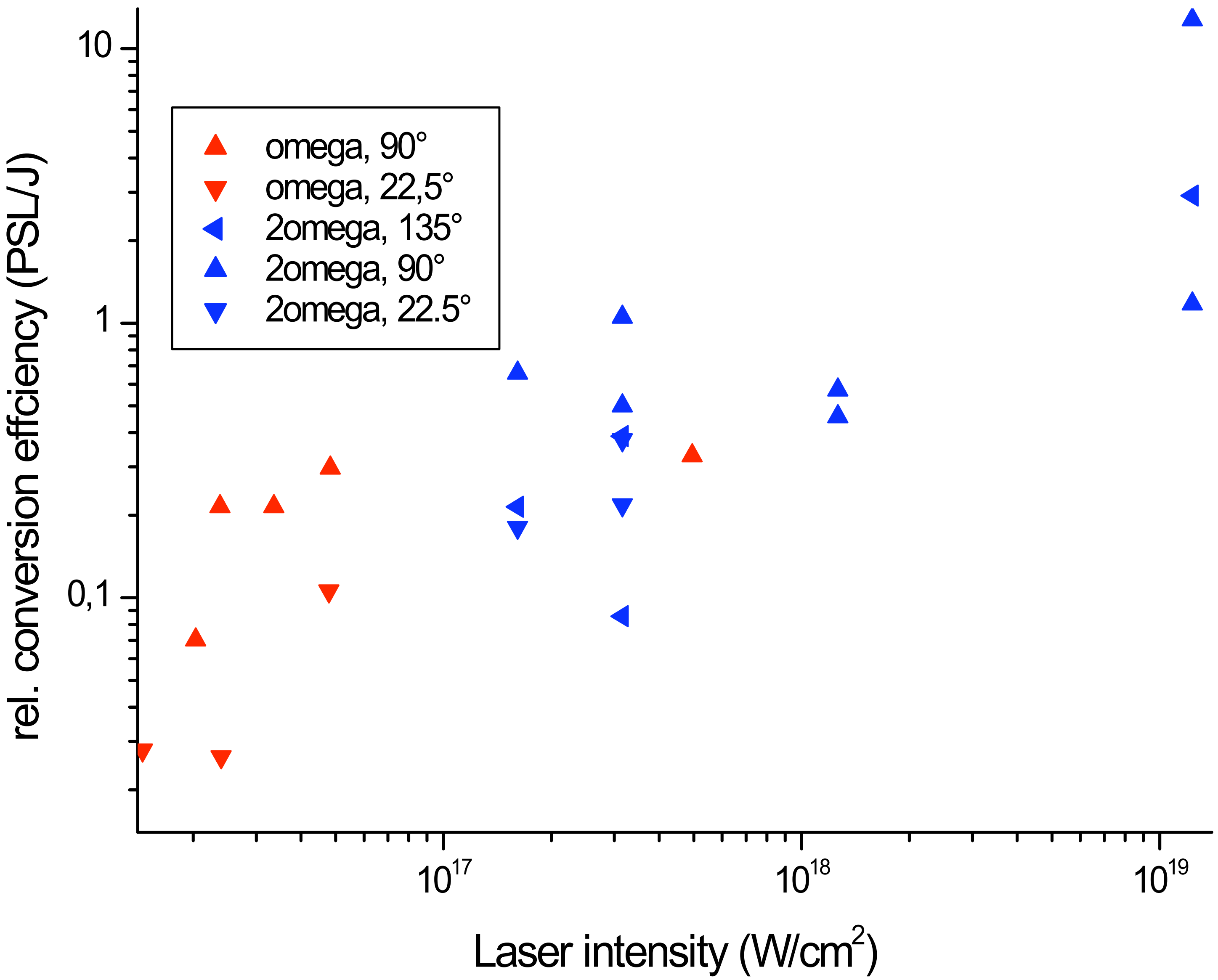
Inelastic scattering
→ electron density and temperature

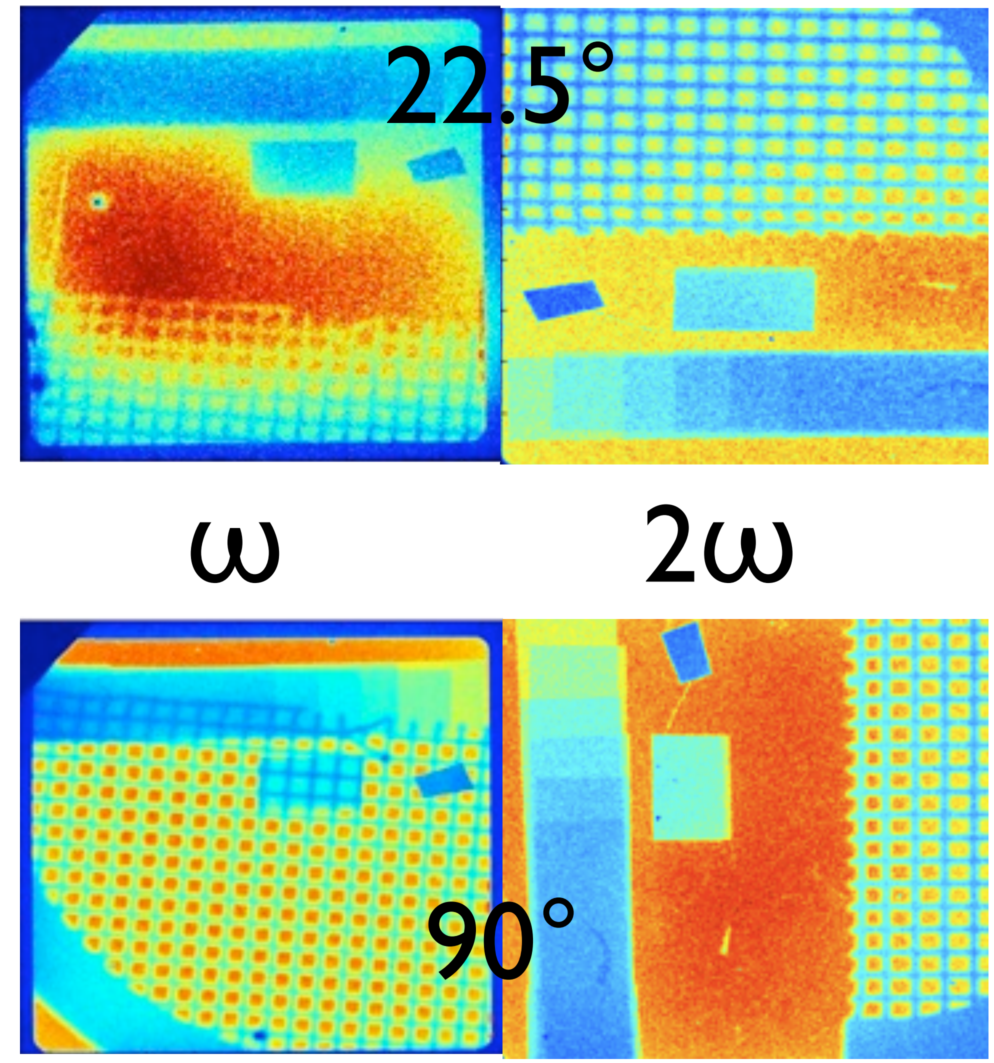


Near edge absorption spectroscopy

→ local chemistry and structure

Optimisation of x-ray source

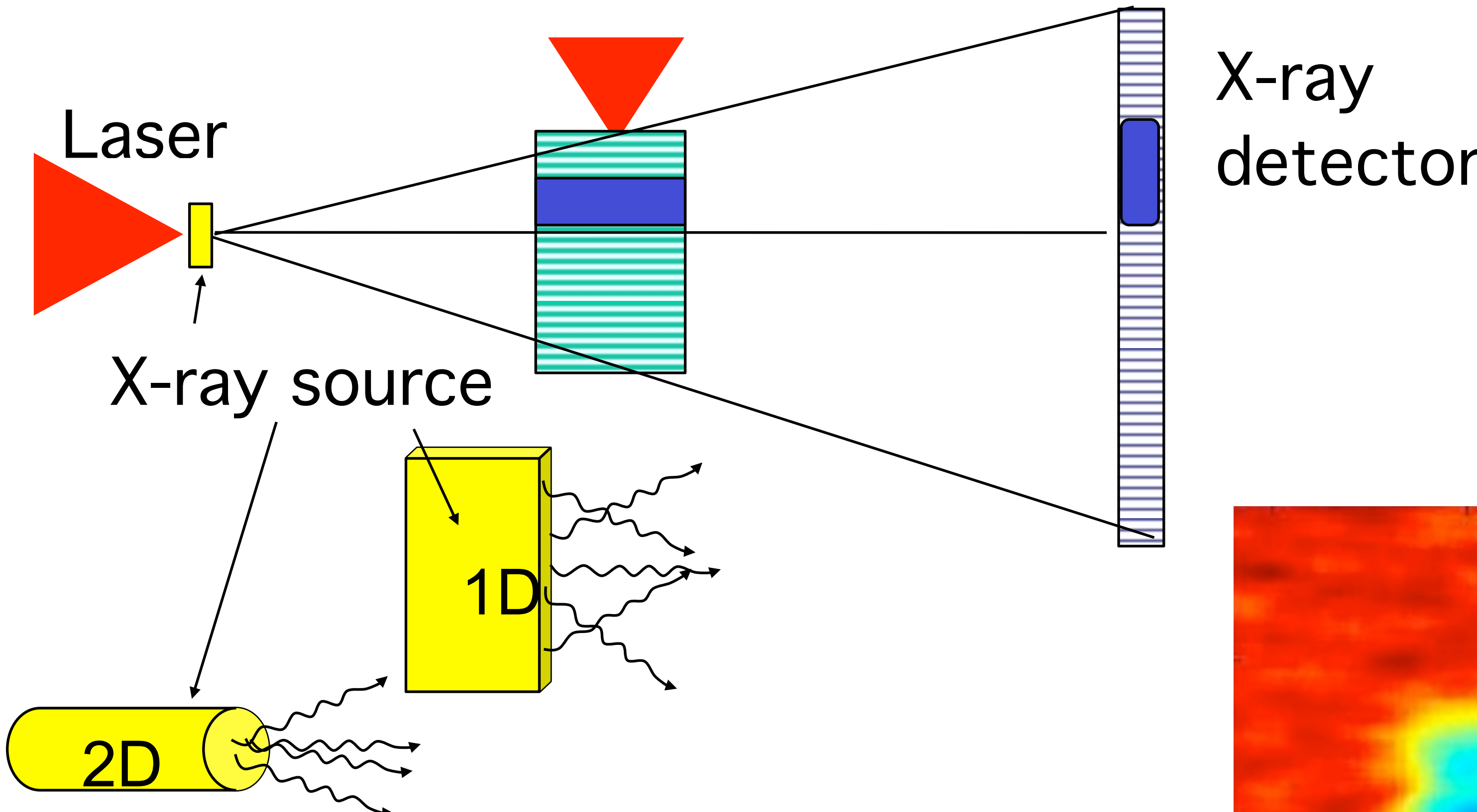




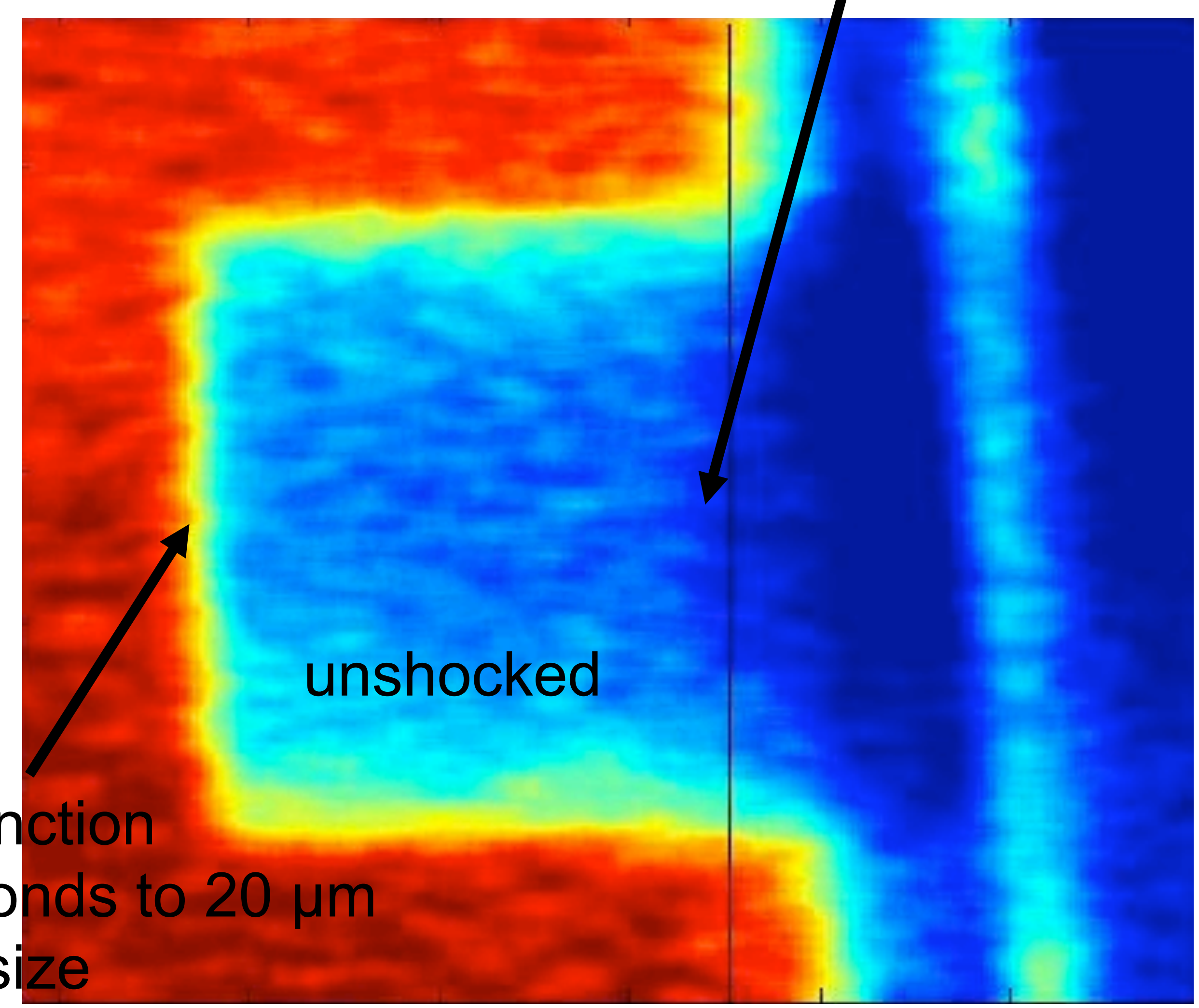
Optimization of laser parameters
targets and experimental geometry

Brambrink et al. PoP 2009

Radiography of shocked iron

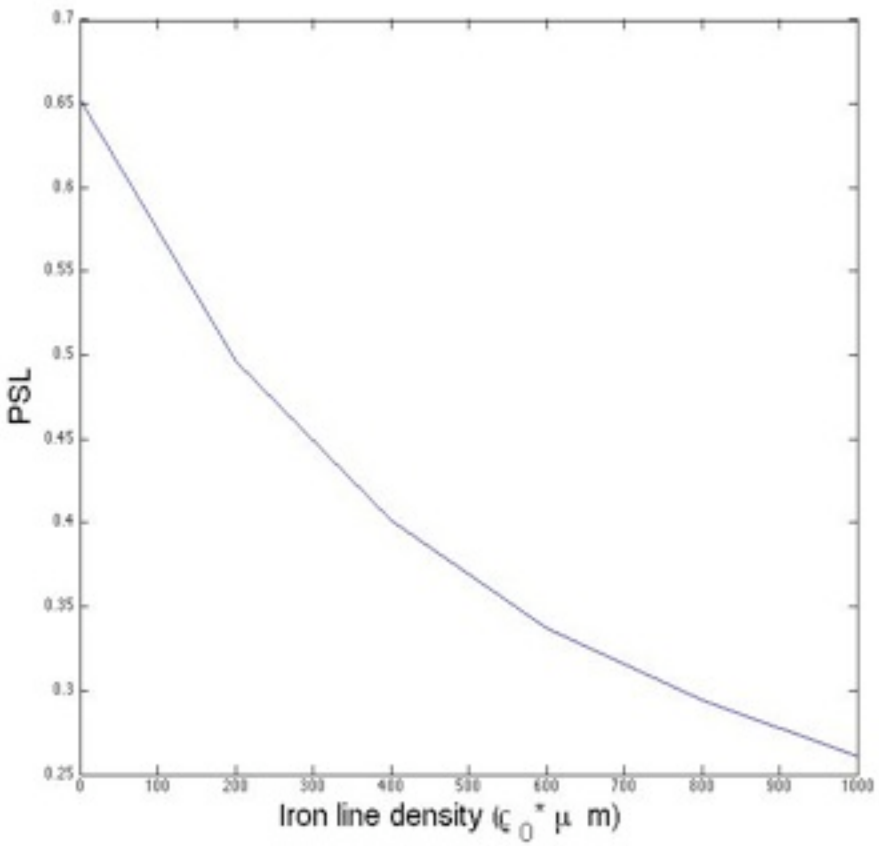


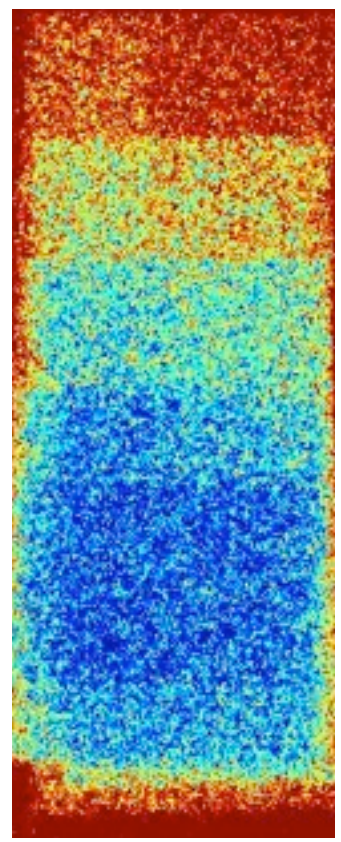
First radiography of mid-Z material using short pulse lasers

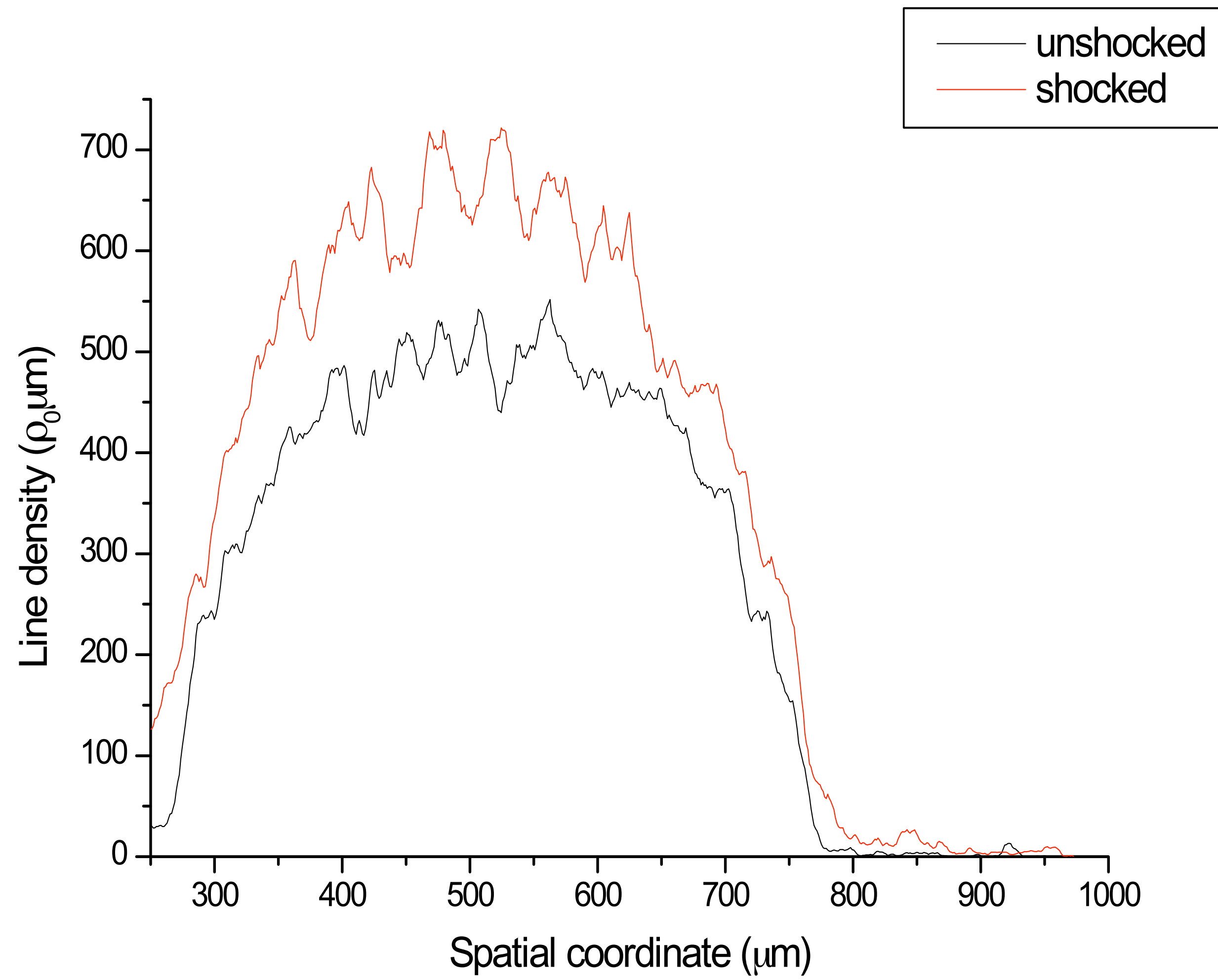


Line density measuremets

Calibrating the line density on shot allows analysis





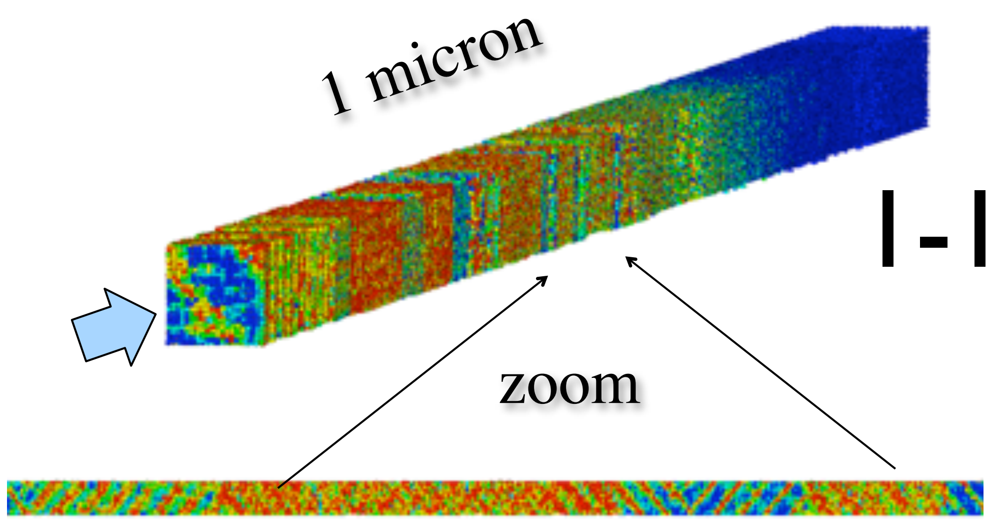


In this experiment, precision was limited to 5-8%, but with a proper x-ray source, 1% is possible!

Hydro and molecular dynamics simulations

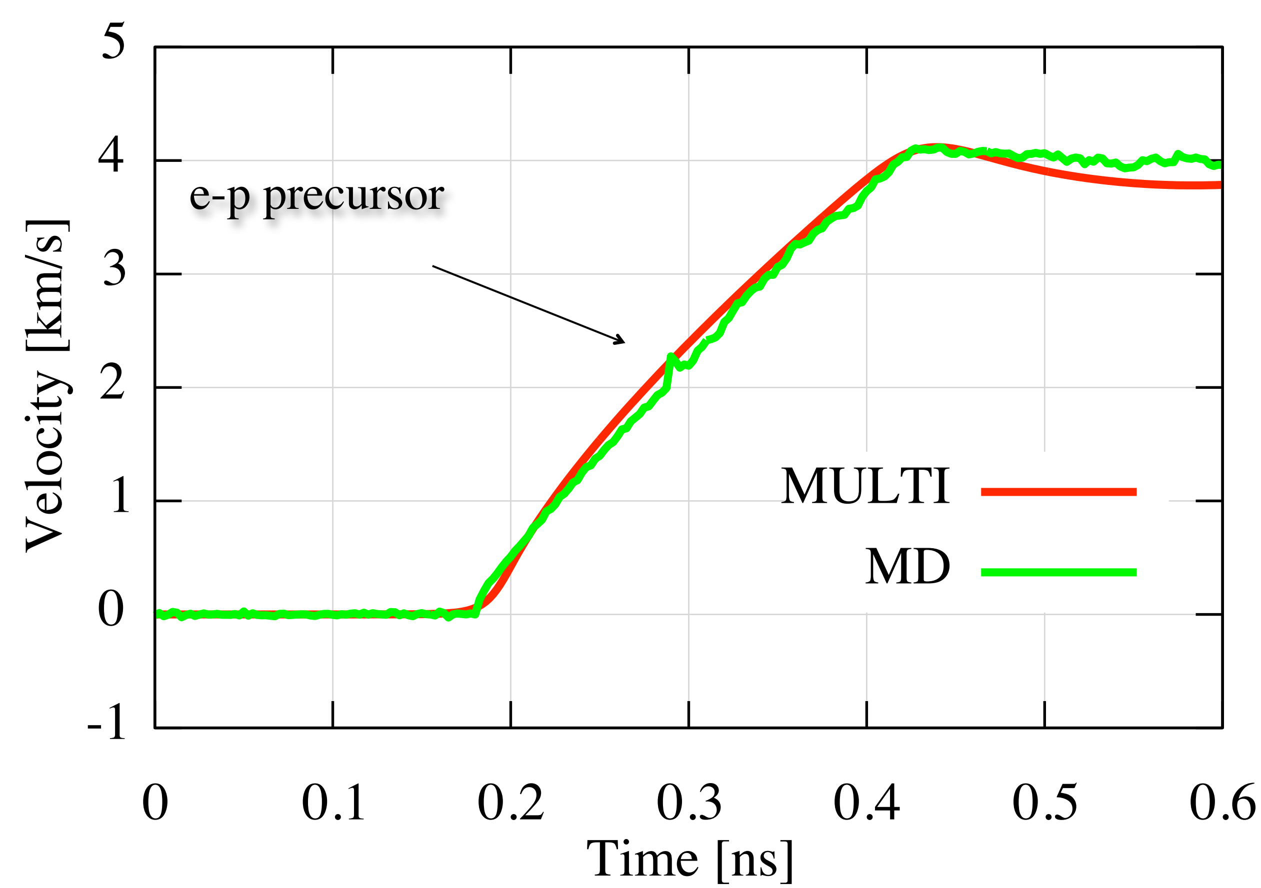
MD simulations

How do phase transformations affect the data analysis?



T. Vinci & S. Mazevet (CEA)

1-100 million atoms



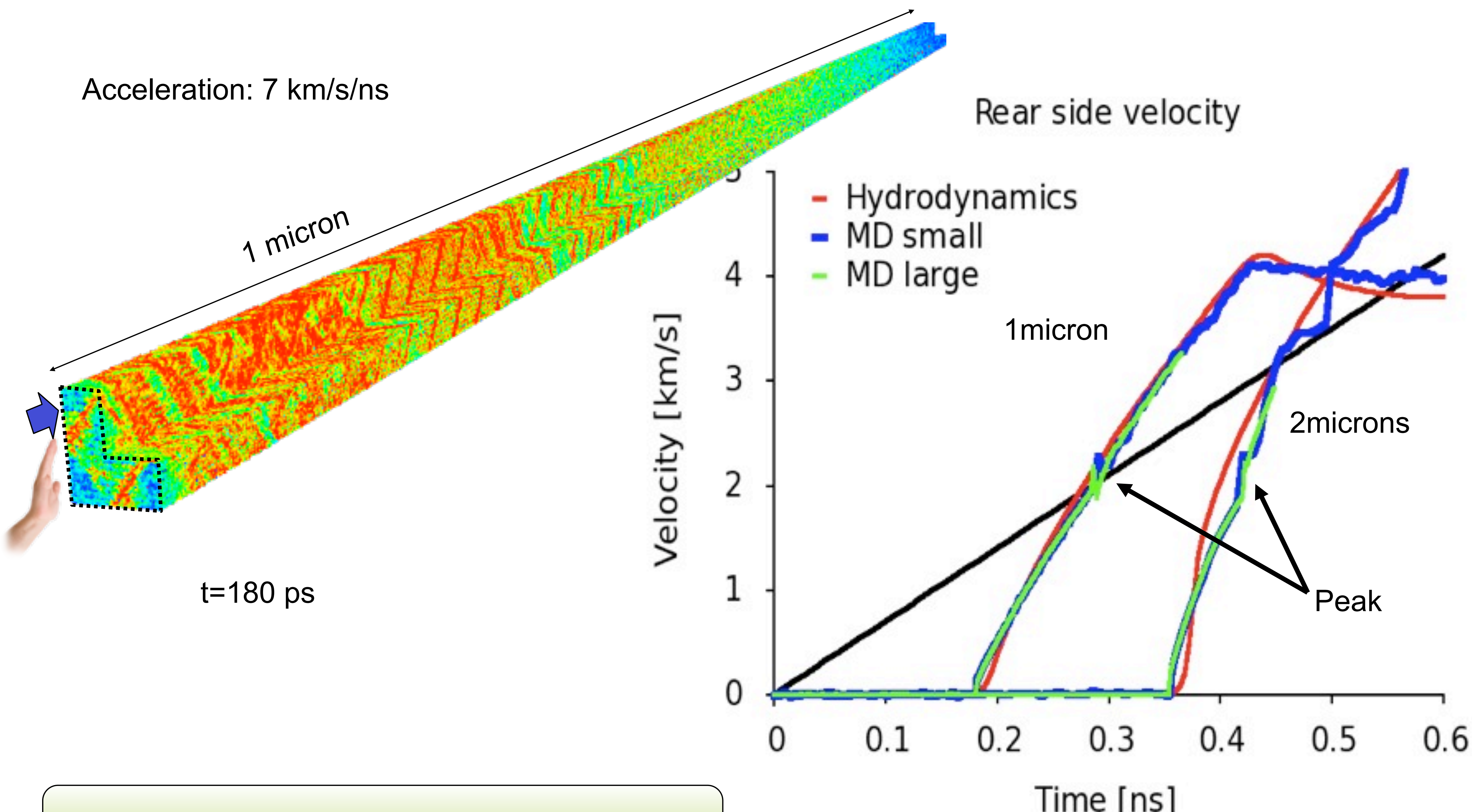
Free surface velocity along the isentrope (measured with VISAR)
- Hydro
- MD

Simulation of Al using a EAM potential
1 and 2 microns thickness over 0.8 ns

Testing data analysis on simulations allows to estimate the errors

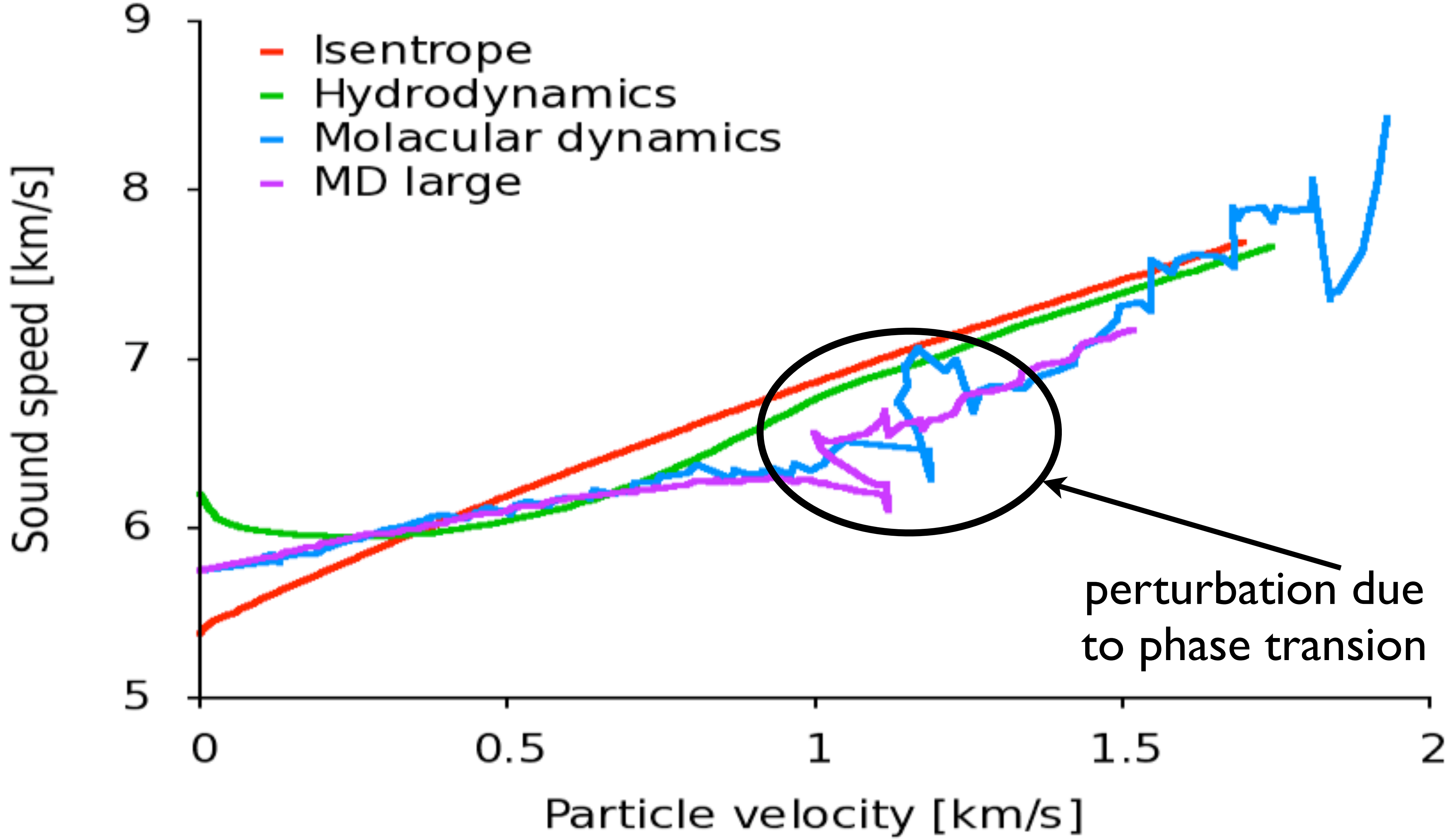
Simulated profils

Aluminum does not have phase transition, nevertheless...



Faults in the material structure

Data analysis



Error due to phase transformation are rather small

Summary

- EOS measurement of iron under earth core conditions requires isentropic ramp compression
- Lasers permit compression to high pressures, but ramp has to be chosen carefully
- Experiments explore pressures up to 2 Mbar, higher pressures are expected
- Development of x-ray diagnostics
- Explore the effect of the phase transition with molecular dynamic simulation

Collaborators

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