Quasi-isentropic compression by ablative laser loading and on Be at Z

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With thanks to:
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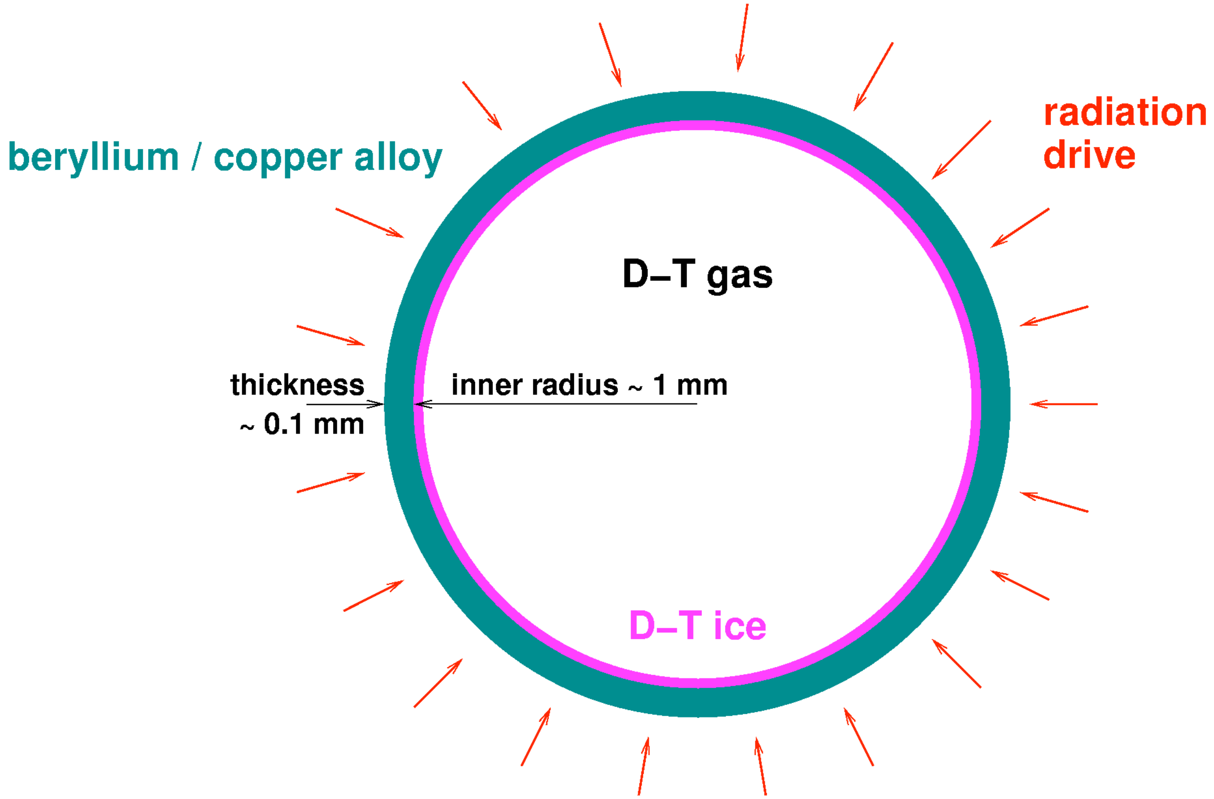
Marcus D. Knudson (SNL), Pedro P. Peralta (ASU)

Outline

- Motivations:
  - Physics-based material dynamics
  - Capsule properties for ICF
- Z ICE experiments on Be
- ICE by laser ablation:
  - Ablative loading: method and modeling
  - LICE at TRIDENT
  - Example data
- Diagnostics

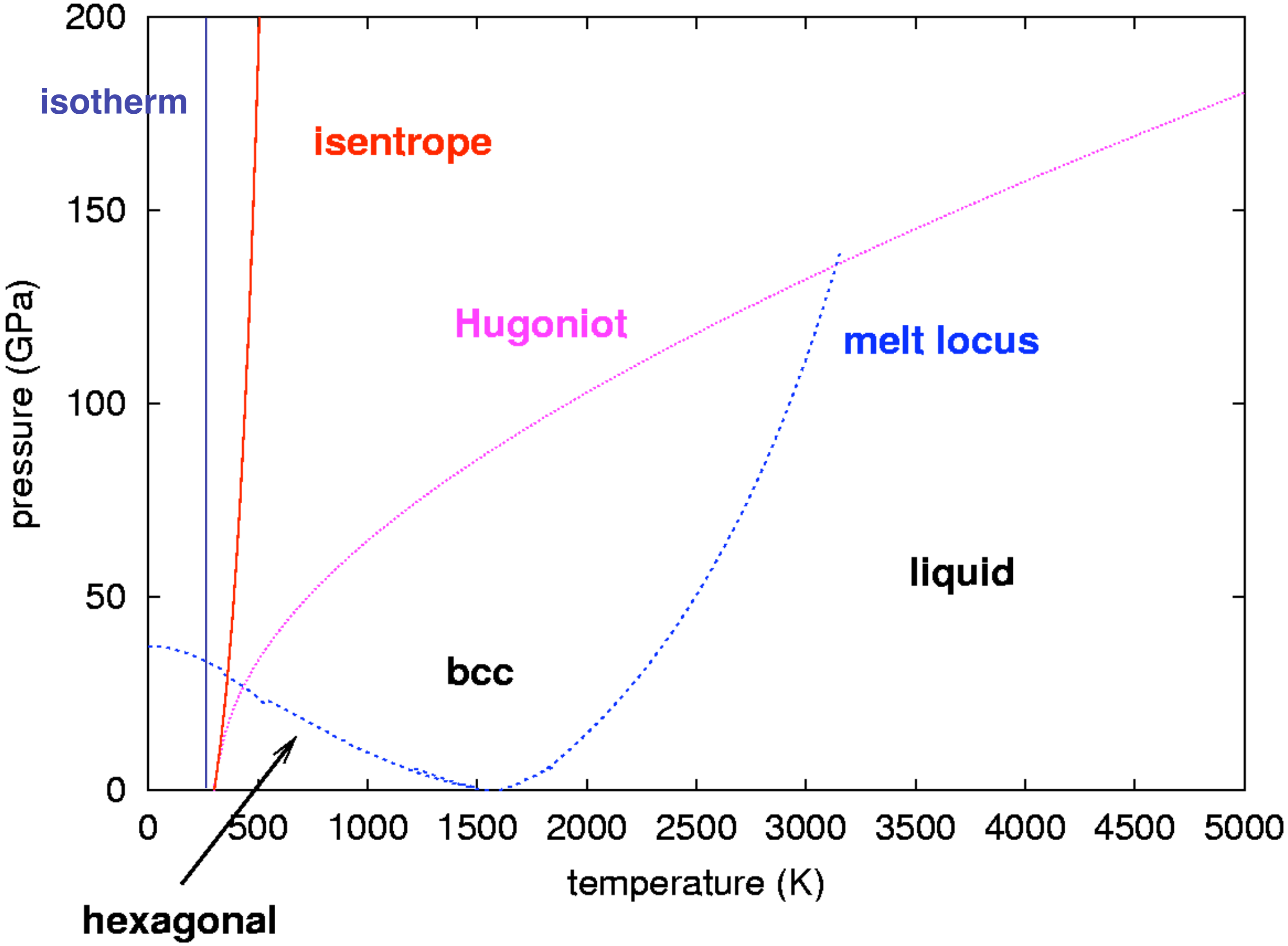
Beryllium capsule design for ICF



imploded capsule
with hotspot

- Variations in acceleration cause asymmetry => reduce yield
- Beryllium: polycrystalline, anisotropic

Be phase diagram



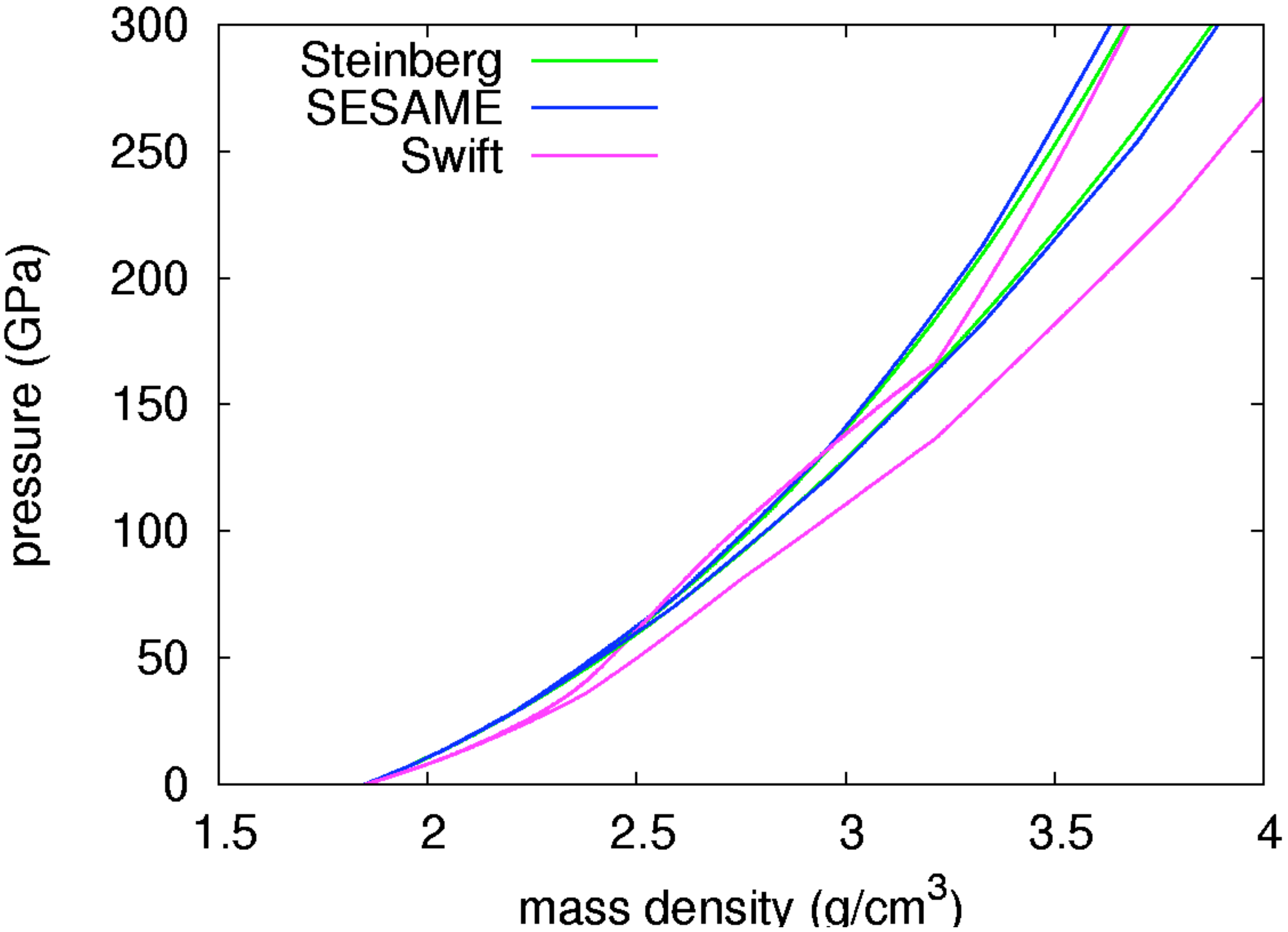
Temperatures are poorly-known (shown: Steinberg)

Isotherm:
static loading
e.g. diamond anvil cell.

Isentrope:
quasistatic,
-p.dv work,
no heat loss.

Hugoniot:
kinetic energy to heat to entropy.

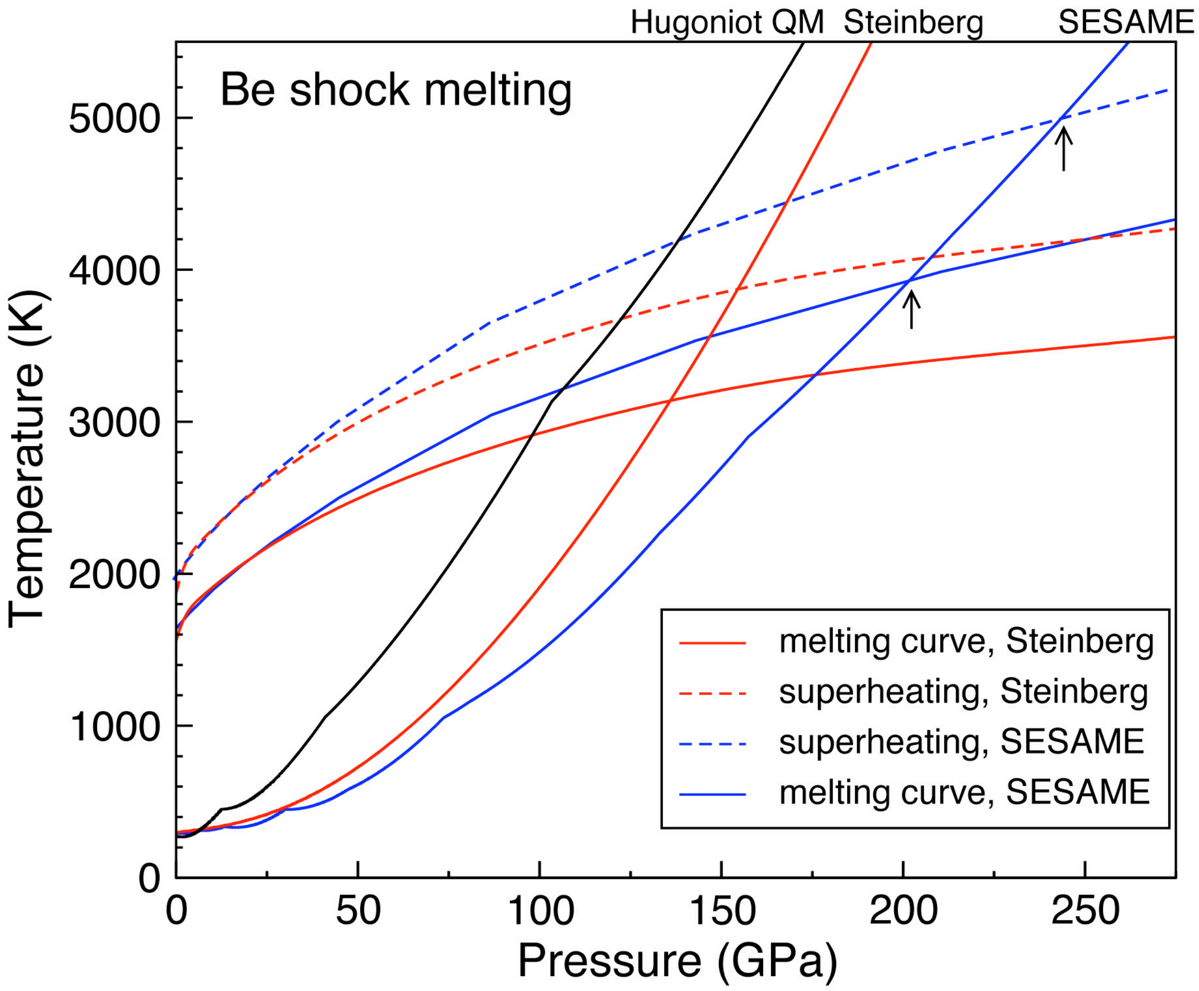
Alternative EOS for Be



Shock Hugoniots are similar up to several hundred GPa (reasonably consistent in Z flyer impact shots to 200 GPa)

STP isentropes vary significantly: a potential discriminant.

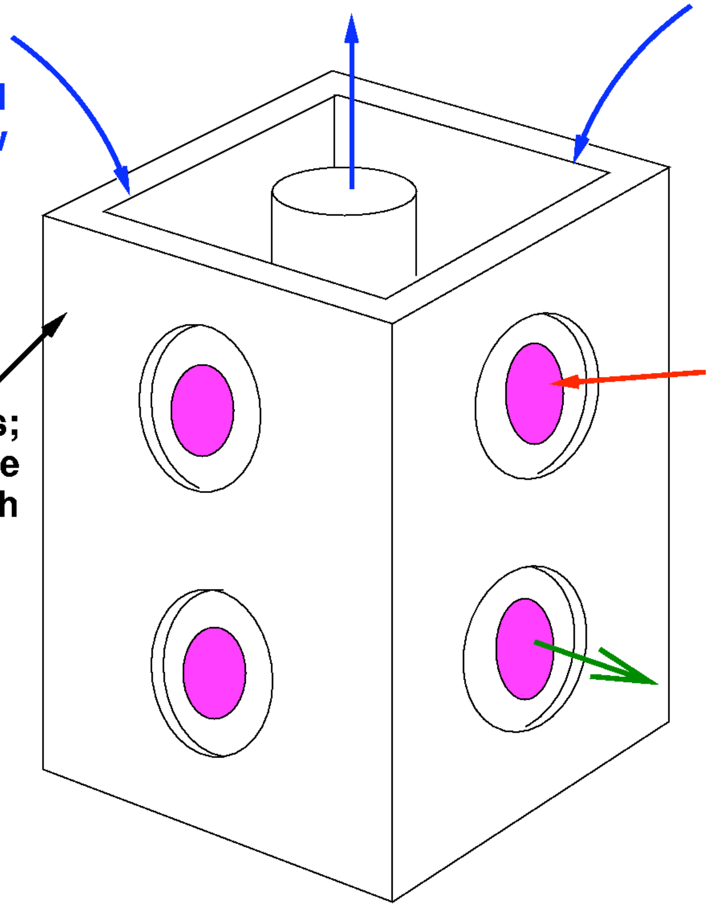
Uncertainty in thermal EOS and dynamics of melting



Unless experiments measure melt under precise NIF loading conditions, we need to resolve equilibrium melting curve for Be *and* understand any dynamic effects.

Dynamic melting theory: Luo et al.

Dynamic materials experiments at Z



electrical
current flow

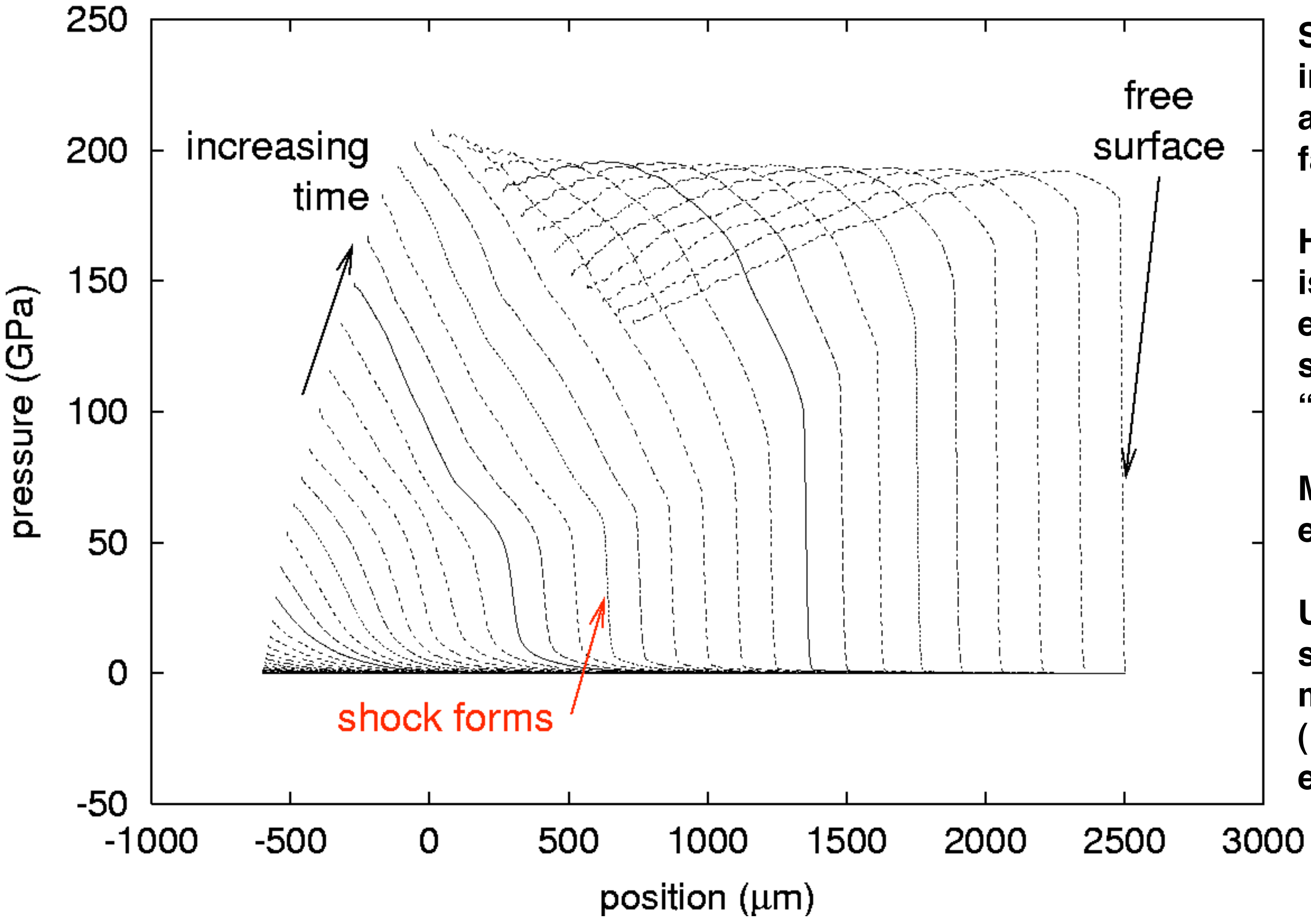
'Square short' configuration

two or four panels;
two or three
experiments on each

each experiment is
performed in a recess
in the panel wall

magnetic pressure
and ablation
accelerate flyer
from surface

(Quasi-) isentropic compression in smooth wave



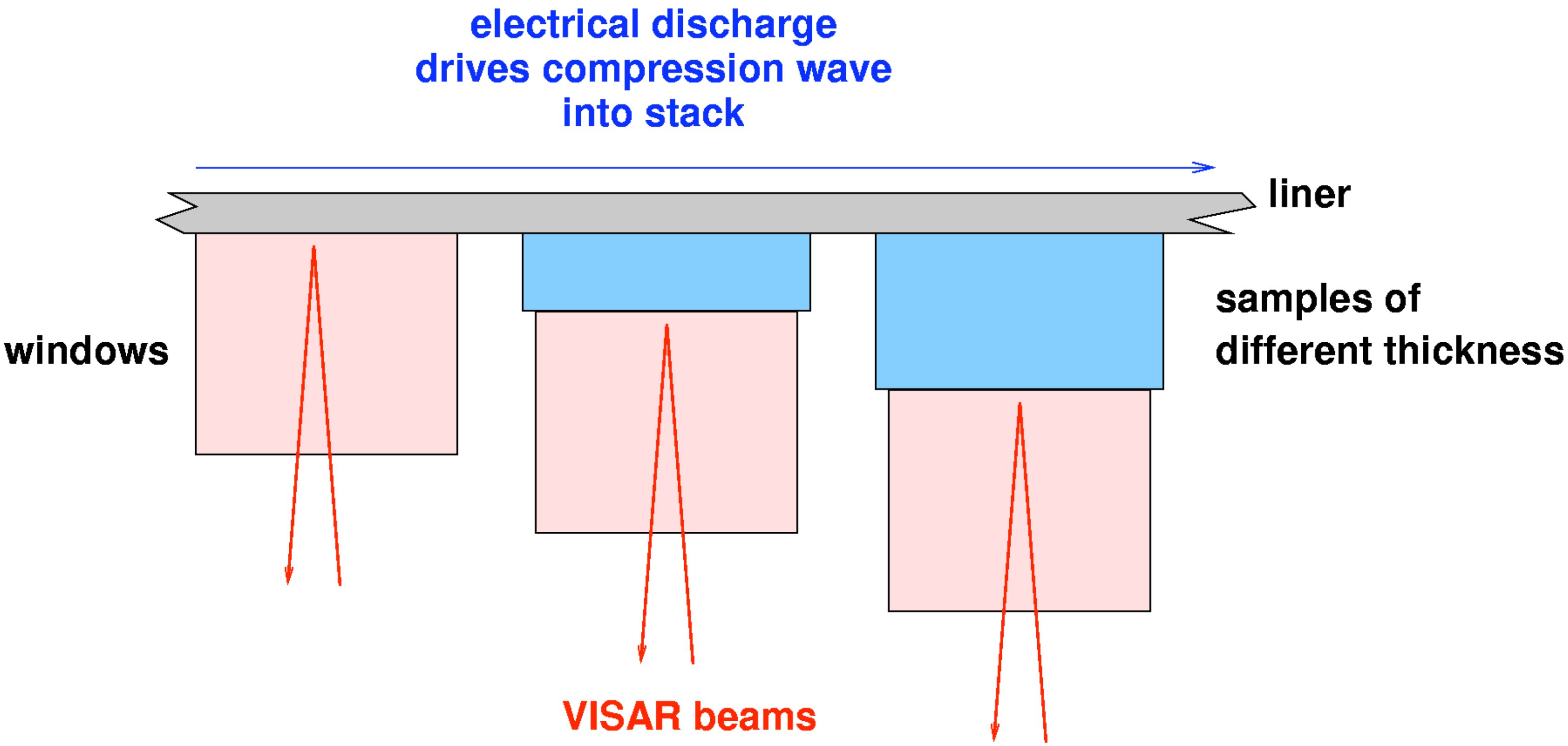
Smoothly increasing load applied to one face of sample.

Heat conduction is slow, so elements of sample are "insulated".

Measure wave evolution.

Uniaxial wave, so plastic flow may occur (increases entropy).

Quasi-isentropic compression at Z



electrical discharge
drives compression wave
into stack

liner

samples of
different thickness

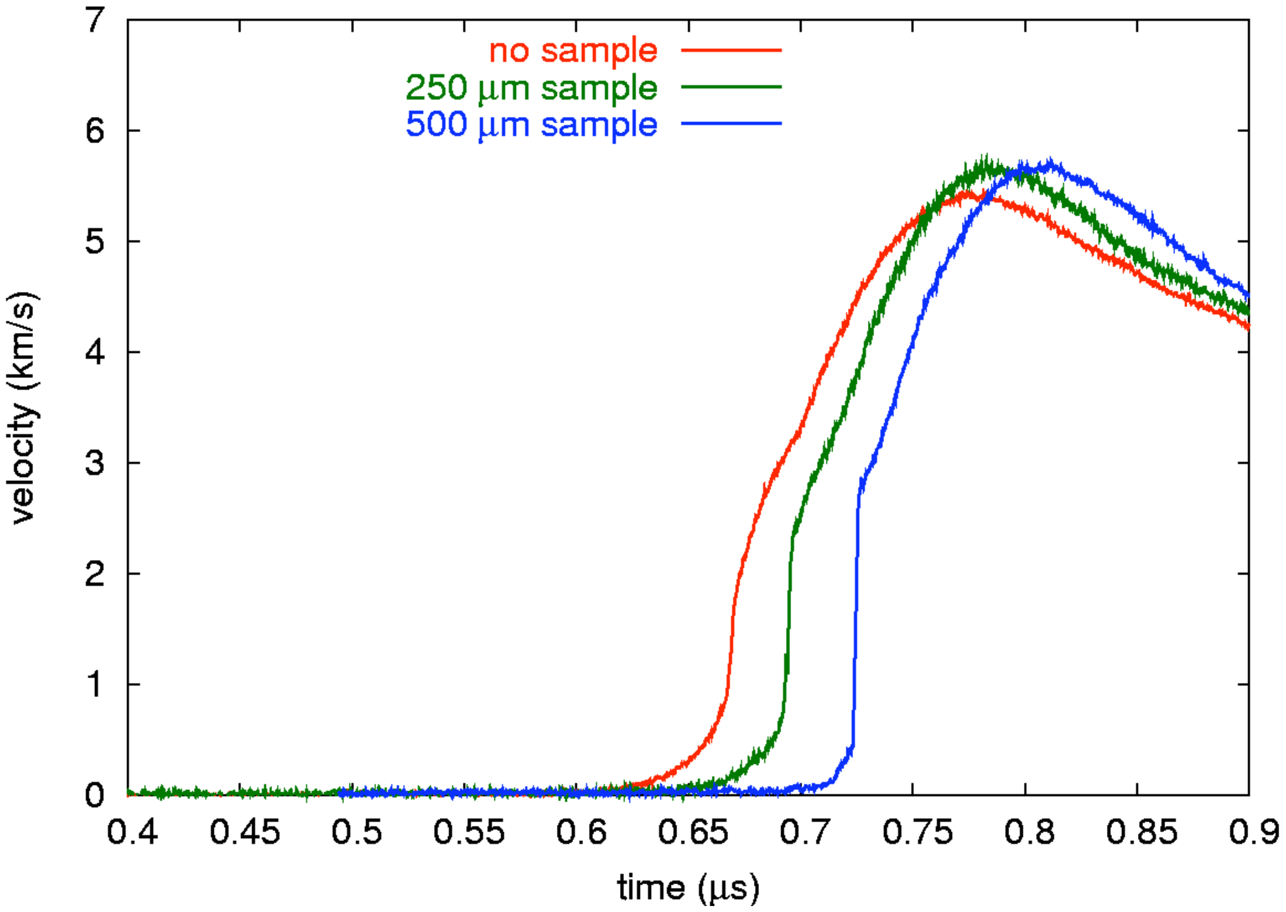
windows

VISAR beams

Vertical scale exaggerated

Observe evolution of compression wave for different sample thicknesses.

Velocimetry shows evolution of ramp wave



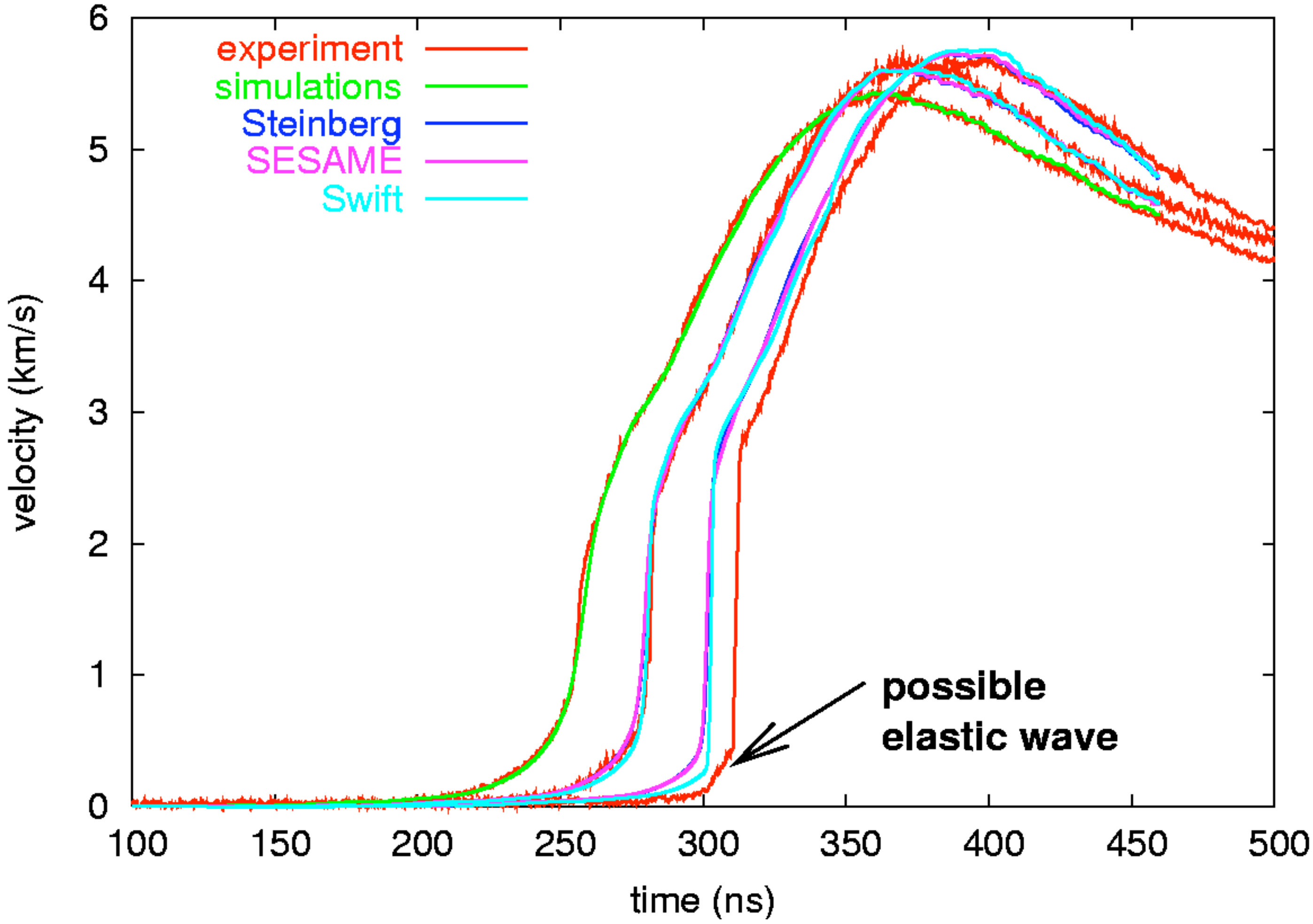
Z shot 843

Be samples
LiF windows

Principal isentrope to
~200 GPa

Swift, Paisley, and Knudson,
Proc APS SCCM'03

Performance of EOS for Z ICE



Forward simulations: Lagrangian finite-difference, artificial viscosity.

Pressure drive adjusted to reproduce Al velocity history.

Very little difference in predicted velocity histories for isentropic compression (and all reproduce the data well).

Some difference during build-up to shock, but strength also matters.

Material dynamics with lasers

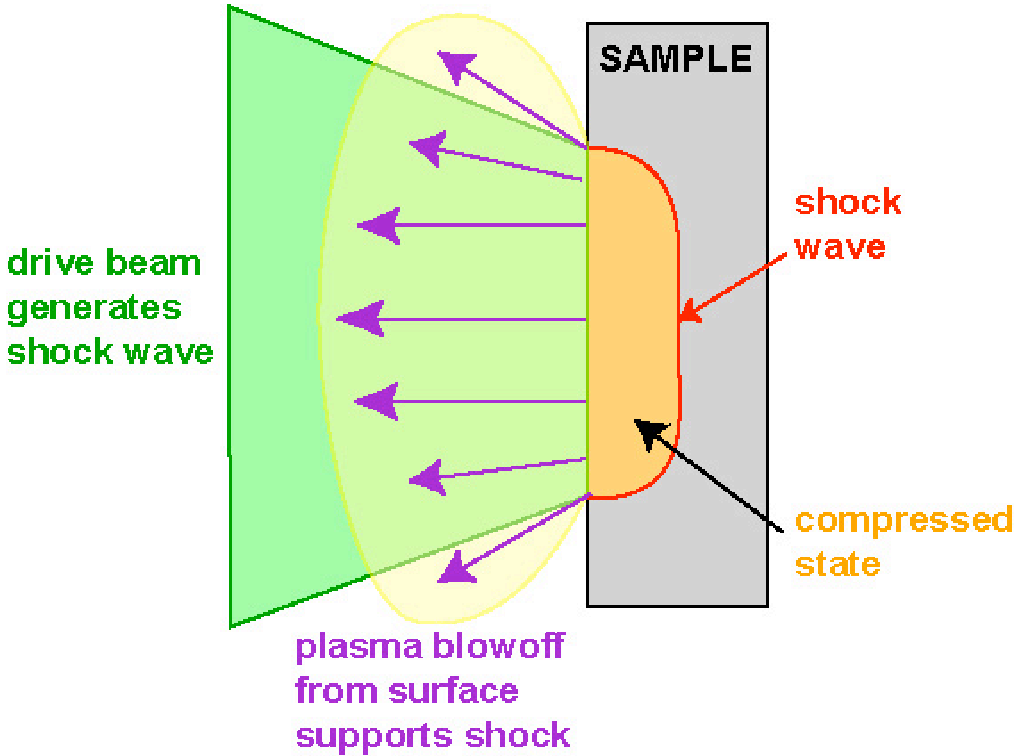
Pros:

- “Easy” synchronization of diagnostics
- Small samples (so easier to obtain crystals hence bridge length scales; hazardous / expensive materials)
- Less “collateral energy and momentum”: easier to recover samples
- Flexibility in applied load

Cons:

- Difficult to generate constant pressure by ablation
- Potential preheat
- Time / length scales shorter than for many shock applications
- Can be difficult to obtain adequate samples

Loading by laser ablation



Pulse: 0.2 to 3.6 ns, 527 nm
2.5 GW/cm^2 to 1 TW/cm^2 (5 mm dia spot)
Sample thickness: tens to hundreds of μm

Shocks in elements:
Swift, Tierney, Kopp, and Gammel,
Phys. Rev. E, 69, 036406 (2004)

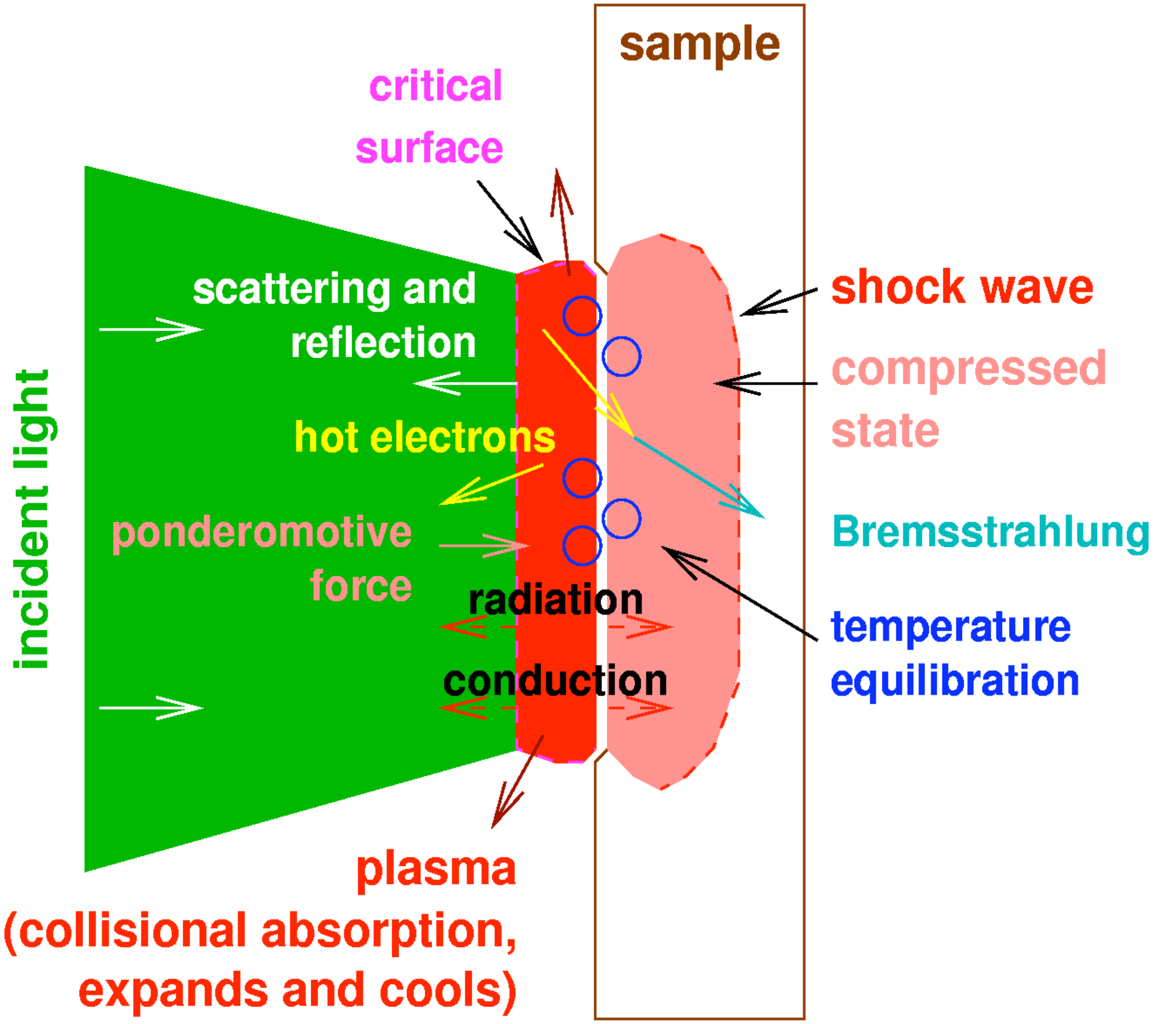
Compounds/alloys:
Swift, Gammel, and Clegg,
Phys. Rev. E, 69, 056401 (2004)

Quasi-isentropic compression ("LICE"):
Swift and Johnson,
Phys. Rev. E (submitted)

Conference papers:
HDP5, APS SCCM'03;
APS DPP '02 and '03

Useful for time-dependent phenomena, such as plasticity and phase changes, and for variable loading histories

Laser-matter interactions



Not all these processes matter in our regime (~0.1-100 GPa, 10-1000 μm, 0.1-1000 ns).

LASNEX and HYADES were used to assess importance in 1D.

Minimal reasonable model:

- **3T hydrodynamics,**
- **laser transport and deposition,**
- **heat conduction,**
- **Thomas-Fermi ionization,**
- **gray radiation diffusion.**

Tested for elements from Be to Au and intermetallic compounds, shock pressures to ~40 GPa

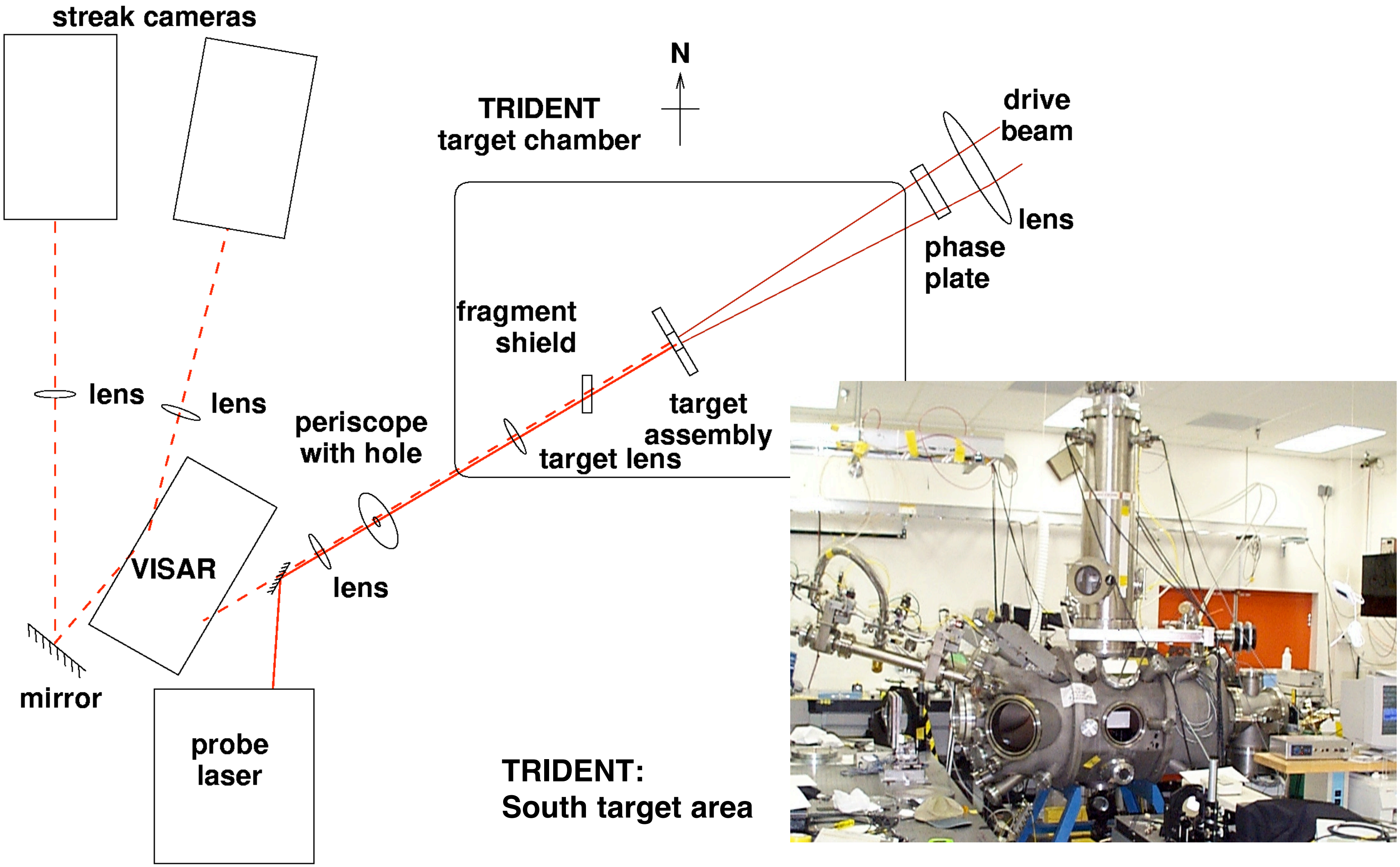
TRIDENT laser facility

- 3 beams, Nd:glass

- ~1 to 1000 J/beam ± ~1 J
- pulse ~100 fs to 3 μs
- 1054 / 527 / 351 nm
- spot size:
  ~50 μm to 50 mm
- controlled intensity
  history
- "nanosecond" mode:
  - 13 elements of 180 ps
    => ~2.5 ns
  - can stack two pulses
    => ~5 ns
  - computer control of
    shape (before amps)

- up to ~8 shots / day,
  or ~25 of below 40 J
- spatial smoothing
- misc. diagnostics

Typical experimental layout



streak cameras

N

TRIDENT
target chamber

drive
beam

lens

phase
plate

fragment
shield

target
assembly

lens

lens

periscope
with hole

target lens

VISAR

lens

mirror

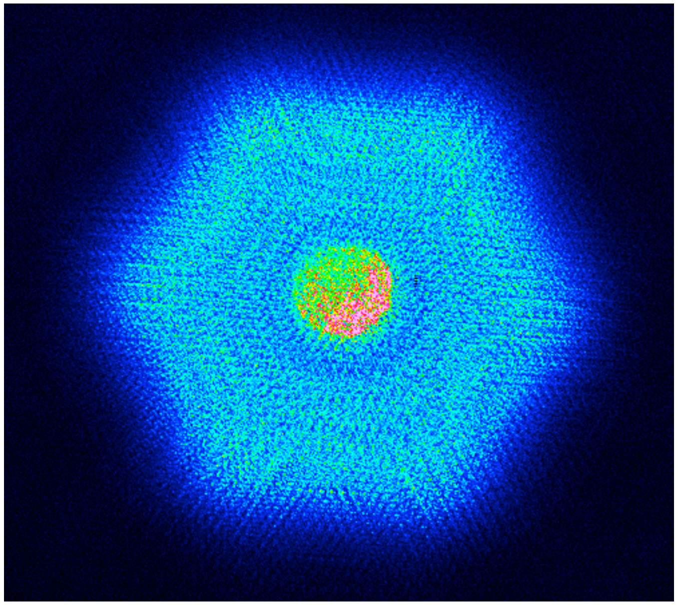
probe
laser

TRIDENT:
South target area

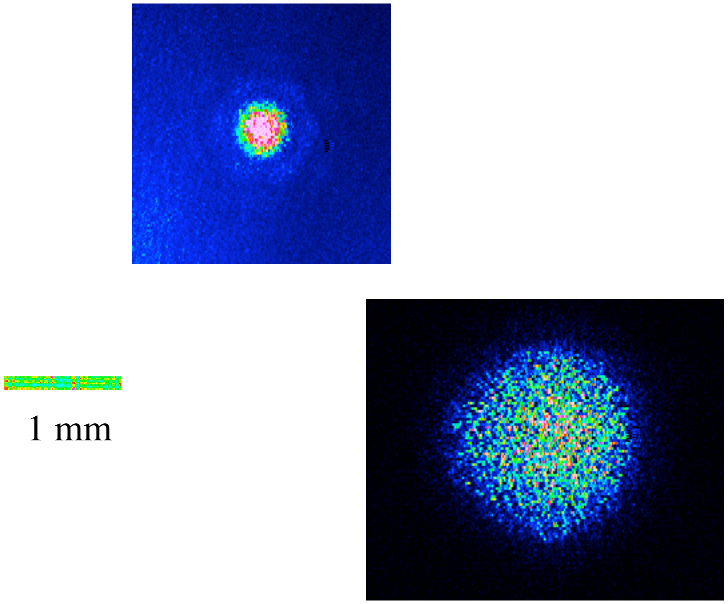
Spatial distribution of laser irradiance

Beams: super-Gaussian, can focus to ~100 μm. Want top-hat with few mm dia.
Use diffractive optical elements; imperfect (undiffracted => hotspot); don't have for all spot sizes.
Defocusing used to remove hotspots or adjust size; introduces some long-λ variation.

Fresnel zone plate
design = 4 mm; defocus to 5 mm

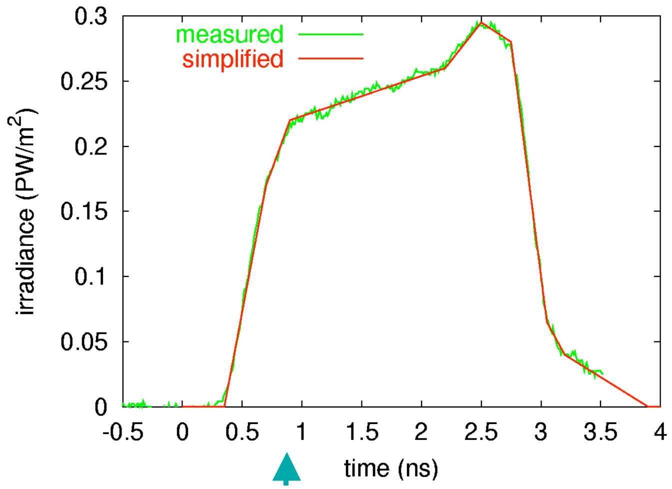


Random phase plate
design = 0.6 mm; defocus to 1-2 mm



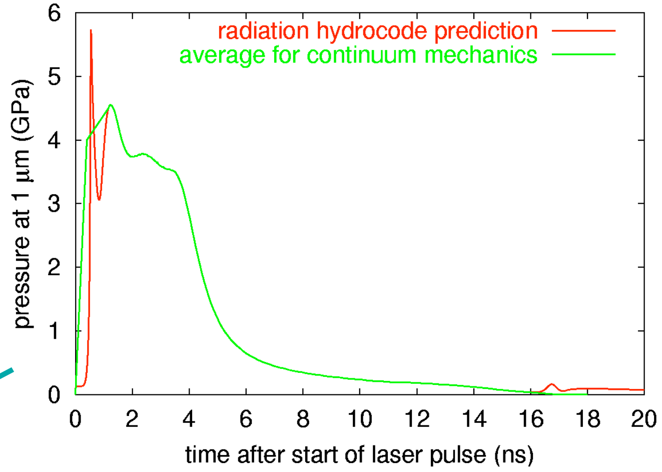
Line-imaging velocimetry has shown no evidence of spatially-varying drive over central ~50%.
Some variation was observed in displacement interferometry (i.e. integrated) after tens of ns.

Time-dependent response: rad-hydro and continuum mechanics



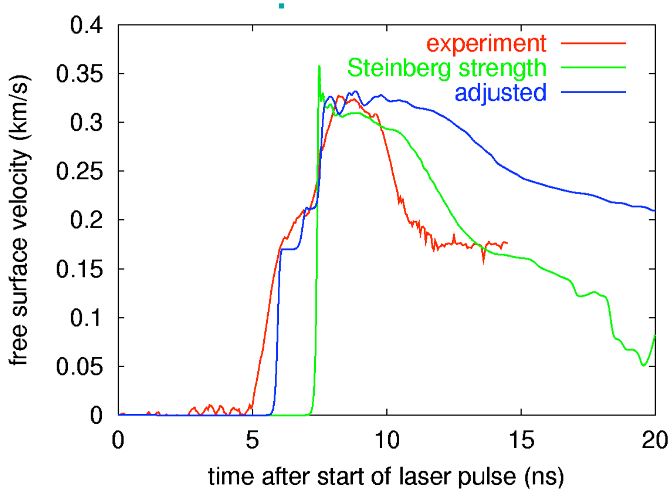
Measured/planned irradiance history

Rad-hydro, simple/no strength (HYADES)



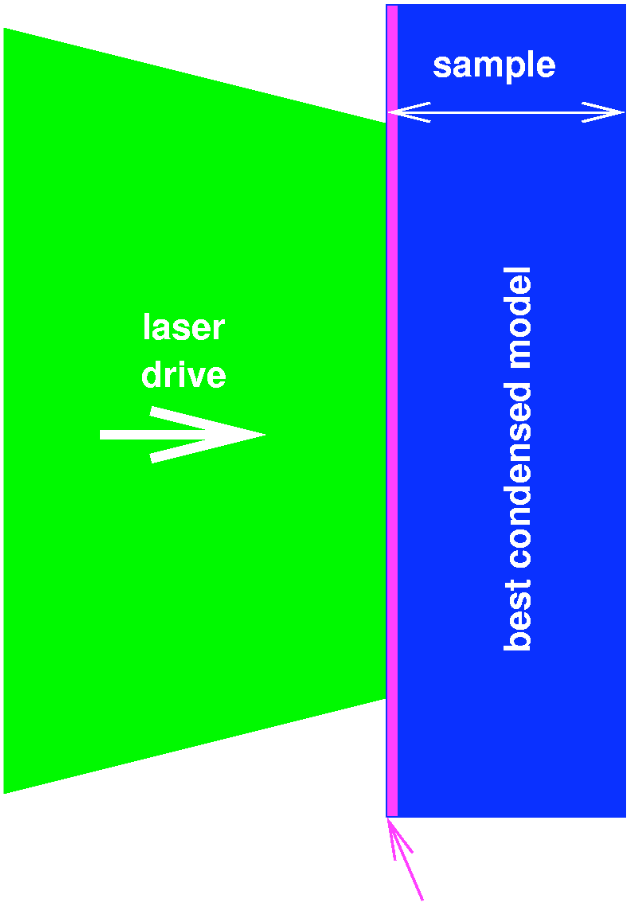
Stress history predicted just inside sample

Continuum mech, strength etc (LAGC1D/LAGC)



Surface velocity history (etc), cf experiment

Radiation hydrodynamics / continuum mechanics simulations



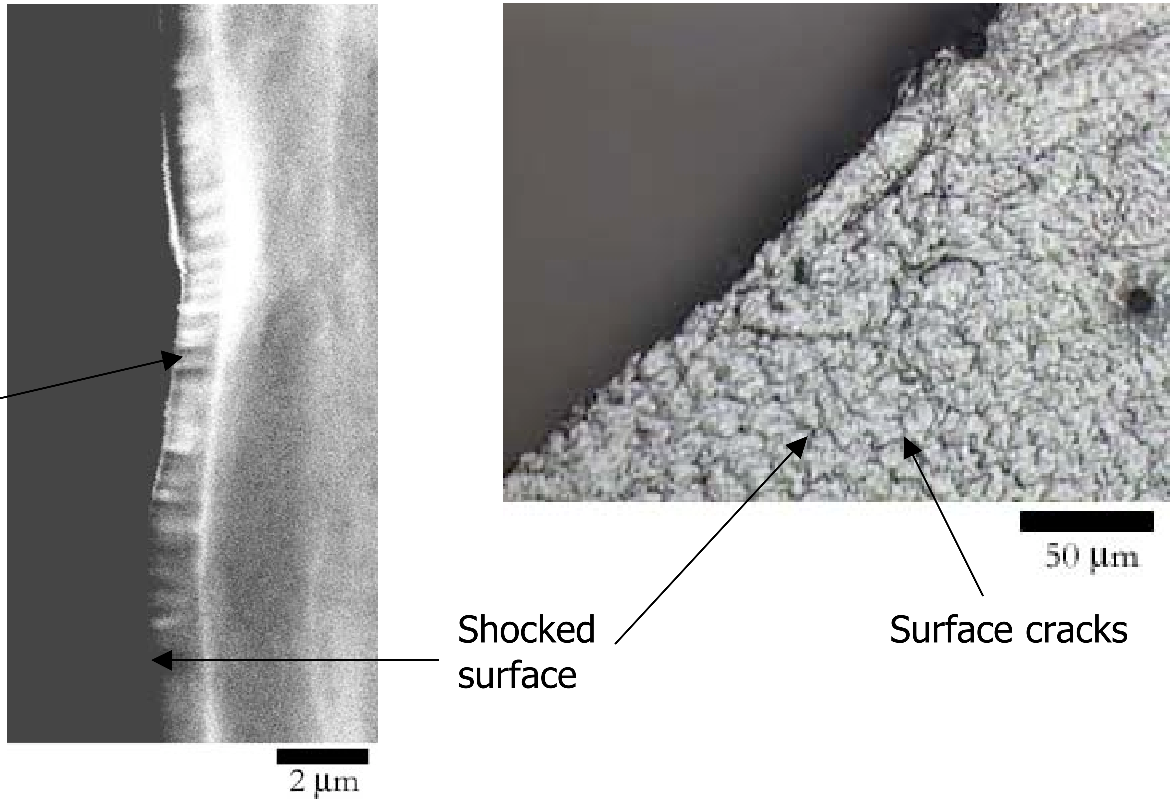
best plasma model
(acceptable for condensed)
thickness: 1 micron

Usual situation:
reasonable condensed model (e.g. QM calculations + shock wave data);
no validated model for (possibly mixed-species) plasma.

Various models used in ablation layer; best condensed model elsewhere.

“Plasma” model should give reasonable initial density and compressibility in condensed phase.

Ablative loading: phenomena near drive surface



Columnar microstructure

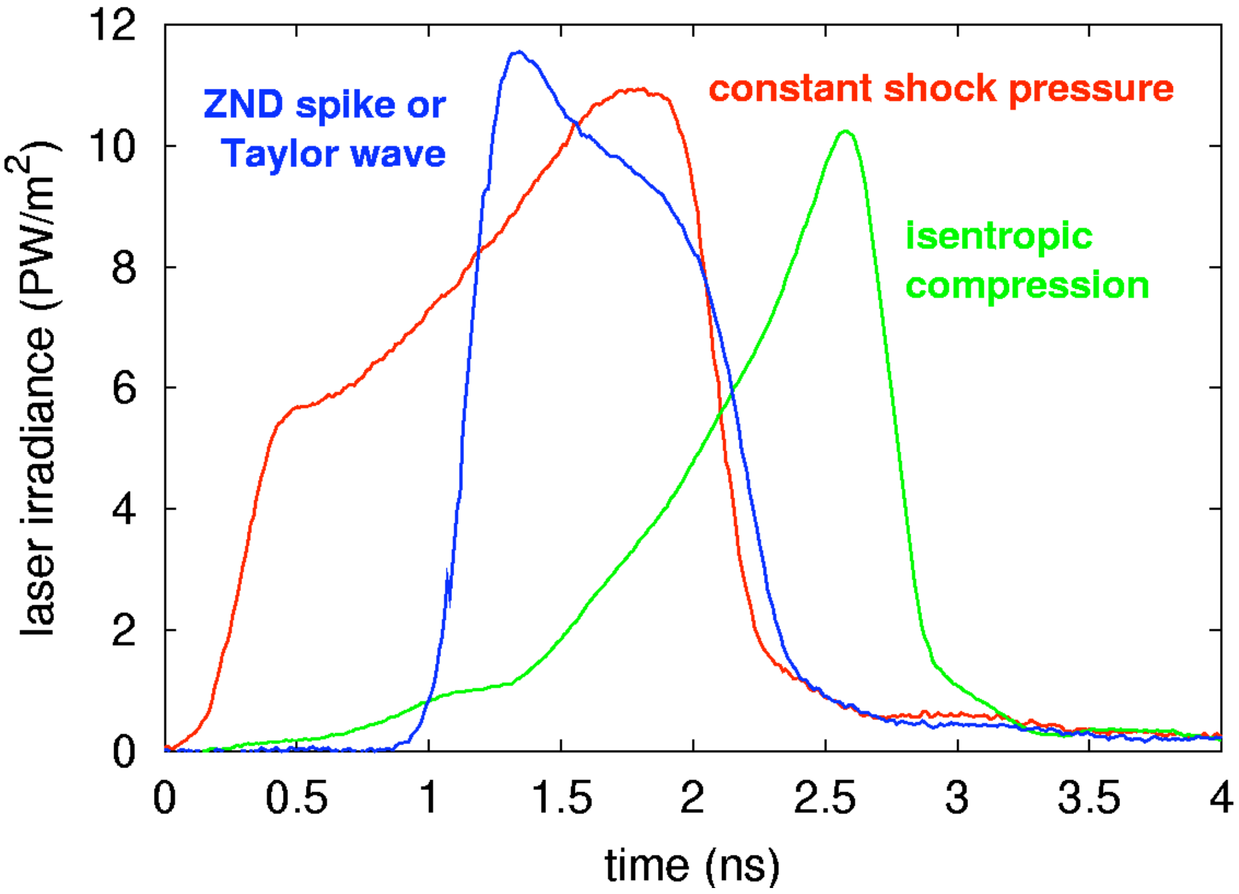
Shocked surface

Surface cracks

Postshot recovered samples (here NiAl crystal: Loomis and Peralta).

~1 ns drive to ~10 GPa: ~1 micron layer shows evidence of recrystallization, presumably following melting; microstructure in bulk is unaffected.

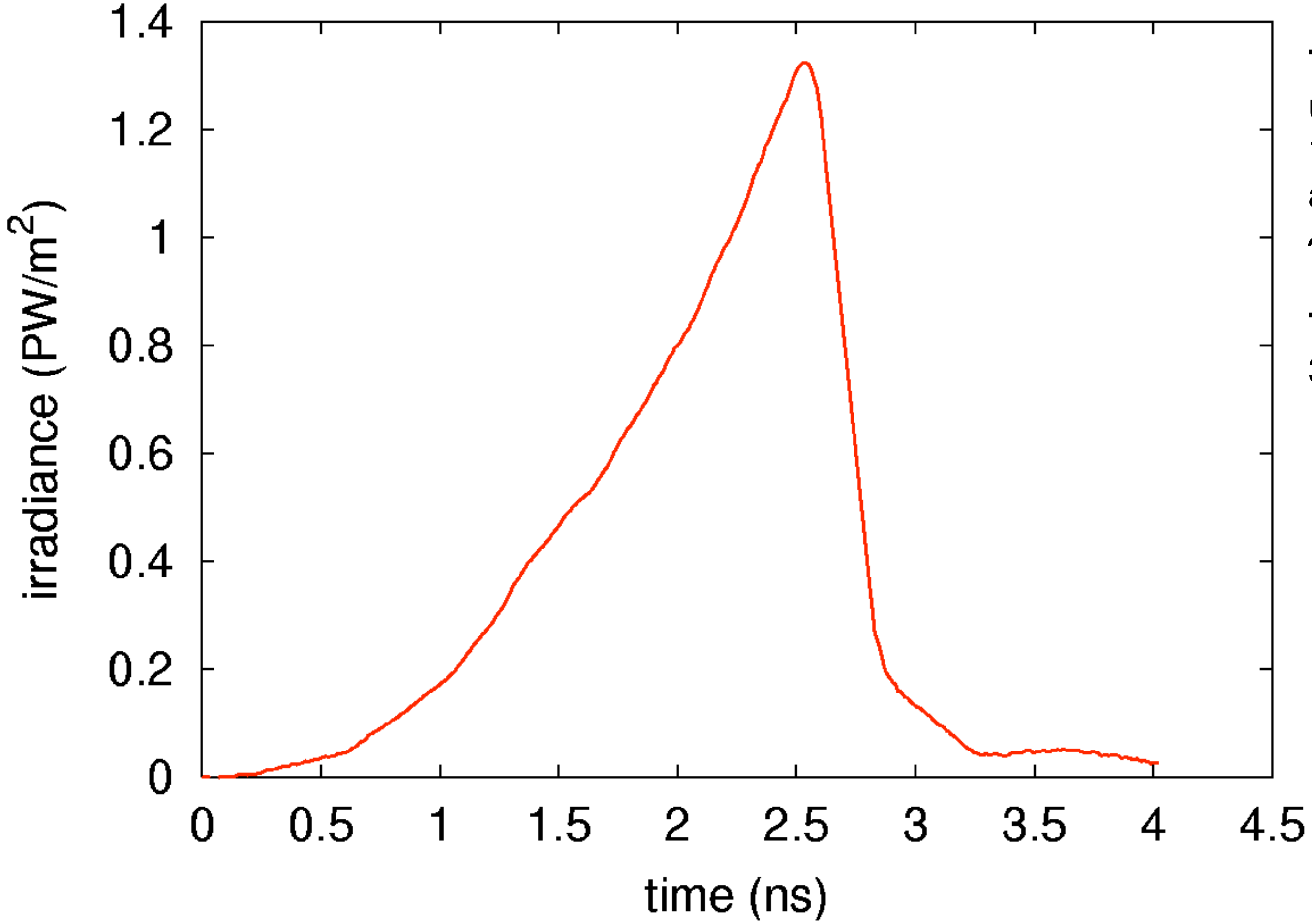
Finite risetimes: “always isentropic”



Heating and breakdown of condensed sample (poorly / arbitrarily modeled) sharpens foot.

Few tens of ps rise: shocks almost always develop from ramp (demonstrated to occur e.g. Be crystal data).

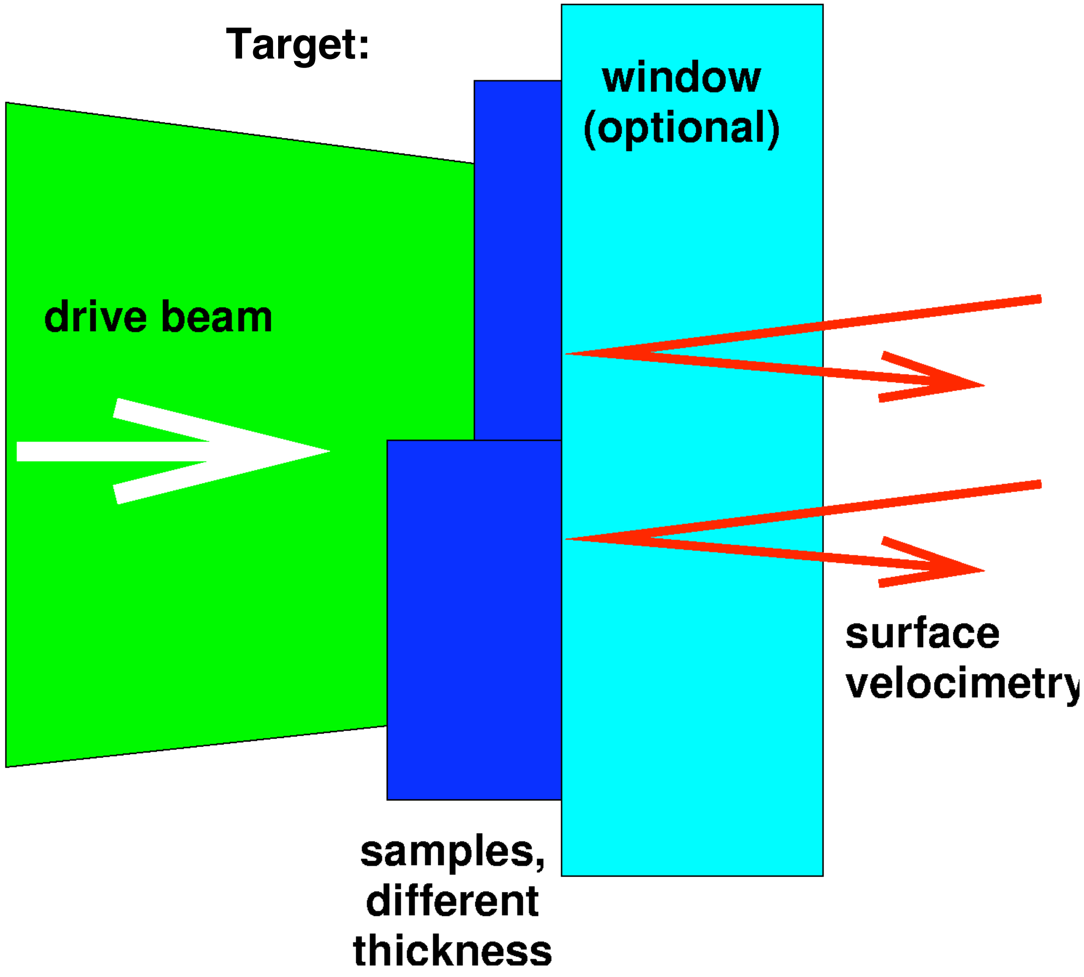
TRIDENT can deliver smoothly ramped laser pulses



TRIDENT in ns mode: up to 13 elements of 180 ps each; amplitudes ~independent.

TRIDENT shot 15018: 33 J

Simultaneous irradiation of multiple samples



Target:

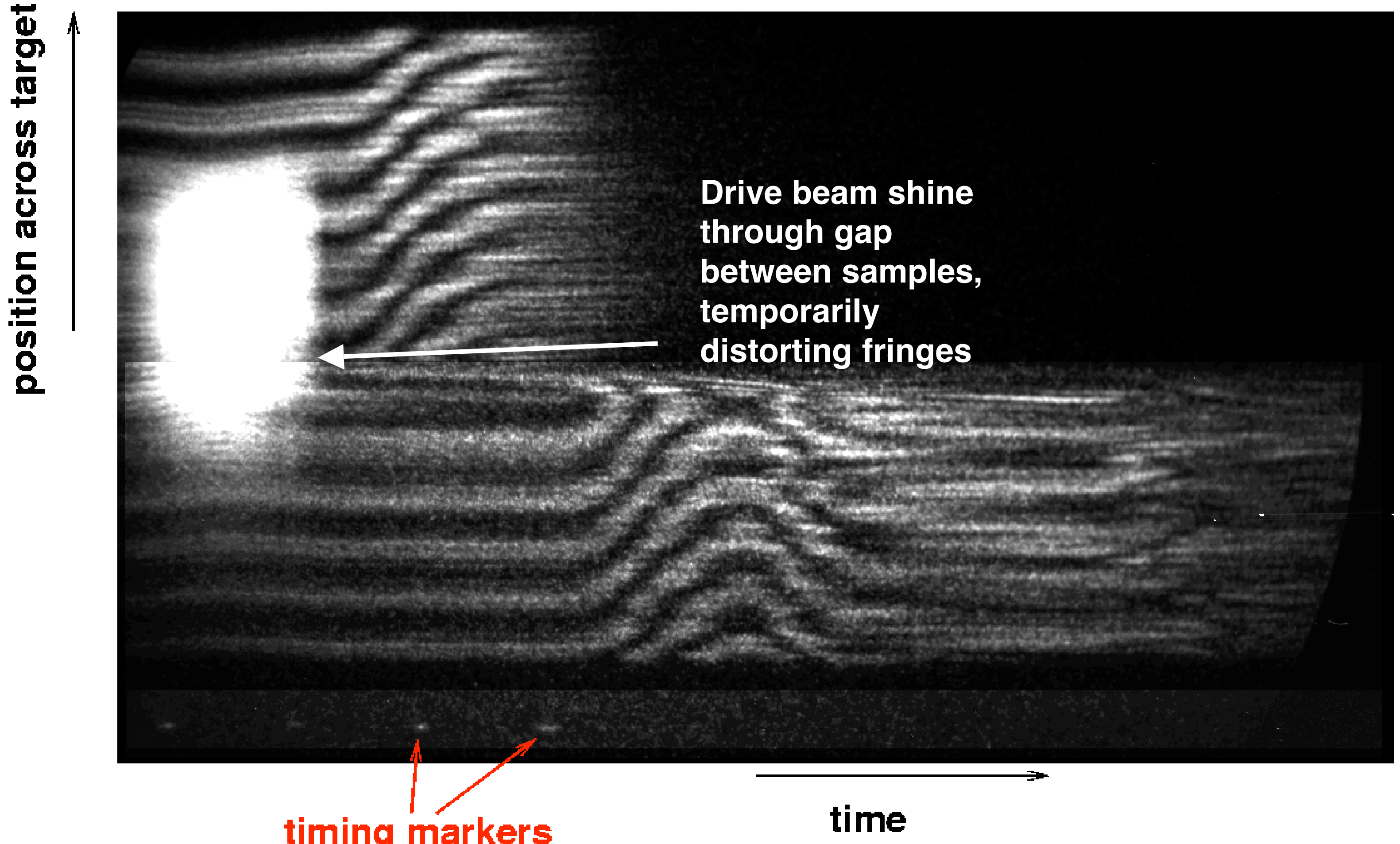
window
(optional)

drive beam

surface
velocimetry

samples,
different
thickness

Example LICE line VISAR record

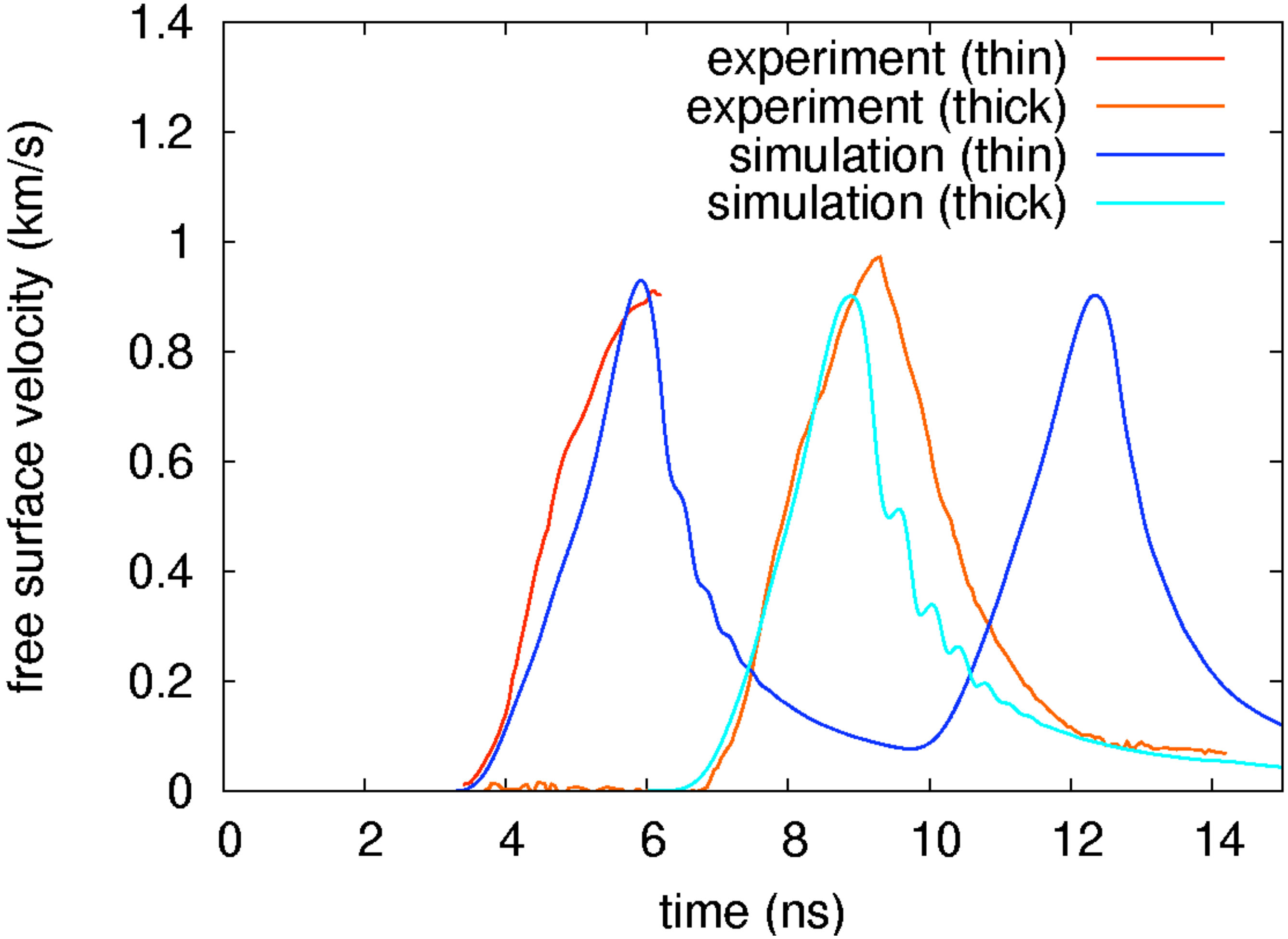


Drive beam shine through gap between samples, temporarily distorting fringes

timing markers (2 ns apart)

TRIDENT shot 15018:
Si (100), 30 and 59 μm; 33 J, 2.4 ns
425 m/s/fringe, 2 mm field

Rad-hydro simulations of LICE data

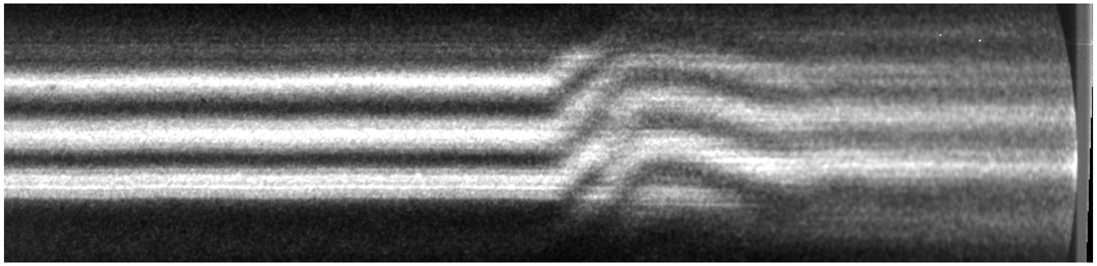


TRIDENT shot 15018:

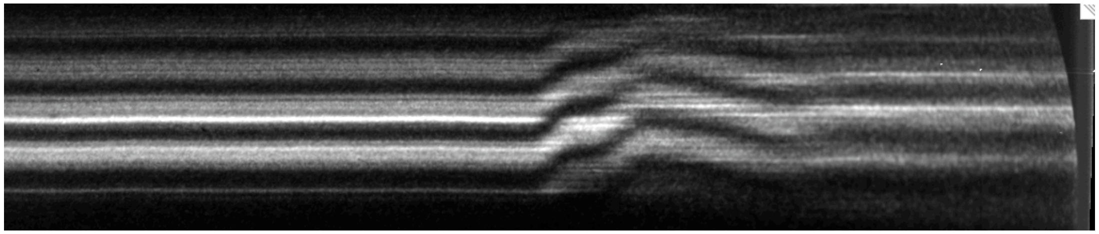
Si (100), 30 and 59 μm;
33 J, 2.4 ns

Shock and quasi-isentropic data for Zr

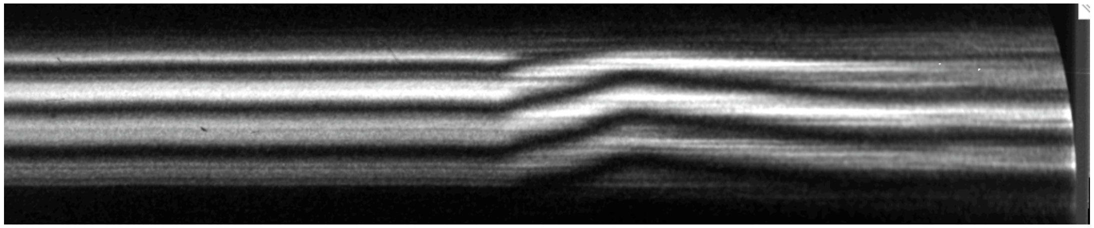
Foils, line-VISAR records, 800 m/s/fringe sensitivity, recording period of 20 ns, different delays:



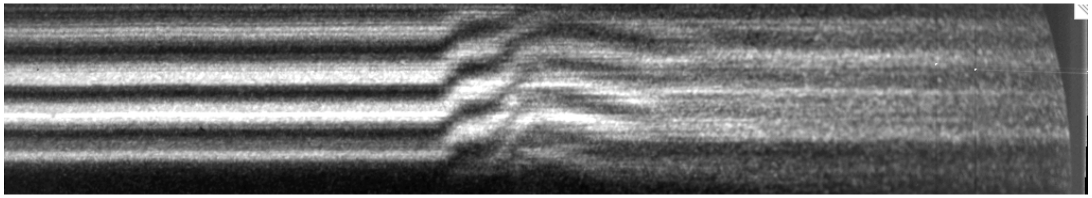
Shock (shot 17130):
26 μm
102 J, 2.5 ns
~17 GPa



LICE (shot 17137):
26 μm
48 J, 2.5 ns



LICE (shot 17138):
61 μm
49 J, 2.5 ns



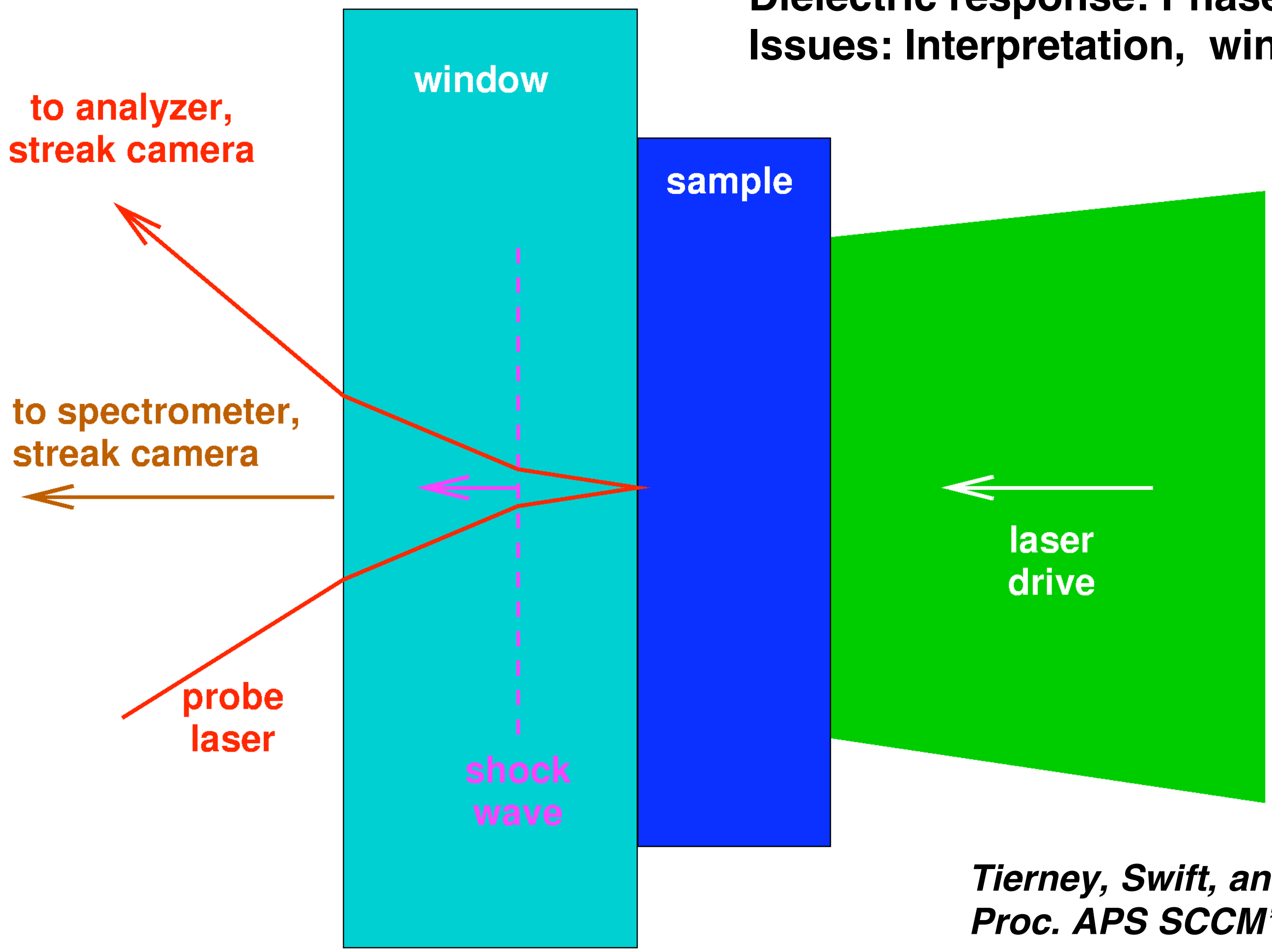
LICE (shot 17139):
26 μm
108 J, 2.5 ns

Diagnostics for material response

- Surface velocimetry: EOS, elastic constants, flow stress, phase changes (through volume change)
- Emission spectroscopy: temperature, hence EOS, phase changes
- Electron-photon and ion-photon interactions: density of states (EOS components), phase changes - e.g. ellipsometry, Raman spectroscopy
- In-situ x-ray diffraction: compression (EOS), lattice deformation (phase changes, elastic and plastic strain)
- Imaging velocimetry and displacement interferometry: polycrystal / grain boundary effects
- Sample recovery and micrography

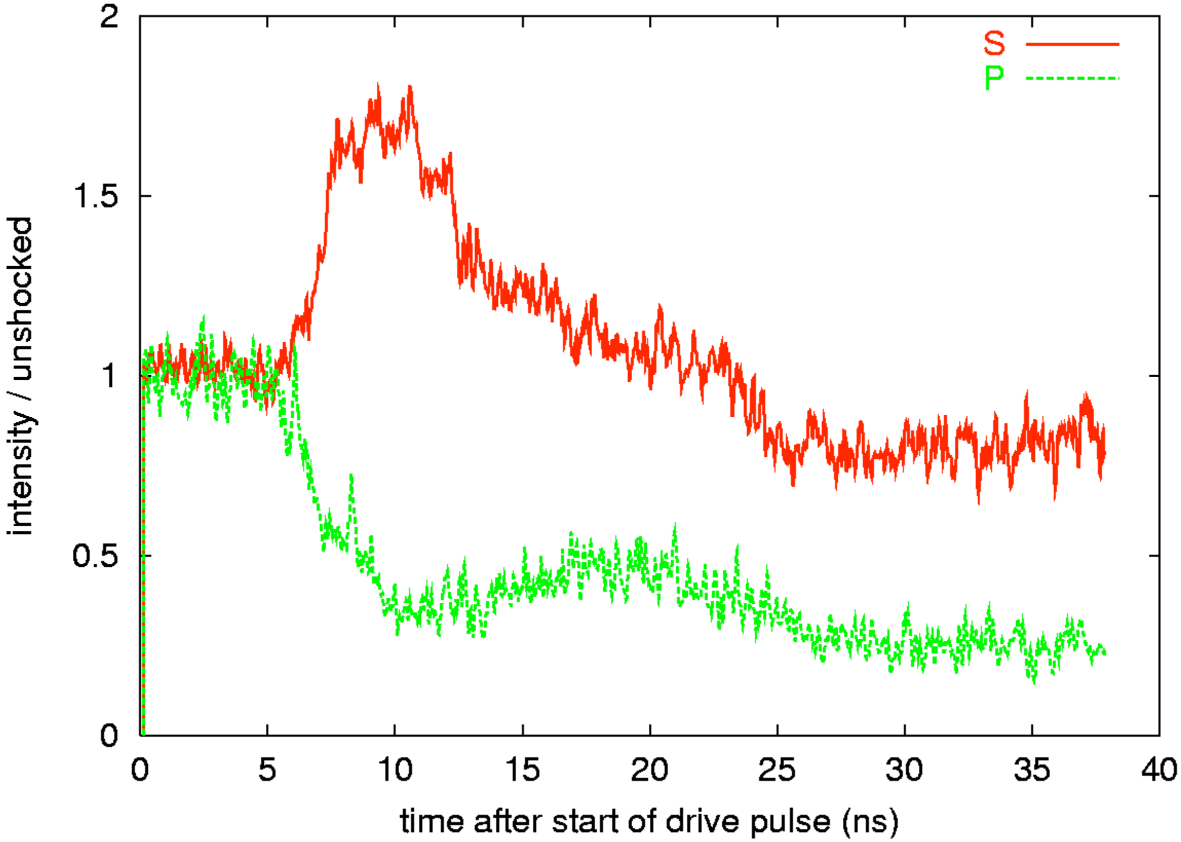
Dynamic ellipsometry and emission spectrometry

Dielectric response: Phase change, temperature
Issues: Interpretation, window corrections



Tierney, Swift, and Johnson,
Proc. APS SCCM'03

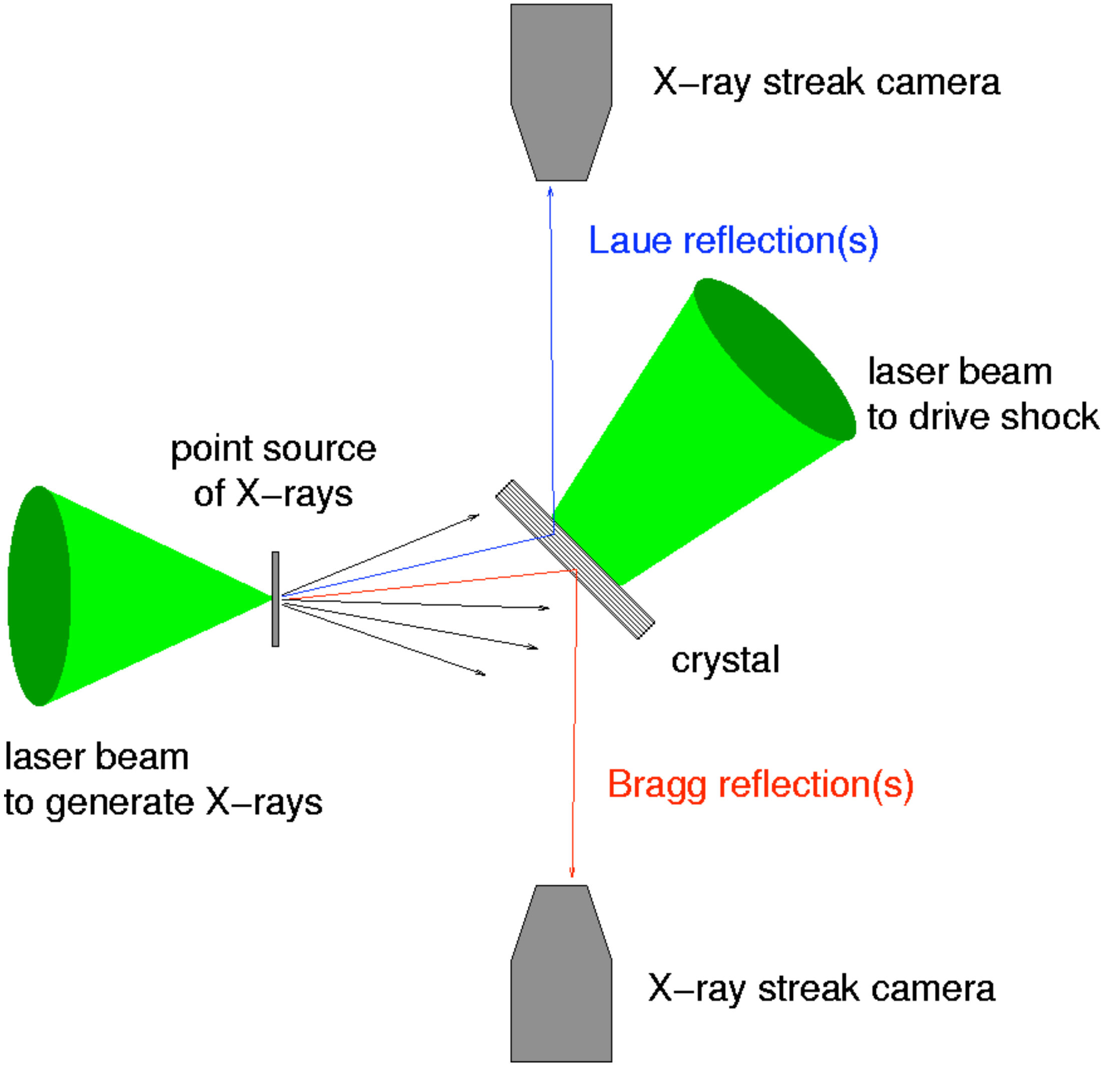
Dynamic ellipsometry



TRIDENT shot 14972: Sn with LiF release window.
Pressure on release = 28 GPa.
(Signals unchanged on release to lower pressures.)

- Indicates phase change at sample surface.
- Scoping experiments performed on Si; melt demonstration on Sn.
- Window characterization shots performed using W/LiF (W not expected to melt or exhibit solid-solid changes up to several hundred GPa)
- Series of shots fired on Be foils: strong signal at relatively low pressures. BeO / band structure?

Transient X-ray diffraction

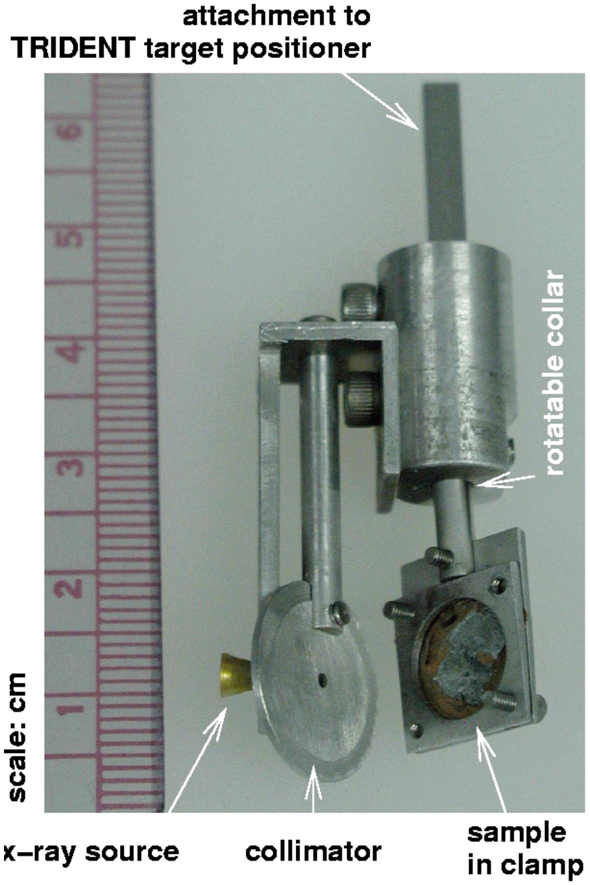


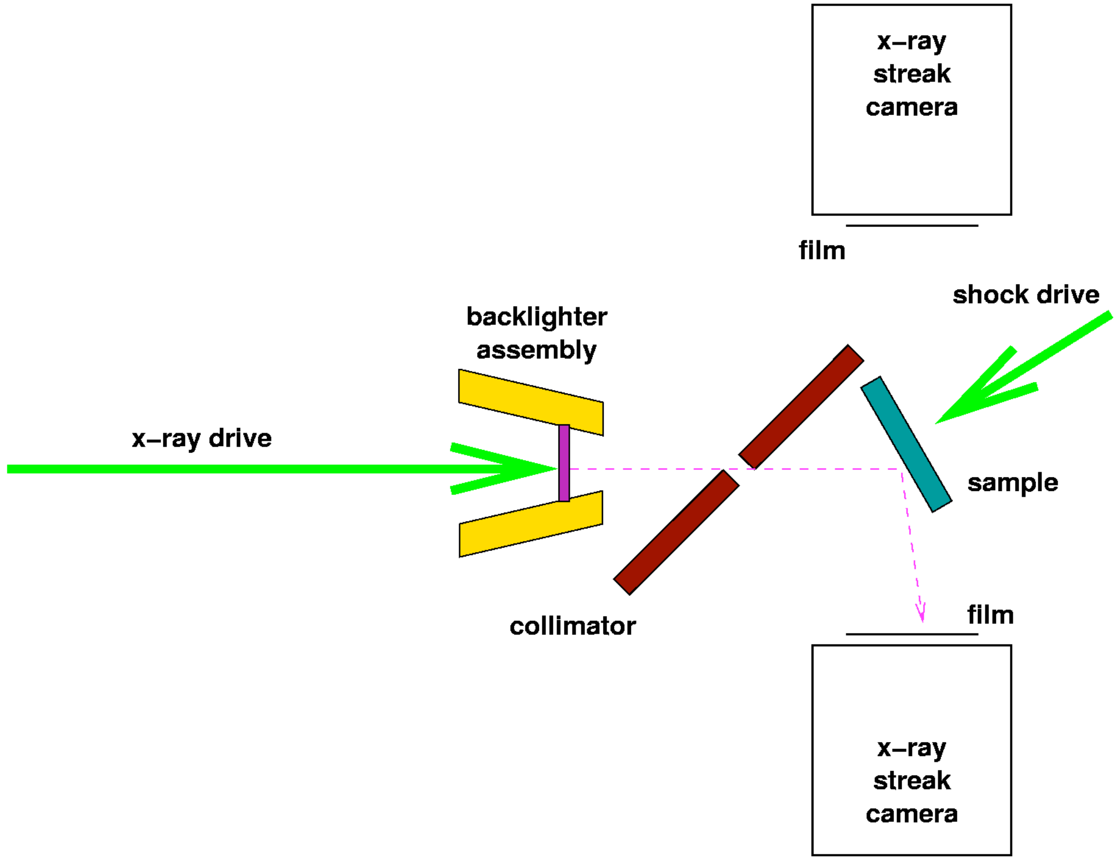
X-rays penetrate
=> sample different states through thickness

Crystal + diverging X-rays:
diffracting point moves across surface with compression.

TRIDENT: max photon energy
~ 6 keV or ~ 2 Å,
~1 ns duration

Polycrystal TXD



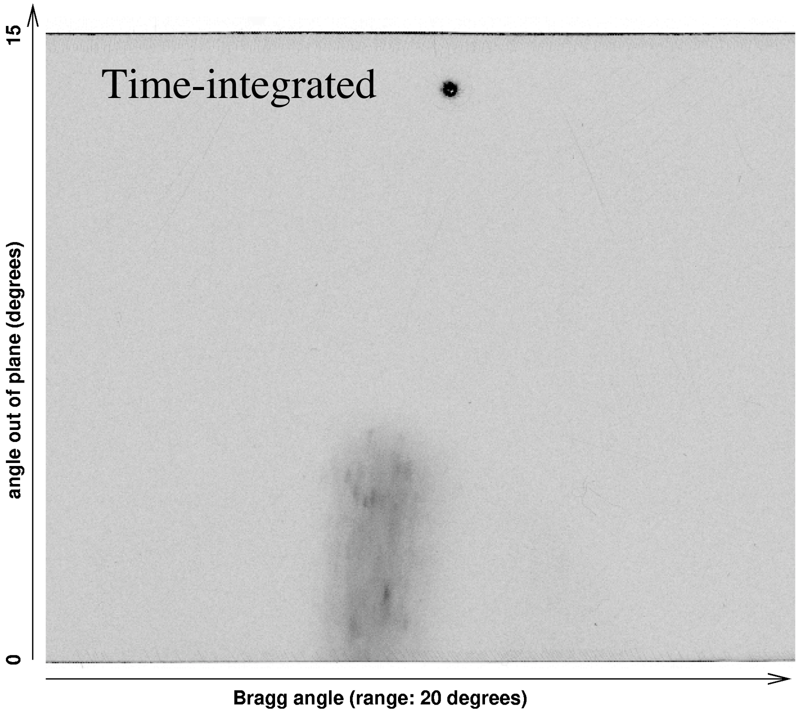


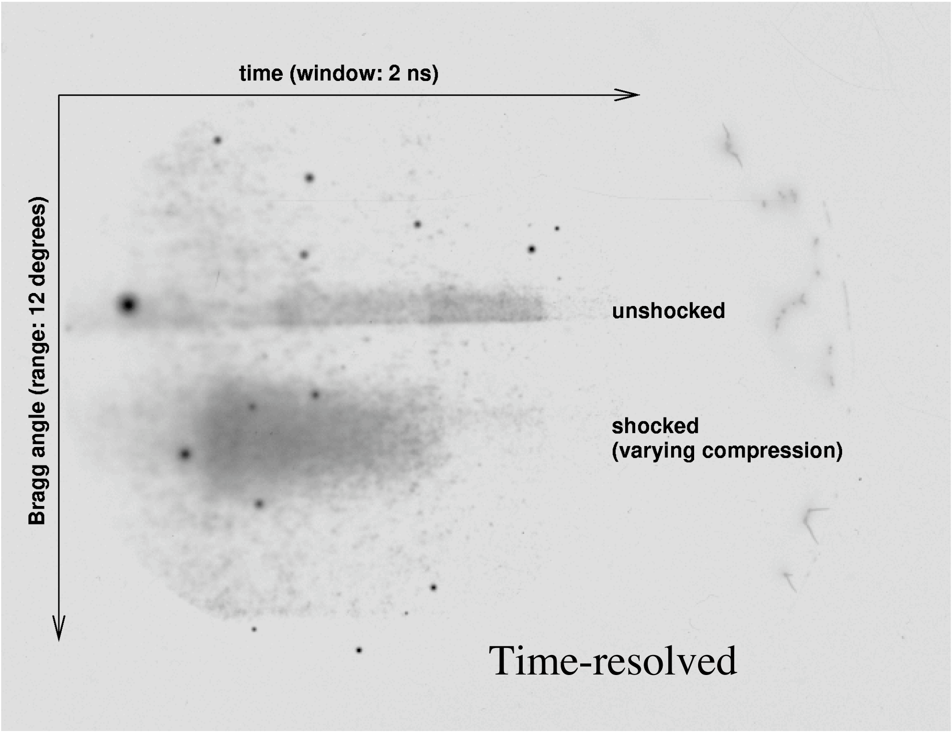
Desirable for TXD at high pressures, requiring smaller drive spot.

May be necessary for response of representative Be-Cu material: fabrication method may matter.

Also desirable to follow phase changes: daughter phase may be polycrystalline.

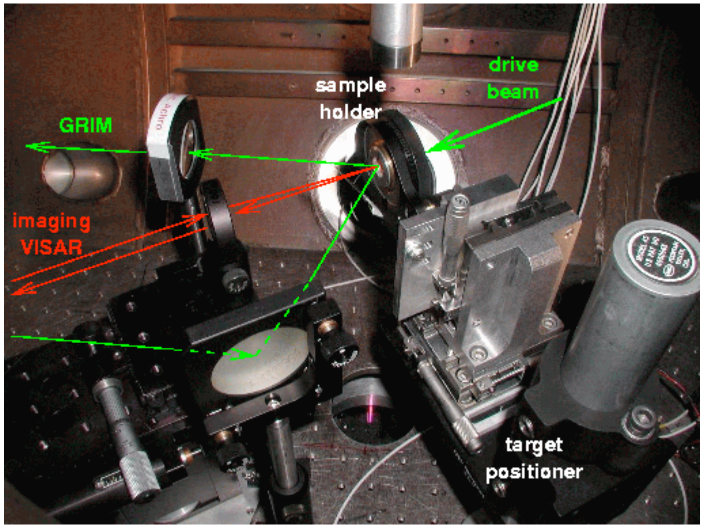
Polycrystal TXD: results

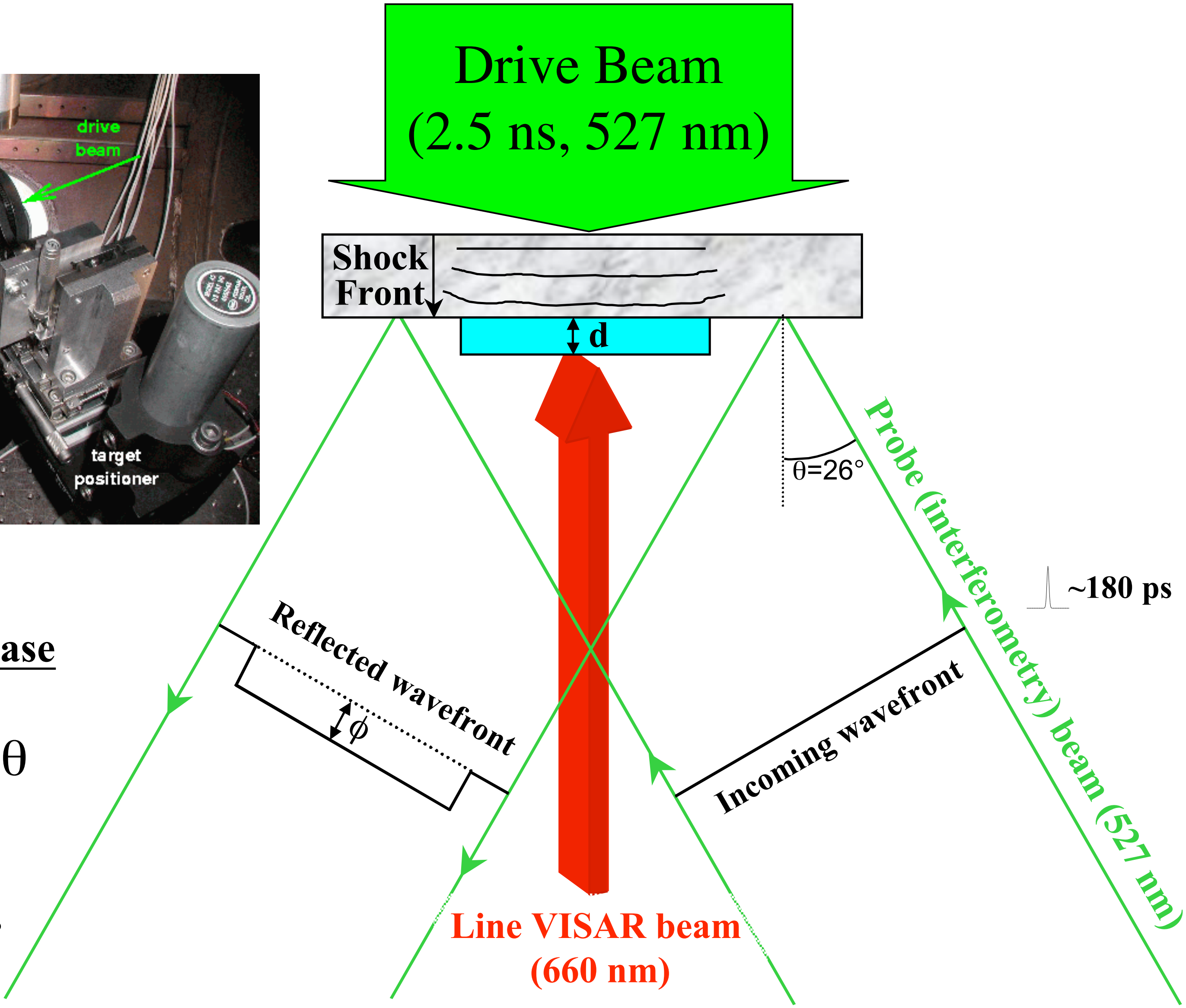




TRIDENT shot 15002: Be foil, 11 GPa shock.
Shocked signal ⇒ 7.1 to 18.4 GPa isotropic, or flow stress = 3.4 to 8.1 GPa (uniaxial)
c.f. observed flow stress in foils ~2.5 to 6 GPa from velocimetry (thickness-dependent)

Imaging displacement interferometry



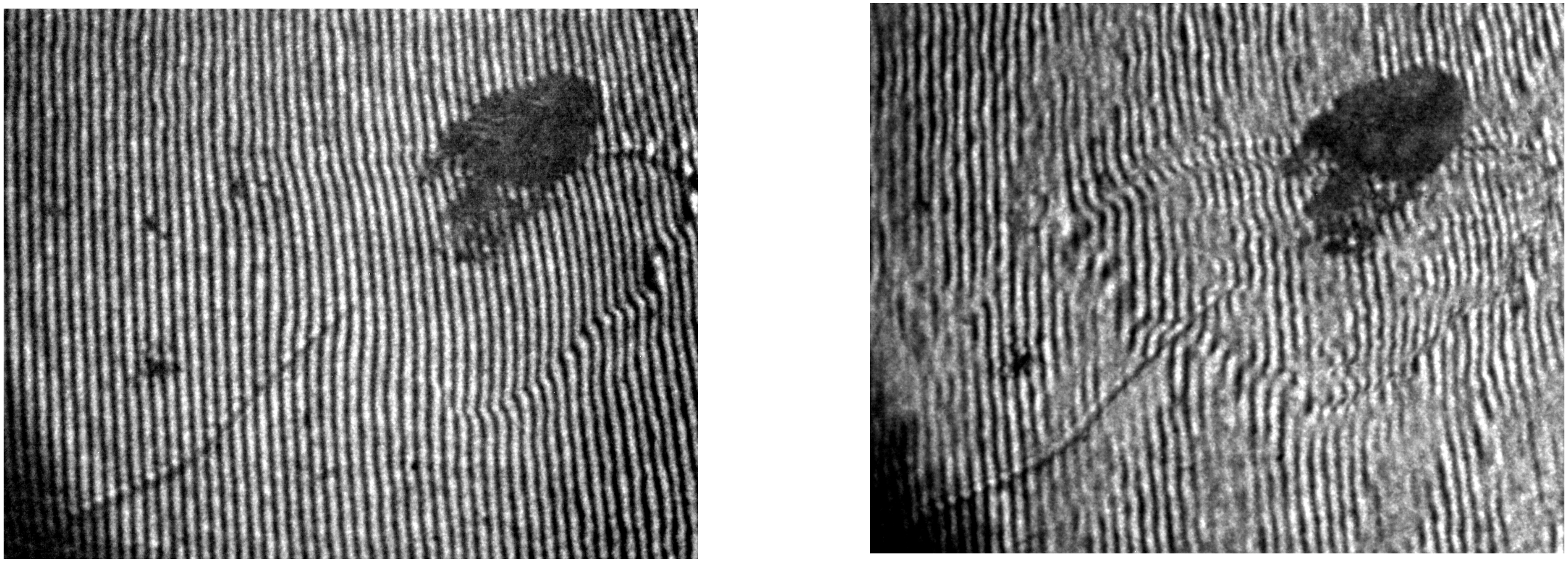


Displacement-phase relationship:

$$d = \phi\lambda / 4\pi\cos\theta$$

S.R.Greenfield et al,
Proc APS SCCM '03

Imaging Michelson displacement interferometry



Shown: NiAl bicrystal, ~1 x 1 mm, frames 6 ns apart after shock breakout.

Fringes show relative surface relief: included grain is rising out of surface.

Greenfield, Koskelo, Swift, Proc. APS SCCM ‘03.

Conclusions

- Versatile loading history from TRIDENT: shock / multiple shock / decaying shock / ramp wave
- Diagnostics demonstrated for EOS, flow stress, phase changes, heterogeneous response, electronic and lattice processes
- Diagnostics include imaging surface velocity and displacement, emission and reflection spectrometry, x-ray diffraction
- Published EOS reproduce mechanical data on Be Hugoniot and isentrope
- Discrimination between EOS (thus Lindemann melt predictions): need more temperature data

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