Possibilities for Opacity Experiments Using TRIDENT Laser Laboratory:

and interesting observations at the OMEGA laser

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(an opacity novice)

P-22: Hydrodynamics and X-ray Physics

Acknowledgements to contributors to this talk

- P-24 Folks: Jonathan Workman, Juan Fernandez, Robert Gibson, Tsutumo (Tom) Shimada, Randall Johnson, Jim Cobble, Damian Swift, Dennis Paisley, ShengNian Luo, Bjorn Manuel Hegelich
- And X-1 people: Nelson Hoffman, Barbara DeVolder, Dave Tubbs, Bob Goldman

Outline of talk

- Current TRIDENT capabilities
- Future TRIDENT design
- Possible opacity+EOS experiment designs for TRIDENT
- An opportune example from OMEGA

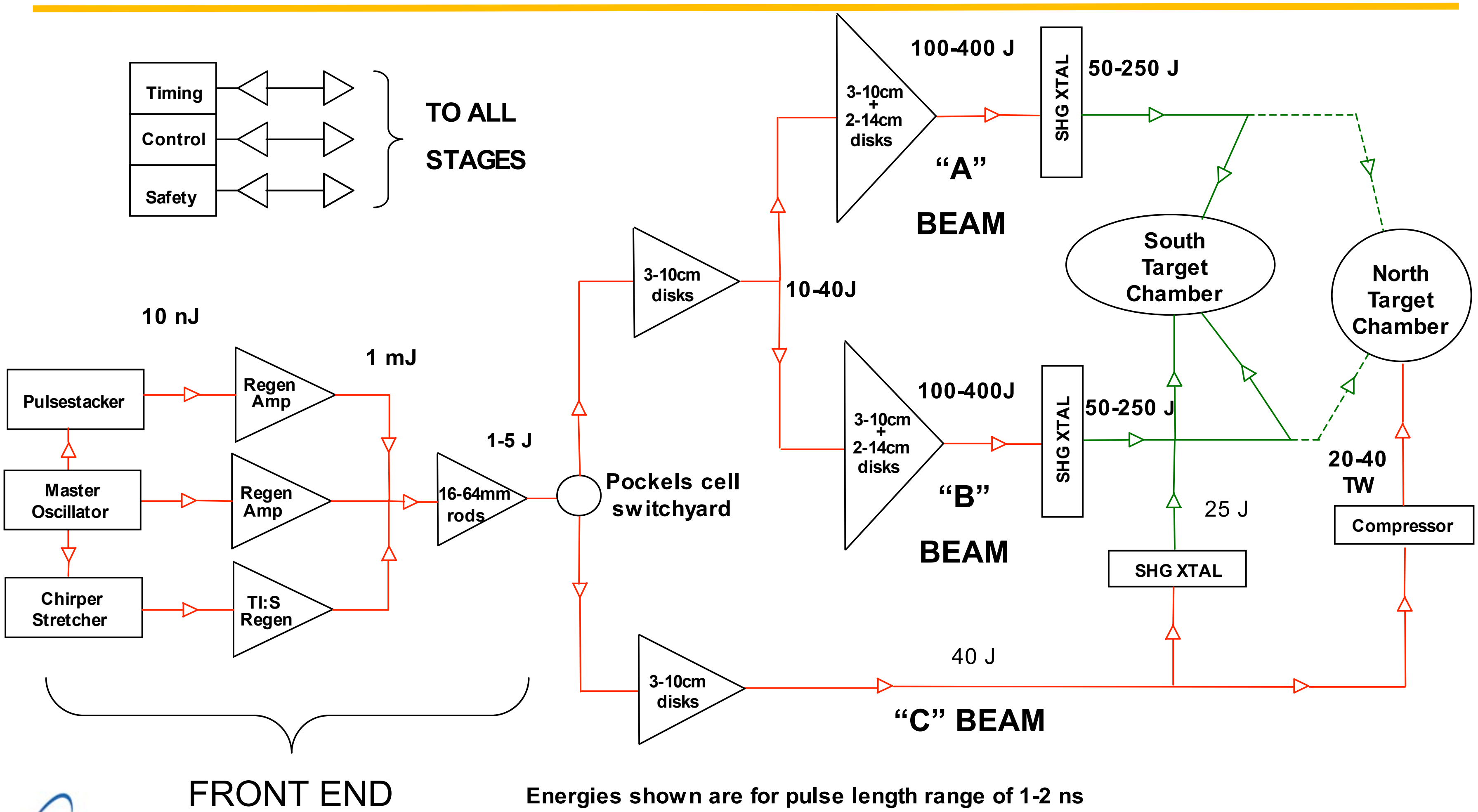
TRIDENT is one of the world's most flexible high-fluence laser facilities

- 3 Nd:glass beams
- Four colors: 1054 / 527 / 351 / 265 nm
- 13 element pulse shaping
- Short pulse ~500 fs to UltraLong pulse ~20 μs
- typical spot sizes: ~10 μm to 8.0 mm
- ~12 shots / day at energies >40 J or
  ~20 shots / day at energies < 40 J

Driver output covers wide parameter space

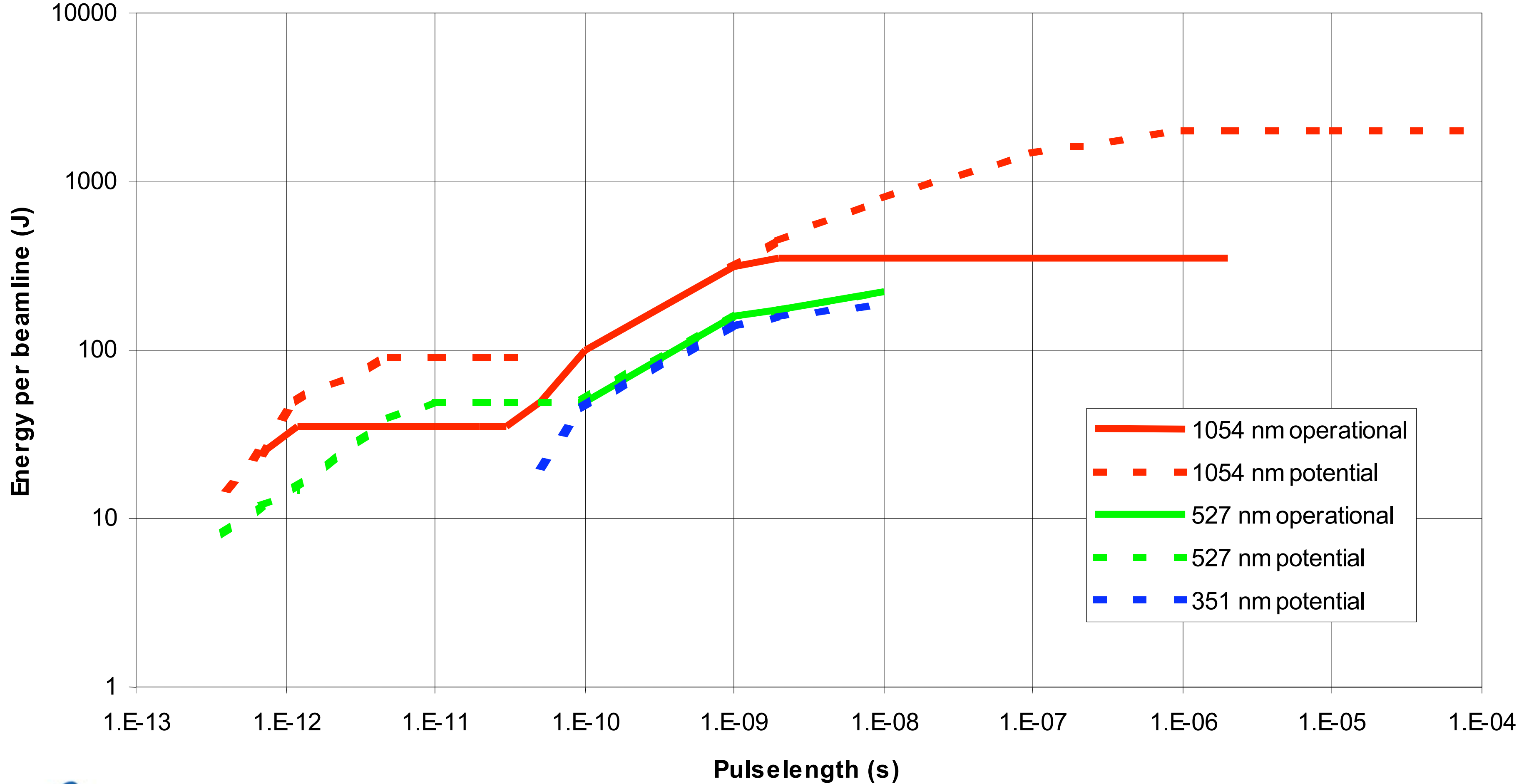
	A & B Beams		C Beam		
Parameter (units)	**Normal**	**Long-pulse**	**Normal**	**SHS**	**Sub-ps**
Wavelength (nm)	527	1053	1053 /527 351	1053 /527 351 /263	1053
Pulse length (ns)	.08-5.0	.08-20000	0.1-2.0	0.1-2.0	0.6 ps
Energy/beam (J)					
100 ps	50	100	50/30/20	5/3/1.5/0.5	30
1-2 ns	250	400	100 /60/40		
100-2000 ns		300			
Spot dia. (μm)	100	100	50	5	20
Irradiance (W cm^{-2})	10^{16}		10^{16}	10^{16}	$>10^{19}$
Number of beams	2	1	1	1	1

TRIDENT has "2½" beams using an Nd:Glass master oscillator, power amplifier (MOPA) laser and 2 target areas

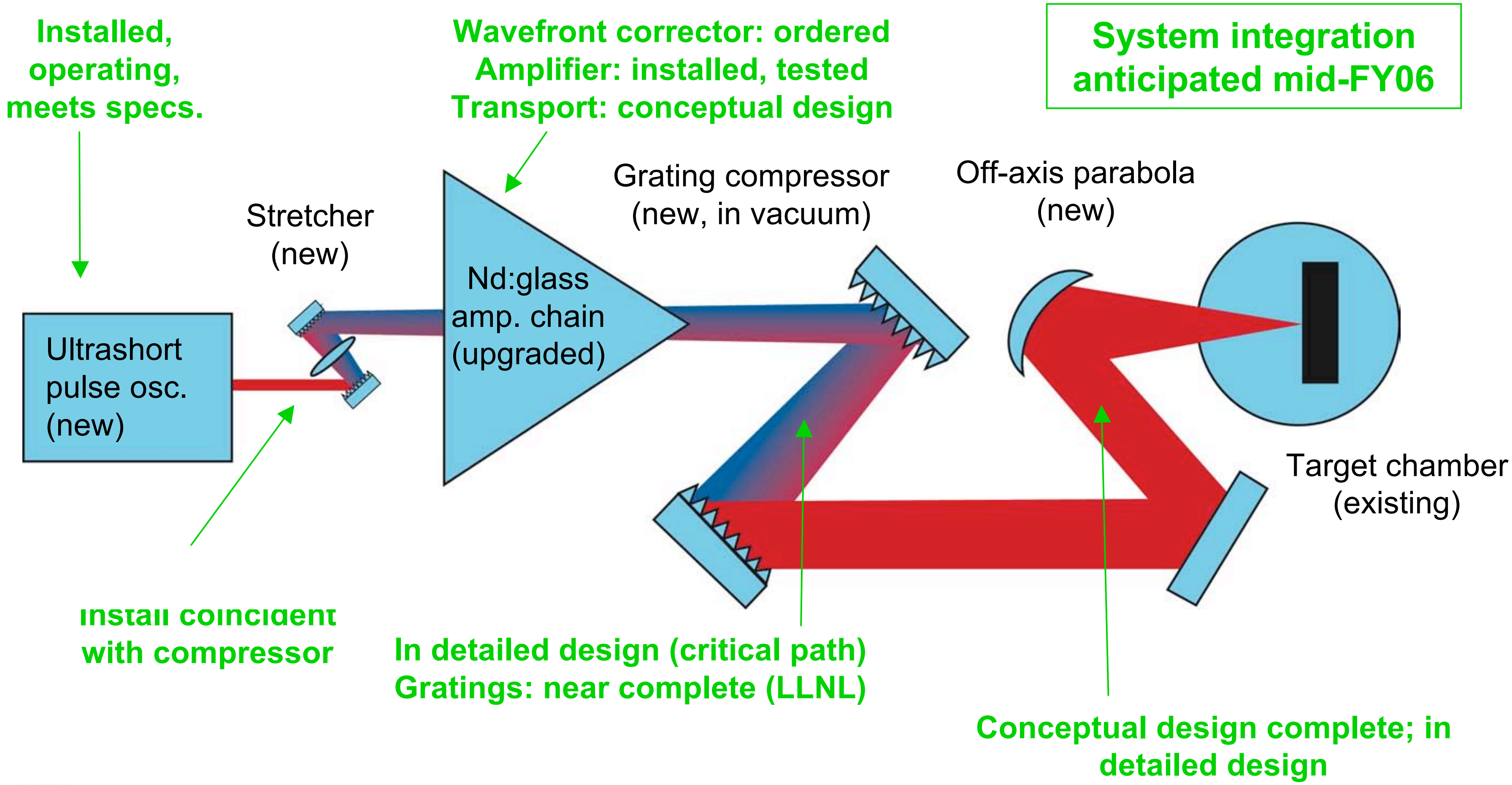


Energies shown are for pulse length range of 1-2 ns

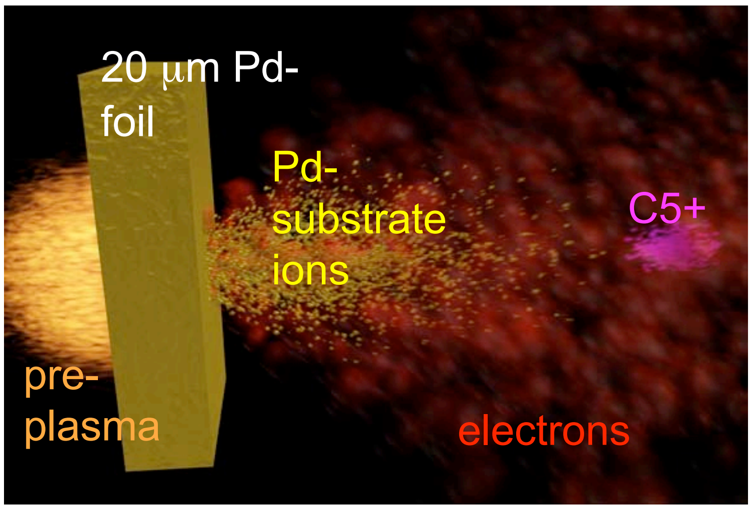
TRIDENT produces energetic pulses over 6.5 orders of magnitude in pulse length.

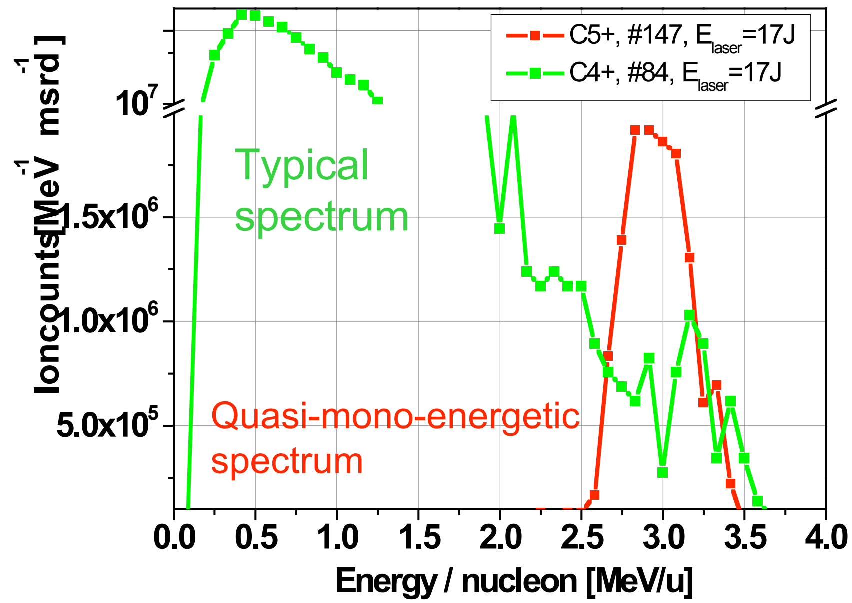


TRIDENT enhancement project is progressing towards a FY06 completion.



First observation of laser-accelerated quasi-mono-energetic ions*



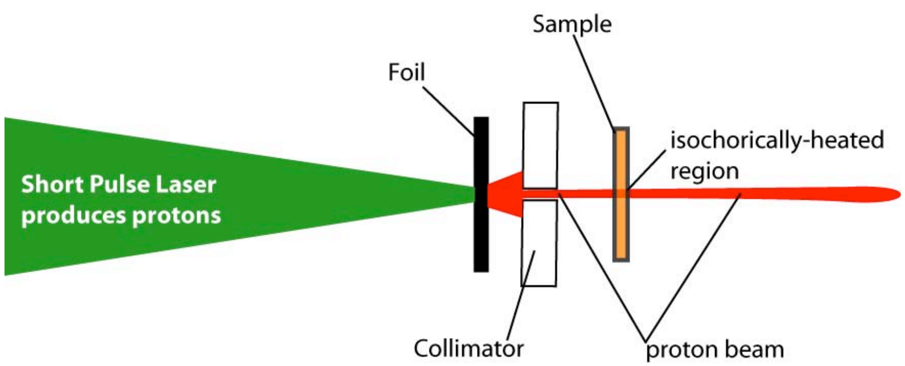


- 2× increase in number of high-energy ions
- 2.5× increase in energy and conversion efficiency
- 3× increase in beam current

*Manuel B. Hegelich, et al. (2005)

Laser-produced proton beams can be used to quasi-isochorically heat a sample to eV temperatures.

- Short pulse laser accelerates ions (protons and heavier particles).
- Ions impact target (mostly transmissive).
- Sample heats ~uniformly if ions penetrate deeply.
- Measurements must be made quickly (possibly NLTE)

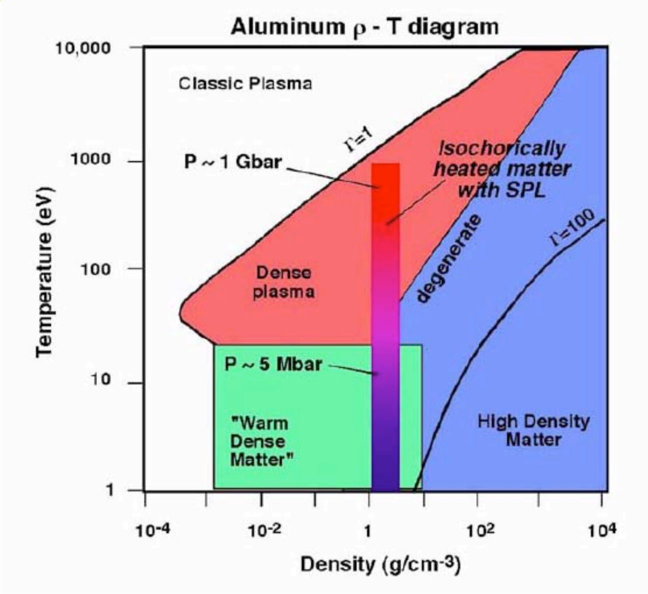


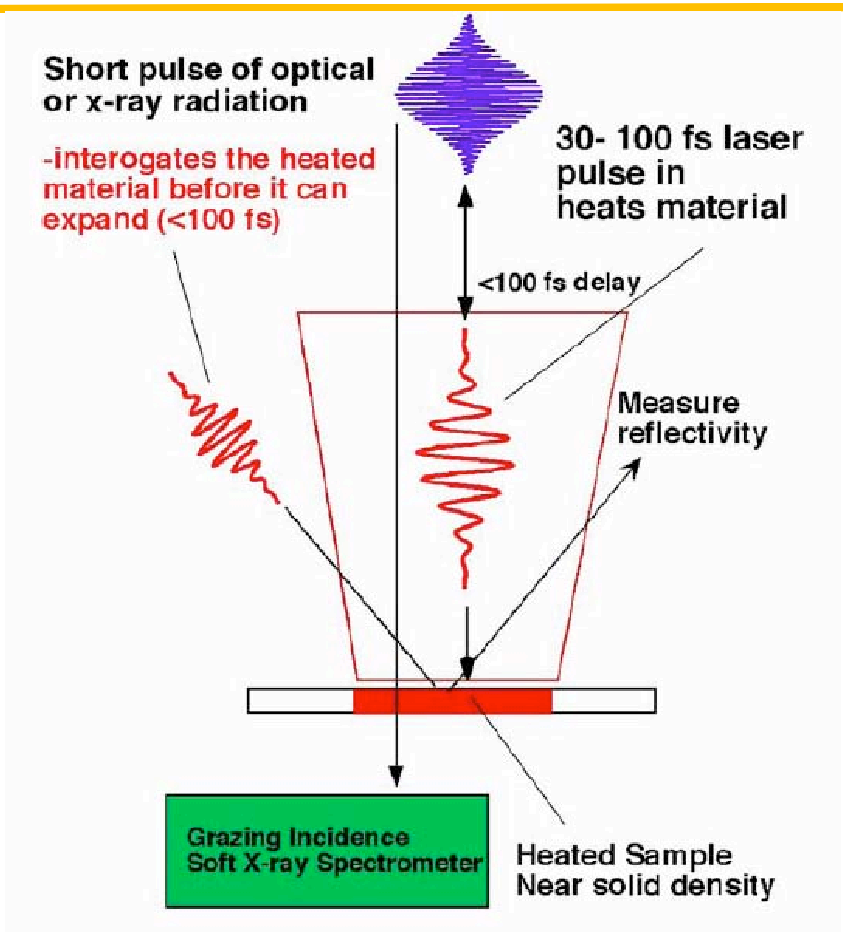
Example:

A 25-µm long, 50-µm diameter aluminum slab can be brought to ~10 eV by a proton beam produced with less than 1-J laser energy in short pulse.

This can be done at TRIDENT

Direct illumination by short pulsed lasers can probe a wide range of pressures along isochors.





- Near Gbar pressures
- Measurements must be made quickly before expansion.
- Likely NLTE.

T. Ditmire et al., Rad. Phys. and Chem., **70**, 535 (2004).

Laser-produced protons can also be used for radiography of samples

Example: LULI experiments

- Up to 10 MeV proton beam produced by 350 fs, $3x10^{19}$ Wcm^{-2}.
- 5 Mbar shock produced by 80 J, 0.5 ns beam.

M. Koenig et al., Nucl.Fusion **44**, S208 (2004)

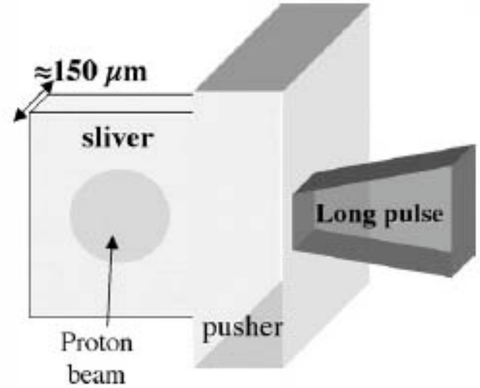


Figure 10. Proton radiography target scheme.

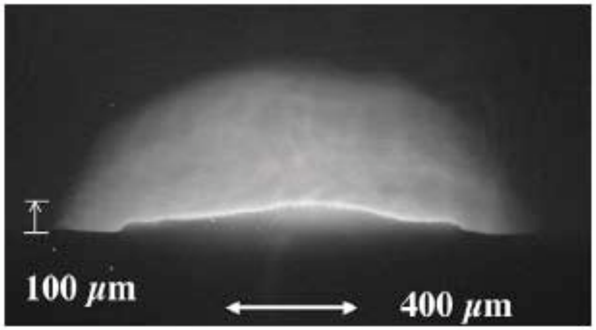


Figure 11. Proton image of an aluminium foil 7 ns after the long pulse beam.

Proton radiography has been performed at TRIDENT by J. Cobble et al, LA-UR-01-6521

Hot electron generation of K-α emission is a very efficient source for hard x-ray production[a]

- Irradiances of ~1.4×10^{18} Wcm^{-2} would produce tin, Sn, K-α at E_k=29.2 keV. (assuming 1-μm wavelength)

- With a 100-TW laser, a 100-μm spot is adequate for producing Sn K-α .

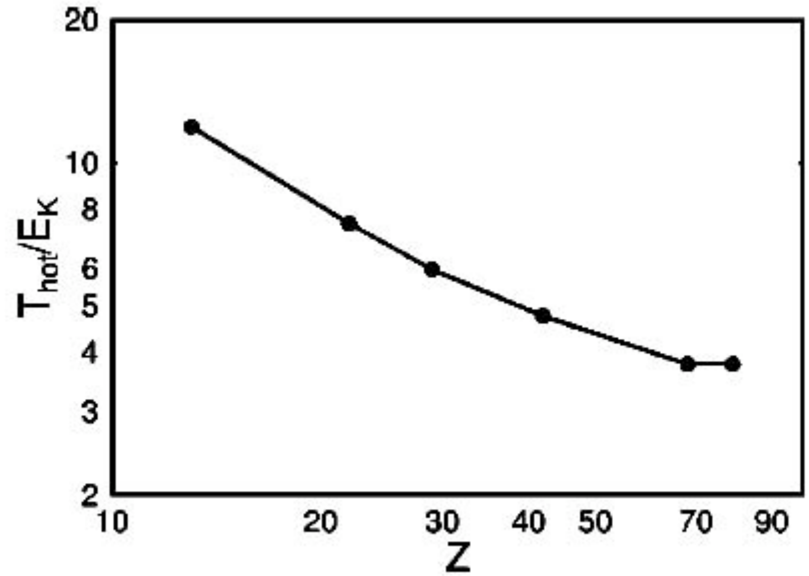


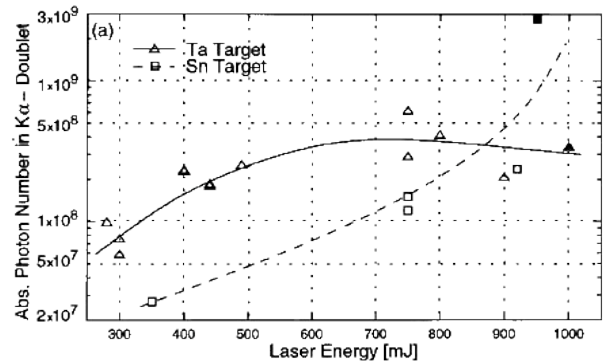
FIG. 5. Optimal ratio of hot-electron temperature to *K*-shell ionization energy for different target materials *Z*.

$$T_{hot} \approx \left(\sqrt{1 + \frac{I\lambda_{\mu}^2}{2.8 \times 10^{18}}} - 1 \right) 511 keV$$

[a]Jonathan Workman, internal memo, P-24-03-086

Previous short pulse laser experiments found high efficiencies and yields in high-Z, K-α x-ray production

- Laser irradiance= 3×10^{17} W/cm^2, with 1 J in 100 fs[a]
- Conversion efficiency to ^{50}Sn K-α (~25 keV) was ~10^{-5}.
- **For TRIDENT: ~10^{11} photons at 100 J[b]**



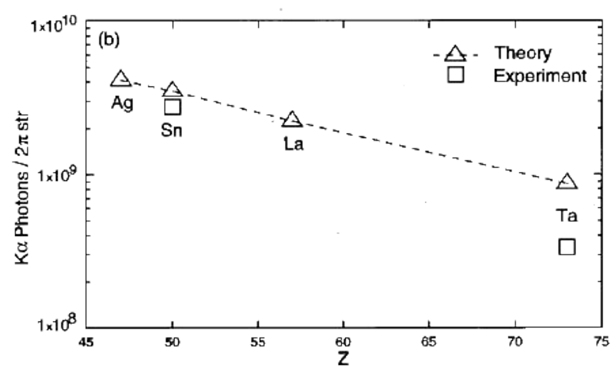
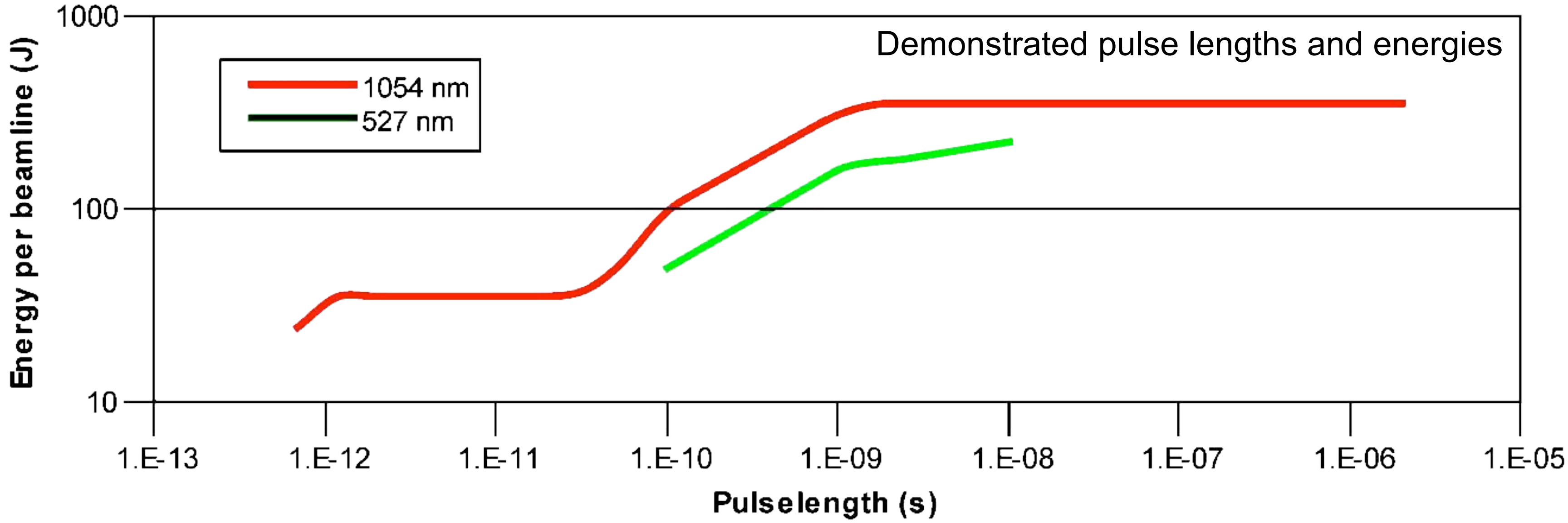


FIG. 10. Comparison of theoretical and experimentally determined $K\alpha$ yield as a function of target material (a) and experimentally determined absolute numbers of photons in $K\alpha$ doublet (b). The curves depict yields calculated using an initial plasma density gradient of $L/\lambda = 1/\lambda[\rho/(d\rho/dz)] = 0.3$. The experimental data in (a) corresponds to the filled points in (b).

[a]Andersson et al., J. Quant. Elec., **33**, 1954 (1997)
[b]Jonathan Workman, internal memo, P-24-03-086

TRIDENT has demonstrated a wide temporal range for dynamic materials experiments.

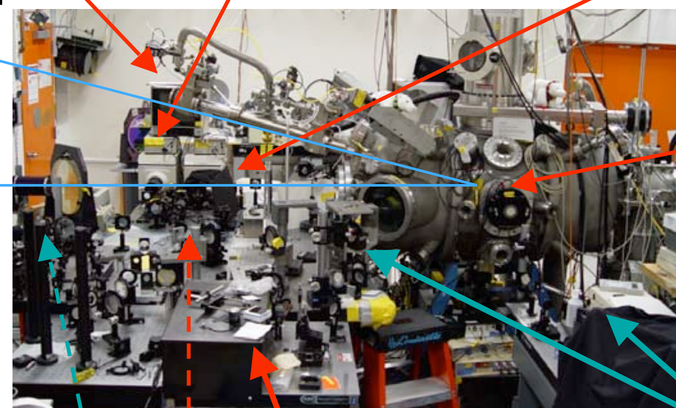


While short pulses are advantageous to producing high energy photons and particles, **shaped** long pulses are ideal for probing a wide range of equation of states for dynamic materials experiments

Many simultaneous diagnostics are used in TRIDENT experiments

sample
collimator
backlighter

x-ray transmission spectrograph
VISAR recording camera(s)
Ellipsometry at 20°



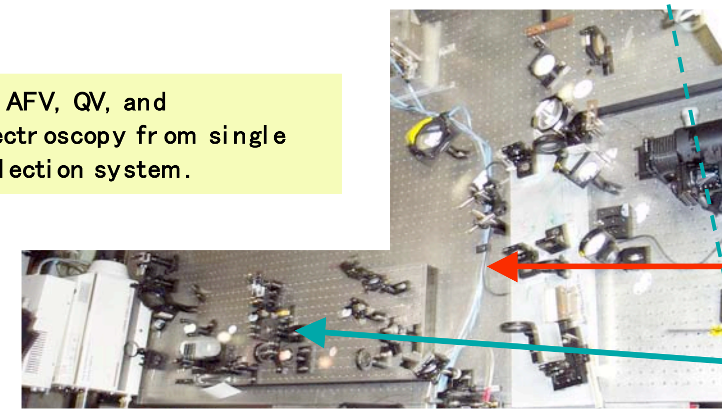
Bragg transient x-ray diffraction cameras (2X)

and crystal spectrometers (inside chamber)

Emission and Raman Spectroscopy In-line with VISAR optics

150 ns, 500 μJ, 660-nm probe laser (1329 nm)

** AFV, QV, and spectroscopy from single collection system.



Line-imaging VISAR (AFV)

Quadrature line-imaging VISAR (QV)

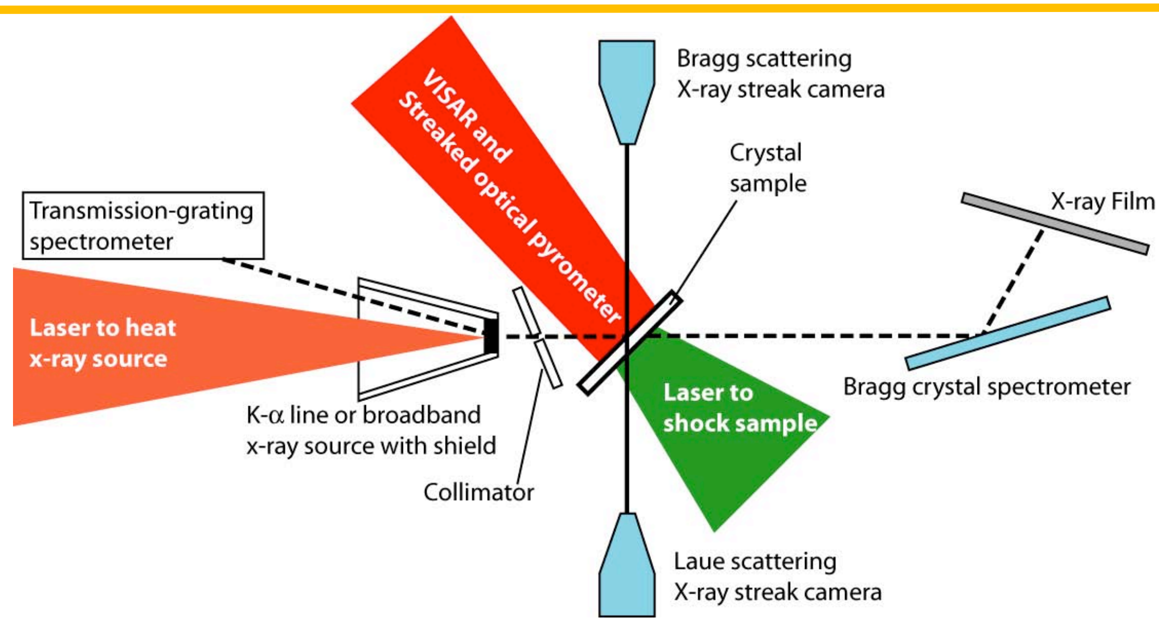
Los Alamos NATIONAL LABORATORY EST. 1943

TRIDENT Los Alamos

The World's Greatest Science Protecting America

NNSA

Direct laser illumination produces Mbar shocks that compress a crystal.

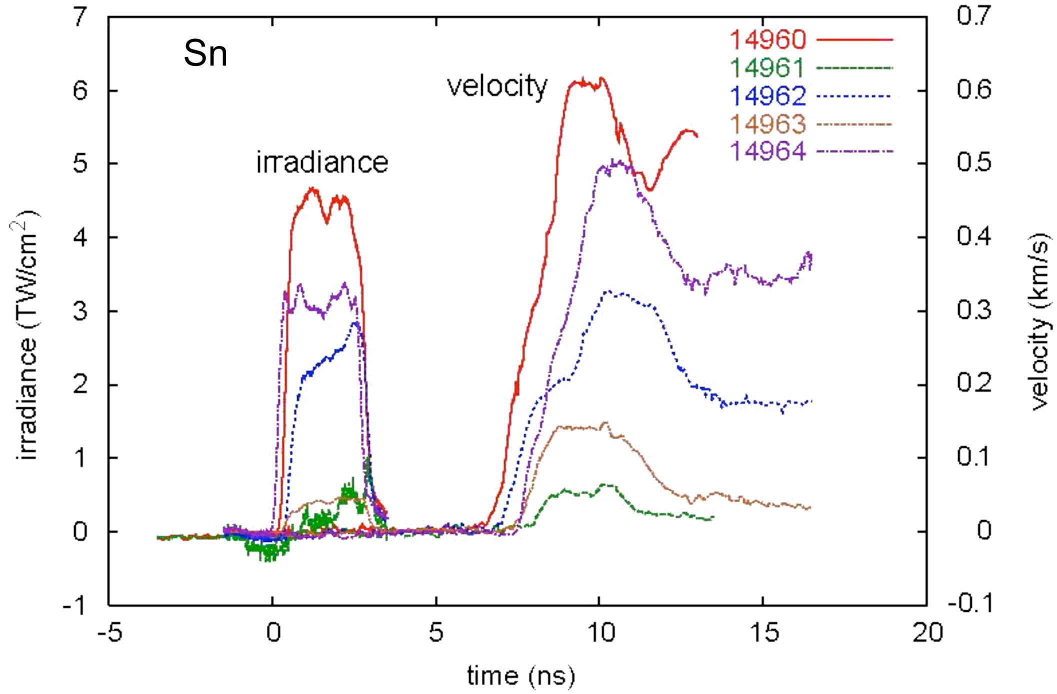


- Either long pulse shock with short pulse x-ray source or short pulse shock with long pulse backlighter
- Sample may include a low-Z “anvil”
- Source spectrum measured during each shot
- Time-resolved spectroscopy is possible

Types of measurements that would be made on a direct-drive compression experiment

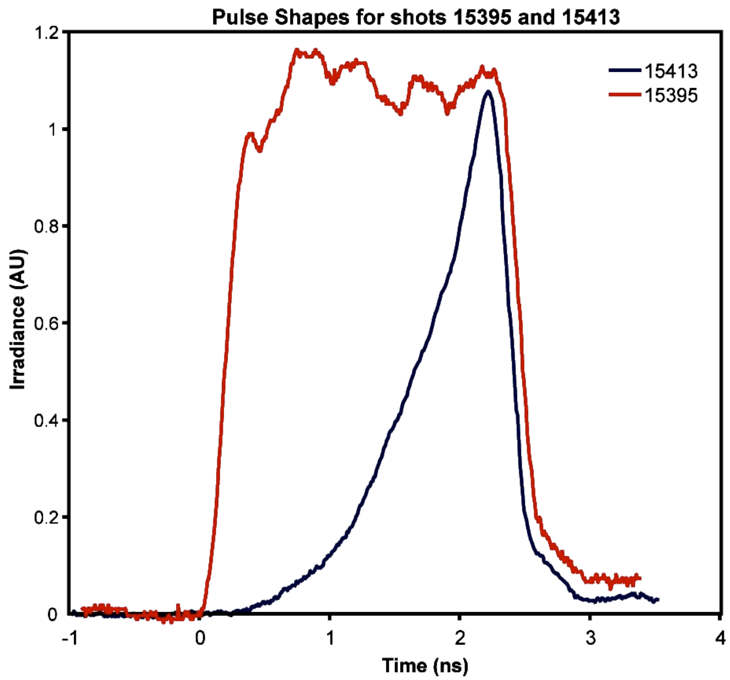
- Line and broadband transmission measurements prior to or at breakout.
- Simultaneous dynamic materials measurements characterize material state(s) and pressure history
  - Velocimetry
  - Pyrometry
  - Ellipsometry
  - Transient x-ray diffraction

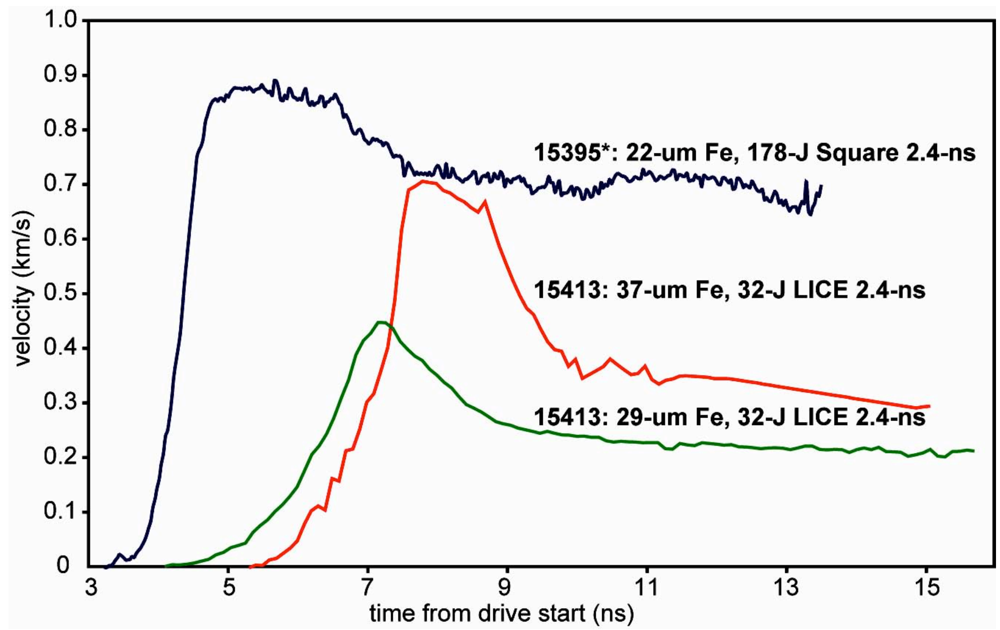
Varying the laser irradiance produces different compression histories.



- 13-element pulse stacker
- Automated feedback for “dial-a-pulse”
- Predictive modeling to compensate for amplification

Laser irradiance shaping produces distinct loading profiles: e.g. (Shocks and LICE)



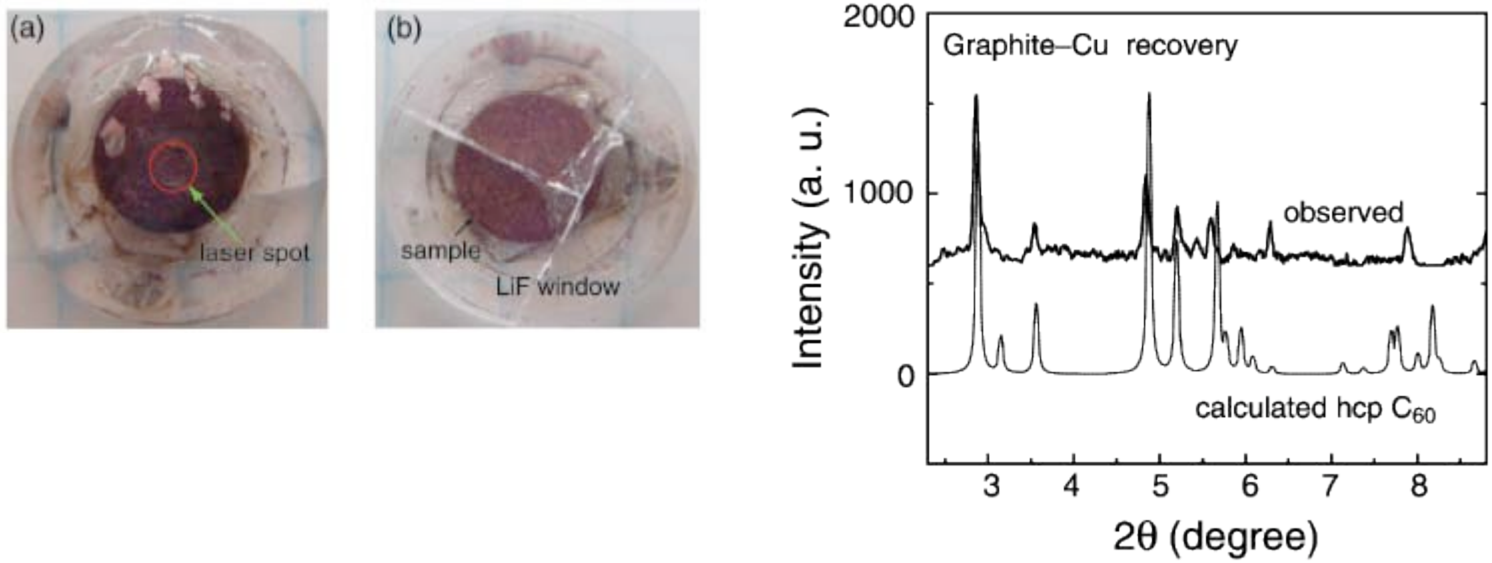


Example of pulse shaping pressure profiles:
VISAR for shocked iron and quasi-isentropic drives on two iron samples.

LICE = "Laser quasi-Isentropic Compression Experiments"

T. Tierney, D. Swift, et al. (2005)

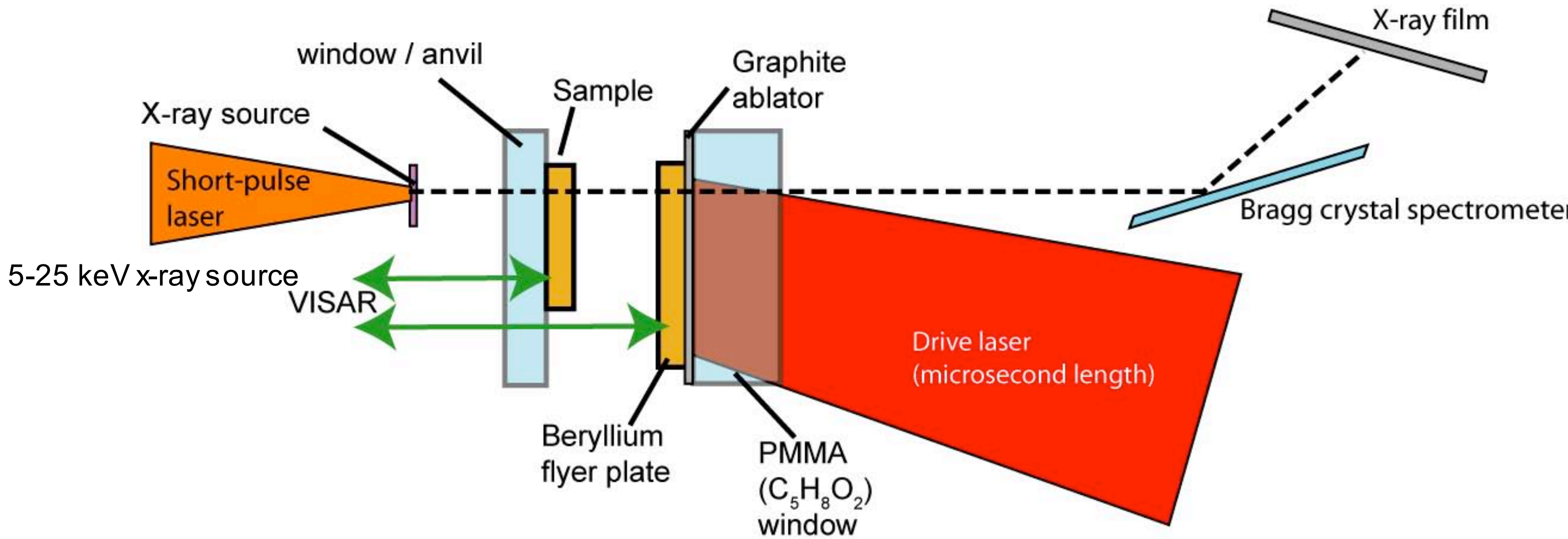
Sample recovery allows for "post-mortem" analysis.



Synchrotron X-ray diffraction pattern (refined) of shocked graphite–Cu mixture (Trident #16726), indicating a hexagonal crystalline phase of two-dimensional polymerization.

O. Tschauner, S. N. Luo *et al.*, High Pressure Research, vol. 24, No. 4, pp471-479 (2004).

Flyer-plate impact can create steady shocks in sample materials (10-700 kbar depending upon materials used)



Shock pressures and duration are dependent upon flyer plate speed and thickness.

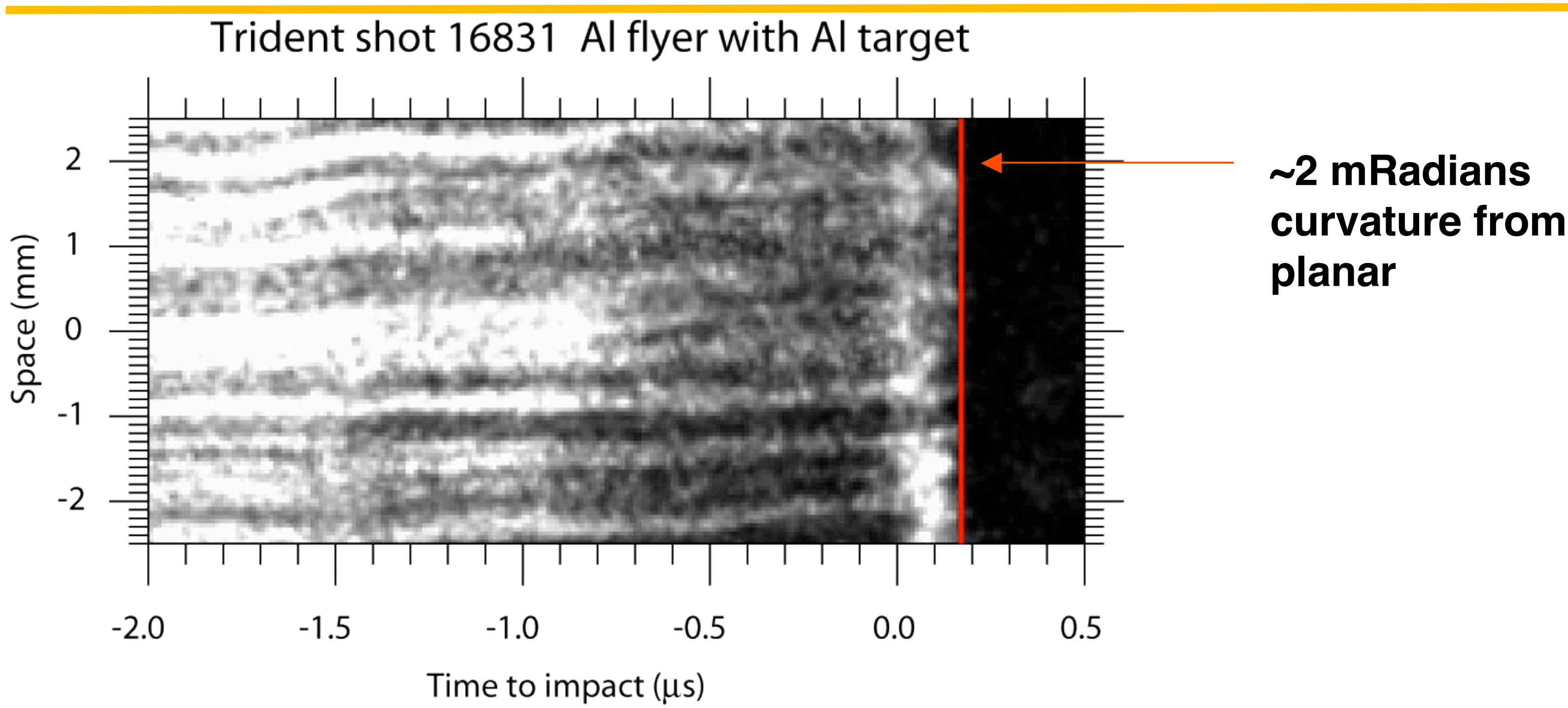
We have launched 2-mm thick aluminum flyers to greater than 400 m/s.

Modeling indicates 25-micron beryllium flyers in excess of 4 km/s

Many measurements are possible on these experiments

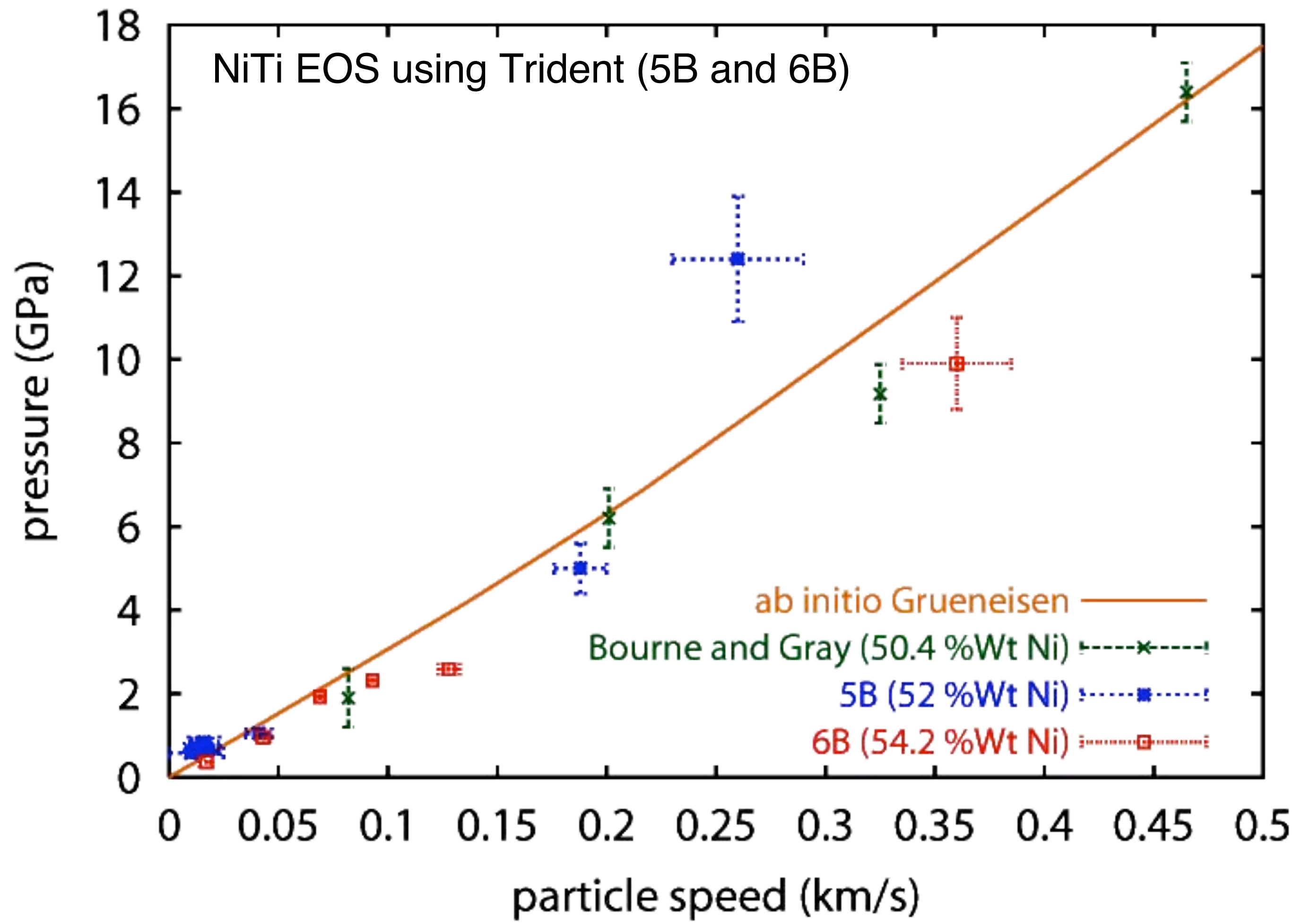
- Source spectrum on all shots
- Spectrum thru Be flyer and Be sample (symmetric impact)
- Spectrum thru Be flyer and target sample
- Breakout surface measurements:
  - Velocimetry
  - Emission spectroscopy
  - Raman spectroscopy

Laser-plasma-accelerated flyers have high planarity.

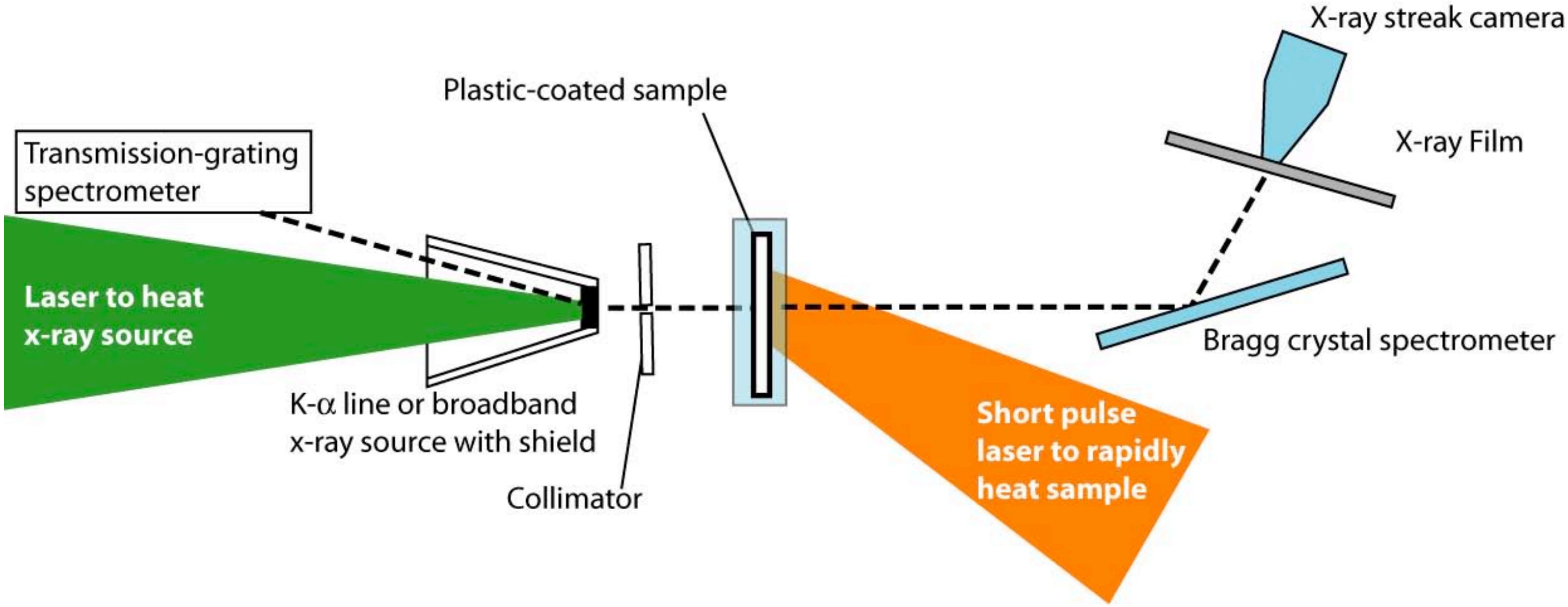


- Laser reflectivity for planarity measurements with high temporal-spatial resolution
- Typical planarity 2-10 mRadians for flyer velocities 0.1-1.0 km/s.

Laser-based flyer-plate experiments can produce data of adequate quality data for equation of state



The short pulse system can rapidly heat a material isochorically



Conclusions for TRIDENT

- TRIDENT's pulse length and shape flexibility allow us to study EOS (and possibly LTE Opacity too).
- Available diagnostics will permit in-depth characterization of material properties during opacity measurements.
- TRIDENT's new Short Pulse Laser capabilities may permit opacity studies of isochorically heated samples
- Laser-produced proton radiography at TRIDENT can be developed as a diagnostic capability.

Example of opacity effects in ICF conditions

Experimental goal:

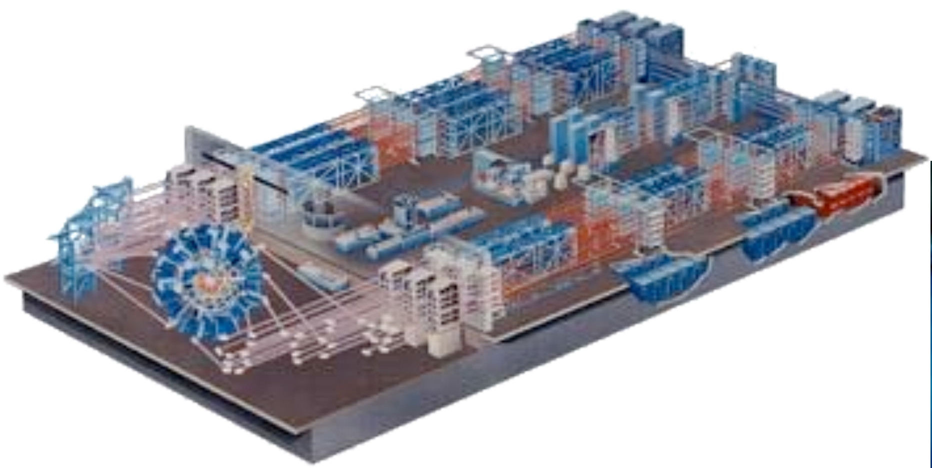
Define a microstructural specification for NIF's Be-Cu ablators.

- Grain-seeded Rayleigh-Taylor instability measurements
- Characteristics of NIF's first shock (80-eV hohlraum): shock velocity and temperature.

Disclaimer:

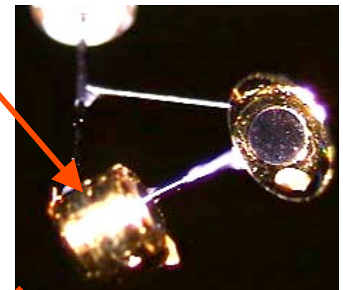
- The "BAMS" OMEGA experiments were not designed to be true opacity measurements.

Omega laser experiments can closely simulate the expected conditions for BeCu ablators.

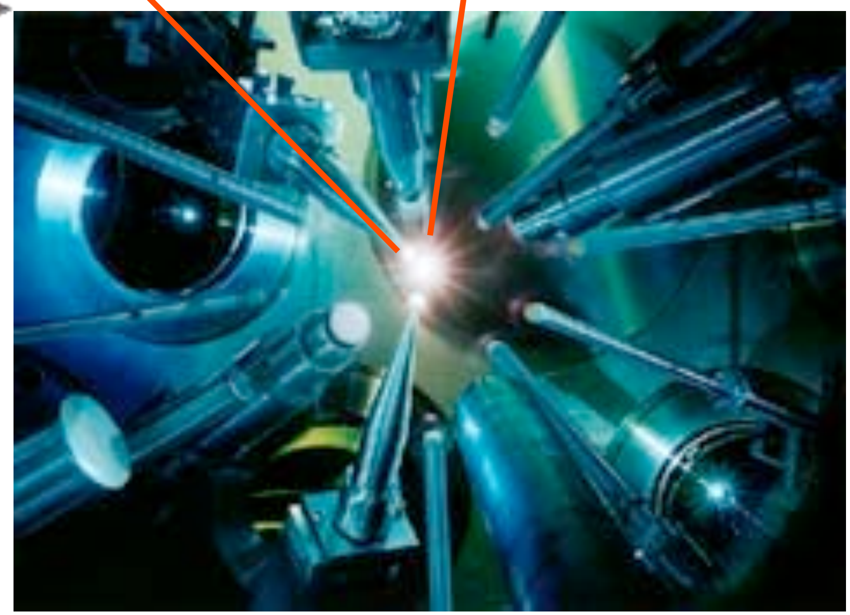


60 beams for total of ~30 kJ

Hohlraum



A target that was fielded at Omega



Indirect drive uses soft x rays and thermal radiation to heat ablators that surround fuel

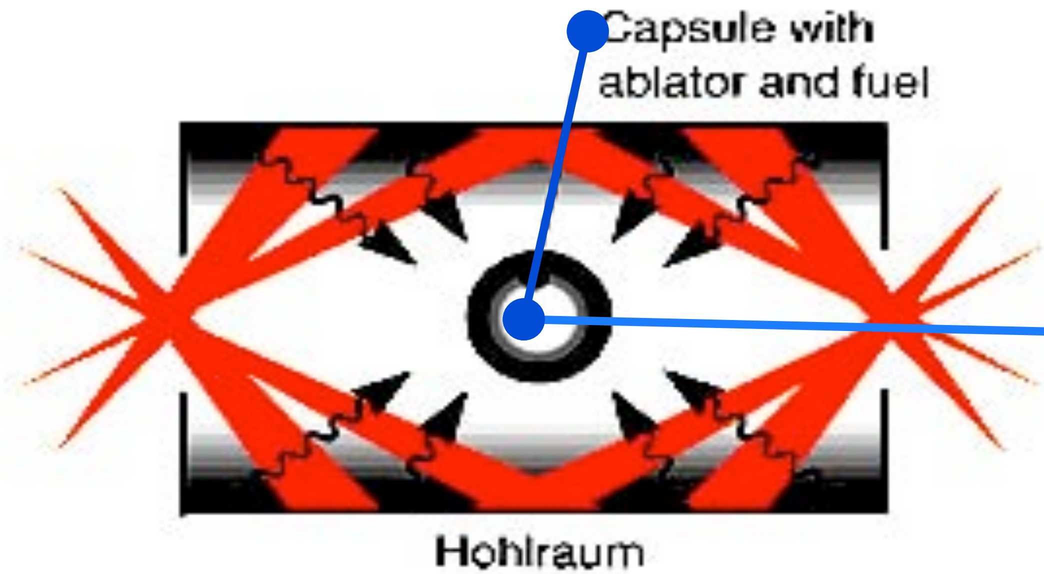
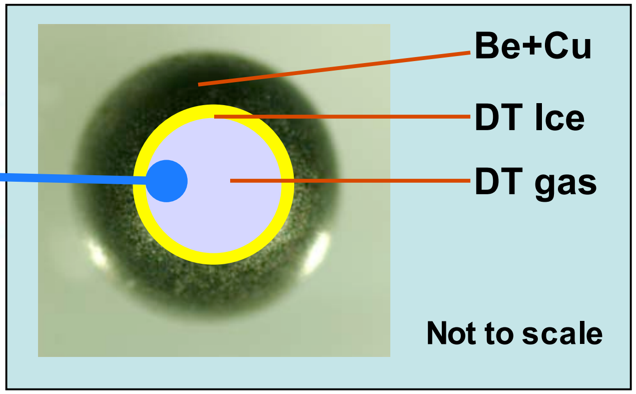


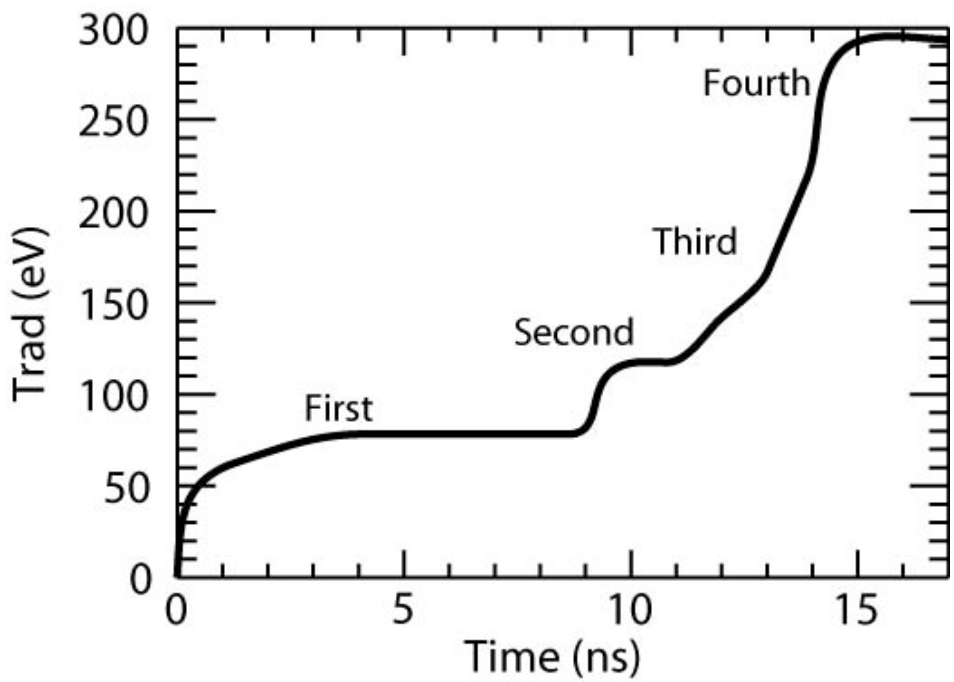
*Diagram courtesy of Steve Haan (LLNL)

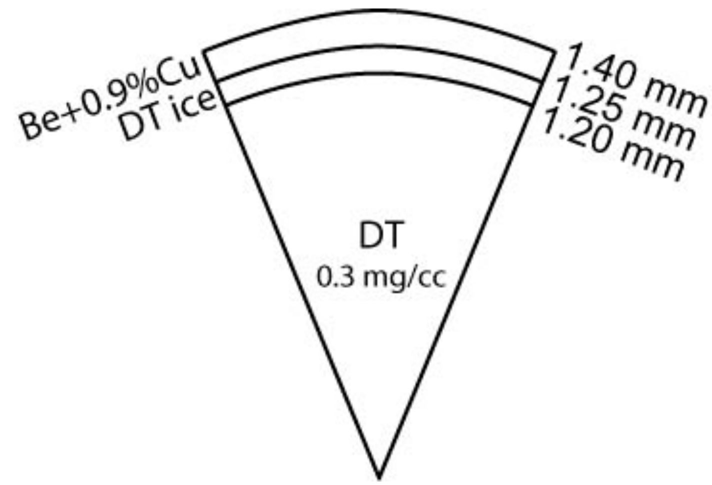


LLNL sputtered Be+0.9%Cu shell

- The National Ignition Facility (NIF) will use up to 192 beams to heat the holhraum and produce soft x rays.
- Some ablator materials being considered:
  - **Be+0.9%Cu, CH+0.6%O+0.23%Br, and $C_{22}H_{10}N_2O_4$**

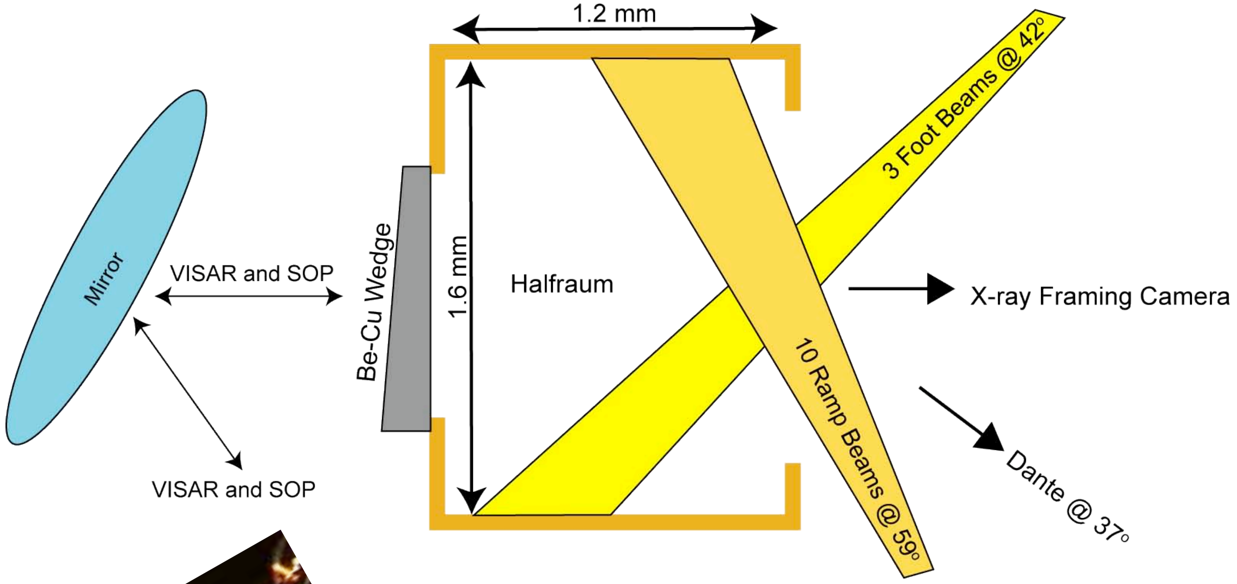
The radiative drive is designed to produce a series of shocks that compress the capsule

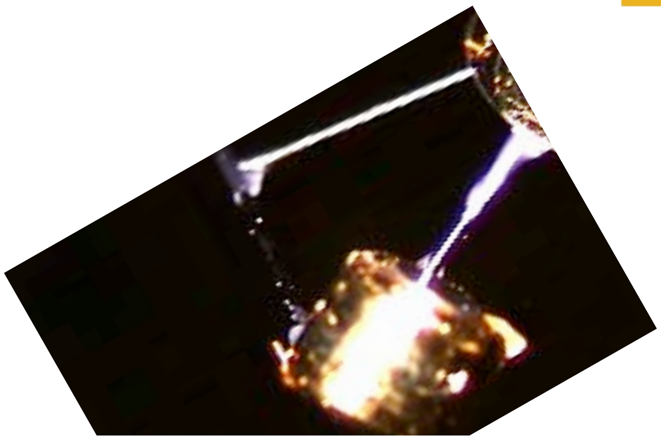




- Iterative 2D and 3D modeling is required to design a laser pulse shape that produces the desired loading profile (temperature history).
- The shocks coalesce within the beryllium-- prior to breaking out into the DT.
- We focus on the first shock, where microstructure effects are most pronounced.

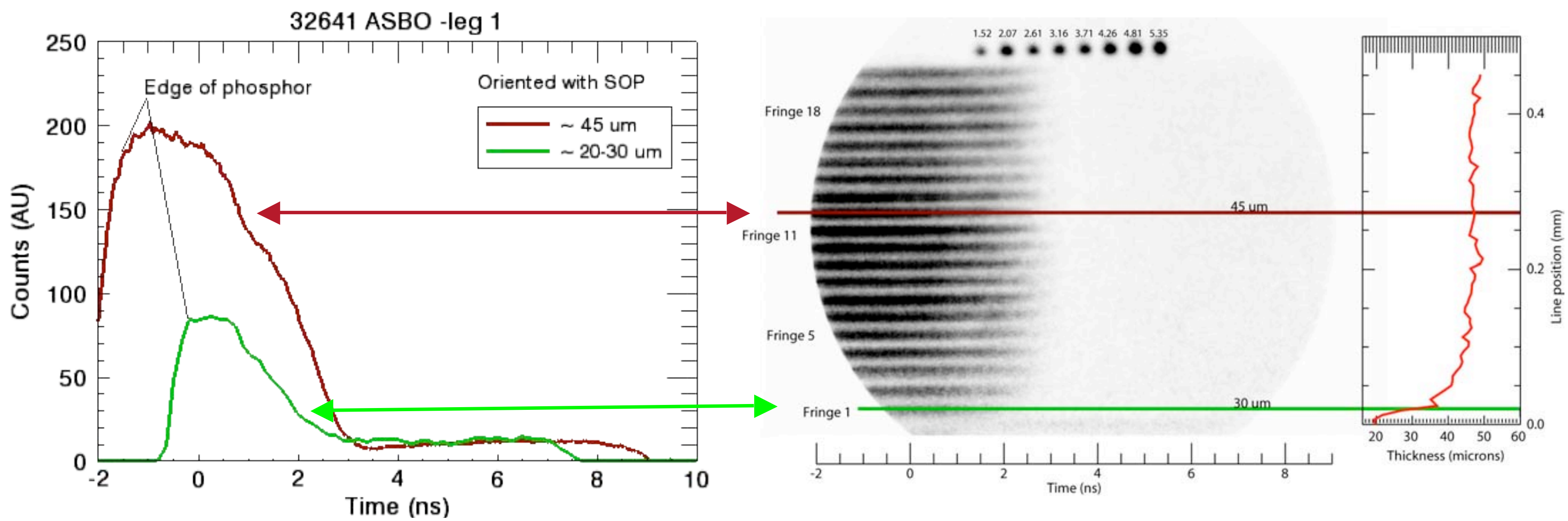
Shock experiments on Be-Cu ablators revealed a preheating source in hohlraum





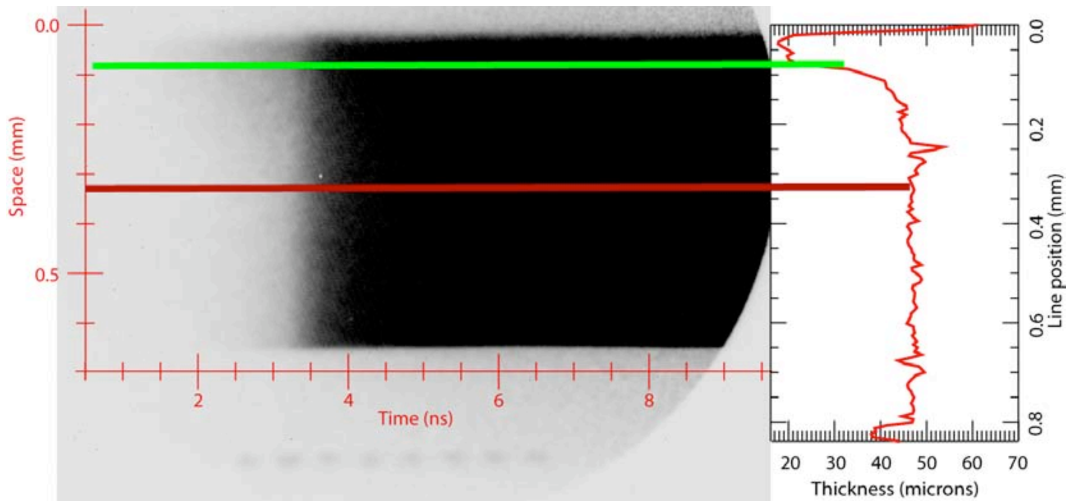
1. VISAR reflectivity decreased while surface emission increased.
2. Lines of constant reflectivity and thermal emission (isotherms) corresponded to times that depended upon thickness.
3. Thinner regions heated more rapidly and lost reflectivity.

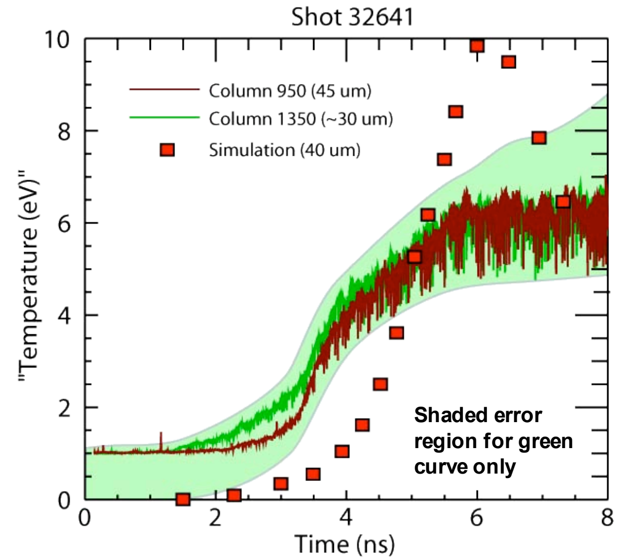
VISAR reflectivity drops to zero at t~ 3 ns-- near shock breakout time.

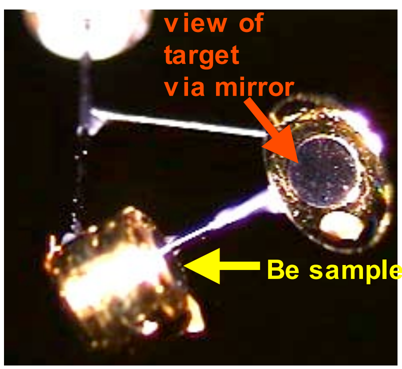


Lineouts along fringes with 50-pixel averages show reflectivity decreasing– more rapidly with thinner regions.

Streaked optical pyrometry observed more preheat than predicted



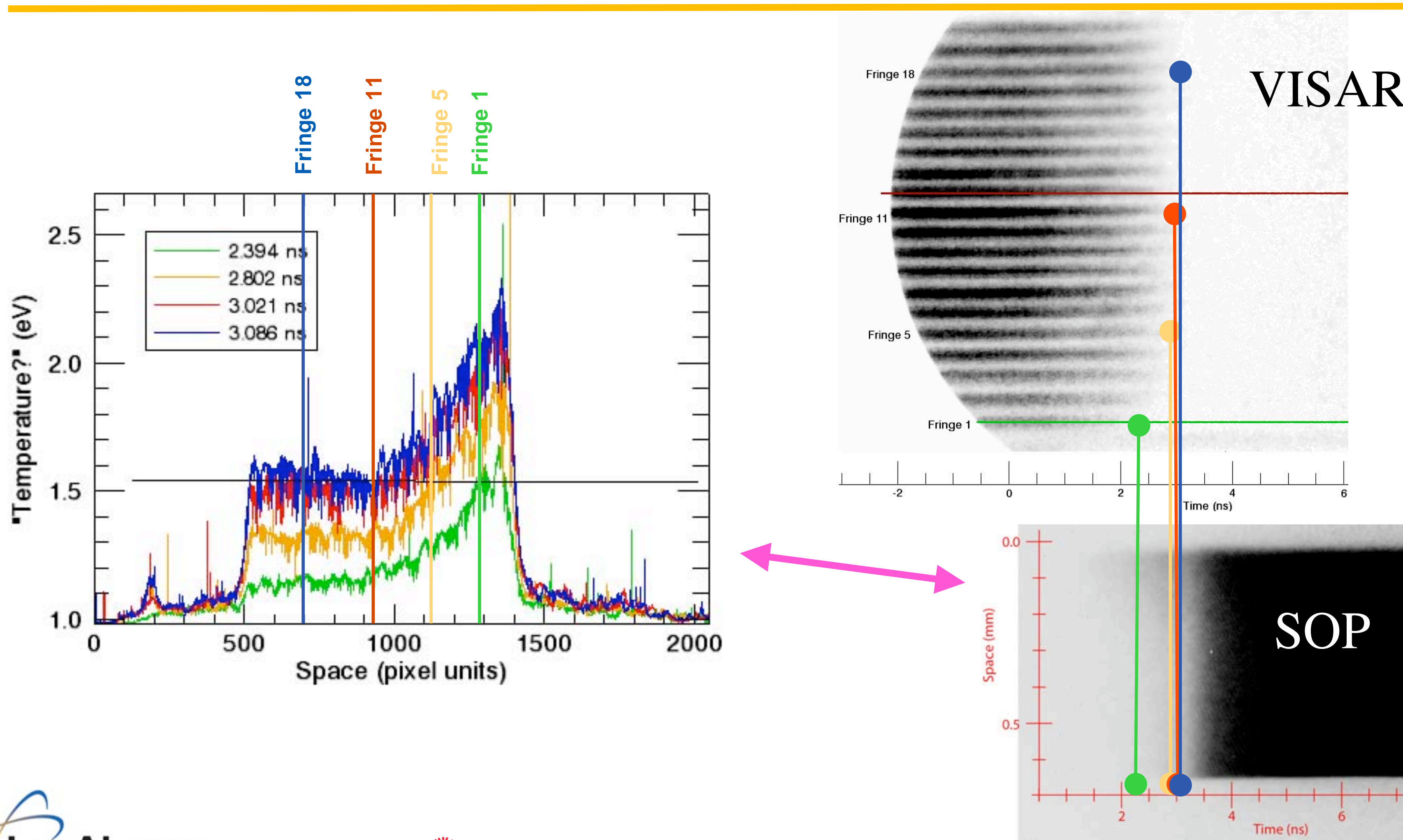




•Simulations are being refined to include laser “hot spots”

•Spectrum driving preheat appears to be between M and N band. Laser intensity to low for Nickel-like gold lines.

Timing of VISAR's reflectivity disappearance is consistent in temperature.



Analysis technique for the preheat using "isotherms"

We calculate the heating due to absorbed x-rays:

$$\frac{\partial T(x,t)}{\partial t} = \int \frac{\rho(x,t)\kappa(\lambda,T)\varphi(\lambda,x,t)}{c_v(T)} d\lambda$$

Where φ is the x-ray flux at time t and position x with wavelength T is temperature, λ is the x-ray wavelength, ρ is mass density, κ is opacity, and c_v is the specific heat capacity.

We invert this equation to find,

$$u_{eff} \equiv \left. \frac{\partial x(t,T)}{\partial t} \right|_T$$

Assuming opacity changes in soft x-ray regime do not change much for a few eV sample,

$$\kappa(\lambda,T) = \kappa(\lambda) \longrightarrow \kappa_\lambda$$

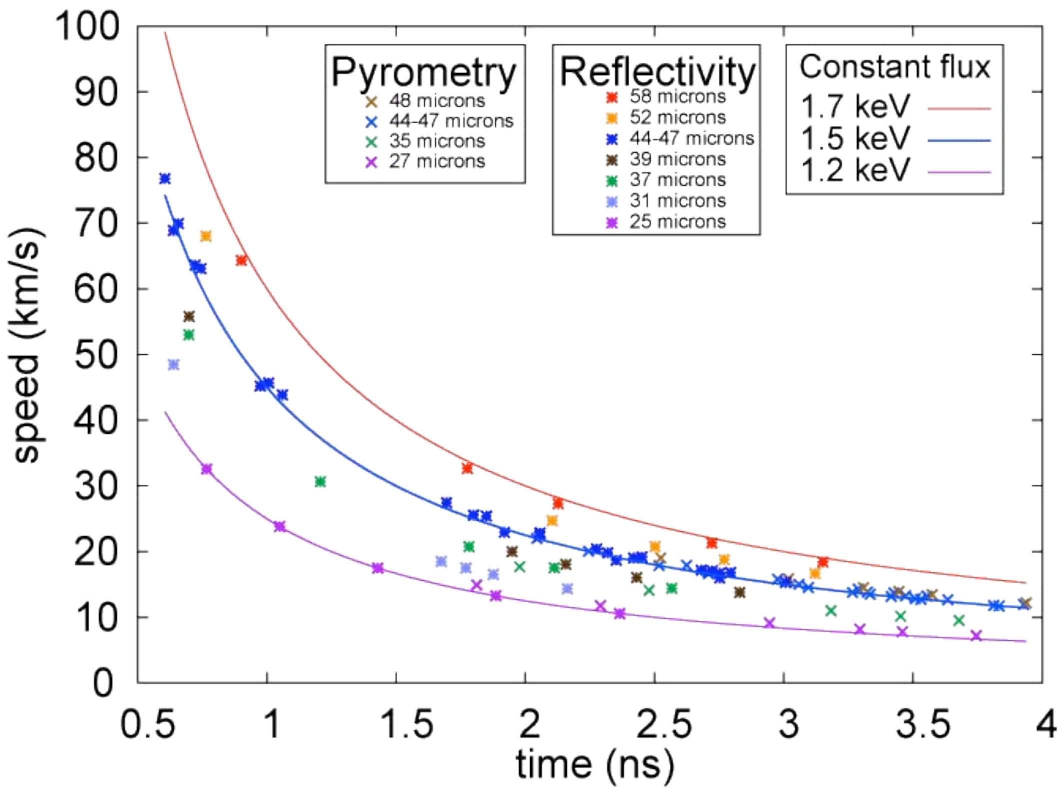
-As an initial assumption*, we then simplify using constant flux to find:

$$u_{eff} = \frac{1}{\rho \kappa_\lambda t}$$

*For the conditions considered here, the "real" flux history can be well approximated as nearly constant for ~3 ns.

Reflectivity decreases and isotherms corresponded well to a broadband source

- “Iso-reflectors” chosen for reflectivity points
  - related to isotherms.
- Isotherms chosen for pyrometry points
- Absolute temperature is not necessary for this analysis technique!



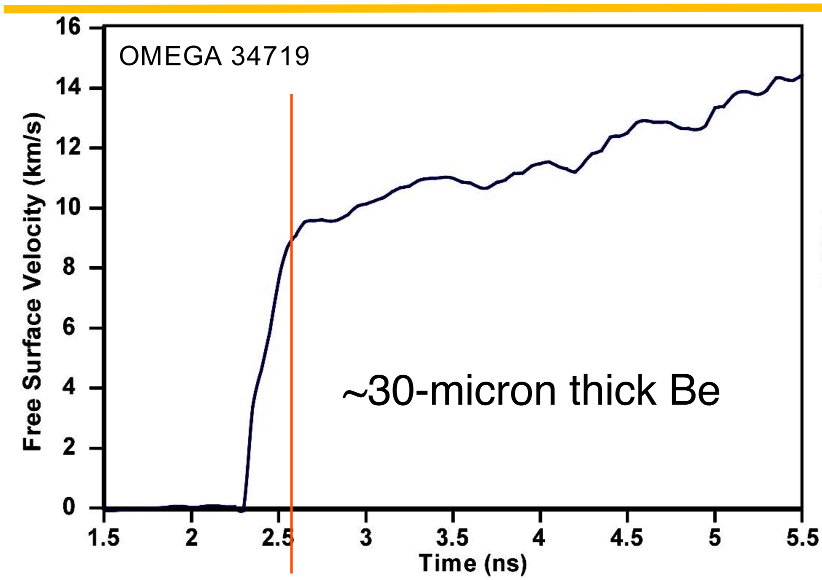
What needs to be done to *really* study opacity of this ablator material?

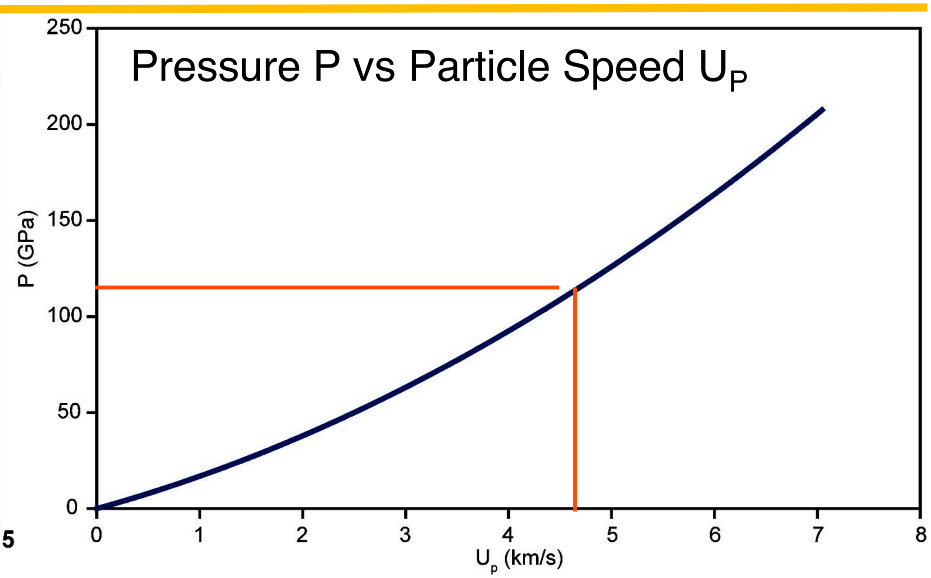
- Time-resolved transmission spectroscopy thru the sample and out the laser-entrance hole.
- 1-D spatially-resolved spectrum.
- 2-D spatially-resolved soft x-ray images with narrow transmission bands.
- A more complete model needs to be developed.

Final Conclusions

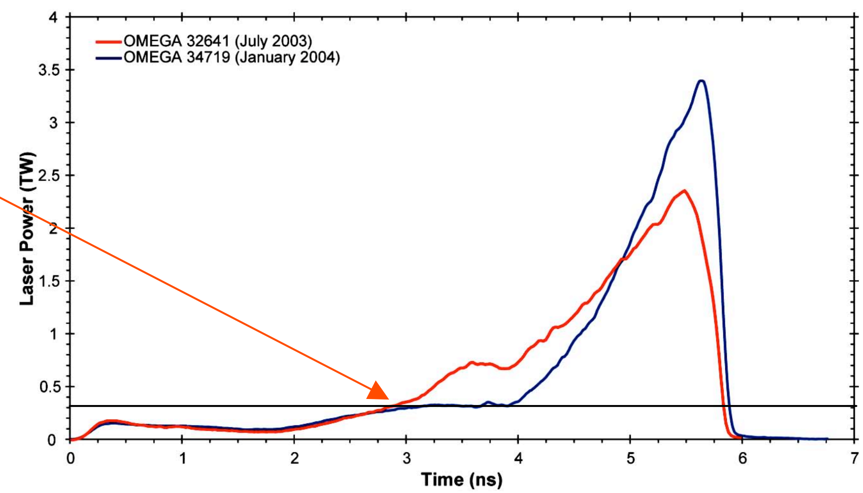
- TRIDENT's recent short pulse addition affords access to new material conditions.
- OMEGA is a good platform for studying ICF-related opacities
- Opacity measurements can be made during well-characterized materials experiments.

VISAR shows Be-Cu free surface velocities when laser drive is kept below 0.3TW.



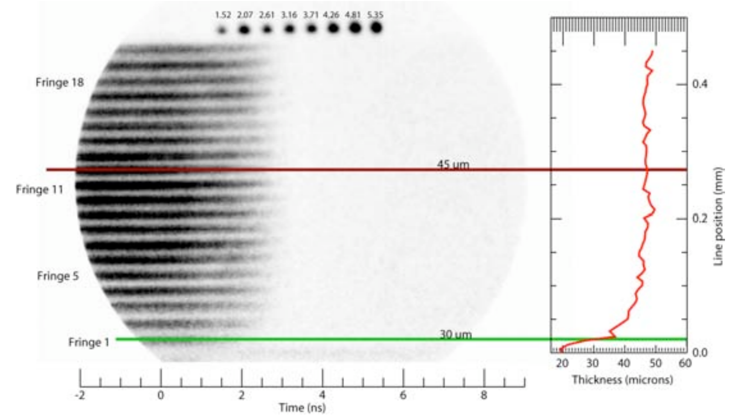


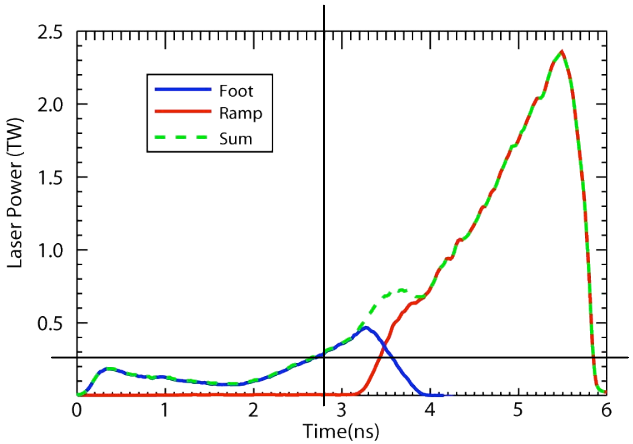
- •Last half of foot drive was kept below 0.3 TW.
- •Free surface velocity measurements consistent with a 1.2 Mbar shock.
- •Predicted breakout at ~3.0 ns.

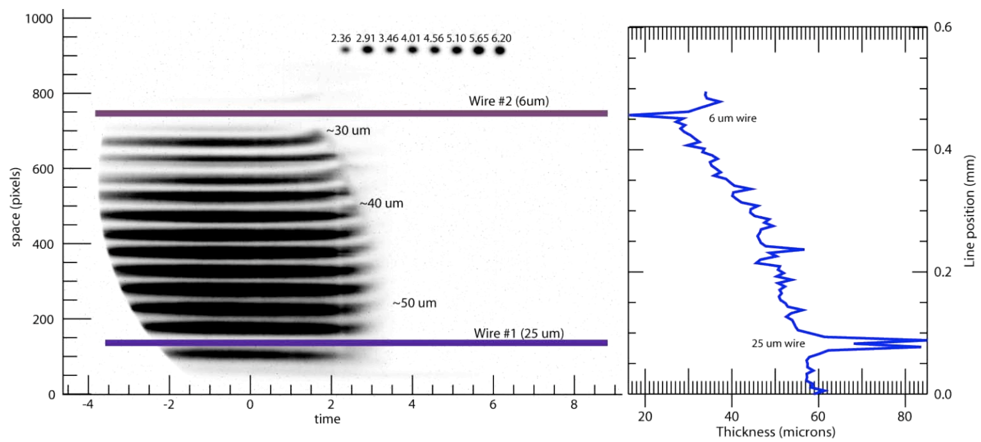


Reflectivity disappeared prior to clear shock breakout.

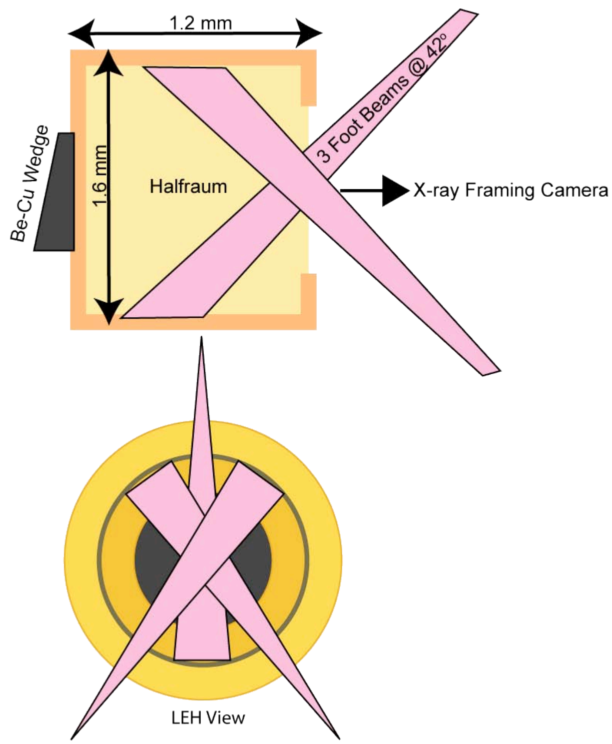
- Vacuum holhraum example #32641
- Powder-pressed Be-0.9%Cu.
- Breakout was expected in range of t~ 3.2-4.0 ns.

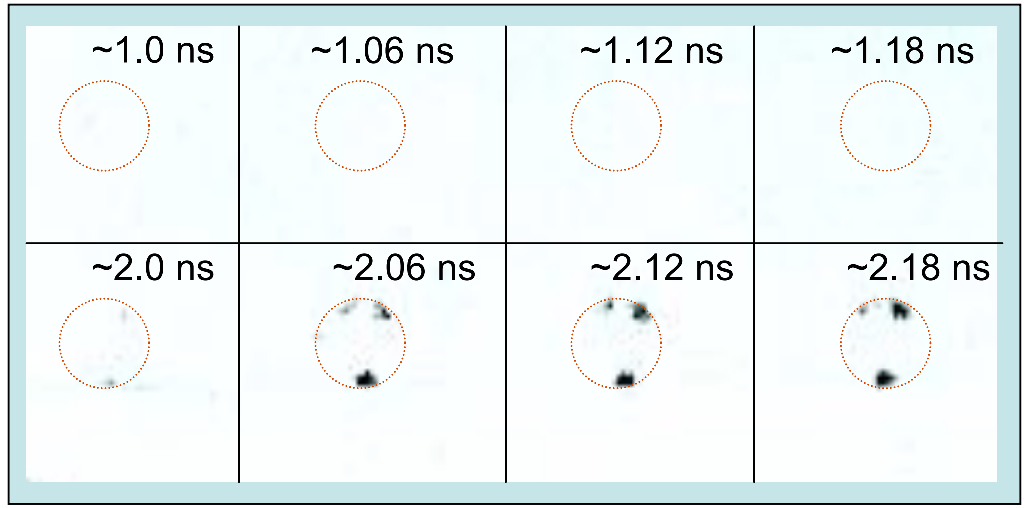






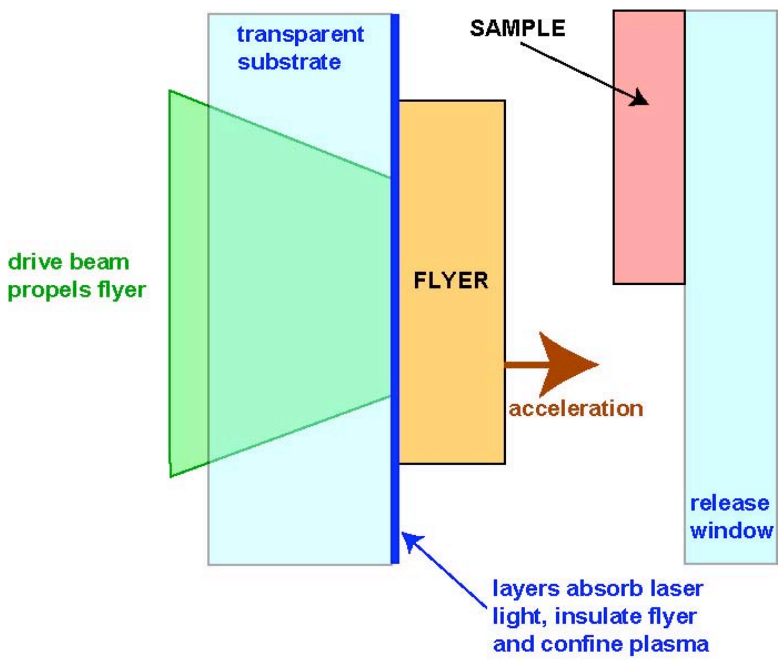
A soft x-ray (> 1 keV) framing camera (XRFC) observed gold ablation and emission





- Gold plasma from wall has ablated to within radius of laser entrance hole (LEH)
- The spots are radiating at energies above 1 keV (0.005” Be filter).

Confined laser plasmas can accelerate flyer plates for dynamic materials experiments.



<u>TRIDENT Drive Characteristics</u>:

- 0.6-20 μs pulse, 1054-nm
- 0.025 to 2.5 GW/cm^2 (0.5-cm dia. target)
- Sample thickness: hundreds of μm