High Pressure X-ray Diffraction Experiments on the Omega and NIF Laser Facilities
+ future experiments at the ESRF

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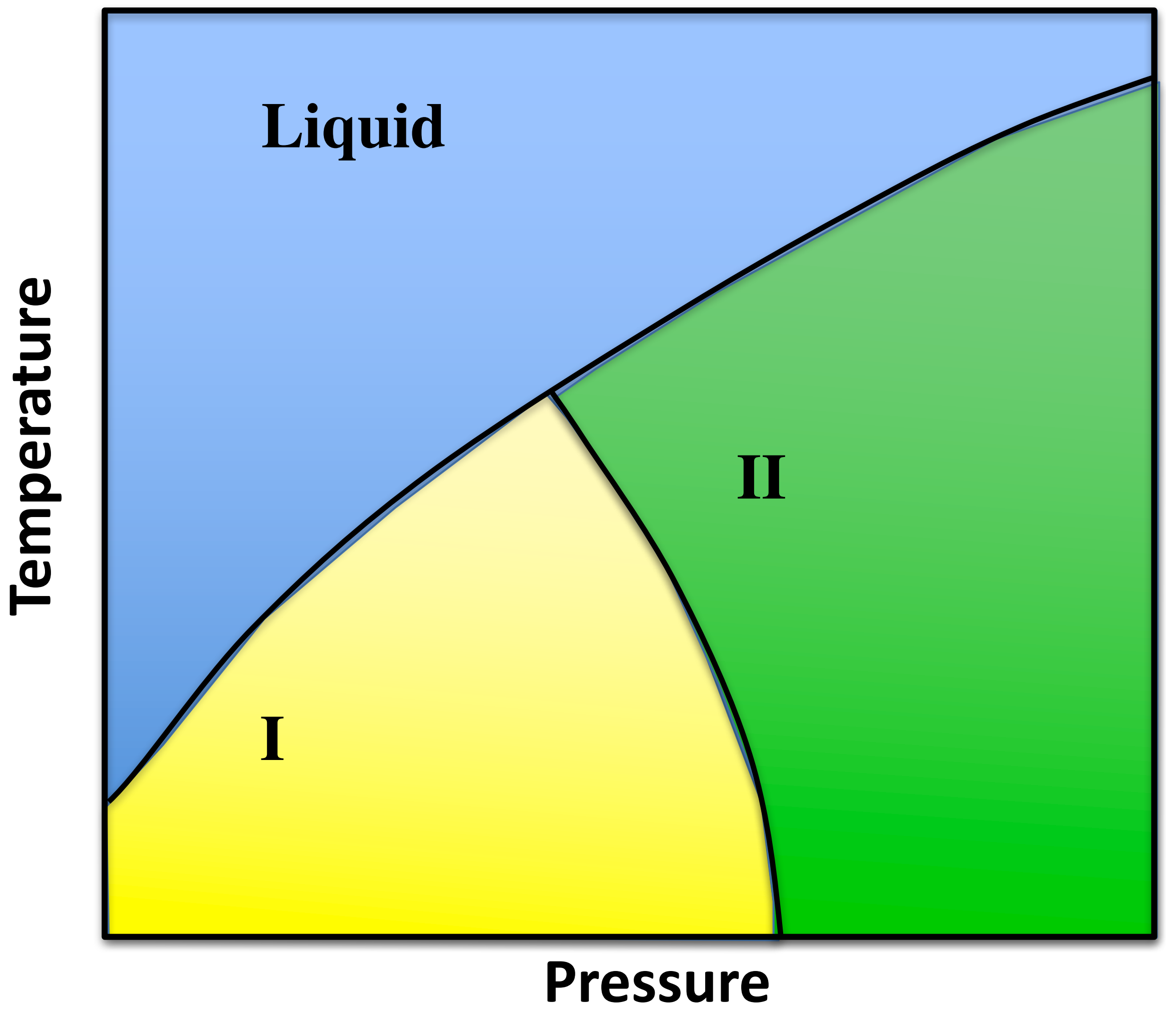
June Wicks, Thomas Duffy (Princeton Univ.)

The nature of high pressure phase transformations can now be explored with using temporally shaped Laser drivers coupled with x-ray sources



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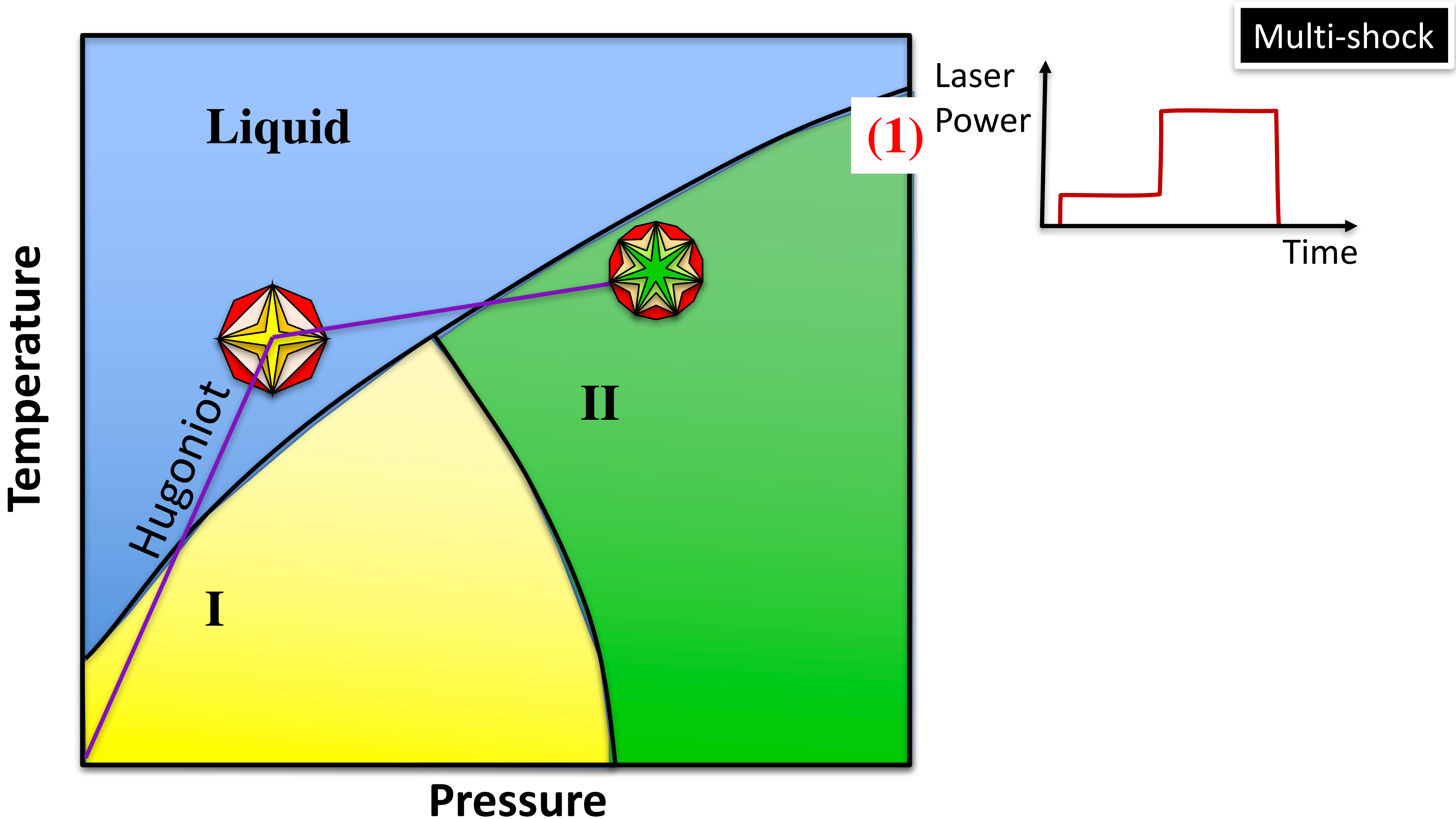

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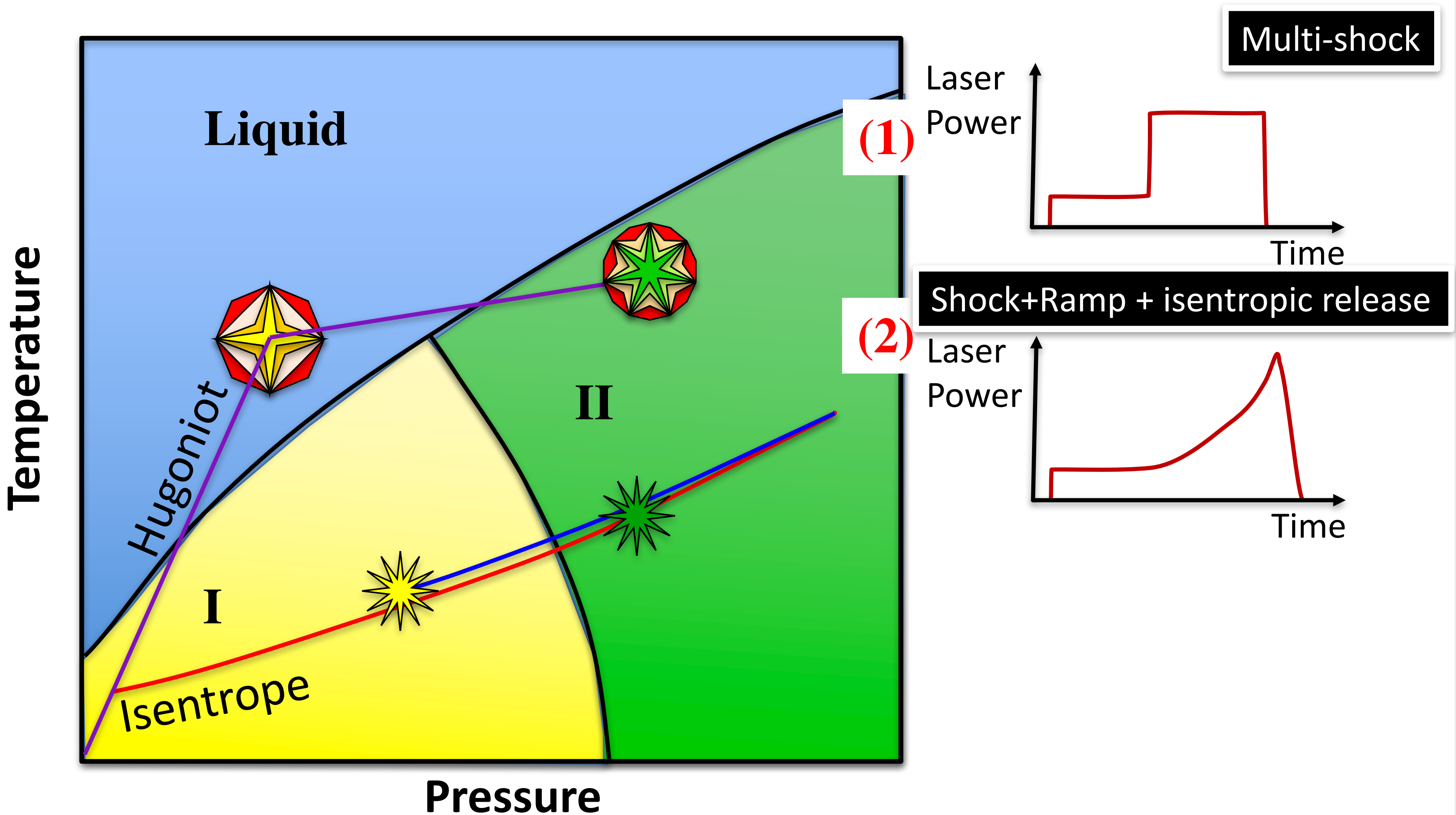

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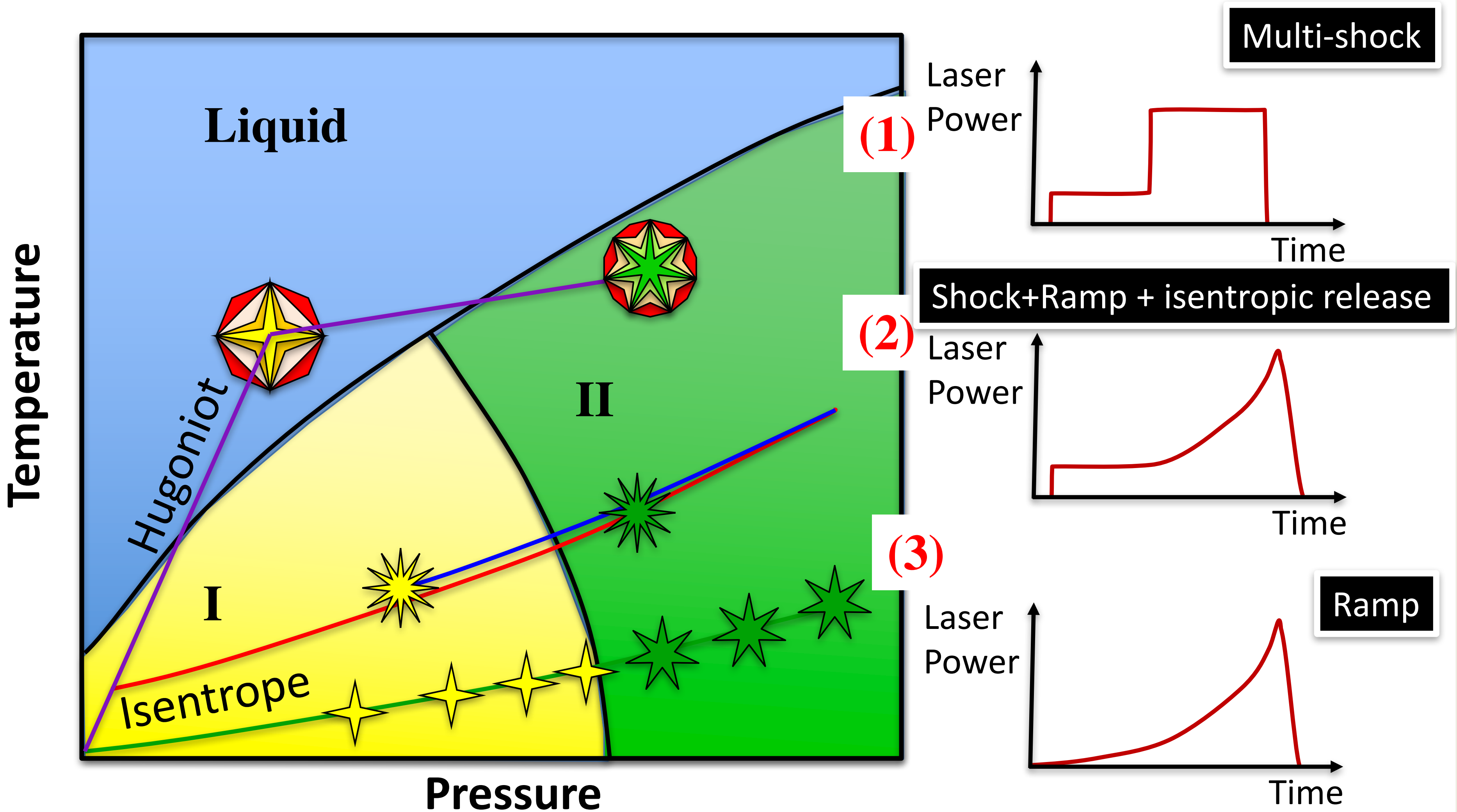
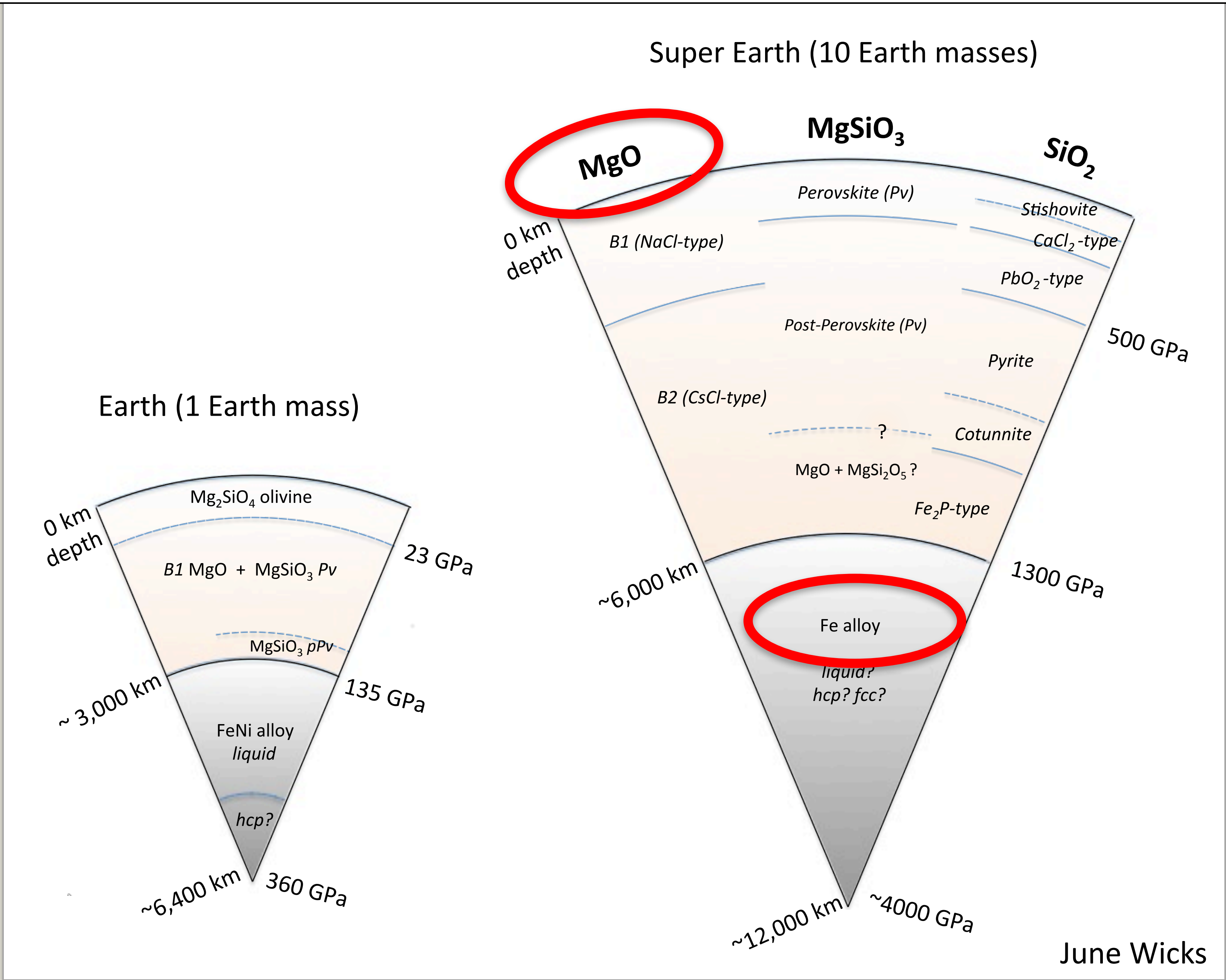
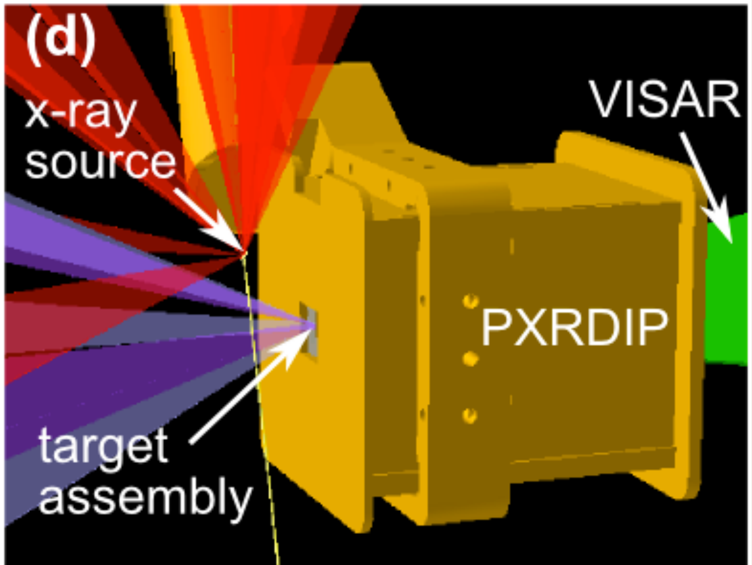


Recent experiments on Omega have focused on determining the high pressure crystal structure of MgO and FeSi alloys

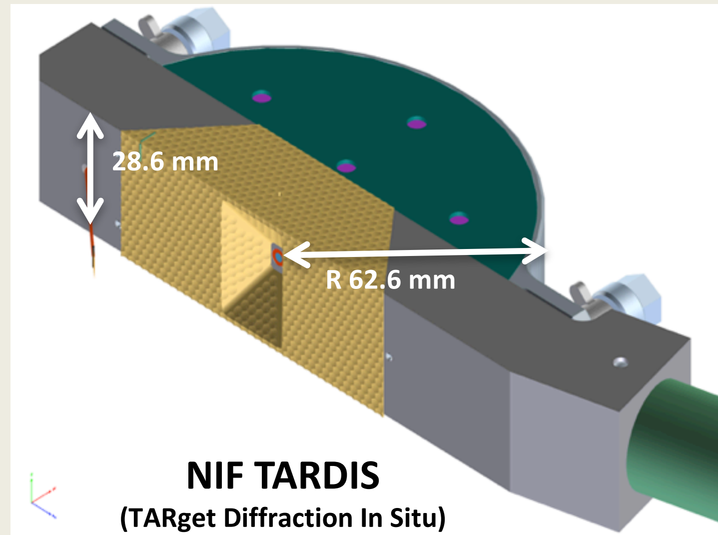


We have developed ns x-ray diffraction platforms on the Omega and NIF Laser facilities

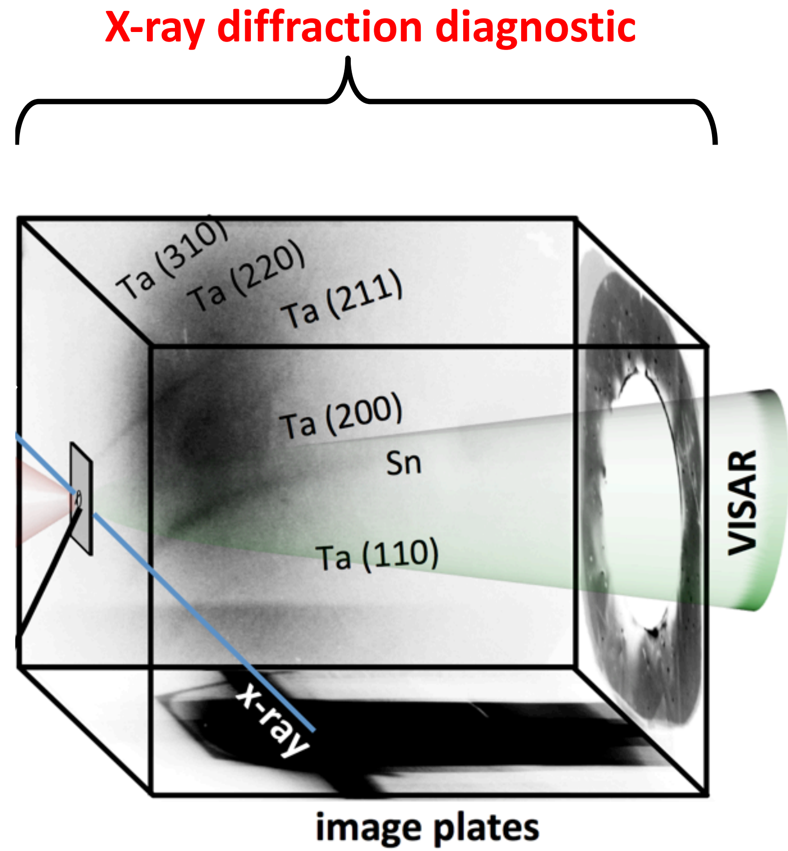
1 TPa = 1000 GPa = 10 Mbar



Demonstrated at Omega, PXRDIP
(Powder X-Ray Diffraction Image Plates)



The PXRDIP diagnostic at the Omega laser records x-ray diffraction in 1 ns



*Rygg, RSI (2012)
*Lazicki, PRL (2015)

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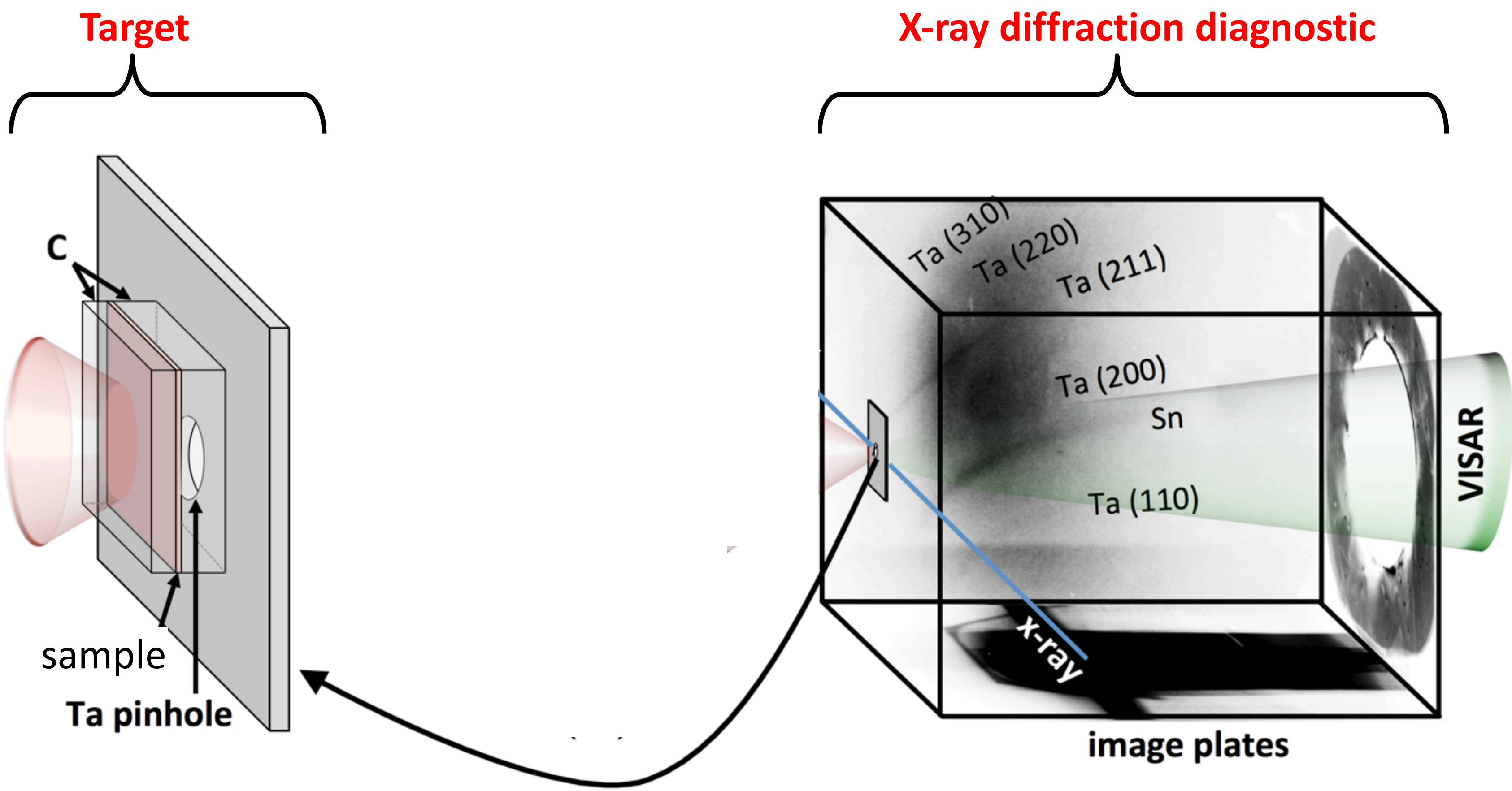

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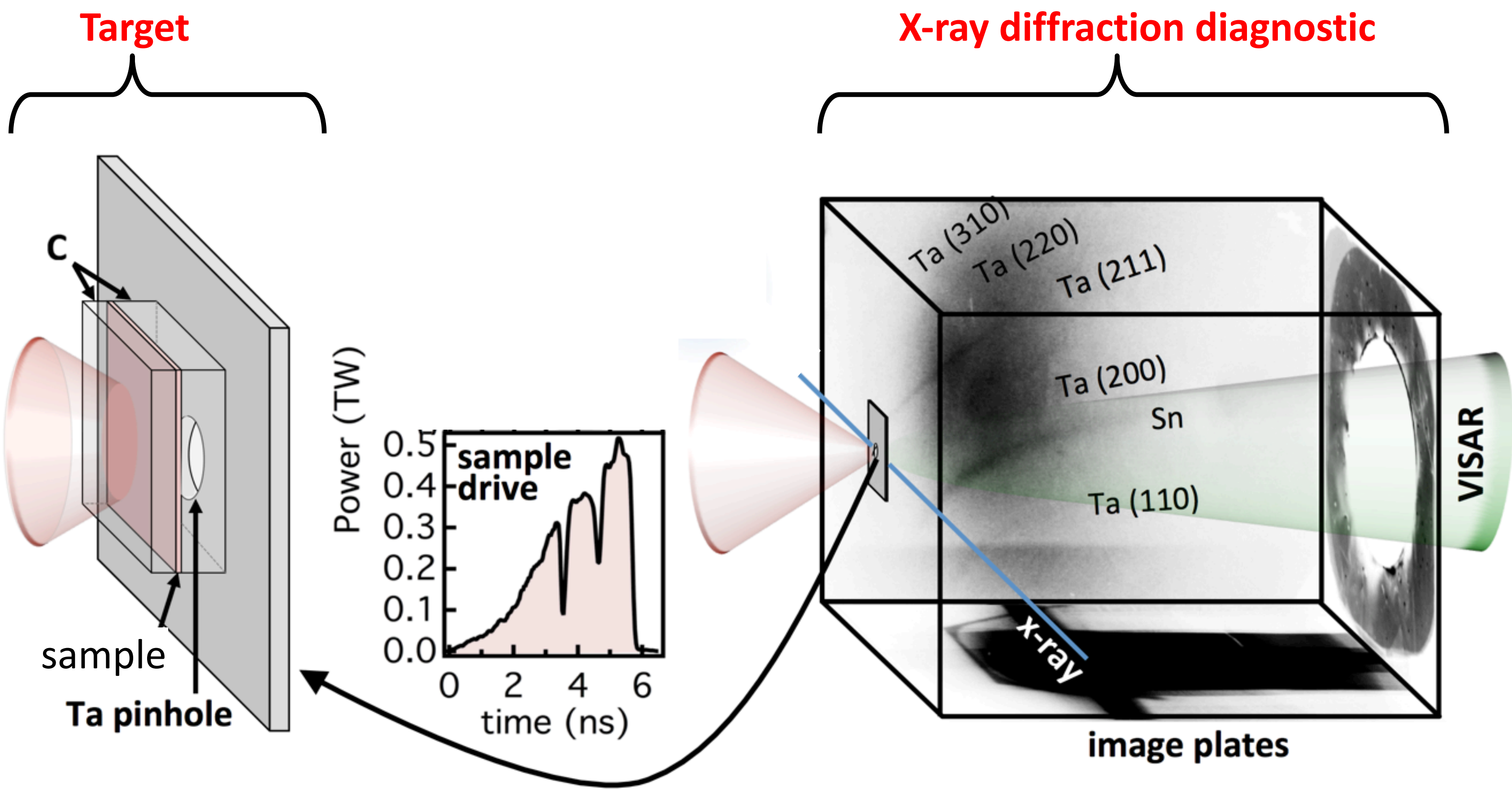

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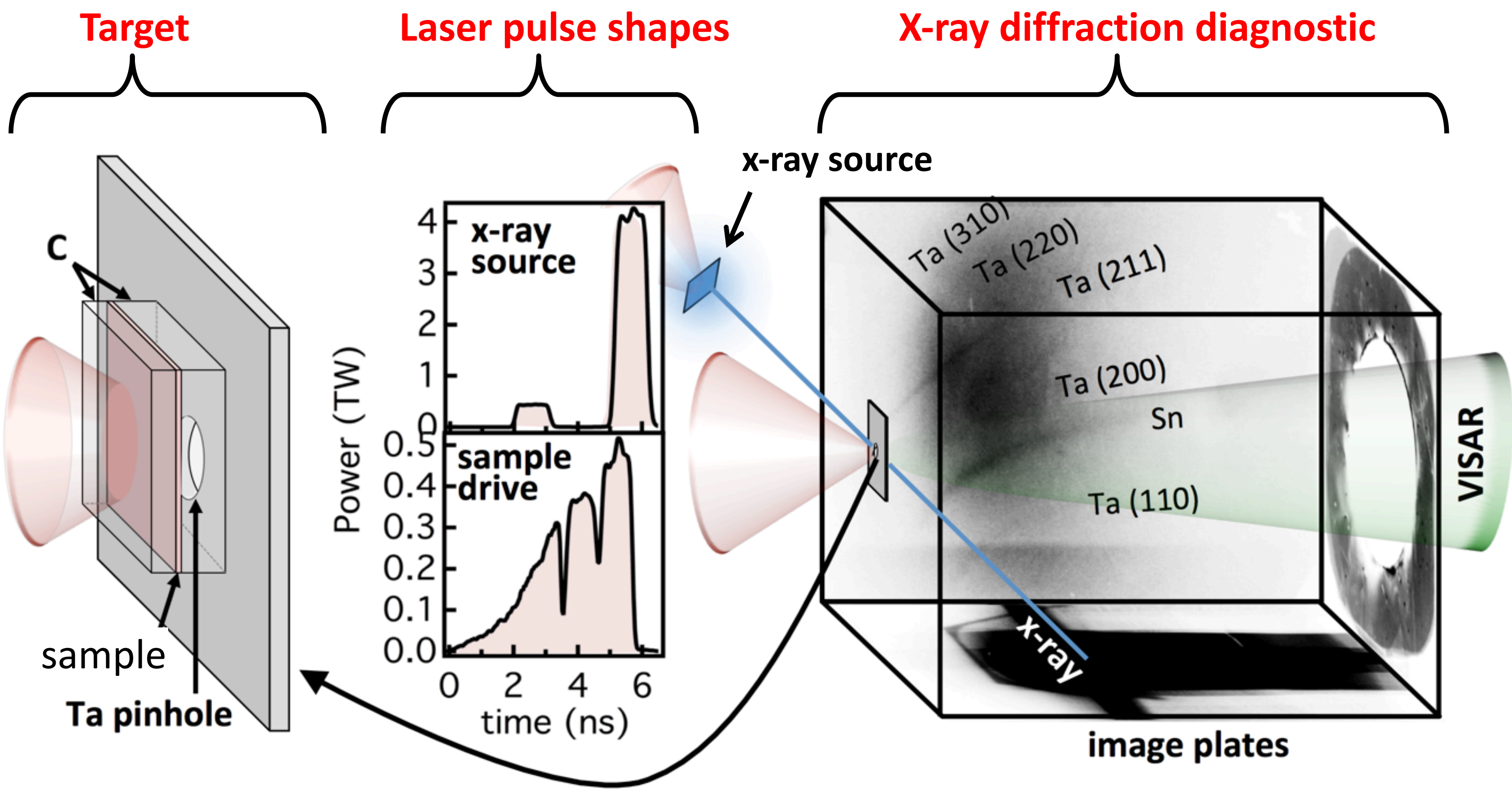
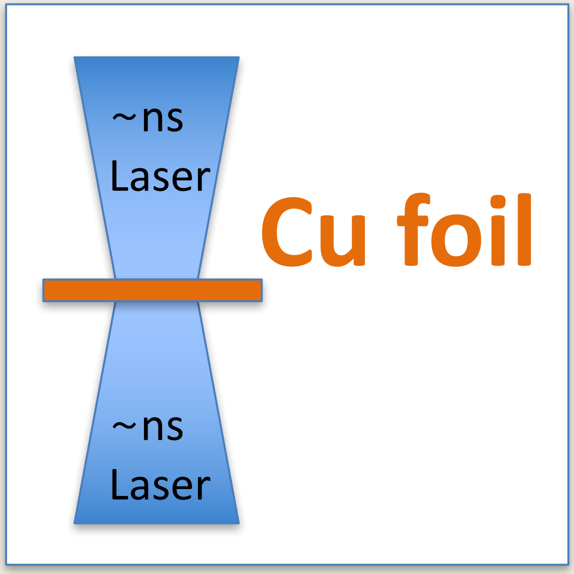
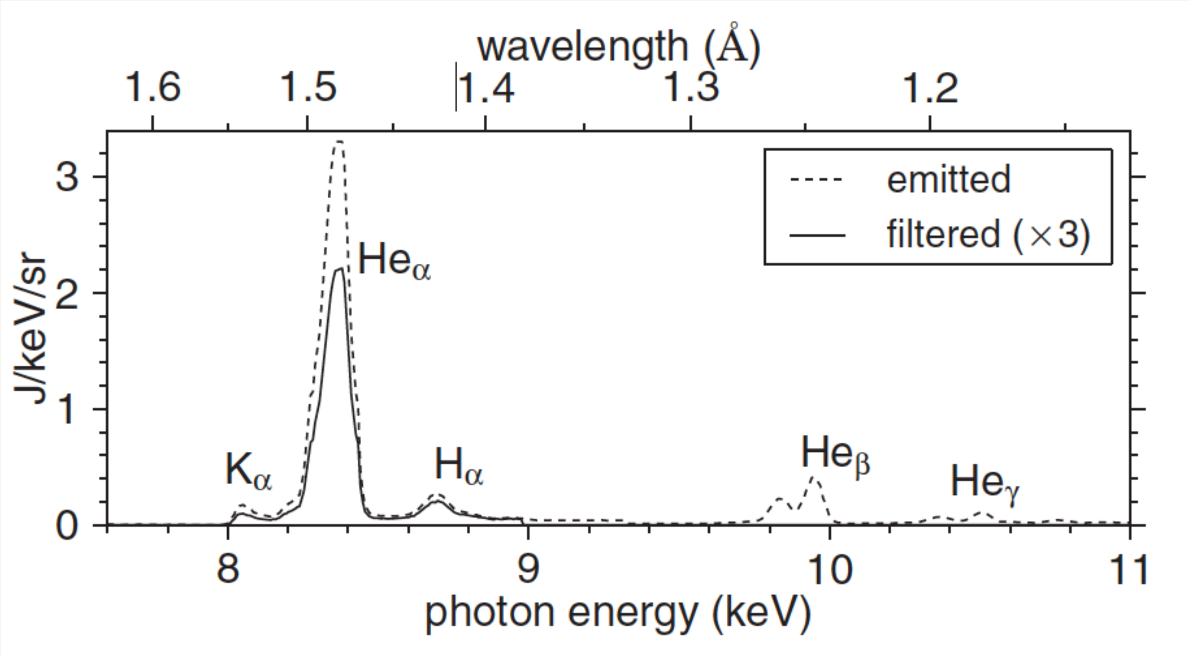


*Rygg, RSI (2012)
*Lazicki, PRL (2015)

On Omega and NIF X-ray probe is quasi-monochromatic He-α line emission



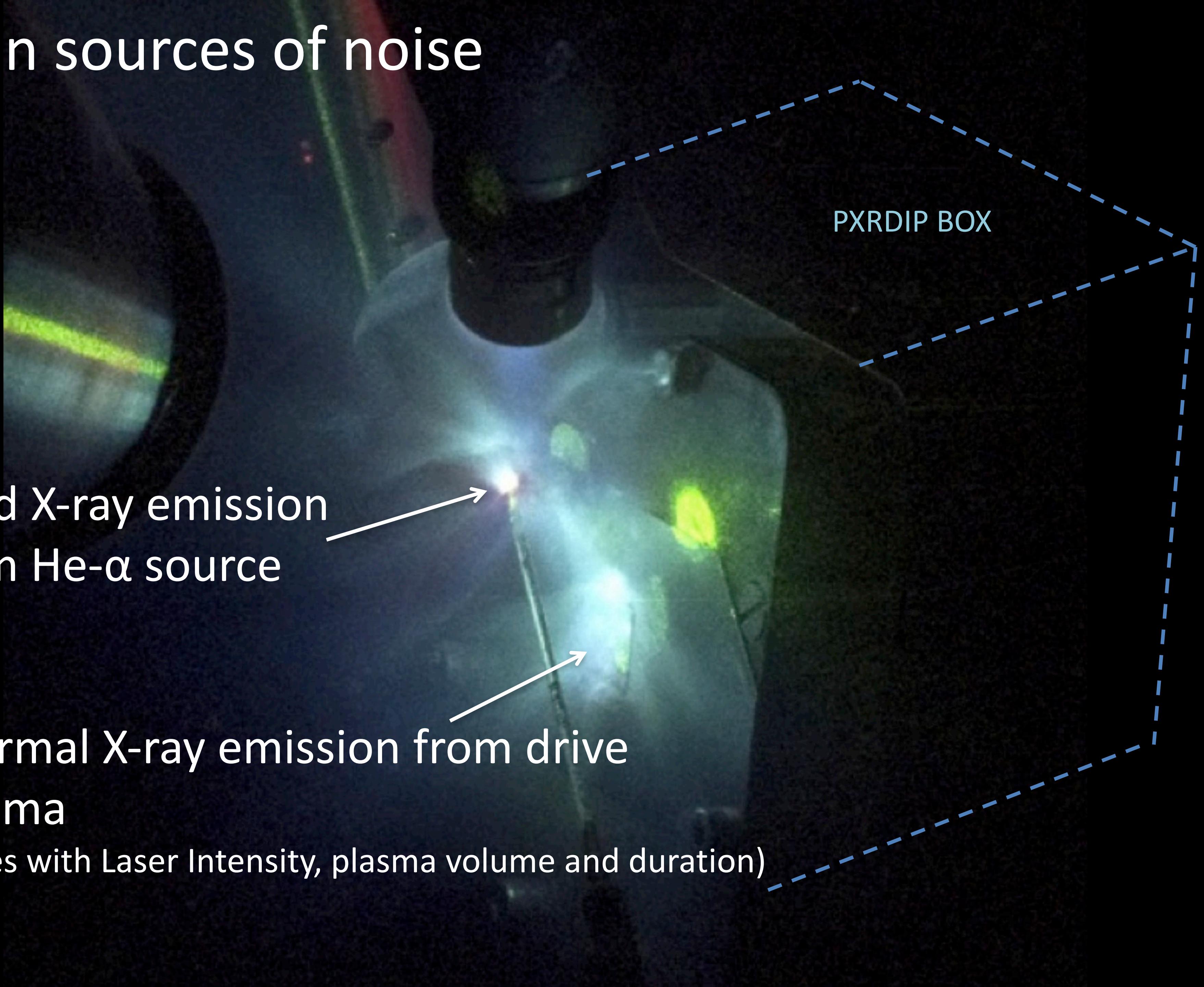
X-ray Spectrum emitted in 4π



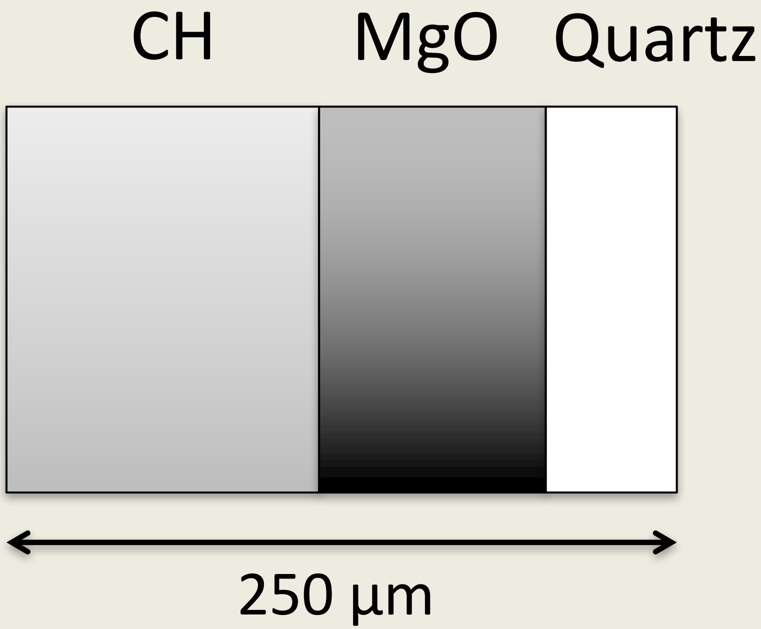
10^{11} - 10^{12} photons incident on sample

3.5% bandwidth

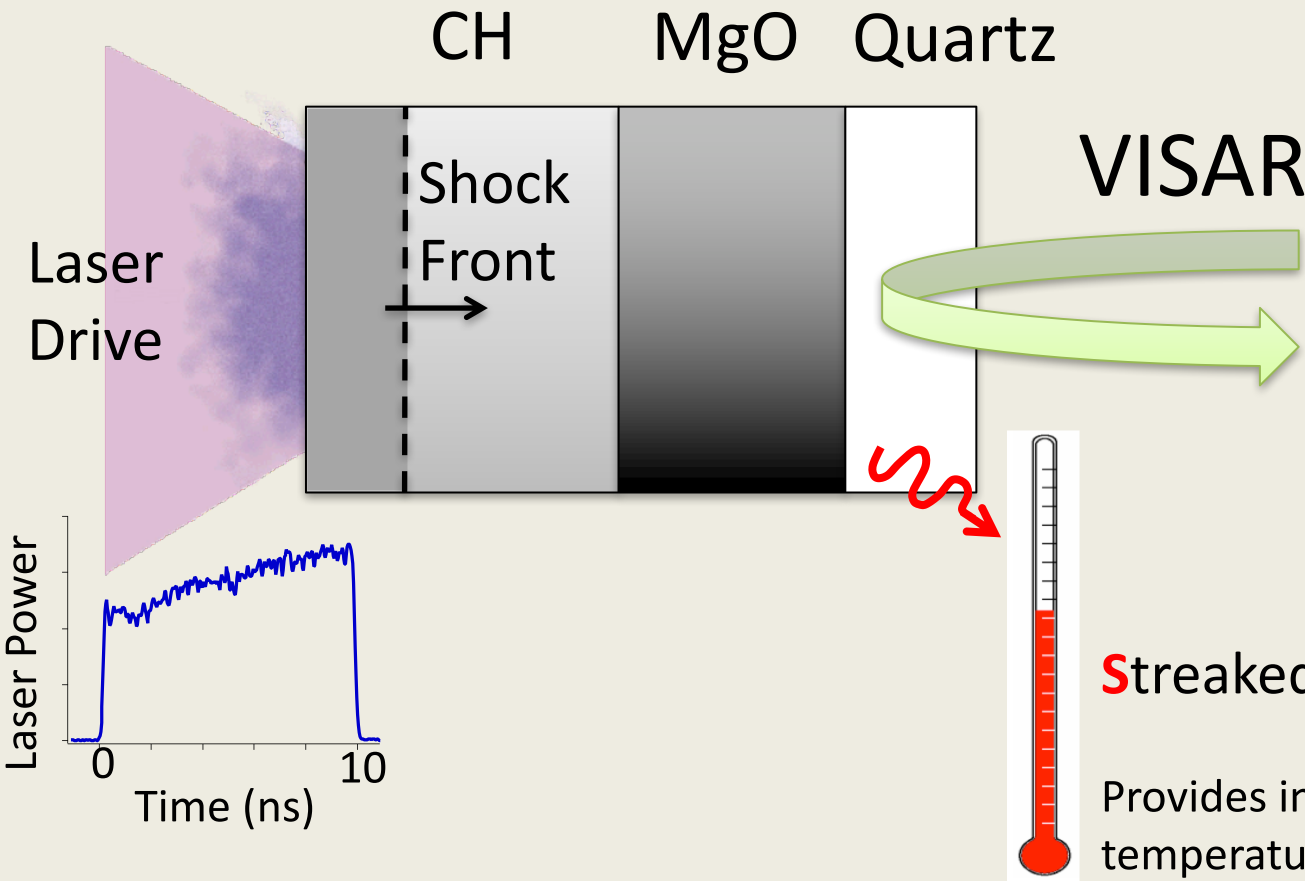
Main sources of noise



Target design



Experimental setup

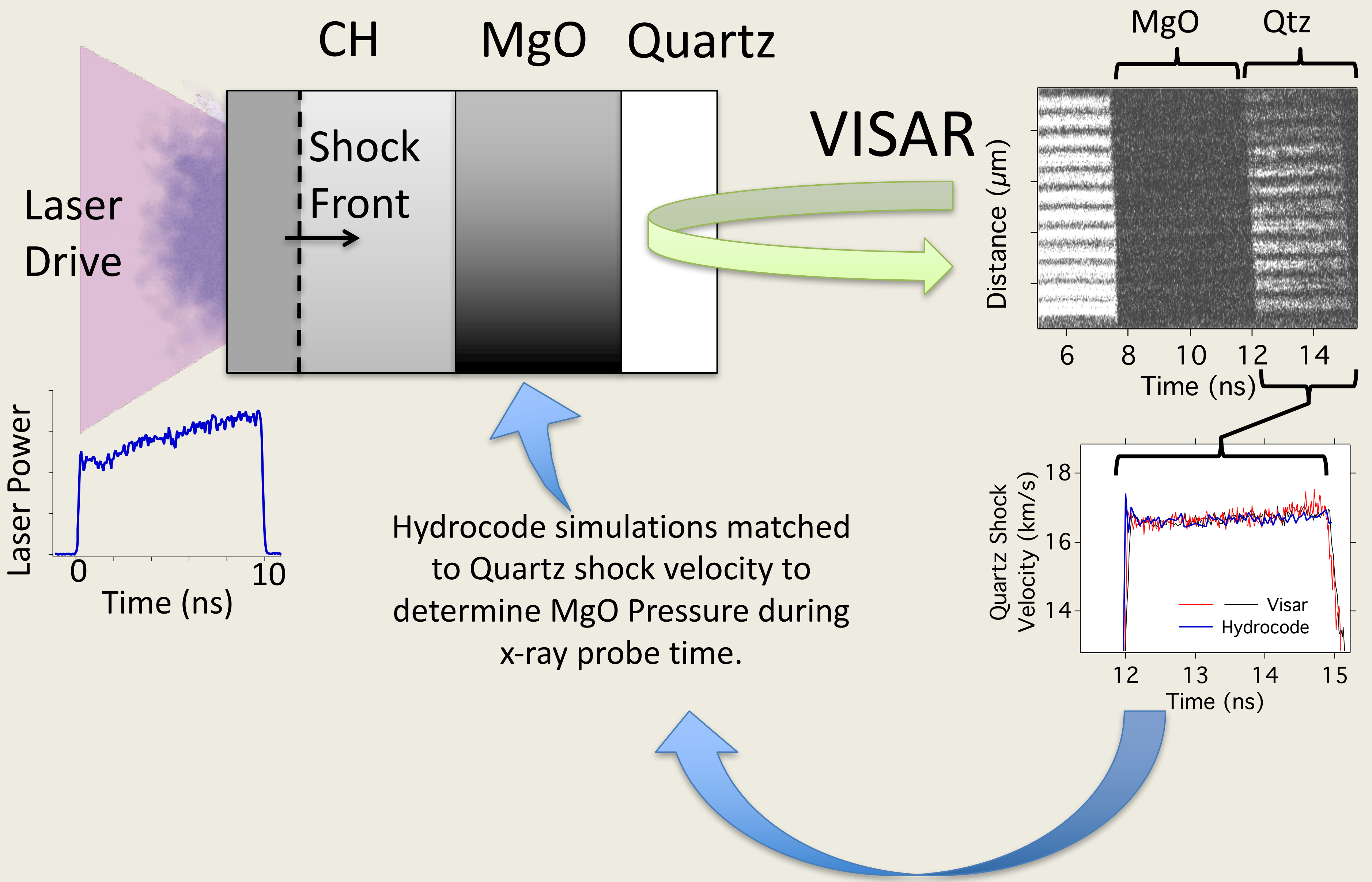


velocity interferometer, provides information on MgO pressure versus time

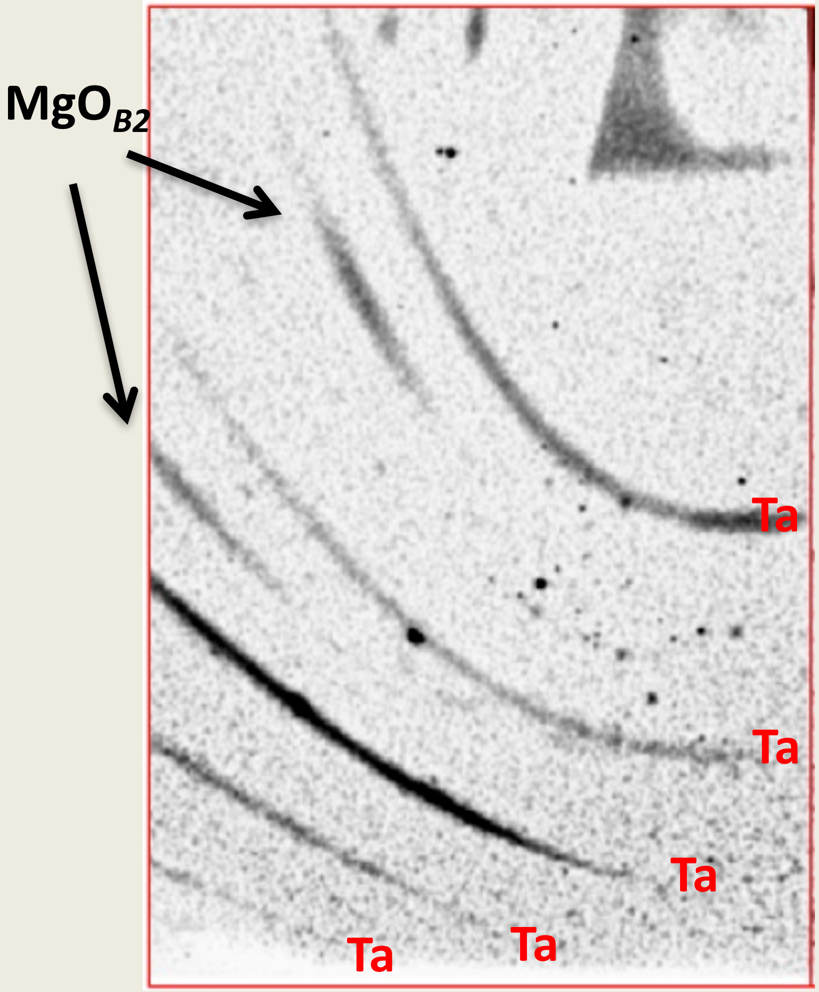
Streaked Optical Pyrometer

Provides information on MgO temperature versus time at the shock front.

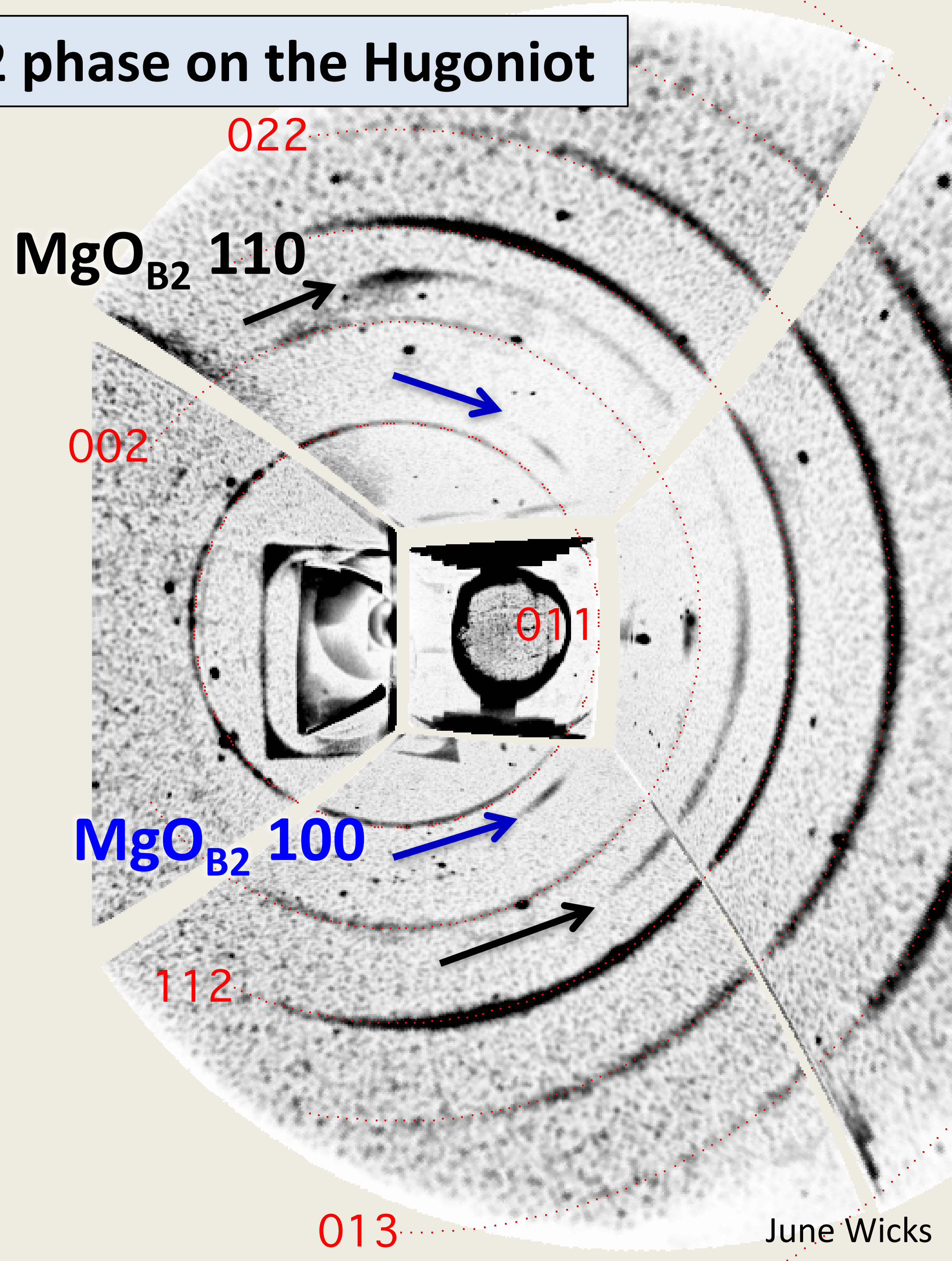
Pressure Determination using reflecting shock in quartz



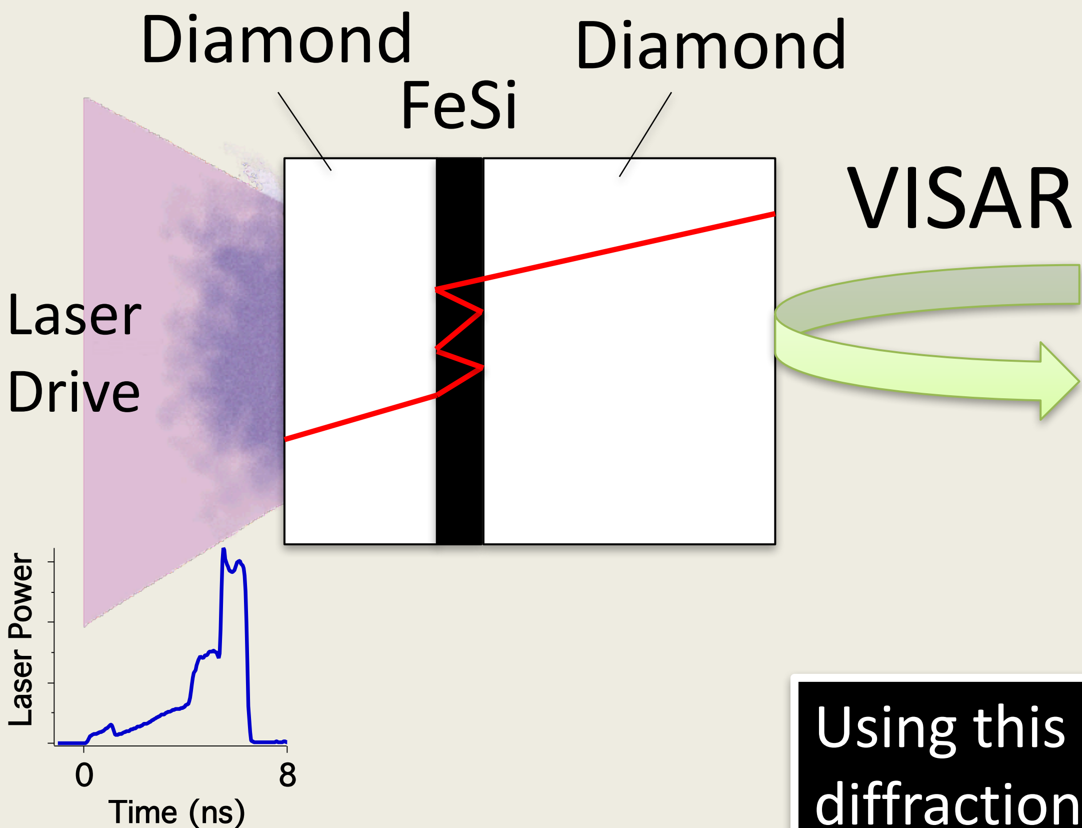
At 515 GPa MgO is in the B2 phase on the Hugoniot



Left panel



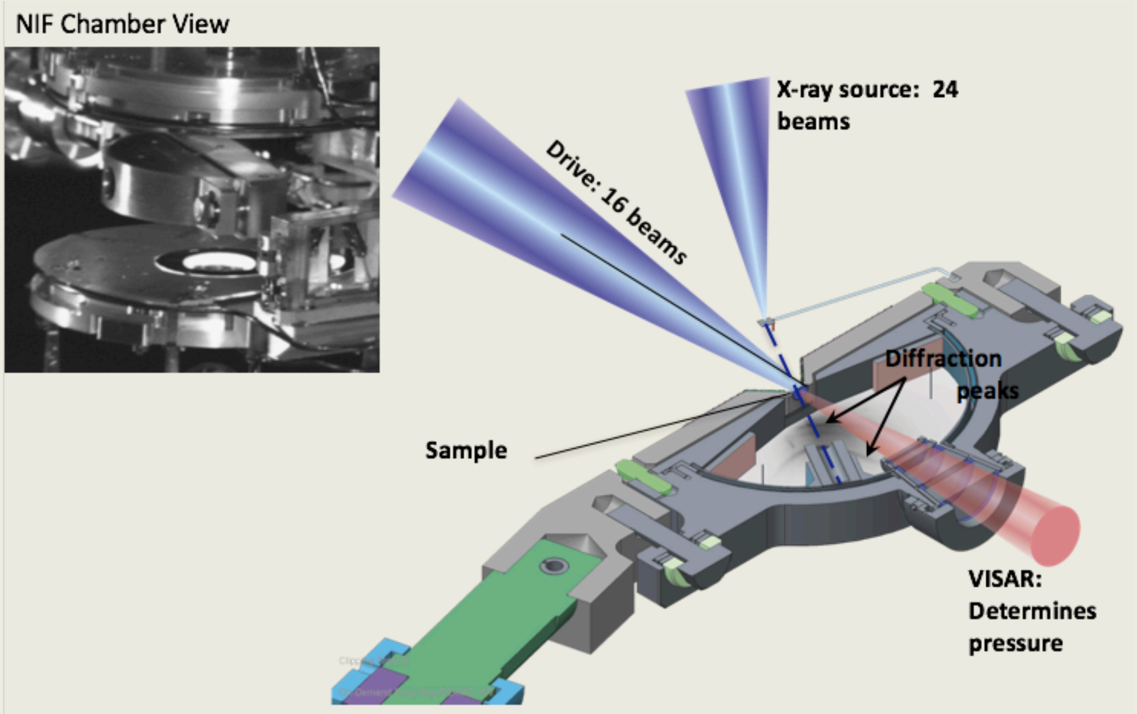
Target design for ramp-compression of FeSi



Using this technique we have obtained diffraction data from solid state FeSi alloys up to 1300 GPa

Conclusions

In recent years X-ray diffraction experiments on Omega and NIF have been very successful in determining high-pressure crystal structures on materials with <u>high symmetry</u> phases.



X-ray diffraction experiments on Omega/NIF and ESRF

- X-ray source
- Required Laser Spot Size
- Signal-to-Noise
- Achievable sample pressures
- Shot Rate

Energy Needed to achieve a given pressure scales with Laser Intensity

For Shock Sample with a CH ablator: $P_{CH} \sim I_{LASER}^{0.8}$

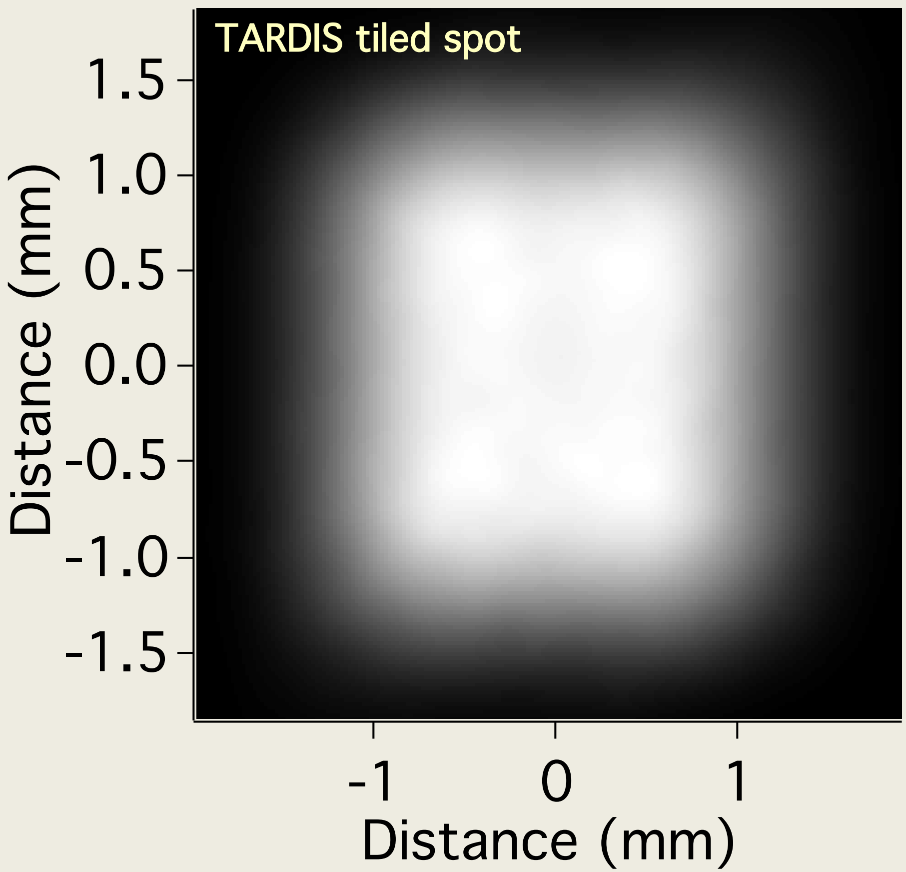
For Ramp Compression Sample with a diamond ablator: $P_{Diamond} \sim I_{LASER}^{0.7}$

Energy Needed to achieve a given pressure scales with Laser Intensity

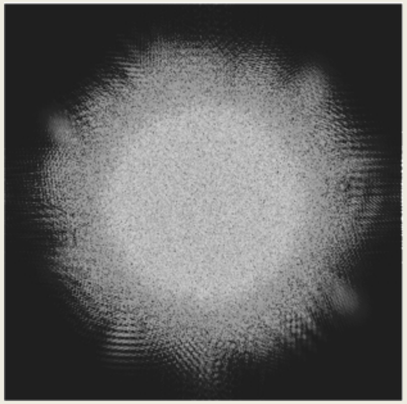
For Shock Sample with a CH ablator: $P_{CH} \sim I_{LASER}^{0.8}$

For Ramp Compression Sample with a diamond ablator: $P_{Diamond} \sim I_{LASER}^{0.7}$

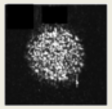
NIF Laser Spot



Omega-EP
1.1 mm phase plate



Future ESRF 250 µm phase plate



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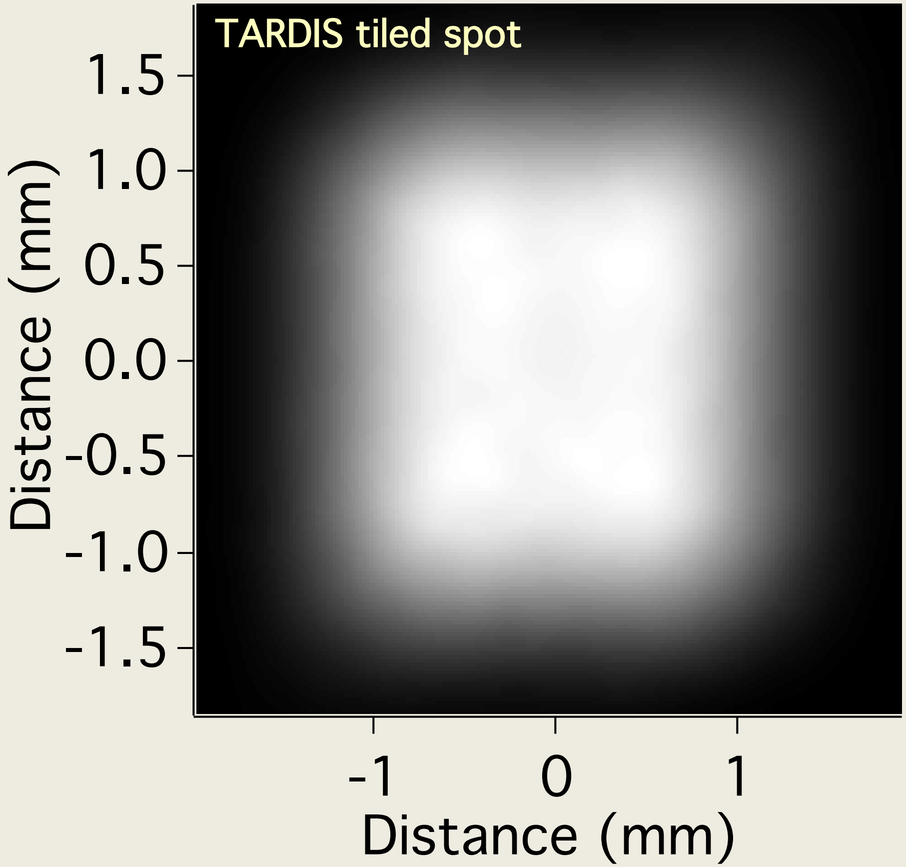
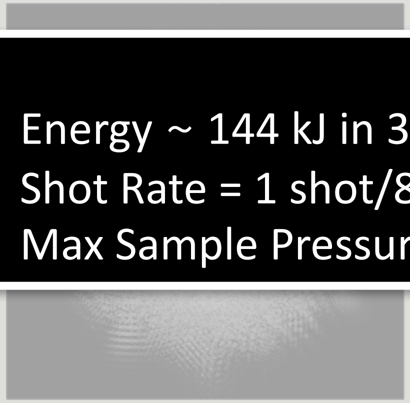
NIF Laser Spot



Omega-EP
1.1 mm phase plate



ESRF
250 μm phase

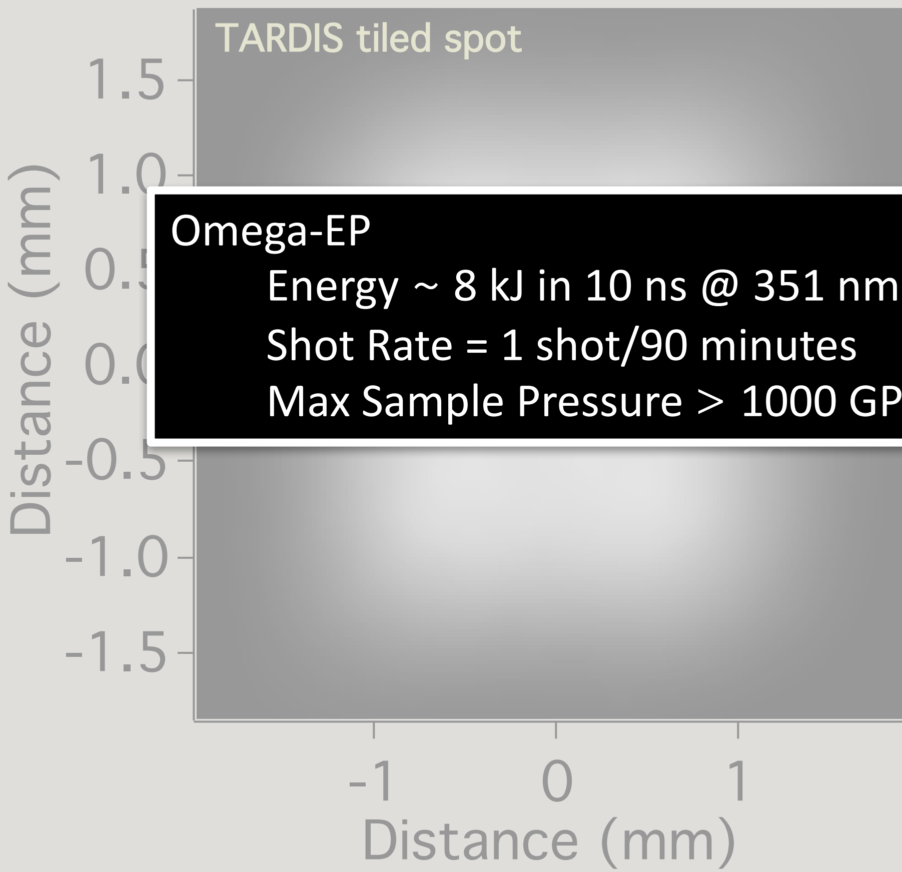
NIF
Energy ~ 144 kJ in 30 ns @ 351 nm
Shot Rate = 1 shot/8 hours
Max Sample Pressure > 3,000 GPa

Energy Needed to achieve a given pressure scales with Laser Intensity

For Shock Sample with a CH ablator: $P_{CH} \sim I_{LASER}^{0.8}$

For Ramp Compression Sample with a diamond ablator: $P_{Diamond} \sim I_{LASER}^{0.7}$

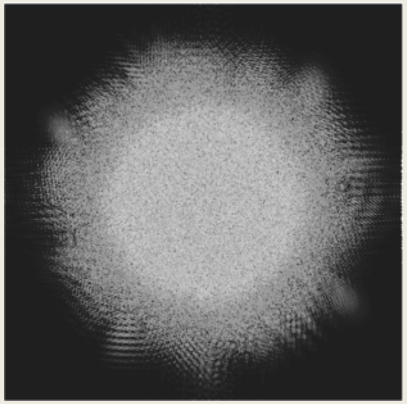
NIF Laser Spot



Omega-EP

- Energy ~ 8 kJ in 10 ns @ 351 nm
- Shot Rate = 1 shot/90 minutes
- Max Sample Pressure > 1000 GPa

Omega-EP 1.1 mm phase plate



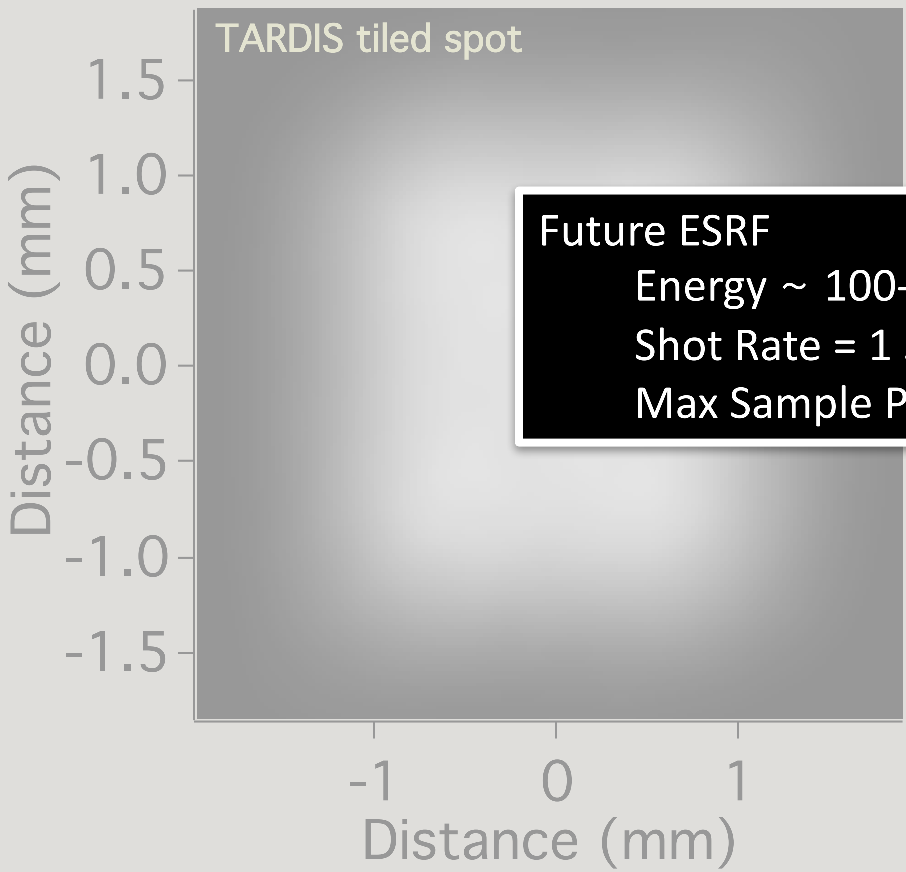
ESRF 250 µm phase plate

Energy Needed to achieve a given pressure scales with Laser Intensity

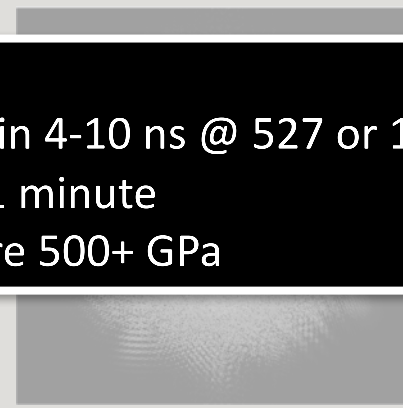
For Shock Sample with a CH ablator: $P_{CH} \sim I_{LASER}^{0.8}$

For Ramp Compression Sample with a diamond ablator: $P_{Diamond} \sim I_{LASER}^{0.7}$

NIF Laser Spot



Omega-EP
1.1 mm phase plate



Future ESRF
250 µm phase plate

Future ESRF

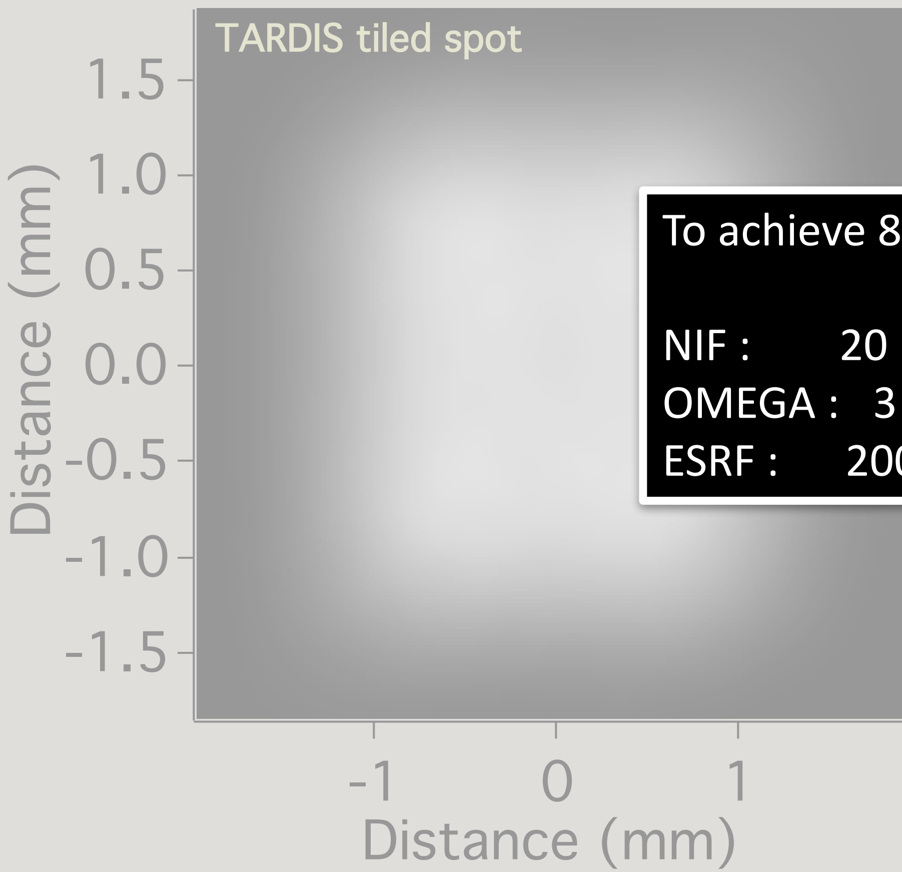
- Energy ~ 100-200 J in 4-10 ns @ 527 or 1054 nm
- Shot Rate = 1 shot/1 minute
- Max Sample Pressure 500+ GPa

Energy Needed to achieve a given pressure scales with Laser Intensity

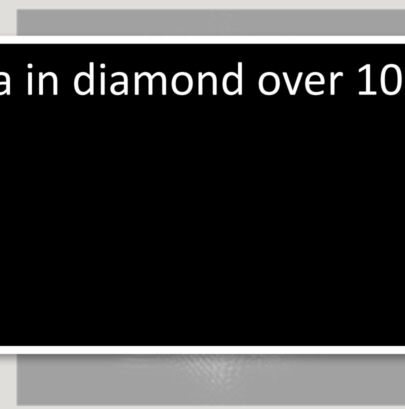
For Shock Sample with a CH ablator: $P_{CH} \sim I_{LASER}^{0.8}$

For Ramp Compression Sample with a diamond ablator: $P_{Diamond} \sim I_{LASER}^{0.7}$

NIF Laser Spot



Omega-EP 1.1 mm phase plate



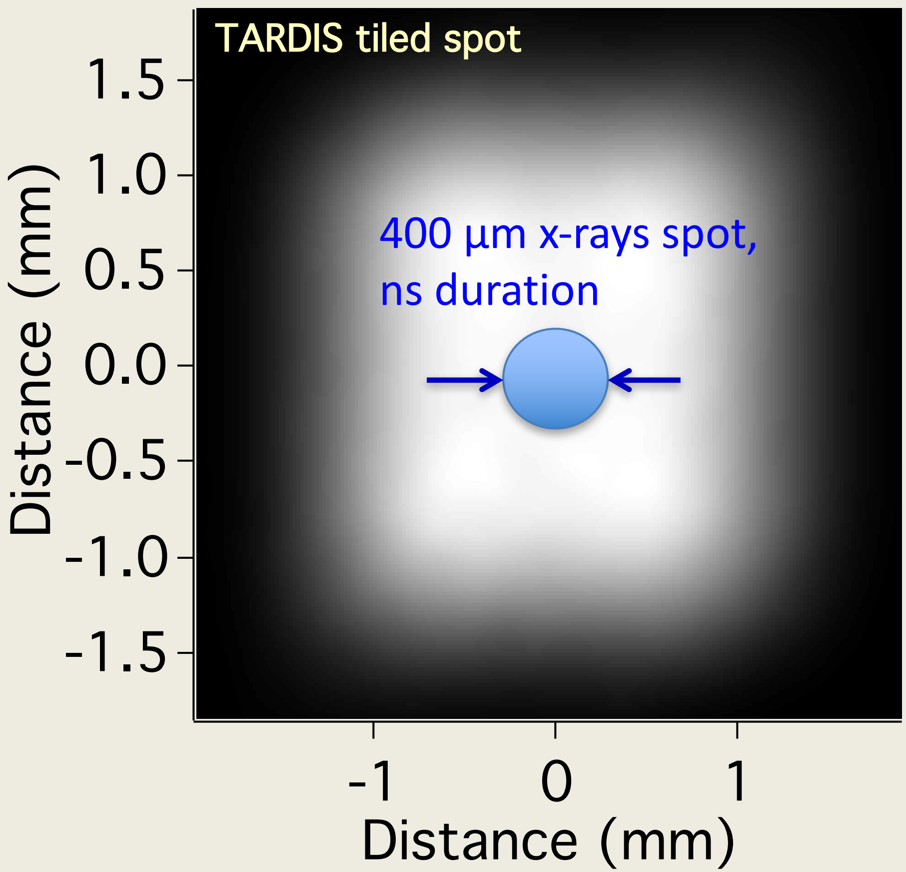
ESRF 250 µm phase plate

To achieve 800 GPa in diamond over 10 ns :

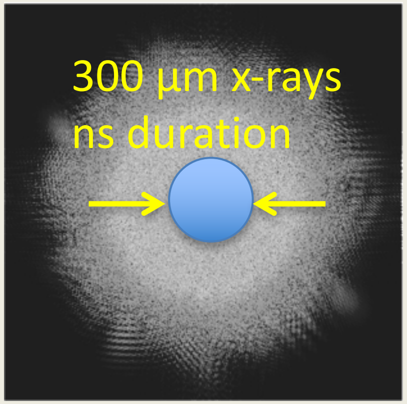
NIF : 20 kJ
OMEGA : 3 kJ
ESRF : 200 J

Laser spots are needed on Omega and NIF to accommodate larger diameter x-ray beams. This improves the signal-to-noise in the diffraction pattern

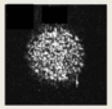
NIF Laser Spot



Omega-EP 1.1 mm phase plate



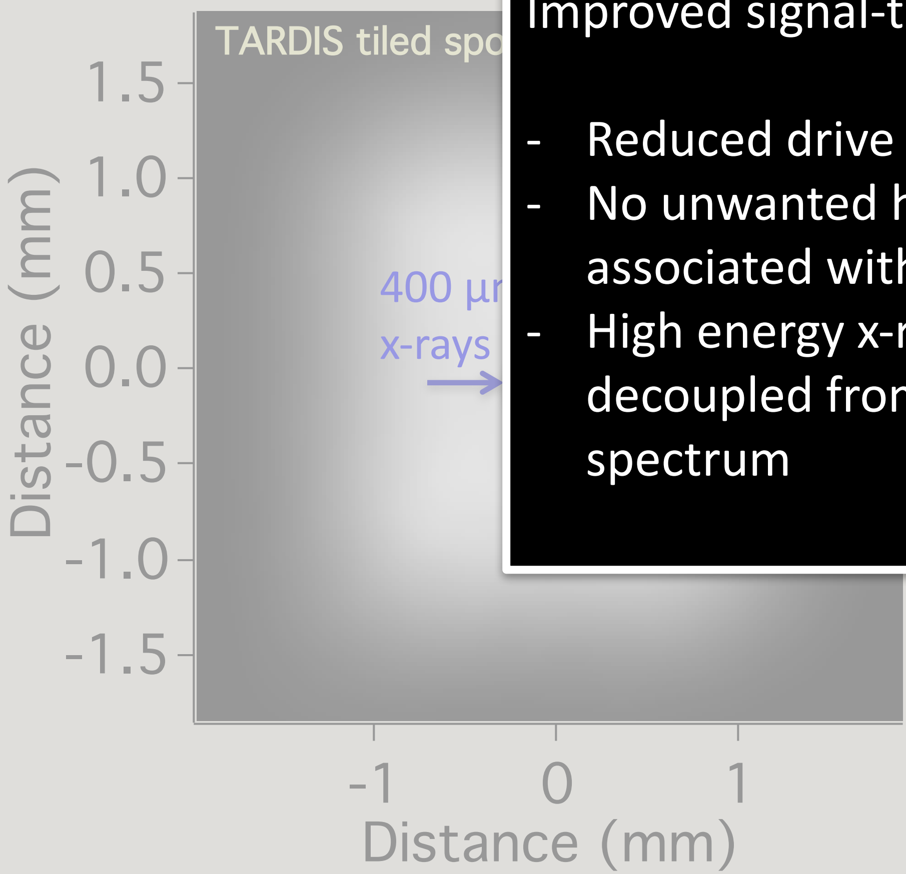
ESRF 250 µm phase plate



20 µm x-rays ?
100 ps duration

Laser spots are needed on Omega and NIF to accommodate larger diameter x-ray beams. This improves the signal-to-noise in the diffraction pattern

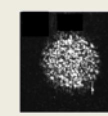
NIF Laser Spot



Improved signal-to-noise at ESRF :

- Reduced drive Laser plasma volume
- No unwanted high energy x-ray emission associated with the x-ray probe
- High energy x-rays from ESRF spectrally decoupled from laser plasma x-ray spectrum

ESRF 250 μm phase plate

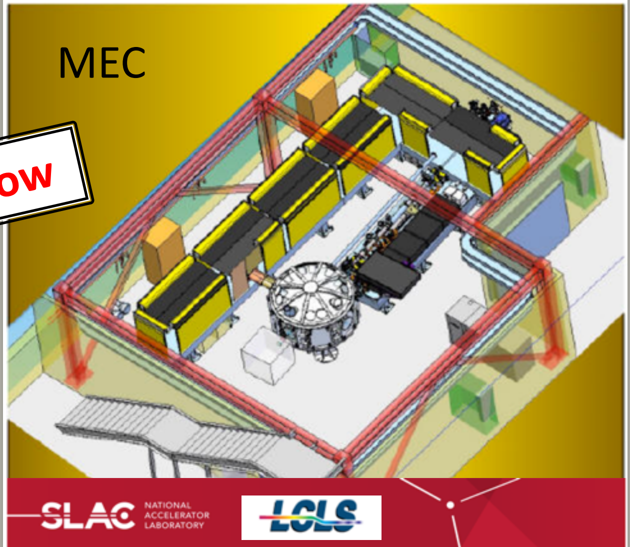


20-80 μm x-rays

New 100-J class, pulse-shaped lasers are being built at X-ray sources around the world.

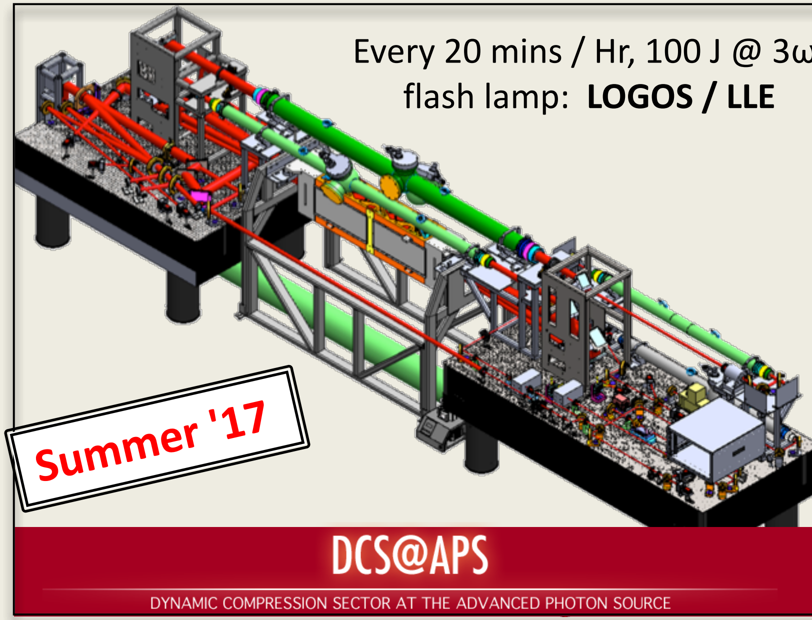
- Continuum laser, 2-20 ns, 2ω
- 40 J in 10 ns, 10 min. rep rate.

Now



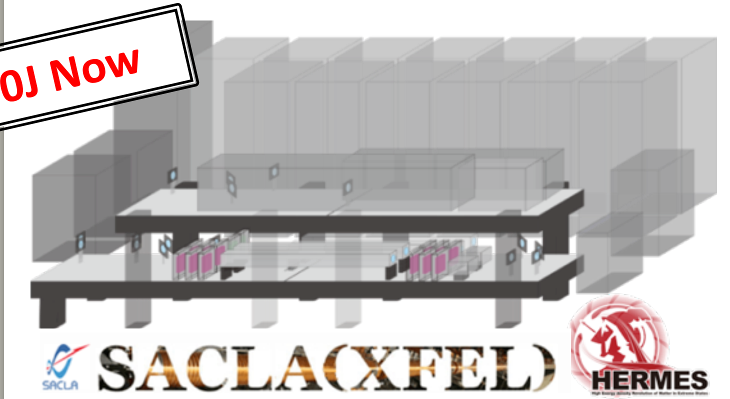
Every 20 mins / Hr, 100 J @ 3ω, flash lamp: **LOGOS / LLE**

Summer '17



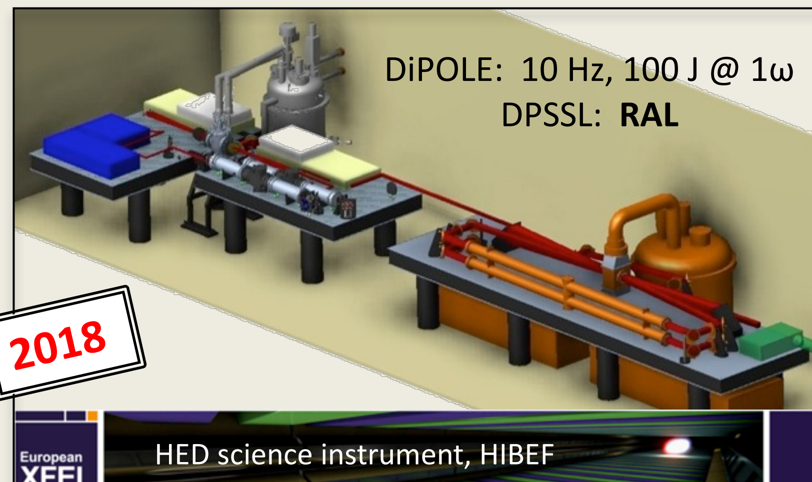
Long pulse Laser (Ceramic)
200J/10-20ns/0.1Hz/532nm

50J Now



DiPOLE: 10 Hz, 100 J @ 1ω
DPSSL: **RAL**

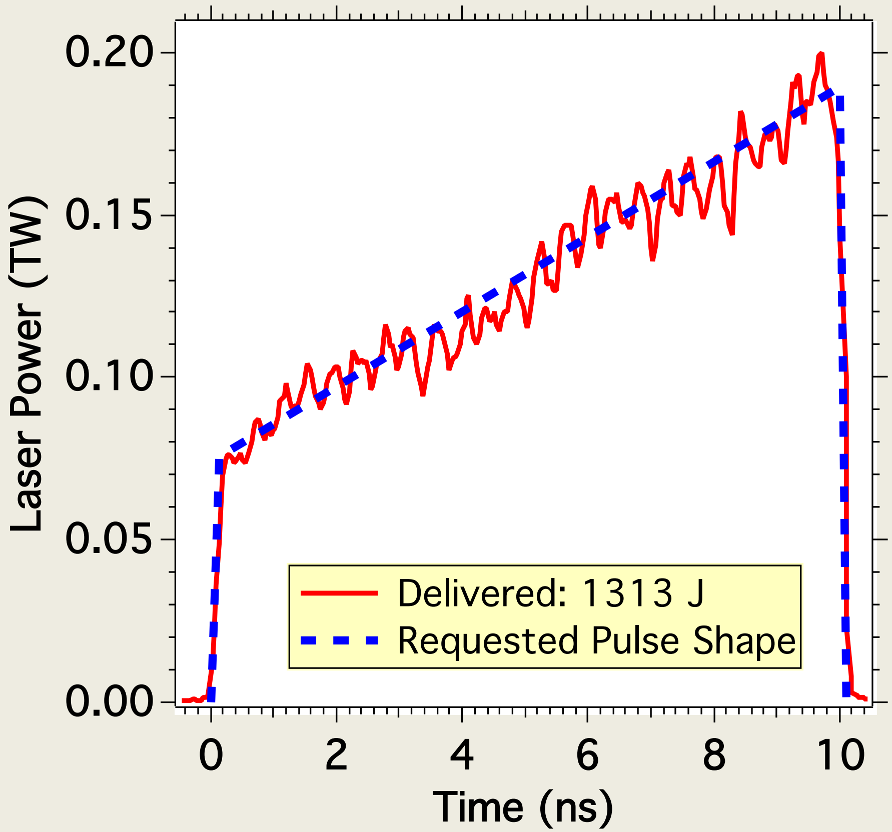
2018



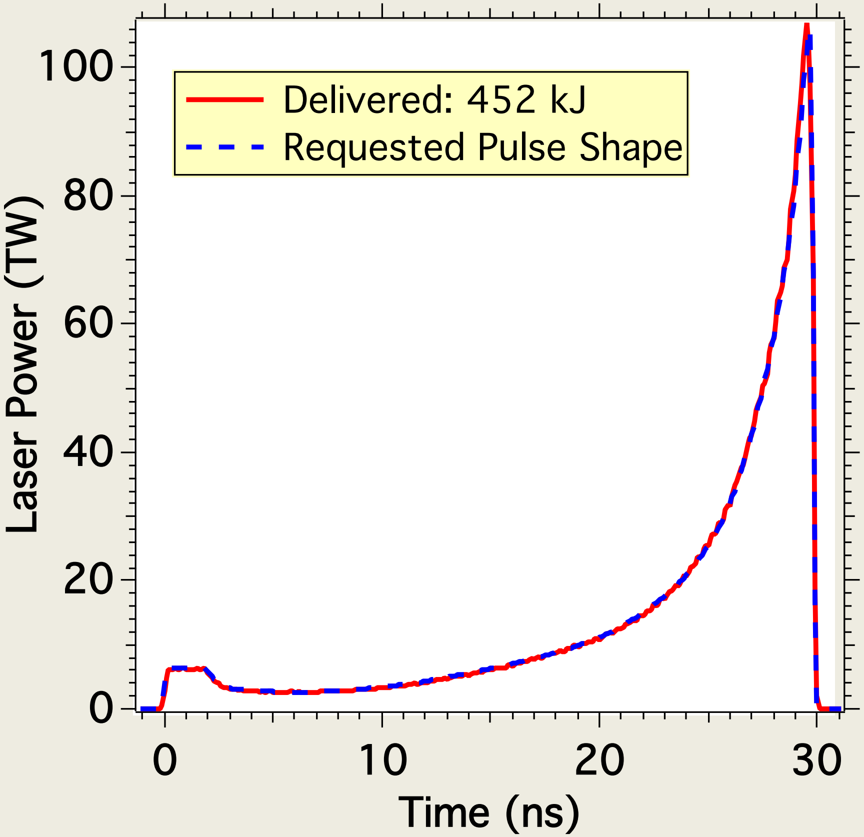
Pulse Shaping is important to access different thermodynamic compression paths

1 TPa = 1000 GPa = 10 Mbar

Omega-EP, Pulse shape to produce a steady shock

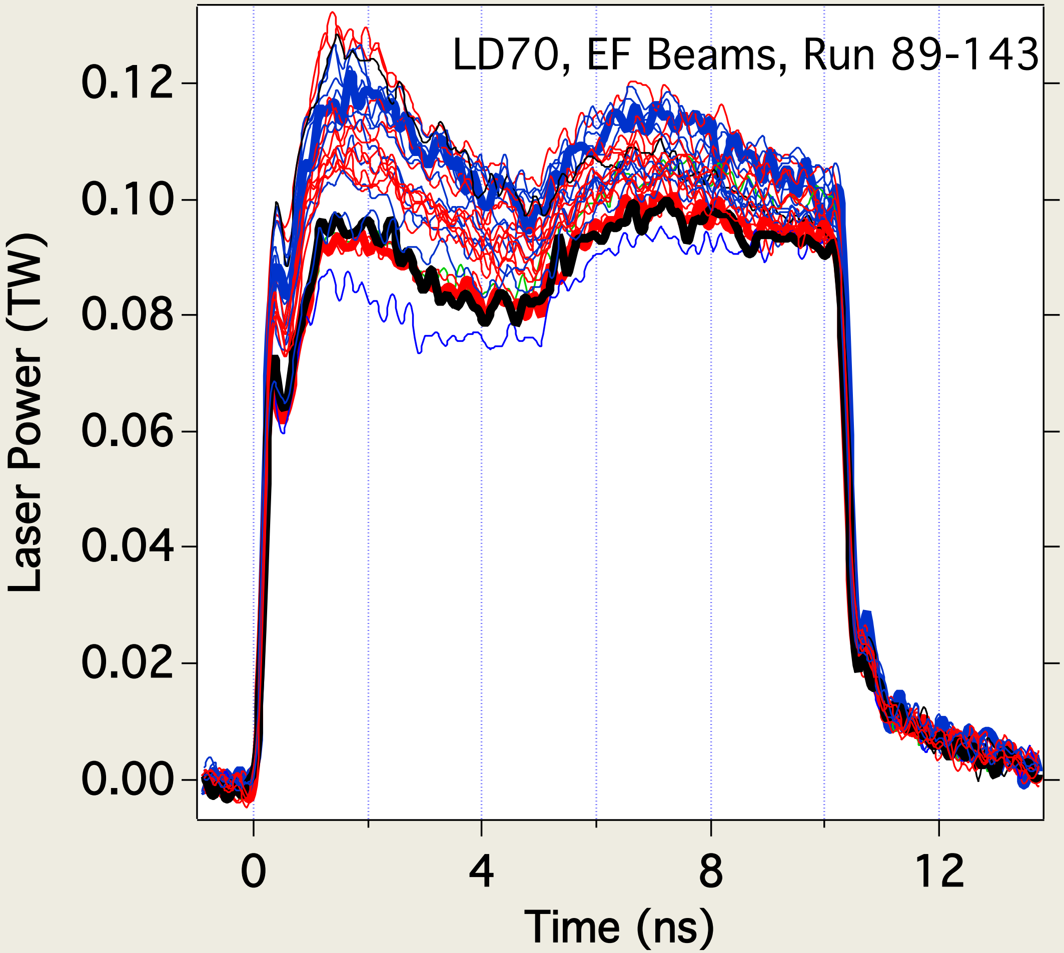


NIF pulse shape to produce a ramp-compression wave



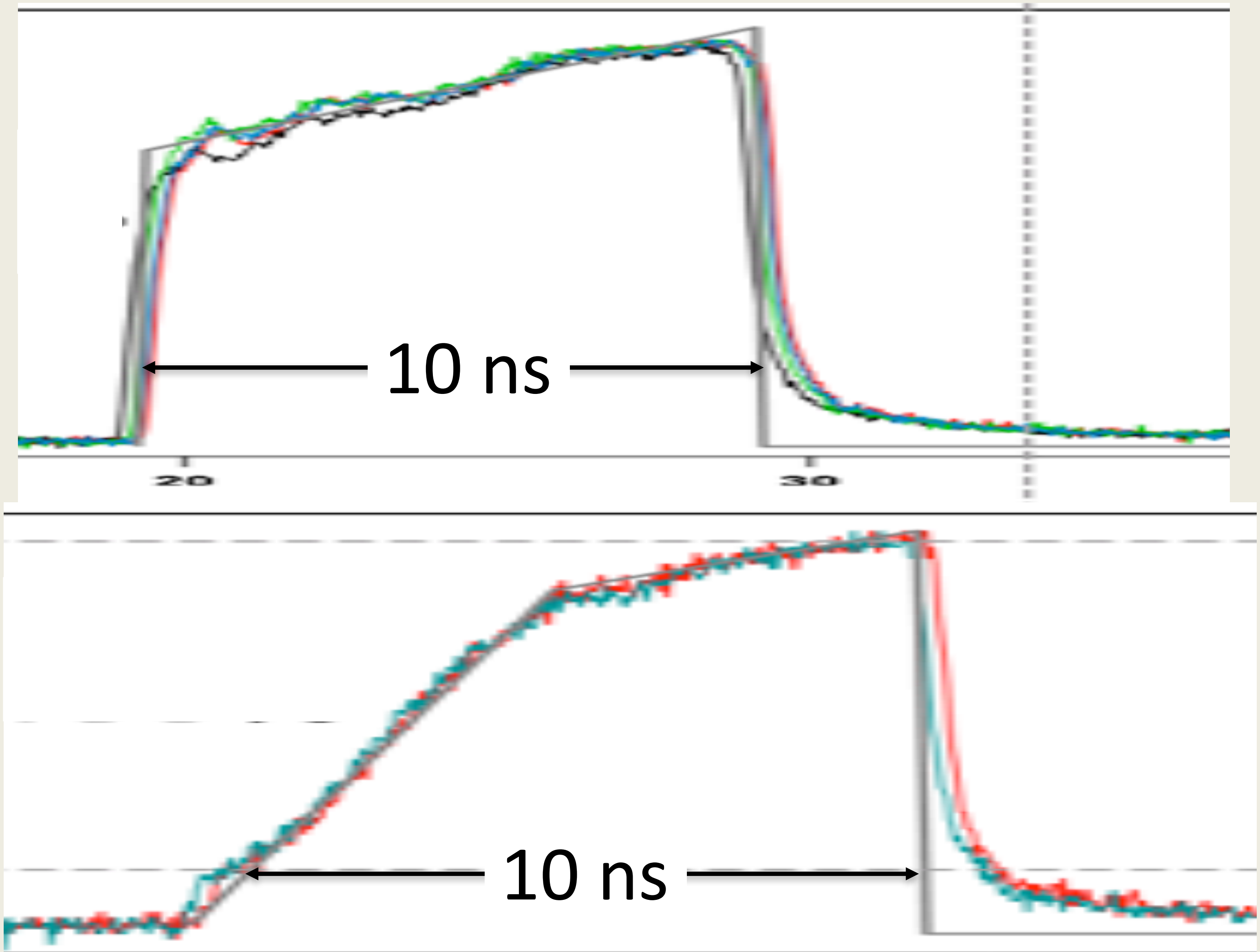
Pulse shaping is available on LCLS/MEC albeit with less fidelity

MEC Laser – April 2014, 25 repeat laser shots



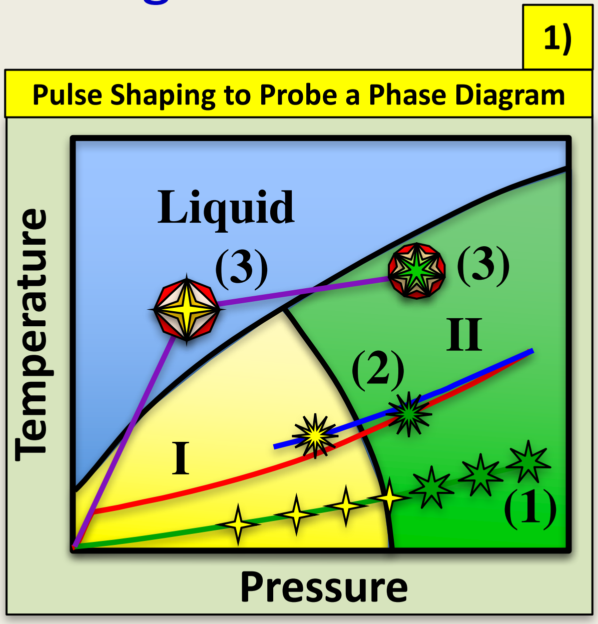
Pulse shaping at APS-DCS

100 J,
3ω,
10 ns



To take advantage of the potential 1 shot/min rep rate we need to develop high repetition rate targets.

1) Quickly map out phase space using variable pulse shapes



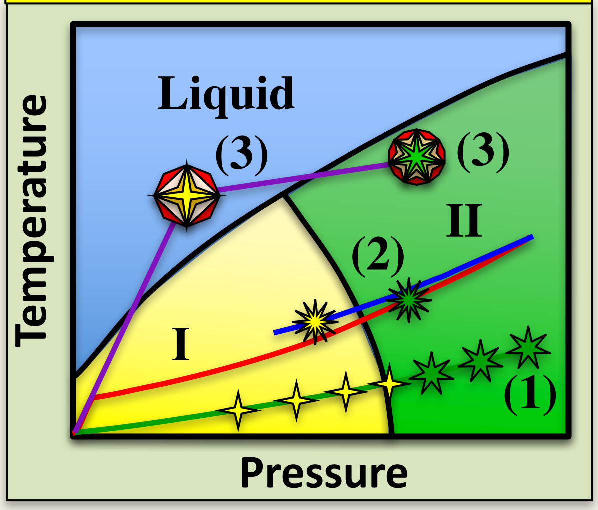
To take advantage of the potential 1 shot/min rep rate we need to develop high repetition rate targets.

1) **Quickly map out phase space using variable pulse shapes**

2) **low-signal phenomena**
   a) **Low Symmetry Phases**

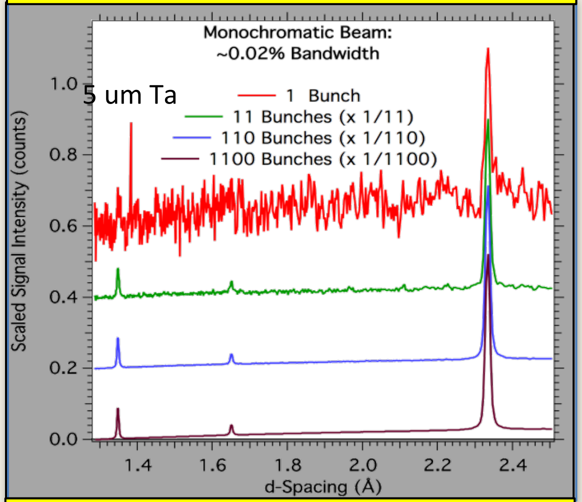
1)

Pulse Shaping to Probe a Phase Diagram



2a)

Monochromatic Diffraction at BioCars



Need to average ~100 shots

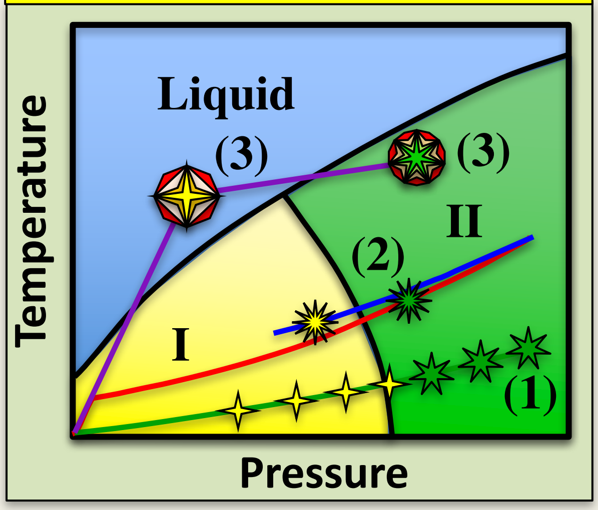
To take advantage of the potential 1 shot/min rep rate we need to develop high repetition rate targets.

1) **Quickly map out phase space using variable pulse shapes**

2) **low-signal phenomena**
   a) **Low Symmetry Phases**
   b) **Liquid diffraction**

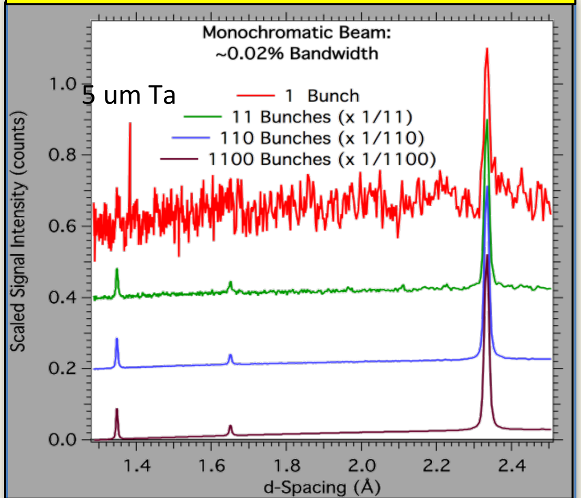
1)

Pulse Shaping to Probe a Phase Diagram



2a)

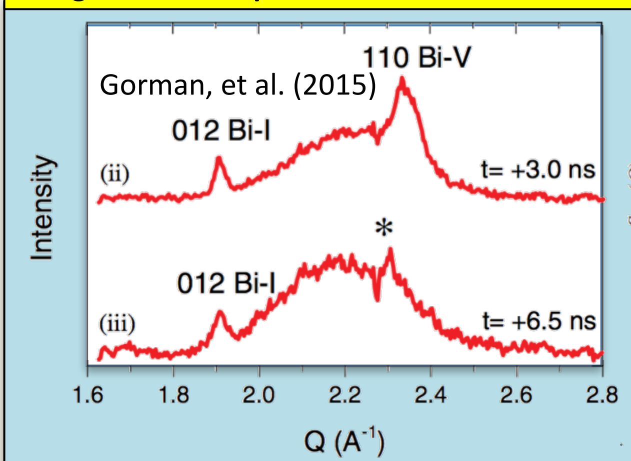
Monochromatic Diffraction at BioCars



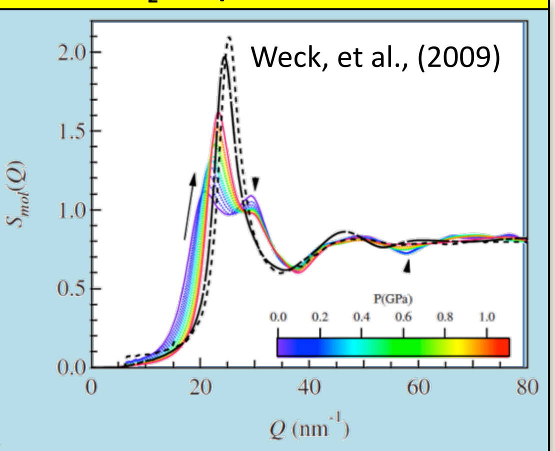
Need to average ~100 shots

2b)

Single-Shot Bi Liquid Diffraction at LCLS



300s H_2O Liquid Diffraction at ESRF



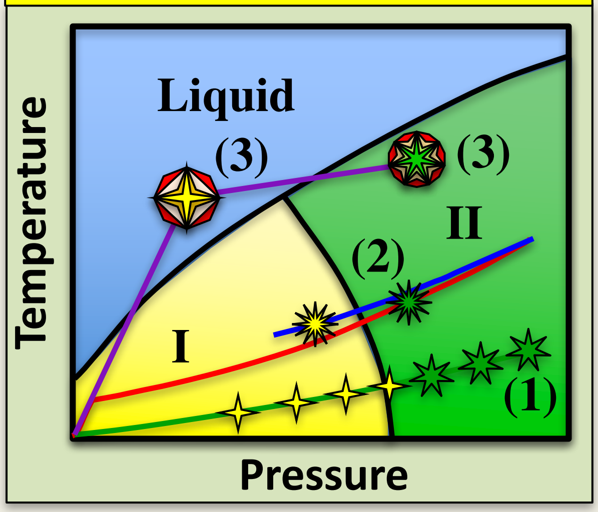
May need to average ~100 shots to obtain high-quality liquid diffraction

To take advantage of the potential 1 shot/min rep rate we need to develop high repetition rate targets.

1) **Quickly map out phase space using variable pulse shapes**
2) **low-signal phenomena**
   a) **Low Symmetry Phases**
   b) **Liquid diffraction**
   c) **EXAFS**

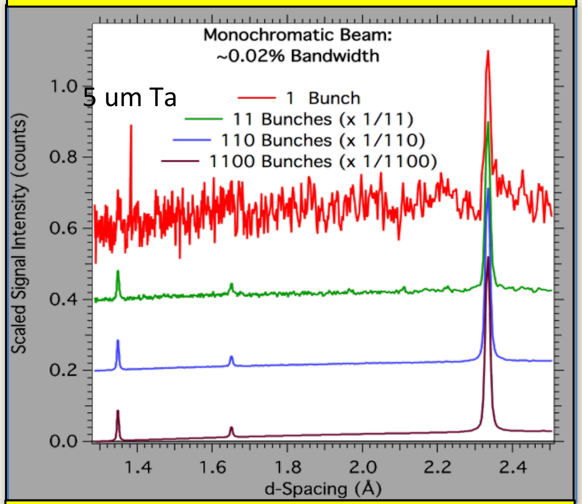
1)

Pulse Shaping to Probe a Phase Diagram



2a)

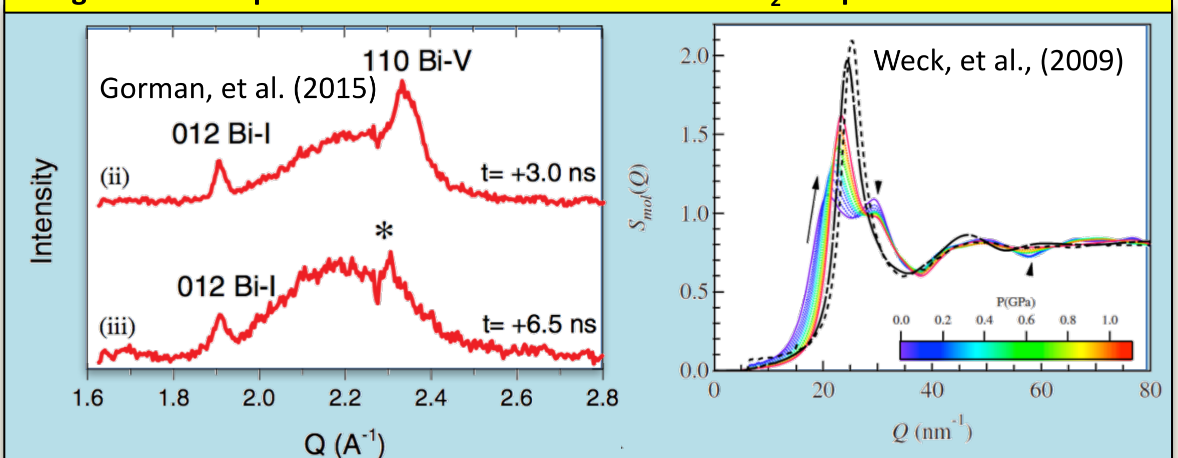
Monochromatic Diffraction at BioCars



Need to average ~100 shots

2b)

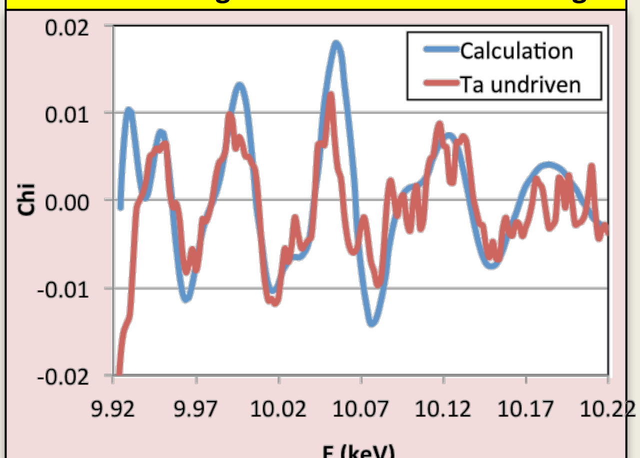
Single-Shot Bi Liquid Diffraction at LCLS **300s H_2O Liquid Diffraction at ESRF**



May need to average ~100 shots to obtain high-quality liquid diffraction

2c)

15-Shot Average Ta L-Shell EXAFS at Omega



Likely need to average 10-50 shots

Conclusions

In recent years X-ray diffraction experiments on Omega and NIF have been very successful in determining high-pressure crystal structures on materials with high symmetry phases.

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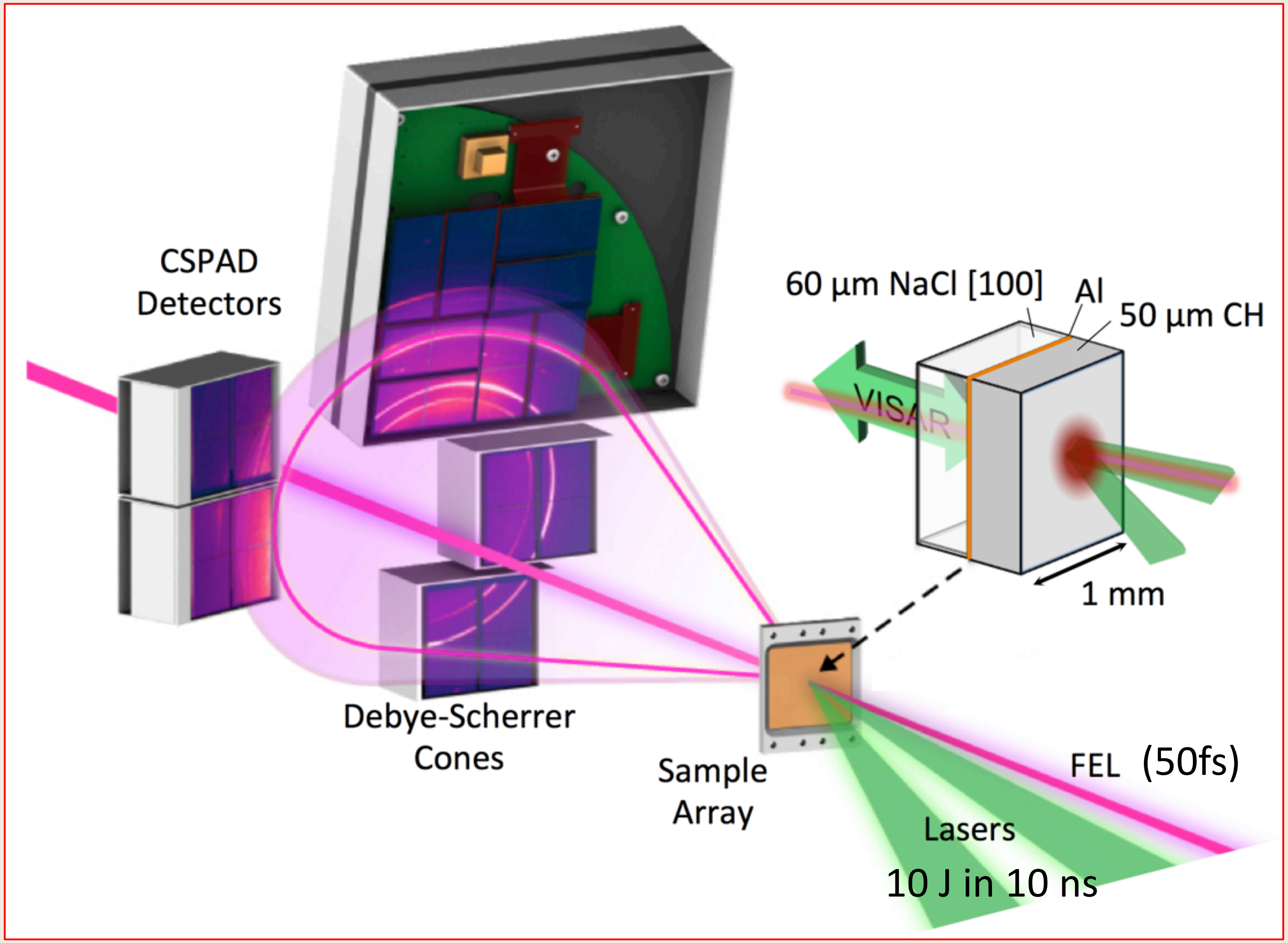
With compact high power laser systems ESRF and other x-ray sources offer exciting possibilities for much improved single-to-noise measurements of high-pressure crystal structure on more complex materials.

Requirements

- Need good phase plates
- Laser Pulse shaping
- High Rep rate targets
- Good VISAR and Pyrometry diagnostics
- Equation of state and hydrocode development to understand target conditions

Backup slides

Experiment setup on the Stanford LCLS-MEC hutch



Recent MEC diffraction publications: Gleason *et al.*, Nat. Comm. (2015)
Gorman *et al.*, Phy. Rev. Letts. (2015)

To take advantage of the potential 1 shot/min rep rate we need to develop high repetition rate targets.

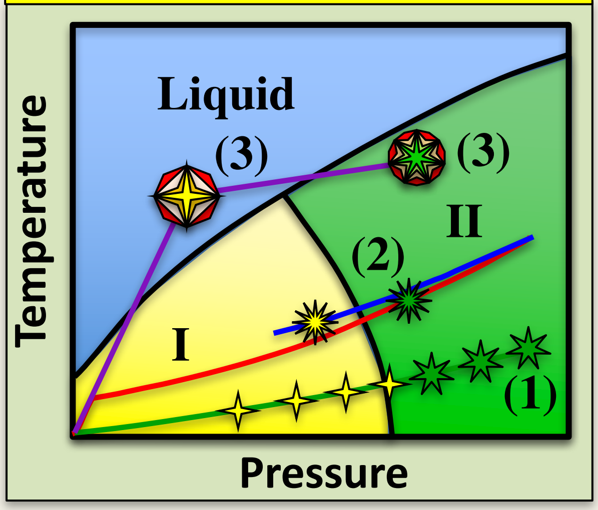
1) **Quickly map out phase space using variable pulse shapes**

2) **low-signal phenomena**
   a) **Narrow-bandwidth diffraction**
   b) **Liquid diffraction**
   c) **EXAFS**

3) **Make movies of transitions using variable time delays over many shots**

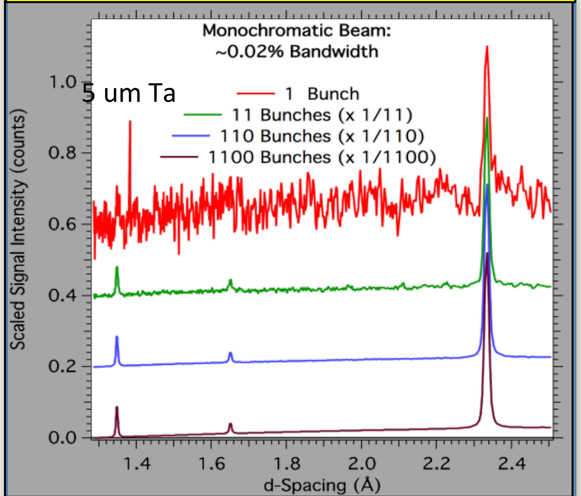
1)

Pulse Shaping to Probe a Phase Diagram



2a)

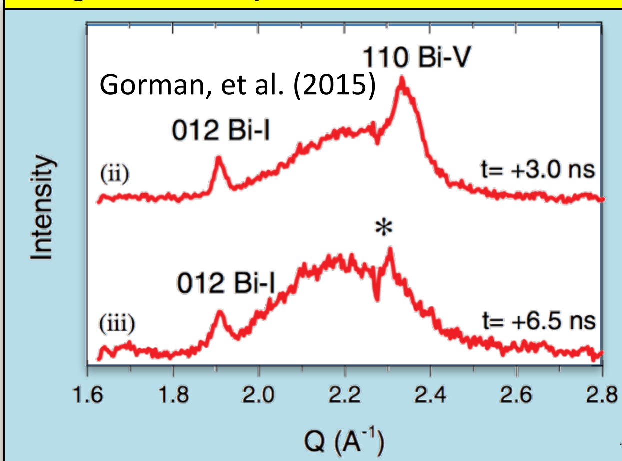
Monochromatic Diffraction at BioCars



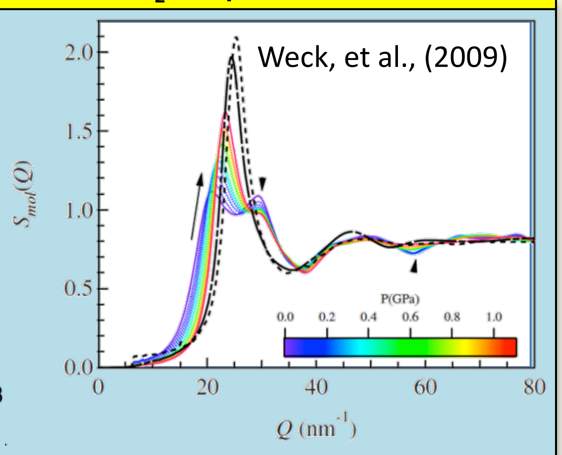
Need to average ~100 shots

2b)

Single-Shot Bi Liquid Diffraction at LCLS



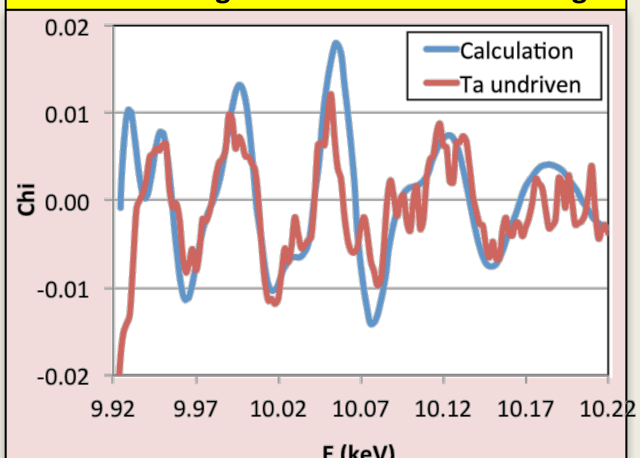
300s H_2O Liquid Diffraction at ESRF



May need to average ~100 shots to obtain high-quality liquid diffraction

2c)

15-Shot Average Ta L-Shell EXAFS at Omega

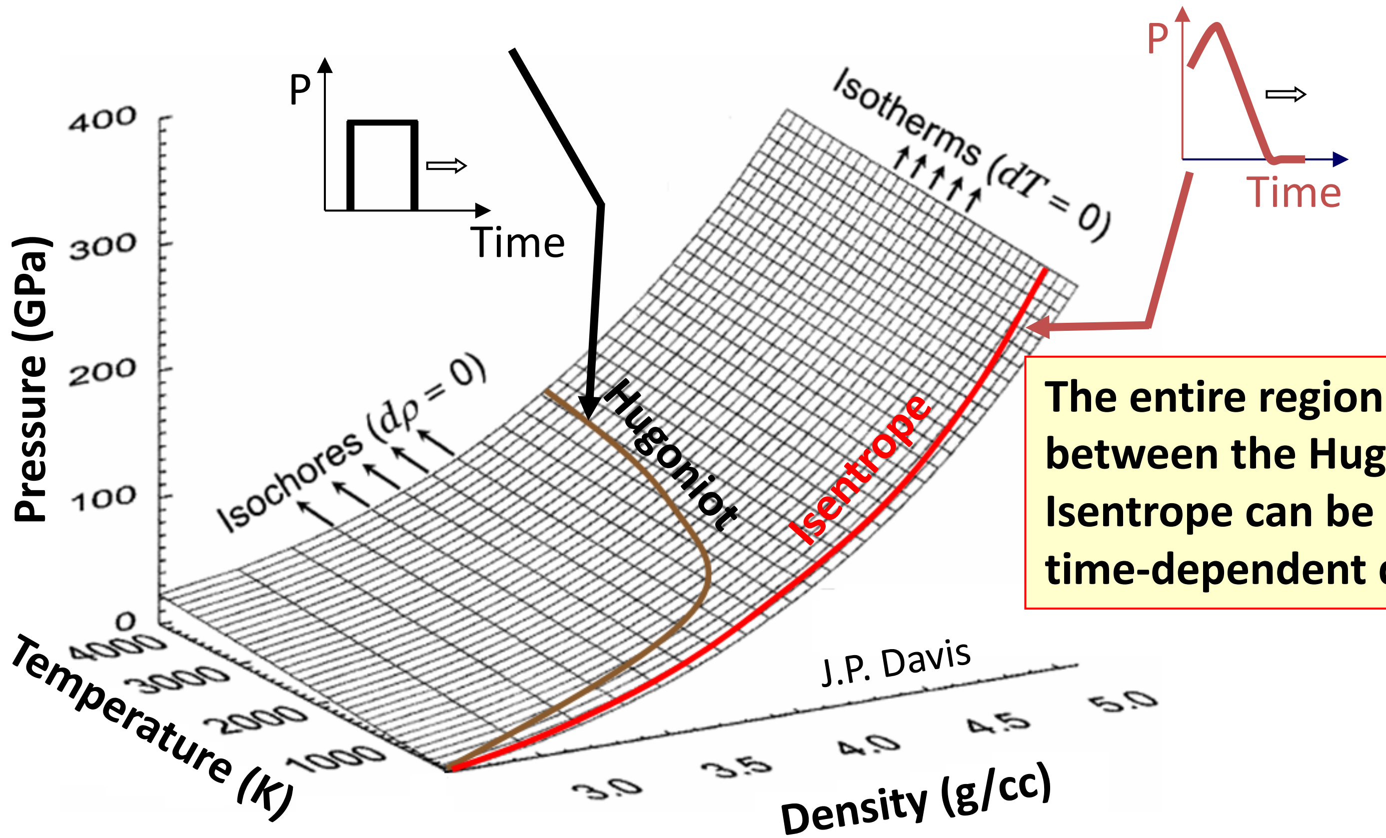


Likely need to average 10-50 shots

Equilibrium thermodynamics is described by an equation-of-state (EOS) surface

Strong shocks probe high-temperature EOS states

Ramped compression waves probe EOS at lower temperatures than shocks



The entire region of phase space between the Hugoniot and the Isentrope can be probed by variable time-dependent drives.

Future experiments using the ESRF laser

Laser
100-200 J, 4-10ns, shaped, 1shot/minute, 1053nm & 528 nm

X-rays
Phase I, the laser will be coupled to a XAS beamline (5-27 keV).
Phase II,, we hope to add a second beamline with XRD, XRI and XES (~ 20 - 60 keV), pink beam (1-2% bandwidth), ~1×10^{11} photons per X-ray pulse in 100 ps.