Lawrence Livermore National Laboratory

Properties of Hydrogen at TPa pressures

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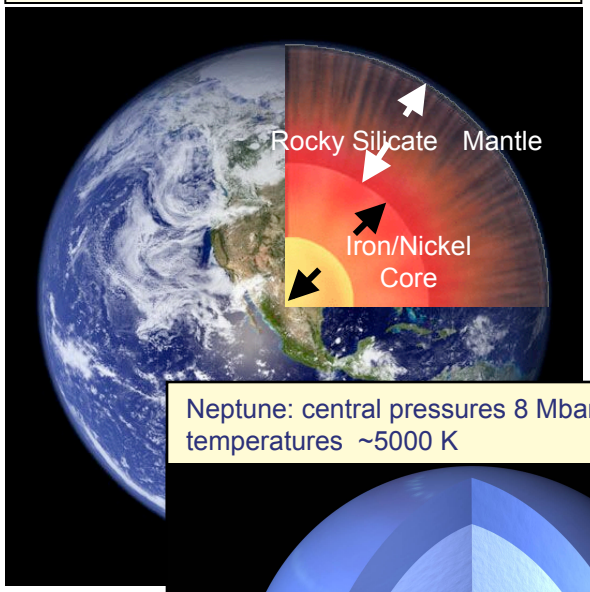
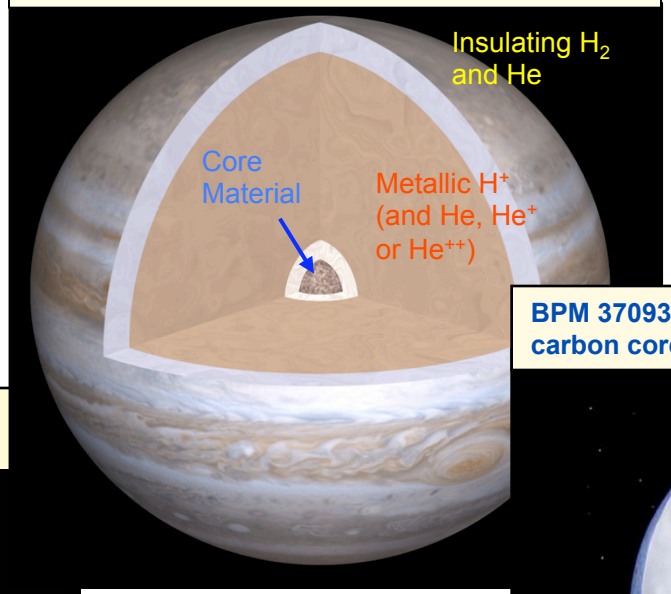
Paul Loubeyre (CEA)
LLNL Liaison – Peter Celliers

Matter at very extreme densities and temperatures is common in our universe

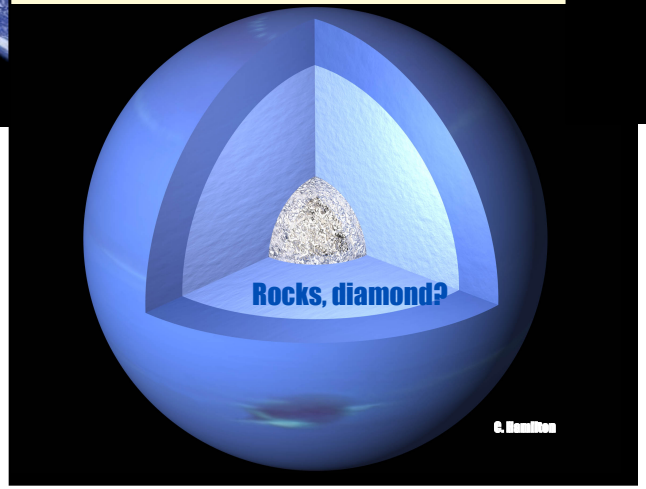
Earth: central pressures ~3.6 Mbar and temperatures ~6000 K



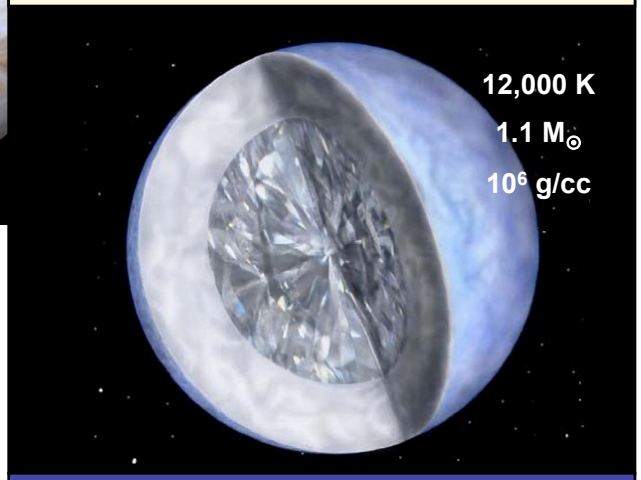
Jupiter: central pressures ~77 Mbar and temperatures ~16000 K



Neptune: central pressures 8 Mbar and temperatures ~5000 K



BPM 37093, a white dwarf star with a solid carbon core

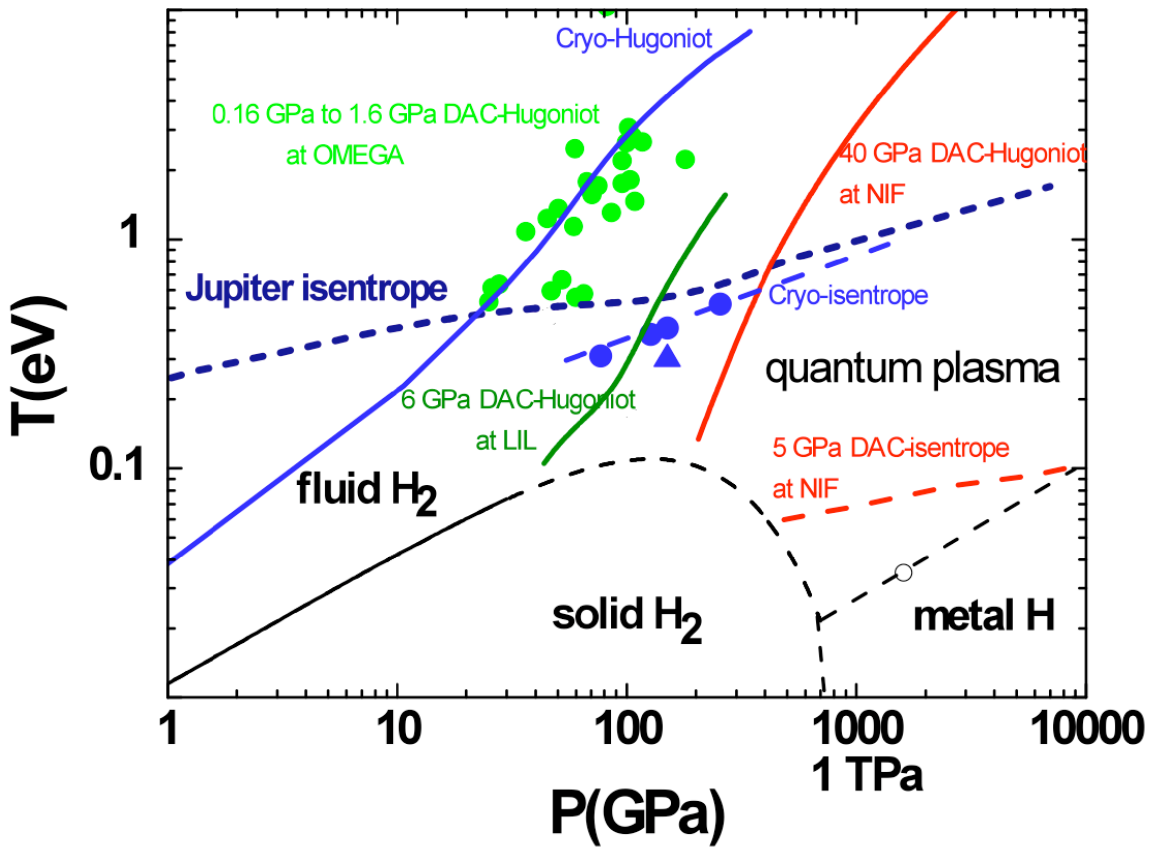


"BPM 37093: A seismological test of crystallization theory in white dwarfs"

Kanaan, et al., A&A (2005)

Hydrogen phase diagram

- NIF has unique capabilities that will allow us to explore the phase diagram over a wide range of parameters



Team

- **UC Berkeley** - Raymond Jeanloz*, Suzanne Ali, Marius Millot
- **Carnegie Institution Washington** - Russell Hemley*, Allen Dalton, Alexander Goncharov, Stewart McWilliams
- **CEA** - Paul Loubeyre*, Stephanie Brygoo, Dylan Spaulding
- **LLNL** – Peter Celliers, Jon Eggert, Damien Hicks, Ray Smith, Ryan Rygg, Dave Braun, Dayne Fratanduono, Amy Lazicki, Federica Coppari, Gilbert Collins

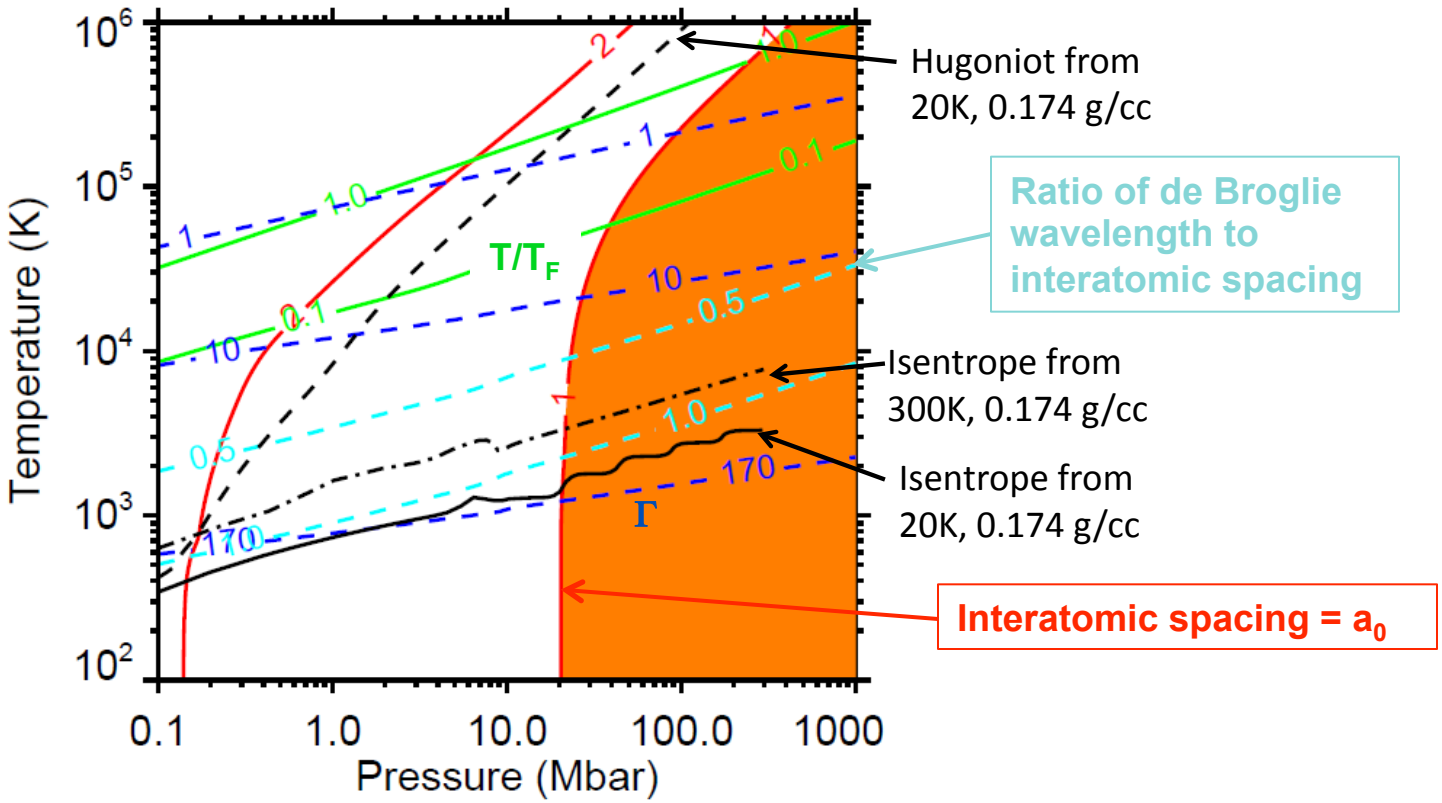
- *Co-Principal Investigators

Scope & overview

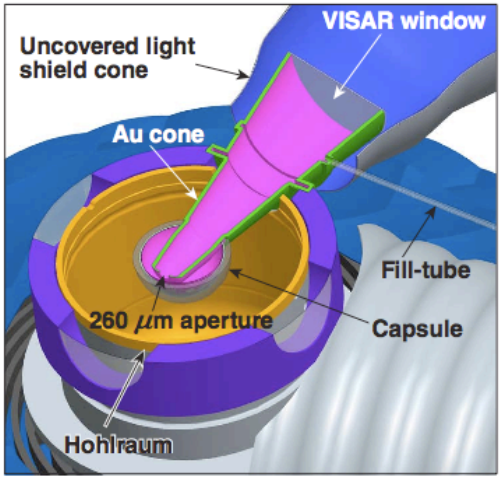
- Scientific Objective
  - Use NIF dynamically to compress H_2 (and/or D_2) to the TPa regime using cryogenic & pre-compressed targets with temporally-shaped lasers pulses
  - Achieve a wide range of PTρ states accessible for the first time in the laboratory
- Experiment Description
  - Indirect drive to send single shocks at 1 TPa and 2 TPa into cryogenic D_2
  - Direct or indirect drive to ramp compress a cryo D_2 sample
  - Indirect drive single shock compression of pre-compressed D_2 samples
  - Indirect drive ramp compression of pre-compressed samples
- Specific measurements
  - Impedance match EOS Hugoniot measurements using a quartz reference, with VISAR/SOP
  - Ramp compression EOS using LiF window, with VISAR/SOP

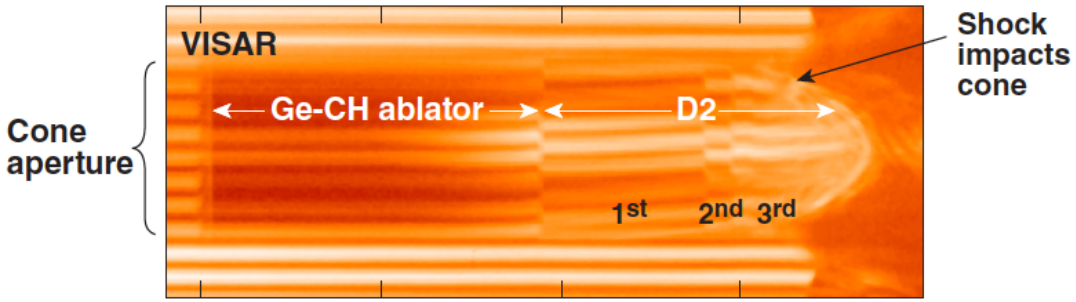
With precompression, ramp and/or multi-shock techniques we are aiming towards quantum plasma states

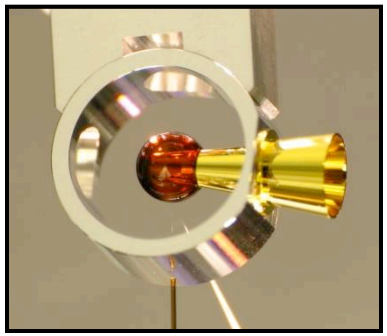
- Approaching a quantum plasma state: strong coupling, zero-point motion and Fermi degenerate, $R_s \sim a_0$



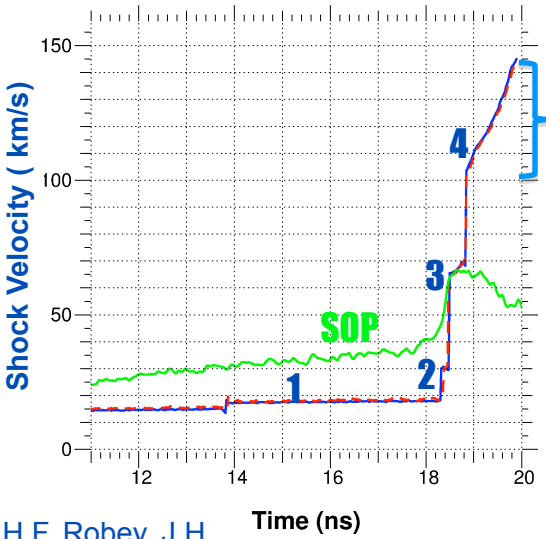
We have already tracked shocks in D_2 up to 3 TPa pressures on NIF

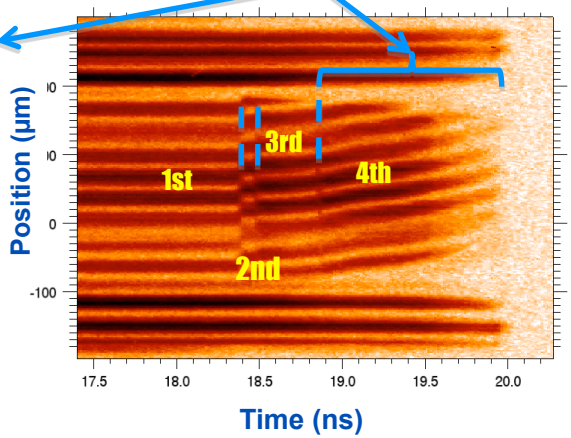






4th wave shows continuous acceleration from 105 to 146 km/s (~3 TPa ,30 Mbar).

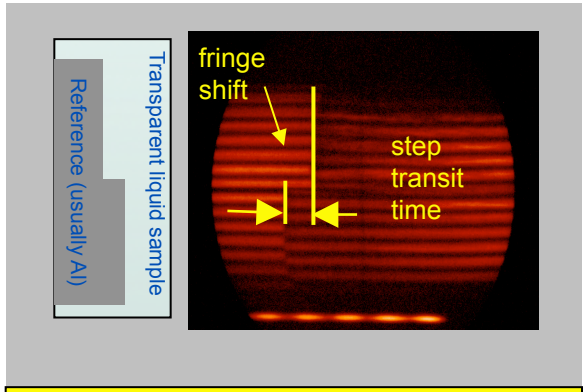




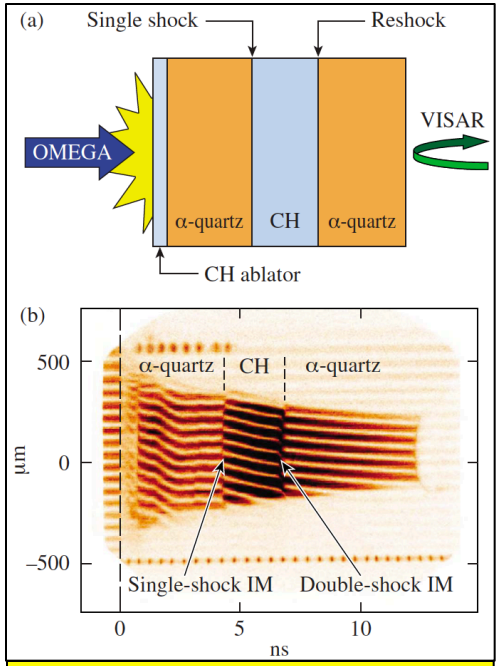
NIC Shock –Timing Work-in-progress with T.R. Boehly, H.F. Robey, J.H Eggert, D.G. Hicks, R.F. Smith, G.W. Collins and many others

Impedance match Hugoniot measurements will be used on the first shots

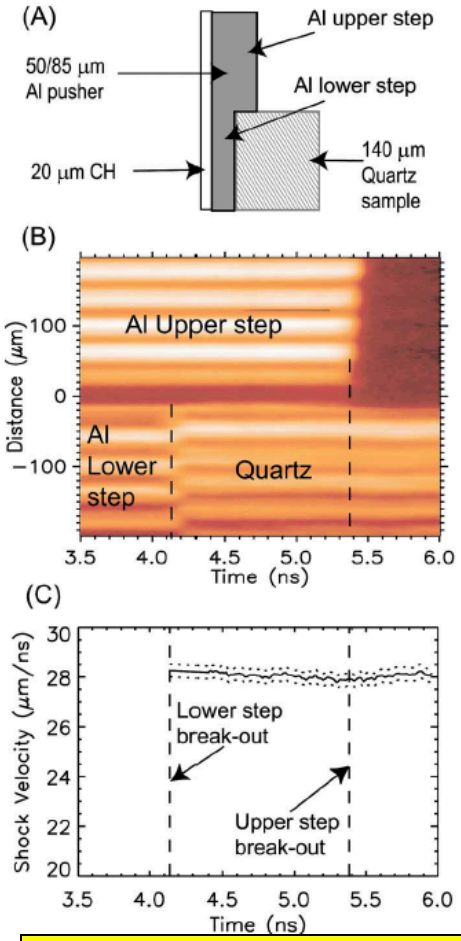
- Two velocities must be measured



P.M. Celliers *et al.*, Phys. Plasmas, **11**, L41 (2004)



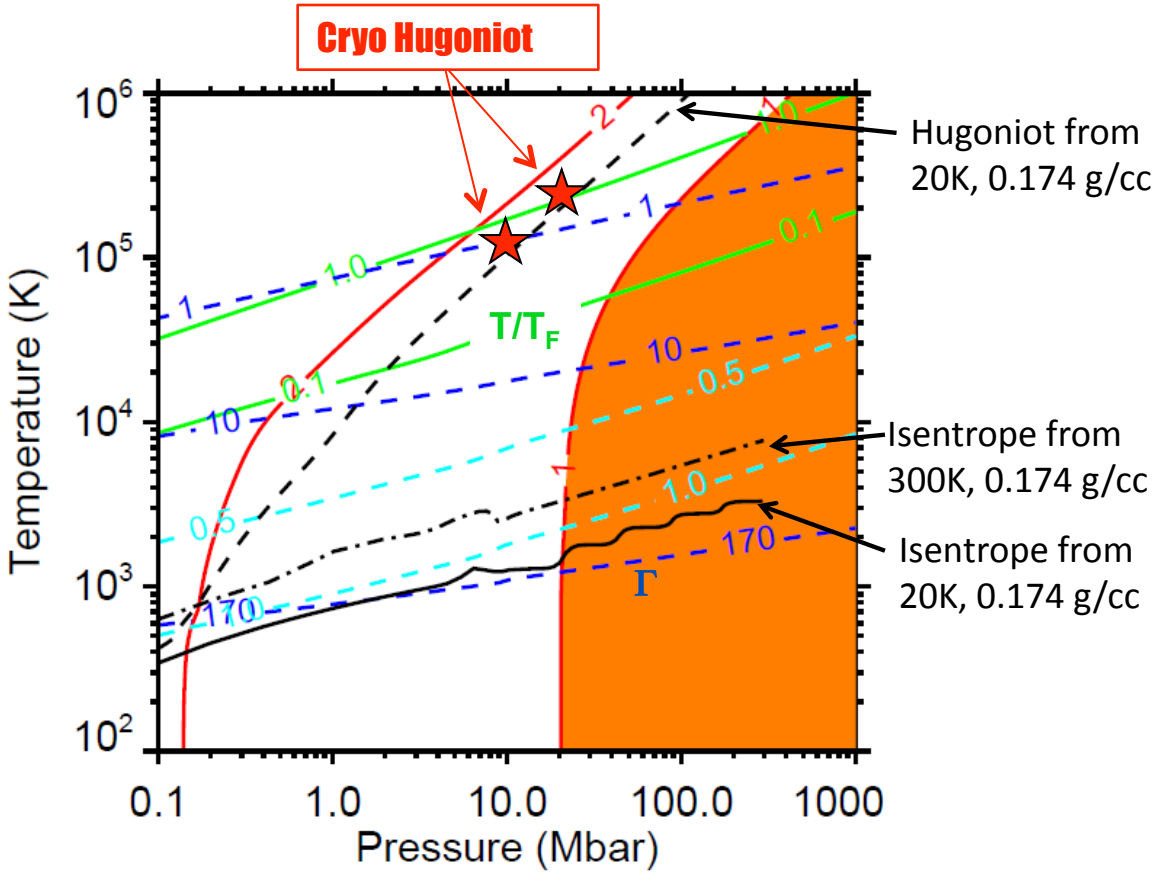
M.A. Barrios *et al.*, Phys. Plasmas, **17**, 056307 (2010)



D.G. Hicks *et al.*, Phys. Plasmas, **12**, 082702 (2005)

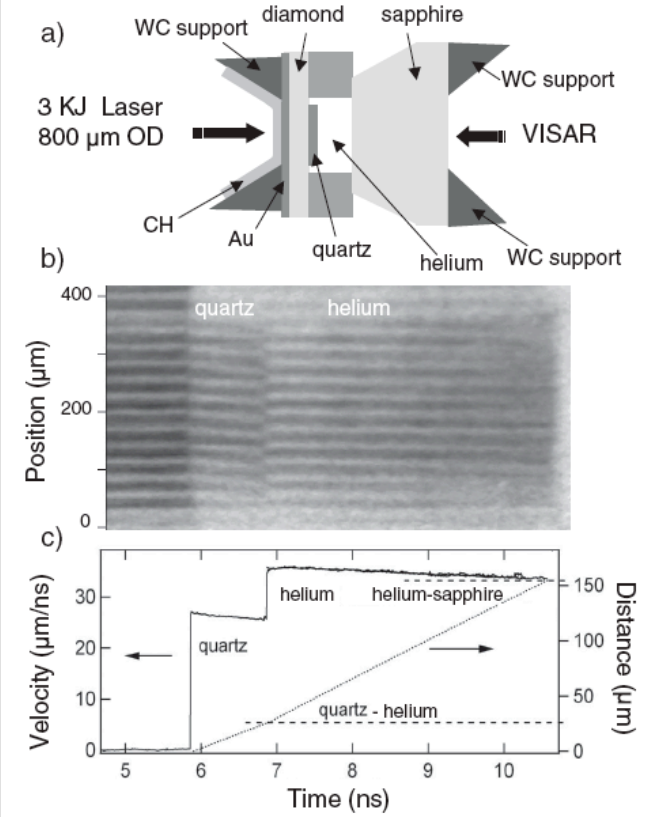
Principal Hugoniot: at TPa pressures a hot dense plasma state

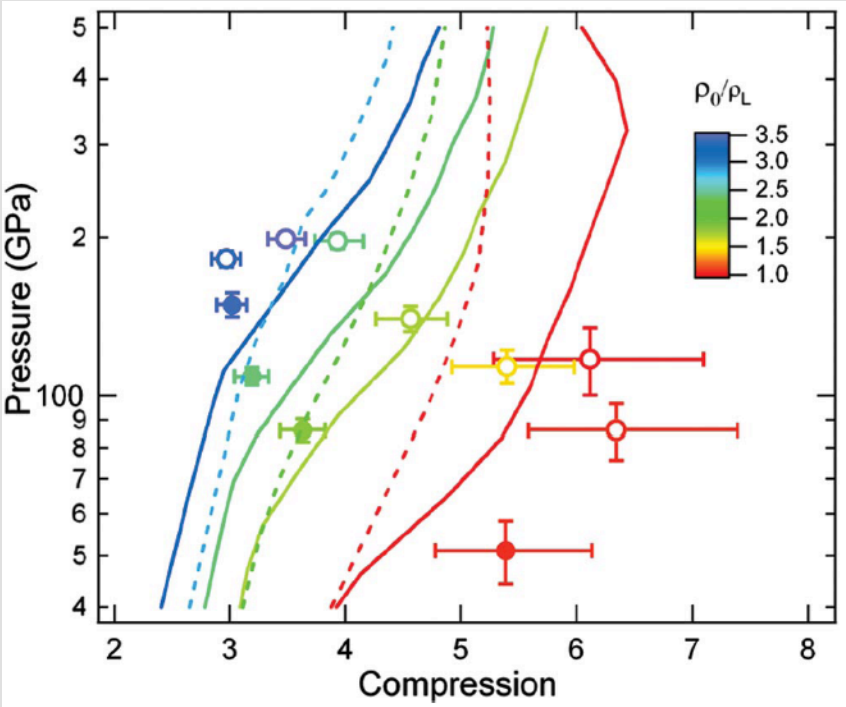
- Approaching a quantum plasma state: strong coupling, zero-point motion and Fermi degenerate, $R_s \sim a_0$



Shock EOS measurements in precompressed targets using VISAR/SOP as diagnostic

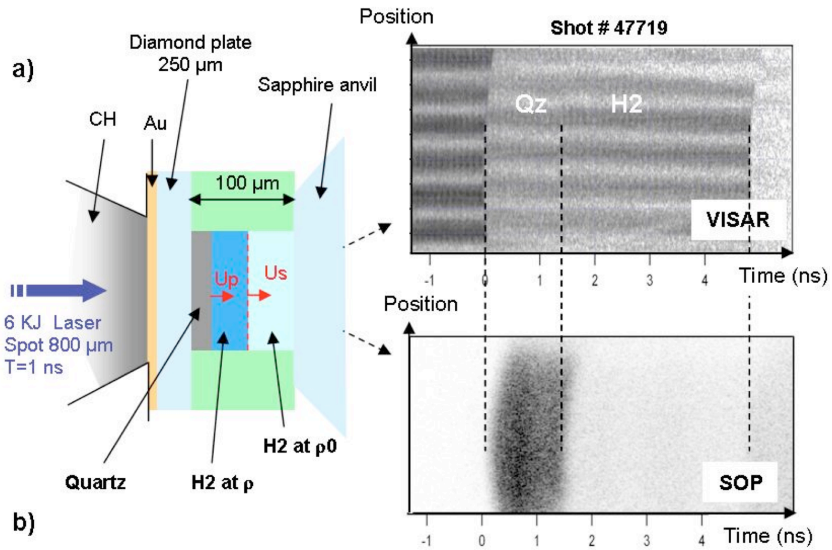
- Demonstrated on various ambient pressure targets as well as in precompressed targets using quartz as an EOS standard

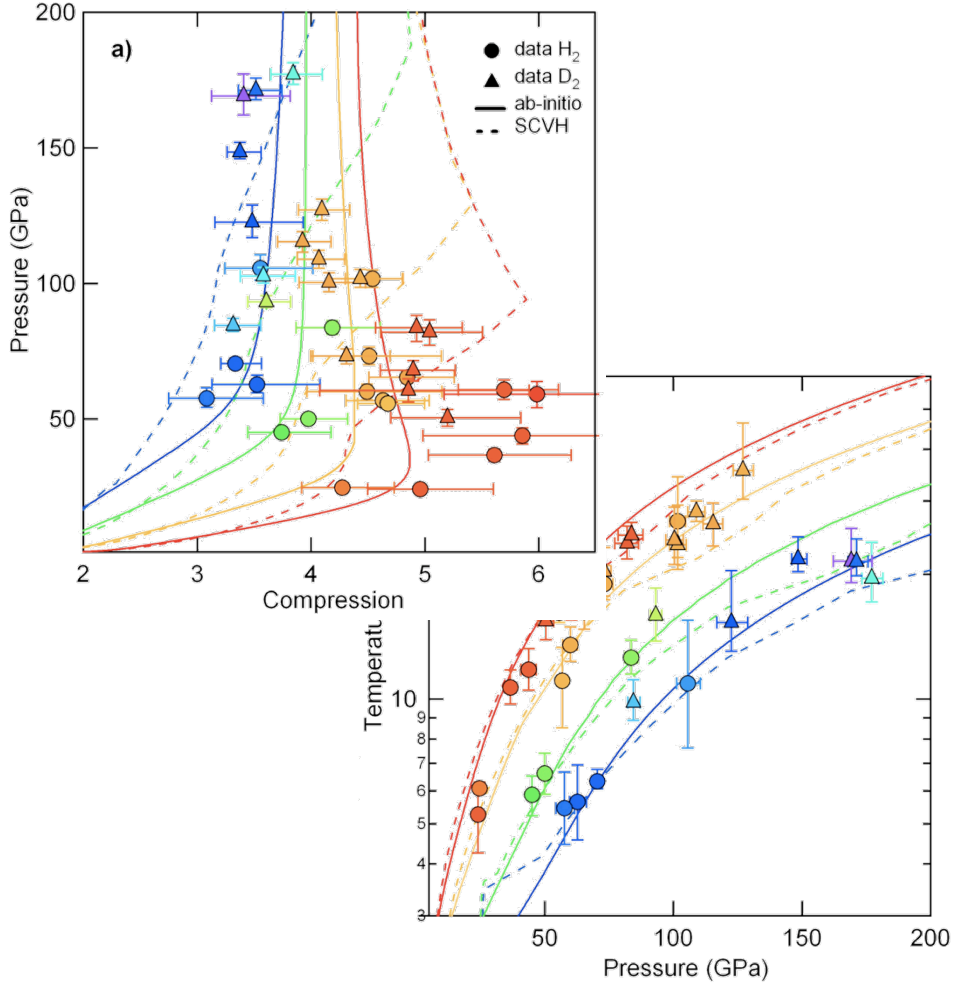


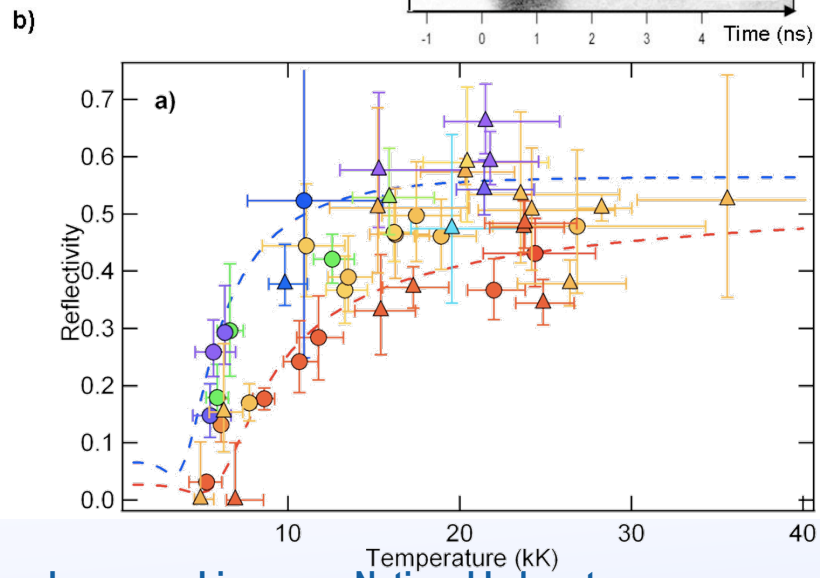


J. Eggert *et al.*, Phys. Rev. Lett, **100** 124503 (2008)

We have accumulated substantial off-Hugoniot data on H_2 and D_2 at OMEGA

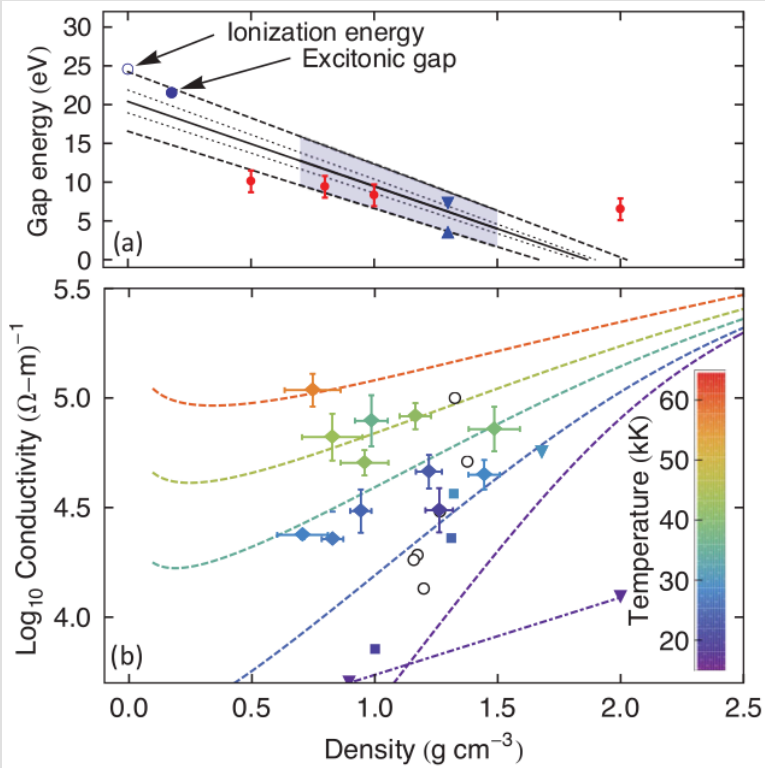




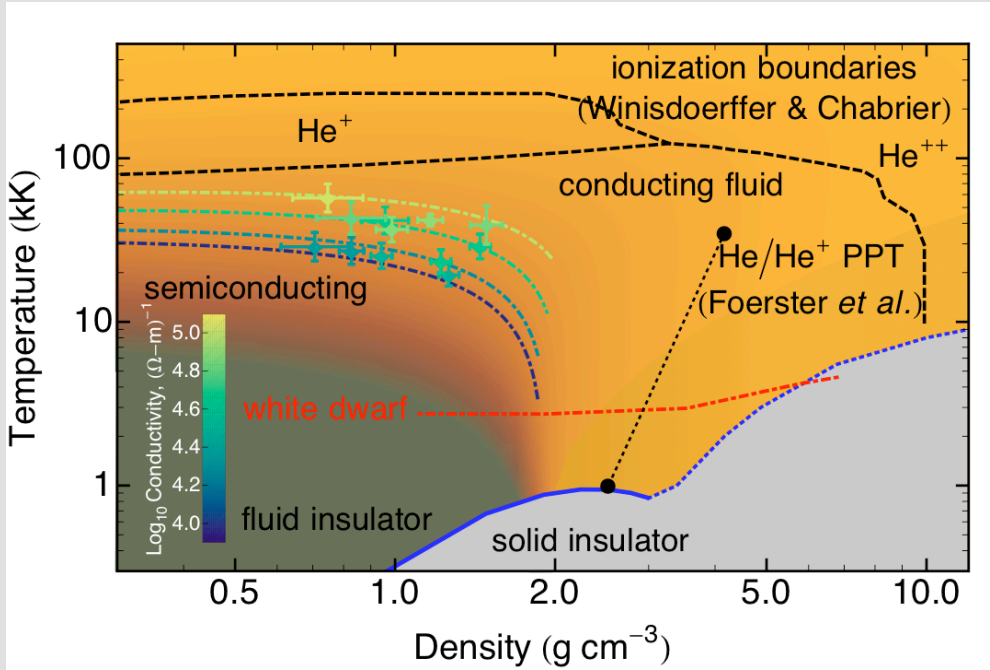


Optical reflectivity data can be used to infer conductivity & electronic structure

He conductivity and gap energy



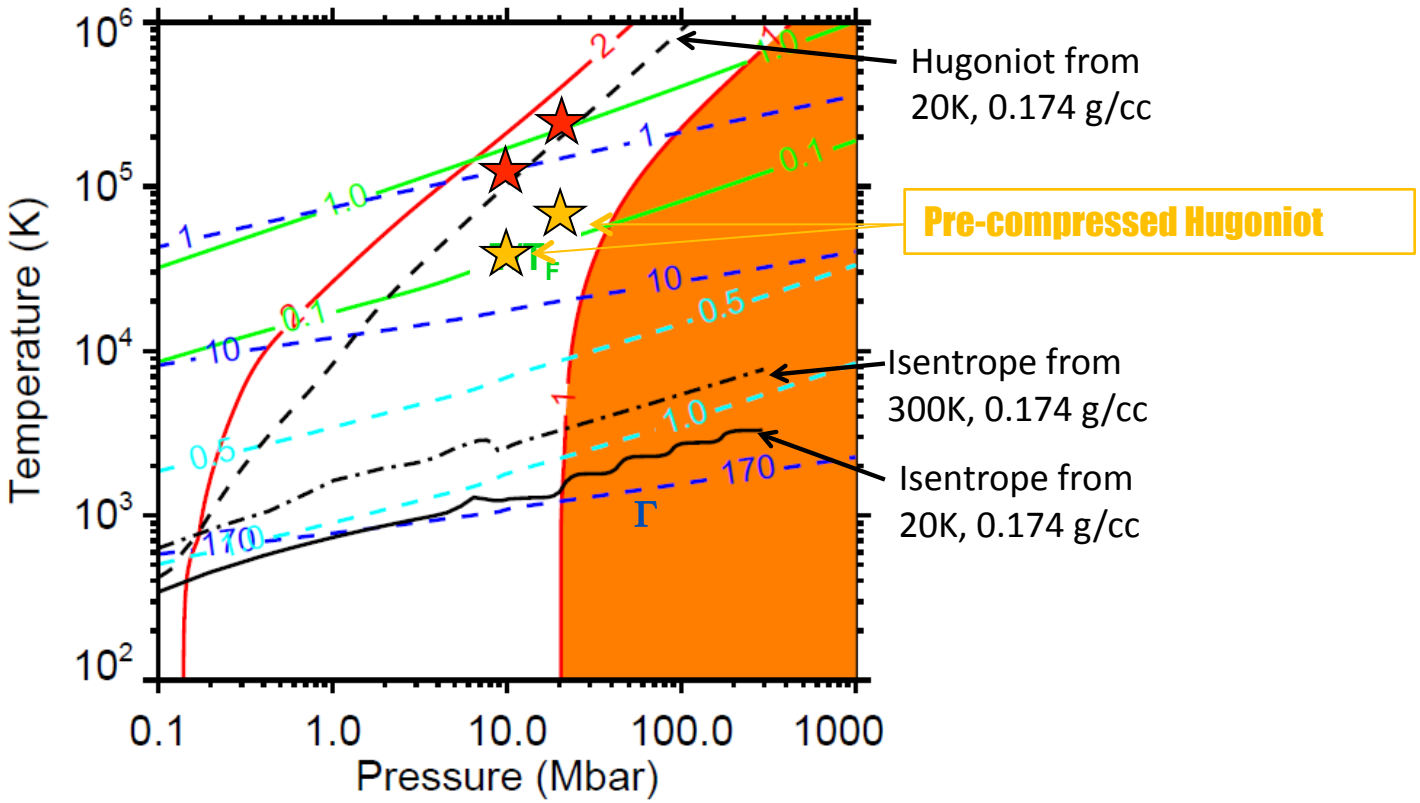
He phase diagram



P.M. Celliers *et al.*, Phys. Rev. Lett, **104** 184503 (2010)

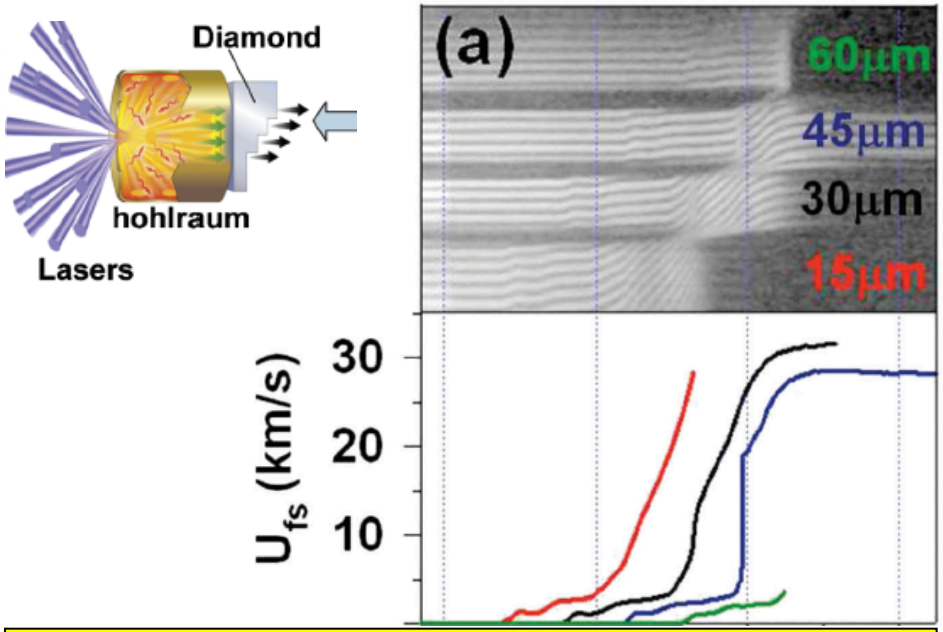
Off-Hugoniont shock precompression reduces the temperature by a factor of a few

- Approaching a quantum plasma state: strong coupling, zero-point motion and Fermi degenerate, $R_s \sim a_0$

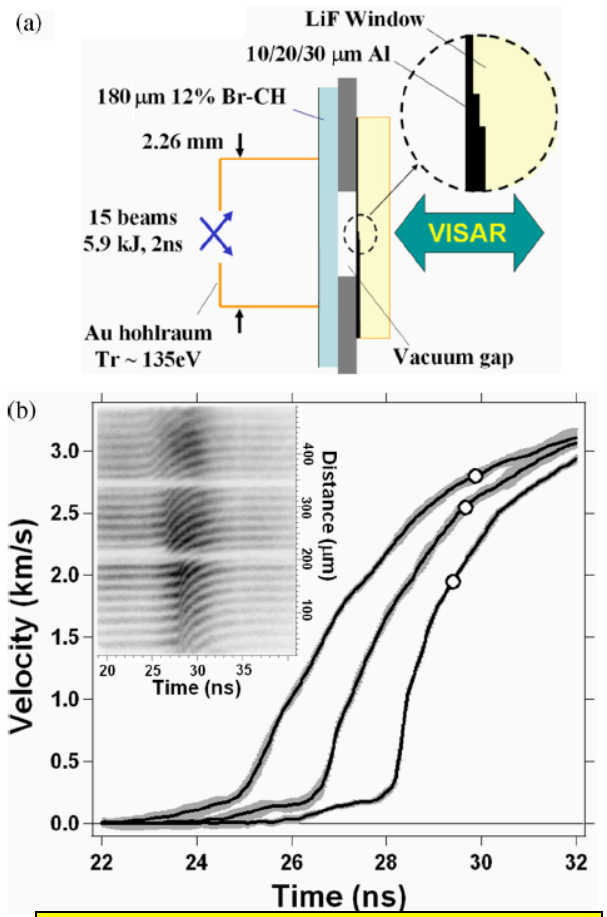


Extensive experience has been gained fielding ramp wave experiments

- Use ramp wave to drive a target package
- Need a continuous and accurate recording of the velocity history of a moving interface in the target
- Two types of package
  - Free surface motion
  - Embedded interface sitting behind a shock "window"



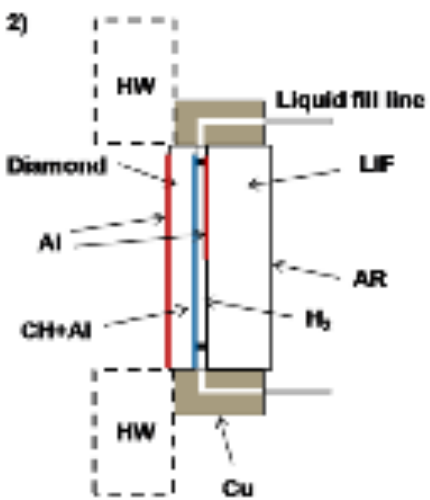
D.K. Bradley *et al.*, Phys. Rev. Lett., **102**, 075503 (2009)

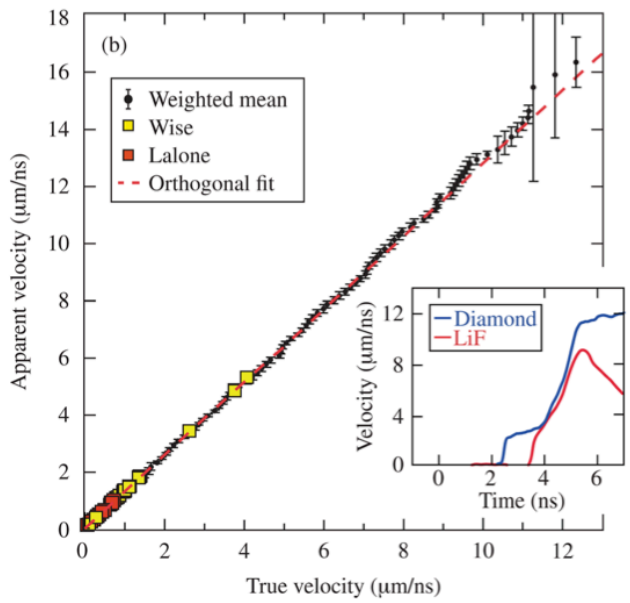


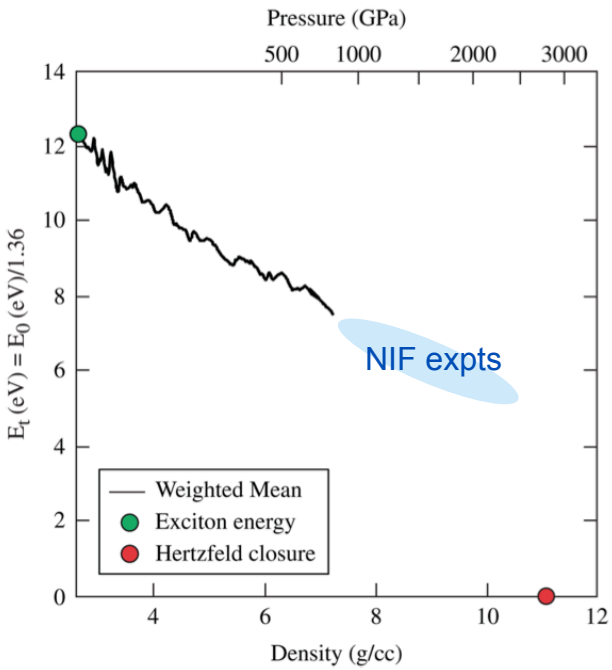
R.F. Smith *et al.*, Phys. Rev. Lett., **98**, 065701 (2007)

Reverberation targets will incorporate LiF windows

- LiF remains transparent above 8 Mbar under ramp compression

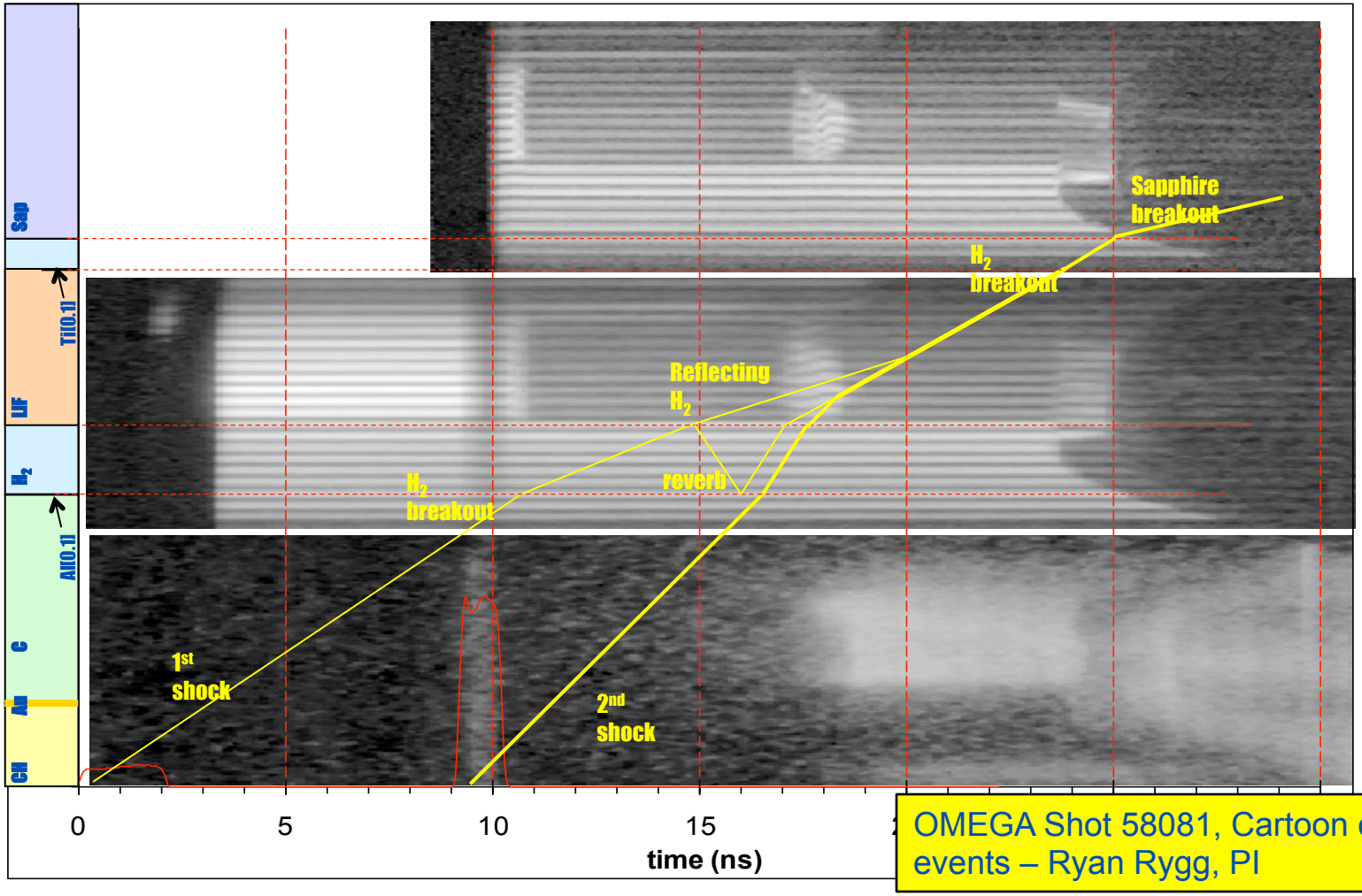






D. Fratanduono et al., J. Appl. Phys. **109** 123521 (2011)

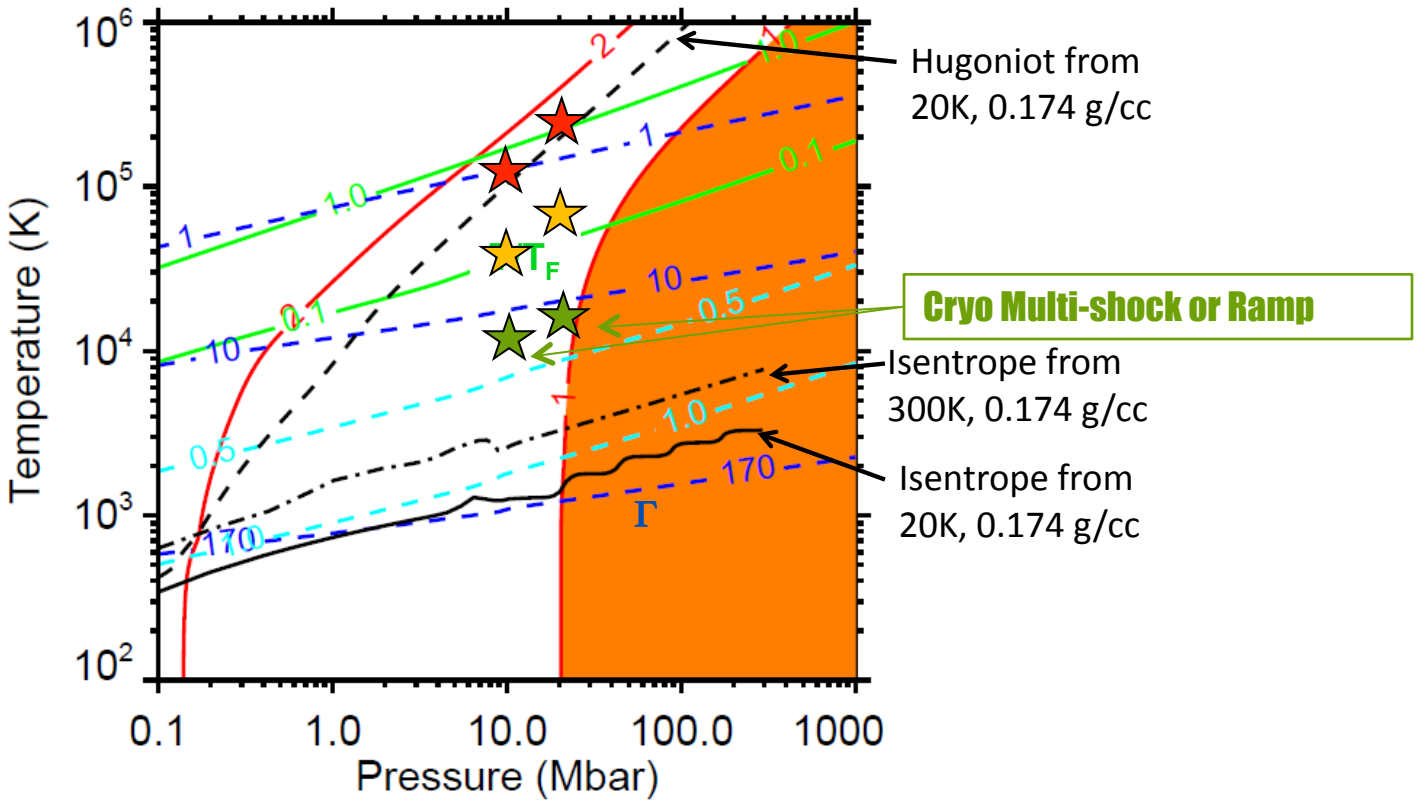
Multi-shock (reverberation) compression is being developed & explored on OMEGA



OMEGA Shot 58081, Cartoon of events – Ryan Rygg, PI

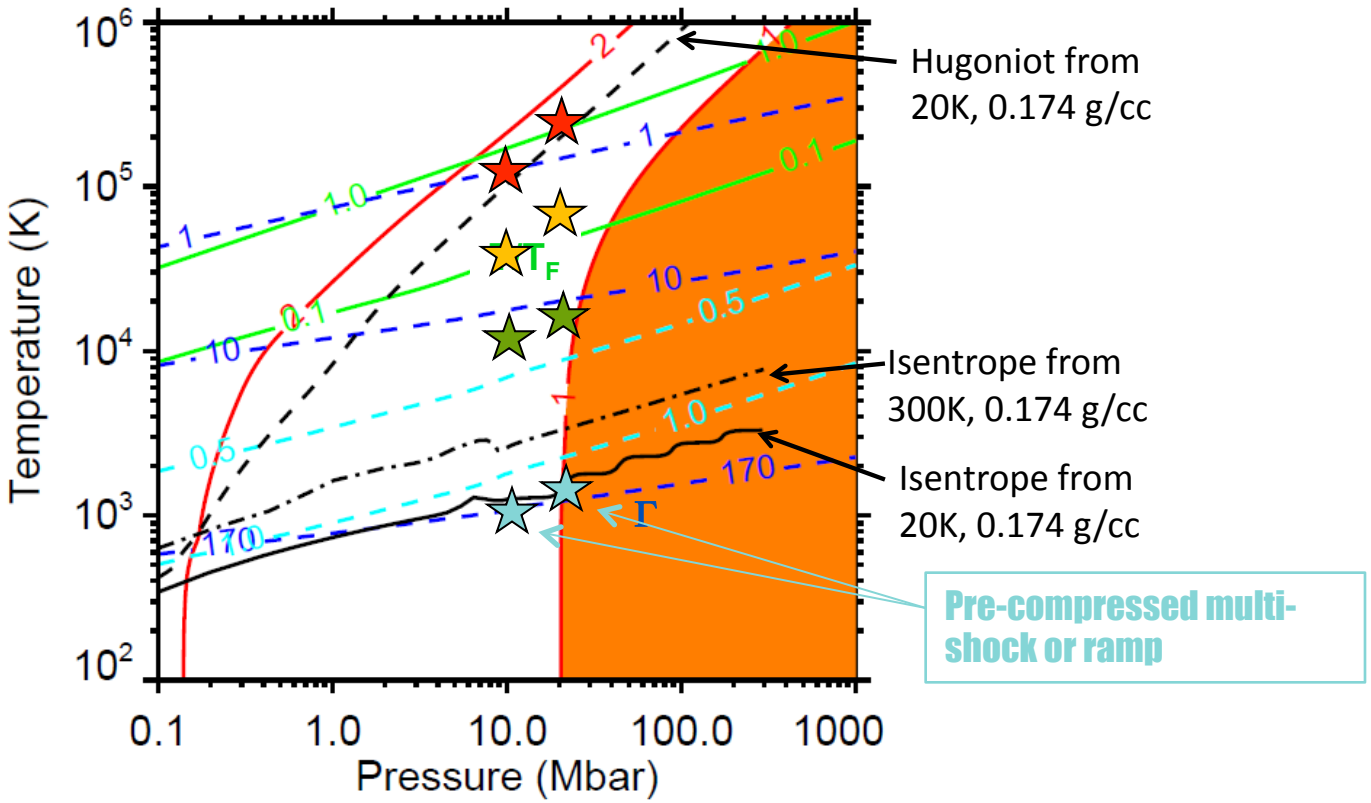
With ramp and/or multi-shock techniques we can reduce the temperature to ~ 1eV

- Approaching a quantum plasma state: strong coupling, zero-point motion and Fermi degenerate, $R_s \sim a_0$

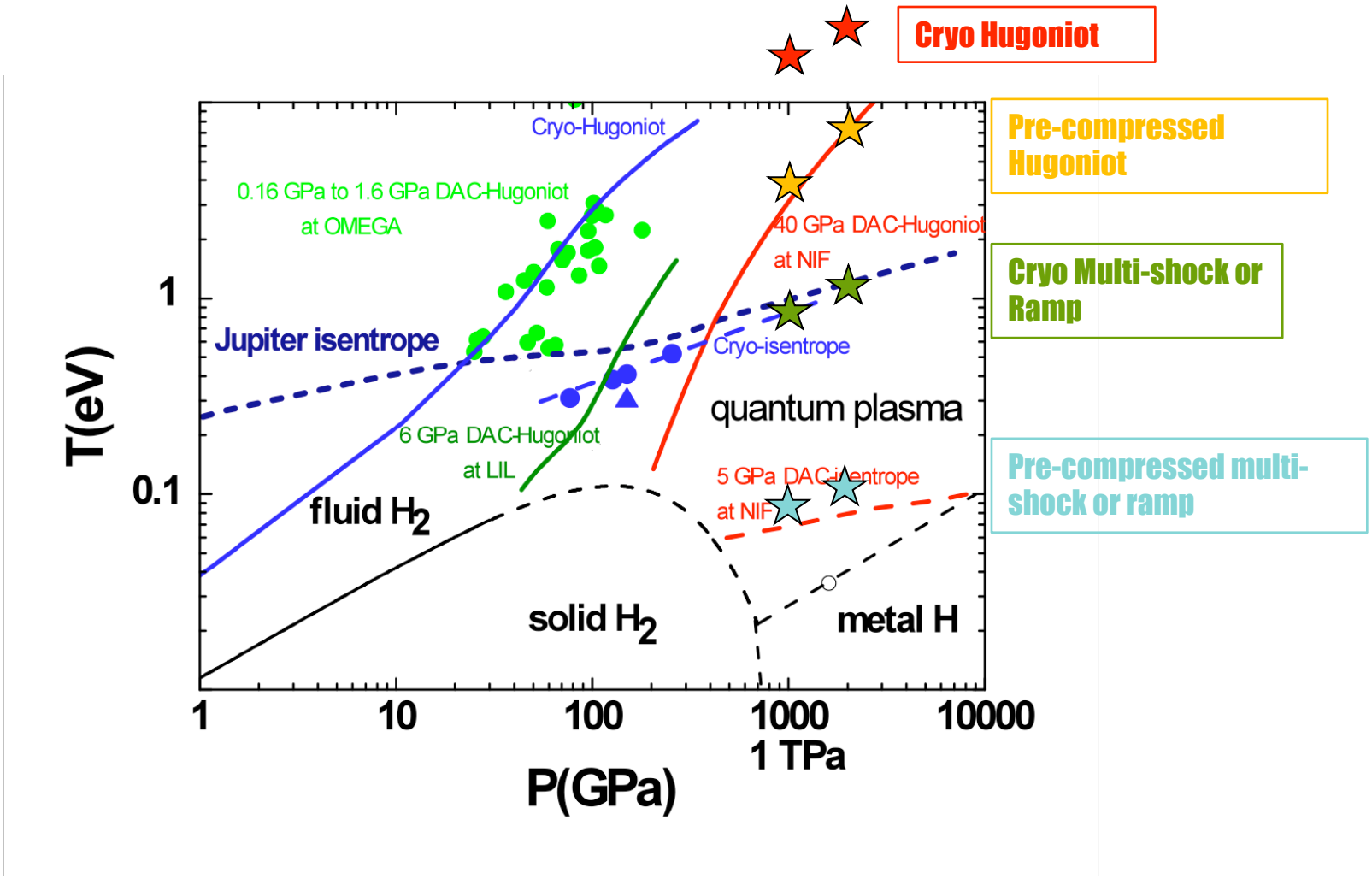


Combine precompression, ramp compression and reverberation to reach quantum plasma states

- Approaching a quantum plasma state: strong coupling, zero-point motion and Fermi degenerate, $R_s \sim a_0$



Hydrogen phase diagram



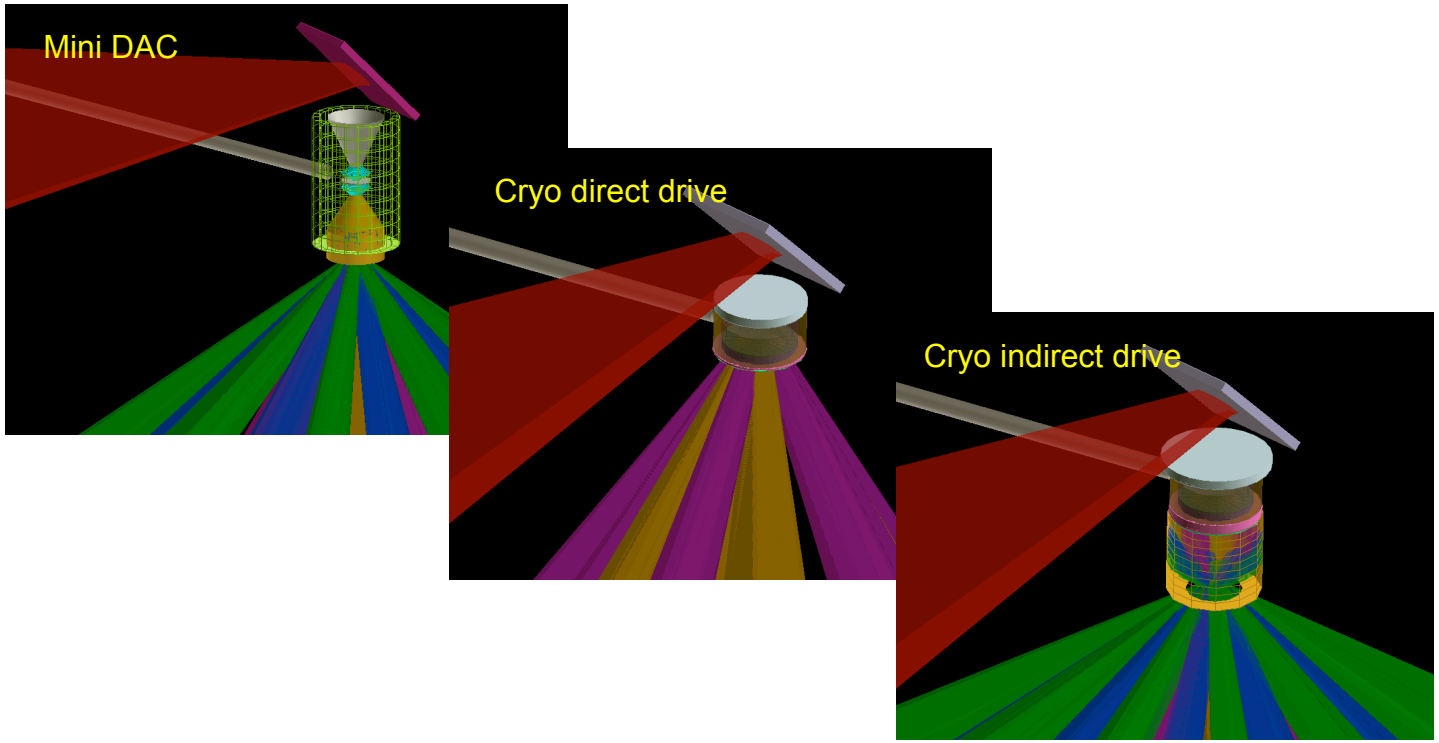
Shot table

Year	Target	Material	Compression	Data Point
FY12	cryo	D_2	Single shock, indirect drive 100 kJ	Hugoniot, ~1 TPa, ~20 eV
FY12	cryo	D_2	Single shock, indirect drive 200 kJ	Hugoniot, ~2 TPa, ~40 eV
FY12	cryo	D_2	Multi-shock or ramp, direct or indirect	Quasi-isentrope, 1 TPa, ~0.8 eV
FY12	cryo	D_2	Multi-shock or ramp, direct or indirect	Quasi-isentrope, 2 TPa, ~0.9 eV
FY13	40 GPa DAC	D_2	Single shock, indirect drive, 100 kJ	Hugoniot, ~1 TPa, 3 eV
FY13	40 GPa DAC	D_2	Single shock, indirect drive, 200 kJ	Hugoniot, ~2 TPa, 7 eV
FY13	5 GPa DAC	D_2	Multi-shock reverberation	Quasi-isentrope, ~1 TPa, 0.07 eV
FY13	5 GPa DAC	D_2	Multi-shock reverberation	Quasi-isentrope, ~1 TPa, 0.07 eV

Generic experiment configuration is based on VISAR/SOP line-of-sight and single-sided drive

TARPOS

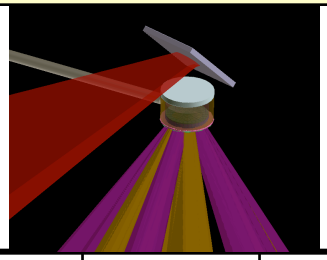
VISAR/SOP, 90-315



Experiment configuration

Experimental configuration

VISAR/SOP in DIM 90-315



Beams	# CPPs	CPP sc.	Pulse	Special
96 beams	96	Scale 1 and 1.07	6 ns	
96 beams	96	Scale 1 and 1.07	15 ns ramped	

Diagnostic	Port	Priority	Type
VISAR/SOP	90-315	1	1
DANTE-1 or 2	143-274	1	3
FABS/NBI	Q31B, Q36B	2	3
FFLEX	90-110	2	3
SXI-1 or 2	161-126, 18-123	2	3
GXD	Polar DIM (upper half irradiation)	3	3

Targets

Various with Hohlraum (ambient temperature) + VISAR cone

TARPOS 90-239 positioner with cryo TMP on the cryo targets

Beams

96 (scale 1 & 1.07 CPPs (standard set)

Pulse Shape – various

Total Energy Requested

Up to 300 kJ in 96 beams

Power Balance

<15% @ foot, 5% at peak

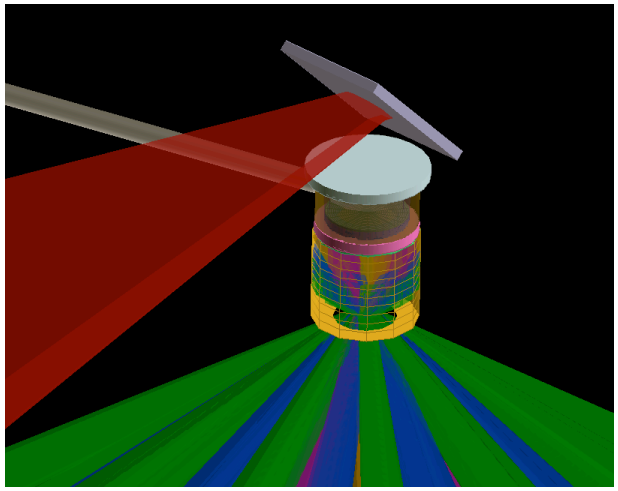
Diagnostics

Primary: VISAR/SOP, DANTE

Secondary: FABS/NBI,SXI,FFLEX

Cryogenic single-shock target

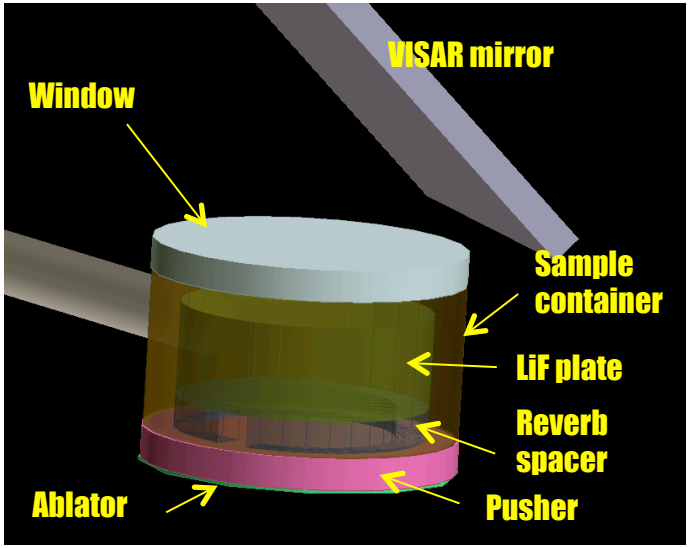
- Liquid D_2
- Indirect drive
- Can adapt existing design experience & infrastructure fairly easily



Component	Material
Sample container	Gold
Halfraum	Gold
Ablator	CH(Br)
Pusher	Al and/or quartz
Window	Quartz
Reverb container	Quartz, Diamond
VISAR Mirror	Silicon
Sample volume	Liquid D2, quartz, LiF

Cryogenic multi-shock target

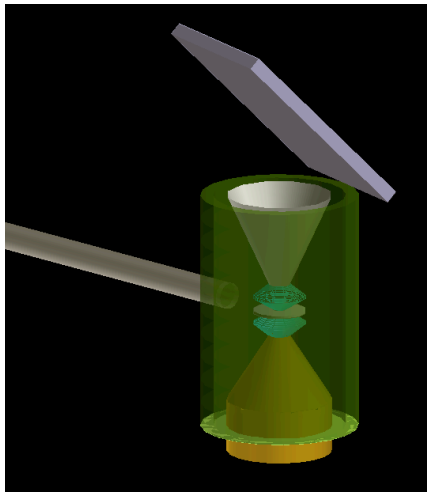
- Crygenic liquid D_2
- Direct or indirect drive
- Can adapt existing design experience & infrastructure fairly easily
  - More complicated than single-shock target

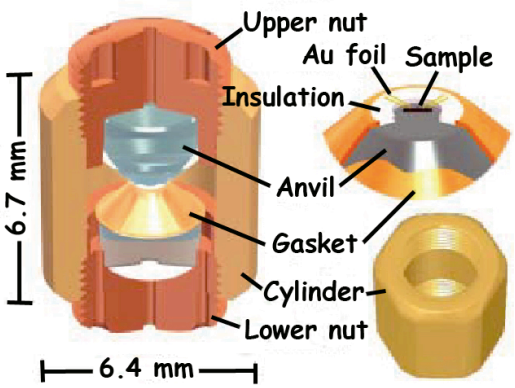


Component	Material
Sample container	Gold
Ablator	CH
Pusher	Quartz or Aluminum
Window	Quartz
Reverb container	Quartz, diamond
VISAR Mirror	Silicon
Sample volume	Liquid D2, quartz, LiF

Mini-DAC target

- Mini-DAC (miniature diamond anvil cell)
- requires engineering & development
- Prototype testing on Jupiter and OMEGA prior to fielding on NIF



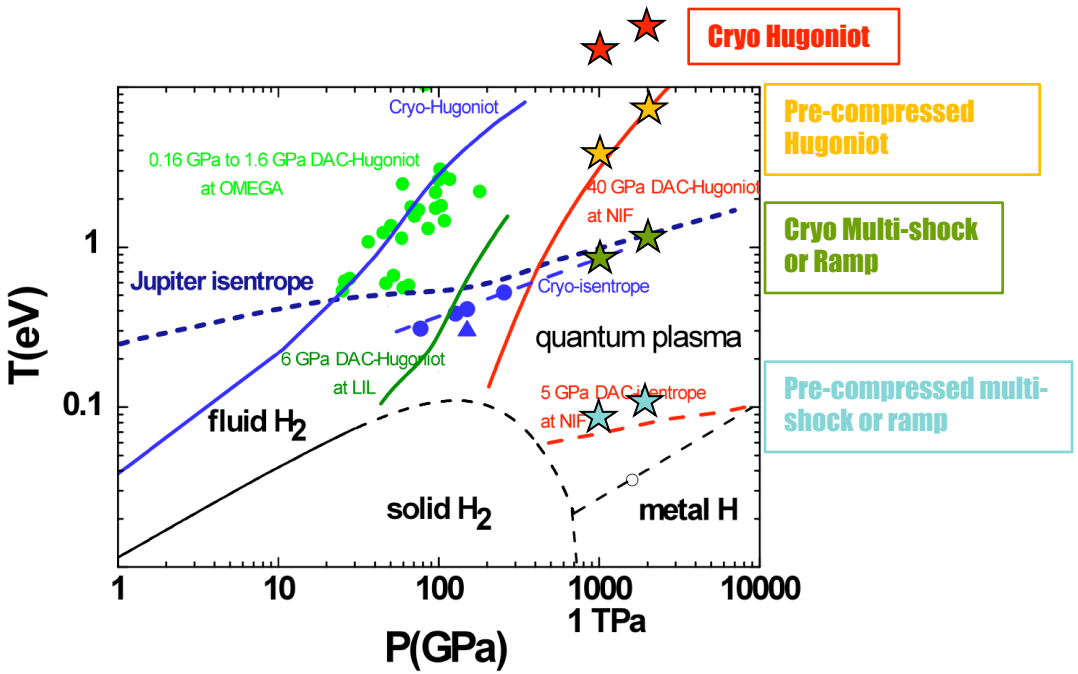


Kano et al., J. Phys. Soc. Jpn. 76 (2007) Suppl. A, pp. 56-57

Component	Material
Anvils	Diamond
Cylinder	High strength steel
Upper/lower nuts	High strength steel
Sample gasket	Rhenium
Sample volume	D2, quartz, LiF
Mirror	Silicon

We have established a plan to explore Hydrogen at TPa pressures on the NIF

- A staged approach beginning on the principal Hugoniot will explore a range of conditions of increasing density and decreasing temperature
- Precompressed targets combined with ramp and/or reverberation compression will reach dense quantum plasma states of Hydrogen

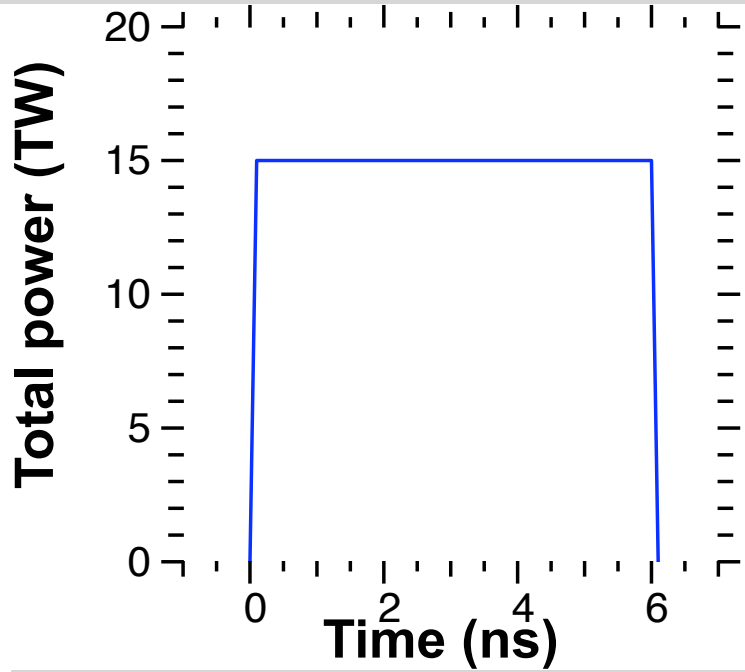


Laser requirements – 1

Laser Parameter	Value
1) Platform to be used	*Radiation transport*
2) Number of beams required	*Up to 96*
3) 3ω energy required per beam (xx kJ/beam maximum)	*2*
4) Peak power per beam (350 TW maximum total peak power)	*0.5*
5) Pulse shape (up to 20 nsec duration) (Options: Square, impulse (88 psec), or shaped; provide plot of power vs. time for shaped pulse on next page)	*Square, shaped*
6) SSD bandwidth (options- 45 to 90 GHz, 45 GHz default)	*45 GHz (modify if desired)*
7) Focal spot size (250-μm (unconditioned) or 1-mm (conditioned))	*1-mm*
9) Delays between beams (up to 10 nsec-all pulses in a quad must have same delay)	*N/A*
10) Backlighter beam energy, pulse duration	*N/A*
11) Other specifications	*N/A*

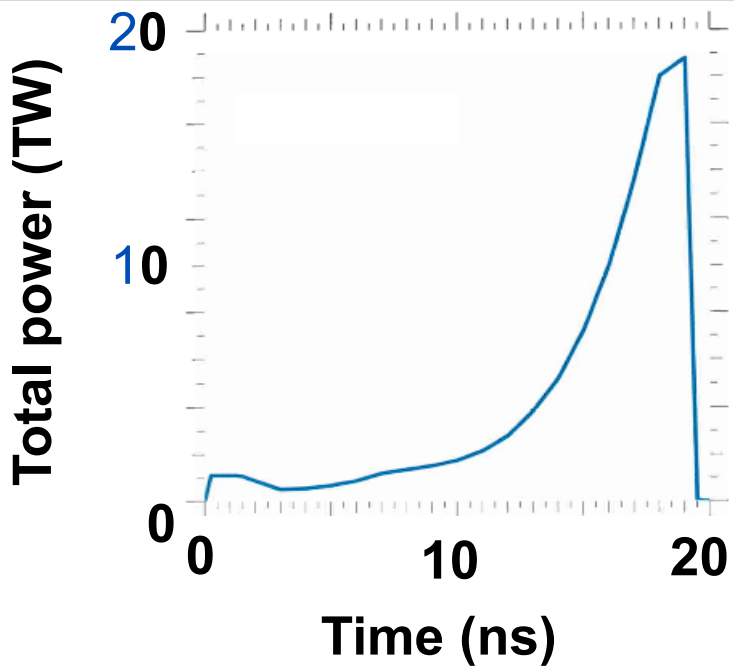
Laser requirements – 2

Single shock EOS, halfraum



- 96 beams
- NIC CPPs
- Power balance: 15% Foot, 5% Peak per Quad (RMS)
- Pointing accuracy: 80μm RMS

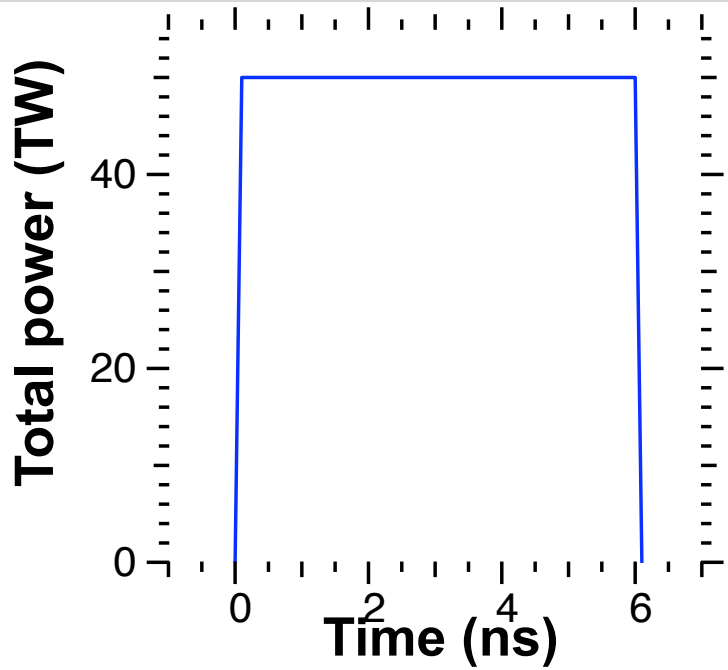
Multi-shock ramp, direct drive



- 48 beams
- NIC CPPs
- Power balance: 15% Foot, 5% Peak per Quad (RMS)
- Pointing accuracy: 80μm RMS

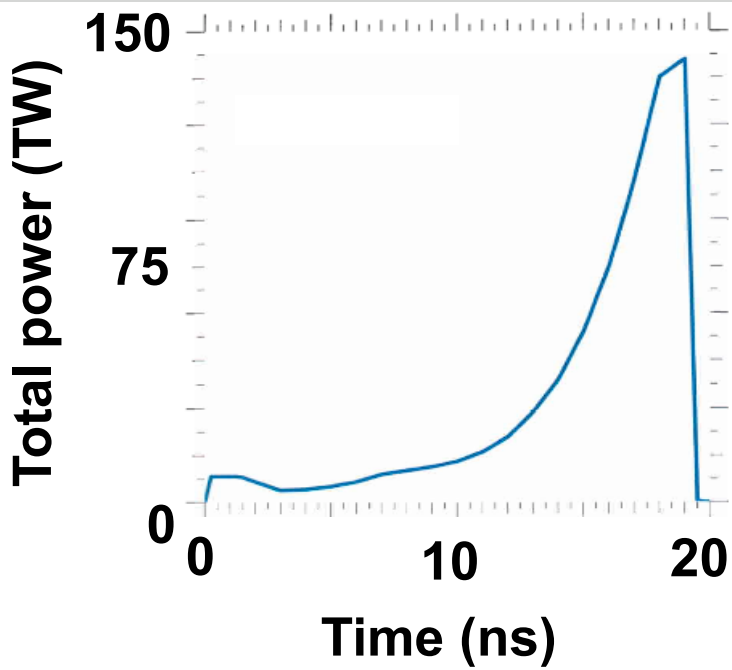
Laser requirements – 3

Single shock, mini-DAC+halfraum



- 96 beams, bottom half of NIF
- Power balance: 15% Foot, 5% Peak per Quad (RMS)
- Pointing accuracy: 80μm RMS

Multi-shock ramp, mini-DAC+halfraum



- 96 beams, bottom half of NIF
- Power balance: 15% Foot, 5% Peak per Quad (RMS)
- Pointing accuracy: 80μm RMS

With precompression, ramp and/or multi-shock techniques we aim to reach dense cool states

- Approaching a quantum plasma state: strong coupling, zero-point motion and Fermi degenerate, $R_s \sim a_0$