

Visualizing the transformation of matter in extreme conditions

Siegfried H. Glenzer (SLAC)

June 8th, 2017

Presentation to:
Lawrence Livermore National Laboratory
HED Physics Seminar



- Introduction
 - What is High Energy Density Physics?
 - Why the answer matters and some insights
- The Axes of the Extremes
- New Discovery Science experiments
 - Insights from the Linac Coherent Light Source
 - Investigate the physics of brown dwarfs on NIF
- Conclusions and Outlook

This presentation includes contributions from a large collaboration

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- **LCLS, USA**
E. Gamboa, H.J. Lee, D. Milathianaki, L. Fletcher



- **UC Berkeley /LBNL, USA**
R.W. Falcone (PI),
D. Kraus*, M. MacDonald, A. Saunders
*now with HZDR Dresden



- **LLNL, USA**
T. Doepfner, A. Kritcher, B. Bachmann, D. Swift,
J. Hawreliak, J. Gaffney, S. Hamel, L. Benedict,
A. Pak, C. Weber, P. Sterne, C. Mauche, J.
Nilson, P. Celliers, O. Landen, G. Collins, A.
Jenei, L. Divol



- **GSI, Germany**
P. Neumayer (PI)
B. Borm



- **AWE, UK**
D. Chapman,
S. Rothman



- **LANL, USA**
A. Yi, J. Kline



- **University of Warwick, UK**
D. Gericke, R. Baggott
- **Univ. of Rostock, Germany**
R. Redmer (PI), B. Witte, P. Sperling, R. Bredow



- **XFEL/DESY,**
C. Fortmann,
S. Toleikis

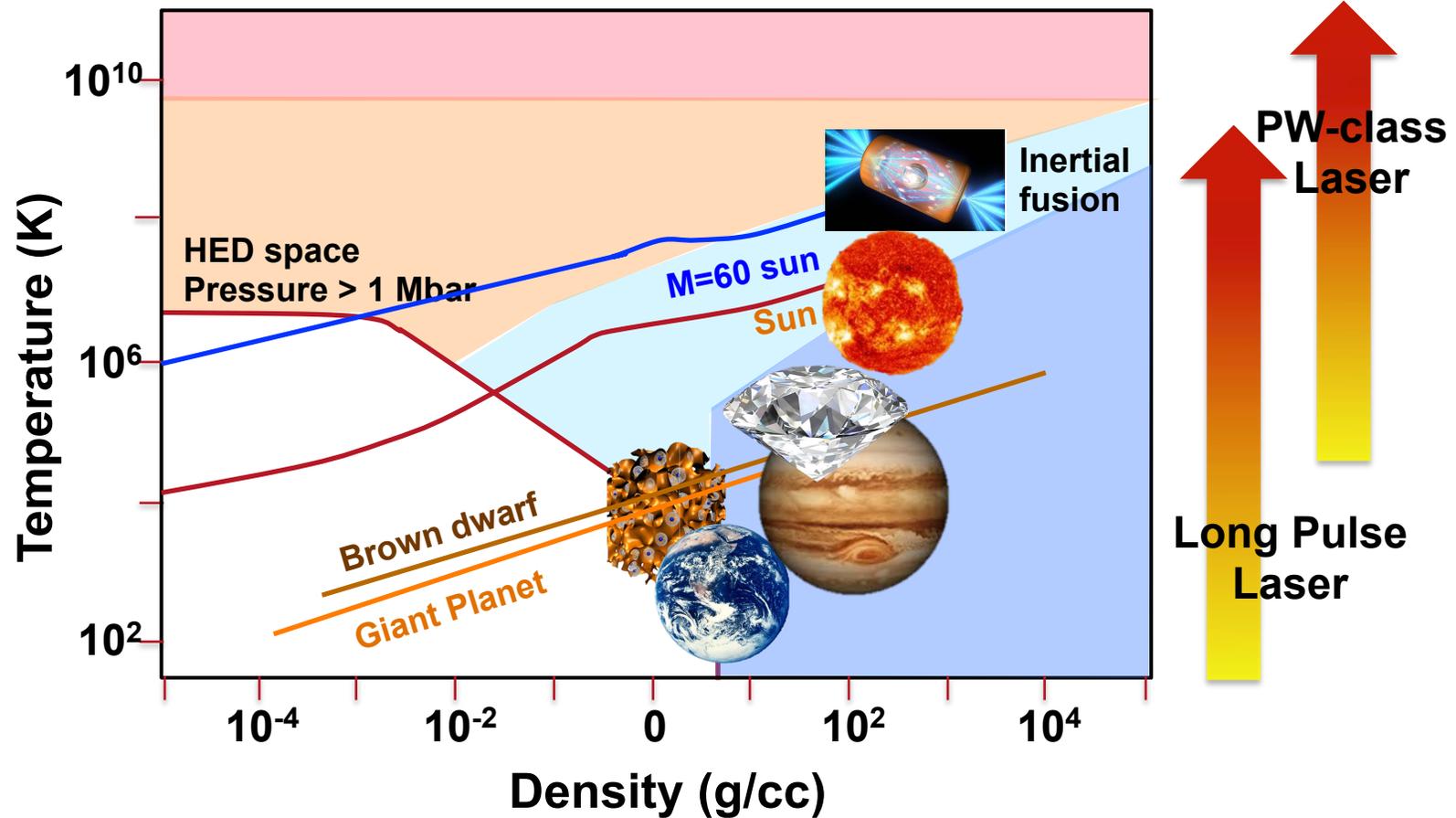


- **Polymath**
B. Afeyan



The High Energy Density Science discovery space

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A majority of interested scientists/students find it difficult to connect with this picture

A new definition...

- The Generation, Study and Control of Self-Organization, Far From Equilibrium, through the Action of Intense Fields
- That is the mission of HEDP to demonstrate and make possible. The study of states far from equilibrium finding nonlinear self-organized stability

Bedros Afeyan, 2017

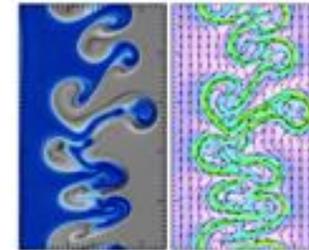
**We defined a new program that pushes the extremes;
- became a major attraction to students and postdocs**



HEDS High Energy Density Science



FEATURED NEWS

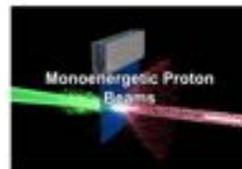


Computing Award a Big Win for High Energy Density Science at SLAC

RESEARCH PROJECTS



Cryogenic Hydrogen Jets



Monoenergetic Proton Beams



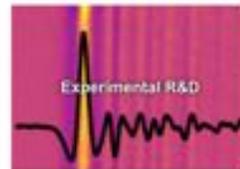
Theory and Simulation



Record Peak Brightness

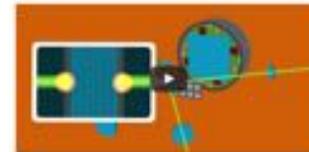


Warm Dense Matter



Experimental R&D

FEATURED VIDEO



HEDS @ SLAC

What Can You Study in Femtoseconds? High Energy Density Science

SLAC Celebrates Femtosecond Week

SLAC Researchers Recreate the Extreme Universe in the Lab

Dawson Award Recognizes SLAC X-ray Laser Experiment that Probed 3.6-million-degree Matter

200-terawatt Laser Brings New Extremes in Heat, Pressure to X-ray Experiments

HEDS LATEST NEWS

Dr. Siegfried Glenzer Featured in SLAC Femtosecond Week Q&A
04/20/2017

DOE funding for cryogenics has shown a new path towards high-energy protons
02/24/2017

SLAC HED will lead new NIF Discovery Science awards
02/22/2017

[view all news >](#)

UPCOMING HEDS EVENTS

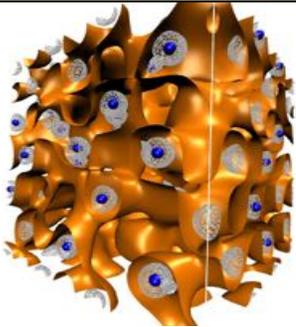
APR 20 9th OMEGA Laser User Group Workshop (OUG Workshop) - 12:00am - 12:00am, Rochester, New York

MAY 21 2017 IEEE International Conference on Plasma Science (ICOPS) - 12:00am - 12:00am, Atlantic City, US

MAY 24 1st JPP Frontiers in Plasma Physics Conference - 12:00am -

The Axes of the Extremes

Structure of Warm Dense Matter



Diamond formation under compression



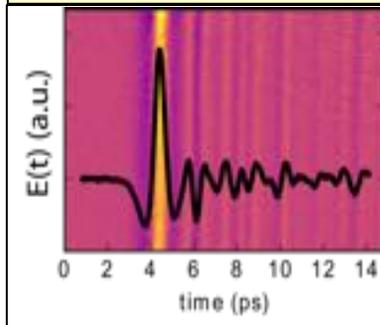
Properties of Hydrogen



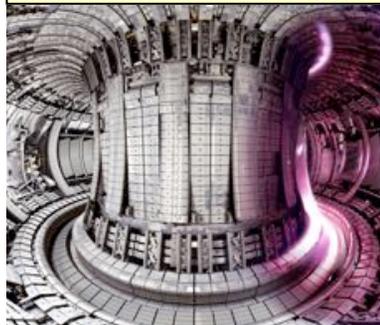
Non-equilibrium Water ultrafast heating



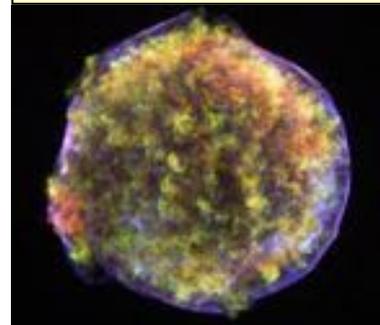
From THz, VUV to hard X-rays



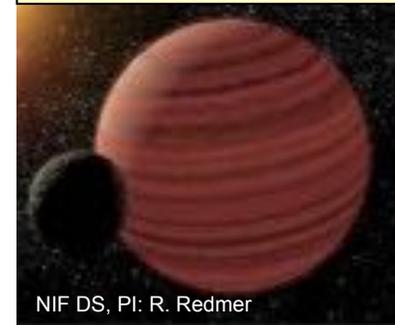
Materials under extreme Radiation



Origin of Cosmic Rays
Extreme B fields



Physics of Brown Dwarfs



NIF DS, PI: R. Redmer



Linac Coherent Light Source at SLAC

X-FEL based on last 1-km of existing 3-km linac

1.5-15 Å
(14-4.3 GeV)

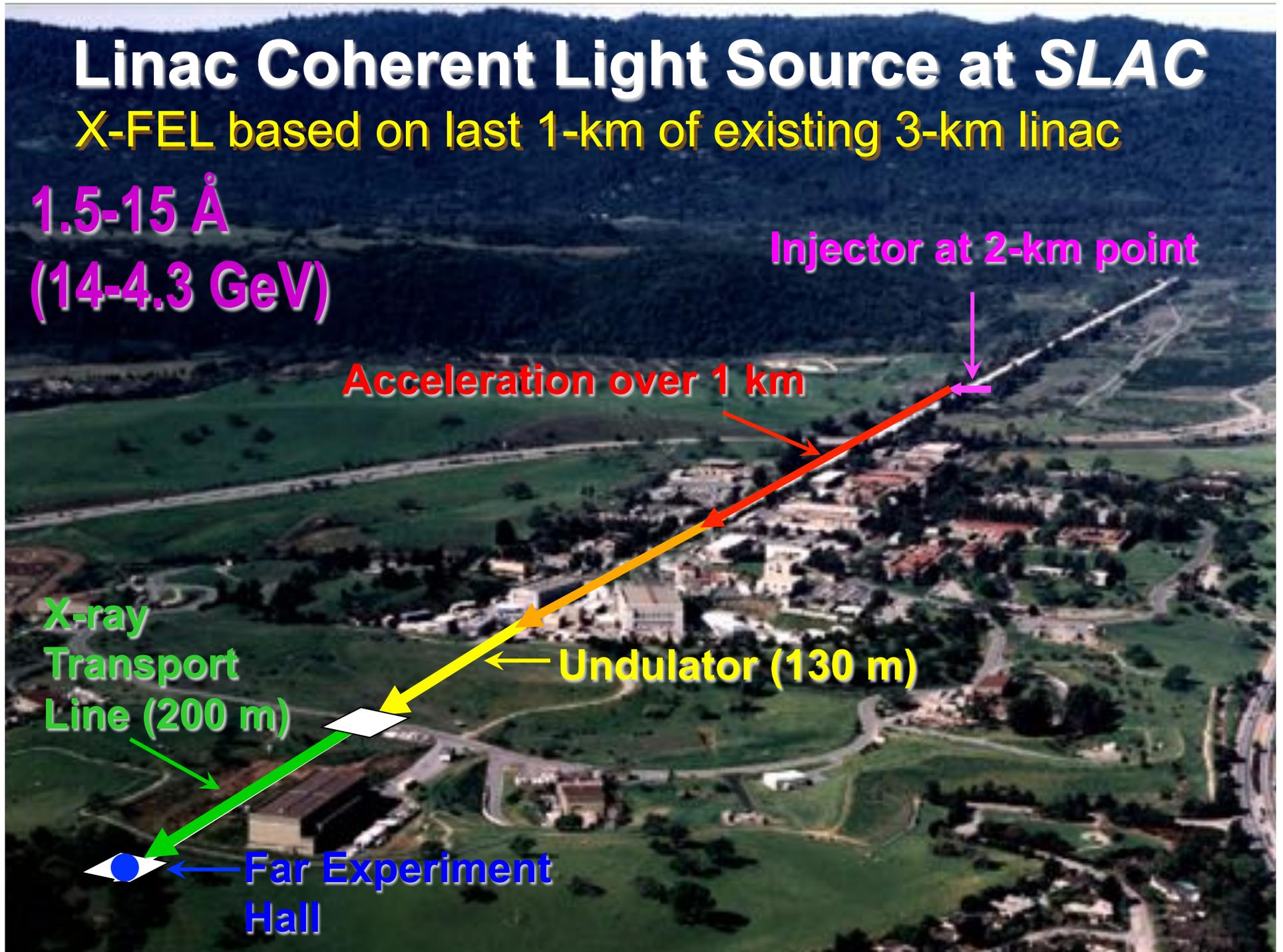
Injector at 2-km point

Acceleration over 1 km

X-ray
Transport
Line (200 m)

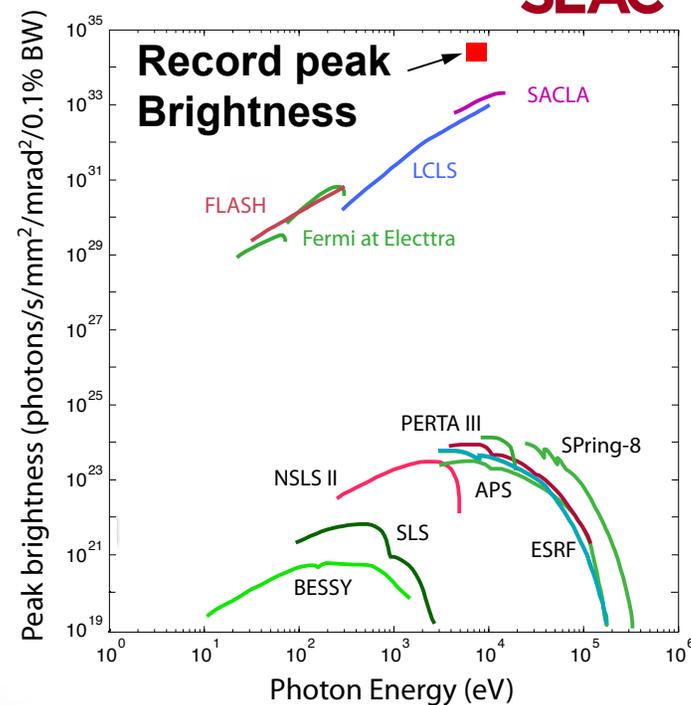
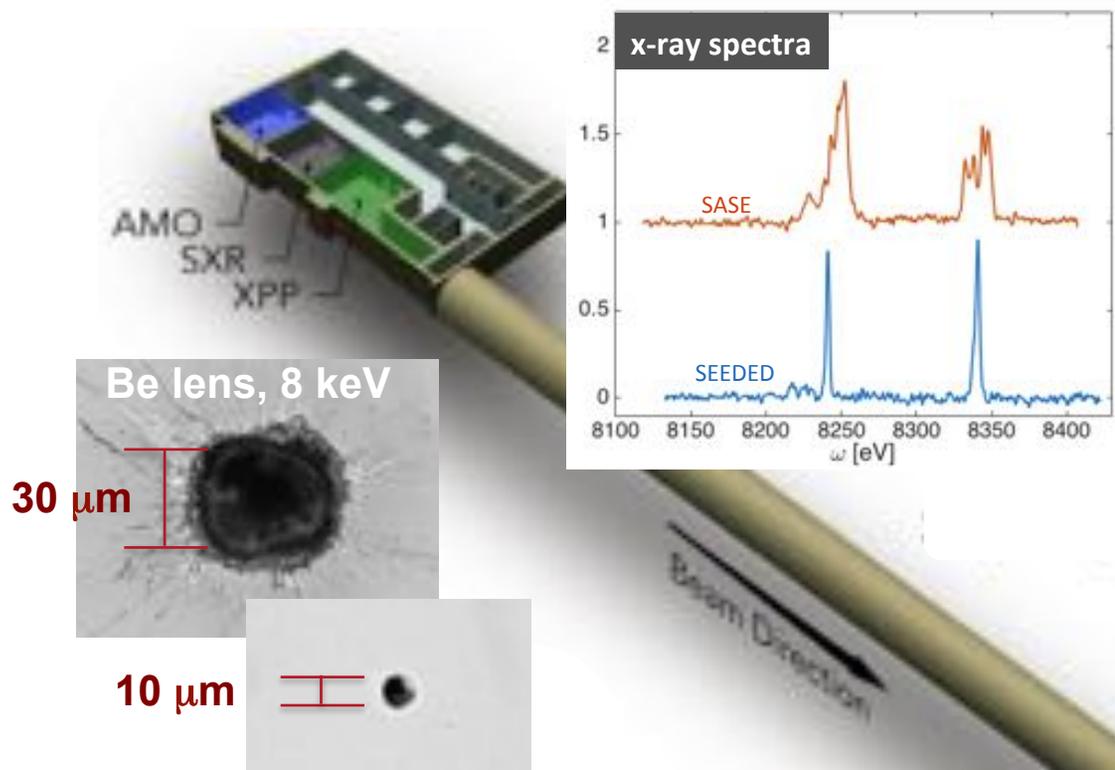
Undulator (130 m)

Far Experiment
Hall

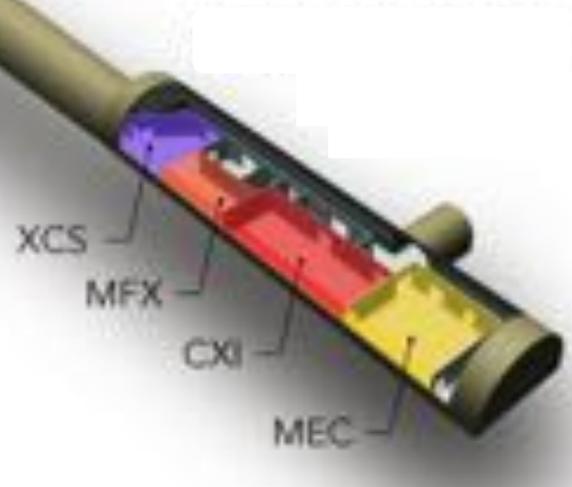
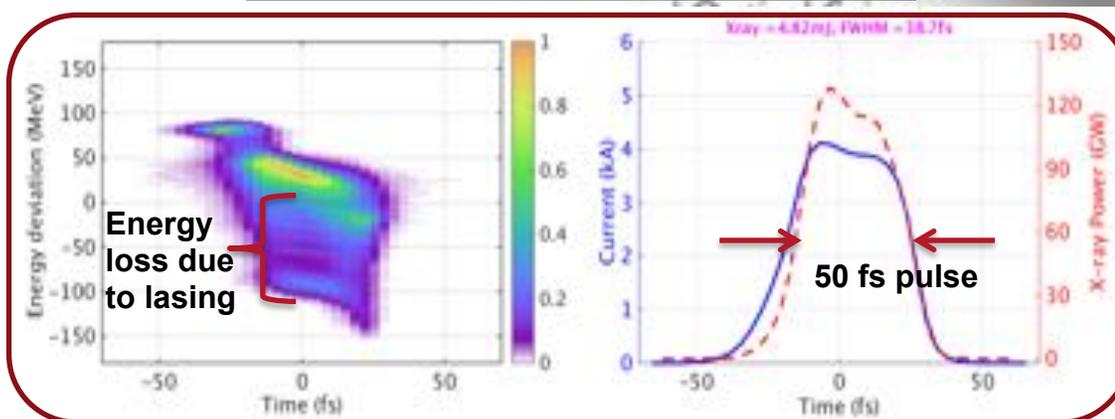


LCLS is an instrument to access extreme conditions

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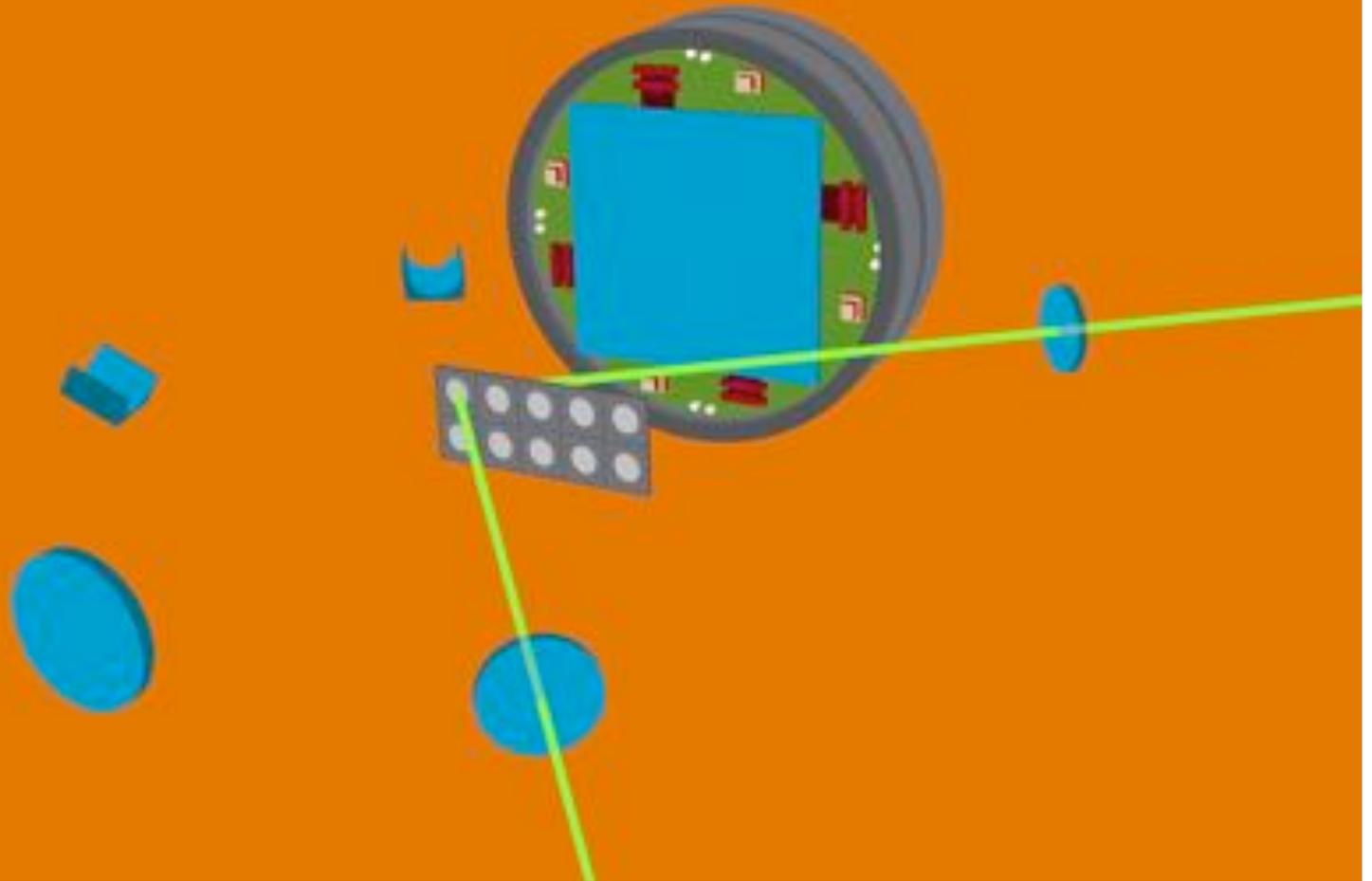
Electron beam streak measurement





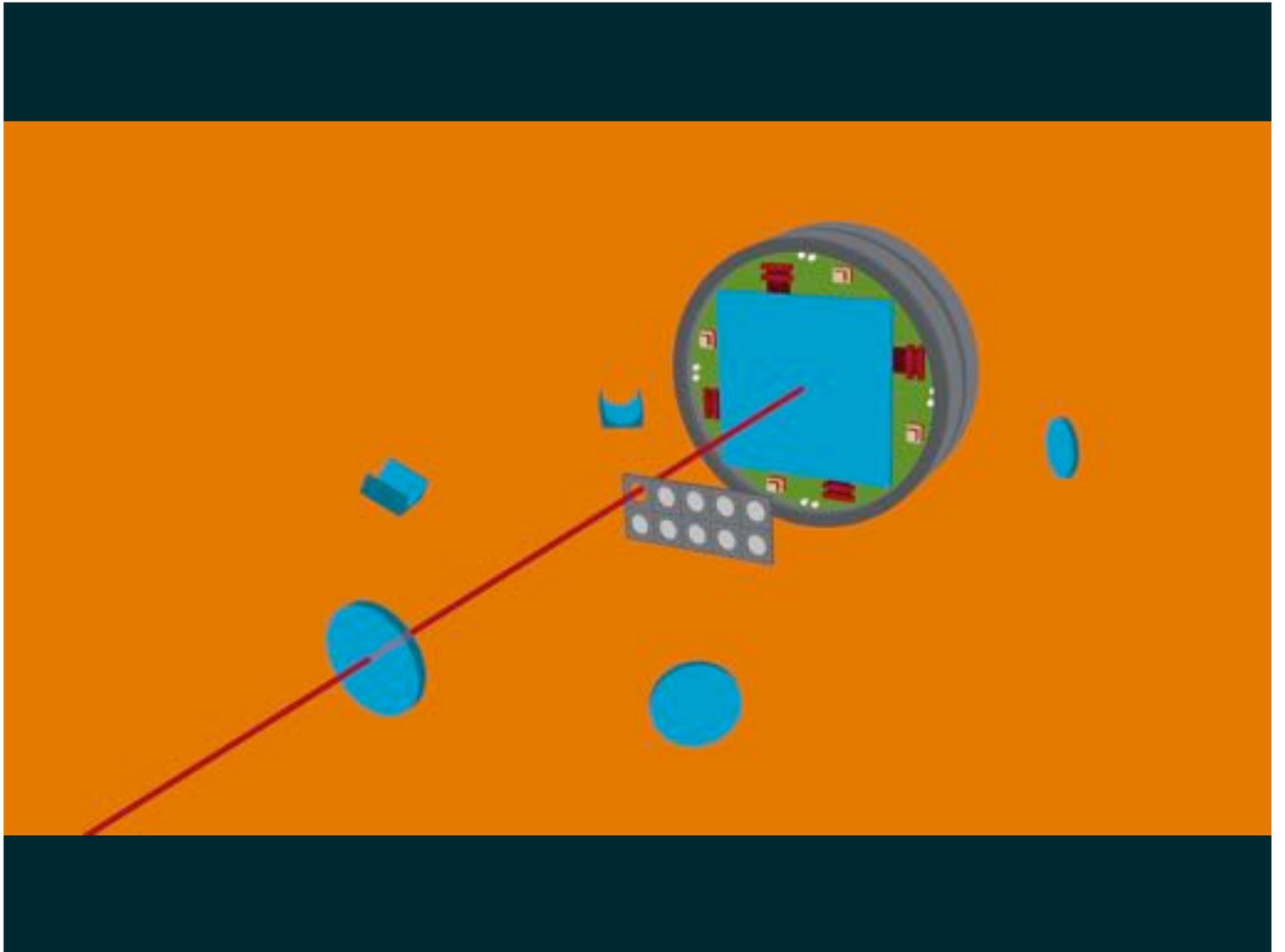
Matter in Extreme Conditions (MEC)

Shaped nanosecond glass laser

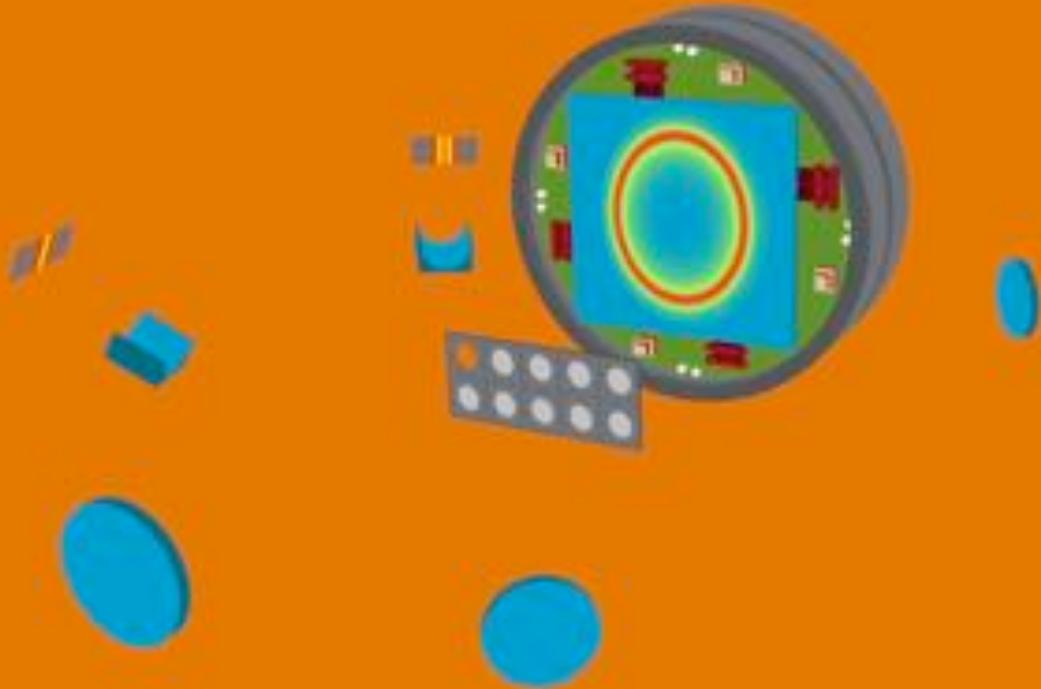


Newton's third law:
Action = Reaction









Record peak brightness experiments have validated DFT simulations of warm dense matter

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Work with high impact; within 4 months another group just published:
“we use recent experimental data [10] to demonstrate the inadequacy of two approximations that are often used in models....”

We now have a validated model to determine thermodynamic state variables:
Equation of State, Line broadening, Stopping Powers, Transport, Opacity,...

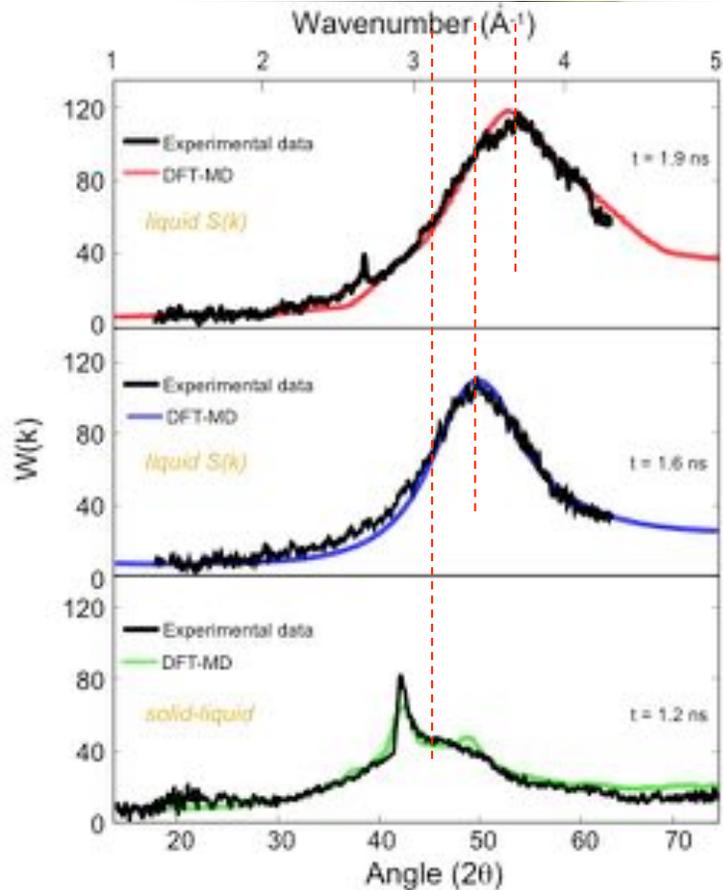
ARTICLES

PUBLISHED ONLINE: 23 MARCH 2015 | DOI: 10.1038/NPHOTON.2015.41

nature
photonics

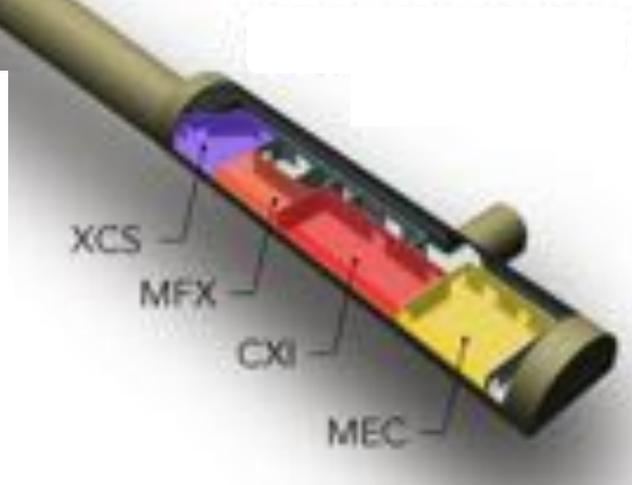
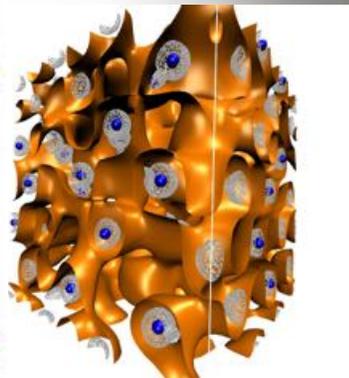
Ultrabright X-ray laser scattering for dynamic warm dense matter physics

L. B. Fletcher^{1,2*}, H. J. Lee¹, T. Döppner³, E. Galtier¹, B. Nagler¹, P. Heimann¹, C. Fortmann⁴, S. LePape³



Experimental Hall

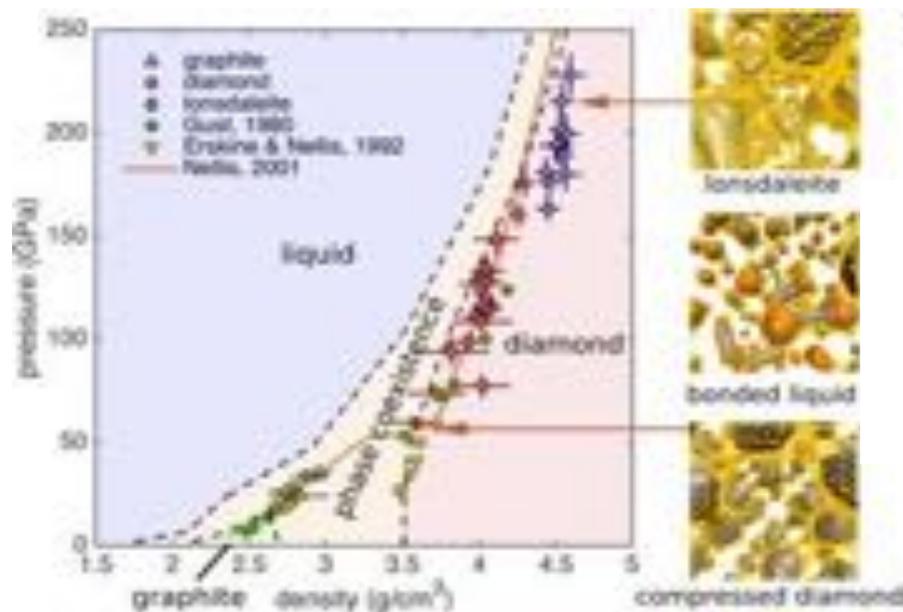
Direction



Dynamic compression experiments have resolved diamond formation and possibly provide strength

Ultra-bright LCLS x-rays have observed lonsdaleite, ie hexagonal diamond

Experiments on the diamond Hugoniot indicate elastic plastic waves



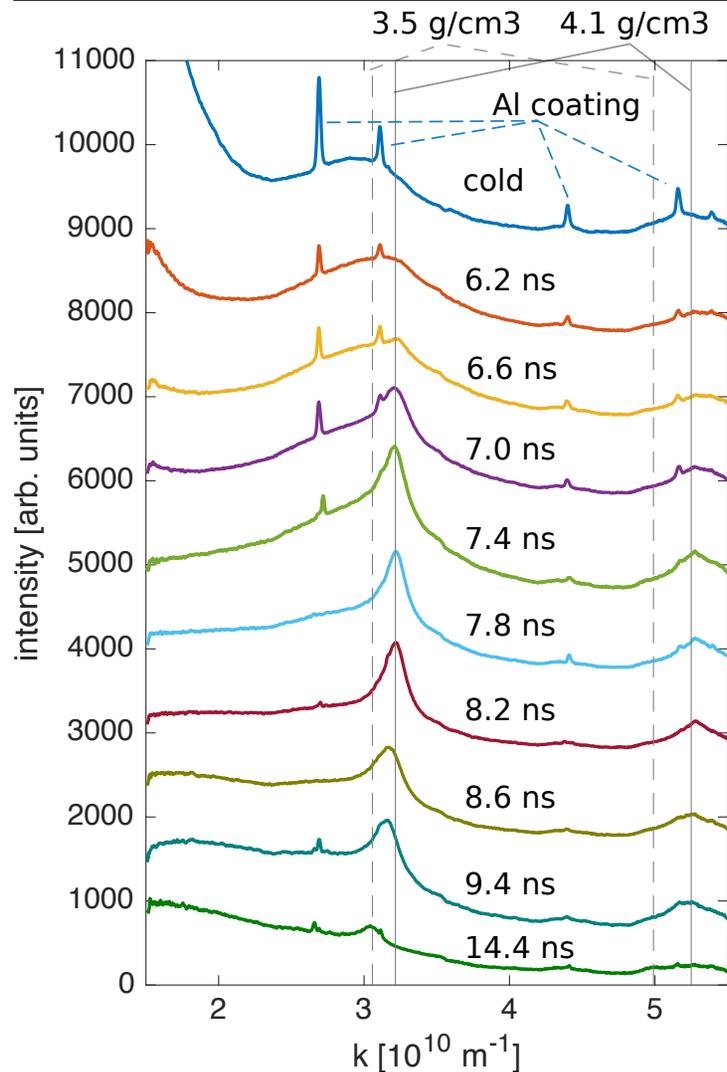
Received 5 Apr 2015 | Accepted 5 Feb 2016 | Published 14 Mar 2016 DOI: 10.1038/ncomms10970 OPEN

Nanosecond formation of diamond and lonsdaleite by shock compression of graphite

D. Kraus¹, A. Ravasio², M. Gauthier², D.O. Gericke³, J. Vorberger^{4,5}, S. Frydrych⁶, J. Helfrich⁶, L.B. Fletcher²

A big surprise: nano-diamonds form by compressing plastic (CH) foils

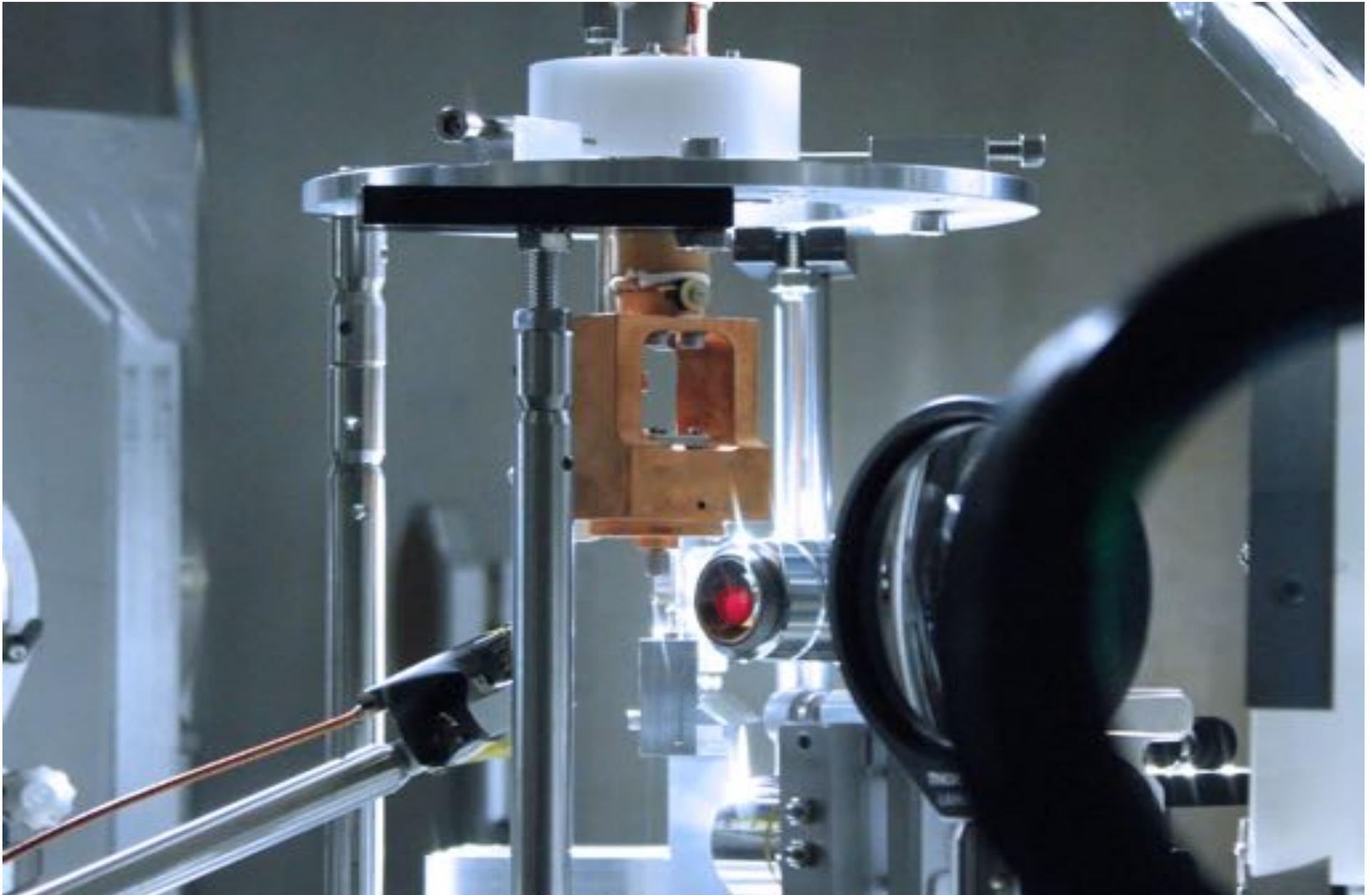
Observation of strong diamond diffraction at 200 GPa



- Important for planetary models and understanding of kinetics in dynamic compression

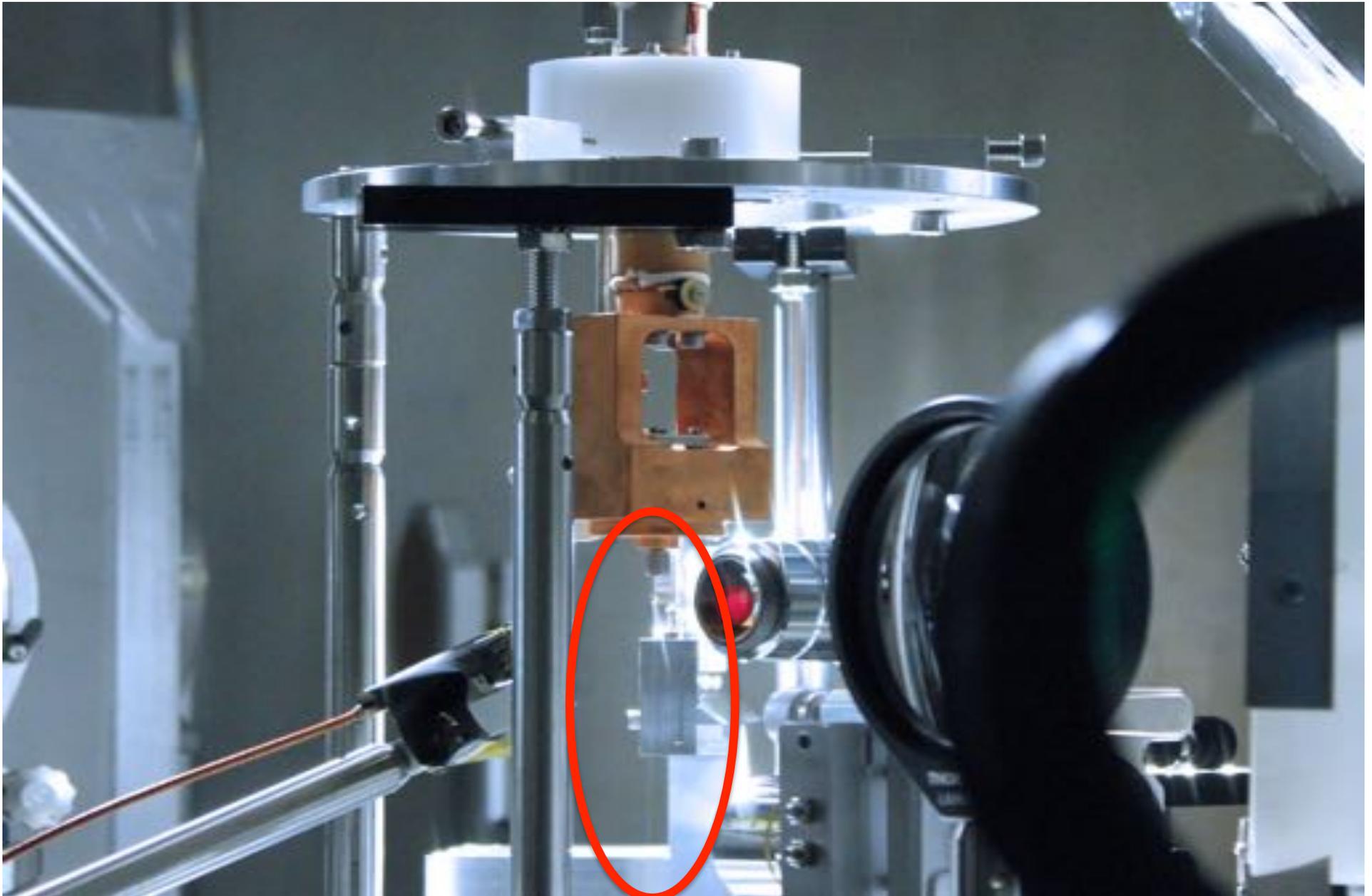
We have developed cryogenic jets for 120 Hz experiments

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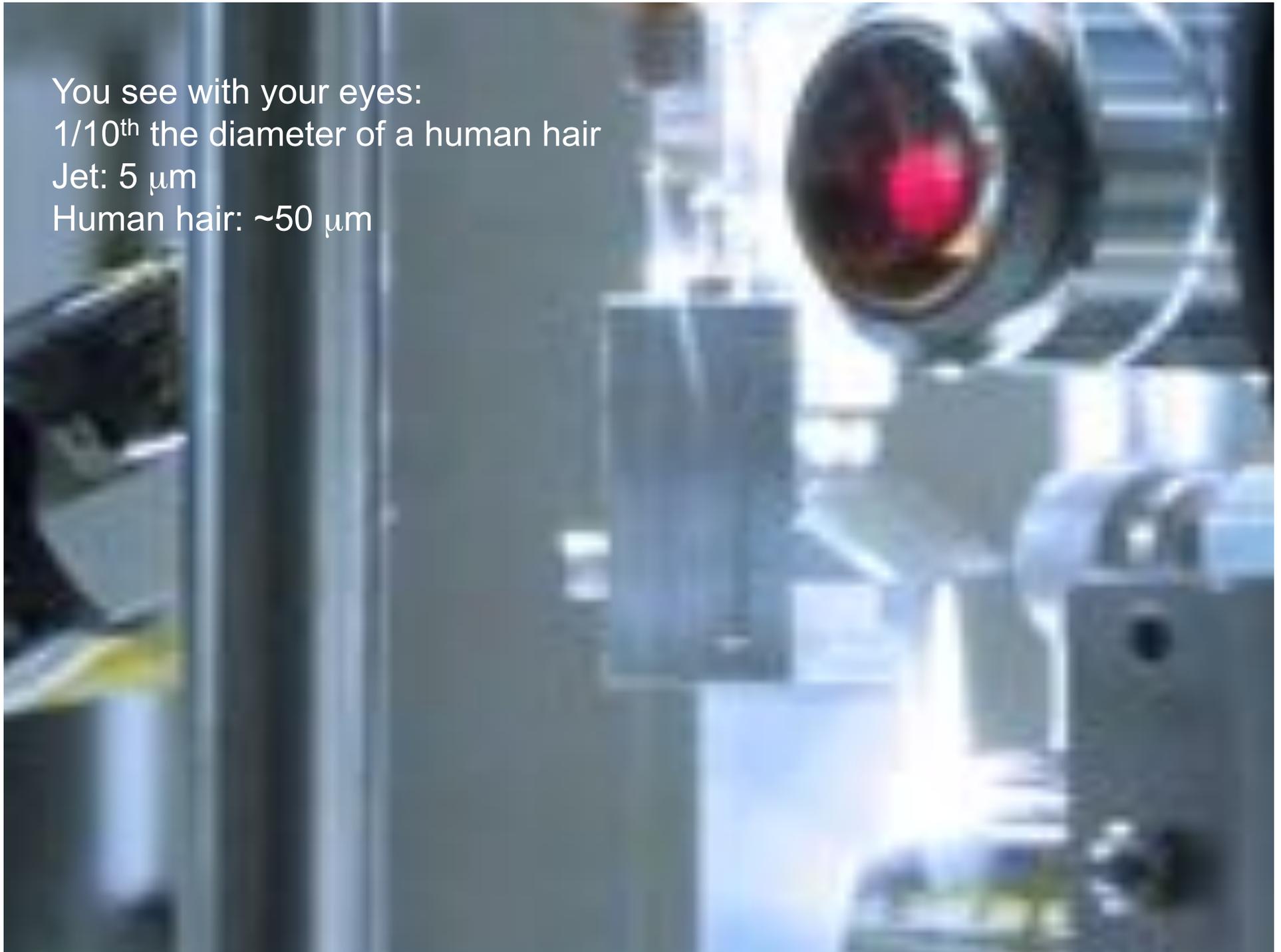


We have developed cryogenic jets for 120 Hz experiments

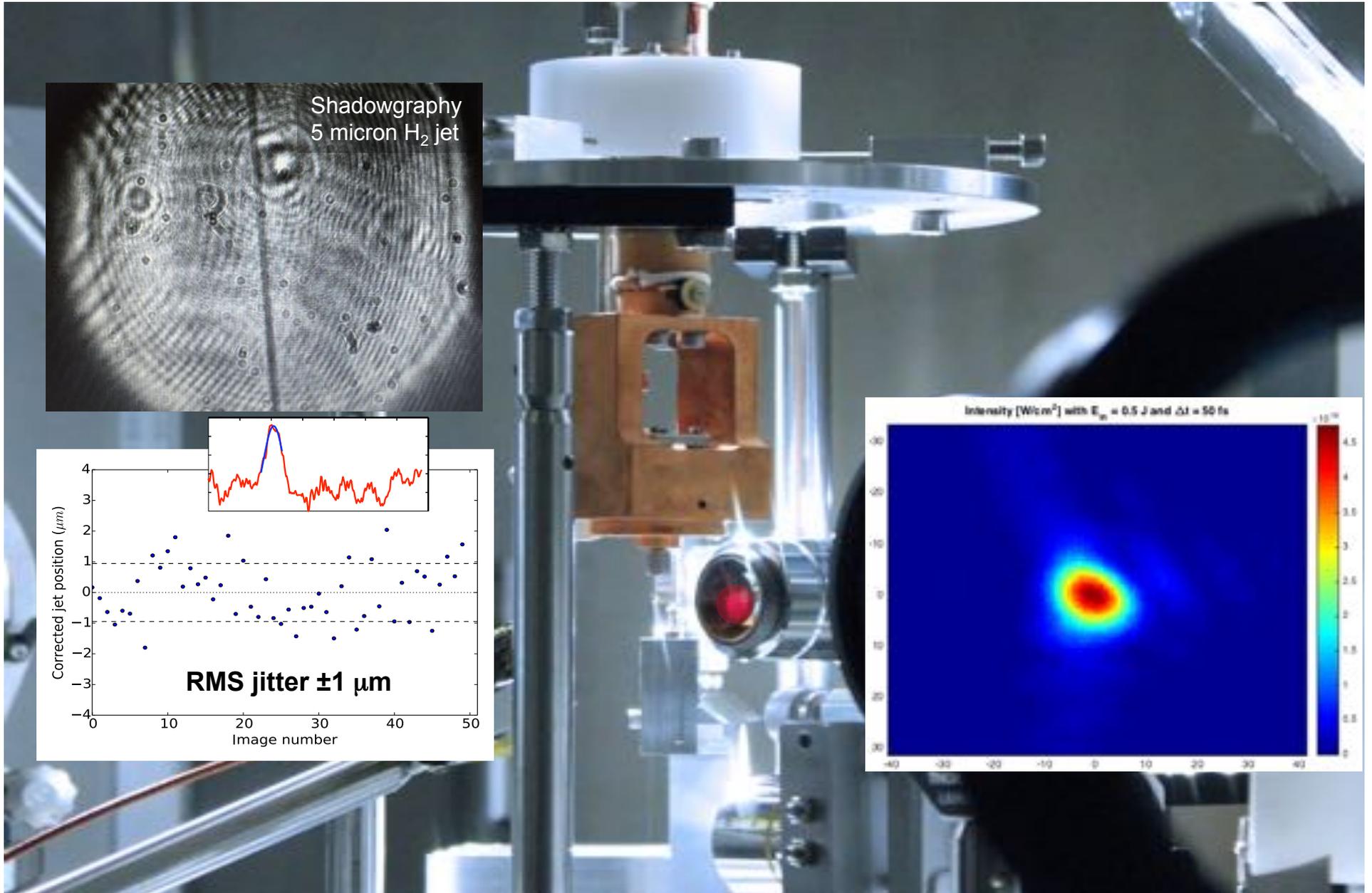
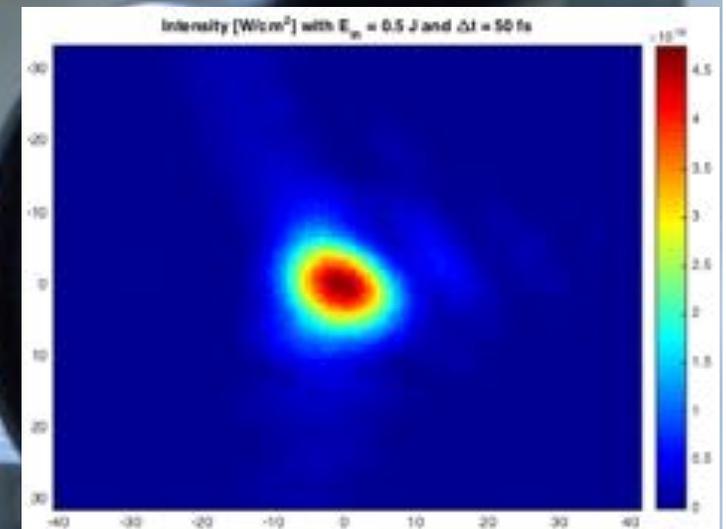
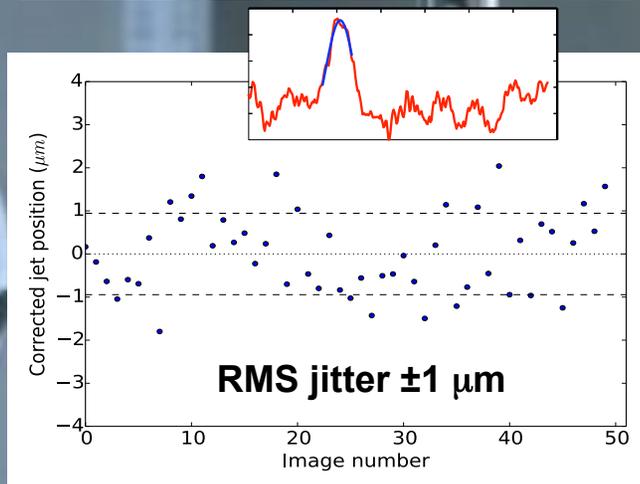
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You see with your eyes:
1/10th the diameter of a human hair
Jet: 5 μm
Human hair: $\sim 50 \mu\text{m}$

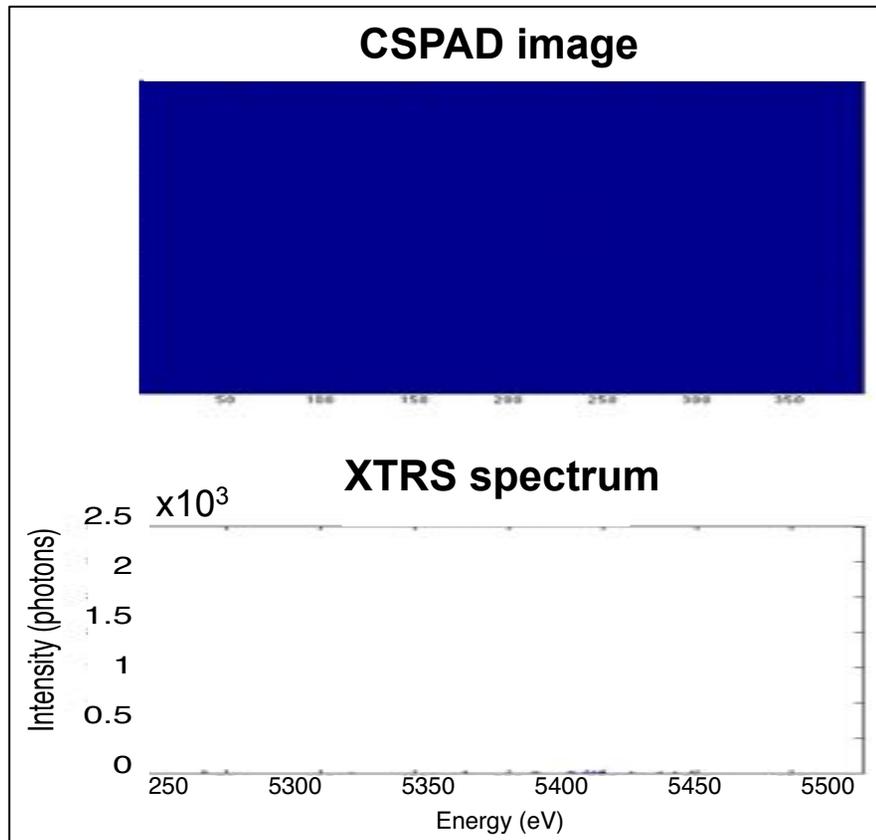


Super-cooled hydrogen icicle

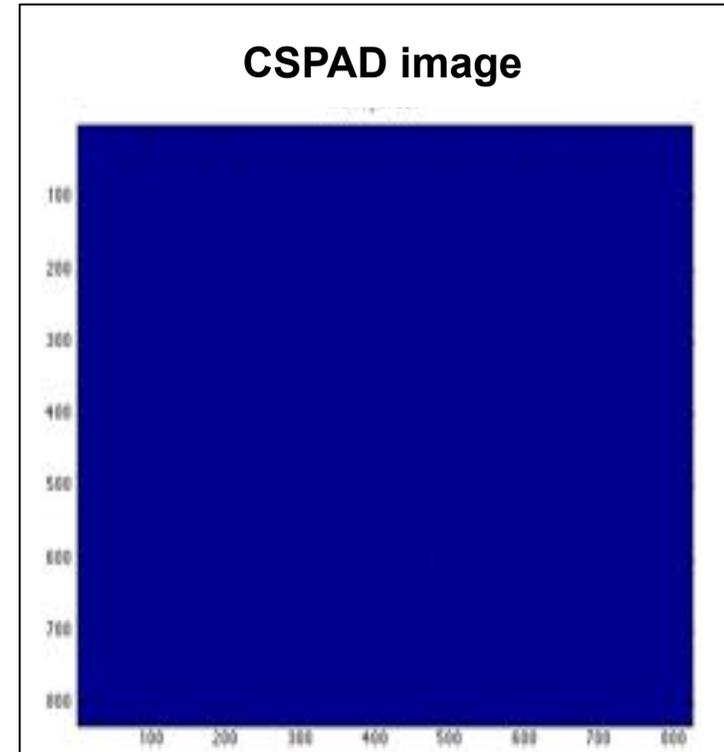


X-ray scattering at 120 Hz

Inelastic single photon x-ray detection
(170°) @ 120 Hz

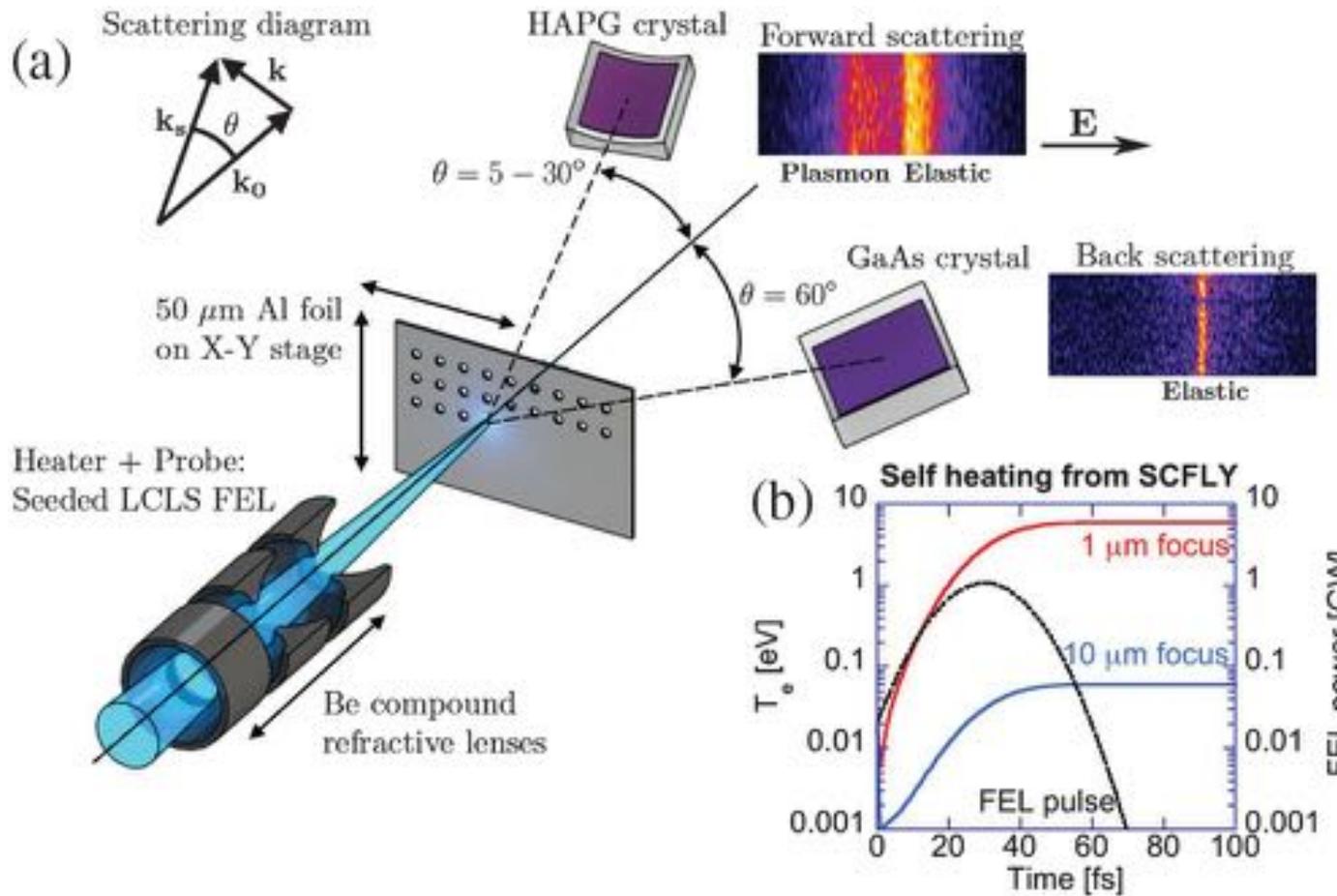


Single crystal x-ray diffraction
(30°-55°) @ 120 Hz



	500 shots	5,000 shots
120 Hz	4 seconds	40 seconds
5 Hz	2 minutes	17 minutes

New discovery science experiments on NIF are motivated by LCLS self-heating experiments

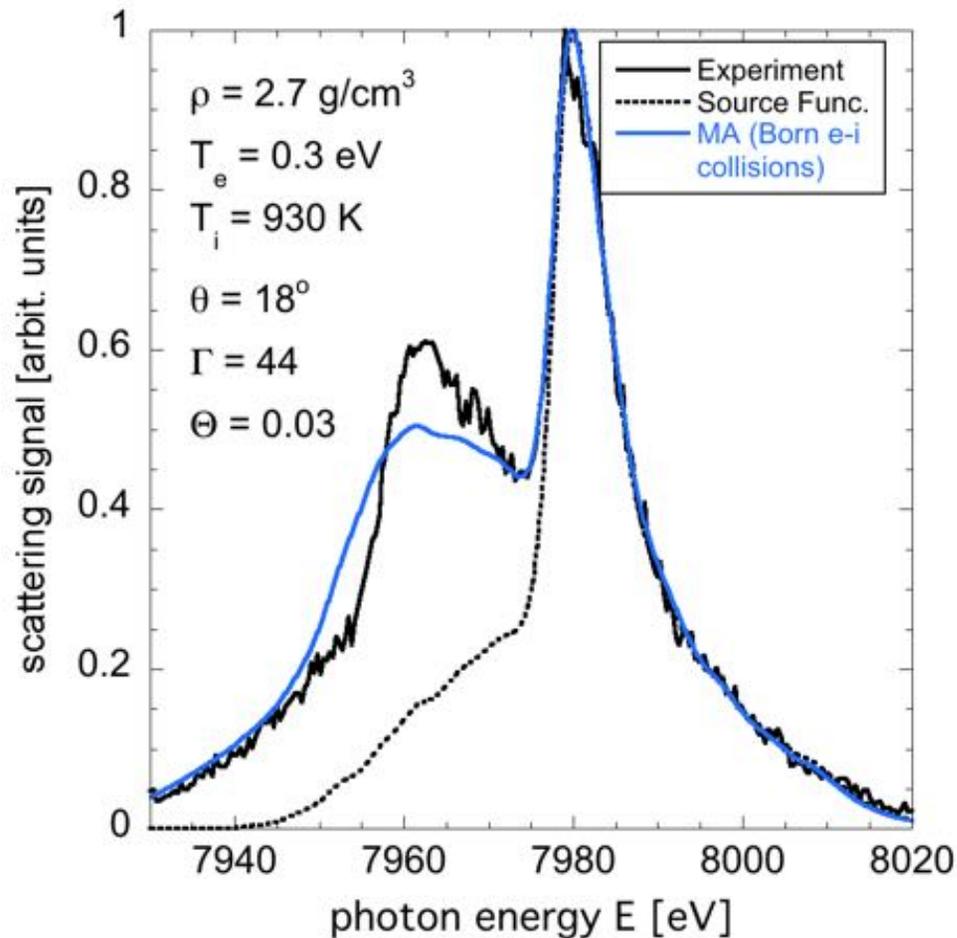


LCLS:

- $\Delta E/E = 25 \times 10^{-4}$
- $E_{ph} = 7.98 \text{ keV}$
- $t_{FWHM} = 25 \text{ fs}$
- $E = 0.1 \text{ mJ}$
- $d_{FWHM} = 1-10 \mu\text{m}$

P. Sperling et al., Phys. Rev. Lett. **115**, 115001 (2015).

LCLS experiments show nonlinear damping; well-established BMA can not predict the width

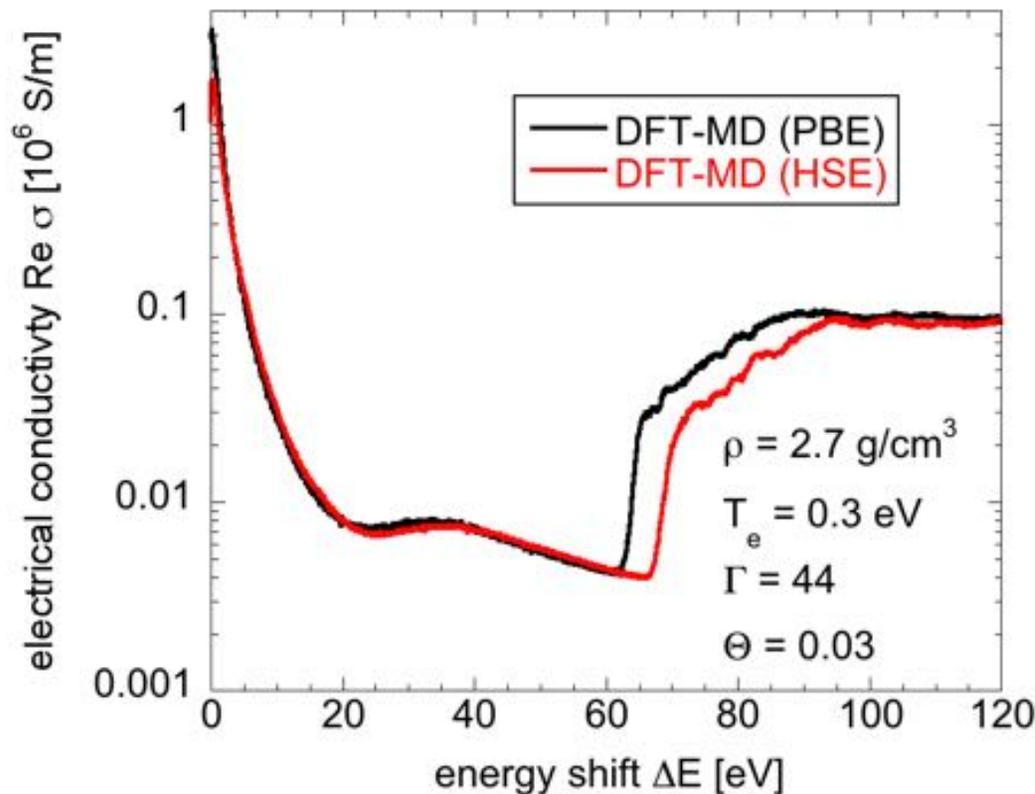


- Experimental plasmon width is too narrow
- Dispersion appears to be matched
- Previous studies have shown agreement with both shift and width
- Temperature from detailed balance

We have applied DFT-MD simulations to further analyze this effect

DFT-MD results are sensitive to the choice of the exchange functional

Conductivity calculated from Kubo-Greenwood formula



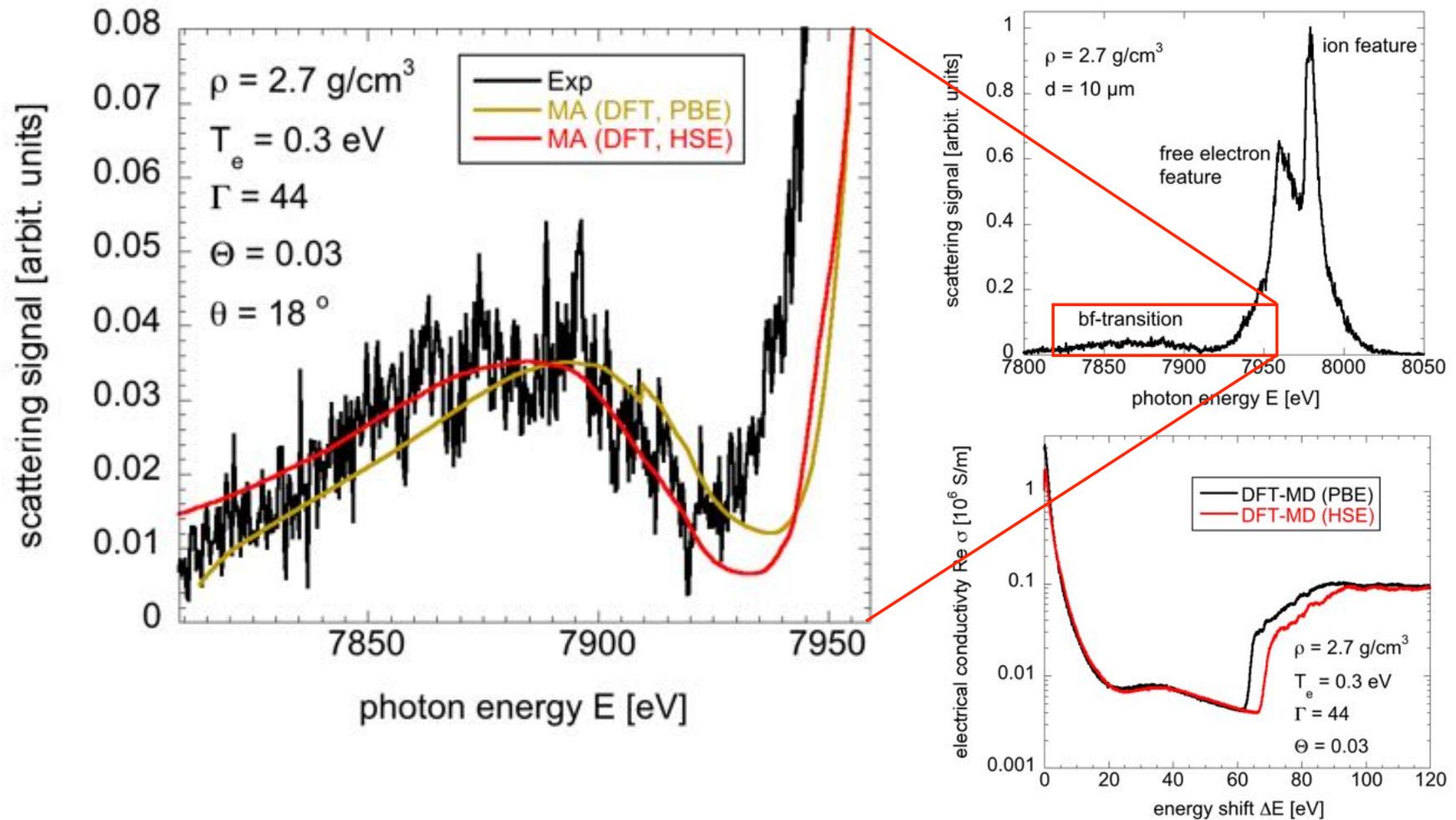
Conductivity show different effects:

- Electron collisions
- Excitations of conduction band electrons
- Excitations of bound electrons

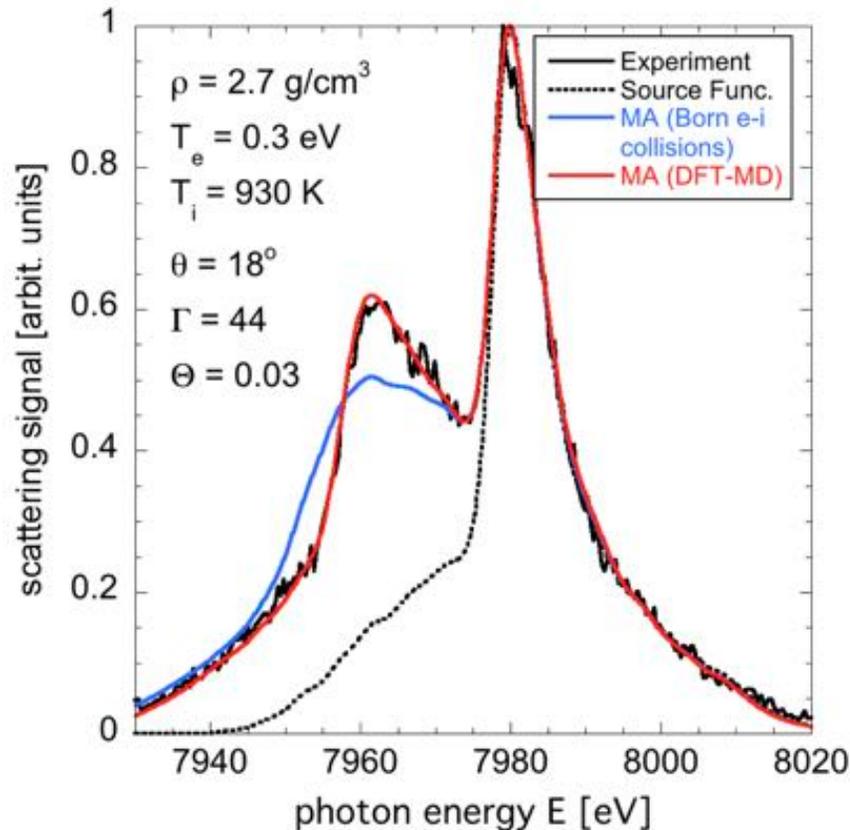
Difference between PBE and HSE functional:

- dc conductivity ($\Delta E \rightarrow 0$)
- ionization edge position

The HSE functional reproduces experimental data



Nonlinear plasmon damping is due to electron excitations: effect opposite to what we predict for NIF



Extraction of collision frequency $\nu(\omega)$:

$$\text{Re } \varepsilon(\omega) = 1 - \frac{1}{\varepsilon_0 \omega} \text{Im } \sigma(\omega)$$

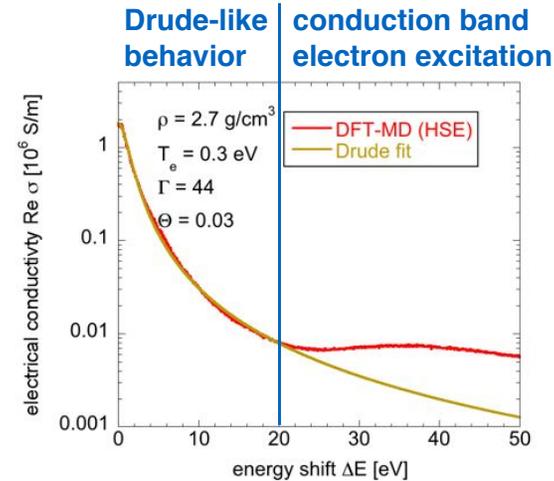
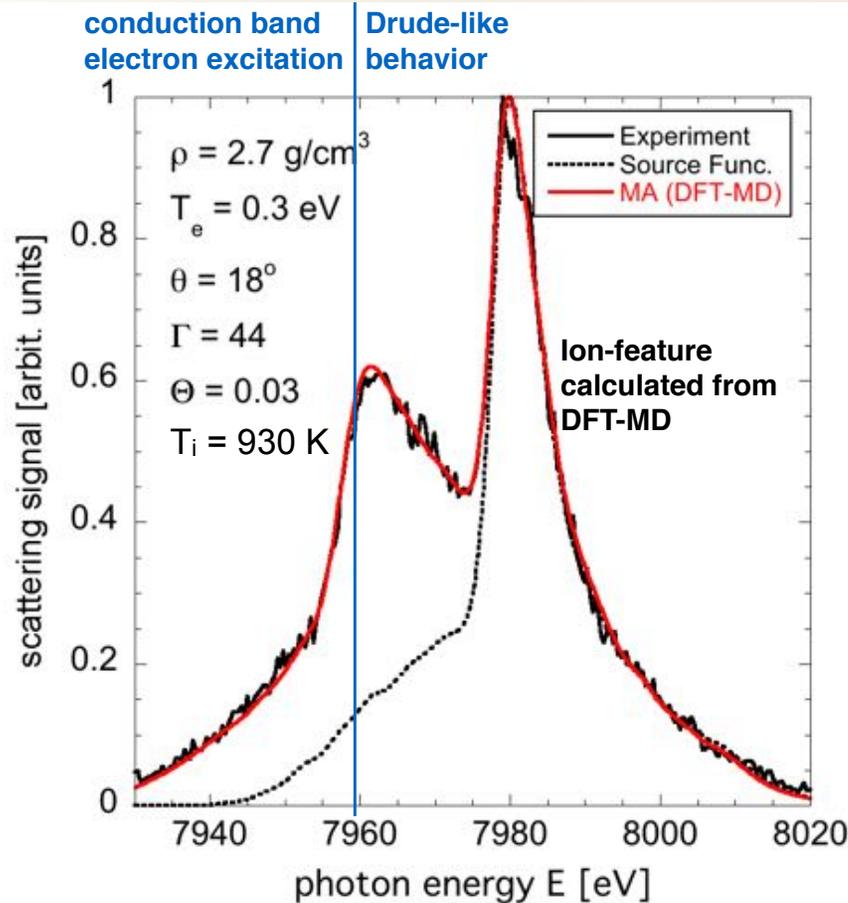
$$\text{Im } \varepsilon(\omega) = \frac{1}{\varepsilon_0 \omega} \text{Re } \sigma(\omega)$$

$$\varepsilon^{\text{DFT}}(\omega, \nu(\omega)) = \varepsilon^{\text{M}}(\omega, \nu(\omega))$$

- additional damping by electron excitations ($\Delta E > 20$ eV) not described by analytical models

Analysis beyond the Chihara approximation shows nonlinear damping
2010 Fields Medal topic

Nonlinear plasmon damping is due to electron excitations: effect opposite to what we predict for NIF



- **Demonstration of non-Drude conductivity at solid density WDM**
- **Previous studies have shown non-Drude behavior in expanding plasmas**

PRL 118, 225001 (2017)

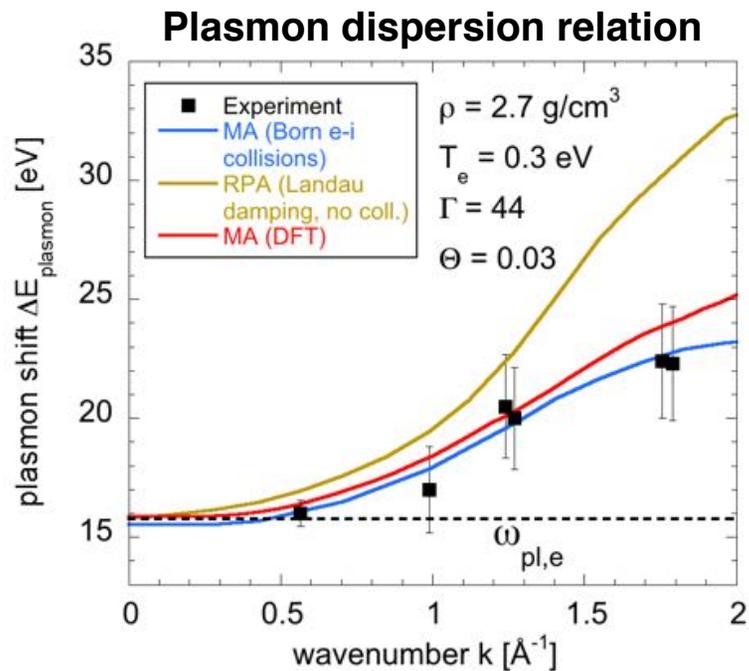
PHYSICAL REVIEW LETTERS

week ending
2 JUNE 2017

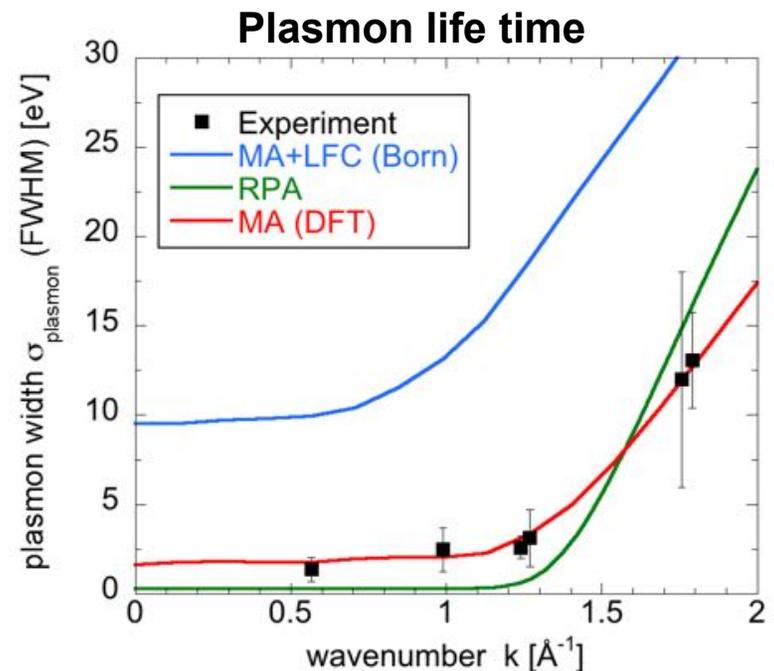
Warm Dense Matter Demonstrating Non-Drude Conductivity from Observations of Nonlinear Plasmon Damping

B. B. L. Witte,^{1,2} L. B. Fletcher,¹ E. Galtier,¹ E. Gamboa,¹ H. J. Lee,¹ U. Zastra,³

We can well reproduce nonlinear plasmon damping; dispersion is well described by BMA



experiment agrees with simulation (DFT) and model (Born)

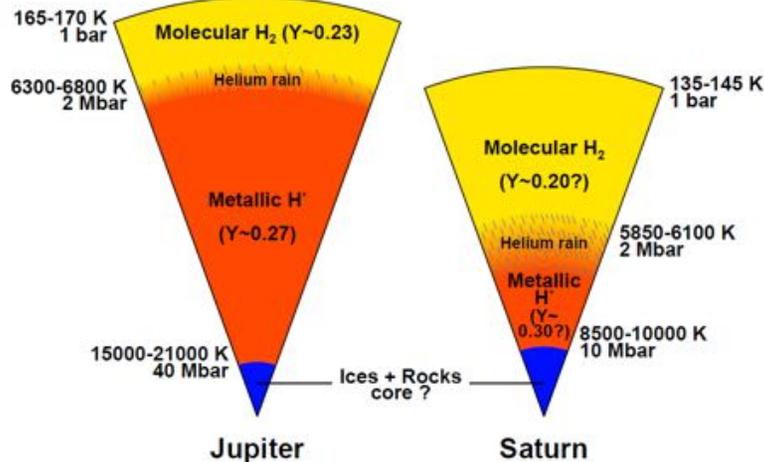


Standard theories fail at Plasmon damping

Creating and measuring the conditions of brown dwarfs

Giant planets in the Solar System:

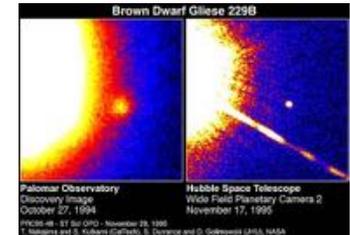
- Layered structure? Size of the core? He rain?
- Interior – evolution – dynamo
- Juno & Cassini missions



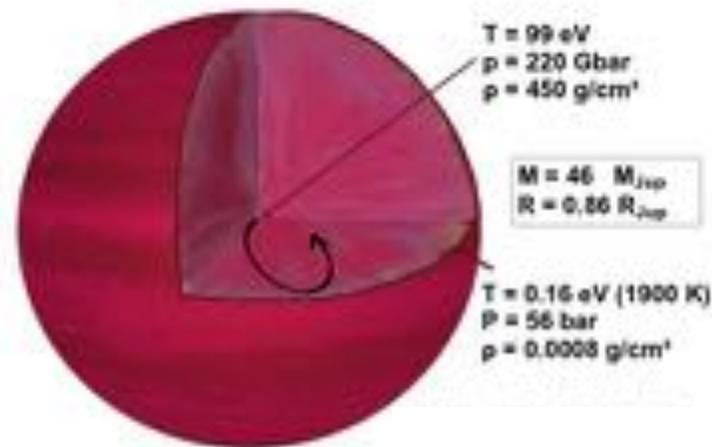
T. Guillot, D. Gautier, *Treatise Geophys.* (2014)

Brown Dwarfs:

- Jupiter-sized
- $13 M_{\text{Jupiter}} < M < 75 M_{\text{Jupiter}}$
- Degenerate matter
- Interior – evolution – dynamo
- Fully convective layer (?)

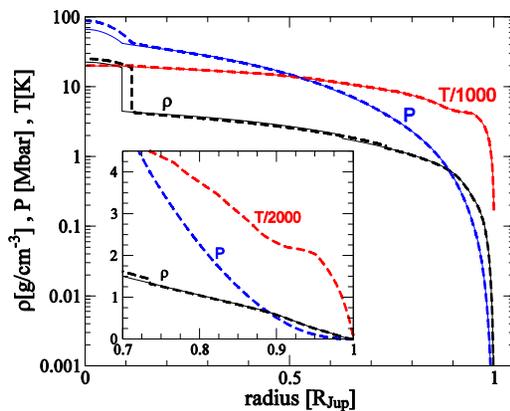
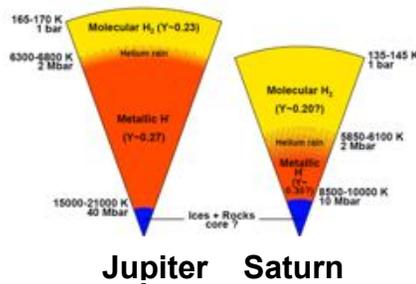


Gliese 229 B
1995, 18.8 ly
M1 + T6 (50 AU)

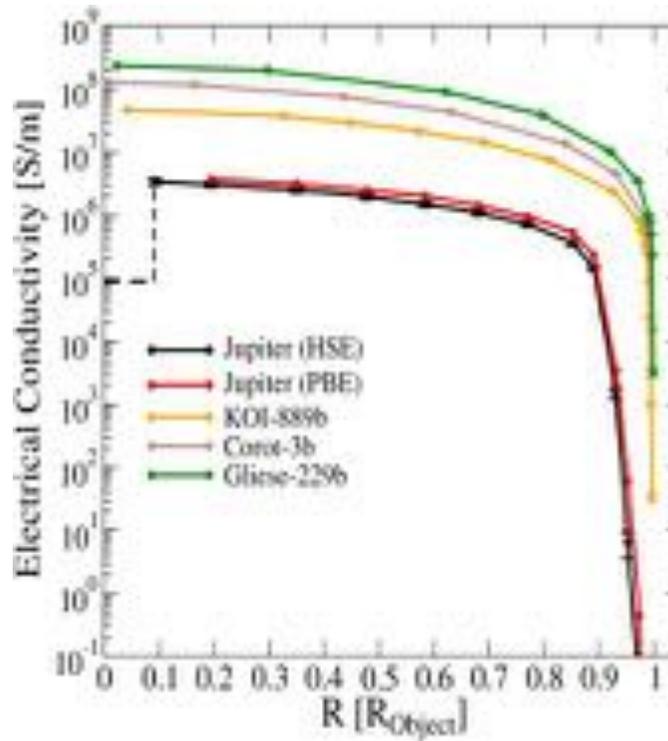


A. Becker et al., *ApJS* **215**, 21 (2014)

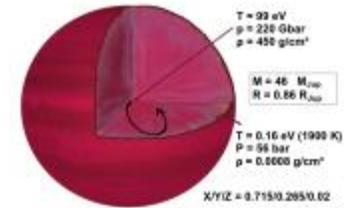
Creating and measuring the conditions of brown dwarfs



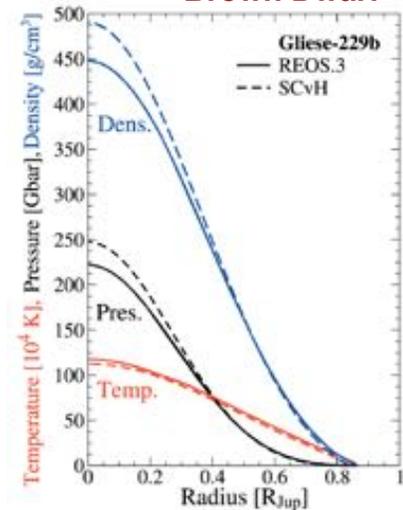
M. French et al., ApJS 202, 5 (2012)



A. Becker et al. (2016)



Brown Dwarf

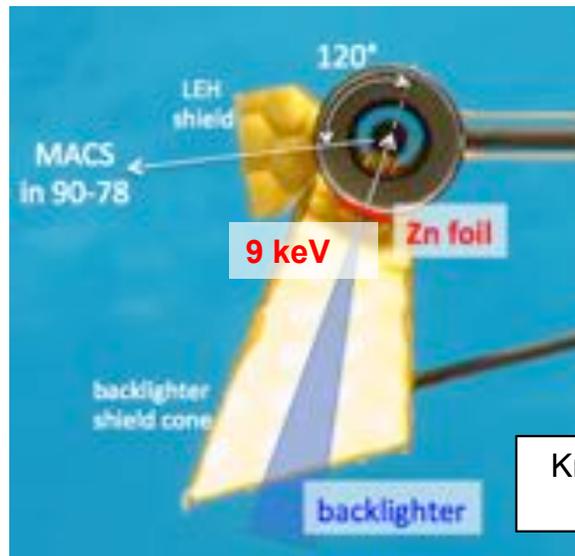
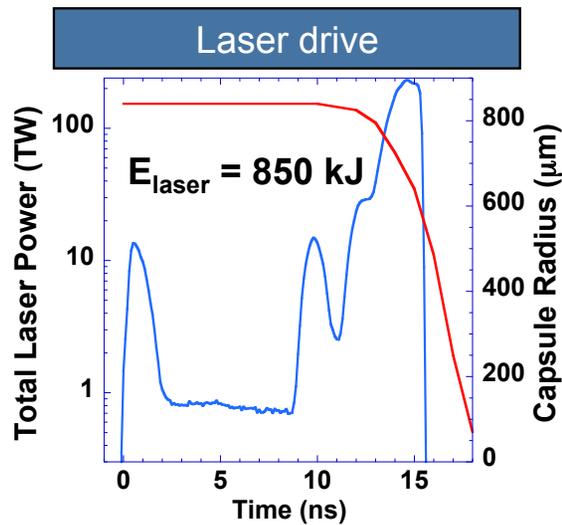


A. Becker et al., ApJS 215, 21 (2014)

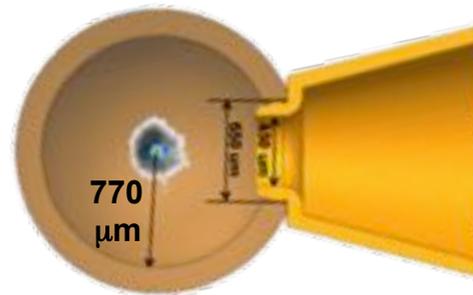
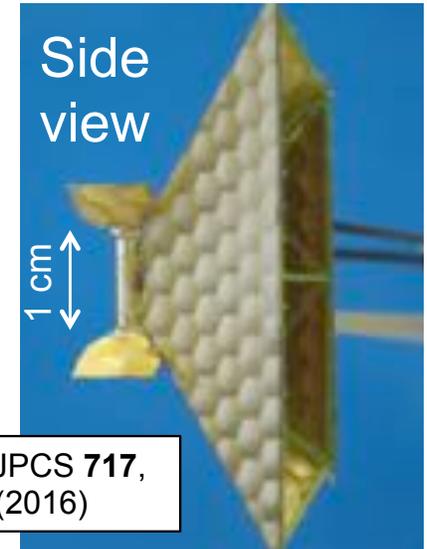
Probe extreme states of matter as deep inside brown dwarfs:
tens of eV and tens of g/cm³

X-ray Thomson scattering has been developed as part of the NIF discovery science program

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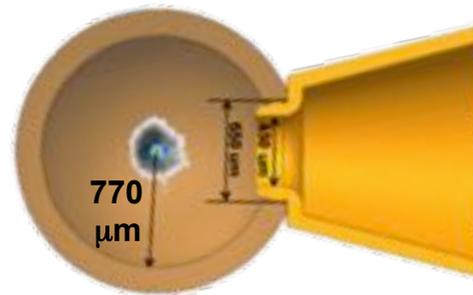
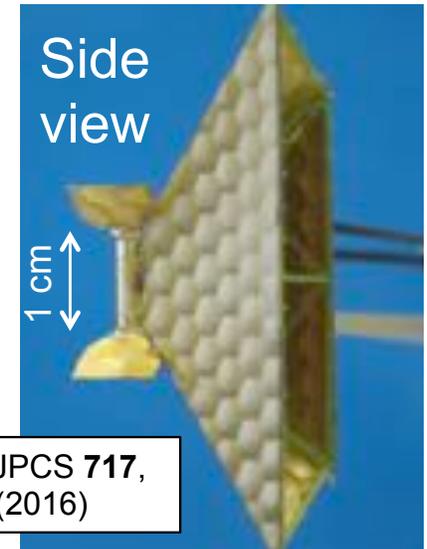
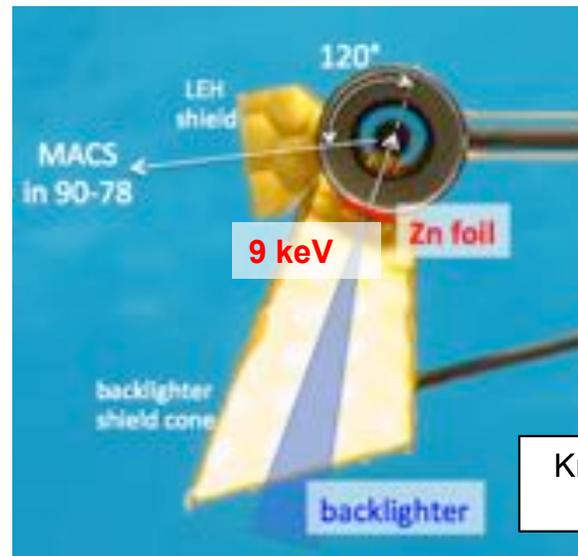
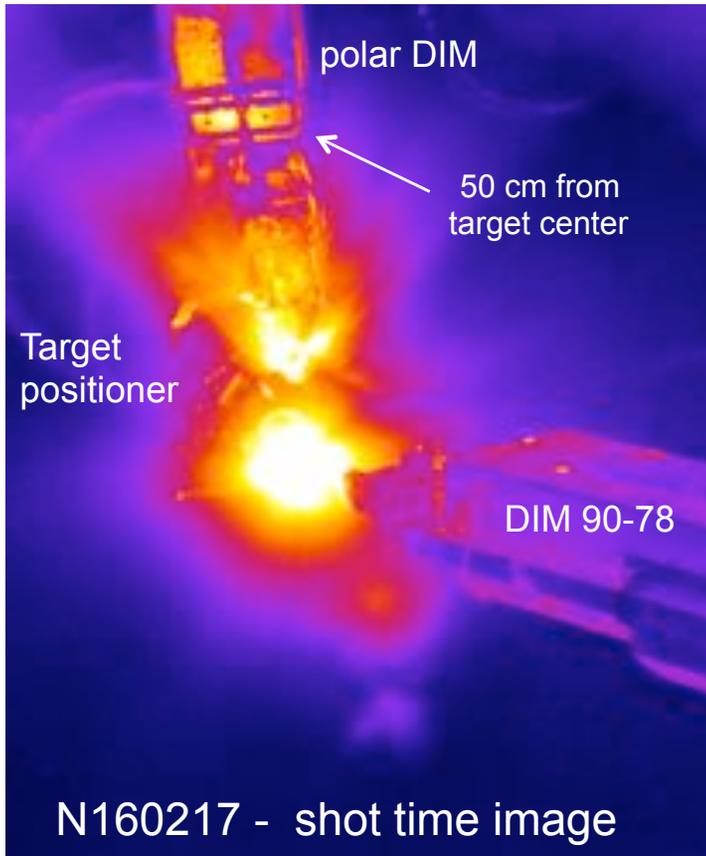
Kraus et al. JPCS 717, 012067 (2016)



NIF X-ray scattering experiments have been demonstrated on CH and Be shell implosions, NIF PI T. Döppner

X-ray Thomson scattering has been developed as part of the NIF discovery science program

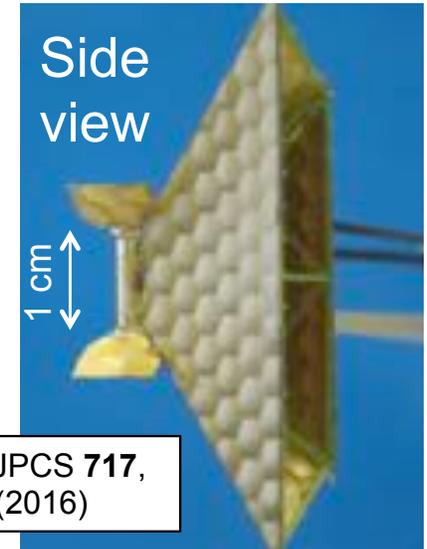
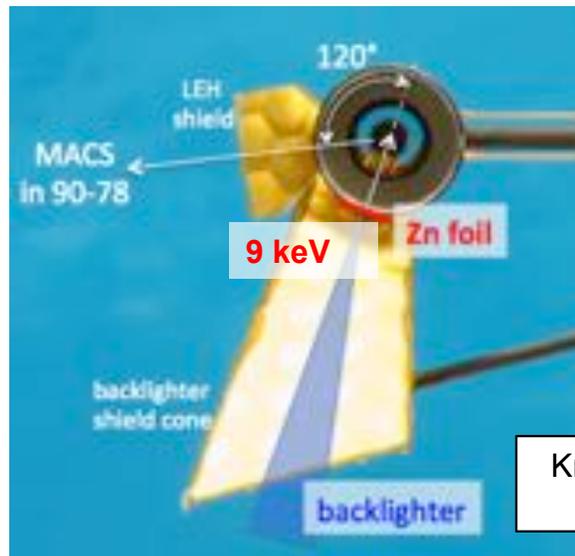
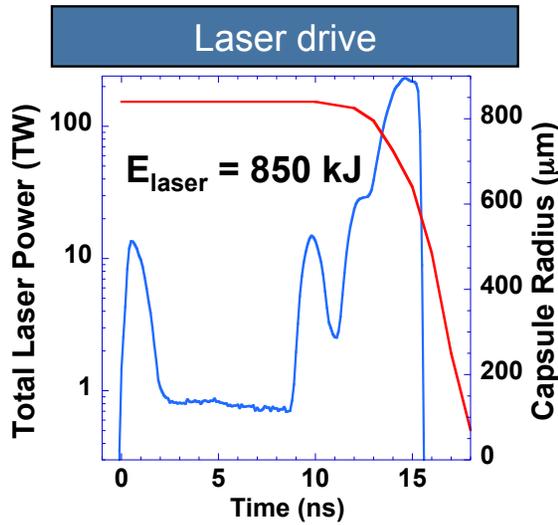
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NIF X-ray scattering experiments have been demonstrated on CH and Be shell implosions, NIF PI T. Döppner

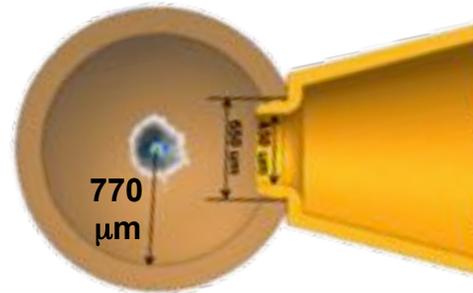
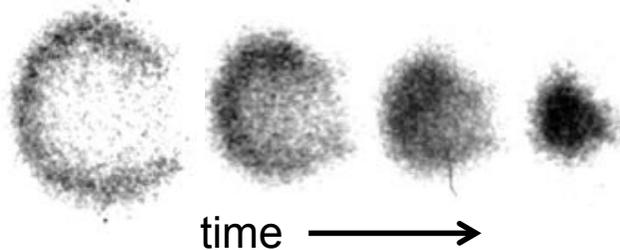
X-ray Thomson scattering has been developed as part of the NIF discovery science program

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Kraus et al. JPCS 717, 012067 (2016)

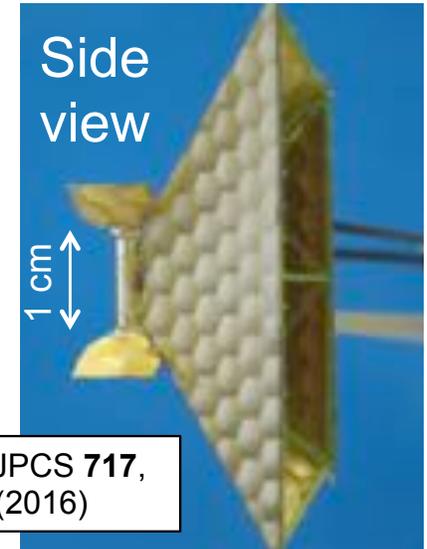
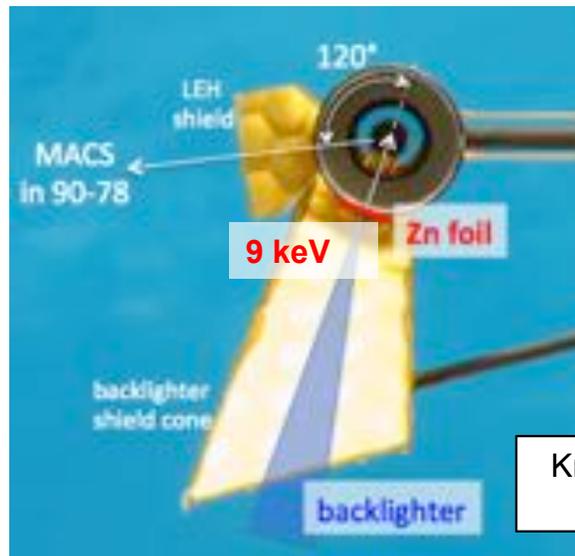
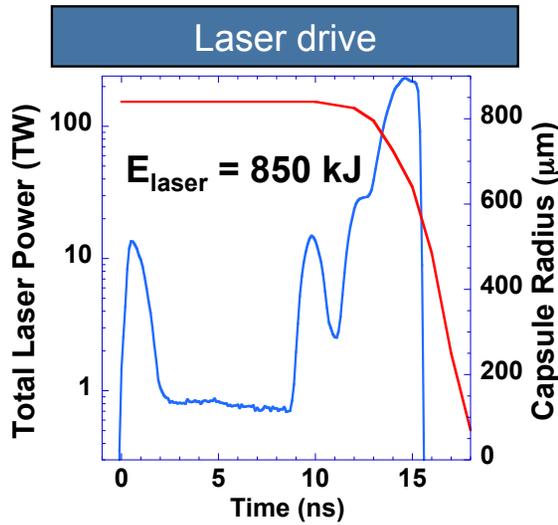
X-ray radiography



NIF X-ray scattering experiments have been demonstrated on CH and Be shell implosions, NIF PI T. Döppner

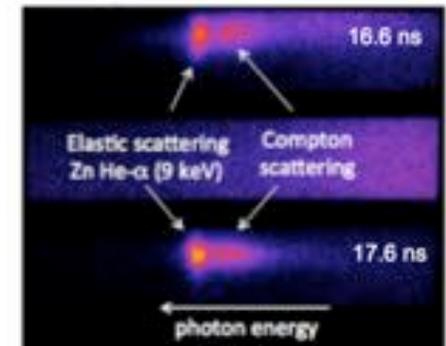
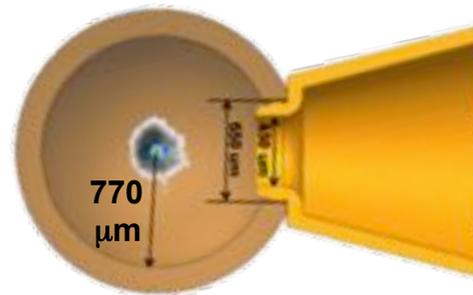
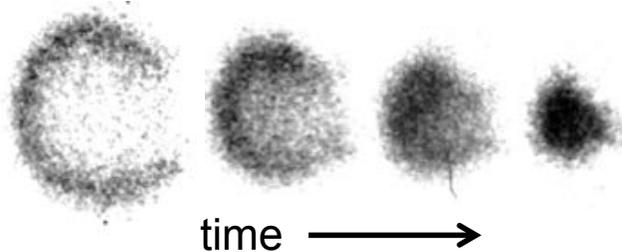
X-ray Thomson scattering has been developed as part of the NIF discovery science program

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Kraus et al. JPCS 717, 012067 (2016)

X-ray radiography



NIF X-ray scattering experiments have been demonstrated on CH and Be shell implosions, NIF PI T. Döppner

XRTS data in the Compton regime show 50 g/cc

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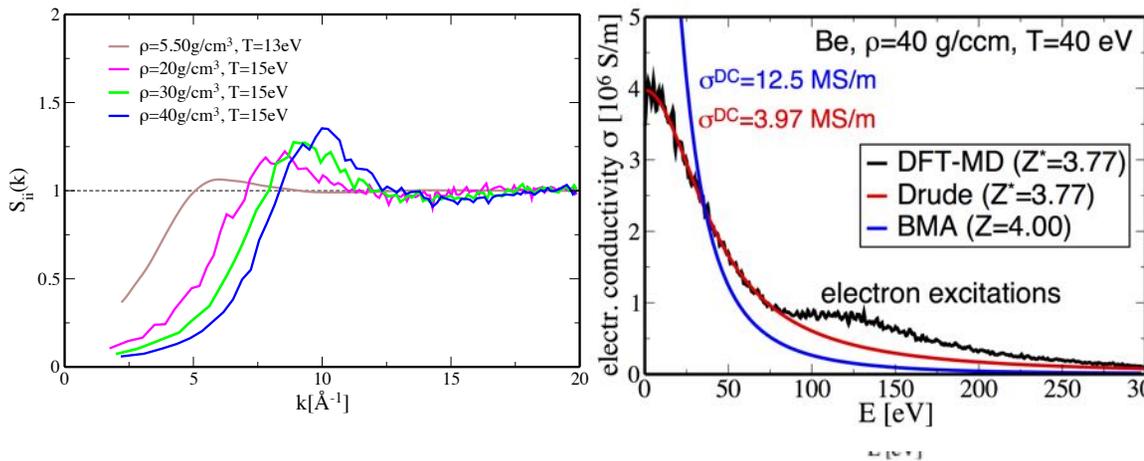
Compton width: sensitive to ρ
Reduced elastic scatter at highest ρ

MUZE (S. Hansen) shows reduction of
atomic scattering and structure factor

Compton width is a robust indicator of ρ demonstrating conditions such
as those found in brown dwarfs

DFT-MD simulations for NIF brown dwarf experiments predict DOS – EOS – sigma – XRTS spectrum

Be as promising test case at NIF



Structure Factor:

- Peak shift as expected
- Important for conductivity

Electrical Conductivity:

- Drude fit yields $Z^*=3.77$
- Electron excitations occur above 80eV (non-Drude)
- Born-Mermin predictions are invalid

XRTS plasmon feature:

- Electron excitations change shape and width of plasmon
- Plasmon damping and dispersion yields dynamic relaxation time and electrical conductivity

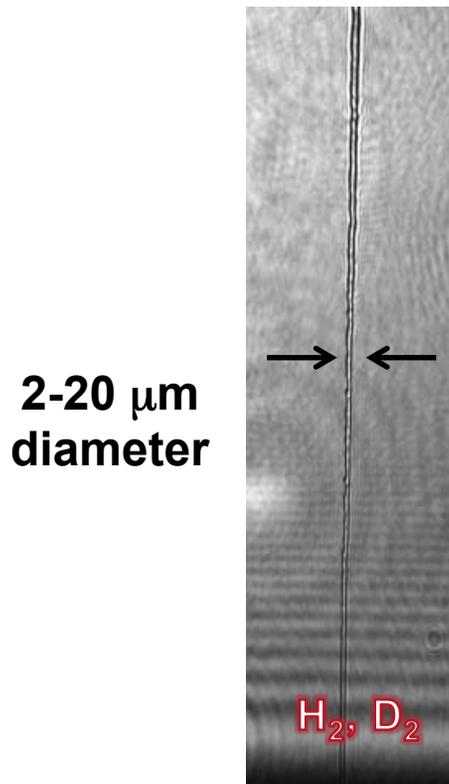
Our predictions for the plasmon scattering spectrum shows significant departures from standard theories

- Introduction
 - What is High Energy Density Physics?
 - Why the answer matters and some insights
- The Axes of the Extremes
- New Discovery Science experiments
 - Insights from the Linac Coherent Light Source
 - Investigate the physics of brown dwarfs on NIF
- Conclusions and Outlook

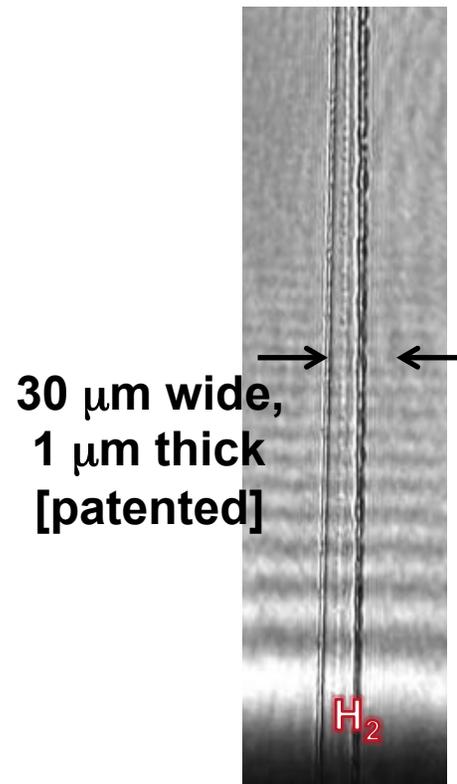
Rapid progress in the development of Cryogenic Jets has resulted in high-energy proton/deuteron beams

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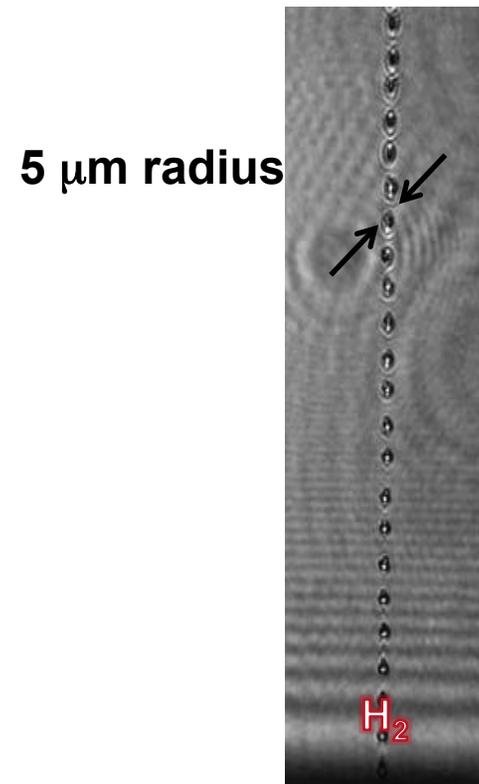
Cylindrical H₂ Jet



Flat H₂ Jet



Droplet H₂ Jet



Cryogenic jets are an excellent tool for HED physics studies

Experiments on cryogenic hydrogen jets have observed the generation of 100 MG Weibel B-fields



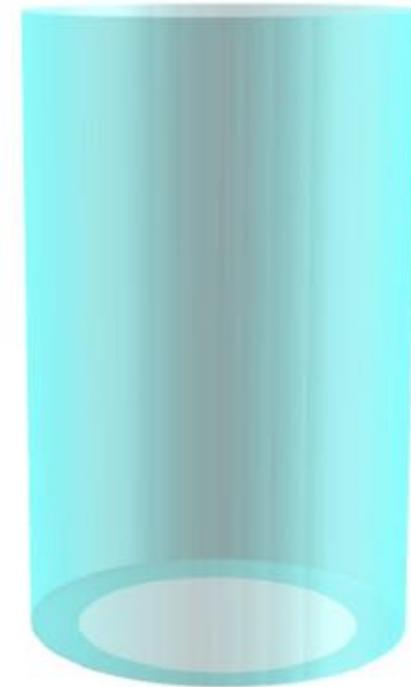
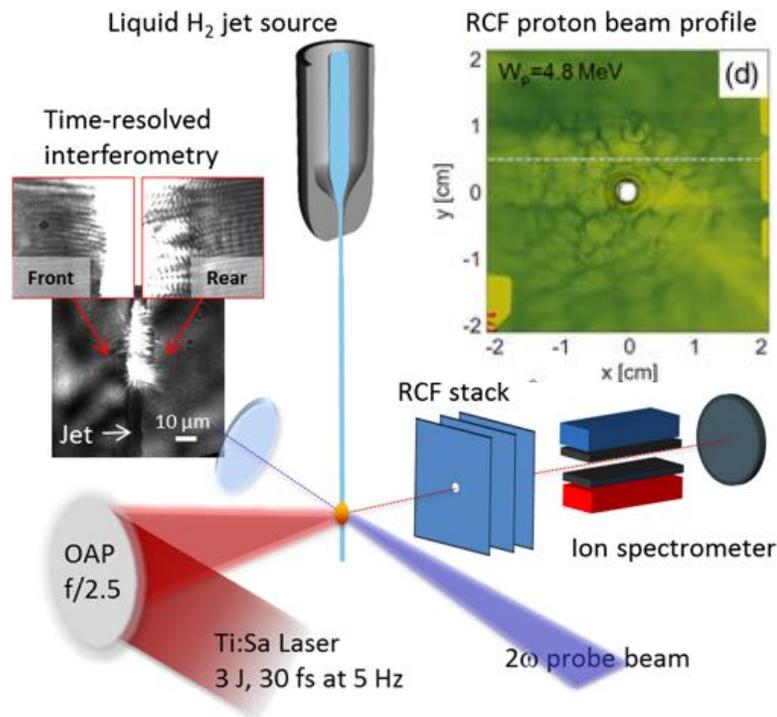
PRL 118, 194801 (2017)

PHYSICAL REVIEW LETTERS

week ending
12 MAY 2017

Relativistic Electron Streaming Instabilities Modulate Proton Beams Accelerated in Laser-Plasma Interactions

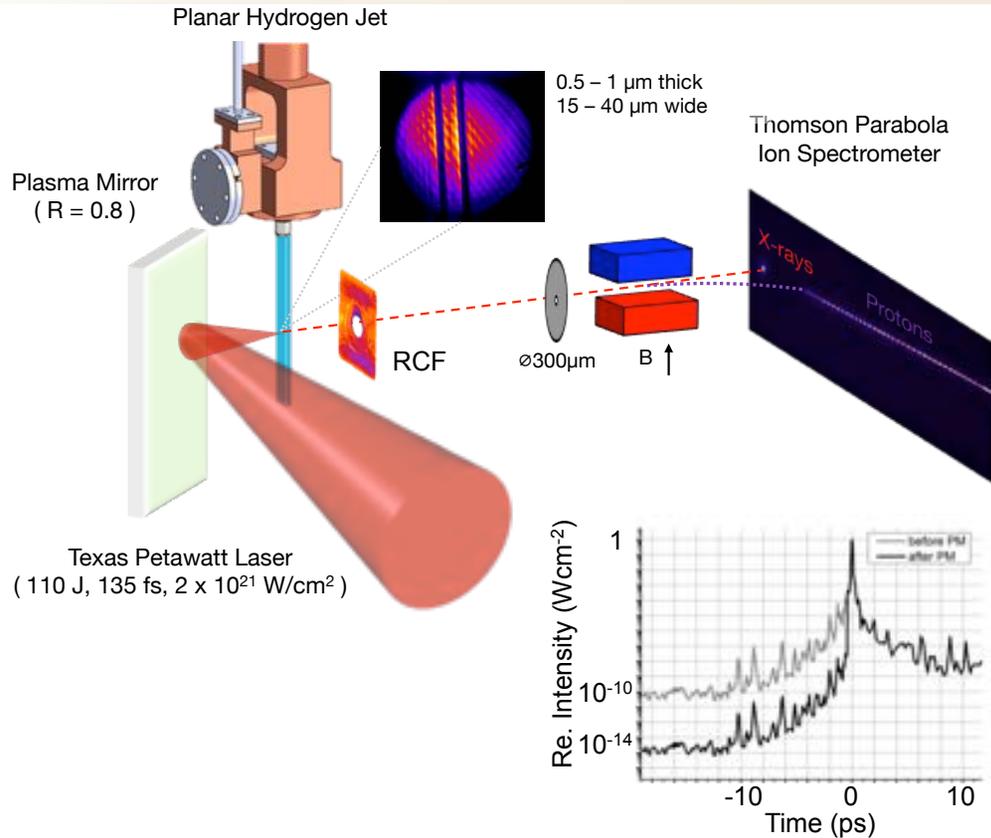
S. Göde,^{1,2} C. Rödel,^{1,3} K. Zeil,⁴ R. Mishra,¹ M. Gauthier,¹ F.-E. Brack,^{4,6} T. Kluge,⁴ M. J. MacDonald,^{1,5}



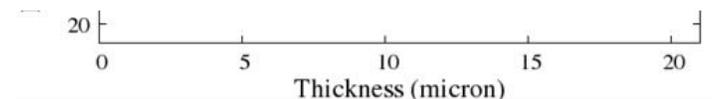
© F. Fiuza | 2017

Modulated laser-accelerated proton beams probe the Weibel instability, not RT

Experiments with cryogenic hydrogen have observed record 80 MeV protons at Texas PetaWatt



- Optimization of target thickness
- Further improve contrast (2 plasma mirrors)
- Increase shot rate

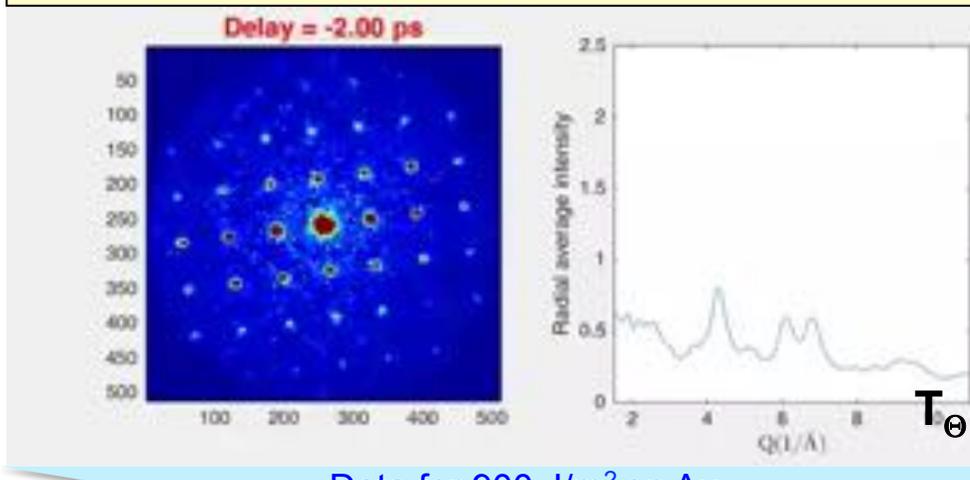


Setting the stage for fusion plasma diagnostics and novel accelerators

Applying our LCLS techniques to visualize the ultrafast transformation of matter to warm dense matter

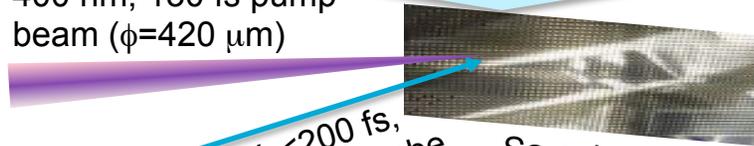
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Observation of Debye-Waller effect and formation of W



Data for 900 J/m² on Au

400 nm, 130 fs pump beam ($\phi=420 \mu\text{m}$)

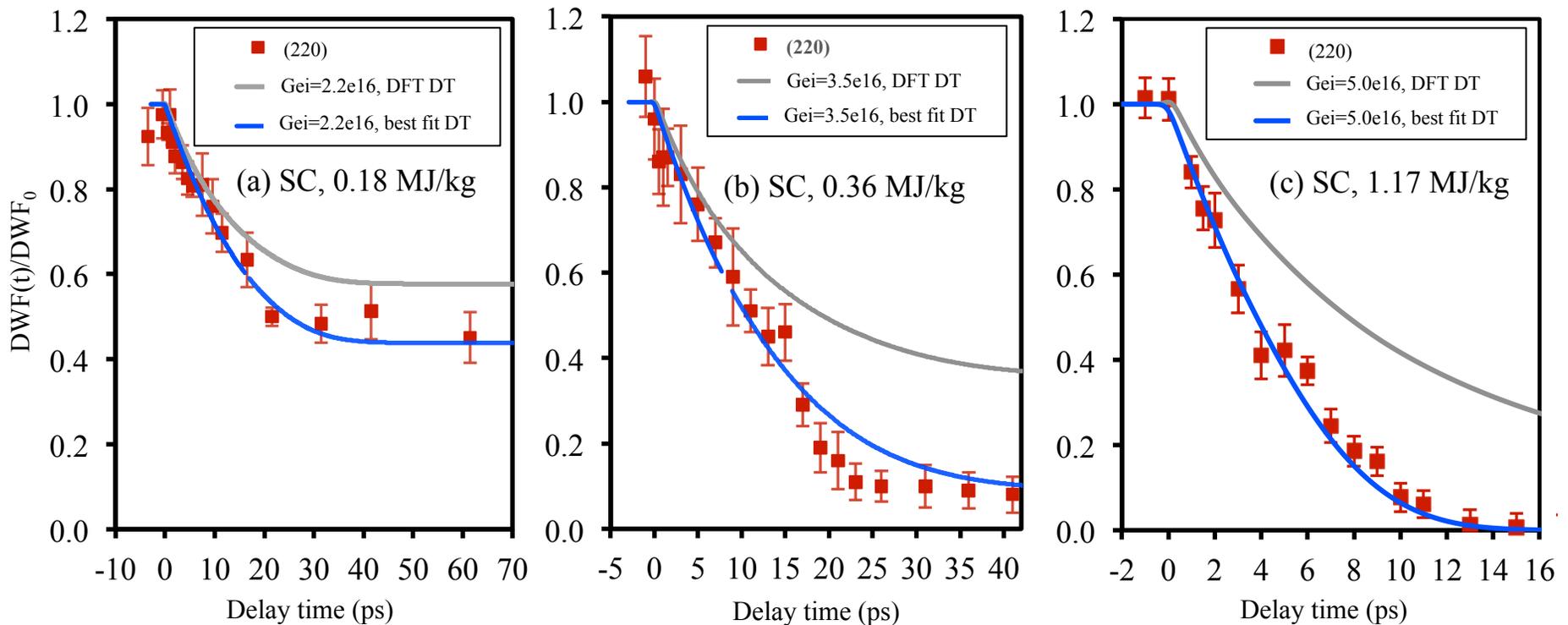


3.2 MeV, <200 fs, 20 fc electron probe

Sample card on motorized stage

Precision experiments provide melting data on atomic scales to test modeling

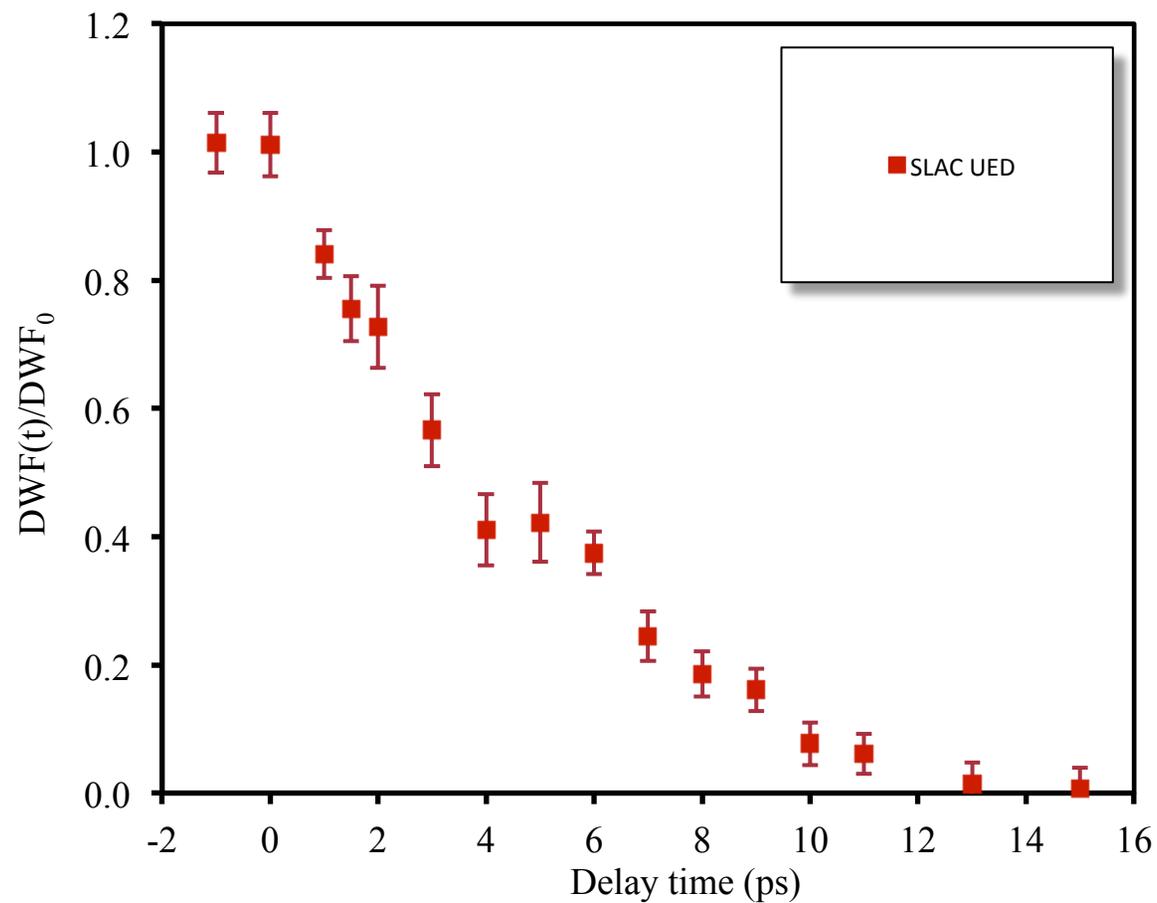
Phonon softening prevails over phonon hardening in the observed three melting regimes in warm dense gold



Our data for various energy densities can be fit with one simple constrain

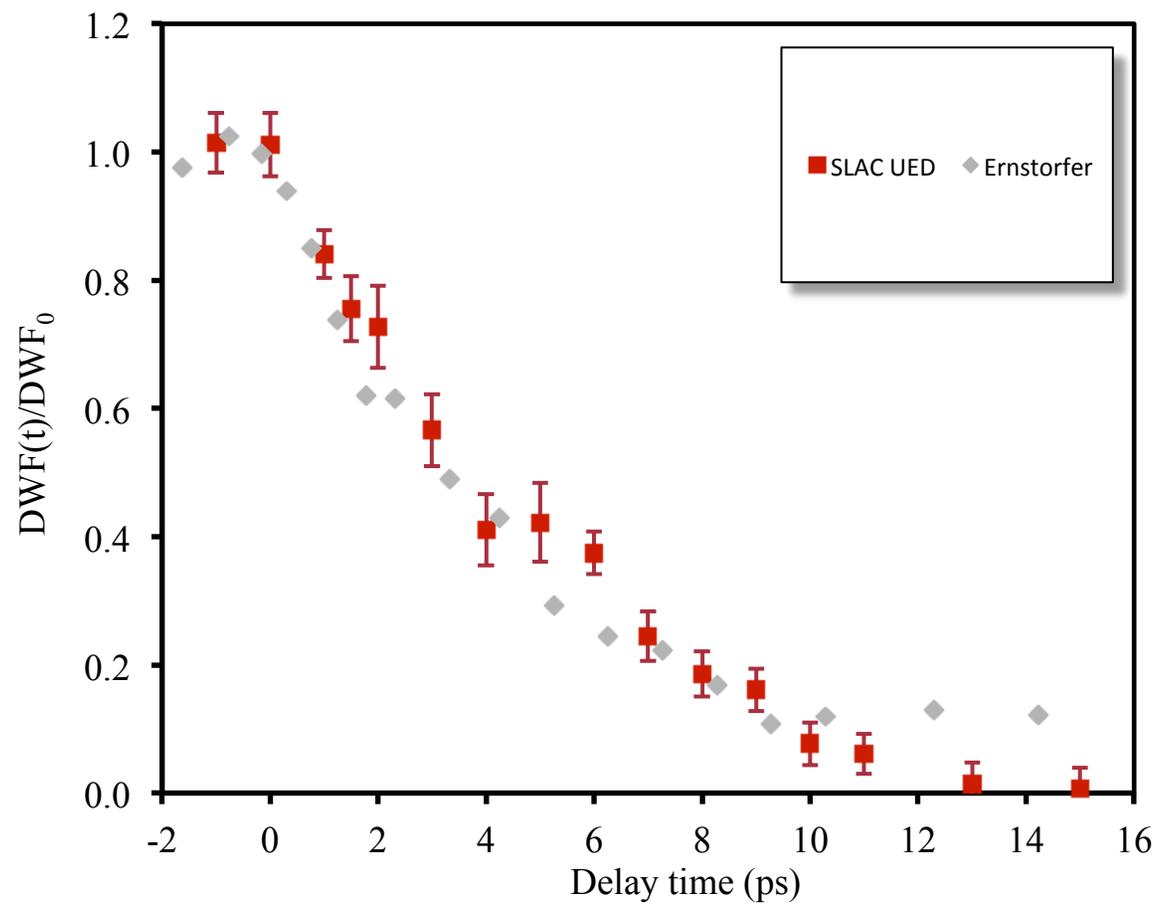
Comparison with Ernstorfer's published data

Debye-Waller decay of (220), 1.2 MJ/kg



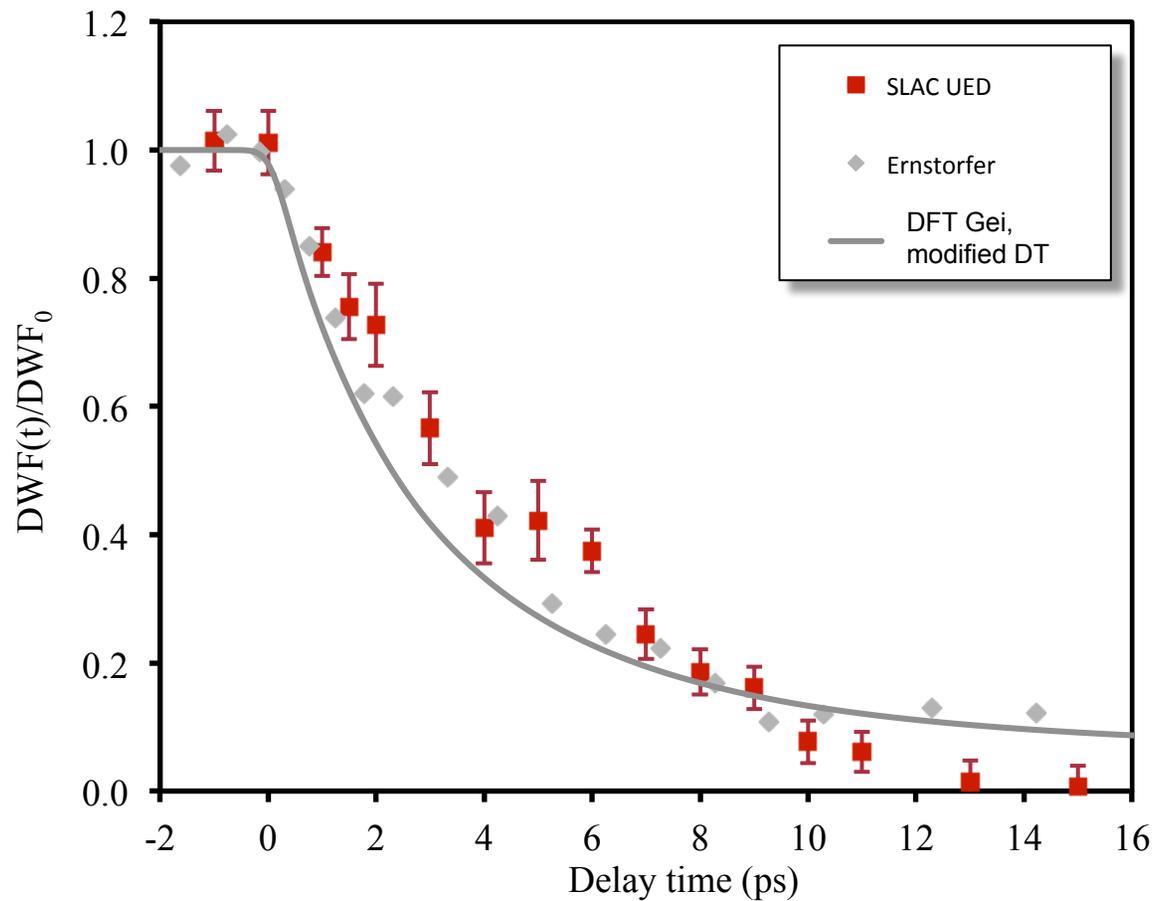
Comparison with Ernstorfer's published data

Debye-Waller decay of (220), 1.2 MJ/kg



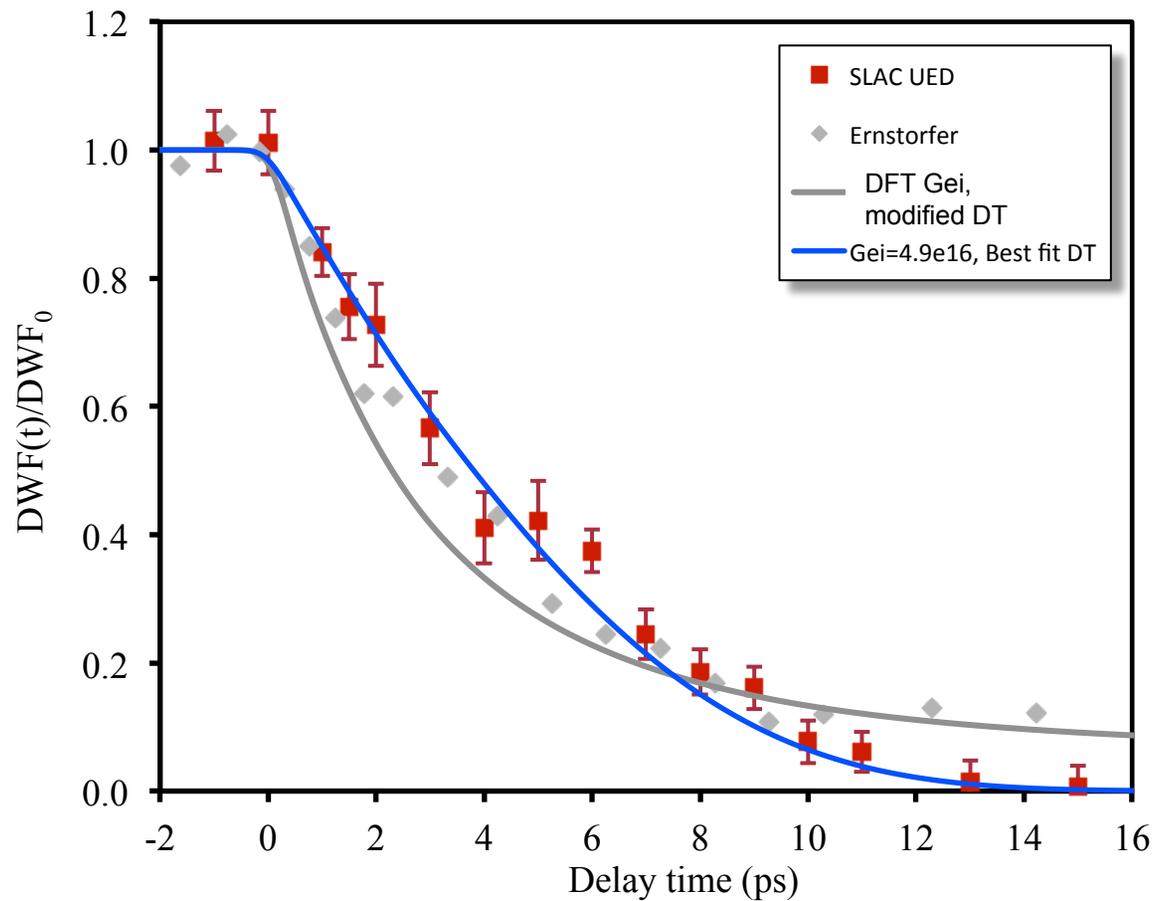
Comparison with Ernstorfer's published data

Debye-Waller decay of (220), 1.2 MJ/kg



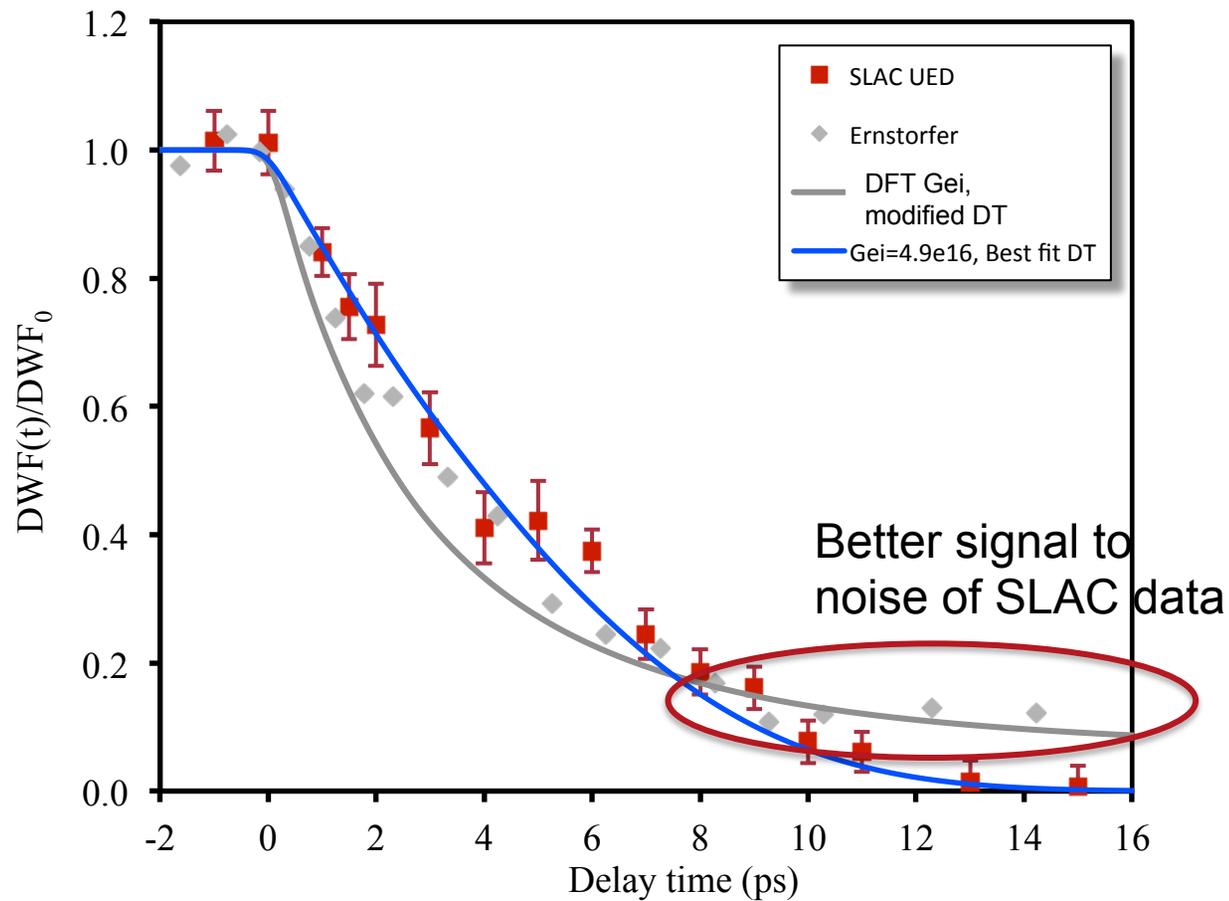
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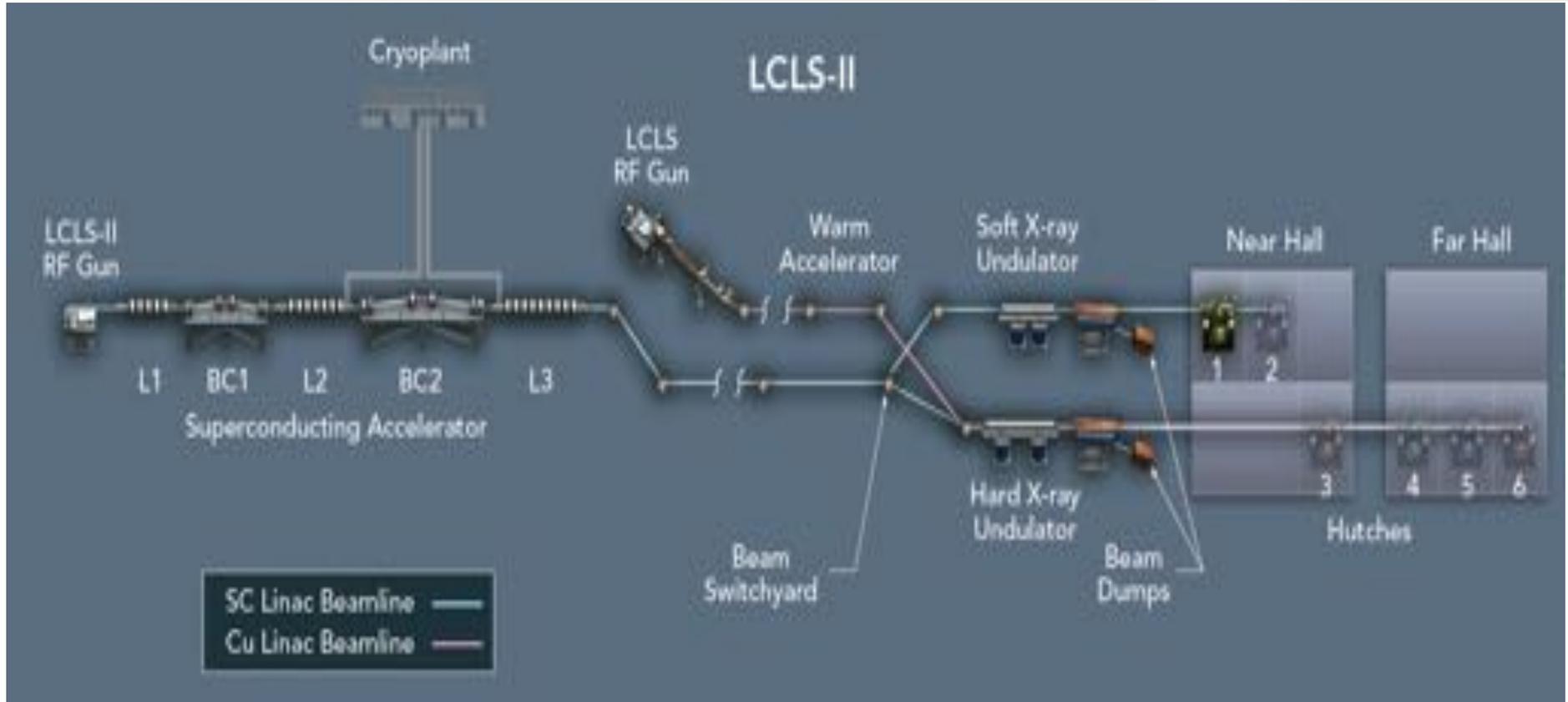


Comparison with Ernstorfer's published data

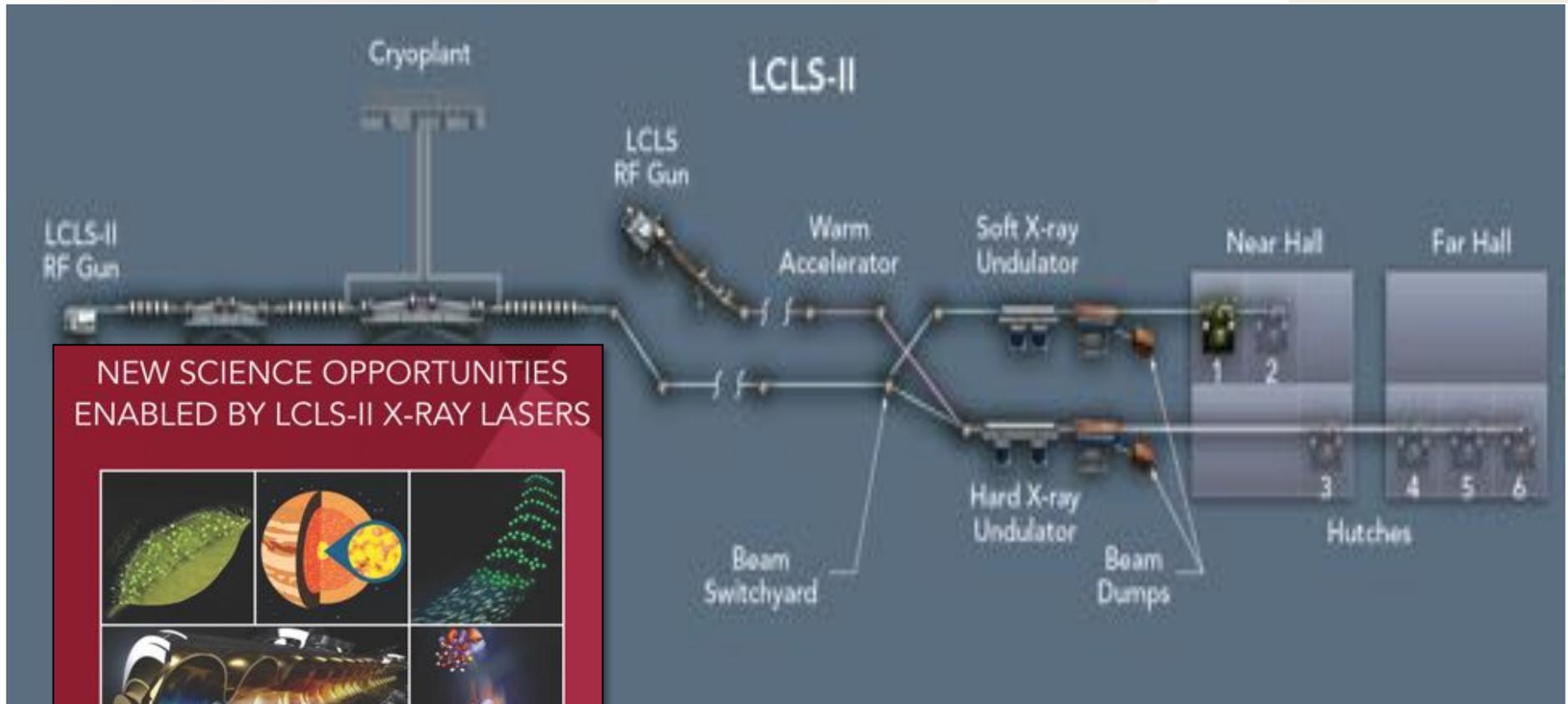
Debye-Waller decay of (220), 1.2 MJ/kg



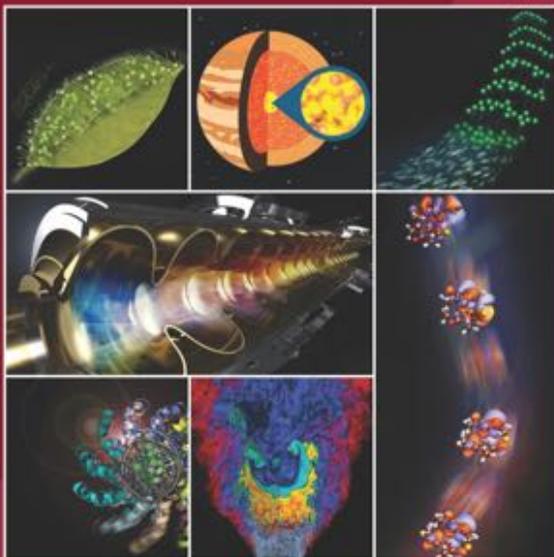
LCLS-II will greatly enhance x-ray capabilities for HED research



LCLS-II will greatly enhance x-ray capabilities for HED research

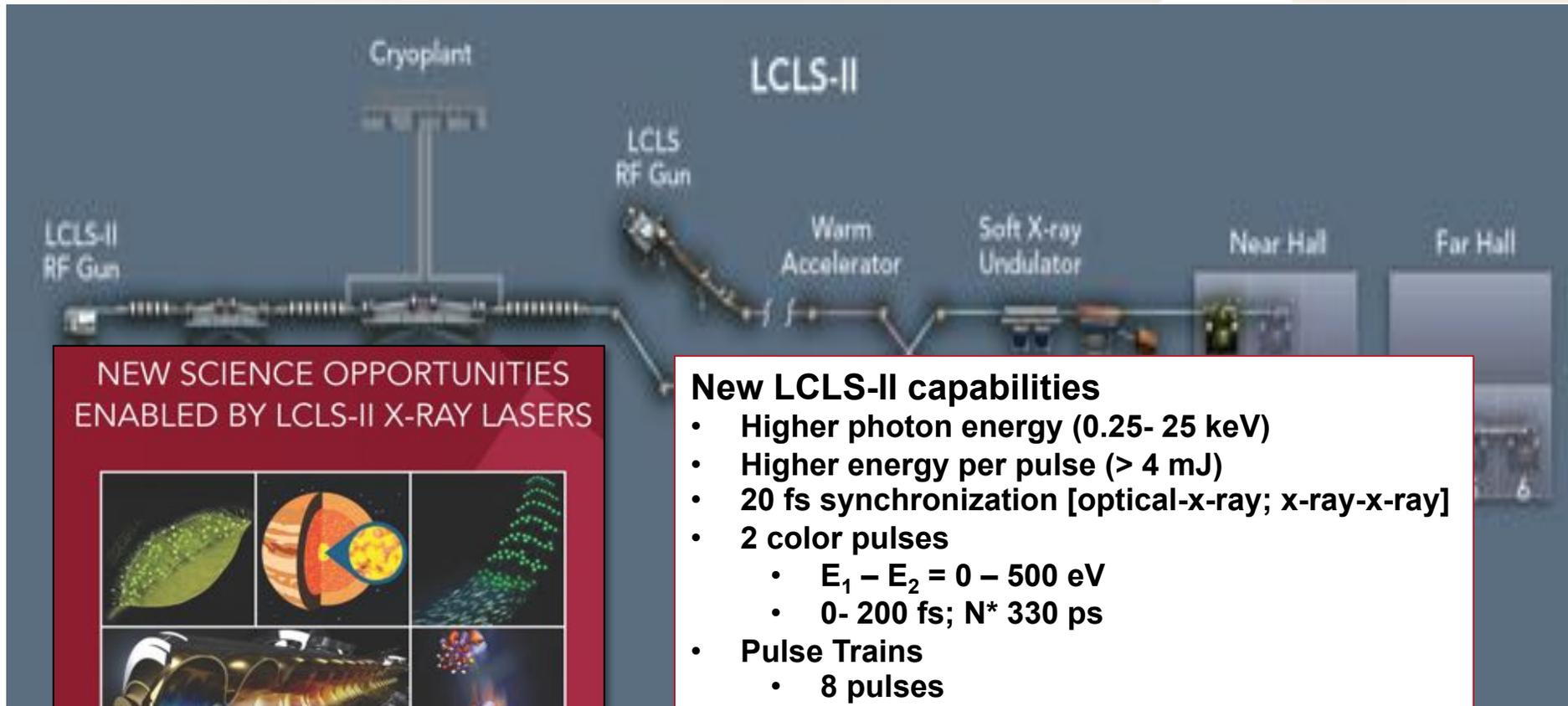


NEW SCIENCE OPPORTUNITIES ENABLED BY LCLS-II X-RAY LASERS

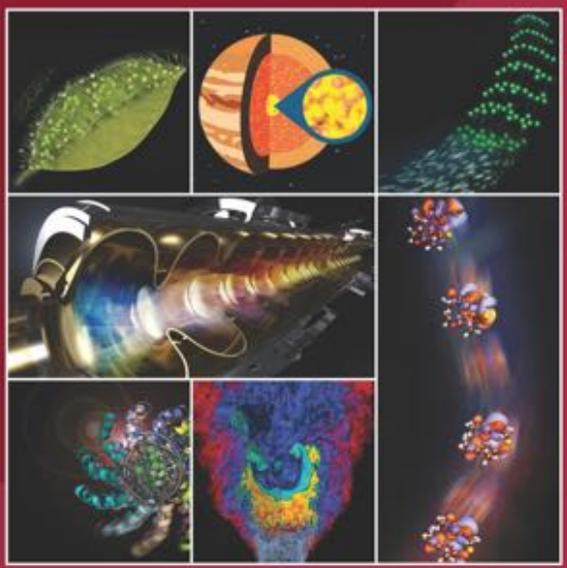


June 1, 2015

LCLS-II will greatly enhance x-ray capabilities for HED research



NEW SCIENCE OPPORTUNITIES ENABLED BY LCLS-II X-RAY LASERS



June 1, 2015

New LCLS-II capabilities

- Higher photon energy (0.25- 25 keV)
- Higher energy per pulse (> 4 mJ)
- 20 fs synchronization [optical-x-ray; x-ray-x-ray]
- 2 color pulses
 - $E_1 - E_2 = 0 - 500$ eV
 - 0- 200 fs; N* 330 ps
- Pulse Trains
 - 8 pulses
 - $\Delta X < 20$ μ m
- Variable bandwidth
 - $10^{-4} - 2\%$
- Attosecond Pulses
 - 0.5fs

SLAC HED is bringing the HED community to MEC and LCLS

SLAC

5TH HIGH-POWER LASER WORKSHOP

September 27-28, 2017
SLAC National Accelerator Laboratory
Menlo Park, CA

The 5th HPL workshop will be held co-jointly with the general LCLS user meeting bringing together the international high-energy density physics community with the LCLS user groups. The workshop will have a dedicated day to discuss recent experimental results from matter in extreme conditions enabled by the combination of high-power laser drivers with the world-class LCLS X-ray beam. During the second day of the workshop, the workshop participants will take part in the general meeting and further have a session related to the MEC instrument. The goal is to discuss the scientific opportunities at the MEC instrument, propose future standard configurations, and provide time to discuss important physics proposals and experimental needs for cutting-edge research at MEC.

The workshop will provide opportunities for presentations by students and postdocs in discussion and poster sessions. Sponsor exhibits will be on display throughout the duration of the workshop.

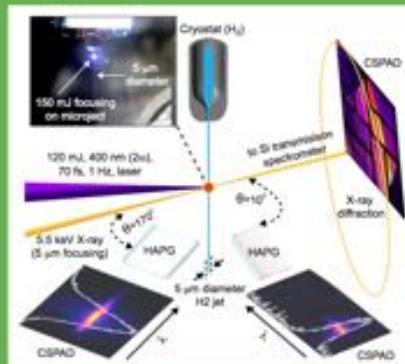
Organizers:

Cindy Bolme, Los Alamos National Laboratory
Siegfried Glenzer, SLAC National Accelerator Laboratory
Eric Galtier, SLAC National Accelerator Laboratory

Important Dates:

Registration deadline: September 15, 2017
Poster abstracts due by: September 15, 2017
PDF of final poster due by: September 8, 2017

Deadline for applications for student/postdoc support: August 15, 2017



conf-slac.stanford.edu/hpl-2017



Thank you!

