SAND2017-6877PE

An overview of warm dense matter experiments

Workshop on current challenges in the physics of white dwarf stars

Presented by John Benage

Sandia National Laboratories*

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Outline of my talk

- Introduction to WDM experiments
- Discussion of experimental approaches
  - Description of each technique
  - Physics issues studied
  - General results
  - Material conditions
- Impact of these experiments
  - General limitations of all these experiments
  - Testing of theoretical models
  - Classical and quantum MD and MC
- What could be next
  - FEL's and light sources
  - Transport properties

Warm dense matter covers a broad range of phase space

- **What is warm dense matter**
  - Initially referred to region where simplifying assumptions in plasma models are not valid
  - Electron temperature and Fermi Energy are similar
  - Ions in plasma strongly coupled, $\Gamma = Z^2e^2/a_ikT > 1$
- **More commonly**
  - Refers to dense material at finite temperature
  - Interactions and excitations may not be simple
  - Density and temperature effects similar
- **Thus it really covers much of strongly coupled plasmas and liquids**

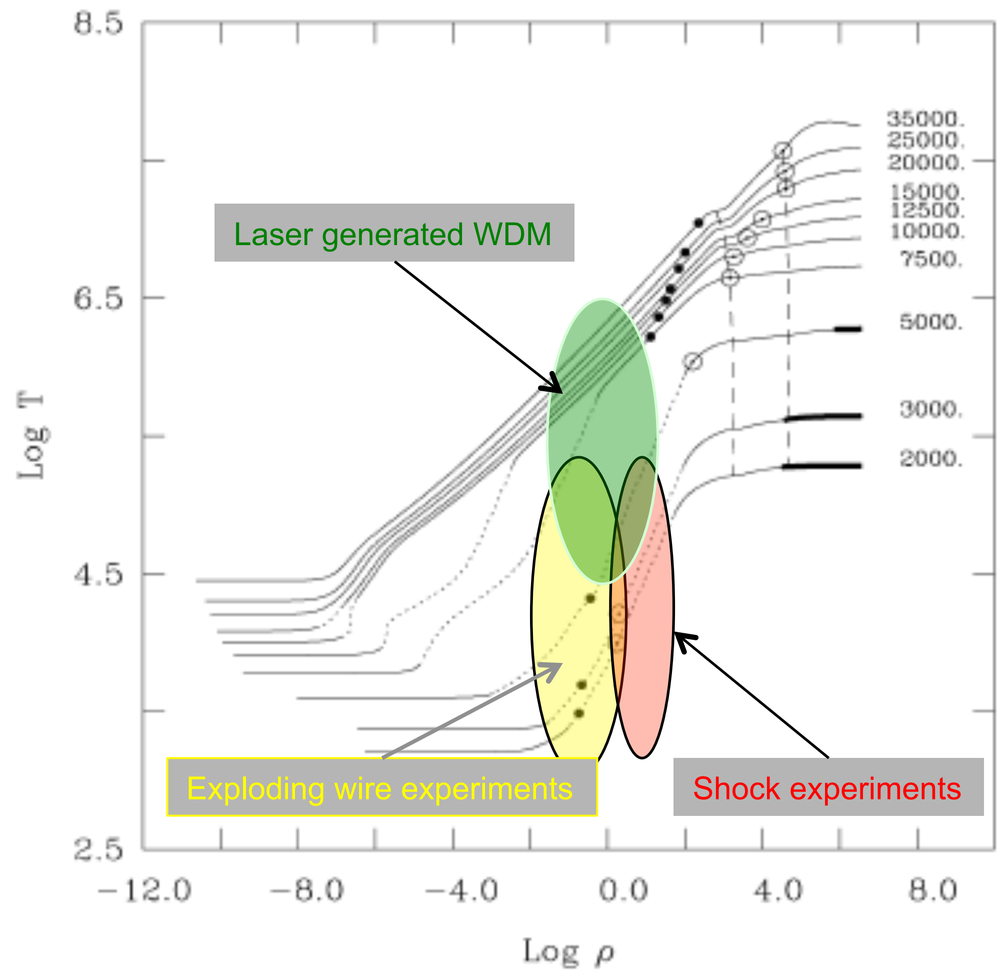
Warm Dense matter experiments can only cover a narrow range of conditions in the WD

At right are various temperature/ density profiles for various WD stars

- Effective temperature shown on rate
- Open circles represent strongly coupled ion transition
- Closed circle represent degenerate electron boundary
- Dashed lines represent composition transition zones
- Dark solid lines show crystallized region

Circled regions identify where warm dense matter type experiments generally are carried out.

For denser regions on the right, must apply models tested from scaled experiments.



Fontaine, et.al. Publications of the Astronomical Soc. of the Pacific, **113**, 409 (2001). Temperature vs Density profiles for various eff. Temperature WD's.

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Experiments studying warm dense matter generally had several issues to address

- Creating warm dense matter conditions
  - Dense, finite temperature systems implies high pressure
  - Requires high power energy sources
- Secondly, to create uniform samples
  - Dynamic generation techniques often lead to gradients
  - Very fast generation techniques often lead to non-equilibrium conditions
  - Solution is often some form of inertial tamping, which complicates…...
- Characterizing the material conditions
  - Tamping materials block access
  - Diagnostics techniques are limited
  - Surface vs bulk
  - Temperature especially difficult

Ion Traps, Dusty Plasmas, Ultra-cold plasmas

- These techniques are focused on low-density, cold plasmas
  - Studies focused on crystallization, structure, wave properties
  - These are often well-modeled by OCP or Yukawa models
  - The main diagnostic is time-resolved imaging of individual particles or light scattering
- Material conditions
  - Not really warm dense matter, since electron density very low
  - Temperatures typically are < 1 eV, sometimes much less
  - Charge states can be very high
- Experiments still going on today

Very strongly coupled ion systems were studied using ion traps

- Ion traps developed by Dave Wineland's group at NIST were capable of creating very low temperature ions
  - Penning traps could contain ion species and laser cool to very low temperatures
  - They could also store a significant number of ions, > 10^5
- These systems enabled them to create a model OCP system where the uniform background was provided by the trap fields
  - Experiments focused on crystallization and demonstrated Wigner crystallization to BCC lattice through scattering measurements

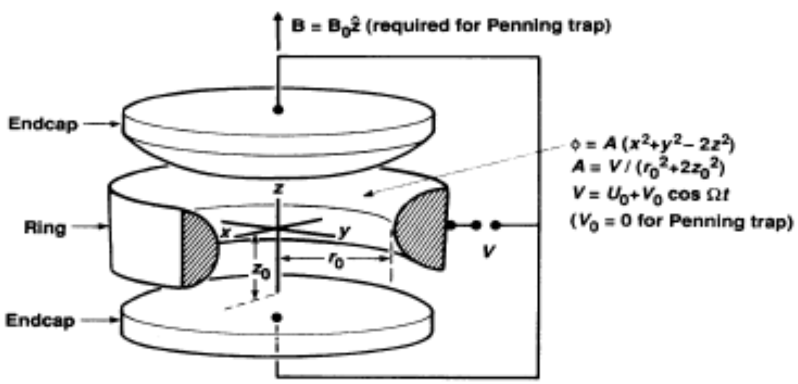
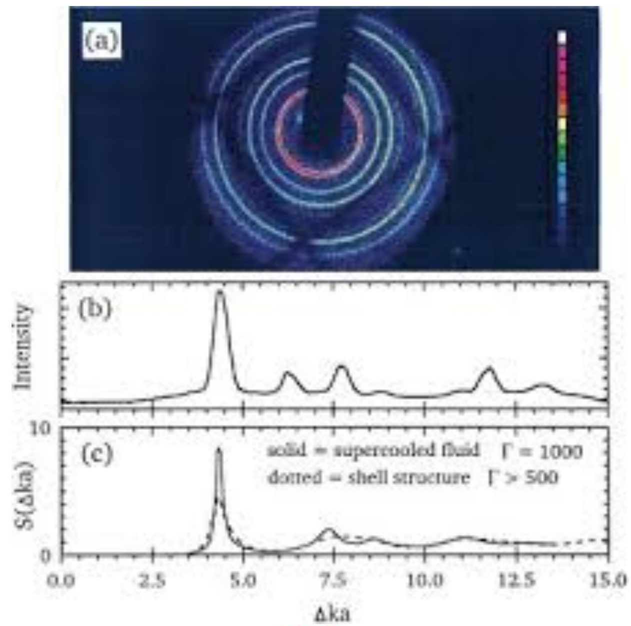


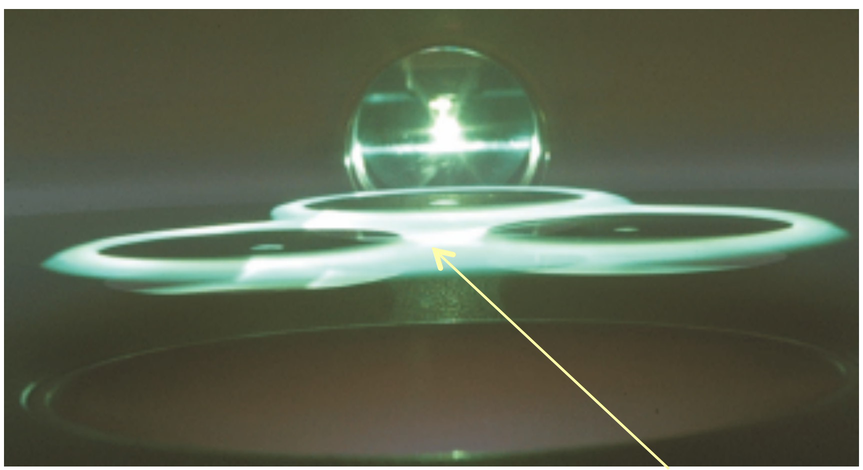
Fig. 1. Electrodes for a Penning or rf ion trap. The electric potential field ϕ is created by applying the voltage V between the endcap electrodes and the ring electrode. The uniform magnetic field **B** is required only for a Penning trap. [Adapted from (*42*) with permission from Plenum Press]



*Tan, Bollinger, Jelenkavic, and Wineland, PRL 75, 4198 (1995)

Another method for creating SCP's involved dust

- **Dusty plasmas in the lab discovered somewhat by accident**
  - **Images were taken of process of making silicon chips**
  - **Discovered dust particles scattering light above the chip**
- **This led to the development of studying dusty plasmas in the lab**
  - **Dust particles in plasma discharge would charge up to high level**
  - **Created systems of strongly correlated dust particles due to very large charge**
  - **Screening provided by ions and electrons**



Rings of dust particles floating above silicon wafer

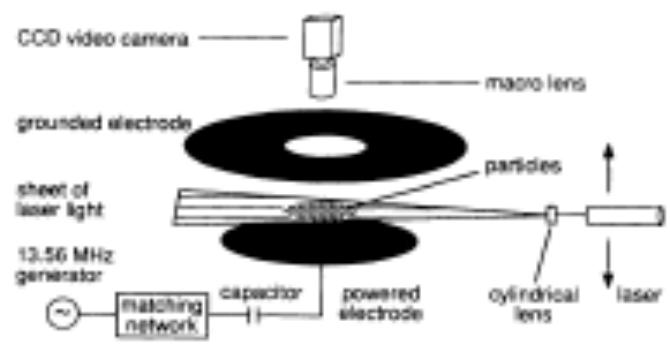


FIG. 1. Schematic of apparatus. A discharge is formed by capacitively coupled rf power applied to the lower electrode. A vacuum vessel, not shown, encloses the electrode assembly. A cylindrical lens produces a laser sheet in a horizontal plane, with an adjustable height. The dust cloud is viewed through the upper ring electrode.

* Selwyn, Singh, and Bennett, J. Vac. Sci. Tech. A7, 2758 (1989)

Dusty plasmas became a field unto itself

- **These dusty plasmas behaved very much as Yukawa systems**
  - **In many cases could be directly compared to MD simulations**
- **Many interesting and previously difficult to study properties could be investigated**
  - **Viscosity, melting, 2D vs 3D systems, …**
  - **These systems have also been studied a great deal on the space station, where gravity doesn't affect the behavior**

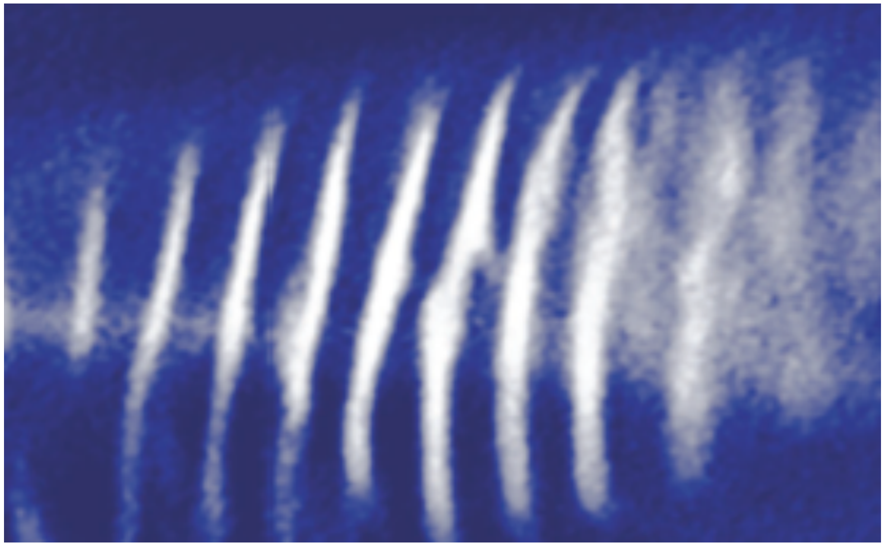
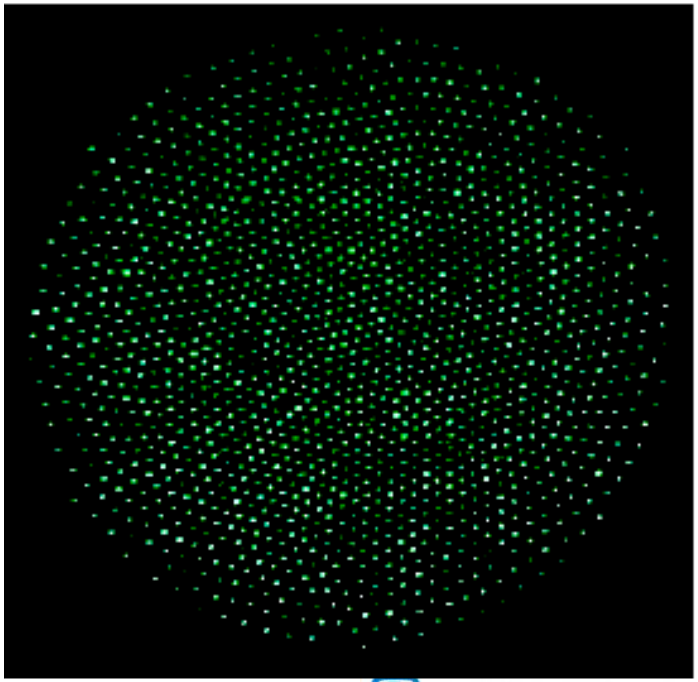


Image of dust acoustic wave

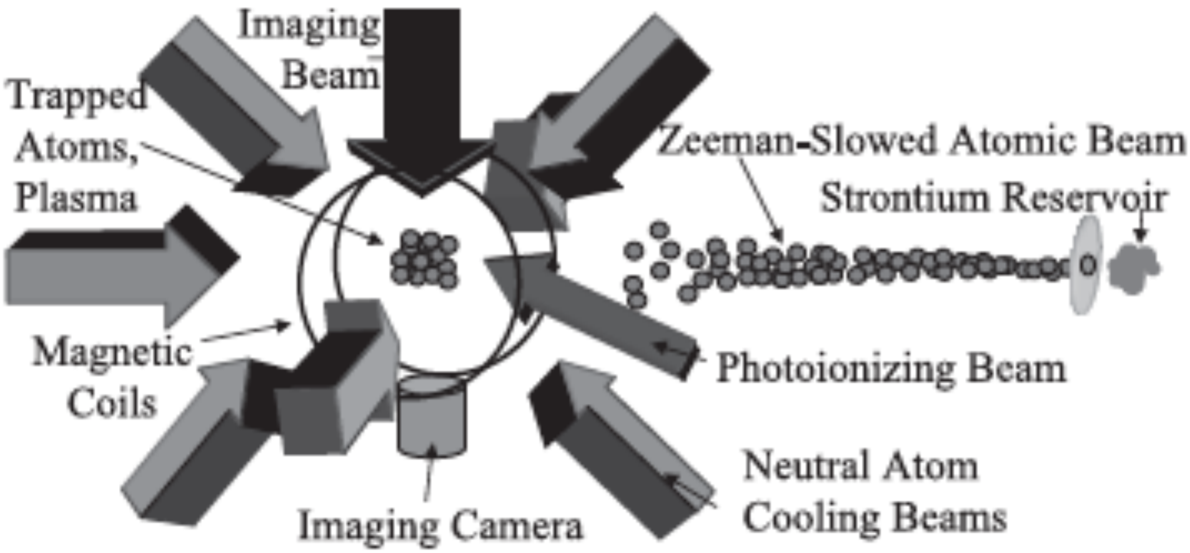
Image of crystallized dusty plasma



* For example, Barkan, etal., Phys. Of Plasmas, 2, 3563 (1995) and Thomas, Morfill, Demmel, and Goree, PRL, 73, 652 (1994).

The creation of BEC's in the lab led to another innovation- Ultra cold plasmas

- These ultra cold systems were produced for the first time in 1995 and led to the Nobel Prize in 2001
  - Began to be studied in several laboratories throughout the world
- Soon (1999) researchers began investigation what happens when these BEC's were ionized quickly through photoexcitation
  - Created a new system, ultra cold plasmas with interesting and surprising characteristics



* Ensher, Jin, Matthews, Wieman, and Cornell, PRL 77, 4984 (1995)

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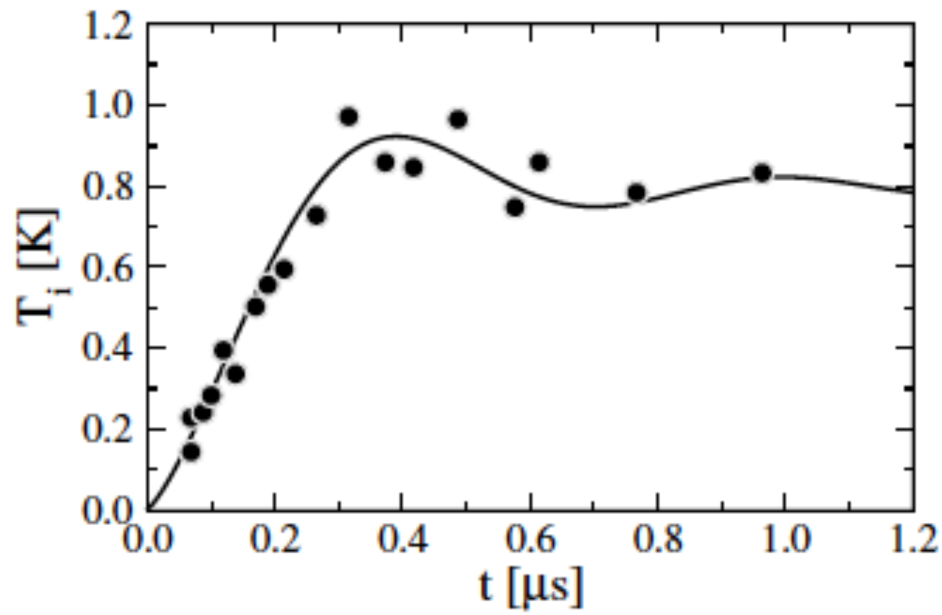
One example of this interesting behavior is disorder induced heating

- **Suggested through MD simulations by Murillo**
  - **Creation of ionized plasma from gaseous system produces a change in the potential energy landscape**
  - **Produces forces on the ions, which respond and heat up**
  - **Oscillations occur in the temperature as plasma equilibrates**
- **Verified through experimental observation by Pohl, Pattard, and Rost**
  - **Saw rapid heating and evidence of oscillitory behavior**
- **Analogous to non-thermal melting in solids**



* Murillo, PRL 96, 165001 (2006).
* Pohl, Pattard, Rost, PRL 94, 205003 (2005).

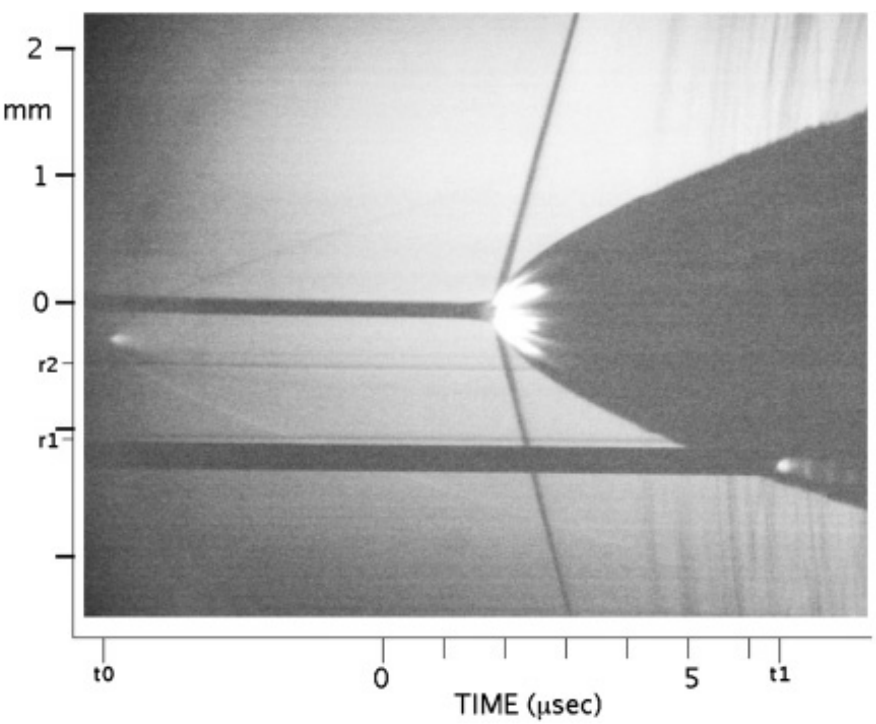
Ohmically heated inertially tamped wires

- Ohmically heated wires (exploding wires) was an early technique to measure properties of materials at WDM conditions
  - Generally focused on measuring electrical conductivity
  - A key issue for these experiments was maintaining uniform material conditions
  - Led to use of tampering material (water)
  - Generally measured current, voltage, radius
- Material conditions
  - Generally these are materials at or below solid density
  - Temperatures range from ~ 1 eV to 25 eV, though temperature not measured, determined from EOS tables
  - Covered range from liquid metal to low degeneracy, including neutral atoms
- Experiments still going on today

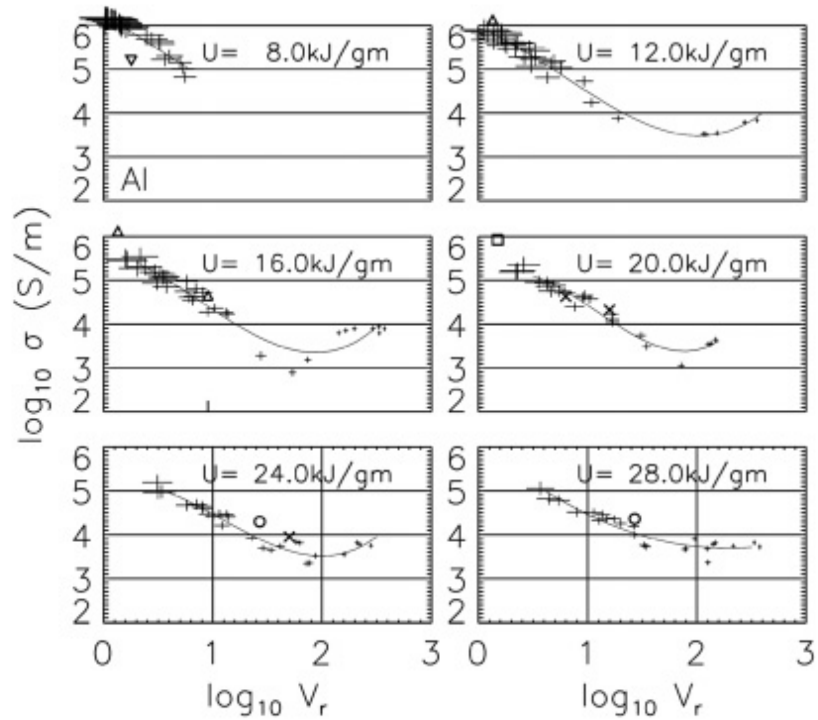
Electrical conductivity measurements of tamped exploding wires

Many experiments were done by several groups, the most complete set by Alan DeSilva and colleagues.

Streaked shadowgraph of electrically heated wire tamped in water.



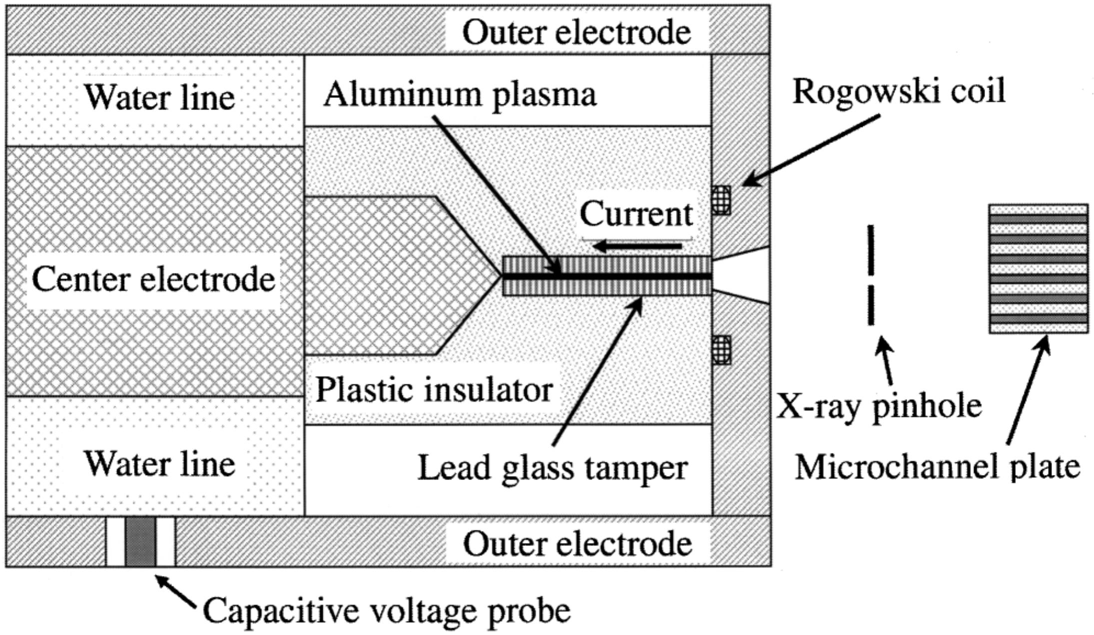
Conductivity for expanded aluminum

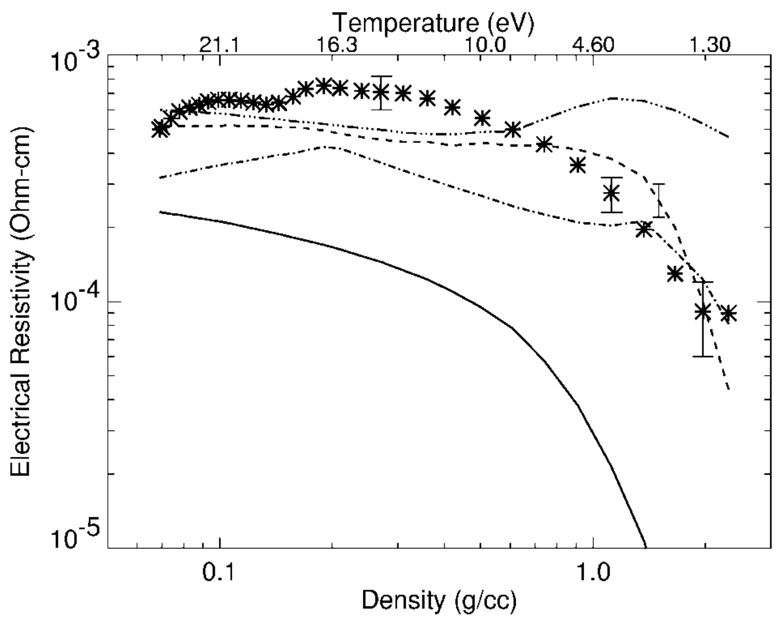


* DeSilva and Katsouras, PRE 57, 5945 (1998)

To reach higher temperatures, higher density tampers were required

Schematic diagram of electrically heated aluminum wire tamped by high density glass.





Model of Dharma-Wardana and Perrot matched experimental results best.

- At lower temperatures and densities, neutral collisions begin to matter

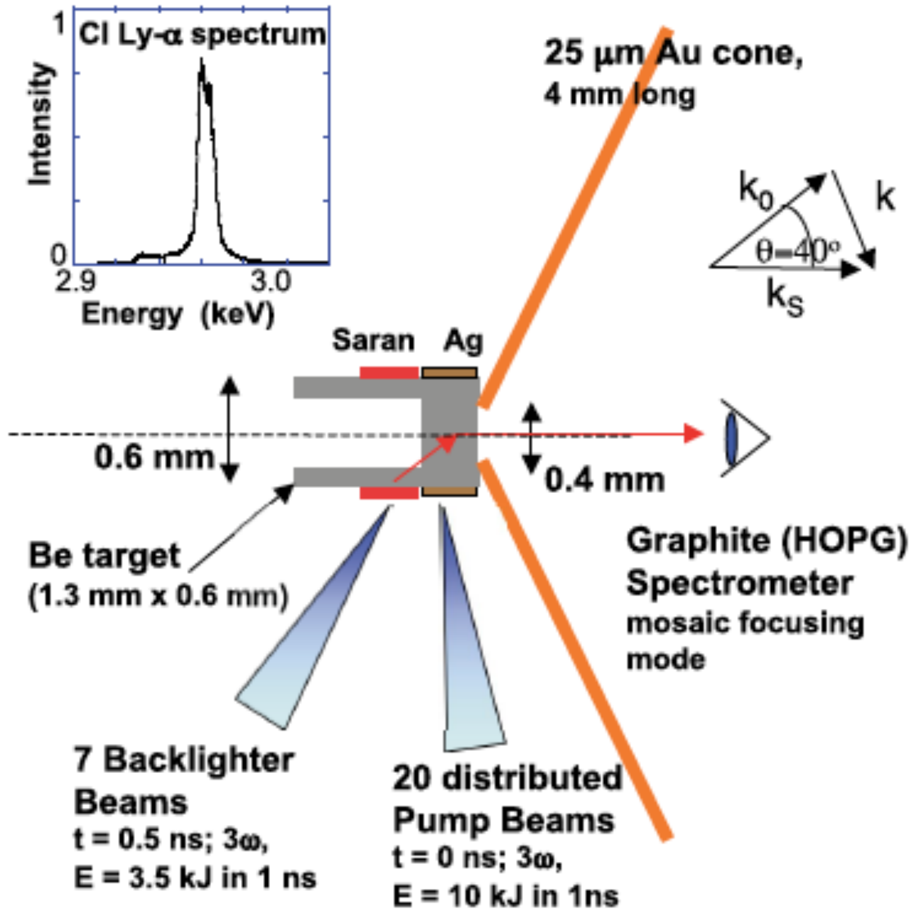
* Benage, Shanahan, and Murillo, PRL, 83, 2953 (1999).

Laser driven experiments

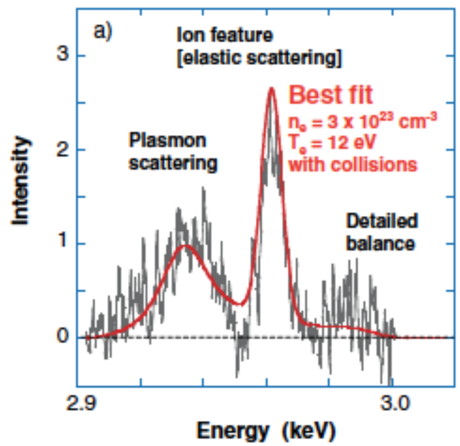
- Laser experiments can potentially investigate a broad region of warm dense matter
  - Often the experiments are focused on target characterization
  - Can produce WDM conditions in a variety of ways
  - Physics issues investigated include EOS, opacity and spectroscopic issues
- Material conditions
  - Generally create solid density to compressed materials
  - Temperatures range from ~ 1 eV to > 100 eV
  - Time-scales are very short, so non-equilibrium effects may be important
  - Can cover ranges of degeneracy
- Such experiments are becoming more important as our experimental tools improve

Large laser driven half-holraum target used to produce solid density plasma and diagnose with XRTS

- **Omega laser used to heat thin Ag cylinder holraum**
  - **Holraum filled with Be slug**
  - **X-rays from Ag walls heat Be target while tamping the expansion**
- **Other laser beams at Omega used to produce Cl x-rays for Thomson scattering measurements**
  - **Measured plasmon scattering for first time in such a system**
  - **Focus was on creation and diagnosis of the conditions.**



Plasmon feature sensitive to density and temperature



Recent experiment produced Be at solid density and temperatures of 12-15 eV.
Glenzer, et.al. PRL **98**, 065002, 2007

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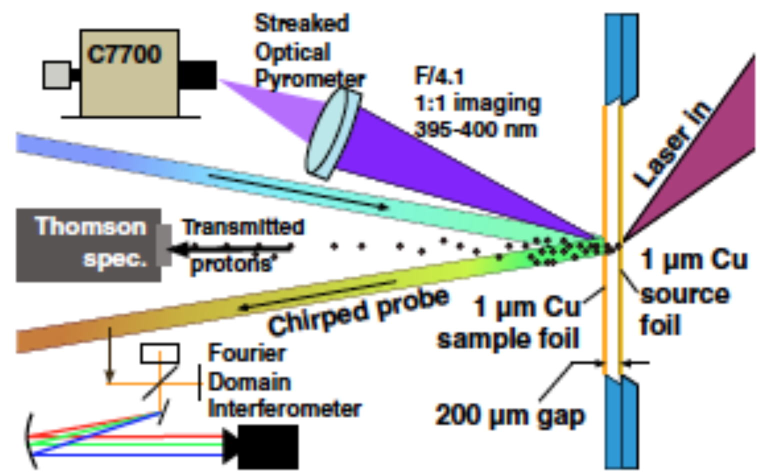
Equation of state experiment of ion-beam heated Cu

- **Ion beams generated by short pulse laser are used to heat Cu foil**
  - **Rapidly heats Cu to peak temperature near 10 eV**
  - **Foil starts at solid density and then expands to ~ half that**
- **Velocity and spectroscopy measurements are done.**
  - **Used to constrain EOS models**
  - **Dependent on electronic properties of expanded plasma**



Recent experiment produced Cu at solid density up to 10 eV.

Dyer, et.al. PRE **95**, 031201, 2017

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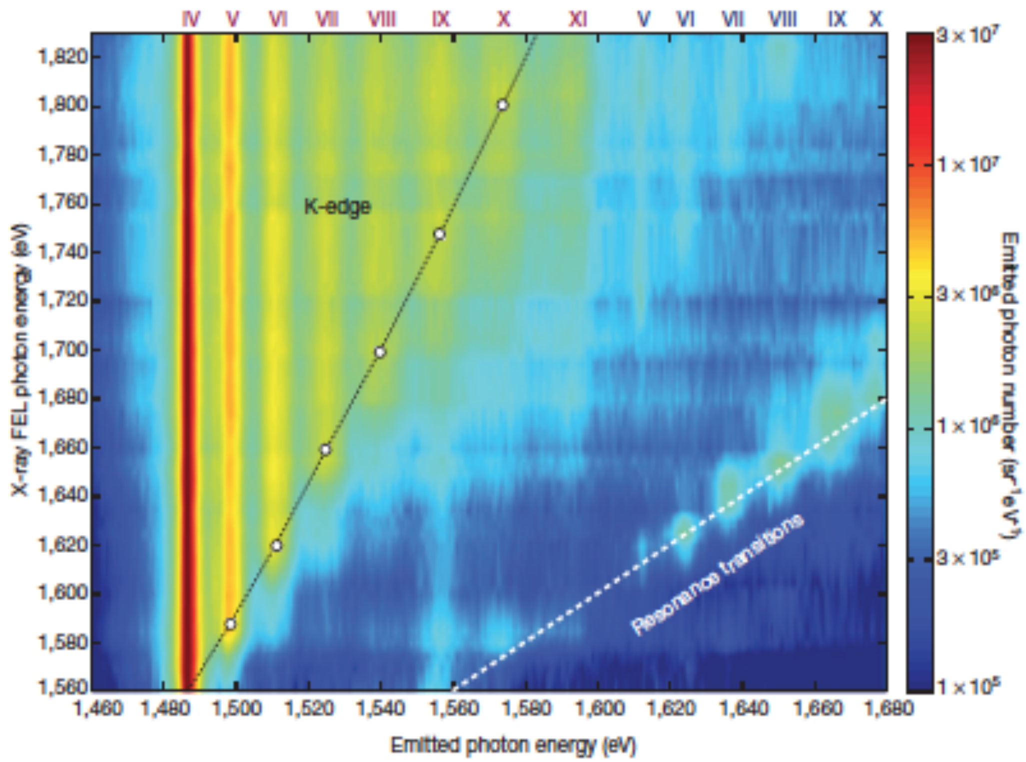
FEL x-ray laser experiment investigating continuum lowering

- **X-ray used both as a pump and a probe**
  - **X-ray energy tuned to K-shell energies at different ionization levels**
  - **X-ray spectra emitted by heated plasma then recorded**
- **The emission was dependent on pump x-ray energy and effective ionization energy of levels.**
  - **Used to constrain continuum lowering models**
  - **Relies on modeling of plasma properties and EOS for computing plasma conditions.**
  - **Determines Temperature to be ~ 100 eV at solid density**



Recent experiment produced Al at solid density and temperatures above 100 eV.
Vinko, et.al. Nature **482**, 10746, 2012

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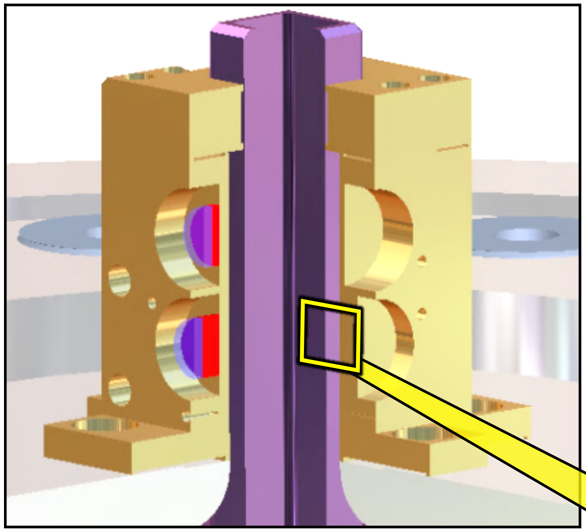
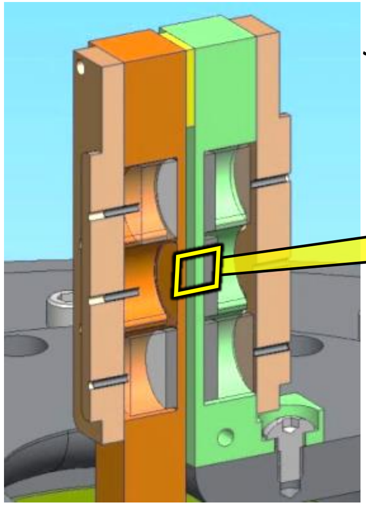
Shock driven experiments

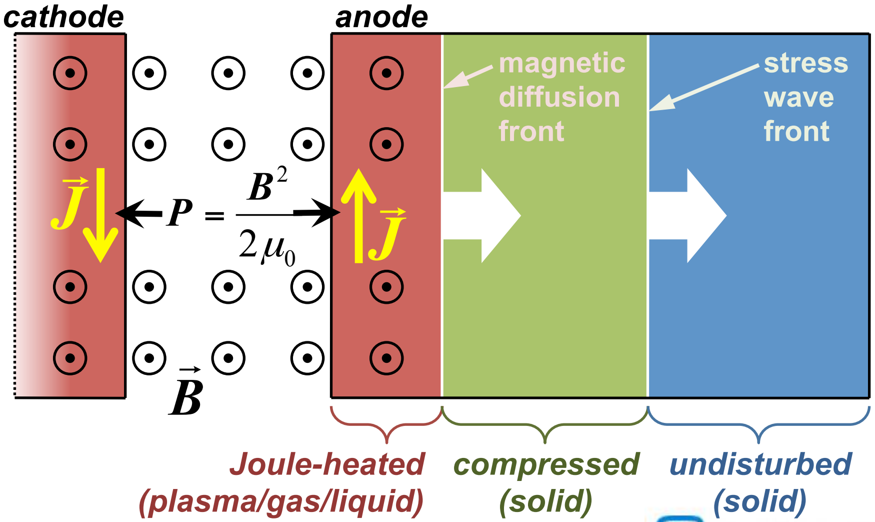
- **Pulsed power facilities and gas guns can also be used to investigate WDM**
  - **These experiments would typically focus on the EOS**
  - **To reach conditions at elevated temperatures requires very high velocities for the impactor**
  - **Generally, these experiments are very accurate and provide very strong constraints for models**
- **Material conditions**
  - **Typically create compressed densities, greater than solid**
  - **Temperatures range from < 1 eV to a few eV**
  - **Energy, density, and pressure are well-constrained, while temperature is usually not measured**
  - **Some modifications to the typical approach could be useful to reach more relevant WDM conditions**

DMP experiments use Z as a pulsed magnetic pressure driver (peak B-field = 100-1200 Tesla)



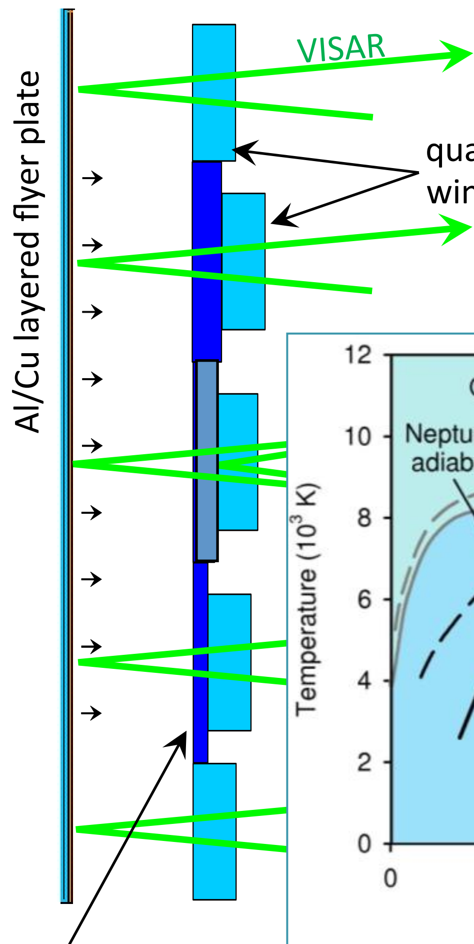
- current pulse of 7-26 MA delivered to load
- controllable pulse shape, rise time 100-1200 ns
- magnetic ($J \times B$) force induces ramped stress wave in electrode material
- stress wave propagates into ambient material, de-coupled from magnetic diffusion front



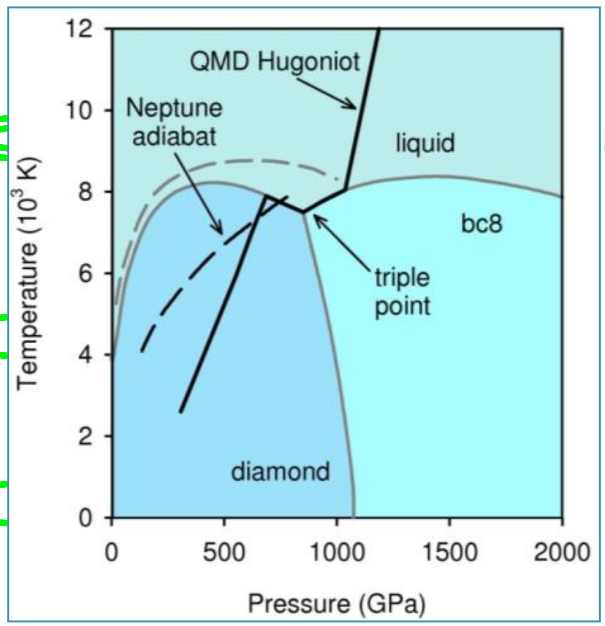


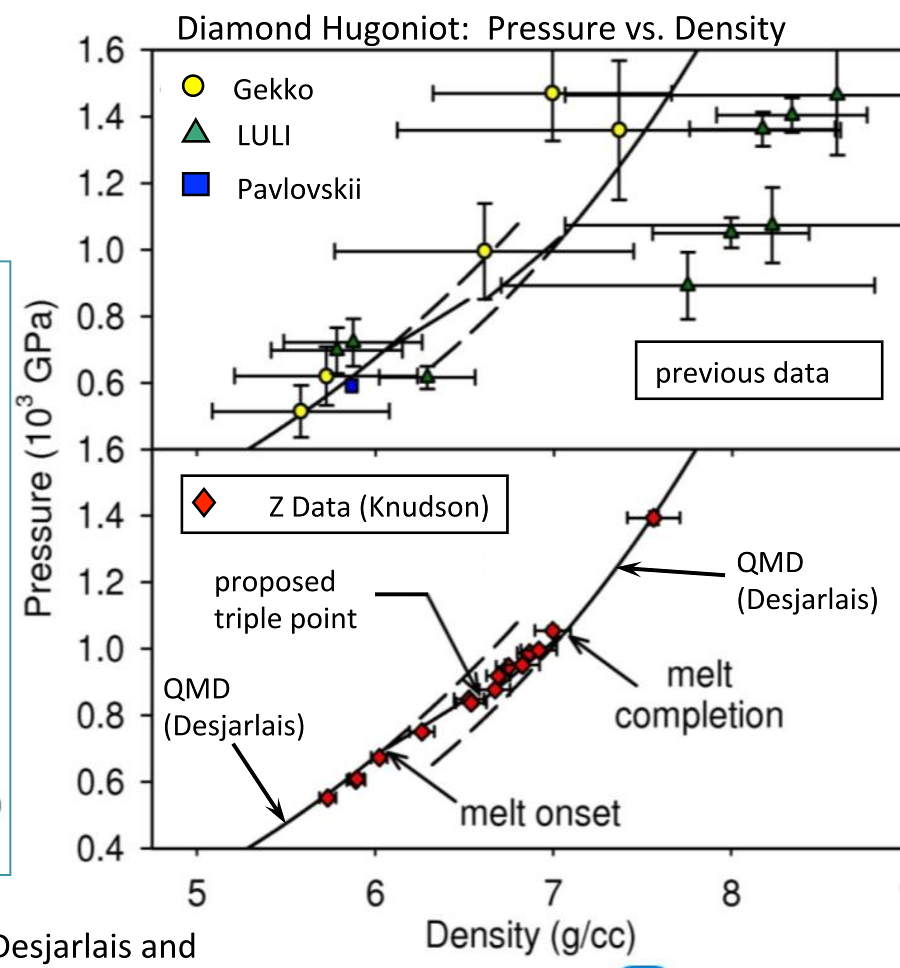
Z flyers provided first experimental evidence of diamond-liquid-BC8 triple point in carbon

Order-of-magnitude improvement in precision over laser-driven shock techniques (larger spatial/temporal scales)



diamond targets (500, 750, and 1000 μm thk, 6 mm dia)





M.D. Knudson, M. P. Desjarlais and D. H. Dolan, *Science* **322**, 1822 (2008)

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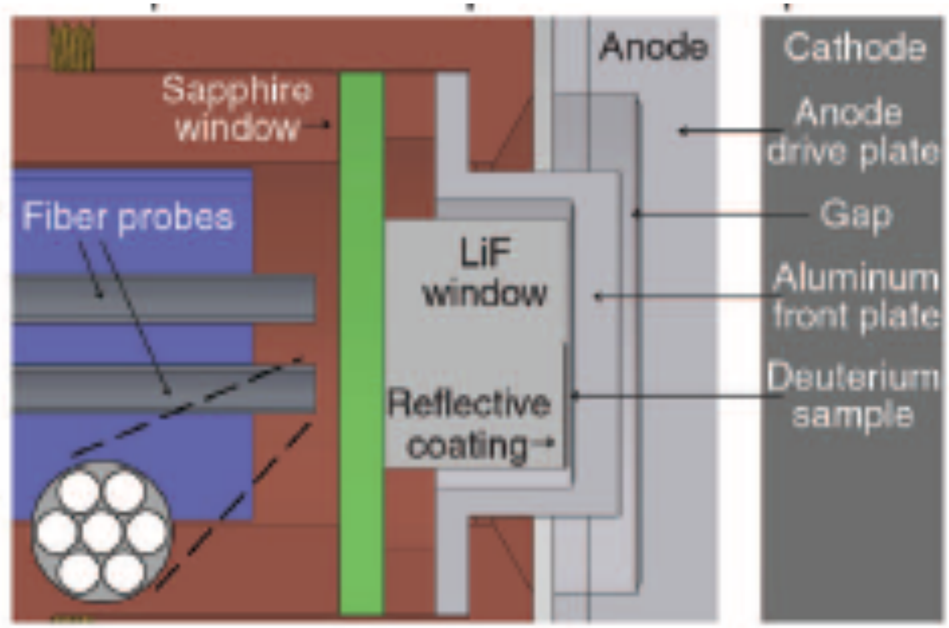
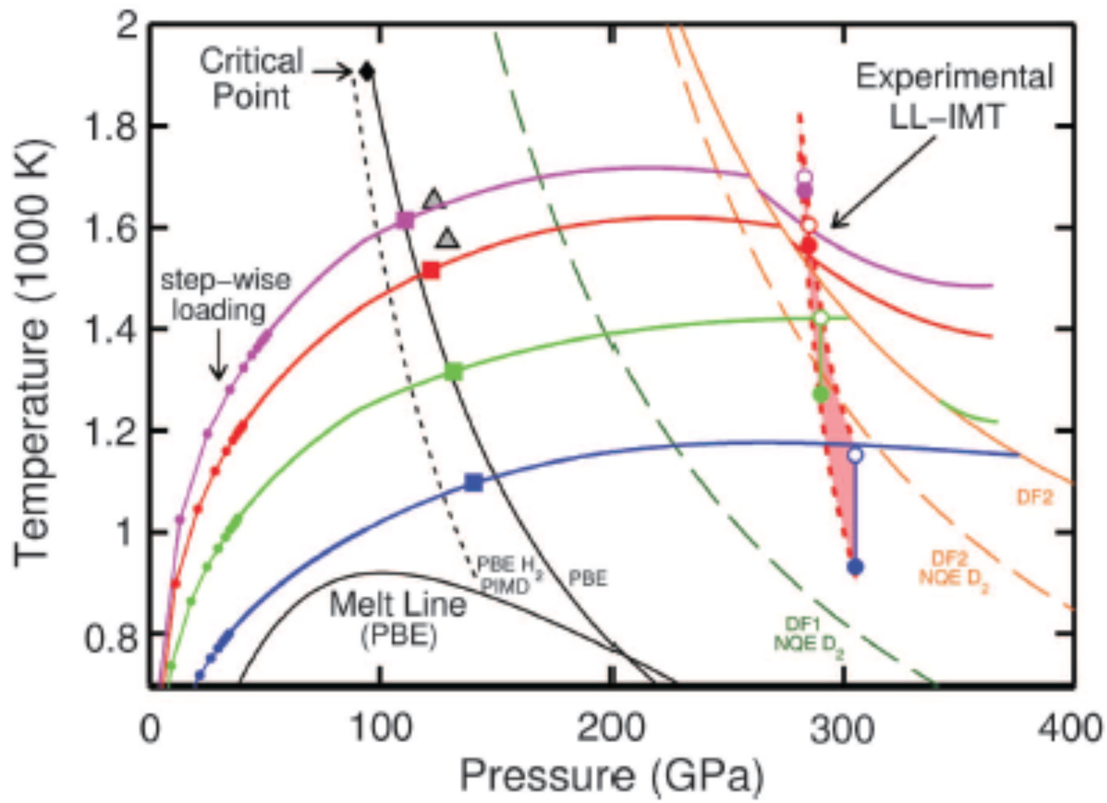
One example of the impact of this work over time is the recent measurement of the metallization of deuterium

- **These experiments were conducted on Sandia's Z machine using pulsed power driven technique**
  - **A shock ramp loading technique was used to pressurize liquid deuterium to densities near 2 g/cm^3.**
  - **Schematic of the experimental setup is shown at right**
- **Velocity profiles and broadband reflectivity is measured as the deuterium is heated and compressed**



One example of the impact of this work over time is the recent measurement of the metallization of deuterium

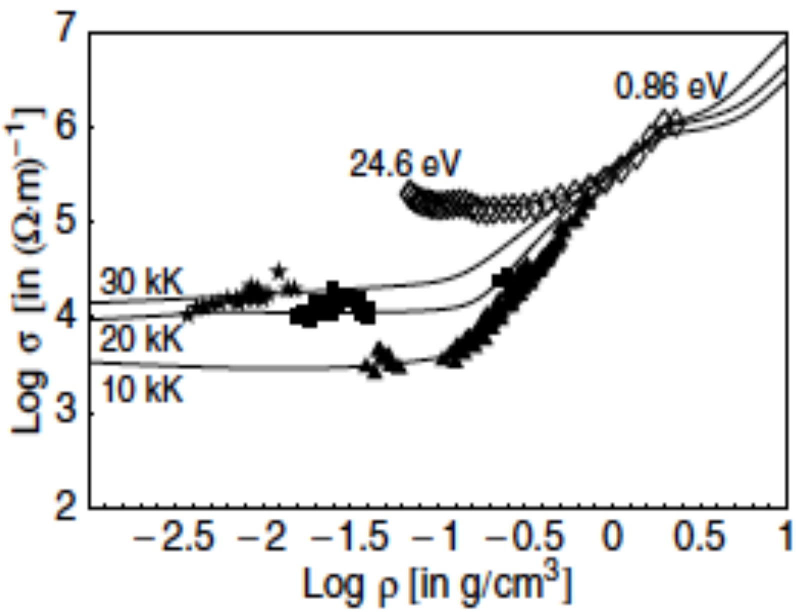
- **The results show a sharp transition to metallic behavior at a pressure near 300 GPa**
  - **This is higher than predicted by most QMD calculations**
  - **Dependence of the transition as function of temperature is also different than any of the QMD models**
- **We are now getting to the point where we can make precise enough measurements to test exchange functionals for DFT**



Knudson, et.al., Science 348, 1455 (2015)

There were major impacts as a result of these experiments

Comparison of modified LM model with aluminum data

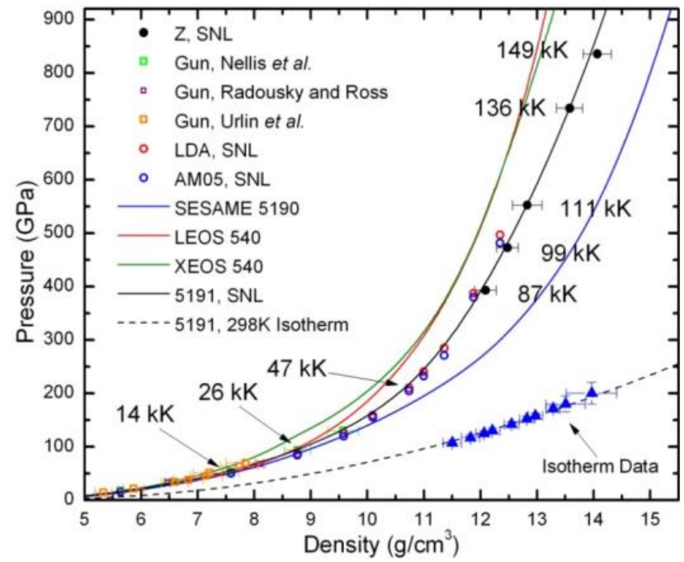


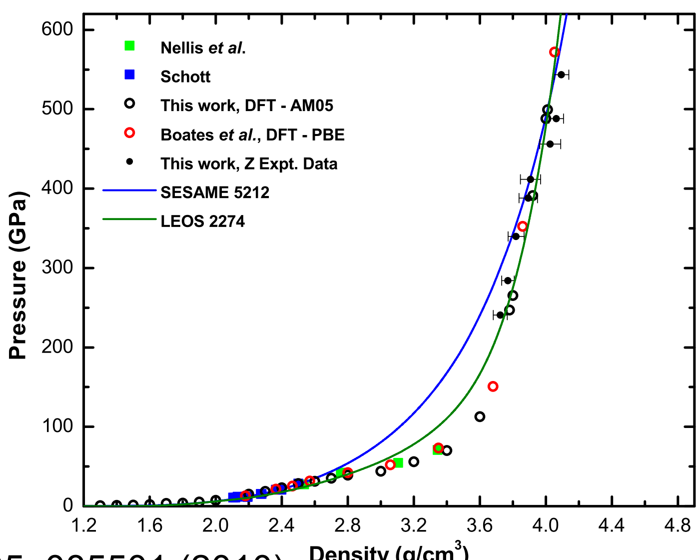
- **A general acceptance of density functional models**
  - **Ionization and structure could be determined more self-consistently**
  - **Quantum effects were important in modeling these correctly**
- **Improved practical models for electrical conductivity**
  - **Desjarlais modified the analytic model of Lee and More to take into account recent experimental results, leading to significantly more accurate conductivity tables**
  - **This enabled a new capability of electrically launched flyer plates for equation of state experiments**
- **More interest in using QMD (quantum molecular dynamics) to model conditions at dense, relatively low temperature systems**
  - **Both for EOS purposes and for electrical conductivity**

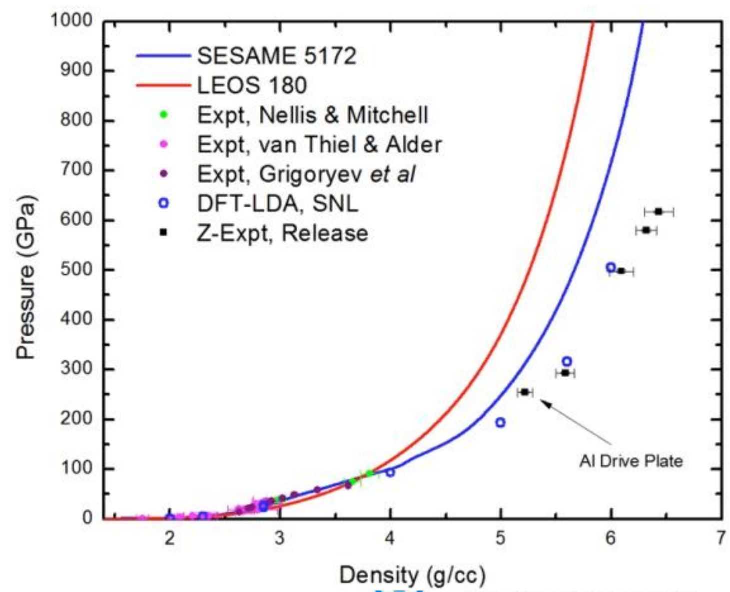
* Desjarlais, Contr. Plasma Physics, 41, 267 (2001).

The significant level of success of QMD calculations

- **Many instances where QMD calculations have provided extraordinarily accurate results for warm dense matter materials**
  - **Shock physics results**
  - **Electrical conductivity**
  - **Phase transitions**
- **Have served as a trusted tool when data is unavailable**
  - **Based on significant success when compared to data**



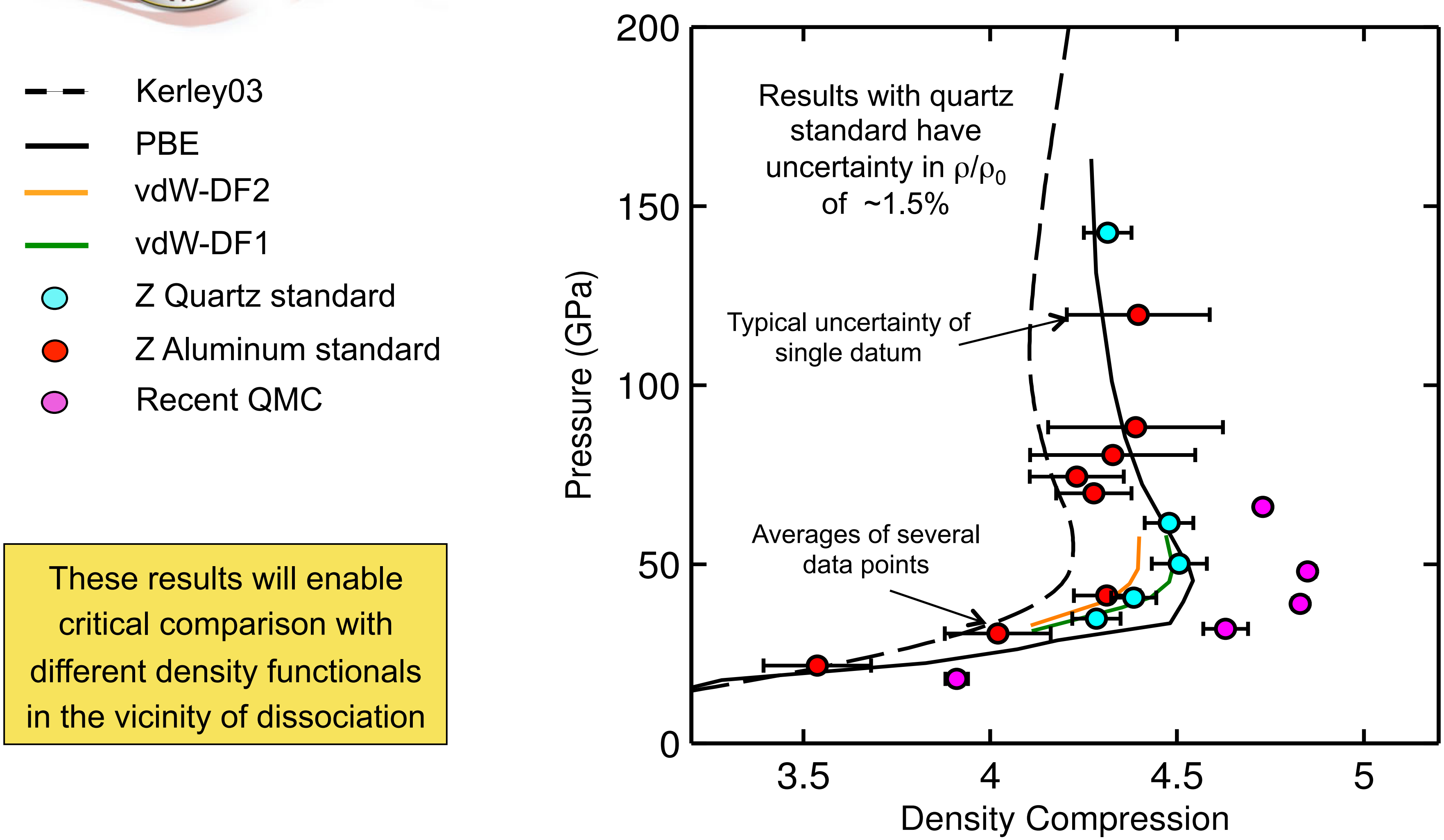




* Root, etal, PRL105, 085501 (2010).

* Desjarlais, Kress, and Collins, PRE 66, 125401 (2002).

Recent Hugoniot measurements of D2 show significant improvement in precision with respect to previous data



These results will enable critical comparison with different density functionals in the vicinity of dissociation

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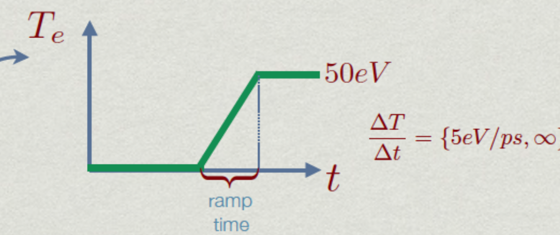
New OFMD simulations are modeling multi-species diffusion in dense plasmas

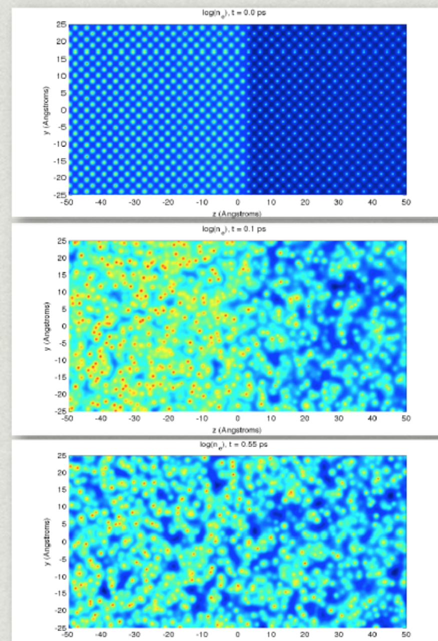
Interface Mixing: Fundamental Tests of Hydrodynamics

- Consider a cold interface that separates fuel (DT) and a plastic ablator (CHO). Energy is sourced in *through the electrons* (e.g., particle beam, radiation).



- **Question #1**: How does such an interface evolve subject to different initial heating rates?
- **Question #2:** Are there large electric fields and how long do they last?
- **Question #3:** Are there definite signatures of non-hydrodynamic behavior?

Current results based on:
N = 11,500,000 particles
z length = ~0.5 micron
time = ~10 ps, ~10^6 steps
aspect ratio = 40



Murillo, Stanton, Glosli, LANL and LLNL report

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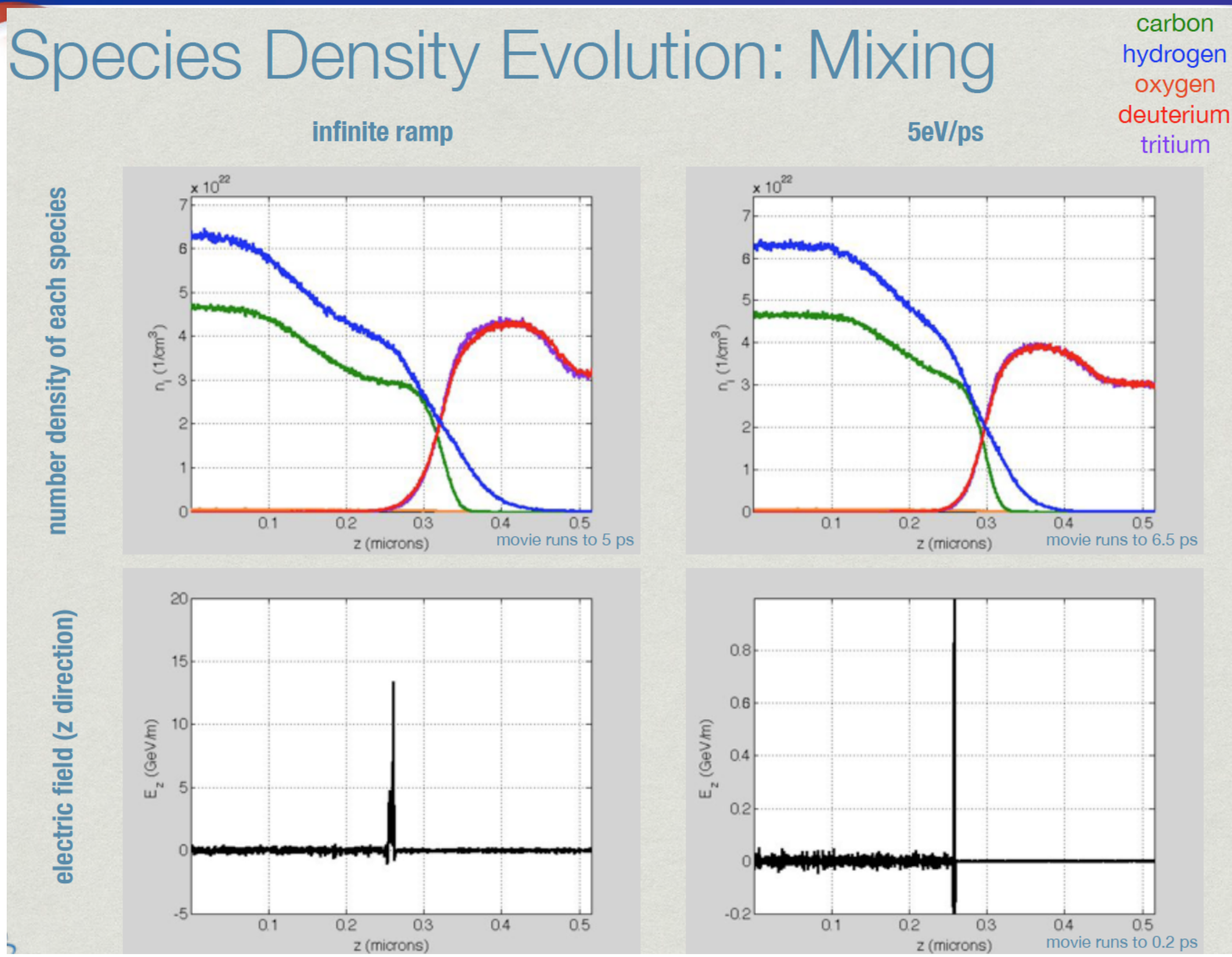
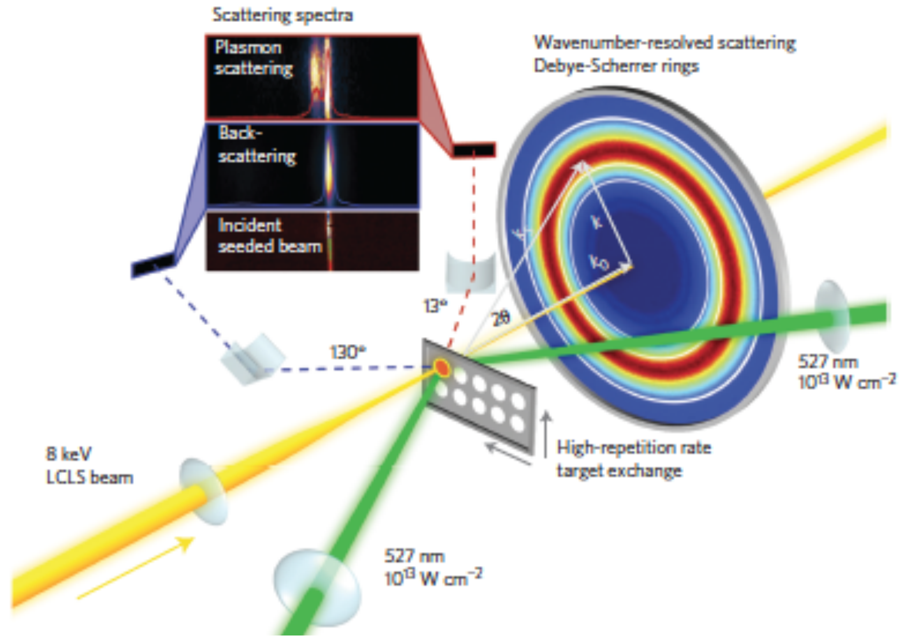
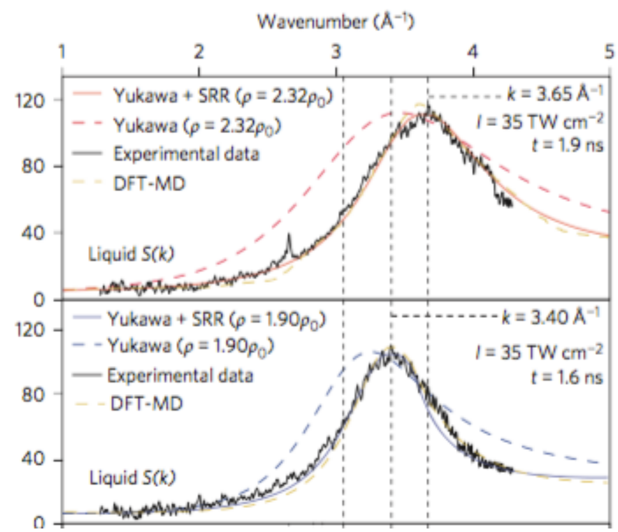
New OFMD simulations are modeling multi-species diffusion in dense plasmas



New experiments are being developed to take advantage of the new light source capabilities

- **WDM experiments created by laser heated targets are being studied at the LCLS**
  - **Counter-propagating lasers produce WDM targets**
  - **The FEL produced x-ray laser is used to probe these targets**
- **X-ray scattering measurements produce a range of important data**
  - **Diffraction measurements give information about ionic structure factors**
  - **Compton scattering gives information about density and temperature of the target**
  - **These measurements can also be combined to determine the pressure in the material**
- **Again, QMD calculations compare favorably to the data**





Recent experiment produced Al at 1.75 eV and 7 g/cm³.
Fletcher, et.al. Nature Photonics 9, 274, 2015

Important limitations for all of these experimental approaches

- **Very difficult to carry out experiments that are the same as those that occur in WD stars**
  - **Nearly all of the star is at densities unreachable in the lab**
  - **Some regions can be addressed, but otherwise must rely on physics scaling**
- **Diagnostics and measurements can be difficult**
  - **Characterizing the conditions in the experiment to compare to theoretical models is historically difficult in this regime**
  - **In particular, temperature is a very difficult measurement**
    - **Leads to significant uncertainties**
  - **Experiments are dynamic/time dependent**
    - **Non-equilibrium issues**
    - **Non-uniform conditions**

Still, these experiments have contributed to important progress in the field

- The application of DFT and molecular dynamics to WDM studies was facilitated by early success when comparing to WDM experiments
  - Early electrical conductivity calculations compared favorably with experiments
  - Many EOS results indicate that QMD codes work extremely well
  - Classical MD using Yukawa model does an excellent job for describing dusty plasma systems
- The net result is that if one can confidently describe the forces between particles, MD may be better than experiment
  - Experiments sensitive to interaction forces can then be used to validate MD models, even if not important for WD
  - The issue of getting into the right physics regime is still important
    - » An example would be reaching relativistic electron gas conditions

Many outstanding physicists have impacted this area

- **A tremendous group of physicists have played important roles in the development of strongly coupled plasmas/warm dense matter**