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An Overview and Historical Perspective of Strongly Coupled Plasma Physics

AFOSR Review Workshop

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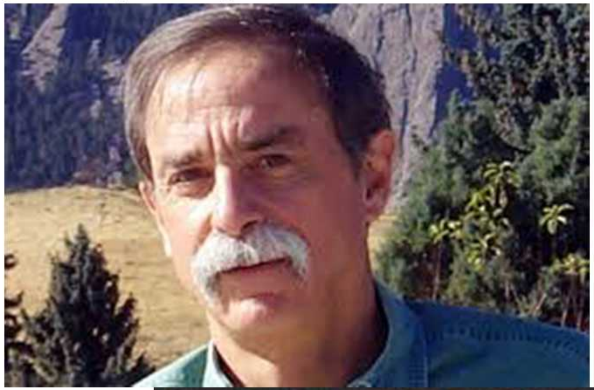
Sandia National Laboratories

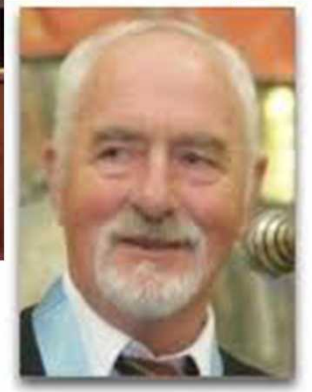
The field of SCP"s has been impacted by several well-known physicists

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







Outline of my talk

- The early years- dense plasmas and OCP's
  - Various theoretical approaches and developments
  - Early experiments
  - Electrical conductivity
- Branching out
  - Classical and quantum MD and MC
  - EOS
- Lower density strongly coupled systems
  - Ion traps
  - Dusty plasmas
  - Ultra cold plasmas
- Where are we now?

The first workshops on strongly coupled plasmas

- Workshop in Santa Barbara in 1986
  - 61 talks, 8 were of experiments
- Near the same time, a series of workshops began in eastern Europe called the PNP (Physics of Non-Ideal Plasmas) workshops
- A wide range of theoretical efforts
  - Density functional theory (TF, Kohn-Sham, etc)
  - Classical statistical models of dense plasmas and liquids
  - One component plasmas (OCP)- MC calculations
  - Hyper-Netted Chain Equation, classical and quantal
- Experiments were focused on methods of creating dense plasmas or on measuring transport properties
  - Very difficult to determine state variables in order to compare to theory
  - Several early experiments on metal vapors in the former Soviet Union
  - Shock and adiabatic compression experiments on gases

Many early experiments focused on electrical conductivity

- Isakov and Likal'ter and others did experiments on alkali metal vapor systems
  - These were pressurized heated vapor cells, reaching temperatures of a few thousand kelvin
  - Results were often confusing and generally not consistent with models

- Pressurized experiments on wires to heated conditions up to vaporization temperatures carried out by Hixon and Shaner
  - These experiments also measured sound speeds but were limited to these lower temperatures

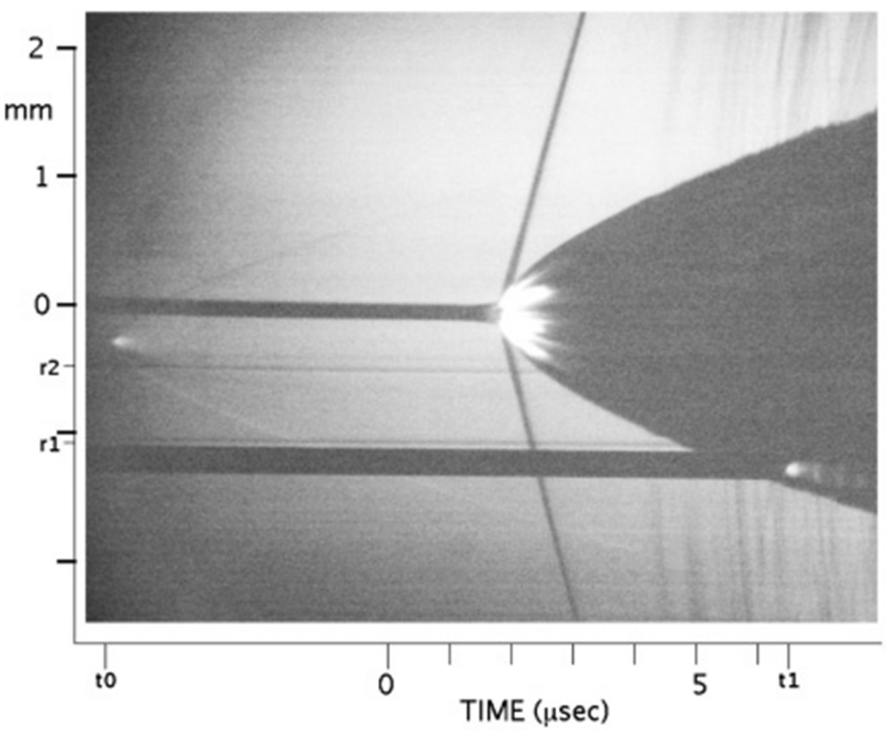
- To reach more plasma like conditions required an innovation

- Tamping the heated wires using some type of solid density insulator worked

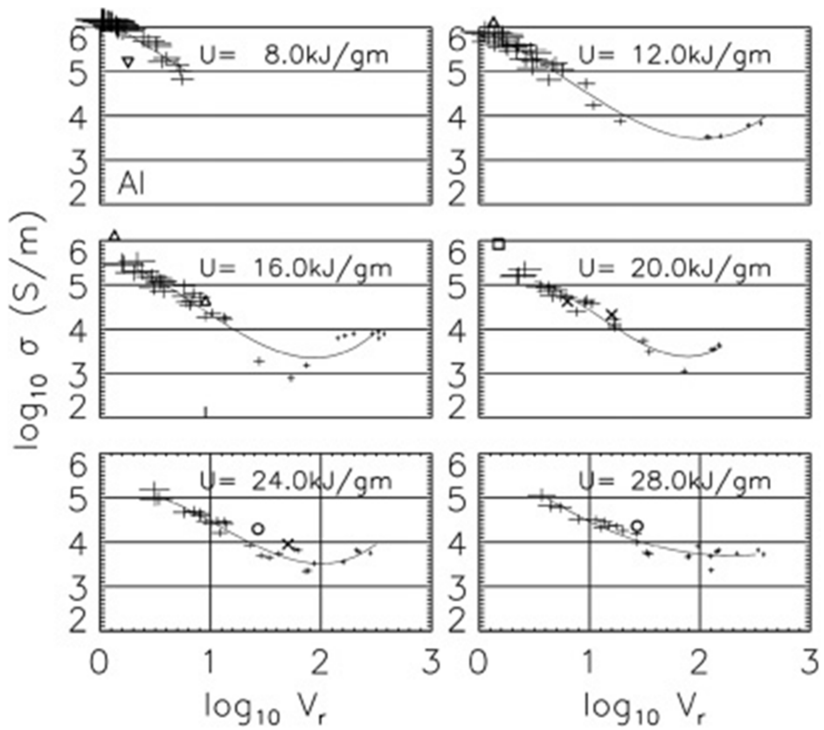
Electrical conductivity measurements of tamped exploding wires

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.



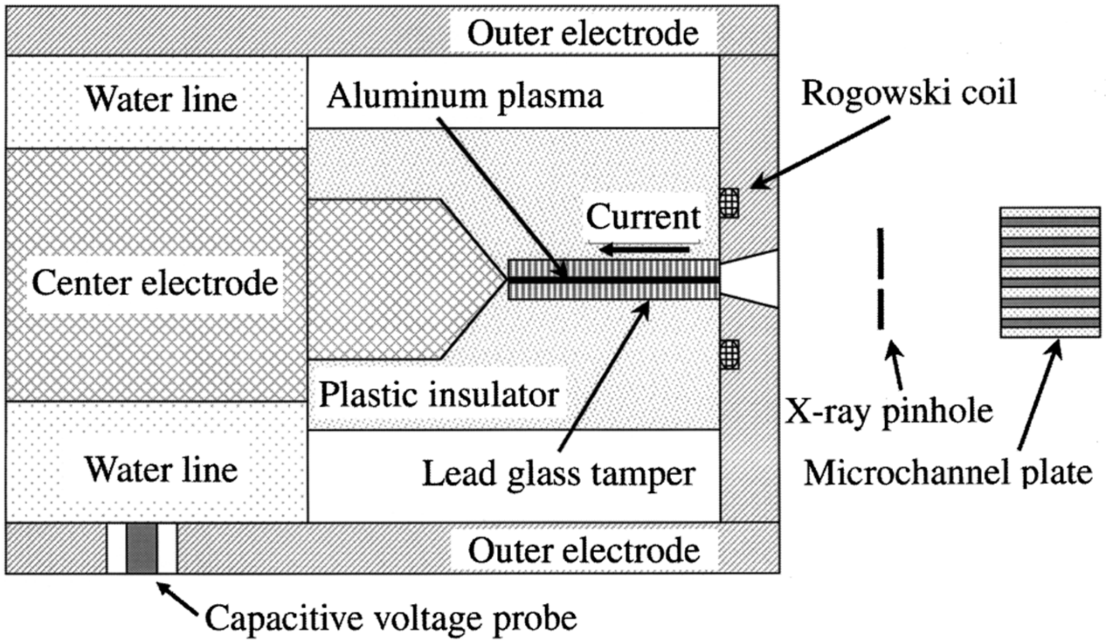
Conductivity for expanded aluminum

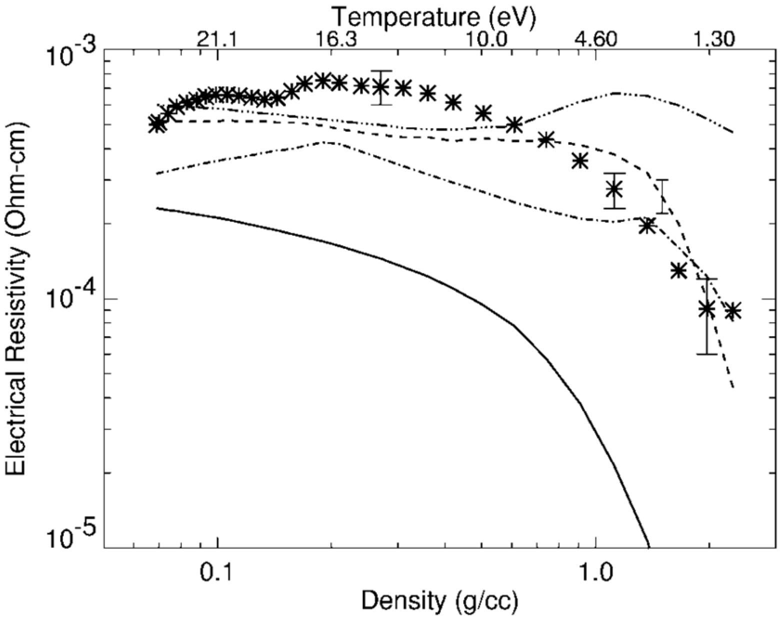


* DeSilva and Katsouras, PRE 57, 5945 (1998)

To reach higher temperatures, higher density tampers were required*

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



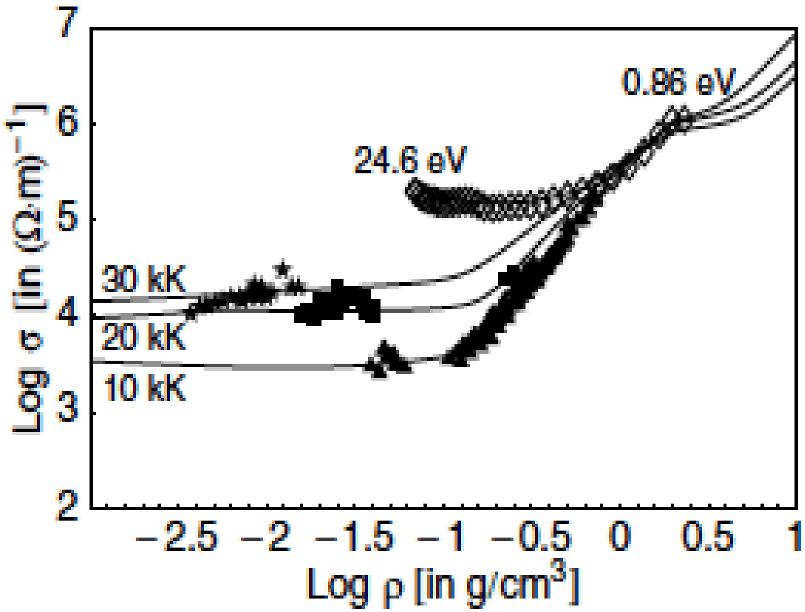


Model of Dharma-Wardana and Perrot matched experimental results best.
- At lower temperatures and densities, neutral collisions begin to matter

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

There were major impacts as a result of these experiments

Comparison of modified LM model with aluminum data

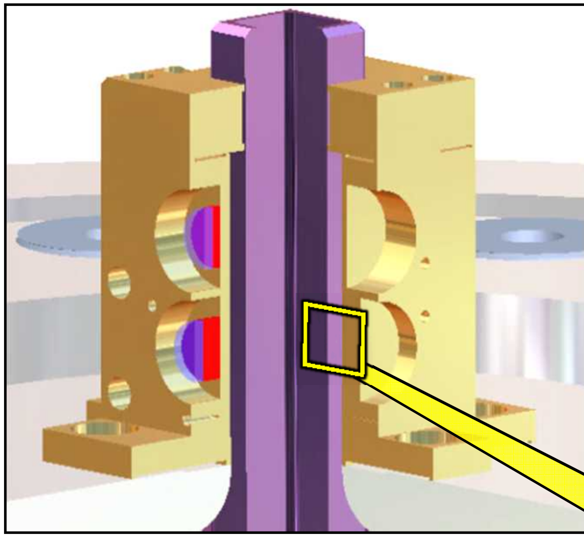


- **A general acceptance of density functional models**
  - **Ionization and structure could be determined more self-consistently**
  - **Quantum effects were important in modeling these correctly**
- **Improved practical models for electrical conductivity**
  - **Desjarlais* modified the analytic model 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**

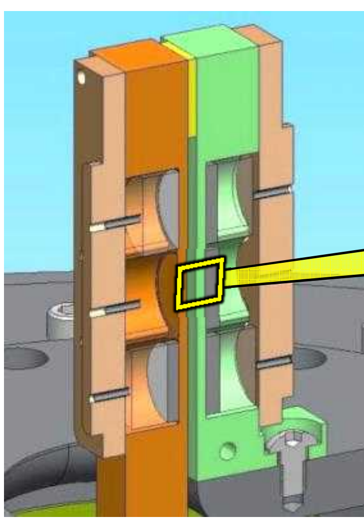
* Desjarlais, Contr. Plasma Physics, 41, 267 (2001).

Dynamic materials experiments use Z as a pulsed magnetic pressure driver (peak B-field = 100-1200 T)

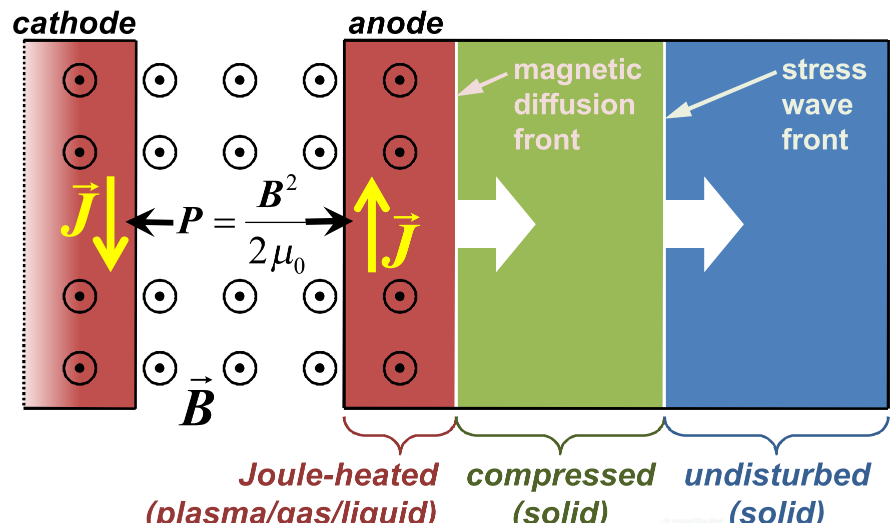
4-sided co-axial



stripline

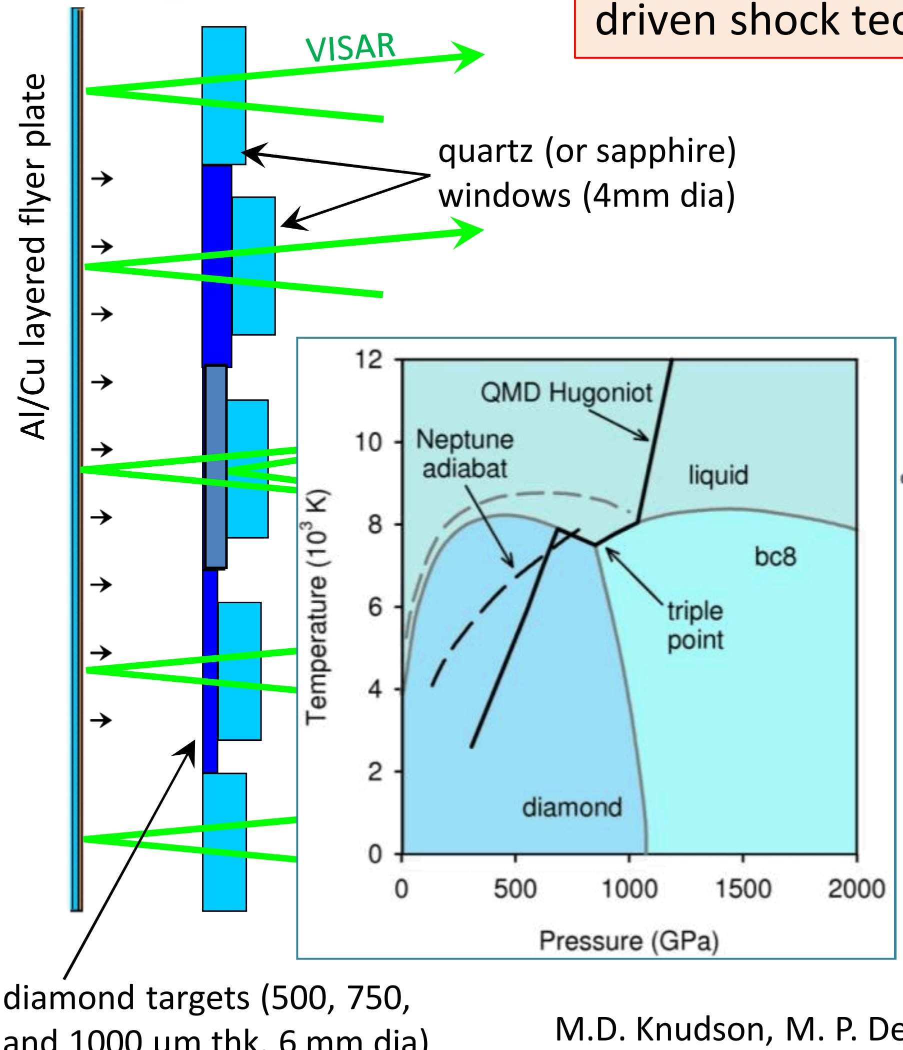


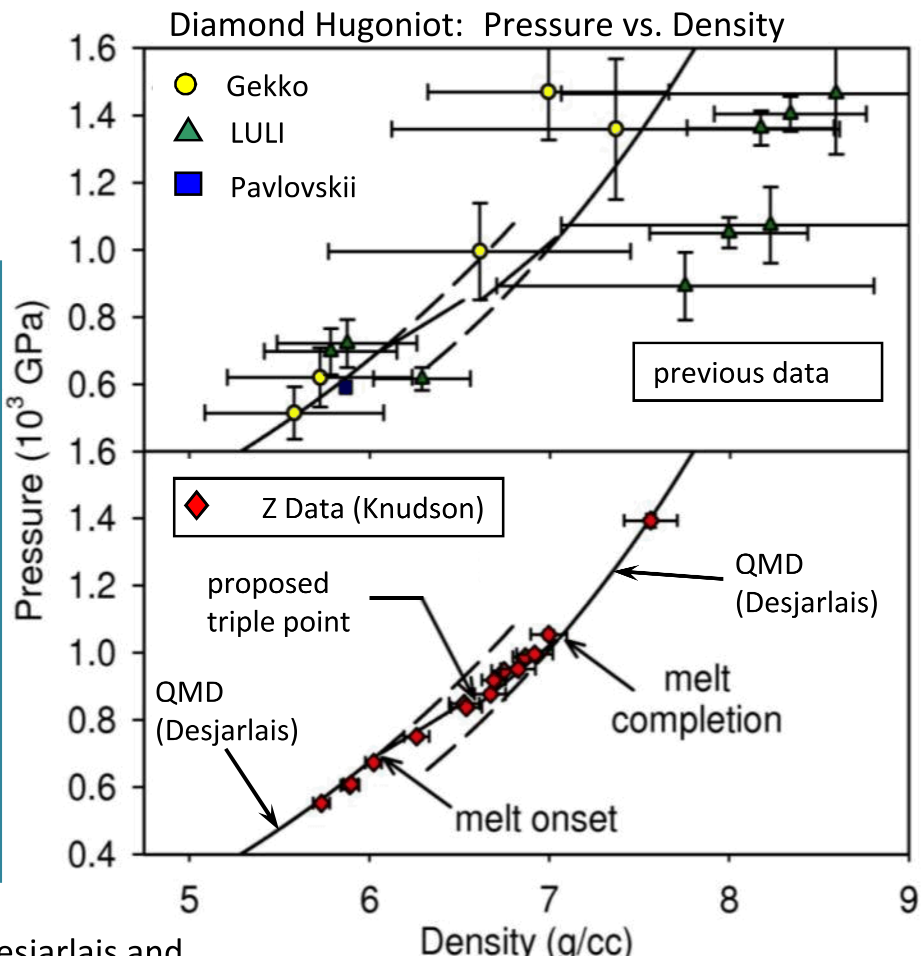
- current pulse of 7-26 MA delivered to load
- controllable pulse shape, rise time 100-1200 ns
- magnetic $(J \times B)$ force induces ramped stress wave in electrode material
- stress wave propagates into ambient material, de-coupled from magnetic diffusion front



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)





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

Concurrently, others began to recognize that SCP's could be produced at low densities

- **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**
  - **Demonstrated Wigner crystallization to BCC lattice through scattering measurements***

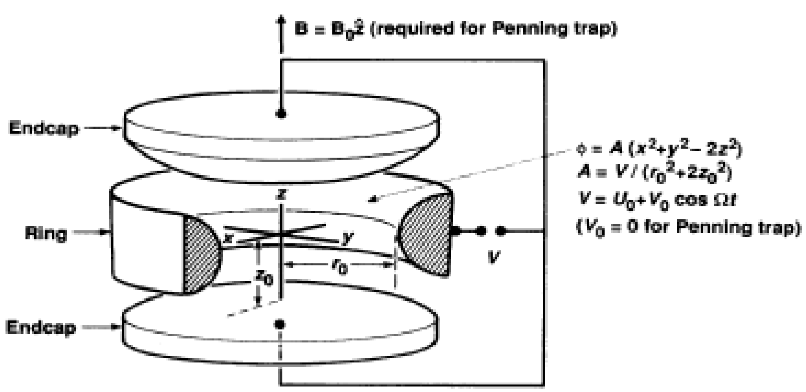
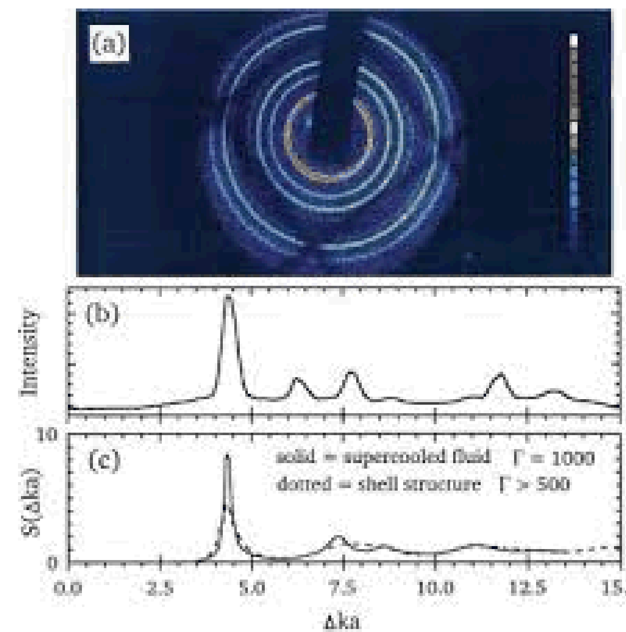


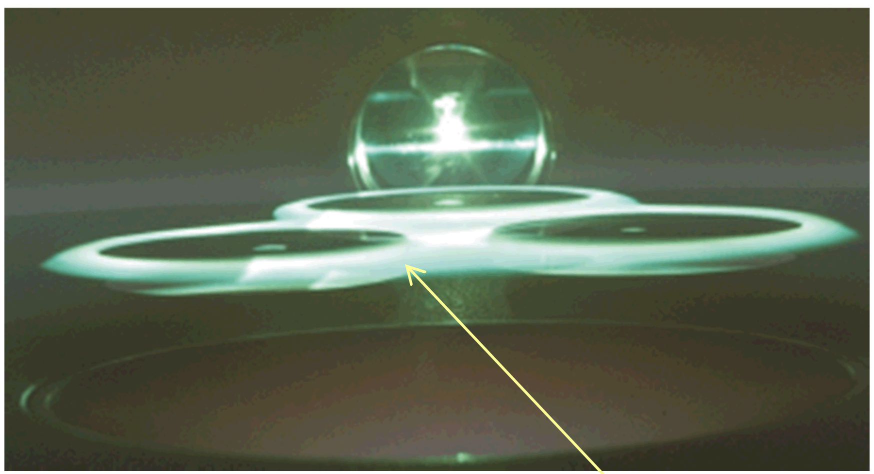
Fig. 1. Electrodes for a Penning or rf ion trap. The electric potential field ϕ is created by applying the voltage V between the endcap electrodes and the ring electrode. The uniform magnetic field **B** is required only for a Penning trap. [Adapted from (*42*) with permission from Plenum Press]



*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**
  - **Dust particles in plasma discharge would charge up to high level**
  - **SCP's created due to very large charge**



Rings of dust particles floating above silicon wafer

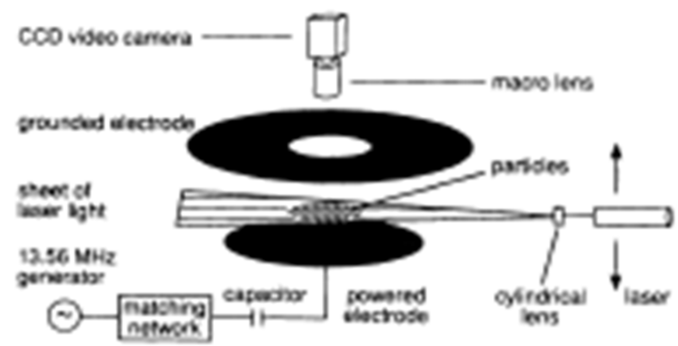


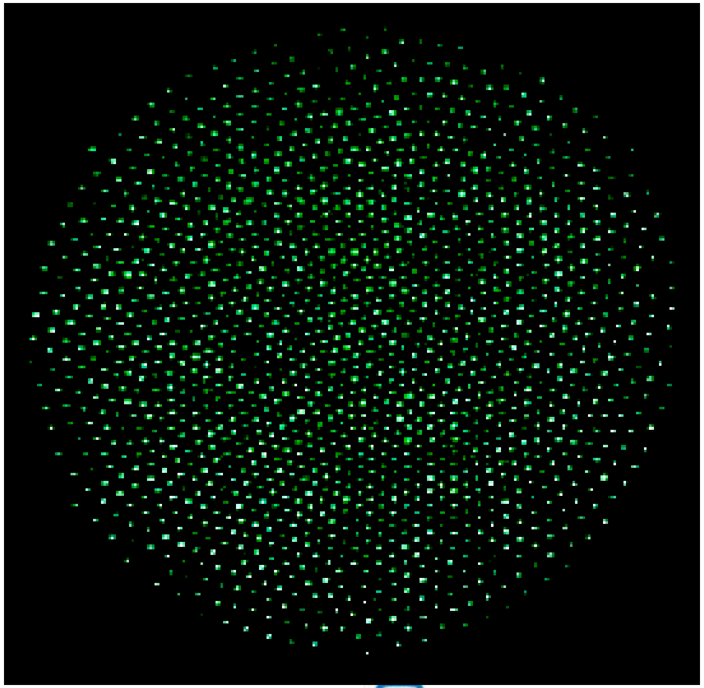
FIG. 1. Schematic of apparatus. A discharge is formed by capacitively coupled rf power applied to the lower electrode. A vacuum vessel, not shown, encloses the electrode assembly. A cylindrical lens produces a laser sheet in a horizontal plane, with an adjustable height. The dust cloud is viewed through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



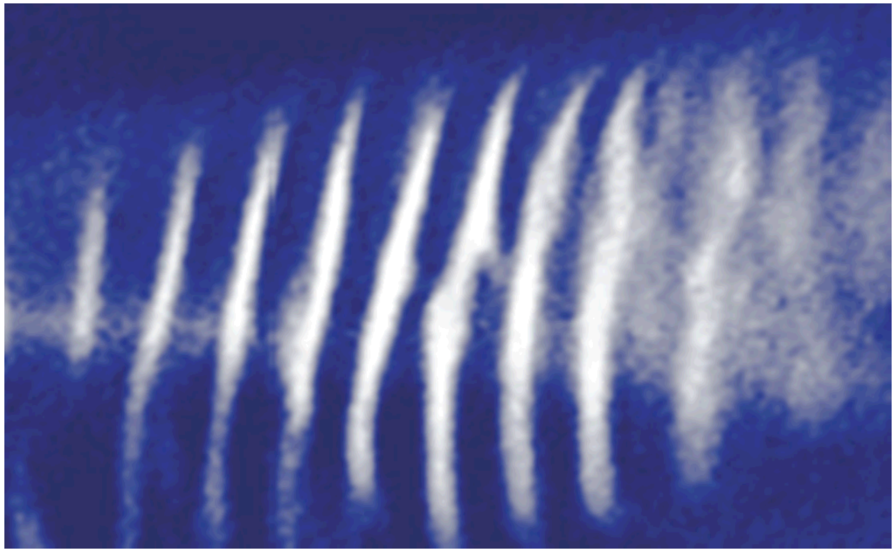
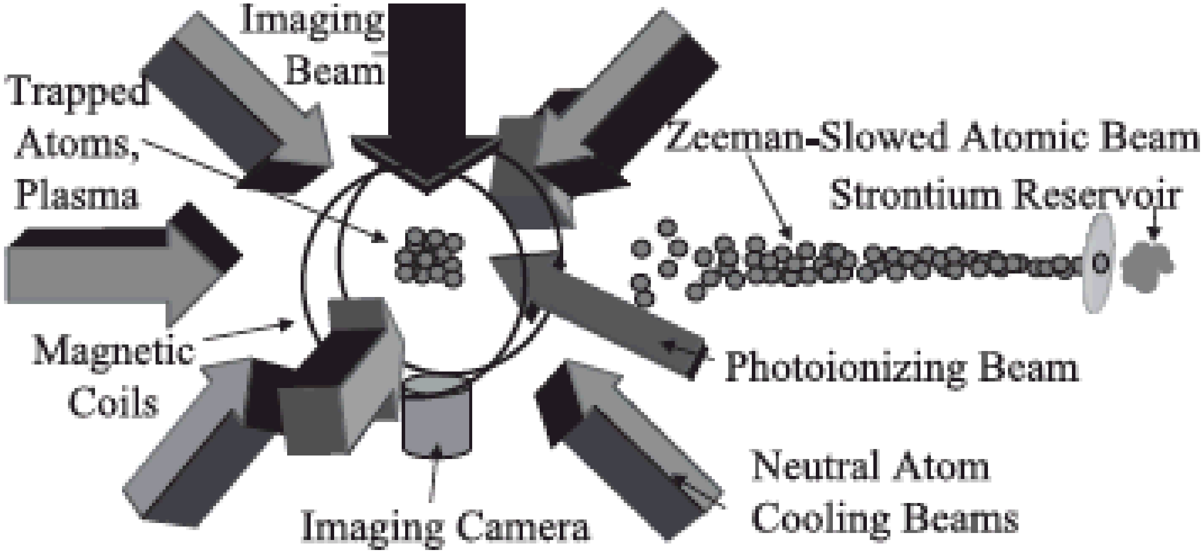


Image of dust acoustic wave

* 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 helped lead to another innovation- Ultra cold plasmas

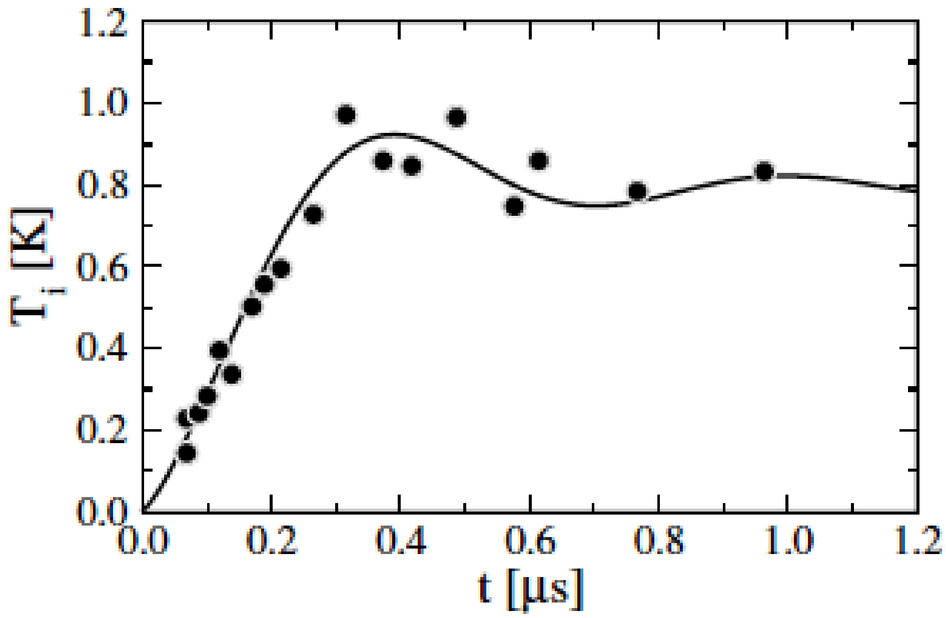
- These ultra cold systems were produced for the first time in 1995* and led to the Nobel Prize in 2001
  - Began to be studied in several laboratories throughout the world
- Soon (1999) researchers began investigation what happens when BEC's or other cooled atom systems were ionized quickly through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



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

One example of this interesting behavior is disorder induced heating

- **Discovered that ions are heated significantly upon ionization**
- **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 and simulation***
  - **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).

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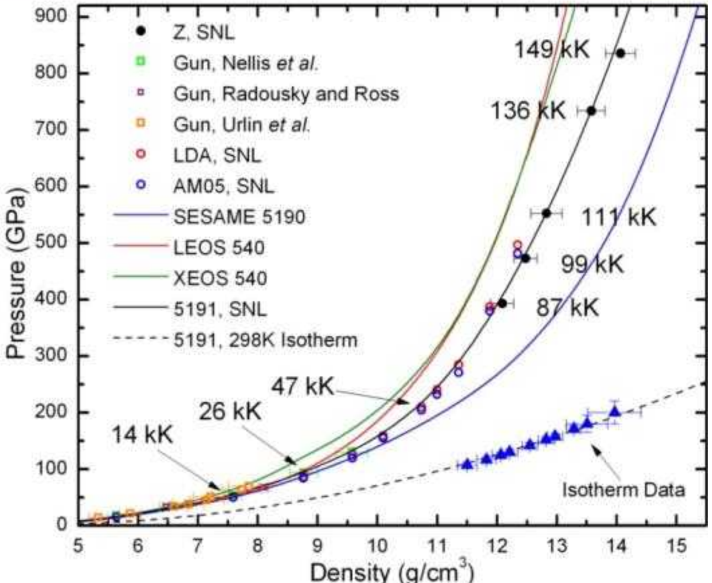
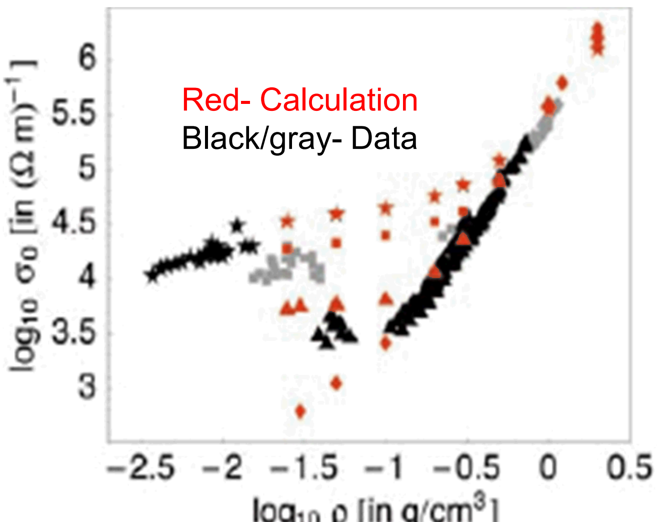
Dusty plasmas, ultra cold plasmas, and warm dense matter now are essentially their own fields

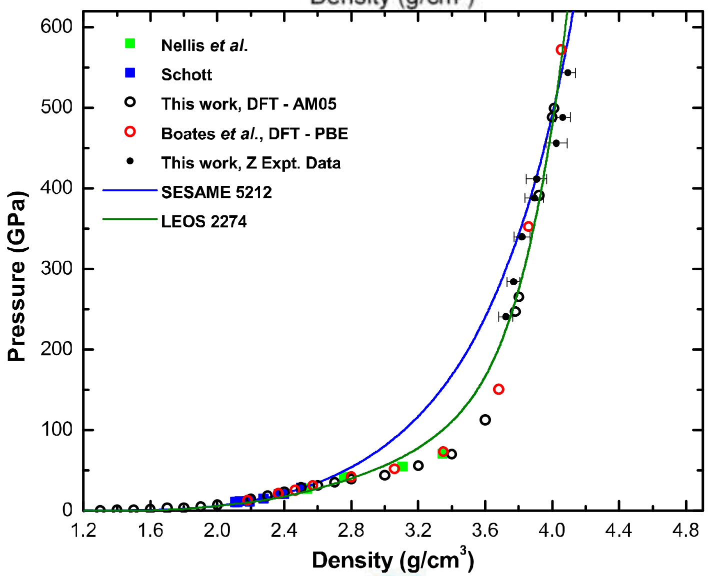
- Dusty plasma workshops
  - First workshop held at San Diego in 1986
  - 14th Workshop being held this month at Auburn University with over 100 participants
- Ultra cold plasma workshops
  - I believe first one held in 2005 at Harvard
  - Since been several others
- Eventually development of a subfield, warm dense matter
  - Strongly coupled, partially degenerate systems
  - Initial seminar held in Vancouver, BC in 1996
  - Eight workshops held since then
- SCCS and PNP are still continuing to this day
  - 11th strongly coupled conference held in Santa Fe in 2014
  - 15th physics of nonideal plasma conference held in Kazakhstan in 2015

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).

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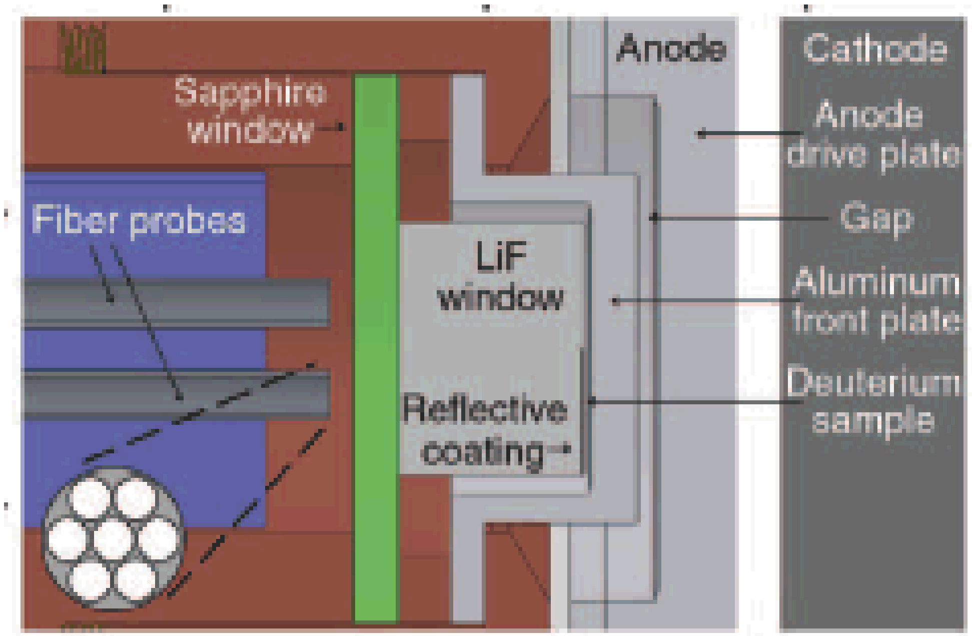
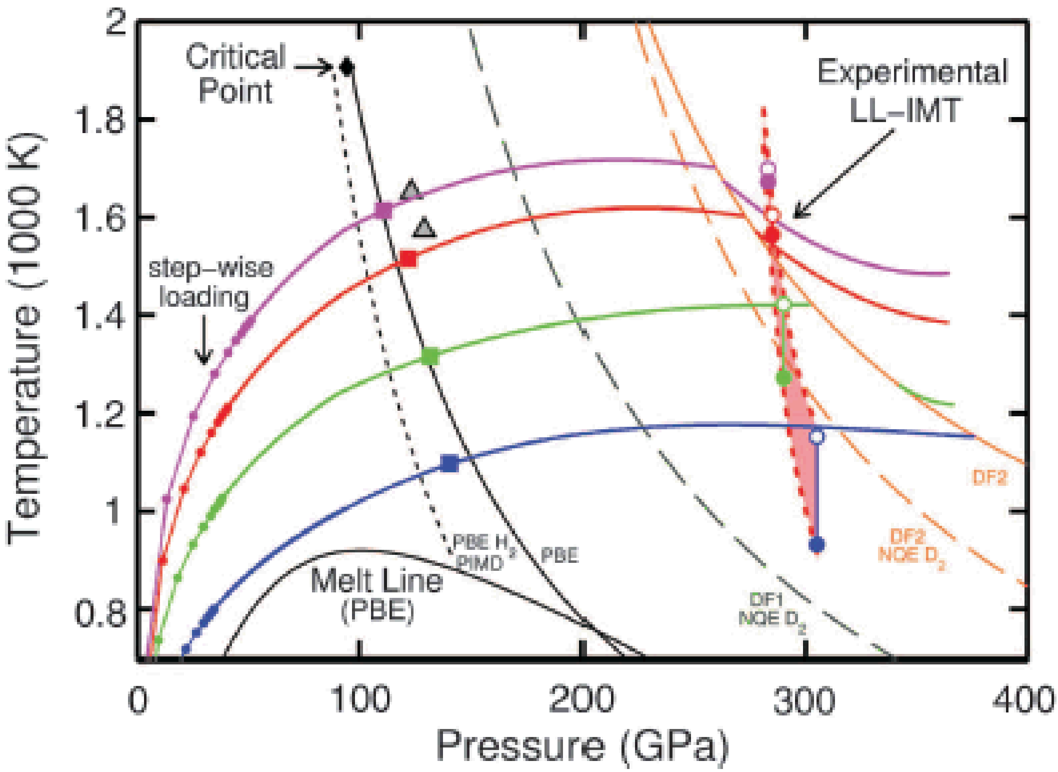
One example of the impact of this work over time is the recent measurement of the metallization of deuterium

- **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*

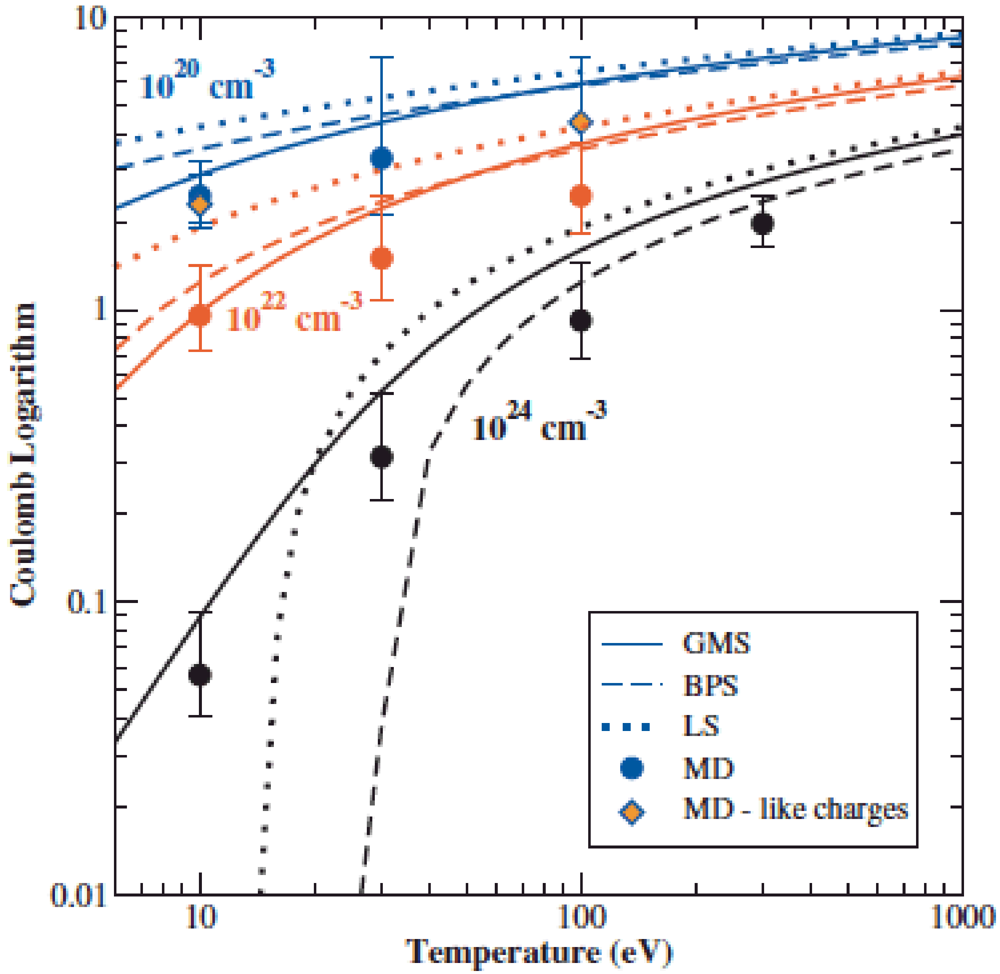
- **The results show a sharp transition to metallic behavior at a pressure near 300 GPa**
  - **This is higher than predicted by most QMD calculations**
  - **Dependence of the transition as function of temperature is also different than any of the QMD models**
- **We are now getting to the point where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



* Knudson, etal, Science 348, 1455 (2015).

Molecular Dynamics now being applied to several plasma physics issues

- **One example is the understanding electron-ion equilibration in a dense plasma**
  - **Amazingly, this has proven very difficult to measure experimentally**
  - **MD calculations have now been done for hydrogen and some other systems***
- **Results likely much more accurate than an experiment could test**



* Glosli, etal, PRE 78, 025401 (2008).
* Dimonte and Daligault, PRL 101, 135001 (2008).

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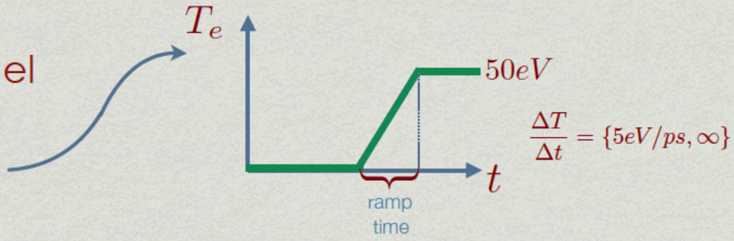
New OFMD simulations are modeling multi-species diffusion in dense plasmas

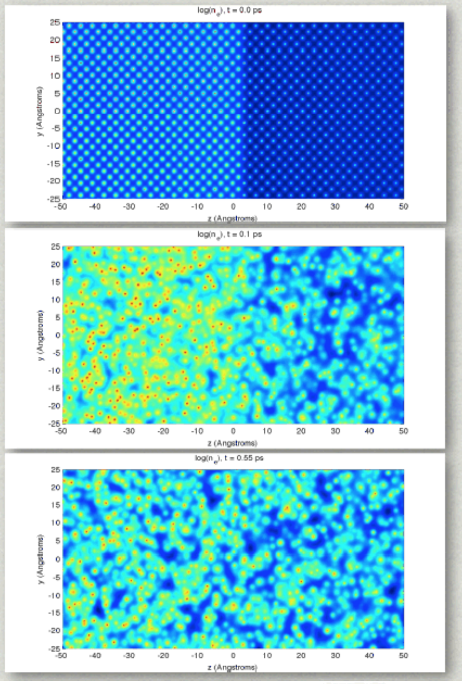
Interface Mixing: Fundamental Tests of Hydrodynamics

- 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).

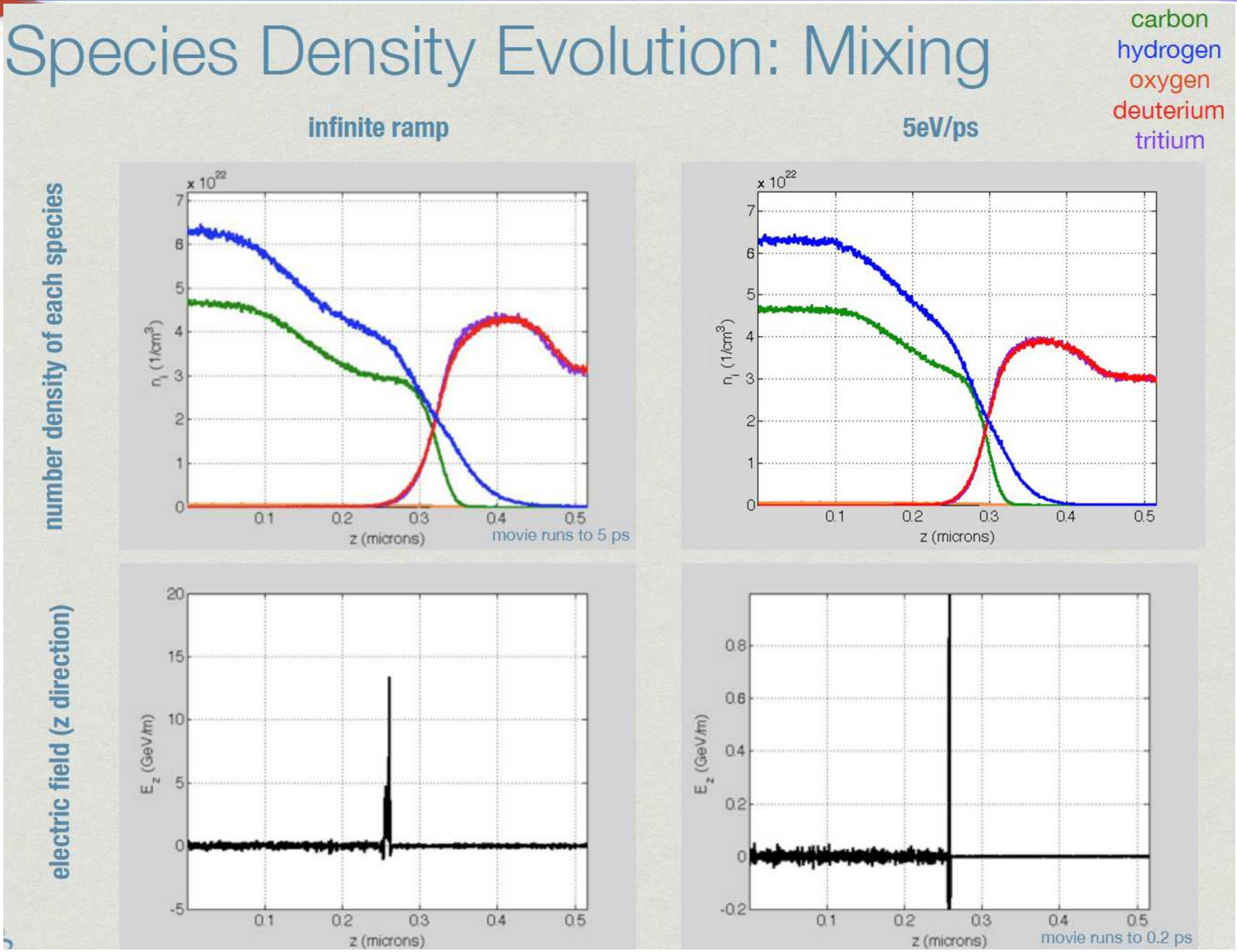


- **Question #1**: How does such an interface evolve subject to different initial heating rates?
- **Question #2:** Are there large electric fields and how long do they last?
- **Question #3:** Are there definite signatures of non-hydrodynamic behavior?

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

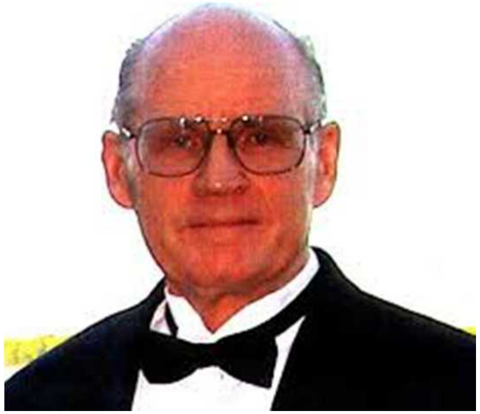


New OFMD simulations are modeling multi-species diffusion in dense plasmas



Field has evolved in surprising ways

- Sophisticated Simulation techniques are being applied to a tremendous range of systems
  - QMD
  - OFMD
  - Path Integral MC
- Multiple sub-fields have been developed or enabled
  - Dusty plasmas
  - Ultracold plasmas
  - Warm dense matter
  - Pulsed power based dynamic materials work
- Almost none of that was foreseen
  - All the work was important



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