Perspectives (II)

Warm Dense Matter Winter School

January 16, 2008

Jonathan Wurtele

UC Berkeley and LBNL

Themes...

	Thursday January 10, 2008	Friday January 11, 2008	Monday January 14, 2008	Tuesday January 15, 2008	Wednesday January 16, 2008	
	BLDG 50 LBNL	BLDG 50 LBNL	BLDG 50 LBNL	BLDG 50 LBNL	BLDG 50 LBNL	
8:00 - 9:00 AM	Registration	Registration	Registration	Registration	Registration	8:00 - 9:00 AM
9:00 - 9:45 AM	Introductory remarks: G. Logan, R. Davidson, J. Barnard	WDM Theory: R. More	WDM Theory: R. More	WDM Theory: R. More	WDM Theory: R. More	9:00 - 9:45 AM
9:45 - 10:30 AM	WDM Theory: R. More	Laser Experiments II: H. Yoneda	Laser Experiments III: H. Yoneda	Paricle beam physics for WDM: J. Wurtele	Laser Applications: S. Mao	9:45 - 10:30 AM
10:30 - 11:00 AM	Working discussions (coffee served)	Working discussions (coffee served)	Working discussions (coffee served)	Working discussions (coffee served)	Working discussions (coffee served)	10:30 - 11:00 AM
11:0 - 11:45 AM	Laser Experiments I: H. Yoneda	QMD EOS and Pulse Power Applications: M. Desjarlais	WDM Experiments on FELs: R. Lee	GSI Experiments: D. Hoffmann	Laser matter interactions confined in high aspect ratio holes: A. Forsman	11:0 - 11:45 AM
11:45 - 12:30 PM	Fundamentals of negative ions: I. Kaganovich	Sandia Experiments: T. Renk	Mercury EOS: H. Kitamura	GSI theory: N. Tahir	WDM in IFE Chambers: C. Debonnel/P. Peterson	11:45 - 12:30 PM
12:30 - 2:00 PM	Working Lunch in B-50 (Meals provided)	Working Lunch in B-50 (Meals provided)	Working Lunch in B-50 (Meals provided)	Working Lunch in B-50 (Meals provided)	Working Lunch in B-50 (Meals provided)	12:30 - 2:00 PM
2:00 - 2:45 PM	X-Ray Diagnostics: S. Glenzer	Ultrafast heating experiments and diagnostics: R. Falcone	Exploding wires in water: A. Grinenko	Ion Beam Heating and Diagnostics I: F. Bieniosek	Future of Computational WDM: P. Colella	2:00 - 2:45 PM
2:45 - 3:30 PM	Hydro motion in WDM: J. Barnard	WDM theory: S. Libby	LANL WDM Expts: Lasers and Wires: J. Benage	Ion Beam Heating and Diagnostics II. P. Ni	Working discussions (coffee served)	2:45 - 3:15 PM
3:30 - 4:00 PM	Working discussions (coffee served)		Working discussions (coffee served)	Working discussions (coffee served)	Perspectives: H. Yoneda	3:15 - 3:45 PM
4:00 - 4:45 PM	LLNL short pulse laser experiments: A. Ng	Poster session (coffee served): 4:00 - 6:15 PM LBNL Cafeteria	Electrically driven WDM experiments: P. Renaudin	Ion stopping in WDM: J. Hasegawa	Perspectives: J. Wurtele	3:45 - 4:15 PM
4:45 - 5:30 PM			Strongly coupled plasmas: M. Murillo	Collective effects in dE/dX: N. Fisch	Concluding remarks/final discussions: G. Logan and the group	4:15 - 5:00 PM
				Banquet 6:00 pm - 8:00 pm LBNL Cafeteria Dinner speaker: A. Sessler		

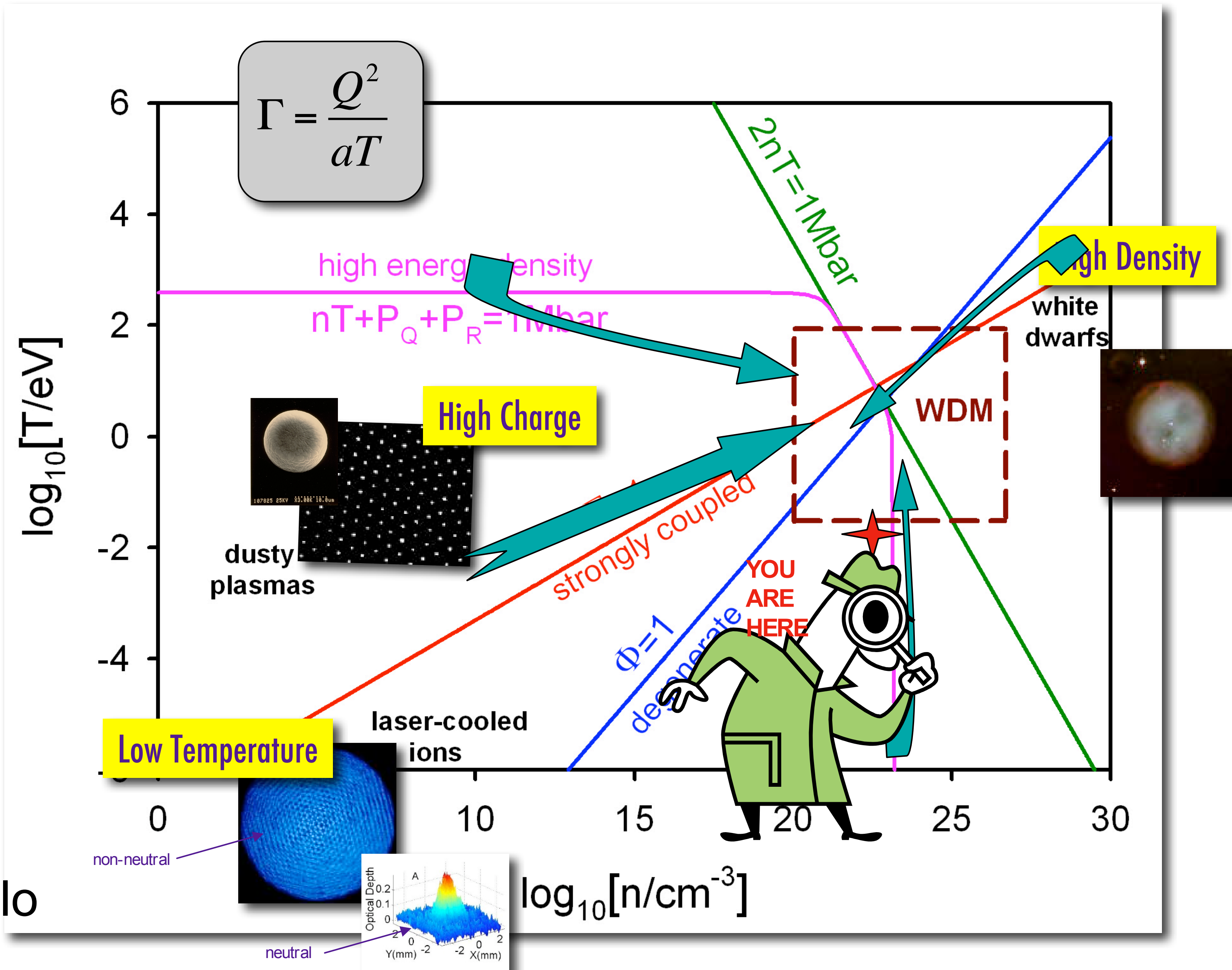
- WDM theory
- Laser drivers
- Electrical current driver
- FEL driver
- Particle beam driver
- Ion stopping
- WDM applications
- Future

Questions we addressed

- What is WDM regime?
- How can we create and study it? Diagnostics and drivers
- How is studied analytically? Theoretical approaches hydro, EOS, QMD, transport coefficients
- How is it studied numerically? Codes, codes, codes
- What are the applications?

There was no unique answers.
Rich and compelling new physics and much discussion of applications

Warm Dense Matter Regime



Murillo

Physics is different

- Transport phenomena (electrical and thermal conductivity, opacity, viscosity)
- Solid properties (melting, ablation, electronic structure)
- Plasma phenomena (collective modes, em wave scattering, wave-particle interactions)
- EOS (planetary interiors, ICF,…)
- Metal-insulator transition
- Two-phase physics (bubbles, cooling,…)
- Generic behavior vs material specific behavior.

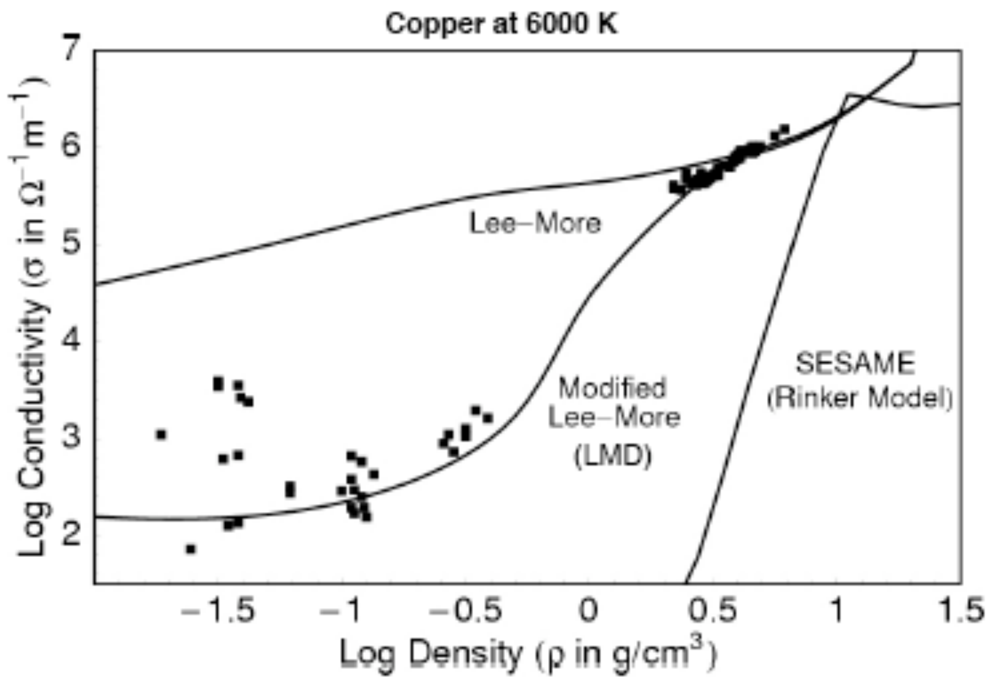
Methods for WDM creation

- Lasers
- Diamond anvil
- High-energy ion rings (GSI)
- Low energy linacs (LBL)
- X-ray FELs (Spring8, DESY,LCLS)
- Thomson backscattering (diagnostic)
- Exploding wires (free space and immersed)
- Z-pinch
- Electrical Discharges

The development of new drivers and diagnostics opens up new horizons for physics experiments and applications. Big science, small science--the important thing is GOOD science.

Theory is important

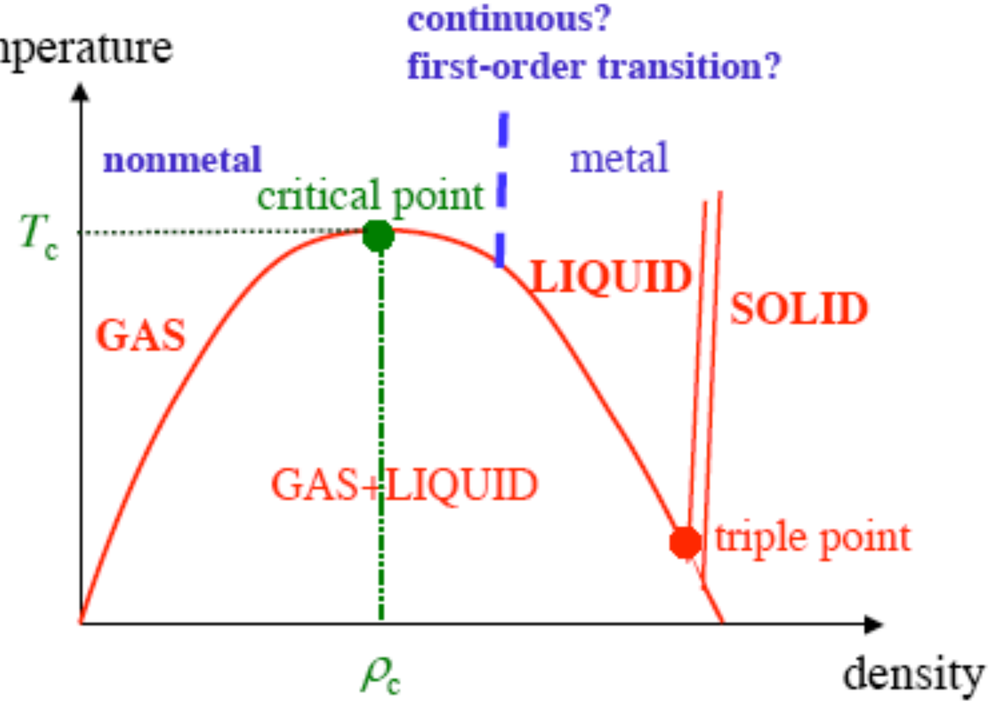
This modified Lee-More model provides much better agreement with DeSilva's copper data



Dejarlais, QMD calculation. Can be coupled to hydro codes.

Kitamura--**EOS for Fluid Mercury**
Based on Interatomic Many-Body Interactions

■ Schematic phase diagram of a metallic element



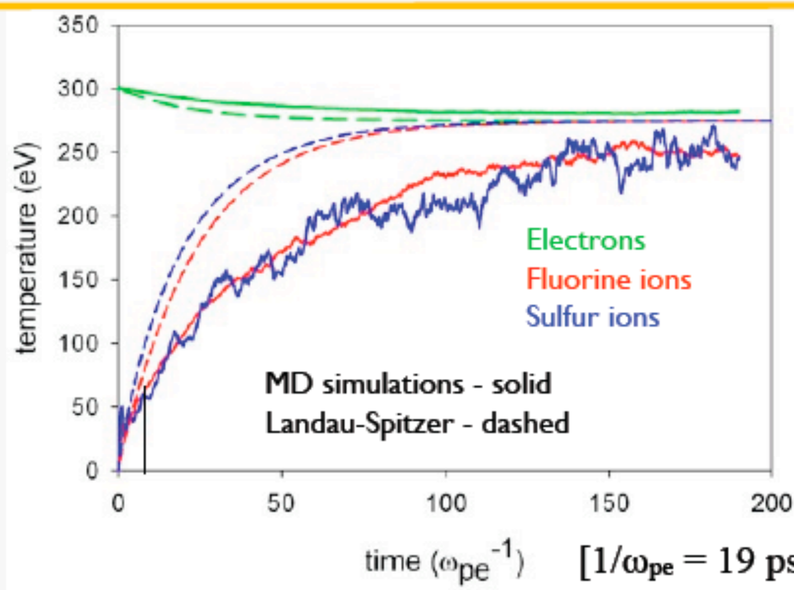
Gas-liquid transition accompanying ***change in the electronic states***

L. Landau & J. Zeldovich, Acta Physiochim. URSS **18**, 194 (1943)

F. Hensel & W.W. Warren, *Fluid Metals* (Princeton, 1999)

Experiments to understand theory

To distinguish between theories we require an accuracy in the temperature equilibration rate of 50% or better



$[1/\omega_{pe} = 19$ ps$]$

For SF_6 plasma at
$T_{e0} = 300$ eV

Rates:
L-S ~ 5.2 eV/ω_{pe}^{-1}
MD ~ 2.3 eV/ω_{pe}^{-1}

$$T_e - T_i = (T_e - T_i)_0 \, e^{-\alpha t}$$

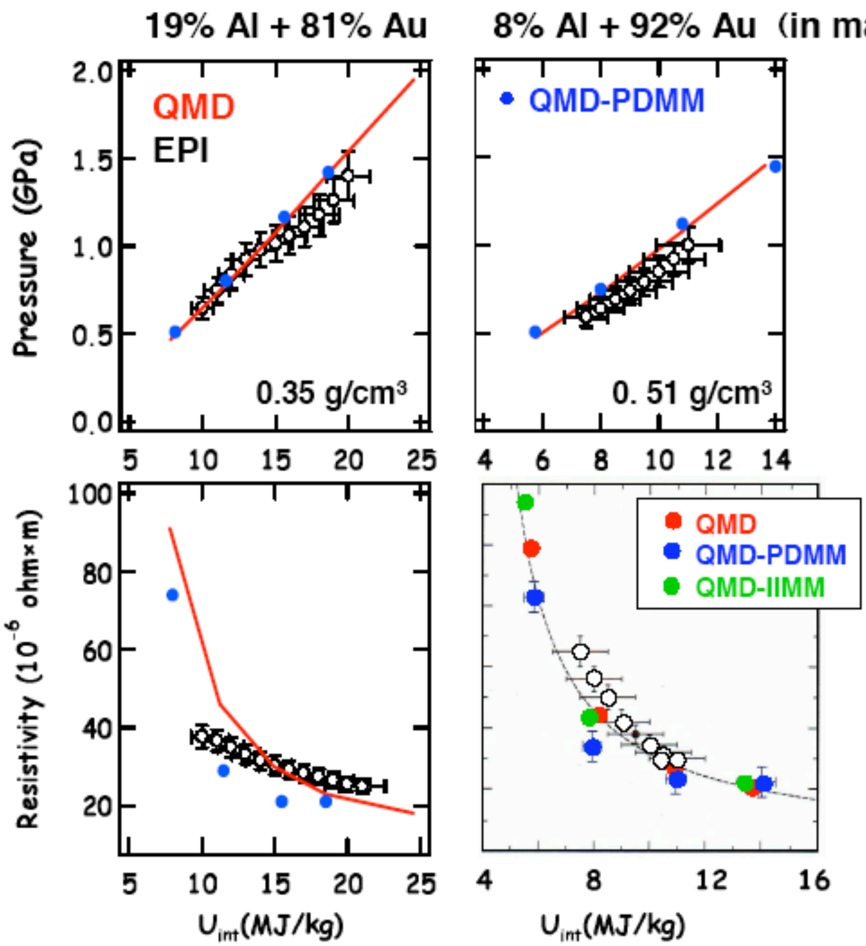
$$\alpha = \nu_{ie} + \nu_{ei} \approx \nu_{ie}$$

Since MD and Spitzer temperature equilibration rates differ by a factor of two, we need to determine this rate (α) to within 50% accuracy to readily distinguish between them.

Los Alamos
NATIONAL LABORATORY
EST.1943

Benage

Experimental data of Al-Au mixture allow to test mixing models



QMD simulations are in good agreement with the experimental data and the sum of the partial pressures

Electrical conductivities calculated with an isothermal-isobaric mixing model are in good agreement with the results of direct simulation

Clérouin *et al.*, Phys. Rev. B 76 (2007)

Renoudin,CEA

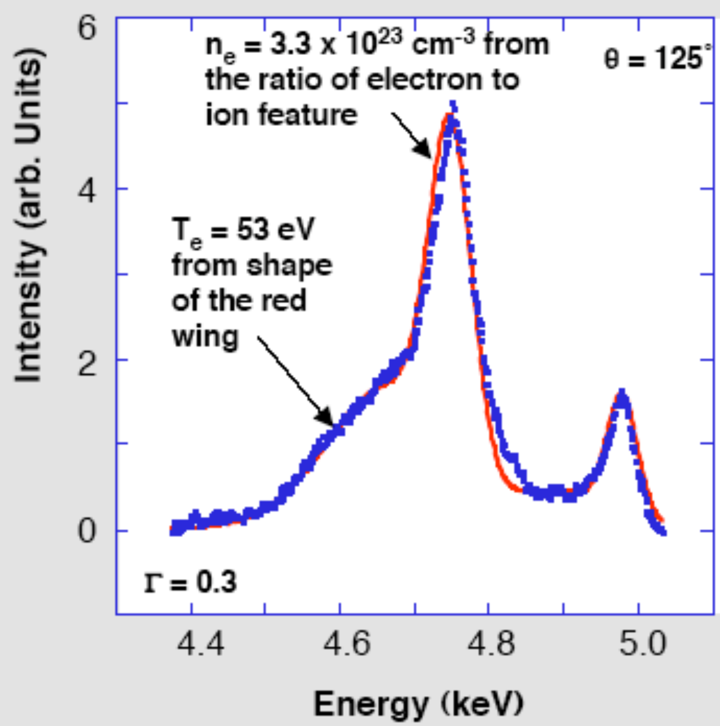
Glenzer, LLNL--developing new diagnostics

X-ray scattering provides accurate temperature measurements in solid-density Be plasmas

Experiment

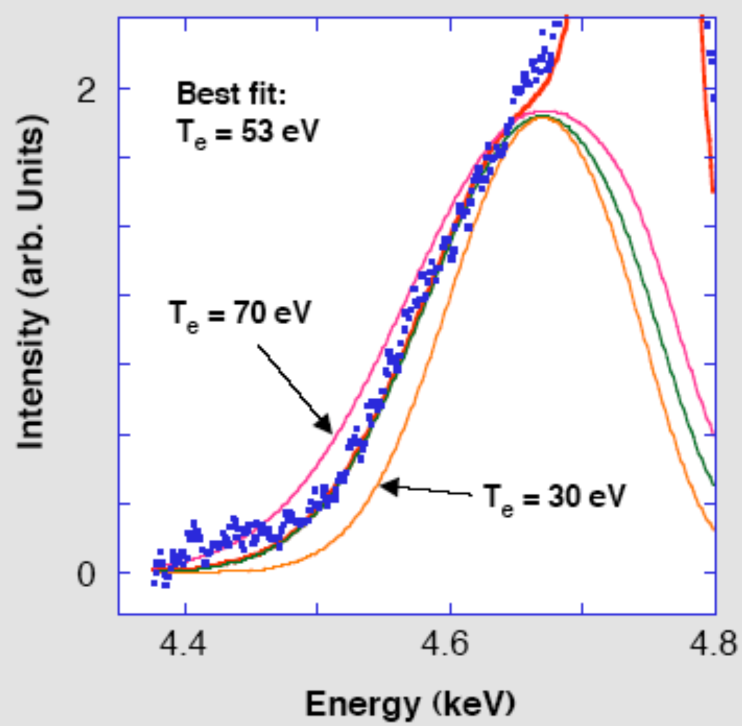
The National Ignition Facility

X-ray scattering spectra provide accurate data on T_e and n_e



From the theoretical fit to the data:
T_e = 53 eV and Z_{free} = 3.1 corresponding to n_e = 3.8 x 10^{23} cm^{-3}

Comparison of experimental data with theoretical calculations for various T_e



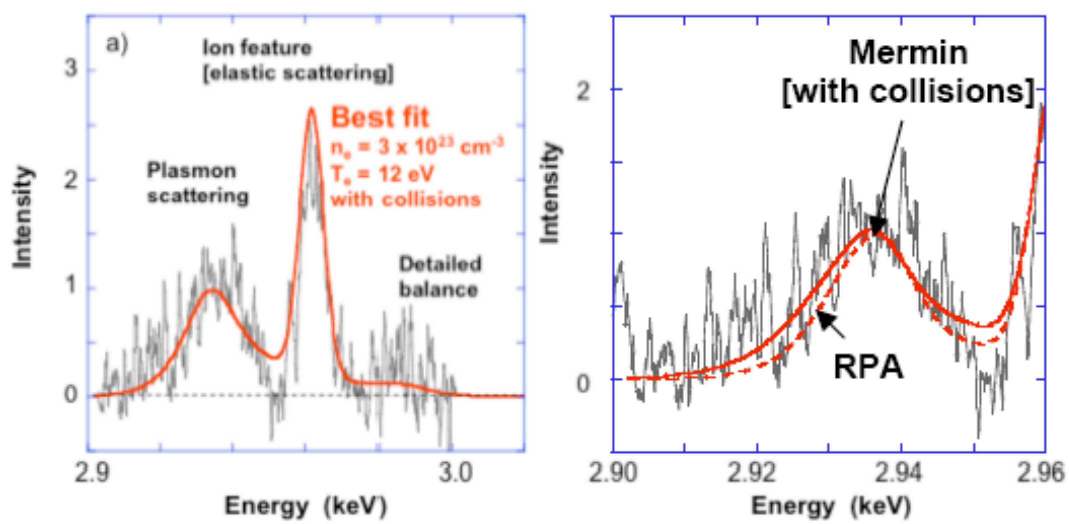
A sensitivity analysis shows that we can measure T_e with an error bar of ~15%

Collisions

Plasmon spectra have been shown to be sensitive to collisions, a fact that can be used to measure conductivity

The National Ignition Facility

Plasmon width is determined by Landau and collisional damping



Dashed curved is collision-less theory: Random Phase Approximation

Solid curves use Mermin theory with collisions, ν_{ei}, in Born approximation

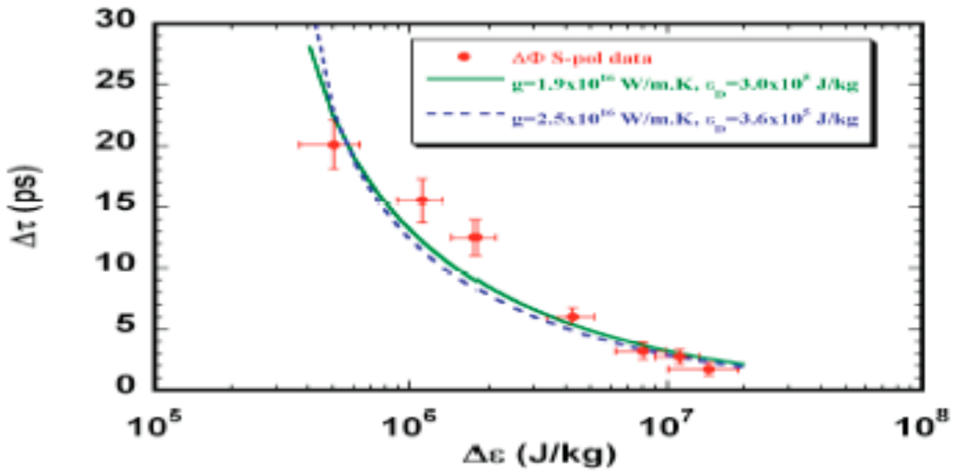
- Here, collisions provide a correction to the width [important to obtain fit with proper T_e values
- To accurately determine n_{ei} and conductivity we will implement improvements access the collision dominated regime
  - FEL experiment [A. Höll et al, HEDP 3 (2007)]
  - New experiments with lower x-ray energy on Omega

S. H. Glenzer et al., Phys. Rev. Lett. 98, 065002 (2007).

The heating-disassembly model shows good agreement with observation

- This yielded the first measurement of the critical lattice energy $\varepsilon_D = (3.3 \pm 0.3) \times 10^5$ J/kg for solid-plasma transition under ultarfast laser excitation

Ng: thin target heated by laser+electrons



Ao *et al.*, Phys. Rev. Lett. 96, 055001(2006)

- The *Idealized Slab Plasma* Concept has been realized in *Isochoric Laser Heating*

- This has become a unique platform for the study of non-equilibrium, high-energy-density Warm Dense Matter free from gradient effects
  - Electrical conductivity
  - Lattice energy density for solid-plasma transition
  - Persistence of band structure in quasi-steady state with non-equilibrium electron DOS

Forsman, laser drilling

Why use double pulse ? **Double Pulse machining improves the quality of percussion drilled holes.**

- **Double pulse format can reliably percussion drill high aspect holes.**

800 shots

Single pulse

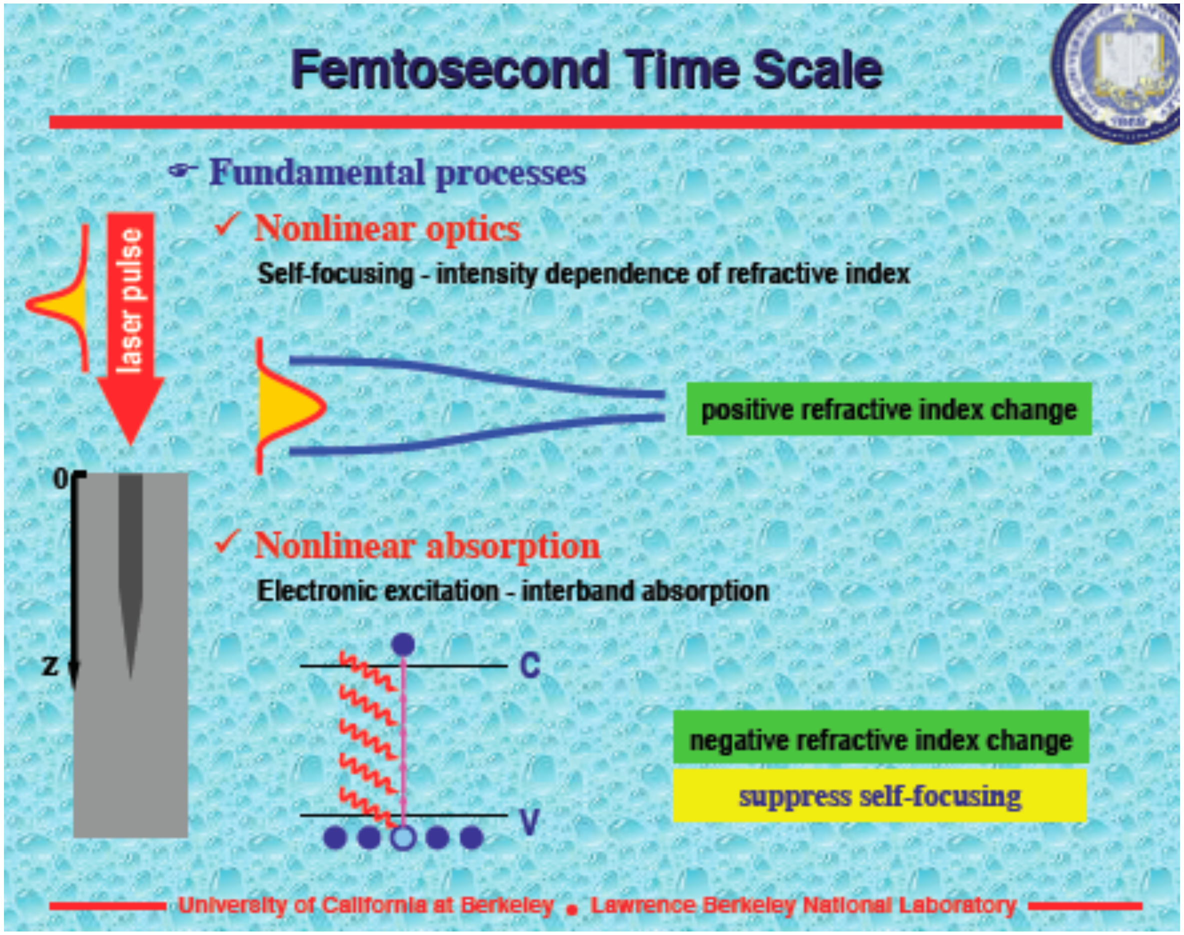
1 mm thick stainless steel.

200 shots

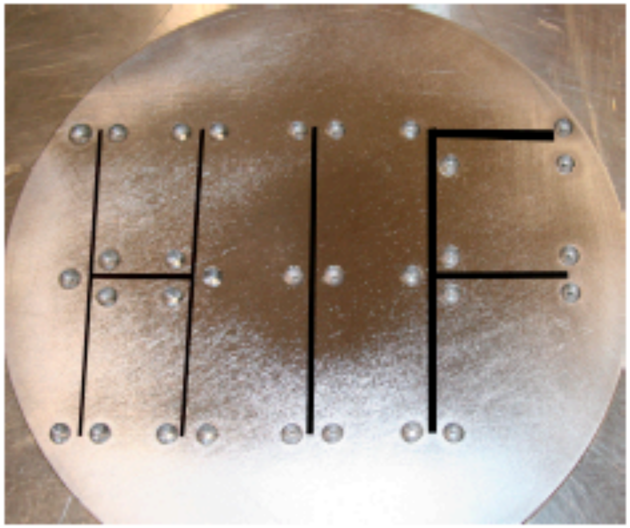
Double pulse format

GENERAL ATOMICS

Mao--alblation fs-ns timescales

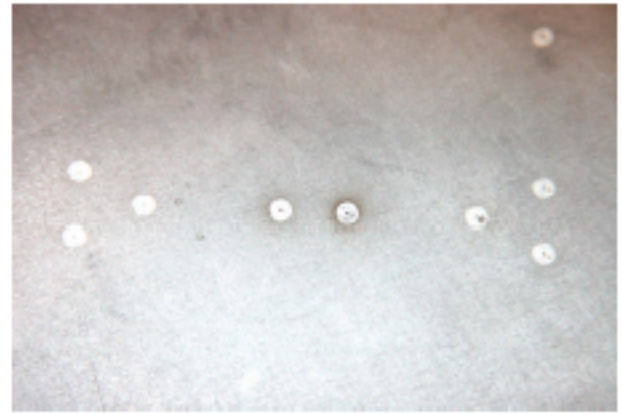


Show-and-Tell Tantalum Witness Plate

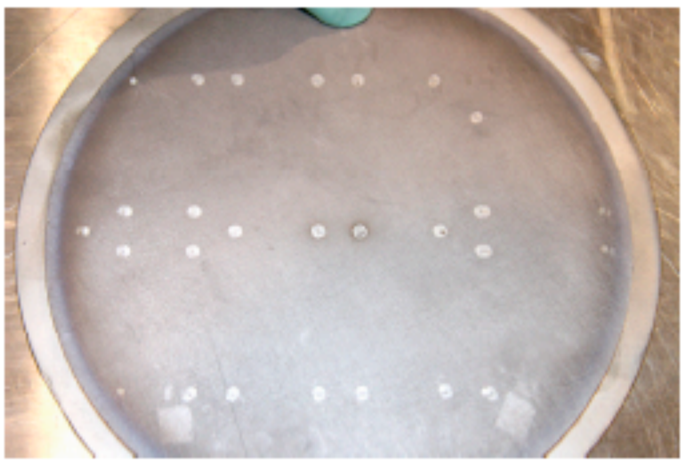


Ta Aperture Plate

Target plate center



- Ta Aperture plate at z = 45cm
- Ta Target plate offset = 0.5 cm. Target plate diameter = 13.5 cm
- 20 pulses oxygen beam
- Center holes ablated, other holes melted to ~ 3 cm radius
- Center of each damage pattern is undamaged (see above)



Ta Target Plate
Diam = 13.5 cm

Sandia National Laboratories

Renk, Ion ablation source RHEPP-1

Negative Ion Plasmas

- Kaganovitch, More

D. J. Economou, R. S. Wise, and A. A. Kubota, IEEE TPS **27**, 60 (1999). Chlorine plasma of ICP.

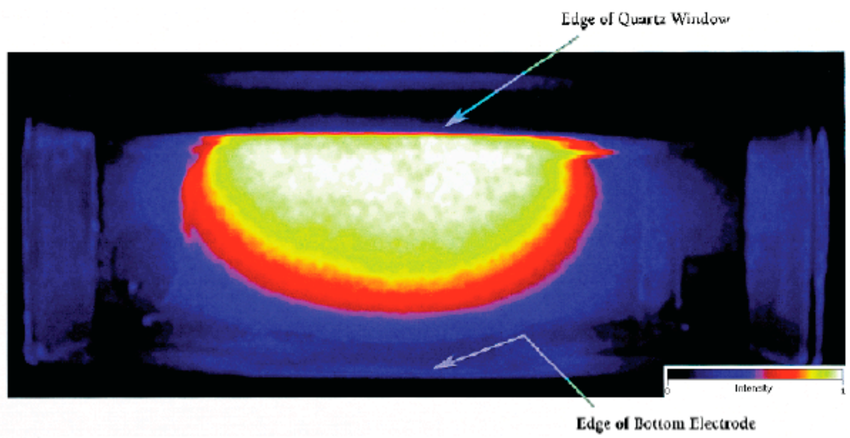
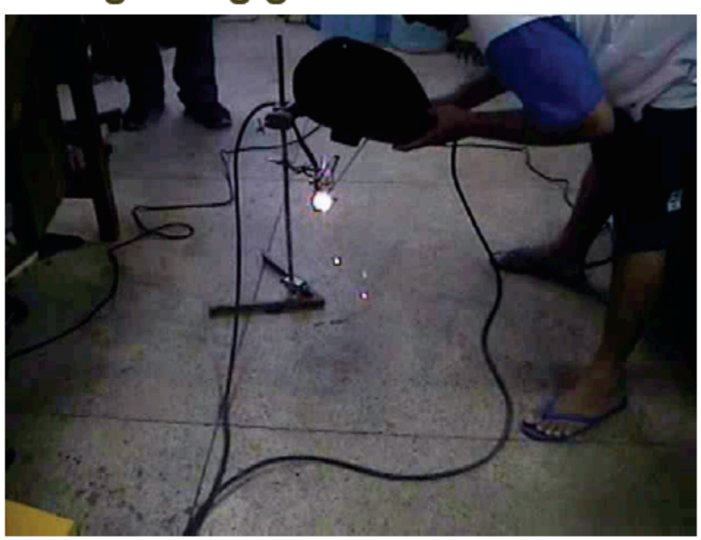


Fig. 1. S… bottom ele…

- Ball lightning goes under the cable



Low temperature plasmas containing negative ions exhibit many nonlinear phenomena.

Plasma separation in time and space into the regions with different ion composition is *universal property* of non-equilibrium plasma.

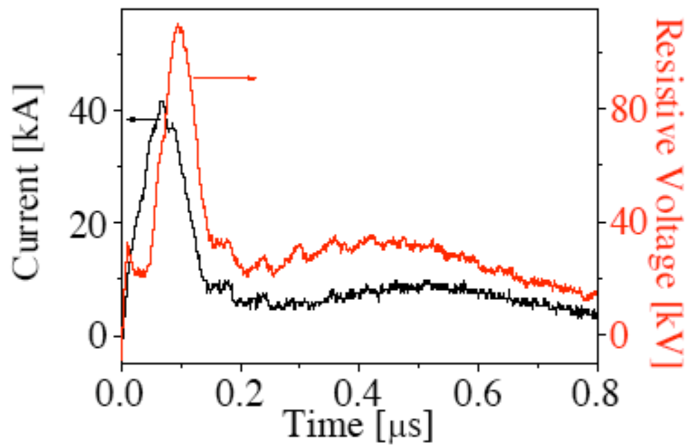
- **Concept of fronts has been successfully applied to plasma ignition, extinction and stationary state.**

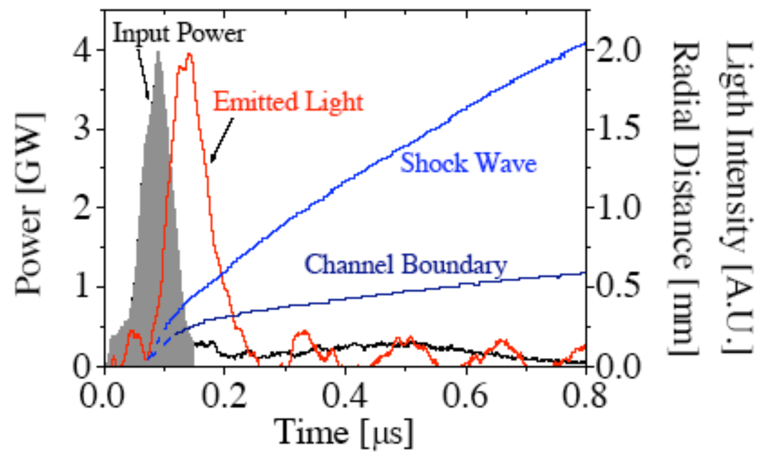
- **A Brazilian team made lightning balls in the lab using a dc arc, "*Phys. Rev. Lett.* 98, 048501 (2007).**
- **The energy from the arc produces silicon nanoparticles, which later burn.**

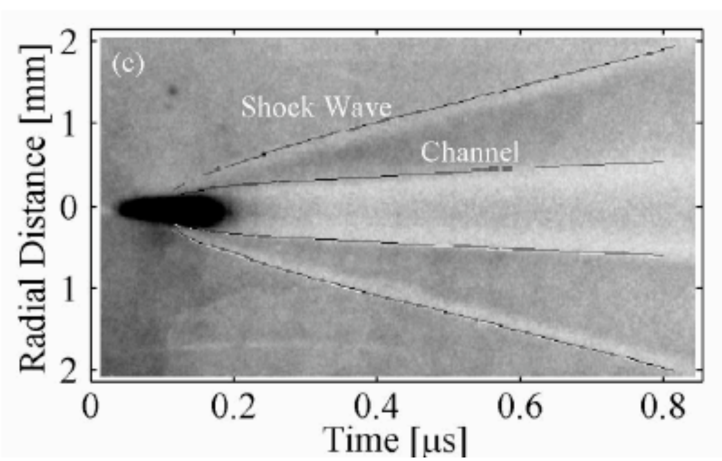
Grinenko, exploding wire in water, fast discharge

Basic Experimental Results

Aperiodic Discharge - Cu Wire 100μm in diameter, 100mm in length, 35 kV charging voltage







Maximum Estimated Pressure

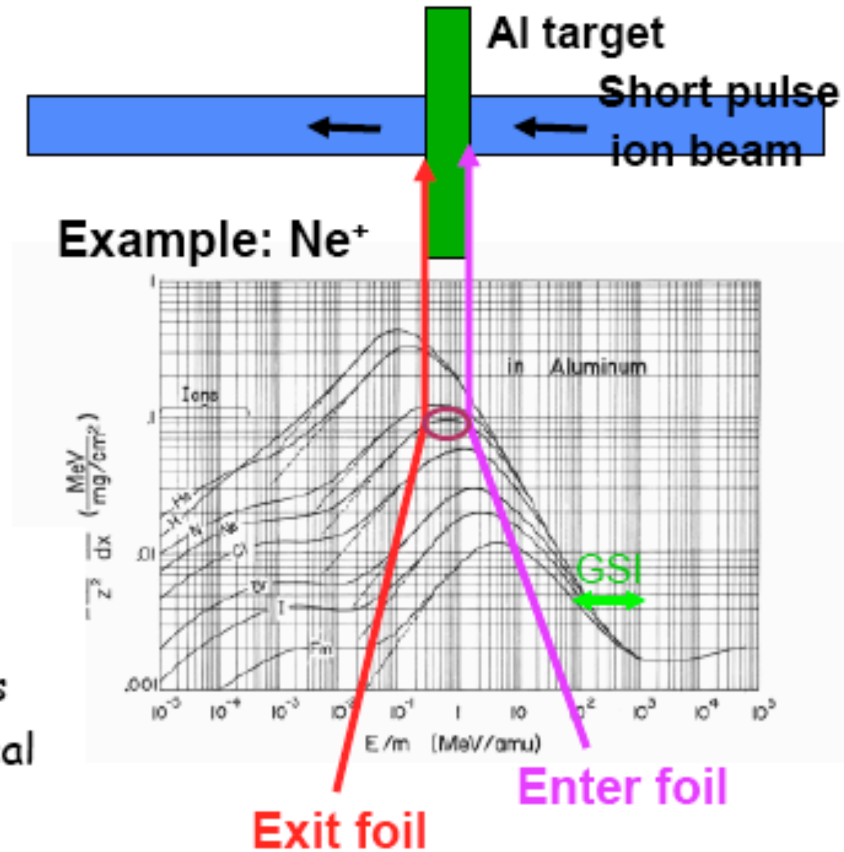
Obtained in this experiment:

$P_{max} \sim 50$ kBar

Bieniosek, Heavy ion wdm.

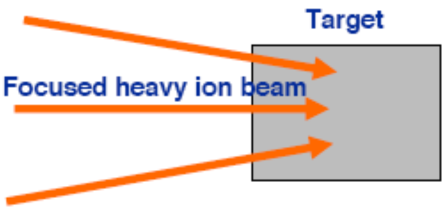
Ion beams provide an excellent tool to generate homogeneous, volumetric warm density matter.

- Warm dense matter (WDM)
  - T ~ 0.1 to 10 eV
  - ρ ~ 0.01 -1 * solid density
- Techniques for generating WDM
  - High power lasers
  - Shock waves
  - Pulsed power (e.g. exploding wire)
  - Intense ion beams
- Some advantages of intense ion beams
  - Volumetric heating: uniform physical conditions
  - High rep. rate
  - Any target material

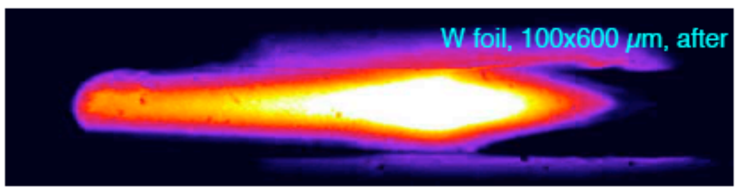


WDM strategy: maximize uniformity and the efficient use of beam energy by placing center of foil at Bragg peak.

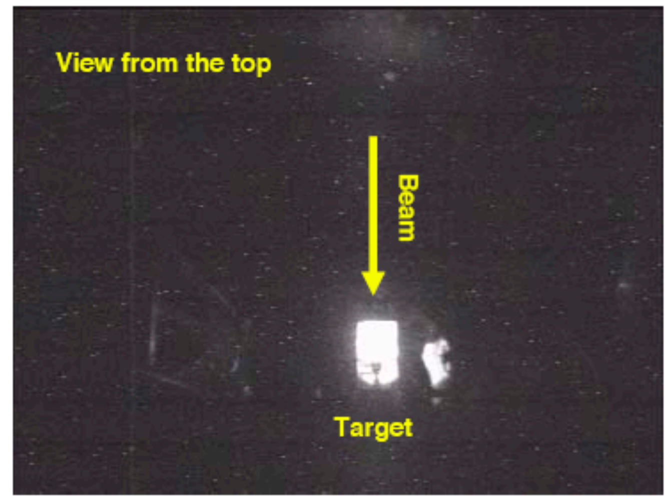
Ni, pyrometer for heavy ion experiments



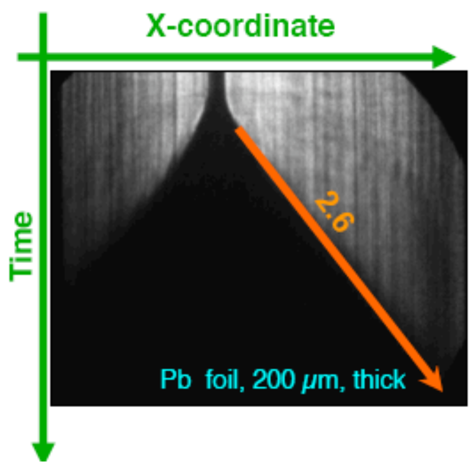
Target self emission (view from the



Explosion of lead target during irradiation
by Uranium beam from SIS-18 (GSI)

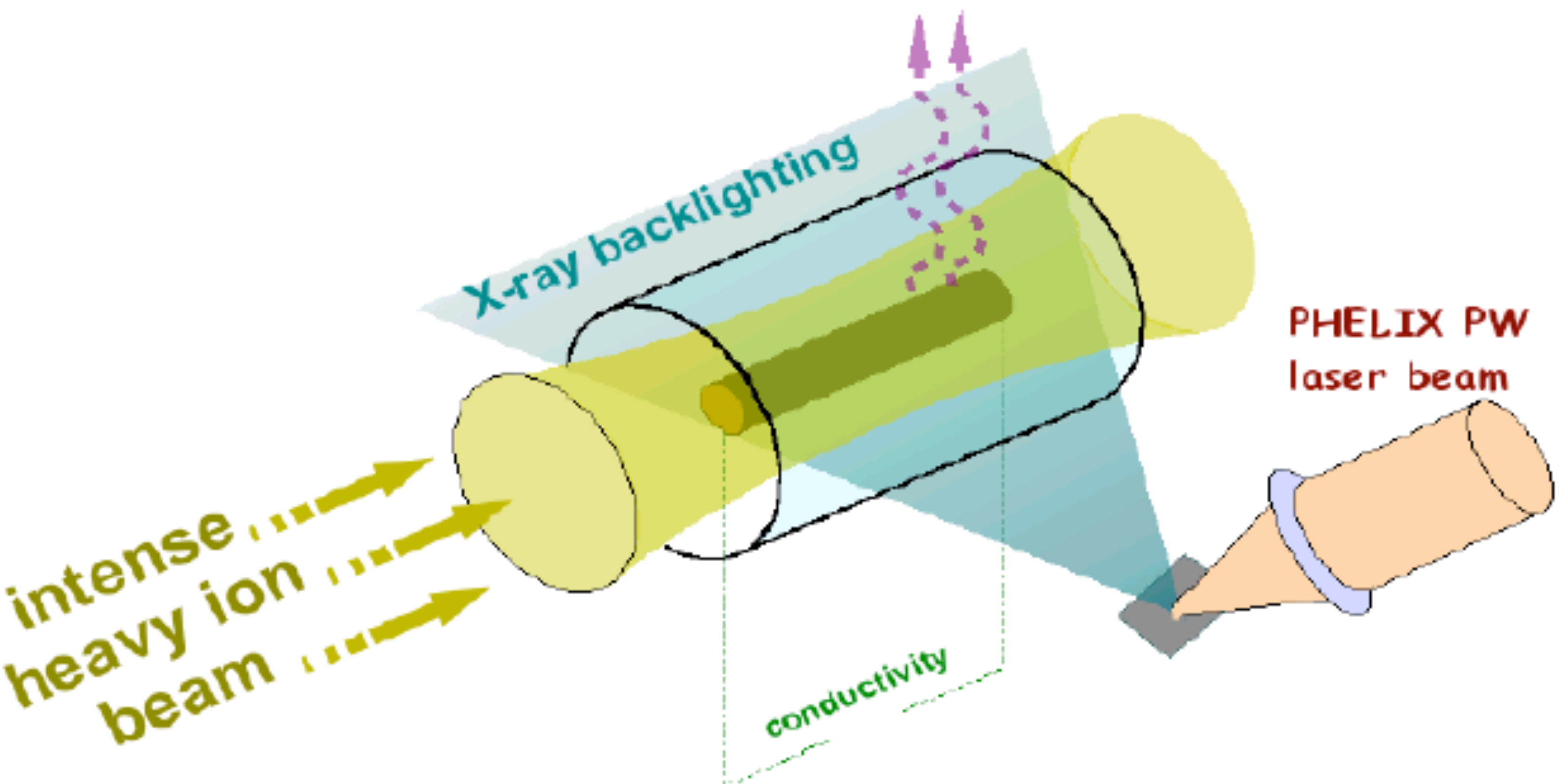


Target expansion emission (view from



How hot is it and what is the expansion velocity?

Cylindrical HIHEX Experiment Design Using Solid Material

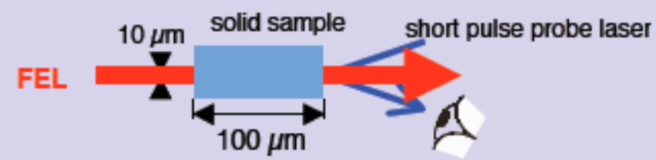


Hoffman, Tahir, et al GSI/FAIR

Future X-ray FEL Experiments (Falcone/Lee)

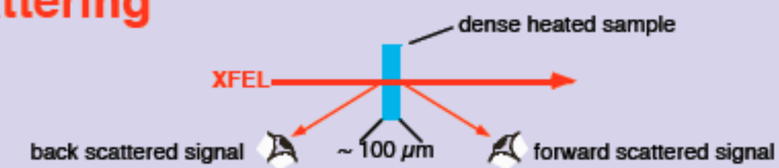
• Creating Warm Dense Matter

- Generate ~ 10 eV solid density matter
- Measure the equation of state



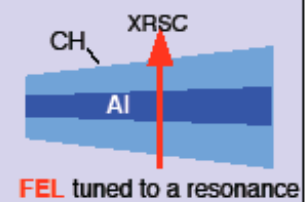
• Probing dense matter with Thomson Scattering

- Perform scattering from solid density plasmas
- Measure n_e, T_e, $\langle Z \rangle$, $f(v)$



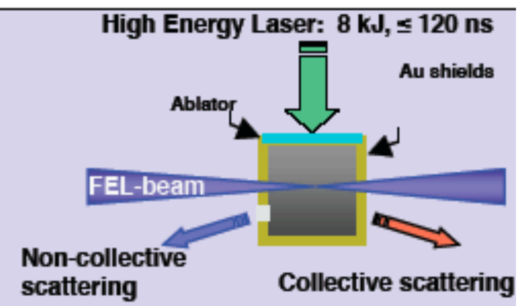
• Plasma spectroscopy of Hot Dense Matter

- Use high energy laser to create uniform HED plasmas
- Measure collision rates, redistribution rates, ionization kinetics

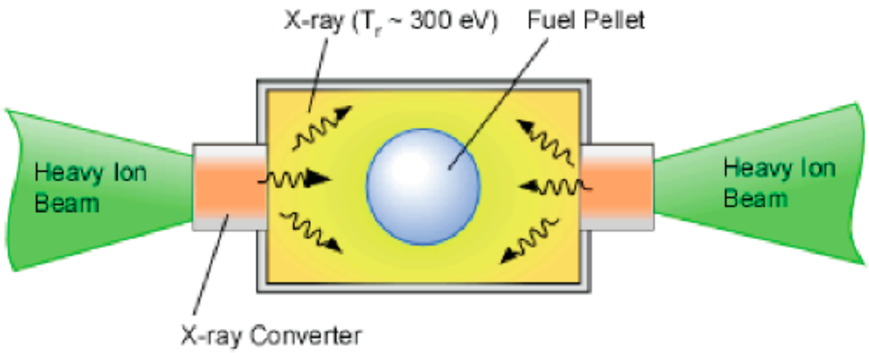


• Probing High Pressure phenomena

- Use high energy laser to create steady high pressures
- Produce shocks *and* shockless high pressure systems
- Study high pressure matter on time scales < 1 ps
- Diagnostics: Diffraction, SAXS, Diffuse scattering, Thomson scattering



Beam-energy deposition profile is very important in HIF target design.



E ~ 10 GeV
I ~ 10 kA
τ ~ 20 ns

- The overall gain of the HIF target strongly depends on the uniformity and time variation of the black body radiation.
- The density and temperature of the X-ray radiator dynamically change within a short period of beam irradiation (~20 ns).

⬇

- To optimize the HIF target design with hydrodynamic simulations including ion stopping processes, reliable data of stopping power over a wide density-temperature range is required.

TOKYO TECH Pursuing Excellence

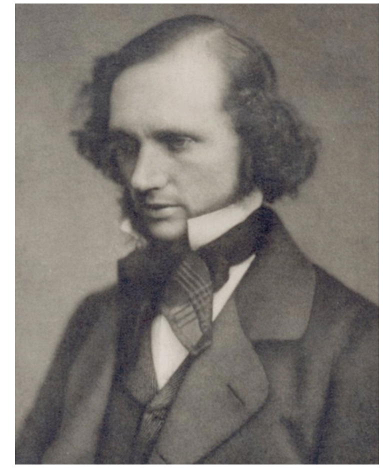
Hasegawa

Fisch: Theory to motivate experiments; use ideas for manipulating ideal plasmas in the WDM regime

Extreme Parameters Enabled by Warm Dense Plasma
-- and Mediated by Plasma Waves

1. Acceleration of charged particles through plasma wakes
    a. What are maximum gradients and energies?
    b. How long need a plasma wave persist?
2. Differential collisionless deceleration of charged particles
    a. Fast ignition with differential core stopping
3. Current Drive in Dense Plasma
    a. What is highest magnetic field that can be generated in the laboratory?
    b. Pose Adjoint Problem -- then integrate to get conductivity!
4. X-ray pulse compression and focusing; fs to as
    a. What are the largest x-ray intensities that can be obtained and focused -- vacuum breakdown?
    b. How long need a plasma wave -- or medium -- persist?

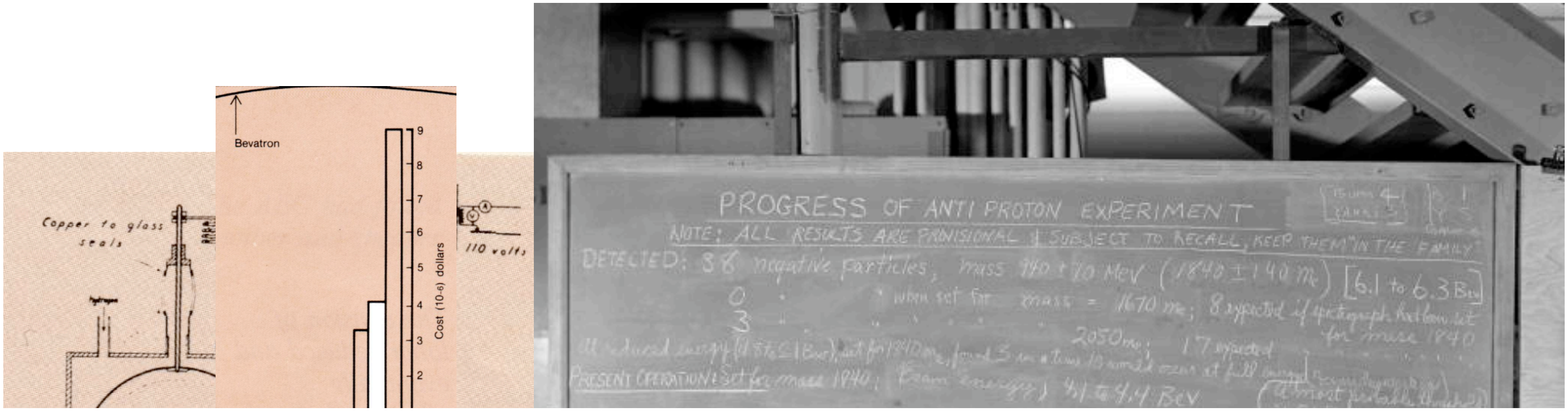
Lord Kelvin



1824-1907

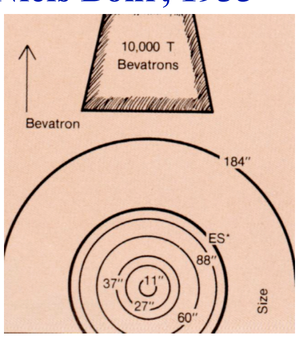
- "When you are face to face with a difficulty, you are up against a discovery."
- "The more you understand what is wrong with a figure, the more valuable that figure becomes."
- "To measure is to know."
- "If you cannot measure it, you cannot improve it."
- "When you can measure what you are speaking about, and express it in numbers, you know something about it; but when you cannot measure it, when you cannot express it in numbers, your knowledge is of a meagre and unsatisfactory kind."
- "I am never content until I have constructed a mechanical model of the subject I am studying. If I succeed in making one, I understand, otherwise I do not."
- "There is nothing new to be discovered in physics now. All that remains is more and more precise measurement."--(*careful what you say after 50 years of physics!*)

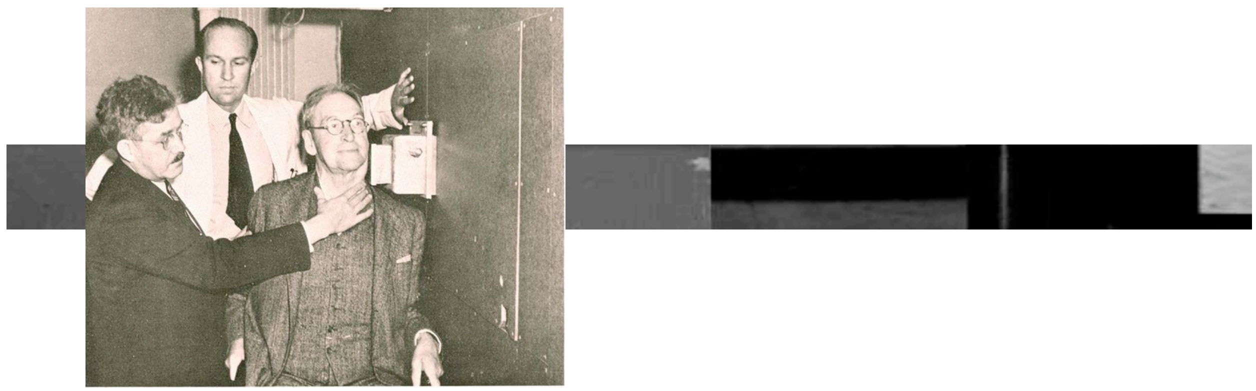
•**Kelvin in his own words (from D. Saxon, physicsworld.com)**



"I must confess that one reason we have undertaken this biological work is that we thereby have been able to get financial support for all of the work in the laboratory. As you know, it is much easier to get funds for medical research."

—Lawrence to Niels Bohr, 1935





Final thoughts on the school

- In one week, it is not possible to give a detailed exposition of a still-not-fully-defined field which exists in a regime where parameters are of order unity and where descriptions used in other branches of physics break down.
- The talks gave an excellent overview of the breadth, richness, and scope of the physics
- New technologies lead to new experiments and challenges
- The notes and website serve as a useful reference for your future graduate studies.
- Someone should write the book….

Thanks for attending!