WDM/Dense Plasma Experiments: Issues and Examples

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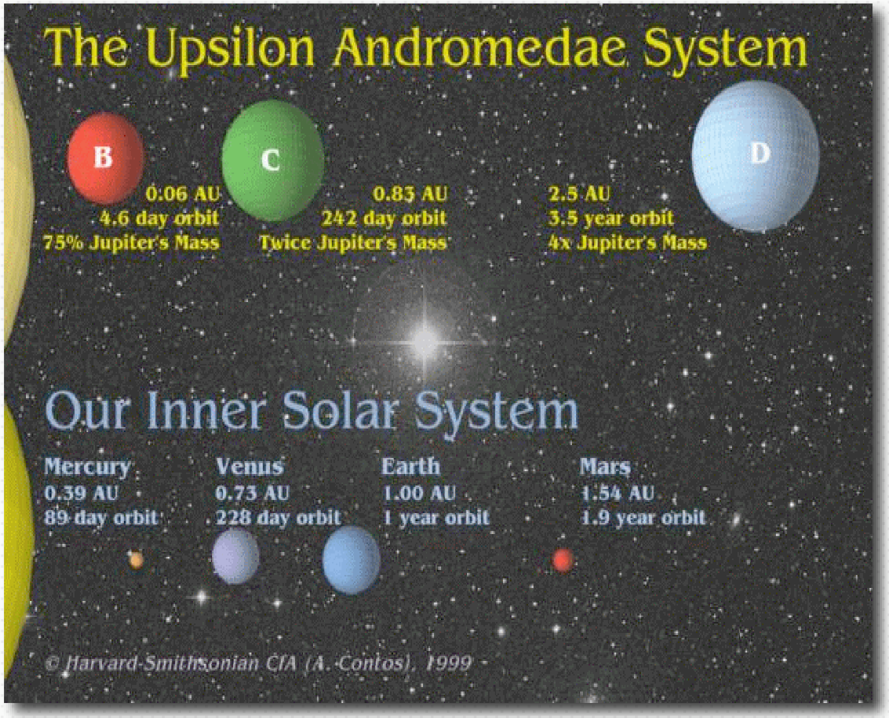
Why are WDM/Dense Plasmas interesting?

WDM and dense plasmas are interesting because;

1) It is difficult to develop theoretical models for material at such conditions.

2) Many exotic objects, such as white and brown dwarfs, neutron stars, giant planets, etc. exist at conditions where much of their makeup is WDM or dense plasma.



What are physics issues for WDM/Dense Plasmas?

- Why is this so difficult theoretically? Mainly because most of the simplifications used for solving other many body physics questions are not appropriate in this regime. (See Michael Murillo's talk later this afternoon.)

- Of course, this implies that nearly all properties of WDM are difficult to predict. For example, even the equation of state for WDM, a critical component for modeling white dwarfs and giant planets, is not well-known.

- Other basic transport properties:
  - electrical conductivity, important for many pulsed power applications
  - opacity, important for modeling laser-plasma expts., holraums, etc.
  - and viscosity, affects growth of instabilities, turbulence

How do we improve our knowledge of WDM?

- Follow the scientific method! First, develop a hypothesis, such as a particular theoretical approach will describe some property, and then test it.
- For some simple questions, this test could be a direct numerical simulation like molecular dynamics, but ultimately one usually needs to do experiments.
- However, not all experiments are equal. For example, an experiment that has small enough error bars to actually distinguish between different theoretical models is essential.
- For WDM experiments, this can be a difficult goal to reach.

Why are WDM experiments difficult?

- In any experiment, it is important to do only one experiment at a time. What do I mean by this?
  - Minimize gradients, both spatially and temporally
  - Measure the material conditions well enough to define the state of the material
- To make these measurements requires access to the material
  - Many times the material is tamped (surrounded by other material to prevent expansion)
  - The density is so high that diagnosing the bulk of the material can be difficult
- Also, since the conditions are transient, the measurements must be time-resolved. This requires higher power to obtain enough signal and thus more expensive tools.
- The end result is that one needs to be very clever or use some of the large facilities. Using large facilities often means large design efforts to help ensure success of expensive experiments.

Detailed examples of WDM/dense plasma experiments

We present two examples of experiments addressing dense plasma physics issues at Los Alamos.

- Electrical conductivity experiments.
  - Many, many theoretical models were developed that could predict electrical conductivity.
  - Electrical conductivity is relatively easy to measure, compared to other properties, and these measurements provided the first critical tests for theory.
  - Experiments were carried out at LANL and several other labs, all following similar techniques.
  - These experiments provided very important data that led to the convergence of several dense plasma conductivity models.

- Temperature relaxation experiment.
  - There were many experiments using relatively short pulse lasers that attempted to understand basic dense plasma properties.
  - In these experiments, it became clear that the electrons and ions were not at the same temperature and modeling this temperature relaxation was critical.
  - This is a new experiment designed to measure temperature equilibration rates between electrons and ions in a dense plasma.

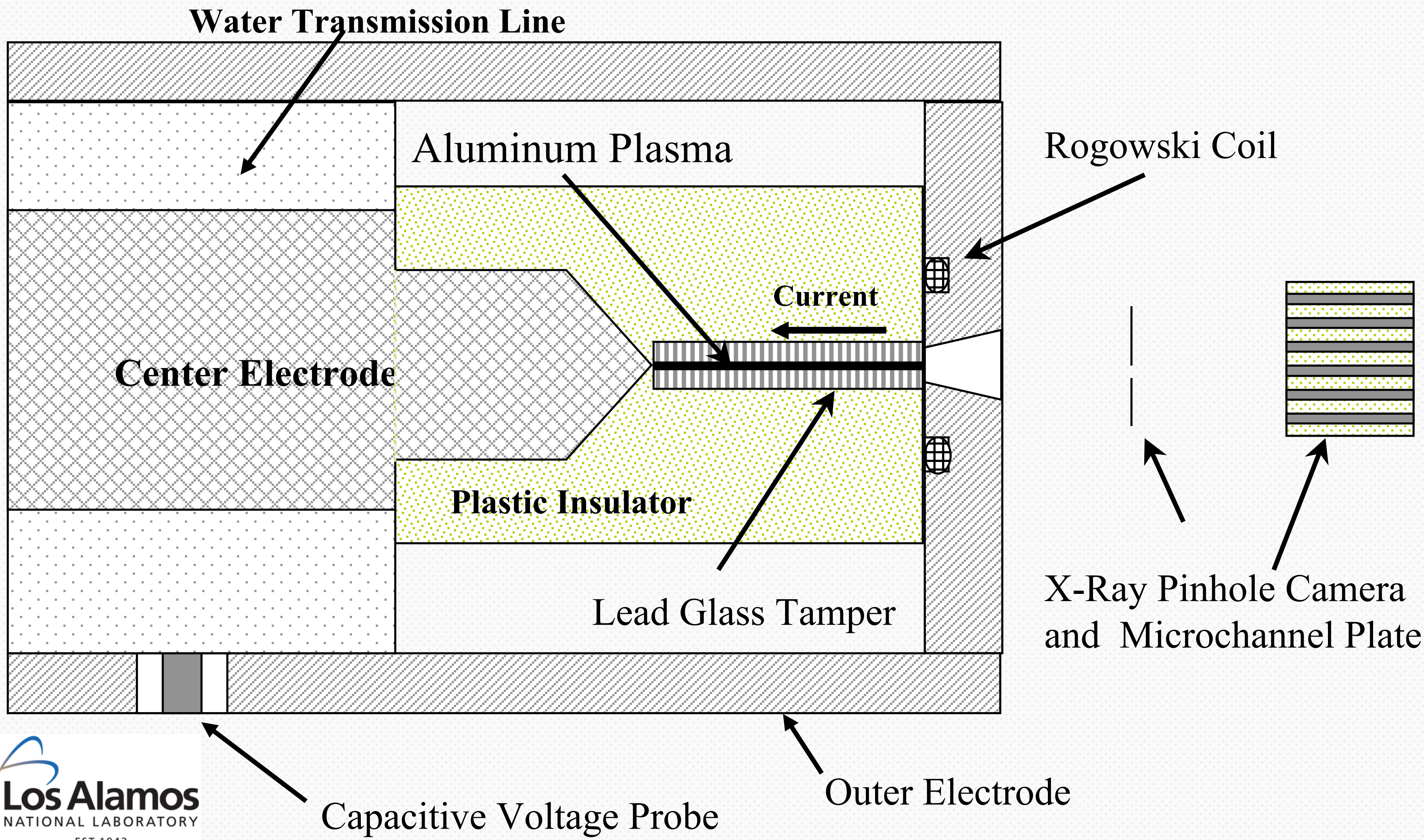
Electrical conductivity experiments, design issues

- Several models were developed to calculate electrical conductivities in dense plasmas.
  - These models all reduced to Spitzer at high temperature and low density, but varied greatly at higher density and lower temperature
  - Needed experiments at high number density and moderate temperatures, several eV near solid density
- To create plasmas at such conditions required some development
  - Materials at these conditions occur at very high pressures and thus expand rapidly
  - Rapid expansion almost always leads to non-uniform densities and temperatures
  - If conditions are non-uniform, conductivity will also be non-uniform
- Diagnosing the plasma conditions is also very difficult
  - The high density makes it difficult to probe the bulk of the material
  - Temperature measurements are extremely difficult
    - This is why x-ray Thomson scattering is so important

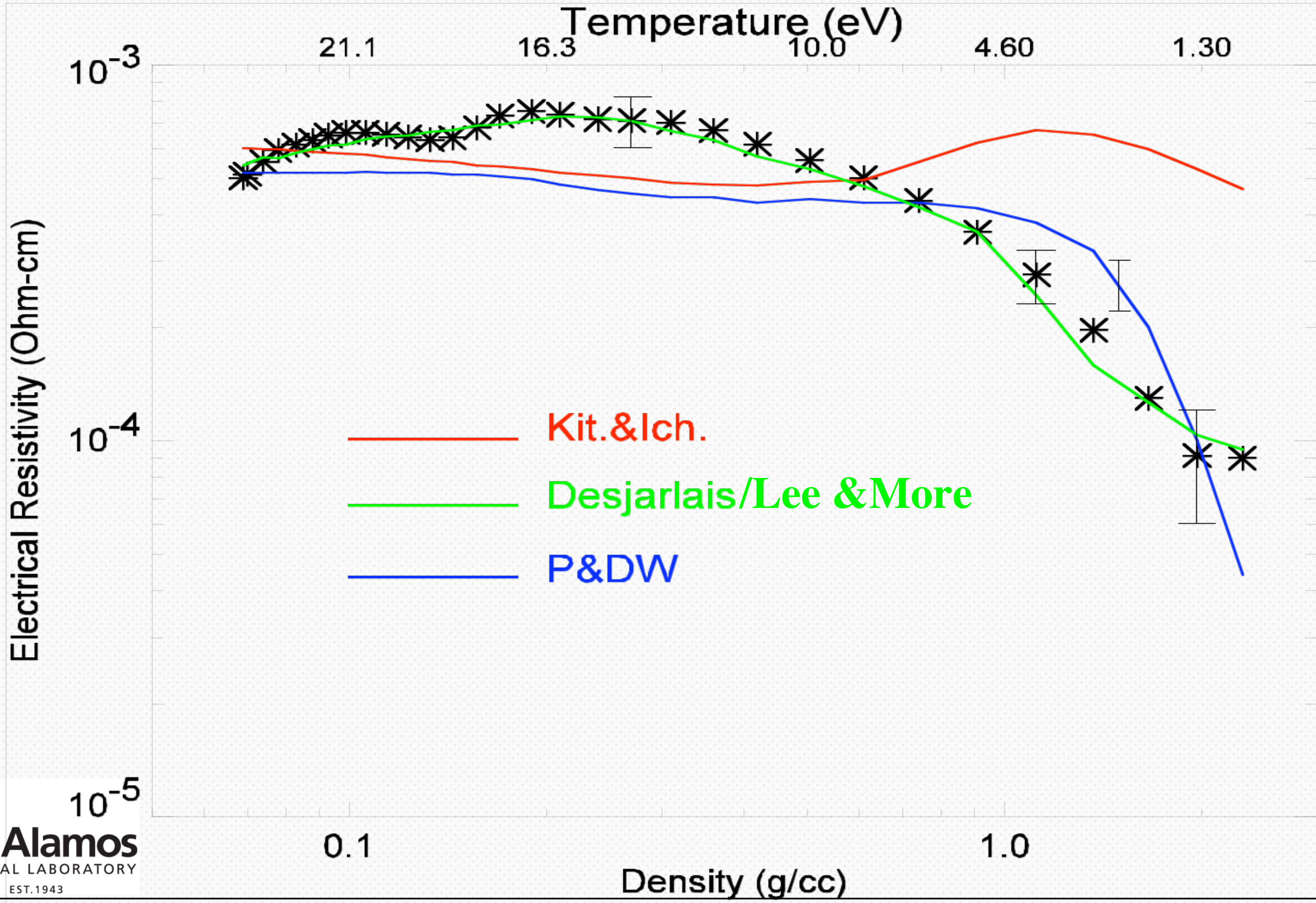
Design issues: continued

- A variety of techniques have been tried, with varying degrees of success
  - Laser produced plasmas
  - Exploding wires
  - Capillary discharges
  - High pressure vapor chambers
- Eventually, the use of tamped exploding wires became the preferred technique.
  - For example, our experiments used high-density lead glass as the tamper
  - Many other experiments, including some discussed here, use water
- These experiments satisfied many requirements
  - The tamping prevents rapid expansion of the heated wire, enabling the material to be uniform
  - Measurement of the current and voltage across the wire enabled one to not only determine the resistance, but also determine the energy absorbed
  - Measurements of the time-dependent radius of the wire were used to determine the density of the material
  - Simulations and emission measurements helped insure the conditions were uniform

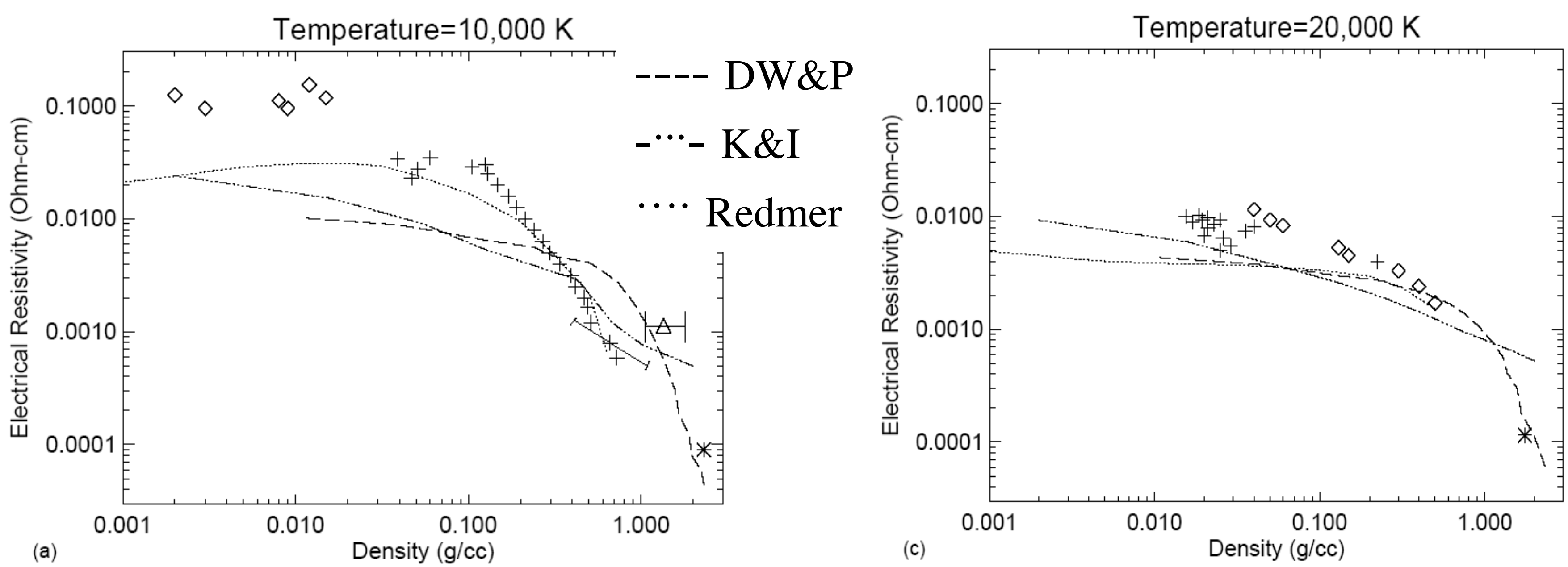
Diagram of LANL tamped exploding wire experiment



Aluminum electrical conductivity experimental results



Results from several aluminum experiments*



Results from multiple experiments on aluminum at fixed temperatures of ~ 1 and 2 eV as a function of density.

* A.N. Mostovych and Y. Chan, PRL **79**, 5094(1997)
A.W.Desilva and J.D.Katsouras, PRE **57**, 5945(1998)
I.Krisch and H.J.Kunze, PRE **58**, 6557(1998)
J.F.Benage, W.R.Shanahan, M.S.Murillo, PRL **83**, 2953(1999)

The aluminum experimental results had several ramifications

- The models using liquid metal theory (those using Ziman formula) matched the data well, provided they did a good job determining the ionization level and the temperature was high enough that not many neutral atoms were present.
- The non-Spitzer kinetic theory plasma type models also matched the data well, except at high density.
- The best model for fitting the data is the empirical model of Lee and More that was improved by Mike Desjarlais.
  - Based on these and other data, he has developed several sets of tables that are the best available.
- These experiments did not resolve the metal-insulator or plasma phase transition issue.

Temperature relaxation experiment, design issues

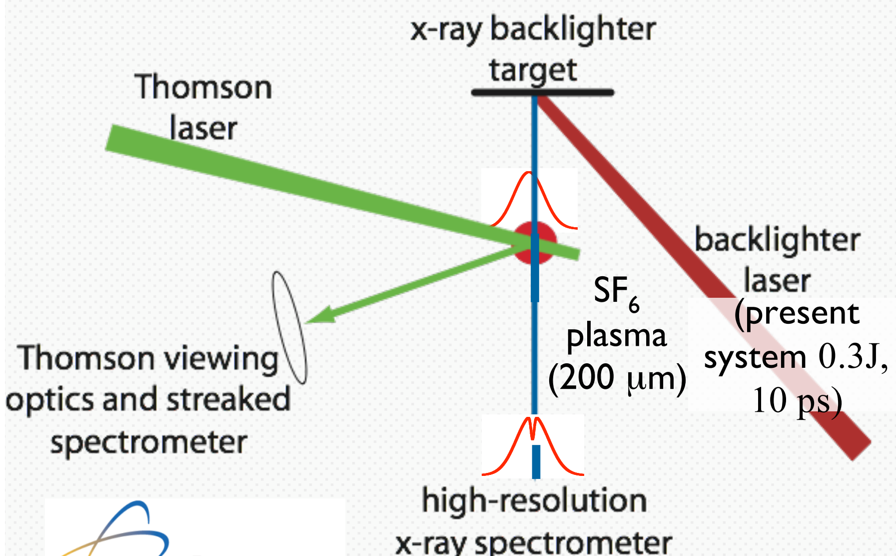
- Recently, many models have been focused on the question of temperature relaxation between electrons and ions in a dense plasma.
  - *Energy relaxation and the quasiequation of state of a dense two-temperature nonequilibrium plasma* (vol E **58**, pg 3705, 1998), Dharma-wardana, MWC; Perrot, F, Physical Review E, **63**, p.069901(2001).
  - *Temperature relaxation in two-temperature states of dense electron-ion systems*. Hazak, G; Zinamon, Z; Rosenfeld, Y; Dharma-wardana, MWC, Physical Review E, **64**, p.066411/1-5 (2001).
  - *Dense plasma temperature equilibration in the binary collision approximation*, Gericke, DO; Murillo, MS; Schlanges, M, Physical Review E, **65**, p. 0364118/1-5(2002).
  - *Charged particle motion in a highly ionized plasma*. Brown, LS; Preston, DL; Singleton, RL, Physics Reports, **410**, p.237-333 (2005).

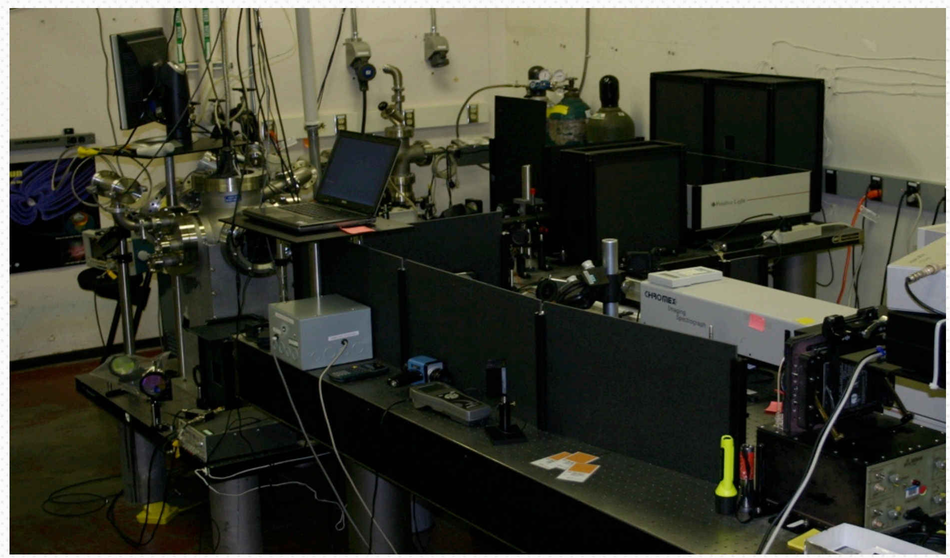
- There has *never* been a direct measurement of this relaxation rate, even in plasmas where the Spitzer rate is expected to be valid.

- A new experiment was needed, one at high number density and moderate temperatures, where electron and ion temperatures could be measured separately.

Experimental setup for temperature relaxation measurement

- We use short-pulse lasers to:
  - form non-equilibrium plasmas (125 eV electrons, 15 eV ions)
  - measure T_e and T_i independently vs. t (with 10-100 ps accuracy)
    - T_e - Thomson scattering
    - T_i - Doppler broadening of x- ray absorption line

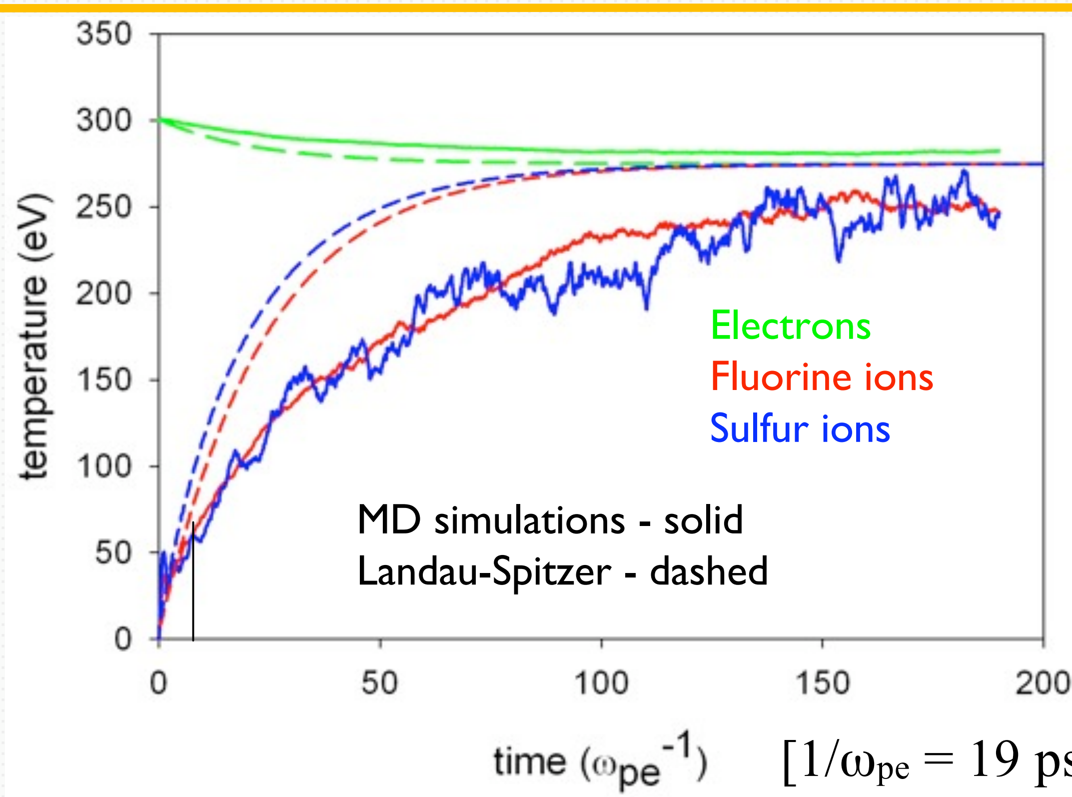




Measuring T_i is crucial, because T_e ~ constant, and it is also very challenging

- We have chosen a technique in Doppler broadened absorption spectroscopy that, in principle, will work, but has not been demonstrated at these conditions.
- This technique requires a small population of moderate *Z* ions like Sulfur (ionized to S^{14+}) and a very high resolution spectrometer, in our case a quartz crystal spectrometer.
- To obtain the time-resolution we need requires development of a ps time-scale x-ray backlighter to produce x-rays at the specific energy needed to measure the absorption profile of this line in the plasma.
- Our first attempts at producing the specific x-ray energies we needed from this backlighter were unsuccessful. This led to a concentrated effort to determine if the absorption spectroscopy ion-temperature measurement could be done with our laser system.

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

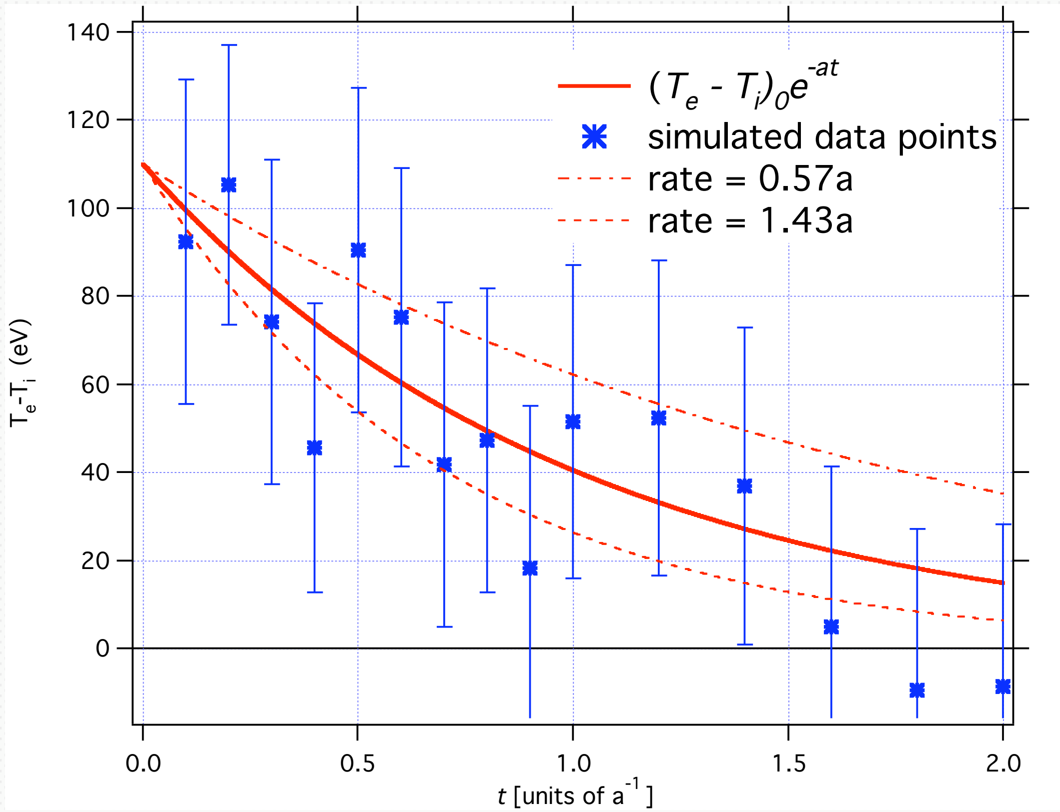
Rates:
L-S ~ 5.2 eV/ω_{pe}^{-1}
MD ~ 2.3 eV/ω_{pe}^{-1}

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

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

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.

Given our requirement of accuracy in α of 50%, we obtain the required accuracy in T_i



The uncertainty in α is given by:

$$\sigma_\alpha = \sqrt{\frac{1}{\Delta}\sum\frac{1}{\sigma_i^2}}$$

where $$\Delta = \sum\frac{1}{\sigma_i^2}\sum\frac{t_i^2}{\sigma_i^2} - \left(\sum\frac{t_i^2}{\sigma_i^2}\right)^2$$

and $$\sigma_i^2 = \left(\frac{\delta(T_e - T_i)}{T_e - T_i}\right)_i^2$$

From: P. Bevington, "Data Reduction and Error Analysis for the Physical Sciences," McGraw-Hill Publishing, New York, N.Y. 1969

Knowing α to 50% defines our uncertainty in T_i (given δT_e):

$$\left(\frac{\delta(T_e - T_i)}{T_e - T_i}\right)_i = \frac{\sqrt{(\delta T_i)_i^2 + \langle \delta T_e \rangle^2}}{T_e - T_i}$$

from $\delta T_e / T_e$ = 0.15 and given 15 data points, gives a required δT_i ~ 30eV

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Required accuracy in T_i determines x-ray source to film distance and thus x-ray flux required

tradeoff on δTi vs x- ray backlighter flux required

- larger x-ray source to film distance *R* → better resolution on width
- but signal on film drops as 1/*R*2

Given:

-film resolution of 4 μm

-Bragg crystal resolving power of 11,500

-source spot size of 12 μm

We obtain an equation for $\delta T_i/T_i$ as a function of R (in cm):

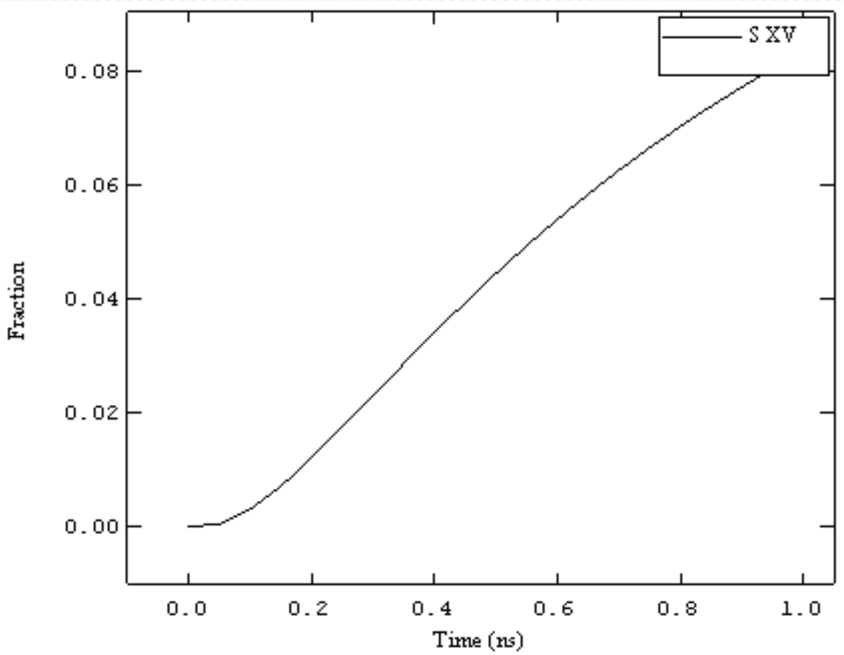
$$\frac{\delta T_i}{T_i} = \frac{8\sqrt{(0.011T_i + 0.445) + 144/R^2}}{0.011T_iR}\left[1 + \frac{0.445 + 144/R^2}{0.445 + 144/R^2 + .011T_i}\right]^{1/2}$$

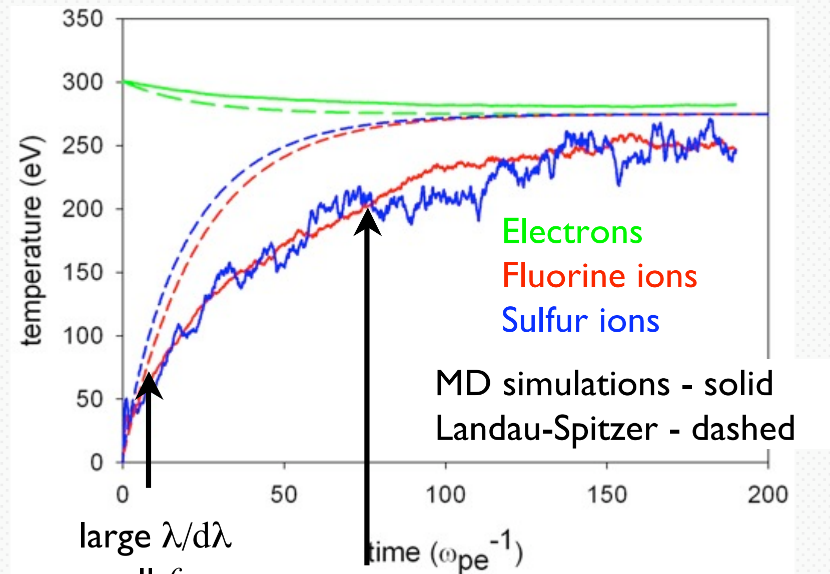
For $\delta T_i \sim 30$ eV ⇒ $R = 35$ cm

To obtain δα/α = 50%, we require the film to be at *R* = 35 cm

How big is the absorption dip relative to the emission peak?

PrismSpect calculation results for SXV show f_{SXV} ~ 0.02 at 200 ps given initial SF_6 neutral density $n_{\mathrm{SF6}} = 1.0\mathrm{X}10^{19}$ cm^{-3}, and $T_e = 125$ eV





large $\lambda/d\lambda$
small f_{S14+}

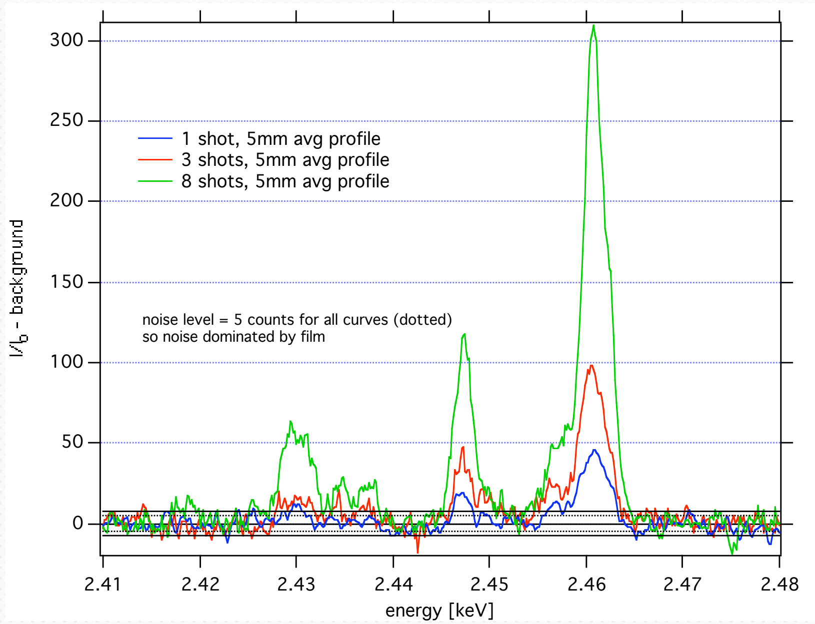
small $\lambda/d\lambda$
large f_{S14+}

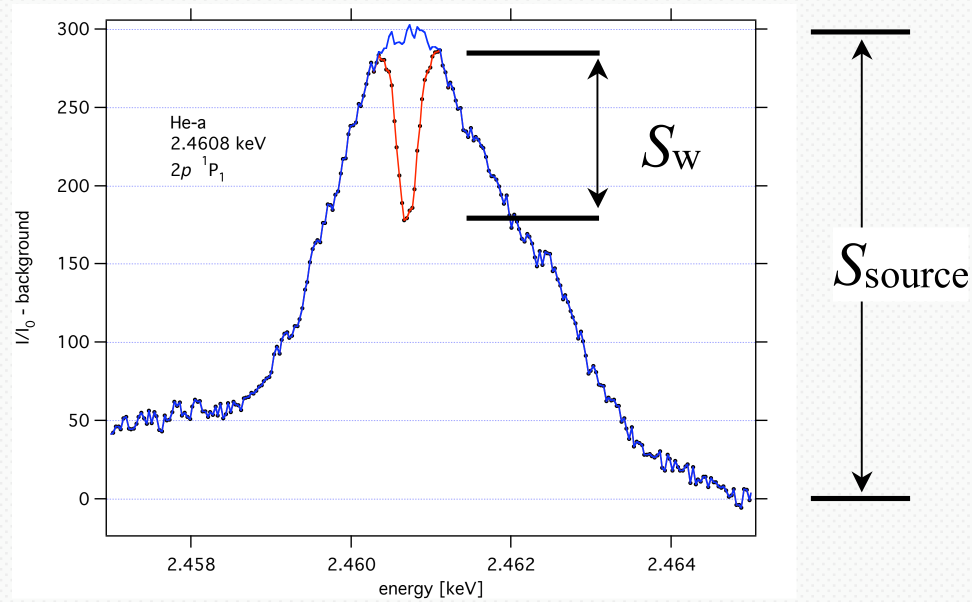
The total optical depth at the center line for SXV ($\equiv S^{14+}$) He-α, for a 200 μm diameter plasma is:

$$\tau = 5.646 \times 10^{-3} \frac{\lambda}{d\lambda} f_{S^{14+}}$$

At $1/e$ time - this results in an absorption of 40%

Given absorption level and *Noise* level determine *Signal* needed on film





data at 1, 3, 8 shots show noise as fn. of flux (or distance) and find ~constant, *N* = 6 counts (dominated by film)

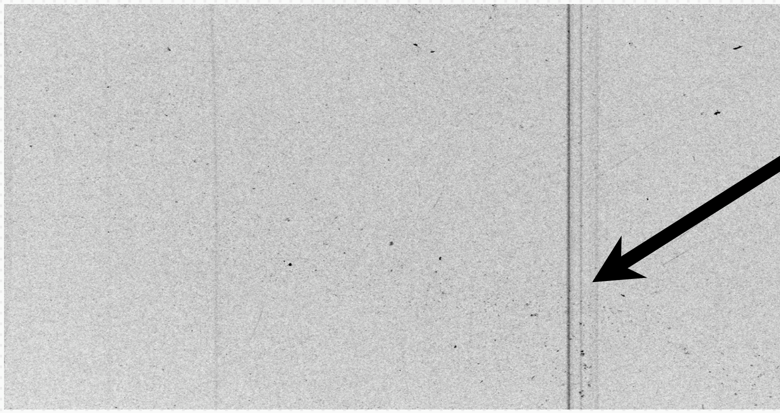
at half-width of absorption dip, **want** *S*/*N* = 10

From expected absorption, $S_w = \frac{1}{2}(40\%) \times S_{source}$

$$S_{source} = \frac{S_w}{0.2} = \frac{10 \times N}{0.2} = 300 \text{ counts}$$

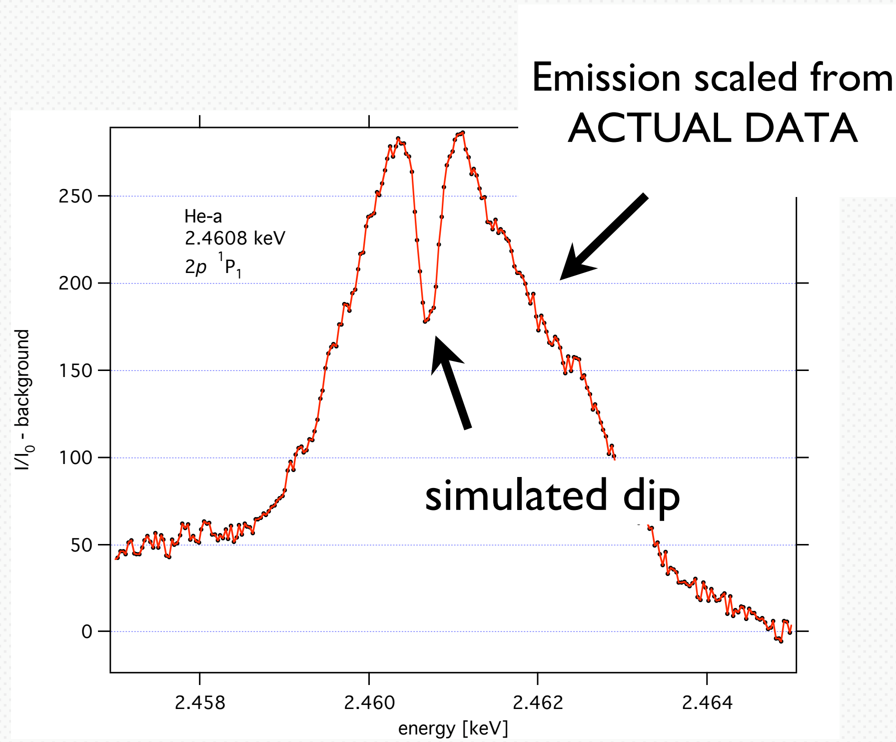
Given absorption level and *S*/*N*, require 300 counts on film

Given x-ray source to film distance, we estimate what our signal should look like



Actual Data @ R = 8.9 cm

- take 8-shot emission results @ 8.9 cm from source
- 'move it' to 35 cm distance:
  - increase dispersion
  - scale down by factor of $1/r2$ (15.5)
- X factor of (15) to get required S/N
- subtract absorption dip (estimated)
- add expected signal noise



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Present status of our temperature relaxation experiment

- Our data so far indicate the experiment will be successful if we can move the detector farther away.
  - Improves the resolution, but requires more energy in the backlighter
- We have purchased a new laser amplifier to increase the energy of the backlighter laser by a factor of 5.
  - We will keep the same laser intensity by increasing the pulse length of the laser
  - This may actually increase the x-ray production efficiency
  - The new amplifier is being implemented as we speak
- We expect then to have our first measurements of the relaxation rate this spring.
  - Further data at other conditions later in the year

Summary

- We have talked about many important aspects of WDM/dense plasma experiments
  - It is important that experiments distinguish between models
  - Experiments need to be well-diagnosed and characterized
  - One must be careful about using simulations to analyze experiments
- We gave two examples of dense plasma experiments
  - Electrical conductivity experiments
    - These experiments have been very successful in leading to much improved theoretical models
  - Temperature relaxation experiments
    - This is an ongoing experiment that has been designed to provide important data that should be able to distinguish among many theories