LBNL, LCLS, LLNL Three-Lab collaboration proposal: R. More, consultant

Is there a 3-Lab collaboration that would be more than just repeating the same experiment 3 ways in 3 places?

Want the total to be greater than the sum of the parts

CONDUCTION → **Thermal** κ **q** $= - \kappa \nabla$ **T**

→ **Electrical** σ **j** $= \sigma$ **E**

$\kappa = \kappa(Z, \rho, T)$, $\sigma = \sigma(Z, \rho, T; \omega)$

κ and σ are material properties

Unknown ?? *Measurable ??* *Important ??*

Are conductivities ***MEASURABLE*** *?*

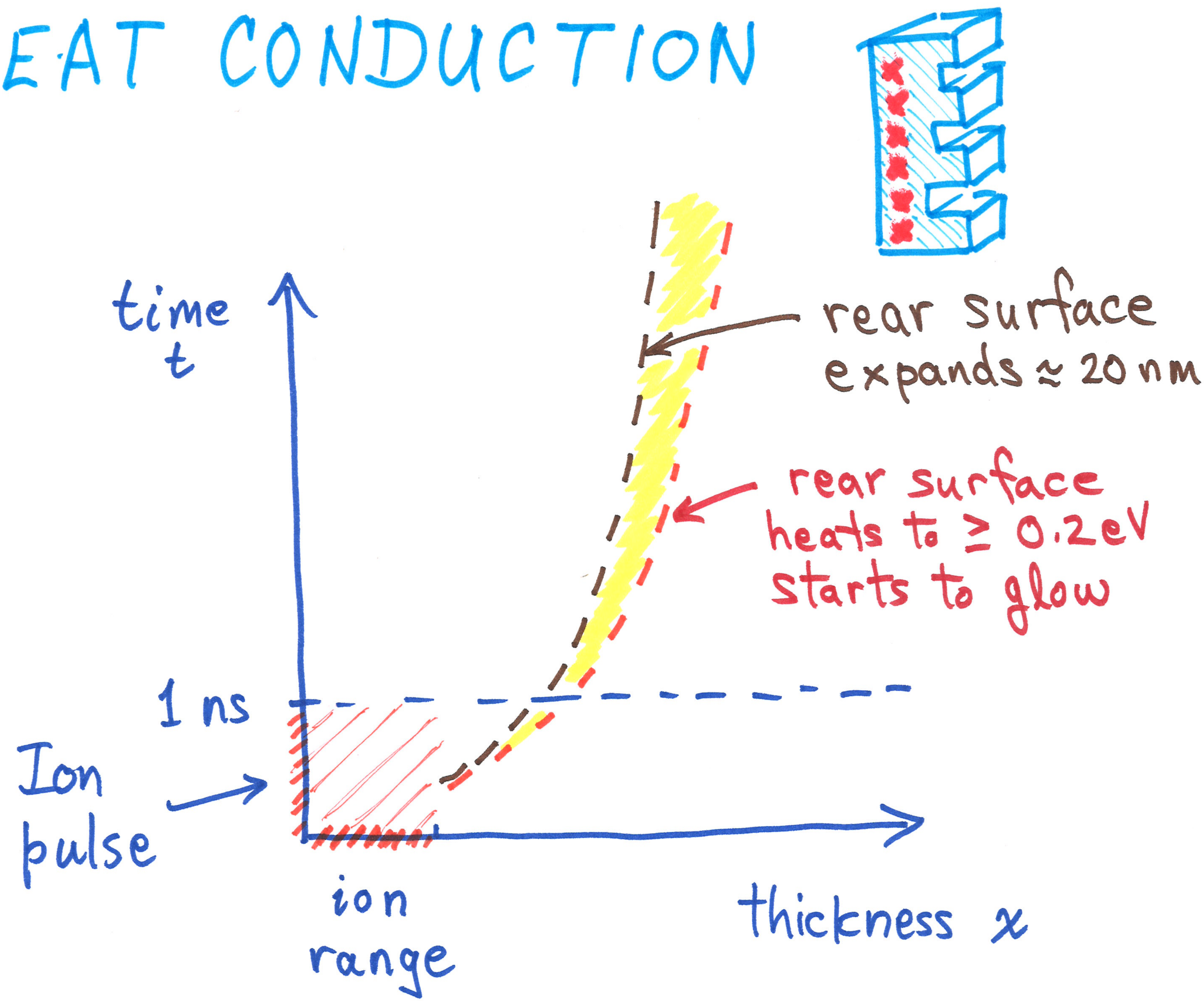
DIFFICULTIES

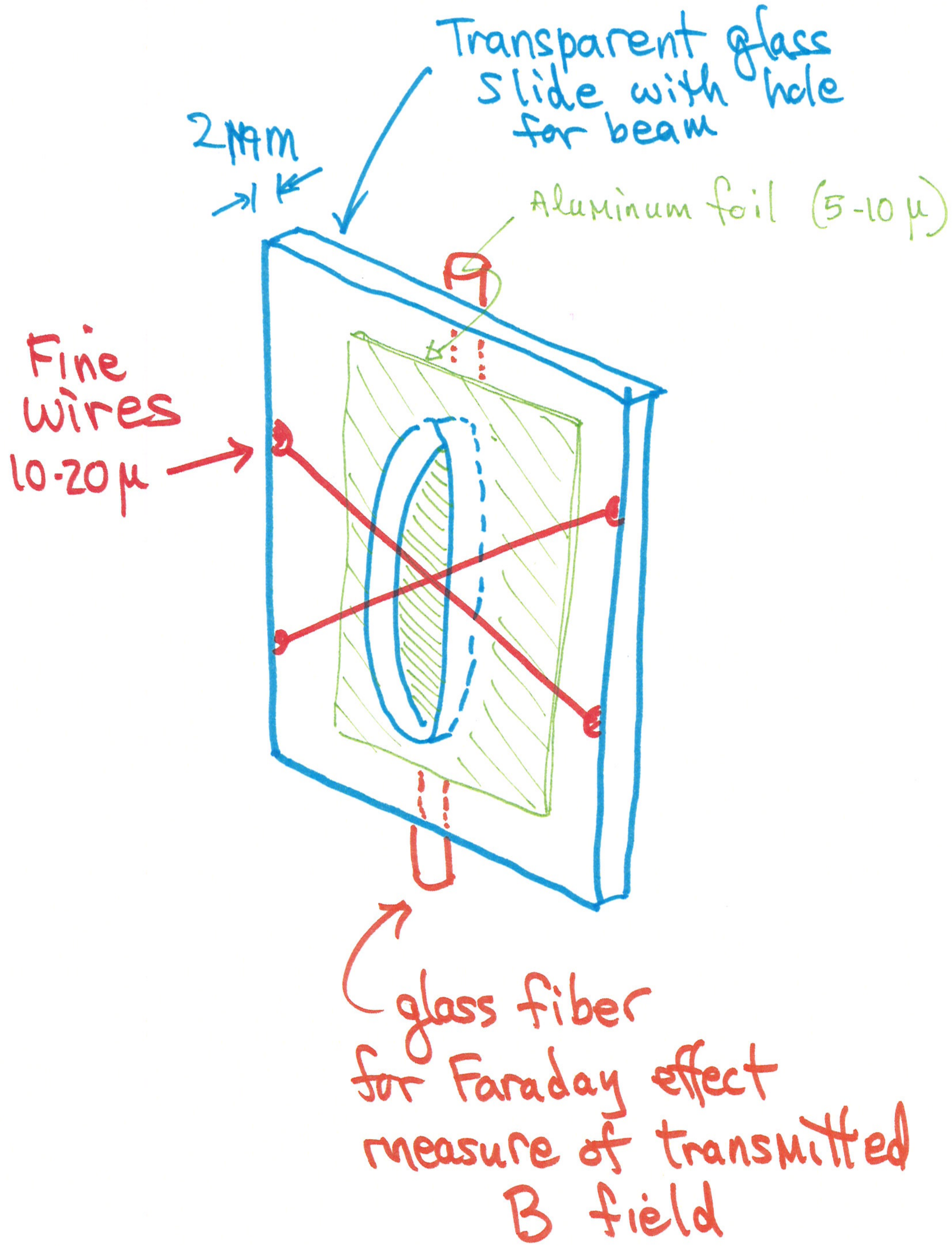
- Junctions, leads and ∇T
- AC
- Inductance and rise-time of B-field
- Hydro motion
- Accurate temperature

There is a limited range ($\rho \sim$ solid, $T \leq 1$ eV) where *things look good*.
All three Labs can do experiments in or near this range.

- **USP Laser** reflection/ellipsometry --> AC conductivity $\sigma(\omega)$
- **Accelerator** - homogeneous volume-heating over 1 micron
  B-field penetration --> Skin effect --> electrical conductivity σ
  Heat conduction --> thermal emission --> conductivity κ
- **X-Rays** --> $S(k) \sim$ atomic pair-correlation --> Predict σ, κ

HEAT CONDUCTION




Transparent glass slide with hole for beam
2mm
Aluminum foil (5-10 μ)
Fine wires 10-20 μ
glass fiber for Faraday effect measure of transmitted B field

SPECIFIC POINTS to TEST

Is κ proportional to σ ?

$$\frac{\kappa}{\sigma T} = L \approx 3.5 \left(\frac{k_B}{e}\right)^2$$

Wiedemann-Franz Law is not verified at WDM conditions.
San Ramon meeting (May, 2012) - participants expressed doubt about it. (Justin Wark)

Does Ziman formula get the right answer ?

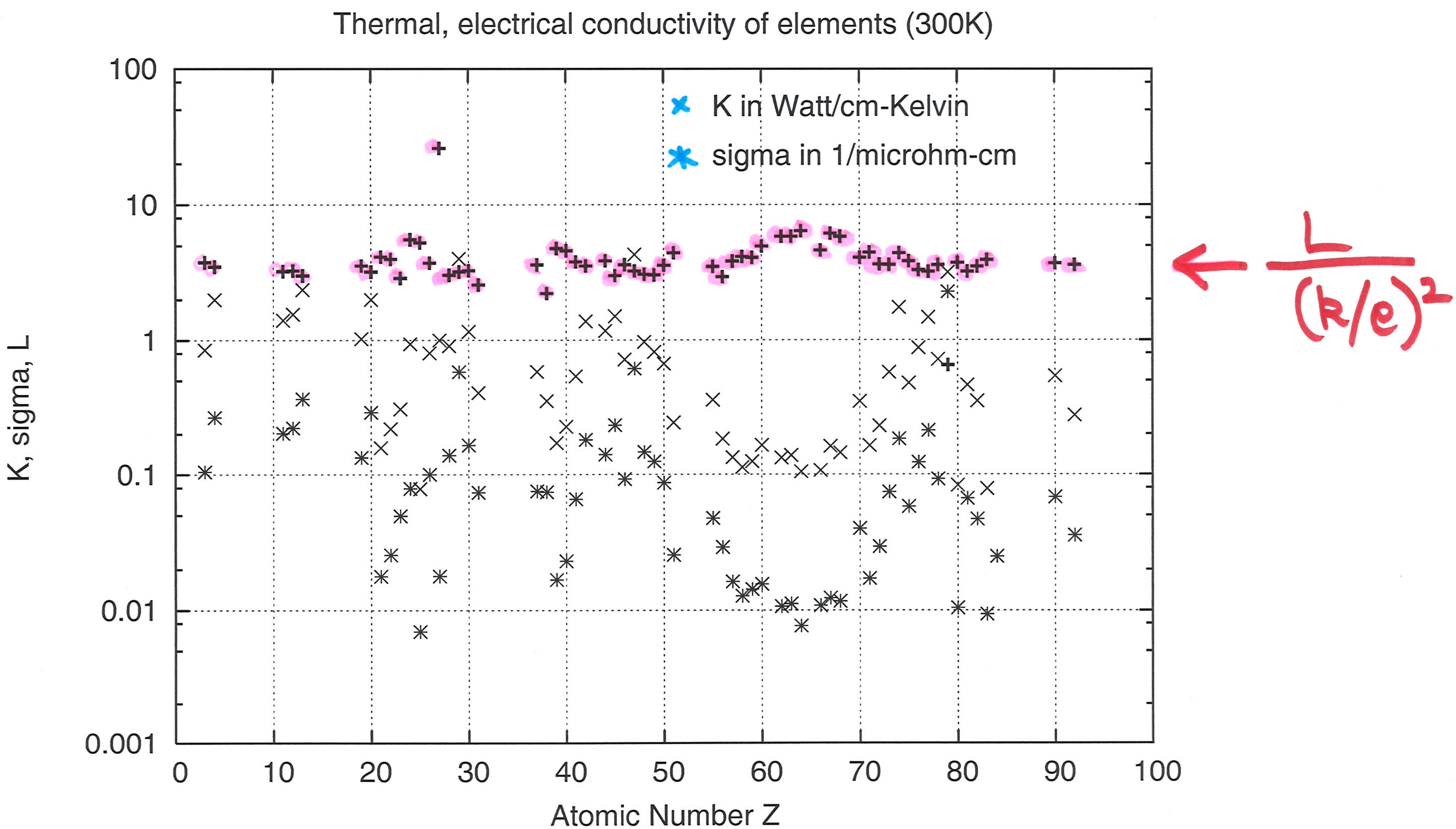
$$\frac{1}{\tau} \cong n_i v_e \sigma_{tr} = n_i v_e \frac{\pi}{k^4}\left(\frac{me}{2\pi\hbar^2}\right)^2 \int q^3 |v(q)|^2 \; S(q)\; dq \qquad \sigma = \frac{n_e e^2 \tau}{m_e}$$

LCLS	X-ray source + laser heating, diagnostics	Measure $S(k)$
LBNL	Accelerator, diagnostics, analytic tools (codes)	Measure σ, κ up to 1 eV
LLNL	Short-pulse laser, target fabrication, diagnostics, codes & modeling	Measure σ at higher T's

Propose experiments using similar targets, similar temperatures.
Compare diagnostics and compare computer models.

Test Wiedemann-Franz' law

$$L = \frac{K}{\sigma T} \approx 3.5\left(\frac{k}{e}\right)^2 ?$$



$$10^6\left(\frac{k}{e}\right)^2 = 139.$$

Is conduction IMPORTANT ?

1) NIF Experiments <== Rayleigh-Taylor <== (RT might be stabilized by heat conduction

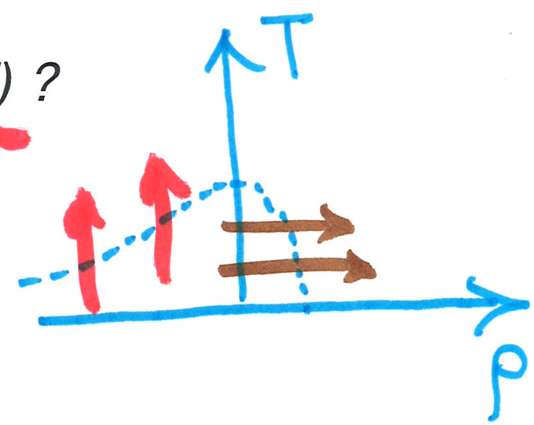
2) Pulsed-Power Experiments <== wires switch conductivity

SNLA - Reno - NRL - Cornell - CEA Bruyeres - Nagaoka - Tokyo

3) Metal-Insulator transition is BL fundamental physics

Mott-Anderson = sharp transition in $\sigma(\rho)$

Is there ever a sharp phase transition in $\sigma(T)$?



Rapid Communications

Optical Constants of Ultra-Short-Pulse Laser Heated Metal

YONEDA Hitoki, MORIKAMI Hidetoshi, UEDA Ken-ichi and MORE Richard M.[1)]
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VOLUME 72, NUMBER 21 PHYSICAL REVIEW LETTERS 23 MAY 1994

Reflectivity of Intense Femtosecond Laser Pulses from a Simple Metal

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Journal of Quantitative Spectroscopy & Radiative Transfer 99 (2006) 409–424

Journal of Quantitative Spectroscopy & Radiative Transfer

www.elsevier.com/locate/jqsrt

Short-pulse lasers and electron dynamics in warm dense matter

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Accepted 26 April 2005

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VOLUME 91, NUMBER 7 PHYSICAL REVIEW LETTERS week ending 15 AUGUST 2003

Ultrashort-Pulse Laser Ellipsometric Pump-Probe Experiments on Gold Targets

Hitoki Yoneda,[1] Hidetoshi Morikami,[1] Ken-ichi Ueda,[1] and Richard M. More[2]
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(Received 25 February 2003; published 14 August 2003)

Ultrashort-pulse laser pump-probe ellipsometry has been performed on gold targets at intensities 2×10^{12}–5×10^{13} W/cm^2. We measured time-resolved p- and s-polarized reflectivity (r_p and r_s) and the s-p phase difference (δ). When plotted as $Y = [2|r_s||r_p|\sin(\delta)]/(\ldots$ $|r_p|^2/|r_s|^2$, the experimental data follow approximately ... pump intensities. Although the i... rapid ...

東京

VOLUME 57, NUMBER 13 PHYSICAL REVIEW LETTERS 29 SEPTEMBER 1986

Electrical Conductivity of a Dense Plasma

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Physics Department, Univeristy of British Columbia, Vancouver, British Columbia V6T 2A6, Canada
and

UBC

VOLUME 61, NUMBER 20 PHYSICAL REVIEW LETTERS 14 NOVEMBER 1988

Resistivity of a Simple Metal from Room Temperature to 10^6 K

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(Received 7 March 1988)

... of temperature over 4 orders of
... nm light pulse

Bell Labs

VOLUME 75, NUMBER 2 PHYSICAL REVIEW LETTERS 10 JULY 1995

Absorption of Ultrashort Laser Pulses by Solid Targets Heated Rapidly to Temperatures 1–1000 eV

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(Received 4 April 1995)

We report measurements of laser absorption for high-contrast ultrashort pulses on a variety of solid targets over an intensity range of 10^{13} to 10^{18} W/cm^2. These data give an experimental determination of the target energy content and an indirect measure of dense plasma electrical conductivity. Our calculations accurately reproduce the behavior of aluminum targets, while the other materials show signs of additional absorption mechanisms. At high intensity all target materials reach a "universal plasma mirror" state and reflect about 90% of the incident light.

PACS numbers: 52.50.Jm, 52.25.Fi, 52.25.Rv

The development of high-power ultrashort pulse lasers has made possible a new type of laboratory investigation of the physical properties of matter heated rapidly to temperatures from 1 to 1000 eV, while retaining a density near that of the initial solid target [1,2]. Even before the development of subpicosecond pulse lasers it was shown that the reflectivity of a 30 ps probe pulse provides information on the ac electrical conductivity of the target plasma [3]. The first subpicosecond reflectivity experiments by Milchberg *et al.* [4], Fedosejevs *et al.* [5], Murnane, Kapteyn, and Falcone [6], and Teubner *et al.* [7] measured the reflectivity of aluminum and other materials at various conditions of laser intensity, pulse length, and prepulse. These experiments stimulated new theoretical calculations of dense plasma conductivity and some discussion about the key physical processes in these plasmas, as recently summarized by Ng *et al.* [8].

The scientific interest of these experiments centers on the possibility of using such short pulses that the uncertainty of plasma density is reduced at the time of peak laser intensity. Then one ... properties of matter ...

The experiments reported here greatly extend the parameter range of this technique. The 120 fs (FWHM) laser pulses are significantly shorter or of higher contrast than previously used. The prepulse intensity contrast ratio is approximately 10^{-7} at 1 ps before the peak power, achieved by harmonic conversion of an already high contrast pulse described below. The intensity range of 10^{13}–10^{18} W/cm^2 enables us to unambiguously identify the interesting region of minimum mean free path at the transition from solid to plasma electronic structure. We report data for several materials (Fig. 1) and can begin to identify characteristic behavior of the different classes of materials.

At low intensities, 10^{13}–10^{14} W/cm^2, there is already evidence of some alteration of the cold-matter electronic structure; for example, quartz and other insulators have high absorption (~90%), very different from their ... temperature behavior. Above ... reflectivity ...

LLNL

LBNL tools for analysis of experiments:

Active collaborations with Princeton (PPPL), Japan (Osaka, Tokyo UEC), France (CEA-Bruyeres), Germany (GSI) and China (BAO)

EM wave code for **short-pulse laser interaction** (reflection - ellipsometry, early-time hydro)
Relates measured reflectivity to electrical properties of hot target

EM wave code for **emission** from warm dense matter with temperature gradient at surface
Relate visible light emission to target temperature (spectra, angles, polarization)

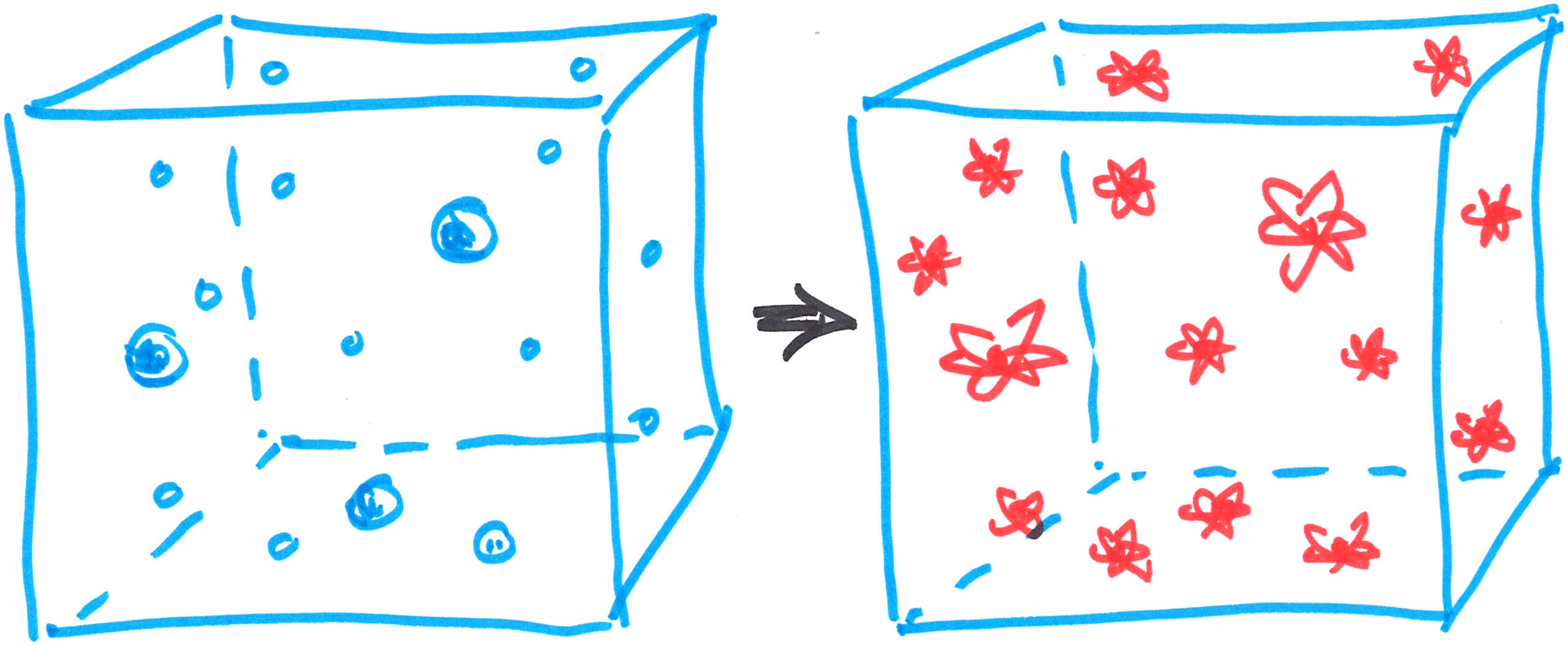
Theory models for electrical & thermal conductivity
Basic model (Lee-More, 1982; Desjarlais, 2002) + New LMD code in development

Livermore ICF code HYDRA; DISH is our own 1-D hydro-code,
ALE-AMR, surface-wave code (laser experiments on Hg liquid)

NEW

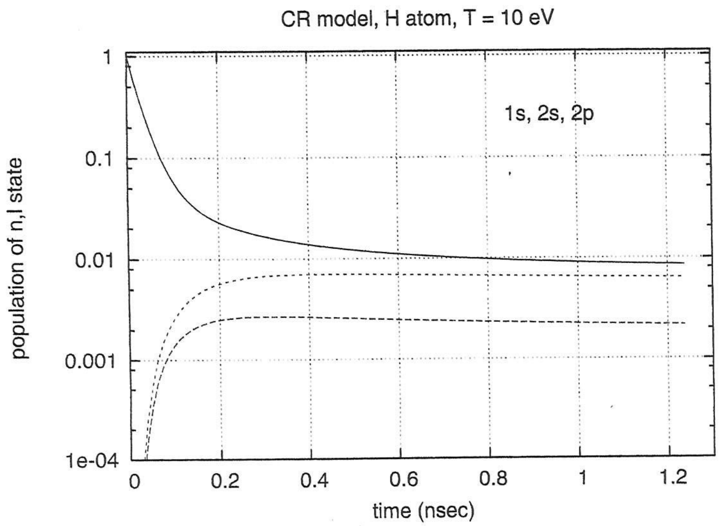
MD+CR Code for short-pulse **high-intensity X-ray interaction** with solids

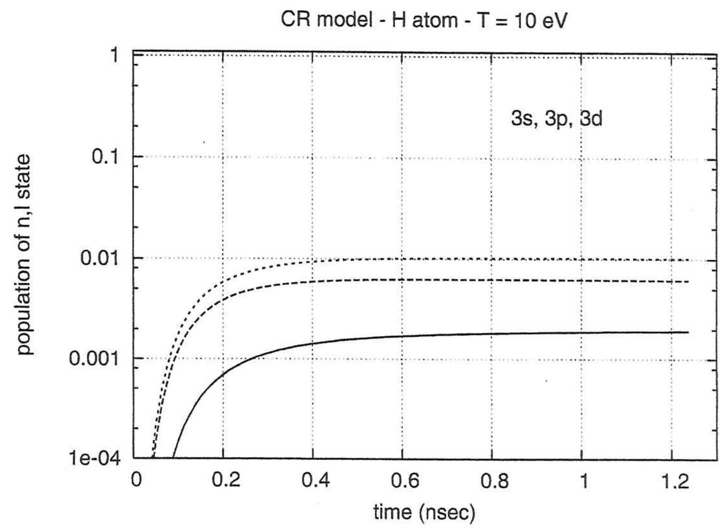
H. Yoneda SPRING-8 experiments with **10^{20} W/cm^2** of **7 keV** X-rays in a **10 fsec** pulse
First code version treats 1000 excited states on 100,000 atoms.
More & Wang, Invited paper at Kobe Conference on Computational Physics (CCP2012)



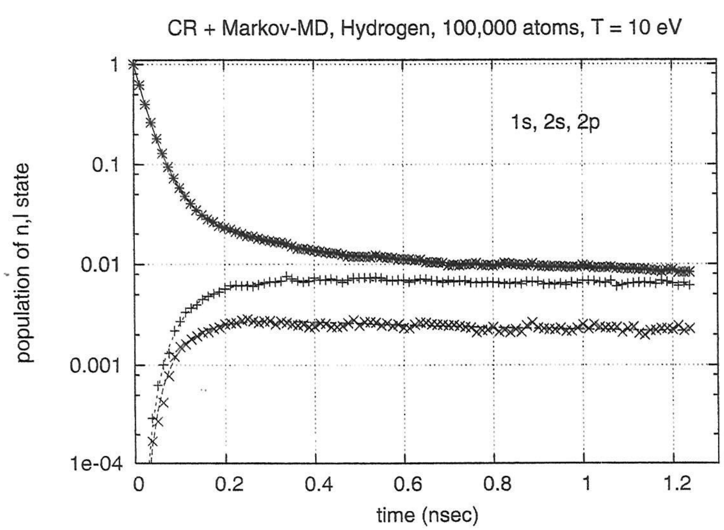
MD + CR Code: TEST for ATOMIC KINETICS:

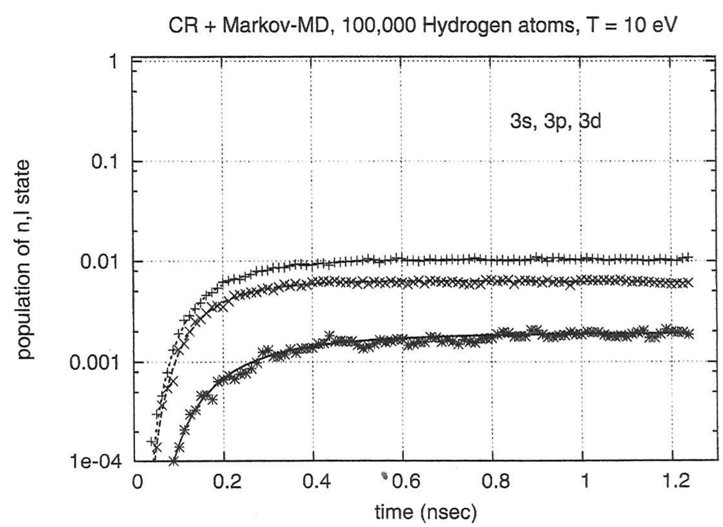
One-atom CR solution for neutral hydrogen 1000 excited states
Starts in groundstate, relaxes to equilibrium





MD + CR simulation, **100,000 atoms,** same 1000 excited states, same rates T_{jk}





AGREE

ANOTHER IDEA for 3-Lab collaboration:

- **Plasma turbulence** is hard to observe, so it is difficult to study turbulence in dynamic HEDP plasmas.

- In a **metal-foam target**, we know the initial spatial structure of the density modulations and they offer a surrogate for turbulence.
  We can measure their hydrodynamic expansion and conductivity.

- Small-angle X-ray scattering can observe the resulting $\delta\rho(r, t)$.

Plasma turbulence can *appear to change* plasma material properties:

EOS - turbulence adds an extra pressure and energy.

Adiabats - turbulent flow has entropy ==> affects compression tracks.

Thermal conductivity - turbulent $\delta\rho(r, t)$ can deflect electrons, change $\boldsymbol{\kappa}$.

These changes are probably not consistently modeled in ICF design codes.

There are several ideas for 3-Lab joint experiments:

Richard More, LBNL, LLNL

1.) **Porous targets** ==> **TURBULENCE surrogate**

Volume-heated porous targets have known size-scale for density variations.
How does small-scale turbulence change EOS, ADIABATS and CONDUCTIVITY ??

2.) **Ion irradiation experiments**

Irradiate similar targets with ions from NDCX-II and from short-pulse laser ion source.
Try to achieve similar energy density and ion range conditions; compare target response.

3.) **Transport properties** of heated matter (T = 0.5 to 10 eV)

Test transport coefficients used in HYDRA, LASNEX, ALLEGRA
Heat conduction might be important for stabilizing Rayleigh-Taylor in NIF targets
Physics to test: metal-insulator transition, Weidemann-Franz law,
magnetic flux diffusion times, electron-ion heat transfer time, viscosity.
A priori conductivities based on ion $S_{ii}(k)$, ion-electron $S_{ei}(k, \omega)$ measured with X-rays

Measure: heat-flow by light emission, magnetic field penetration time by Faraday rotation,
laser reflection, X-ray probe of hot sample, direct electrical measurements.

LLNL can do short-pulse reflectivity measurements sensitive to AC conductivity $\sigma(\omega)$,
LCLS can heat targets and measure $S(k)$ (= structure factor) for transiently heated matter
Can easily measure $S(k)$ but it's a challenge to do it at the same plasma ρ, T conditions where σ is measured,
LBNL can heat 1μ foils and measure electrical conductivity σ and thermal conductivity κ.
The experiments will work best at ~ 1 eV temperature where the sample melts, evaporates but does not expand violently.