X-Ray Diagnosis Techniques for Warm Dense Matter


Workshop on Accelerator Driven Warm Dense Matter Physics

Pleasanton, CA

Feb 23, 2006
Warm dense matter spans bound and conduction electron to quantum and classical free electron physics.

Diagram:
- Bound and conduction electron bands
- Quantum Plasma
- Classical Plasma
- Strongly Coupled electrons
- Crystal
- Liquid

Key parameters:
- $n_e$: electron density (cm$^{-3}$)
- $T_e$: electron temperature (eV)
- $T_i = T_{melt}$
- $\boxed{\text{ee}} = 1$
- $\boxed{\text{ii}} = 10$
- $\boxed{\text{i}} = 4$
- $\boxed{\text{ii}} = 4$
- $T_e = T_{\text{Fermi}}$
Physics issues amenable to laser-based experiments abound in warm dense matter regime
Several operating regimes for preparing warm dense matter using high energy lasers

Laser experiments
- H,D,T: Lindl/Haan
- Ge: Springer/Heeter
- LiH: Collins/Glenzer
- Be: Landen/Glenzer
- CH₂: Edwards
- Si, Cu: Kalantar
- Ti: Yaakobi
- Al: Riley, Wolfrum
- Mo, H₂O: Collins/Celliers/Bradley

**Diagram:**
- Low adiabat implosion
- ICE Planar shock
- Supersonic Wave CH₂
- Volumetric Heating
- Release Al
- H₂O Al Mo
- Ti Cu H₂O Al Mo

**Parameters:**
- $n_e$ (cm⁻³)
- $T_e$ (eV)
A variety of transient x-ray techniques have already been deployed.

- Radiography
- EXAFS
- Diffraction
- Scattering
- Transmission / Opacity
- Absorption Spectroscopy
Material strength inferred from radiographing hydroinstability growth upon sample acceleration

High energy Radiography measures $\Delta x$ changes (expansion, shock compression, hydroinstability growth)
Both point projection and area backlighting envisaged for high energy x-ray radiography

Acceptable brightness criterium:
SNR ≥ 20 at 10 μm resolution, with transmission and detector efficiency at 10% each
Extended x-ray absorption fine structure (EXAFS) is being used to characterize metals shocked to ~Mbar pressures.

Spectral modulation frequency measures lattice d spacing
Envelope and broadening measures disorder = f ( T_i/T_{Debye} )
X-ray diffraction used to measure dynamic response of crystal lattice to compression

Kalantar, Wark

- Si responds uniaxially on a ns time scale to compression 2x over elastic limit
- Trident experiments have observed signals suggestive of a diamond - BCT solid phase change

"splitting" of shocked diffracted signal above 200 Kbar

Spectral shift measures lattice d spacing, phase changes
X-ray coherent scattering experiments are sensitive to ion-ion structure factor and ion temperature.

Al, 1g/cc, 2.4 eV

K-resolved Scattering measures ion structure factor = f (T_i, \theta)

D. Riley et. al., PRL (2000)

Peak angle = f(n^{1/3})

T_i = 0.2 eV << T_e to explain correlated ion behavior
1-100 eV

X-ray scattering from free electrons (Thomson) for measuring velocity distribution

Spectrally-resolved Incoherent Scattering measures:

Free and weakly bound electron momentum distribution = f (T_e . T_{Fermi} . I.P.)
Ratio of free/weakly bound / tightly bound electrons
X-ray “Thomson’ scattering in warm solid density matter

- $T_e$ broadening was predicted in 1928: Chandrasekhar: “scattering will not be influenced by ranges of temperatures available in the laboratory” Proc R.S. A 125, 37 (1929)

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

From the theoretical fit to the data:
\[ T_e = 53 \text{ eV} \] and \[ Z_{\text{free}} = 3.1 \] hence \[ n_e = 3.8 \times 10^{23} \text{ cm}^{-3} \]

A sensitivity analysis shows that we can measure \( T_e \) within \( \sim 15\% \).
Collisionally broadened plasma resonance for cold plasmas is model sensitive

Linnebur and Duderstadt (1973) Theory
Cauble and Boercker (1983)

\[ n_e = 5 \times 10^{17} \text{ cm}^{-3} \]
\[ T_e = 4.5 \text{ eV} \]
\[ a = 3.5 \]
\[ G = 0.005 \]

\[ n_e = 2 \times 10^{24} \text{ cm}^{-3} \]
\[ T_e = 14 \text{ eV} \]
\[ a = 3 \]
\[ G = 2 \]

XRTS experiment could validate collisionality model at high \( n_e \), variable \( a \)

Collisionality, plasma wave behavior in Fermi degenerate and strongly coupled plasmas
Spectrally-resolved forward x-ray scatter can test dense matter energy transport models

### Theory

<table>
<thead>
<tr>
<th>Energy shift (eV)</th>
<th>Intensity (arb. units)</th>
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<tbody>
<tr>
<td>-60</td>
<td>0.02</td>
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<tr>
<td>-50</td>
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<tr>
<td>-30</td>
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</tr>
<tr>
<td>-10</td>
<td>0.005</td>
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<tr>
<td>0</td>
<td>0</td>
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</tbody>
</table>

Cl Ly-$
\alpha$ probe ($\alpha=1.5$)

$T_e=20$ eV $n_e=3.0\times10^{23}$ cm$^{-3}$

LFC, SLFC, RPA

### First data

<table>
<thead>
<tr>
<th>Energy (kJ)</th>
<th>Intensity</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.9</td>
<td>1</td>
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<tr>
<td>3.0</td>
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Ion feature [elastic scattering]

Plasmon scattering

Best fit

Detailed balance

Spectrally-resolved Collective Scattering measures:

Free electron density from plasmon shift

Ratio of $T_e/T_i$ from ratio of ion feature to plasmon

May distinguish between $\frac{\alpha}{\alpha_i}$ collisionality models
Soft x-ray laser used to demonstrate increased opacity at increased density

Al, 4 g/cc, \( n_e = 3 \times 10^{23} \) cc\(^{-1}\), \( T_e = 1 \) eV

20 nm X-ray laser transmission image

Opacity increase

Stimulated or spontaneous X-ray line transmission measures opacity
Characterization of Warm Dense Matter: EOS and Opacity of shocked material at Omega/NIF

- Objective: Elucidate atomic properties in strongly-coupled matter — EOS, ionization and opacity are all uncertain in this regime
- Build upon ongoing successful shock EOS/VISAR experiments
- Possible candidate for NEL experiment; PRL⁺ if it works
- Initial exploration/validation study on Omega, late FY02 or early FY03

Absorption spectroscopy measures ionization state, opacity
Spectral measurement of ionization state will help differentiate between plasma EOS models.

We will use these experiments to benchmark codes for states in correlated plasmas.

Shepherd, Ng, Heeter, Foord, Iglesias, Rogers, Springer
A variety of transient x-ray techniques have already been deployed.

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- Diffraction
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Diagram:
- Loss of Diffraction, EXAFS
- RT growth
- Coherent Scattering
- Opacity
- Compton Scattering
- Absorption Spectroscopy

Axes:
- $n_e (\text{cm}^{-3})$ on the y-axis
- $T_e (\text{eV})$ on the x-axis

Values:
- $10^{26}$
- $10^{25}$
- $10^{24}$
- $10^{23}$
- 0.1, 1, 10, 100