X-ray Thomson scattering in dense plasmas with a seeded x-ray laser

Siegfried H. Glenzer (SLAC)

September 23, 2013

Presentation to: 16th international symposium on Laser Aided Plasma Diagnostic
Outline

- **LCLS Free Electron Laser facility.**
  - Unprecedented capabilities at the MEC instrument [since 4/2012]
    - $10^{12}$ x-ray photons for pump-prober experiments
    - High spectral resolution (seeded beam)
    - High wavenumber resolution (x-ray laser)
    - High temporal resolution (20-50 fs)

- **Novel X-ray scattering experiments**
  - First observation of Plasmon shift in compressed matter
  - First continuous measurements of the dynamic structure factor
  - First observations of ion acoustic waves in warm dense matter
    - Pressures approaching 10 Mbar at 3x compressed Al
    - Evidence of negative screening
    - Test of theoretical methods to determine pressures of dense matter

- **Summary**
  - High power laser upgrade

We have a new precision tool to measure physical properties and to make new discoveries in High-Energy Density physics.
The big science questions

Develop and apply precision pump-probe experiments with the world-class LCLS beam to answer the most important questions in high energy density (HED) science

- **Strong shocks and High Pressure phenomena:** The use of LCLS will probe high pressure states found at the center of the large Jovian planets, the earth’s deepest interior and in inertial confinement fusion with unprecedented precision

- **Relativistic laser plasma interactions:** Uncover the physical mechanisms for ultra short pulse laser matter interactions, plasma heating and particle acceleration

- **Laboratory astrophysics:** Ultra-high power optical lasers offer the unique opportunity to produce and characterize collision-less shocks, particle acceleration, and anti-matter plasmas
We perform novel pump-probe measurements of plasma conditions and shocks with 1 \( \mu \)m, 30 fs resolution.
Linac Coherent Light Source at SLAC

X-FEL based on last 1-km of existing 3-km linac

1.5-15 Å
(14-4.3 GeV)

Existing 1/3 Linac (1 km)
(with modifications)

Injector (35°)
at 2-km point

X-ray
Transport
Line (200 m)

Undulator (130 m)

Near Experiment Hall

Far Experiment Hall
Experimental Halls

Near Experimental Hall

X-ray Transport Tunnel
200 m

AMO: Atomic, Molecular and Optical
SXR: Soft X-Ray materials sciences
XPP: X-ray Pump-Probe

Start of operation
AMO: Oct-09
SXR: May-10
XPP: October-10
CXI: February-11
XCS: November-11
MEC: April-12

XCS: X-ray Correlation Spectroscopy
CXI: Coherent X-ray Imaging
MEC: Materials under Extreme Conditions

Glenzer, IFSA, September 13, 2013
LCLS Materials under Extreme Conditions (MEC) Instrument

Target Chamber

X-ray optics and diagnostics

Short pulse laser system including Vacuum Compressor

Harmonic rejection mirrors

Be focusing lenses

<table>
<thead>
<tr>
<th></th>
<th>Baseline performance</th>
<th>Current performance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Photon energy range</td>
<td>830 to 8300 eV</td>
<td>480 to 10,000 eV</td>
</tr>
<tr>
<td>FEL pulse length</td>
<td>230 fs</td>
<td>5 - 500 fs</td>
</tr>
<tr>
<td>FEL pulse energy</td>
<td>up to 2 mJ</td>
<td>up to 4 mJ</td>
</tr>
</tbody>
</table>

Glenzer, IFSA, September 13, 2013
At MEC, LCLS provides $10^{12}$ X-ray photons at 120 Hz in a well-controlled focal spot for allowing unprecedented x-ray pump-probe experiments.
Long pulse laser system

- Shock compression
- High pressure states

<table>
<thead>
<tr>
<th>Long Pulse Laser</th>
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<tbody>
<tr>
<td>Wavelength</td>
<td>527 nm</td>
</tr>
<tr>
<td>Pulse Width</td>
<td>2-200 ns</td>
</tr>
<tr>
<td>Repetition Rate</td>
<td>1 shot per 10 minutes</td>
</tr>
<tr>
<td>Pulse Energy</td>
<td>2 x 15 Joules</td>
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</tbody>
</table>
Short pulse laser system

- Ultrafast probing combined with nanosecond beams or LCLS x-ray beam
- To be upgraded in two steps to 200 TW for pump-probe experiments

<table>
<thead>
<tr>
<th>Short Pulse Laser</th>
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<tbody>
<tr>
<td>Wavelength</td>
<td>800 nm</td>
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<tr>
<td>Pulse Width</td>
<td>35 fs</td>
</tr>
<tr>
<td>Repetition Rate</td>
<td>10 Hz</td>
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<tr>
<td>Pulse Energy</td>
<td>120 mJ</td>
</tr>
</tbody>
</table>
# MEC Target Diagnostics: VISAR, FDI

**Velocity Interferometer System for Any Reflector (VISAR)**

**Fourier Domain Interferometer (FDI)**

<table>
<thead>
<tr>
<th>Item</th>
<th>Purpose</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>VISAR</td>
<td>Measure shock velocity</td>
<td>Nanosecond time scale 5x10⁴ ~ 5x10⁶ cm/s</td>
</tr>
<tr>
<td>Fourier Domain Interferometer (FDI)</td>
<td>Measure surface motion</td>
<td>Accurate to λ/100 for 800 nm probe</td>
</tr>
</tbody>
</table>
## MEC Target Diagnostics: XRTS, XUV

### Forward Scattering X-ray spectrometer

### Backward Scattering X-ray spectrometer

### XUV spectrometer

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<th>Item</th>
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</thead>
</table>
| **X-ray Scattering Spectrometer (XRTS)** | Measure electron density and temperature  
**Forward XRTS:** automatic change of scattering angle, $0^\circ < \theta < 90^\circ$ | Spectral resolution of $\Delta E/E \sim 4 \times 10^{-3}$ at 8 keV  
temperature (1 \text{-} 100 \text{ eV}) |
| **XUV spectroscopy**          | Measure electron temperature and study electronic band structures | Spectral resolving power of $\lambda/\Delta\lambda \sim 300$ at 21 nm  
temperature (0.1 \text{-} 50 \text{ eV}) |
High resolution x-ray scattering observations of plasmons in Al using the seeded beam at 8 keV.
Options for free electron lasers

Introduction to the Physics of Free Electron Lasers Kwang-Je Kim (ANL) and Zhirong Huang (SLAC)

Glenzer, IFSA, September 13, 2013
Hard X-ray Self Seeding at LCLS

15.7 GeV e\(^{-}\) → 1 GW SASE → 2.5 mm x-ray diamond → seeded

U1-U15 (60 m) chicane, U16 (4 m) U17-U33 (68 m)

5-20 GW gas detector 5 MW e\(^{-}\) dump

detector

FEL spectrum after diamond crystal

Self-seeding of 1-μm e\(^{-}\) pulse at 1.5 Å yields 10\(^{-4}\) BW with 20-pC mode

Power dist. after diamond crystal

Wide-band power

Monochromatic seed power

6 μm 20 fs

Geloni, Kocharyan, Saldin, DESY 10-133

Glenzer, IFSA, September 13, 2013
High resolution x-ray scattering observations of plasmons in Al using the seeded beam at 8 keV

- Plasmon resonance determined by plasma frequency $\omega_{pe} = [n_e e^2/m_e \varepsilon_0]^{1/2}$
  - Glenzer et al., 2007 PRL
  - Kritcher et al., 2008 Science
- First observation of acoustic resonances at $\omega_{ac} \sim [kT_e/m_i]^{1/2}$
  - T. G. White et al. N3+O
High resolution x-ray scattering observations of plasmons in Al using the seeded beam at 8 keV

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Theoretical fit to the plasmon spectrum determines nearly ambient conditions

![Plasmon Shift](image)

Total cross-section includes free, tightly, and weakly bound states

\[
\frac{\partial^2 \sigma}{\partial \Omega \partial \omega} = \sigma_T \frac{\kappa_{1T}}{\kappa_{0r}} S((k,\omega))
\]

\[
S(k,\omega) =
\]

Ion Feature:

\[
|f_i(k) + q(k)|^2 S_i(k,\omega)
\]

Electron Feature:

\[
+ Z_f S_{ee}^0 (k,\omega)
\]

Bound-Free Feature:

\[
+ Z_c \int S_{ce} (k,\omega - \omega') S_{ce} (k,\omega') \, d\omega'
\]

We now have an accurate (first-principals) method that determines the physical properties of warm dense matter: \( n_e = 1.8 \times 10^{23} \text{ cm}^{-3} \pm 5\% \)

Glenzer, IFSA, September 13, 2013
Theoretical fit to the plasmon spectrum determines nearly ambient conditions

![Graph showing intensity vs energy (eV)](image)

Total cross-section includes free, tightly, and weakly bound states

\[
\frac{\partial^2 \sigma}{\partial \Omega \partial \omega} = \sigma_T \frac{k_1}{k_o} S(k, \omega)
\]

\[S(k, \omega) = \]

Ion Feature:

\[|f_i(k) + q(k)|^2 S_{ii}(k, \omega)\]

Electron Feature:

\[+ Z_f S^o_{ee}(k, \omega)\]

Bound-Free Feature:

\[+ Z_c \int S_{ce}(k, \omega - \omega') S_{ce}(k, \omega') \, d\omega'\]

We now have an accurate (first-principals) method that determines the physical properties of warm dense matter: \(n_e = 1.8 \times 10^{23} \text{ cm}^{-3} \pm 5\%\)
Plasmon measurements accurately determine 3x compressed Al at temperatures of 2.5 eV

We now have an accurate (first-principals) method that determines the physical properties of warm dense matter: \( n_e = 5.4 \times 10^{23} \text{ cm}^{-3} \pm 5\% \)
Plasmon measurements accurately determine temperature and density

- **Ion temperature variation:**
  \[ T_i = 2.5 \text{ eV} \pm 20\% \]

- **Electron density variation:**
  \[ n_e = 5.4 \times 10^{23} \text{ cm}^{-3} \pm 10\% \]

- Strong sensitivity to structure factor \( S_{ii}(k) \)

- Strong sensitivity to plasma frequency
  \[ \omega_{pe} = \left[ n_e e^2 / m_e \varepsilon_0 \right]^{1/2} \]
Clear evidence of double shock compression at the time of shock coalescence

**Bragg peaks in cold Al**

Run 162 - FEL only

(111) – Al Bragg

**Ion-ion correlation peak**

Run 141 - Probe Time = 1.6 ns

**Bragg equation**

\[ n\lambda = 2d \sin \theta \]

**Shock coalescence**

Run 157 - Probe Time = 1.8 ns

**Helios simulation**

Shock coalescence = 1.8 ns

Probe time = 1.6 ns

Ambient Al = 0 ns

Glenzer, IFSA, September 13, 2013
Wavenumber resolved scattering data indicate negative screening

Using short pulse repulsion provides an excellent fit for $S_{ii}(k)$

Using short pulse repulsion provides an excellent plasmon fit

Plasmon data
Fit for 2.5 eV, $n_e = 5.4 \times 10^{23} \text{ cm}^{-3}$

Using densities and temperatures from plasmon data yields critical experimental test $S_{ii}(k)$

Glenzer, IFSA, September 13, 2013
The plasmon data show that the shift of $S_{ii}(k)$ is determined by short range repulsion.

The peak of the ion-ion structure factor provides a well pronounced diagnostic feature.

After calibration against plasmon scattering the wavenumber of the maximum of $S_{ii}(k)$ can be used to infer densities.

Short-range repulsion is an indication of negative screening.

Important consequences when determining the pressure.

The ion-ion structure factor is a central quantity that determines collisionality and pressure of dense plasmas.
Continuous S(k) measurements yield pressure

Fletcher O.Mo_B3
Total pressure - \( P(n_e, T_e, S(k)) \)

\[
P_{\text{tot}} = P_i + P_e
\]

**Ion pressure**

\[
P_i = P^x + P_G
\]

**Excess ion pressure** \[1\]

\[
p^x = \frac{n_i U^{(0)}}{3N} - \frac{n_i (Ze)^2}{12 \pi^2} \int_{0}^{\infty} S(k) \frac{k_i^3}{(k_i^2 + k_e^2)^2} \, dk
\]

**Ideal gas pressure**

\[
P_G = n_i k_B T_i
\]

**Electron pressure**

\[
P_e = P_F + P_{\text{deg}} + P_C + P_{\text{xc}}
\]

**Fermi pressure** \[2\]

\[
P_F = \frac{\hbar^2}{20 m_e} \left( \frac{3}{\pi} \right)^{2/3} n_e^{5/3}
\]

**Quantum electron degeneracy pressure** \[3\]

\[
P_{\text{deg}} = \frac{\pi m_e^4 c^5}{3 \hbar^3} \left[ R (R^2 - 3) \sqrt{1 + R^2} + 3 \sinh^{-1} R \right] \quad R = \frac{P_F}{m_e c}
\]

**Coulomb negative pressure** \[3\]

\[
P_C = -\frac{8 \pi^3 m_e^4 c^5}{h^3 \alpha Z^{2/3}} \left[ \frac{\alpha Z^{2/3}}{10 \pi^2} \left( \frac{4}{9 \pi} \right)^{1/3} \right] R^4 \quad \alpha = \frac{e^2}{4 \pi e_0 \hbar c}
\]

**Electron-exchange pressure** \[3\]

\[
P_{\text{xc}} = -\frac{2 \alpha m_e^4 c^5}{h^3} \beta
\]

---


The ion-ion correlation peak has been measured in a number of shock-compressed samples.

**Aluminum**

Radial lineout

Relative Intensity (A.U.)

![Graph](image)

**Magnesium**

Radial lineout

Relative Intensity (A.U.)

![Graph](image)

**Carbon**

Radial lineout

Relative Intensity (A.U.)

![Graph](image)

Glenzer, CLEO, June 11, 2013
First observation of a double-peaked ion-ion structure factor confirms modeling of the liquid carbon phase

- Dominik Kraus, PRL 2013 submitted, O.Mo_B4
- 20 fs LCLS beam measures the dynamics of the graphite – liquid – liquid phase transition
- We’ll look into diamond next

Glenzer, CLEO, June 11, 2013
Phase Contrast Imaging of shocks

Figure 1: Shock wave in glass for different time delays. Specific values are indicated in each image.
LCLS experiments of the microphysics have provided new insights in ICF ablator physics

- X-ray Thomson scattering experiments at Omega have shown densities of $n_e = 10^{24}\text{cm}^{-3}$ a factor of 2 higher than standard radiation-hydrodynamic simulations with a Thomas-Fermi model
- Using improved continuum lowering models tested in LCLS experiments (Stewart-Pyatt, Ecker-Kröll) provide excellent agreement
- The conditions emulate ICF capsule ablator conditions during ICF implosions - accurate modeling of these plasmas is important to calculate hydrodynamic instabilities and compression

** O. Ciricosta et al., PRL 109, 065002 (2012)
This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract No. DE-AC52-07NA27344.
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• Summary
  • High power laser upgrade

We have a new precision tool to measure physical properties and to make new discoveries in High-Energy Density physics
High-Power Laser Workshop

SAVE THE DATE: October 1-2, 2013

SLAC National Accelerator Laboratory, Menlo Park, USA

This workshop will bring together the international science community to discuss the unique physics opportunities enabled by the new 200 TW laser at the Linac Coherent Light Source (LCLS). Coupling this laser to the world-class LCLS x-ray beam at the recently commissioned Matter in Extreme Condition (MEC) instrument will allow exquisite pump-probe experiments to address the most important physics questions of high-power laser plasma interactions physics in areas of high-energy density physics, laboratory astrophysics, laser-particle acceleration, and non-linear optical science.

The workshop will highlight recent results from MEC, describe the scientific opportunities for laser experiments at 200 TW and PW power and present and discuss the user access policy for performing laser experiments at MEC.

Hosts

Dr. Roger Falcone
Director of the Advanced Light Source, Lawrence Berkeley National Laboratory

Dr. Siegfried Glenzer
Distinguished Staff Scientist, SLAC National Accelerator Laboratory

Dr. Stefan Hau-Riege
Physicist, Lawrence Livermore National Laboratory
A 200 TW-class laser will be required to access important areas of Matter at Extreme Conditions

A high power laser will produce conditions important for fast ignition, energetic particles, and QED

Accurate probing of physics mechanisms will be accomplished by X-ray Thomson scattering with the LCLS beam

Provides accurate temperature and density measurements

Resolve micron scale length and 10 fs time scales

Determine laser coupling, heating, and pressure conditions

Path towards optimizing use of high power petawatt lasers
X-ray probing with LCLS will measure temperatures and densities from first principles

- Simulations predict high temperatures and plasma filaments
- Pressures of ~1 Gbar in densities previously not accessible
- Temperature measurements with X-ray Thomson scattering

- These experiments will test for the first time detailed simulations of ultra intense laser plasma interactions and the generation of intense particles
Future PW laser upgrades
Example Apollon: 400J green will pump a 40fs laser

- 23 m² for racks plus
  1.5 x 6 m footprint
- Building with shielding
  and infrastructure
- High access option
Combining High-Power lasers with the world-class LCLS beam will allow novel experiments

<table>
<thead>
<tr>
<th>Coupling of high-power lasers with matter</th>
<th>Physical properties of hot dense matter</th>
<th>Laboratory astrophysics</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image1.png" alt="Diagram of laser particles" /></td>
<td><img src="image2.png" alt="Proton radiograph" /></td>
<td><img src="image3.png" alt="Proton radiograph of E &amp; B fields" /></td>
</tr>
</tbody>
</table>

- **Fundamental laser-particle acceleration physics**
  - 100+ MeV protons
  - Positrons
  - 10+ GeV electrons

- **X-ray Thomson scattering on matter**
  - Mbar pressures
  - Isochorically heated matter
  - Ultrafast phase transitions

- **Laboratory astrophysics**
  - Self organization in plasmas
  - Weibel instabilities
  - Collisionless shocks
  - Cosmic rays

This field holds great promise for the future!
End of Presentation
We observed oscillatory motion in the electron spectra and distinguish betatron x-rays

- Betatrons are highly collimated and will allow novel ultrafast x-ray pump x-ray probe experiments of MEC
LCLS data is consistent with previous Omega campaigns

Measured ion-ion correlation peak

*The shift and change in peak intensity of the correlation peak for 1.8x and 2.7x compressed aluminum, modeled using HNC-Y+SRR, can serve as a dynamic density diagnostic*
Existing MEC short pulse laser system

Legend

- Oscillator
- Stretcher
- Regen
- MPA
- Powerlite Pump Laser
- Vacuum Compressor

Properties:
- 0.2 J
- 40 fs
- 10 Hz
Phase 1 upgrade of MEC short pulse laser system

Legend

Oscillator
Stretcher
Regen

Pump Laser
Compressor

Prepulse Cleaner
Stretcher

GAIA 7J
5Hz Pump

120 Hz
Pump Laser

Vacuum Compressor

MPA

Existing
Phase 1

1 J
40 fs
5 Hz

30 mJ
150 ps
120 Hz
Phase 2 upgrade of MEC short pulse laser system

Legend

Oscillator → Stretcher → Regen → Prepulse Cleaner

Pump Laser ↓ Compressor ↓ Stretcher

Existing ns laser +LBO

MPA

Deformable Mirror

GAIA 7J 5Hz Pump

MPA

Vacuum Compressor

120 Hz Pump Laser

Existing Phase 1

Phase 2

6-8 J
40 fs
200 TW
3min/shot
Thomson scattering: frontier of modern science

- High density plasmas
- Implosions
- Basic Science
  - High Gamma
  - Warm Dense Matter
- Astrophysics
  - Collisionless Shocks
  - Jets
  - Radiative Shocks
Back- and forward scatter have been demonstrated to accurately characterize dense matter

**Compton (back-) scatter measures $T_e$ from broadening**

![Graph showing intensity vs. energy for Compton scattering with labels showing $T_e = 53$ eV and $\theta = 125^\circ$]

**Forward scatter on Plasmons measures $n_e$ from shift**

![Graph showing intensity vs. energy for forward scattering with labels showing $4.5 \times 10^{23}$ cm$^{-3}$ and $1.5 \times 10^{23}$ cm$^{-3}$]

**Non-collective Scattering**

**Collective Scattering**

\[
\lambda^* > \lambda_S \quad \text{or} \quad \alpha = \frac{\lambda^*}{\lambda_S} = \frac{k^{-1}}{\lambda_S} = \frac{\lambda_0}{4\pi \lambda_S \sin(\theta/2)} > 1
\]