An Overview of High Energy Density Science on Free-electron Lasers


LULI, UC Davis, LANL, Uppsala, LLNL, IST-GoLP, UC Berkeley, Jena, CELIA, LBNL, RAL, Stanford, PSI/SLS, Czech Academy, QU Belfast, Polish Academy, SLAC, MPI, TU Berlin, Kinema, NIST, Stockholm, Rostock, AWE, Marseille, Alberta, Warsaw, Essen, GSI, DESY, Oxford, LIXAM...
Interest in HEDS is growing within the scientific community at large

• 2003: Two NAS reports highlighted HEDS:
  • Connecting Quarks with the Cosmos: Eleven Science Questions for the New Century
  • Frontiers in High Energy Density Physics: The X-Games of Contemporary Science

• 2004: National Taskforce on HEDS formed to set priorities and develop coordinated interagency plan
  • Specifically addressed “fostering…HED physics in US”
    • Frontiers for Discovery for High Energy Density Physics (Davidson Report, July 2004).
High Energy Density matter is interesting because it occurs widely

- **Hot Dense Matter (HDM)** occurs in:
  - Supernova, stellar interiors, accretion disks
  - Plasma devices: laser produced plasmas, Z-pinches
  - Directly and indirectly driven inertial fusion experiments

- **Warm Dense Matter (WDM)** occurs in:
  - Cores of large planets
  - Systems that start solid and end as a plasma
  - X-ray driven inertial fusion experiments
A HEDS experimental station should cover broad range of applications

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Estimates of HED time scales

Elastic e⁻-e⁻ collision frequency:
\[ \nu_{ee} \approx 6 \times 10^{-6} n_e \lambda_{ee} / T^{3/2} \quad \| \quad T(eV), n_e(cm^{-3}), \lambda_{ee} \equiv \ln \Lambda_{ee} \sim 2 \]

Elastic ion-e⁻ collision frequency:
\[ \nu_{ie} \approx 1 \times 10^{-9} n_i Z^2 \lambda_{ie} / T^{3/2} \quad \| \quad n_i(cm^{-3}) \]

Inelastic ion-e⁻ collision rate:
\[ R_{\text{excitation}} \approx 3 \times 10^{-8} n_e e^{-\left(\frac{E_{UL}}{T}\right)} \frac{E_{UL}}{E_{UL} \sqrt{T}} \quad \| \quad E_{UL} = \text{excitation energy (eV)} \]
\[ R_{\text{ionization}} \approx 3 \times 10^{-6} n_e e \frac{E_1(I_p / T)}{I_p \sqrt{T}} \quad \| \quad \varepsilon = \# \text{valence e}^-; I_p = \text{ionization potential (eV)} \]

Photopumping Rate:
\[ R_{\text{photo}} \approx 774 f_{LU} \frac{F}{\Delta_{\text{laser}}} \frac{E_{laser}^2}{E} \quad \| \quad f_{LU} = \text{absorption oscillator strength}; F = \text{flux (W/cm}^2) \]
\[ \Delta = \text{fractional bandwidth}; E = \text{laser energy (eV)} \]

Spontaneous Decay Rate:
\[ A_{\text{value}} \approx 4.7 \times 10^8 Z^2 \quad \| \quad \text{atomic } # = Z; \text{ H-like } 2 \rightarrow 1 \]

Ion plasma frequency:
\[ \nu_{pi} \approx 141 \sqrt{\frac{n_i}{Z}} \]

Hydrodynamic time scale:
\[ t_{\text{hydro}} \approx \frac{1.2 \times 10^{-10}}{\sqrt{T}} \quad \| \quad \text{time surface moves 1 } \mu\text{m} \]
WDM and HDM rates indicate short pulses required to access the physical processes

<table>
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<tr>
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<th>WDM Z~ 1, n_e<del>10^{23} cm^{-3}, T</del>10 eV</th>
<th>HDM Z~ 10, n_e<del>10^{22} cm^{-3}, T</del>500 eV</th>
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<tr>
<td>\nu_{ee}</td>
<td>2x10^{16}</td>
<td>1x10^{13}</td>
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<tr>
<td>\nu_{ei}</td>
<td>3x10^{12}</td>
<td>9x10^{9}</td>
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<td>R_{excitation} (E_{ul}~T)</td>
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<td>2x10^{11}</td>
<td>2x10^{11}</td>
</tr>
<tr>
<td>A_{value}</td>
<td>5x10^{8}</td>
<td>5x10^{10}</td>
</tr>
<tr>
<td>\nu_{ion plasma}</td>
<td>5x10^{13}</td>
<td>2x10^{12}</td>
</tr>
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- To remove hydrodynamic effects one requires probe/pump at less than 1 ps
Hot Dense Matter
For HDM the short pulse intense x-ray source creates a unique initial state

- Population kinetics is complex for realistic cases
  - The model construct requires vast amounts of atomic data
    - Atomic data: Energy levels, oscillator strengths, autoionization rates
    - Collisional cross-sections for excitation (BB) and ionization (BF) processes
  - Due to the vast number of states and the effects of the plasma environment, additional model assumptions are required
    - Ionization potential depression
    - Rydberg states
    - Level details

- Comparisons with benchmark data would be a key to make progress
  - However, there are very, very few cases where the plasma temperature, density, charges state distribution and spectrum have been measured.
Example of the state of affairs in NLTE kinetics: Fe ionization balance

• The case is for a low density chosen for astrophysical applications

• Models are from 7 different codes

• Basic result: near a closed shell, e.g., Ne-like, the agreement improves

• In general, large discrepancies are found away from the closed shells
XFEL provides an opportunity for HEDS plasma spectroscopy - like AMO

**AMO atomic physics case:**
- Source for hollow ion experiment prepared as an atomic beam

**HED ‘atomic physics’ case:**
- Source for hollow ion experiment prepared by high energy laser

**Photoionization:**
$$\text{Ne}^+ + h\nu > 870\text{eV} \rightarrow \text{Ne}^{+\ast}(K) + e$$

**Auger Decay:**
$$\text{Ne} + h\nu > 870\text{eV} \rightarrow \text{Ne}^{+\ast}(K) + e \rightarrow \text{Ne}^{2+\ast}(LL) + e \rightarrow \text{Ne}^{3+\ast} + e$$

**Sequential multiphoton ionization:**
$$\text{Ne} + h\nu > 870\text{eV} \rightarrow \text{Ne}^{+\ast}(K) + e + h\nu > 993\text{eV} \rightarrow \text{Ne}^{2+\ast}(KK) + e \rightarrow \text{Ne}^{3+\ast} + e \rightarrow \ldots$$
$$\text{Ne} + h\nu > 870\text{eV} \rightarrow \text{Ne}^{+\ast}(K) + e + h\nu > 993\text{eV} \rightarrow \text{Ne}^{3+\ast}(KLL) + e$$

**Direct multiphoton ionization:**
$$\text{Ne} + 2h\nu > 932\text{eV} \rightarrow \text{Ne}^{2+\ast}(KK) + 2e$$

**Photoionization of multiple ion species:**
$$K^xL^yM^z + h\nu_{\text{XFEL}} \rightarrow K^{x\ast-1}L^yM^z + e \quad (x=1,2; \ y=1-8; \ z=1,2)$$

**Auger Decay of multiple ion species:**
$$K^xL^yM^z + h\nu_{\text{XFEL}} \rightarrow K^{x\ast-1}L^yM^z + e \rightarrow K^xL^{y\ast 2}M^z + e$$

**Sequential multiphoton ionization:**
$$K^xL^yM^z + h\nu_{\text{XFEL}} \rightarrow K^{x\ast-1}L^yM^z + e + h\nu_{\text{XFEL}} \rightarrow K^0L^yM^z + e + h\nu_{\text{XFEL}} \rightarrow K^0L^{y\ast 1}M^z + e + h\nu_{\text{XFEL}} \rightarrow \ldots$$
$$K^xL^yM^z + h\nu_{\text{XFEL}} \rightarrow K^{x\ast-1}L^yM^z + e + h\nu_{\text{XFEL}} \rightarrow K^{x\ast-1}L^{y\ast 2}M^z + 2e$$

**Direct multiphoton ionization:**
$$K^xL^yM^z + 2h\nu_{\text{XFEL}} \rightarrow K^0L^yM^z + 2e$$
Non-LTE kinetics simulations requires basic atomic data previously inaccessible

• For example, hollow ion studies generate much needed data
  • Require a setup similar to that planned for the AMO initial experiments
  • Controllable source of moderately charged ion is necessary

• Use of a modern EBIT will provide ideal capability
  • EBIT specifications
    • Extracted beam of ions, e.g., Mg, \( >10^8 / \text{cm}^3 / \text{pulse} \)
    • In 1 mm\(^2\) x 10 cm can have \( >10^7 / \text{cm}^3 \)
    • Size: 1.5 m x 0.5 m x 0.5 m plus stand
    • Tests at GSI on the PHELIX laser coupled to the EBIT have been performed

• An EBIT exists and could be available for the AMO XFEL experiments
  • Collaboration: Harvard-Smithsonian, NIST, U. of Stockholm, GSI, LLNL
High Peak Brightness of 4\textsuperscript{th} generation x-ray light sources are well matched to HEDS

- For Hot Dense Matter the plasma collision rates and spontaneous decay rates are large

- To effectively move population, pump rate, $R_{\text{photo}}$, must be greater than radiative decay rate, $A_{\text{value}}$

  \[ \Rightarrow R_{\text{photo}} > A_{\text{value}} \]

- For $I = 10^{14}$ W/cm\textsuperscript{2}

  \[ R_{\text{photo}}/A_{\text{value}} \sim 10^{-4} \frac{g_u}{g_L} \lambda^4 \]

- FELs attains needed excitation strength

  \[ \lambda \sim 10 \text{ Å} \Rightarrow R_{\text{photo}}/A_{\text{value}} > 1 \]

- To obtain brightnesses $\sim 10^{31}$ the effective blackbody radiation temperature for 2.5 Å would be $\sim 63$ MeV
To provide NLTE benchmarks pumping K-shell emitters provides critical data.

**Schematic experiment**

- 25 μm Al
- 0.1 μm CH
- Visible laser
- t = 0 laser irradiates Al dot
- t = 100 ps FEL irradiates plasma
- FEL tuned to 1869 eV
- Observe emission with x-ray streak camera

**Simulation**

- He-like
- H-like
- Simulated emission spectra before and after pump:
  - He-like n = 2
  - Emission before and after pump
  - XFEL pump
Line intensity, line position, and line shape are effected by HED environment

- Simple form for emission illustrates the observable aspects

\[ I(\omega) = n_i A_{UL} h \nu_{UL} \phi(\omega) \]

\[ \phi(\omega) = \int d\varepsilon P(\varepsilon) J(\omega, \varepsilon) \quad \| \ P(\varepsilon) \text{ is the ion microfield} \]

\[ J(\omega, \varepsilon) \sim \frac{\text{Im}}{\pi} \left( \Delta \omega_{UL} + \delta(\omega) + i\gamma(\omega) \right)^{-1} \]

- Investigate \( \phi(\omega) \) and \( \gamma(\omega) \) to look at effects on shape

- Investigate \( \delta(\omega) \) to look at line position (shift)
Using an XFEL to pump within a line transition is fundamentally important

- Measuring redistribution within a Stark-broadened bound-bound profile

  - Assumption of complete redistribution within a profile can be invalid; but, depend on

    - ion field fluctuations rates
    - inelastic collision rates

- Measuring the detailed redistribution of population by pumping within a transition can indicate relative plasma rate process
First a very little theory:

Line shapes and redistribution functions

- To “pump” a bound-bound transition one wants the pump frequency, $\omega_L$, to be near the transition energy $\omega$.

- The response of the atom will depend on the pump intensity and the overlap with the line shape $I(\omega)$.

  - Assume the pump is an experimentally determined quantity.
  - $I(\omega)$ absorption probability at $\omega$, and depends on atom-plasma interaction.

\[
I(\omega) = \text{Im} \langle V | G | V \rangle = \text{Im} \left[ \left\langle d^* \left\{ \frac{1}{\omega - L_o} \right\} d \rho \right\rangle \right] \rightarrow \frac{c(\omega - \delta) + a \gamma}{(\omega - \delta)^2 + \gamma^2}
\]

  - $\gamma$ is width
  - $\delta$ is shift
  - $a$ is amplitude
  - $c$ due to complex $L_o$

  - If there are many ion fields, i.e., a quasi-static distribution we get

\[
I(\omega) = \sum_i \frac{c_i(\omega - \delta_i) + a_i \gamma_i}{(\omega - \delta_i)^2 + \gamma_i^2}
\]

  - $i$ is ion field index
A simple picture explains the theory and illustrates radiation redistribution

- When ion field fluctuates or the e⁻ collision time is finite - need new theory

\[ \sum_i \frac{c_i(\omega - \delta_i) + a_i \gamma_i}{(\omega - \delta_i)^2 + \gamma_i^2} \]

now $i$ is mixed at rate $\nu_i$

$\gamma_c \gg \gamma_s \gg \nu_i$
Ultimate test is the study of the radiation redistribution function $R(\omega_L, \omega_S)$

- $I$ is the power spectrum of the radiation emitted at $\omega_S$ by a system pumped at $\omega_L$

\[
I(\omega_S, \omega_L) \propto \lim_{\eta \to 0} \text{Im} \sum_{i,f} p_i \langle \langle V_S | G_\omega (i\eta) | V_L \rho_0 \rangle \rangle_{i,f}
\]

- $R(\omega_L, \omega_S)$ is the redistribution function

\[
R(\omega_L, \omega_S) = \frac{I(\omega_L, \omega_S)}{\iint I(\omega_L, \omega_S) d\omega_L d\omega_S}
\]

- One can now investigate the redistribution using the XFEL
The XFEL with reduced bandwidth can tune through a line to provide plasma rate data

- Example: pumping Li-like Fe $1s^2 2l - 1s^2 4l$

- Collision rates and plasma field fluctuations can be measured
Warm Dense Matter
Broadly speaking, there are two paths to producing WDM

- As the issue with WDM is not to just create it
  - Because it occurs widely and is easily realized

- Need to create it so that it can be studied in well defined conditions

  - **One:** Use a great deal of energy to make a large enough volume of WDM so that gradient at the boundaries are a small part of the sample

  - **Two:** Use an intense fast x-ray source to heat the matter uniformly and rapidly. Then make measurement before hydrodynamic expansion
On the other hand, intense short pulse x-ray sources can create WDM

• For a 10x10x100 μm thick sample of Al
  
  • Ensure sample uniformity by using only 66% of beam energy
  • Equating absorbed energy to total kinetic and ionization energy

\[
\frac{E}{V} = \frac{3}{2} n_e T_e + \sum_i n_i I_p^i \quad \text{where } I_p^i = \text{ionization potential of stage } i - 1
\]

• Find 10 eV at solid density with \( n_e = 2 \times 10^{22} \text{ cm}^{-3} \) and \( <Z> \approx 0.3 \)

• State of material on release can be measured with a short pulse laser

• Material, rapidly and uniformly heated, releases isentropically
WDM created by isochoric heating will isentropically expand sampling phase space

- Concept is straightforward

- XFEL can heat matter rapidly and uniformly to create:
  - Isochores (constant $\rho$)
  - Isentropes (constant entropy)

- Using underdense foams allows more complete sampling
  - Isochores (constant $\rho$)
  - Isentropes (constant entropy)
Creating Warm Dense Matter with FLASH is initial step for eventual XFEL research

- Isochoric heating
  - 40 fs 60 Å VUV-FEL heats a Al foil 500 Å uniformly

\[
\frac{E}{V} = \frac{3}{2} n_e T_e + \sum_i n_i I_i \Rightarrow (10^{12} \times 200 \text{ eV}) / \text{Volume} = 3/2 \times (1.7 \times 10^{23}) \times 10 \text{ eV}
\]
  - Volume = Area x 500 Å \Rightarrow Area = 50 \mu m spot
  - For 1 eV plasma a 140 \mu m spot is needed

- Isentropic expansion
  - A optical FDI probe measures the isentropic expansion
Simulations of FLASH VUV-FEL confirm simple estimates for creating WDM:

- 500 Å Al irradiated by split FLASH 40 fs beam

- Temperature and density at 200 fs after the FLASH pulse
FLASH experiment are straightforward: Transmission vs Intensity

- Disparity between the various approximations represents the state of uncertainty

- Varying intensity to $>10^{16}$ accesses important regime
  - $5 \times 10^{16}$ represents $\sim 40 \ \mu$J - within current FLASH operation

Thin uniformly heated sample is essential

50 nm Si$_3$N$_4$ foil

13.5 nm

diode

Absorbed fraction vs Intensity $I$ (W/cm$^2$)

- $\triangle$ IB
- $\square$ Cold $\kappa_v<.025$ eV; EOS $.025$ eV
- $\bigcirc$ Cold $\kappa_v< 10$ eV; EOS $> 10$ eV
Plasma Physics
Plasma physics of photoionized gases

• Important to understand heating of gases and clusters

• Photoionization (PI) of gas jets provided a mechanism to produce unique engineered plasmas with densities $\sim 10^{19}$

• PI with high energy photons and long collisional relaxation $\Rightarrow$ NLTE
  • Self Thomson scattering as function of angle provides a probe of the velocity distribution.

• Depending on the plasma and the photon energy, both photoelectron Weibel (PEW) and two stream (PETS) instabilities can occur

• Characteristic times scales:
  • $T_{\text{Thermalization}} \sim 1 \text{ps} \ (10^{19}/n_e)$
  • $T_{\text{growth PEW}} \sim 2 \text{ ps} \ (10^{19}/n_e)^{1/2}$
  • $T_{\text{growth PETS}} \sim 100 \text{ fs} \ (10^{19}/n_e)^{1/2}$

• Signatures vary with gas density and observation angle
**Plasma Instabilities**

Photo electron two stream (PETS) instability:

\[
\gamma_{\text{PETS}} = 0.21kv_0 \frac{3 - (kv_0 / \omega_{pe})^2}{\sqrt{1+1.1(kv_0 / \omega_{pe})^2}}
\]

\[
\gamma_{\text{max}} \approx 0.31 \omega_{pe} \text{ at } k \approx 0.82 \omega_{pe} / v_0, \theta_0 = 0
\]

Photo electron Weibel (PEW) instability:

\[
\gamma_{\text{PEW}} = \frac{1}{4} k v_0 \frac{2 - (kc / \omega_{pe})^2}{\sqrt{1+(kc / \omega_{pe})^2}}, \theta_0 = \pi / 2
\]

\[
\gamma_{\text{max}} \approx 0.22 \omega_{pe} (v_0 / c) \text{ at } k \approx 0.7 \omega_{pe} / c
\]

2. PEW:

\[G = \left(\frac{\gamma}{\omega_{pe}}\right)\left(\frac{c}{v_0}\right), \theta_0 = 0, K = kc / \omega_p\]

1. PETS:

\[G = \frac{\gamma}{\omega_{pe}}, \quad \theta_0 = \pi / 2, K = kv_0 / \omega_{pe}\]
To study XFEL interaction with matter need non-Maxwellian electron kinetics

• Study a VUV-FEL case:
  • 200 eV; 200 fs pulse; ΔE/E~0.003; 10^{12} photons; 40μm spot

- Electron thermalization due to elastic collisions with e⁻ and ions
- Collisional excitation/de-excitation and ionization/recombination
- Sources such as collisional, photo and Auger electrons
- Sinks such as 3-body, radiative recombination and e⁻ capture

- Elastic losses to phonon (deformation potential) scattering
- Ionization potential depression using quasi-bound states
- Treatment of extremely fast particles
FEL-solid interaction creates unique photoelectron generated plasmas

- Case study for $\lambda \sim 200$ eV (FLASH)
- Primary innershell photoelectrons produced at 105 eV
- $e^-$ thermalize due to *inelastic* electron-ion collisions
- Average $e^-$ energy sharply decreases then rises

- At 5 attoseconds:
  - $T_e \sim 65$ eV
  - $N_e \sim 10^{16}$ cm$^{-3}$
  - $N_i \sim 6\times10^{22}$ cm$^{-3}$

  - $e^-$-$e^-$ elastic $v_{ee}$:
    - Coulomb $\sim 1.4\times10^9$ s$^{-1}$
  - $e^-$-ion inelastic $v_{ei}$:
    - excitation $\sim 5\times10^{16}$ s$^{-1}$
    - ionization $\sim 2\times10^{16}$ s$^{-1}$
High Pressure States
Two areas of interest for studies of dynamics of materials under high pressure

- For studies of material strength one requires both high pressure and high strain rates.

  - *In situ* studies of dislocation dynamics can be performed at LCLS
  - Phenomenology and MD simulation predict dislocation densities orders of magnitude larger than measured post-shock
    - Creation and destruction of dislocation is dynamic => need short duration high intensity x-ray pulse as an *in situ* probe

- For phase transformations the LCLS HEDS capability will provide information on sub-ps timescales

  - Phase transformations can occur on times scales <100 ps
  - MD simulations indicate, e.g., Fe goes through a ~1ps phase transformation
High pressure studies illustrate a unique feature of the intense short pulse x-rays

• Hydrodynamic times are usually considered slow (>> 1ps)

• In cases where phase changes occur two aspects of diffraction require sub-ps pulses

  • First, when one wants to look at a sample the undergoes bulk solidification the smearing of the signal due to locally rapid modification will compromise the data (Ta study by Steitz)

  • Second, there are currently indication that some, i.e., diffusionless or Martensitic, transitions may undergo phase changes very rapidly (Fe study by Kadau)
Lasers provide shocks and high divergence probe - LCLS provides low divergence probe

- Schematic of High Energy Laser shock experiment
- Schematic of LCLS XFEL shock experiment

- Laser creates a shock in a single-crystal sample
- Delayed beams create ns-scale highly divergent x-ray source
- Angular spread of the x-ray source samples many crystal planes
- Technique provides critical data on dynamics at high pressure

- Laser creates a shock in a polycrystalline sample
- XFEL creates fs-scale non-divergent monochromatic source
- Grains in the polycrystal diffract the beam
- Low Divergence $\Rightarrow$ nm-scale fs diffraction of real solids
Iron is important due to our geophysics and developments of modern technology

- Phase diagram shows Fe is BCC at ambient conditions and under a shock goes to HCP

A.M. Dziewonski and D. L. Anderson

Shockwave induced solid-solid phase transitions predicted to occur on ps, or shorter, time scales

MD simulations of BCC iron: $v_s = 470 \text{ m/s}, t = 8 \text{ ps}$

transformed grains, HCP

uni-axial compressed BCC

Kadau et. al. 2002
LCLS enables real-time, *in situ* study of deformation at high pressure and strain rate

- MD simulation of FCC copper
- X-ray diffraction image using LCLS probe of the (002) shows *in situ* stacking fault data

Diffuse scattering from stacking fault

Peak diffraction moves from 0,0 due to relaxation of lattice under pressure

Periodic features ⇒ average distance between faults
MD simulations of Ta show nucleation and solidification the XFEL can probe

- Uniform speckle
- Non-uniformity of speckle
- Higher intensity spots

• Goal of in situ x-ray diffraction of shocked solids at granular level is to understand the microscopic to inform mesoscopic, and then macroscopic

• Study how individual grains respond elastically and plastically to high pressure as a function of orientation with respect to a given uniaxial shock wave

• XFEL is ideally suited to probe via diffraction polycrystalline high pressure solids because it is an ultra-bright, non-diverging, monochromatic source.
XFEL as a probe
Current x-ray phase-contrast imaging at ~ 5 μm resolution uses laser-plasma sources. Current techniques are limited by spatial coherence & flux of laser-plasma x-ray source [D. G. Hicks 2006]
LCLS will enable coherent diffractive x-ray microscopy at the nanoscale

Dynamic processes on the nanoscale: shock front size (viscosity), phase transition kinetics, nucleation & growth, grain structure deformation
X-ray ‘Thomson Scattering’ will provide a unique probe for HED matter

• Scattering from free electrons provides a measure of the $T_e$, $n_e$, $f(v)$, and plasma damping
  ⇒ structure alone not sufficient for plasma-like matter

• Due to absorption, refraction and reflection neither visible nor laboratory x-ray lasers can probe high density
  ⇒ little to no high density data

• FEL scattering signals will be well above noise for all HED matter
Scattering of the XFEL will provide data on free, tightly-, and weakly-bound electrons

- Weakly-bound and tightly-bound electrons depend on their binding energy relative to the Compton energy shift.

For a 25 eV, 4x10^{23} cm^{-3} plasma the XFEL produces 10^4 photons from the free electron scattering.

- Can obtain temperatures, densities, mean ionization, velocity distribution from the scattering signal.
XFEL provides a scattering probe of \( \geq \) solid density \textit{finite} temperature matter

- **X-ray laser output:** at 12 Å \( \sim \) \(10^{12}\) photons
- **Plasma probed:** \( n_e = 4 \times 10^{23} \text{ cm}^{-3}, \ T_e = 25 \text{ eV}, \ L = 10^{-2} \text{ cm} \)
- **Scattering parameter:** \( \alpha = \frac{\lambda}{4\pi\lambda_D} = \frac{12 \text{ Å}}{(4\pi \times 0.6 \text{ Å})} \approx 2 \)
- **Scattered fraction:** \( \sigma n_e L = 7 \times 10^{-25}/2(1+\alpha^2) \times 4 \times 10^{23} \times .01 \approx 3 \times 10^{-4} \)
- **Collected fraction:** \( \Omega/4\pi \times \text{efficiency} \sim \times 4 \times 10^{-4} \times 10\% = 4 \times 10^{-5} \)
- **# photons collected:** \(10^{12} \times 4 \times 10^{-5} \times 3 \times 10^{-4} \approx 10^4 \)
- **Signal / Planckian:** > \(10^8\) for 300 \(\mu\text{m}\) probe size at \(T_e = 25 \text{ eV}\)
- **\(\Delta\lambda/\lambda\) required:** \(\Delta\lambda/\lambda \sim \sqrt{(n_e/n_c)/\alpha^2} = \sqrt{(4 \times 10^{23}/4 \times 10^{28})/4} \approx .006\)
Thomson Backscattering diagnosis of solid density Be in WDM regime: $T_e \sim 55$ eV

A sensitivity analysis shows that $T_e$ measured with an error of $\sim 15\%$

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

Comparison of the experimental data with the theoretical calculations for various electron temperatures

From the theoretical fit to the data from the heated Be we obtain $T_e = 53$ eV and $Z_{\text{free}} = 3.1$ corresponding to $n_e = 3.8 \times 10^{23}$ cm$^{-3}$
Thomson forward scattering provides data from collective regime: plasmon feature provides additional diagnostics

- Plasmon peak intensity related by detailed balance, i.e., $\exp(-2\Delta E/T)$

- Experiments with independent $T_e$ measurement are needed to determine correct approximation for collisions
In Warm Dense Matter regime the hollow ions provide time-resolved diagnostic information

- XFEL forms unique states and can provide in situ diagnostics with 100 fs resolution
  - 5x10^{10} 1.85 keV photons in 30 \mu m spot into a n_e=10^{23} \text{ cm}^{-2} plasma
  - Strong coupling parameter, \Gamma_{ji} = \text{Potential/Kinetic Energy} \sim 10

- Spectra vary measurably with T_e
- At high n_e emission lasts \sim 100 fs
Saturating the continuum using the FEL may provide a ~100 fs absorption source

- He-like B plasma at 30 eV, $5 \times 10^{22}$ cm$^{-3}$, 1 mm in length
- FEL tuned to H-like 1-2 transition
Summary of HEDS using sub-ps intense x-ray sources

- For both the hot and warm dense matter regimes the possibilities opened up by the FELs are important

- For WDM the FELs provide:
  - Fast uniform heating source to create WDM
  - Diagnostic potential: Thomson Scattering, $K_\alpha$ temperature measurement, fast absorption sources, phase contrast imaging, diffraction for high pressure states

- For HDM the FELs provide:
  - Fast deposition may create hot, high pressure matter (not shown)
  - Plasma spectroscopic probes of kinetic and radiative processes
  - Diagnostic potential: Thomson scattering

- The future looks bright
The End