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

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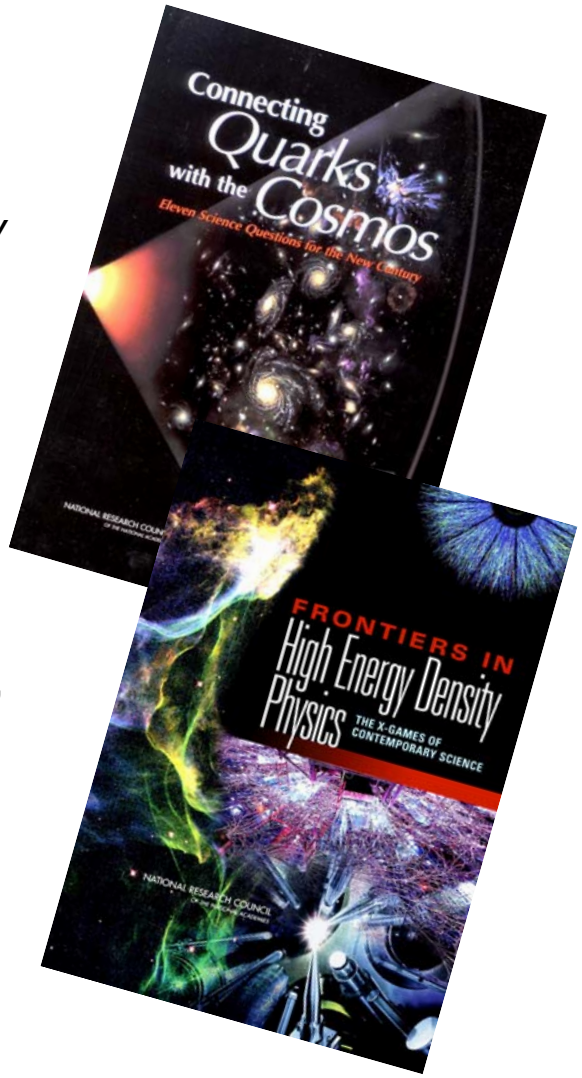
LULI, UC Davis, LANL, Uppsala, LLNL, IST-GoLP, UC Berkeley, Jena, CELIA, LBNL, RAL, Stanford, PSI/SLS, Czech Academy, QU Belfast, Polish Academy, SLAC, MPI, TU Berlin , Kinema, NIST, Stockholm, Rostock, AWE, Marseille, Alberta, Warsaw, Essen, GSI, DESY, Oxford, LIXAM…

Interest in HEDS is growing within the scientific community at large

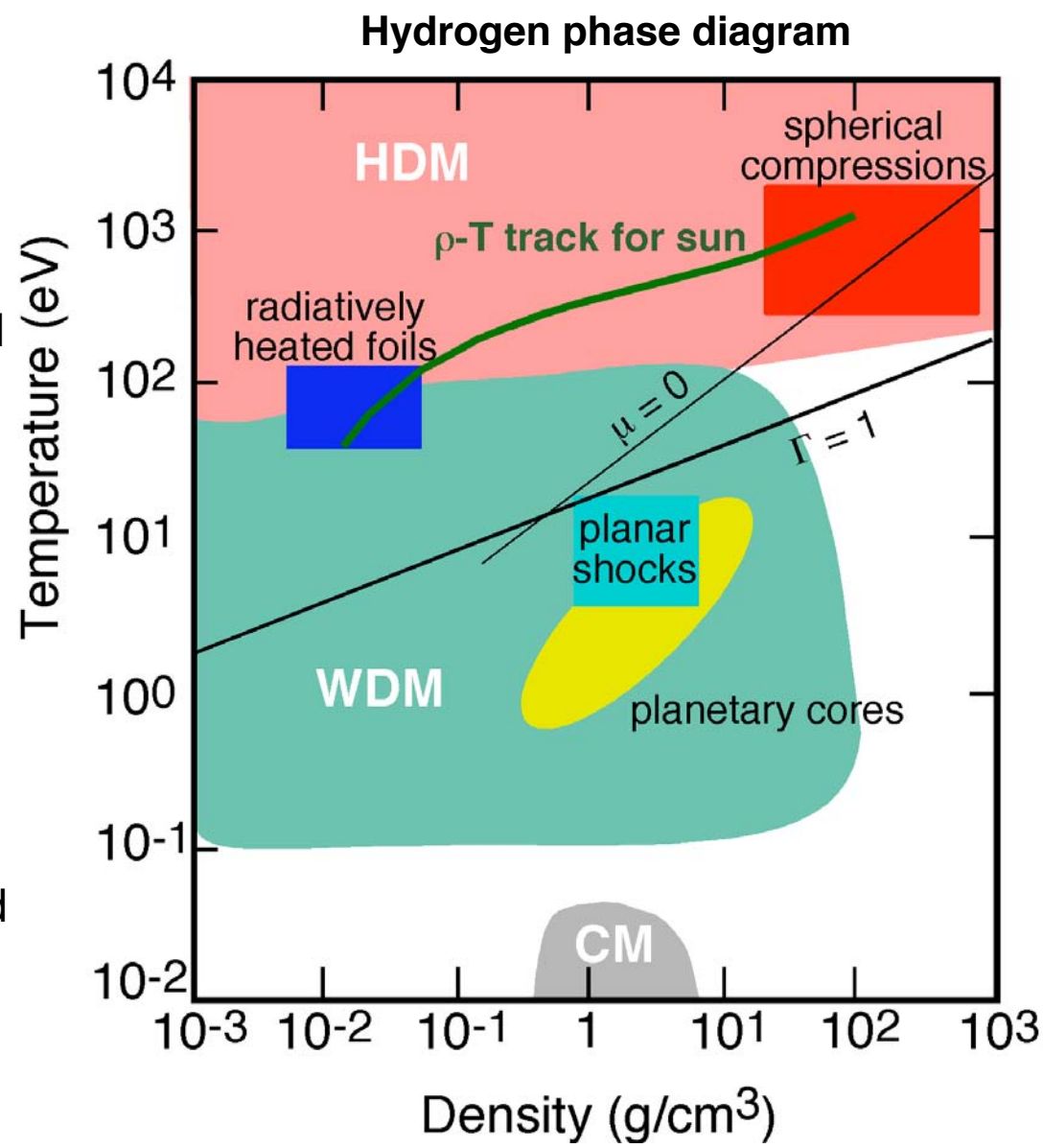
- 2003: Two NAS reports highlighted HEDS:
  - *Connecting Quarks with the Cosmos: Eleven Science Questions for the New Century*
  - *Frontiers in High Energy Density Physics: The X-Games of Contemporary Science*



- 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

Experiment	Description
Warm Dense Matter Creation	Using the XFEL to uniformly warm solid density samples
Equation of State	Heat / probe solids with XFEL to obtain material properties
Absorption Spectroscopy	Heat solids with optical laser or XFEL / use XFEL to probe
High Pressure Phenomena	Create high pressure with high-energy laser, probe with the XFEL
Surface Studies	Probe ablation/damage processes
XFEL / Gas Interaction	Create exotic, long-lived highly perturbed electron distribution functions in dense plasmas
XFEL / Solid Interaction	XFEL directly creates extreme states of matter
Plasma Spectroscopy	XFEL pump/probe for atomic state
Diagnostic Development	Develop Thomson scattering, SAXS, interferometry, and radiography

Estimates of HED time scales

Elastic e^--e^- collision frequency:

$$\nu_{ee} \approx 6 \cdot 10^{-6} n_e \lambda_{ee} / T^{3/2} \quad \| \quad T(eV), n_e(cm^{-3}), \lambda_{ee} \equiv \ln \Lambda_{ee} \sim 2$$

Elastic ion-e^- collision frequency:

$$\nu_{ie} \approx 1 \cdot 10^{-9} n_i Z^2 \lambda_{ie} / T^{3/2} \quad \| \quad n_i(cm^{-3})$$

Inelastic ion-e^- collision rate:

$$R_{excitation} \approx 3 \cdot 10^{-8} n_e \frac{e^{-(E_{UL}/T)}}{E_{UL}\sqrt{T}} \quad \| \quad E_{UL} = \text{ excitation energy (eV)}$$

$$R_{ionization} \approx 3 \cdot 10^{-6} n_e \varepsilon \frac{E_1(I_p/T)}{I_p\sqrt{T}} \quad \| \quad \varepsilon = \#\text{valence } e^-;\ I_p = \text{ionization potential (eV)}$$

Photopumping Rate:

$$R_{photo} \approx 774 f_{LU} \frac{F}{\Delta_{laser} E_{laser}^2}$$

f_{LU} = absorption oscillator strength; F = flux (W/cm^2)
Δ = fractional bandwidth; E = laser energy (eV)

Spontaneous Decay Rate:

$$A_{value} \approx 4.7 \cdot 10^8 Z^2 \quad \| \quad \text{atomic \#} = Z;\ \text{H-like } 2 \rightarrow 1$$

Ion plasma frequency:

$$\nu_{pi} \approx 141 \sqrt{n_i / Z}$$

Hydrodynamic time scale:

$$t_{hydro} \approx \frac{1.2 \cdot 10^{-10}}{\sqrt{T}} \quad \| \quad \text{time surface moves 1 } \mu\text{m}$$

WDM and HDM rates indicate short pulses required to access the physical processes

	WDM Z~ 1, n_e~10^{23} cm^{-3}, T~10 eV	**HDM** Z~ 10, n_e~10^{22} cm^{-3}, T~500 eV
ν_{ee}	$2x10^{16}$	$1x10^{13}$
ν_{ei}	$3x10^{12}$	$9x10^{9}$
$R_{excitation}$ (E_{ul}~T)	$3x10^{13}$	$1x10^{10}$
$R_{ionization}$ (E_{IP}~T)	$5x10^{14}$	$5x10^{11}$
$R_{photopump}$ (f~0.2;Δ~0.003, F=10^{14}, E_L~5000)	$2x10^{11}$	$2x10^{11}$
A_{value}	$5x10^{8}$	$5x10^{10}$
$\nu_{ion\ plasma}$	$5x10^{13}$	$2x10^{12}$

- To remove hydrodynamic effects one requires probe/pump at less than 1 ps

Hot Dense Matter

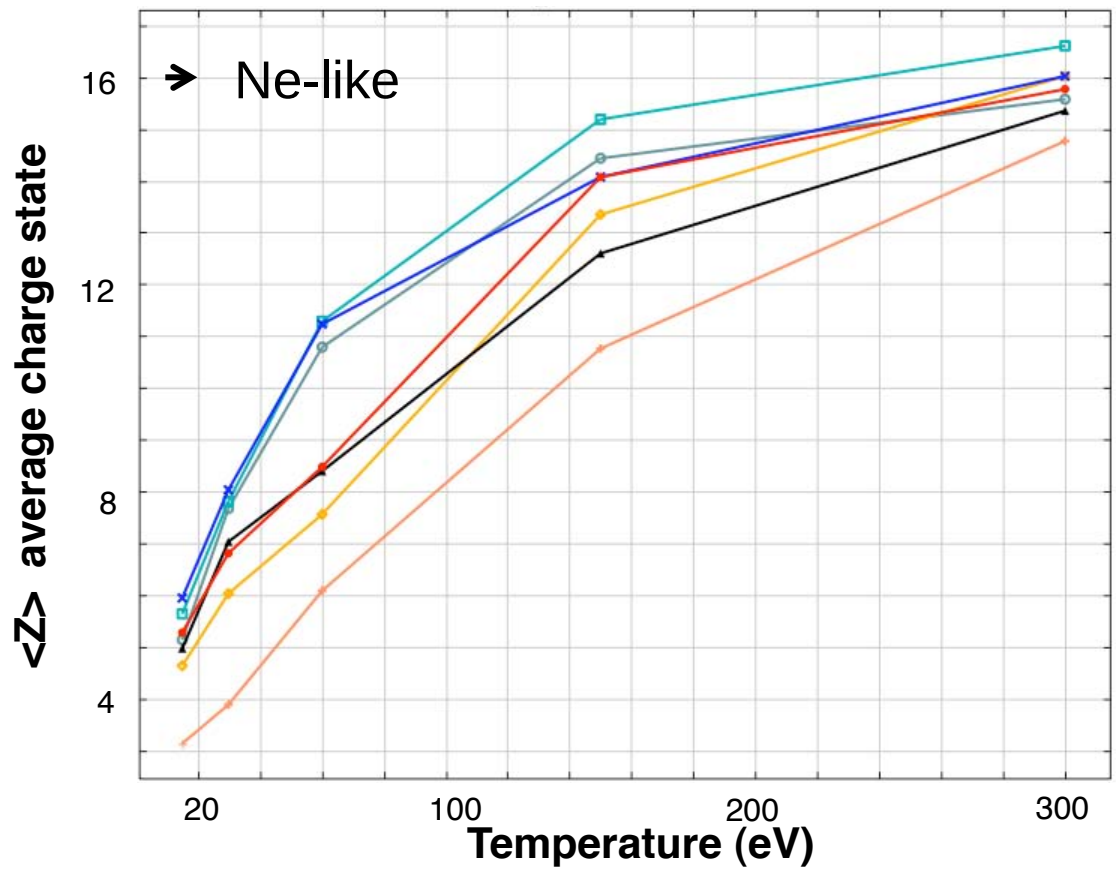
For HDM the short pulse intense x-ray source creates a unique initial state

- 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

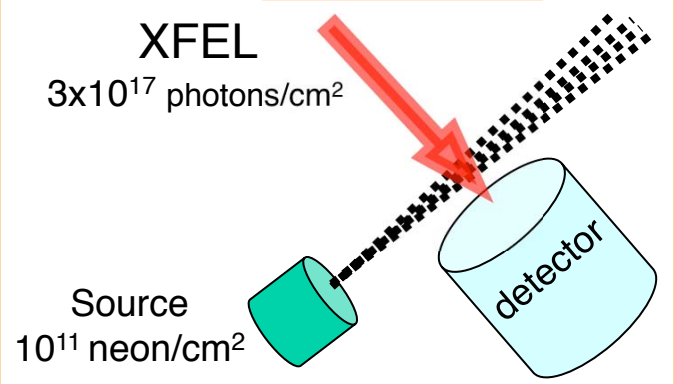
- The case is for a low density chosen for astrophysical applications
- Models are from **7** different codes
- Basic result: near a closed shell, e.g., Ne-like, the agreement improves
- In general, large discrepancies are found away from the closed shells

Case ID	Total # of Points	Parameter	Grid	# Points
Fe	25	T_e	15, 30, 60, 150, 300	5
		N_e	10^7	1
		T_{rad}	15, 50	2
		U_x	0, 0.1, 10	3
		Spectrum	10-1000 eV, ΔE = 1 eV (for T_e = 30 and 150 eV only)	991



XFEL provides an opportunity for HEDS plasma spectroscopy - like AMO

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

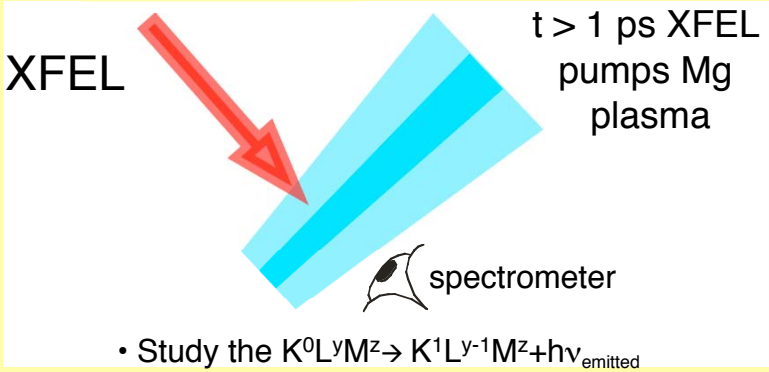


- **Photoionization**:
  $Ne+h\nu_{>870eV} \rightarrow Ne^{+*}(K)+e$
- **Auger Decay:**
  $Ne+h\nu_{>870eV} \rightarrow Ne^{+*}(K)+e \rightarrow Ne^{2+*}(LL)+e \rightarrow Ne^{3+*}+e$

XFEL only

- **Sequential multiphoton ionization:**
  $Ne+h\nu_{>870eV} \rightarrow Ne^{+*}(K)+e+h\nu_{>993eV} \rightarrow Ne^{2+*}(KK)+e$
  $\rightarrow Ne^{3+}+e \rightarrow Ne^{4+}+e \rightarrow \ldots$
  $Ne+h\nu_{>870eV} \rightarrow Ne^{+*}(K)+e+h\nu_{>993eV} \rightarrow Ne^{3+*}(KLL)+e$
- **Direct multiphoton ionization:**
  $Ne+2h\nu_{>932eV} \rightarrow Ne^{2+*}(KK)+2e$

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



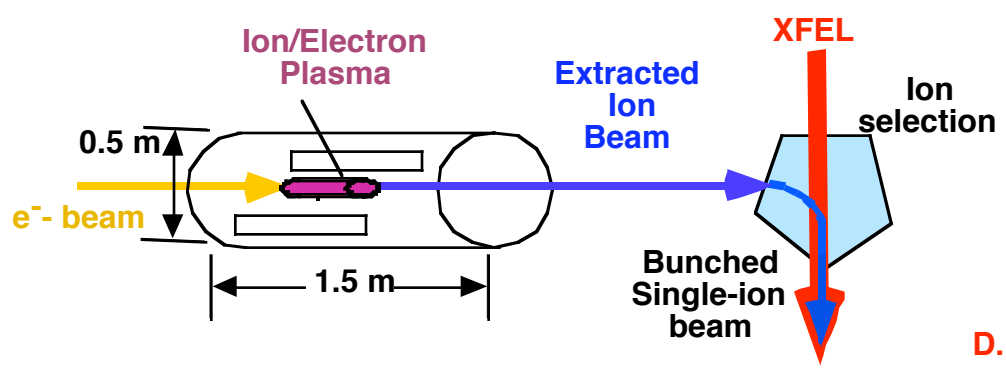
- **Photoionization of multiple ion species**:
  $K^xL^yM^z+h\nu_{XFEL} \rightarrow K^{x-1}L^yM^z+e$ (x=1,2; y=1-8; z=1,2)
- **Auger Decay of multiple ion species:**
  $K^xL^yM^z+h\nu_{XFEL} \rightarrow K^{x-1}L^yM^z+e \rightarrow K^xL^{y-2}M^z+e$
- **Sequential multiphoton ionization:**
  $K^xL^yM^z+h\nu_{XFEL} \rightarrow K^{x-1}L^yM^z+e+h\nu_{XFEL} \rightarrow K^0L^yM^z+e+h\nu_{XFEL}$
  $\rightarrow K^0L^{y-1}M^z+e+h\nu_{XFEL} \rightarrow \ldots$
  $K^xL^yM^z+h\nu_{XFEL} \rightarrow K^{x-1}L^yM^z+e+h\nu_{XFEL} \rightarrow K^{x-1}L^{y-2}M^z+2e$
- **Direct multiphoton ionization:**
  $K^xL^yM^z+2h\nu_{XFEL} \rightarrow K^0L^yM^z+2e$

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, $>10^8/cm^3$/pulse
    - In $1mm^2$ x 10cm can have $> 10^7/cm^3$
    - 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



D. Schneider and E. Silver

High Peak Brightness of 4th 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_{photo}, must be greater than radiative decay rate, A_{value}

$$\Rightarrow R_{photo} > A_{value}$$

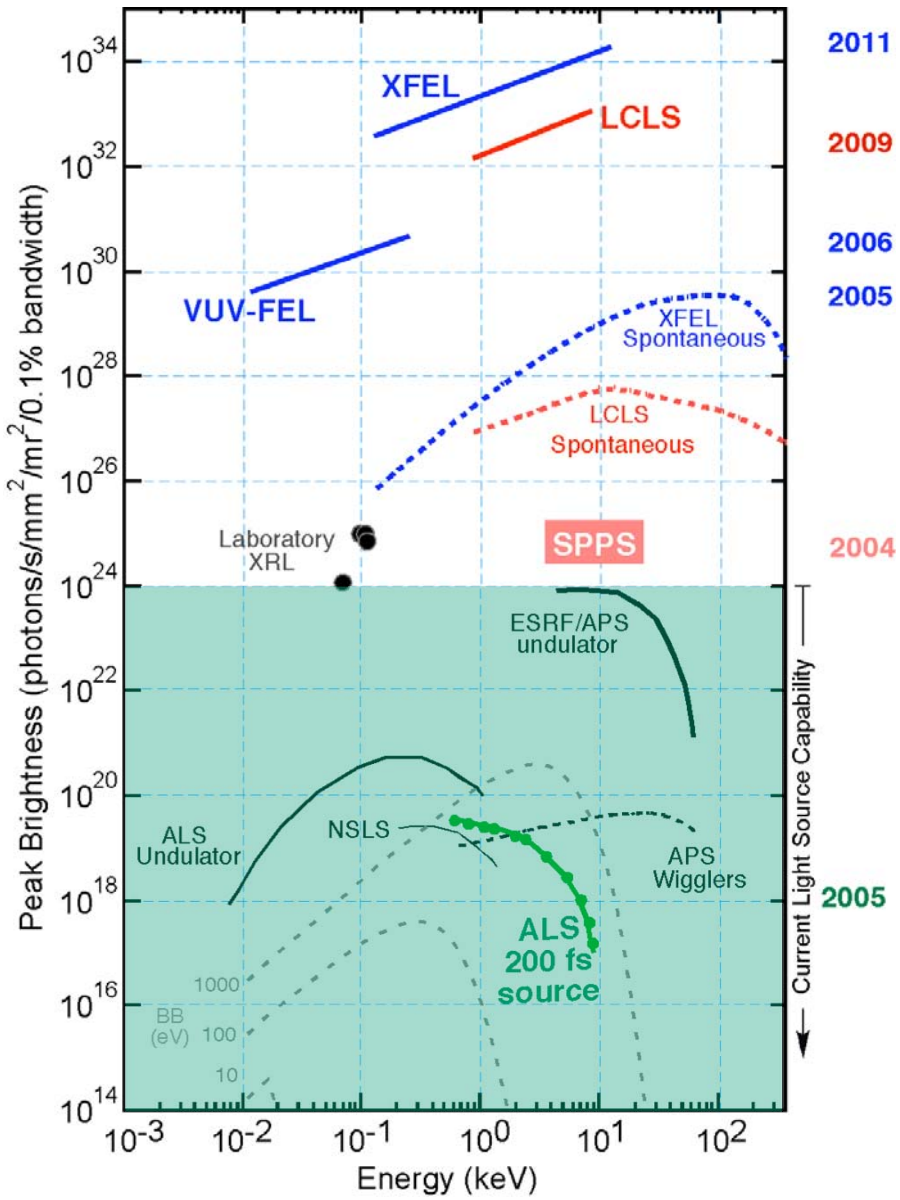
- For $I = 10^{14}$ W/cm^2

$$R_{photo}/A_{value} \sim 10^{-4}\, g_U/g_L\, \lambda^4$$

- FELs attains needed excitation strength

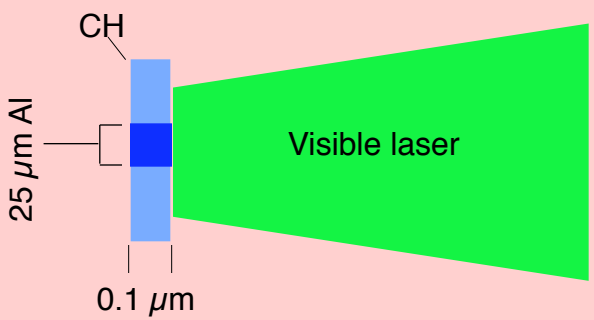
$$\lambda \sim 10\ \text{Å} \Rightarrow R_{photo}/A_{value} > 1$$

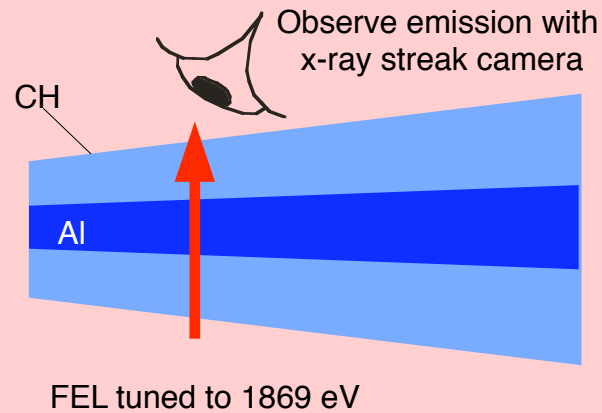
- To obtain brightnesses ~ 10^{31} the effective blackbody radiation temperature for 2.5 Å would be ~ 63 MeV



To provide NLTE benchmarks pumping K-shell emitters provides critical data

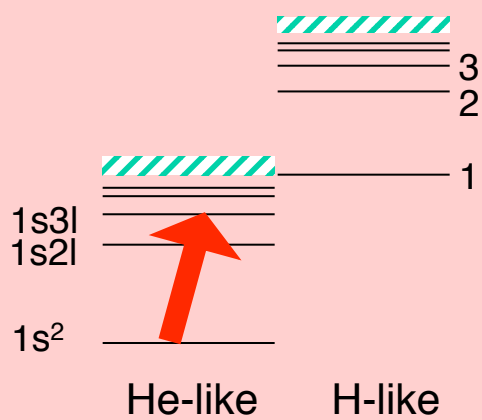
- **Schematic experiment**

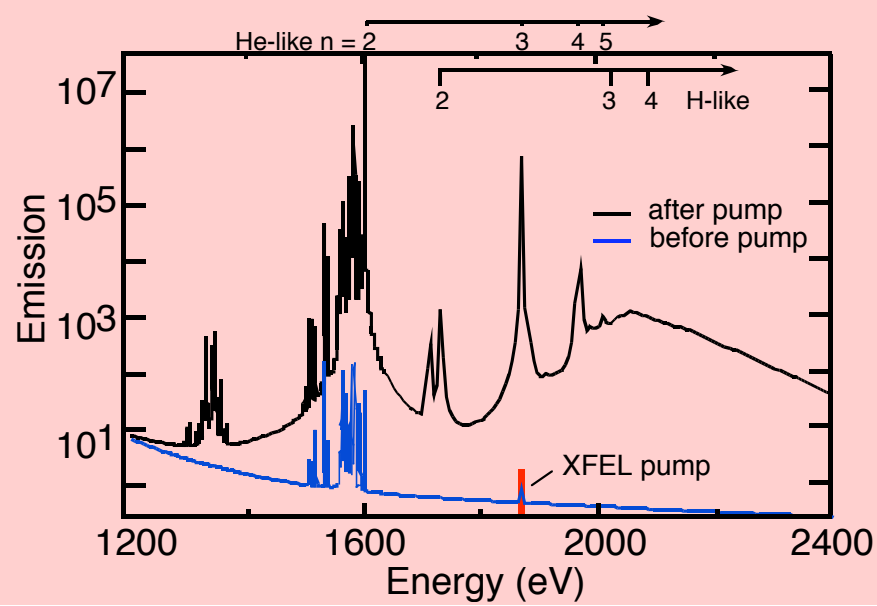




- **t = 0 laser irradiates Al dot**
- **t = 100 ps FEL irradiates plasma**

- **Simulation**





Line intensity, line position, and line shape *are* effected by HED environment

- Simple form for emission illustrates the observable aspects

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

$$\phi(\omega) = \int d\varepsilon P(\varepsilon) J(\omega,\varepsilon)$$ ll $P(\varepsilon)$ is the ion microfield

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

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

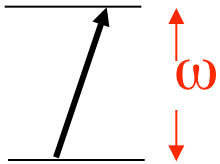
- Investigate $\delta(\omega)$ to look at line position (shift)

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, ω_L, to be near the transition energy



- 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 ω, and depends on atom-plasma interaction

$$I(\omega) = \mathrm{Im}\langle\langle V|G|V\rangle\rangle = \mathrm{Im}\left\langle\left\langle d^* \left|\frac{1}{\omega - L_o}\right| d\rho_o \right\rangle\right\rangle \longrightarrow \frac{c(\omega-\delta)+a\gamma}{(\omega-\delta)^2+\gamma^2}$$

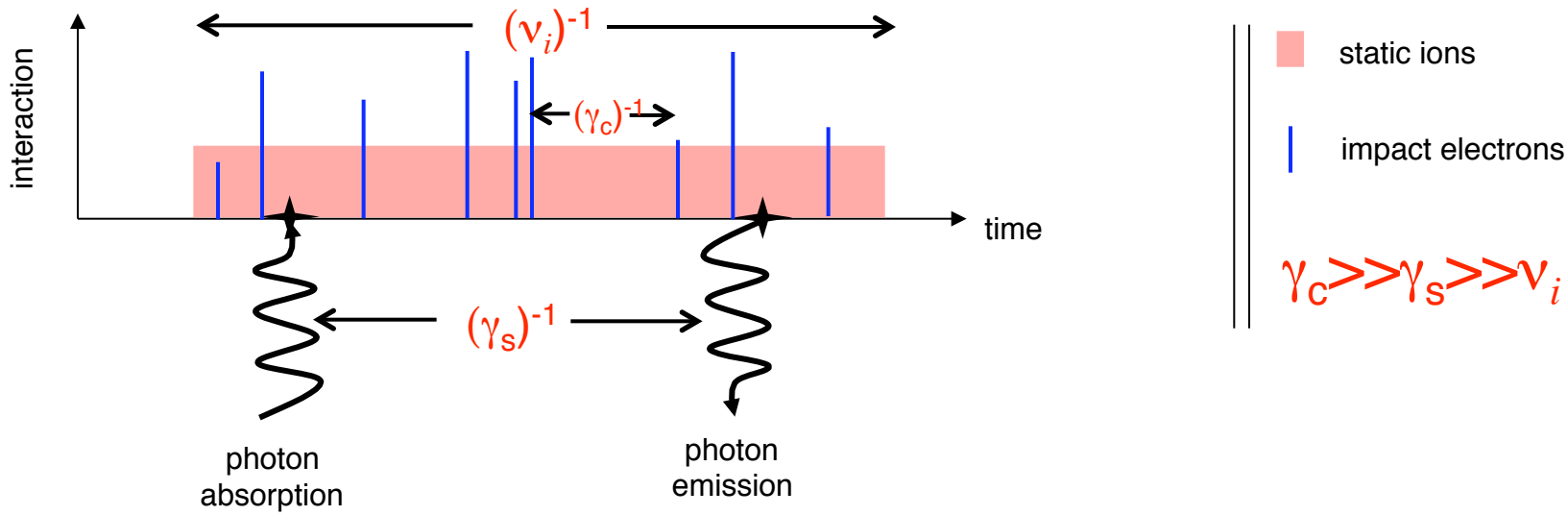
γ is width
δ is shift
a is amplitude
c due to complex L_o

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

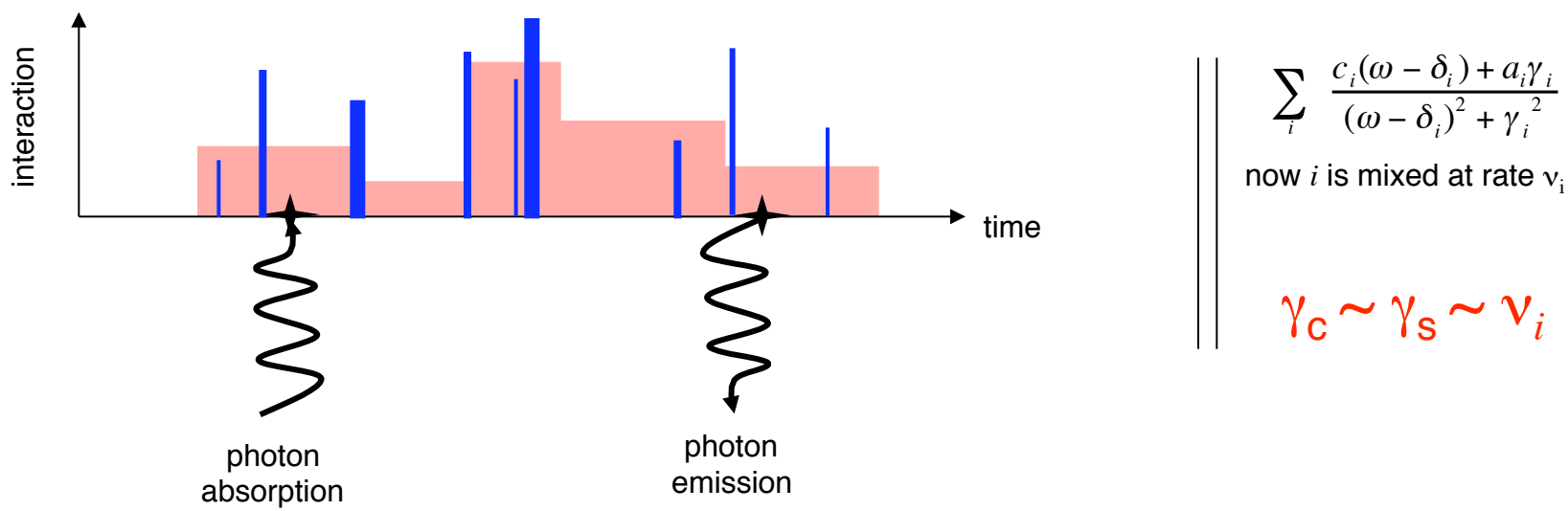
$$I(\omega) = \sum_i \frac{c_i(\omega-\delta_i)+a_i\gamma_i}{(\omega-\delta_i)^2+\gamma_i^2}$$

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



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 ω_S by a system pumped at ω_L

$$I(\omega_S,\omega_L) \propto \lim_{\eta\to 0} \mathrm{Im} \sum_{i,f} p_i \left(\langle\langle \mathbf{V}_S | \mathbf{G}_\omega(\mathrm{i}\eta) | \mathbf{V}_L \rho_o \rangle\rangle \right)_{i,f}$$

V_S= interaction for emission
V_L = interaction with pump
G = resolvent of the evolution

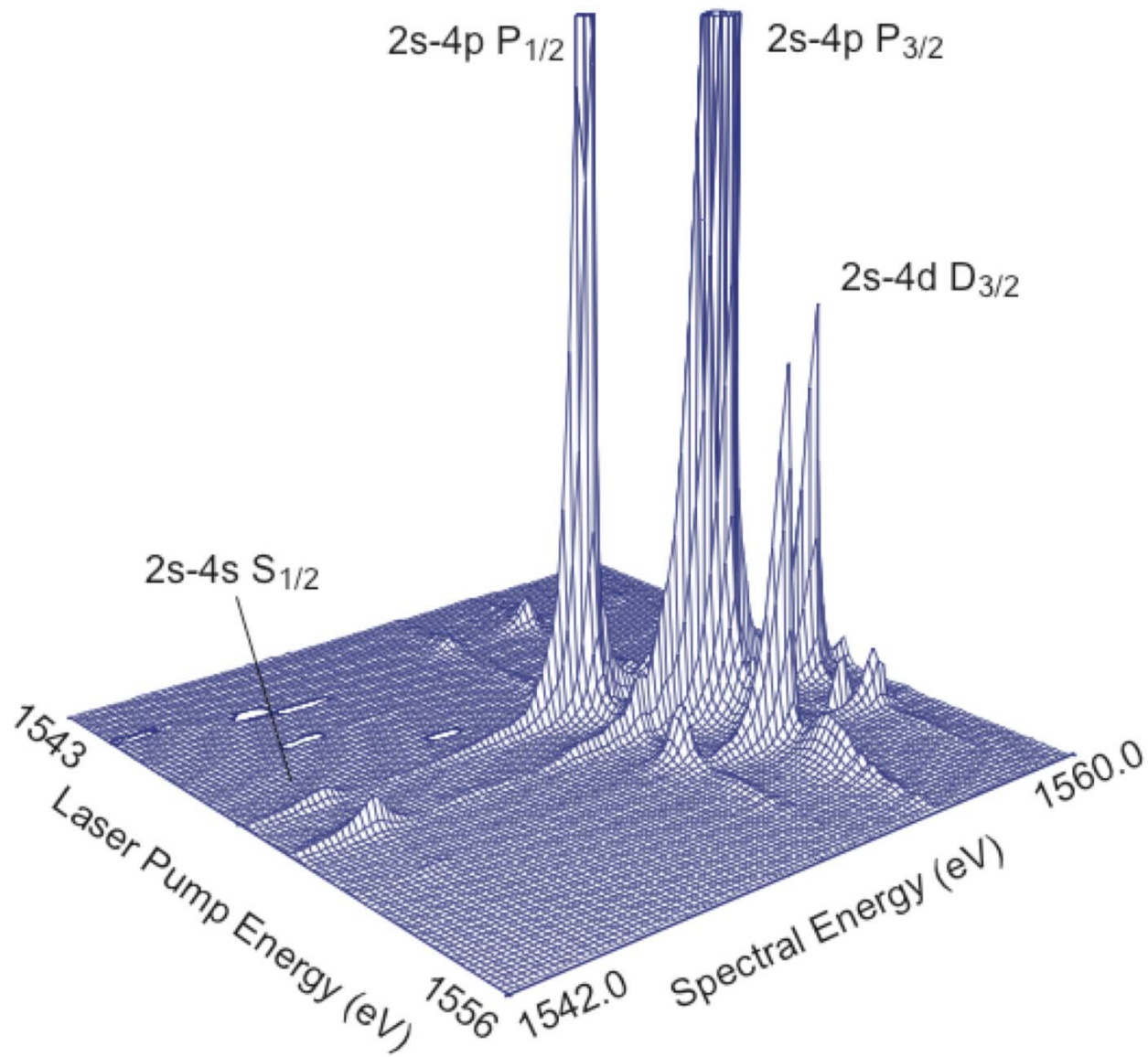
- $R(\omega_L,\omega_S)$ is the redistribution function

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

- 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

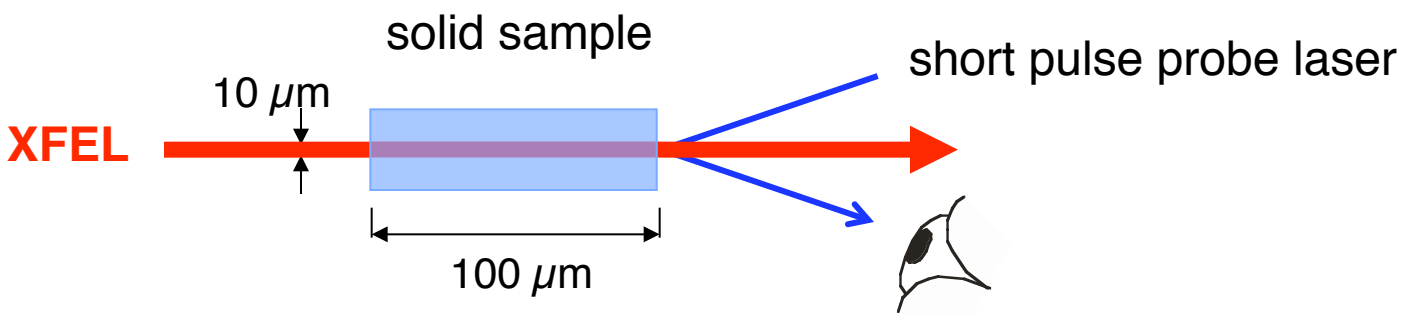
- As the issue with WDM is not to just create it
  - Because it occurs widely and is easily realized

- 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



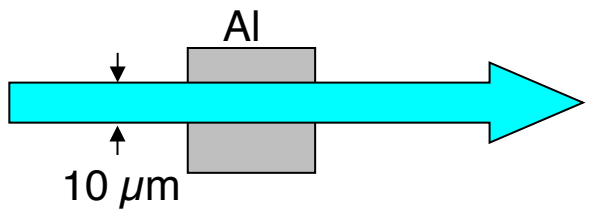
- For a 10x10x100 μm thick sample of Al
  - Ensure sample uniformity by using only 66% of beam energy
  - Equating absorbed energy to total kinetic and ionization energy

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

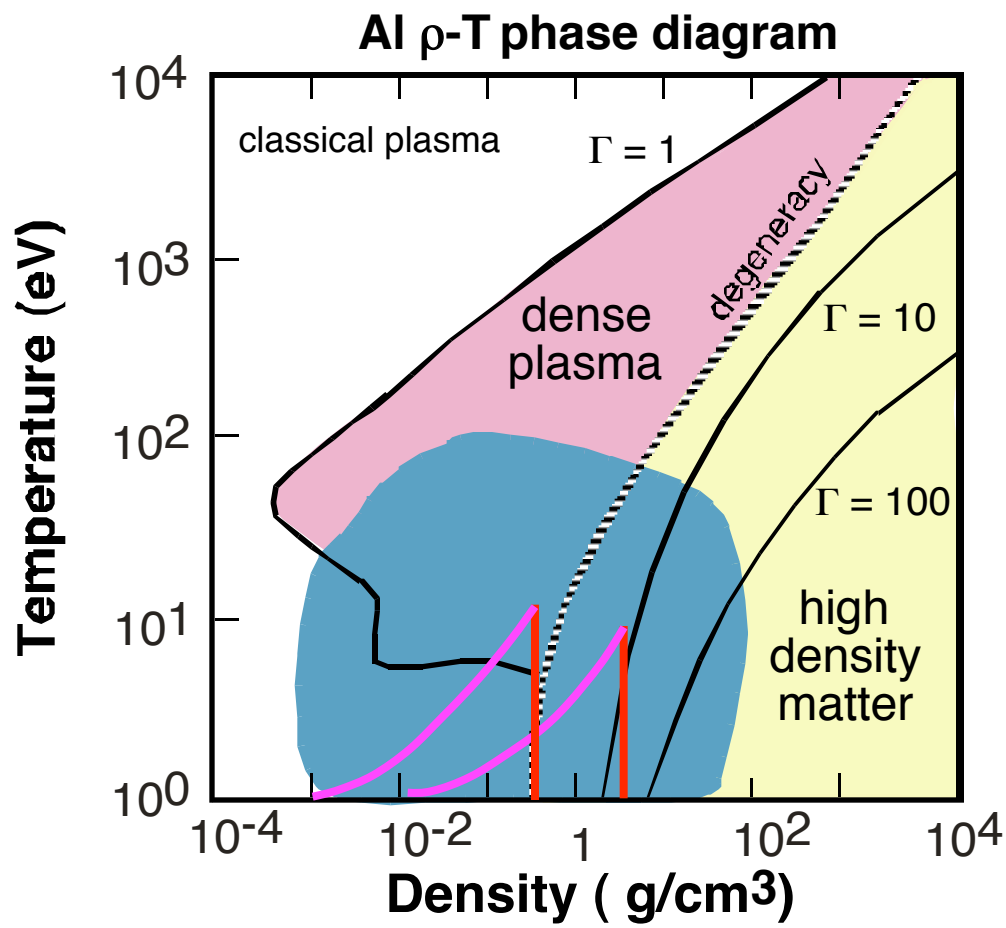
  - Find 10 eV at solid density with $n_e = 2\text{x}10^{22}$ cm^{-3} and <Z> ~0.3
- State of material on release can be measured with a short pulse laser
- Material, rapidly and uniformly heated, releases isentropically

WDM created by isochoric heating will isentropically expand sampling phase space

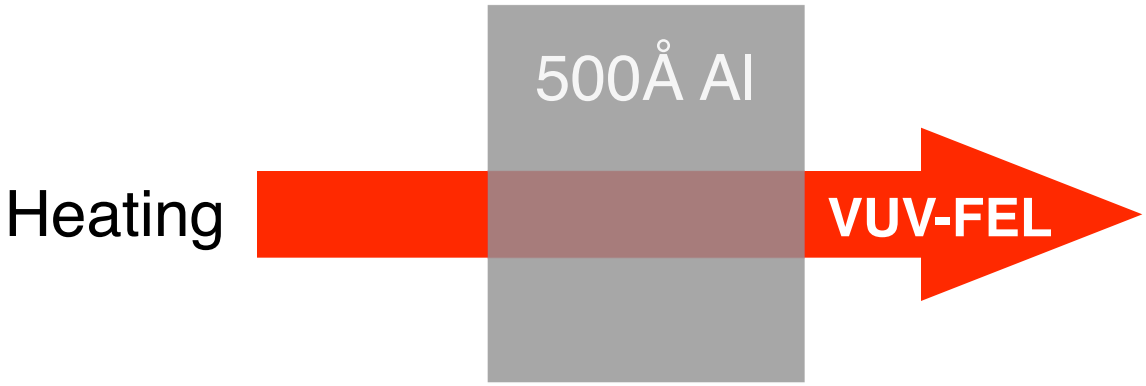
- Concept is straightforward



- XFEL can heat matter rapidly and uniformly to create:
  - Isochores (constant ρ)
  - Isentropes (constant entropy)
- Using underdense foams allows more complete sampling
  - Isochores (constant ρ)
  - Isentropes (constant entropy)



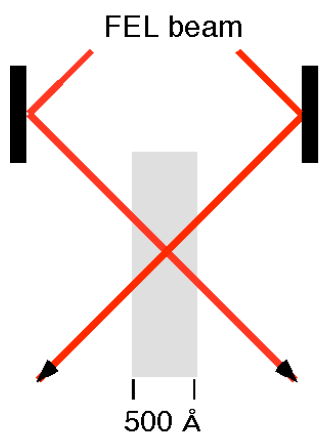
Creating Warm Dense Matter with FLASH is initial step for eventual XFEL research

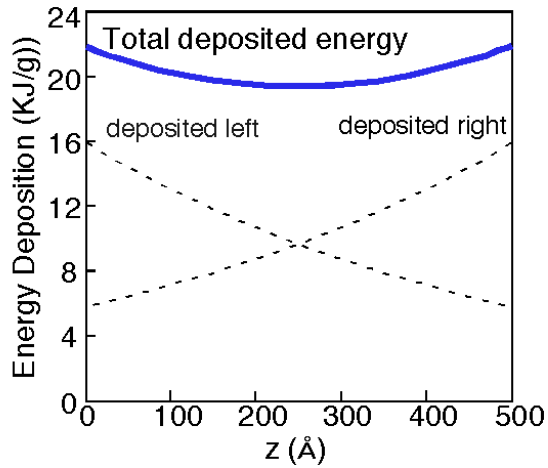


- Isochoric heating
  - 40 fs 60 Å VUV-FEL heats a Al foil 500 Å uniformly
  - $\frac{E}{V} = \frac{3}{2} n_e T_e + \sum_i n_i I_P^i \Rightarrow$(10^{12} x 200 eV) / Volume = 3/2 (1.7x10^{23}) x 10 eV
    - Volume = Area x 500 Å $\Rightarrow$ Area = 50 μm spot
    - For 1 eV plasma a 140 μm spot is needed
- Isentropic expansion
  - A optical FDI probe measures the isentropic expansion

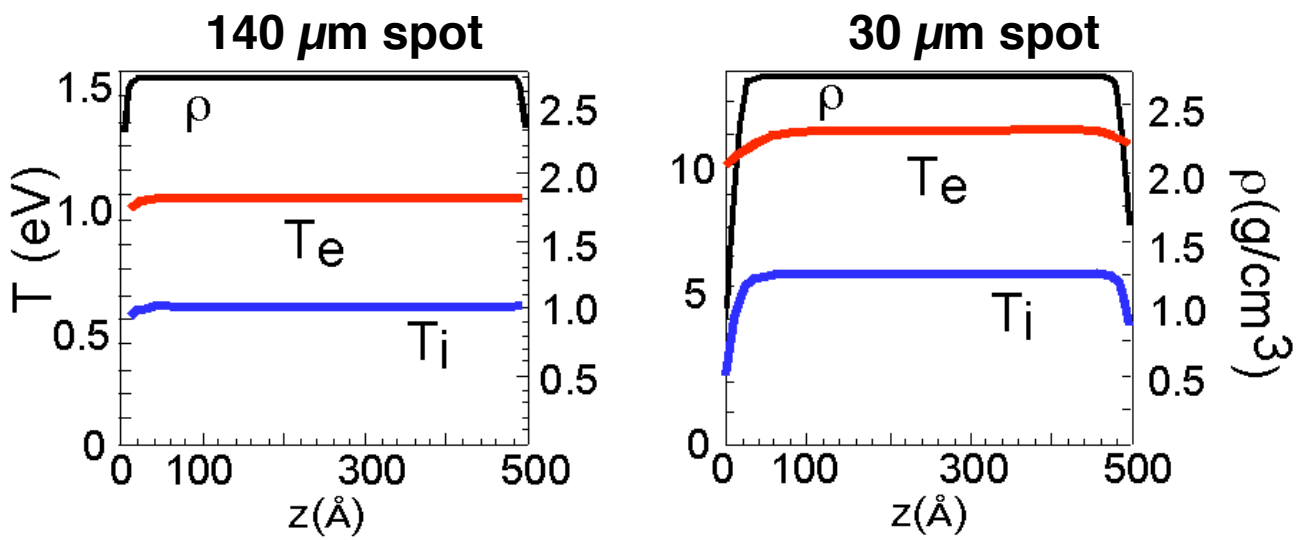
Simulations of FLASH VUV-FEL confirm simple estimates for creating WDM:

- 500 Å Al irradiated by split FLASH 40 fs beam



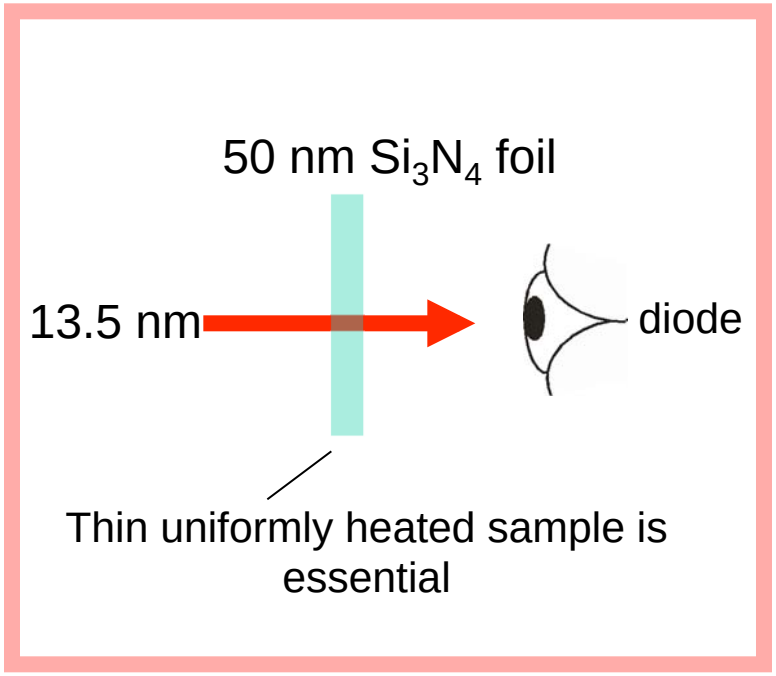


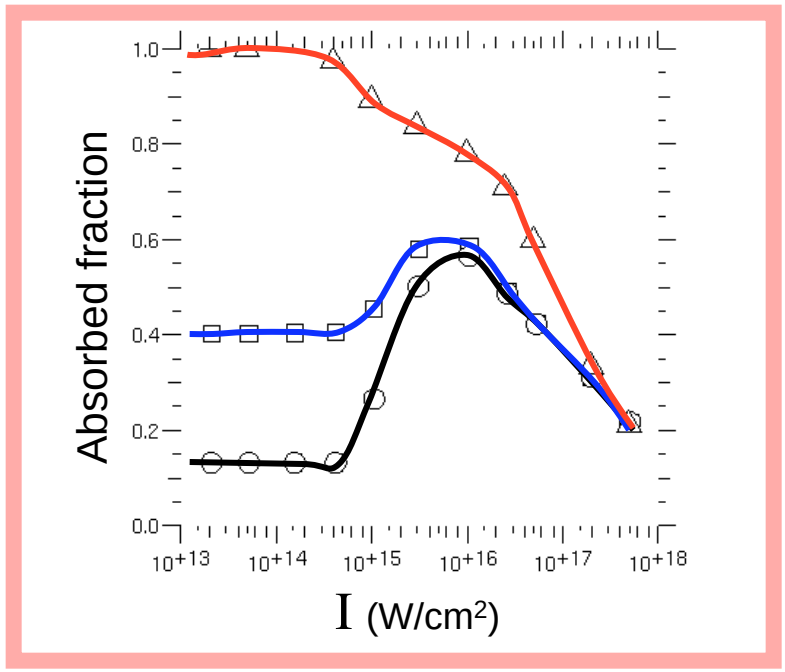
- Temperature and density at 200 fs after the FLASH pulse



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
  - 5×10^{16} represents ~40 μJ - within current FLASH operation





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Cold κ_ν<.025 eV; EOS >.025 eV
Cold κ_ν< 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 ~10^{19}

- PI with high energy photons and long collisional relaxation => 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:
  - $T_{\text{Thermaiization}} \sim 1\text{ps}\ (10^{19}/n_e)$
  - $T_{\text{growth PEW}} \sim 2\text{ ps}\ (10^{19}/n_e)^{1/2}$
  - $T_{\text{growth PETS}} \sim 100\text{ fs}\ (10^{19}/n_e)^{1/2}$

- Signatures vary with gas density and observation angle

Plasma Instabilities

Photo electron two stream (PETS) instability:

$$\gamma_{PETS} = 0.21 k v_0 \frac{3 - (k v_0 / \omega_{pe})^2}{\sqrt{1 + 1.1 (k v_0 / \omega_{pe})^2}}$$

$$\gamma^{max} \cong 0.31 \omega_{pe} \text{ at } k \cong 0.82 \omega_{pe} / v_0, \theta_0 = 0$$

Photo electron Weibel (PEW) instability:

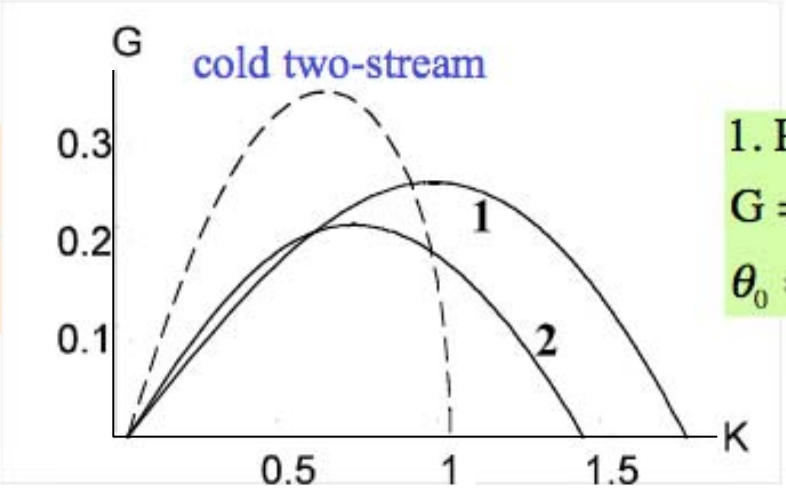
$$\gamma_{PEW} = \frac{1}{4} k v_0 \frac{2 - (kc / \omega_{pe})^2}{\sqrt{1 + (kc / \omega_{pe})^2}}, \theta_0 = \pi / 2$$

$$\gamma^{max} \cong 0.22 \omega_{pe} (v_0 / c) \text{ at } k \cong 0.7 \omega_{pe} / c$$

2. PEW:

$G = (\gamma / \omega_{pe})(c / v_0)$,

$\theta_0 = 0, K = kc / \omega_p$



1. PETS:

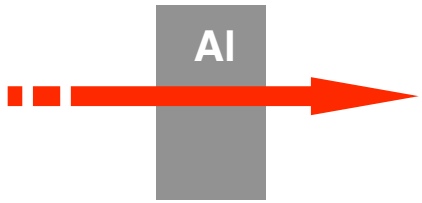
$G = \gamma / \omega_{pe}$,

$\theta_0 = \pi / 2, K = k v_0 / \omega_{pe}$

W. Rozmus

To study XFEL interaction with matter need non-Maxwellian electron kinetics

- Study a VUV-FEL case:
  - 200 eV; 200 fs pulse; $\Delta E/E \sim 0.003$; 10^{12} photons; 40μm spot



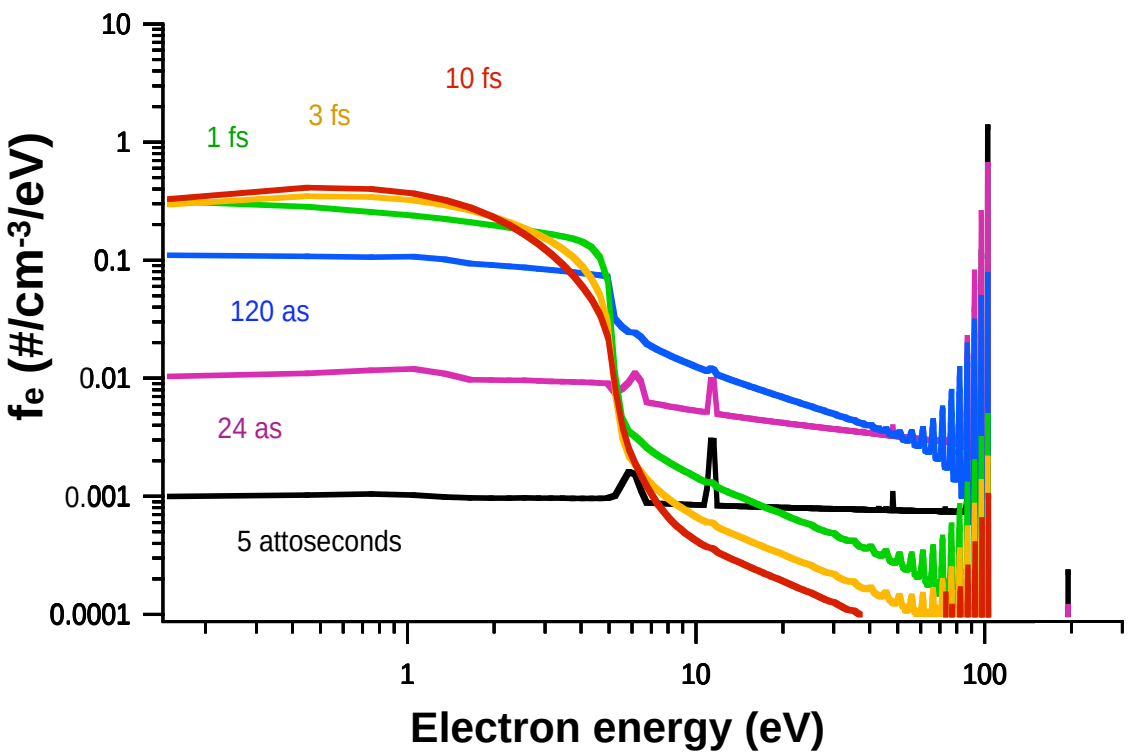
$$\frac{\partial n_e(\varepsilon)}{\partial t} = \left[\frac{\partial n_e(\varepsilon)}{\partial t}\right]_{Elastic} + \left[\frac{\partial n_e(\varepsilon)}{\partial t}\right]_{\substack{Inelastic \\ \& Superelastic}} + \left[\frac{\partial n_e(\varepsilon)}{\partial t}\right]_{Sources} - \left[\frac{\partial n_e(\varepsilon)}{\partial t}\right]_{Sinks} + \left[\frac{\partial n_e(\varepsilon)}{\partial t}\right]_{\substack{Electron- \\ Electron}}$$

- ✓ 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 ~65 eV
  N_e ~10^{16} cm^{-3}
  N_i ~6×10^{22} cm^{-3}
- e^--e^- elastic ν_{ee} :
  Coulomb ~1.4×10^{9} s^{-1}
- e^--ion inelastic ν_{ei} :
  excitation ~5×10^{16} s^{-1}
  ionization ~2×10^{16} s^{-1}

H.-K. Chung

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)

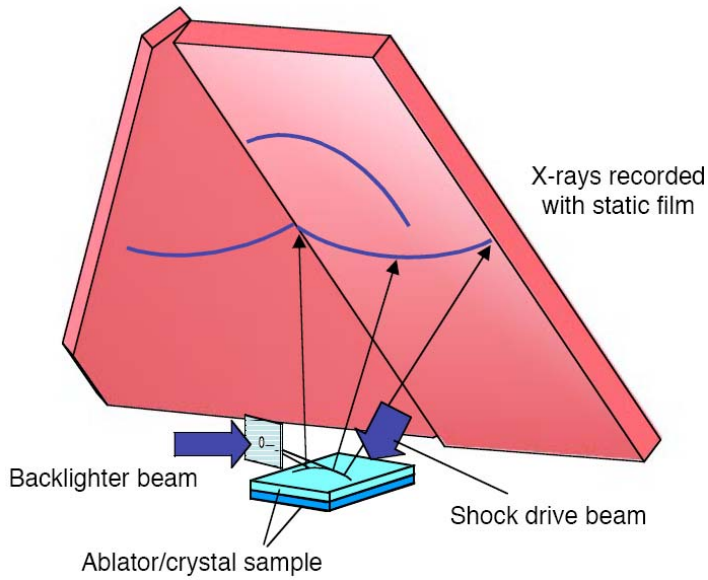
- In cases where phase changes occur two aspects of diffraction require sub-ps pulses

  - 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)

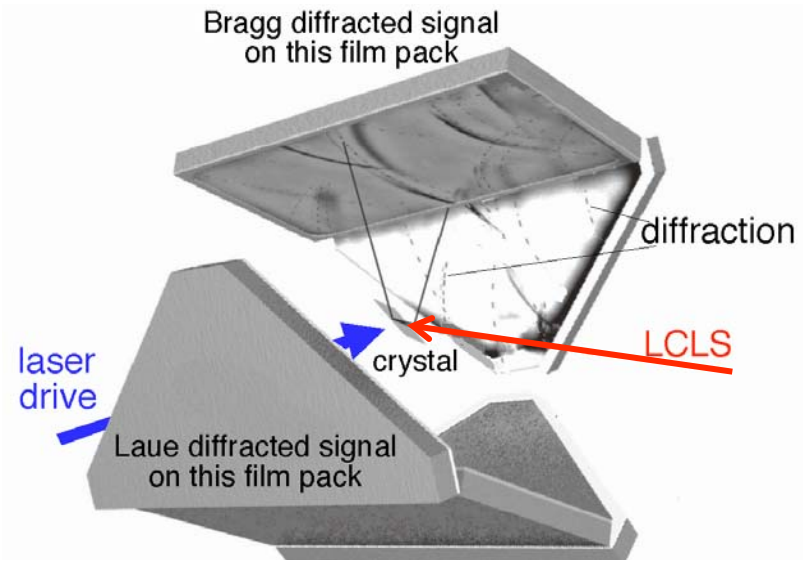
Lasers provide shocks and high divergence probe - LCLS provides low divergence probe

- **Schematic of High Energy Laser shock experiment**



- 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**

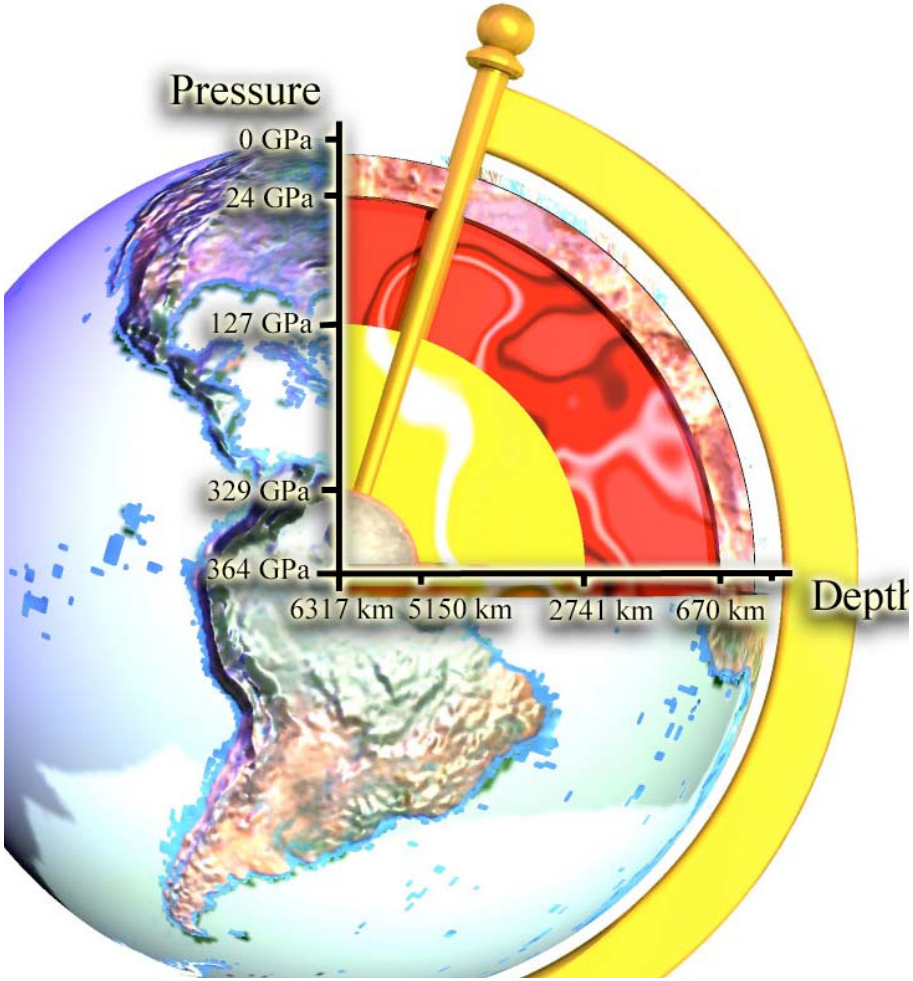
- **Schematic of LCLS XFEL shock experiment**



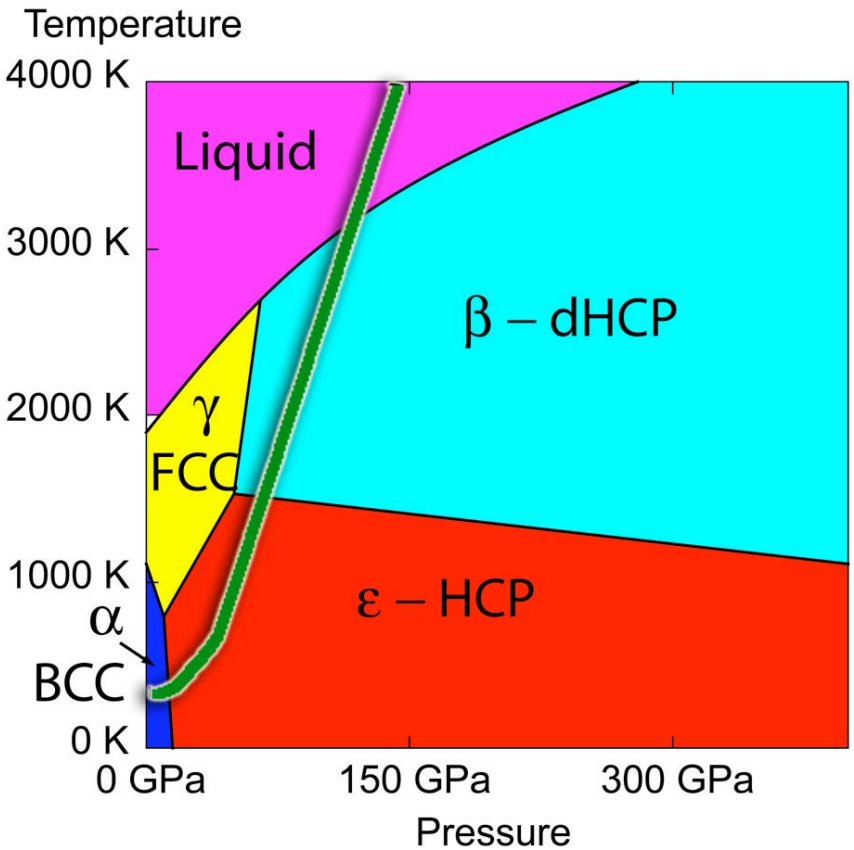
- Laser creates a shock in a polycrystalline sample
- XFEL creates fs-scale non-divergent monochromatic source
- Grains in the polycrystal diffract the beam
- **Low Divergence ⇒ *nm-scale fs diffraction of real solids***

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



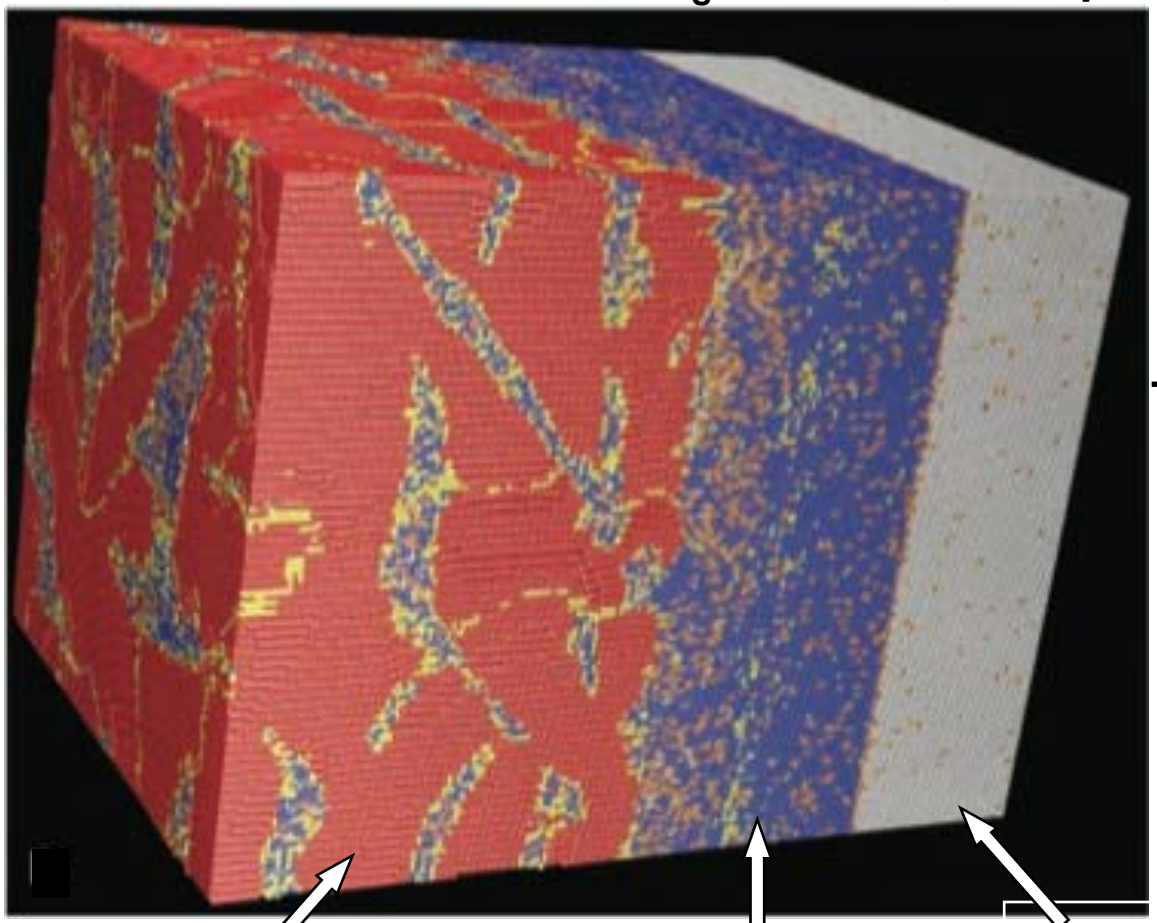
A.M. Dziewonski and D. L. Anderson
Physics of the Earth and Planetary Interiors **25**, 297 (1981).



S. K. Saxena & L. S. Dubrovinsky, American Mineralogist **85**, 372 (2000).
J. C. Boettger & D. C. Wallace, Physical Review B 55, 2840 (1997).
C. S. Yoo et al., Physical Review Letters **70**, 3931 (1993).

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

MD simulations of BCC iron: v_s = 470 m/s, t = 8 ps



shock direction

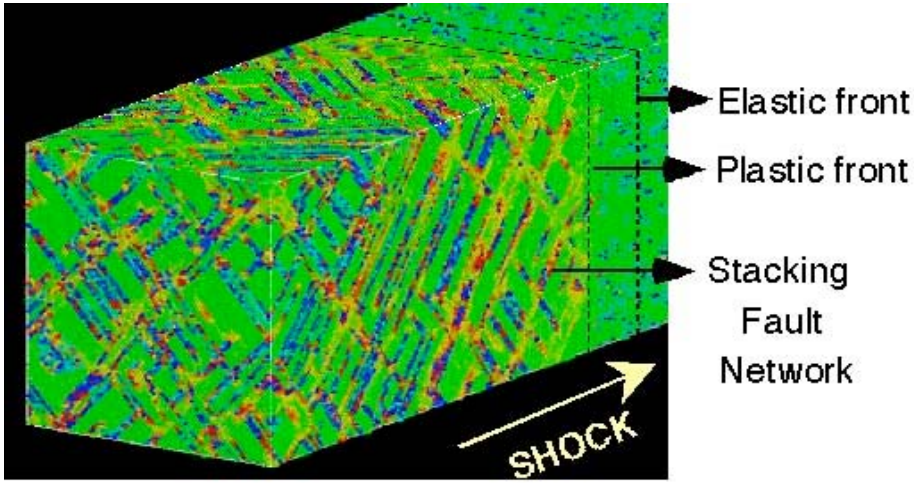
unshocked

transformed grains, HCP

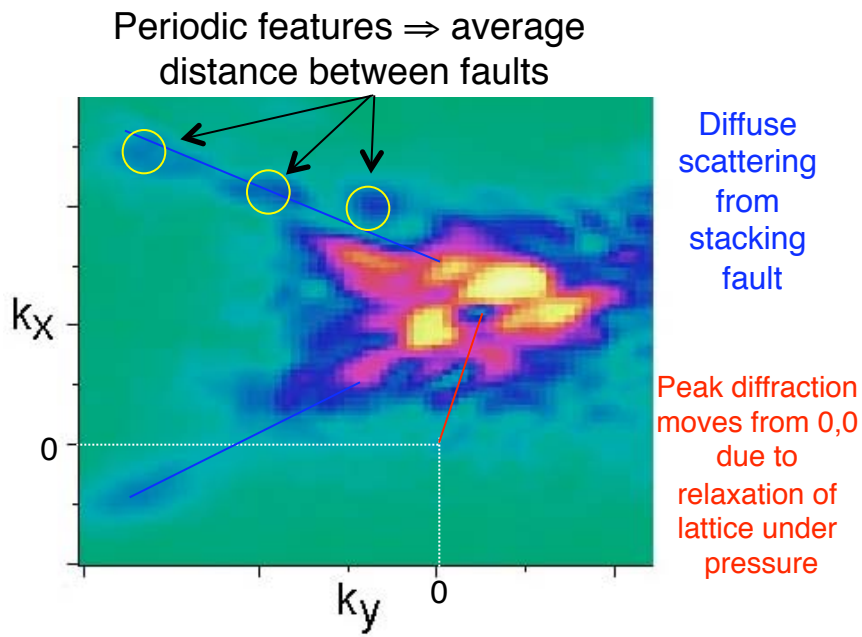
uni-axial compressed BCC

Kadau et. al. 2002

LCLS enables real-time, *in situ* study of deformation at high pressure and strain rate

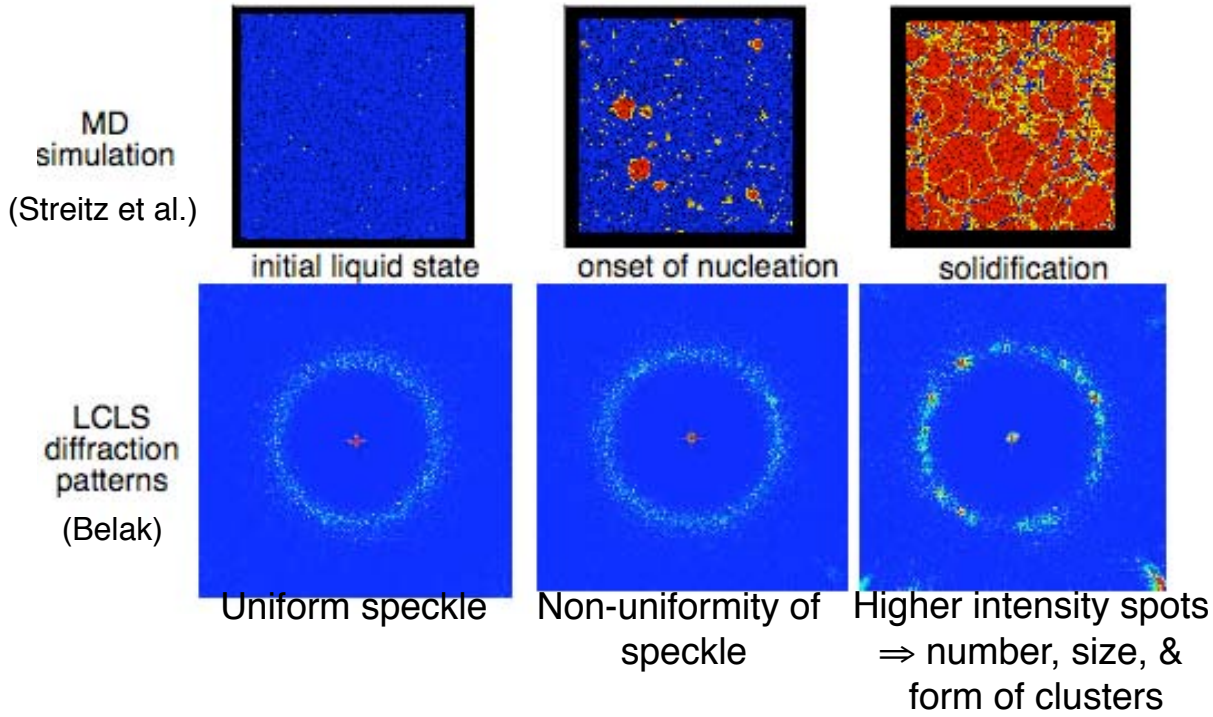


- **MD simulation of FCC copper**



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

MD simulations of Ta show nucleation and solidification the XFEL can probe



50 nm cube
16M atoms

$>10^9$ photons
signal degradation

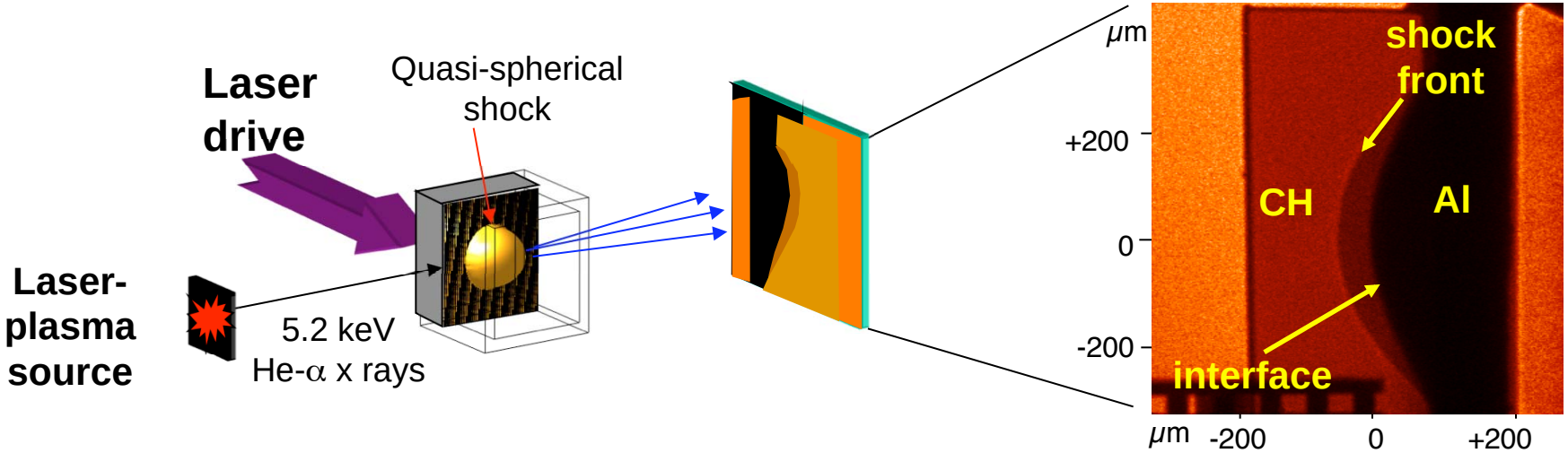
- Goal of *in situ* x-ray diffraction of shocked solids at granular level is to understand the microscopic to inform mesoscopic, and then macroscopic
- Study how individual grains respond elastically and plastically to high pressure as a function of orientation with respect to a given uniaxial shock wave
- XFEL is ideally suited to probe via diffraction polycrystalline high pressure solids because it is an ultra-bright, non-diverging, monochromatic source.

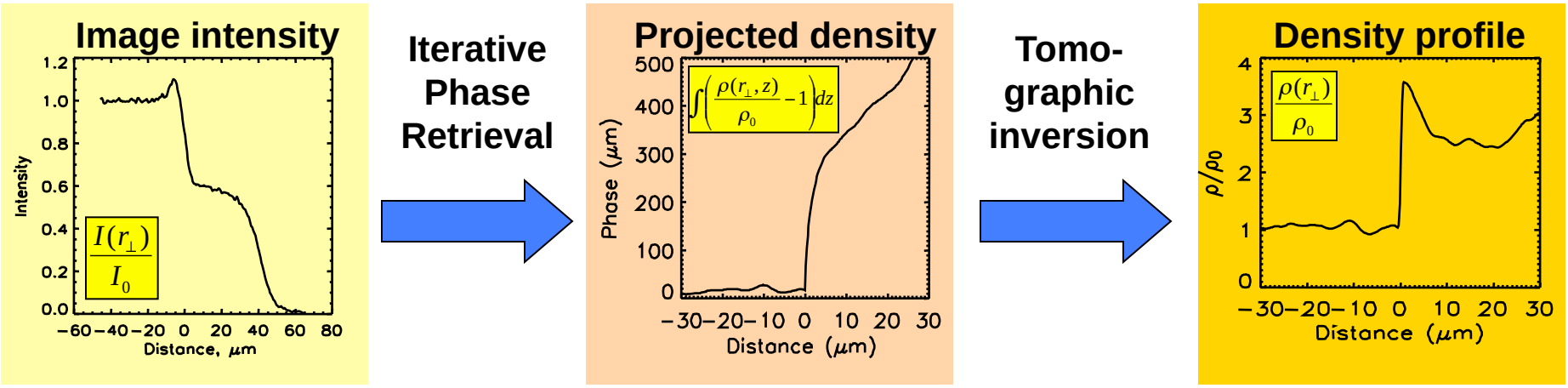
XFEL

as a

probe

Current x-ray *phase-contrast imaging* at ~ 5 *μ*m resolution uses laser-plasma sources



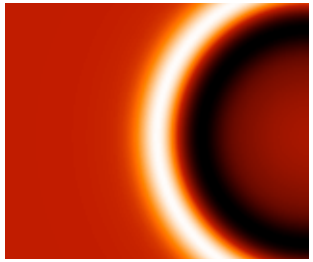


Current techniques are limited by spatial coherence & flux of laser-plasma x-ray source [D. G. Hicks 2006]

LCLS will enable coherent diffractive x-ray microscopy at the nanoscale

Shock front @ 2 μm resolution

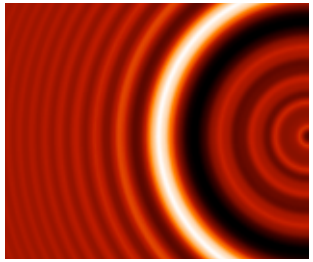
Phase-contrast imaging (near-field)



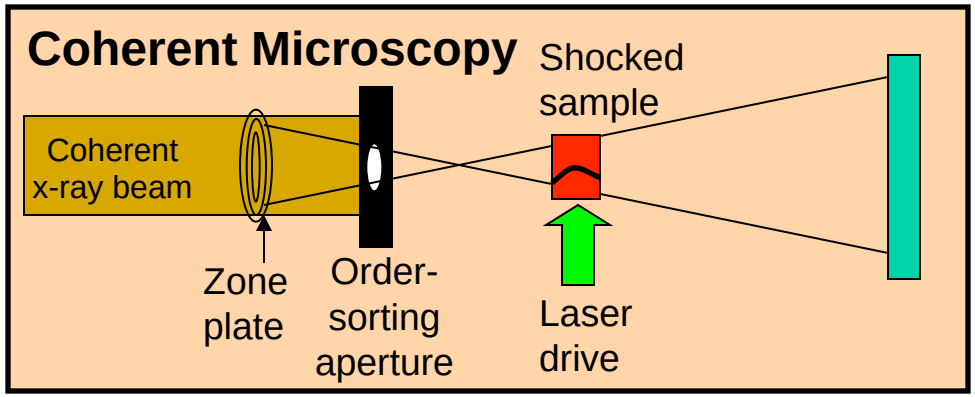
Coherent XFEL beam

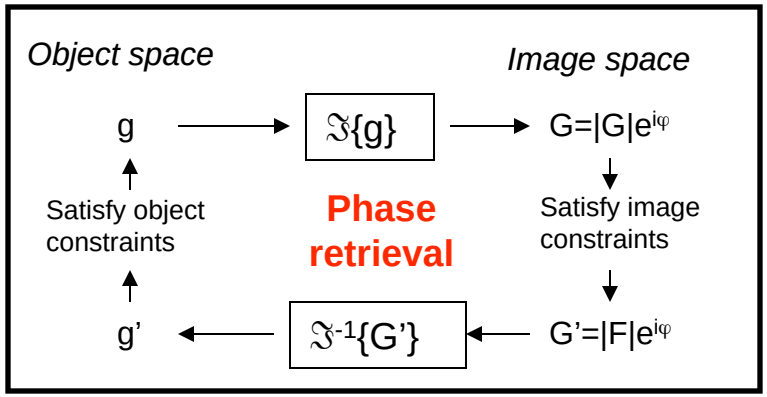
Single-pulse imaging: > 10^7 photons/pulse

Shock front @ 50 nm resolution



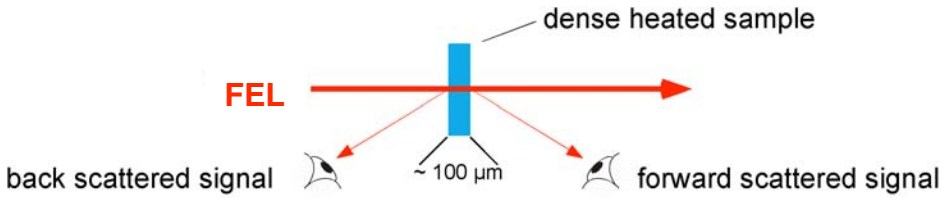
Coherent-diffractive imaging (far-field)



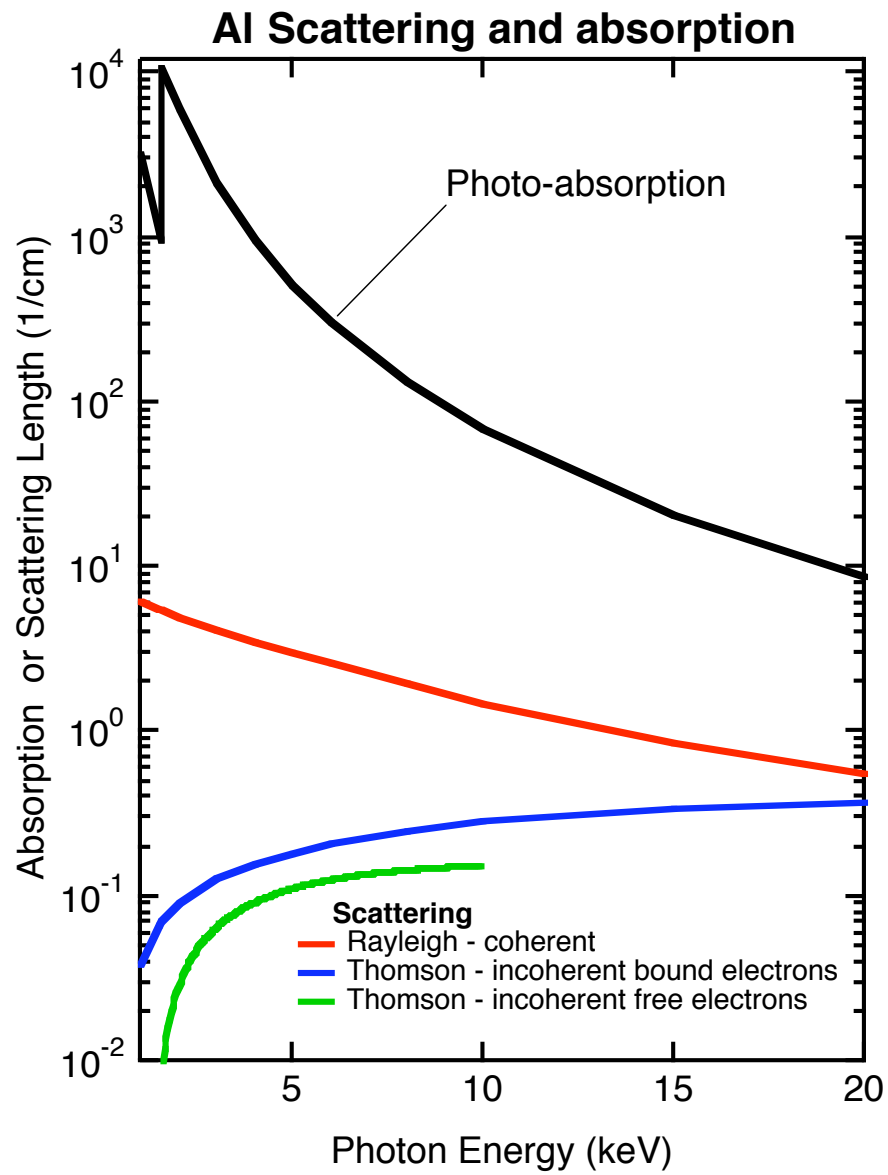


Dynamic processes on the nanoscale: shock front size (viscosity), phase transition kinetics, nucleation & growth, grain structure deformation

X-ray '*Thomson Scattering*' will provide a unique probe for HED matter

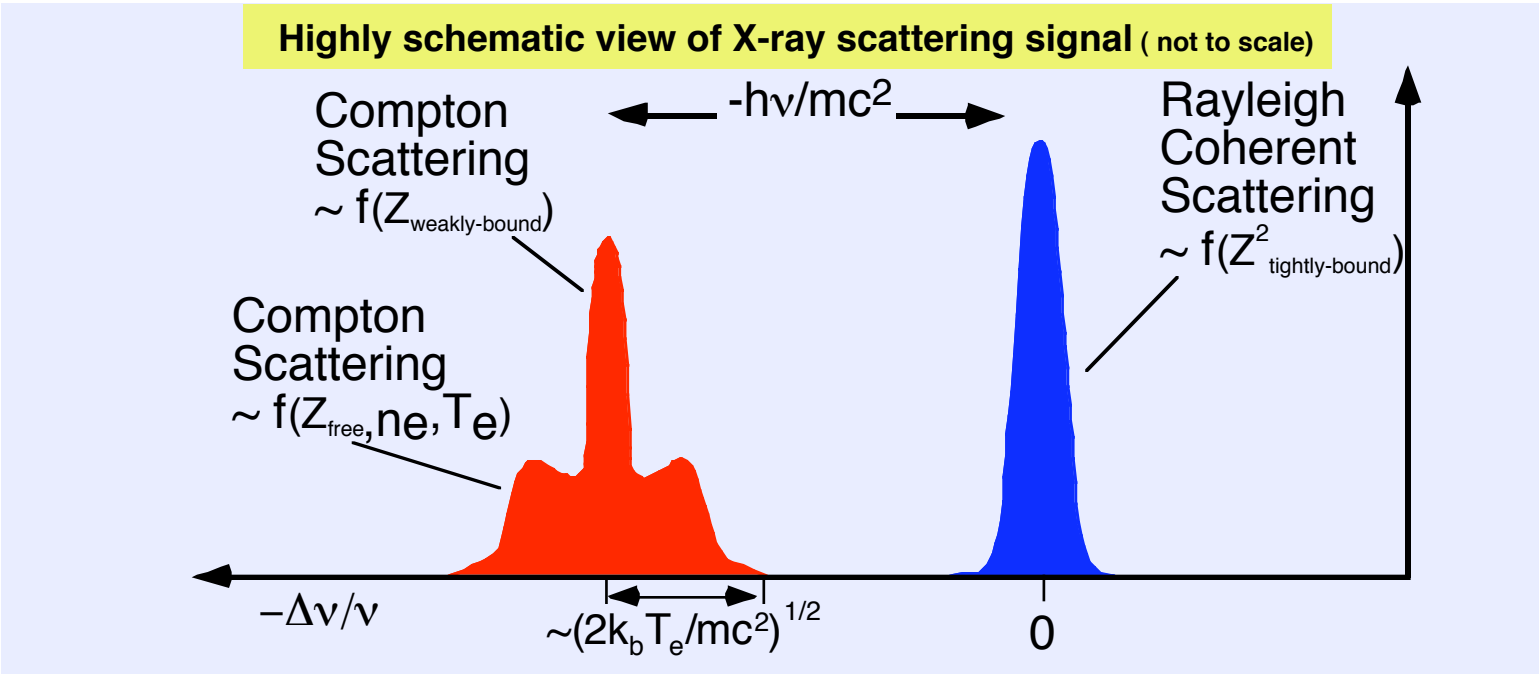


- Scattering from free electrons provides a measure of the T_e, n_e, *f*(v), and plasma damping
  - ⇒ structure alone ***not*** sufficient for plasma-like matter
- Due to absorption, refraction and reflection neither visible nor laboratory x-ray lasers can probe high density
  - ⇒ little to no high density 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

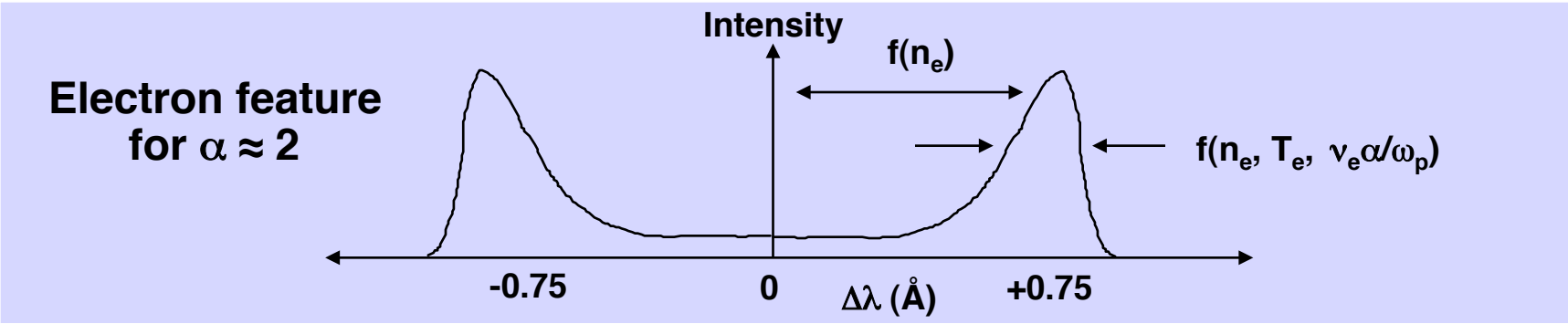


- For a 25 eV, 4×10^{23} cm^{-3} plasma the XFEL produces 10^4 photons from the free electron scattering

- Can obtain temperatures, densities, mean ionization, velocity distribution from the scattering signal

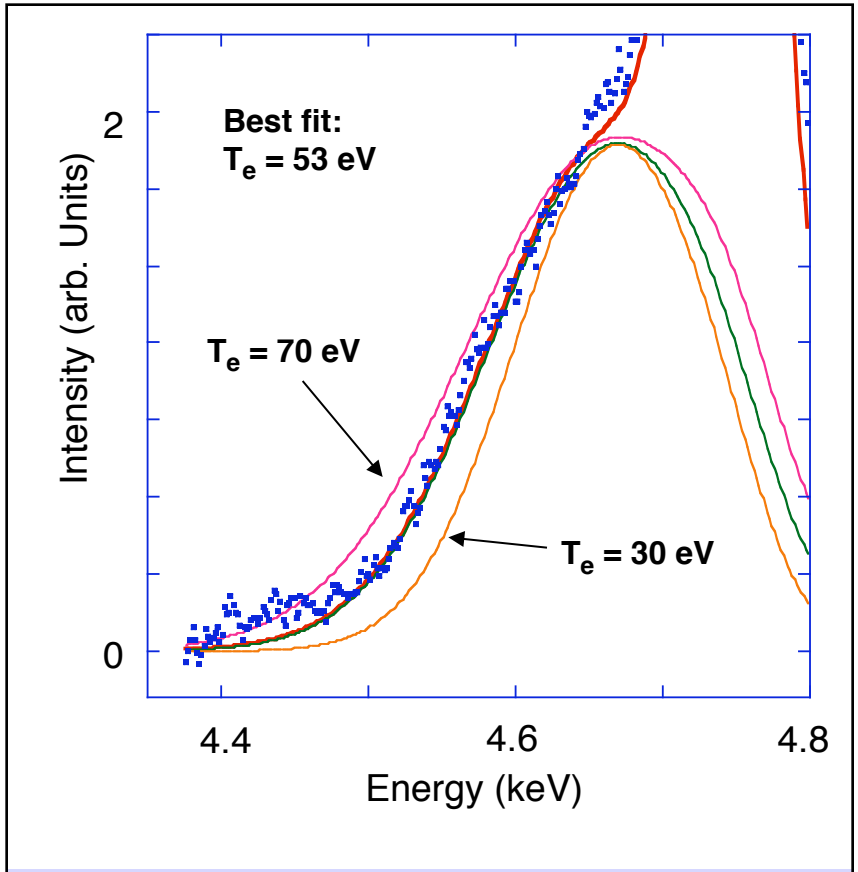
XFEL provides a scattering probe of ≥ solid density *finite* temperature matter

- X-ray laser output: at 12 Å ~ 10^{12} photons
- Plasma probed: $n_e = 4\times10^{23}$ cm^{-3}, $T_e = 25$ eV, $L = 10^{-2}$ cm
- Scattering parameter: $\alpha = \lambda/4\pi\lambda_D = 12$ Å / ($4\pi \times 0.6$ Å) ≈ 2
- Scattered fraction: $\sigma n_e L = 7\times10^{-25}/2(1+\alpha^2) \times 4\times10^{23} \times .01 \approx 3\times10^{-4}$
- Collected fraction: $\Omega/4\pi$ x efficiency ~ 4×10^{-4} x10% = 4×10^{-5}
- # photons collected: $10^{12} \times 4\times10^{-5} \times 3\times10^{-4} \approx$ **10^4**
- Signal / Planckian: > 10^8 for 300 μm probe size at $T_e = 25$ eV
- $\Delta\lambda/\lambda$ required: $\Delta\lambda/\lambda \sim \sqrt{(n_e/n_c)}/\alpha^2 = \sqrt{(4\times10^{23}/4\times10^{28})}/4 \approx$ **.006**



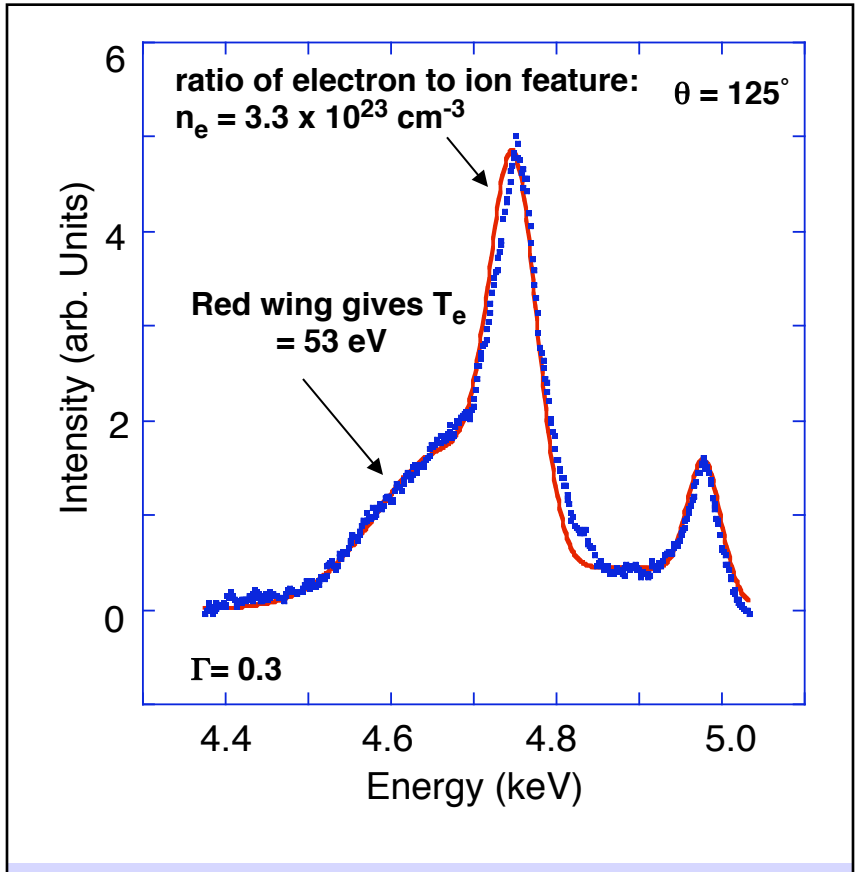
Thomson Backscattering diagnosis of solid density Be in WDM regime: $T_e \sim 55$ eV

A sensitivity analysis shows that T_e measured with an error of ~15%



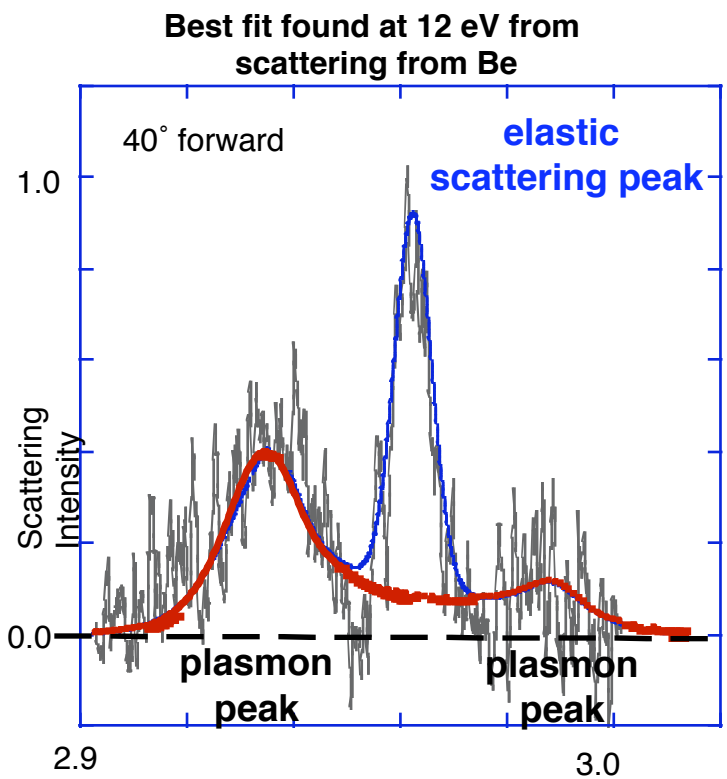
Comparison of the experimental data with the theoretical calculations for various electron temperatures

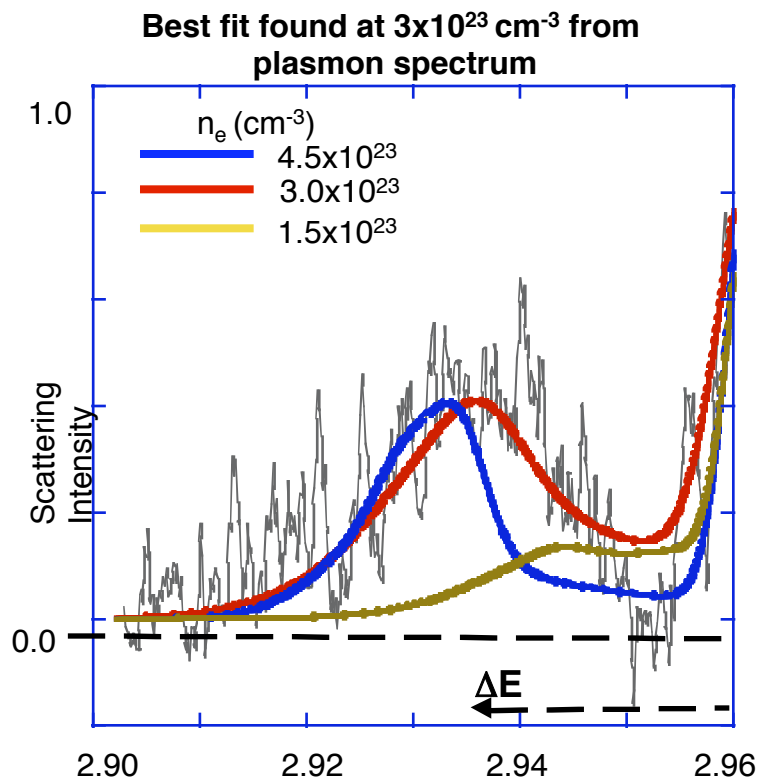
X-ray Thomson scattering spectra provide accurate data on T_e and n_e



From the theoretical fit to the data from the heated Be we obtain T_e = 53 eV and Z_{free} = 3.1 corresponding to $n_e = 3.8 \times 10^{23}$ cm^{-3}

Thomson rorward scattering provides data from collective regime: plasmon feature provides additional diagnostics

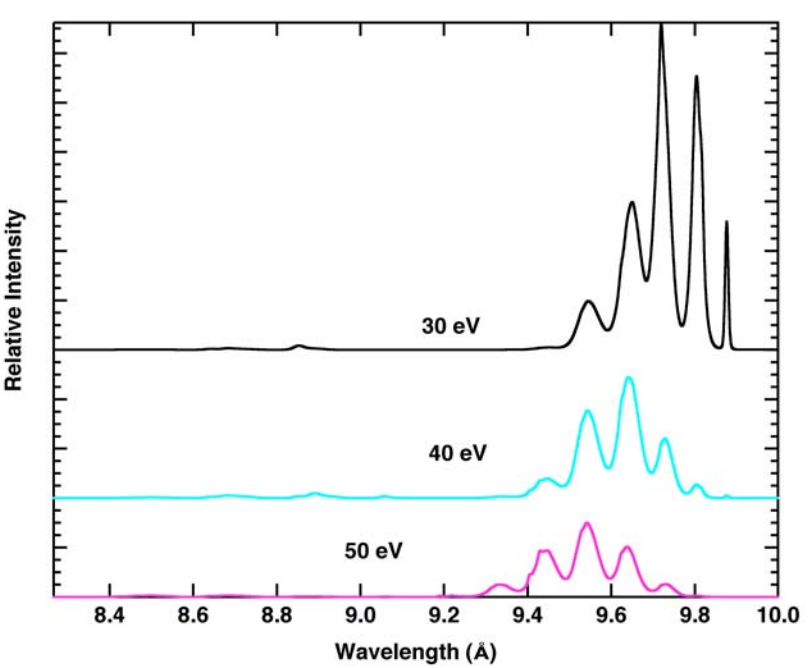




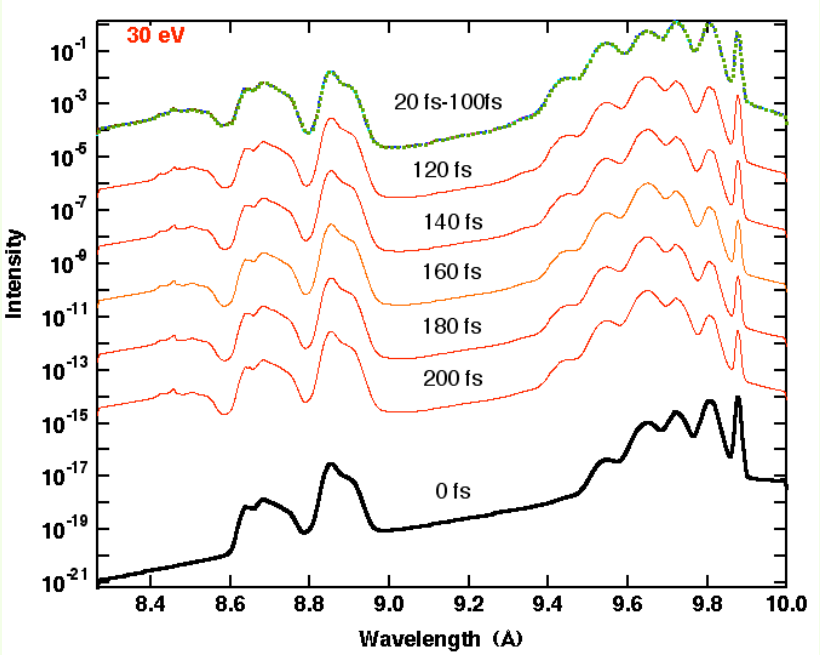
- Plasmon peak intensity related by detailed balance, i.e., $\exp(-2\Delta E/T)$
- Experiments with independent T_e measurement are needed to determine correct approximation for collisions

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
  - 5×10^{10} 1.85 keV photons in 30 μm spot into a $n_e = 10^{23}$ cm^{-2} plasma
  - Strong coupling parameter, Γ_{ii} = Potential/Kinetic Energy ~ 10



• Spectra vary measurably with T_e

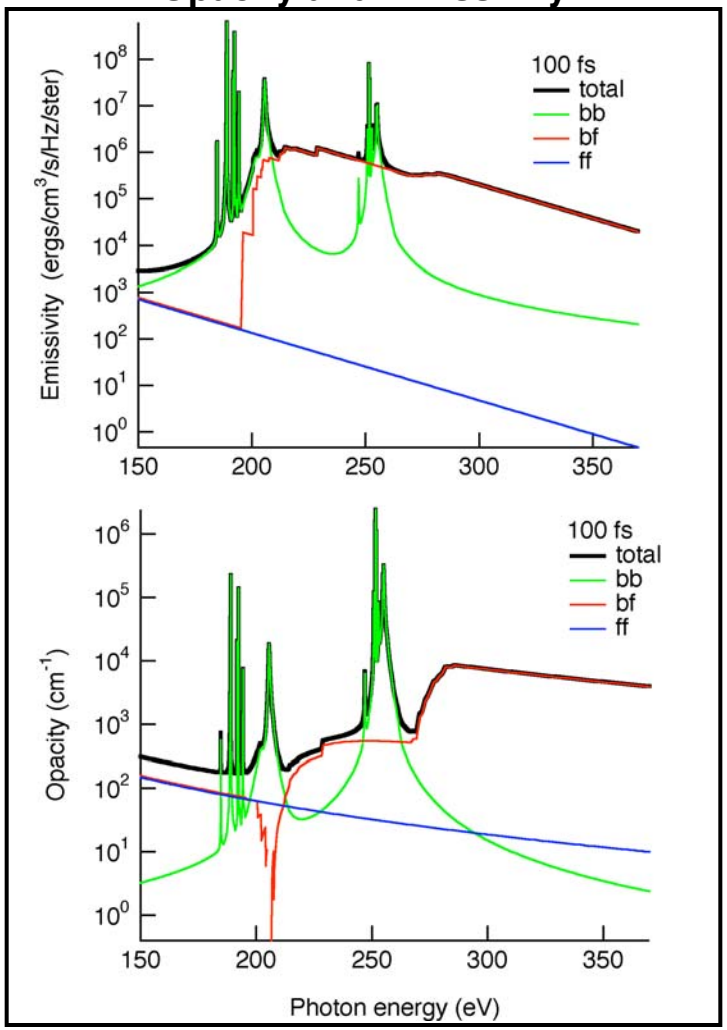


• At high n_e emission lasts ~100 fs

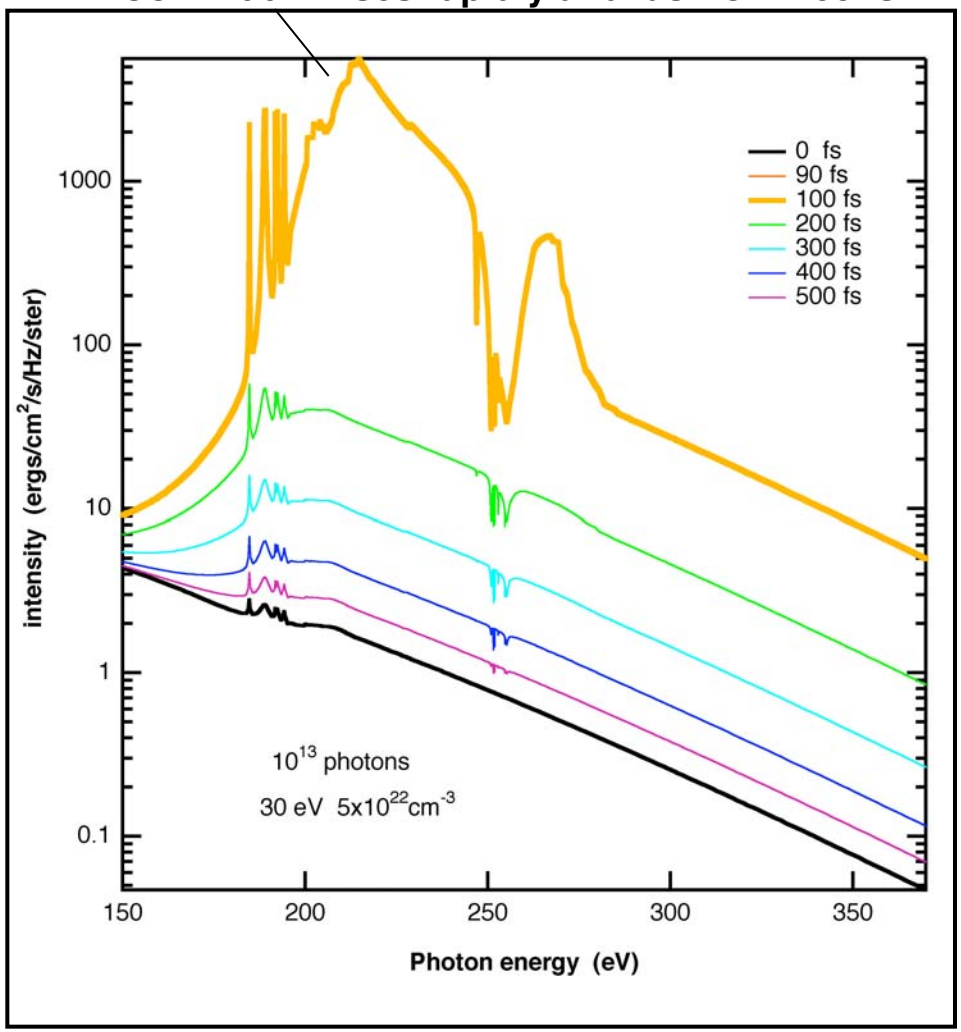
Saturating the continuum using the FEL may provide a ~100 fs absorption source

- He-like B plasma at 30 eV, 5×10^{22} cm^{-3}, 1 mm in length
- FEL tuned to H-like 1 -2 transition

Opacity and Emissivity



Continuum rises rapidly and last for ~100 fs



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_α 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