HEDP experiments at JLF: Review/Plans

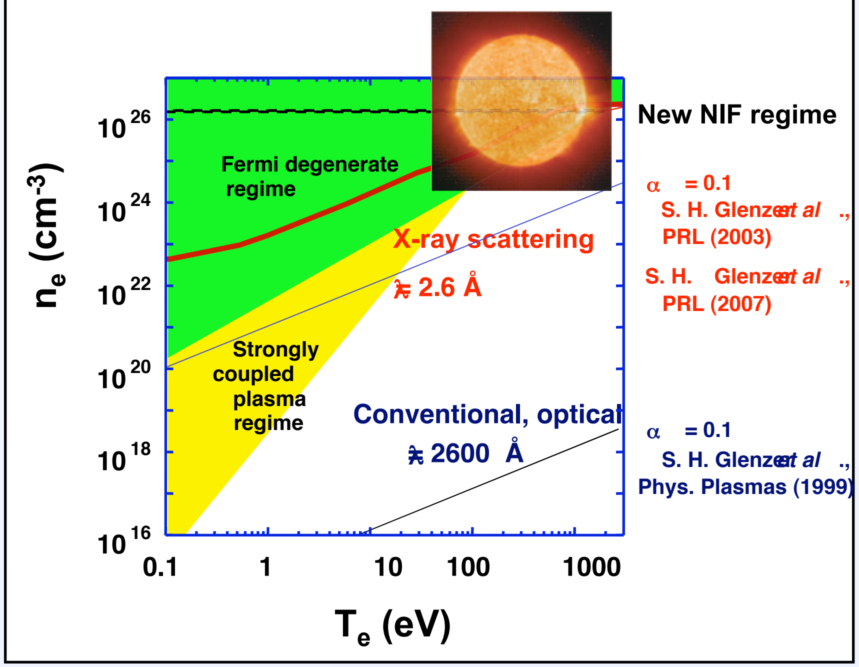
S. H. Glenzer

"West Coast High Energy Density Science Cooperative" Workshop, January 22- 23, 2013, Berkeley, Stanford

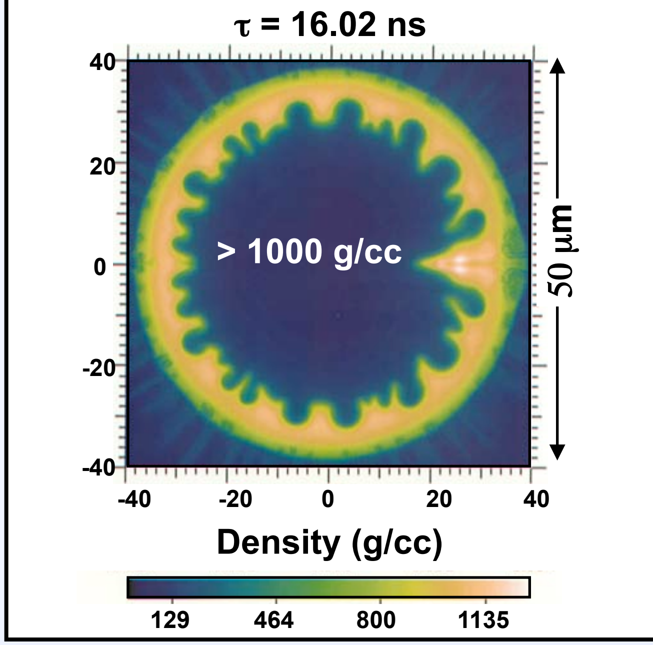
Lawrence Livermore National Laboratory

Our facilities can now produce material conditions at pressures higher than the interior of stars

NIF will produce conditions found in stellar interiors (1000 times solid density)



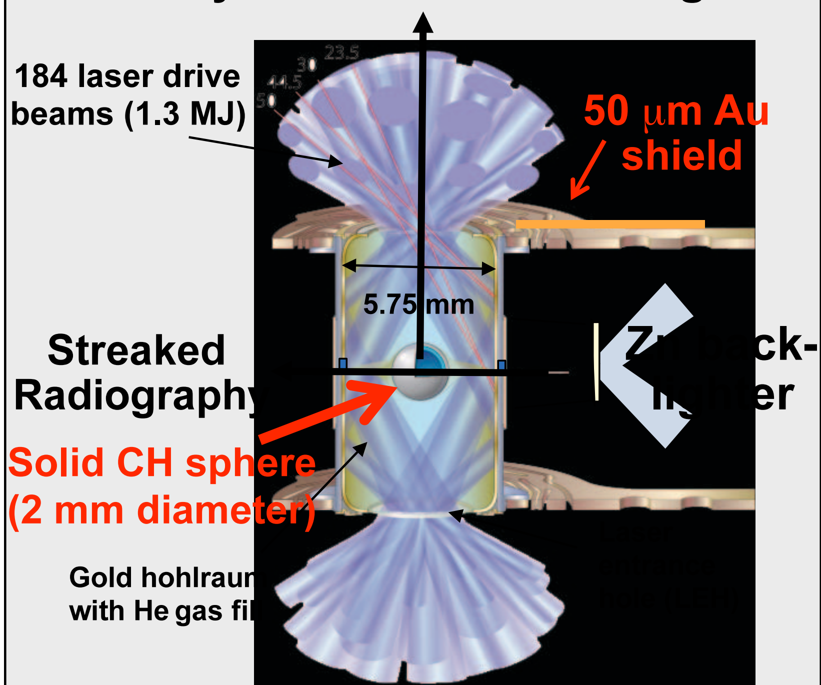
Radiation-hydrodynamic simulations of NIF implosions



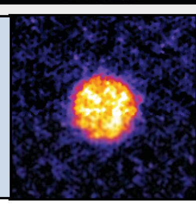
- X-ray scattering provides temperature and density
- Need intense high-energy radiation to penetrate through the capsule and to avoid bremsstrahlung emission
- Access matter at 1 Mbar to 100 Tbar
- First fundamental science experiments on NIF to study CH at 1 Gbar

Radiography of a spherically converging shocks driven with hohlraums heated by 1.3 MJ laser energy indicates 300 Gbar

Experimental configuration

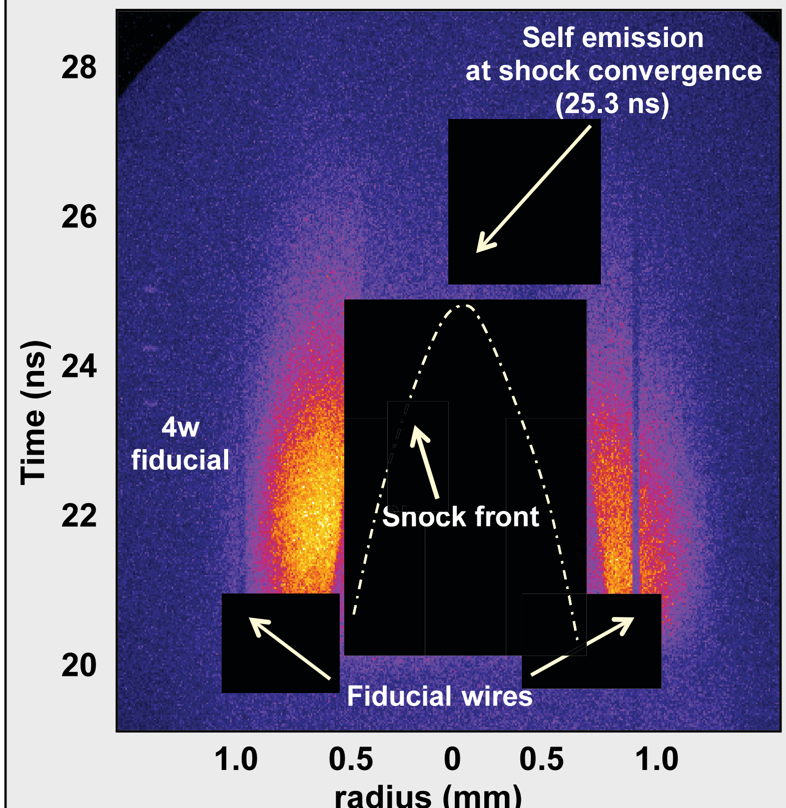


Polar x-ray emission indicates symmetry



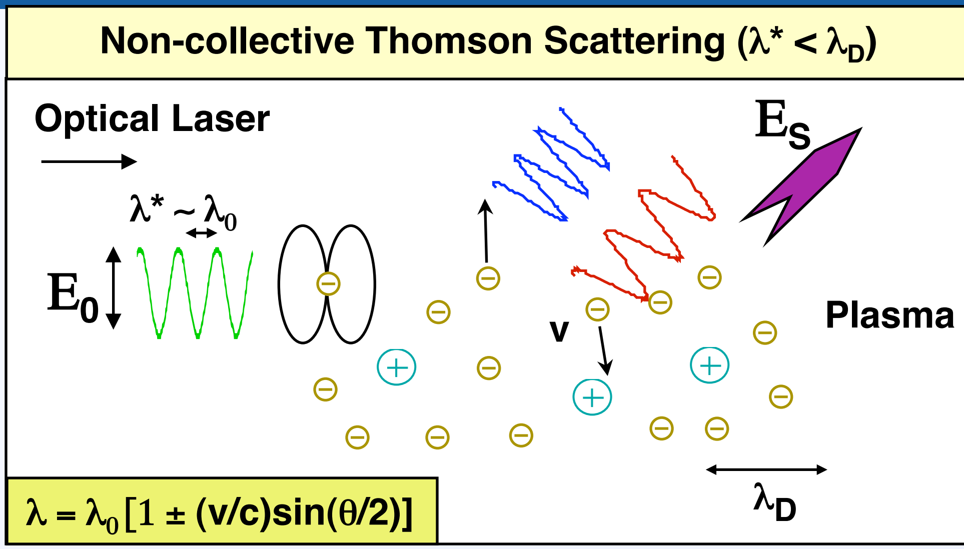
Talk by Doeppner, Jan. 8

Experimental radiograph DISC (90-78) indicating V_S = 200 km/s

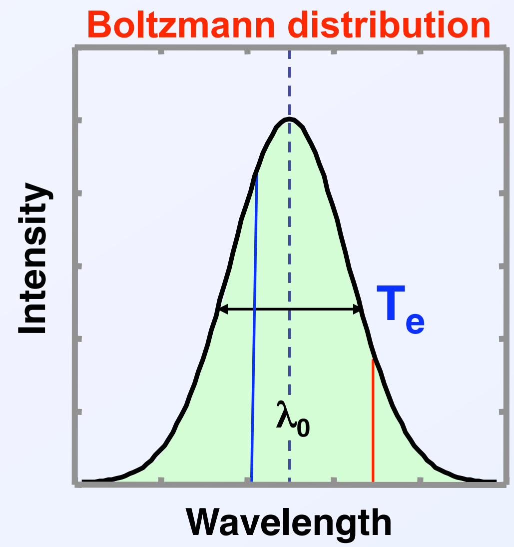


GBar pressures are present close to shock coalescence

From optical "Thomson scattering" to x-ray "Compton" Scattering

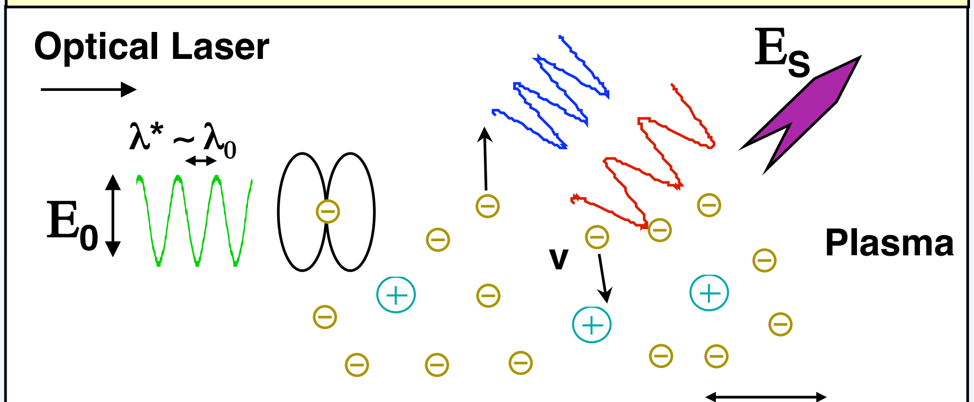


Scattering on free electrons



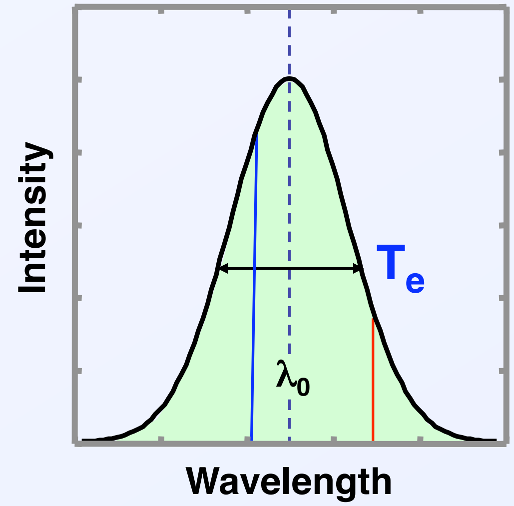
From optical "Thomson scattering" to x-ray "Compton" Scattering

Non-collective Thomson Scattering ($\lambda^* < \lambda_D$)

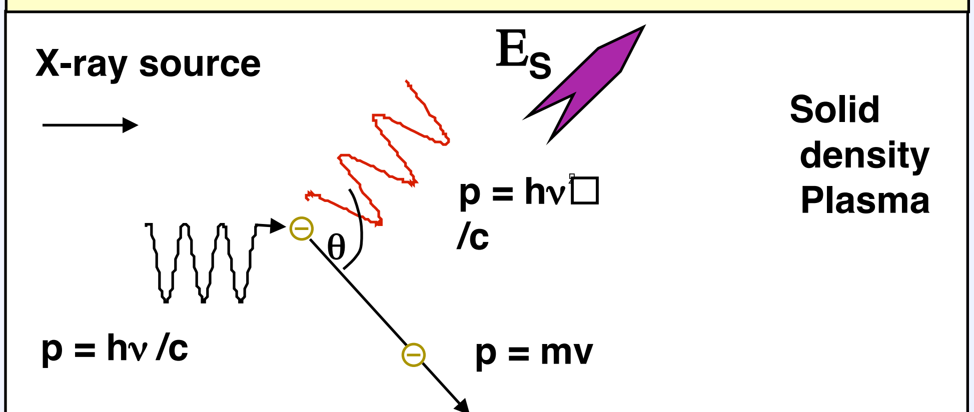


$\lambda = \lambda_0[1 \pm (v/c)\sin(\theta/2)]$

Scattering on free electrons

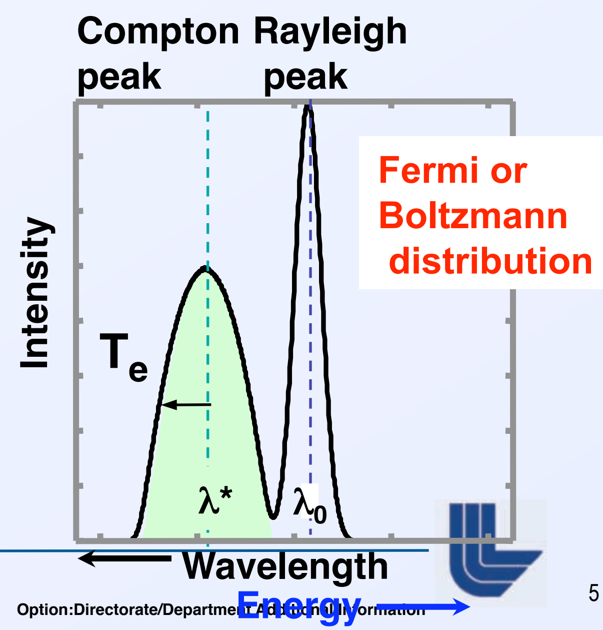


X-ray "Compton" scattering



$\lambda = \lambda_0[1 + 2(h\nu/mc^2)\sin^2(\theta/2) \pm (v/c)\sin\theta/2]$

Scattering on free and weakly bound electrons

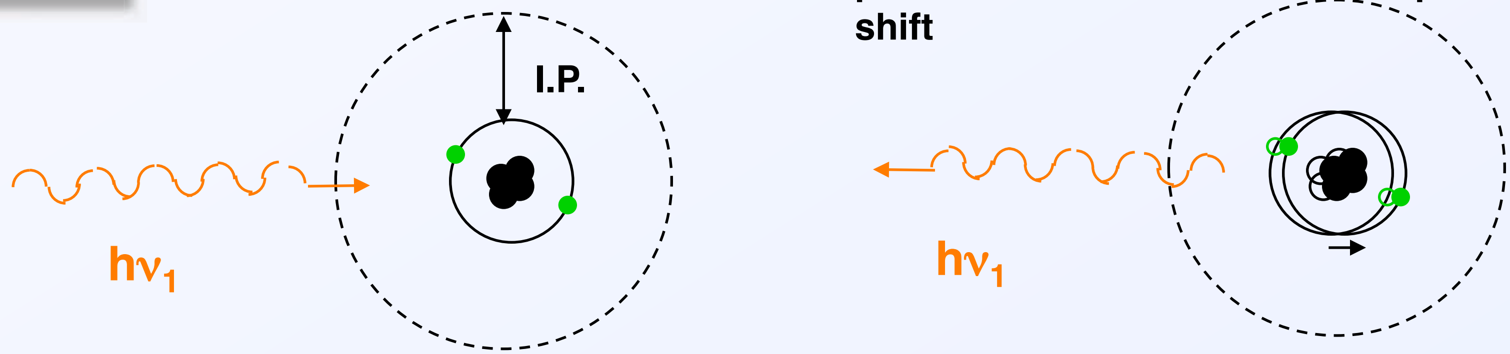


X-ray scattering divided between elastic (Rayleigh) and inelastic (free plus weakly bound) components

Elastic

Tightly bound e^-
I.P. > $(h\nu/m_e c^2)h\nu$

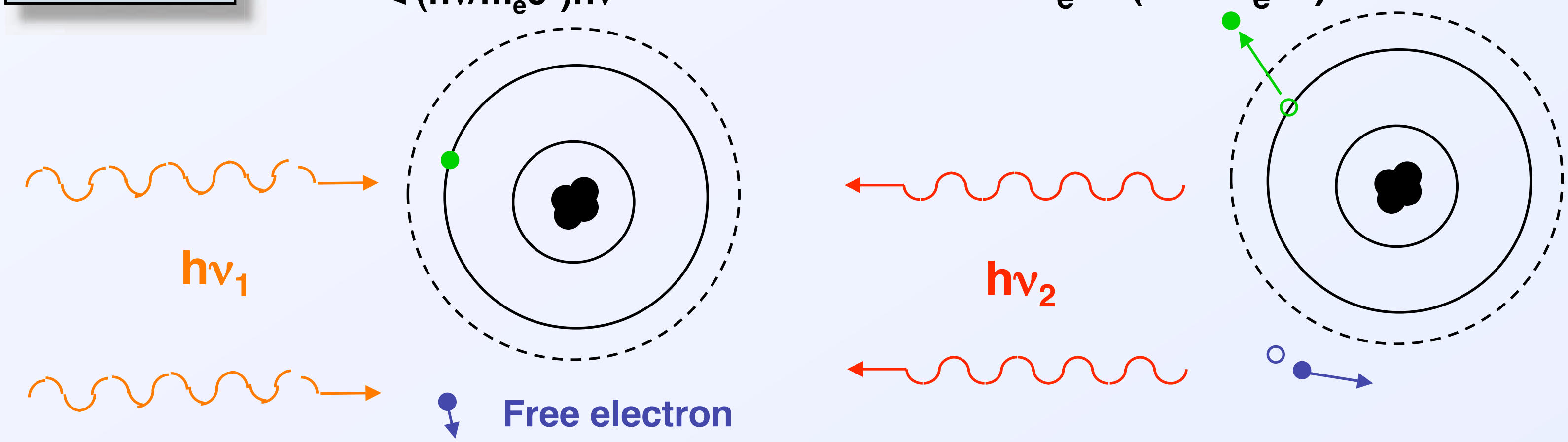
Tightly bound electrons give Rayleigh peak and correction to the Compton shift



Inelastic

Weakly bound e^- I.P. < $(h\nu/m_e c^2)h\nu$

$\Delta E_e = (h\nu/m_e c^2)h\nu$

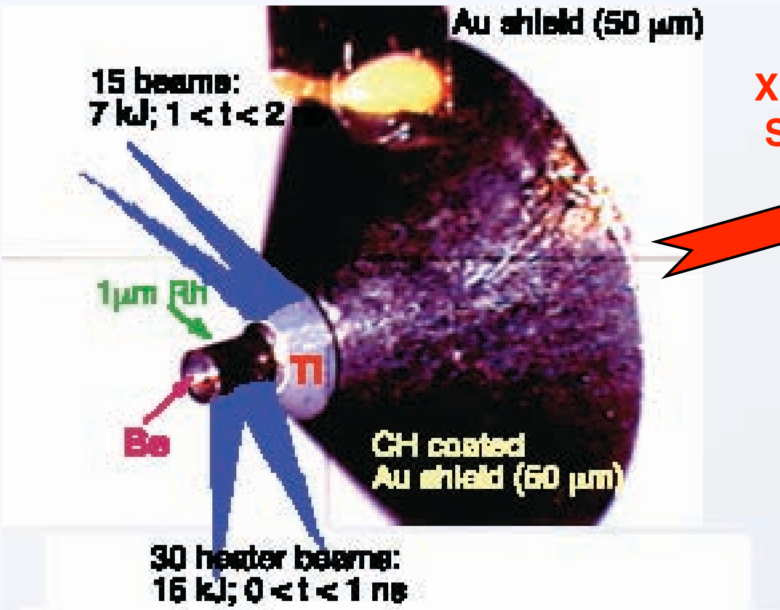


O. L. Landen et al., JQSRT 71, 465 (2001):

$h\nu_2 = h\nu_1 - (h\nu/m_e c^2)h\nu(1-\cos\theta)$ (Compton) $\pm\, 2h\nu(v_e/c)\sin\theta/2$ (Doppler)

Max. θ: ⇒ max. Compton shift
max. Doppler broad.

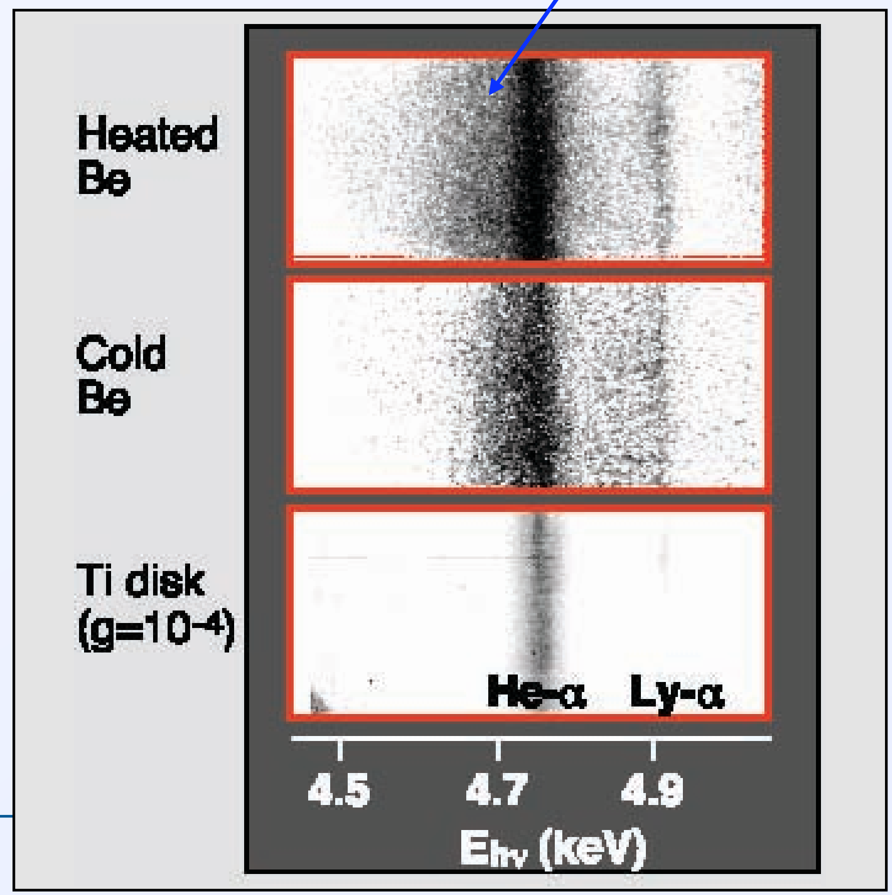
X-ray "Thomson" scattering in warm solid density matter was first demonstrated on beryllium at the Omega laser



X-ray Scattering

Gated HOPG spectrometer

Compton downshifted and Doppler broadened Thomson spectrum observed as expected



- T_e broadening was predicted in 1928: Chandrasekhar:

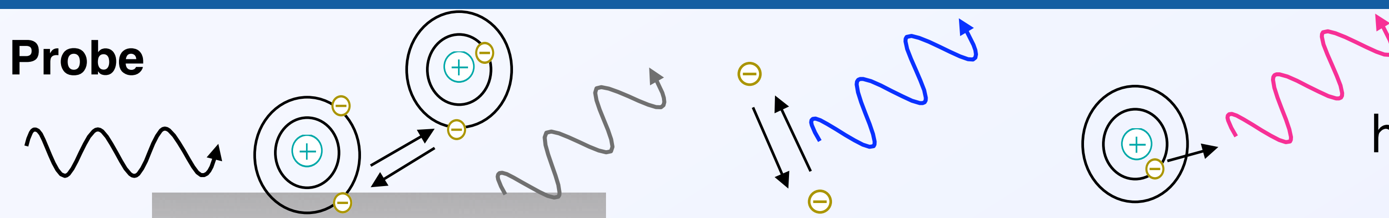
"scattering will not be influenced by ranges of temperatures available in the laboratory"

Proc R.S. A 125, 37 (1929)

S. H. Glenzer et al., Phys. Rev. Lett. 90, 175002 (2003).

Option:UCRL#

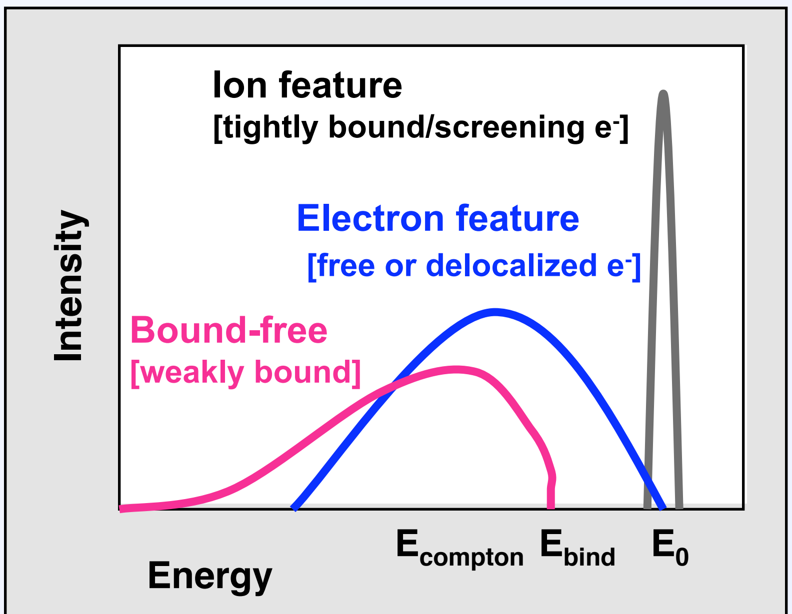
The theoretical form factor for x-ray scattering provides reliable plasma parameter for back scatter experiments



$h\omega = h\omega_1 - h\omega_0$

$$S(k,\omega) = \left|f_I(k) + q(k)\right|^2 S_{ii}(k,\omega) + Z_f S^0_{ee}(k,\omega) + Z_b \int \tilde{S}_{ce}(k,\omega-\omega')S_s(k,\omega')d\omega'$$

Ion feature | **Electron feature** | **Bound-free**



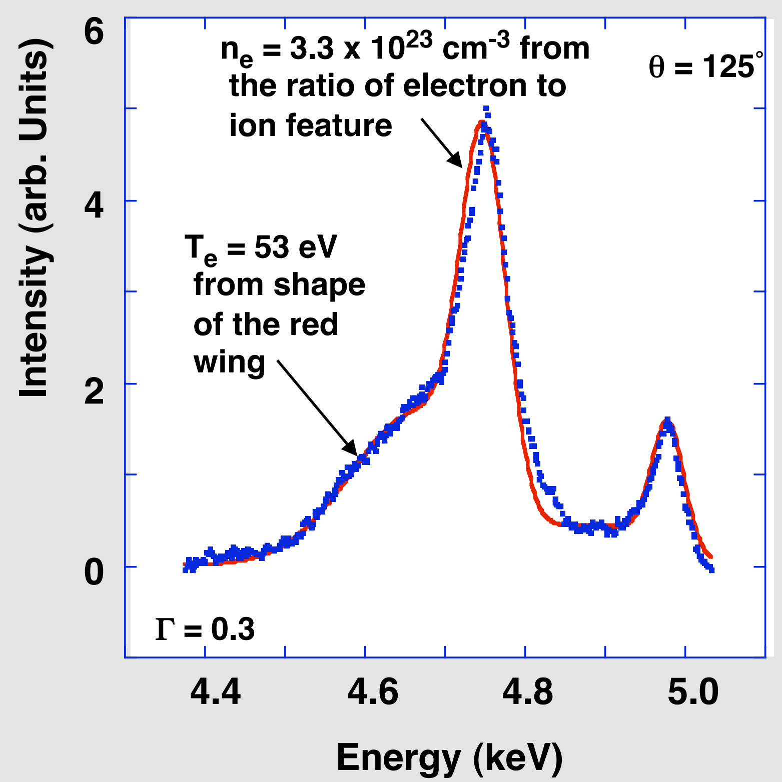
Schematic Scattering spectrum

- Free or delocalized electrons result in the Compton down-shifted line, $Z_f S_{ee}(k,\omega)$
- Bound-free contribution also results into down-shifted spectrum
- $Z_b S_{ce}(k,\omega)$
- The momentum of bound e^- causes broadening
- The ion feature describes elastic scattering $S_{ii}(k,\omega)$
- In backscatter: theoretical approximations agree

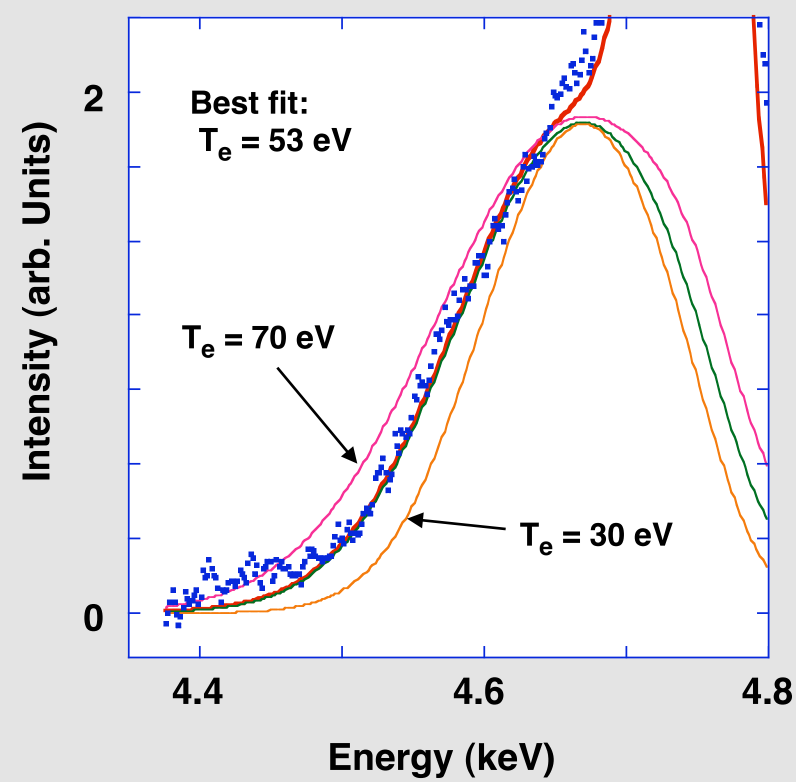
Chihara, PRE (2000), Gregori et al, PRE (2003)

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

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



Comparison of experimental data with theoretical calculations for various T_e

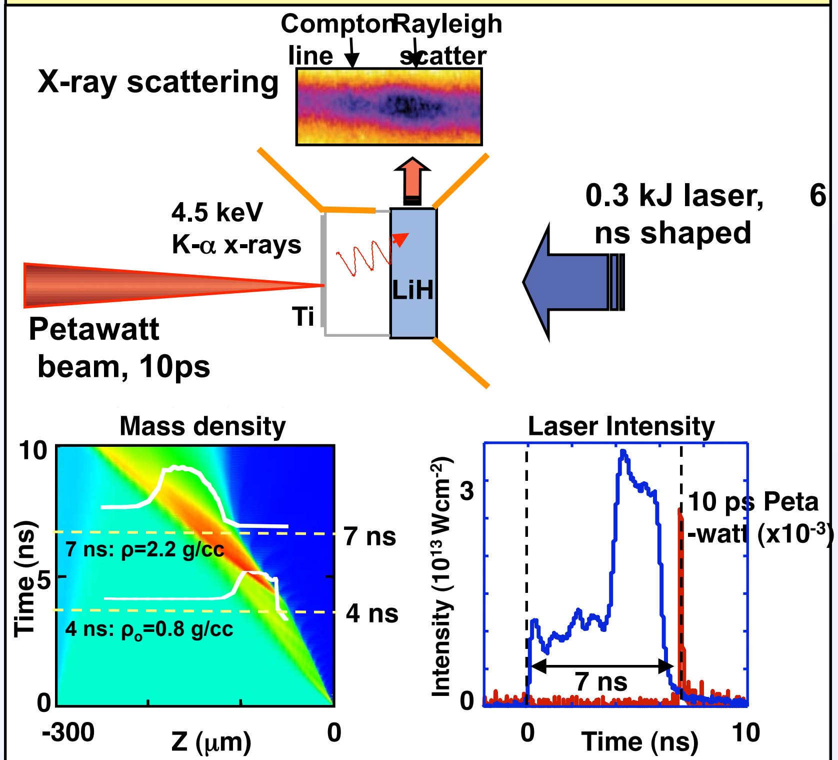


From the theoretical fit to the data:
T_e = 53 eV and Z_{free} = 3.1 corresponding to n_e = 3.8 x 10^{23} cm^{-3}

A sensitivity analysis shows that we can measure T_e with an error bar of ~15%

K-α Compton scattering on the LLNL's Titan laser measures temperature in shock-compressed matter with 10 ps resolution

K-α x-rays at 4.5 keV have been applied to scatter on dense compressed LiH



Shaped drive launches two shocks that coalesce at 7ns with n_e = 1.7 x 10^{23} cm^{-3}

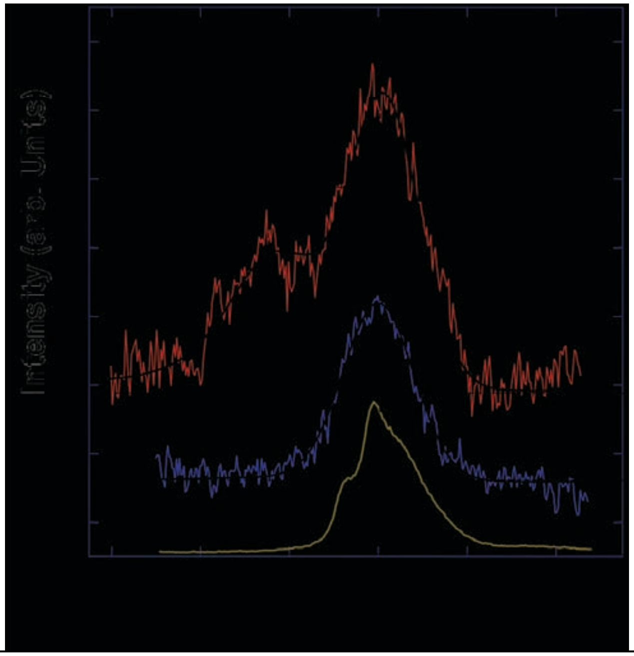
- **K-α scattering has been developed to provide accurate characterization of dense matter**
- **Compressed Matter experiment**
  - **First successful experiments on compressed LiH**
  - **Data from Titan are of sufficient quality to test radiation-hydrodynamic modeling**
- **Density is constraint by the width of the Compton feature**
  - **Consistent with x3 compression**

- **Characterize shock-compressed matter with ultra-high temporal resolution of 10 ps and with 10^{12} photons**

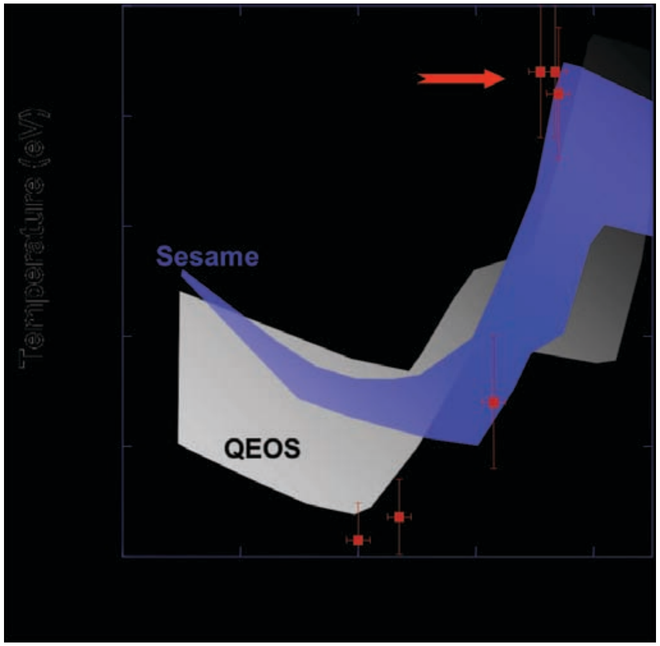
The Thomson scattering data test hydrodynamic modeling of the temperature evolution in shocked matter

- **Temperatures in hydrodynamic modeling is primarily determined by the equation of state [10ps probe can resolve differences of EOS models]**
- **This technique will need to be further developed to establish a diagnostic for heating**

Single shot K-alpha scattering on shock-compressed LiH



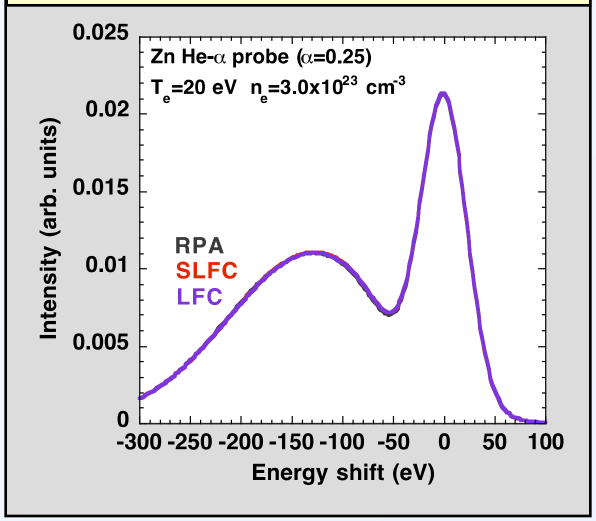
The x-ray scattering data test radiation-hydodynamic modeling of compressed LiH



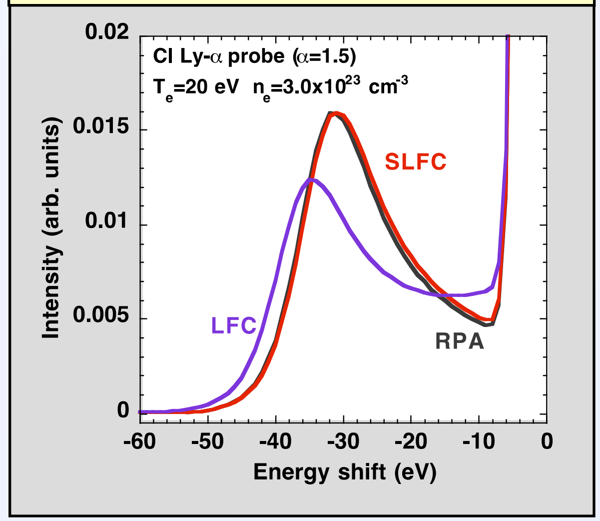
A. L. Kritcher et al., Science 322, 69 (2008).

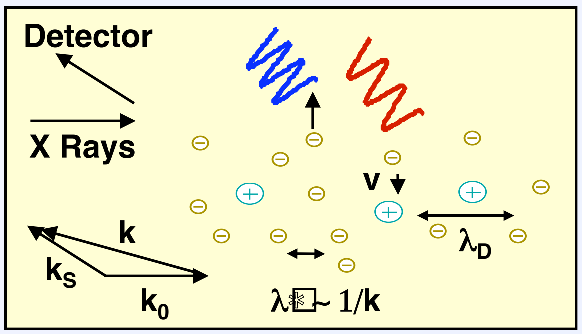
Forward scatter will directly measure Plasmons for $\lambda^* > \lambda$ or $\alpha > 1$ with $\alpha = \lambda / 4\pi \lambda_\Sigma \sin\theta/2$

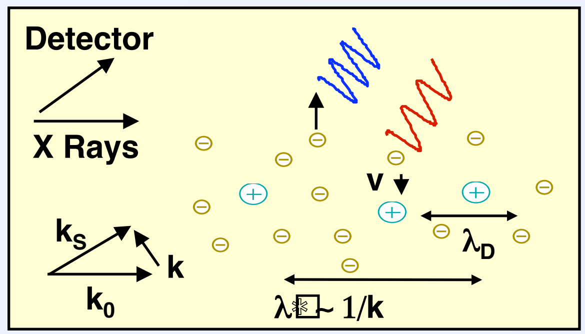
Backscatter provides T_e: theories agree



Forward scatter will test dense matter theory

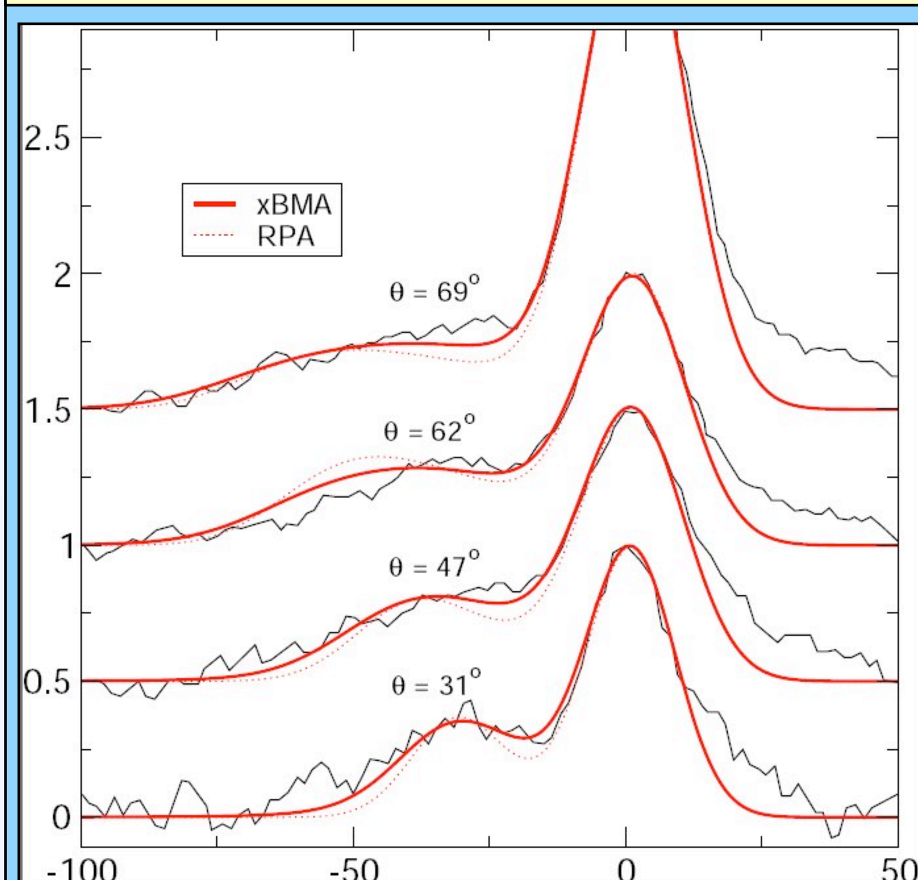






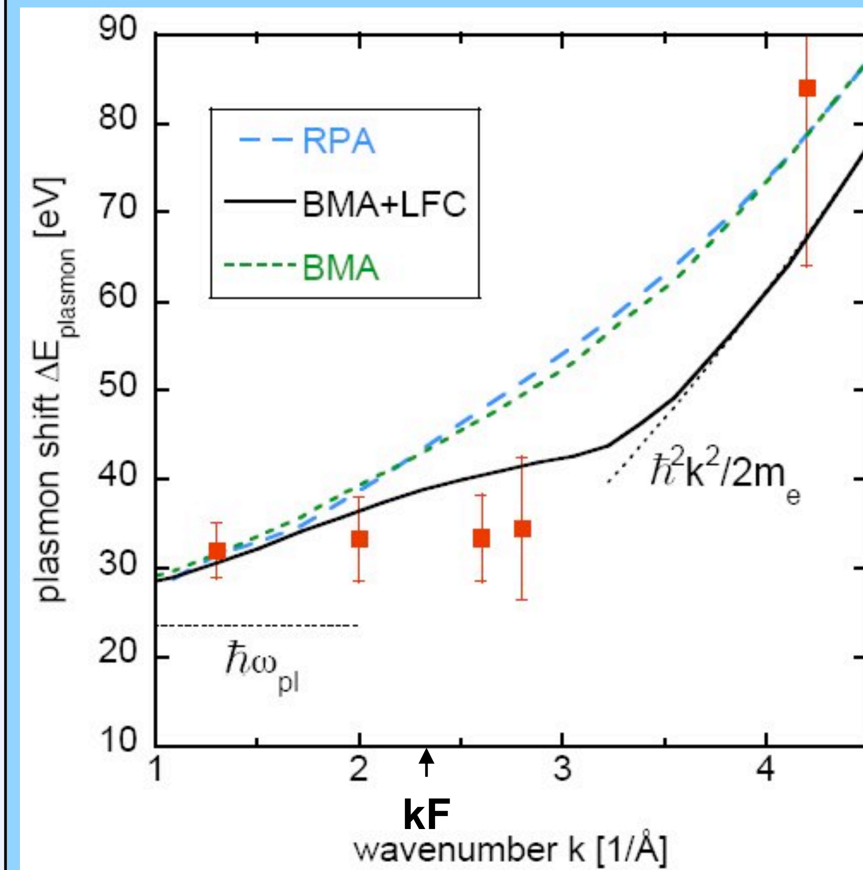
Measurements at different scattering angles provide the plasmon dispersion is measured at 5 k vectors

The plasmon shift is (approx.) constant between k=1.3/A – 2.8/A



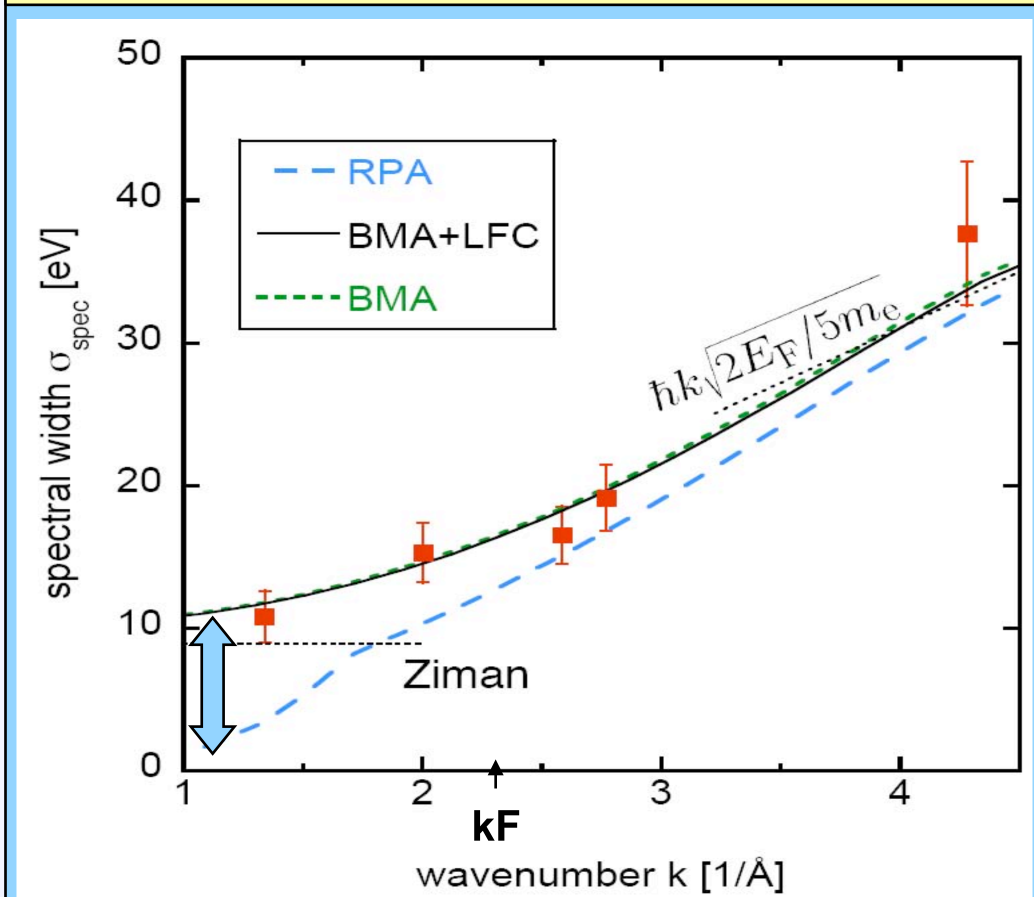
energy shift [eV]

The weak plasmon dispersion reveals strong electron-electron correlations



We observe collisional plasmon damping

Landau damping decreases ~k^2 below critical wavenumber kc=1.8/A



$$m^{(n)}(k) = \int_{-\infty}^{\infty} d\omega\,\omega^n S(k,\omega)$$

$$m^{(0)} = S(k)$$ **e-e structure factor**

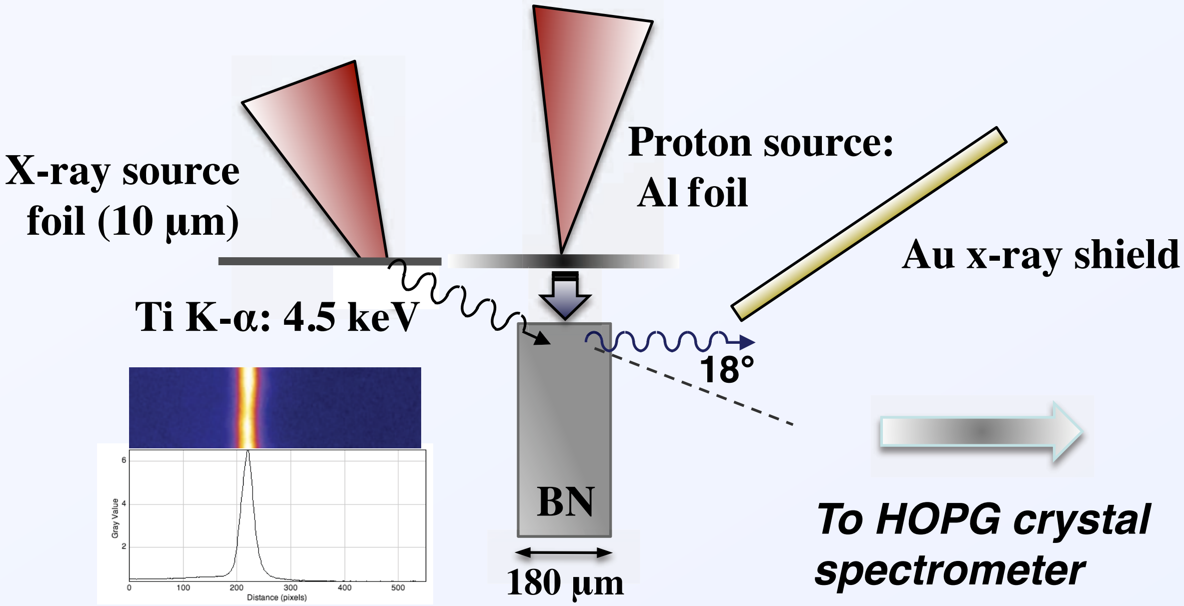
$$m^{(1)} = S(k)\cdot <\omega> = -\frac{\hbar k^2}{m_e}$$

$$m^{(2)} = S(k)\cdot <\omega^2>$$ **f-sum rule**

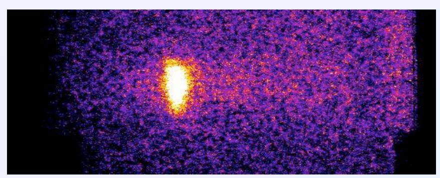
$$\sigma_S^2 = <\omega^2> - <\omega>^2$$

mean square width, additive under convolution

Recently, we demonstrated proton heated matter at Titan by splitting the short pulse beam



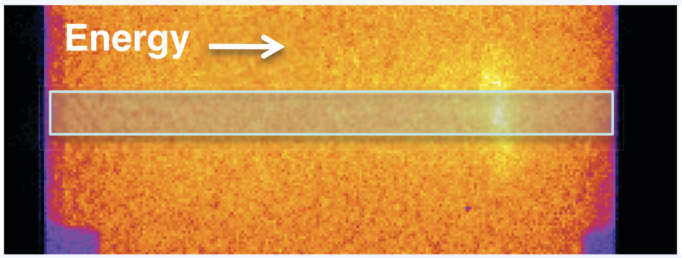
10^{-4} fraction of incident laser energy is converted into the K-α line



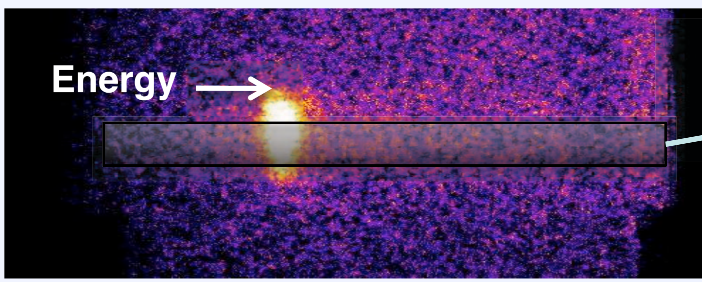
Proton beam: 80 J
X-ray source: 160 J
Duration: 5 ps
X-rays arrive 300 ps after heating: thermal equilibrium

Scattering parameters
α= 0.77 -1.4
k = 7 (1/nm)

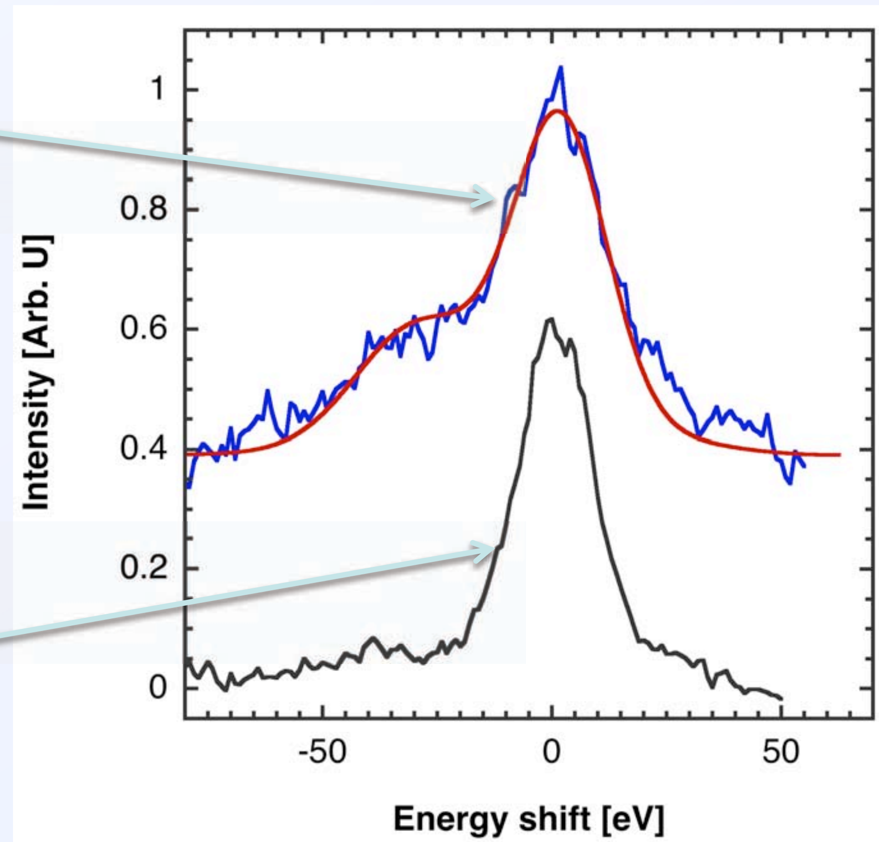
Experimental data in Boron shows plasmon indicating an ionization of 2.5 ± 0.5 at about 18 eV



Scattered signal from hot boron

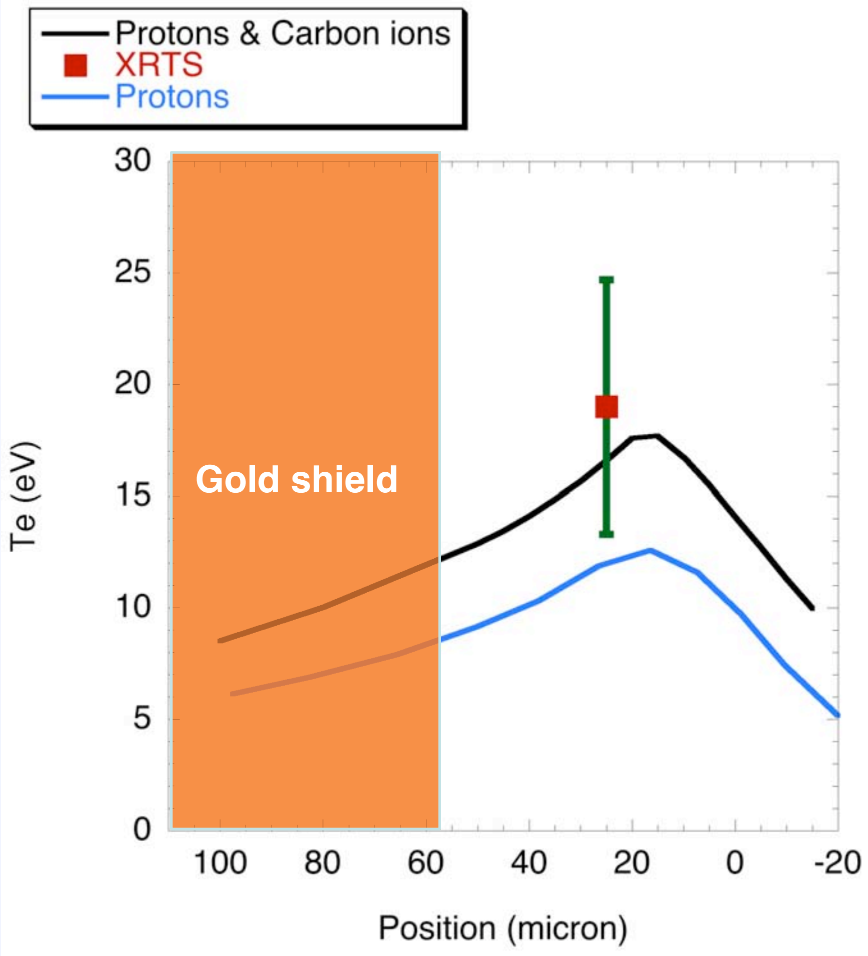


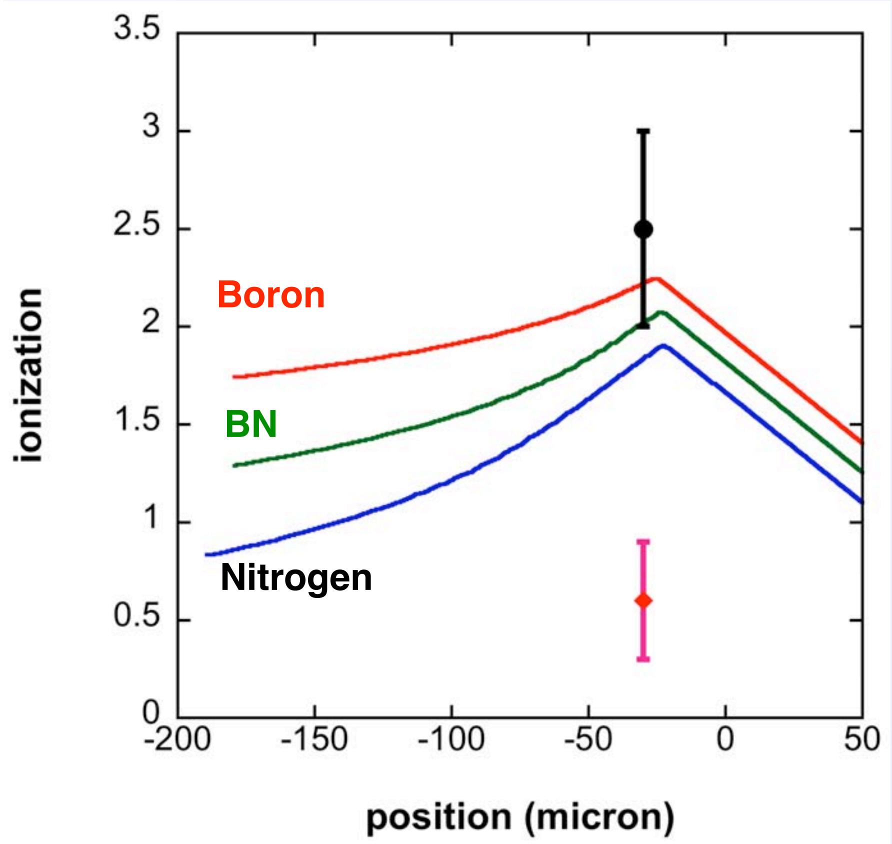
Scattered signal from cold boron



$\alpha \sim 1.4$, T_e=18 eV, ρ =2.4 g/cc

Lasnex simulations show good agreement with temperature measurement, but not with ionization for the Boron nitride





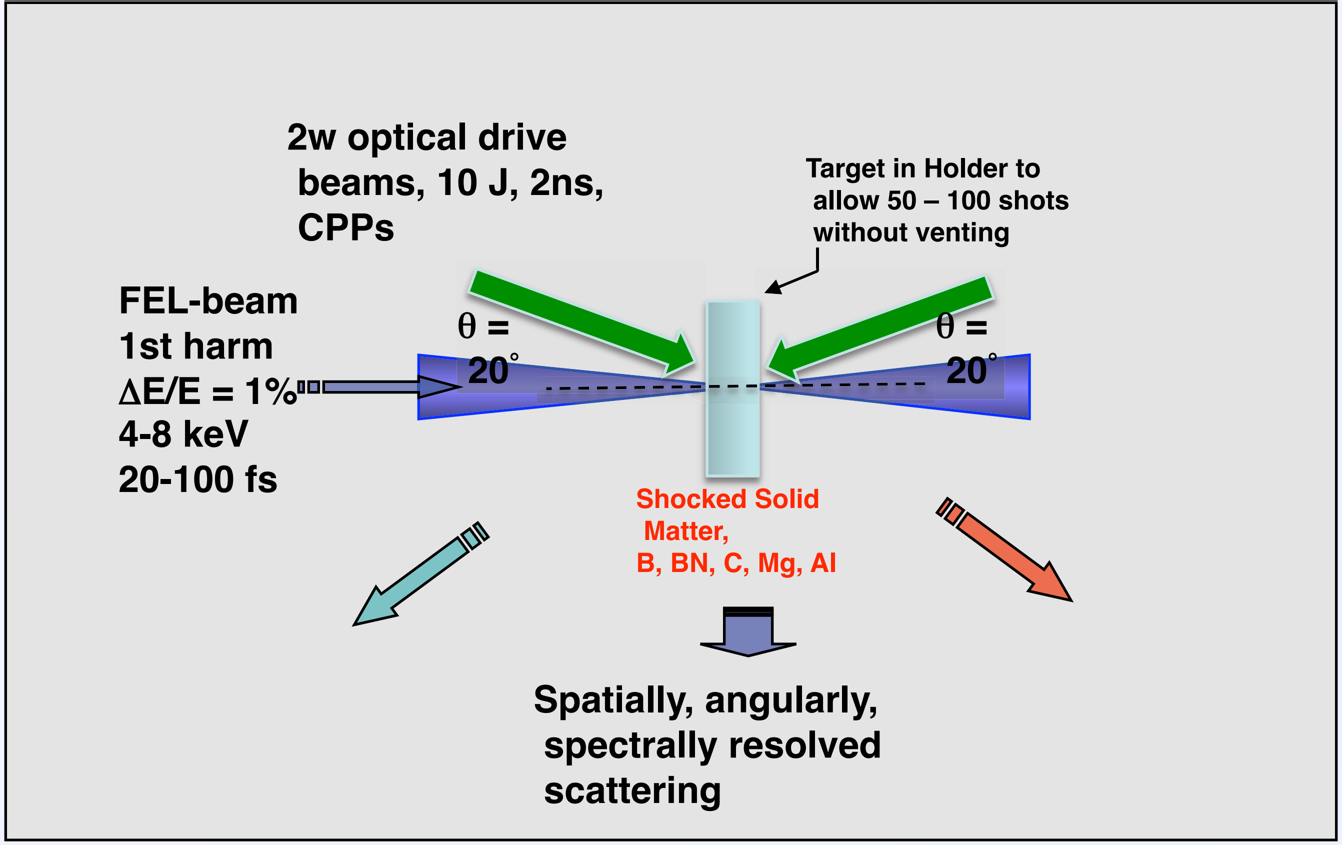
There is a new effort to include band gap model to describe the target heating

Scattering Experiments provide important physical properties of shocked/heated matter

Diagnostics	Observation	Parameter	Physical Property
Forwad Scatter	Plasmons	n_e	Compressibility
		ν_{ei}	Conductivity
	Detailed Balance	T_e	Heating
	Elastic feature	T_i, S_{ii}	EOS
			V_{Shock}
		Z_{eff}	Ionization Balance
Back Scatter	Compton line	T_e	Heating
		T_{Fermi}	Compressibility
	Elastic feature	T_i, S_{ii}	EOS
		Z_{eff}	Ionization Balance
Side Scatter	Elastic/Inel. vs x	$Z_{eff}(x)$	Hydrodynamic Mix
	Elastic vs θ	$S_{ii}(k)$	EOS
	Inelastic vs θ	$\varepsilon(k,\omega)$	Dispersion/EOS

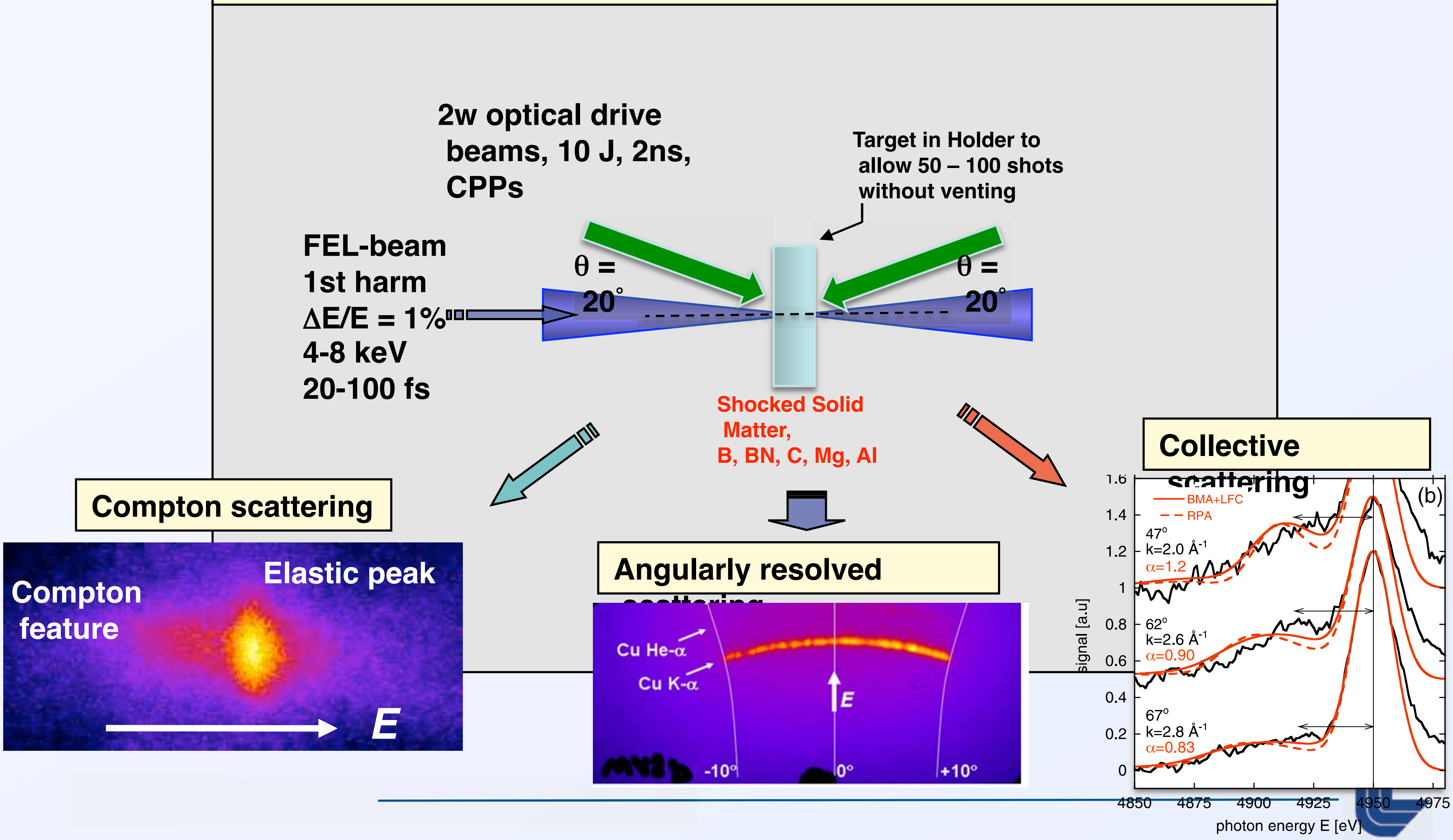
Experimental geometry will use counter propagating long pulse lasers and a delayed LCLS beam

April 2013 X-ray Free Electron Laser Experiment



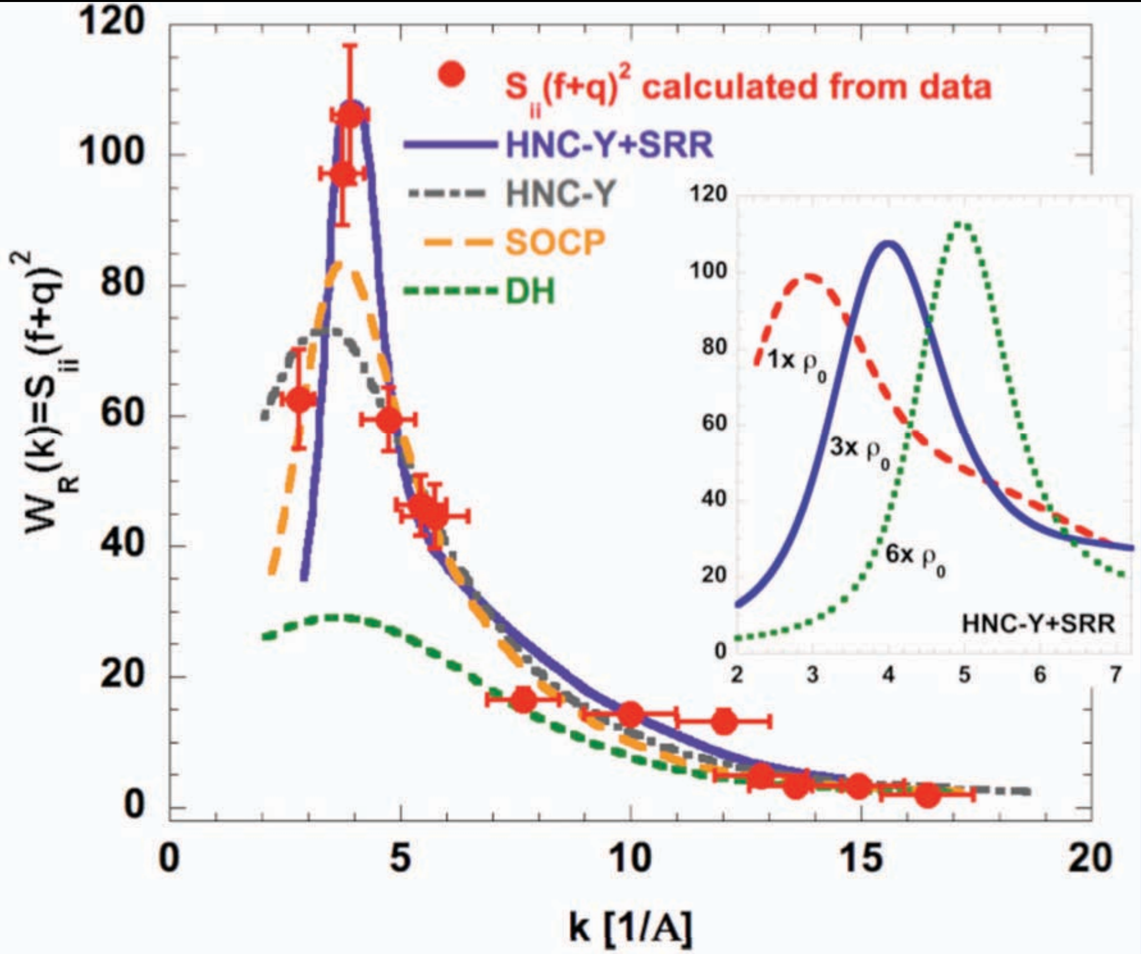
Experimental geometry will use counter propagating long pulse lasers and a delayed LCLS beam

April 2013 X-ray Free Electron Laser Experiment



The new MEC experiments provides important data in a previously unexplored regime

Structure factor measurements from Omega directly provide compression

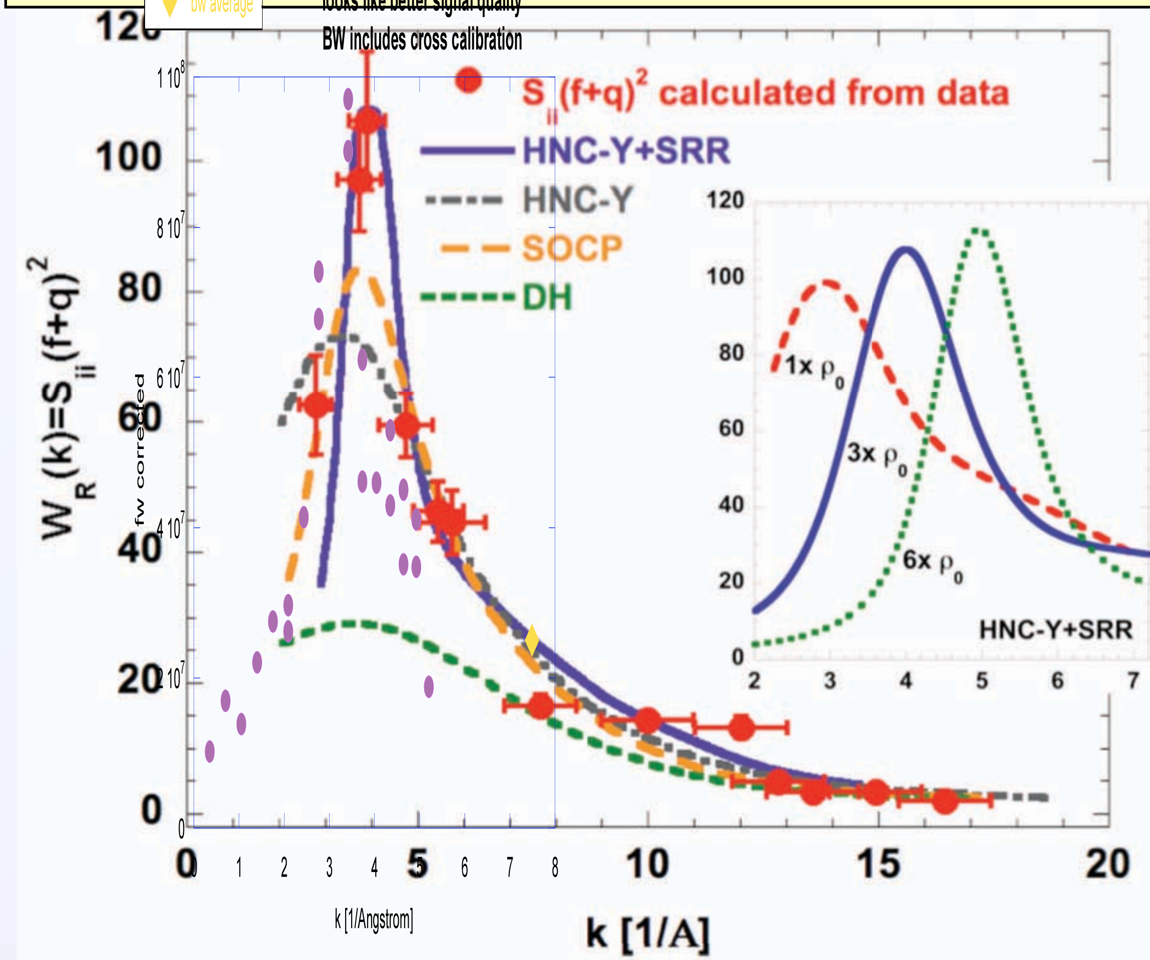


- The peak of the structure provides ρ
- The width of the structure may be developed into a temperature measurement
- This capability can be developed at the 4 BA HED facilities

T. Ma et al., PRL, *in print* (2013)

The new MEC experiments provides important data in a previously unexplored regime

Structure factor measurements from Omega directly provide compression

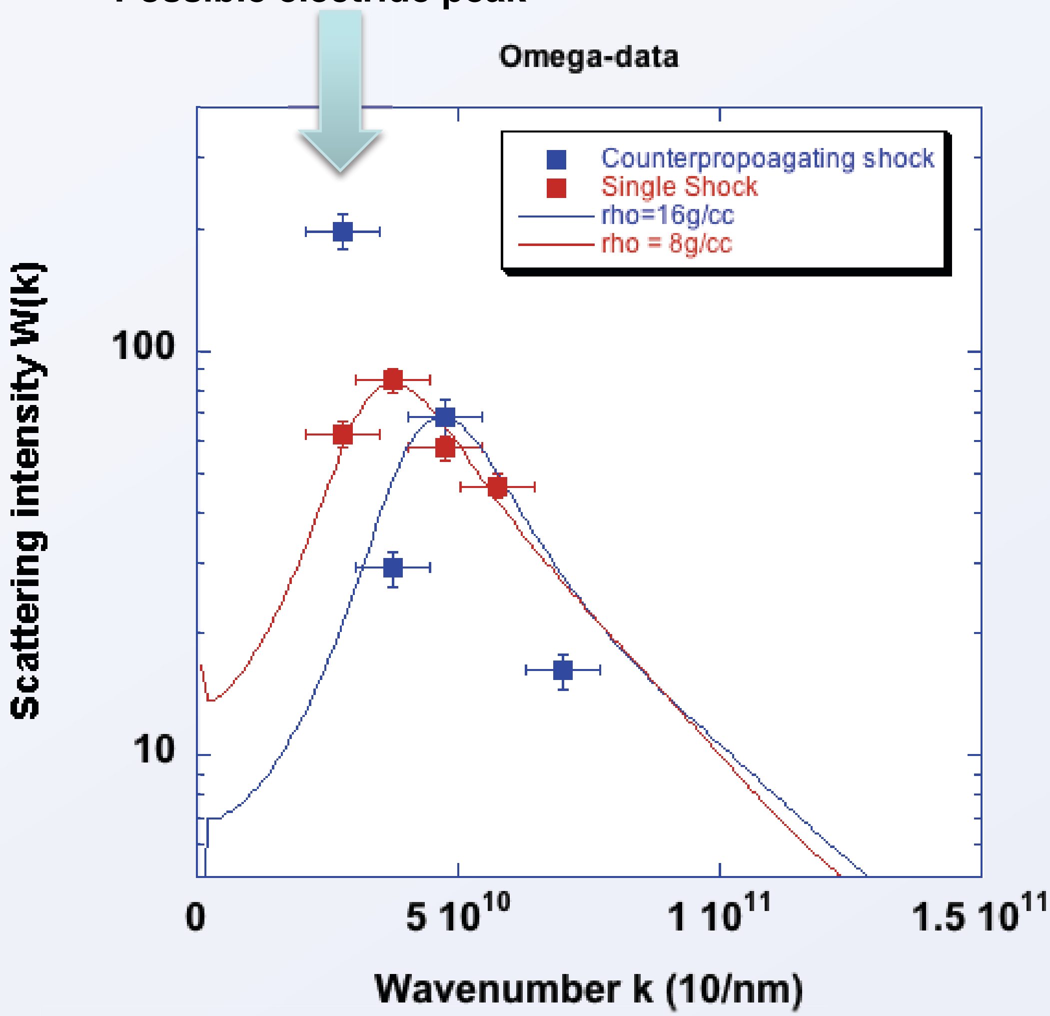


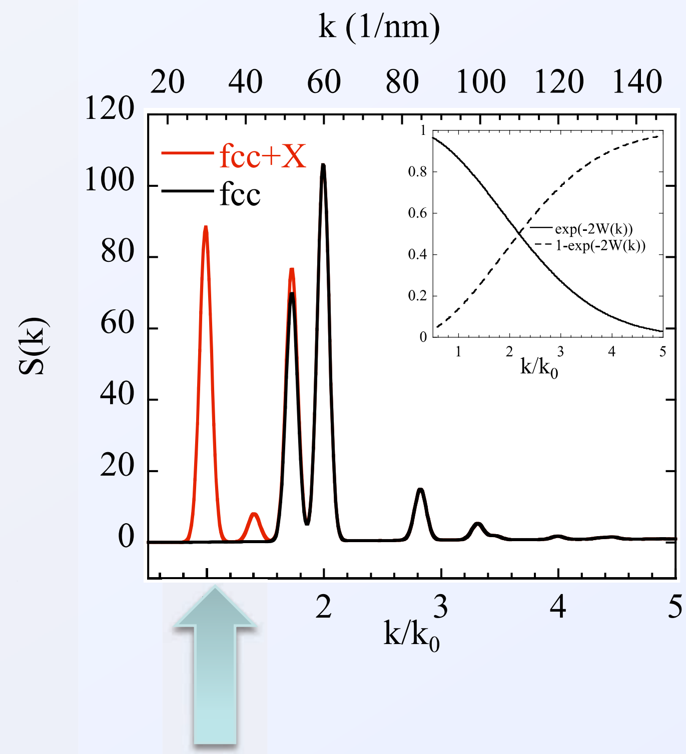
- The peak of the structure provides ρ
- The width of the structure may be developed into a temperature measurement
- This capability can be developed at the 4 BA HED facilities

T. Ma et al., PRL, *in print* (2013)

Recent Omega experiments close to 100 Mbar have shown features that indicate electride properties

Possible electride peak

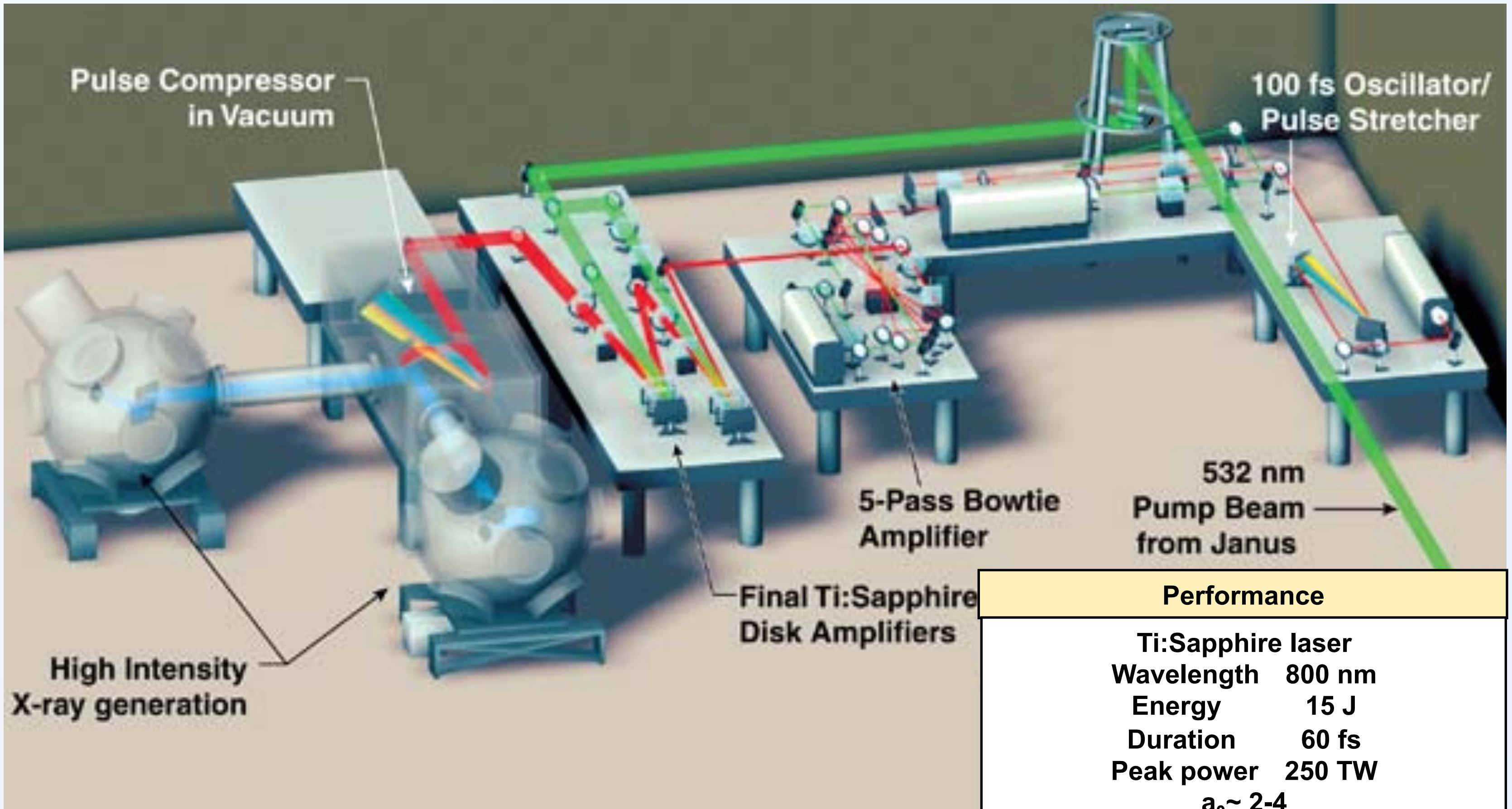




Predicted electride position for Mg

Fortmann, Niemann, Glenzer, PRB (2012)

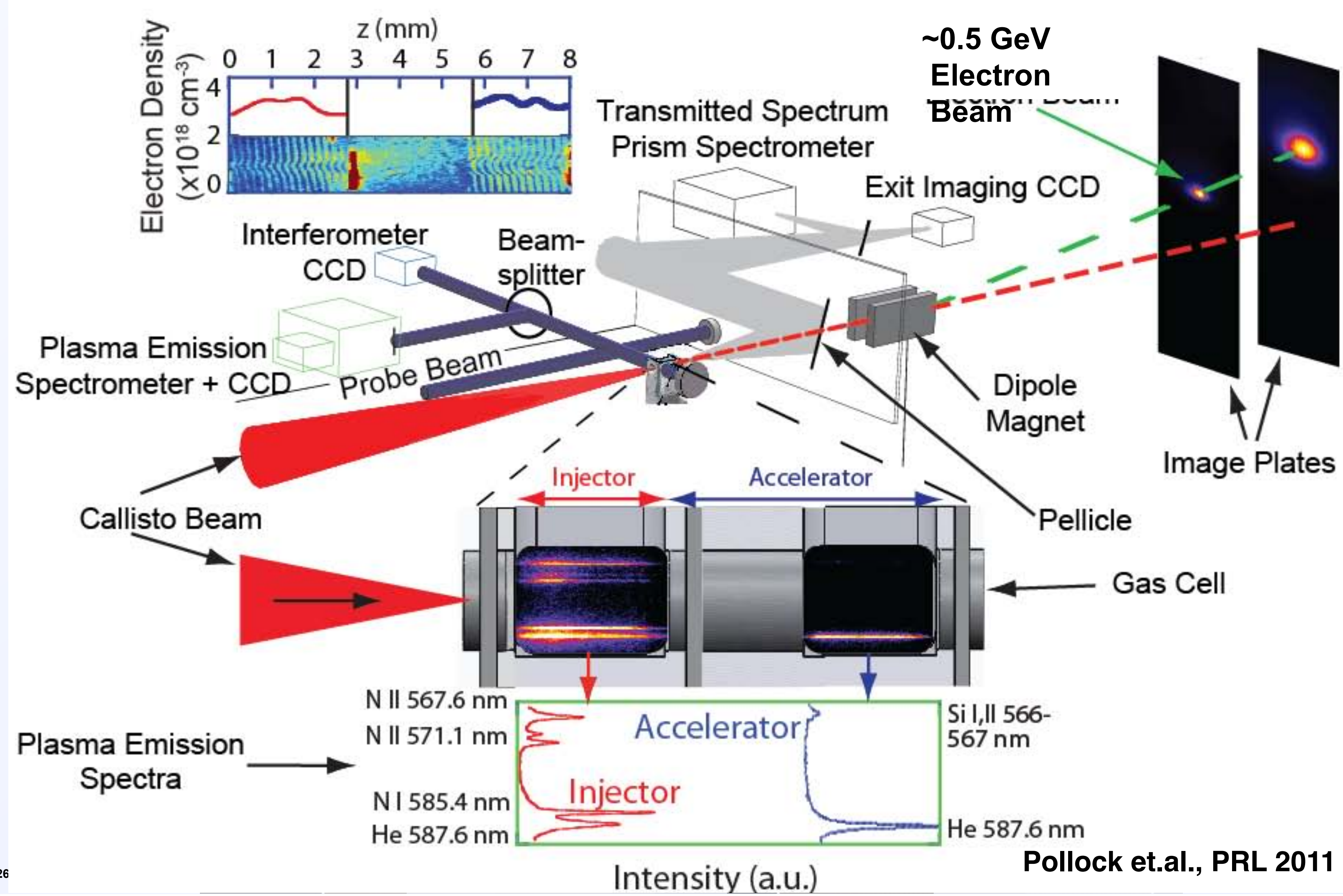
LLNL experiments performed using the Callisto laser



Performance	
Ti:Sapphire laser	
Wavelength	800 nm
Energy	15 J
Duration	60 fs
Peak power	250 TW
a_0~ 2-4	

Laser normalized potential $a_0 = 8.5\times 10^{-10}\,\lambda[\mu\text{m}]\sqrt{I[\text{W/cm}^2]}$

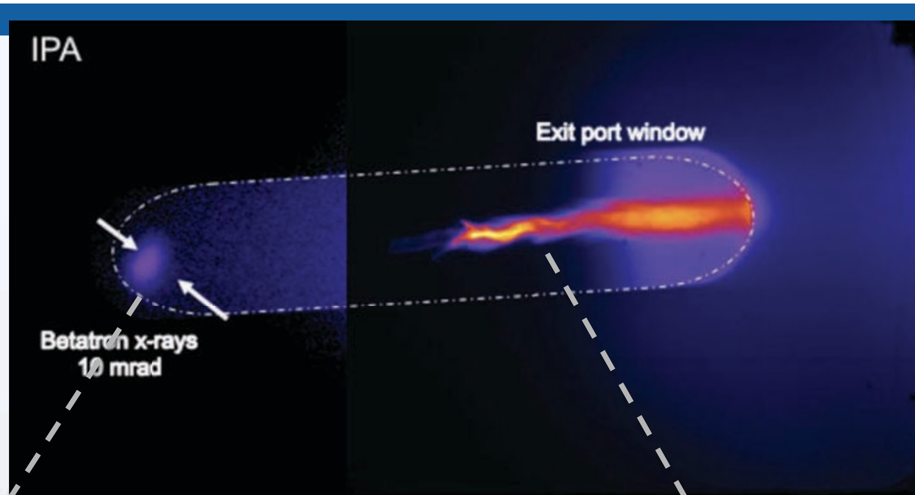
These self-guiding experiments are performed with the 200 TW, 60 fs Callisto laser at LLNL

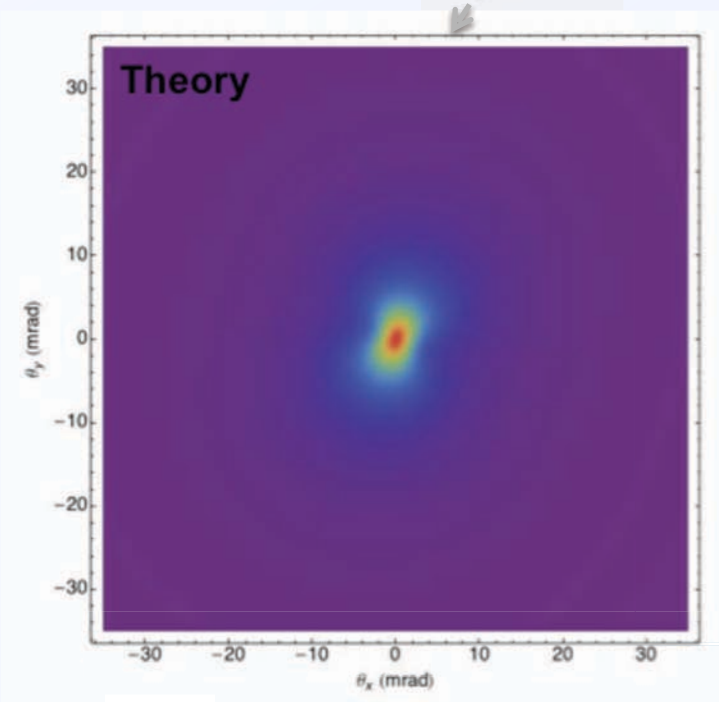


Pollock et.al., PRL 2011

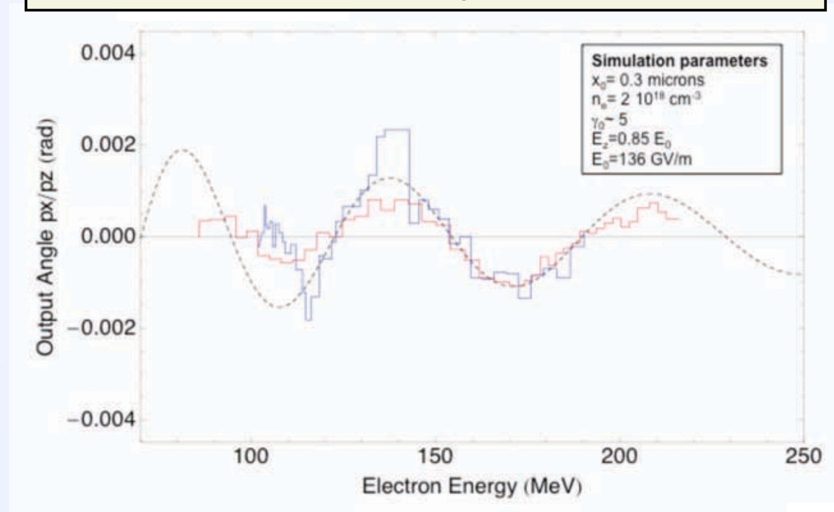
26

Calisto produces a 100 fs broadband highly collimated betatron x-ray source

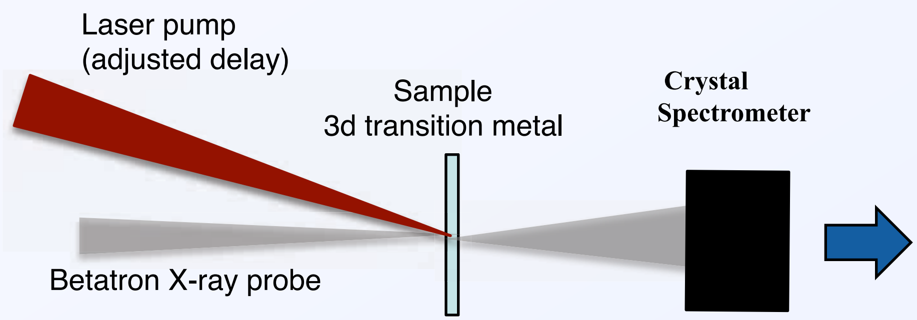




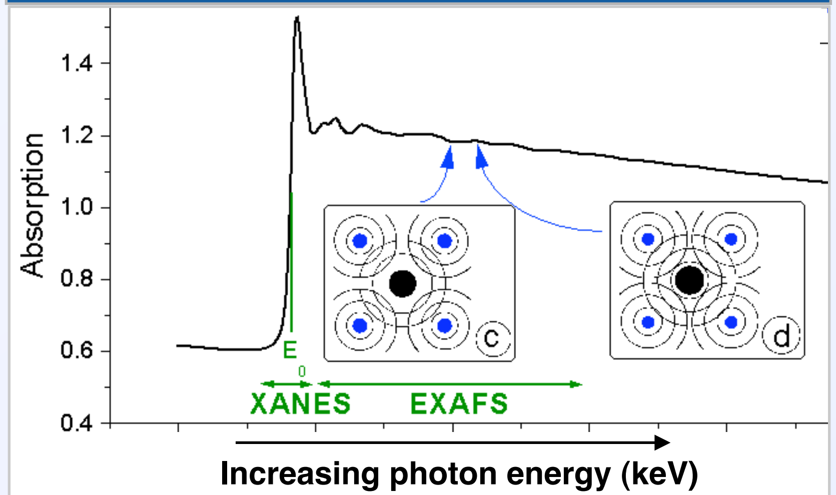
Sub-micron reconstruction of electron trajectories in plasma with betatron x-ray radiation



Single shot ultrafast absorption spectroscopy



Transmitted spectrum near absorption edge



- Ultrafast absorption spectroscopy: powerful tool to study the local atomic structure in materials.
- Sensitive to charge transfer, orbital occupancy and symmetry.
- We will be able to do this on the “natural” (fs) time scale of electronic and molecular motion.
- *In situ* monitoring 3d transition metals dynamics in real time.

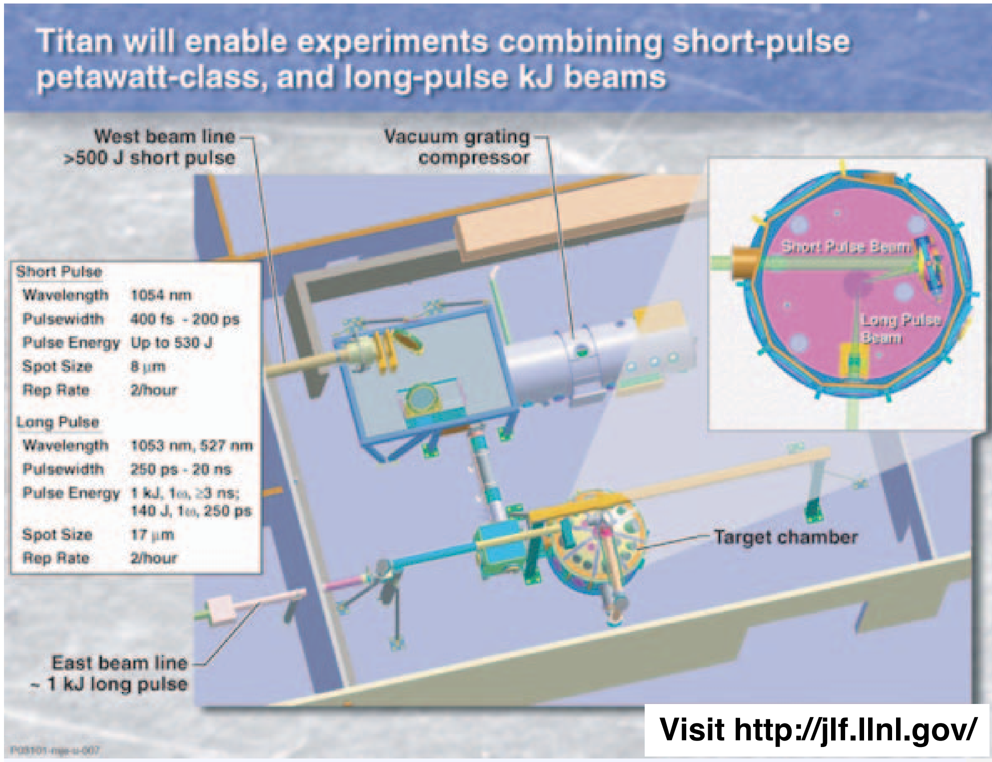
First proof-of-principle experiment of ultrafast XAS with the Betatron source

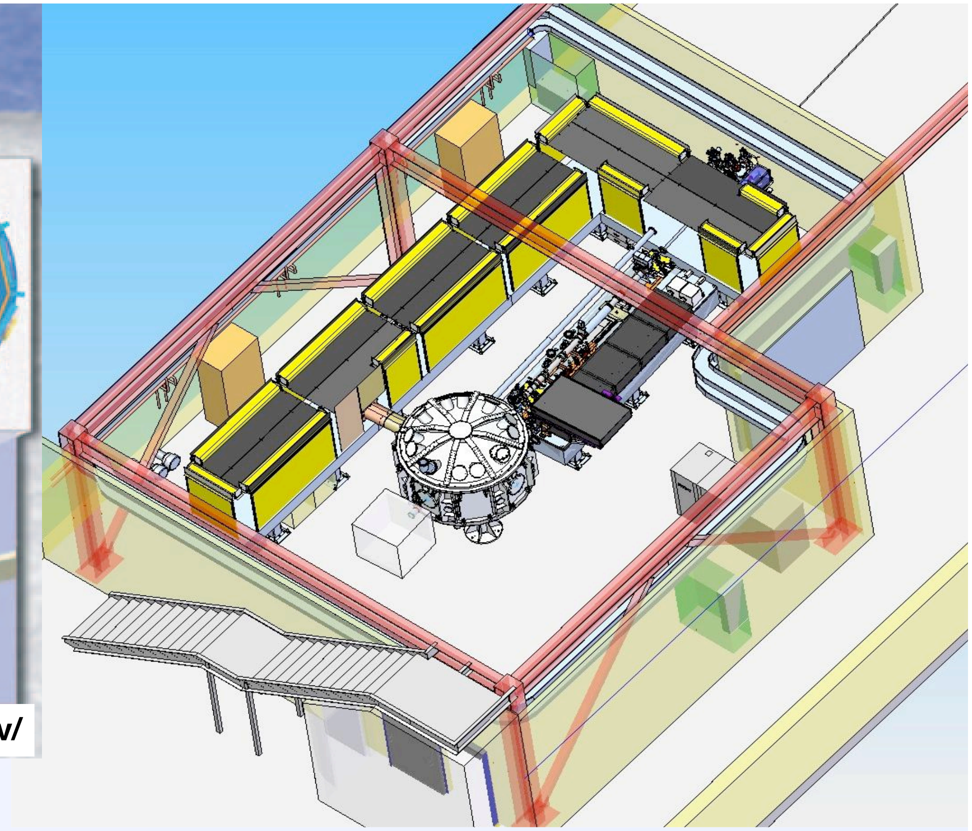
Fundamental science questions for warm dense matter research

- Determine the phase space of warm dense matter accessible at BA HEDS C
  - T_e, T_i, n_e, ρ,, Z, especially $T_e \leq T_F$
- Physical (microscopic) properties
  - Electron-ion equilibration
  - Conductivity
  - Optical reflectivity
- Material response
  - Heat wave propagation
  - Electron-ion equilibration
  - Radiative properties
- Discoveries/Applications
  - Phase transitions
  - New materials (e. g., electrides, metallic properties)

The West Cost laboratories have developed experimental capabilities to answer the fundamental questions related to warm dense matter

Thank you





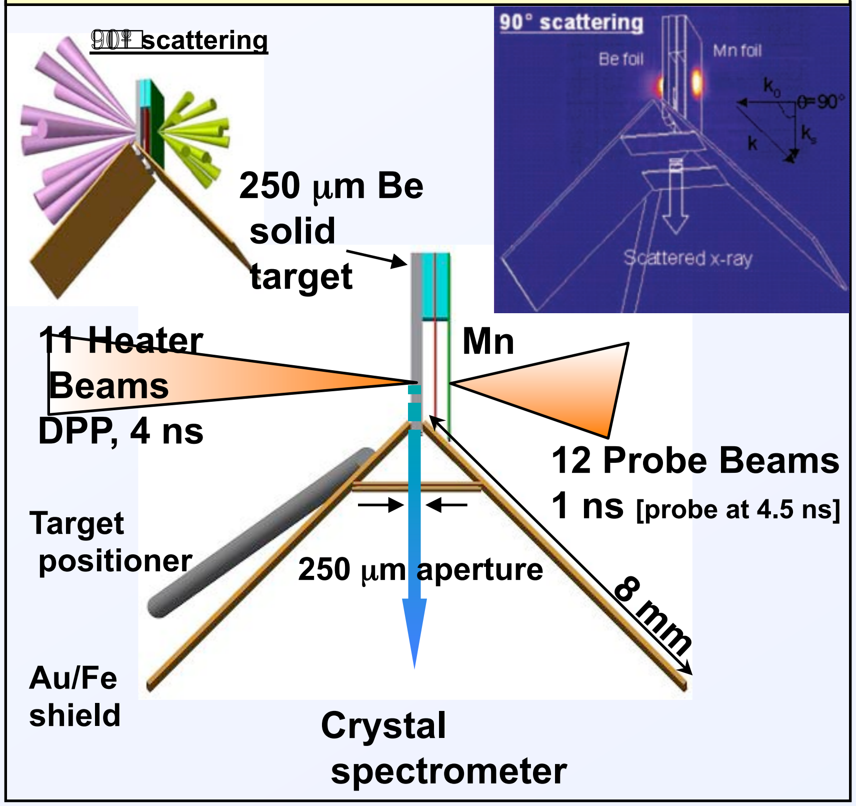
- NSDXII 1st year: Li+ 1.2 MeV; <3rd year 8 J cm2; Al 0.07 Mbar; 10^10 x-ray photons and ns- lasers
- MEC-LCLS: 10^12 x-ray photons, ns- lasers, 4 TW 35 fs laser
- ALS: mJ 800nm laser, 10^6 photons, 10-100 shots; De/E = 3%; 60 eV width: 1 eV at solid

Proposal – who will it be addressed to?

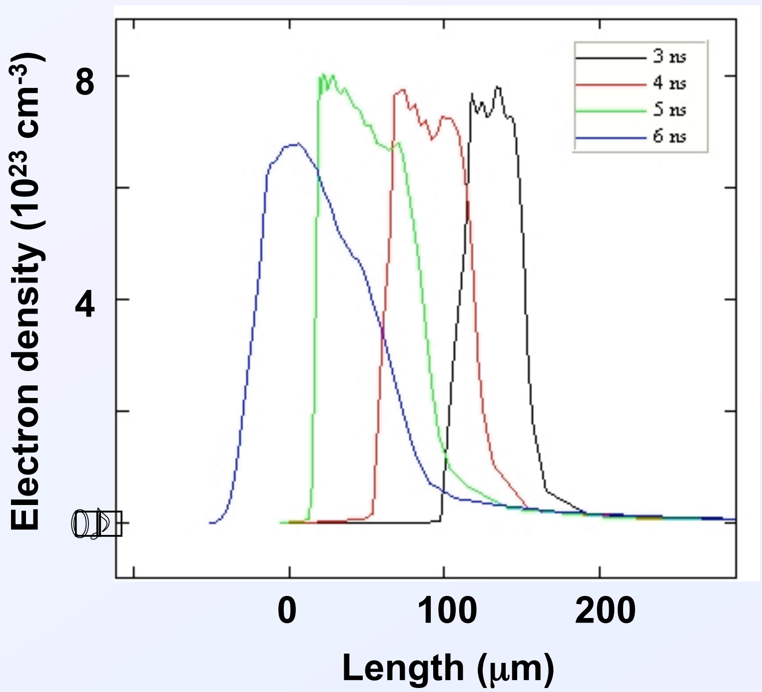
- Define T rho space
- Define sigma versus T and range possible at the various facilities
- Define diagnostics
- Define overlap of diagnostics
- Define target materials and overlap

Compressed Be at 30 Mbar has been characterized with x-ray Thomson scattering

X-ray scattering on compressed Be has been performed at 90˚ and 25˚ scattering angle



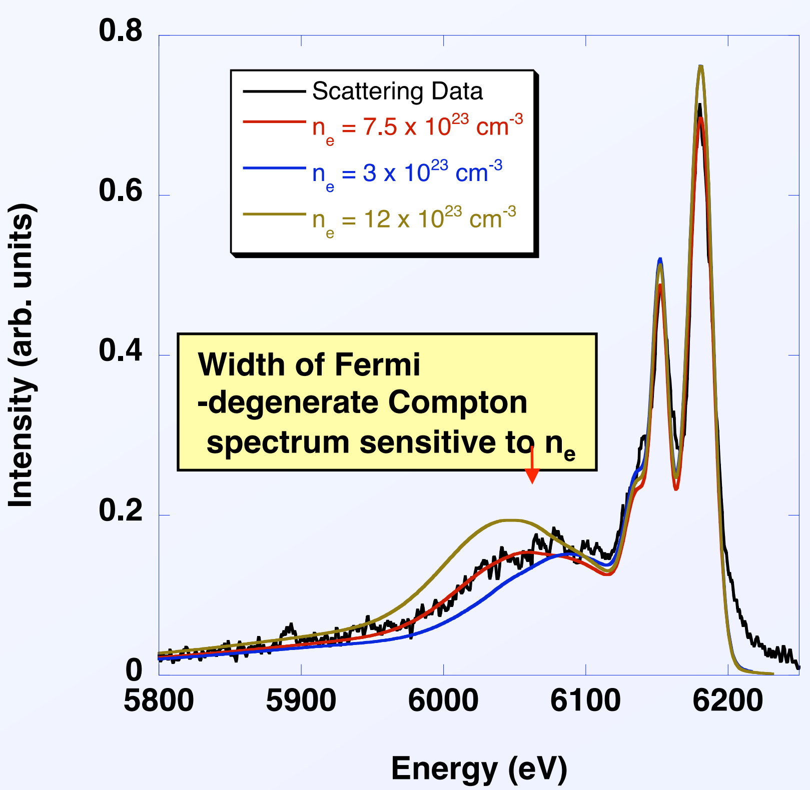
1-D Helios simulations indicate density of n_e = 7.5 x 10^{23} cm^{-3} [x3 compression]

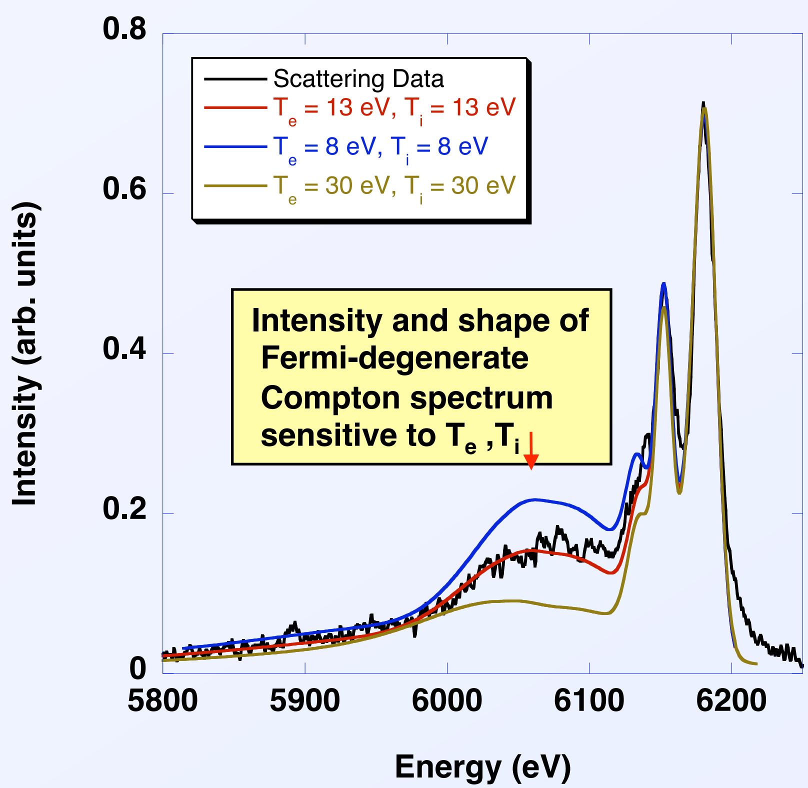


- A new Mn He-α backlighter at 6 keV was applied to penetrate through the dense compressed Be
- Disadvantage: double peaks from He-α and intercombination line

First X-ray Thomson scattering spectrum from compressed matter (Be)

Scattering data at 4.6 ns measure compressed matter density [E_F = 30 eV] and temperature

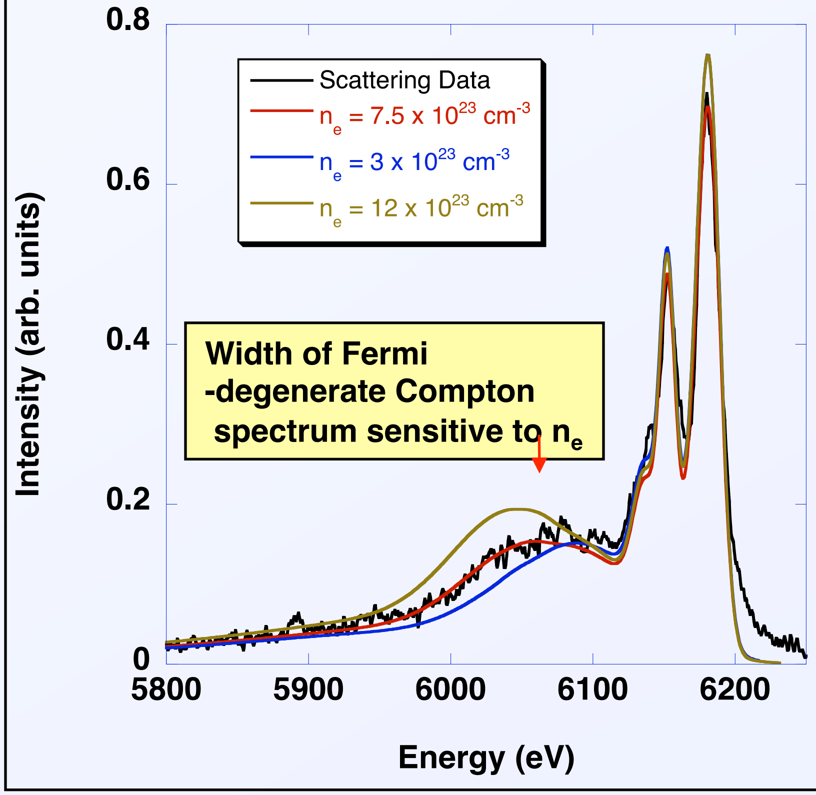


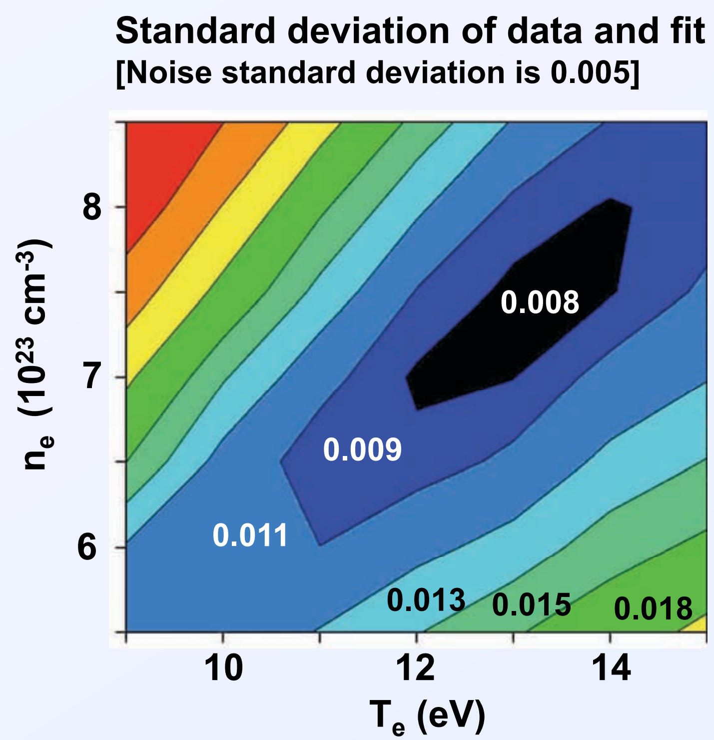


- **90˚ scatter, non-collective regime: n_e=7.5x10^{23} cm^{-3}, T_e=13 eV, Z=2, α~0.5**
- **Consistent with simulations and forward scatter results**
- **First direct measure of increased Fermi energy and adiabat in laser-compressed matter**

First X-ray Thomson scattering provides accurate characterization data

Scattering data at 4.6 ns measure compressed matter density [E_F = 30 eV] and temperature

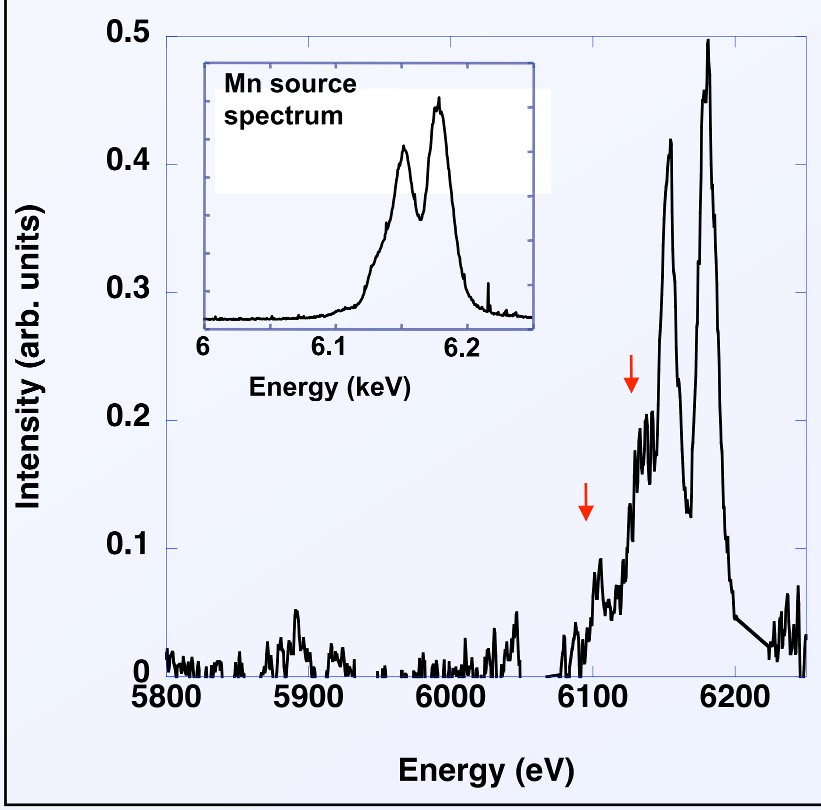




- Density and temperature are determined with an error bar of <10%
- High accuracy due to additional constraints on Z by the forward scattering data

Forward scattering data show plasmons at small energy shifts : collective regime , 25°

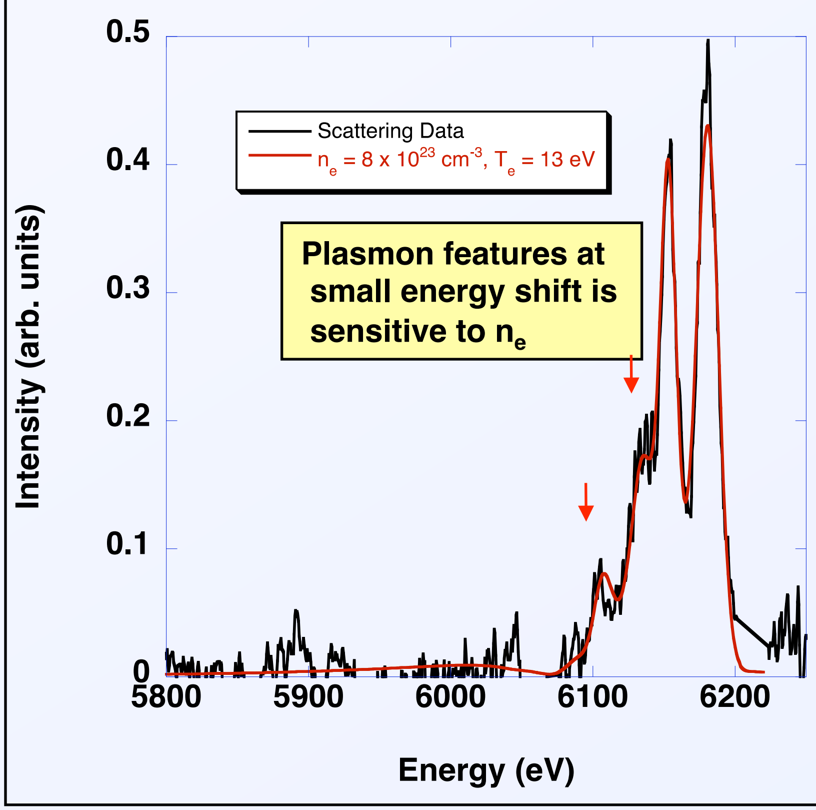
Scattering data at 4.4 ns measure compressed matter density [E_F = 30 eV]

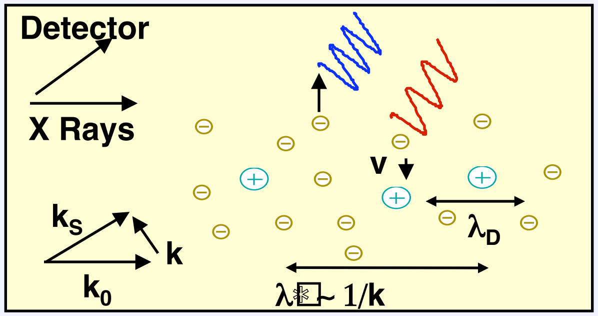


- Forward scatter: n_e=7.5x10^{23} cm^{-3}, T_e=12 eV, Z=2, α~1.6
- Forward scatter and backscatter results both provide compression of x3
- First direct measure of increased Fermi energy and adiabat in laser-compressed matter

Forward scattering data show plasmons at small energy shifts : collective regime , 25º

Scattering data at 4.4 ns measure compressed matter density [E_F = 30 eV]

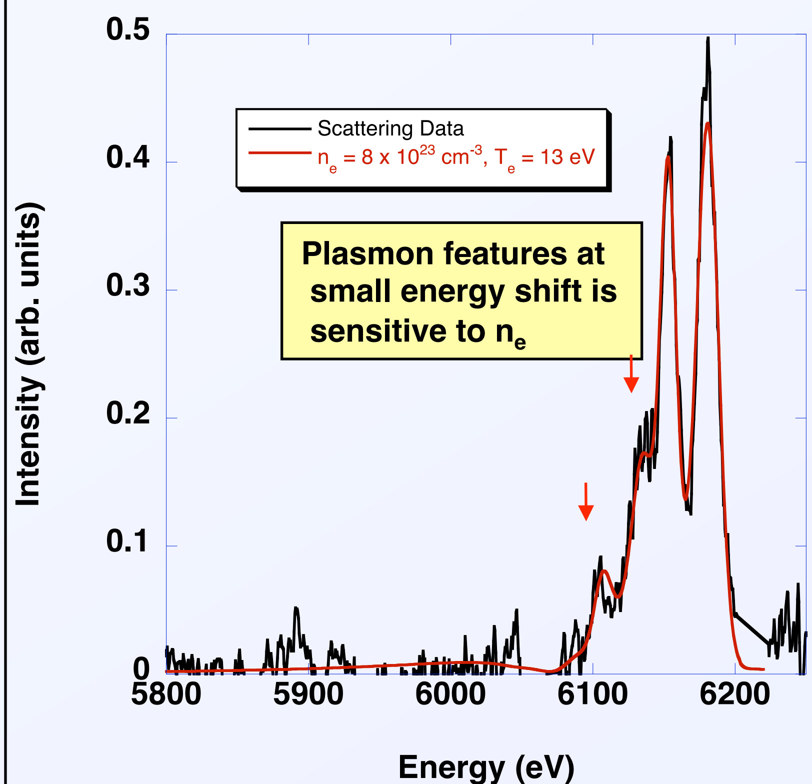


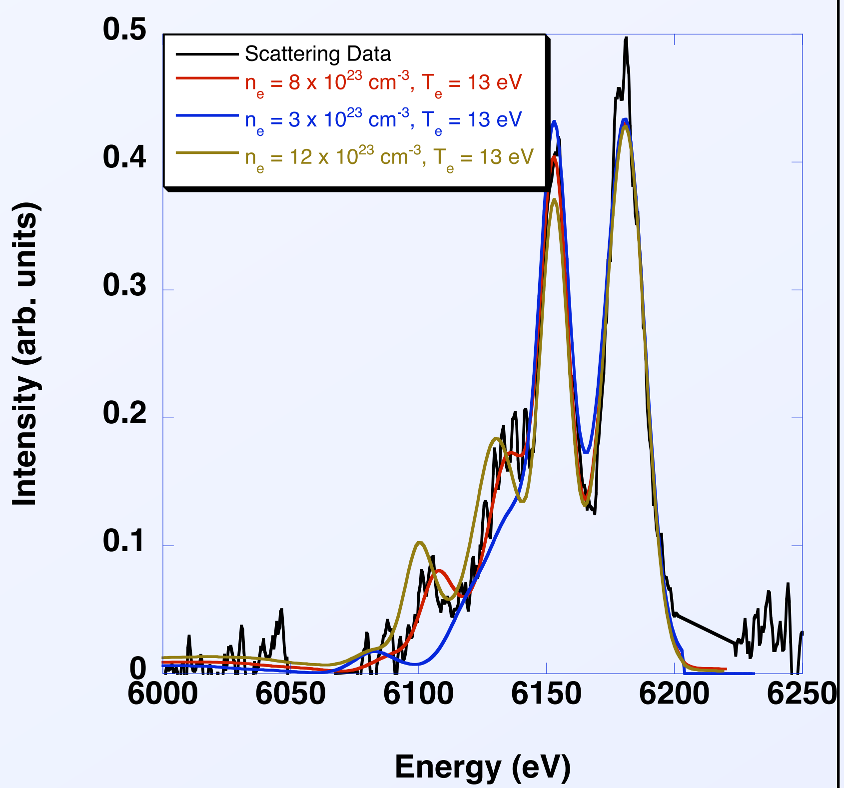


- Forward scatter: n_e=7.5x10^{23} cm^{-3}, T_e=13 eV, Z=2, α~1.6
- Forward scatter and backscatter results both provide compression of x3
- First direct measure of increased Fermi energy and adiabat in laser-compressed matter

Forward scattering data show plasmons at small energy shifts : collective regime , 25º

Scattering data at 4.4 ns measure compressed matter density [E_F = 30 eV]

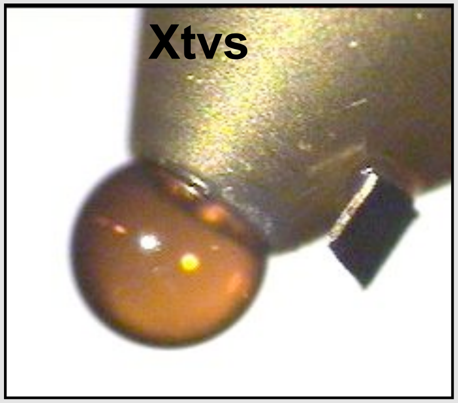


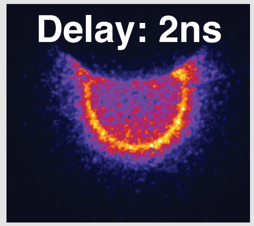


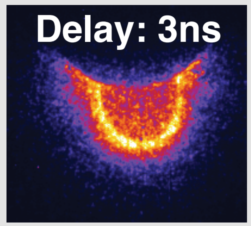
- **First direct measure of increased Fermi energy, plasmons, and adiabat in laser-compressed matter**
- **Accurate characterization tool of laser-compressed matter**

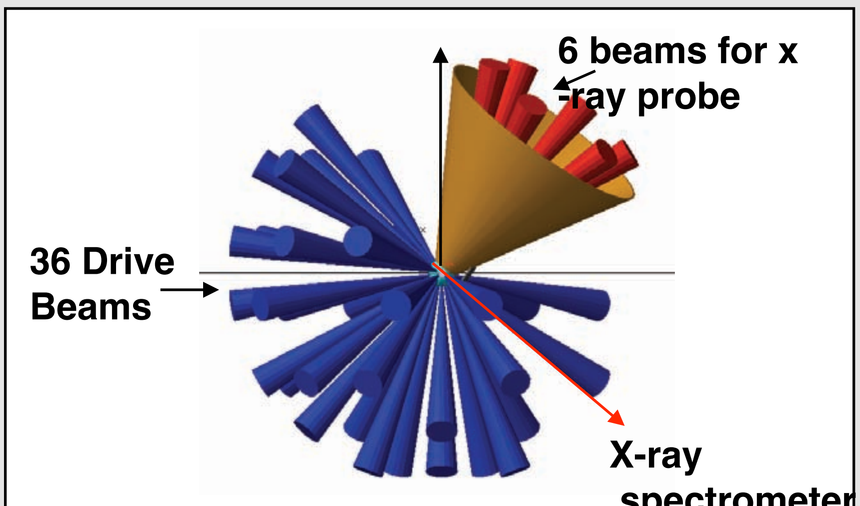
Possible Applications to NIF

Experimental Geometry

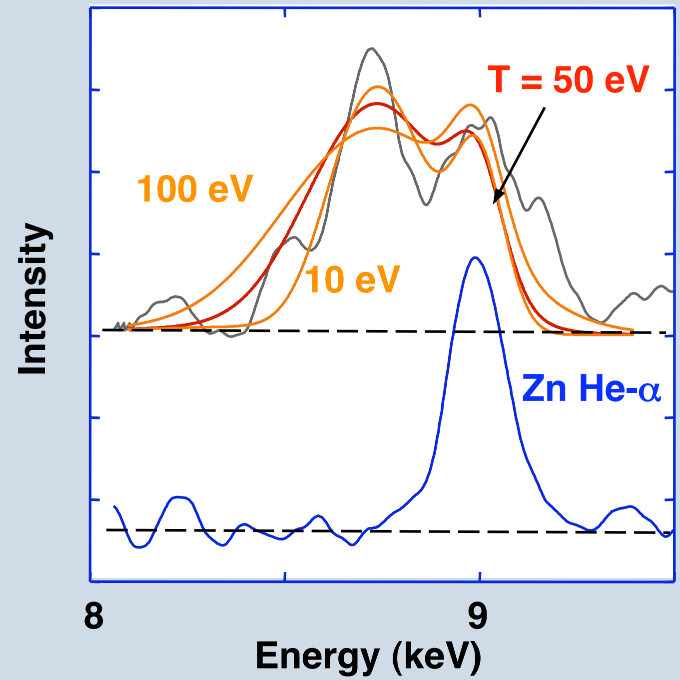








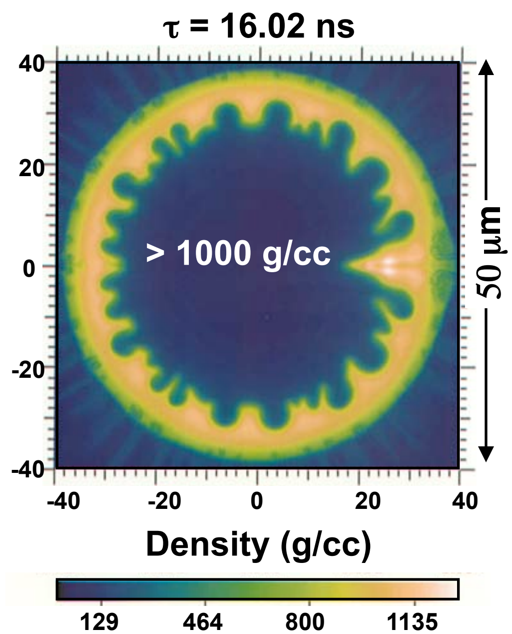
Scattering data at 3.7 ns indicate T ≤ 50 eV



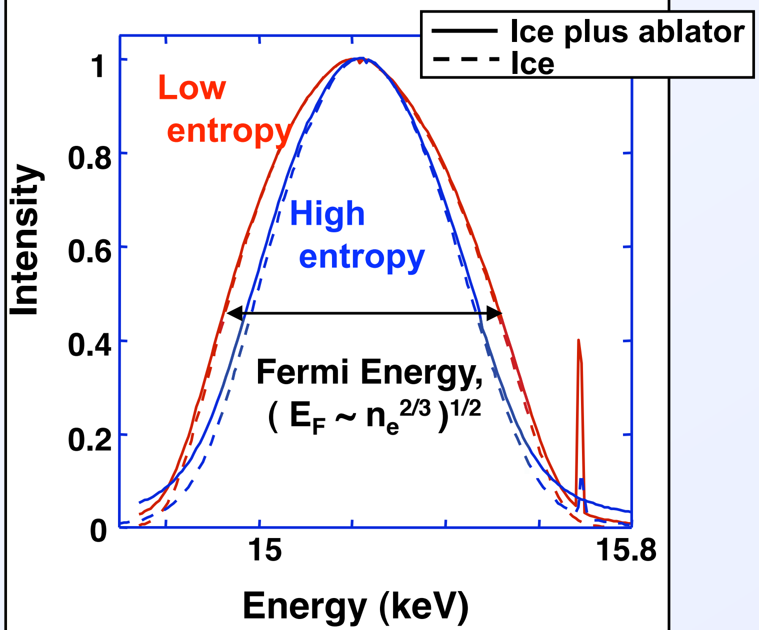
We have begun x-ray scattering experiments on capsule implosions with $n_e > 10^{24}$ cm^{-3}; $\alpha = T_e/T_F \sim 1$

X-ray scattering measures Compton and Plasmon features directly providing T_e/T_F

Radiation-hydrodynamic simulations of NIF implosions



Simulated X-ray Thomson scattering from implosions



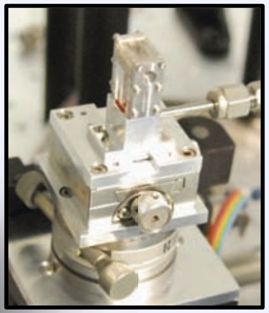
- **The width of the X-ray Thomson scattering spectrum reflects the dense fuel**
  - **The width provides a measure of the Fermi energy**
  - **Not sensitive to contributions from ablator - weighted towards the dense ice**

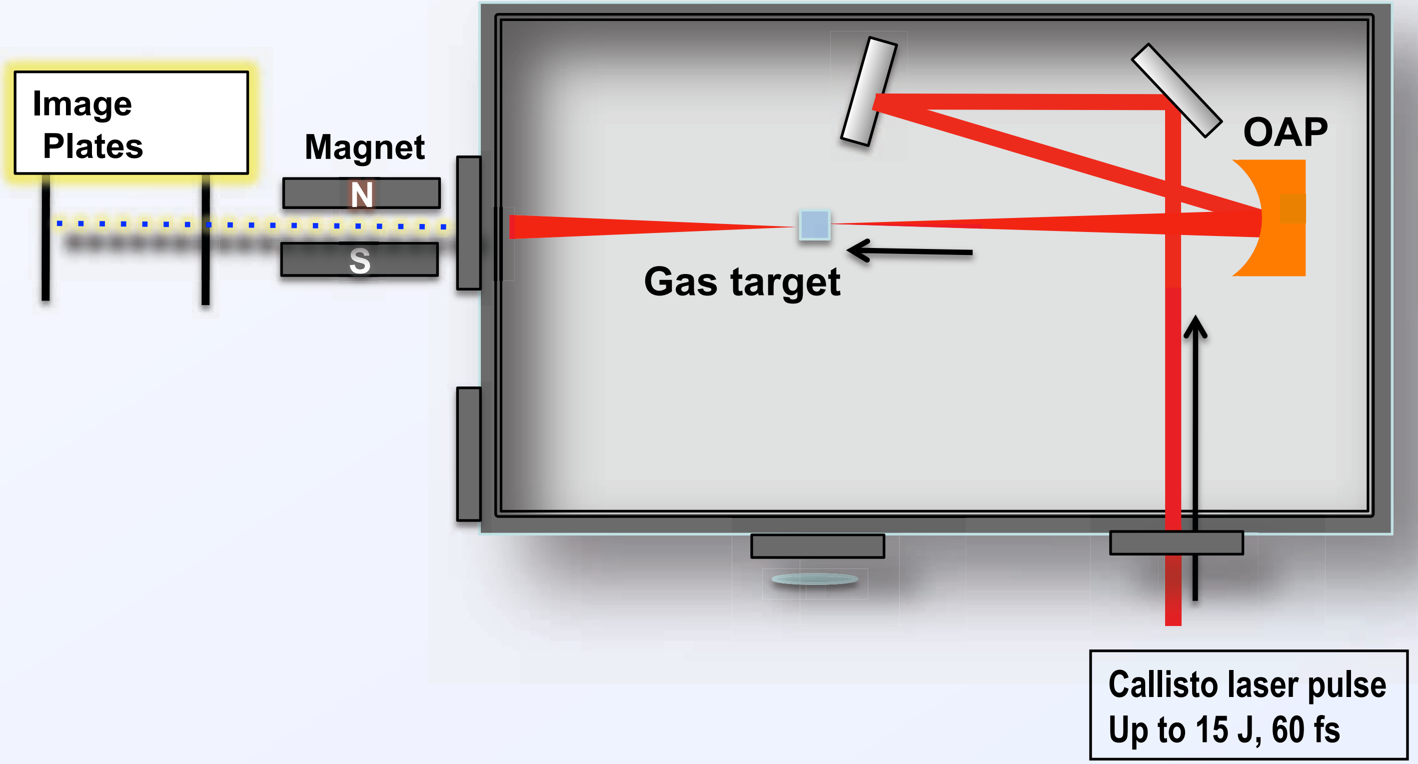
Ultrashort pulse lasers will enable X-ray probing techniques

- Betatron
- X-ray Compton
- Backlighters

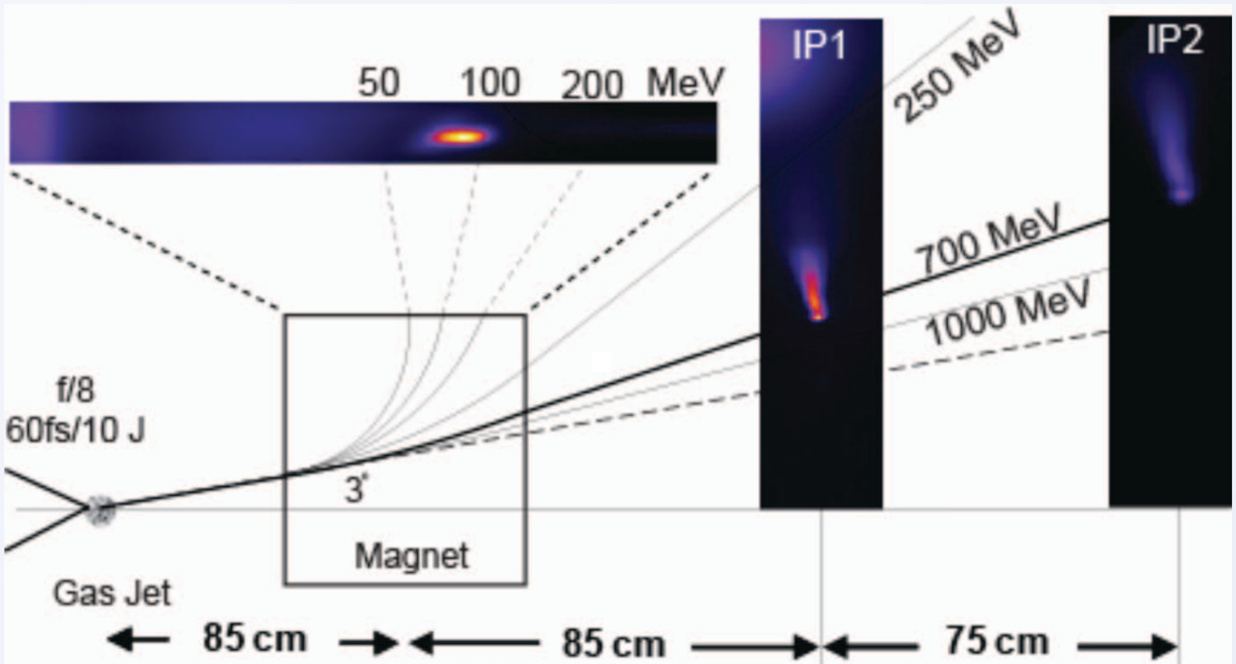
Experimental setup for laser wakefield acceleration

Focal Spot Size = 15 μm (f/8)





Electron beam detected with a two screen spectrometer

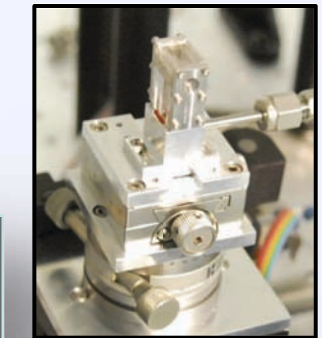


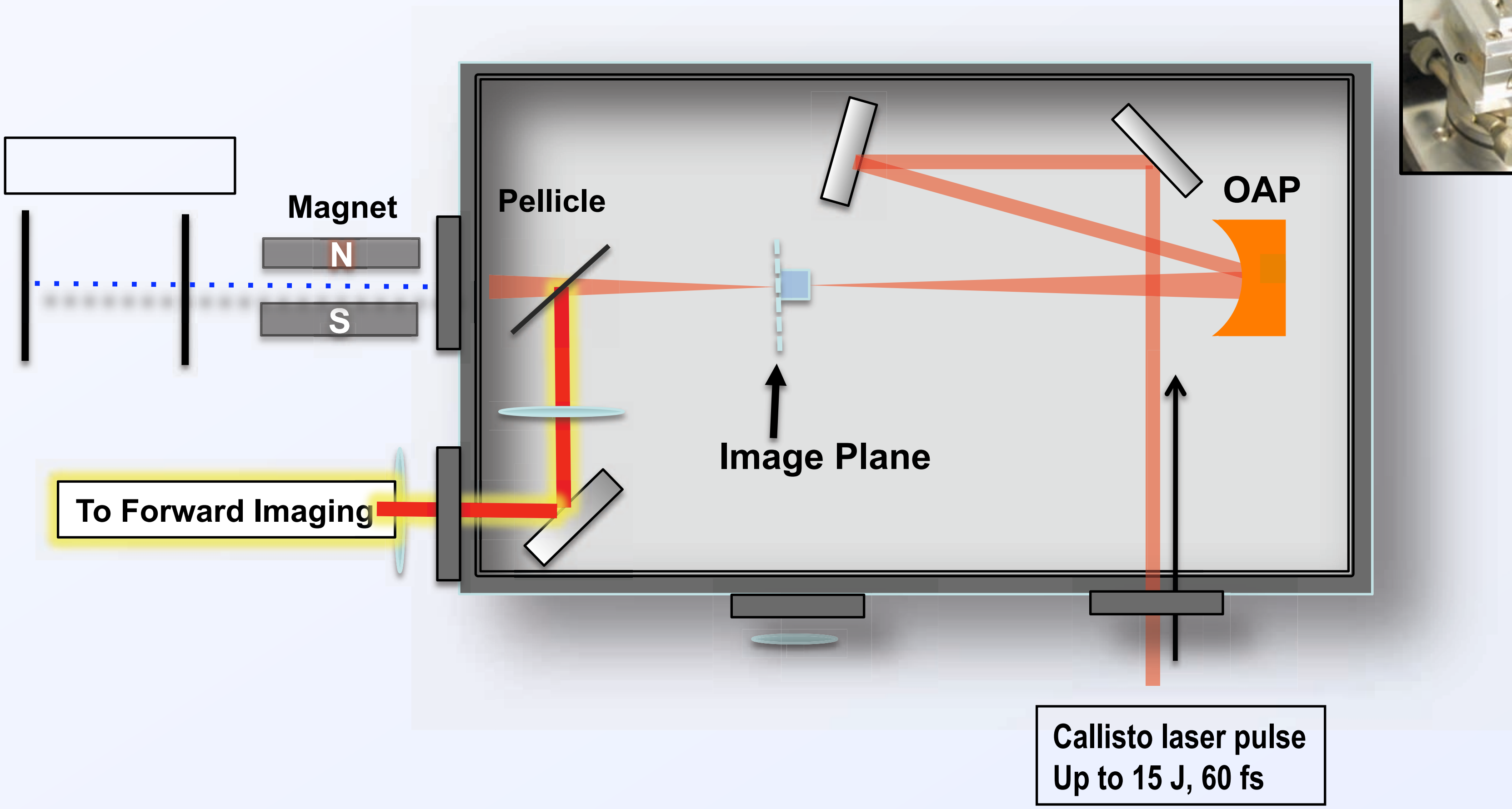
Electron angle and energy calculated from information on the two forward image plates

B.B. Pollock, proceedings of PAC09, Vancouver
I. Blumenfeld et. al, Nature, 445, 741 (2007)

We look at the exit of the target to show that the laser is self-guiding

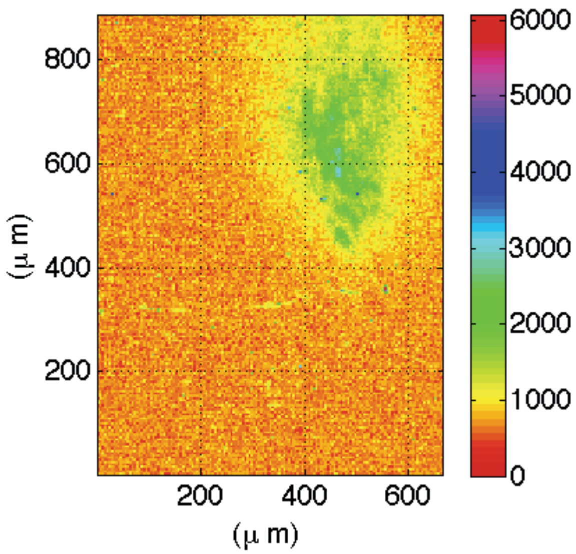
Focal Spot Size = 15 μm (f/8)





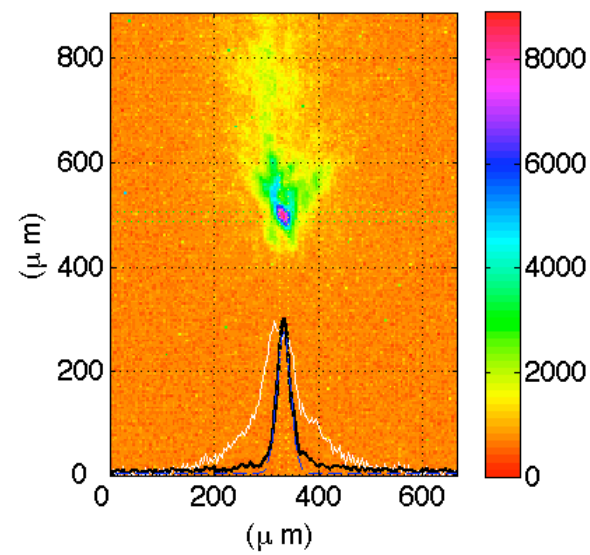
Self-guiding is the evidence for driving a plasma wake

An image of the vacuum spot at the exit of the 14 mm gas cell



Spot radius 1/e² is 290 μm at 14 mm from focus

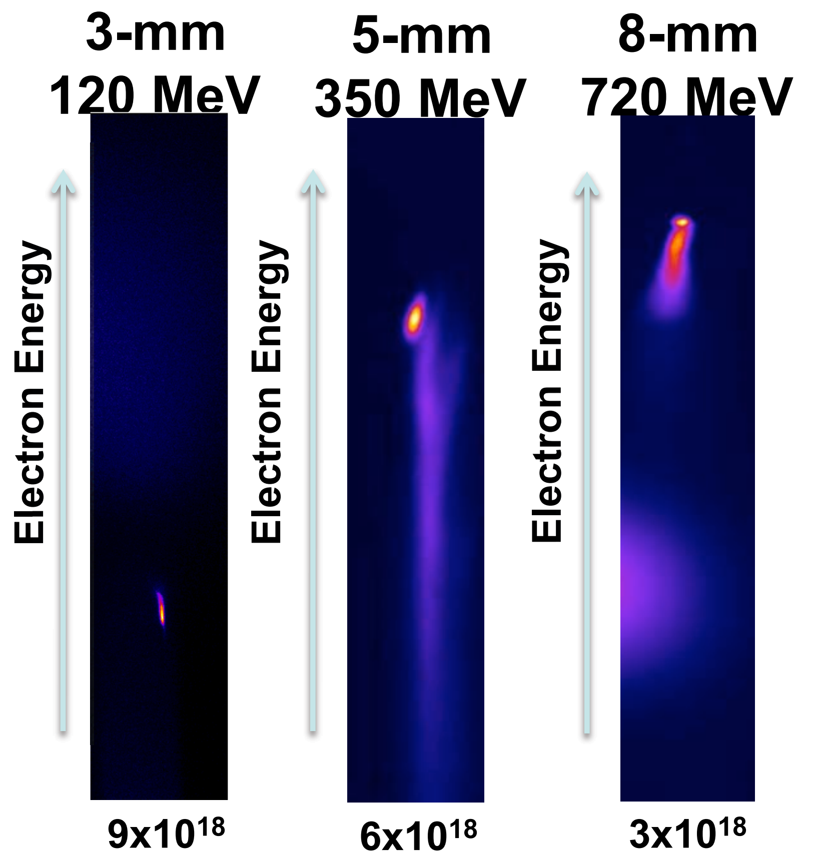
An image of the self-guided spot at the exit of the plasma with density of 1.3 x 10^{18} cm^{-3}



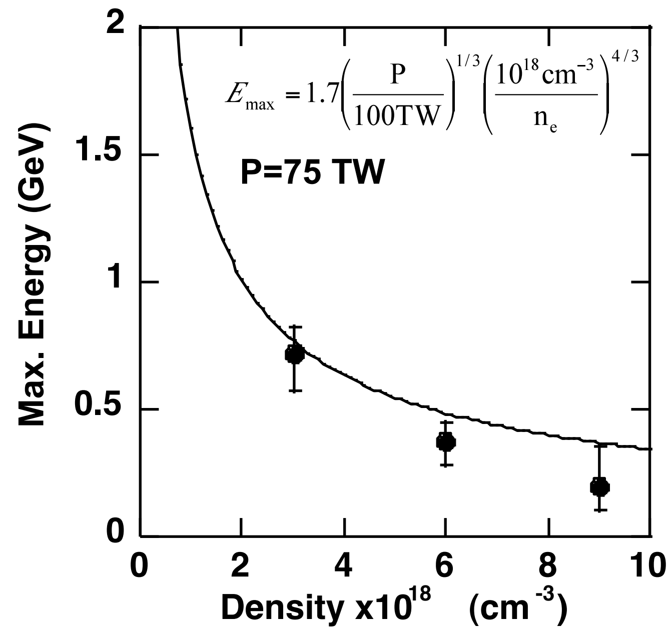
Spot radius 1/e² is 25 μm at the exit of the gas cell

J.E. Ralph et al, PRL 102, 175003 (2009)
J.E. Ralph et al, Phys. Plasmas, 17, 056709 (2009)

Our experiments agree with the blowout regime model



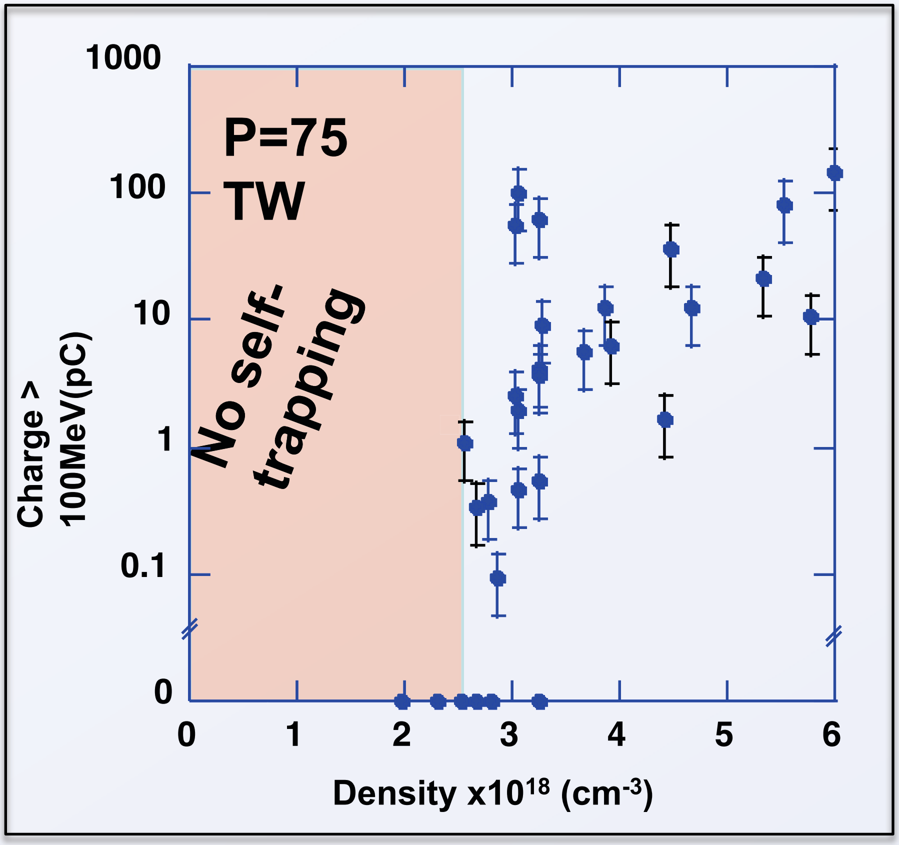
Increasing electron energy with decreasing density



No electrons accelerated below $3x10^{18}$ cm^{-3}

D.H. Froula et al, PRL, 103, 215006 (2009)
J.E. Ralph et al, Phys. Plasmas, 17, 056709 (2009)

No electrons are accelerated below ~ 3 x 10^{18} cm^{-3}



But there is a problem:

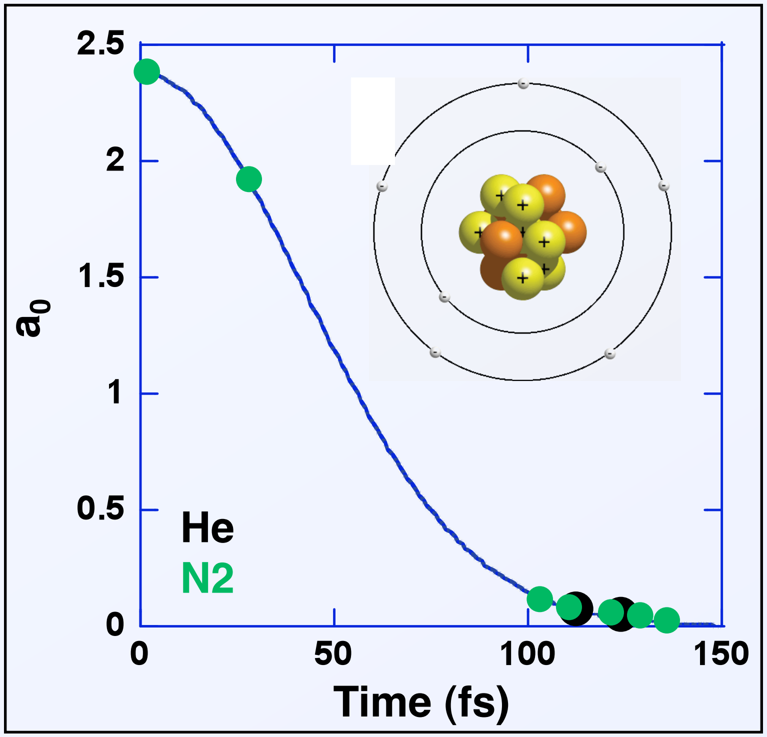
The lower the density, the longer the dephasing length

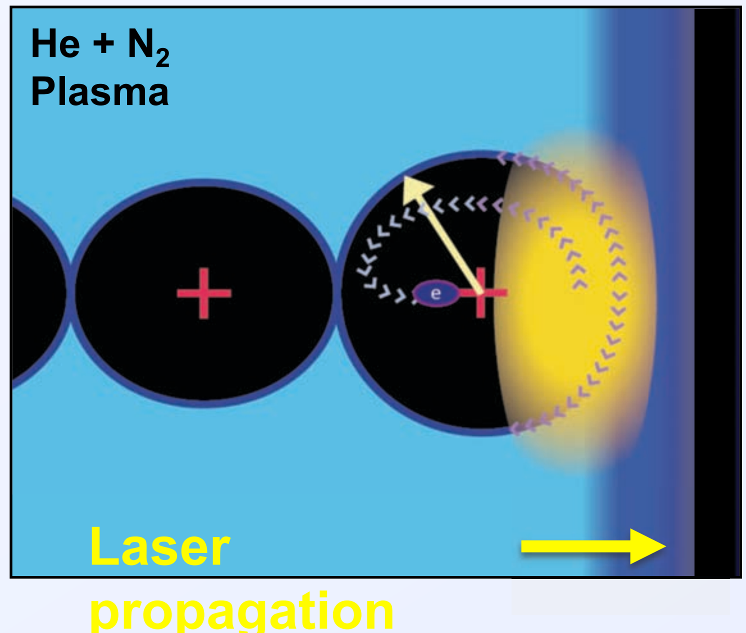
$$L_{dp} = \frac{2}{3}\frac{n_c}{n_e}R_b$$

We need another mechanism to accelerate electrons to GeV energies

The solution is ionization induced trapping

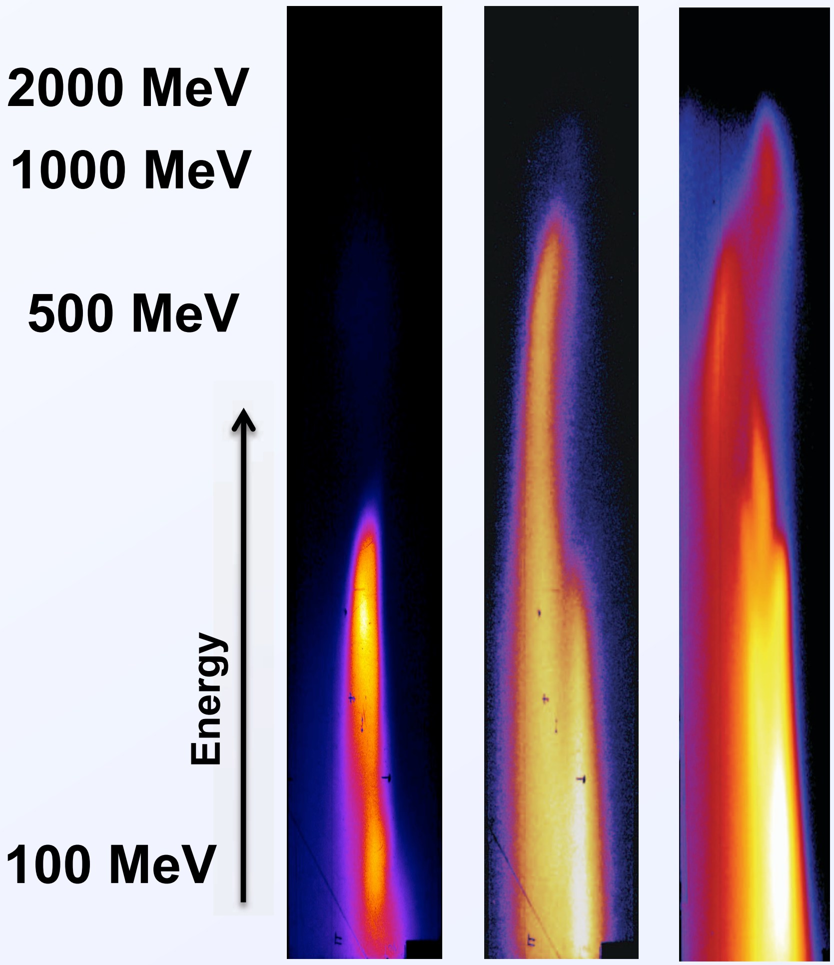
Idea: Introduce a small amount of "dopant" in the Helium gas





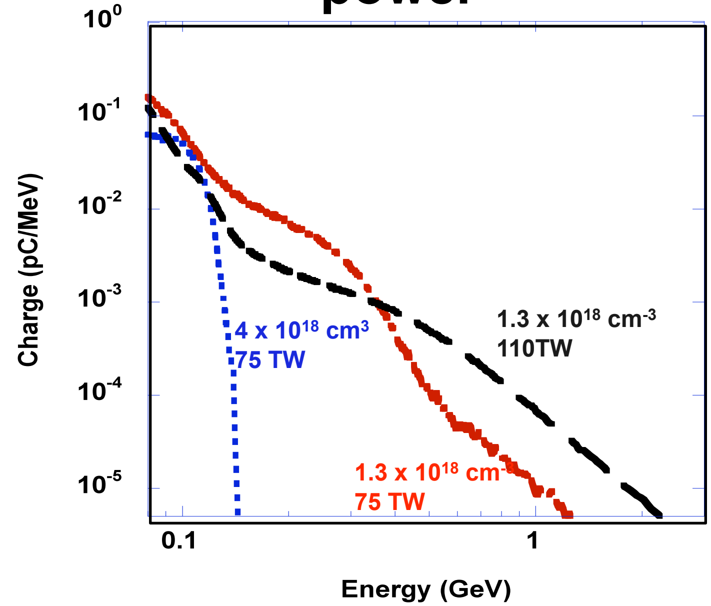
Inner shell electrons are ionized and trapped directly inside the bubble

We can then go down to lower densities to accelerated GeV electrons



4x10[18] 1.2x10[18] 1.2x10[18]
Density (cm^{-3})

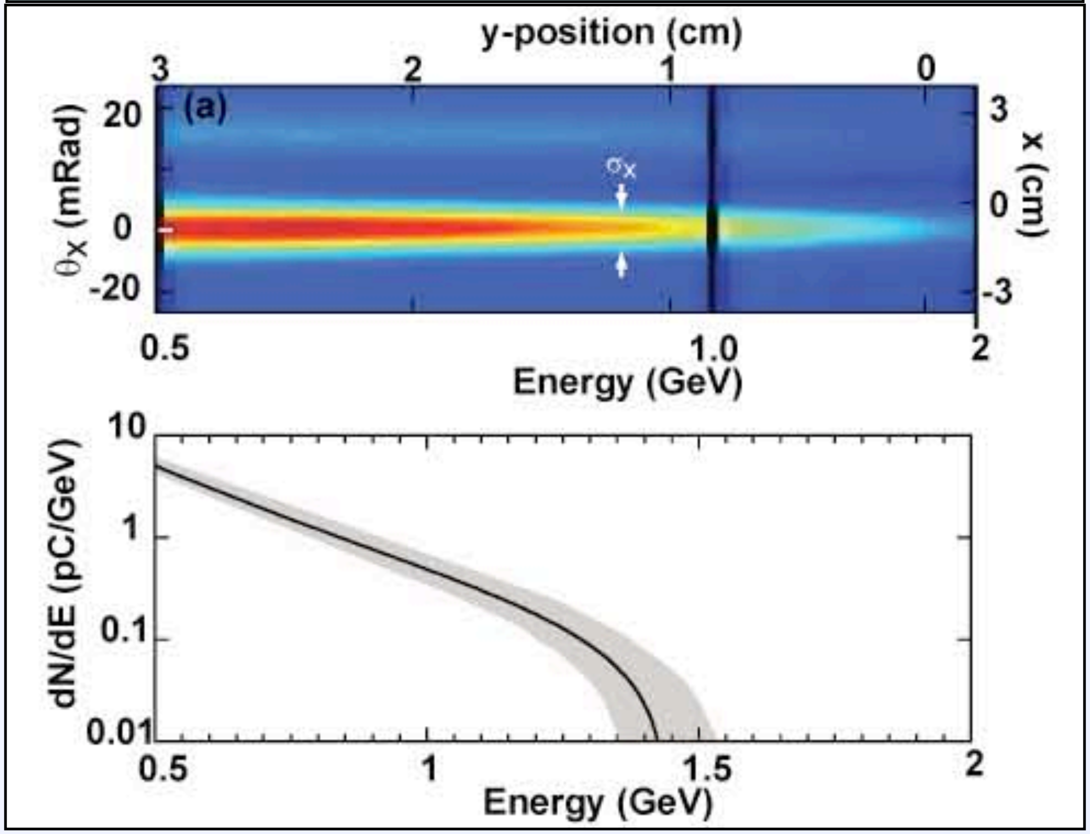
Charge vs. energy shows scaling with density and power



Charge can be seen beyond 1 GeV at a density of 1.2 x 10^{18} cm^{-3}

We have shown the world record electron energy from laser wakefield acceleration

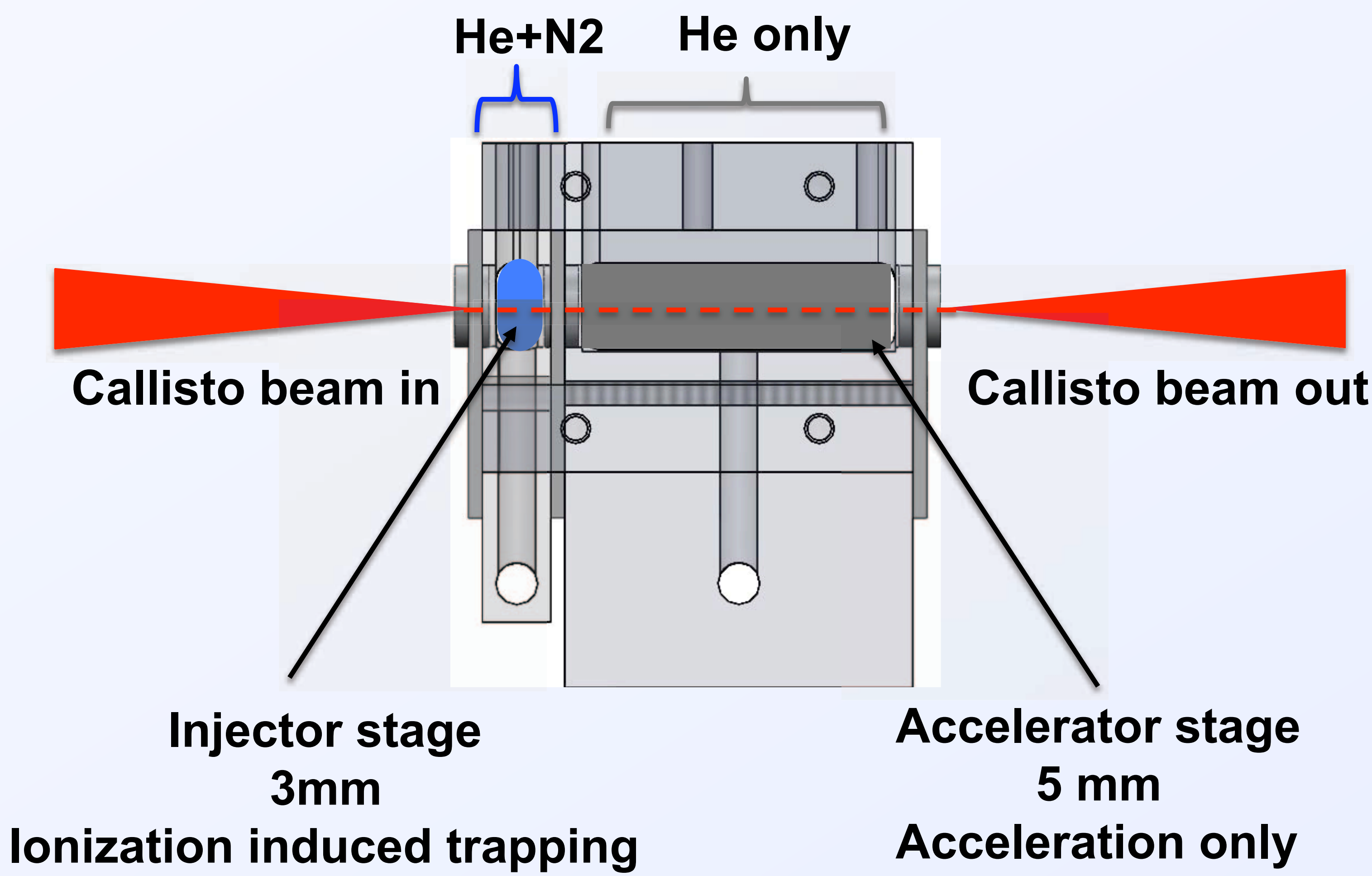
1.4 GeV record energy



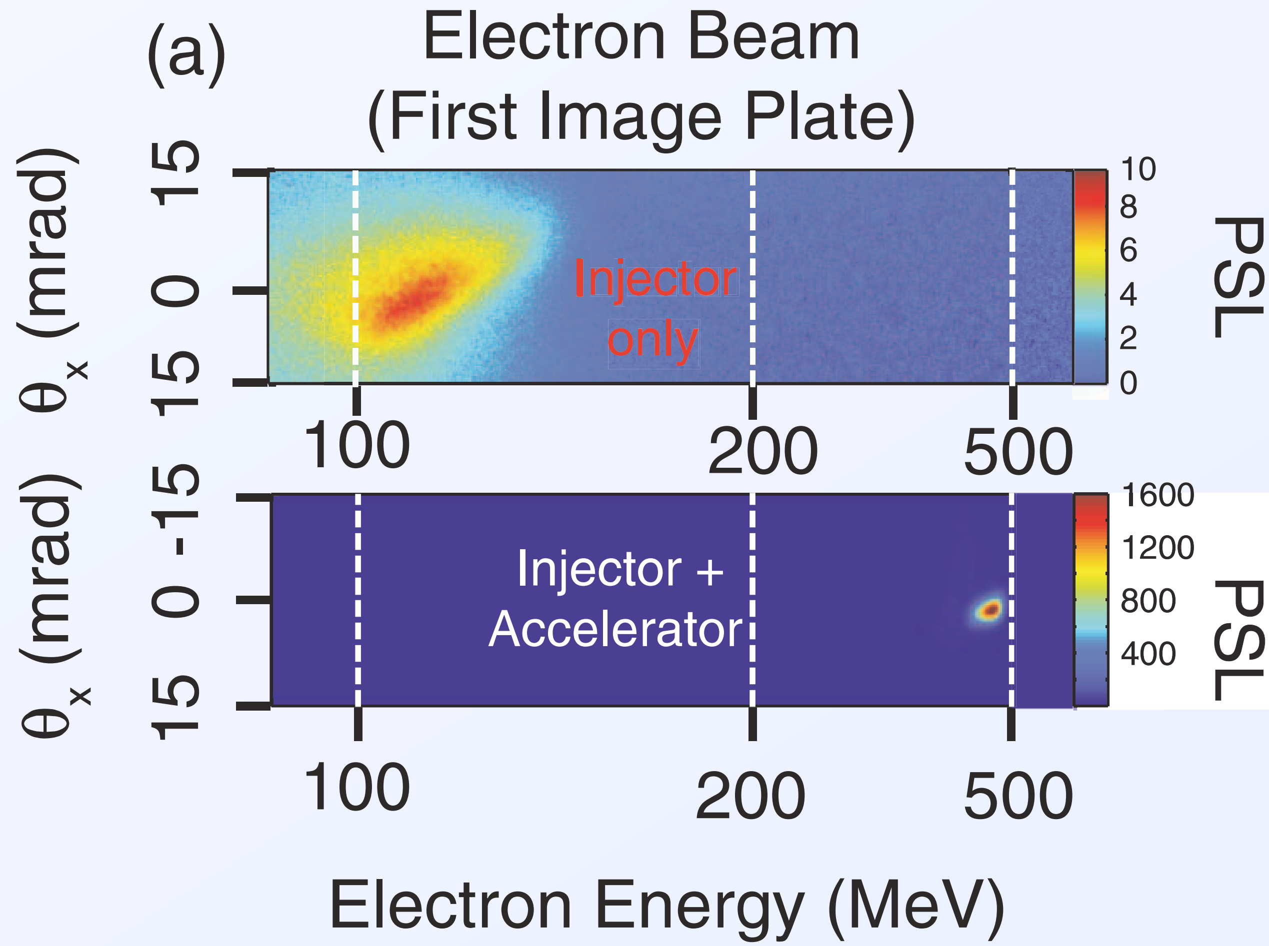
C.E. Clayton et. al, PRL, 105003 (2010)

High energy but continuous trapping does not allow for monoenergetic beams

A two stage gas cell can localize the trapping

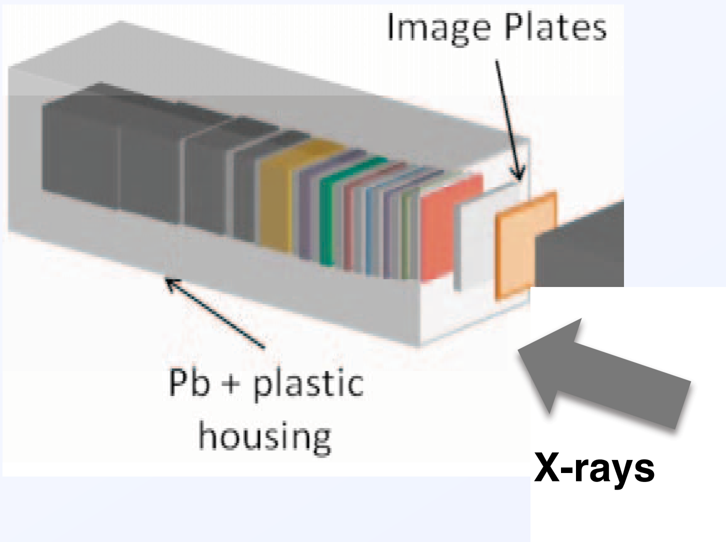


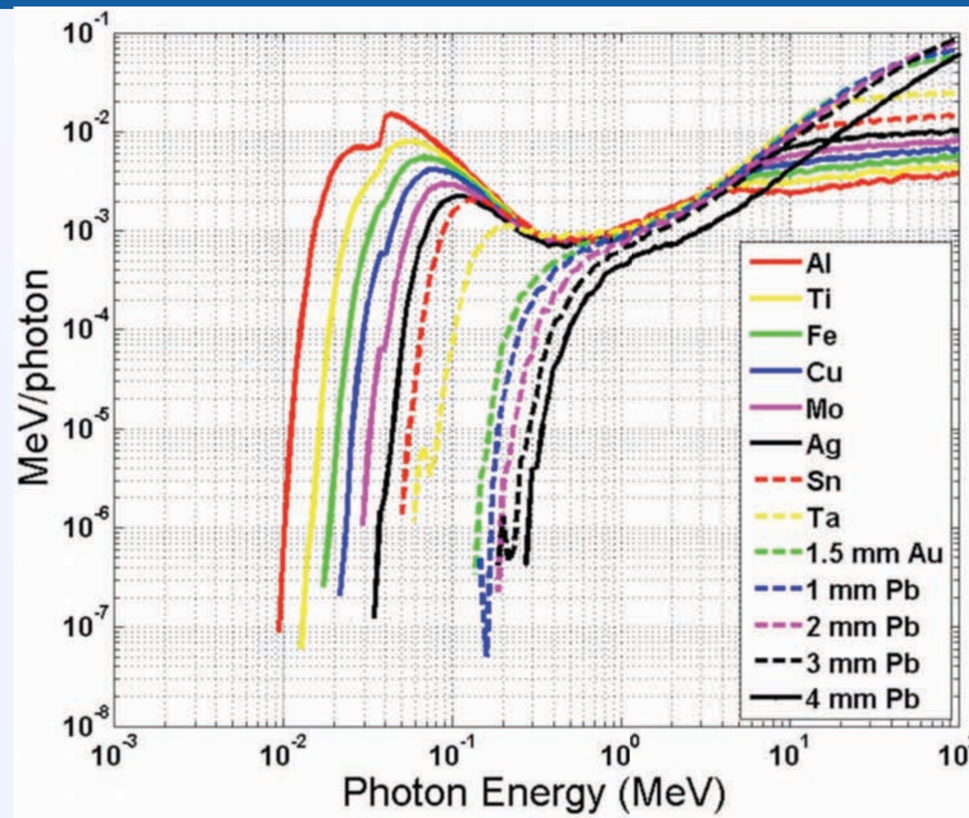
0.5 GeV Narrow energy spread electron beam from two-stage accelerator



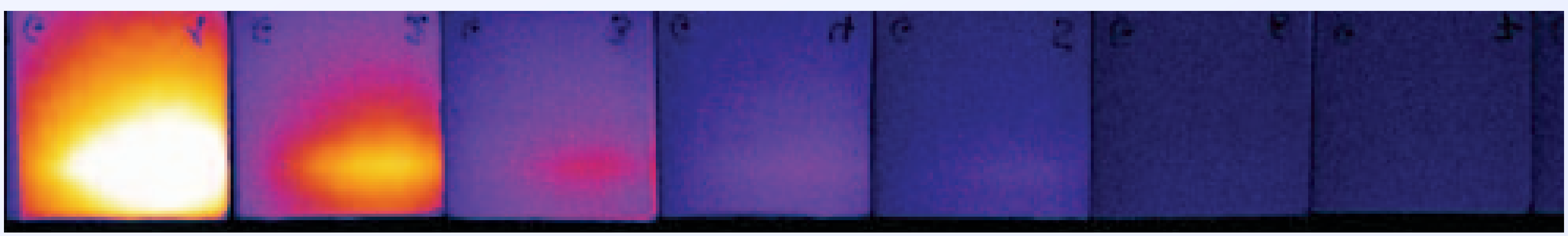
B.B. Pollock et. al, PRL 107 045001 (2011)

Implementation of cannon spectrometer to measure spectral and spatial information





Signal up to channel #5: X-rays > 20 keV



Al **Ti** **Fe** **Cu** **Mo**