X-ray diagnostics of laser produced warm-dense plasmas *)

2nd EMMI Workshop
on
Plasma Physics with Intense Laser and Heavy Ion Beams
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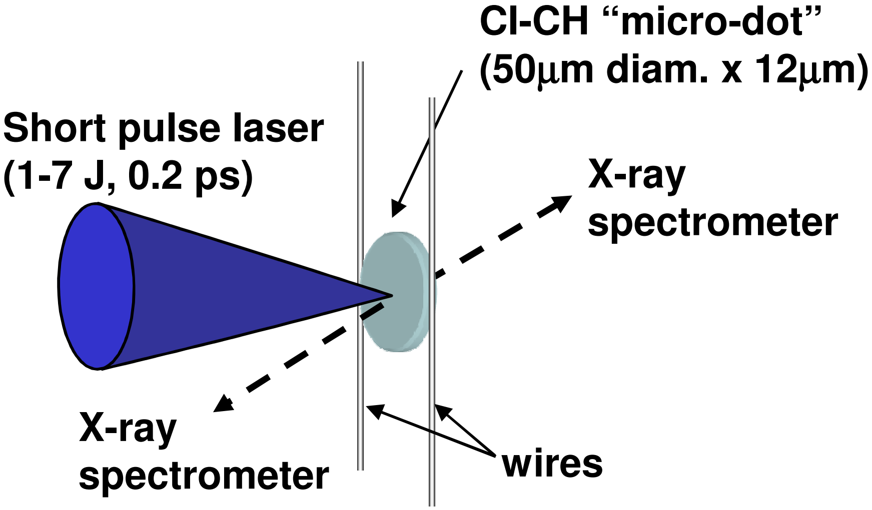
Outline

- Generation of WDM
  - Using energetic laser pulses (E_{laser} = 1J…20kJ)
  - Isochoric heating (e-, x-ray), single/multiple shock compression
- Diagnostics
  - K-shell emission spectroscopy
  - X-ray Thomson scattering
- Measurements
  - Plasma parameters (n_e, $T_{e,i}$, Z)
  - WDM specific features (degeneracy, strong coupling)
- Applications
  - Hot-electron coupling, test of rad-hydro modeling, ionization balance

K-alpha spectroscopy from isochorically heated reduced-mass targets

- Ultra-intense laser pulse generates hot electron
- Hot-e^- exchange energy with bulk-e^-
- Hot-e^- produce K-shell emission



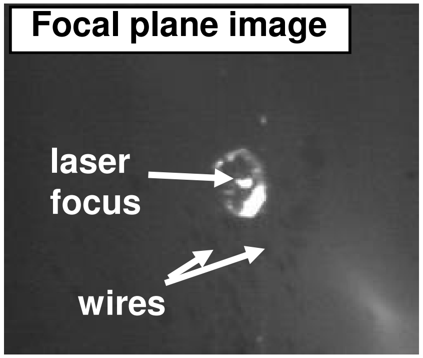
Cl-CH “micro-dot” (50μm diam. x 12μm)

Short pulse laser (1-7 J, 0.2 ps)

X-ray spectrometer

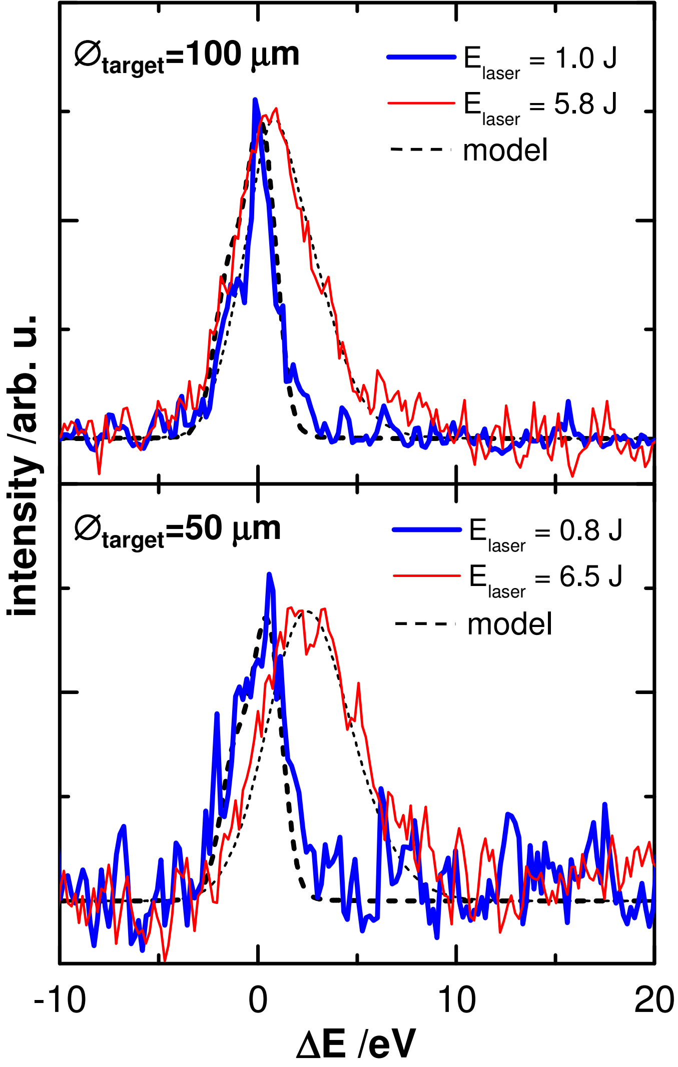
X-ray spectrometer

wires

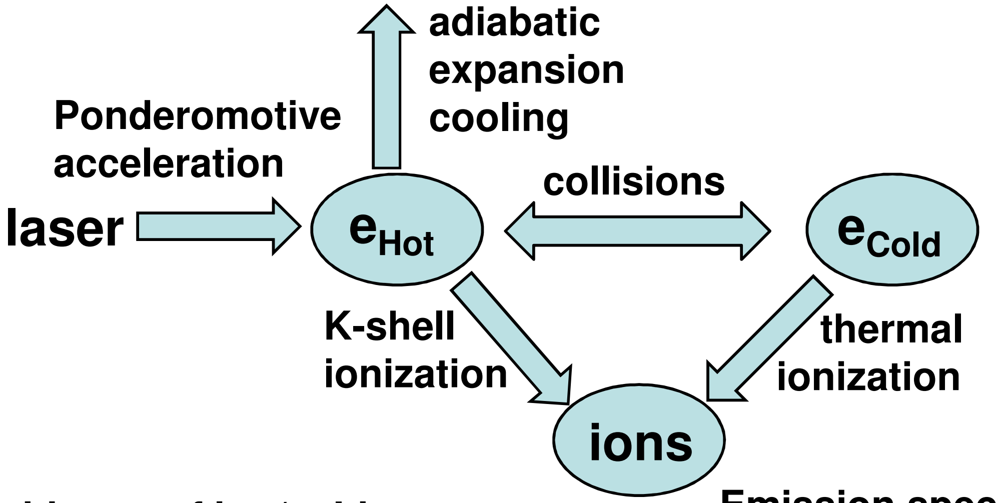


Focal plane image

Chlorine K-alpha (~2.62 keV) emission spectra



We employ a simple 2-temperature equilibration model to simulate the experiment



adiabatic expansion cooling

Ponderomotive acceleration

collisions

laser

e_{Hot}

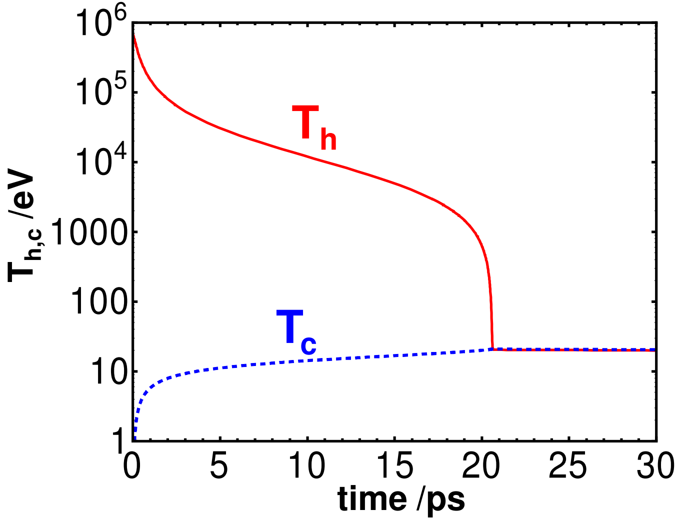
e_{Cold}

K-shell ionization

thermal ionization

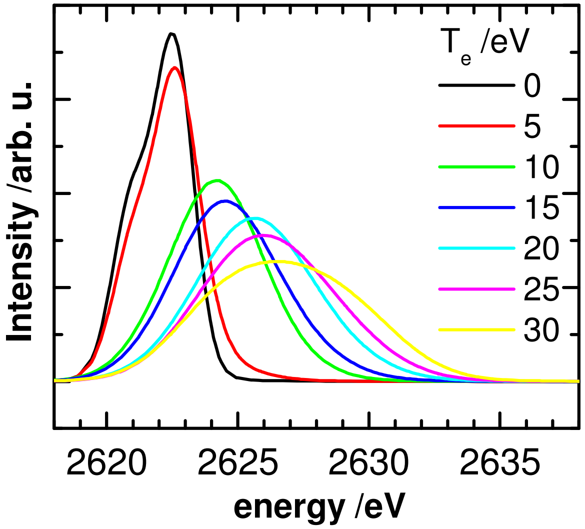
ions

Time history of hot/cold electron fraction



Rapid adiabatic cooling of hot electrons

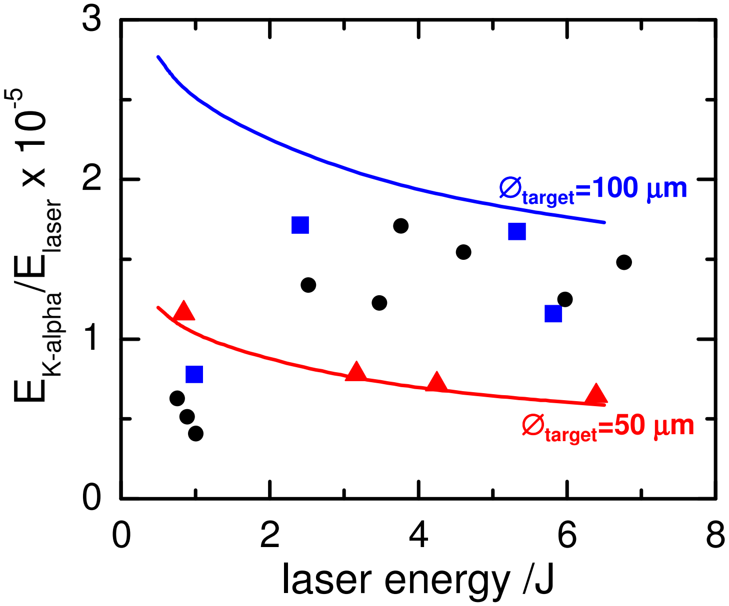
Emission spectra calculation with FLYCHK *)



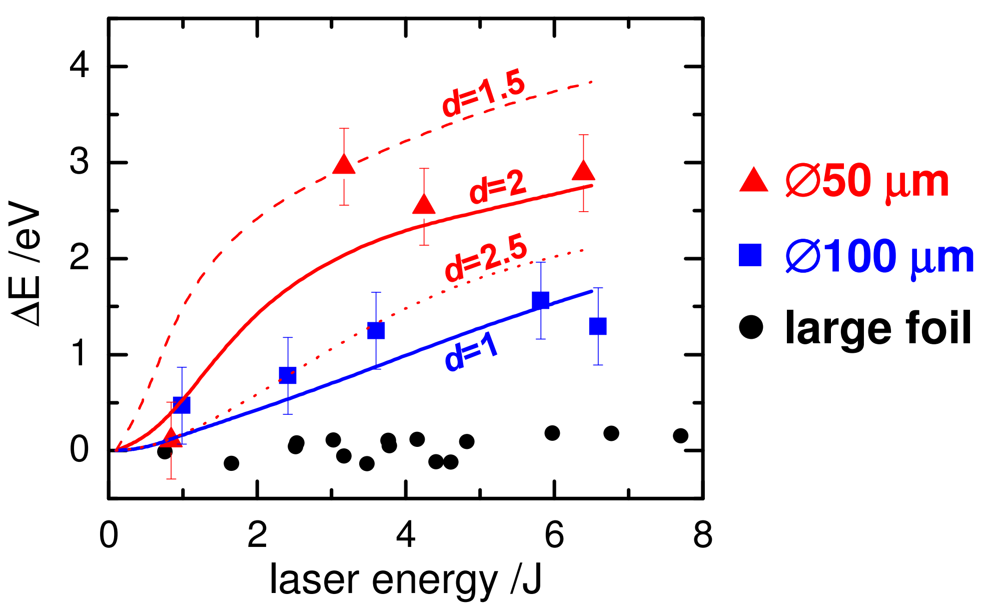
Blue shift of K-alpha emission due to thermal ionization

*) H.-K. Chung et al., HEDP **1** 3 (2005)

The simple model successfully reproduces the measured K-alpha yields and spectral line shifts



Decrease in conversion efficiency for smaller targets due to faster expansion cooling



Smaller targets reach higher energy densities, but show rather 2D-like expansion

P. Neumayer *et al.*, HEDP (2009), accepted

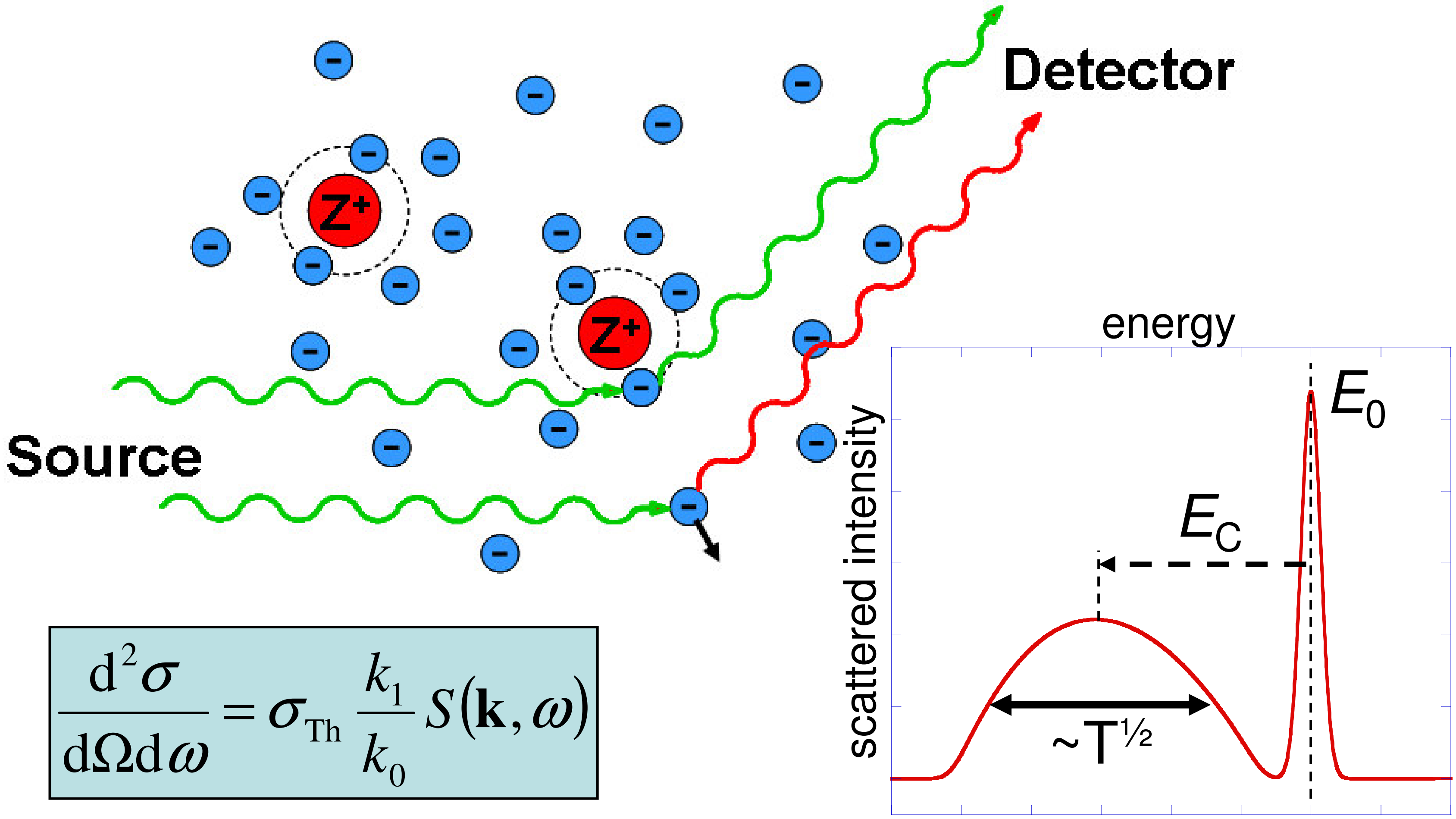
We develop x-ray scattering as a tool to study dense matter properties

- **Dense matter: solid-density, x-times solid (x=1…1000)**
  - **Shock-compressed matter (compressibility)**
  - **compressed ICF fuel**
- **Characterize: n_e, T_e**
  - **But also Z^*, T_i, θ, Γ, $S_{ii,ee}$, ν_{ee} Ł much to gain (*)**
  - **Depends on experimental design, data quality (S/N), and <u>dense matter theory/model</u> Ł much to understand**

Overview of recent experiments on x-ray scattering experiments in dense plasmas

(*) S. Glenzer *et al.*, PRL **90**, 175002 (2003), PRL **98**, 065002 (2007), G. Gregori *et al.*, JQSRT **99**, 225 (2006), E. Saiz *et al.*, Nat. Phys. doi:10.1038/nphys1103 (2008), A. Kritcher *et al.*, Science **322**, 69 (2008)

Simple picture of an x-ray scattering experiment



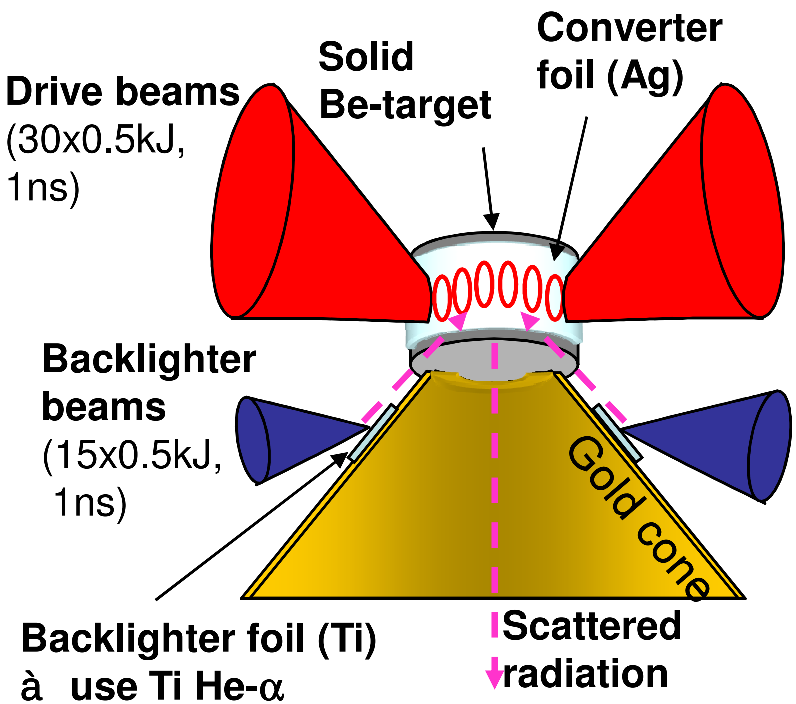
$$\frac{\mathrm{d}^2\sigma}{\mathrm{d}\Omega\,\mathrm{d}\omega} = \sigma_{\mathrm{Th}}\,\frac{k_1}{k_0}\,S(\mathbf{k},\omega)$$

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

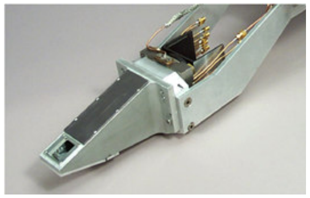
Chihara, PRE (2000), Gregori et al, PRE (2003)

First demonstration of x-ray scattering in radiatively heated, warm-dense matter

Experiment at the Omega laser facility, Rochester/NY



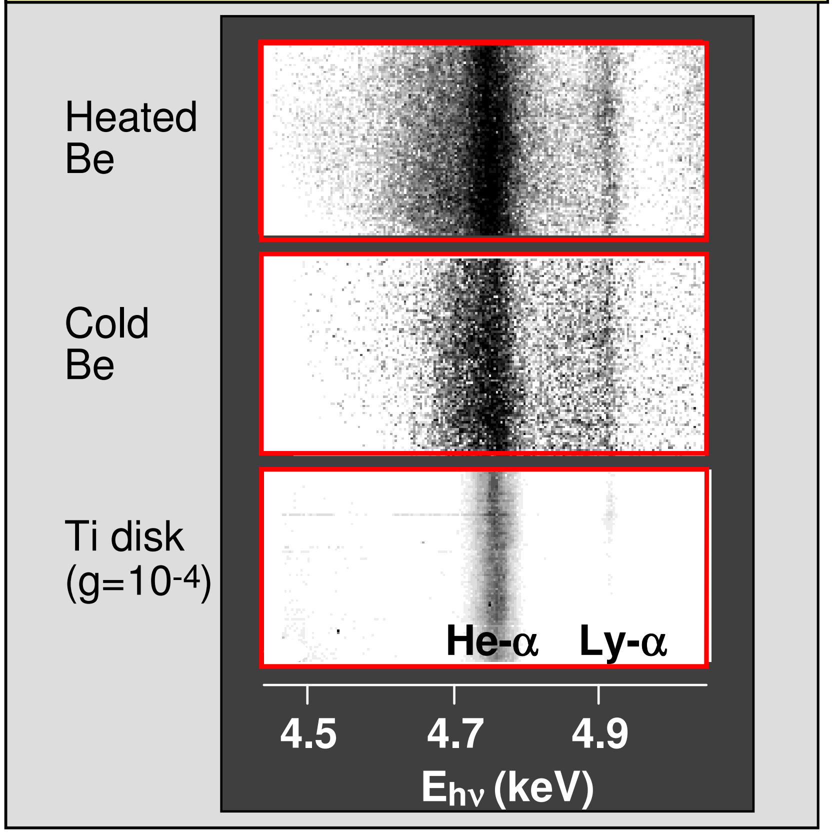
Gated HOPG spectrometer



S. H. Glenzer et al., PRL **90**, 175002 (2003).

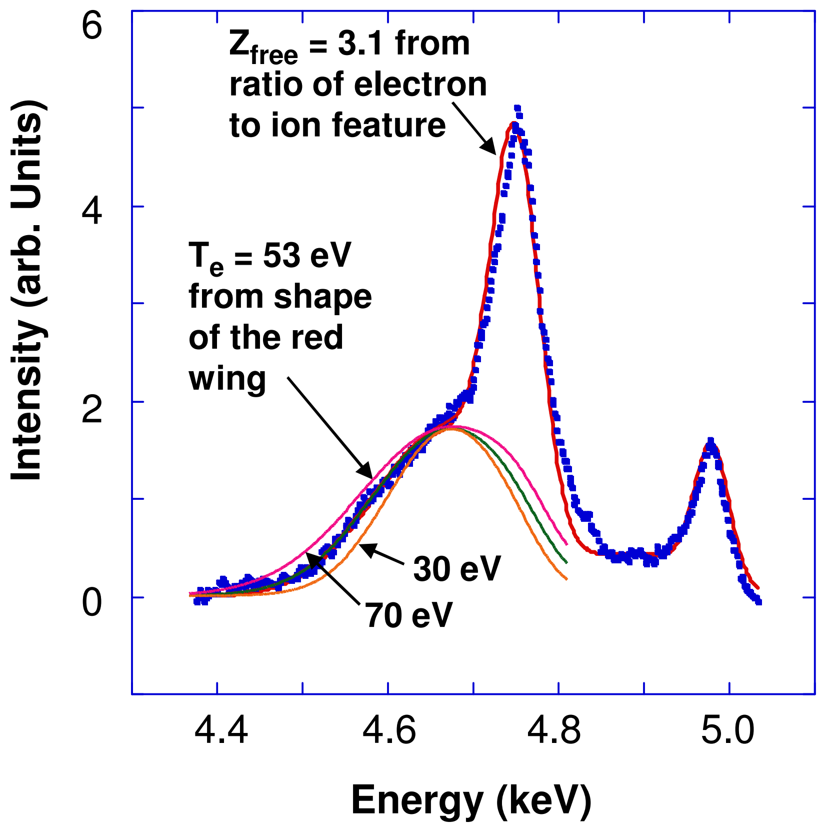
T_e broadening was predicted in 1928.
Chandrasekhar: "… scattering will not be influenced by ranges of temperatures available in the laboratory…" Proc R.S. A 125, 37 (1929)

Compton downshifted and Doppler broadened Thomson spectrum observed



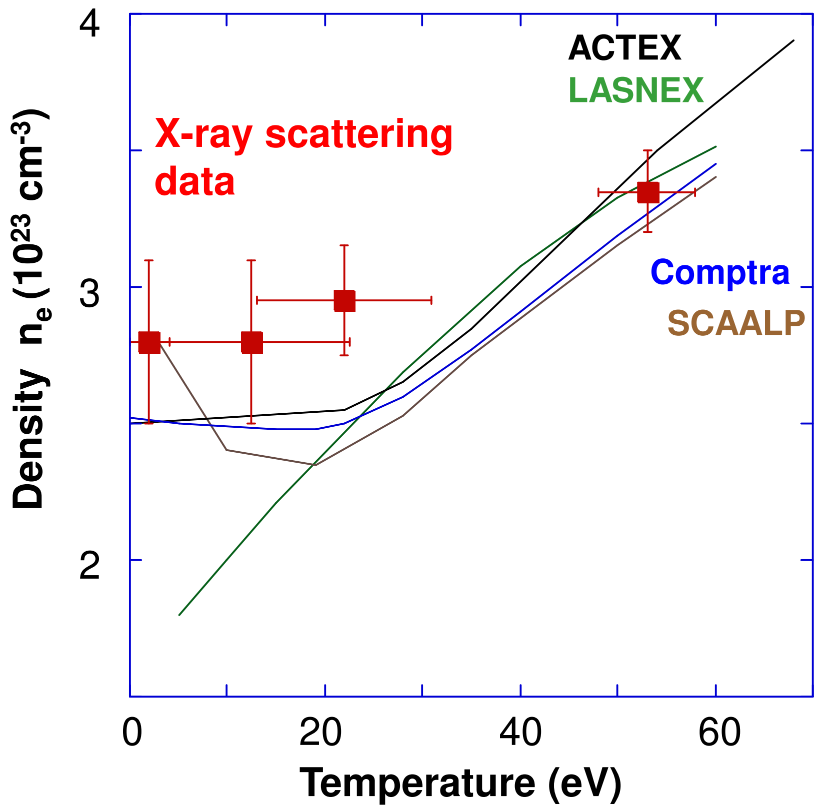
X-ray scattering provides accurate temperature measurements in solid-density Be plasmas

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



From the theoretical fit to the data:
T_e = 53 eV and Z_{free} = 3.1 corresponding to $n_e = 3.3 \times 10^{23}$ cm^{-3}

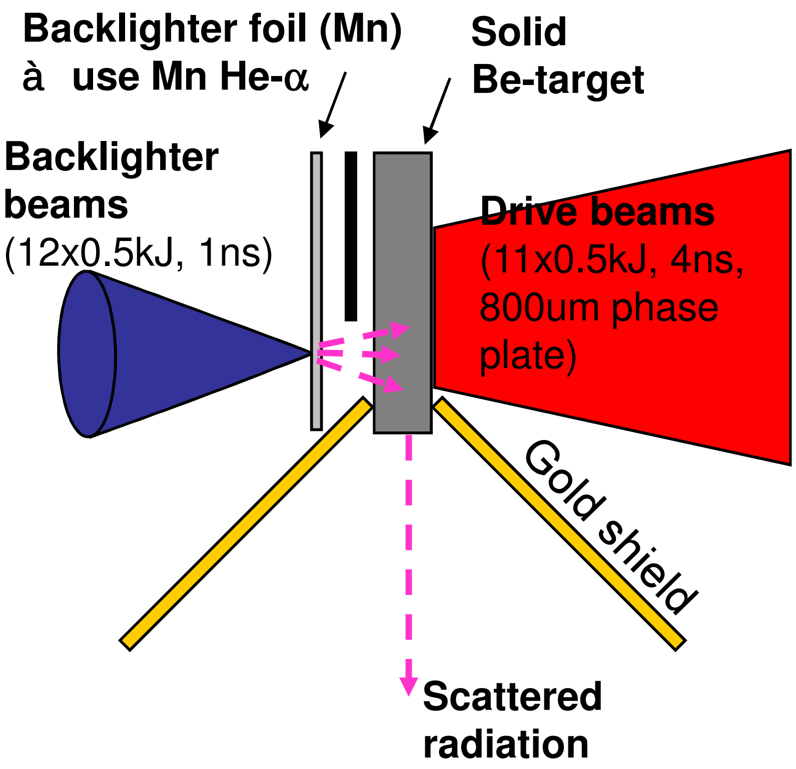
Application: test of ionization balance models in dense plasmas



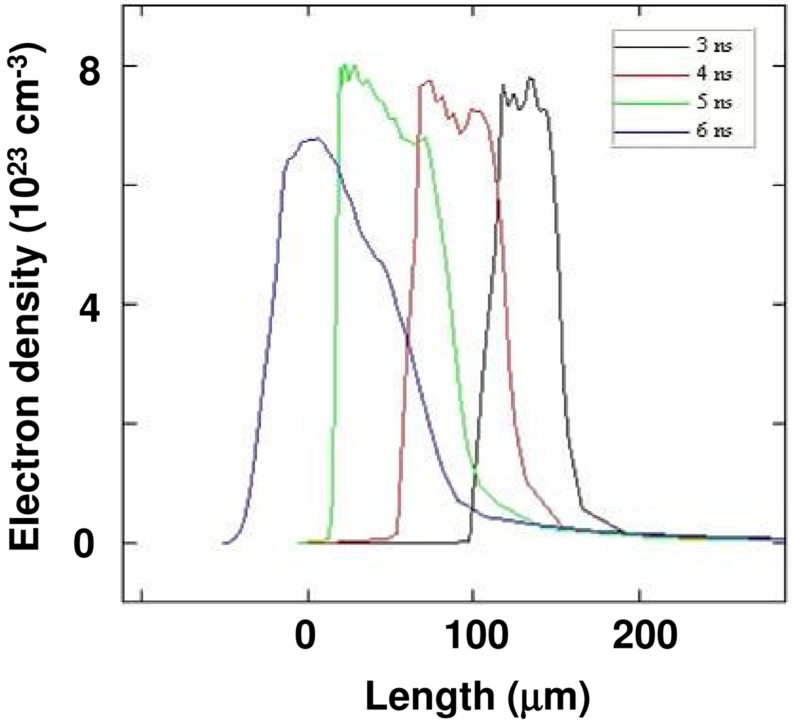
G. Gregori et al., Phys. Plasmas **11**, 2754 (2004)

X-ray scattering on shock-compressed matter

Experiment at Omega: scattering off shock compressed Be at 90 scattering angle



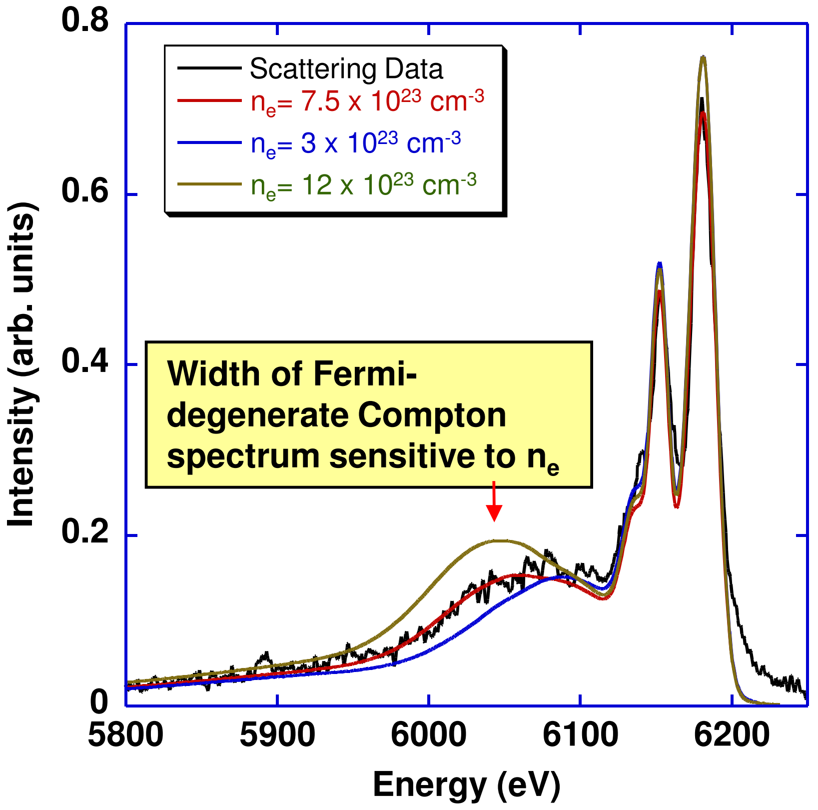
1-D rad-hydro simulations indicate density of $n_e = 7.5 \times 10^{23}$ cm^{-3} [x3 compression]



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

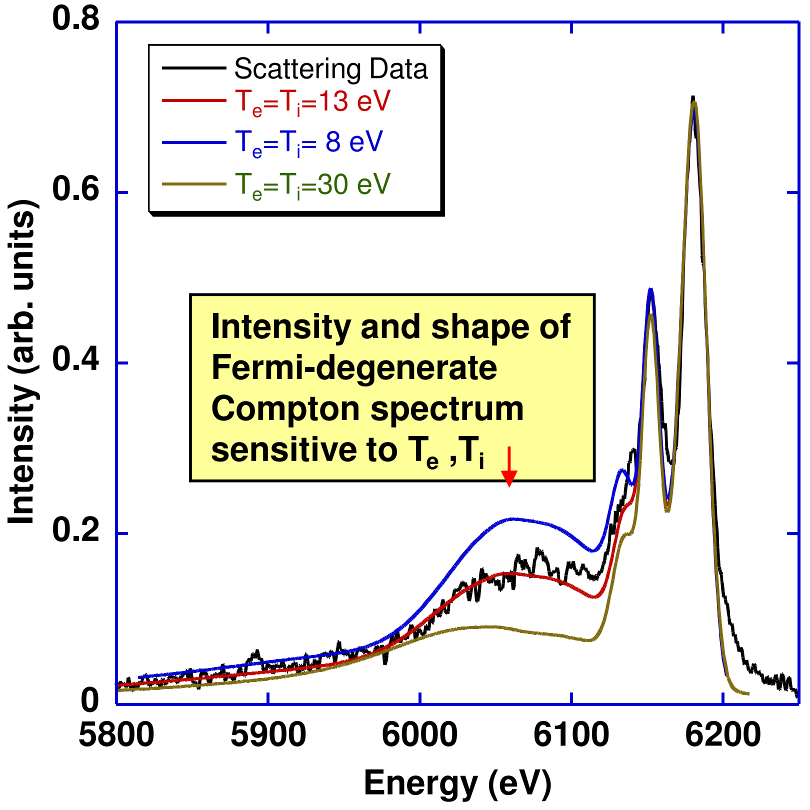
First X-ray Thomson scattering spectrum from compressed matter *)

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



Width of Fermi-degenerate Compton spectrum sensitive to n_e

Ion peak intensity sensitive to ion temperature



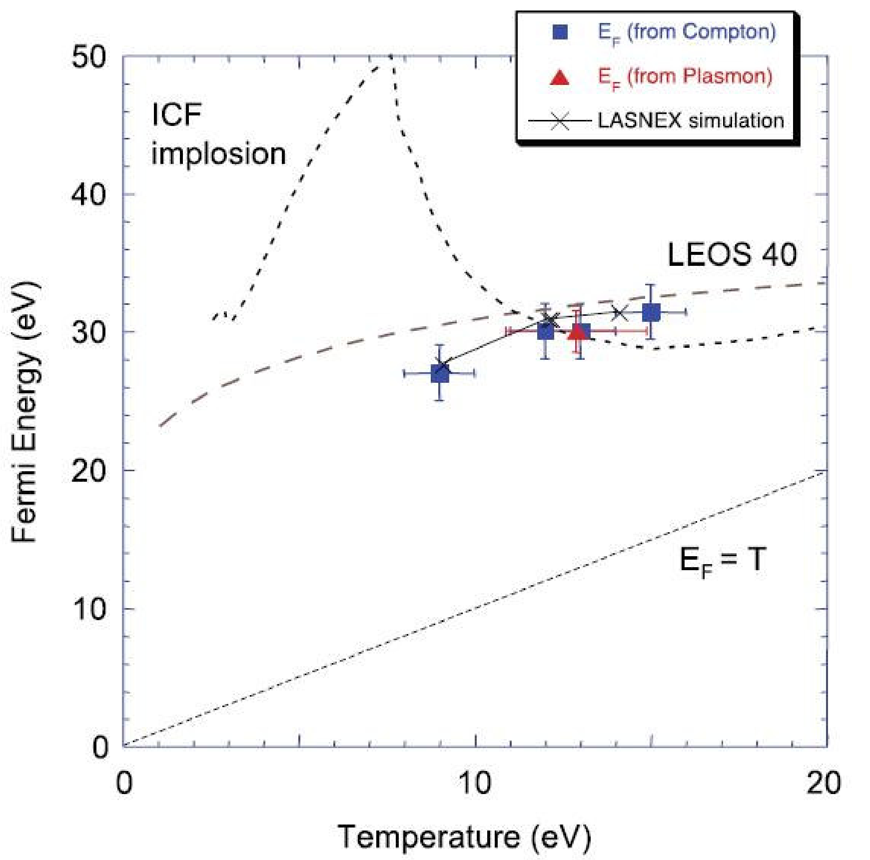
Intensity and shape of Fermi-degenerate Compton spectrum sensitive to T_e ,T_i

- **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**

*) H.-J. Lee *et al.*, PRL **102**, 115001 (2009)

Scattering data test hydrodynamic simulations of compressed matter conditions

Temperature and density for varying laser drive (pressure)

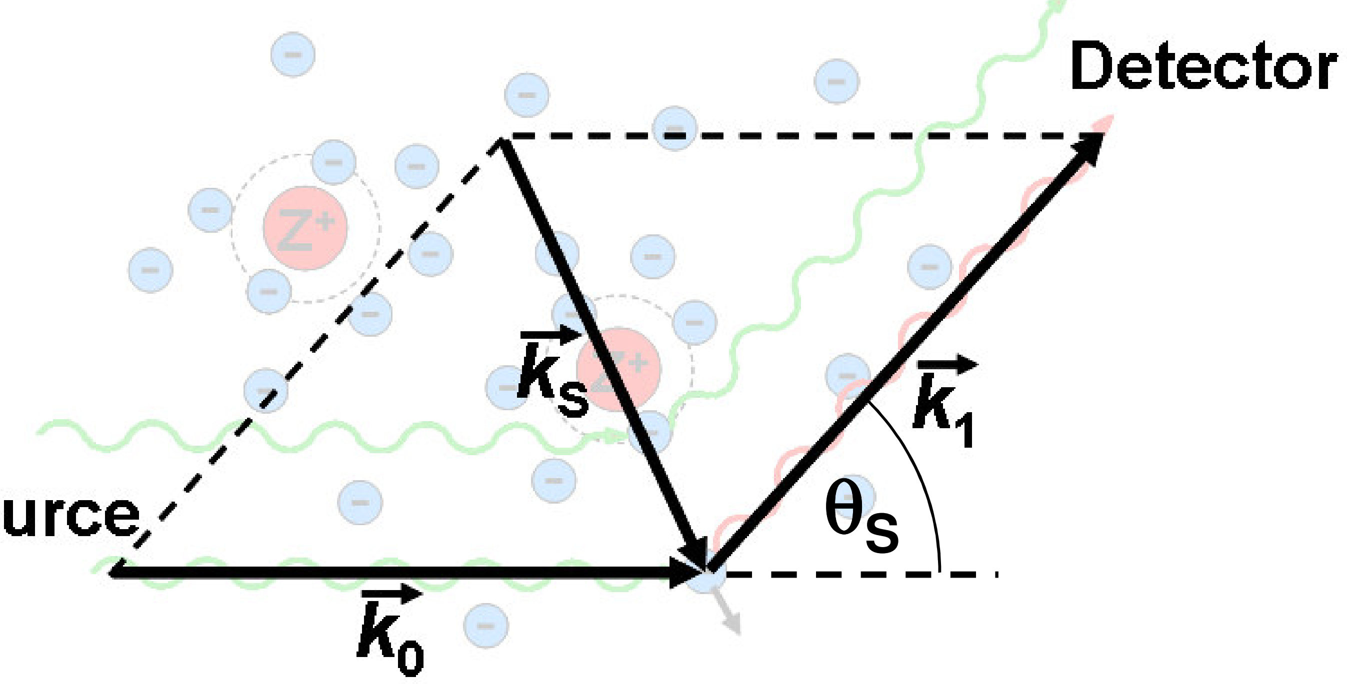


Comparison with LASNEX calculations (solid line) shows excellent agreement.

- **Direct measurement of temperature and density in shock compressed matter**
- **Promising technique to measure capsule adiabat in ICF capsules**
- **Ultimate application goal: measure T_e/T_F in compressed ICF fuel (1000g/cc)**

Scattering regime determined by scattering parameter α

Scattering vector $|\mathbf{k}_S| = 4\pi\, E_0/hc \sin(\theta_S/2)$

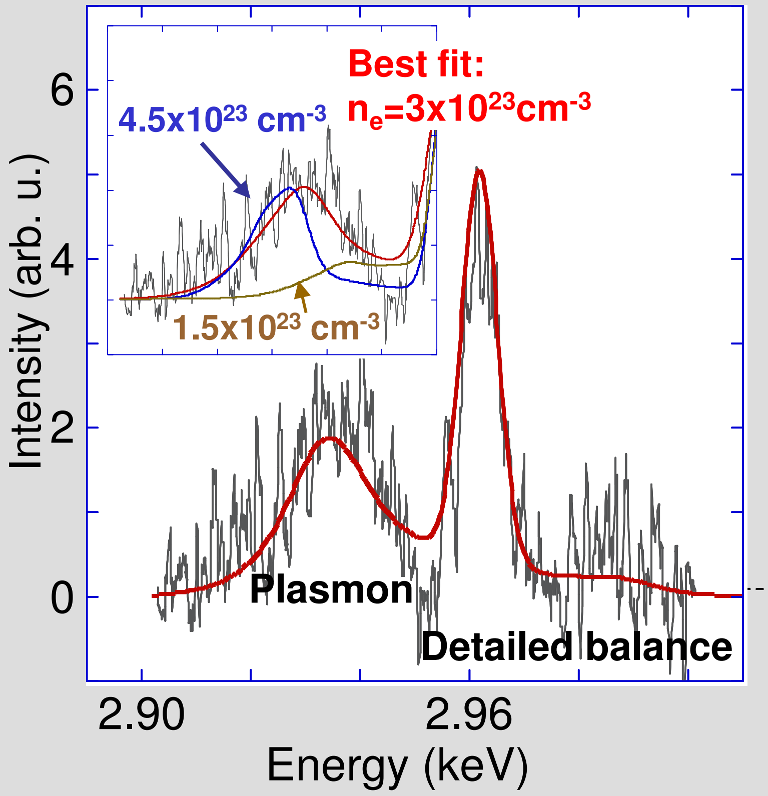


Scattering parameter $\alpha \equiv (k_S\lambda_D)^{-1}$

$$\alpha \begin{cases} \ll 1, \text{ scattering on individual particles à electron motion} \\ \gg 1, \text{ scattering on collective excitations (“plasmons”)} \end{cases}$$

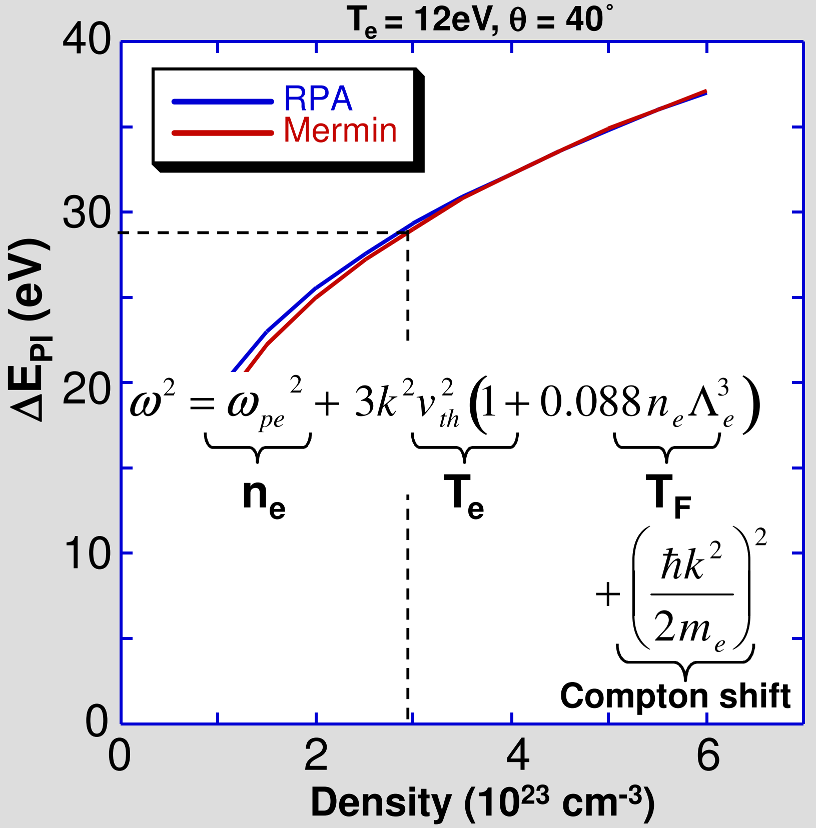
Collective scattering on isochorically heated Be at Omega

Scattering on Plasmons in forward (30°) geometry using Cl Ly-α (3keV)



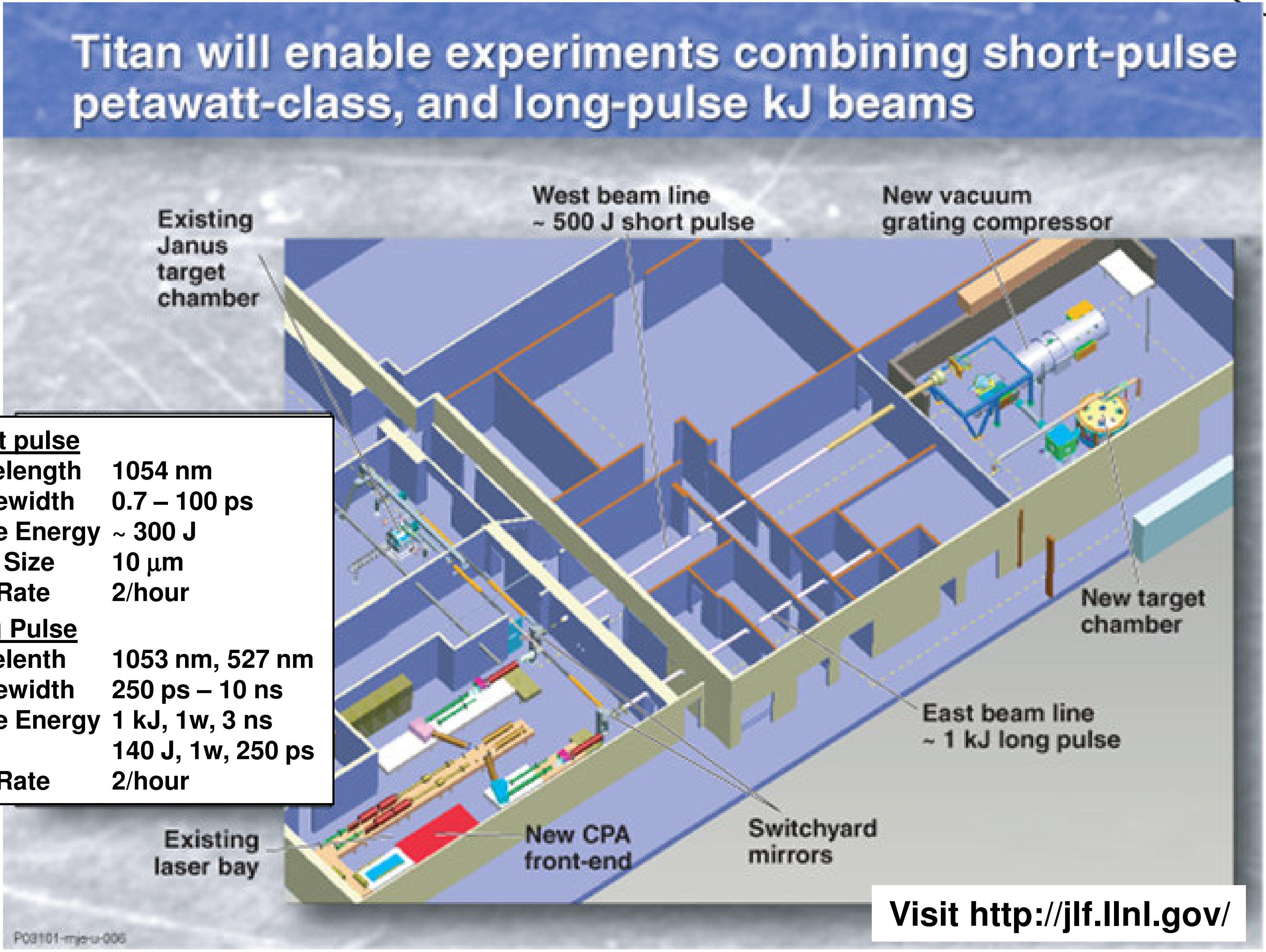
S. H. Glenzer et al., PRL **98**, 065002 (2007)

Plasmon dispersion relation indicates accurate density measurement



Density consistent with non-collective measurement

Experiments performed at the Titan laser (Jupiter Laser Facility, LLNL)



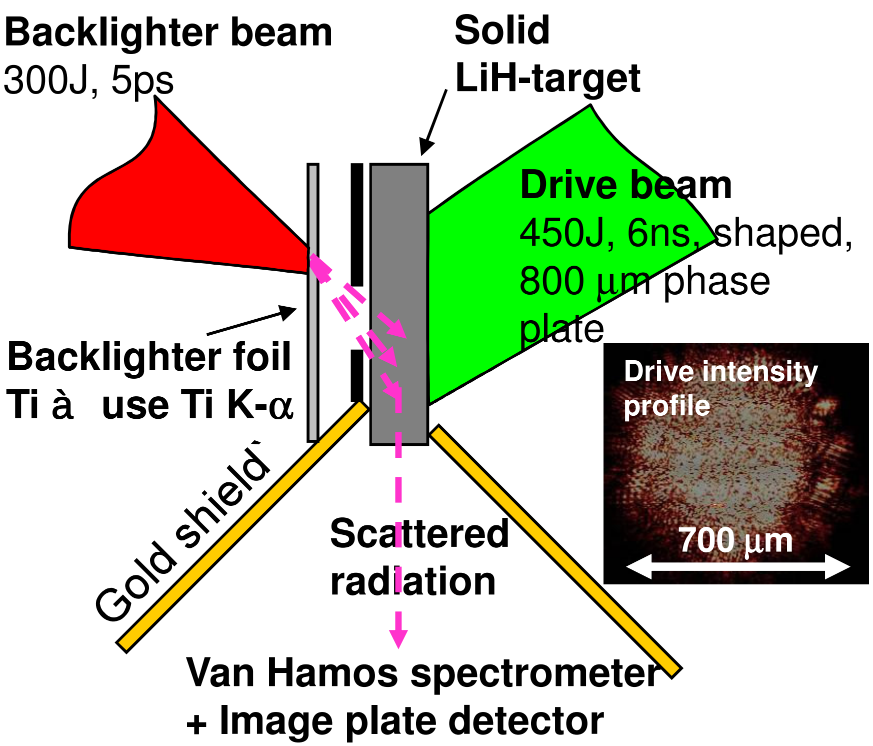
Titan will enable experiments combining short-pulse petawatt-class, and long-pulse kJ beams

Short pulse	
Wavelength	1054 nm
Pulsewidth	0.7 – 100 ps
Pulse Energy	~ 300 J
Spot Size	10 µm
Rep Rate	2/hour
Long Pulse	
Wavelenth	1053 nm, 527 nm
Pulsewidth	250 ps – 10 ns
Pulse Energy	1 kJ, 1w, 3 ns 140 J, 1w, 250 ps
Rep Rate	2/hour

Visit http://jlf.llnl.gov/

We use the Titan long pulse to compress the target, the short pulse to generate a K-α probe source

X-ray scattering on shock compressed LiH, 40 scattering angle (à α~1.1)



Backlighter beam
300J, 5ps

Solid LiH-target

Drive beam
450J, 6ns, shaped, 800 µm phase plate

Backlighter foil
Ti à use Ti K-α

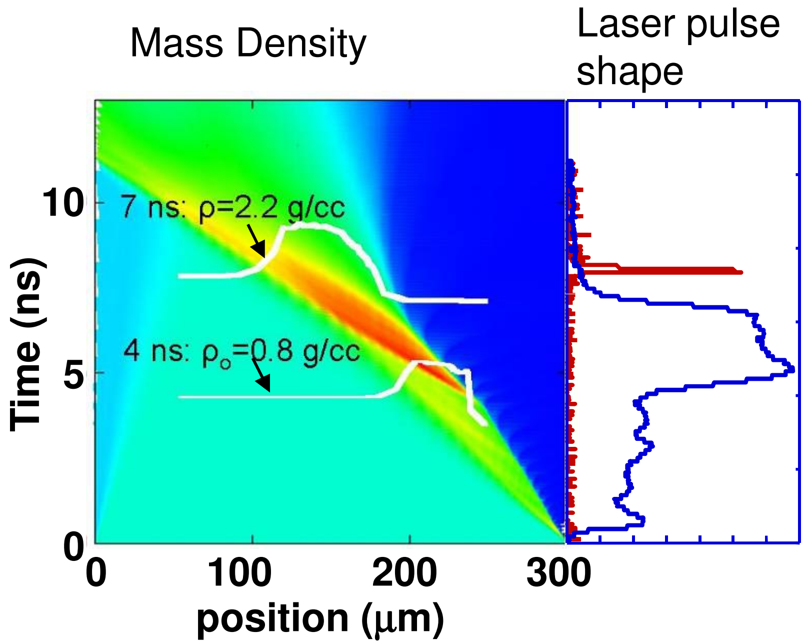
Gold shield

Scattered radiation

Van Hamos spectrometer + Image plate detector

First demonstration of x-ray scattering using short-pulse generated K-alpha radiation

1D radiation-hydrodynamic simulations using experimental laser pulse shape



Mass Density

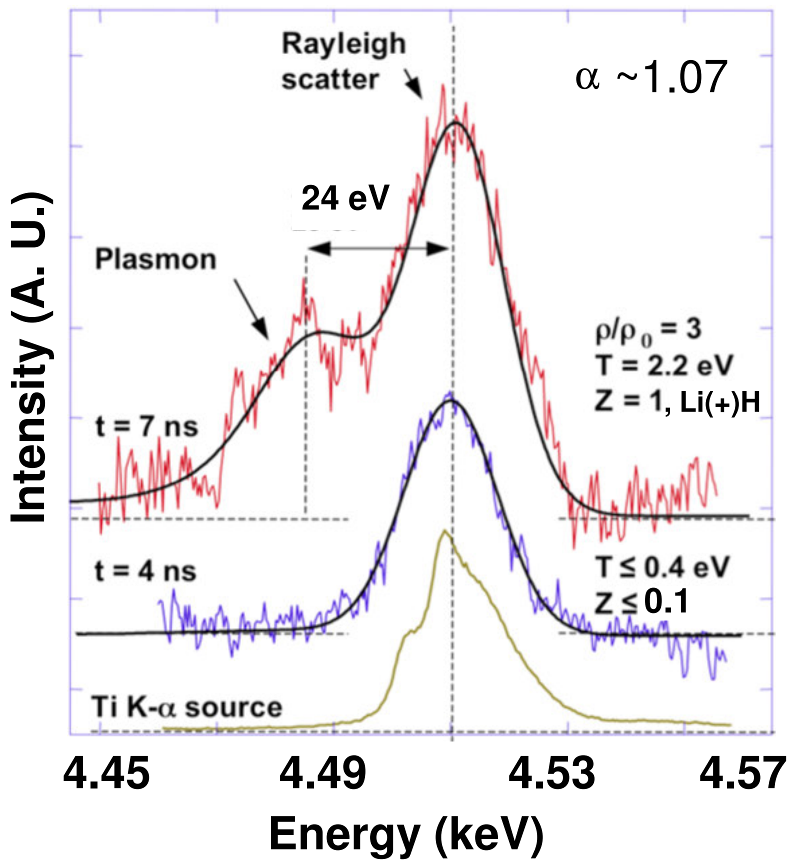
Laser pulse shape

Double-shock experiment to achieve higher compression. Shock coalescence at ~7ns

Advantages of K-alpha radiation to x-ray scattering:
short duration (ps time resolution), satellite-free red wing

Experimental data show Plasmons indicating transition to a dense metallic plasma

Scattering spectra show Plasmon resonance at time ~7 ns

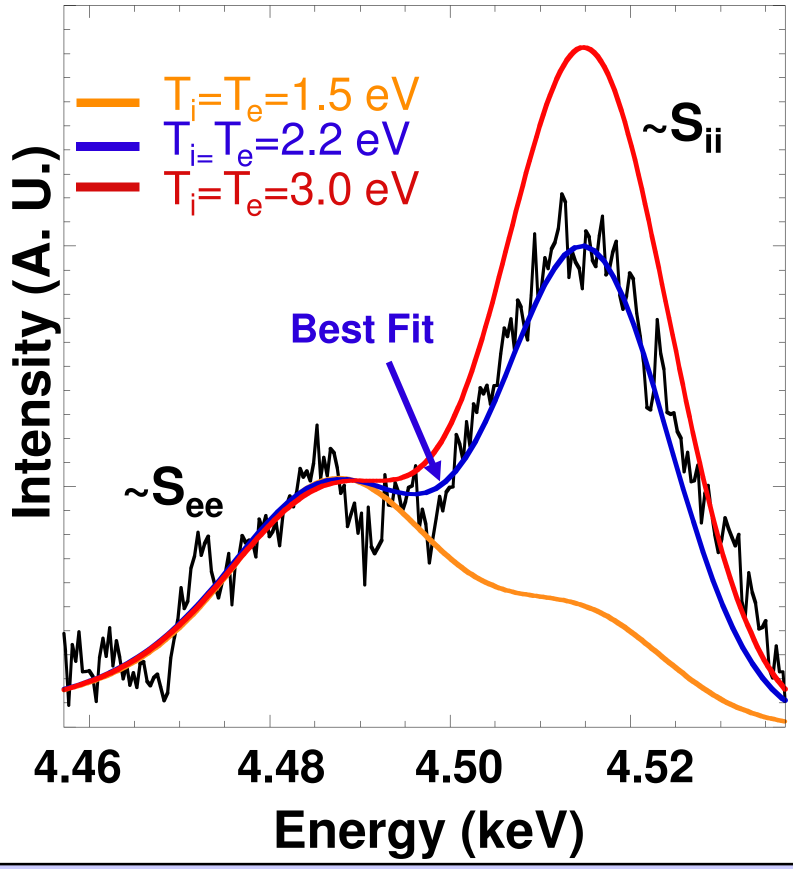


A.L. Kritcher *et al.*, Phys. Plasmas **16**, 056308 (2009)

- Scattering at 4 ns shows small inelastic signal indicating low T, Z*
- Observation of plasmon at 7ns indicates transition from an insulator to a dense metallic state
- Fit of scattering spectra yields T_e>2eV, n_e~1.7e23/cc
- FT-DFT-MD calculations using measured plasma parameters indicate delocalized electrons and strong increase in conductivity

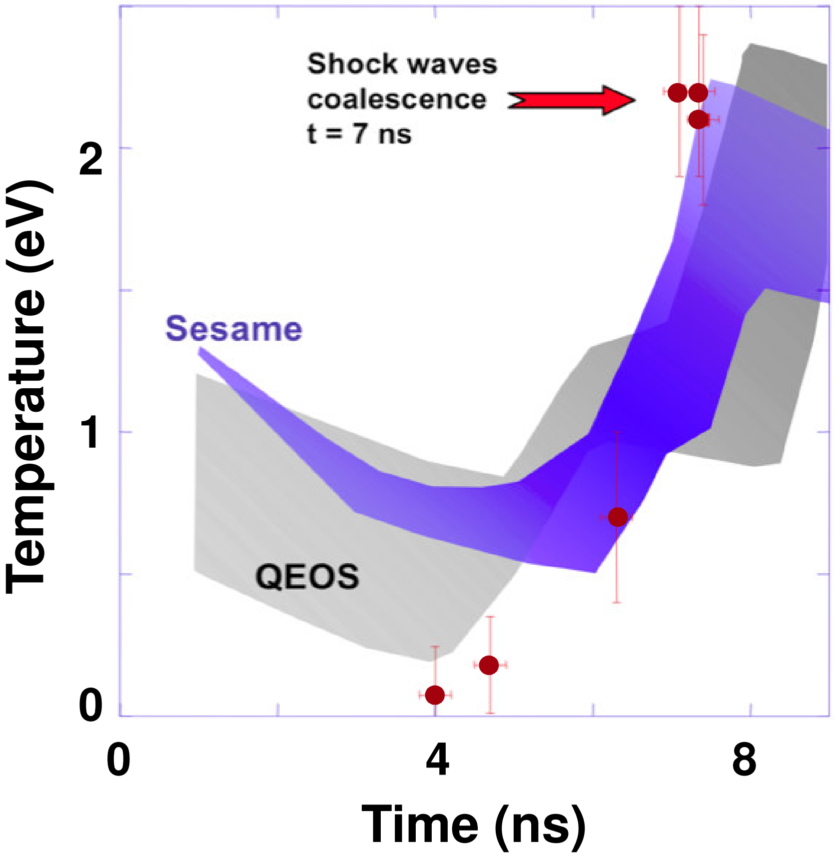
The intensity of the elastic scattering yields temperature during shock progression

Sensitivity of elastic peak to T_i allows temperature measurement



Temperature sensitivity of S_{ii} is a strong coupling effect. Experimental test of models.

Varying the probe timing we resolve the temperature evolution

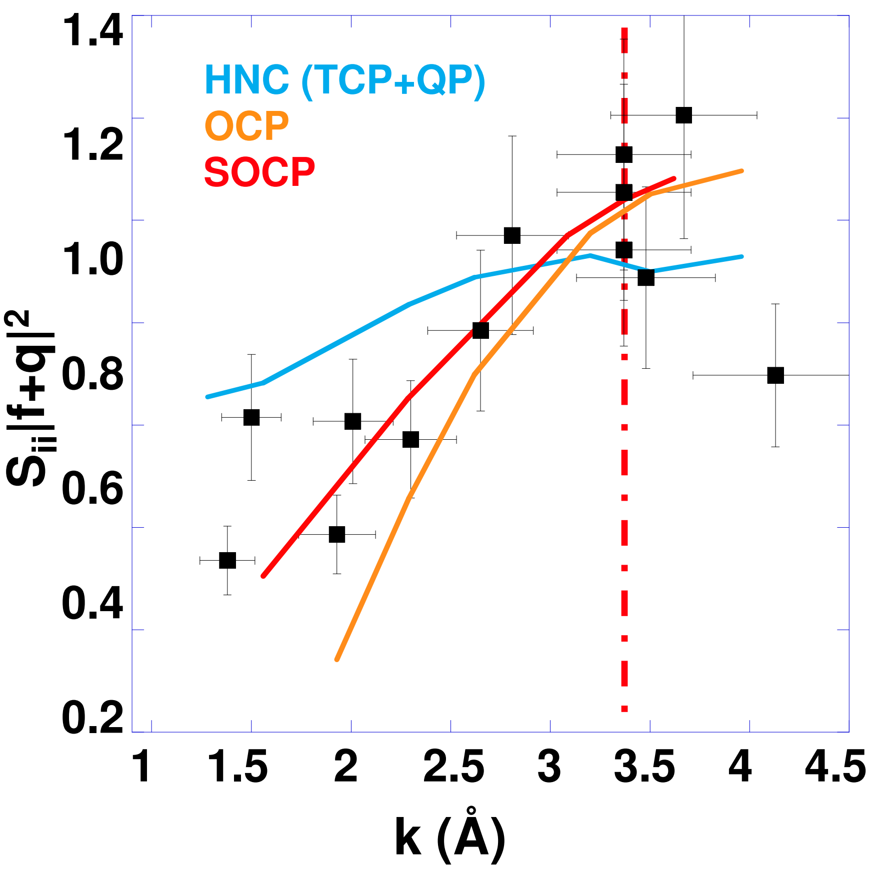


- **Rapid heating indicates shock coalescence**
- **10 ps resolution to differentiate models is advantageous**

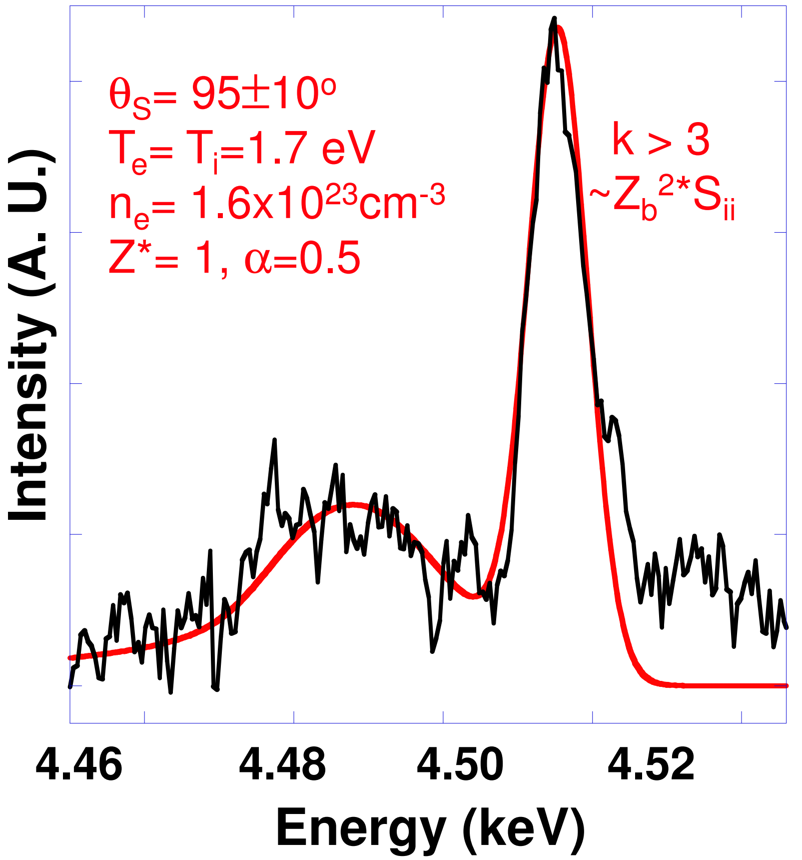
A. L. Kritcher *et al.*,*Science* **322**, 69 (2008)

Newer experiments to test structure factor models at similar conditions

Structure Factor Measurements: Compressed LiH



Compton Scattering at 95±10° to calibrate the elastic scattering

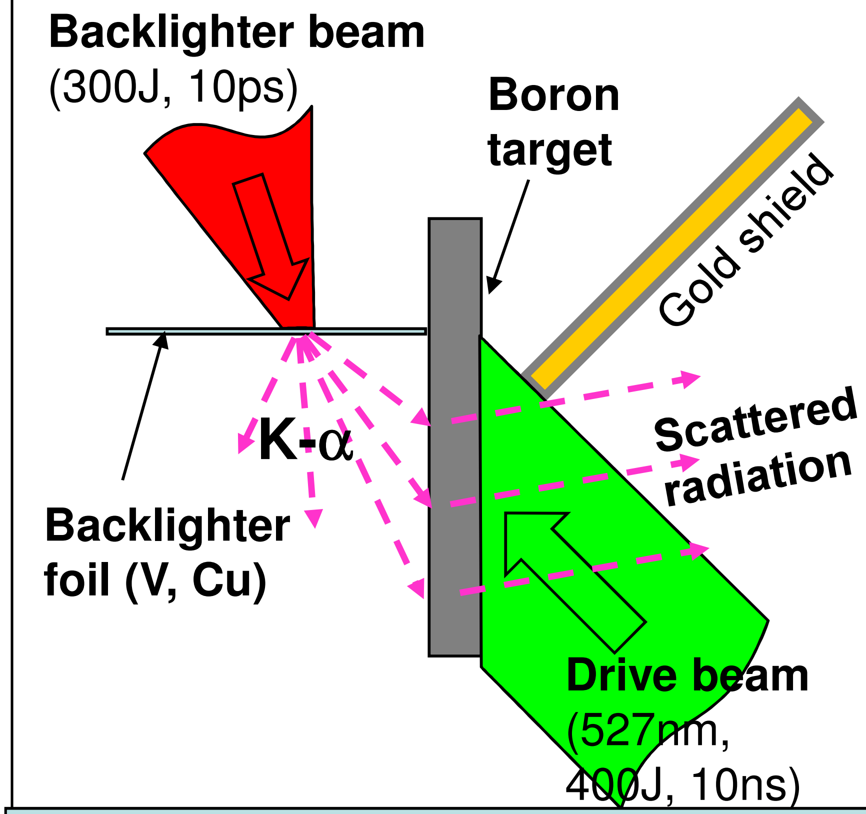


-Structure factor values are consistent with S_{ii} measured at smaller angles (i.e. 40°) from plasmon scattering

-Absolute measurement of $S_{ii}(k)$ with absolute calibration of S_{ii}

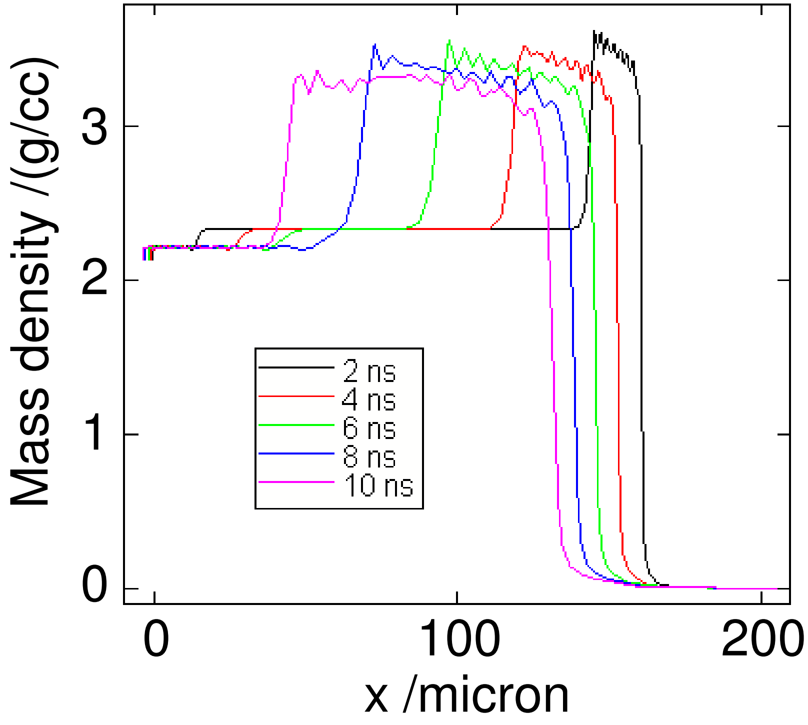
We performed K-alpha scattering to measure the plasmon dispersion in dense plasmas

X-ray scattering on shock compressed Boron



Variation of previously fielded target platform

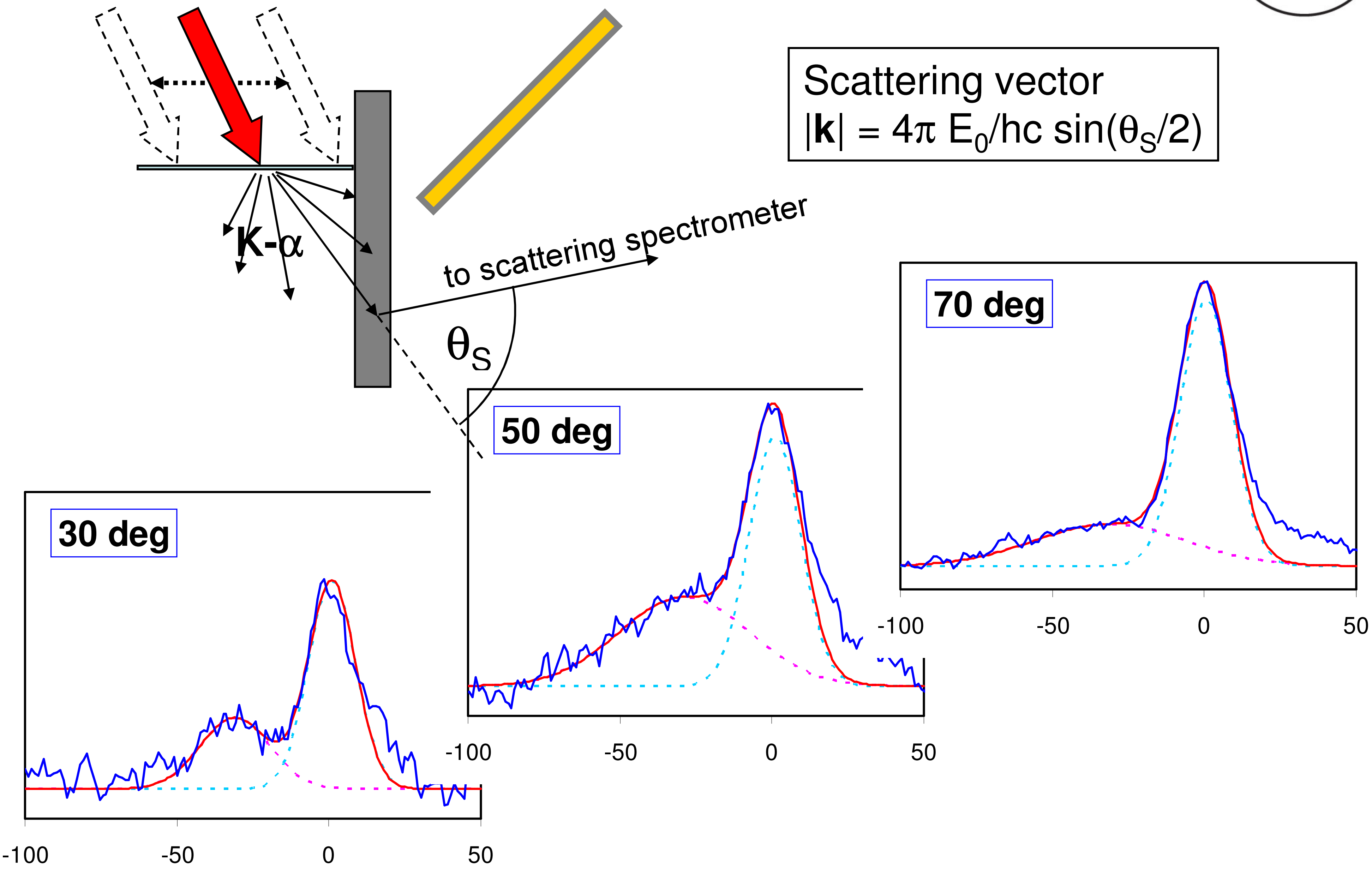
Drive intensity 0.7x10^{13} W/cm^2 yields compression of x1.5



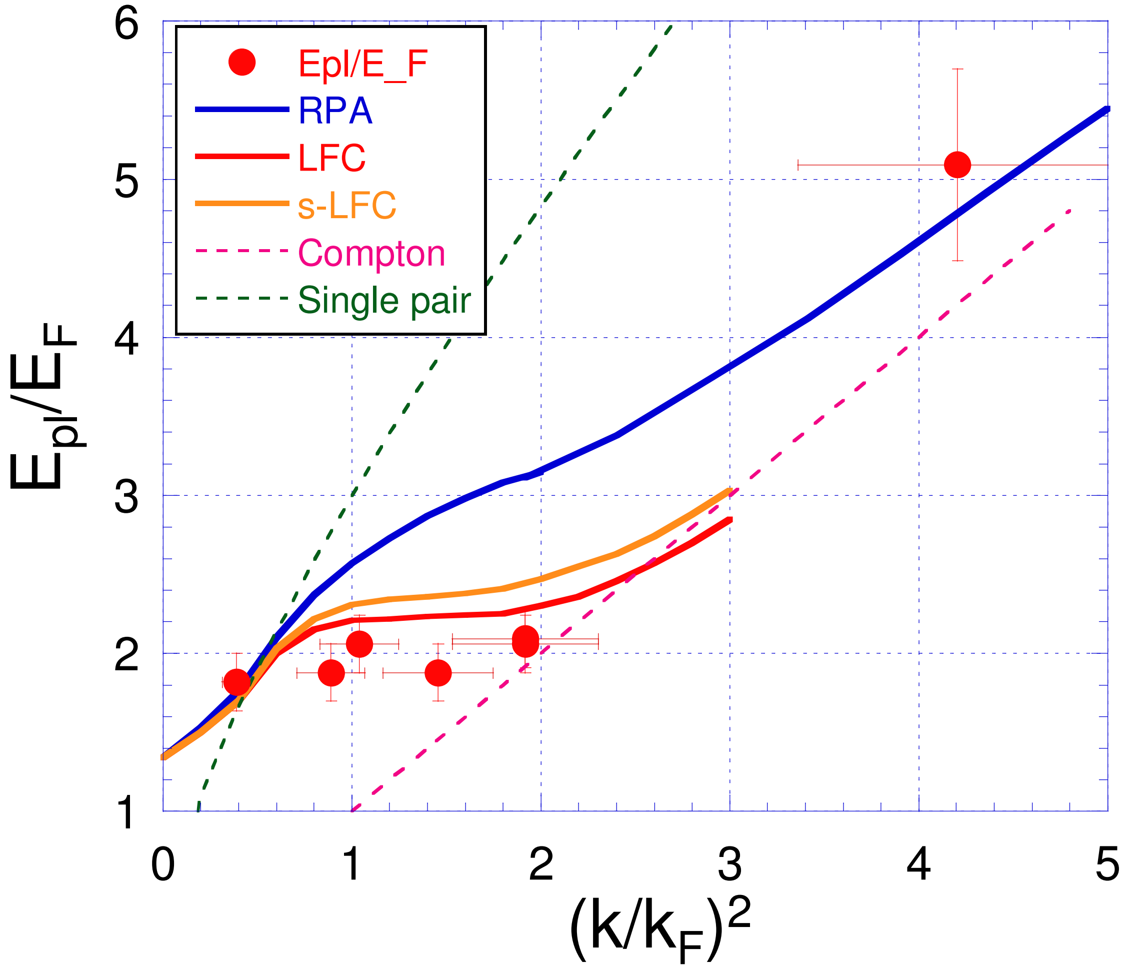
Pressure in shocked material exceeds 1 Mbar à band gap closure predicted at ~1.6 Mbar, i.e. metal transition

The scattering angle θ_S is selected by varying the source location (short pulse focus)

Scattering vector
$|\mathbf{k}| = 4\pi\, E_0/hc \sin(\theta_S/2)$



Test of e-e structure factor calculations over wide scale range



- At $(k/k_F)^2<0.5$ models agree à determine electron density from plasmon shift E_F=16.5eV (±20%), r_S=1.75
- LFC model is more adequate than RPA to describe the strongly coupled electron liquid
- At short scales (large k) RPA is applicable

- Newer calculations by Univ. Rostock (Germany) including e-i-collisions (Mermin ansatz) show excellent agreement

Conclusions and outlook

- Laser-produced hot electrons efficiently heat reduced-mass targets. K-shell emission can provide (model dependent) diagnostic
- X-ray scattering has been demonstrated to be a valuable tool to characterize dense plasmas, important applications
- Measurements can be used to test dense matter theory or benchmark dense matter codes

Outlook

- Application of these diagnostic techniques to characterize heavy-ion produced plasmas at GSI

Collaborators

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