X-ray Thomson scattering of shock-compressed matters*

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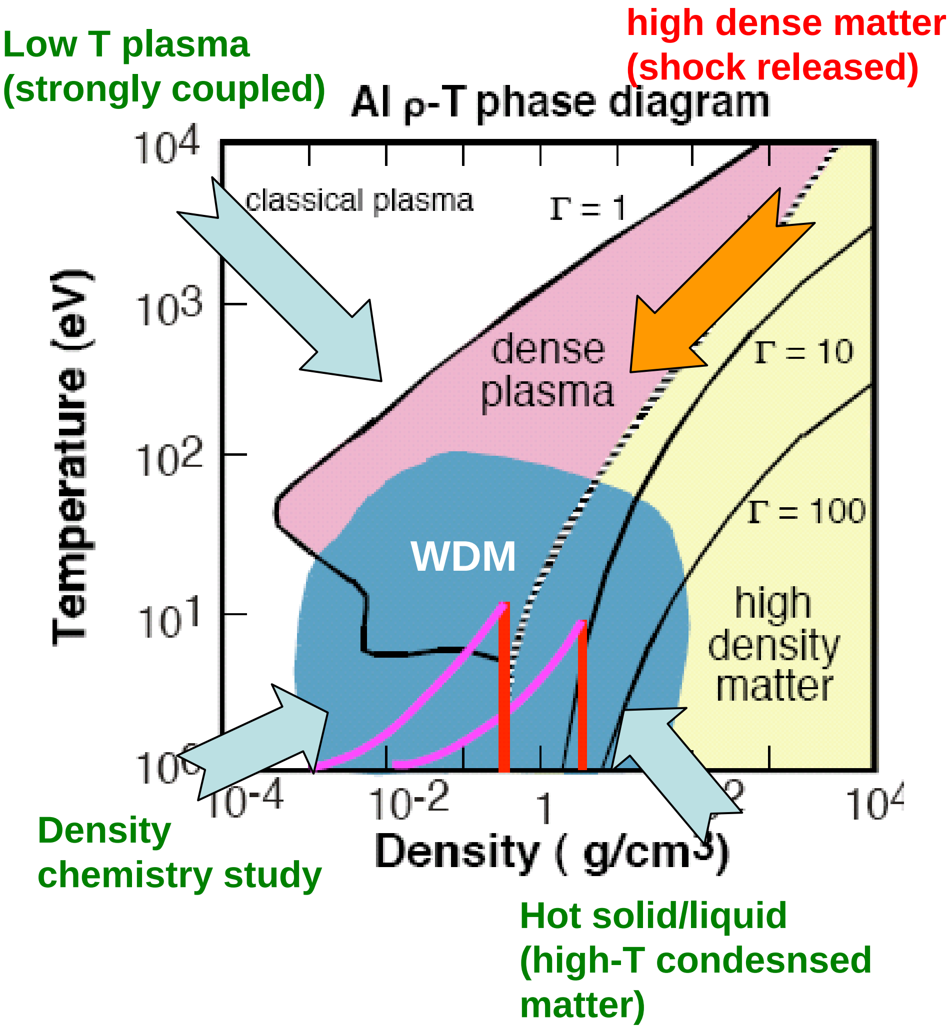
Can we describe and measure new state of matter?



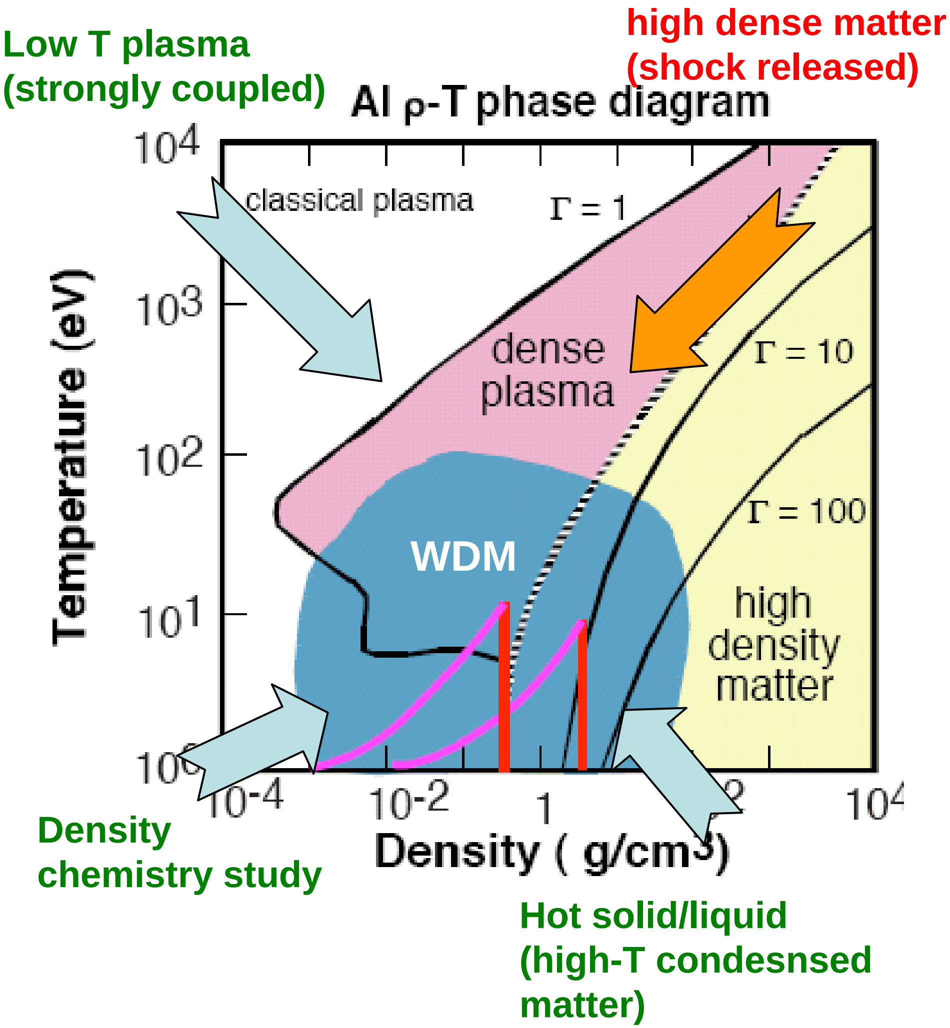
WDM/HDM range:

- Not like solid, not like plasma,
- No simple interpolation,
- Each material is unique

Remarkable prediction in WDM/HDM :

- Heating, specific heat
- Liquid-vapor transition
- Hydrodynamic expansion
- Conductivity change (low σ → high σ)
- Optical properties
- Black glass (Im(ε) > Re(ε) > 0)
- Electronegative plasma
- Neutral phase of ionic solids,
  (Na^+Cl^-(solid)→Na^+Cl^- (liquid)→Na^0Cl^0(plasma)
- Mixed valence and self-crossing
- Quantum hall effect

Can we describe and measure new state of matter?



Sources to create WDM/HDM for science:

- **Electrical heating, laser heating, x-ray heating, Ion-beam heating**

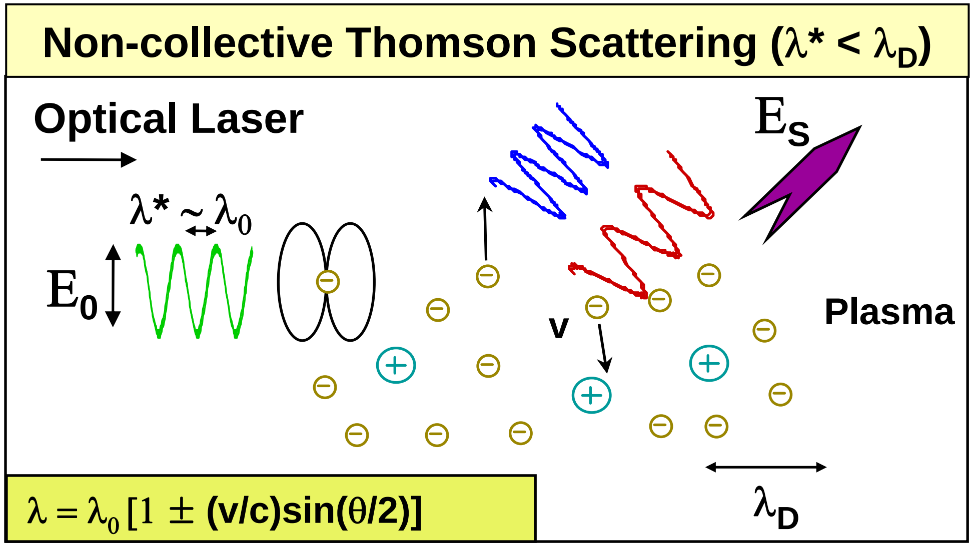
With powerful laser or particle beams, high pressure conditions above 100 Mbar have been predicted for inertial confinement fusion experiments.

Several possible researches to study DM :

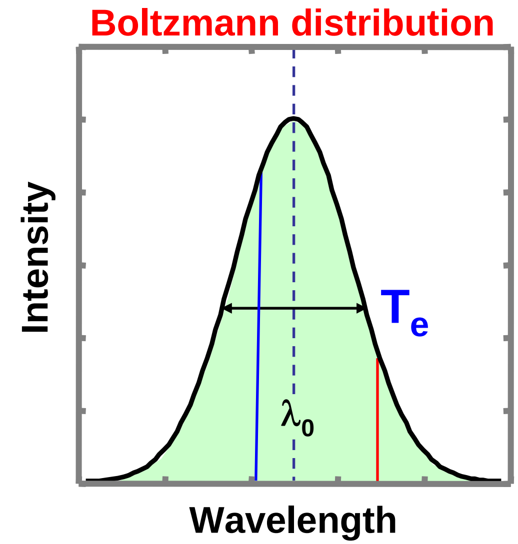
- **Hydrodynamic release L ~ 3C_s(ρ,T)**
- **Electrical conductivity, σ (ω,T)**
- **Optical emission I_ω= ε(ω,ρ,T)B_ω(T)**
- **X-ray diffraction/absorption spectroscopy or scattering (TS)**
- **Radiography …**

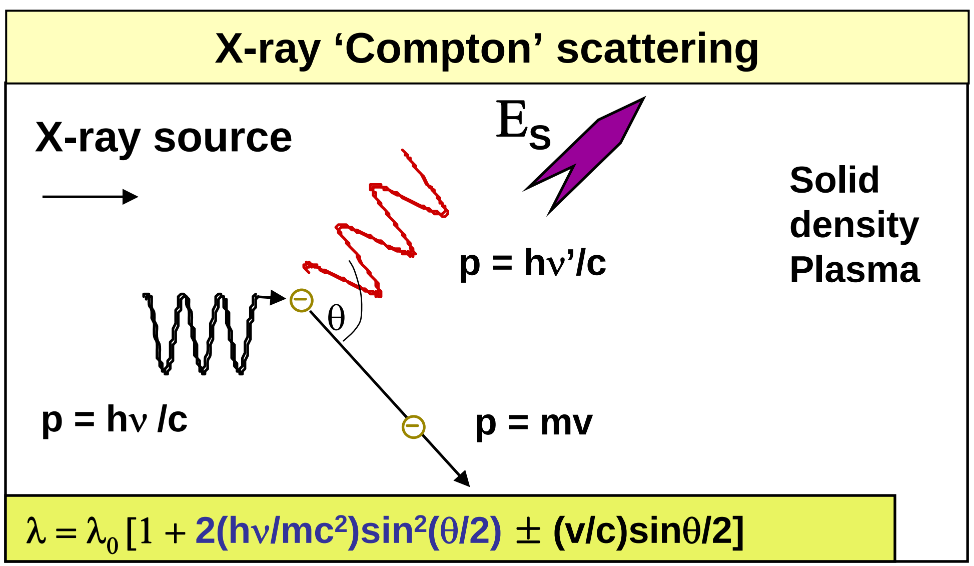
To measure accurately temperature, density, charge state is a key part of understanding new state of matter, like as warm dense matter and high dense matter.

X-ray Thomson scattering is a powerful diagnostic for probing dense matter

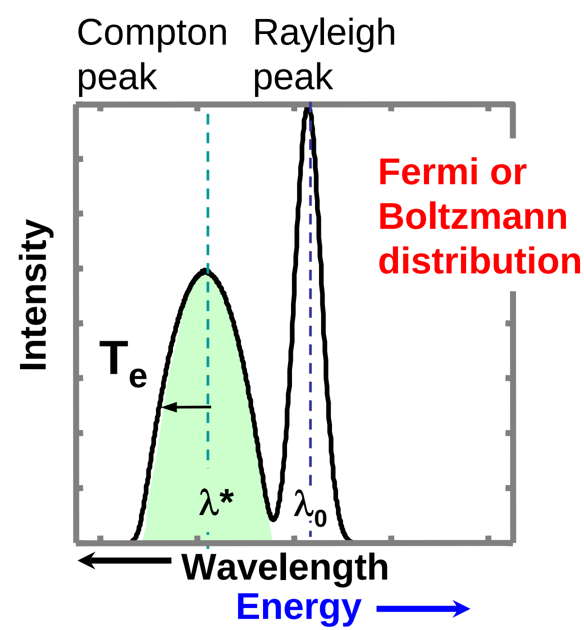


Scattering on free electrons



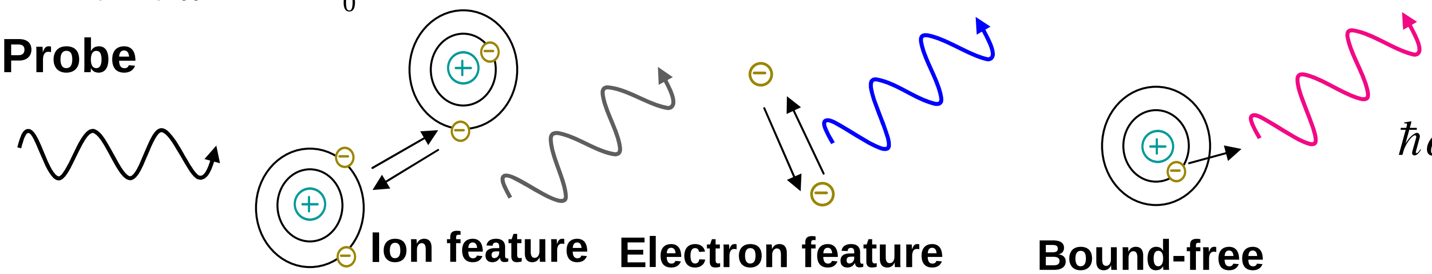


Scattering on free and weakly bound electrons



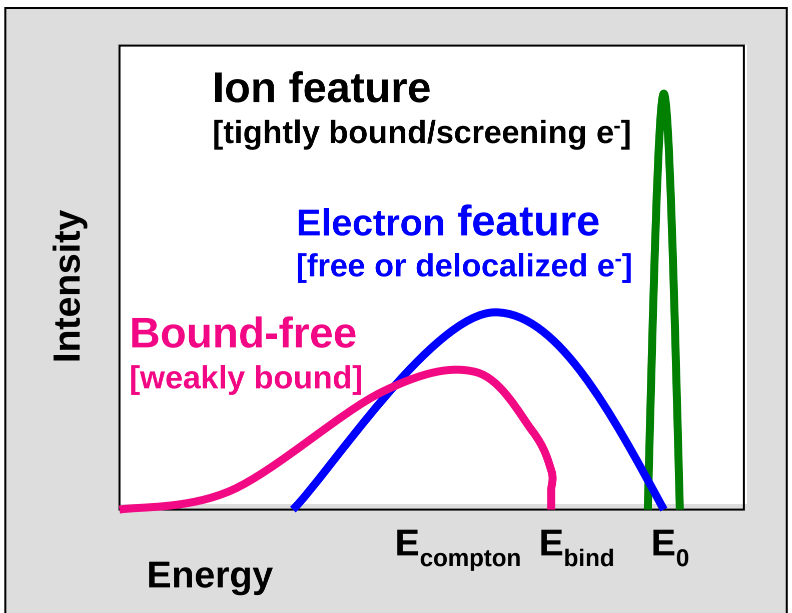
The theoretical form factor for x-ray scattering provides reliable plasma parameter for back scatter experiments

$$\frac{d^2\sigma}{d\Omega d\omega} = \sigma_T \frac{k_1}{k_0} S(k,\omega), \qquad S(k,\omega) = \frac{1}{2\pi N}\int e^{i\omega t} < \rho_e(\mathbf{k},t)\rho_e(-\mathbf{k},t) > dt$$



$$\hbar\omega = \hbar\omega_1 - \hbar\omega_0$$

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



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, $S_{ii}(k,\omega)$

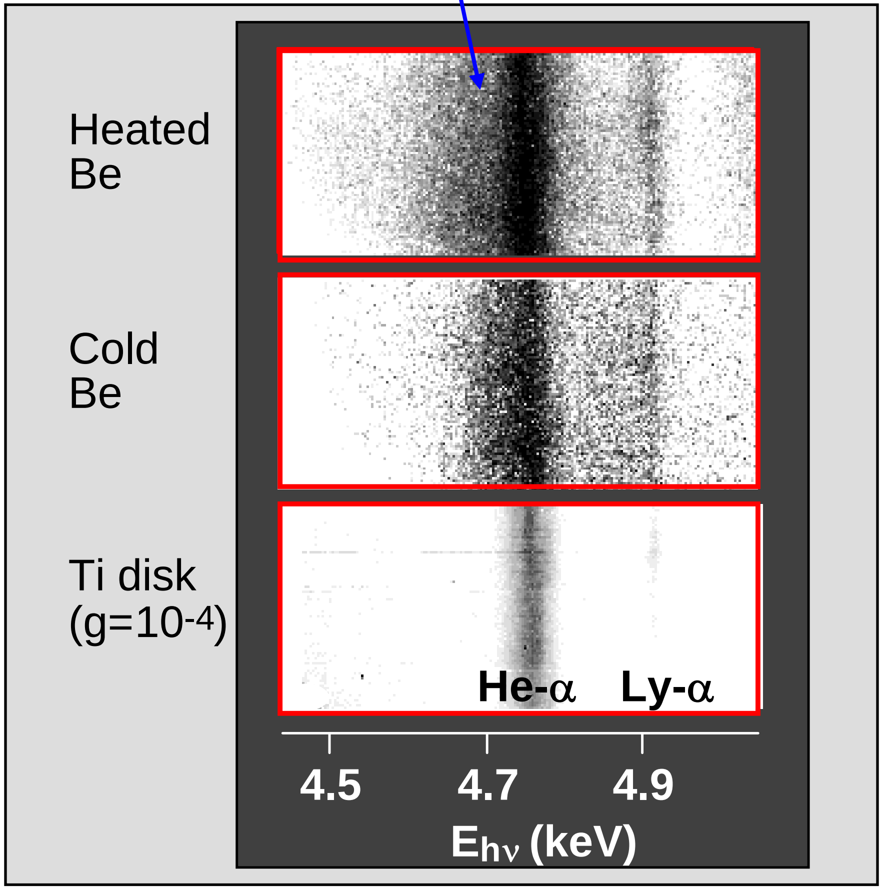
In backscatter: theoretical approximations agree

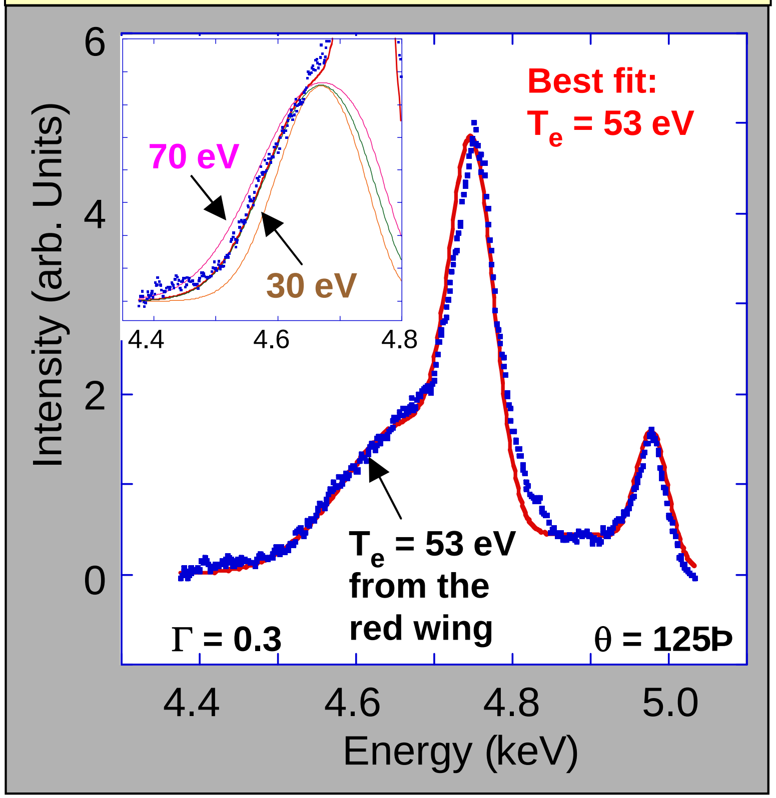
Chihara, PRE (2000), Gregori et al, PRE (2003)

X-ray "Thomson' scattering in warm solid density matter was first demonstrated on beryllium

Compton downshifted and Doppler broadened Thomson spectrum observed as expected

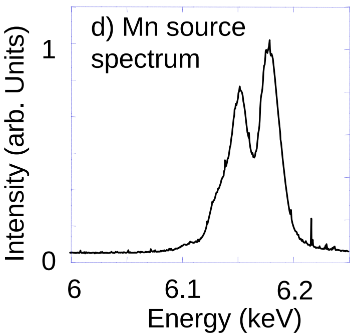
$$\alpha = \frac{\lambda^*}{\lambda_S} = \frac{k^{-1}}{\lambda_S} = \frac{\lambda_0}{4\pi\lambda_S \sin(\theta/2)} < 1$$

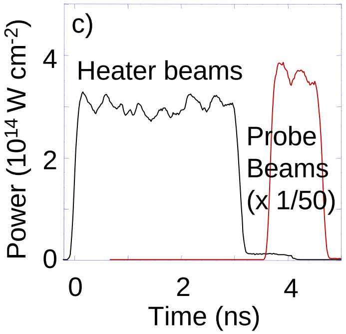


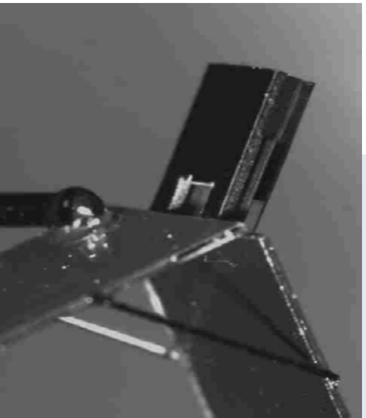


Glenzer et al, PRL 90 175002 (2003).

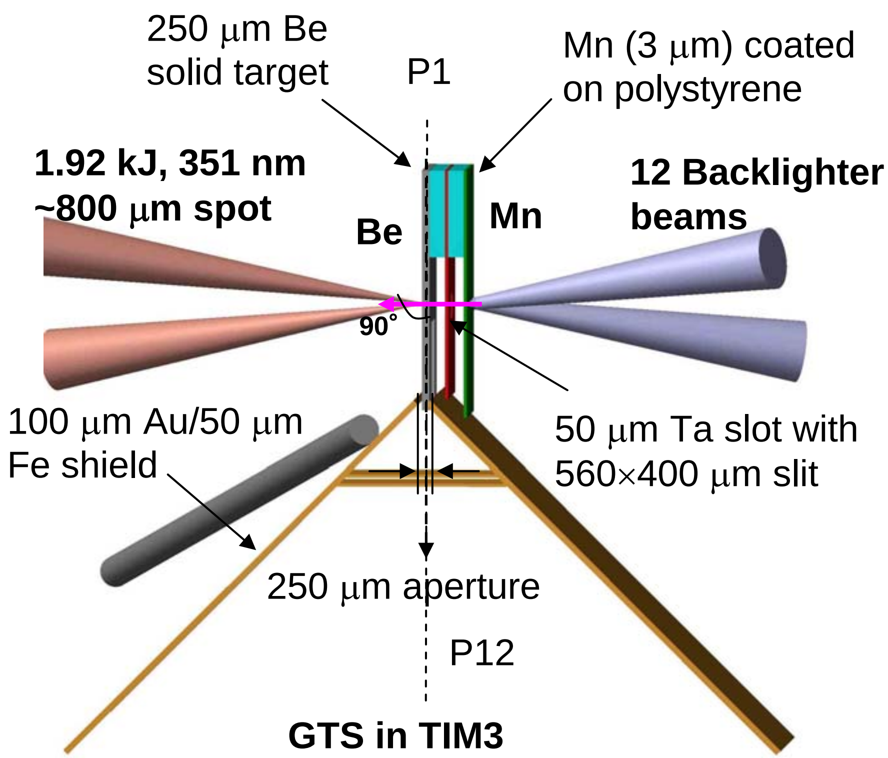
Scattering targets are designed to produce compressed Be plasmas for x-ray Thomson scattering

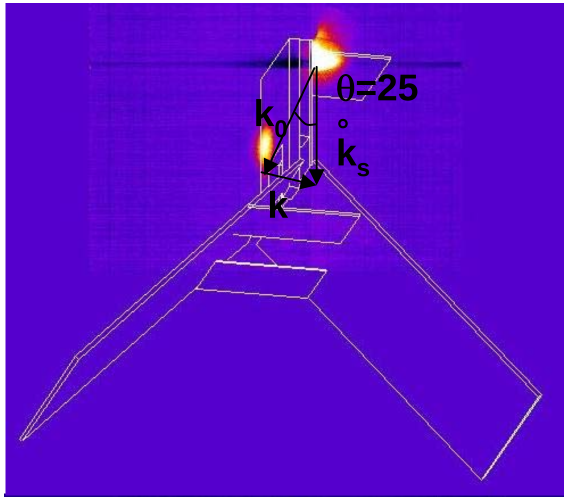


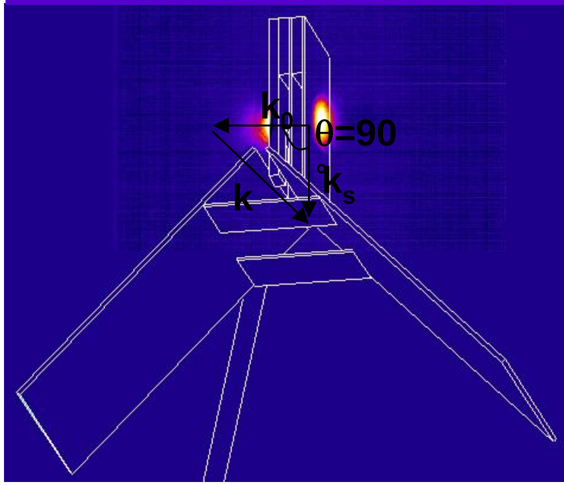




<u>Target for 90º scattering</u>



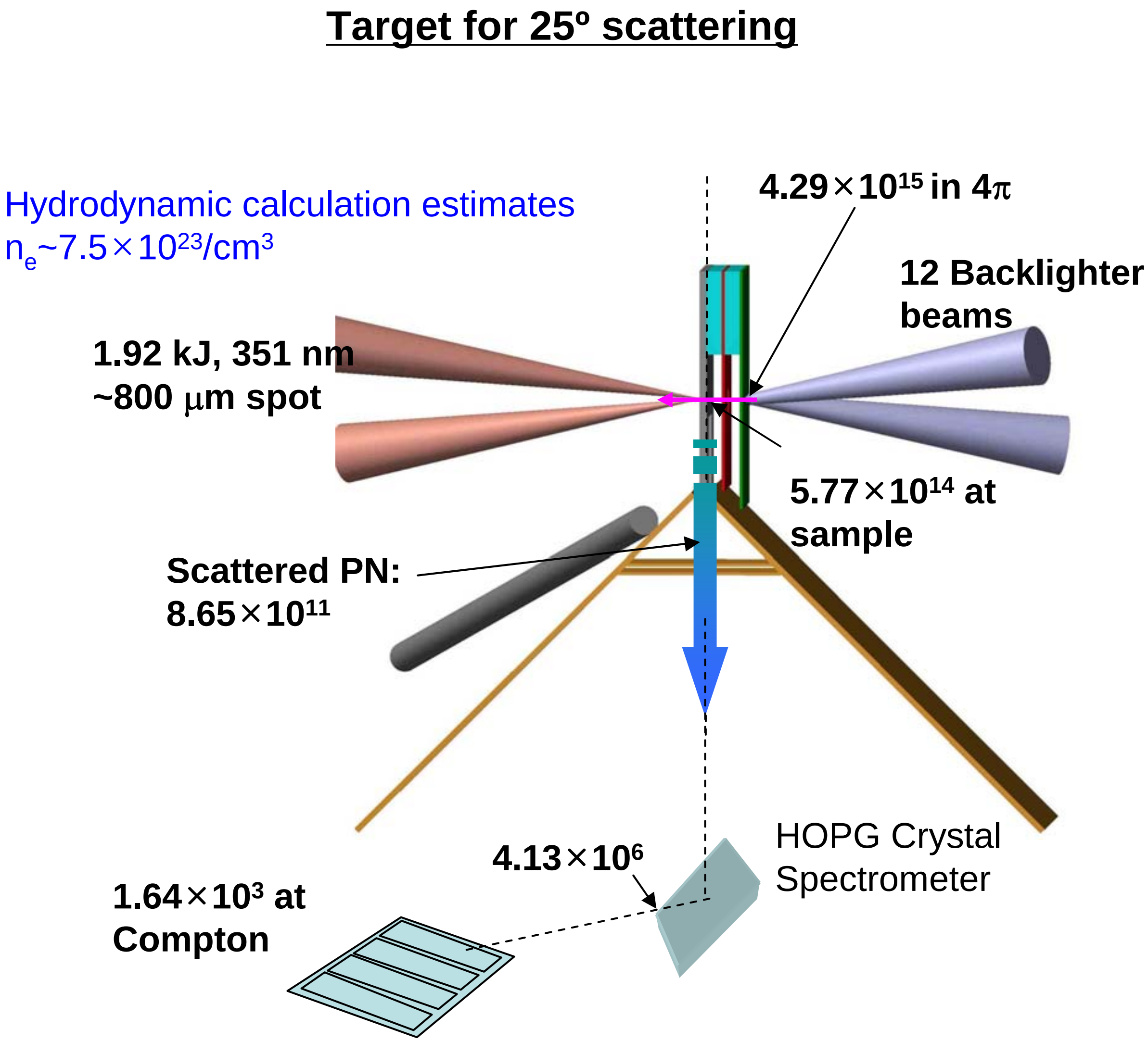




A new Mn He-α backlighter at 6 keV was applied to penetrate through the dense compressed Be

Disadvantage: double peaks from He-α and intercombination line

Estimation of photon numbers from scattering targets



Backlighter

1 ns pulse, 12 beams (480J/beam), 200 μm spot size
→ 2.6×10^{16}W/cm^2

Mn He-α (6.18 keV)

C.E~5×10^{-4}
→ 4.29×10^{15} in 4π

Solid angle through Ta slit

400×560 μm, 300 μm distance
→ PN: 5.77×10^{14}

Scattered fraction:

$\sigma_{Th} x n_e x L x T/(1+\alpha^2)$
α~0.5, n_e~7.5×10^{23}/cm^3, L~40 μm, T~0.94
→ 0.0016
→ PN: 8.65×10^{11}

HOPG spectrometer

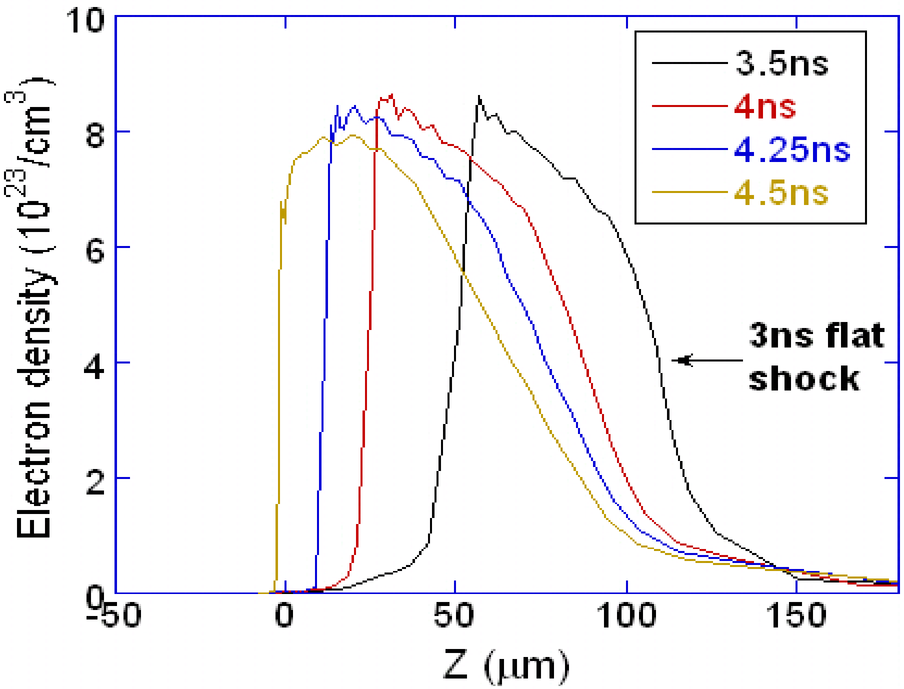
Acceptance angle/strip~20mrad
Integrated reflectivity~3mrad
→ Collected fraction~4.77×10^{-6}
→ PN: 4.13×10^6

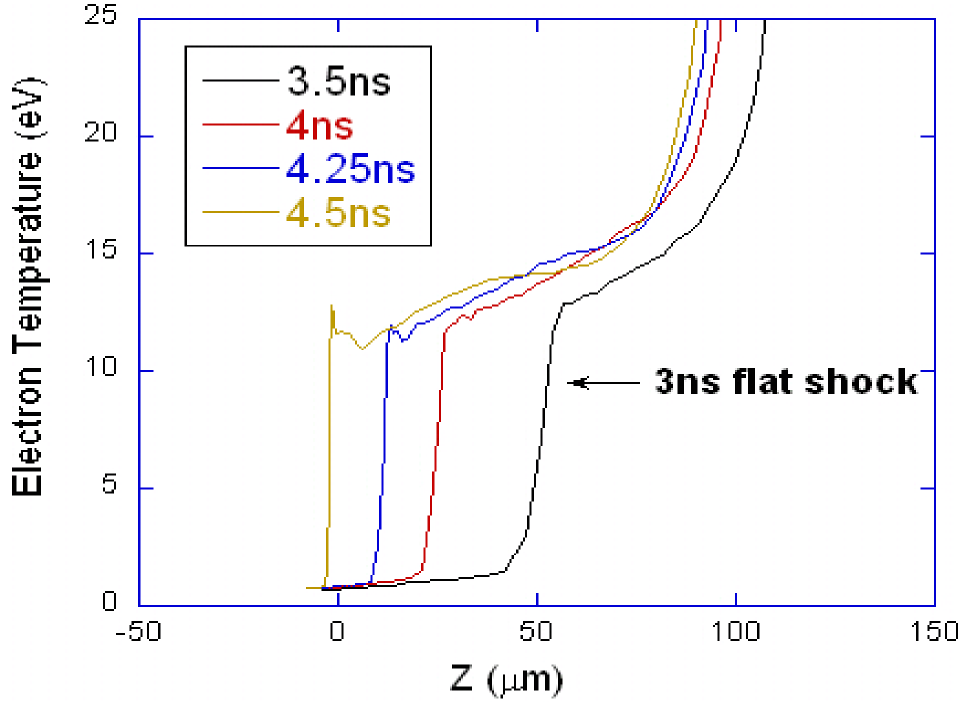
Frame CCD

Gating time~0.2ns
Q.E of MCP~4%
T of Be filter~50%

→ PN: 1.64×10^3 at Compton peak

1-D radiation hydrodynamic modeling calculates dense matter condition with shock-propagation

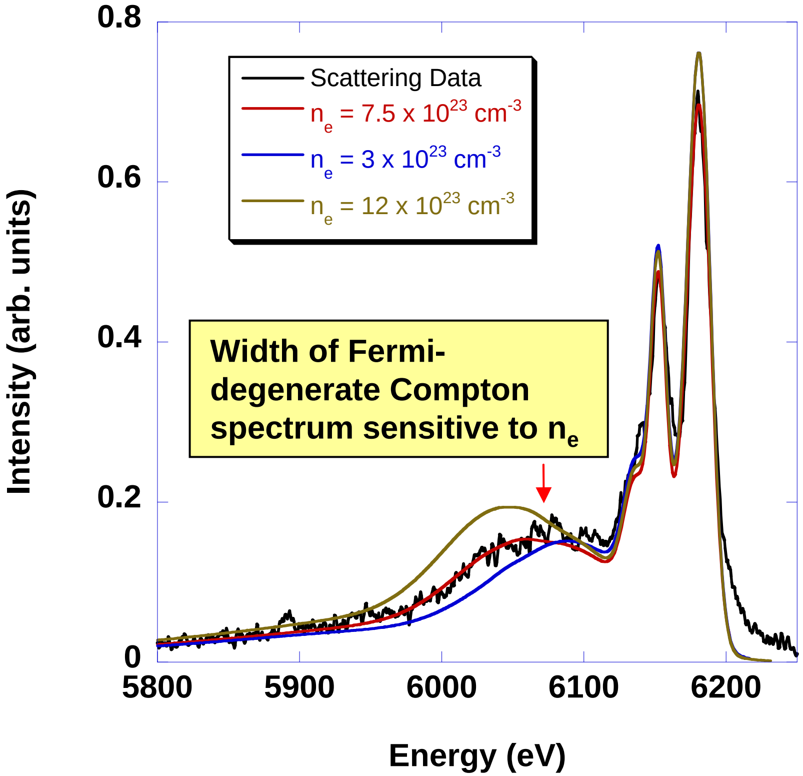


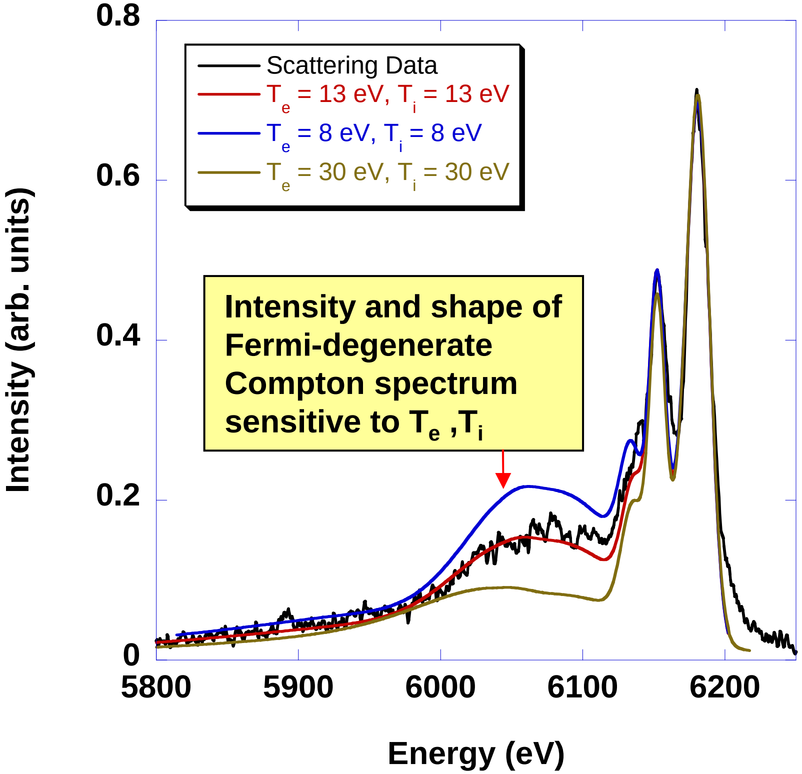


Electron density of n_e = 7 ~ 8 x 10^{23} cm^{-3} [~ 3.3 compression] and temperature of T_e = 10~14 eV are expected under the experimental conditions.

First X-ray Thomson scattering spectrum from compressed matter (Be) : non-collective regime, 90º

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



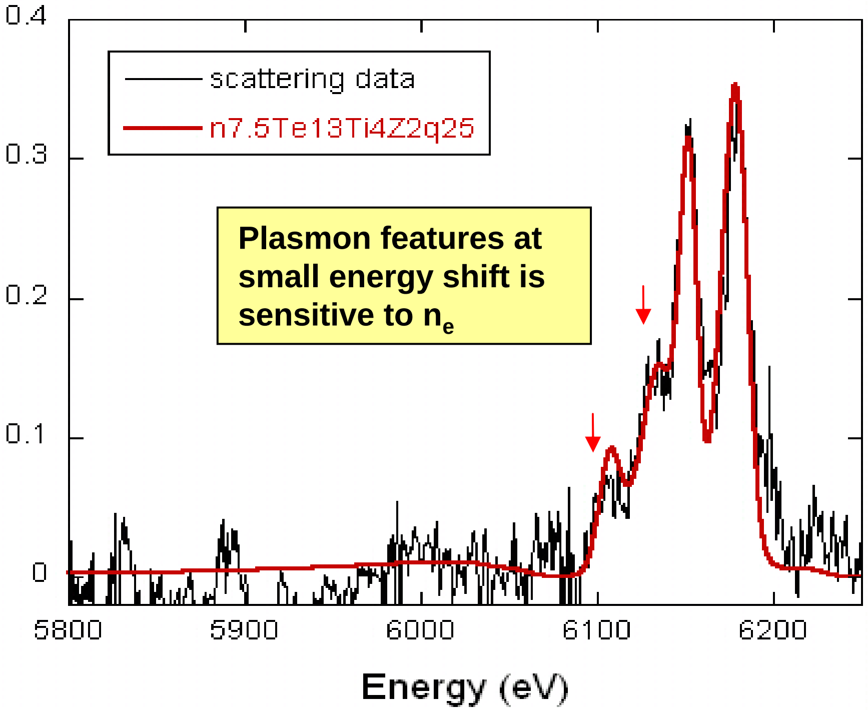


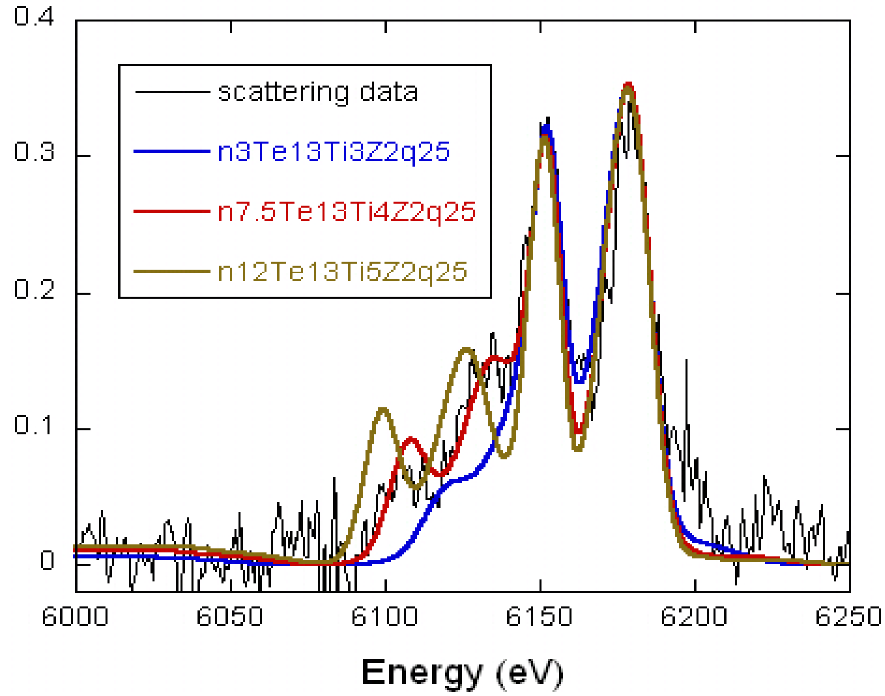
- **Compton energy, $E_C=\hbar^2k^2/2m_e$=74 eV**
- **For a Fermi-degenerate system, the width of the Compton spectrum yields the Fermi energy, $E_F= \hbar^2(3\pi^2n_e)^{2/3}/2m_e$=30 eV**
- **Backscatter: n_e=7.5x10^{23} cm^{-3}, T_e=13 eV, Z=2, α~0.5 consistent with simulations**

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

Forward scattering data show plasmons at small energy shifts

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

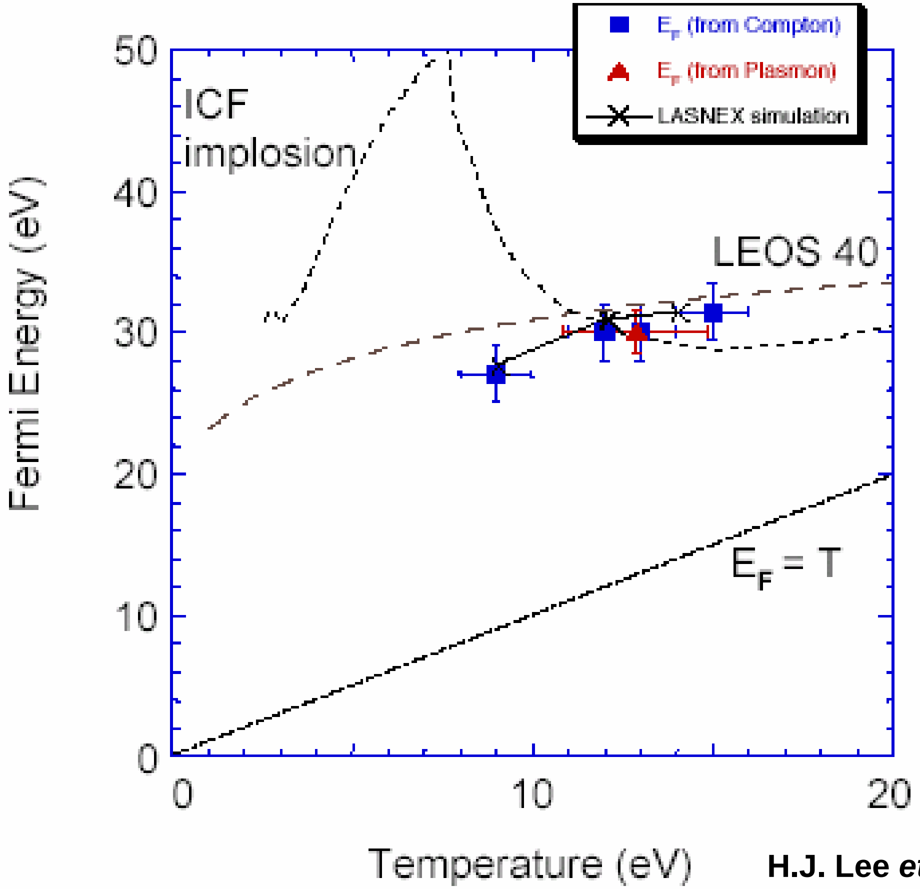




- **First direct measure of increased Fermi energy, plasmons, and adiabat in laser-compressed matter, E_{Pl}= ~40 eV**
- **Accurate characterization tool of laser-compressed matter**
- **Forward scatter: n_e=7.5x10^{23} cm^{-3}, T_e=13 eV, Z=2, α~1.55, consistent with backscatter results**

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

The experiments demonstrate a direct measurement of the degeneracy and adiabat in single-shocked foils

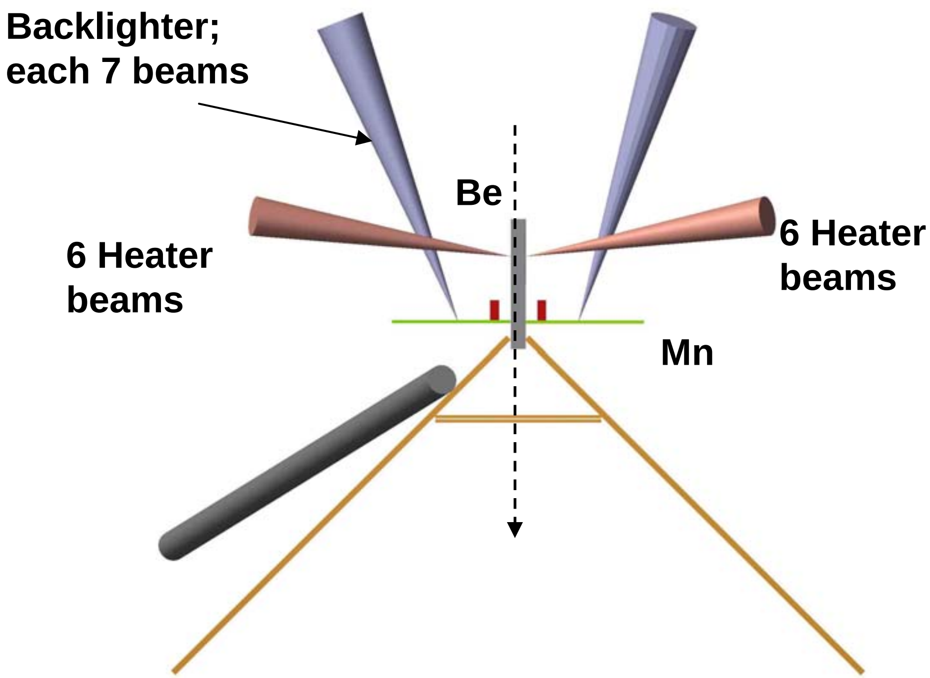


H.J. Lee *et al*. PRL 102, 115001 (2009).

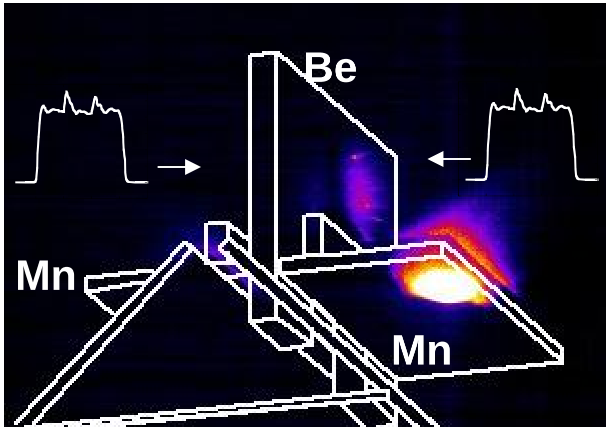
- For a Fermi-degenerate system, the width of the Compton spectrum yields the Fermi energy; $E_F = \hbar^2 / 2m_e (3\pi^2 n_e)^{2/3}$
- Fermi energies inferred from the measured densities from the Compton and plasmon scattering data are compared with the Hugoniot data predicted by LEOS.

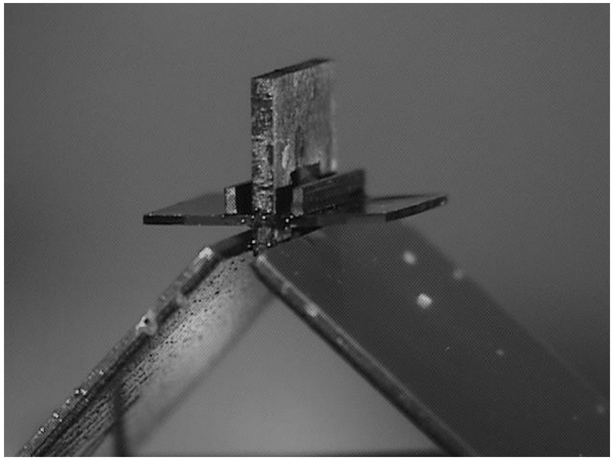
Experimental conditions for counter-propagating shocks

For 140° scattering experiment



Pinhole camera image of counter-propagating shock





Axis : **P1-P12, TIM5 as a target positioner**

Laser : Driver: SG1018**, Max Power [1ns, 500 J]**

12 heater beams with SG4s

No DPR, stacked to 3 ns pulses

14 BL beams**: delayed to ~3 ns, No SSD, No DPR, No DPP**

Primary diagnostics : **XRFC4 coupled to** GTS **in TIM3; CCD5**

Secondary TIM diagnostics : **2x pinhole XRFC in TIM2 and TIM4, SSCA in TIM1**

Shock velocity estimation from 3-4 ns single pulse

From the Rankine-Hugoniot relation,

$$P - P_0 = \rho_0 u_s u_p$$

$$\frac{\rho}{\rho_0} = \frac{u_s}{u_s - u_p}$$

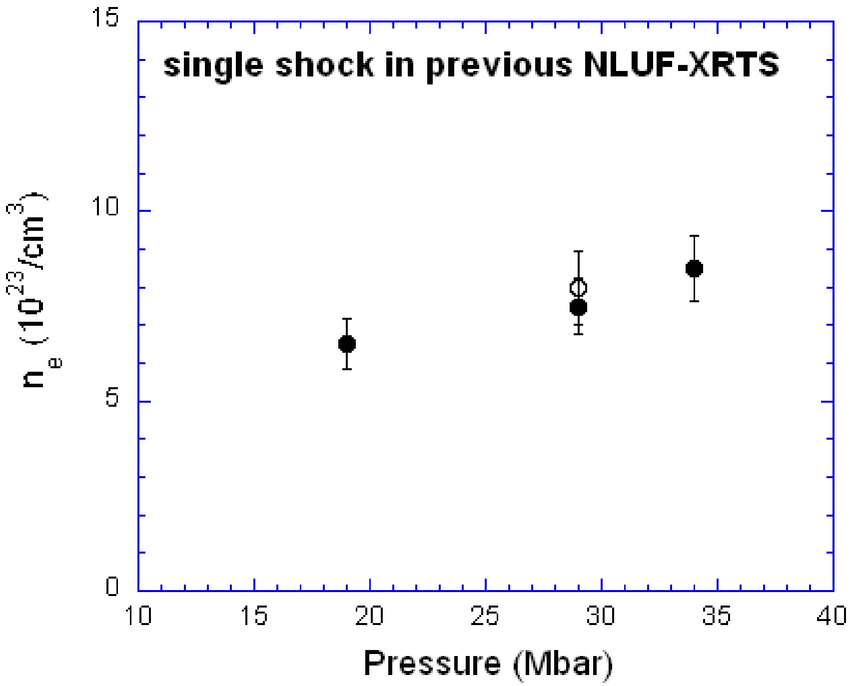
$$E - E_0 = \frac{1}{2}(P + P_0)(\frac{1}{\rho_0} - \frac{1}{\rho})$$

ρ_0, P_0, E_0 and ρ, P, E: mass density, Pressure, and Energy of before and after shock travel.

u_s: shock velocity
u_p: particle velocity behind the shock.

$$u_s = \sqrt{\frac{\rho P}{\rho_0(\rho - \rho_0)}} \times 10$$

$u_s[\mu m / ns]$,
$\rho[g / cm^3]$,
$P[Mbar]$

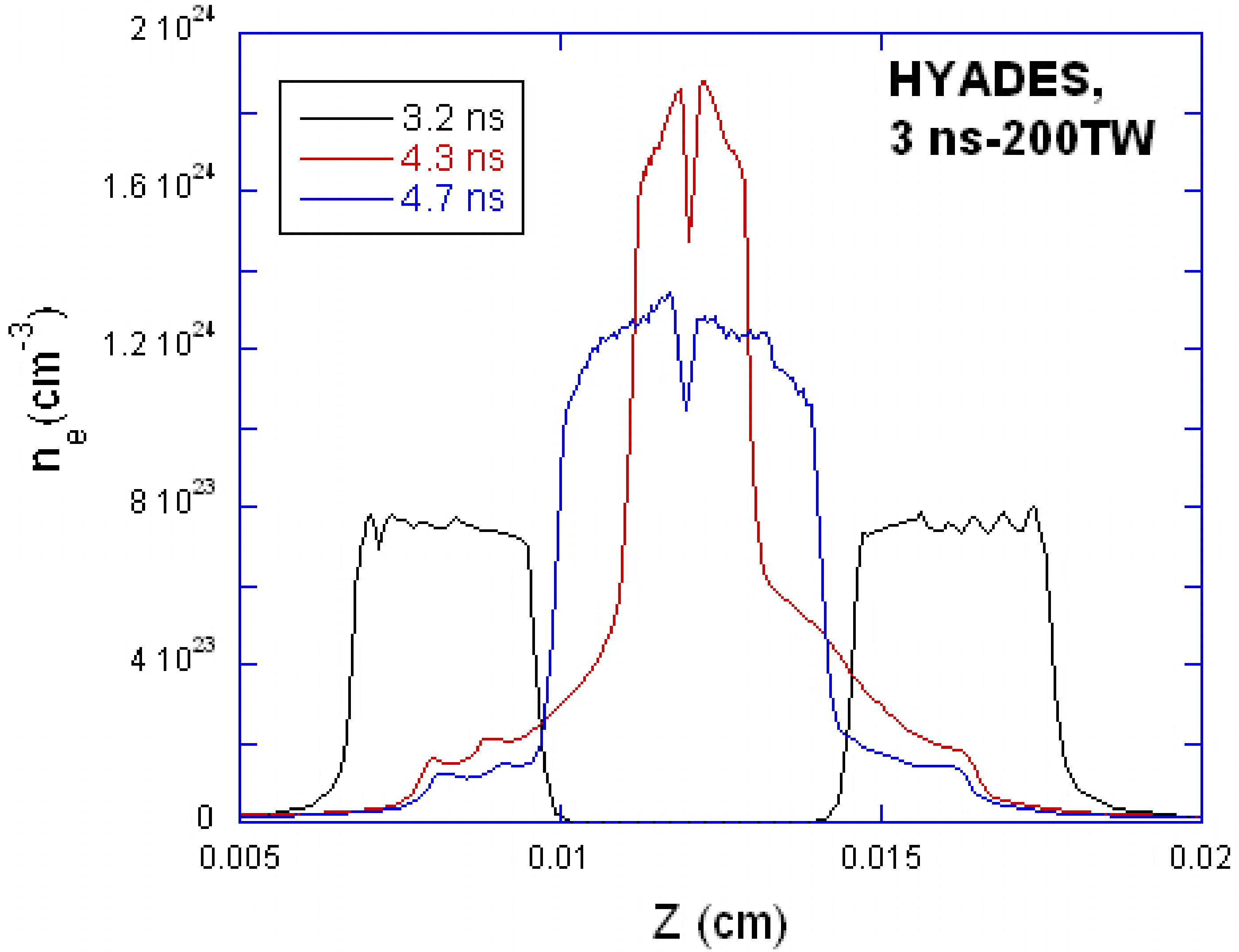


From experimental data,
shock travels into solid Be with u_s ~ 40 μm/ns.

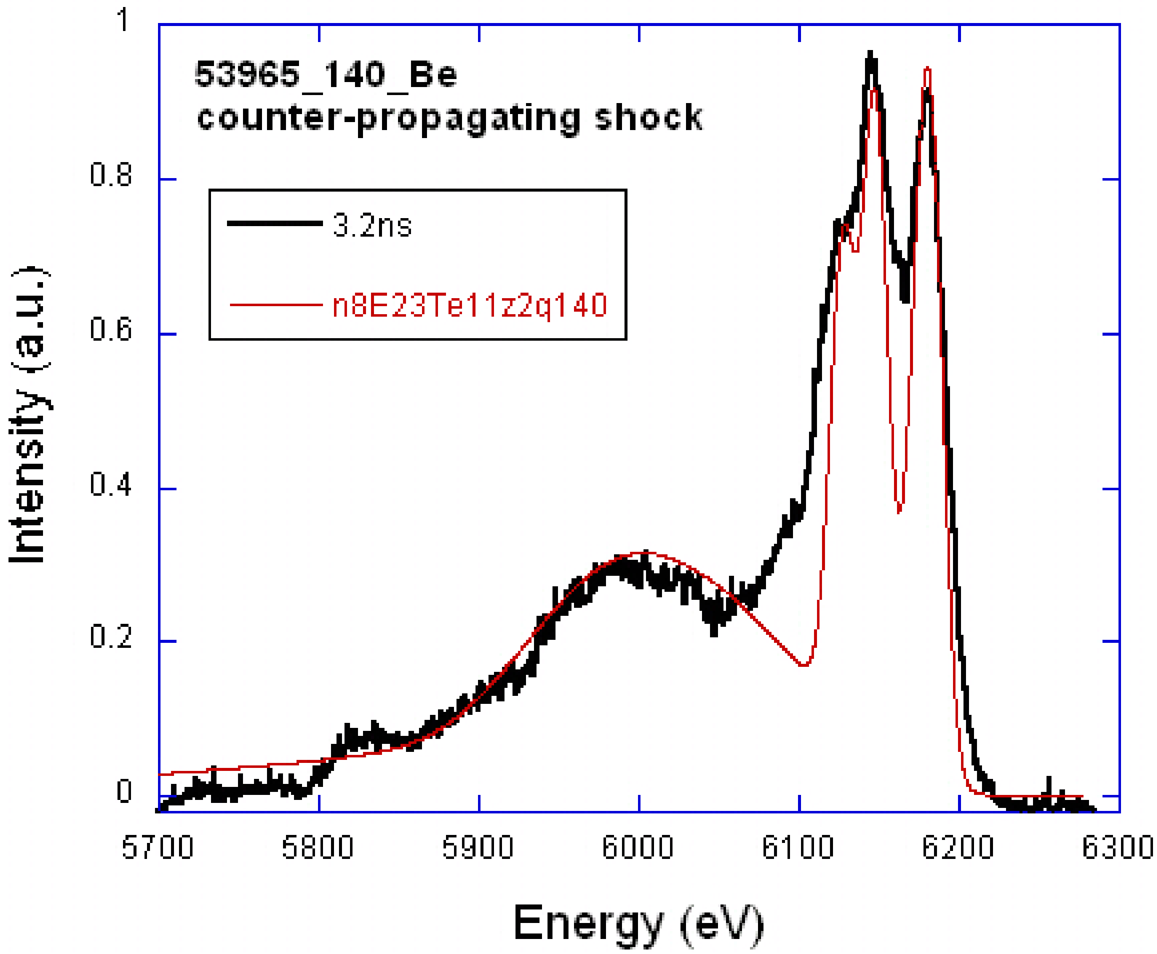
In case of counter-propagating shock, two shocks starts colliding at ~ 3.1 ns.

This agrees well with the radiation-hydrodynamic simulation.

Hydrodynamic simulation of counter-propagating shocks

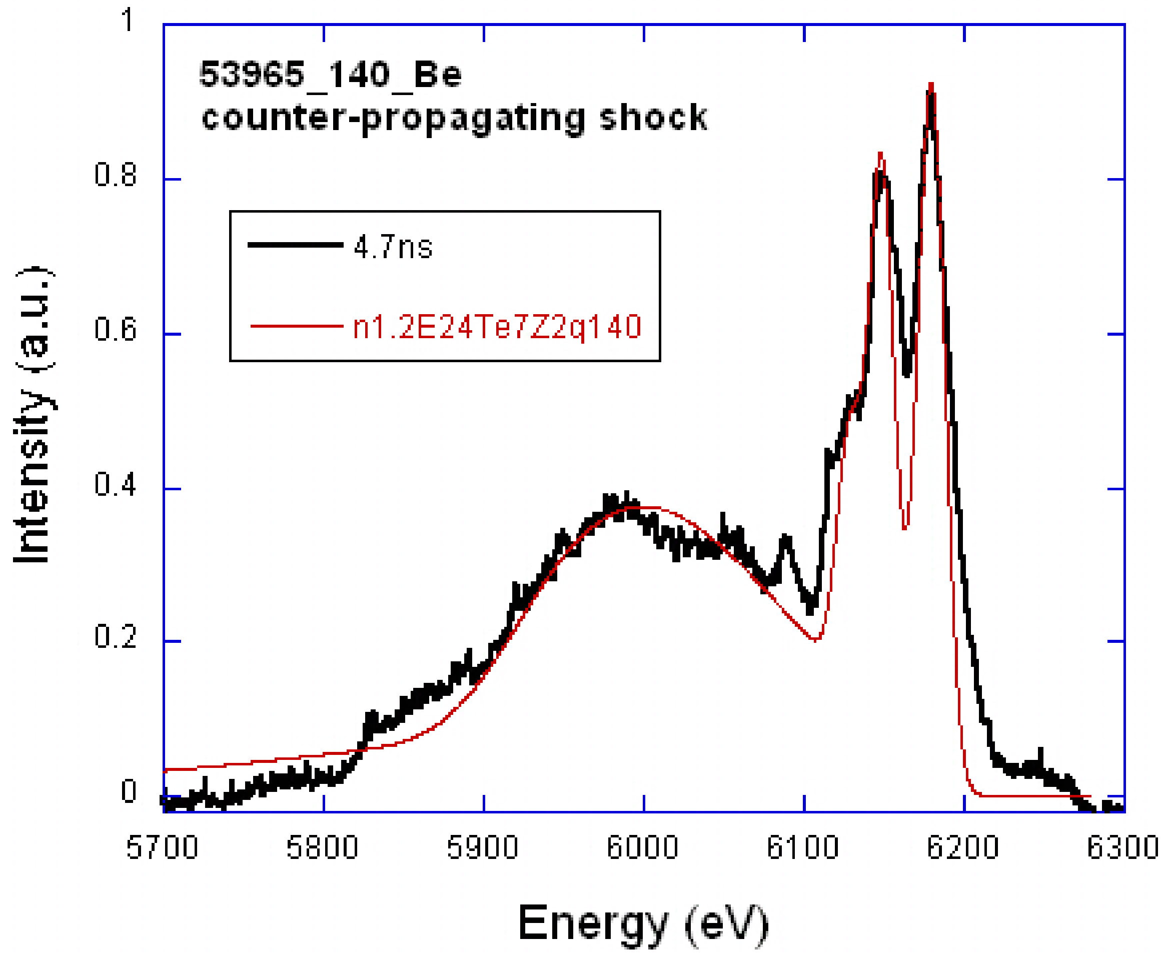


Compton spectrum before counter propagating shocks collide



Compton scattering spectrum reflects the density and temperature of shock-compressed Be by single shock from 3ns heater beams.

Compton spectrum after counter propagating shocks collide



Compton scattering spectrum shows that we could reach over 4 times compression by colliding two shocks.

Conclusions

- **X-ray Thomson scattering has been developed for accurate measurements of temperatures and densities in dense matter**

- **Non-collective scattering (Back scatter)**
  - **Intensity and shape of Compton spectrum is sensitive to T_e**
  - **Width of Fermi-degenerate Compton spectrum is sensitive to n_e**
  - **Elastic (Rayleigh) scattering: Z_{free} diagnostics**
- **Collective scattering (Forward scatter)**
  - **Observation of Plasmons: n_e**

- **Combination of collective and non-collective x-ray scattering provide the capability to measure accurately the plasma quantities of electron density, electron temperature, and Z**

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

- **Higher compression over 4 times can be reached through counter-propagating shocks or multiple shocks. (under analysis)**