X-ray Thomson Scattering for Measuring Dense Be Plasma Collisionality*

Darmstadt, 7 June 2010

Tilo Döppner

Lawrence Livermore National Laboratory, P. O. Box 808, Livermore, CA 94551

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LLNL-PRES-433642

Outline

- Introduction
    - X-ray Thomson scattering is important for the National Ignition Campaign
- Non-collective Thomson scattering experiments
    - Measure density in capsule implosions and shock compressed matter
- Collective Thomson scattering
    - Measure collision rate through plasmon broadening
- Conclusions

Collaborators

SH Glenzer, C Fortmann, AL Kritcher, OL Landen, RW Lee, S. Le Pape
(Lawrence Livermore National Laboratory, USA)

P Neumayer *(GSI Darmstadt, Germany),* PF Davis, RW Falcone, (*UC Berkeley, USA)*

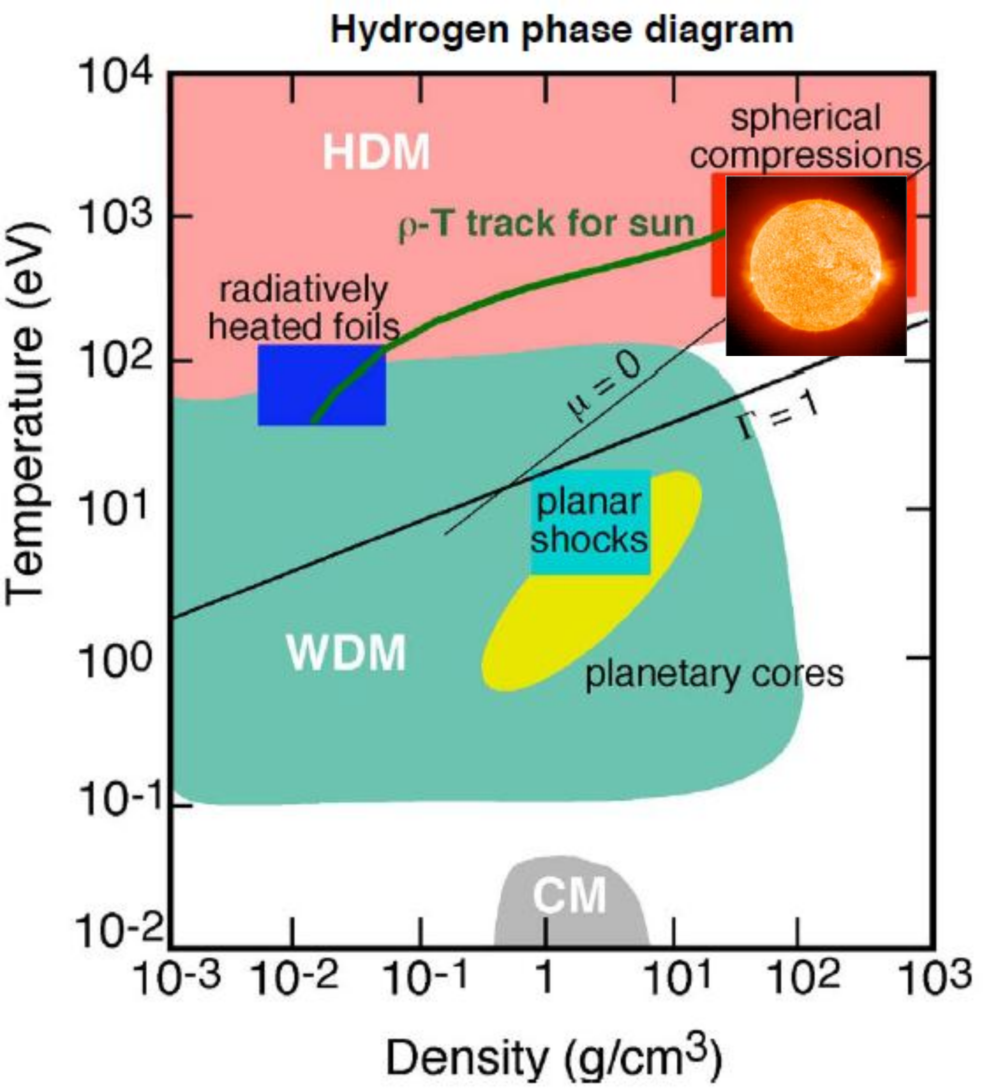
HJ Lee (*SLAC, Stanford, USA), T. Tschentscher, S. Toleikis (DESY , Germany)*

E. Foerster (Jena, Germany), SP Regan (*LLE, Rochester, USA*)

G. Gregori *(University of Oxford, UK), D. Gericke (Warwick, UK)*

R Thiele, R Redmer *(University of Rostock, Germany)*

Accurate measurements of warm dense matter properties have been developed applying X-ray Thomson scattering

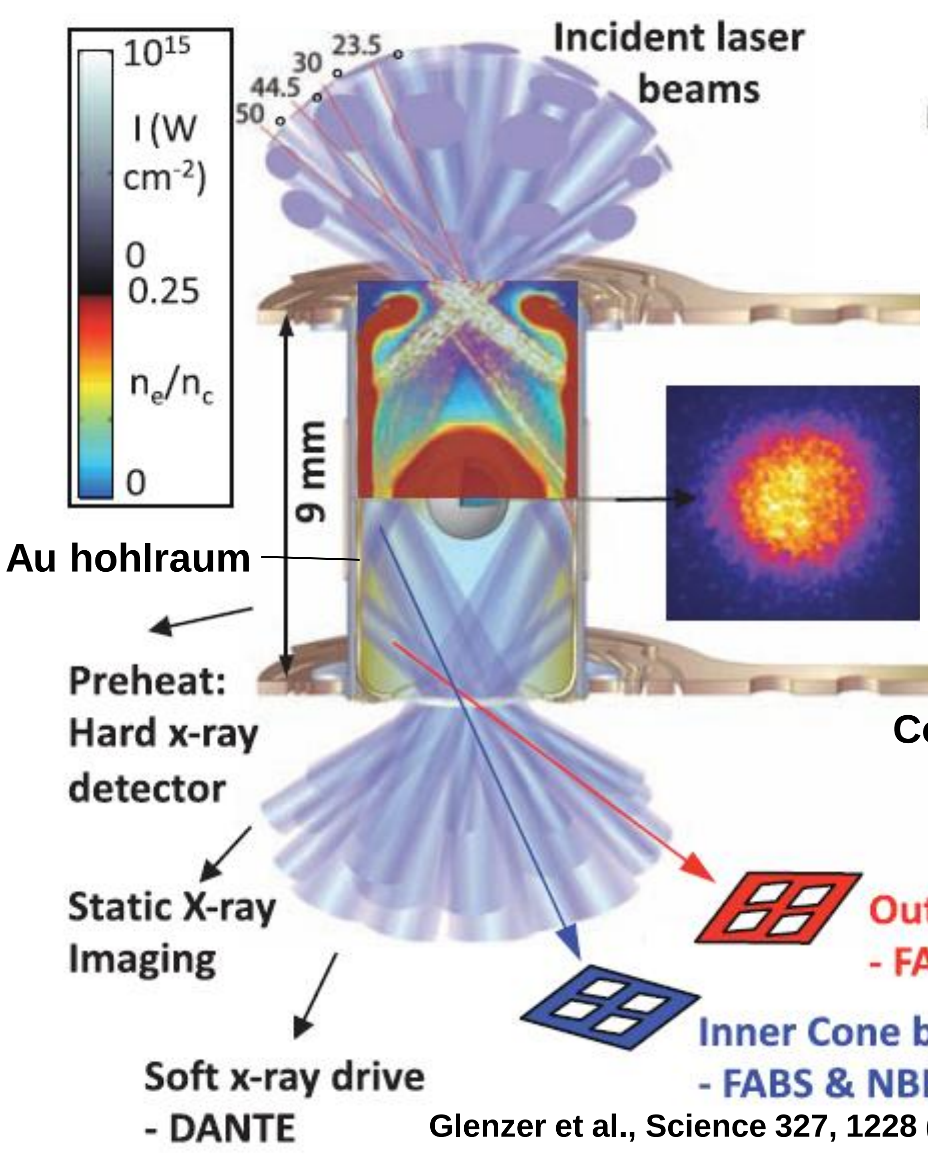


- **Current XRTS experiments are conducted in the warm dense matter (WDM) regime**
- **WDM is challenging to describe by theory, since coupling and correlations are important**

$$\Gamma = \frac{Z^2 e^2 / a}{k_B T} = \frac{\textbf{Coulomb}}{\textbf{Thermal}} \sim 1$$

- **Measurements are required for guidance of theoretical models**

The first experimental campaign (Hohlraum energetics) at the National Ignition Facility (NIF) was successfully completed in 2009

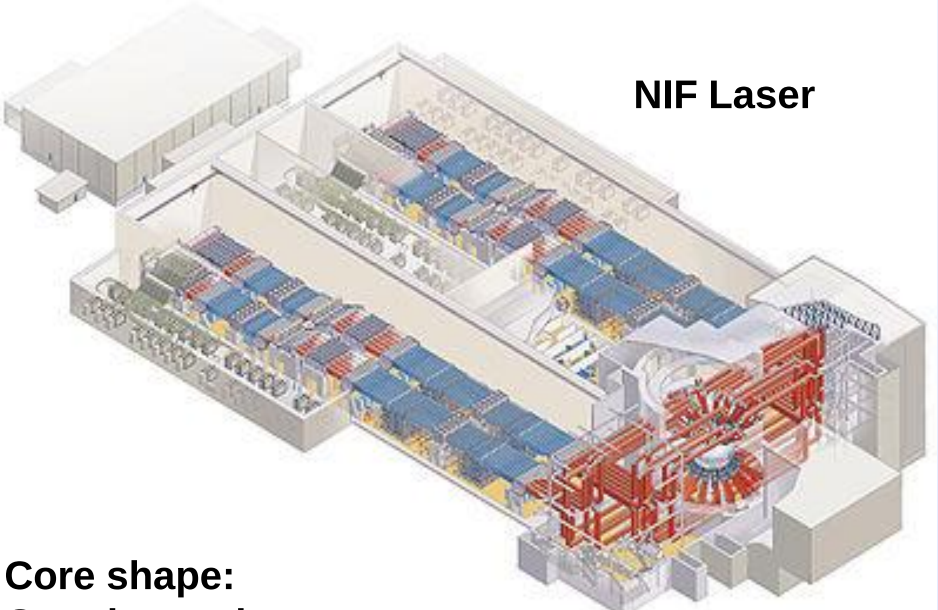


Au hohlraum

Core shape:
Gated x-ray imager

Cold fingers

Glenzer et al., Science 327, 1228 (2010)

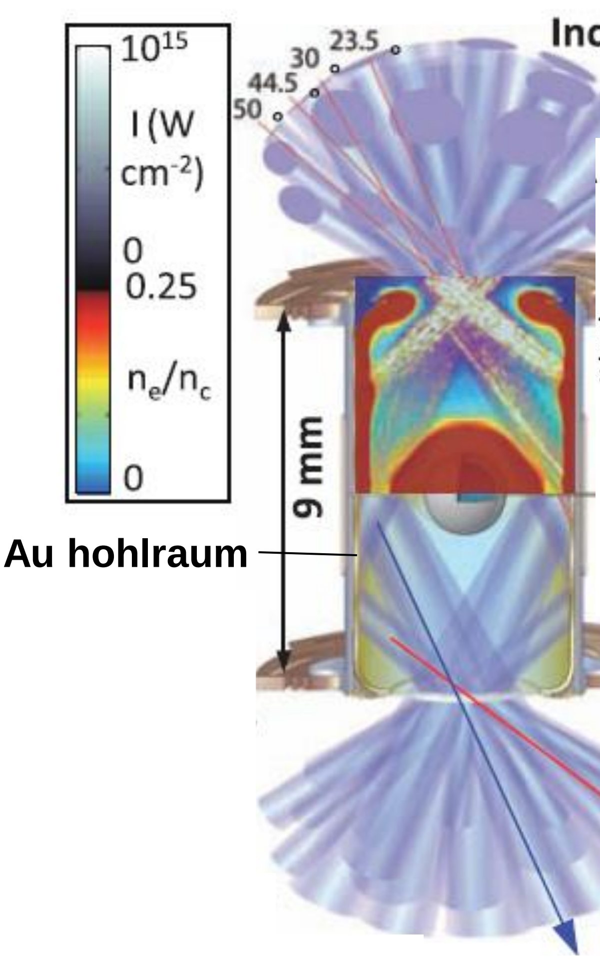


NIF Laser

- 192 beams at 351 nm
- total energy on target up to 1.2 MJ
- pulse length ~ 20 ns
- over 90% of energy absorbed in hohlraum
- hohlraum radiation temperature up to 305eV
- up to 3 shots per day

The symmetry was tuned by changing the difference in wavelength between inner and outer cones

- **increased x-ray drive at equator due to energy transfer from the outer cones to the inner cones**



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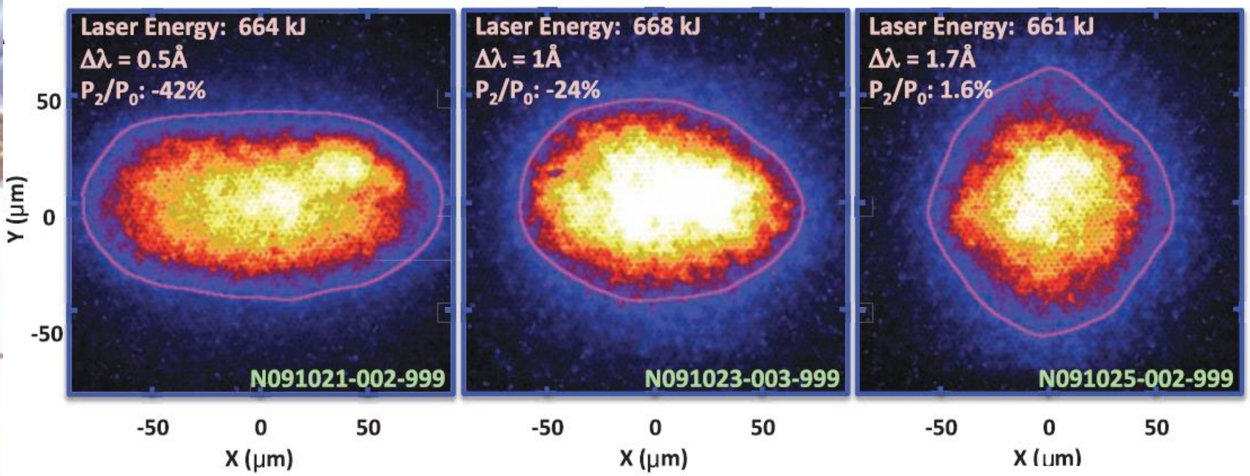
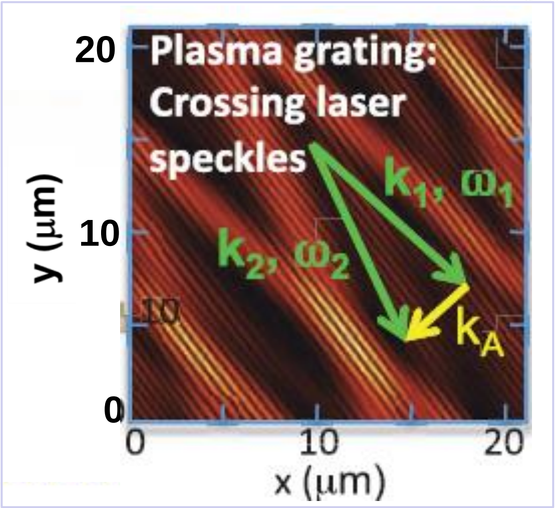
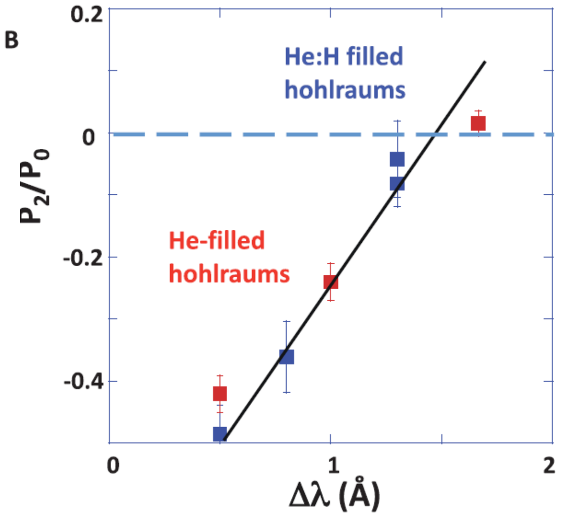
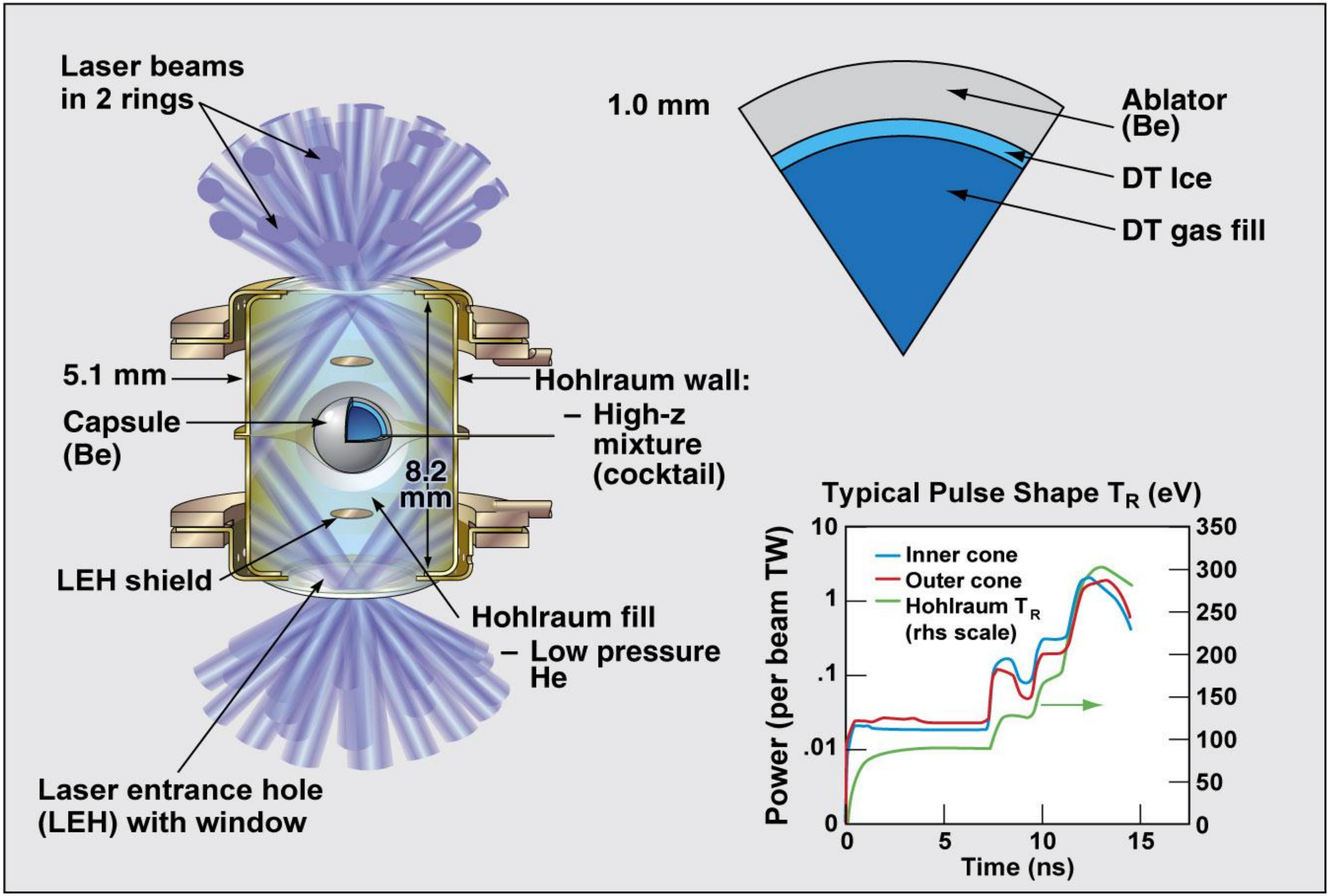






Glenzer et al., Science 327, 1228 (2010)

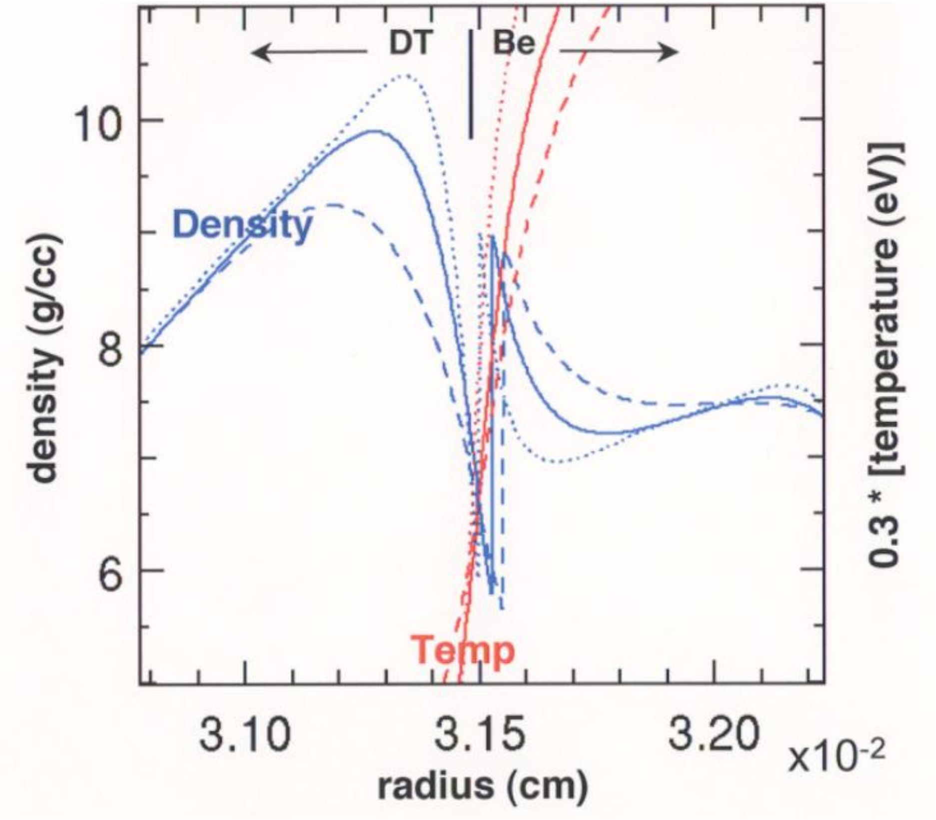
NIF Indirect Drive target point design



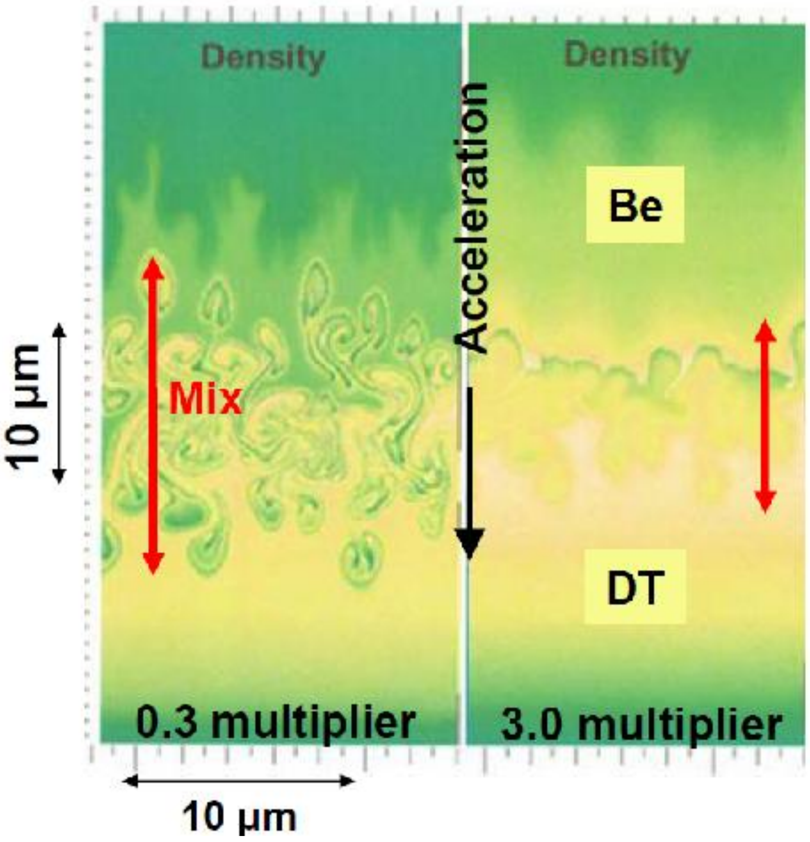
Thermal conductivity is important to correctly model ICF implosions

Conductivity affects the density gradient at the ablator/ fuel interface …

… and the density gradient directly impacts high-mode stability



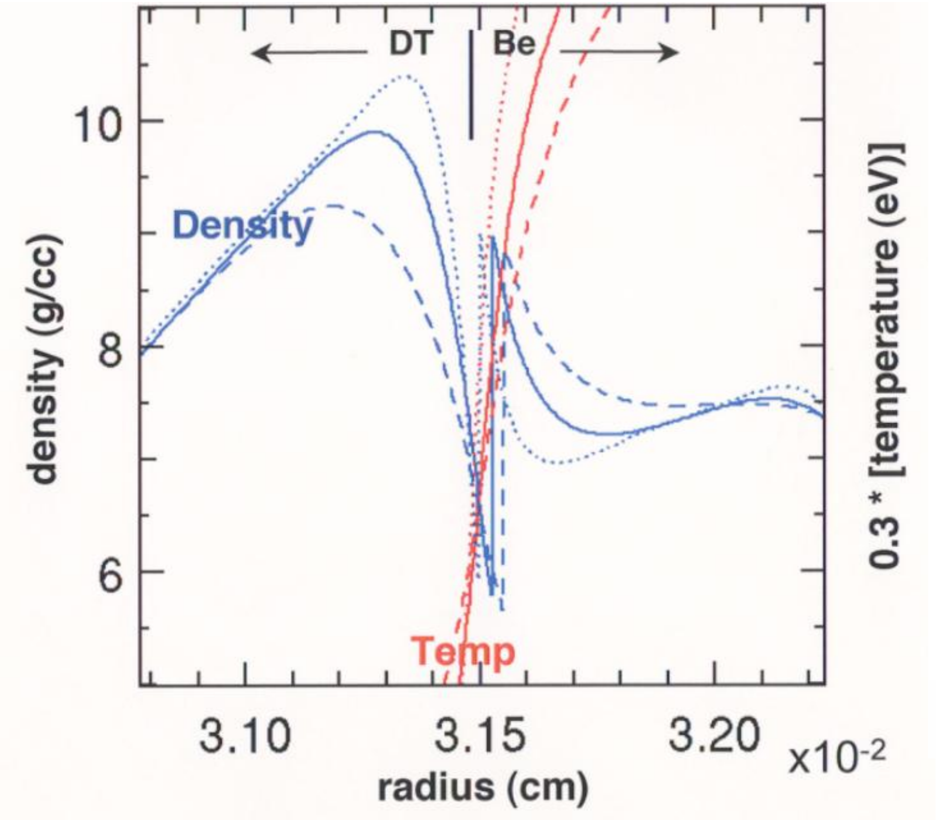
Variation in the profiles for 0.3 (dot), 1.0 (solid), and 3.0 (dash)times the nominal thermal conductivity (Lee-More).



Hammel et al., J.Phys. Conf. Ser. 112, 022007 (2008)

However, conductivity of beryllium remains uncertain to within a factor of 2-3

Conductivity affects the density gradient at the ablator/ fuel interface ..



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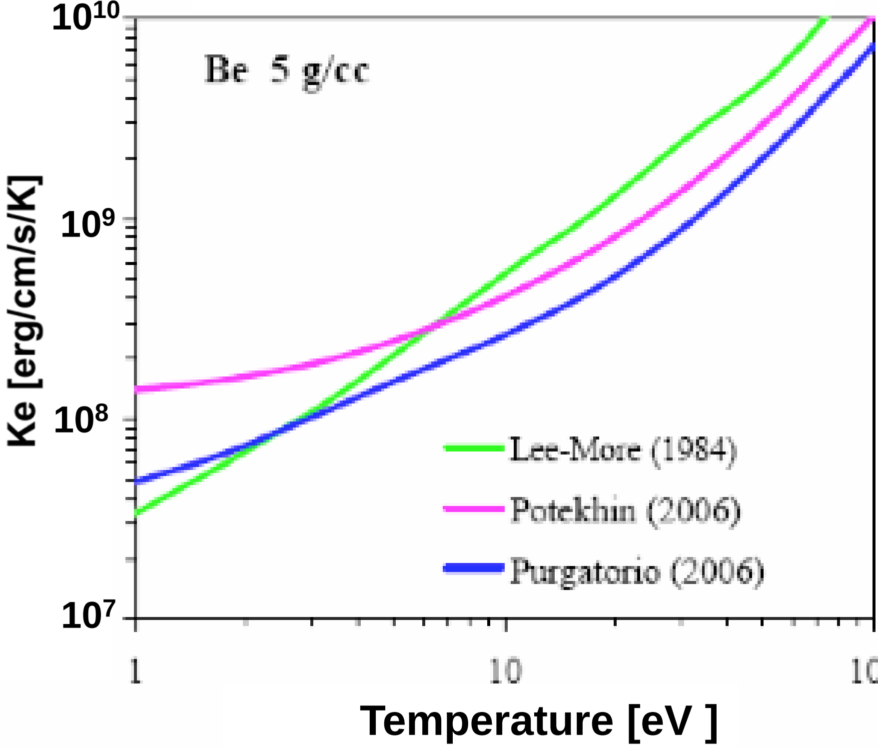
Electron thermal conductivity



S. Hansen

Hammel et al., J.Phys. Conf. Ser. 112, 022007 (2008)

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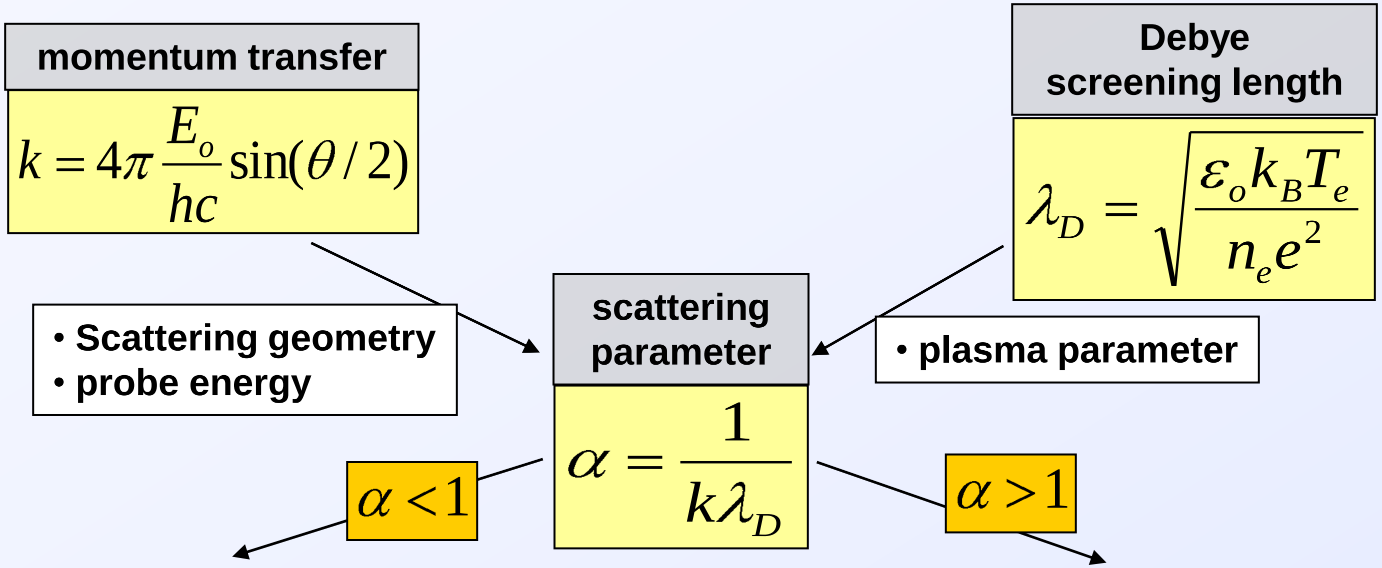
Experimental geometry and probe energy define scattering regime (non-collective vs. collective scattering)



momentum transfer

$$k = 4\pi \frac{E_o}{hc}\sin(\theta/2)$$

- **Scattering geometry**
- **probe energy**

Debye screening length

$$\lambda_D = \sqrt{\frac{\varepsilon_o k_B T_e}{n_e e^2}}$$

- **plasma parameter**

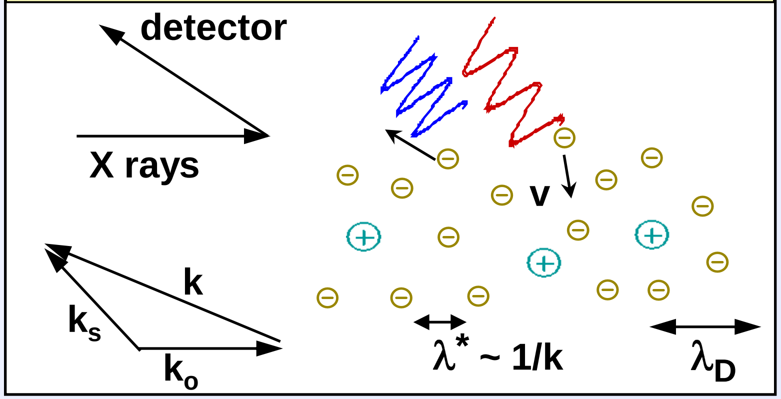
scattering parameter

$$\alpha = \frac{1}{k\lambda_D}$$

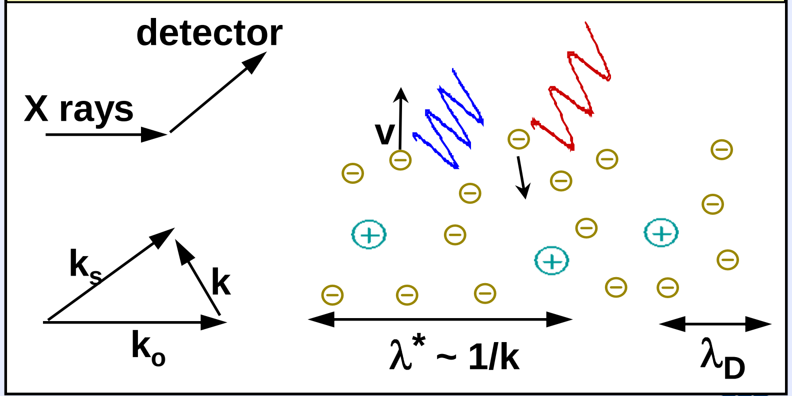
$\alpha < 1$

$\alpha > 1$

Non-collective scattering **($\lambda^* < \lambda_D$)**
probe individual particle motion



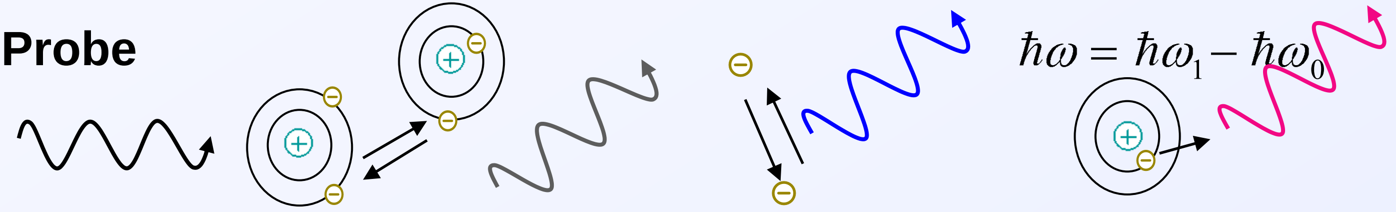
Collective scattering **($\lambda^* > \lambda_D$)**
probe plasma waves (plasmons)



SH Glenzer et al., PRL 90, 175002 (2003)
SH Glenzer et al., PRL 98, 065002 (2007)

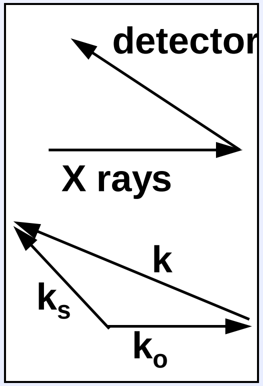
X-ray Thomson scattering has been developed to characterize warm dense plasmas

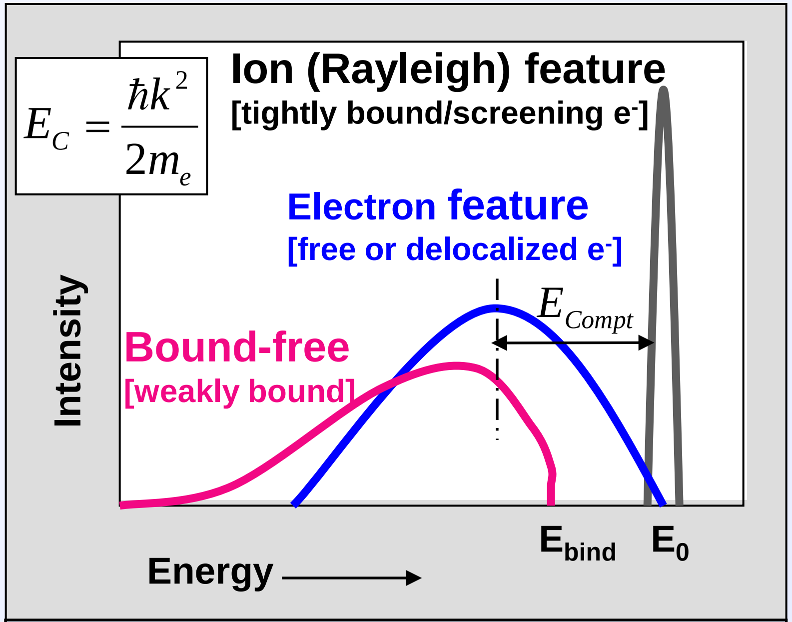
Probe



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

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



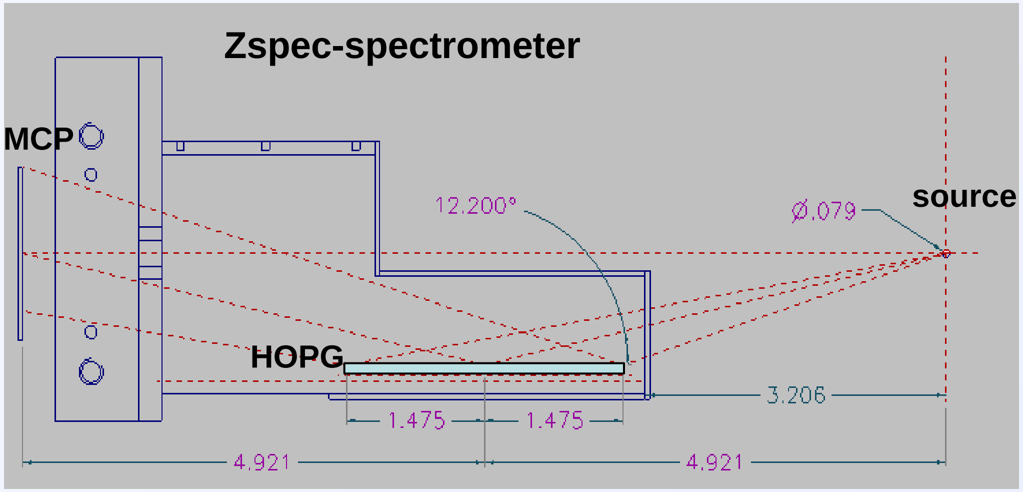


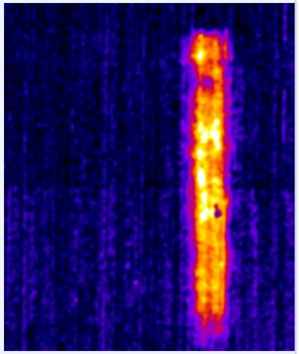
Schematic Scattering spectrum

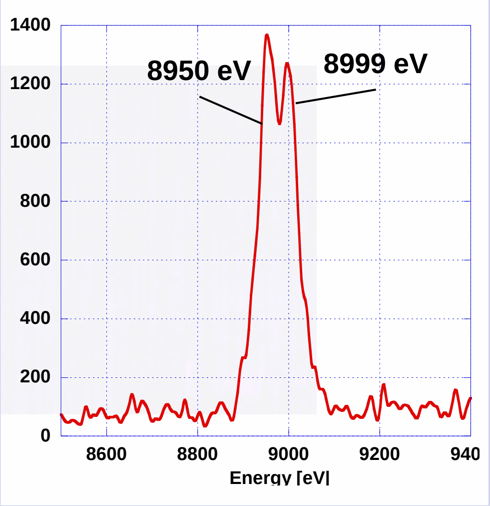
- Free or delocalized electrons result in the Compton down-shifted line, $Z_f S_{ee}(k,\omega)$
- Bound-free contribution also results into down-shifted spectrum
- $Z_b S_{ce}(k,\omega)$
- The momentum of bound e^- causes broadening
- The ion feature describes elastic scattering $S_{ii}(k,\omega)$
-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

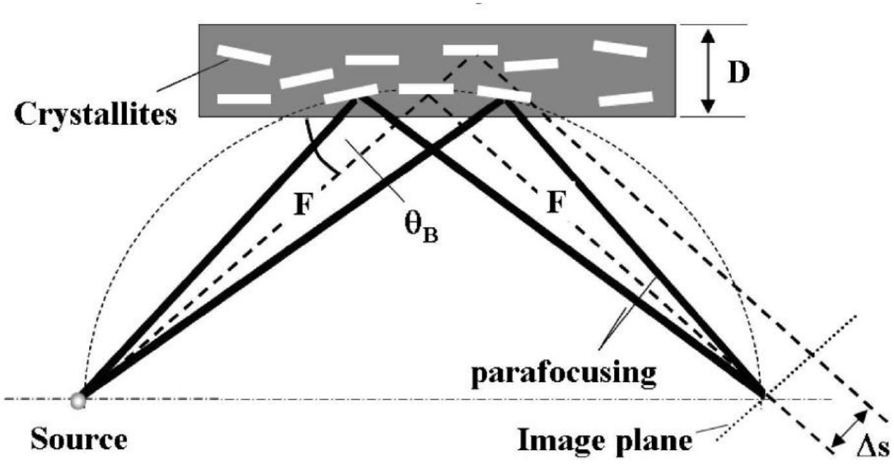
Chihara, JPCM (2000); Gregori et al., PRE (2003)
Glenzer et al, PRL (2003, 2007); Glenzer, Redmer RMP (2009)

We use Zn He-α at 9 keV as x-ray probe which is able to penetrate dense plasmas









HOPG has the highest known integrated reflectivity

Bragg condition

$$n\lambda = 2d\sin\theta_B$$

dispersion

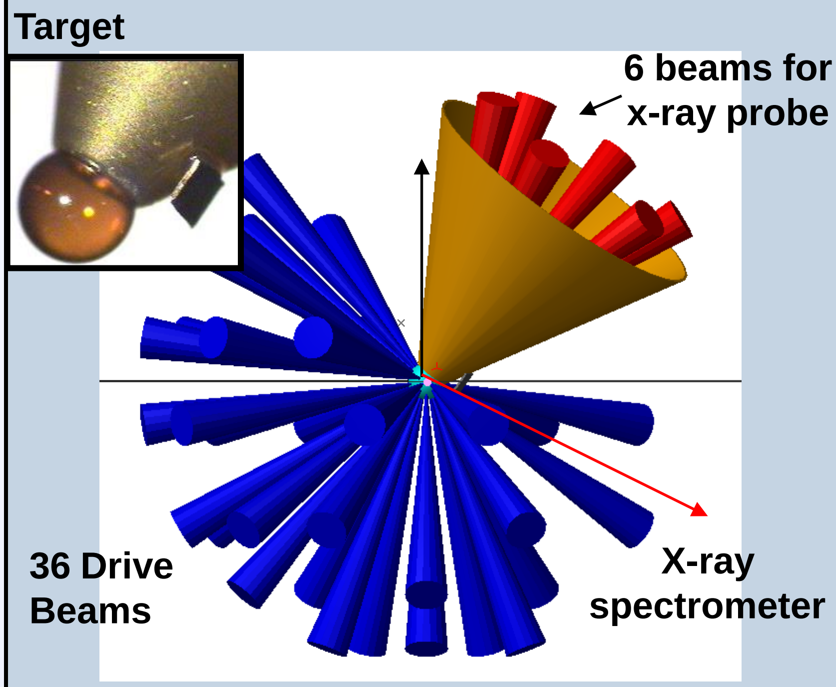
$$\frac{dE}{ds} = \frac{E}{2F\tan\theta_B}$$

A. Pak et al., RSI 75, 3747 (2004)

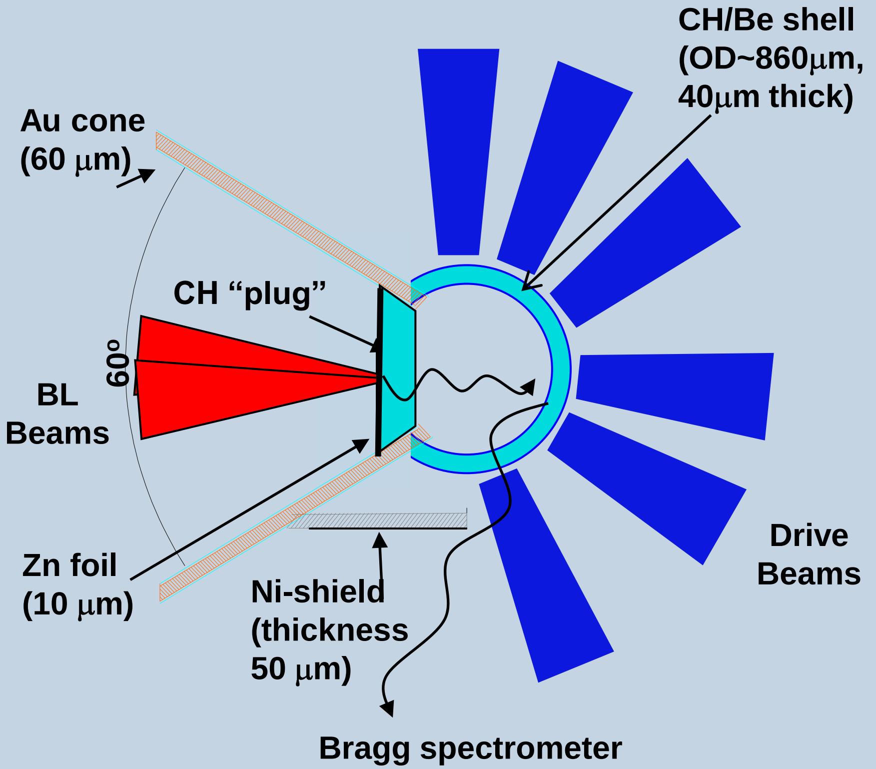
Capsule implosions
PI: A Kritcher

We have started experiments that apply Thomson scattering to measure the ablator properties of an implosion-type target

36 beams drive compression and 6 beams created x-ray probe

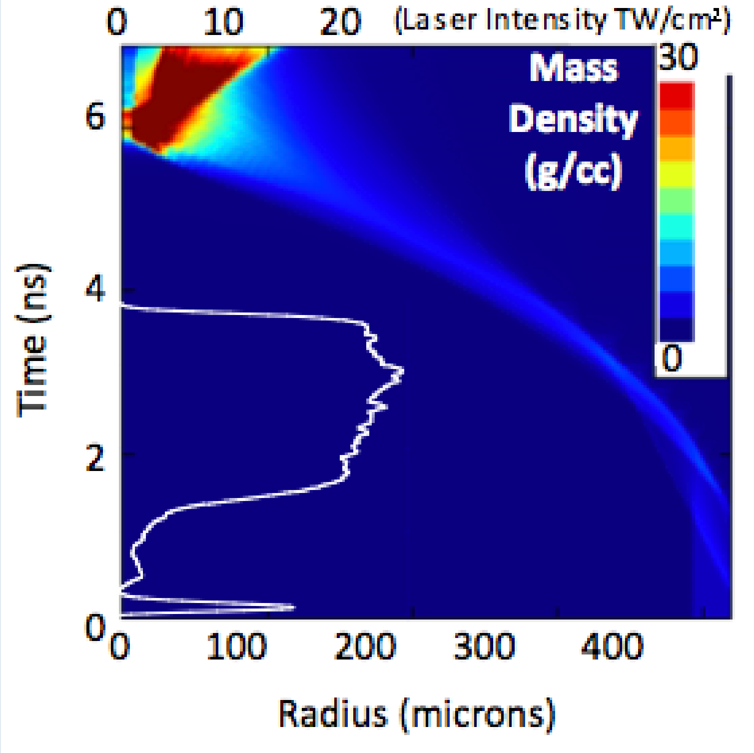


Zn (He-alpha @ 9keV) x-rays are scattered at 113° from the imploding CH shell

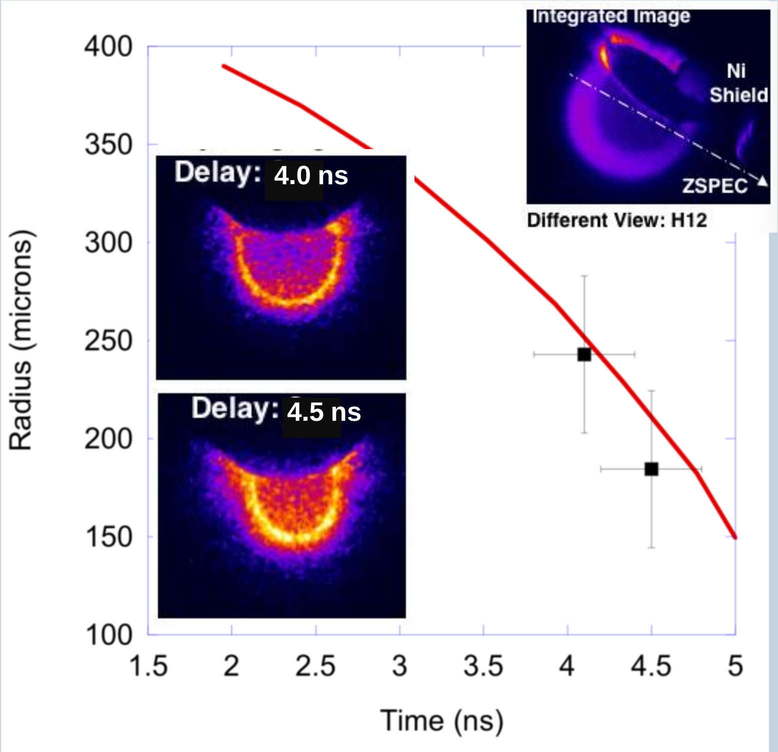


Rad-Hydro simulations were used to guide the experimental setup

Radiation hydrodynamic simulations of the shock compression of the Ablator shell



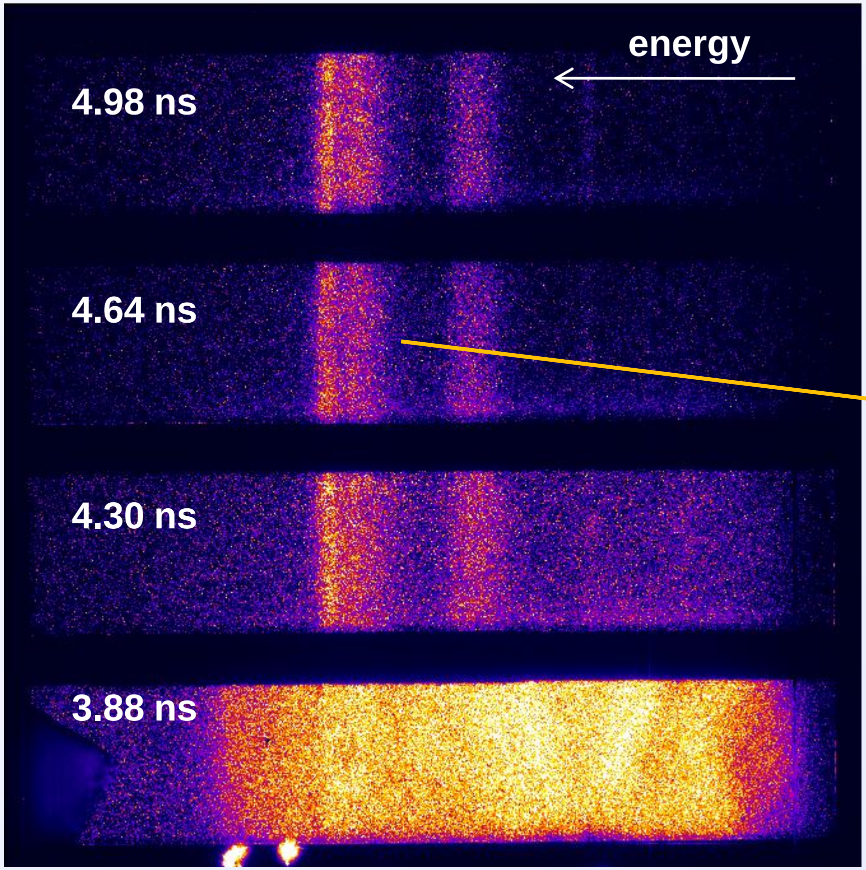
Pinhole images provide implosion velocity estimate



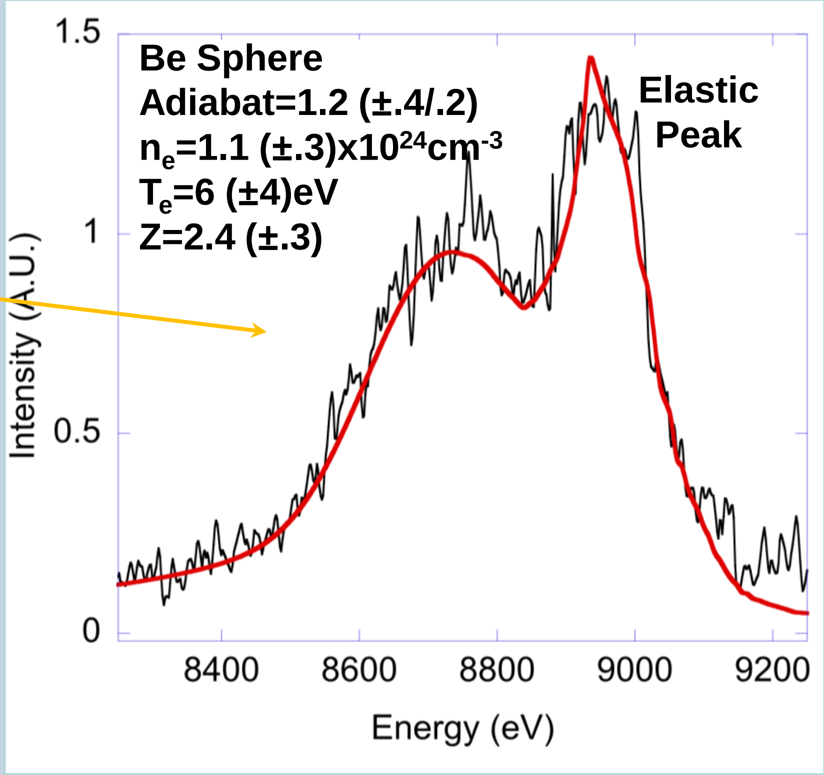
Capsule implosions
PI: A Kritcher

Time resolved scattering spectra show electron densities up to $n_e = 1.1 \times 10^{24}$ cm^3

Shot 56593



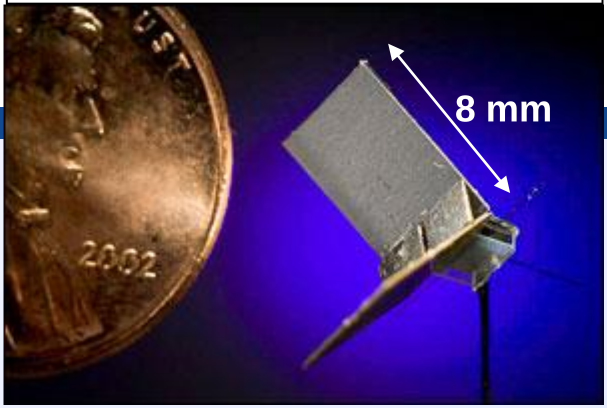
Experimental data and best fit

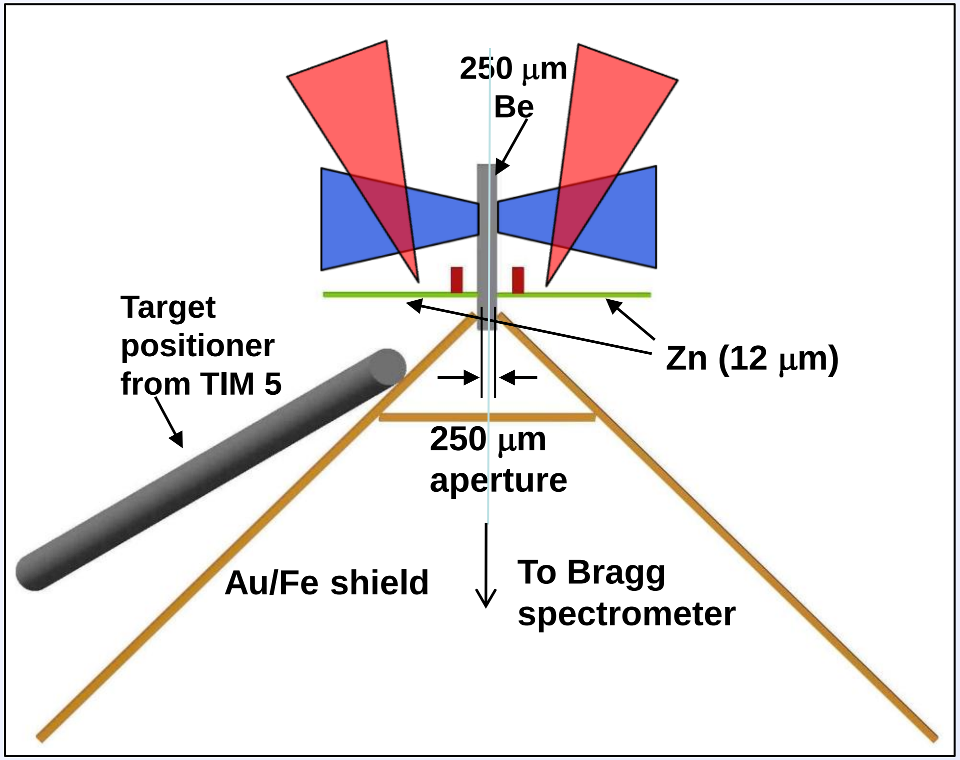


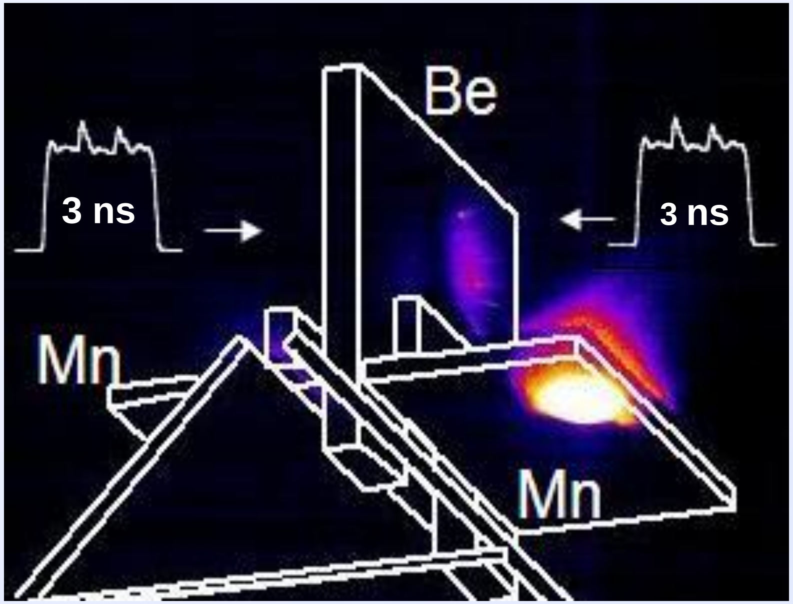
We have successfully developed a platform to study laser-driven shock-compressed matter at the Omega laser

Planar shocks PI: HJ Lee

XRTS target





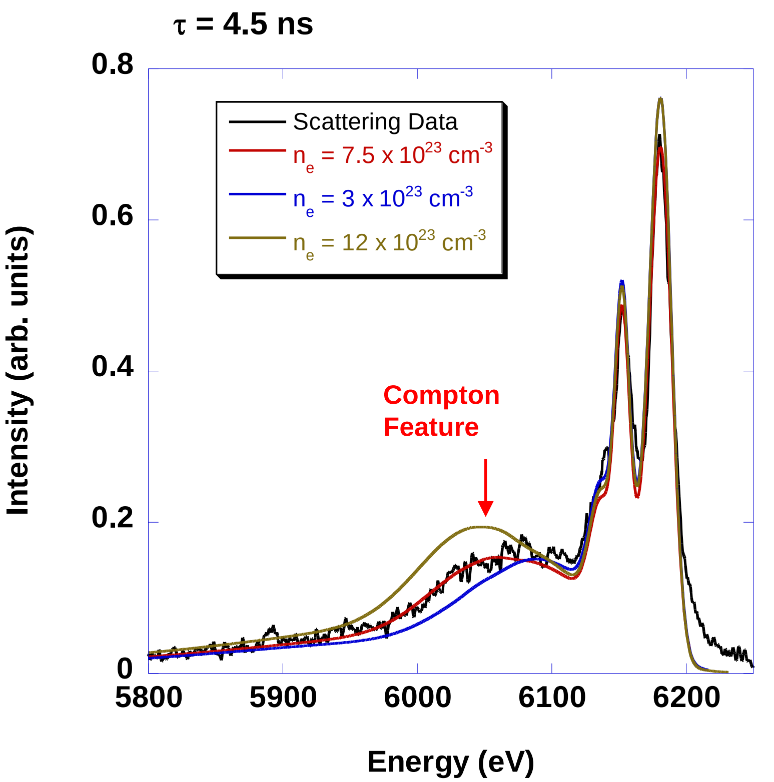


H.J. Lee, Phys. Rev. Lett. 102, 115001 (2009)

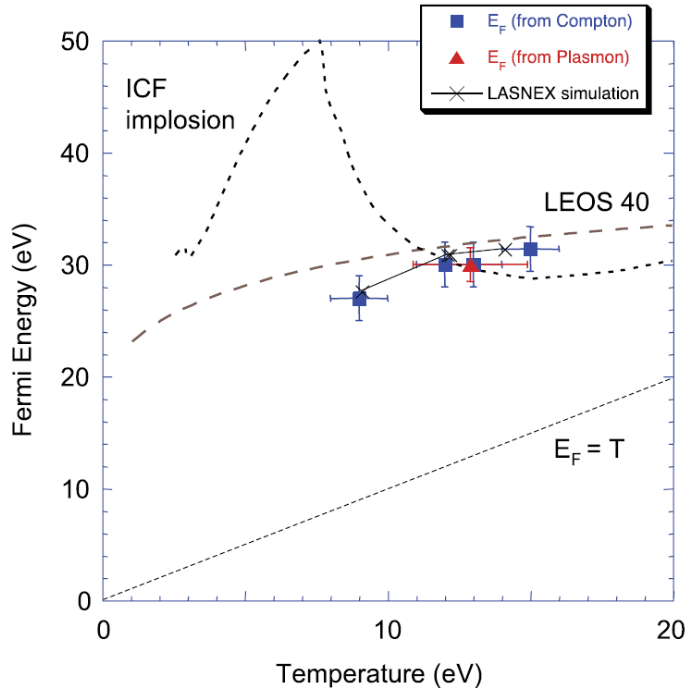
Planar shocks
PI: HJ Lee

Single shock experiments measured up to 4x compression in beryllium and tested conditions encountered in ICF implosions

Width of Fermi-degenerate Compton spectrum sensitive to n_e



Scattering data have tested modeling in conditions of ICF implosions

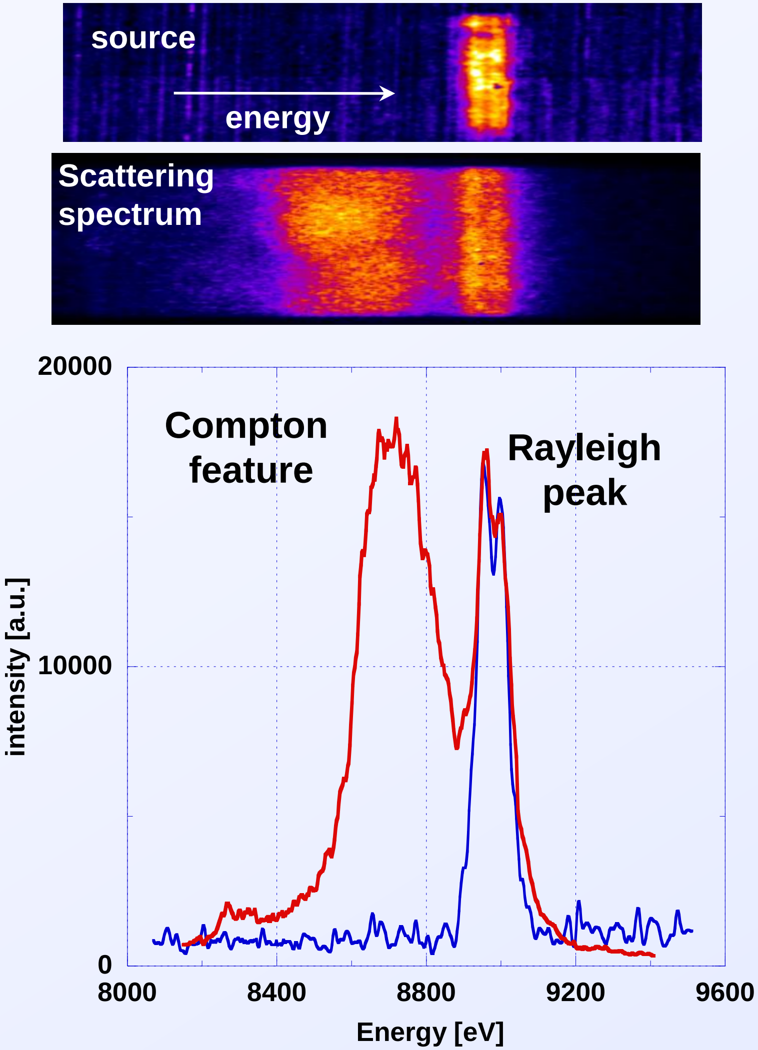


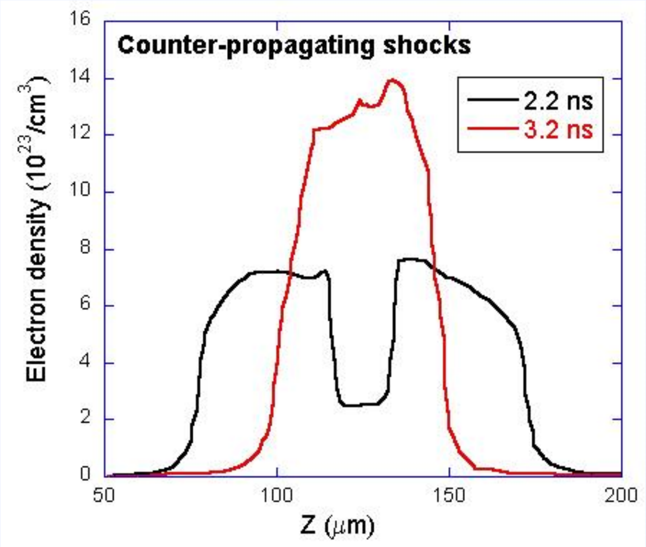
- **Initial experiments used Mn He-α backlighter at 6.18 keV**
- **Disadvantage: double peaks from He-α and intercombination line**

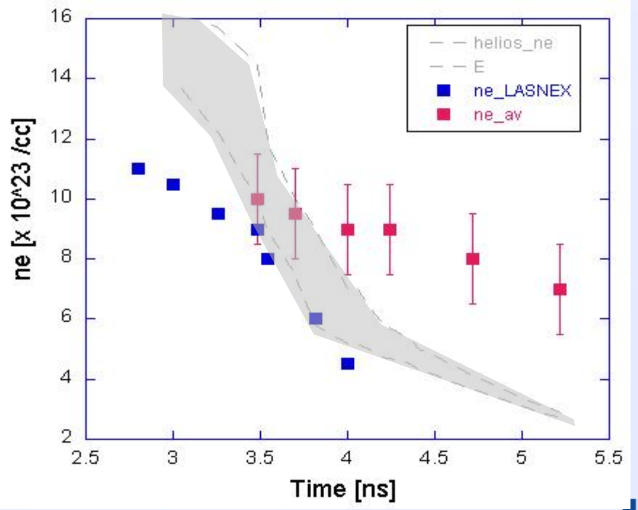
H.J. Lee, Phys. Rev. Lett. 102, 115001 (2009)

Planar shocks
PI: HJ Lee

Experiments with counter-propagating shocks observe slowly decaying high density plasma at $n_e \sim 1 \times 10^{24}\ \mathrm{cm}^{-3}$







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momentum transfer

$$k = 4\pi \frac{E_o}{hc}\sin(\theta/2)$$

- Scattering geometry
- probe energy

Debye screening length

$$\lambda_D = \sqrt{\frac{\varepsilon_o k_B T_e}{n_e e^2}}$$

- plasma parameter

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$\alpha < 1$

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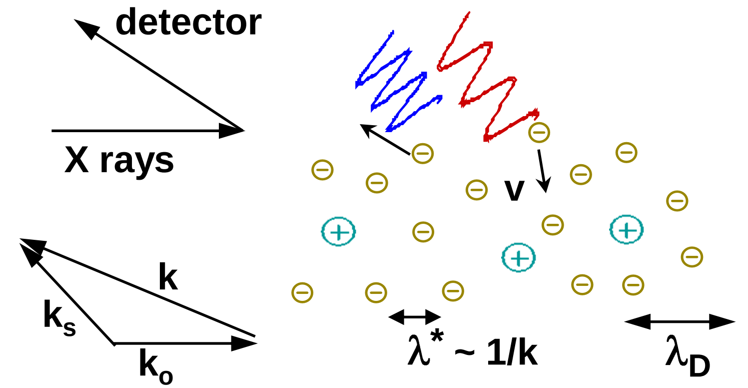
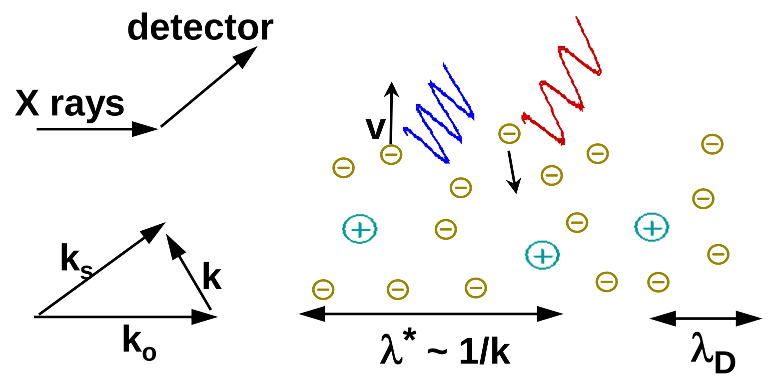
Non-collective scattering ($\lambda^* < \lambda_D$)

probe individual particle motion



Collective scattering ($\lambda^* > \lambda_D$)

probe plasma waves (plasmons)

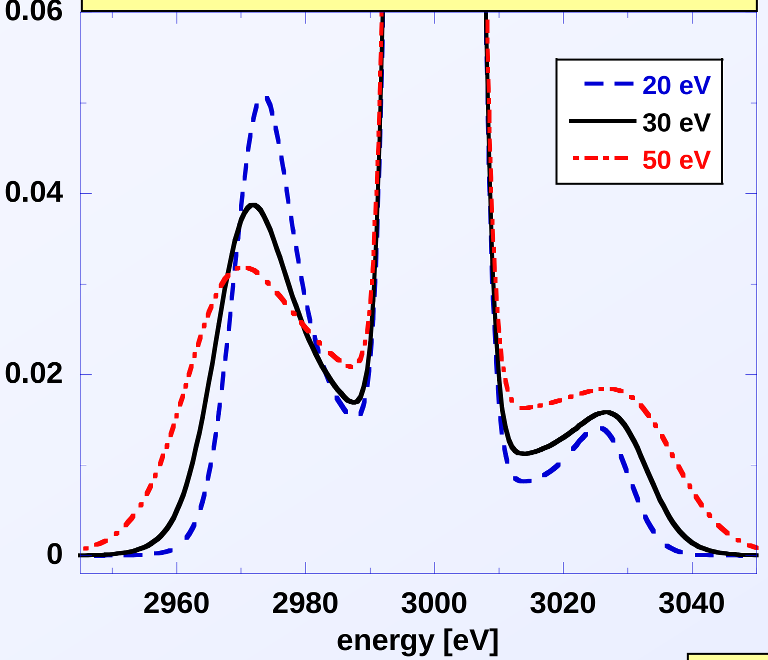


SH Glenzer et al., PRL 90, 175002 (2003)
SH Glenzer et al., PRL 98, 065002 (2007)

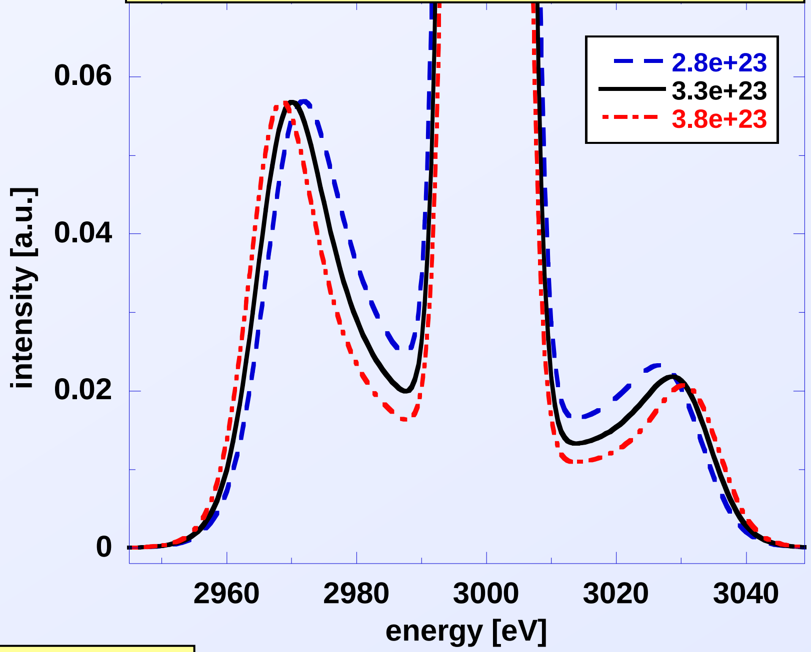
Simulations *(Be plasma, 3 keV probe, 30° scattering, 8 eV instrument function)*

The plasmon shift is sensitive to electron temperature and density

Temperature sensitivity at ne = 2.8e+23/cc



Sensitivity on electron density at Te = 30 eV



Detailed balance

$$\frac{S(-\mathbf{k},-\omega)}{S(\mathbf{k},\omega)} = \exp\left(-\frac{\hbar\omega}{k_B T}\right)$$

resonance frequency

$$\omega_{res}^2 = \omega_p^2 + 3k^2 v_{th}^2 (1 + 0.088 n_e \Lambda^3) + \left(\frac{\hbar k^2}{2m_e}\right)^2$$

plasma frequency

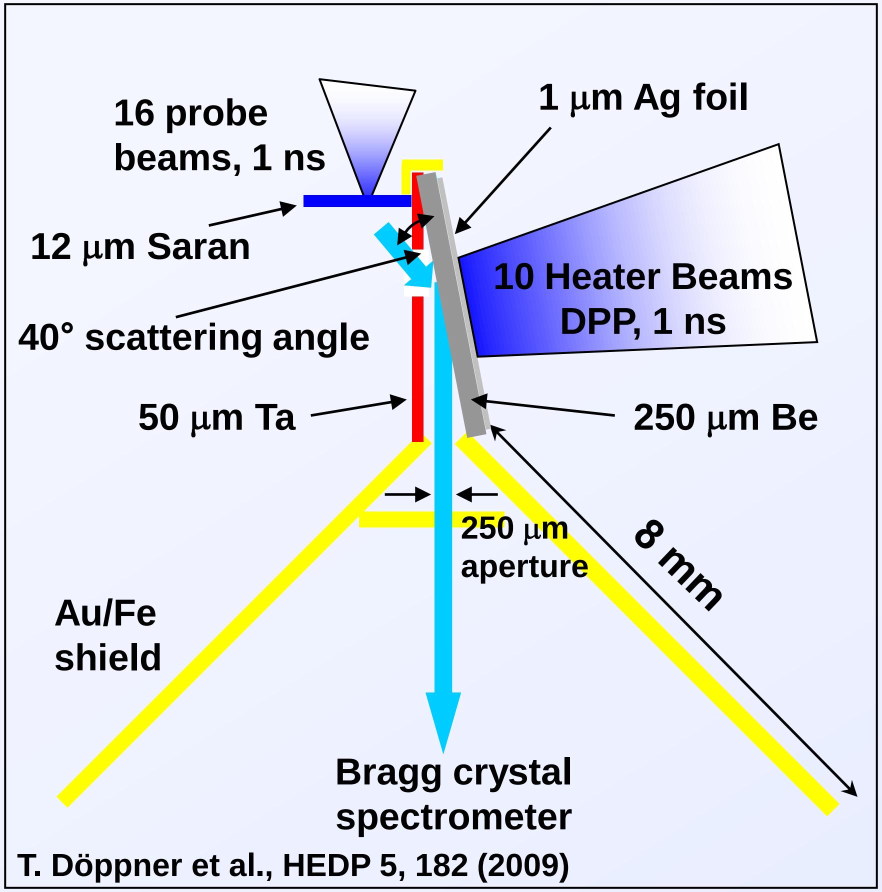
$$\omega_p = \sqrt{\frac{n_e e^2}{\varepsilon_o m_e}}$$

$$v_{th} = \sqrt{\frac{k_B T}{m_e}}$$

thermal velocity

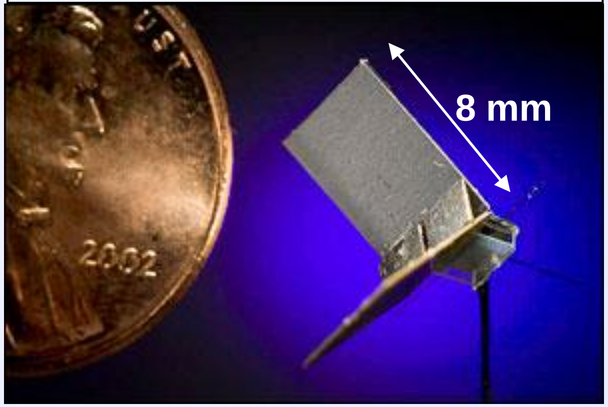
G Gregori et al., PRE 67, 026412 (2003)
SH Glenzer et al., PRL 98, 065002 (2007)

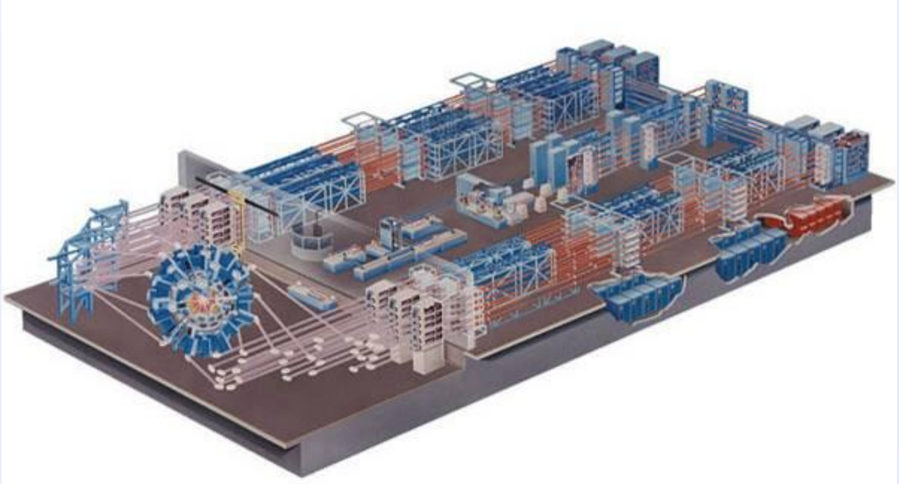
A collective scattering experiment with Cl Ly-a probe (2.96 keV) was performed at the Omega Laser



T. Döppner et al., HEDP 5, 182 (2009)

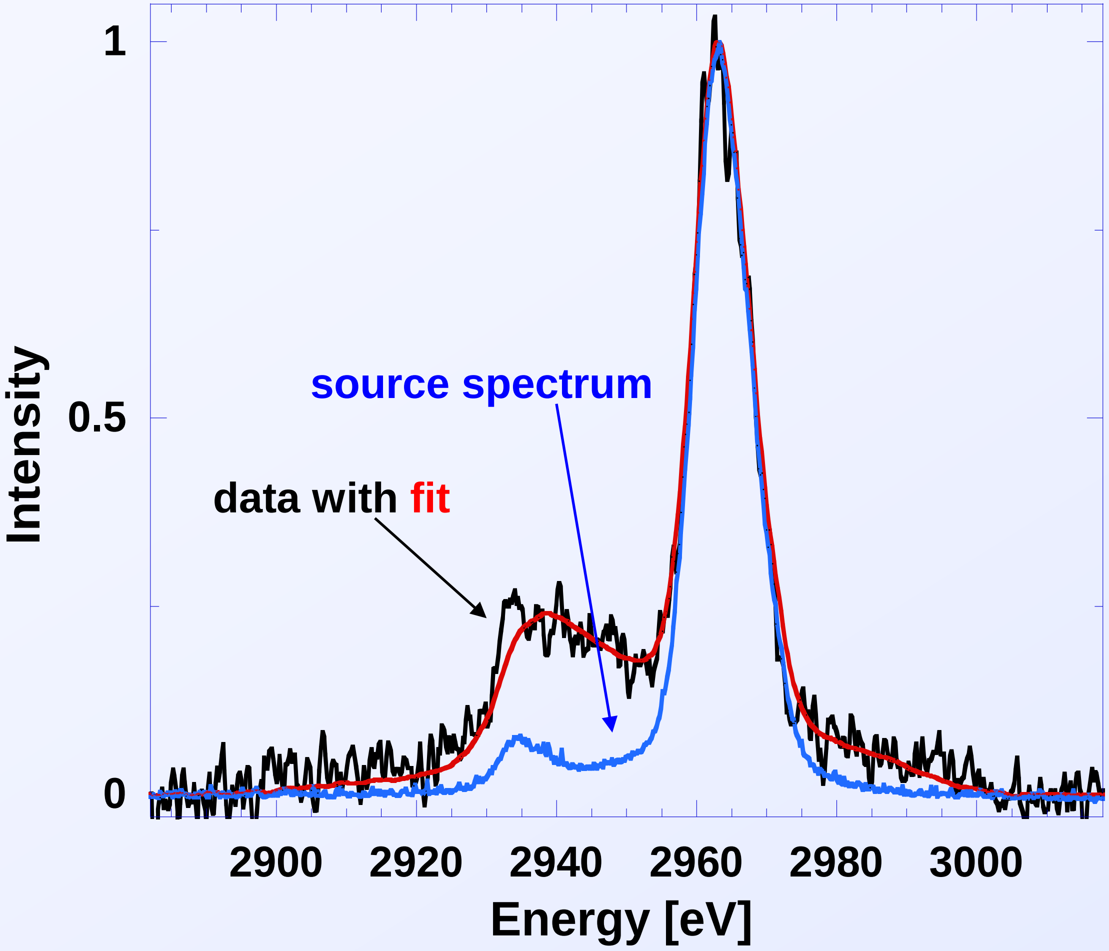
XRTS target





- **Ag L-shell x-rays at ~3.5 keV are utilized to isochorically heat beryllium**

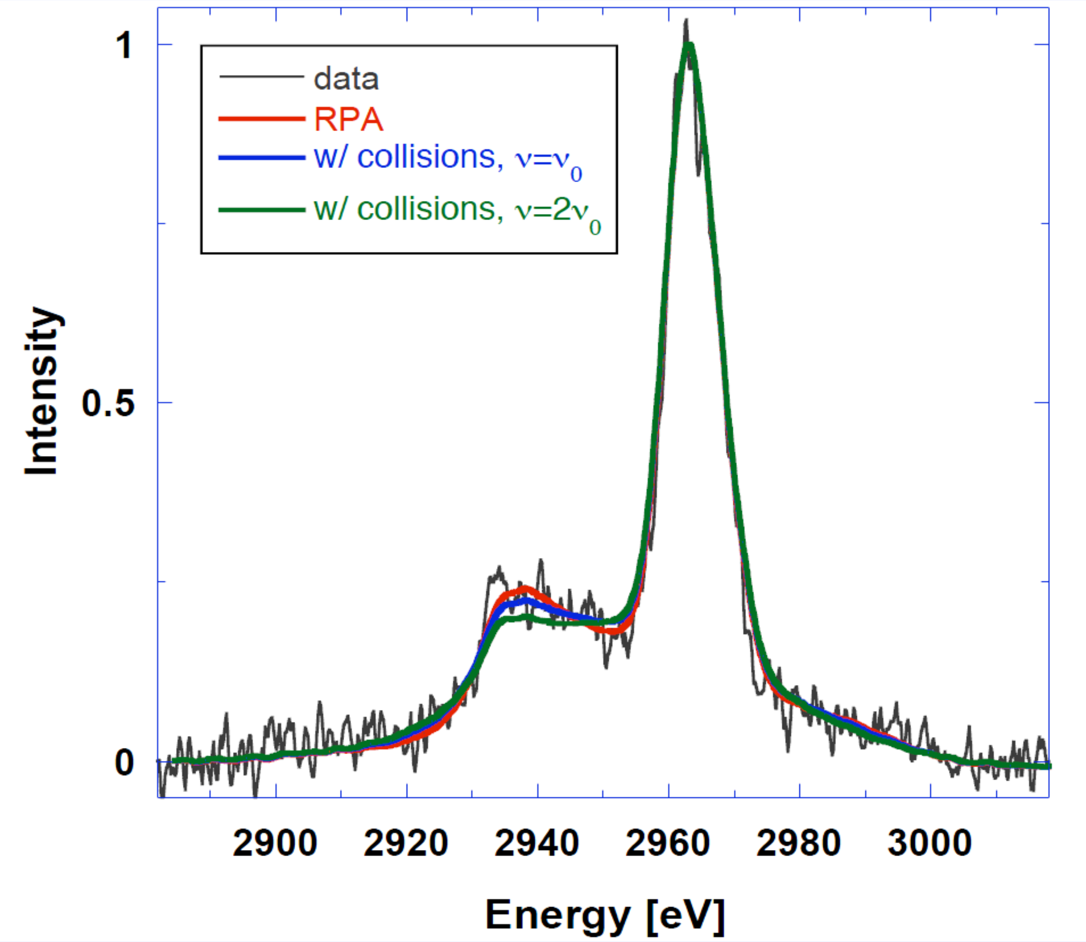
Te = 18 eV and ne = 1.8e+23 are inferred from the scattering spectrum



- collective scattering from plasma waves (α = 1.2)
- asymmetry of up- and down-shifted plasmons (detailed balance) quantitatively observed
- source spectrum yields instrument function
- synthetic spectra are fitted to data
- best fit obtained for Te = 18 eV, ne = 1.8e+23 /cc,
- Zf = 2.3 yields ρ=1.2 g/cc

T. Döppner et al., HEDP 5, 182 (2009)

At α = 1.2 the plasmon feature is not very sensitive to collisions



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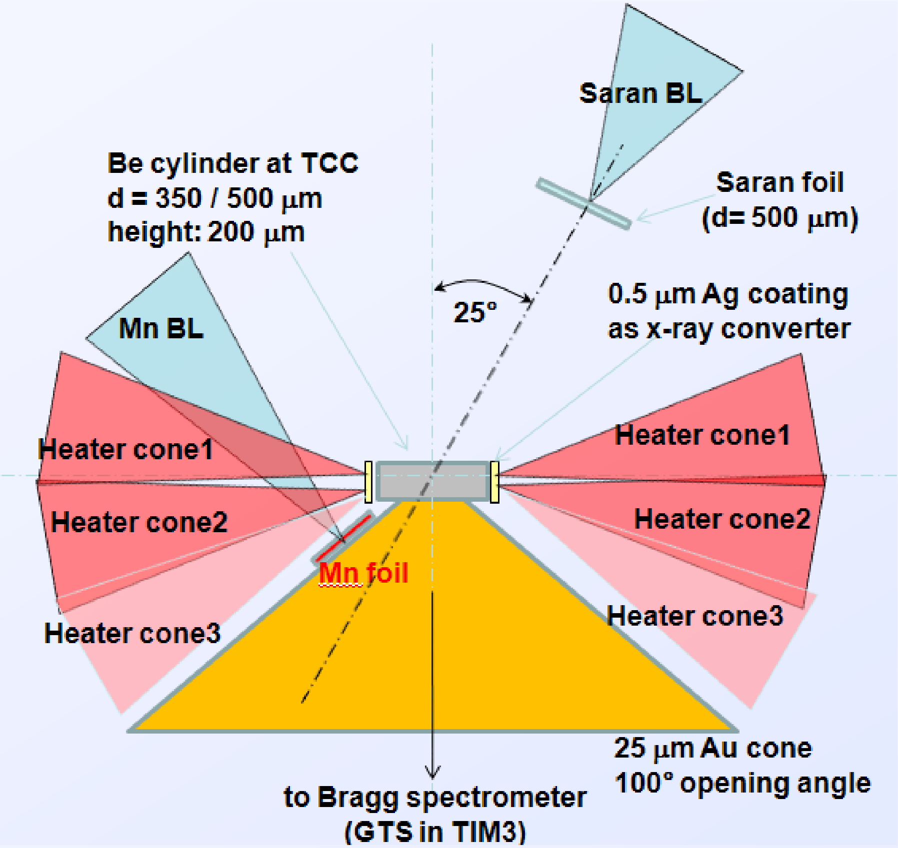
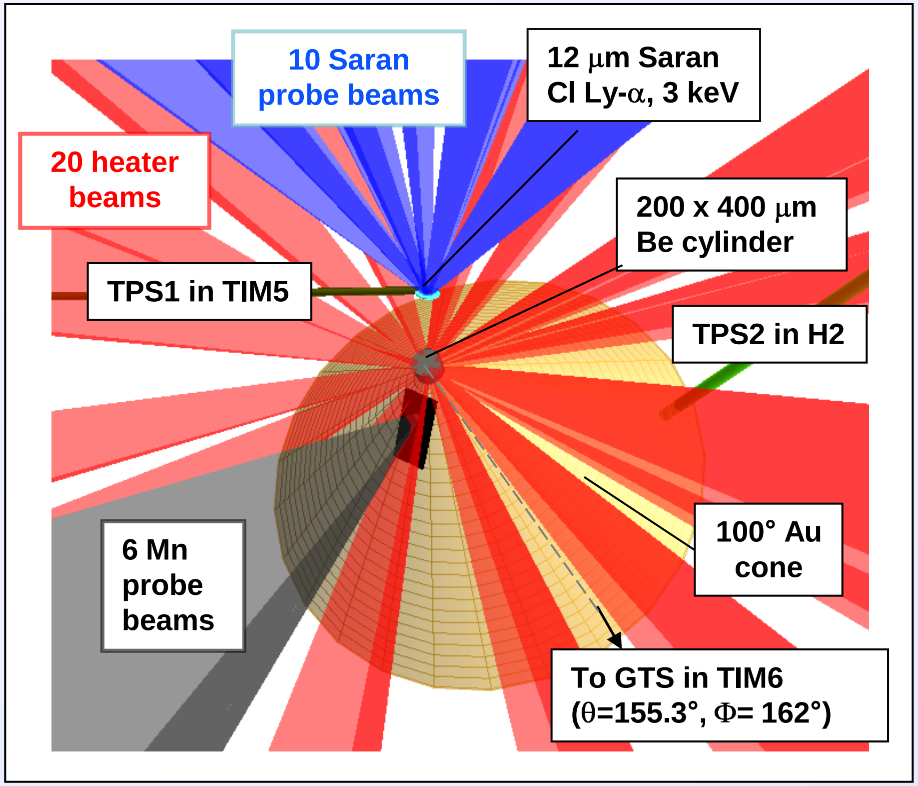
- **Zf = 2.3 yields ρ=1.2 g/cc**

T. Döppner et al., HEDP 5, 182 (2009)

We have designed an experiment at the Omega laser to measure plasmon broadening due to collisions in solid density Be

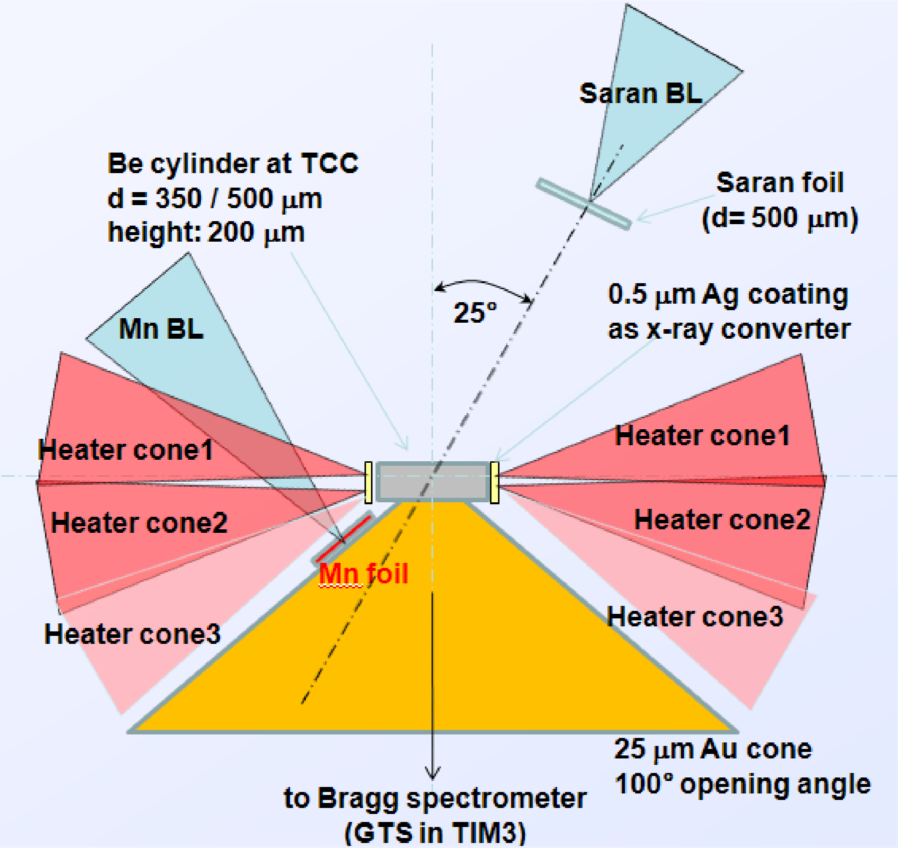


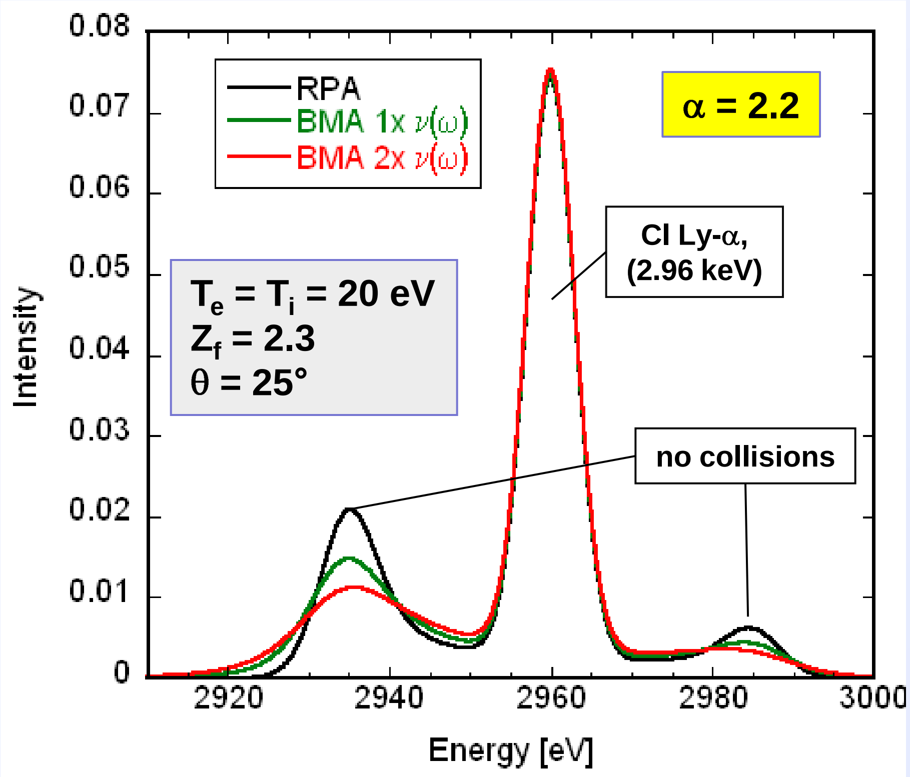


- **solid Be is isochorically heated with Ag L-shell x-rays, created by up to 30 heater beams (230 J per beam) in 450 ps to 20-30 eV**

C. Fortmann et al., Laser Part. Beams 27, 311 (2009)
T. Döppner et al., J. Phys.: Conf. Proc., in print (2010)

At α > 1.7 the plasmon width is very sensitive to collision frequency ν_{ei}





- **Collision rate is calculated in Born approximation and included with a Mermin ansatz**
- **from plasmon broadening collision rate ν_{ei} can be determined**
- **knowledge of ν_{ei} allows to infer conductivity**

C. Fortmann et al., Laser Part. Beams 27, 311 (2009)
T. Döppner et al., J. Phys.: Conf. Proc., in print (2010)

Summary

- X-ray Thomson scattering (XRTS) is a valuable technique to characterize warm dense matter
- Non-collective scattering experiments have measured the density in capsule implosions and shock compressed matter
- Quantitative measurement of plasmon asymmetry (detailed balance) allows temperature measurement based on first principles
- We have designed a collective scattering experiment to measure the e-i collision rate in solid density Be, allowing to infer conductivity at conditions relevant for the NIF.
- XRTS measurements are important for guidance of theoretical models