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2370-2

School and Training Course on Dense Magnetized Plasma as a Source of Ionizing Radiations, their Diagnostics and Applications

8 - 12 October 2012

Laser Scattering by Plasmas

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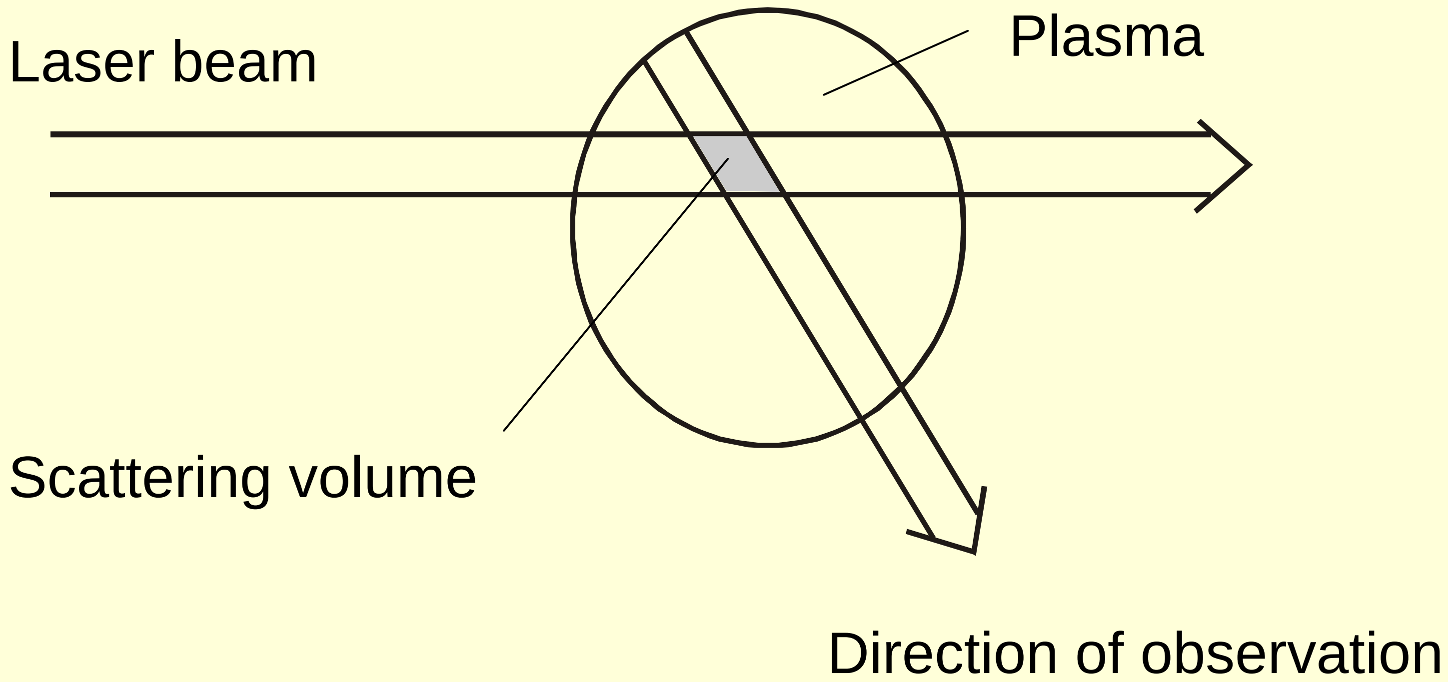
ICTP, Trieste, October 8 -12, 2012

Injection of a laser beam into a plasma allows localized measurements



Information due to scattering is from the gray volume in the Plasma, plasma radiation is collected along the line of sight

Laser beams interact with

electrons
ions
atoms
molecules

Due to

tuneability and possible high power of lasers

interactions are numerous inclusive heating of plasma

a) $\Rightarrow$ Modification of the primary transmitted beam

b) $\Rightarrow$ Scattering

a) Laser atomic absorption spectroscopy (LAAS)

with tunable diode lasers much applied in low density plasmas

reduction of the intensity by absorption $\int .....ds$

modification of the

phase $\Rightarrow$ interferometry $\int n_e ds$

plane of polarization $\Rightarrow$ Faraday rotation $\int n_e B ds$

Scattering by atoms, ions, and molecules

laser induced fluorescence (LIF)

Rayleigh scattering

Raman scattering

Coherent anti-Stokes Raman scattering (CARS)

Scattering by electrons --- Thomson scattering

All techniques employing lasers are treated by

K. Muraoka, M. Maeda,

Laser-aided Diagnostics of Plasmas and Gases

IOP, Bristol 2001

Since 1963 Thomson scattering by plasma electrons matured into one of the most powerful diagnostic methods for the determination of plasma parameters

Latest development: employing x-rays at near solid state density plasmas
scattering experiments on warm density matter using a FEL

Reviews:

H.-J. Kunze, in *Plasma Diagnostics*, ed. W. Lochte-Holtgreven
North-Holland, Amsterdam 1968

D. E. Evans and J. Katzenstein,
Rep. Prog. Phys. **32**, 207 (1969)

A. W. DeSilva and G. C. Goldenbaum
in *Methods of Experimental Physics Vol. **9A,***
ed. H.R. Griem and R.H. Lovberg,
Academic Press, New York 1970

J. Sheffield, Plasma Scattering of Electromagnetic Radiation
Academic Press, New York, 1975

D, H. Dustin, S. H. Glenzer, N. C. Luhmann Jr., J. Sheffield
Plasma Scattering of Electromagnetic Radiation
Elsevier, Amsterdam 2001

Incoherent Thomson scattering

Principles

Theory is well understood:

Electromagnetic waves are focused into the plasma

$\Rightarrow$ charged particles oscillate and radiate like dipoles;

because of small mass (m_e<< M) acceleration of the

ions is much smaller and

essentially only electrons contribute

$\Rightarrow$ scattered radiation

Cross-section
(Thomson)

$$\sigma_{Th} = \frac{8}{3}\pi r_e^2 \cong \frac{2}{3} 10^{-24}\ cm^2$$

is extremely small ⟶

$\Rightarrow$ to have enough scattered photons one needs

- long observation times (stationary plasmas) or

  phase-locked observation over many cycles of rf-produced plasmas

and/or • high intensity of incident radiation

$\Rightarrow$ scattered radiation should be clearly above plasma background radiation $\Rightarrow$ lasers

At *low* densities all electrons scatter independently

no correlation between the electrons

scattered intensities simply add

$$\frac{\mathrm{d}\sigma}{\mathrm{d}\Omega} = n_e\,\sigma_e = n_e\,r_e^2 \sin^2\varphi = n_e\,\frac{3}{8\pi}\sigma_{Th}\sin^2\varphi \propto n_e$$

In the plasma electrons move fast $\Rightarrow$ considerable Doppler shift

Doppler shift has to be considered twice

Incoming wave $(\omega_o, \vec{k_o})$

Scattered wave $(\omega_s, \vec{k_s})$

Scattering angle $\sphericalangle(\vec{k_s}, \vec{k_o}) = \theta$

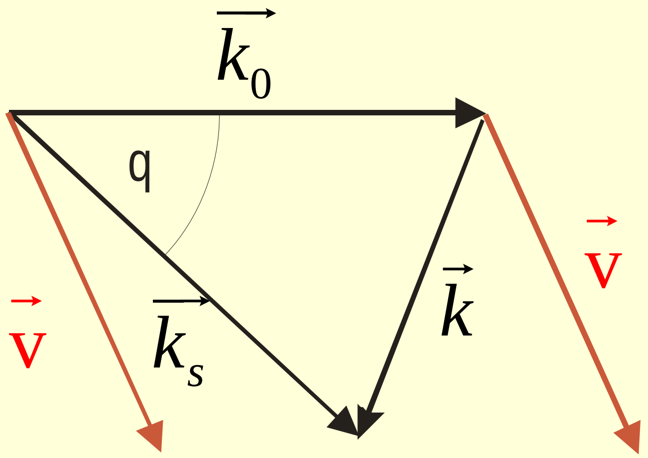
$$\omega = \omega_s - \omega_o = \vec{k}\vec{\mathrm{v}}$$

$$\vec{k} = \vec{k_s} - \vec{k_o}$$

multiplication with $\hbar$

equations correspond to conservation of energy and momentum

$\vec{k}$ scattering vector



$$\vec{k}_s \simeq \vec{k}_o$$

$$k \simeq 2k_o \sin\frac{\theta}{2} \simeq \frac{4\pi}{\lambda}\sin\frac{\theta}{2}$$

$$\omega = \omega_s - \omega_o = \vec{k}\vec{\mathrm{v}} = \mathrm{k\ v_k}$$

Only the component v_k in the direction of the scattering vector $\vec{k}$ is responsible for a Doppler shift !

hence

The Doppler broadened scattered radiation mirrors the one-dimensional velocity distribution function $f_k(v_k)$!

$$\mathrm{v}_k = \frac{(\omega_s - \omega_o)}{k} \quad \Rightarrow \quad f_k(\mathrm{v_k}) \quad \Rightarrow \quad f_k\left(\frac{\omega_s - \omega_o}{k}\right)$$

Fraction of electrons dn_e *giving the same Doppler shift*

$$\mathrm{d}n_e = n_e \; f_k(\mathrm{v}_k)\,\mathrm{d}\mathrm{v}_k = n_e \frac{1}{k} f_k\left(\frac{\omega_s - \omega_o}{k}\right)$$

Differential scattering cross-section

$$\frac{\mathrm{d}^2\sigma}{\mathrm{d}\Omega_s \mathrm{d}\omega_s} = \frac{3}{8\pi} n_e \; \sigma_{Th} \sin^2\varphi \frac{1}{k} \; f_k\left(\frac{\omega_s - \omega_o}{k}\right)$$

n_e and f_k are measured

Maxwellian velocity distribution function

scattered profile is of Gaussian shape

FWHM

$$\Delta\lambda_{1/2} = 4\,\lambda_0 \sin\frac{\theta}{2}\left(\frac{2k_B T_e}{m_e c^2}\ln 2\right)$$

Example: l$_0$ = 694.3 nm (ruby laser) and q = 90^o

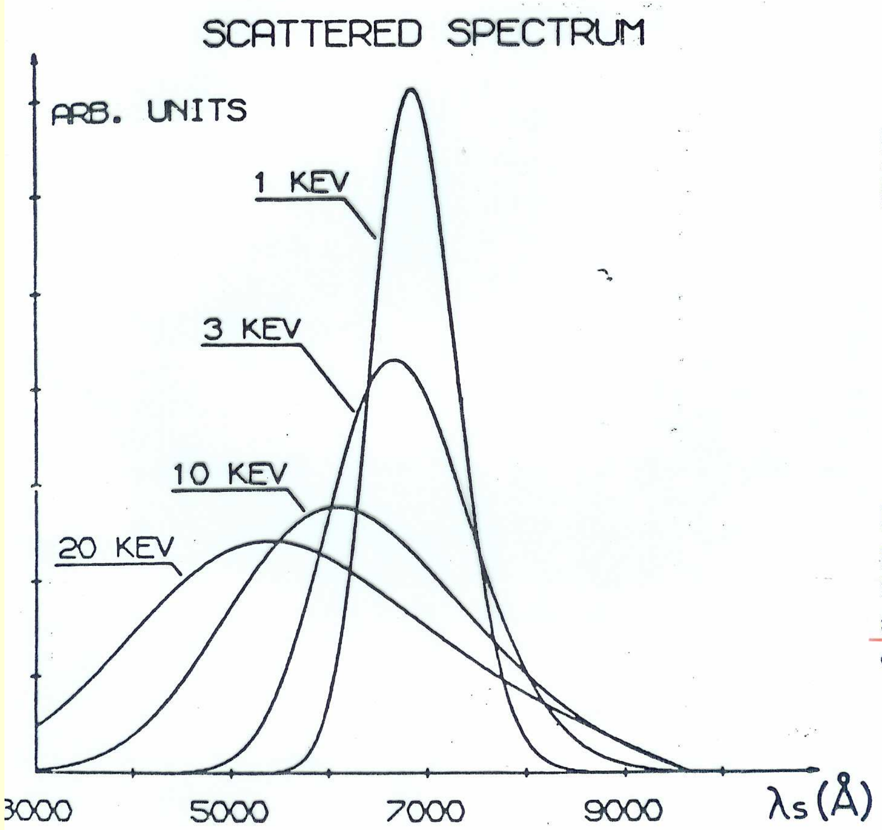
$$k_B T_e = 100\,eV \qquad \Delta\lambda_{1/2} = 32.4\,nm$$

$$k_B T_e = 1\,eV \qquad \Delta\lambda_{1/2} = 3.24\,nm$$

Large widths! Low resolution instruments suffice

High temperatures ? Relativistic effects !

At higher temperatures ⟶ relativistic treatment



Calculated scattering spectra at $\vartheta = 90°$ for various temperatures. Incident wavelength $\lambda_0 = 694{,}3$ nm.

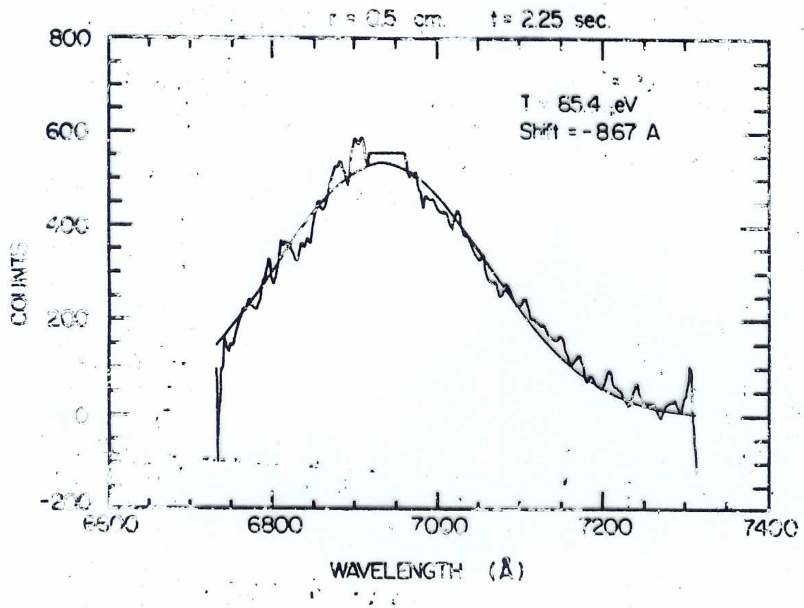


FIG. . Scattering spectrum obtained from one discharge for a high-density plasma ($\sim 10^{16}$ cm^{-3}). The shift parameter is obtained from a least squares fit to a Gaussian. The first-order relativistic correction predicts a – 9.4 Å shift. The temperature is determined from a fit to the relativistically corrected Gaussian.

K. C. Maffei and H. R. Griem 3030

Experimental constraints and techniques

Pulsed experiments $\Rightarrow$ powerful lasers
to have sufficient scattered photons

$\Rightarrow$ spectroscopic instruments with high throughput necessary
good detectors of high quantum efficiency
CCD cameras give the whole spectrum
if stigmatic spectrograph
spatially resolved measurements are possible
polychromators with fiber bundles connected to photo-
multipliers have been used

One major problem is always stray light !

Imagine	incident	100 MW
	scattered	μW and less

Brewster windows on entrance and exit ports

Well-designed baffle systems (a series of diaphragms) for laser and observation

Beam dump for laser

Viewing dump

Triple grating instrument

Heating of plasma by laser beam has to be watched !

Heating is by absorption by the process of inverse bremsstrahlung

Absolute calibration of the complete scattering system including the laser

Rayleigh or Raman scattering in a gas of known cross-section filled into the discharge chamber

full geometry and detector remain identical

In technical plasmas:

Rayleigh scattering off neutrals

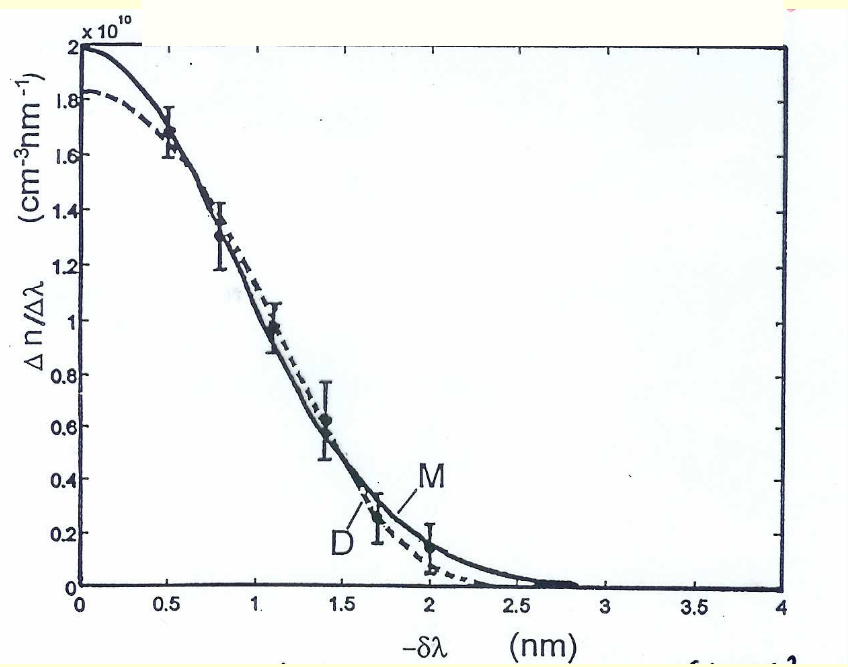
LIF from excitation of neutrals and molecules

Possible improvement by gating detector since fluorescence radiation is much longer than laser pulse

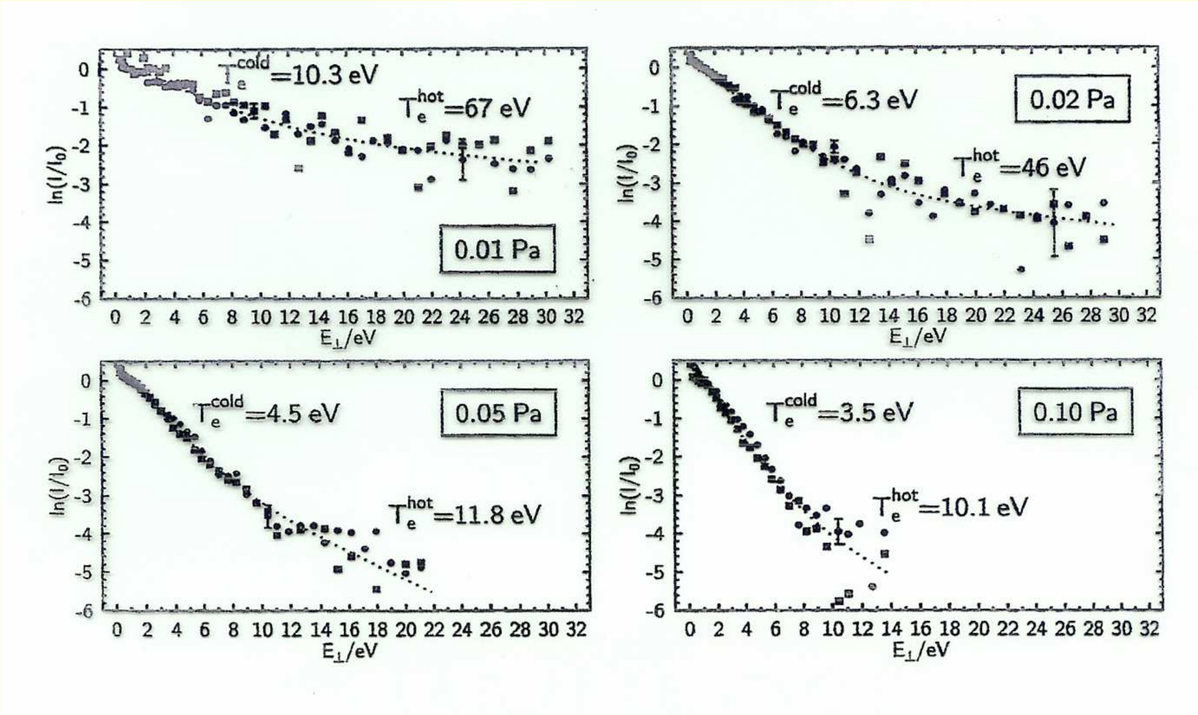
At very low density plasmas the number of scattered photons becomes too small

$\Rightarrow$ different approach

Use of lasers with lower power but with high repetition rate
less than one photon now must arrive at the detector per pulse and *synchronized photon counting*



M: Maxwell distribution
D: Druyvesteyn distribution



Hemmers et al.
Düsseldorf

ECR Discharge

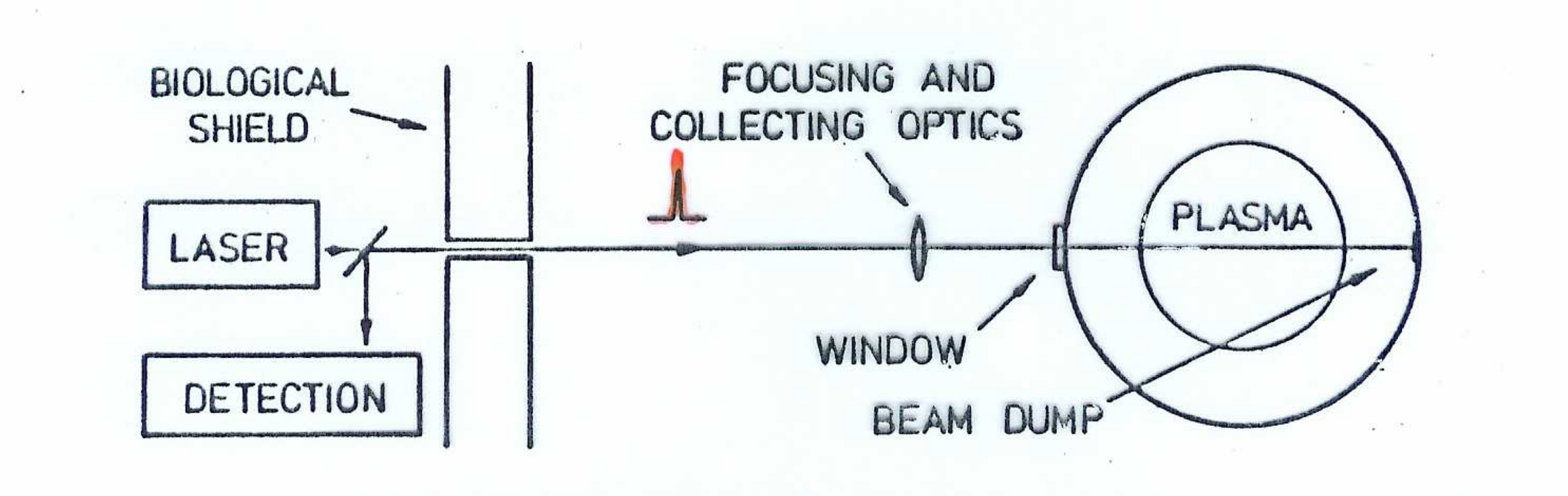
NdYAG laser, frequency doubled, 10 Hz

11 channel detetcor system with PM

Scattering on large fusion devices

Salzmann and Hirsch proposed a backscattering scheme employing a sub-nanosecond laser pulse and time-of-flight analysis with high-speed detectors

LIDAR: Light detection and ranging



First implemented on JET, laser duration was 300 ps (9 cm long!)

Collective Thomson scattering

With increasing density correlations between the plasma particles start to become noticeable

Not the scattered intensities add

but the electric fields

A measure of the influence of correlations is 1/*k*, i.e. the distance over which the particles are sampled in relation to the Debye length λ_D

$$\frac{1}{k} \ll \lambda_D \Rightarrow k\lambda_D \gg 1 \Rightarrow \alpha = \frac{1}{k\lambda_D} \ll 1 \qquad \text{no correlations}$$

$$\frac{1}{k} > \lambda_D \Rightarrow k\lambda_D < 1 \Rightarrow \alpha = \frac{1}{k\lambda_D} > 1 \qquad \text{correlations}$$

a is called the scattering parameter

$$\alpha = \frac{1}{k\lambda_D} \approx \frac{\lambda_o}{4\pi\lambda_D \sin(\theta/2)}$$

Thus the influence of correlations on the scattered spectrum can be varied by varying l_o and the scattering angle q

Theory

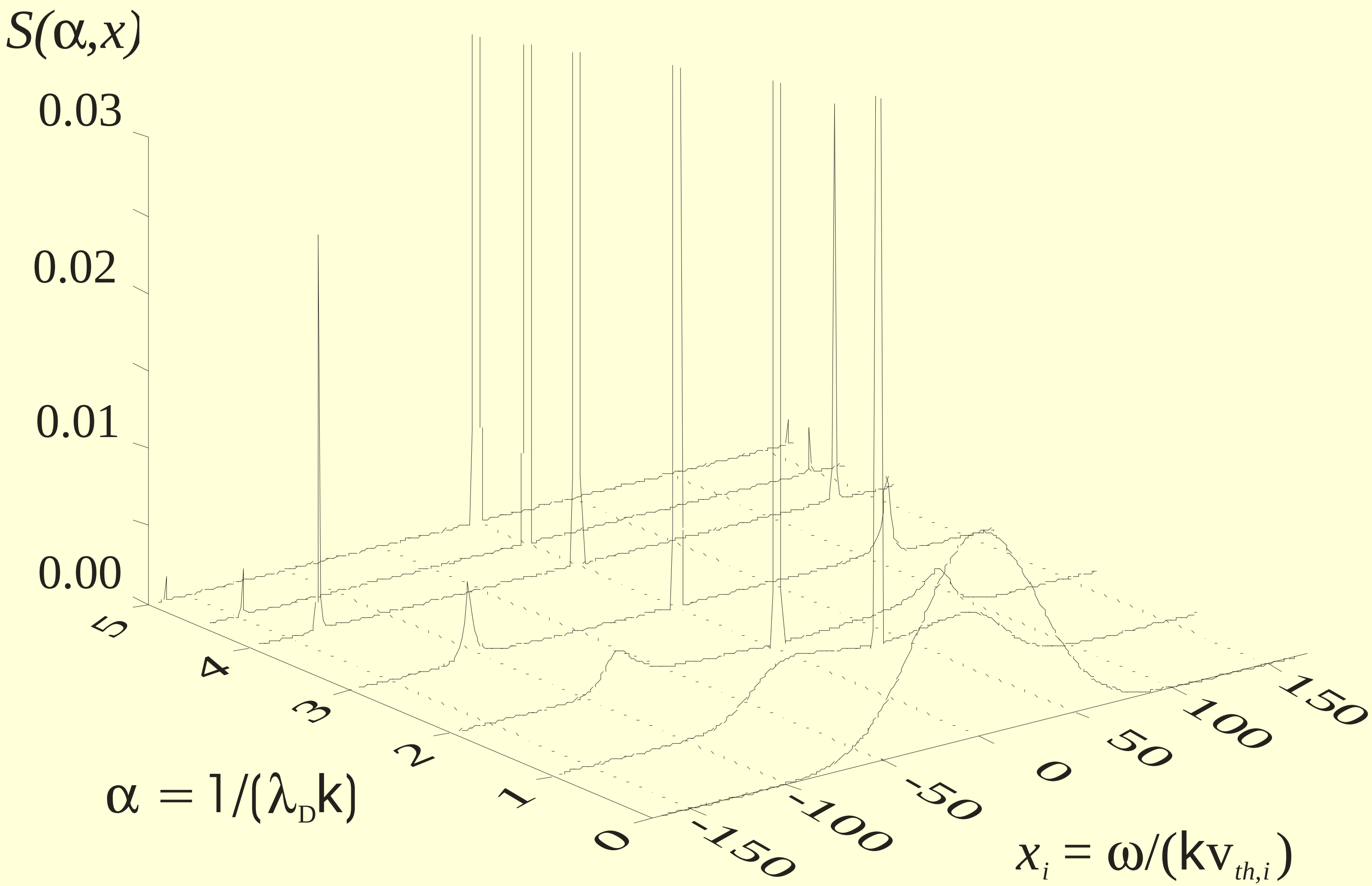
$$\frac{\mathrm{d}^2\sigma}{\mathrm{d}\Omega\mathrm{d}\omega} = r_e^2 \sin^2\varphi\, n_e\, S(\vec{k},\omega)$$

First two factors: scattering property of free electron

$S(\vec{k},\omega)$: is known as dynamic form factor and contains the properties of the system of electrons

$S(\vec{k},\omega)$ has been calculated by many authors and is, at present, studied again for high density warm matter

Analytical representation was given by
Salpeter, Phys. Rev. **120**, 1528 (1960)



(Wrubel)

$$S(\vec{k},\omega) = S_e(\vec{k},\omega) + S_i(\vec{k},\omega)$$

$S_e(\vec{k},\omega)$ electron feature, it reflects scattering by electrons, which move uncorrelated or are correlated with the motion of other eletcrons

$S_i(\vec{k},\omega)$ ion feature, contains scattering contributions of those electrons which are correlated with the motion of the ions

$\Rightarrow$ two scale lengths for the Doppler shifts

$$x_e = \frac{\omega}{k \mathrm{v}_{th,e}} \quad \text{and} \quad x_i = \frac{\omega}{k \mathrm{v}_{th,i}}$$

$$S_e(\vec{k},\omega) = \Gamma_\alpha(x_e)\,\mathrm{d}x_e \quad \text{and} \quad S_i(k,\omega) = \frac{Z\alpha^4}{(1+\alpha^2)^2}\Gamma_\beta(x_i)\mathrm{d}x_i$$

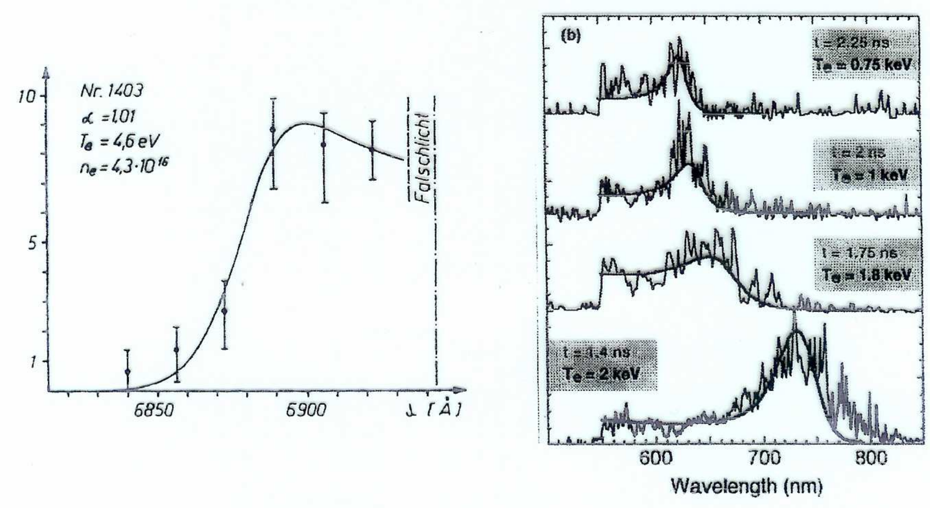
$\Gamma_\alpha(x)$ Salpeter shape function, and $\beta^2 = Z\dfrac{\alpha^2}{1+\alpha^2}\dfrac{T_e}{T_i}$

Electron feature $S_e(\vec{k},\omega)$, correlated motion of the electrons

$\Rightarrow$ plasma waves

Position of maximum is given by the Bohm-Gross dispersion relation

$$(\omega_s - \omega_o)^2 = \omega_{BG} = \omega_p^2 \frac{3k_B T_e}{m_e} k^2$$

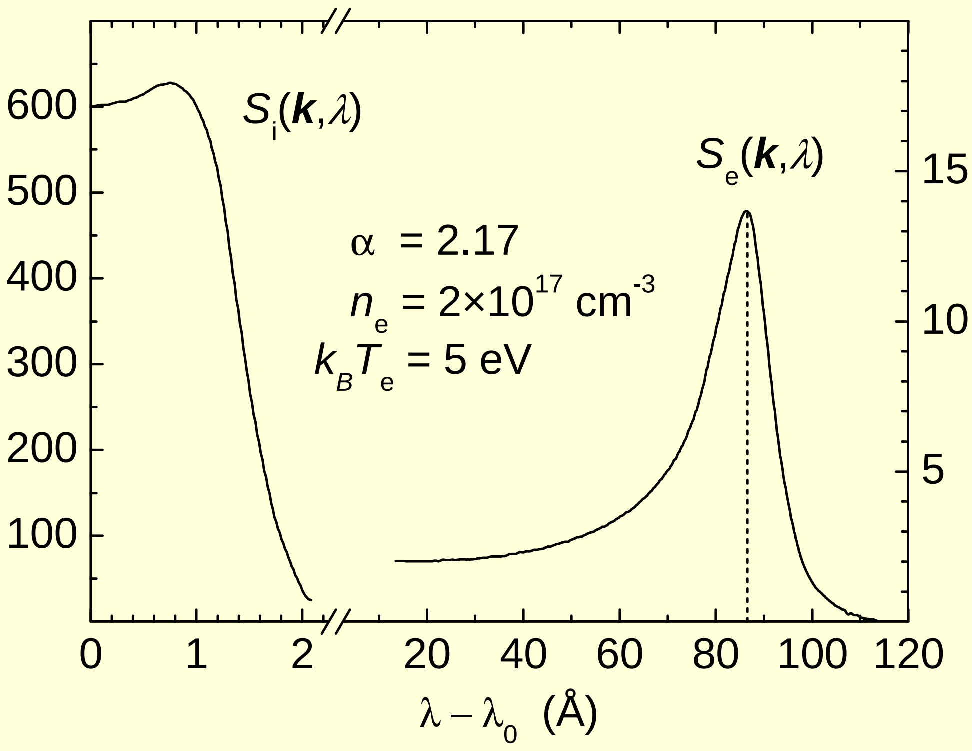


Theta pinch 1964 — highly ionized gold plasma produced by laser, 1999 (Livermore, Glenzer et al.)

Around α ~1
shape of electron feature changes very much and
shape alone gives
n_e and T_e,
no absolute calibration necessary!

Problem at large α: $S_e(\vec{k}) = S_e(\vec{k},\omega)\mathrm{d}\omega = \dfrac{1}{1+\alpha^2}$ small

Theoretical spectrum, λ_o= 694.3 nm, θ = 90º, α = 2.17



Advantage ion feature: remains large
narrow, easily above plasma background

123305-2 I. E. Olivares and H.-J. Kunze J. Appl. Phys. **99**, 123305 (2006)

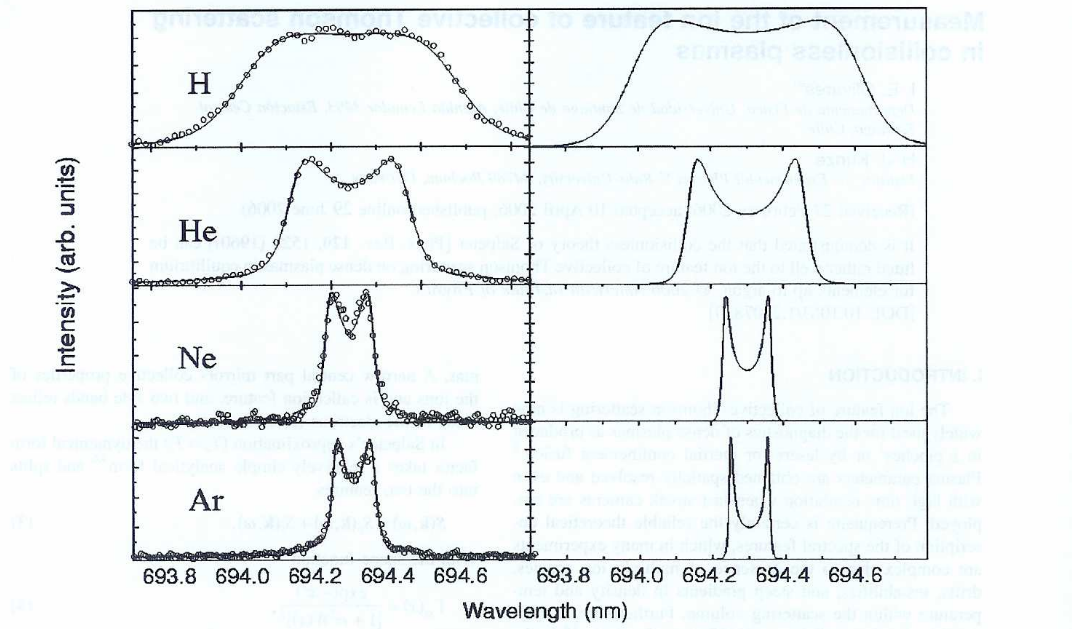
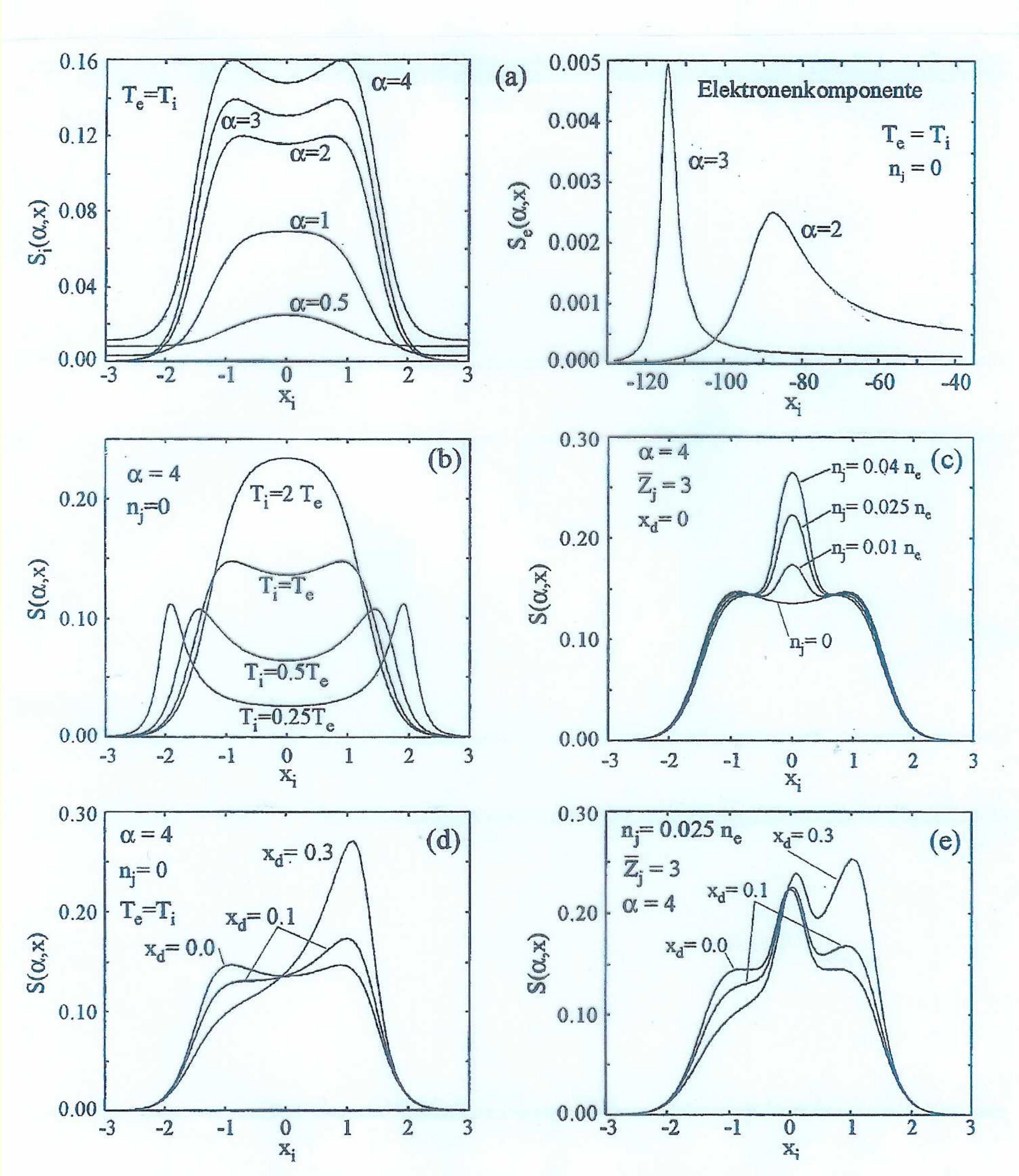


FIG. 1. Thomson scattering spectra of collissionless plasmas at optimal conditions of the gas liner pinch: (a) hydrogen: 0.02 nm/pixel, $n_e=0.62\times10^{18}$ cm^{-3}, $T_e=T_i=22$ eV, Z=1; (b) helium: 0.02 nm/pixel, $n_e=6.05\times10^{18}$ cm^{-3}, $T_e=T_i=16$ eV, Z=2; (c) neon: 0.0064 nm/pixel, $n_e=0.55\times10^{18}$ cm^{-3}, $T_e=T_i=12$ eV, Z=2.6; (d) argon: 0.0064 nm/pixel, $n_e=0.96\times10^{18}$ cm^{-3}, $T_e=T_i=14$ eV, Z=3.6.

Scattering in a linear pinch discharge with different gas fillings

Peaks correspond to ion acoustic modes

$$(\omega_s-\omega_o)^2 = \left(\frac{Zk_BT_e}{m_i}\frac{\alpha^2}{1+\alpha^2}+\frac{3k_BT_i}{m_i}\right)k^2$$



Hydrogen plasma

Damping of ion acoustic modes determines details of the shape

Damping

- $\dfrac{T_e}{T_i}$

- drift between electrons and ions

Impurities

Shift of ion feature, readily measured, macroscopic motion of plasmas

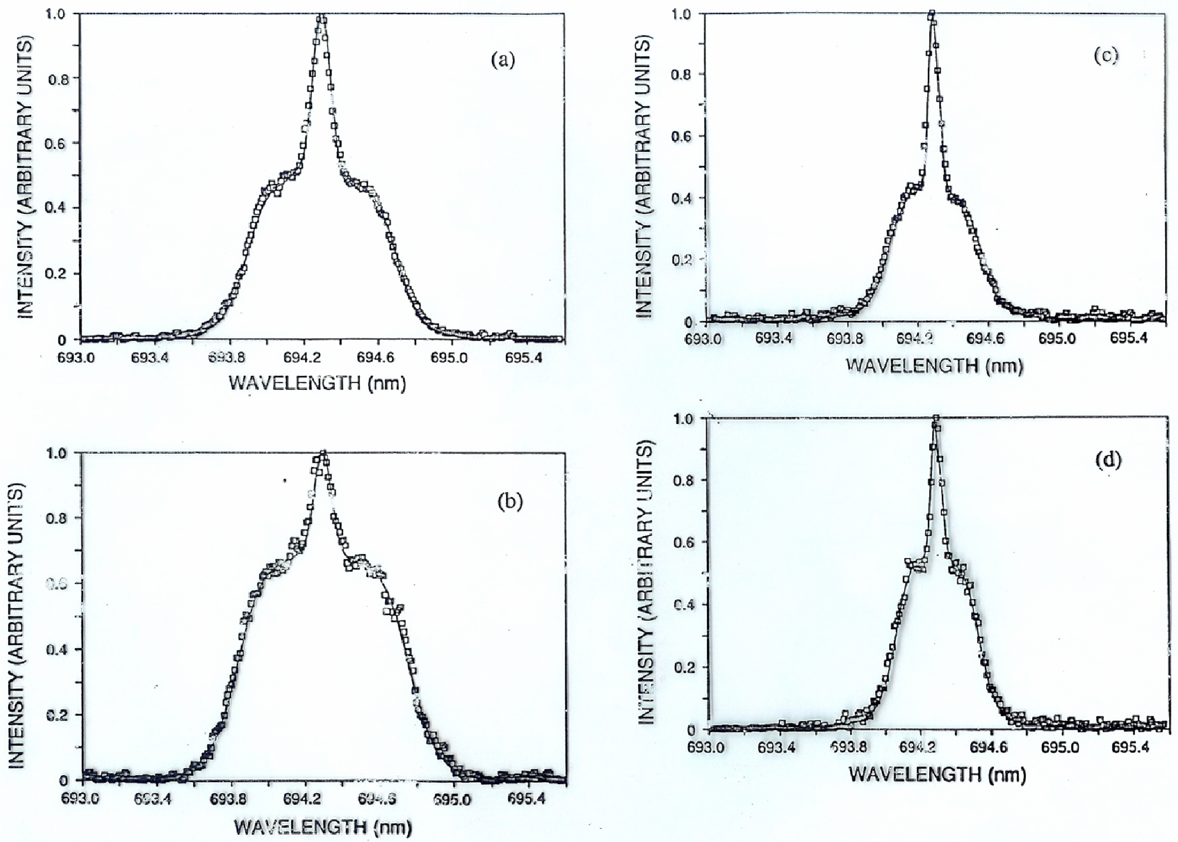
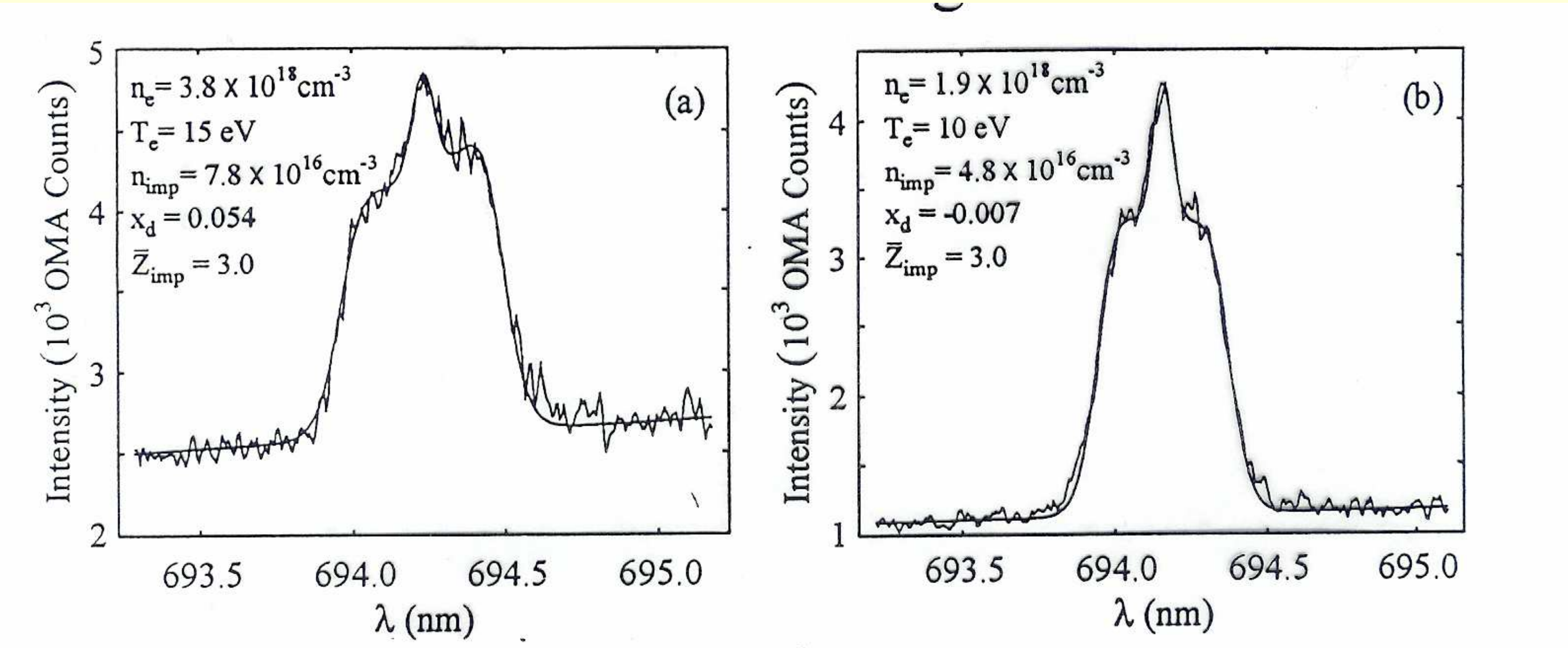


FIG. 5. Measured single-shot scattered light spectra for hydrogen plasmas with noble gas additive. Square points are OMA data, solid line is best fit to theory. Parameters from fitting to theory are (a) 1% argon, $T_i = 35$ eV, $n_e = 8\times 10^{24}$ m^{-3}, $Z^* = 7.5$. (b) 0.29% argon, $T_i = 46$ eV, $n_e = 2\times 10^{24}$ m^{-3}, $Z^* = 7.9$. (c) 4.5% xenon, $T_i = 17.5$ eV, $n_e = 2.5\times 10^{24}$ m^{-3}, $Z^* = 3.8$. (d) 4.8% xenon, $T_i = 17$ eV, $n_e = 1\times 10^{24}$ m^{-3}, $Z^* = 2.7$.

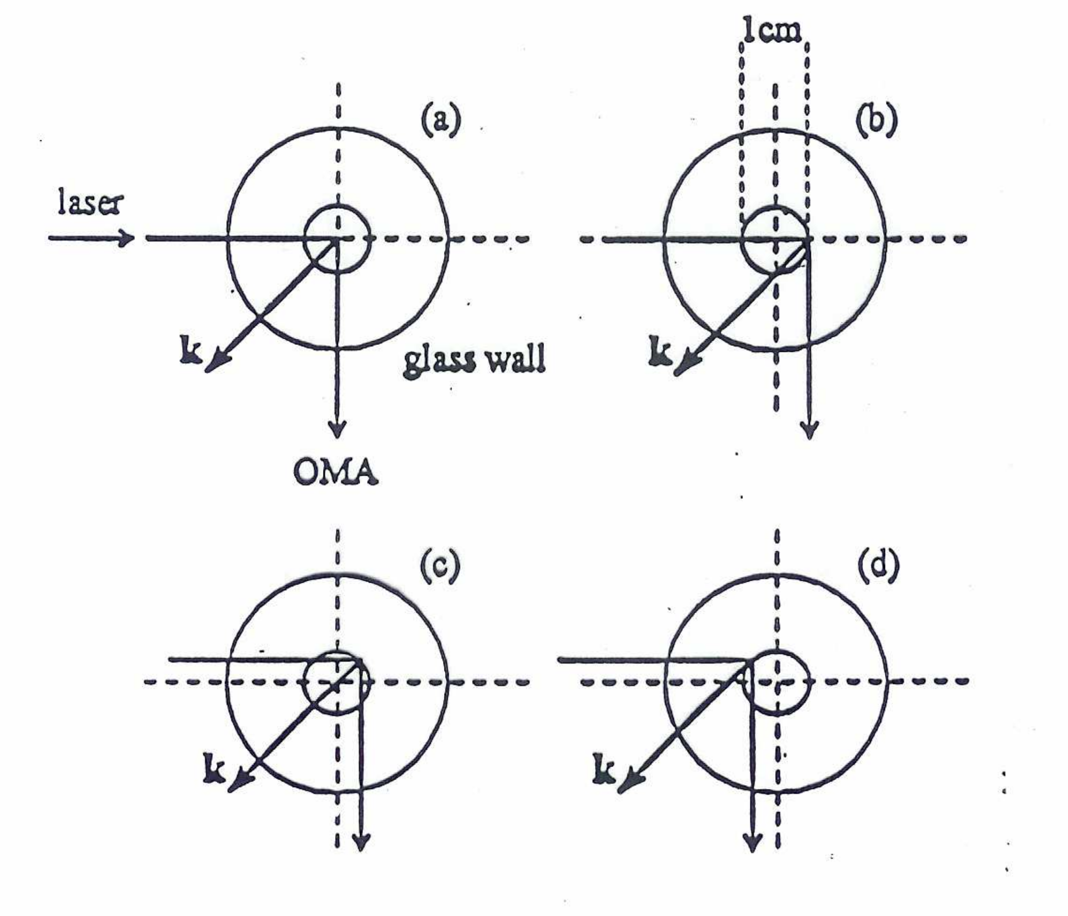
Impurities !

n_{imp} can be determined if Z is known

Examples of spectra obtained in the gas-liner pinch (Z-pinch)



Selection of scattering direction and scattering volume

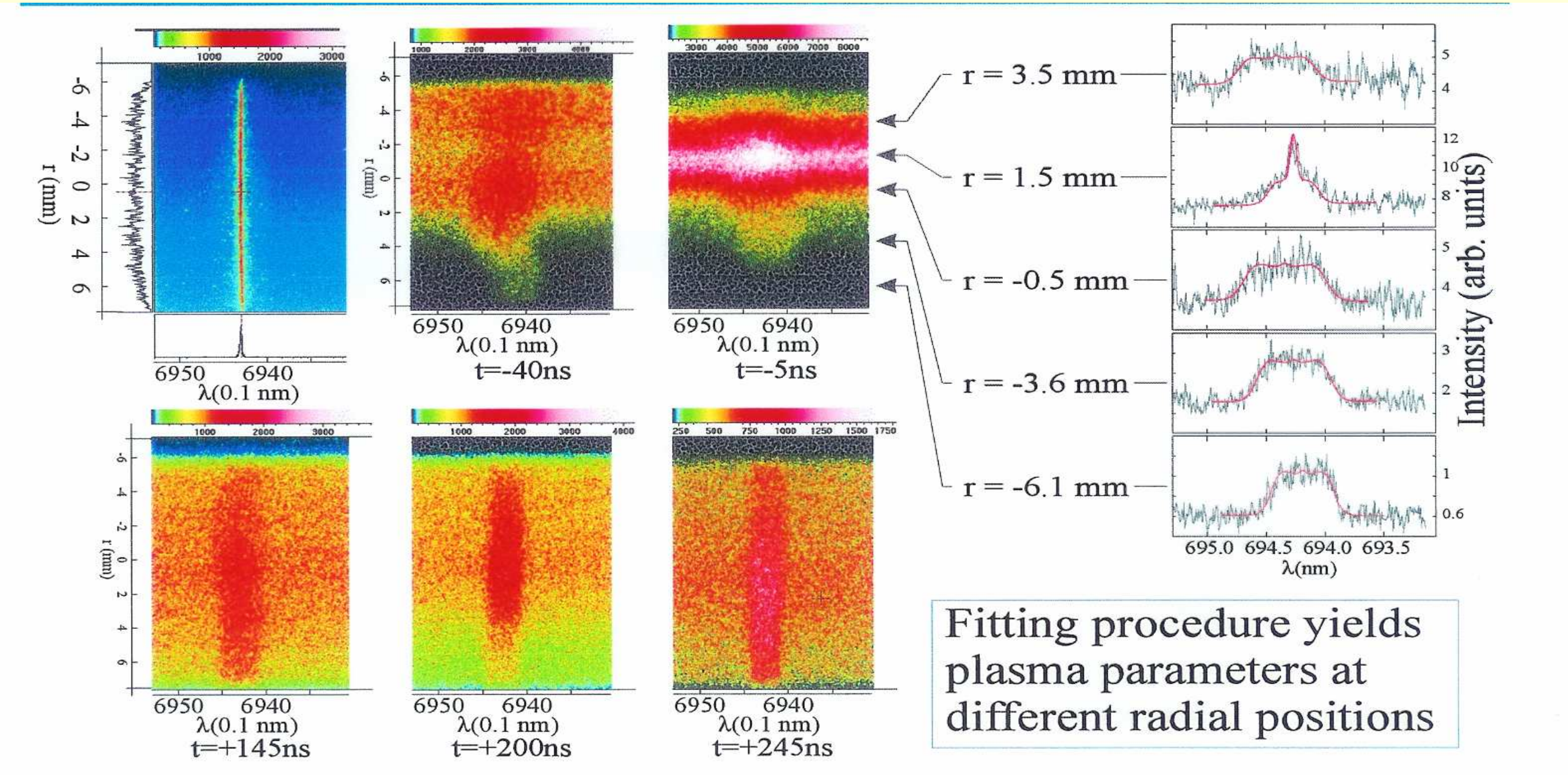


Radial and tangential motion and drifts

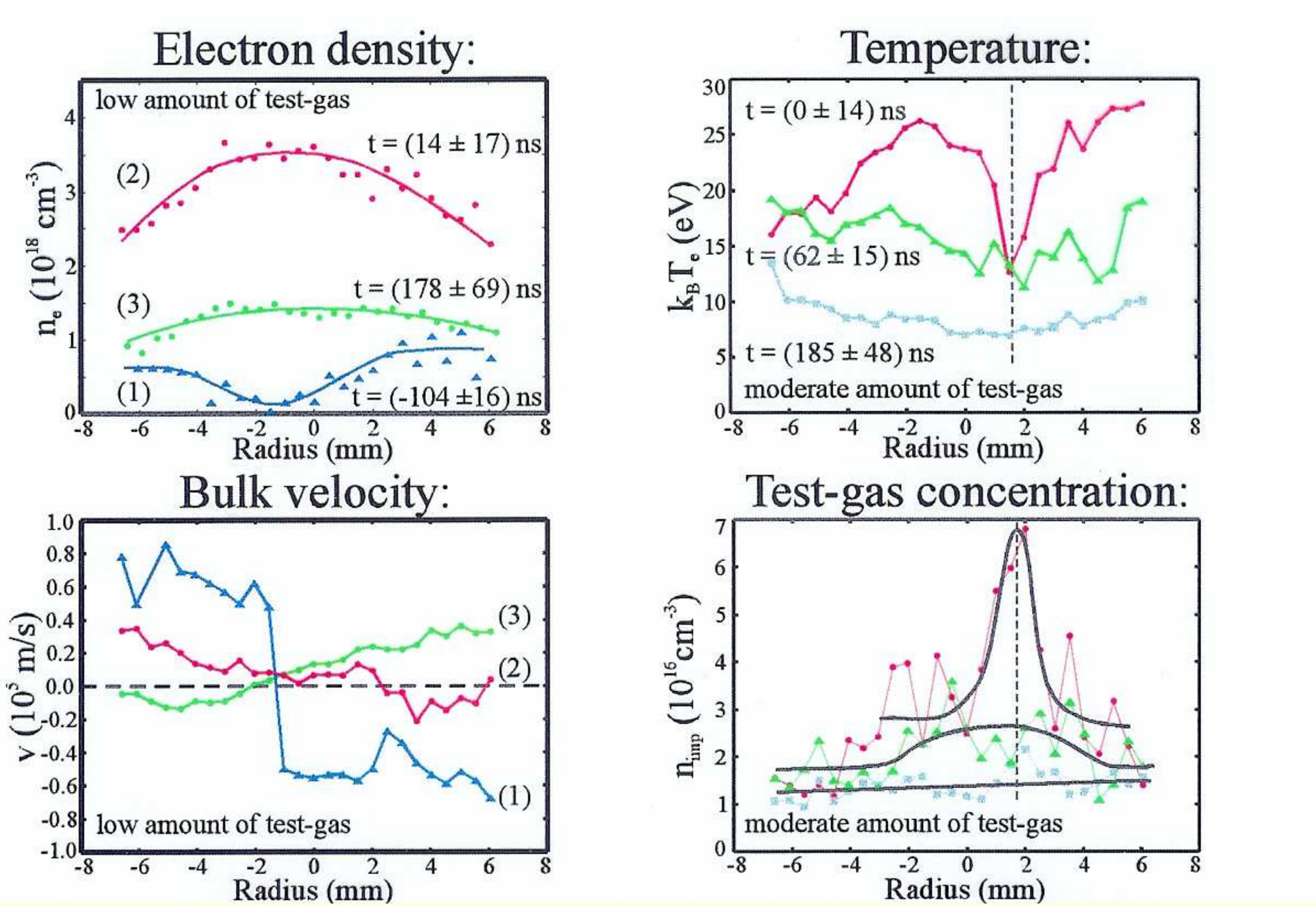
Stigmatic spectrograph and CCD detector

$\Rightarrow$ spatially resolved measurements

Here: along the radius of a gas-liner pinch



Results



Electron density:
low amount of test-gas
t = (14 ± 17) ns
(2)
t = (178 ± 69) ns
(3)
(1)
t = (-104 ±16) ns
n_e (10^18 cm^-3)
Radius (mm)
Temperature:
t = (0 ± 14) ns
t = (62 ± 15) ns
t = (185 ± 48) ns
moderate amount of test-gas
k_B T_e (eV)
Radius (mm)
Bulk velocity:
(3)
(2)
(1)
low amount of test-gas
v (10^5 m/s)
Radius (mm)
Test-gas concentration:
moderate amount of test-gas
n_imp (10^16 cm^-3)
Radius (mm)

High Z laser-produced plasmas (LLNL)

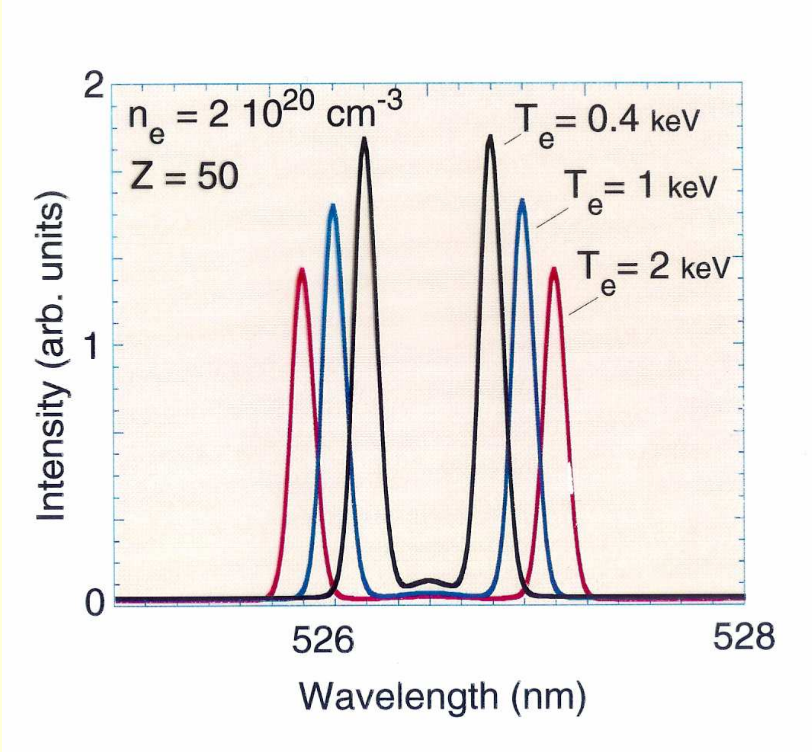
$$(\omega_s - \omega_o)^2 = \left(\frac{Z k_B T_e}{m_i} \frac{\alpha^2}{1+\alpha^2} + \frac{3 k_B T_i}{m_i} \right) k^2$$

$$= \frac{k_B T_e}{m_i} \left(Z \frac{\alpha^2}{1+\alpha^2} + 3 \frac{T_i}{T_e} \right) k^2$$

For large α, large Z, and T_i § T_e

$$(\omega_s - \omega_o)^2 = Z \frac{k_B T_e}{m_i} k^2$$

Separation of the ion acoustic lines is a linear function of Z and T_e



High density plasma:

One limit is given by the plasma frequency because for a laser beam to propagate in a plasma

$$\omega_{laser} > \omega_p$$

$$\frac{\lambda_{laser}}{\text{nm}} < 3.3\times10^{13}\,\frac{1}{\sqrt{n_e/\text{cm}^{-3}}}$$

i.e. $n_e = 10^{20}\ \text{cm}^{-3}$ $\longrightarrow$ $\lambda <$ 330 nm

An even lower limit is given by absorption of the laser beam in the plasma

Optical depth: $$\tau \sim \kappa\,\ell \sim \lambda^3\,\frac{n_e^2}{\sqrt{kT_e}}\,\ell$$

Incoherent scattering of x-rays by solid-density plasmas

Scattering on tightly bound electrons

$\Rightarrow$ Rayleigh peak

Scattering of free or weakly bound electrons

$\Rightarrow$ Compton peak

Successful, e.g. Glenzer et al,

Physics of Plasmas Phys. **10**, 2433 (2003)

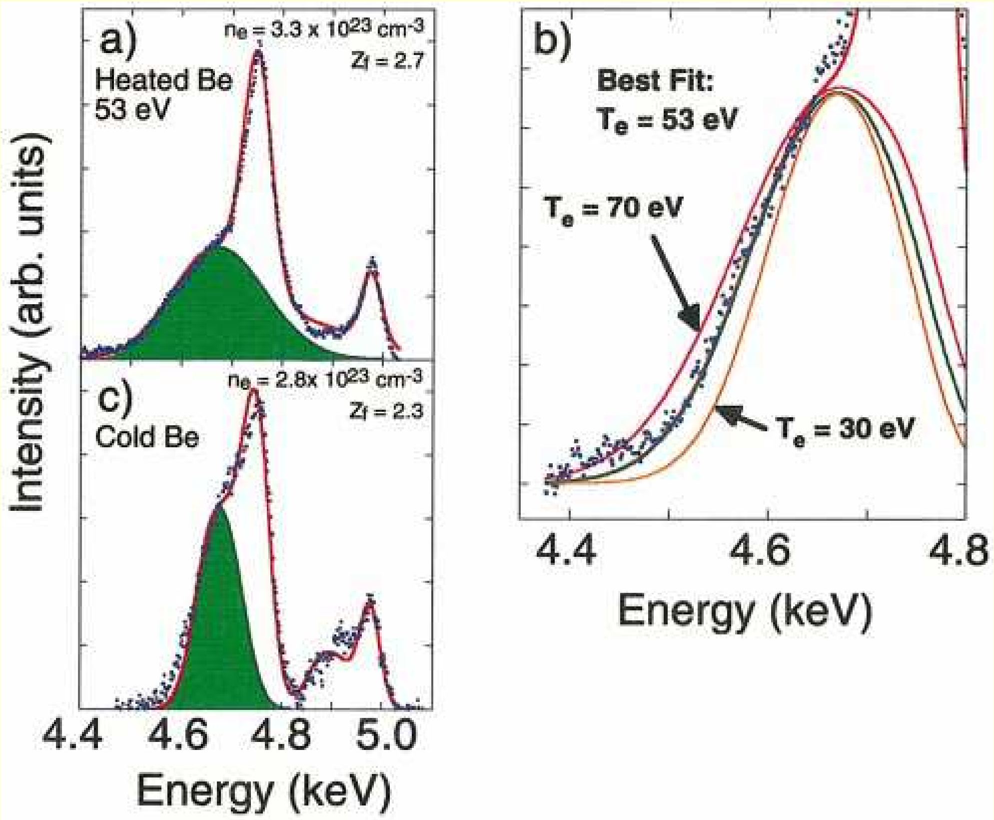
Both target plasma (Be) and source plasma (Ti) are produced by powerful lasers (employing the 30 kJ laser facility at Rochester)

Source emits strong He-α line at 4.75 keV and

weaker Ly-α line at 4.96 keV

Backscattering spectrum of titanium He-α radiation at 4.75 keV

Ly-α radiation at 4.96 keV



Rayleigh peak and downshifted Compton peak are clearly seen for heated and cold Be plasma

T_e is obtained from the shape of the Compton peak;

(b) shows fit and sensitivity of fit

$$\alpha = \frac{1}{k\lambda_D} \approx \frac{\lambda_o}{4\pi\lambda_D \sin(\theta/2)}$$

At low plasma densities and high temperatures the collective regime may be reached

by large λ_o powerful gyrotrons with λ_0 ~ mm considered for α-particle diagnostics in ITER

or

by going to a small scattering angle θ forward scattering

Several methods have been developed heterodyne and homodyne mixing in the detector