The Abdus Salam
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Educational, Scientific
and Cultural Organization

International Atomic
Energy Agency

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WORKSHOP ON PLASMA PHYSICS

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Plasma Diagnostics

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Plasma Diagnostics

H.-J. Kunze

Laboratory plasmas:

Size:

10^{-16} m^3 (micropinch) to 50 m^3 (tokamak)

Density: 10^{14} to 10^{30} m^{-3}

Temperature: 10^3 to 10^8 K

(1 eV = 11600 K)

Numerous diagnostic techniques:

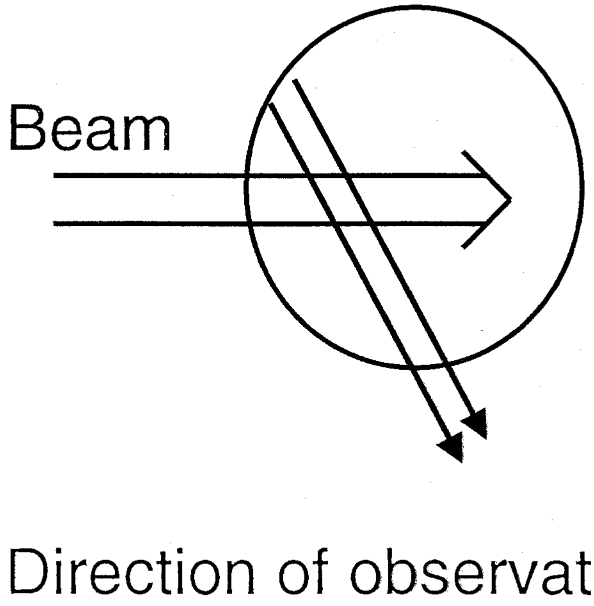
Some general books:

Principles of Plasma Diagnostics
I. H. Hutchinson
Cambridge University Press, 1987

Plasma Diagnostics
W. Lochte-Holtgreven
North-Holland Publ., Amsterdam, 1968

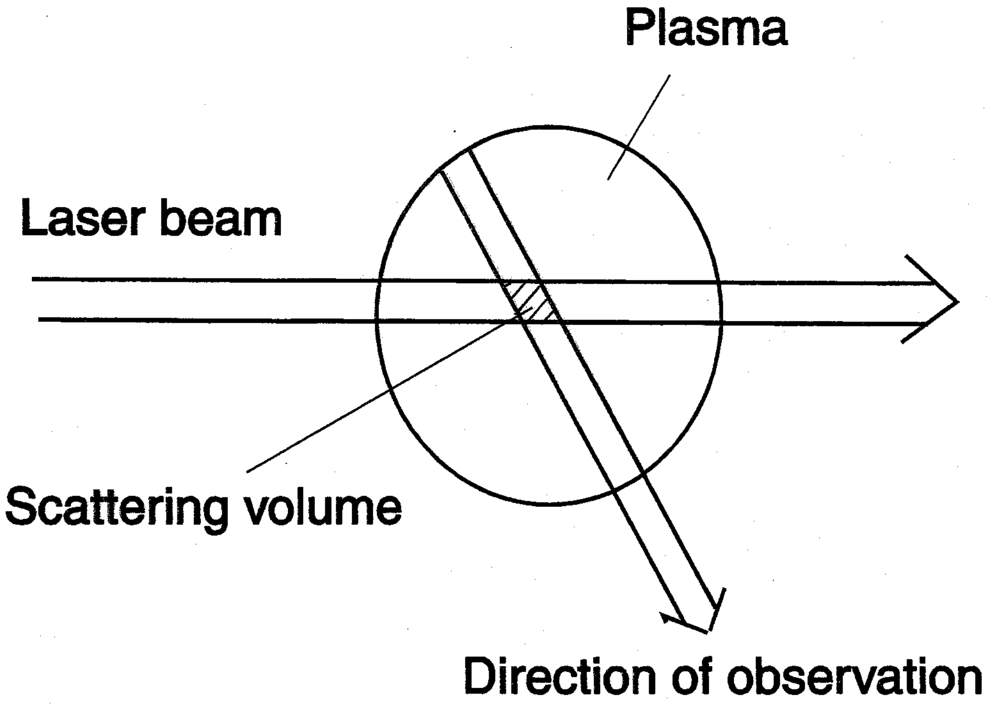
Plasma Diagnostic Techniques
R. H. Huddlestone and S. L. Leonard
Academic Press, New York, 1965

Injection of neutral particle beams:



Specific local information from the intersection region can be identified

Laser beam:



Laser beam interacts with

electrons
ions
atoms
molecules

Due to

tunability and possible high power of lasers interactions are numerous inclusive heating of plasma

a) ⇒ Modification of primary transmitted beam

b) ⇒ Scattering

a) Laser atomic absorption spectroscopy (LAAS)

with tunable diode lasers much applied in very low density plasmas

modification of phase ⇒ interferometry

$$\int n_e\, ds$$

plane of polarization ⇒ Faraday rotation

$$\int n_e B\, ds$$

Scattering by atoms, ions and molecules

- Laser induced fluorescence (LIF)
- Rayleigh scattering
- Raman scattering
- CARS

Scattering by electrons --- Thomson scattering

During 40 years now scattering by the plasma electrons has matured into one of the most powerful diagnostic methods for the determination of plasma parameters

Latest development this year:

scattering of x-rays by plasmas near solid state density

Reviews:

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

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

W. DeSilva and G. C. Goldenbaum in *Methods of Experimental Physics 9A*
Ed. H. R. Griem and R. H. Lovberg, 1970

J. Sheffield, *Plasma Scattering of Electromagnetic Radiation*, 1975

S. Glenzer et al.
Demonstration of Spectrally Resolved X-Ray Scattering in Dense Plasmas
Phys. Rev. Lett. **90**, 175002 (2003)

Incoherent scattering–Thomson scattering

Theory well understood:

Electromagnetic waves are focused into the plasma

⇒ charged particles oscillate and radiate like dipoles

because of small mass ($m_e << M$) essentially only *electrons* contribute

Cross-section

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

Extremely small

⇒ high intensities are needed

a) to have enough scattered photons (*or nowadays long observation times* !)

b) scattered light to be above plasma radiation

⇒ **lasers**

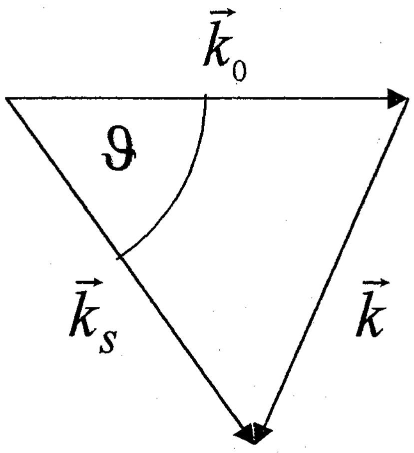
Scattered intensities add incoherently (at low densities)

$$\frac{d\sigma}{d\Omega} = n_e\,\sigma_e = n_e\,r_e^2\,\sin^2\vartheta$$

i.e. $\Rightarrow \propto n_e$

Motion of the moving electron

$\Rightarrow$ Doppler shift



$\vec{k} = \vec{k}_s - \vec{k}_0$ *is the scattering vector*

$$k \approx 2\,k_0\,\sin\frac{\vartheta}{2}$$

$$\omega_s - \omega_0 = \omega = \vec{k}\cdot\vec{\mathrm{v}}$$

Spectrum mirrors thus the velocity distribution function of the electrons in the direction of k!

i.e. we obtain $f_e(v_k)$,

and if $f_e(v_k)$ is Maxwellian $\Rightarrow$ T_e

Profile is Gaussian

Half width $\Delta\lambda_{1/2} = 4\lambda_0 \sin(\vartheta/2)\sqrt{\frac{2\kappa T_e}{mc^2}\ln 2}$

Typical half width for $\lambda_0 = 694.3$ nm, $\vartheta = 90^0$,

$kT_e = 1$ eV

$\Delta\lambda_{½} = 3.24$ nm

Powerful diagnostic technique

for n_e, T_e, $f_e(v)$

For some time experiments were carried out with pulsed ruby lasers at $\lambda_0 = 694.3$ nm

- scattered light was detected by

  polychromator and photomultipliers

  $\Rightarrow$ spectrum and T_e

- *Absolute calibration*: Rayleigh scattering in gases with known cross-section $\Rightarrow n_e$

Problems:

- *Stray light*: Brewster entrance and exit windows,

  baffle system on entrance and exit side

  beam dump for laser

  viewing dump

- *Heating* of plasma by laser beam

Heating: absorption by inverse Bremsstrahlung

Later: high-repetition rate NdYAG lasers at 1.06μm

or second harmonic at 532 nm

yielded time evolution of plasma parameters

excimer lasers

dye lasers

Detector improvement:

Optical multichannel analyzer (OMA)

CCD cameras: spectral and spatial image

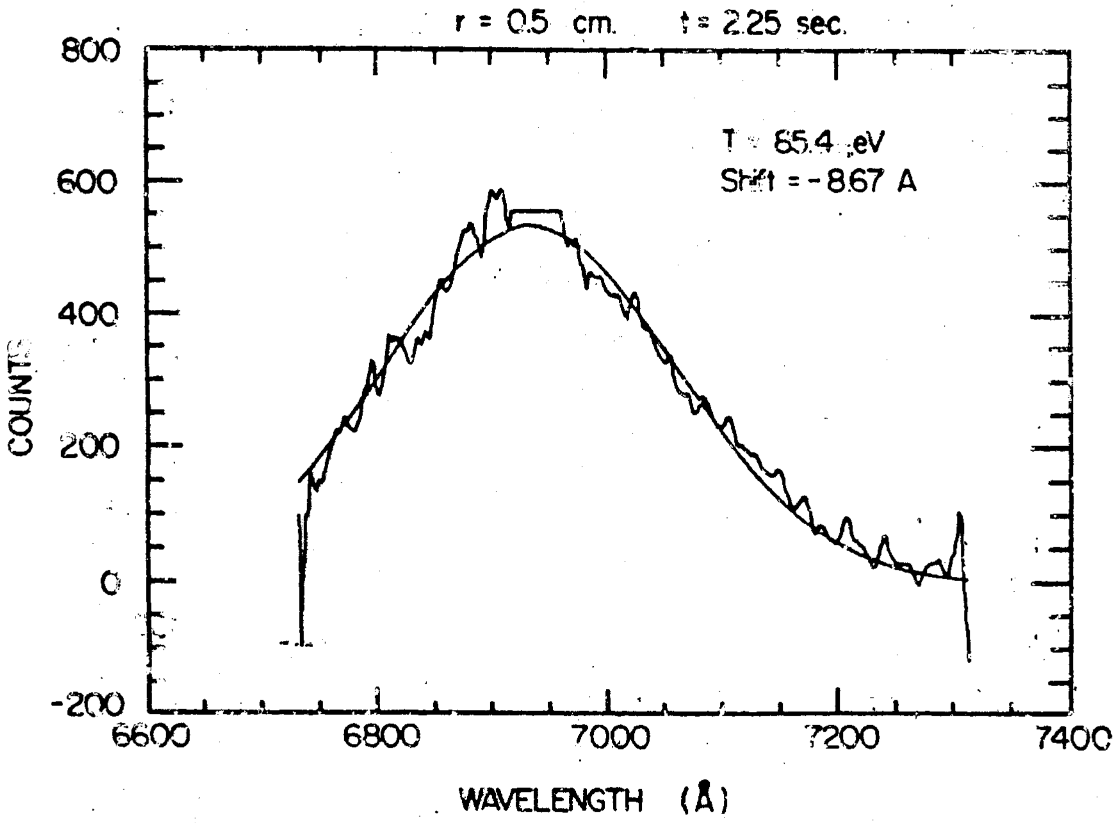
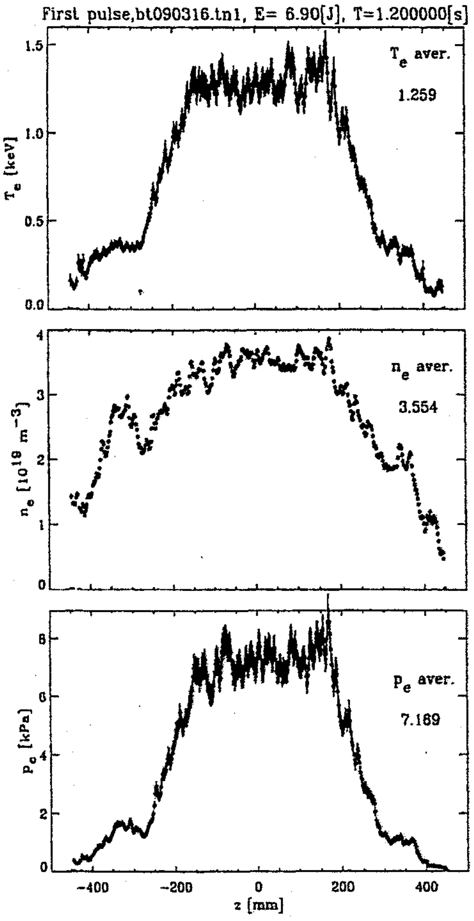


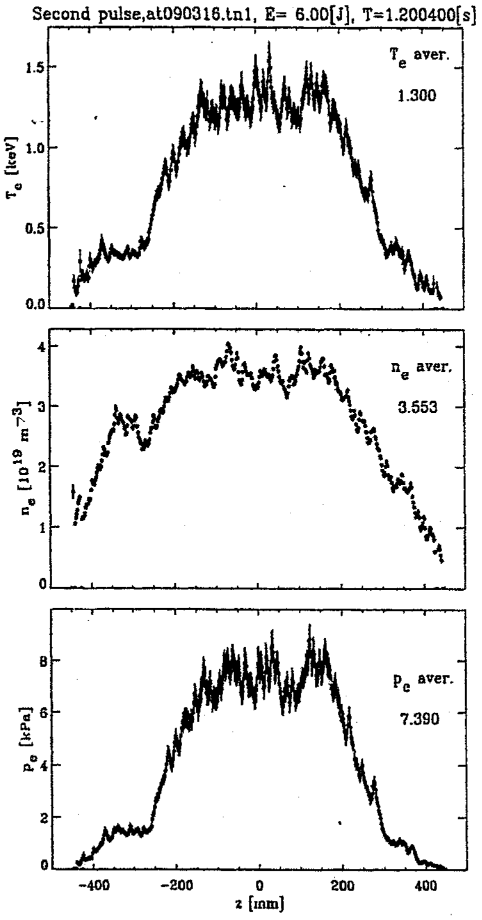
FIG. Scattering spectrum obtained from one discharge for a high-density plasma ($\sim 10^{16}$ cm^{-3}). The shift parameter is obtained from a least squares fit to a Gaussian. The first-order relativistic correction predicts a $-$ 9.4 Å shift. The temperature is determined from a fit to the relativistically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

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

Measurements

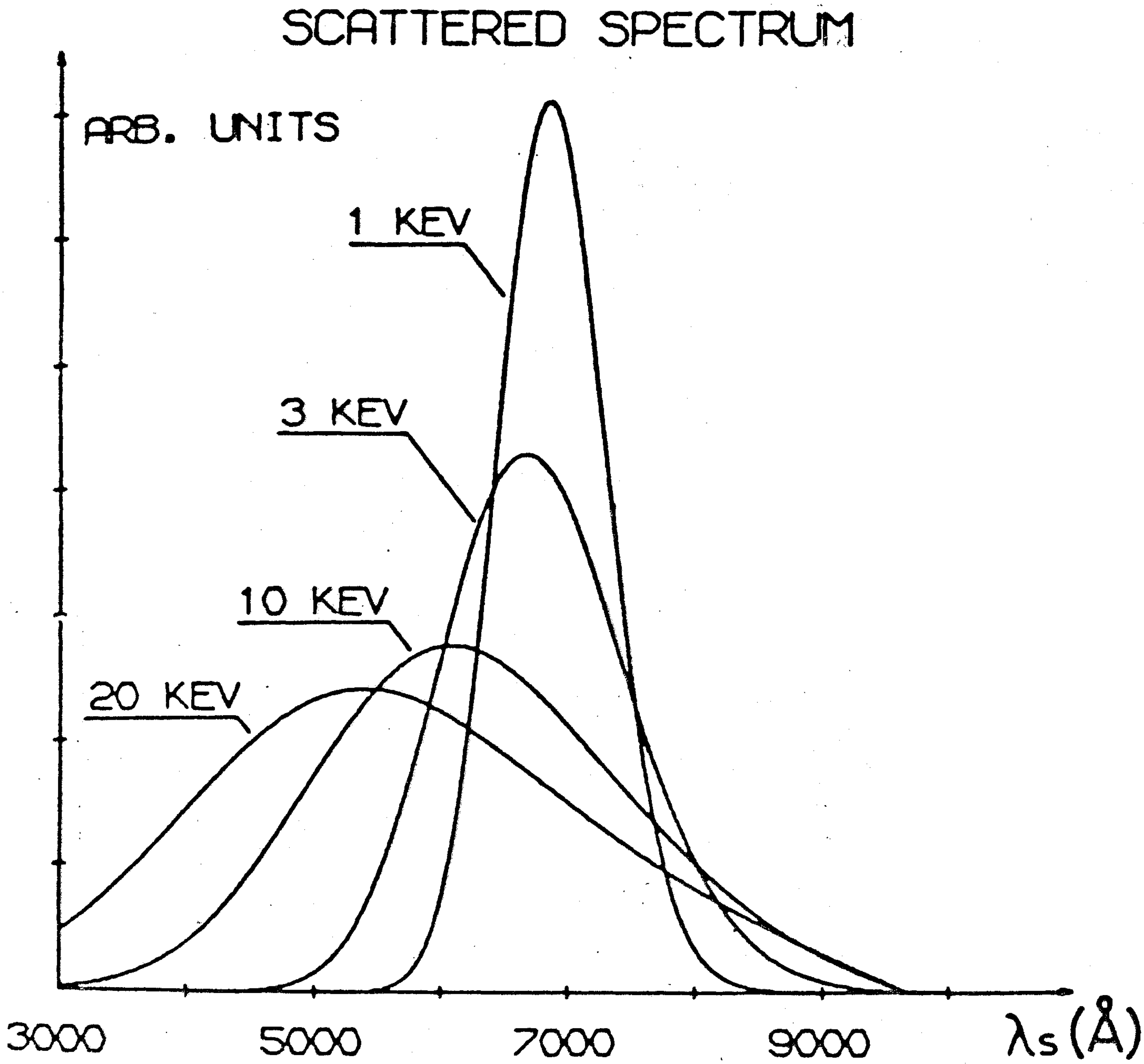


TEXTOR 90316, t=1.2000 s, first laser pulse. Magnetic islands, m/n = 2/1.



TEXTOR 90316, t=1.2004 s, second laser pulse.

At higher temperatures ⟶ relativistic treatment



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

Scattering on large fusion devices:
Activation will be a problem !

Salzmann and Hirsch proposed backscattering plus subnanosecond laser pulses plus time-of-flight analysis with high-speed detectors.

<u>LIDAR</u> : light detection and ranging

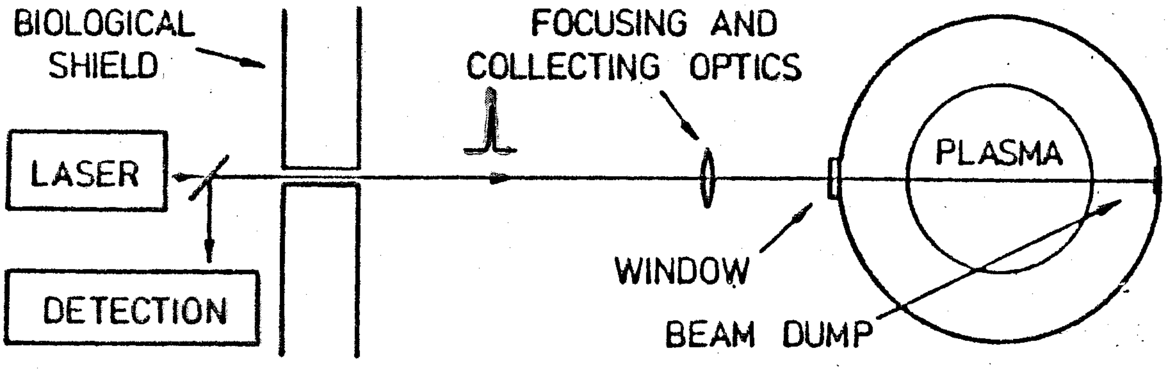


FIG. 1. Scheme of the Thomson backscattering arrangement.

Spatial resolution: pulse duration of laser and response time of detection system

System at tokamak JET :
5 Joule ruby laser with 300 p s duration

Low density plasmas

At low electron densities number of scattered photons becomes too small

$\Rightarrow$ different approach !

Use of low laser power *but* laser with high repetition rate

less than *one* photon arriving at a detector per laser pulse

synchronized photon counting

heating by laser has to be negligible

Nd:YAG system, frequency doubled at 532 nm, 10 kW, 70 ns duration, 10 kHz repetition rate

Problems:

Rayleigh scattering off neutrals

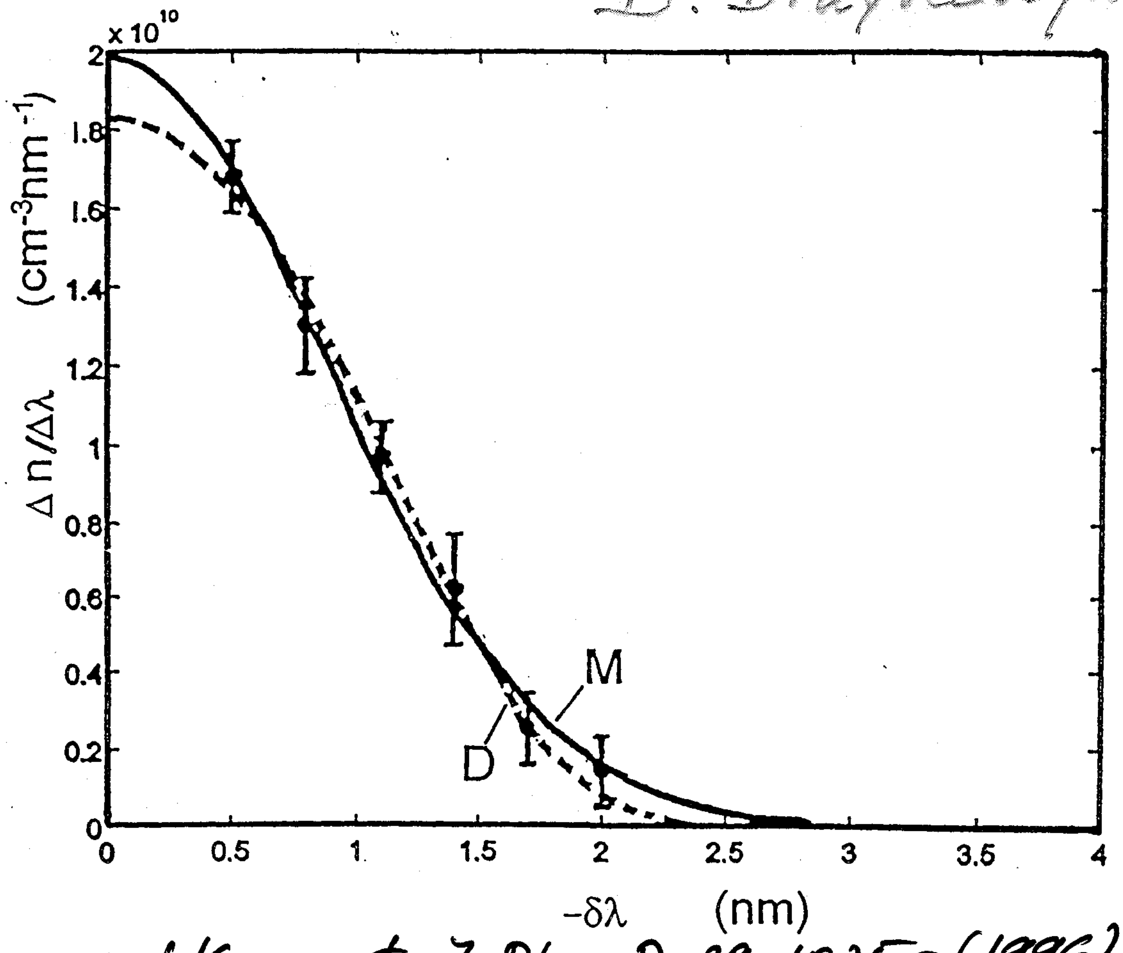
Stray light (proper design of arrangement and diameter of apertures at entrance and exit of laser, operating at TEM_{00} mode and imaging near field pattern into plasma, light dump)

Continumm background (bremsstrahlung due elastic electron atom collisions)

LIF from excitation of molecules

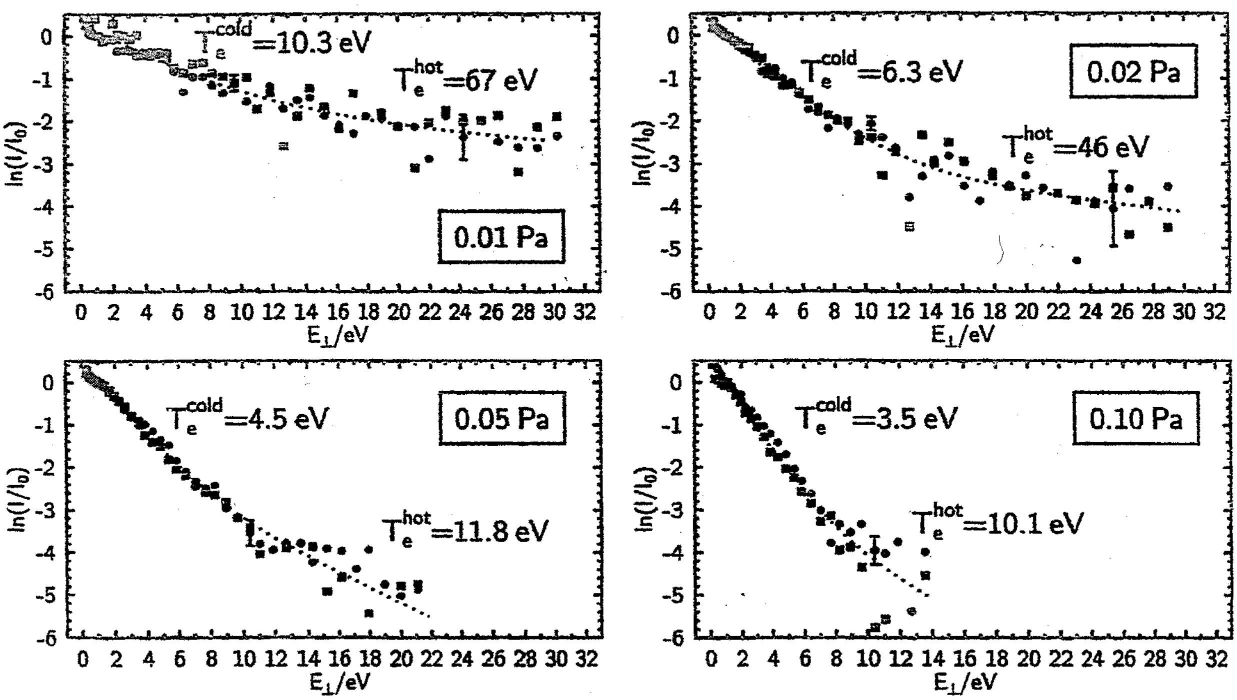
Spectrum:

Fits: M : Maxwellian
D : Druyvesteyn



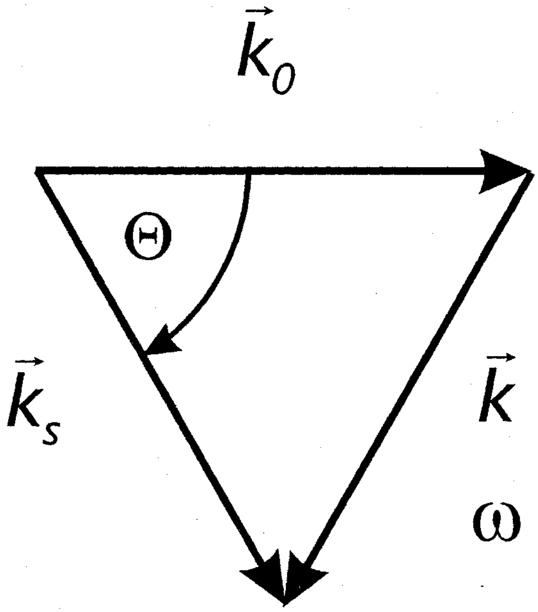
Weßeling and Kronast: J. Phys. D 29, 1035 – (1996)

Hemmers et al, Düsseldorf
ECR discharge,
NdYAG laser, ferequency doubled, 10 Hz,
11 channel detector system with PM



Low energy part: Maxwellian

High energy part: overthermal electrons



$$\vec{k} = \vec{k}_s - \vec{k}_0$$

$$\omega = \omega_s - \omega_0$$

$$= \vec{k}.\vec{v}$$

$$S(\vec{k},\omega)$$

Inverse scattering vector 1/k
and the Debye length λ_D
are the two relevant scale lengths

$$1/k > \lambda_D \rightarrow \alpha = \frac{1}{k\lambda_D} > 1 \rightarrow$$ *correlations between electrons*

$$1/k < \lambda_D \rightarrow \alpha = \frac{1}{k\lambda_D} < 1 \rightarrow$$ *no correlations*

a) Coherent or collective scattering
b) Incoherent scattering

$\vec{k}$ *depends on λ_0 and scattering angle Θ*

Theory gives scattering cross section:

$$\frac{d^2\sigma}{d\Omega d\omega} = \sigma_e \, S(\vec{k},\omega)$$

$S(\vec{k},\omega)$ spectral density function
or dynamic form factor

it contains the scattering properties of the whole ensemble of electrons.

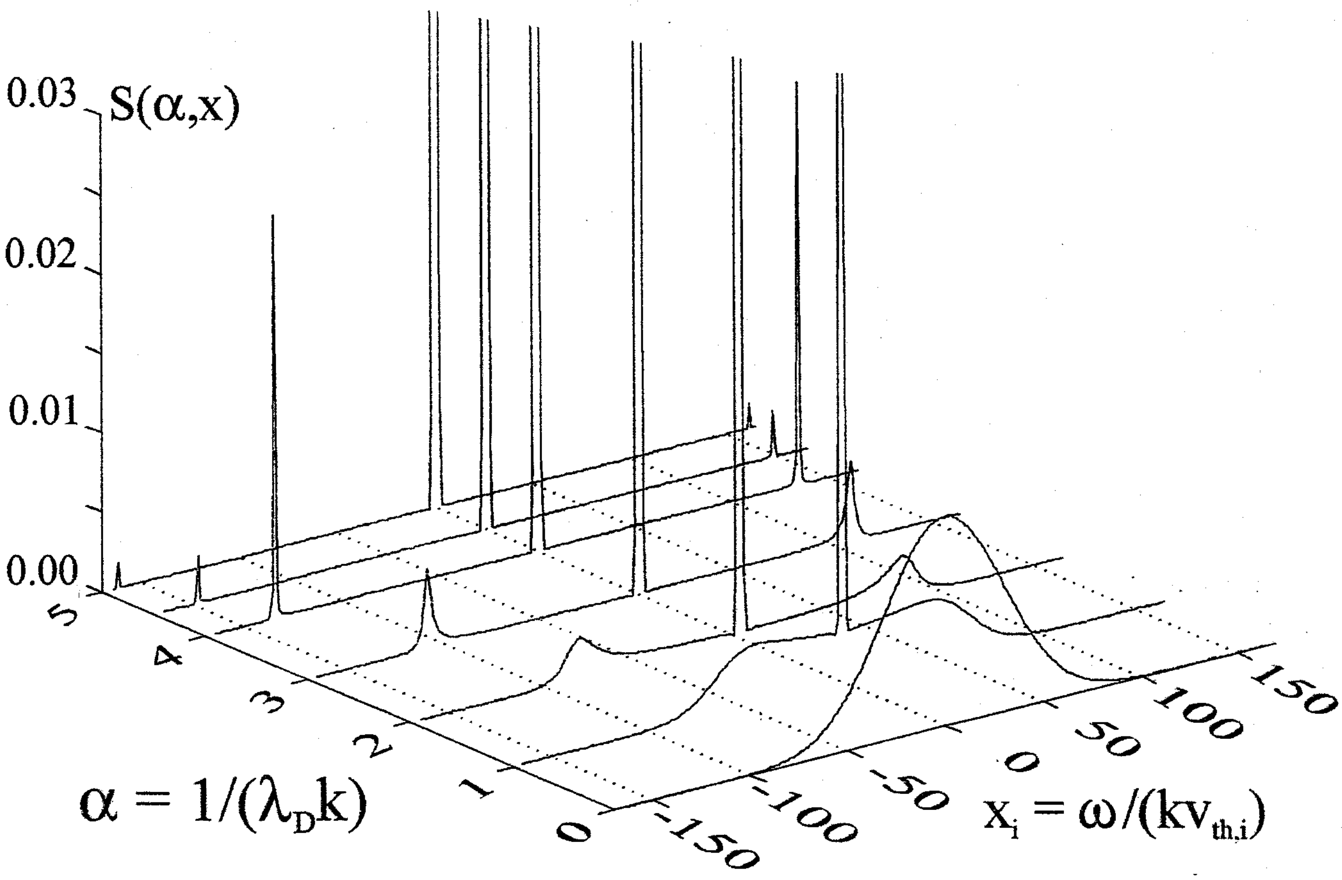
In general, it is the time - and space - Fourier transform of the time - dependent electron density pair correlation function

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

$S_e(\vec{k},\omega)$ *electron feature*

$S_i(\vec{k},\omega)$ *ion feature*

Thomson scattering - Form factor



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

Electron feature reflects correlated motion of electrons ⇒ plasma waves

Maxima given by Bohm-Gross dispersion

$$(\omega_s - \omega_0)^2 = \omega_p^2 + \frac{3\kappa T_e}{m_e} k^2$$

relation

Damping depends on T_e,

In principle,

shape of electron feature gives n_e and T_e,

without absolute calibration!

Problem for large α:

$$\text{Integral} \quad S_e(k) = \frac{1}{1+\alpha^2}$$

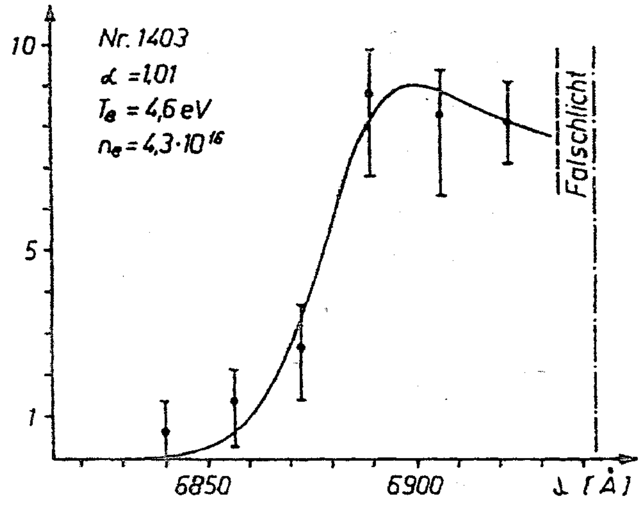
$\alpha \geq 1$

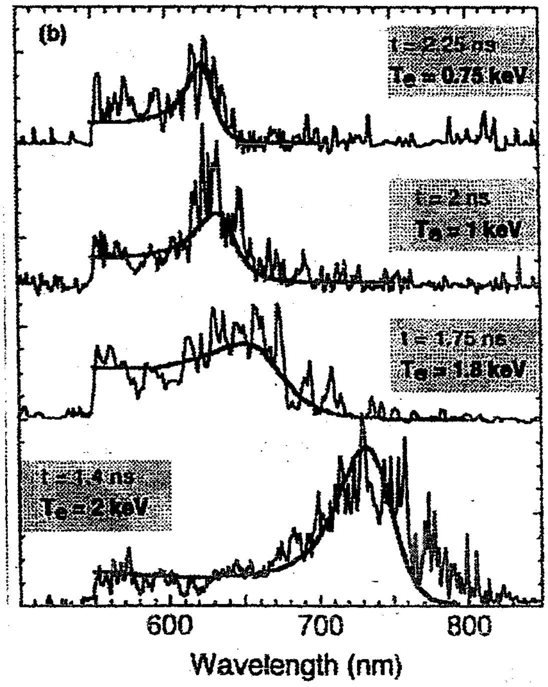
Electron component $S_e(\vec{k},\omega)$

Shape (!) gives n_e and T_e around $\alpha \approx 1$

Position of maximum given by Bohm-Gross dispersion relation

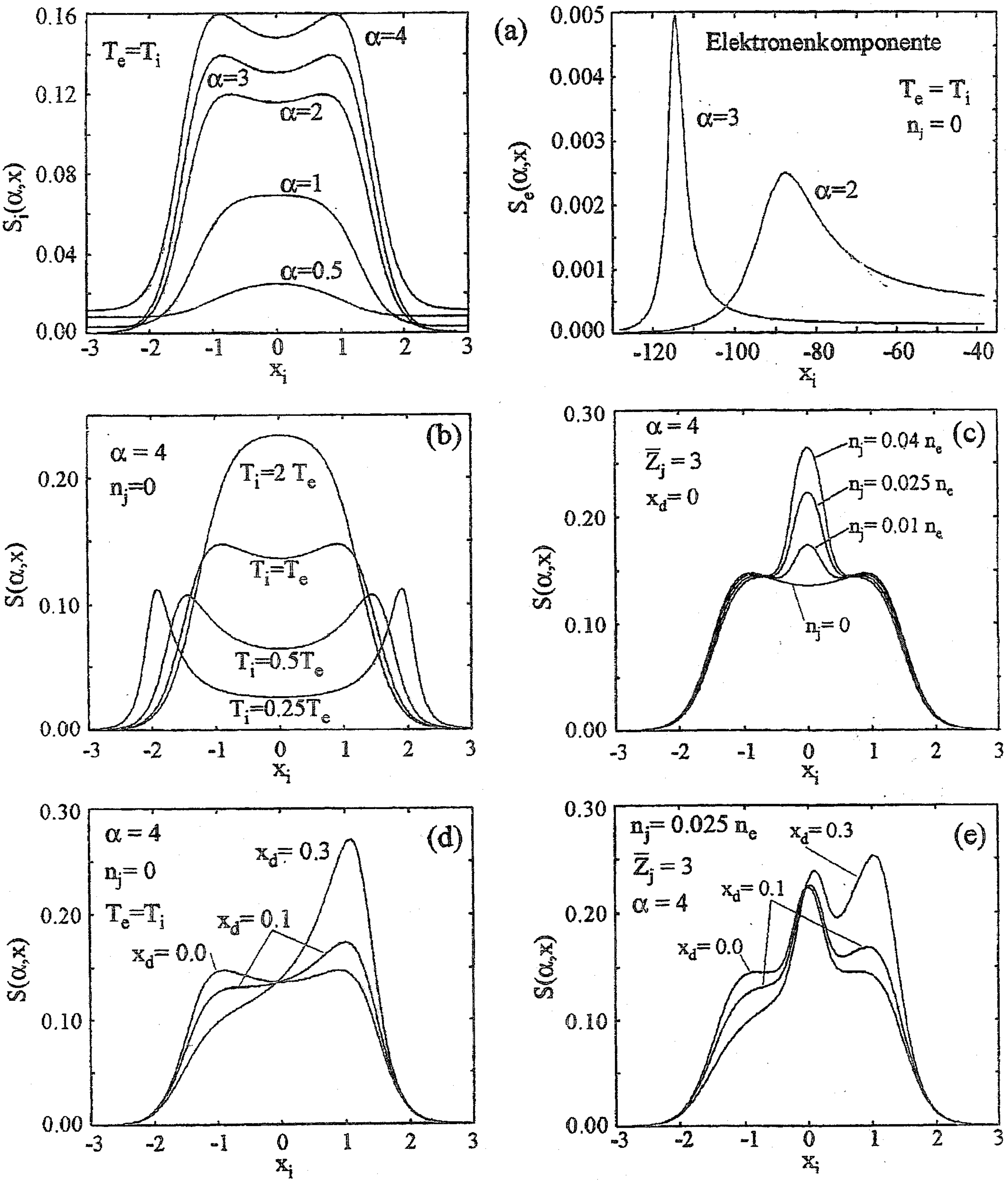
$$(\omega_s - \omega_0)^2 = \omega_p^2 + \frac{3\kappa T_e}{m_e} k^2$$



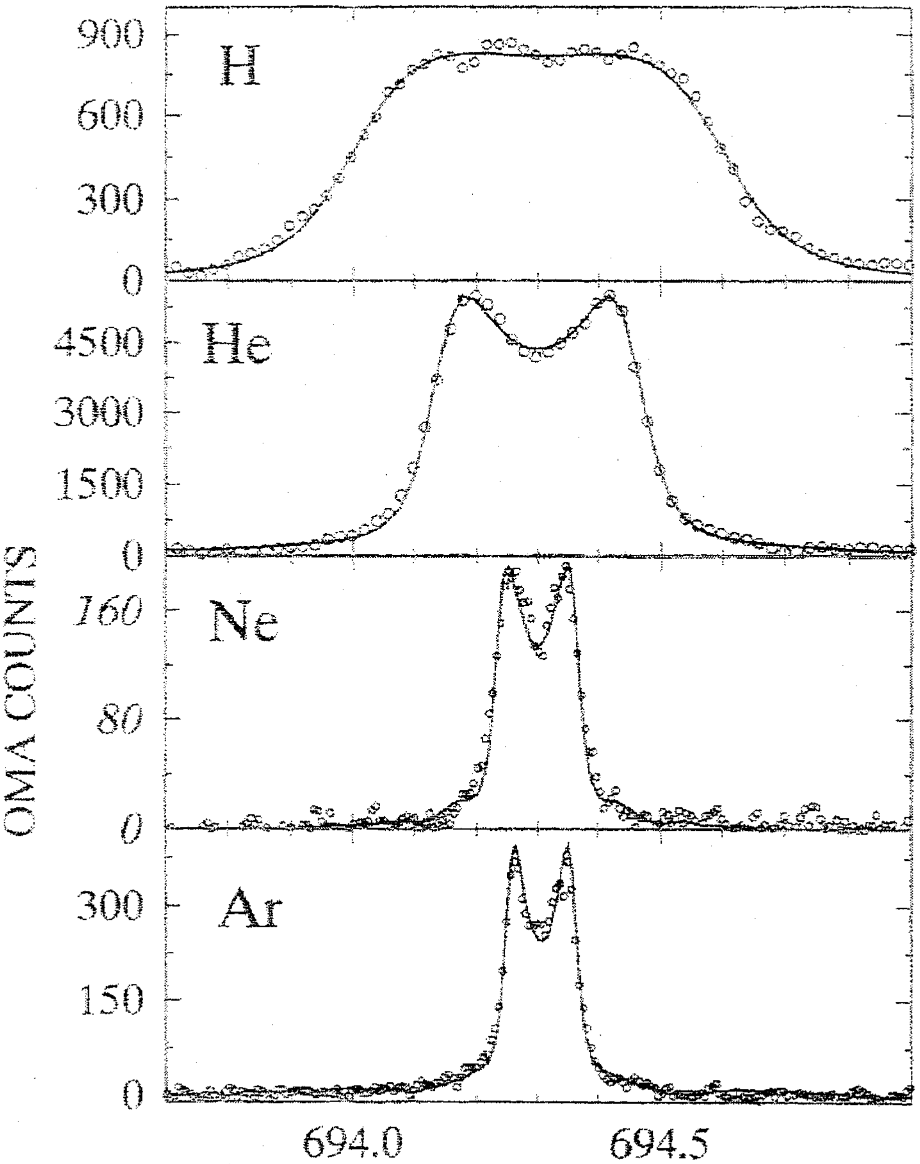


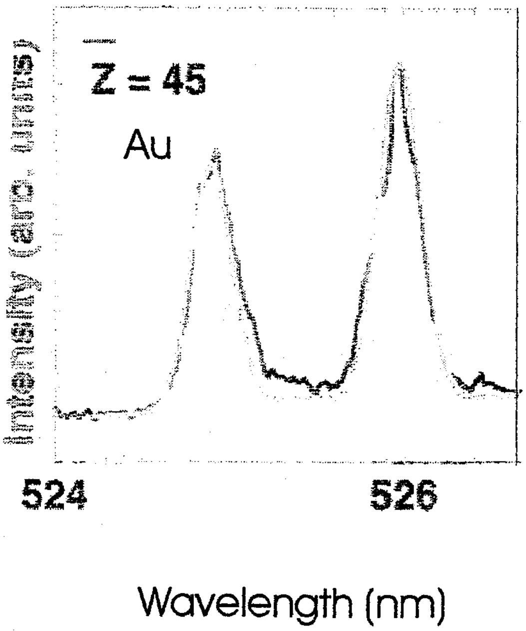
Theta pinch 1964

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



In addition: macrosopic motion ⇒ shift


OMA COUNTS
H
900
600
300
0
He
4500
3000
1500
0
Ne
160
80
0
Ar
300
150
0
694.0
694.5


Z = 45
Au
Intensity (arb. units)
524
526
Wavelength (nm)

Ion feature is determined by motion of the ions

$\Rightarrow$ macroscopic motion of plasma

$\Rightarrow$ thermal motion

$\Rightarrow$ ion acoustics waves

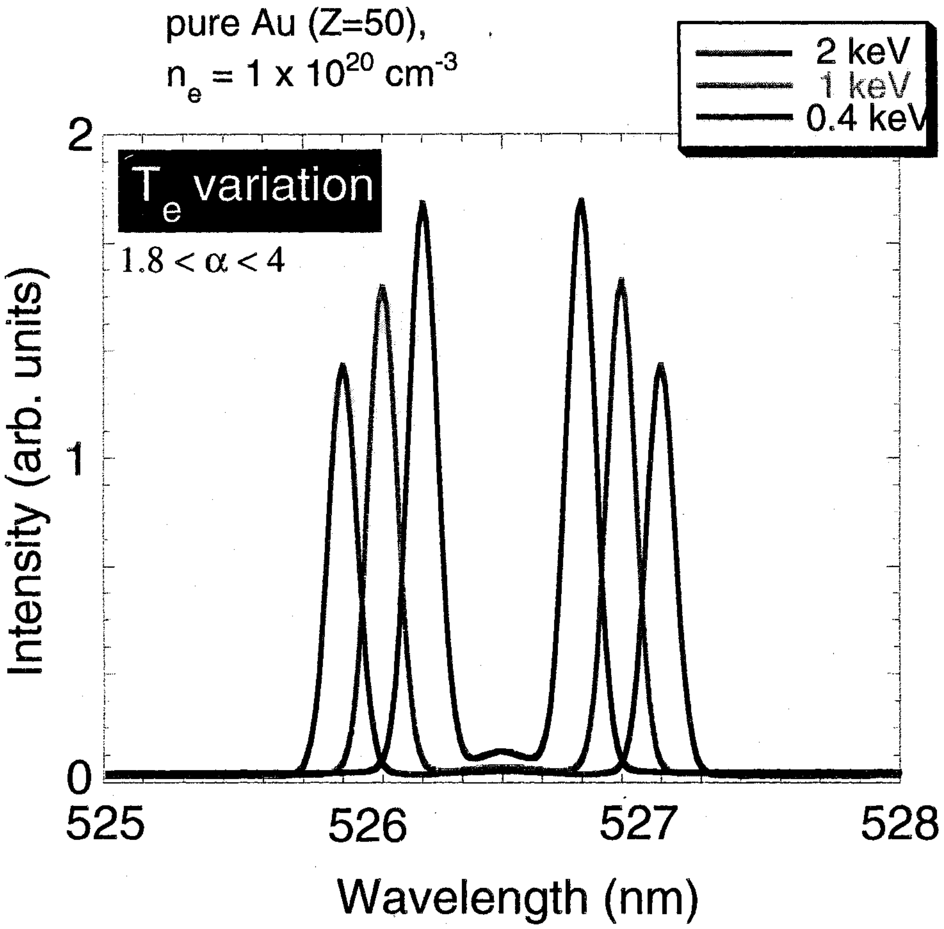
(*it is relatively narrow*)

Maxima correspond to resonances and are at

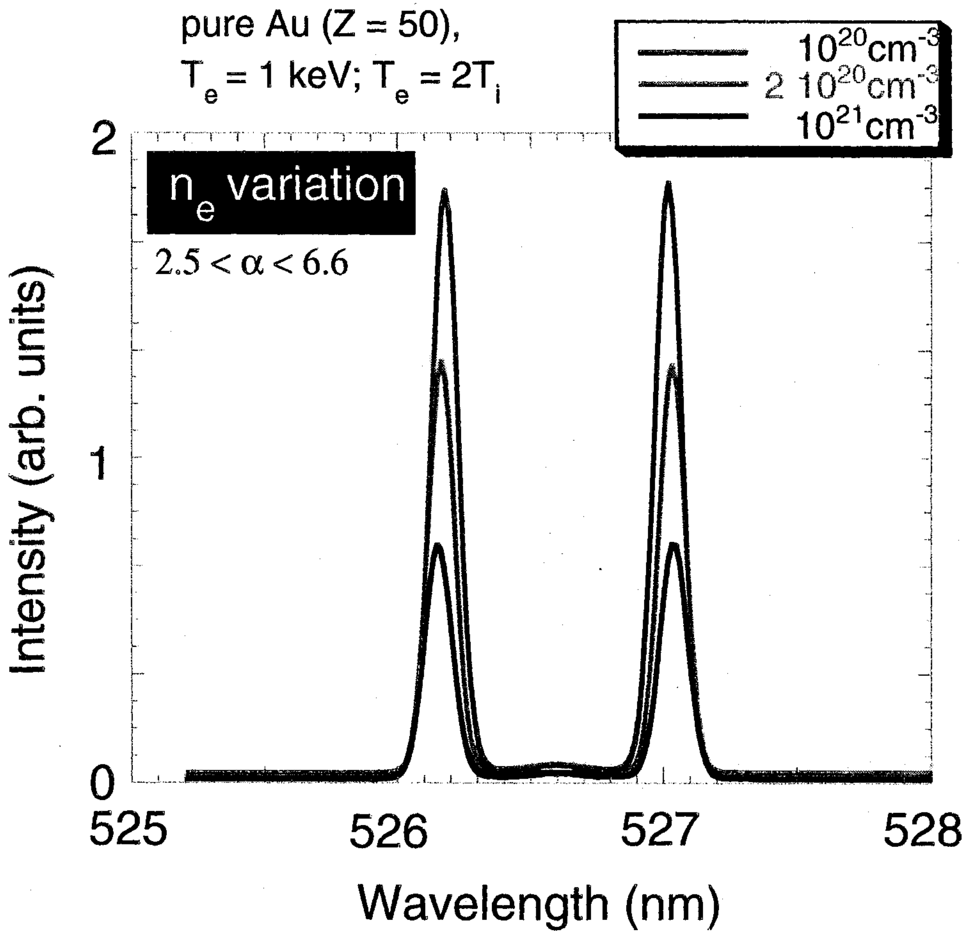
$$(\omega_S - \omega_0)^2 = \left(\frac{Z\kappa T_e}{m_i} \frac{\alpha^2}{1+\alpha^2} + \frac{3\kappa T_i}{m_i} \right) k^2$$

Shape depends on damping and hence on T_e/T_i

The separation of the ion acoustic features gives T_e



pure Au (Z=50),
$n_e = 1 \times 10^{20}$ cm^{-3}



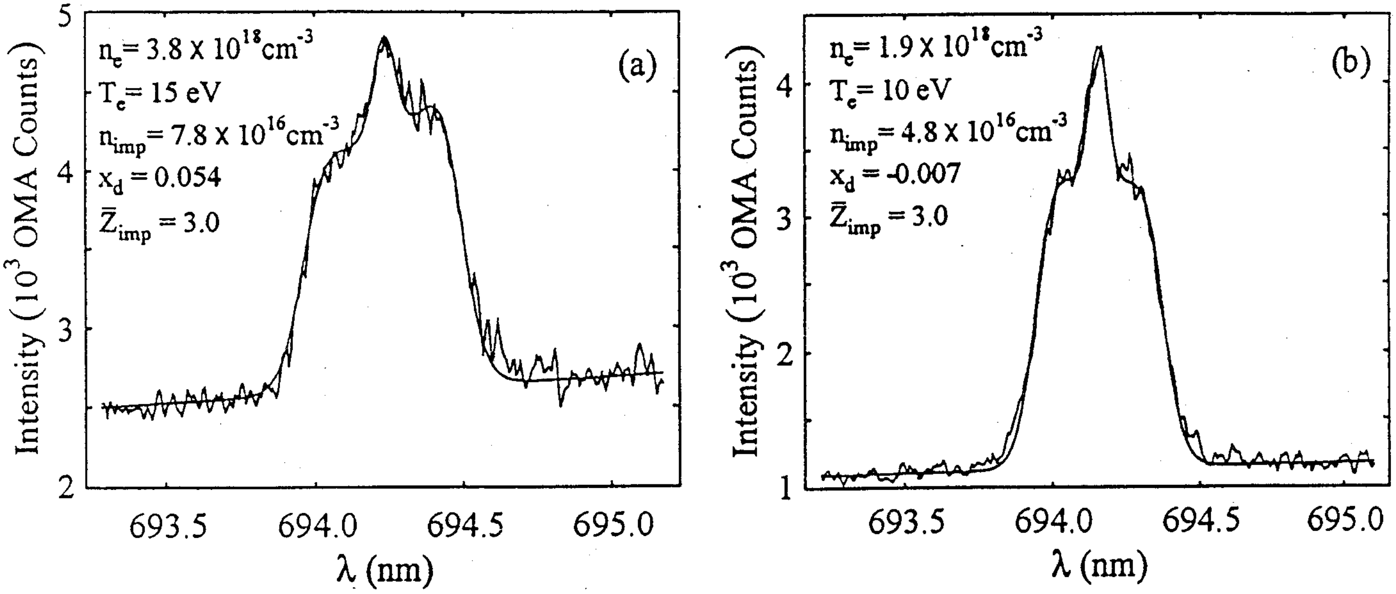
pure Au (Z = 50),
T_e = 1 keV; $T_e = 2T_i$

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

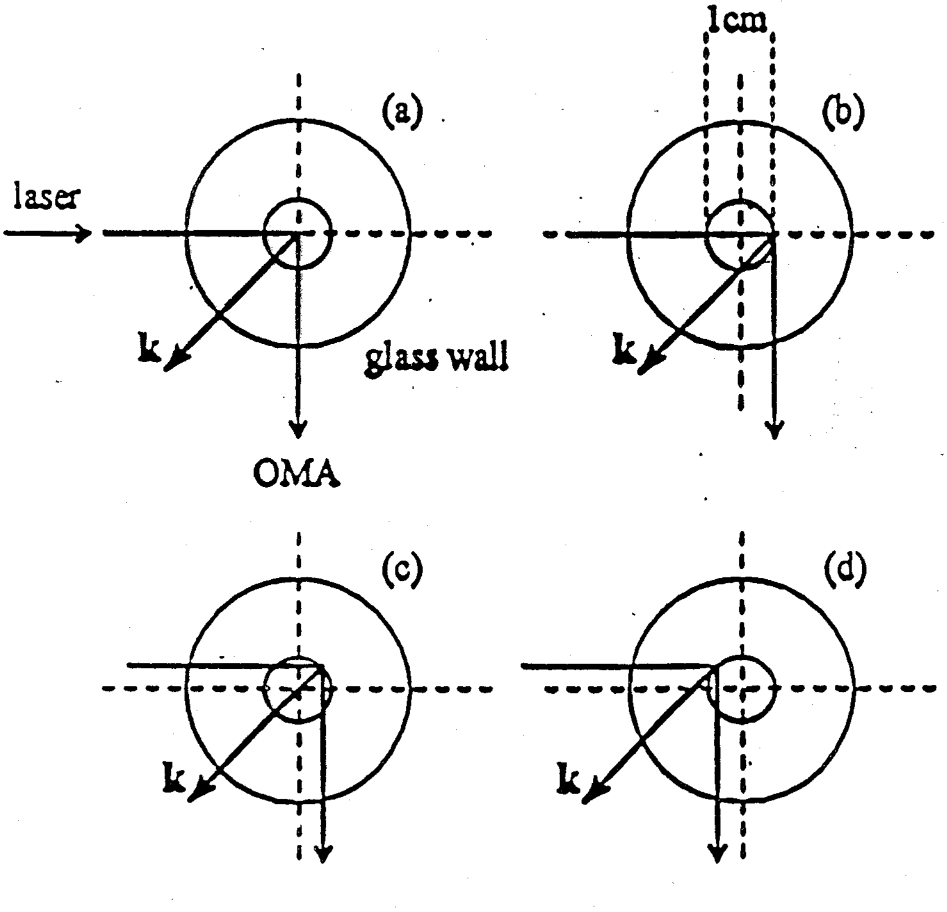
- Wavelength separation of the ion acoustic waves do not depend on density for $\alpha > 2$

Investigation of drifts

in the direction of the scattering vektor $\vec{k}$



Proper selection of scattering direction and scattering volume



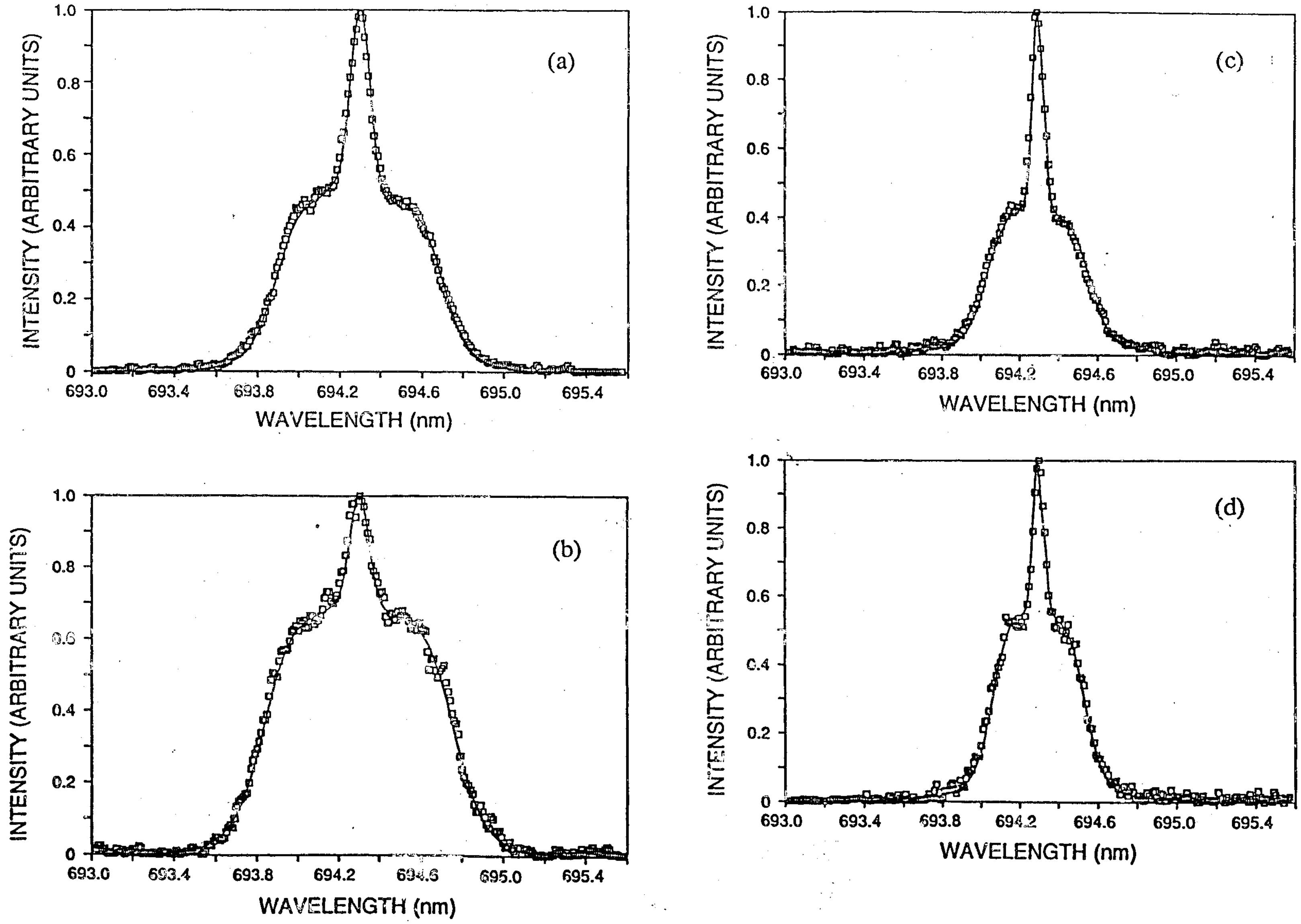
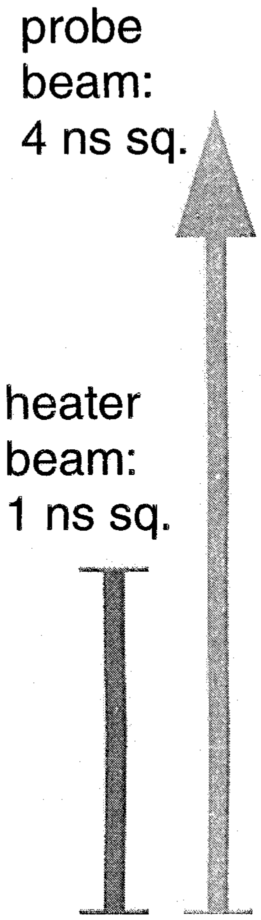
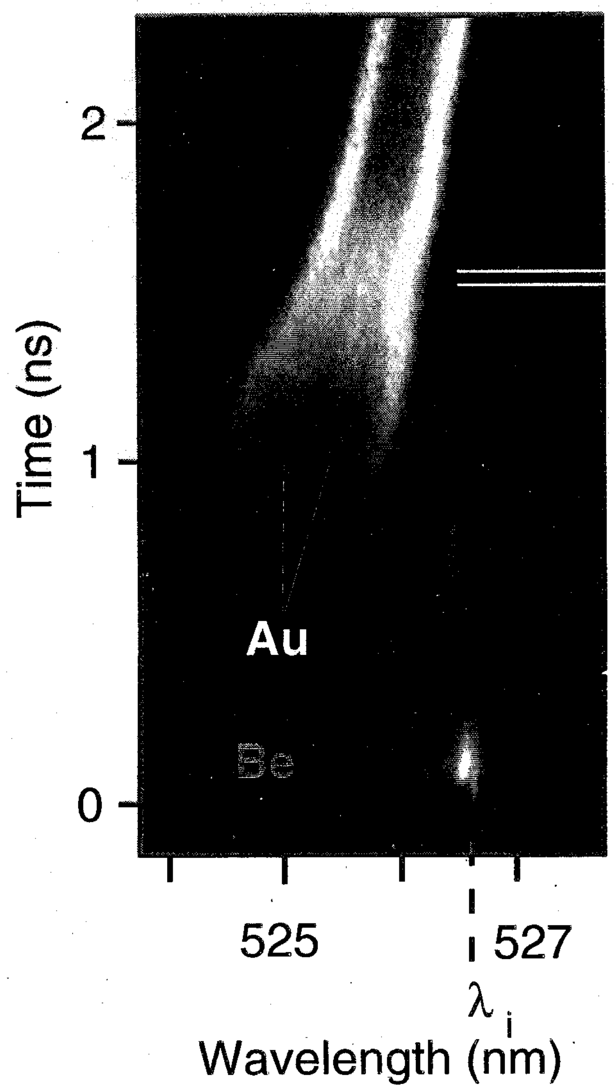


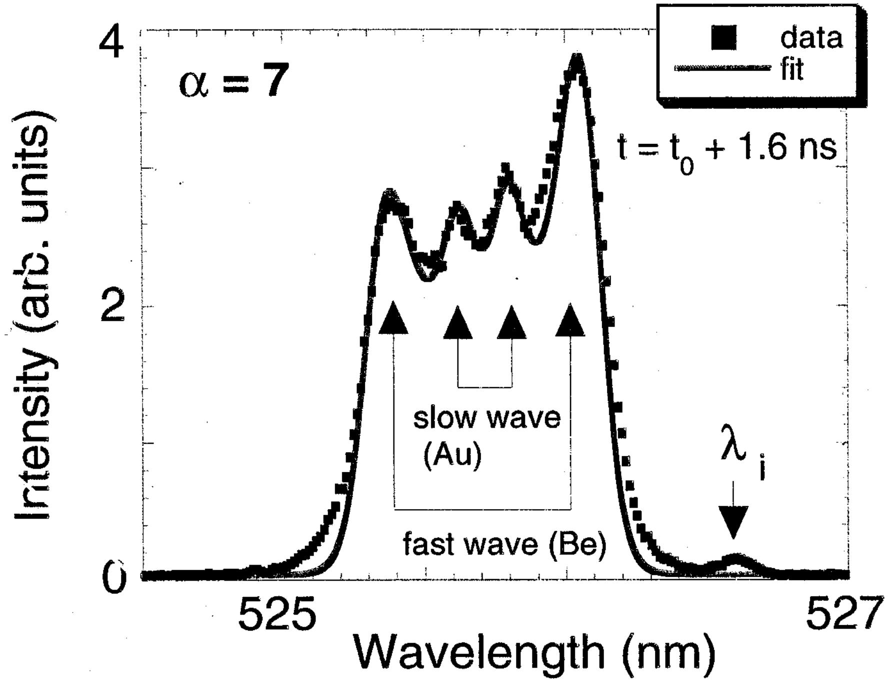
FIG. 5. Measured single-shot scattered light spectra for hydrogen plasmas with noble gas additive. Square points are OMA data, solid line is best fit to theory. Parameters from fitting to theory are (a) 1% argon, $T_i = 35$ eV, $n_e = 8\times10^{24}$ m^{-3}, $Z^* = 7.5$. (b) 0.29% argon, $T_i = 46$ eV, $n_e = 2\times10^{24}$ m^{-3}, $Z^* = 7.9$. (c) 4.5% xenon, $T_i = 17.5$ eV, $n_e = 2.5\times10^{24}$ m^{-3}, $Z^* = 3.8$. (d) 4.8% xenon, $T_i = 17$ eV, $n_e = 1\times10^{24}$ m^{-3}, $Z^* = 2.7$.

For disk plasmas with two-species, the observation of two ion-acoustic waves excludes the presence of turbulence



4% Au, 96% Be; multilayer disk





Fit yields considerable information

- $T_e = 230$ eV ($\pm$ 10%) from the **wavelength separation of Be** ion acoustic waves;
- $T_i = 260$ eV ($\pm$ 10%) from **relative damping** of the ion acoustic waves
- $Z_{Au} = 40$ ($\pm$ 15%) from the **wavelength separation of Au** ion acoustic waves;
- [$n_e = 2 \times 10^{20}$ cm^{-3} from LASNEX]

S. H. Glenzer et al., Phys. Rev. Lett. **77**, 1496 (1996)

Because of the energetic photons now the Compton shift has to be taken into account.

Electron density and temperature could be derived and thus also the ionisation balance !

Future: interesting possibilities to study electronic properties of solid-density plasmas

Scattering of X-rays by solid-density plasmas

30-kJ Omega laser facility was used

target was a Be cylinder coated with 1 μm thick rhodium

L-shell x-rays from Rh heat the Be cylinder to about 30 eV at densities (2-3)×10^{23} cm^{-3}

15 other laser beams produce (1 ns delayed) a second Ti plasma, which emits the strong He-α line at 4.75 keV, and scattering of this line by the first plasma is studied.