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CO-OPERATIVE SCATTERING OF LASER LIGHT BY A THETATRON PLASMA

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CO-OPERATIVE SCATTERING OF LASER LIGHT BY A THETATRON PLASMA

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A B S T R A C T

Frequency distributions of ruby laser light scattered on the MAGGI II thetatron plasma have been measured under conditions in which the ratio of correlation length to Debye length, α, was between 1.2 and 1.5. This regime is important diagnostically because both electron temperature and electron density can be calculated from the shape of the spectrum, without having recourse to a subsidiary Rayleigh scattering experiment.

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It is now well known that the illumination of a plasma by a monochromatic unidirectional light beam results in a spectral distribution of scattered light whose shape depends upon the ratio, α, of the scale length for scattering to the plasma Debye length. Theoretical work[1] has shown that the spectrum may be regarded as the sum of two parts, first the electron feature which predominates when $\alpha \ll 1$ and has a Gaussian shape, and second, the ion feature which accounts for most of the scattered light when $\alpha \gg 1$. In the neighbourhood of $\alpha = 1$ the electron term is no longer Gaussian but begins to be depressed in the centre and to show some signs of resonances displaced from the centre frequency by $\pm \sqrt{2}\,\omega_p$, the plasma frequency. By the time α is 3 or 4 these resonances are well developed and the Gaussian character of the distribution has entirely vanished. Evidence for the deformation of the Gaussian electron feature near $\alpha = 1$ has been reported by Kunze et al[2] and Ramsden and Davies[3], and more recently, letters describing the appearance of the plasma frequency resonance for higher α have been published by Chan and Nodwell[4] and Ramsden and Davies[5].

This letter reports measurements of the distribution of light scattered into the electron feature in circumstances when α varied between 1.2 and 1.5. A Kerr-cell Q-switched ruby laser and amplifier provided 70 MW pulses within a divergence angle of 6.7 milliradians and these were used to illuminate the plasma produced by a 45 kJ (30 kV) theta pinch machine, MAGGI II. The experimental arrangement is shown in Fig.1. Laser light is focussed into a 6 mm diameter cylinder along the axis of the coil within which the plasma is formed, by the usual arrangement of lenses and stops, and is conveyed away through a 3 m long tube to a system of absorbers of blue glass (Chance OB10) chosen for its very low coefficient of surface scatter. Light scattered at 5° to the forward direction by a 10 cm length of plasma at the centre of the coil passes through an annular window concentric about the coil axis, then through an axicon from which it emerges parallel to the axis. This is followed by a silvered mirror which reflects the light through 90°, a lens of focal length 3 m, and in its focal plane a 5 cm aperture which defines the range of angles around 5°, viz. $\pm 0.5^{\circ}$, into which light is accepted by the detector. The latter consists of a dielectric multilayer filter supplied by Thin Films Inc., and an RCA 7265 photomultiplier having a photocathode with an S20 response. The filter is centred at 6943 Å and has a half-width of 5 Å when illuminated normally by monochromatic light reaching it through the system described above. Its pass-band shifts to shorter wavelengths as it is tilted away from normal incidence, thus permitting its use as a spectral resolving instrument, though confining investigation of the spectrum to the blue side of the laser wavelength.

Spectral distributions of scattered light obtained under various machine operating conditions are presented in Fig.2. They were built up from a series of individual shots, approximately 100 shots being required to produce each spectrum. Each point represents the difference between the average of a set of shots with plasma, and that of a set without plasma at the same setting of the filter. The errors on the points are experimental in that they are derived from the root mean square deviation from the mean of the sets of experimental readings. Probable sources of the observed error are plasma light noise and fluctuations in the plasma parameters from shot to shot. Variations in the intensity of the laser output were detected by a photodiode monitor and were normalized out of scattered light signals. A residual fluctuation in the normalized stray light signals suggests an additional source of noise which has not been identified as yet. Stray light at the laser frequency was equivalent in intensity to that which would be produced by Rayleigh scattering on cold nitrogen gas at a pressure of approximately 160 mm of Hg, so that although scattered light could be detected at the centre of the spectra, it gave an enhancement over the stray light of only about 20%. Nevertheless, the contrast of the filter was so high that beyond about 4 Å from the centre, scattered light was readily distinguished from stray.

To each set of experimental points a theoretical spectrum function of the form

$$\Gamma_{\alpha}(x) = e^{-x^2} \left([1 + \alpha^2 - \alpha^2 f(x)]^2 + \pi\alpha^4 x^2 e^{-2x^2}\right)^{-1}$$

where

$$f(x) = 2\, x e^{-x^2} \int_0^x e^{t^2}\, dt$$

was fitted. The abscissa was scaled according to the relation

$$\frac{x}{x_s} = \frac{\Delta\lambda}{(\Delta\lambda)_s}$$

in which the subscript 's' refers to the value of x or $\Delta\lambda$, the wavelength shift, at the peak or shoulder of the function. It is of interest that where α lies between 1 and 2, $x_s \simeq \alpha$ to better than 5%, from which it follows that the position of the peak or shoulder depends only upon plasma density. By a process of trial and error the value of α was determined to the nearest tenth, for example in the first of the spectra it became plain that $\alpha = 1.3$ was a better fit than either 1.2 or 1.4. Similarly the position of the peak value, $(\Delta\lambda)_s$, was estimated to be correct to the nearest Ångstrom unit, since a change of 2 Å either way produced a readily detectable deterioration in the apparent goodness of fit.

The first two spectra were observed when the discharge tube was filled with hydrogen at a pressure of 20 millitorr and 1 kilogauss of reverse bias field was applied. A pre-ionizing pulse (110 J, 34 kV) ensured breakdown of the gas in the first half-cycle of the discharge of the main condenser bank. The first spectrum was measured half way in time to the peak of the first half-cycle current pulse, the second was measured at the peak. The difference between the two is attributed to the change in the plasma properties as compression takes place. The best fit for the first spectrum was characterized by the parameters $\alpha = 1.3 \pm 0.05$ and $(\Delta\lambda)_s = 16$ Å $\pm$ 1 Å, from which electron density $n_e = (6.0 {}^{+1.0}_{-0.6}) \times 10^{15}\,cm^{-3}$ and electron temperature $T_e = 103 {}^{+29}_{-17}$ eV were calculated. The second spectrum yielded $\alpha = 1.2 \pm 0.05$ and $(\Delta\lambda)_s = 22$ Å $\pm$ 1 Å giving an electron density $n_e = (1.16 {}^{+0.14}_{-0.06}) \times 10^{16}\,cm^{-3}$ and electron temperature $T_e = 233 {}^{+51}_{-28}$ eV.

The third distribution in the figure was measured at the peak of the first half-cycle of the current at a filling pressure of 50 millitorr of hydrogen and in the presence of 500 gauss of reverse bias field. The best fit in this case gave $\alpha = 1.5 \pm 0.05$ and $(\Delta\lambda)_s = 30$ Å $\pm$ 1 Å corresponding to density $n_e = (2.15 \pm 0.15) \times 10^{16}\,cm^{-3}$, and electron temperature $T_e = 278 {}^{+40}_{-36}$ eV.

An independent measurement of the electron temperature in this plasma has been made under the same plasma conditions as those applying to the second of the three distributions in the figure by D. Beach et al.[6]. Their experiment, also a laser light scattering one, was performed at 90^o and so had an $\alpha \ll 1$. Their estimate of temperature is $T_e = 240 \pm 36$ eV which agrees favourably with that measured by us.

We consider that the importance of these measurements lies in their application as a plasma diagnostic technique, for it is only when α is in the neighbourhood of 1 or 2 that measurements of T_e and n_e may both be derived from the spectrum of the scattered light without any knowledge of the absolute intensity.

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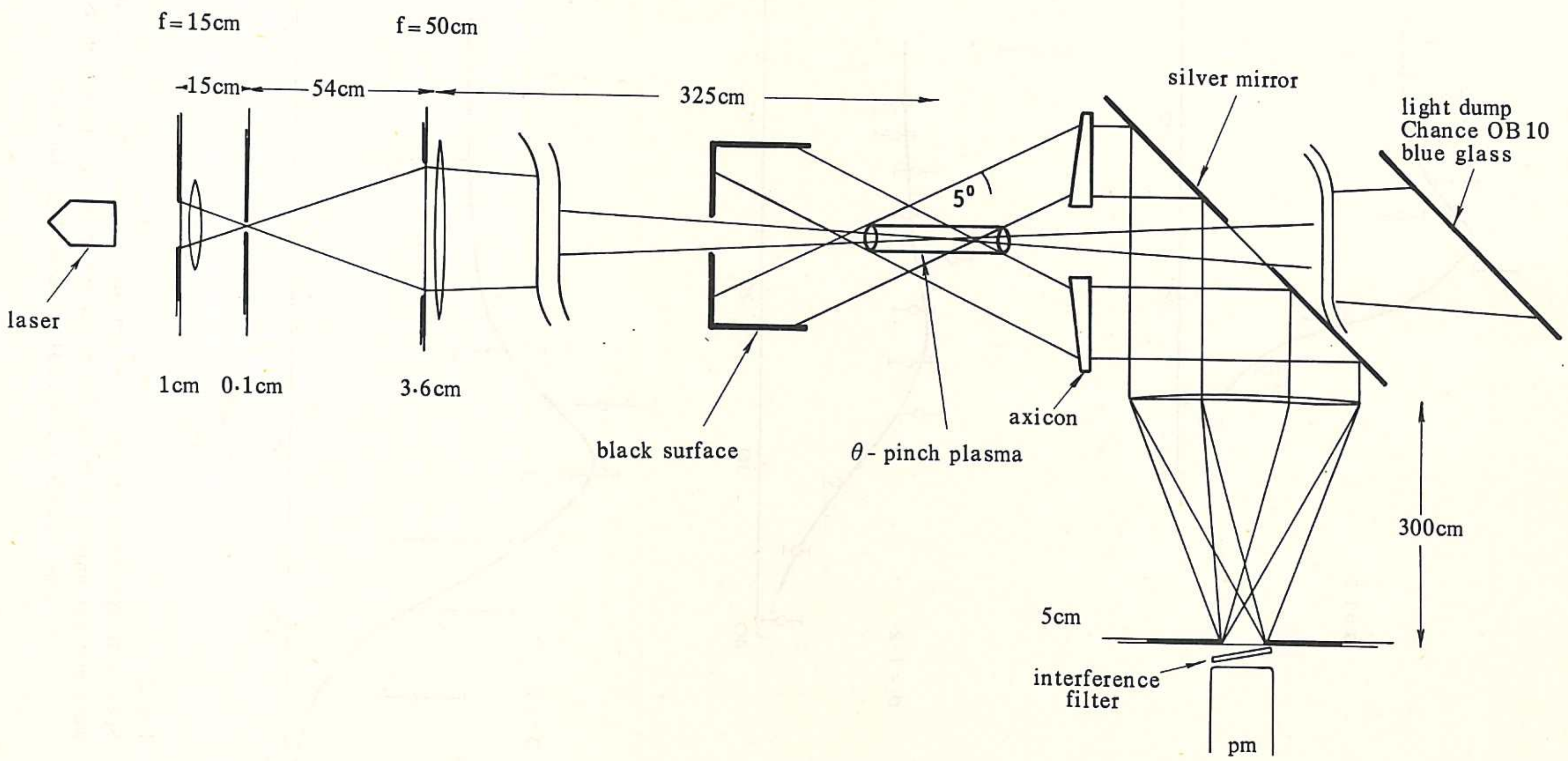

Fig. 1 Schematic diagram of the experimental layout (CLM-P 104)

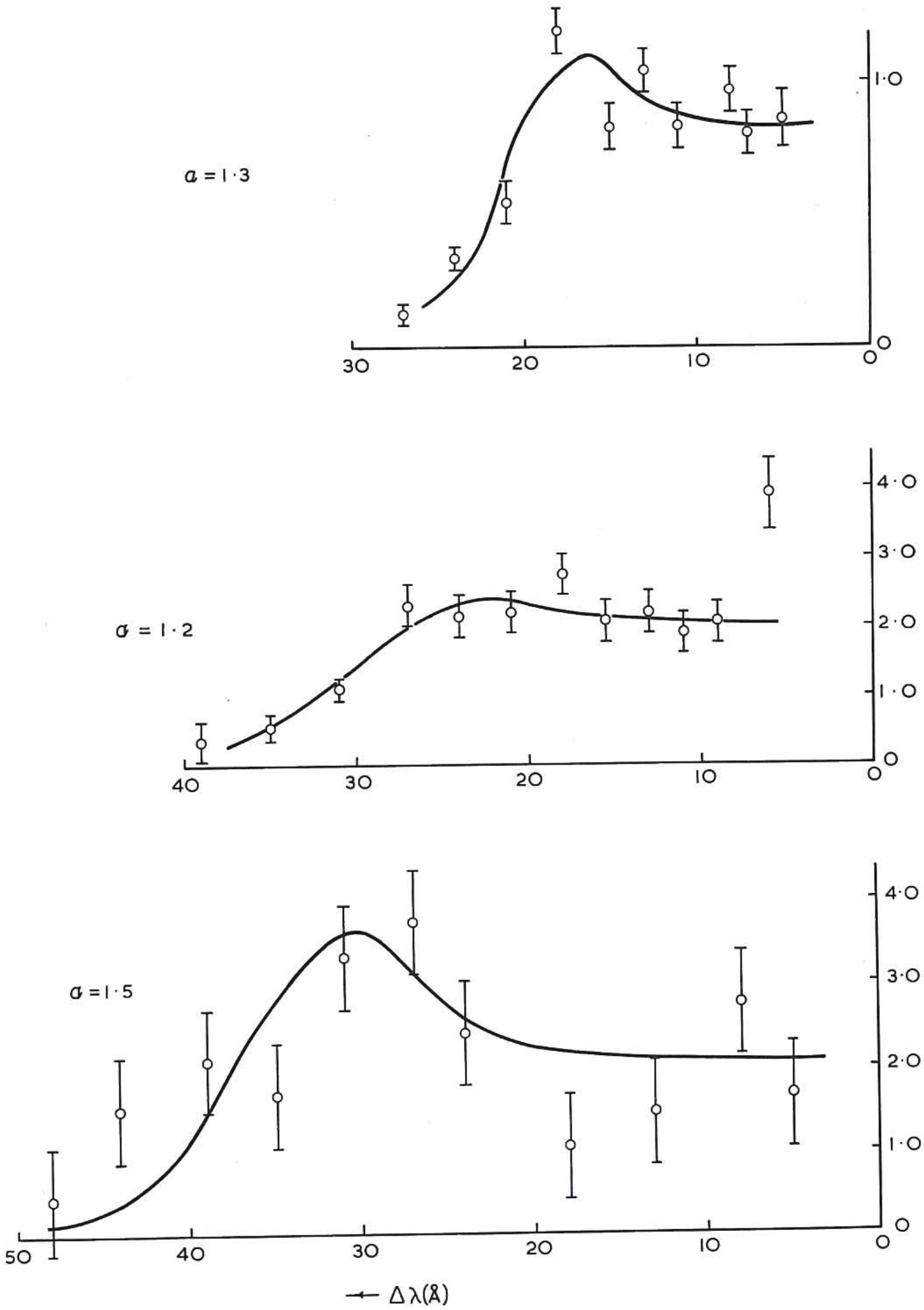

Fig. 2 (CLM-P104)

Spectra of light scattered at 5°. Abscissa is the shift from the laser wavelength in angstrom units. Ordinates are arbitrary intensity units. Curves are best fit theoretical scattered light functions.