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D. E. EVANS
M. J. FORREST
J. KATZENSTEIN

Culham Laboratory,

Culham, Abingdon, Berkshire

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ABSTRACT

In an experiment designed to display the ion term in the light scattering cross section of a thetatron plasma, a spectrum is obtained which is asymmetrically distributed about the laser light wavelength. This is interpreted as being due to a relative drift velocity between the electrons and the ions of the plasma leading to the onset of an ion wave instability. Estimation of the plasma parameters is attempted by comparison of the measured spectrum with curves computed from the theoretical work of Rosenbluth and Rostoker.

U.K.A.E.A. Research Group,
Culham Laboratory,
Nr. Abingdon,
Berks.

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In an experiment designed to display the ion term in the light scattering cross-section of a plasma[1] we have obtained a spectrum of scattered light which is asymmetrically distributed about the incident light wave-length. The experiment was conducted on the MAGGI II thetatron using an arrangement similar to that described in Evans et al[2] except that a KORAD KQ-1 giant pulse ruby laser delivering 50 MW pulses was used to obtain a narrow emission line, and the dispersing element at the detector was a pressure scanned Fabry-Perot interferometer which had a free spectral range of 2.55 Å. A single order was isolated by means of a narrow band dielectric filter, and light which passed through a focal plane stop whose diameter was a resolution width for the Fabry-Perot was detected by a photomultiplier. The wave-length spectrum of the scattered light was built up from a sequence of more than 200 shots during the course of which the interferometer's pass band was moved backwards and forwards over two fringes. The resulting spectrum is exhibited in Fig.1, together with a spectrum of the stray light from the laser. The individual measurements in the two specta were obtained sequentially, the plasma being fired on every second laser shot. The stray light spectrum serves to mark the positon of the centre wavelength from which scattered light is shifted.

The 45 kJ thetatron was operated at 30 kV and the initial gas pressure was 50 millitorr of hydrogen. A 500 gauss reverse bias field was applied, and a pre-ionization pulse ensured the presence of a plasma from the outset of the discharge of the main bank. Scattered light was measured at the peak of the first half cycle of the current. This condition has been investigated previously[2] when the following parameters were measured: electron temperature $T_e = 278^{+40}_{-36}$ eV. and electron density $n_e = 2.15 \pm 0.15 \times 10^{16}$ cm^{-3}

The striking feature of the scattered light spectrum is the enhancement of the wing to the short wavelength side of the laser line. We interpret this as due to a relative drift velocity $\underline{u}$ between the electrons and the ions of the plasma leading to the onset of an ion wave instability in the way described by Rosenbluth and Rostoker[3]. They show that such a drift causes an asymmetric enhancement of one wing of the thermal plasma spectrum, and that the strength of the enhancement is a function of $\underline{u} \cdot \underline{k}$, the component of the drift in the direction of the differential wave vector $\underline{k}$ defining the spatial component of the electron density fluctuation which gives rise to scattered light. They show further that the spectrum is reflected in the y-axis if $\underline{u} \cdot \underline{k}$ is replaced by $-\underline{u} \cdot \underline{k}$, that is, the enhancement occurs to the blue or red side of the central wavelength according to whether the electron drift is parallel or anti-parallel to the $\underline{k}$ vector.

In this experiment, the detector collects light which has been scattered at 5° to the forward direction, and which emerges from one end of the plasma vessel through an annular window concentric with the axis of the thetatron coil and the laser beam. Thus, from each point in the plasma the rays of scattered light which will reach the detector lie on the surface of a cone. To each ray there corresponds a characteristic, nearly radial, $\underline{k}$ vector, and rays on opposite sides of the cone have $\underline{k}$ vectors which are the mirror image of each other. However, at a point in the plasma from which scattered light arises, there must be a unique electron electron drift $\underline{u}$ so that each ray of scattered light has associated with it its own value of $\underline{u} \cdot \underline{k}$, and so its own spectral distribution. Rays on opposite sides of the cone must have spectral distributions which are mirror images of each other, and it follows that the composite spectrum built up by summing contributions over the whole of the annular window cannot fail to be symmetric. It happens that in our experiment, only three out of four quadrants of the annular window permit light to pass through, because the fourth quadrant lies in the shadow of the laser beam light dump tube. The spectrum which we have observed is then consistent with a current $\underline{u}$ in the direction of the opaque quadrant. Fig.2 illustrates the situation in which the upper and lower quadrants of the window, where $\underline{u}$ is approximately perpendicular to $\underline{k}$, are expected to contribute weakly asymmetric distributions, one the exact reverse of the other, so that between them, they result in no net asymmetry. The left and right hand quadrants contain the strong enhancement, and since the former is occulted, the latter makes a strong asymmetrically enhanced contribution to the spectrum which is finally observed.

An alternative explanation of the observed distribution in terms of a bulk motion of the plasma has been attempted, but we have failed to construct a spectrum which resembles the experimental result.

Estimation of plasma parameters has been attempted by comparison of the measured spectrum with curves computed on the basis of Rosenbluth and Rostoker's theory. According to this theory, the scattered light spectrum should be represented by a function of the form

$$\frac{R^2(-y) + I(-y)^2}{\left[\frac{1}{\alpha^2} + R(-y) + \frac{T_e}{T_i} R(x_i)\right]^2 + \left[I(-y) + \frac{T_e}{T_i} I(x_i)\right]^2} e^{-x_i^2}$$

when

$$R = 1 - 2x\, e^{-x^2} \int_0^x e^{p^2}\, dp$$

$$I = \sqrt{\pi}\, x\, e^{-x^2}$$

$$y = \frac{\underline{u} \cdot \underline{k}}{\underline{v}_e\, k}$$

$$x_i = \frac{2\pi c}{k v_i\, \lambda^2} \Delta\lambda$$

some examples of which are illustrated in the accompanying diagrams (Fig.3). Curves were constructed for scattering parameter $\alpha = 1.5$, which was the value measured in the previous experiment, and for a values of the ratio of electron to ion temperature, $\frac{T_e}{T_i} = 5, 2, 1, 0.5,$ and $\frac{T_e}{T_i}$ values of the drift velocity, expressed as a fraction of the electron thermal speed, $\frac{u}{v_e} \cdot \frac{k}{k}$, between zero and unity. The experimentally determined parameters on the basis of which the comparison between experiment and theory was carried out, are the shift of the enhanced wing from the centre as determined by the position of the laser line, 0.42 ± 0.1 Å, the apparent width of the resonance, 0.59 Å, which is made up of the convolution of the laser line, width 0.39 Å and the true resonance width, 0.44 Å, and the ratio of the height of the enhanced wing to the height of the suppressed wing, $= 4$, which owing to the composite nature of the observed spectrum must be a lower limit. The requirement that this ratio should exceed 4 at the same time that the ratio $\frac{\text{resonance width}}{\text{resonance displacement}} \simeq 1$ eliminated all families of curves under consideration except that for which $\frac{T_e}{T_i} = 1$, provided attention was restricted to values of drift velocity lower than the electron thermal speed. The uncertainty to be attached to $\frac{T_e}{T_i}$ can be estimated on the grounds that the curves for $\frac{T_e}{T_i} = 1.5$ and 0.75 cannot be completely excluded. By inspection, the curve from this family which appeared to give the best fit corresponded to a drift velocity $= 0.65\ v_e$, and curves for drift velocities 0.7 and 0.6 could be seen to give either, on the one hand, a too small width to displacement ratio, or on the other hand, a too small wings ratio. The shift of the peak of the spectrum with respect to the laser wavelength determines the ion wave phase velocity and hence the electron temperature, which we find to be $T_e = 220 \pm 80$ eV where the error depends almost entirely upon the uncertainty in determining the position of the peak. The ion temperature is obtained with the help of the ratio $\frac{T_e}{T_i}$ and is accordingly $T_i = 220 \pm 105$ eV. The error on T_i is compounded of that on T_e and the uncertainty in the temperatures ratio. The value of T_e obtained here is not inconsistent with that measured in the first experiment, namely $T_e = 278$ eV.

It is of interest to compare these results with those recently published by Kronast et al[4] and Ramsden et al[5] which were also scattering experiments in the forward direction on theta-pinch plasmas whose discharge parameters did not differ greatly from our own. Kronast et al measure a spectrum with a displaced maximum and interpret this result as either an ion wave enhanced by electron drift or as an electron temperature appreciably higher than the ion temperature. As seven of their eight spectral channels were arranged to observe the low frequency wing of the spectrum they were unable to establish whether or not their spectrum was asymmetric and hence distinguish the two possibilities. Ramsden et al measure a symmetric spectrum. Their experimental arrangement differs from that of Kronast and our own in that they collect light from the full range of azimuthal angles. As pointed out previously, this would lead to a symmetric spectrum even if there were an incipient ion wave instability.

Thus Ramsden's interpretation of his results as indicating an electron-ion temperature ratio greater than unity could be equally well interpreted as superposed enhanced ion wave spectra.

It should be noted that such asymmetric spectra have been observed in the backscatter of radar on the ionosphere and attributed to plasma waves excited by the auroral or equatorial electrojet[6].

The origin of the electron drift which gives rise to the observed spectrum of scattered light is conjectural. Given the direction of the thetatron current in the coil, and the assumption that the drift is azimuthal, we propose that the plasma may have moved above the axis of the laser beam at the time of the experiment, as shown in Fig.2, thereby producing an electron drift u at the intersection of the laser beam with the plasma, towards the occulted quadrant, as required by our interpretation.

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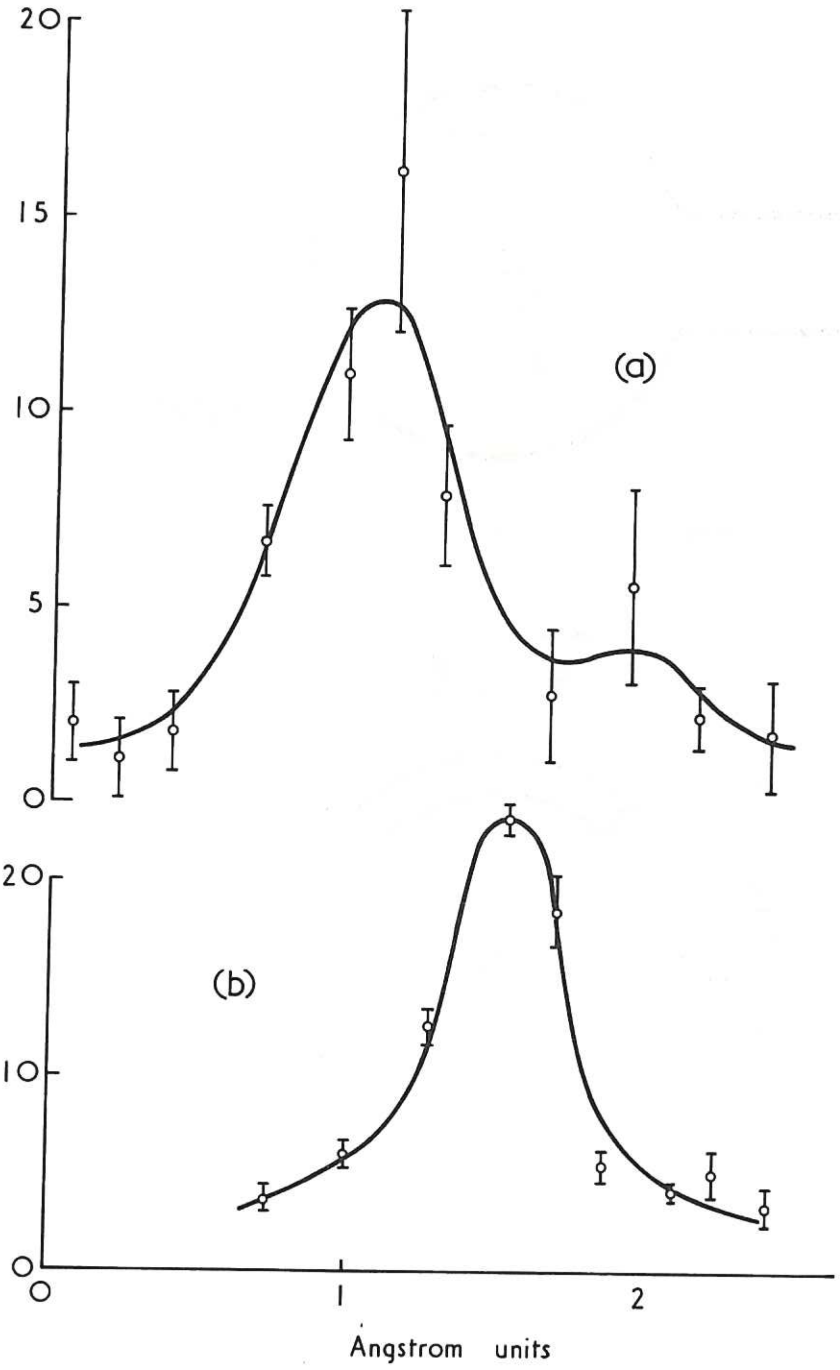

Fig. 1

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(a) Spectrum of scattered light produced by subtracting stray laser light, (b) from total signal obtained in the presence of plasma. Abscissa is common to both distributions. Errors shown are based on statistical fluctuations arising from averaging over several shots. Shift of resonance is 0.42 Å to the blue side of the laser line; measured width of resonance is 0.59 Å, width of laser line is 0.39 Å, giving true width of resonance 0.44 Å

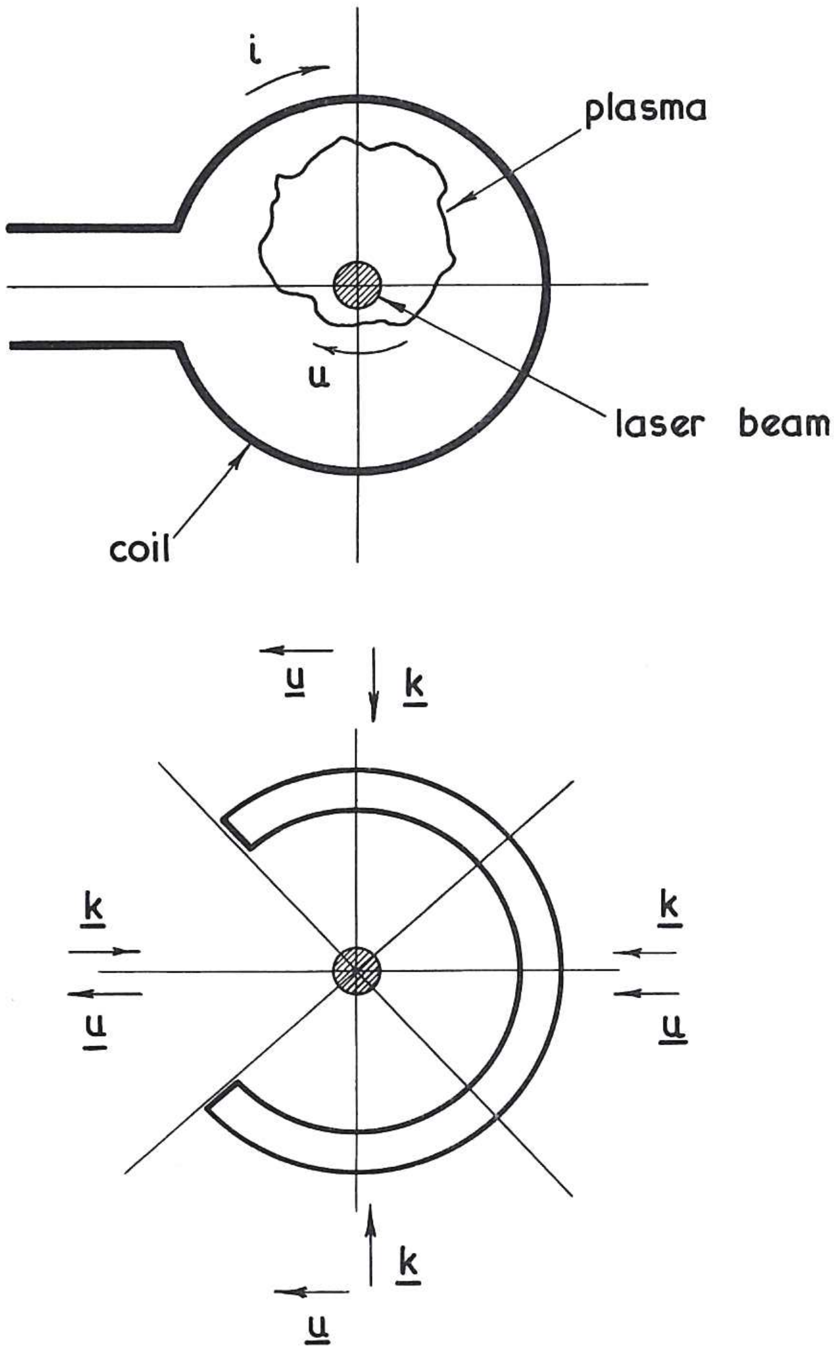

Fig. 2 (CLM-P113)

Upper part shows thetatron coil viewed from the end. Thetatron current is i which gives rise to an azimuthal electron current in the plasma, u. The plasma is shown drifting above the coil's median plane. The lower part shows the annular window in the axicon through which scattered light emerges. The composition of the term u . k which determines the shape and strength of the scattered light spectrum is shown in the three quadrants of the azimuth where light is collected

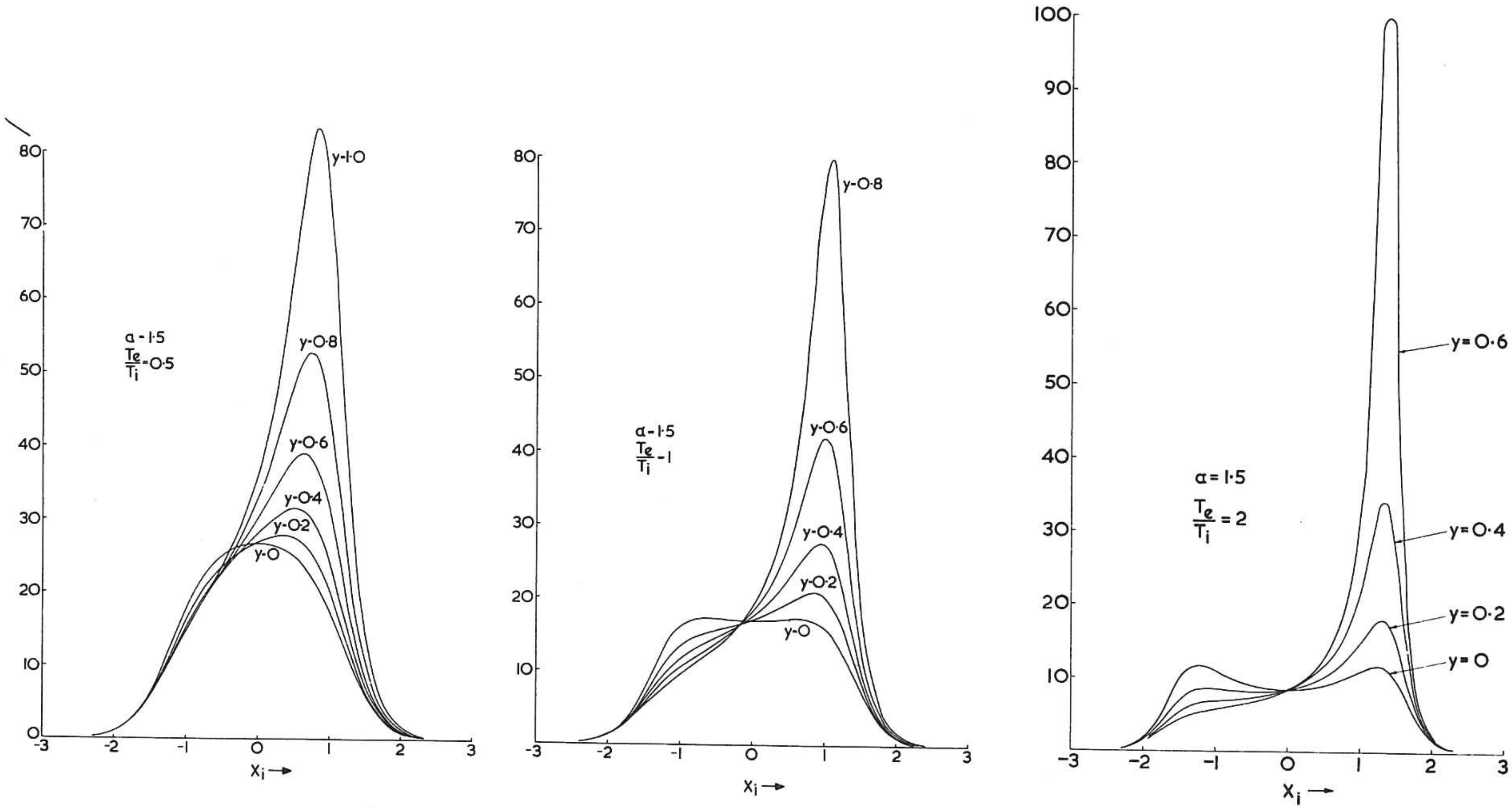

Fig. 3

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Spectra calculated from theory(3) for $\alpha = 1.5$ and values of T_e/T_i and y as shown