CLM-P201

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MEASUREMENT OF LIGHT SCATTERED FROM DENSITY FLUCTUATIONS WITHIN A COLLISIONLESS SHOCK

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1969

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We report measurements of the scattering of laser light from the micro-turbulence within a collisionless shock. These measurements demonstrate the presence of ion waves with a fluctuation level which is sufficient to explain the observed collisionless heating within the shock.

COLLISIONLESS SHOCK WAVE EXPERIMENT

We have previously described a collisionless shock with low Alfven Mach number (M_A), which propagates perpendicular to a magnetic field[1,2,3]. The shock is produced by the radial compression of an initial hydrogen plasma within a linear z-pinch. The initial plasma is 85% ionized with electron density $n_{e1} = 6{\cdot}4 \times 10^{20}$ m^{-3}, and temperatures $T_{e1} = T_{i1} = 1{\cdot}2$ eV, and is in an axial magnetic field $B_{z1} = 0{\cdot}12$ Wb m^{-2}. The shock propagates radially inwards through the initial plasma with a steady velocity $V_s = 240$ km s^{-1} ($M_A = 2{\cdot}5$), and with a steady structure of width $L_s = 1{\cdot}4$ mm and compression ratio $F = 2{\cdot}5$. The measured electron temperature behind the shock, $T_{e2} = 44$ eV, implies a resistivity within the shock which is about two orders of magnitude greater than the classical collisional value[4]. This demonstrates the collisionless nature of the shock. The effective mean resistivity ($\bar{\eta}$), obtained from the power balance equation,

$$\bar{\eta}(F-1)^2 \left(\frac{B_{z1}}{\mu_o L_s}\right)^2 L_s = (n_{e1}\ V_s)\ 1{\cdot}5\ \kappa (T_{e2} - T_{e1}) \qquad \text{(M.K.S.)}$$

corresponds to a collision frequency,

$$\bar{\nu} = 3{\cdot}4 \times 10^{9} \text{ Hz} .$$

The currently accepted theories of such shocks[3,5,6] invoke ion wave turbulence[7] to explain the structure and collisionless heating.

SCATTERING EXPERIMENT

When light is scattered by plasma waves[8], the change of optical wave vector and frequency from incident to scattered light are equal to the plasma wave vector ($\bar{k}$) and frequency (ω) ,

$$\bar{k}_i - \bar{k}_s = \bar{k} \quad \text{and} \quad \omega_i - \omega_s = \omega .$$

The differential scattering cross section per electron, $\sigma_s(\omega,k)$, measures the level of density fluctuation in terms of its Fourier transform ,

$$\sigma_s(\omega,k) = \frac{\langle \delta n_e^2(\omega,k) \rangle}{n_e} \sigma_e = S(\omega,k)\sigma_e ,$$

where σ_e is the appropriate Thomson scattering cross section for a single electron.

We have studied the light forward scattered from a 50 MW ruby laser beam of diameter 2 mm, during the passage of the shock through the beam. The laser pulse width of 35 ns is greater than the transit time of the shock through the laser beam (10 ns). The relative timing is obtained from the shock luminosity or from an electric probe which is azimuthally out of the optical paths. The incident and scattered light paths intersect symmetrically in the mid-plane of the discharge tube at an angle of 4·5 degrees. Both light paths are in a plane which is tangential to the shock front when at 9 cm radius. All the measurements of the scattered power are normalised to a monitor of incident laser power.

The plasma waves responsible for this scattering have wave vector $\bar{k}$ collinear with the azimuthal current within the shock and within the range $|\bar{k}| = k_m = 7{\cdot}1 \pm 2{\cdot}5 \times 10^5\ m^{-1}$. The nature of the waves depends on the parameter $\alpha = 1/(k\,\lambda_D)$, where λ_D is the Debye distance. For this experiment α varies in the range, $4{\cdot}4 > \alpha > 1{\cdot}2$, between the front and rear of the shock respectively, with $\alpha = 1{\cdot}3$ for the mean conditions.

ENHANCED SCATTERING FROM ION WAVES

The scattered light, measured by a photomultiplier, appears as a pulse, shown in Fig.1, which is much shorter than the laser emission, and corresponds in time and duration with the passage of the shock through the laser beam. Although there is no space or time resolution within the shock, there is clearly an enhanced level of scattering and consequently an enhanced level of fluctuation within the shock.

Spectral resolution of this scattered light is obtained by using interference filters with 3 Å or 35 Å pass band centred on the laser line, and a pressure scanned Fabry-Perot interferometer with 0·08 Å resolution within a 3 Å free spectral range. The measured normalised scattered power within the 3 Å and 35 Å pass bands is the same within the experimental accuracy (± 15%). Thus the scattering produces a change of wavelength $\Delta\lambda < 1{\cdot}5$ Å and must arise from plasma fluctuations with frequencies appreciably less than the electron plasma frequency, for which $\Delta\lambda = 5$ Å. As there is no reason to expect appreciable Doppler shifting of the plasma frequency, this result excludes the possibility of an enhanced level of electron plasma waves[9]. The measurements with the Fabry-Perot interferometer

demonstrate that all the scattered light lies within the wavelength range $\pm 0{\cdot}15$ Å from the centre of the ruby line, as shown in Fig.2. The spectral half width $\Delta\lambda = 0{\cdot}075$ Å, which is about twice that of the incident light, is equivalent to a frequency change $\Delta\omega = 3 \times 10^{10}$ Hz. This corresponds to scattering from plasma waves with

$$\omega = \Delta\omega < \omega_{pi}$$

where the ion plasma frequency $\omega_{pi} = 5 \times 10^{10}$ Hz. The measurements provide clear evidence for the presence of enhanced ion wave fluctuations within the shock.

The average scattering cross section within the shock has been measured by comparing the power scattered from the shock, with that Rayleigh scattered[10] from nitrogen gas. This method of calibration has been checked by showing that the normalised power scattered from nitrogen, is proportional to gas pressure and independent of laser power, while giving the correct ratio to the scattering from neon gas to within 10%. An independent, but less accurate, calibration of the laser power and photomultiplier sensitivity, agreed to within 30% with that obtained from the Rayleigh scattering.

The comparison of scattered power from the shock and from nitrogen gas yields a level of fluctuation within the shock ,

$$\langle \delta n_e^2(k_m) \rangle = 4{\cdot}2 \times 10^{23} \ m^{-3} \ .$$

This corresponds to,

$$\sigma(k_m) = 3{\cdot}3 \times 10^{27} \quad \text{and} \quad S(k_m) = 430 \ ,$$

for the mean value of n_e within the chock, while for the limiting values at the front and rear,

$$780 > S(k_m) > 290$$

respectively. The same level of fluctuation is measured with and without the electric probe in the plasma. The standard deviation of

these measurements is 15%, but some records vary by as much as a factor of two. It is interesting to note that this enhancement is not observed for the higher Mach number shock ($M_A = 3{\cdot}7$) reported previously[1,2,3].

ION WAVE TURBULENCE

For a stable homogeneous unmagnetised plasma with $T_e \geq T_i$ but no current, scattering theory[8] states that $S(k) \leq 1{\cdot}0$. The presence of a uniform current, unless very close to instability, does not appreciably alter this result nor does the presence of a homogeneous magnetic field.

The high value of $S(k_m)$ observed in this experiment implies the presence of instability and subsequent non-linear limitation. The free energy driving this instability must be associated with the current flow or the inhomogeneities within the shock. In a resistive shock these are interdependent and although no complete theory exists, ion wave turbulence is predicted[5,6].

A non-linear theory of homogeneous ion wave turbulence has been developed by Kadomtsev[7]. For the mean shock conditions, this theory predicts a level of isotropic turbulence,

$$\langle \delta n_e^2(k_m) \rangle = 1{\cdot}2 \times 10^{24} \ m^{-3}$$

which is nearly three times the measured value.

The measured level of fluctuation can be used to estimate the total energy in the turbulence, assuming that it is isotropic. The ion wave dispersion relations[11] are used to obtain the relations between the three forms of potential energy $\langle \delta n_e^2(k) \rangle$, $\langle \delta n_i^2(k) \rangle$ and $\langle E^2(k) \rangle$ in the waves for a given k value. The turbulence is assumed to have an electric field following a power law dependence on

k , given by $\langle E^2(k) \rangle \propto k^N$. For such a spectrum to have finite total energy, we must have $N \geq -1$. This limiting value $N = -1$, which is the form of spectrum predicted by Kadomtsev, gives the maximum turbulent energy. The measured level of fluctuation yields a maximum turbulent energy which is 9% of the electron thermal energy.

TURBULENT COLLISION FREQUENCY

The effective collision frequency (ν^*) resulting from this turbulence can be estimated by considering an electron with the mean thermal velocity (c_e), in an isotropic fluctuating electric field. The Fokker-Plank perpendicular diffusion coefficient[12] is used to obtain the collision frequency for ion wave fluctuations ($\omega \ll kc_e$) in the form,

$$\nu^* = \frac{1}{6\pi^2}\left(\frac{e}{m}\right)^2 \frac{1}{c_e{}^3} \int^{1/\lambda_D} \langle E^2(k) \rangle \, k dk \ .$$

The upper limit for the integration is consistent with the range for appreciable growth rate of ion wave instability as predicted by both Stringer[13] and Krall[6].

The integration involves the k-spectrum of the turbulence, while our measurements are, as yet, confined to a single value $k = k_m$. However, for a power spectrum of turbulence with finite energy (i.e. $N \geq -1$), the above integral depends mainly on the magnitude of fluctuations at the upper limit of integration $k = (1/\lambda_D)$, that is at the ion wave resonance. As our measurements of the fluctuation level are made near this upper limit (e.g. $\alpha = 1.3$), our estimate of the collision frequency is not sensitive to the form of the k-spectrum assumed.

We have assumed a spectrum of the form predicted by Kadomtsev ($N = -1$) and used the dispersion relations[11] to convert the

measured $\langle \delta n_e^2(k_m) \rangle$ into $\langle E^2(k_m) \rangle$. The resulting collision frequency for the mean shock conditions is

$$\nu^* = 4{\cdot}5 \times 10^9 \text{ Hz} .$$

Even if the power law is changed to $N = +2$, ν^* is only halved. The limiting values of ν^* for conditions at the front and rear of the shock with $N = -1$ are $10 \text{ GHz} > \nu^* > 2{\cdot}3 \text{ GHz}$ respectively.

The collision frequency (ν^*) for the mean shock conditions, is only 30% higher than that ($\bar{\nu}$) derived more directly through the resistivity. The measured level of fluctuation within the shock is therefore sufficient to explain the observed electron heating. Thus we have obtained experimental evidence for a self-consistent model of a collisionless shock based on ion-wave turbulence.

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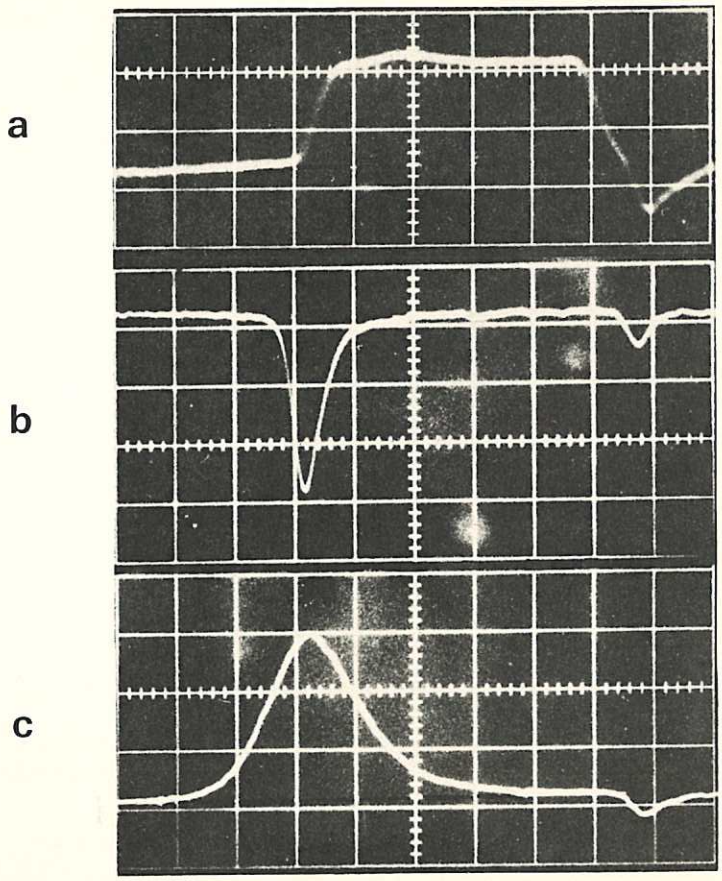

Fig. 1 (CLM-P201)
Enhanced forward scattering from the shock. Synchronized records of one event with 20 nsec per large division.
(a) Electric probe monitor of the shock[1]; (b) Forward scattered power with 3 Å filter; (c) Incident laser power.

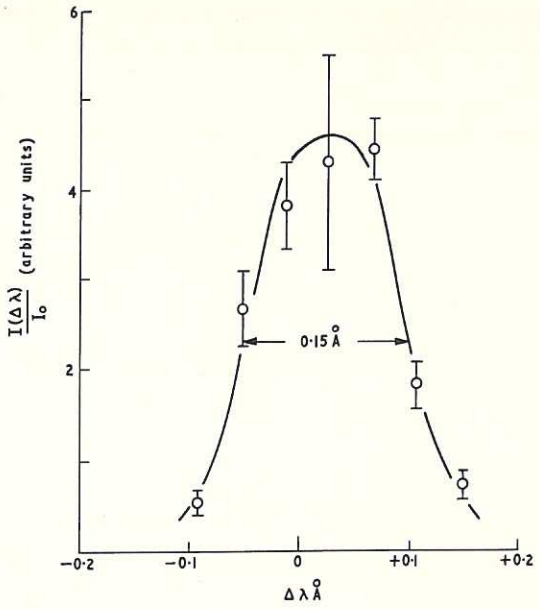

Fig. 2 (CLM-P201)
Spectral profile of light scattered from the shock. Spurious background of 6% automatically subtracted by pulsed nature of the signal