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MEASUREMENT OF SPECTRUM OF TURBULENCE WITHIN A COLLISIONLESS SHOCK BY COLLECTIVE SCATTERING OF LIGHT

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We present experimental evidence for the presence of current-driven ion-wave turbulence within a collisionless shock. The frequency and wave-number spectra of this turbulence have been measured by scattering light from the shock front. These measurements are compared with the assumptions and predictions of nonlinear theory.

Shock experiment.—We are studying[1-3] a collisionless shock with low Alfvén Mach number ($M_A < 3$), which propagates perpendicular to a magnetic field. The shock is produced by the radial compression of an initial hydrogen plasma by a linear z pinch. The initial plasma conditions ($n_{e1} = 6.4\times10^{20}\,\mathrm{m}^{-3}$, $T_{i1}=T_{e1}=1.2$ eV, $B_{z1}=0.12$ T) and the shock parameters ($M_A=2.5$, $V_s=240$ km sec^{-1}, $L_s=1.4$ mm) have been described previously. The electron heating within the shock ($T_{e2} = 44$ eV) implies a resistivity which is two orders of magnitude larger than the Spitzer value; the corresponding effective electron collision frequency $\nu^*\sim 3$ GHz.

The compression of the magnetic field in the shock front gives rise to an azimuthal current with an electron drift velocity $V_D > C_s$, the ion-sound speed. Linear stability theory[4-6] predicts current-driven ion-wave instability, while nonlinear theory[7] predicts ion-wave turbulence.

Scattering experiments.—We have previously[2,3] measured a suprathermal level of ion-wave fluctuations within the shock front. The measured level, about 400 times thermal, agrees with that required by a stochastic model of the electron heating.

We now report measurements of the wave-number (k) spectrum and the frequency (ω) spectrum of these ion-wave fluctuations, using essentially the same technique of scattering ruby-laser light.[3,8-10] This yields the Fourier transform of the electron density fluctuations in the form $S(\omega,\vec{k}) \propto \langle \delta n_e^2(\omega,\vec{k})\rangle$, with $S(\vec{k}) = \int S(\omega,\vec{k})d\omega$ and $S_k(\omega) = S(\omega,\vec{k})$ for constant $\vec{k}$.

In the experiments light is scattered from a 50-mW ruby-laser beam during the transit of the shock through the beam. The pulse of scattered light is detected by a photomultiplier, either directly or after spectral resolution. The geometry of the incident- and scattered-light paths defines a mean wave vector $\vec{k}_m$, with $|k_m| \sim 1/\lambda_{Dm}$ (λ_{Dm} is Debye length for mean shock conditions) and with $\vec{k}_m$ in the (r,θ) plane at an angle φ to the azimuthal electron current in the shock front.

Spectrum $S(\vec{k})$.—The observations are made through a window which is covered by different masks in order to vary either the scattering angle within the range $3.3° < \theta < 6.9°$ and hence $|k|$, or the scattering plane within the range $-16° < \varphi < +16°$. Over this range of φ the scattered signal is independent of φ to an accuracy of ±15%.[11] The dependence of $S(\vec{k})$ on $|\vec{k}|$ is shown in Fig. 1;

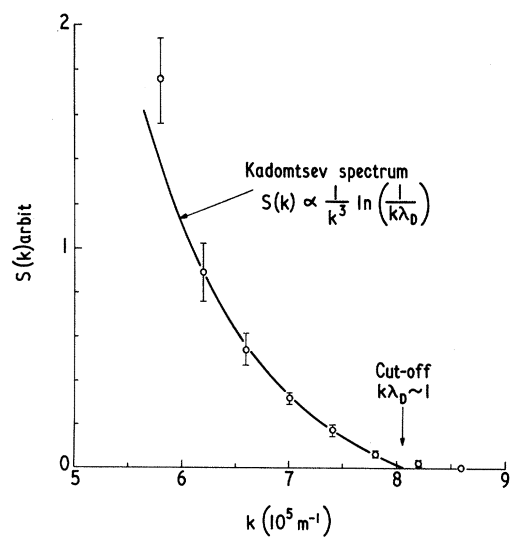

FIG. 1. Wave number spectrum $S(k)$: Experimental points are mean of five measurements and error bars are standard deviation of the mean. The curve is a Kadomtsev spectrum.

$S(\vec{k})$ decreases with increasing $|\vec{k}|$ to a cutoff at $k = k_0 = 8.1 \times 10^5$ m^{-1} with $k_0\lambda_{Dm} = 0.9$.

Spectrum $S_k(\omega)$.—We have measured $S_k(\omega)$ using a viewing aperture with an effective mean $k = k_e = 7.1 \times 10^5$ m^{-1}. The spectrum $S_k(\omega)$ is obtained by spectrally resolving the scattered light, using a Fabry-Perot interferometer with resolution 20 mÅ. The spectral width of the incident light is also 20 mÅ (after instrumental correction) as shown in Fig. 2(a). This narrow laser line is produced by using a triple etalon resonant reflector in the laser cavity.

The spectral profiles are scanned, shot by shot, by varying the refractive index (pressure) of the gas in the interferometer. The transmitted light within the central fringe is detected by a photomultiplier and is normalized to the incident scattered light.

The spectral profile of the light scattered from the shock is shown in Fig. 2(b). The width of the profile at half intensity, $\delta\lambda = 55$ mÅ, is much broader than the incident laser line. The peak of the profile is shifted to the red by $\Delta\lambda_p = 70$ mÅ

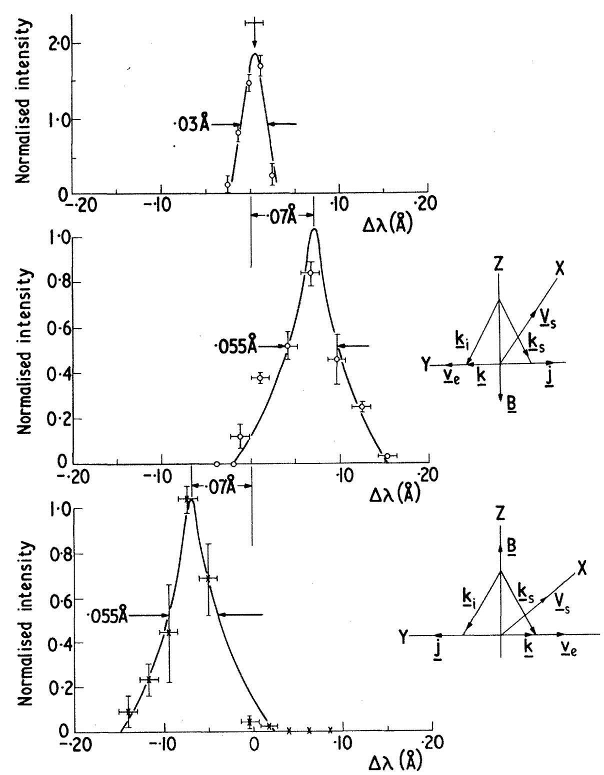

FIG. 2. Frequency spectrum $S_k(\omega)$: Spectral profiles of (a) incident laser light; (b) and (c) scattered light, i.e., $S_k(\omega)$, for opposite directions of $\vec{B}_{z1}$ and $\vec{V}_D$ as shown. Experimental points are mean of five measurements and error bars are standard deviation of the mean.

from the laser line. The scattered powers at $\pm\Delta\lambda_p$ differ by a factor of more than 50.

The direction of the shift $\Delta\lambda_p$ corresponds to scattering from plasma waves propagating in the same direction as the azimuthal electron current (i.e., $\vec{V}_D$) in the shock front. The vector directions are shown in Fig. 2. The direction of $\vec{V}_D$ in the shock front can be reversed simply by reversing B_{z1}. In a z pinch, with orthogonal drive and initial magnetic fields, such a reversal has no effect on the plasma behavior other than to change the "hand." Reversal of the azimuthal current in this way results in a reversal of the sign of the wavelength shift as shown in Fig. 2(c). The smooth curves shown in Figs. 2(b) and 2(c) are the best fit to the whole set of observations, irrespective of the sign of the wavelength shift.

Ion waves.—The peak of the scattered spectrum occurs for a shift $\Delta\lambda_p$ corresponding to scattering from plasma waves with a frequency $\omega_0 = 28$ GHz near ω_{pi}, the ion-plasma frequency. The mode (ω_0, k_e) fits the ion-wave dispersion curve ($\gamma_e = 1$, $\gamma_i = 3$) for the mean conditions in the shock ($\omega_0 = 0.65\ \omega_{pim}$ and $k_e\lambda_{Dm} = 0.78$).

However, in this experiment the electron-cyclotron frequency $\omega_{ce} \approx \omega_{pi}$. Thus, electron Bernstein modes have to be considered.[6] The dependence of ω_0 on ω_{pi}, rather than on ω_{ce}, is established by measuring the spectrum of light scattered from a similar shock ($M_A = 2.3$) with the same λ_{Dm} but $\omega_{pim}' = 0.75\omega_{pim}$ and $\omega_{ce}' = 1.3\omega_{ce}$. Spectral profiles, similar to those of Fig. 1, are obtained but with shift $\Delta\lambda_p' = 50$ mÅ and width $\delta\lambda'$ 40 mÅ. Both shift and width scale as ω_{pi} and not as ω_{ce}. Thus, the fluctuations are clearly identified as ion waves.

Current-driven turbulence.—The reversal of the shift $\Delta\lambda$ with the reversal of $\vec{V}_D$ allows us to identify the electron drift as the driving source of the ion-wave fluctuation.

The profiles $S_k(\omega)$ are similar in shift and reversal to those predicted by Rosenbluth and Rostoker[10] for a stable plasma with large $\vec{V}_D$ and $T_e > T_i$. However, our observed profiles are more enhanced[3] and broader than predicted for a stable plasma. Asymmetric profiles $S_k(\omega)$ have been observed in other experiments,[10] but none of these shows a well-defined shift with an identified cause.

Nonlinear theory.—We can now compare our results with the assumptions and predictions of nonlinear theory. Kadomtsev[7,3] has developed a theory of current-driven ion-wave turbulence in the absence of a magnetic field. He balances the linear growth rate against nonlinear scattering of the ion waves by the ions and derives a spectrum of the form

$$S(k) \propto k^{-3} \ln(k_c/k),$$

where the cutoff at k_c results from the absence of linear growth for $k > k_c \sim 1/\lambda_D$. Our measured spectrum has a cutoff at $k_0\lambda_{Dm} = 0.9$ and fits the form of the Kadomtsev spectrum as shown in Fig. 1. However, the balance described would yield a narrow frequency spectrum $S_k(\omega)$; in fact, Kadomtsev assumes that $S_k(\omega) = \delta(\omega - \omega_0)$. This is not consistent with our observations.

In Kadomtsev's model (for $V_D \gg C_s$) the turbulence is spread over the hemisphere of k space surrounding the direction of $\vec{V}_D$.[11,12] The observed anisotropy with respect to $\vec{V}_D$ and the lack of dependence of $S(\vec{k})$ on the angle φ are consistent with this model.

Stochastic heating.—Finally, we reconsider some of the assumptions used previously[2,3] when constructing a model of the stochastic heating of electrons by ion waves within this shock. In this model the electrons experience a random change of phase after a time $t = c_s\tau/v_e = (m/M)^{1/2}\tau$, where τ is the coherence time of the ion waves. If we interpret the width of $S_k(\omega)$ as a measure of the lifetime (τ_0) of the mode (ω_0, k_e), we obtain $\tau_0 \sim 0.3$ nsec, which is comparable with the period. This mode $(k \sim 1/\lambda_D)$ dominates the model so $\tau \sim \tau_0$, and consequently, $t \sim 7 \times 10^{-12}$ sec. Thus, in one effective electron collision time $(1/\nu^* \sim 3 \times 10^{-10}$ sec) the electron experiences about 40 random changes of phase, consistent with the stochastic approach.

Two other assumptions made in this model have been verified; namely, the cut off for $k > 1/\lambda_D$, and the Kadomtsev form of $S(k)$. The observation that the turbulence is not isotropic, as was assumed, is not expected to make an appreciable difference to the stochastic heating.

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