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MEASUREMENT OF ELECTRON TEMPERATURES PRODUCED BY COLLISIONLESS SHOCK WAVES IN A MAGNETISED PLASMA

by

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ABSTRACT

Direct measurements, by Thomson scattering, of electron temperatures resulting from the shock heating of electrons by a collisionless shock front are reported.

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This letter reports measurements of the shock heating of electrons resulting from the propagation of collisionless shock fronts through a highly ionized plasma in a direction perpendicular to an initial magnetic field. Three different types of shock structure arise as the Alfvén Mach number is increased ($M_A = 2{\cdot}5,\ 3{\cdot}7,\ 6{\cdot}3$) by decreasing the initial magnetic field. The structure of the magnetic field (B_z) and the radial electric potential (V_R) within these shock fronts was reported previously(1) and their collisionless nature deduced indirectly. Direct measurements of the electron temperature (T_e) by Thomson scattering of ruby laser light are reported here. These conclusively demonstrate that the binary particle collision approximation for resistivity and viscosity is inadequate to account for the observed shock structures and electron heating. The collective approximation involving wave-particle and wave-wave interactions appears to be more appropriate.

In the experiments the shock front, driven by the fast compression of a linear Z-pinch(2), propagates radially inwards (velocity $\sim 2{\cdot}5 \times 10^7$ cm/sec) through an initial hydrogen or deuterium plasma(1) ($n_{eo} \sim 10^{15}$ cm^{-3} and $T_{eo} = T_{io} \approx 1$ eV) in a direction perpendicular to an initial axial magnetic field ($B_{zo} \sim 1$ kG). A 400 MW, 20 nsec laser pulse is passed across the diameter of the discharge tube at the midplane. The light, scattered into the axial direction from a 1 cm length of the laser beam centred at 9 cm radius, is detected by a photomultiplier. The laser pulse is timed relative to the shock structure using an electric probe at 9 cm radius but moved azimuthally out of the field of view.

The spectral profile of ruby laser light scattered through 90^0 by these plasmas should be Doppler broadened by the random motion of the electrons(3). For thermal electrons, with temperature T_e in eV, the profile should be Gaussian with half intensity half width $\Delta\lambda_{\frac{1}{2}} = 16\sqrt{T_e}$ Å. In the experiment, spectral resolution of the scattered light is obtained by placing in front of the detecting photomultiplier various interference filters with narrow pass-bands (3 Å to 35 Å) and high rejection ratio ($\sim 10^{-4}$). The scattered profile $I(\Delta\lambda)$ is derived from about four measurements at each of about five wavelength shifts ($\Delta\lambda$) using two independent calibration methods which agree to within 5 per cent. Assuming that the electrons are thermal, the temperature can be calculated from the gradient of the best fit straight line through the ($\log I(\Delta\lambda)$, $(\Delta\lambda)^2$) data. The total error in the temperature, including statistical (~ ± 10%) and estimated systematic errors, does not exceed ± 15%. The experimental data, with standard deviation of about ± 15% at each wavelength, is not sufficiently accurate or extensive to verify that the electrons are thermal. However the theoretical electron thermalization times have been calculated from the measured temperatures. These times are such that the electrons should be thermal by the time the temperature measurements are made.

RESULT FOR $M_A = 2{\cdot}5$ (Fig.1a)

At Alfvén Mach number $M_A = 2{\cdot}5$ in hydrogen ($n_{eo} = 7 \times 10^{14}$ cm^{-3}, $B_{zo} = 1.15$ kG) the shock front has a single sharp transition (e.g. V_R rises in 6 nsec, 1·4 mm) with high current density. The measured temperatures are given in Fig.1a as a function of time (τ) after this sharp transition. These temperatures can be compared with the theoretical predictions of plane geometry conservation relations(4), $T_e + T_i = 42$ eV, and with the cylindrical collapse computer program(5,6),

$T_e + T_i = 49$ eV, both assuming $\gamma = 5/3$. This collapse computation has been shown previously to be in good agreement with the measured dynamics of the experiment and consequently should predict the total shock heating $(T_i + T_e)$ independently of the heating mechanism. The measured temperature nearest to the shock front, $T_e = 44$ eV ($\tau = 20$ to 40 nsec) agrees well with the theoretical predictions provided that the electrons are shock heated and not the ions. This absence of appreciable ion heating is in agreement with previous deductions from the observed V_R(1).

Changing the initial plasma conditions from hydrogen to deuterium at half the number density should not and does not affect the dynamics (e.g. M_A). Consequently the same amount of thermal energy should be given to half the number of particles doubling the temperature. This simple scaling law is confirmed by the measured temperature of $T_e = 91$ eV ($\tau = 40$ to 60 nsec).

Consider the collisional transport processes (binary particle collision approximation) which might transfer the directed ion energy into random electron energy within the shock.

1. Ion viscosity (ion collisions with ions or neutrals) was dismissed previously(1) and would heat ions rather than electrons.
2. Viscous electron heating (electron collisions with electrons or ions) has been calculated using the observed radial motion (from V_R) and azimuthal electron motion (from B_z) through the appropriate coefficients(7) and found to be negligible.
3. Resistive electron heating (electron-ion collisions), the only remaining process, has been calculated using the appropriate coefficient(8) with the observed fields. For hydrogen this heating is only 15%, of that observed (even less in deuterium). Also

collisional resistivity decreases with increasing temperature and consequently the hotter deuterium shock would need to be narrower than for hydrogen with the same energy dissipation. The measured width in deuterium(1) is twice that in hydrogen which is inconsistent with collisonal resistivity.

Also the binary collision times, τ_{ee} and τ_{ei} at the rear of the deuterium shock, derived from the measured temperatures are appreciably longer than the shock rise time making such collisions ineffective for heating. Thus the observed heating and structure are inconsistent with the binary particle collision approximation.

The observed potential V_R and the critical Mach number effect $(M_A^* \sim 2{\cdot}8)$(1) both suggest that a resistive process dominates for $M_A < M_A^*$. Such a resistive process, although by the above argument not collisional, can be described by an effective collision frequency (ν^*). An average ν^* can be derived from the measured heating, $\overline{\nu^*} \sim 0{\cdot}6 \times 10^{10}\ \mathrm{sec}^{-1}$ for both hydrogen and deuterium.

The most probable mechanism for these shocks is the excitation of electrostatic waves by electron-ion streaming instabilities in the high current density transition. The subsequent interaction and damping of these waves heats the electrons. An analysis of this collective mechanism by Sagdeev(9) yields a theoretical effective collision frequency

$$\nu^* \approx 10^{-2} \left(\frac{T_e}{T_i} \right) \sqrt{\frac{M_i}{kT_e}}\, v_{ed}\, \omega_{pi}$$

where v_{ed} is electron current drift velocity. For the average conditions within the shock (derived from the measurements in hydrogen or deuterium), this theoretical prediction yields $\overline{\nu^*} \sim 5\times10^{10}\mathrm{sec}^{-1}$; this is within an order of magnitude larger than the value derived above from the measured heating. The above formula also predicts the observed scaling of shock width between hydrogen and deuterium at the same mass density.

RESULTS FOR $M_A = 3{\cdot}7$ (Fig.1b)

At Mach number $M_A = 3{\cdot}7$ in hydrogen ($n_e = 6 \times 10^{14}$ cm^{-3}, $B_{zo} = 0{\cdot}75$ kG) the shock front has a sharp transition (~ 6 nsec, 1.5 mm) preceded by a distinct slow feature (~ 60 nsec, 1·5 cm). This double structure appears for $M_A > M_A^* \sim 2{\cdot}8$. This is the theoretically predicted critical Alfvén Mach number above which any resistive process is unable to satisfy the conservation relations and an additional viscous process, probably to be identified with the slow feature, must be present(10,11).

The average electron temperature of the slow feature has been measured, $T_e = 6$ eV for $\tau = -40$ to -20 nsec, with 1 cm space resolution. This heating is five times greater than that calculated from collisional resistivity and electron viscosity (binary ion-electron energy exchange is negligible). Consequently there must be a collisionless mechanism, probably of a viscous nature, which produces the electron heating; sufficient heating in fact to account for the theoretical deficiency of the resistive process.

The main plasma compression has been shown from the total scattered intensity to occur in the sharp feature. Behind the sharp transition for $\tau = 20$ to 40 nsec the measured temperature is $T_e = 56$ eV. This additional heating is again much greater than can be accounted for by the binary collision approximation and presumably involves the same mechanism as for $M_A = 2{\cdot}5$. The measured average temperature is higher than for $M_A = 2{\cdot}5$ but lower than the theoretical total heating predicted by planar conservation, $T_e + T_i = 72$ eV, or the collapse computation, $T_e + T_i = 84$ eV ($\gamma = 5/3$). However these predictions do not consider the observed double structure.

RESULTS FOR $M_A = 6\cdot3$ (Fig.2)

At Mach number $M_A = 6\cdot3$ in hydrogen ($n_e = 4\cdot4 \times 10^{14}$ cm^{-3}, $B_z = 0\cdot43$ kG) there is no sharp feature. The measured temperatures appear to follow the magnetic field up to its first plateau. Here it reaches a peak with $T_e = 44$ eV for $\tau = 160$ to 170 nsec which is much greater than can be accounted for by the binary collision approximation. This peak electron temperature is much lower than the total temperature ($T_e + T_i$) predicted by planar conservation (140 eV) or the collapse computation (145 eV). However such comparisons are not necessarily relevant because the calculations give the total shock heating behind a thin shock while the measurements are within the broad shock structure, which is also not well separated from the driving piston.

The gradual development of the slow feature from the foot at $M_A = 3\cdot7$ into the whole structure at $M_A = 6\cdot3$ indicates that the same mechanism operates in both cases. This high Mach number mechanism is clearly shown in both cases to produce appreciable electron heating and to be inconsistent with the binary collision approximation. (Unfortunately at present there is no evidence as to whether ions are heated or not.) The mechanism has not yet been identified but it is thought to be a collective effect, the viscous analogue of the resistive process considered for lower Mach numbers.

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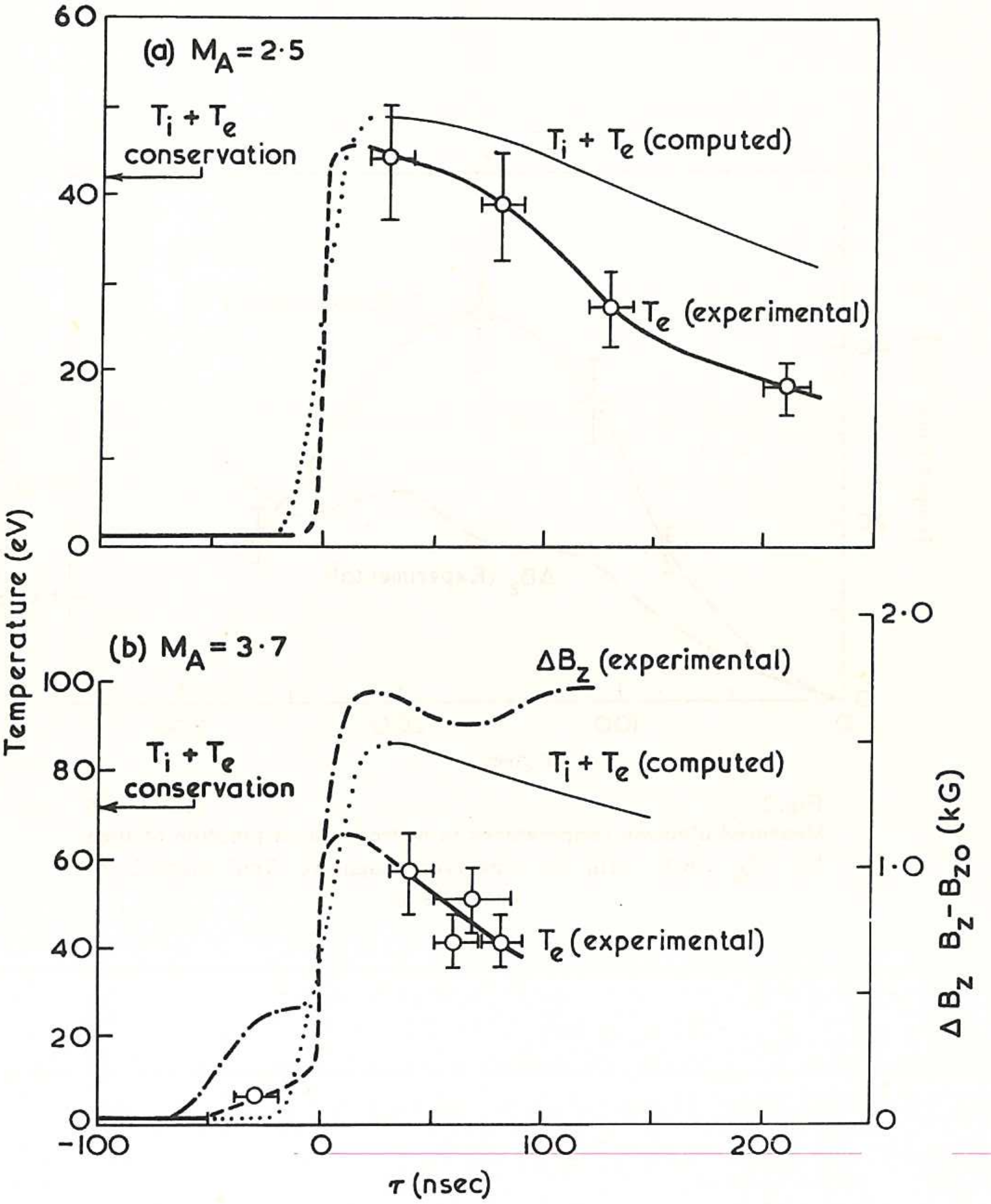

Fig. 1

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Measured electron temperatures in hydrogen as a function of time and a comparison with predictions. (a) $M_A = 2.5$ (b) $M_A = 3.7$ with the observed magnetic field plotted to show the slow feature.

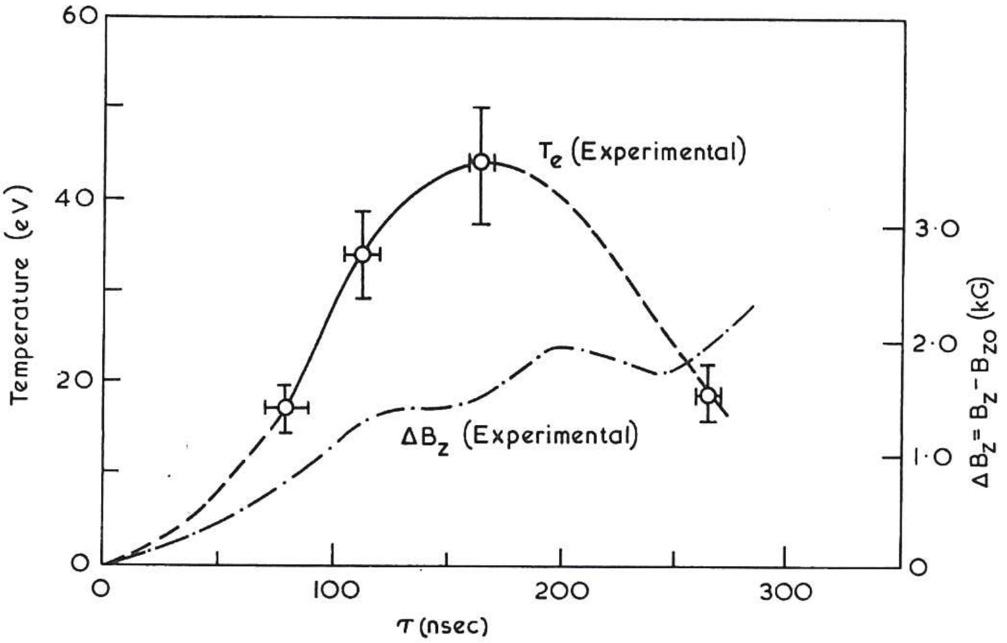

Fig. 2 (CLM-P 142)

Measured electron temperatures in hydrogen as a function of time for $M_A = 6.3$ with the observed magnetic field plotted for comparison.