COLLISIONLESS SHOCKS AND TURBULENT HEATING

On the Mechanism of Energy Dissipation in Collisionless Shock Waves[+)]

by

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Abstract: In shock waves with Mach numbers $M \lesssim M_{crit}$ strong electron heating is observed indicating a suprathermal level of fluctuations. Collective scattering of laser light shows that within the shock ion wave fluctuations are up to a factor 10 above the thermal level, whereas electron waves are thermal. For $M > M_{crit}$ non-adiabatic ion heating takes place.

This paper deals with the investigation of collisionless plasma heating by shock waves. The shock waves are produced by the fast rising magnetic field of a theta pinch discharge (0.5 µs rise to 12 kG in a coil of 15.8 cm diameter and 60 cm length) /1/. They propagate into a high β ($\beta_1 = 0.3 - 5$) hydrogen or deuterium plasma of density $2 - 5 \times 10^{14}\,cm^{-3}$ formed by a theta pinch preionization/2,3/. In contrast with similar experiments at other laboratories, the ion temperature in the initial plasma is larger ($T_{i1} = 20 - 50$ eV) than the electron temperature ($T_{e1} = 3 - 8$ eV) and remains higher during the shock heating process. By properly choosing the initial conditions and the voltage of the shock bank almost stationary collision-free shock waves with magneto-sonic Mach numbers M ranging from 1.5 to 5 can be produced /2,3/.

Electron heating for $M \lesssim M_{crit}$

As reported previously /2/, in shock waves with intermediate Mach numbers ($M \approx 2 - 3 \lesssim M_{crit}$) strong electron heating is observed yielding an effective collision frequency about two orders of magnitude higher than the frequency for binary collisions. To gain an insight into the nature and magnitude of the collective fluctuations causing this effective collision frequency, two diagnostic techniques were employed that are sensitive to fluctuations of electric field and density respectively: Observation of satellites of forbidden lines and collective scattering of laser light.

As pointed out by /4/, strong oscillating electric fields can cause satellite lines disposed symmetrically in pairs about forbidden atomic lines, their total intensity being proportional to $\langle E^2 \rangle$ and their distance from the forbidden line being equal to the frequency of the electric field. In our experiment we used the He I line at 4922 Å, the profile of which was recorded with high time resolution using an 8 channel photomultiplier arrangement. The plasma to which 15 % He was added was viewed end-on through an annular diaphragm (r = 3.5 cm, Δr = 1 cm).

Fig.1 shows typical measured line profiles at different times within the shock. Owing to the relatively high plasma density the forbidden line already shows up as a result of the microfield of the ions (c.f. line profile in front of shock), thereby reducing the sensitivity of this method to fluctuating fields. Therefore only an upper limit can be placed on the amplitude of fluctuating electric fields, this being $\sqrt{\langle E^2 \rangle}$ = 6 kV/cm averaged over the observed plasma annulus. This value would be about two orders of magnitude above the thermal level.

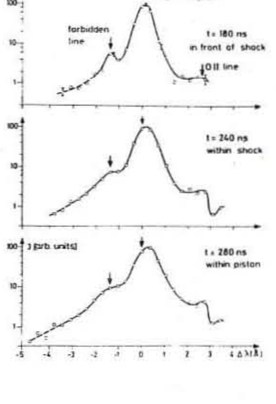

Fig. 1

The experimental arrangement for the laser forward scattering measurements is shown in fig.2. The scattering angle is 4°, giving $\alpha = 1/k\,\lambda_D = 1.5$ for the mean conditions in the shock. The scattering vector k is collinear with the azimuthal current within the shock. The bandwidth of the interference filter is chosen to transmit both the electron and ion lines, whereas the first F.-P. transmits only the ion line, which is then spectrally resolved by the second F.-P.. At the same time the density and electron temperature of the plasma at the point of observation are measured by 90° laser scattering.

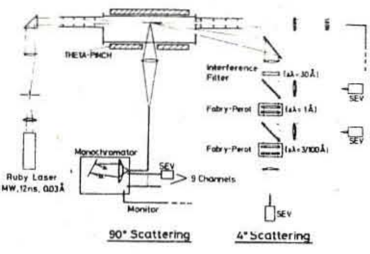

Fig. 2

Fig.3 shows the measured level of fluctuations within the ion feature of the scattered light (absolute calibration was obtained by comparison with Rayleigh scattering from H_2). Within the shock the fluctuations are clearly enhanced, being up to an order of magnitude above the thermal level which was calculated using the measured plasma parameters. On the other hand, electron waves do not seem to be enhanced, as indicated by measurement of the total scattered light (electron plus ion line). Measurements of the spectral profile of scattered light are currently under way and will be presented at the conference together with a discussion of the possible nature of instabilities involved.

Ion heating for $M > M_{crit}$

Since the shock waves are almost stationary the total shock heating $(T_e + T_i)_2$ can be derived from the steady state conservation relations /3/. As T_{e2} is measured by laser scattering, the ion temperature behind the shock T_{i2} can be calculated separately. In fig.4 the ratio of observed total ion heating to calculated adiabatic ion heating $T_{i2} / T_{i2\,ad}$ is plotted as a function of $M - M_{crit}$. For $M \lesssim M_{crit}$ the ions are only heated adiabatically, but for $M > M_{crit}$ additional non-adiabatic heating takes place that increases with Mach number. This indicates that above M_{crit} a collisionless dissipation process that heats the ions sets in.

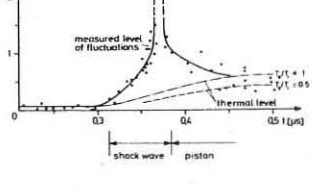

Fig. 3

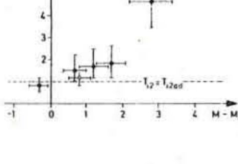

Fig. 4

/1/ R.Chodura et al., Plasma Physics and Contr. Nuclear Fusion Research, Vol.I, 81 (1969)

/2/ M.Keilhacker et al., Z.Physik 223, 385 (1969)

/3/ M.Kornherr, Z.Physik 233, 37 (1970)

/4/ M.Baranger and B.Mozer, Phys.Rev. 123, 25 (1961)

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