OBSERVATION OF COLLISIONLESS PLASMA HEATING BY STRONG SHOCK WAVES +)

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Strong shock waves (Mach number between 2 and 4) are produced in a tube of 14 cm inner diameter by the fast rising magnetic field (rise to 12 kG in 0.5 μsec) of a theta pinch discharge (coil length 60 cm). The shock waves propagate into an almost homogeneous, 50 percent ionized hydrogen or deuterium plasma formed by a fast theta pinch preionization. The initial density ranges from 2 to 5 x 10^{14} cm^{-3}, the electron temperature from 3 to 10 eV (both quantities determined by 90^{o} laser scattering) and the ion temperature (from Doppler-broadening of the H_α or D_α-line) from 15 to 30 eV (H_2) or 25 to 50 eV (D_2). The radial distribution of the magnetic field B_o trapped in the initial plasma is measured with six magnetic probes. By slightly varying the filling pressure or the voltage of the preionization theta pinch conditions can be found where the radial variation of B_o is less than 10 %. The amplitude of B_o can be varied between 300 and 1000 G, thereby changing the local β of the initial plasma (β_o = 0.2 - 4) and the Mach number of the shock waves $M = u/\sqrt{V_{Ao}^2+V_{So}^2}$ (u = shock velocity, V_{Ao} = Alfven velocity, V_{So} = sound velocity).

In a previous paper [1] we reported that under the above conditions almost stationary shock waves can be observed with a clear separation between shock front and piston. From a comparison of the measured shock width with the mean free path for Coulomb collisions it was concluded that the shock waves were collision-free. To check this inference and to get insight into the heating mechanism a local measurement of density and electron temperature in the shock wave was carried out using the Thomson scattering of laser light (600 MWatt, 12 nsec laser pulse; spatial resolution 3 mm; spectral resolution by narrow band width interference filters).

Fig. 1 shows a typical example of the measured variation of magnetic field B, density n and electron temperature T_e in a shock wave propagating with M = 2.5 into a preionized deuterium plasma (filling pressure 1o mtorr, B_o = + 900 G, β_o = 0.7). Profiles measured at two radial positions, at r = 3.5 cm (solid lines) and at r = 2.3 cm (dotted lines), demonstrate that in this region the shock front is almost stationary. The first rise in B, n and T_e corresponds to the shock front whose width is about 1 cm, corresponding to 0.6 c/Ω_p (Ω_p = ion plasma frequency).

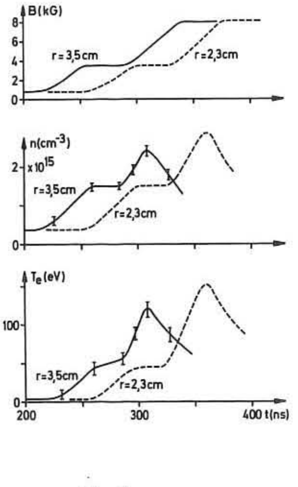

Fig. 1

The jumps in density and magnetic field across the shock front are 3 to 4 and the electron temperature increases from 3 eV in the initial plasma to 45 eV behind the shock. The second rise in temperature to 120 - 150 eV occurs in the piston of the shock wave and is probably due to turbulent heating caused by the high current densities in the piston region. More examples of measured shock profiles are published in ref. [2].

We now check whether the rise in electron temperature measured in the shock front can be ascribed to adiabatic compression and Ohmic heating. The energy equation for the electrons in a plane, stationary shock front moving in x-direction is

$$\frac{3}{2} n k u_x \frac{dT_e}{dx} = - n k T_e \frac{du_x}{dx} + \eta j^2 \qquad (1)$$

The current density j and the velocity u_x can be calculated from measured magnetic field and density profiles, using Ampere's law and continuity equation, respectively. Inserting Spitzer's resistivity ($\eta \sim T_e^{-3/2}$), integration of (1) leads to a temperature profile given by the dotted line in Fig. 2. Comparison with the measured profile shows that only 20 % of the observed electron heating can be accounted for by collisional resistive and adiabatic heating, indicating that appreciable collisionless electron heating takes place. The measured profile can be gained from (1) inserting $\eta = \eta_{turb} = m_e \nu_{eff}/ne^2$ assuming a constant collision frequency ν_{eff} almost two orders of magnitude higher than the classical value and roughly equal to the ion plasma frequency Ω_p.

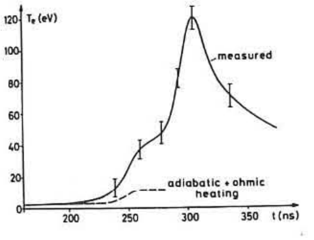

Fig. 2

From the steady state conservation relations the total shock heating $(T_e + T_i)_2$ can be derived. As T_{e2} is known from the laser scattering measurements, the ion temperature T_{i2} behind the shock can be estimated. For the example of Fig. 1 we get $T_{i2} \approx$ 110 eV, which in the main can be explained by adiabatic ion heating. For shock waves with higher Mach numbers however the calculated ion temperatures exceed those one would expect for a merely adiabatic heating.

The time dependent complete profiles of magnetic field, density, electron and ion temperature were calculated using a two fluid model [3]. The classical electron-ion collision frequency $\nu_{Spitzer}$ was increased by an effective collision frequency $\nu_{eff} \sim \sqrt{n}$ ($\nu_{eff} \approx \Omega_p \gg \nu_{Spitzer}$). Ion heating was assumed to be adiabatic.

[1] R. Chodura, M. Keilhacker, M. Kornherr, H. Niedermeyer; Proc. of IIIrd Conf. on Plasma Physics and Controlled Nuclear Fusion, Novosibirsk 1968, paper CN - 24/A - 3

[2] M. Keilhacker, M. Kornherr, K.-H. Steuer; Z.f.Physik (in press 1969)

[3] R. Chodura; Phys. Fluids, 11 (1968), 4oo

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