Reports of the Academy of Sciences of the USSR

PHYSICS

1969

SovietRxiv

Abstract

Full Text

Reports of the Academy of Sciences of the USSR
1969. Volume 184, No. 4

PHYSICS

A. A. IVANOV, L. L. KOZOROVITSKII, V. D. RUSANOV

HEAT PROPAGATION IN A PLASMA ALONG A MAGNETIC FIELD (SUBSTITUTION WAVE)

(Presented by Academician E. K. Zavoiskii, 5 VI 1968)

A small part of a cylindrical plasma column placed in a uniform magnetic field (Fig. 1*a*) was heated during a short time interval ($\sim 10^{-7}$ sec) by a nonlinear oblique magnetosonic (n.k.m.-z.) wave ([1,2]).

The initial plasma was produced by two h.f. generators; the concentration $n_e \sim 4 \cdot 10^{12} \div 2 \cdot 10^{13}$ cm^{-3}, the electron temperature ~ 10 eV or less than 1 eV in the afterglow regime; the ion temperature did not exceed 2 eV. The discharge was produced in hydrogen or argon at a pressure of $2 \cdot 10^{-4}$ mm Hg. The diameter of the plasma column was 7 cm. The intensity of the static magnetic field H_0 was 500-1000 G. The amplitude of the n.k.m.-z. wave, generated by a pulsed circuit with a narrow coil ($d = 8$ cm, $L = 3$ cm), reached 1800 G. The characteristic rise time was $\sim 20 \cdot 10^{-9}$ sec.

In Fig. 1*b* is shown the distribution of the pressures of the n.k.m.-z. wave field $H^2/8\pi$ and of the plasma nT along the axis of the column. The wave amplitude was measured by means of a magnetic probe, and the plasma pressure by a diamagnetic pickup surrounding the chamber. The probe and the diamagnetic pickup could be moved along the axis of the discharge chamber. The energy of the n.k.m.-z. wave is rapidly absorbed by the plasma, and at distances ~ 20 cm from the central plane of the coil the plasma pressure substantially exceeds the wave pressure.

Fig. 1. *a* —schematic diagram of the apparatus; *b* —distribution of the pressures of the wave $H^2/8\pi$ (1) and of the plasma nT (2) along the length of the tube

In Fig. 2 are presented oscillograms of the diamagnetic signal obtained at different distances from the coil. The maximum propagation velocity of the diamagnetic signal is $\sim 10^9$ cm/sec and, for the given cross section, depends on the energy input as the power 1/2. The propagation velocity of nT did not change with variation of H_0 and did not depend on the atomic weight of the gas, as

Fig. 2

Figure 1: Fig. 2

Fig. 3

Figure 2: Fig. 3

experiments with argon showed. This velocity also did not depend on the initial temperature (experiments in the afterglow). Measurements of the electron density with an 8-millimeter interferometer showed that during the heating and propagation of nT the concentration does not change within the accuracy of the measurements (10%).

The signal from an electric probe, at floating potential, is shown in Fig. 3. The propagation velocity of the perturbation of the plasma potential coincides with the propagation velocity of nT; the amplitude of the perturbation is ~ 1000 V.

It may be concluded that in the experiments there is observed a transfer of particle energy with a velocity close to the thermal velocity of the heated electrons ($T_e \sim 100$ eV).

Processing of oscillograms of the diamagnetic signals obtained at different points along the chamber axis made it possible to construct an instantaneous profile of the transverse temperature (Fig. 4). It is seen that the characteristic scale of the spatial distribution of T_e is less than 20 cm, which is several orders of magnitude less than the electron mean free path at $T_e = 100$ eV.

Fig. 2. Signal of the diamagnetic probe in different sections of the plasma column ($\tau_\phi \sim 10^{-7}$ s).

Let us interpret the experimental data by means of a nonlinear solution, which we shall henceforth call a replacement wave. Indeed, in the absence of collisions the process of heat propagation in the simplest case may be represented as follows.

Let at the time $t = 0$ the half-space $x < 0$ be occupied by hot particles with $T_\| = T_\perp$, while the half-space $x > 0$ is occupied by cold particles ($T_\| = T_\perp = 0$). Owing to the pressure gradient, the hot particles will enter the half-space $x > 0$ and create a potential. The cold particles will be accelerated in the electric field and move to the left. As soon as the cold particles are displaced to the position of the departed hot ones, the latter will begin to propagate farther. Thus the propagation of heat (i.e., $T_\perp$) will be associated with the propagation of hot particles from the left half-space. We shall show that, with such a simple formulation of the problem, self-similar solutions may exist.

Fig. 3. Signal of the electric probe in two sections of the plasma column

We shall describe the hot particles by means of the distribution function $f(v, x, t)$ (v is the longitudinal velocity), satisfying the Boltzmann equation (1), and the cold particles by the hydrodynamic equations (2), (3):

$$\frac{\partial f}{\partial t}+v\frac{\partial f}{\partial x}+\frac{e}{m}\frac{\partial \varphi}{\partial x}\frac{\partial f}{\partial v}=0; \tag{1}$$

$$\frac{\partial v_x}{\partial t}+v_x\frac{\partial v_x}{\partial x}=\frac{e}{m}\frac{\partial \varphi}{\partial x}; \tag{2}$$

$$\frac{\partial n_x}{\partial t}+\frac{\partial}{\partial x}(n_x v_x)=0. \tag{3}$$

Since we are interested in the propagation of waves with large velocities $\sim v_{T_e}$, at which the displacement of ions may be neglected, the latter

can be considered to be at rest; we shall denote their unperturbed density by n_0. In addition, the characteristic scales of the front observed experimentally are larger than the Debye radius; therefore we use the quasineutrality condition

$$n_x+\int_{-\infty}^{\infty} f\,dv=n_0. \tag{4}$$

Then the system (1)–(4) has self-similar solutions. Introduce the variables $\tau=(\sqrt{2T_0/m})^{-1}(x/t)$ (T_0 is the initial temperature) and $\bar{v}=(\sqrt{2T_0/m})^{-1}v$, $\bar{v}_x=(\sqrt{2T_0/m})^{-1}v_x$,

$$\bar{f}=\frac{1}{n_0}\left(\frac{2T_0}{m}\right)^{-1/2}, \quad \bar{\varphi}=\frac{e\varphi}{2T_0}, \quad \frac{n_x}{n_0}=\bar{n}_x;$$

then the system (1)–(4) takes the form

$$(-\tau+\bar{v})\frac{\partial \bar{f}}{\partial \tau}+\frac{\partial \bar{\varphi}}{\partial \tau}\frac{\partial \bar{f}}{\partial \bar{v}}=0; \tag{1'}$$

$$(-\tau+\bar{v}_x)\partial\bar{v}_x/\partial\tau=\partial\bar{\varphi}/\partial\tau; \tag{2'}$$

$$(-\tau+\bar{v}_x)\partial\bar{n}_x/\partial\tau+\bar{n}_x\partial\bar{v}_x/\partial\tau=0; \tag{3'}$$

$$\bar{n}_x+\frac{1}{\sqrt{\pi}}\int_{-\infty}^{\infty}\bar{f}\,d\bar{v}=1. \tag{4'}$$

Fig. 4. Plasma-temperature profiles for a specified instant of time. 1—$T_0=0.5$ eV; 2—10 eV.

Fig. 4. Plasma-temperature profiles for a specified instant of time. 1–$T_0 = 0.5$ eV; 2–10 eV

Figure 3: Fig. 4. Plasma-temperature profiles for a specified instant of time. 1 –$T_0 = 0.5$ eV; 2–10 eV

Eliminating $\bar{\varphi},\ \bar{v}_x,\ \bar{n}_x$, with the condition $\bar{\varphi},\ \bar{v}_x = 0$ at $x = -\infty$, we obtain an equation for the distribution function $\bar{f}$

$$(-\tau + \bar{v})\frac{\partial \bar{f}}{\partial \tau} - \frac{\partial n_x}{\partial \tau n_x}\left(\int_{-\infty}^{\tau} n_x \, d\tau / n_x\right)^2 \frac{\partial \bar{f}}{\partial \bar{v}} = 0, \quad \bar{n}_x = 1 - \frac{1}{\sqrt{\pi}}\int_{-\infty}^{\infty} \bar{f}\, d\bar{v}. \quad (5)$$

Denoting the coefficient in front of $\partial \bar{f}/\partial \bar{v}$ by $F(\tau)$, we obtain the equation for the characteristics

$$d\bar{v}/d\tau = -F/(\bar{v} - \tau). \quad (6)$$

The form of the distribution function, and consequently the particle density at the front, can be obtained by integration along the characteristics, as was done in work ([3]). The characteristic velocities of motion of the front are $\sim v_{Te}$. Thus, in principle, the formation of a replacement wave propagating with velocity v_{Te} is possible.

Let us now consider another case. Suppose that in the region $L/2 \leq x \leq L/2$ there is a hot plasma with density n_0 (the particle distribution over velocities at $t = 0$ is Maxwellian), while for $|x| > L/2$ there is a cold plasma of the same density. We take into account collisions of the cold particles with one another and use equations (1), (3), (4) with the additional condition of conservation of the total number of hot particles:

$$\int f \, dv \, dx = n_0 L. \quad (7)$$

Now the system of equations (1), (3), (4), (7) contains the length scale L. Introduce variables as follows: $v = \bar{v}(\sqrt{2T/m}),\ v_x = \bar{v}_x(\sqrt{2T/m}),\ x = \bar{x}L,\ t = \bar{t}L/\sqrt{2T/m},\ \nu = \bar{\nu}L/v_{Te}$. Then

$$\frac{\partial \bar{f}}{\partial \bar{t}} + \bar{v}\frac{\partial \bar{f}}{\partial \bar{x}} + \frac{\partial \bar{\varphi}}{\partial \bar{x}}\frac{\partial \bar{f}}{\partial \bar{v}} = 0; \quad (8)$$

$$\nu \bar{v}_x = \partial \bar{\varphi}/\partial \bar{x}; \quad (9)$$

$$-\frac{\partial \bar{n}_\Gamma}{\partial \bar{t}} + \frac{\partial}{\partial \bar{x}}\left[\bar{v}_x(1-\bar{n}_\Gamma)\right] = 0, \quad n_\Gamma = \frac{1}{\sqrt{\pi}}\int \bar{f}\,d\bar{v}; \tag{10}$$

$$\frac{1}{\sqrt{\pi}}\int \bar{f}\,d\bar{v}\,dx = 1. \tag{11}$$

Introduce the self-similar variables $\xi = \bar{x}/\bar{t}^n$, $\eta = \bar{v}/\bar{t}^s$, $g = \bar{f}/\bar{t}^{s+n}$, $N = \bar{n}_r\bar{t}^n$, $\bar{v}_x = v_x\bar{t}^q$, $\varphi = \Phi\bar{t}^l$, and consider the values $|x| \gg L$. The latter corresponds to the smallness of n_r compared with unity in equation (10). Introducing the self-similar variables into equations (8)–(11), we obtain

$$-(n+s)g - \frac{\partial g}{\partial \xi}n\xi - \frac{\partial g}{\partial \eta}s\eta + \eta\bar{t}^{s-n+1}\frac{\partial g}{\partial \xi} + \bar{t}^{l-s-n+1}\frac{\partial \Phi}{\partial \xi} = 0; \tag{8'}$$

$$\bar{v}v_x = \bar{t}^{l+n-q}\partial\varphi/\partial\xi; \tag{9'}$$

$$\left(-N - \xi\frac{\partial N}{\partial \xi}\right)n + \bar{t}^{q+1}\frac{\partial}{\partial \xi}v_x = 0. \tag{10'}$$

It follows from this that $s-n+1=0$, $l-s-n+1=0$, $l-q+n=0$, $q+1=0$, or $q=-1$, $n=1/3$, $l=-4/3$, $s=-2/3$.

Thus, $\bar{x} = \bar{t}^{1/3}\xi$, $\bar{v} = \eta\bar{t}^{-2/3}$. The values of ξ and η at the front of the replacement wave can be found by integration along the trajectories of equation (8). It is then seen that the temperature of the hot particles varies as $1/x^2$, while the coordinate of the front varies proportionally to $t^{1/3}$. Consequently, the observed phenomenon can be satisfactorily described by means of a replacement wave.

Received
6 V 1968

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Note: Figure translations are in progress. See original paper for figures.