“CALORIMETRIC” MEASUREMENT OF THE ELECTRON TEMPERATURE OF PLASMA IN A COLLISIONLESS SHOCK WAVE

PHYSICS

1969

SovietRxiv

Abstract

Full Text

UDC 533.9.082.5

PHYSICS

G. E. SMOLKIN, E. A. STRIGANOVA, G. V. SHOLIN

"CALORIMETRIC" MEASUREMENT OF THE ELECTRON TEMPERATURE OF PLASMA IN A COLLISIONLESS SHOCK WAVE

(Presented by Academician E. K. Zavoisky, 26 VIII 1968)

1. An important characteristic of dissipative processes in a collisionless shock wave is the jump in electron temperature $\Delta T_e = T_{e2} - T_{e1}$ at the front. The temperature T_{e1} ahead of the wave front is usually known in advance with sufficiently good accuracy. It is determined by the method used to create the preionization plasma and, as a rule, has a fairly low value. For example, in the afterglow plasma used by us in previous experiments (1), the electron temperature T_{e1} was set by the delay time t_3 of the start of the shock wave relative to the preionization current and was measured from the time-resolved spectrum of three-body electron–ion recombination. When t_3 was increased from 10^{-5} to $5 \cdot 10^{-4}$ sec, the temperature fell approximately from 2 to 0.1 eV and below.

Considerably greater difficulties arise in measuring the electron temperature T_{e2} behind the shock-wave front. This is mainly due to the fact that the lifetime of the high-temperature plasma in experiments with shock waves is very short. Often such a plasma state decays before it reaches thermodynamic equilibrium.

Under the conditions of real experiments in open-type systems, cooling of the electrons heated by the shock wave can occur for two reasons: as a result of the escape of fast electrons to the ends and walls of the discharge chamber, and due to inelastic collisions with neutral and incompletely ionized atoms. One can deliberately choose the experimental conditions so that only the second cooling mechanism acts predominantly. For this, obviously, it is necessary to include sufficiently effective magnetic plugs and to choose a sufficiently low degree of ionization in the plasma ahead of the wave front.

Under such conditions, the electron temperature T_{e2} acquired at the front of a collisionless shock wave can be measured by the so-called calorimetric method (2, 3). The calorimetric method was first applied by E. K. Zavoisky and coworkers to measure the temperature of turbulently heated plasma (3). Its essence is to measure the increase in plasma concentration $\Delta n = n_2 - n_1$ over a sufficiently long time interval after heating. Assuming that this increase is

Fig. 1

Figure 1: Fig. 1

entirely associated with the cooling of hot electrons as a result of inelastic collisions with gas atoms, the electron temperature behind the shock-wave front can be expressed as

$$T_{e2} = \frac{\Delta n}{n_1} I,$$

where I is the cost of ionization, equal to the average electron energy losses per one act of ionization. In a plasma whose electron temperature is comparable with the ionization potential I_0 or higher, the cost of ionization may be taken approximately equal to $2I_0$. Therefore, for hydrogen $I \approx 27$ eV.

2. The experiments were carried out on the UV-2 device, described in (^{4}). The shock wave was excited by a trapezoidal pulse of magnetic field $\tilde{H}$, produced at the boundary of the plasma column, which was located–

in a constant magnetic field H_1. The pulse had a rise time $\tau_0 = 4 \cdot 10^{-8}$ sec, a duration $T = 4{\cdot}10^{-7}$ sec, and an amplitude $|\tilde{H}| = 1.2{\div}1.5$ kOe. It was generated by a shock circuit, which was an artificial line. Generally speaking, the circuit generated not one, but several magnetic-field pulses following one another and alternating in sign. In the present case, however, the experiments were carried out at amplitudes $|\tilde{H}| \geq 3.5|H_1|$, which correspond to Alfvén-Mach numbers $M_A \geq M_A^* = 2 \div 3$. At such Mach numbers, as was shown in (^{5}), only one shock wave is excited in the plasma, corresponding to the first positive (relative to the field H_1) pulse of the field $\tilde{H}$. After this wave passes, the pressure

$$p = nT + H^2/8\pi$$

in the plasma volume increases so much that, under the action of the subsequent positive pulses of the field $\tilde{H}$, shock waves are not excited. This can be judged, for example, from the signals of differentiating magnetic probes shown in Fig. 1. Oscillogram 1 in this figure was obtained near the inner wall of the discharge chamber. The signal on it corresponds to the derivative $d\tilde{H}/dt$ of the magnetic field at the boundary of the plasma column. Oscillograms 2 and 3 were obtained at mid-radius and on the axis of the plasma column, respectively. The signals on them correspond to the derivative dH/dt of the magnetic field in the wave (for more detail see (^{4})).

Fig. 1. Oscillograms of signals from differentiating magnetic probes located near the inner wall (1), at mid-radius (2), and on the axis (3) of the discharge chamber.

Fig. 2

Figure 2: Fig. 2

The electron concentration was measured from the Stark broadening of the Balmer line H_β (^{6}). The width of the H_β line was determined from the interference pattern obtained in an ISP-51 spectrograph coupled with an IT-51 Fabry-Perot interferometer. The photographing of time-resolved interference spectra was carried out with the aid of an electro-optical converter (EOC).

3. A characteristic photograph of the time sweep of the interference pattern in the light of the H_β line, obtained in these experiments at an initial hydrogen pressure in the discharge chamber of $\sim 10^{-2}$ mm Hg and with the magnetic probes switched on (probe ratio ~ 5), is shown in Fig. 2. The dispersion region of the Fabry-Perot etalon used was $\Delta\lambda_s = 2$ Å. The magnitude of the resolved spectral interval was determined by the EOC and was 0.1 Å.

The graph of the plasma density as a function of time, constructed as a result of photometric processing of such photographs, is shown in Fig. 3. The course of the curve in the region $n_e < 2 \cdot 10^{13}$ cm^{-3} was corrected using radio-interferometric measurements (^{7}), since in this region the accuracy of measurements by Stark broadening becomes insufficient.

It is evident from the data presented that, in the process of preliminary ionization ($t = 0$), the plasma density reaches the value $n_0 = 1.5 \cdot 10^{14}$ cm^{-3}. Then it slowly decreases because of diffusion and recombination of the plasma in the magnetic field and, by the time the shock wave starts ($t = 1.5 \cdot 10^{-4}$ sec), reaches

gives the value $n_1 \approx 6 \cdot 10^{12}$ cm^{-3}. Under the action of the shock wave, the plasma density increases by a factor of $10 \div 20$ and reaches the initial value n_0.

Hence we obtain $T_{e2} = \dfrac{\Delta n}{n_1} I \sim 0.3 \div 0.5$ keV.

The accuracy of measuring the jump in electron temperature at the shock-wave front by the method described above is determined, obviously, by the accuracy of measuring the concentrations of charged particles. The latter, in turn, depends on

Fig. 2. Photograph of the time sweep of the interference pattern in the light of the H_β line. Dispersion region $\Delta\lambda_s = 2$ Å

the accuracy of the theory of Stark broadening of the H_β line (^{8}), errors in photometry of the interference pattern, and the error arising from the procedure of matching the radio-interferometric and optical data (^{7}). All this together gives an accuracy of about 30%.

Fig. 3. Time behavior of the concentration, demonstrating an increase in n_e after passage of the shock wave

Fig. 3

Figure 3: Fig. 3

An additional error in the measurements of T_{e2} would seem able to arise because of the appearance of an impurity in the plasma. This error can be estimated on the basis of an analysis of the time dependence of the total intensity of the H_β line in the recombination phase, since the amount of light emitted in this phase is proportional to the number of recombined hydrogen ions. Such an analysis showed that the measured increase in concentration Δn is associated mainly with hydrogen ions. The fraction of impurity does not exceed 30%, but since the ionization potentials of possible impurity atoms (O, N, C, Si) are close in magnitude to the ionization potential of hydrogen, the impurity-related error in the measurements of the electron temperature T_{e2} turns out to be small.

4. The measured electron temperature cannot be explained on the basis of the mechanism of binary collisions. Indeed, it can be shown that, as a result of binary Coulomb collisions, the electron temperature at the wave front increases by the amount:

$$(\Delta T_e)_{\text{Coul}} \approx \left(5\pi\Lambda_e^4\sqrt{mn_e\delta_i v_{\text{dr}}^2/4u}\right)^{2/5},$$

where Λ is the Coulomb logarithm; e and m are the charge and mass of the electron. Under the conditions of our experiments ($n_e \approx 3\cdot 10^{13}$ cm^{-3}, $H_1 = 300$ Oe, $|\tilde{H}| = 1200$ Oe), the wave velocity u was about $3\cdot 10^7$ cm/s, the width of the wave front was $\delta_i = 2 \div 3$ cm, and the drift velocity of the electrons at the front was

$$v_{\text{dr}} = \frac{\tilde{H}c}{\delta_i\cdot 4\pi n_1 e} \approx 10^8 \text{ cm/s}.$$

Hence we obtain $(\Delta T_e)_{\text{Coul}} \approx 10$ eV.

The jump measured in the experiment, $\Delta T_e = T_2 - T_1 \approx 0.3 \div 0.5$ keV, can be explained only by the existence of a collision frequency $\nu \geq 10^9$ s^{-1}, which is almost 100 times greater than the mean frequency of pair Coulomb collisions at $T_e \approx 10$ eV and $n_e \approx 3\cdot 10^{13}$ cm^{-3}, and also greater than the frequency of all other collisional processes. The appearance of such a high effective frequency of electron scattering in the plasma can be connected only with the development of small-scale turbulence due to the instability of the current at the wave front ([2,9,10]).

In conclusion, the authors express their gratitude to E. K. Zavoisky for valuable discussion of the results of the work and to S. P. Zagorodnikov for assistance in carrying out the experiment.

Received
11 VII 1968

REFERENCES

1. S. P. Zagorodnikov, L. I. Rudakov et al., ZhETF, **46**, 1717 (1964); Pis'ma v redaktsiyu ZhETF, **2**, 238 (1965).

2. E. K. Zavoisky, *Atomic Energy*, **14**, 57 (1963).

3. M. V. Babykin, P. P. Gavrin, E. K. Zavoisky et al., ZhETF, **43**, 411 (1962).

4. S. P. Zagorodnikov, G. E. Smolkin, G. V. Sholin, ZhETF, **52**, 1178 (1967).

5. S. P. Zagorodnikov, G. E. Smolkin, G. V. Sholin, Reports at the International Symposium on the Physics of Shock Waves in Plasma, Novosibirsk, 1–5 VIII, 1967.

6. S. P. Zagorodnikov, G. E. Smolkin, G. V. Sholin, *High-Temperature Physics*, **6**, 224 (1968).

7. P. I. Blinov, S. P. Zagorodnikov et al., ZhETF, **48**, 61 (1965).

8. H. R. Griem, *Plasma Spectroscopy*, N. Y., 1964.

9. R. Z. Sagdeev, ZhTF, **31**, 1955 (1961).

10. A. A. Vedenov, E. P. Velikhov, R. Z. Sagdeev, *Nuclear Fusion*, **1**, 82 (1961).

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

Source: Math-Net.Ru and CyberLeninka. Machine translation. Verify with the original.