SCATTERING OF AN ION BEAM BY TURBULENT OSCILLATIONS OF A PLASMA

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Fig. 1

Figure 1: Fig. 1

Abstract

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SCATTERING OF AN ION BEAM BY TURBULENT OSCILLATIONS OF A PLASMA

(Presented by Academician R. Z. Sagdeev, September 29, 1969)

To elucidate the physical mechanism underlying turbulent heating of a plasma $(1, 2)$, it is expedient to carry out experiments connected with determining the spectrum of collective oscillations and the degree of their turbulence.

In the present work, for the first time, in order to determine the energy density W of the oscillations, it is proposed to use the interaction of a monoenergetic, well-collimated proton beam with plasma fluctuations. A calculation carried out by D. D. Ryutov shows that if the phase velocity of the oscillations is less than the velocity of the probing beam, $v_\phi < v_0$, then the root-mean-square deviation of the beam particles from their initial position $\langle \vec{\rho}^{\,2} \rangle^{1/2}$ can be related to the quantity W as follows:

$$\langle \vec{\rho}^{\,2} \rangle \simeq 40 \, \frac{Z^2 e^2}{M^2 v_0^4} \left[(L + l)^3 - L^3 \right] \frac{W}{k_0}, \qquad (1)$$

where M and v_0 are the mass and velocity of the beam particles; l is the path of the beam in the plasma; L is the distance from the plasma to the point at which the beam is recorded; k_0 is the characteristic wave vector of the oscillations.

Fig. 1

The experiment was carried out on the turbulent plasma of a high-voltage direct discharge. The experimental arrangement is shown in Fig. 1. A glass chamber of diameter 5.5 cm was filled with air to a pressure of $\sim 10^{-4}$ mm Hg. In a stationary homogeneous magnetic field $H_0 = 200$ oersted, initial ionization was produced by means of a Penning discharge ($C_1 = 0.5\,\mu$F, $R = 200\ \Omega$)

gas. The main discharge arose between copper electrodes ($d = 3$ cm) when the capacitor $C_2 = 0.1\,\mu$F, charged to the voltage $U_0 = 12$ kV, was switched

Fig. 2

Figure 2: Fig. 2

Fig. 3

Figure 3: Fig. 3

on through a controlled spark gap. As in the preceding experiments (3), the character of the turbulent regime depended substantially on the concentration n_0 and the electron temperature T_{e0} of the preliminary plasma. Figure 2a shows a typical oscillogram of the discharge current, obtained under the following initial conditions: $n_0 \simeq 5 \cdot 10^{11}$ cm^{-3}, $T_{e0} \simeq$ 2-5 eV. The initial stage of the current has a distinctly aperiodic character; the resistance of the discharge gap at this stage varies within the limits $50 \div 1$ ohm, always remaining higher than the resistance due to pair collisions. Figures 2b and 2c show oscillograms of microwave radiation at the electron plasma frequency and of microwave probing at wavelength λ 3 cm.

Fig. 2

A stationary beam of protons with energy 50 keV, current $\sim 20\,\mu$A, and diameter $\simeq 2$ mm was produced by an rf source with an electrostatic focusing lens.

Fig. 3

The beam crossed the plasma at a distance of 15 cm from the cathode (Fig. 1). On emerging from the plasma, it entered deflecting plates to which, from a special generator, two rectangular pulses of duration $\tau = 300$ nsec were applied, with controlled triggering and an adjustable time interval between them. The beam size was monitored by means of the first pulse, which deflected the beam onto a phosphor screen only before the direct-discharge current was switched on. In the experiment it was established that broadening of the beam in the preliminary plasma was negligibly small. The second pulse deflected the beam onto the phosphor screen in a preselected phase of the current; then both spots (the control and the perturbed one) were photographed from the luminescent screen with an electro-optical converter.

The probing results showed that the beam undergoes the most noticeable scattering at the moment of the first current surge and especially on the rise of the main current maximum (Figs. 2a, 3a). From Fig. 3a it is seen that if the initial beam diameter is $\simeq 2$ mm, then in current phase II the beam broadens by approximately a factor of two. On the sinusoidal part of the current, no beam broadening is observed (Fig. 3b), although the plasma density at this time is considerably higher. This means that the beam broadening cannot be due to Coulomb scattering of the beam particles by plasma particles. The anisotropy in the broadening of the beam in the vertical direction (Fig. 3a, II) is apparently connected with a change in the H_z component of the magnetic field as a result

Fig. 4

Figure 4: Fig. 4

of paramagnetism. A simple calculation shows that under the conditions of the present experiment the increase of the beam size in this direction may reach 0.7 mm. The change in the H_φ component

component of the magnetic field during the passage of the beam particles through the plasma, as well as the change in the component E_z of the main discharge field during the recording time ($\sim$ 300 nsec), can give a beam blurring in the horizontal direction of $\lesssim 0.3$ mm.

Fig. 4

The field E_z was determined by the method described in Ref. [3]. For the above-mentioned instant of time, most of the voltage $\sim$ 1.4 kV is concentrated near the discharge anode, the cathode drop is $\sim$ 300 V, and the field strength E_z in the main column is $10 \div 50$ V/cm. Photometric processing (Fig. 4) of the EOP-grams in the horizontal direction made it possible to determine the effective broadening of the beam $\langle \rho^2 \rangle^{1/2}$, which turned out to be $\simeq 0.8$ mm. As is seen from Fig. 3a, the broadening of the beam is diffusive in character and can be explained by scattering of the beam by oscillations with a period much shorter than the recording time, i.e., with frequencies from ten megahertz and higher. Using formula (1), one can estimate the energy density of the oscillations. For our experiments ($v_0 = 3.6 \cdot 10^8$ cm/sec, $L = 46$ cm, $l = 4$ cm, $n \simeq 10^{12}$ cm^{-3}, $T_e \simeq 100$ eV, $Z = 1$, $M = 1.67 \cdot 10^{-24}$ g), we find $W \simeq 1.25 \cdot 10^{11}$ eV/cm^3, assuming that $k_0 = \omega_{0e}/v_{Te}$, where ω_{0e} is the plasma frequency and v_{Te} is the thermal velocity of the electrons. Consequently, the degree of plasma turbulence in this discharge is $\xi = W/nT \simeq 1.25 \cdot 10^{-3}$. The data on the electron temperature were obtained from diamagnetic measurements and the ionization time (Fig. 2b).

In the current phase for which the beam broadening is shown in Fig. 3a, the electron drift velocity $v_{\text{tok}} = I/enS \simeq 6 \cdot 10^8$ cm/sec is close to the thermal velocity of the plasma electrons. Under these conditions, excitation is possible both of an ion-acoustic instability and of a current or beam instability, if the current is carried not by all the plasma electrons. Determining which of these instabilities is realized in the present experiments is a subject for subsequent experiments. In principle, the method described makes it possible to resolve this problem, since the interaction of the beam should be most intense under the condition $v_0 \simeq v_\phi$.

Thus, the effect of scattering of an ion beam by collective plasma oscillations has been experimentally detected, and has been used to study phenomena developing in a turbulent plasma.

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