EXPERIMENTAL OBSERVATION OF NONLINEAR STABILIZATION OF THE INSTABILITY OF ELECTRON BEAMS IN A PLASMA

L.P. Zakatov, A.S. Kingsep, and A.G. Plakhov
Submitted 25 December 1972
ZhETF Pis. Red. 17, No. 6, 280 - 284 (20 March 1973).

The phenomenon of nonlinear stabilization of beam instability in a plasma was first investigated theoretically by Shapiro and Tsytovich [1]. It was shown that nonlinear redistribution of the noise over the spectrum can lead to an effective removal of the noise from the phase-space region corresponding to Cherenkov resonance between the waves and the beam particles. As a result, quasilinear relaxation of the beam is either nonexistent or much slower than expected from the estimates of the linear theory; the beam deceleration length in the plasma is accordingly increased.

Under the condition of most plasma-beam experiments, the principal nonlinear process is the scattering of Langmuir waves by the plasma ions. We note that the induced scattering under the conditions of weak turbulence has not been observed experimentally so far - there are only several effects that can be attributed to such a process.

We can assume the following conditions to be satisfied in our experiments:

$$\frac{\epsilon}{T_e} << \frac{M}{m}\frac{T_e}{T_i}, \qquad (1)$$

where ε is the beam-particle energy, and the remaining symbols are standard. Under condition (1), the principal nonlinear effect is wave scattering by the ions, and leads to a reflection of the wave with negligible momentum loss [2]:

$$\vec{k}' \approx -\vec{k}(1-\delta)$$
$$\delta \sim \sqrt{\frac{mT_i}{MT_e}\frac{\epsilon}{T_e}} << 1. \qquad (2)$$

The order of magnitude of the nonlinear increment under these conditions is

$$\gamma_n \sim \omega_{oe}\frac{W}{nT}, \qquad (3)$$

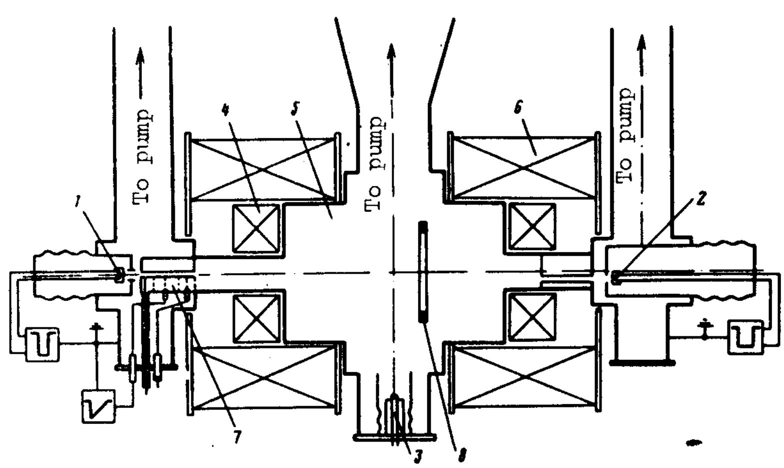

Fig. 1. Experimental set-up: 1 - Electron gun EP-1, 2 - electron gun EP-2, 3 - plasma injector, 4 - 4 - mirror coils, 5 - vacuum chamber, 6 - principal magnetic field coils, 7 - electrostatic analyzer, 8 - diamagnetic probe.

where W is the integral density of the noise energy. If the nonlinear increment (3) exceeds the characteristic linear increment $\gamma_1 \sim \omega_{0e}(n'/n)(\varepsilon/\Delta\varepsilon)$, where n' is the beam density and $\Delta\varepsilon$ is its energy width, an effective stabilization of the instability becomes possible. It is necessary for this purpose that the wave $\vec{k}'$ defined by condition (2) no longer be at resonance with the beam particles. The conditions for nonlinear stabilization can be satisfied in best fashion by the following organization of the experiment.

Assume that two countermoving electron beams are injected into the plasma. The energy of each of them satisfies the condition (1), and the energy difference is

$$\frac{\epsilon_2 - \epsilon_1}{\epsilon_1} \sim \delta ,$$

where δ is defined by condition (2). Then the beam with higher energy produces in the plasma noise that stabilizes effectively the other beam. Since the electron temperature (and all the more the ion temperature) is determined only very approximately in plasma-beam experiments, the value of δ corresponding to the best stabilization must be chosen by experiment.

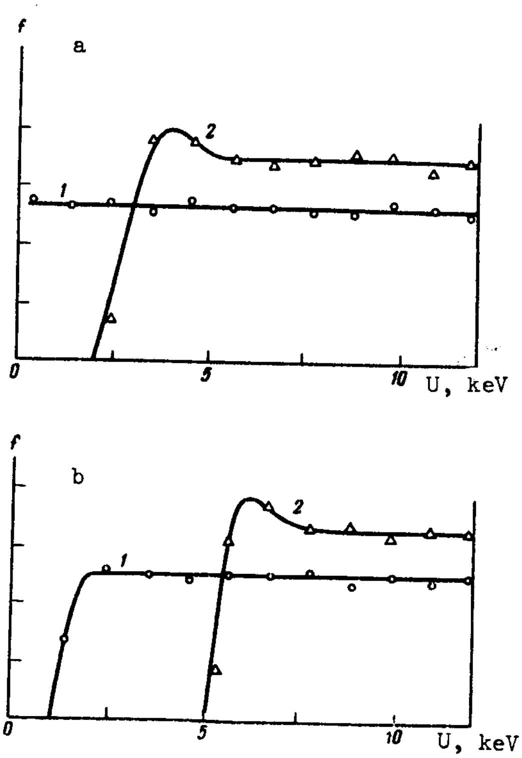

Fig. 2. Longitudinal electron energy distribution function in the test beam as it leaves the plasma: a) curve 1 - without stabilizing beam, curve 2 - with stabilizing beam. Test beam current 8 A, energy 12 keV, stabilizing-beam current 8 A, energy 13 keV; b) the same for a test beam current 5 A.

Experimental Setup

The experimental setup is shown in Fig. 1. The magnetic-mirror field configuration was produced by two pairs of coils with distance 85 cm between their centers. The magnetic field intensity was 5 kOe in the mirrors and 1 kOe in the central part. The residual vacuum in the chamber was 10^{-6} mm Hg. A titanium plasma injector placed in the central part of the apparatus perpendicular to the magnetic field was used to fill the trap with cold hydrogen plasma to a concentration $(2 - 5) \times 10^{-2}$ cm^{-3}. The electron guns EP-1 and EP-2 were placed on opposite ends of the installation behind the mirrors. The beam currents and their energies could be varied in a wide range to obtain optimal operating conditions. The durations of the current pulses from EP-1 and EP-2 were 250 and 130 μsec, respectively. The electron gun EP-1 and the plasma injector were turned on simultaneously, while EP-2 was turned on with a delay of 100 or 300 μsec. This has made it possible to inject the EP-2 beam into a plasma with a high level of oscillations excited by the EP-1 beam in the former case, and into a plasma with a thermal noise level in the latter case. A multigrid electrostatic probe, with which the distribution functions could be plotted within a single discharge pulse [3], was used to determine the longitudinal-energy distribution in the electron beam from EP-2. Information on the heating of the plasma particles was obtained from diamagnetic measurements.

The plasma concentration was monitored with microwave interferometers at wavelengths 0.8 and 3 cm.

Measurement Results

The beam stabilization in the plasma was observed directly by measuring the longitudinal-energy distribution functions of the beam particles. In our experiments we used two oppositely moving beams injected into the plasma along the magnetic field in the time sequence indicated above. At different fixed currents of the two beams, we obtained the optimal energy ratios of the stabilizing and test beams. It turned out that the stabilization effect is most clearly pronounced when the beam energies are nearly equal, and the energy difference does not exceed (1 - 2) keV at a stabilizing-beam energy 13 keV and at currents of 10 A. Figure 2a (curve 1) shows the distribution function in the test beam from EP-2 at the entrance to the plasma in the absence of the stabilizing beam from EP-1. The distribution has the usual "plateau" form down to zero energy. When the beams pass through the plasma simultaneously, the distribution function is altered: the beam is less "smeared out" with respect to energy, i.e., it becomes stabilized (curve 2). A decrease of the test-beam current leads to better stabilization, as can be seen from Fig. 2b, which shows distribution functions analogous to Fig. 2a. The incomplete stabilization of the instability may be due to the fact that the beam interaction regions overlap only inside the trap, and before entering the trap the beams relax independently of each other.

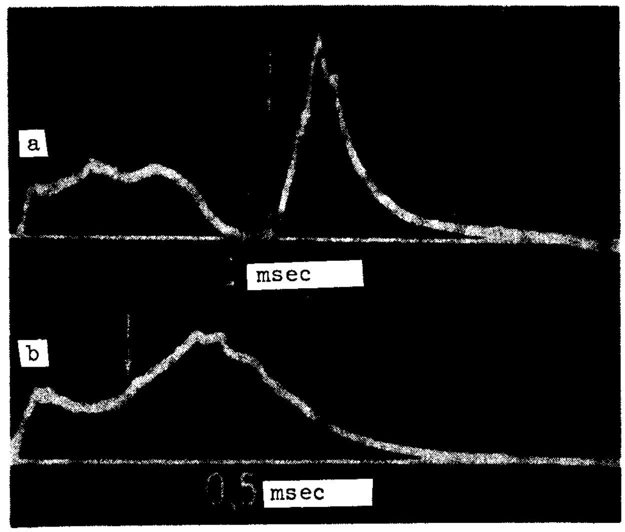

Fig. 3. Oscillograms of diamagnetic signals: a) EP-1 and EP-2 beams turned on separately; b) both EP-1 and EP-2 beams turned on. EP-1 - beam current 10 A, energy 15 keV; EP-2 - beam current 10 A, energy 17 keV. The arrow indicates the instant when EP-2 beam is turned on.

Measurements of the plasma diamagnetism have shown an appreciable decrease of the test-beam heating efficiency in the presence of the stabilizing beam. In Figs. 3a and 3b are shown the diamagnetic signals due to the action of each beam separately and due to their joint action, respectively. The stabilization effect is more noticeable in the diamagnetic signal, for in this case one measures values that are averaged over the entire volume of the trap, and failure to satisfy the stabilization conditions in individual local zones, as well as the "smearing" of the beam prior to entering the trap, has a negligible effect in this case.

Thus, we were able, for the first time, to separate in our experiments uniquely one of the main nonlinear effects that stabilize the beam stability in a plasma.

The authors thank L.I. Rudakov for valuable discussions.

[1] V.D. Shapiro and V.N. Tsytovich, Nuclear Fusion 5, 228 (1965).
[2] A.S. Kingsep and L.I. Rudakov, Zh. Eksp. Teor. Fiz. 58, 582 (1970) [Sov. Phys.-JETP 31, 313 (1970)].
[3] L.P. Zakatov and A.G. Plakhov, ibid. 60, 588 (1971) [33, 320 (1971)].