Stabilization of the drift-cone instability by a flow shear

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An experimental result indicating suppression of plasma turbulence by a flow shear at the "elementary level," i.e., with respect to separately existing, weakly developed turbulence, is presented. The object is the drift-cone mode on impurities which develops in a long mirror trap. End electrodes were used to introduce a controllable **E** × **B** shear into the plasma. It was determined that a sufficiently strong shear completely quenches the instability. The threshold value of the shear agrees with an estimate based on simple considerations. © *1995 American Institute of Physics.*

In the last few years special attention has been focused on the question of the quenching effect of flows with slipping of layers — sheared flow or flow shear — on plasma turbulence. This question is now especially important primarily in connection with the possibility of making substantial progress in the field of tokamaks, if regimes with improved confinement, known as *H* and *VH* modes, are mastered. In these regimes the thin outer layer of plasma is less turbulent. As a result, transverse transport is sharply reduced there, and because the "transport barrier" which arises in this manner, overall plasma confinement is improved. It is now believed that the decrease in the turbulence in the outer layer is due to the establishment of flows with sufficiently strong shear in this layer (see, for example, Refs. 1–4).

Regardless of tokamaks, however, the turbulence suppression effect in the presence of flow shear is an important physical phenomenon itself, which requires a detailed, primarily experimental, study. Tokamaks are not best suited for this purpose, because their plasma is subjected to complicated and predetermined conditions. Apparently, it is more productive to investigate the flow-shear effect on less cumbersome machines, and under more variable and more easily controllable conditions, specifically, with an arbitrarily prescribed geometry and magnitude of the flow shear. Such experiments have been performed in Refs. 5–9 (this list is probably incomplete). It would be even better to study the effect under discussion not only with respect to the complicated state called "turbulence," which is sometimes studied by itself, but also at the level of "basic building blocks," i.e., well-understood instabilities of one type or another, which exist by themselves and which are not particularly strongly developed. Some of the studies mentioned above, such as Ref. 9, are already oriented in this direction. In Ref. 9, where the stabilizing action of the flow shear with respect to an instability associated with a gradient of the ion temperature was investigated under well-controlled conditions.

The results reported below pertain to an experiment on the effect of flow shear on an isolated instability, specifically, on the drift-cone mode — the DCI. This well-known

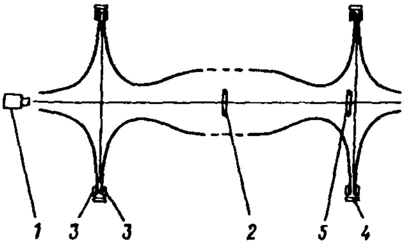

FIG. 1. Diagram of the experimental setup. *1* — Plasma source; *2* — ring-shaped limiter; *3* — slotted electrodes; *4* — supporting electrode; *5* — ring-shaped electrode at a cusp.

instability (it is the DCLC mode), which at one time presented a serious danger for open traps, arises in a plasma whose ion distribution function has a cutout, cone-type deformation, such as that in the case of magnetic mirror confinement.[10–12] The DCI is not characteristic of closed systems, so that for the narrow purposes of a tokamak, suppression of this instability is not critical. However, the results obtained are obviously of interest for the general study of flow-shear-stabilization phenomenon.

The experiment was performed on the PR-8 setup,[13] whose magnetic field has the configuration of a long mirror system with cusp-shaped cells at the ends which play the role of MHD anchors (Fig. 1). The central part is 4 m long, the magnetic field in it is equal to about 3 kG, the mirror ratio is 2, and the field in the ring in the ring-shaped and axial "magnetic slits" is 10 kG and 20 kG, respectively. An external source is used to fill the confinement system with hydrogen plasma, whose parameters at the end of the injection pulse are $n \approx 3 \times 10^{11}$ cm^{-3}, $T_i \approx 50$ eV, $T_e \approx 20$ eV, and $p_0 \approx 1 \times 10^{-6}$ torr. The diameter of the plasma column is equal to about 10 cm.

Shear flow in a column is produced by imparting to the plasma a differential drift $\mathbf{E} \times \mathbf{B}$ rotation around an axis, i.e., a rotation such that the different cylindrical layers have a different angular velocity $\Omega = v_{dr}/r$. It is therefore essential that the radial electric field not be proportional to the radius, $E_r/r \neq$ const. To obtain the desired profile $E(r)$ artificially, we applied bias voltages (in some combination), which influence the plasma potential, to the electrodes: the limiter encompassing the plasma, electrodes which are the walls of the ring-shaped magnetic slits, supporting electrodes which partition the slits crosswise, and a ring-shaped electrode inside one of the cusp-shaped cells. The latter electrode with the other electrodes grounded was mainly used in the experiments being described. The introduction of an electrode at a cusp and the application of a bias voltage do not appreciably affect the plasma confined in the central confinement system, but merely changes the radial profile of the plasma potential. By moving the electrode along the axis of the cusp it is possible to move in the radial direction the disturbance produced by the electrodes in the potential in the central part of the plasma confinement system.

The main working phase of each plasma cycle ("shot") was the decay tail of the accumulated plasma. This stage is usually quietest, and for this reason it is especially convenient for revealing and studying subtle effects. In the PR-8 setup plasma decays, judging from all factors, mainly as a result of the classical Coulomb scattering of ions in the loss cone, as is indicated by the characteristic time over which the density decreases

(τ of the order of 1 ms) and by other factors. However, several weak instabilities arise against the background of this smooth process. During approximately the first 200 μs of the decay process, while T_e remains comparable to T_i (T_e then decreases to a value of $\lesssim 0.1\, T_i$), a low-frequency (~ 50 kHz) drift instability develops.[13] This drift instability then vanishes, and when the last residues of the cold source plasma leave the system, a DCI with a frequency of about 4 MHz appears. After a further long period of time (of the order of 2τ), pronounced oscillations with a frequency of about 320 kHz develop; a detailed study identified these oscillations as a DCI on the impurity ions N^+ and, possibly, O^+.[14] Its appearance is associated with the fact that at the later stages of decay the relative content of singly charged impurity ions increases strongly, because the more easily scattered hydrogen ions escape first. Finally, when the density decreases to several percent of the initial value, the anchoring action of the cusps is no longer adequate and a turbulent MHD flute-like instability develops and quickly and completely ejects the plasma from the confinement system. We note again that all instabilities, except for the last one, are weak: The amplitude of the oscillations is small, the oscillations themselves are almost regular and not turbulent, and the losses which are generated remain virtually unnoticeable against the background of the classical Coulomb losses. It was assumed that this weakness of the instabilities is explained by the effect of the cusp-shaped cells.

We chose the instability on the impurities as the object of the experiment. The DCI consists of flute-like electrostatic waves with a frequency of about ω_{Bi} and with $k_\theta \rho_i > 1$ (ρ_i is the ion Larmor radius, and θ is the azimuthal angle). They propagate along the azimuth in the ion direction with phase velocity $v_{\text{ph}} < v_{T_i}$ (the thermal velocity of the ions). For an impurity mode in PR-8 the wavelength is $\lambda_\theta \approx 1.5-2$ cm and the phase velocity is $v_{\text{ph}} = (5-7) > \times 10^5$ cm/s.

The impurity and not the hydrogen mode was chosen because in the latter case it would be necessary to introduce into the plasma a much stronger electric field. We shall consider in greater detail the question of the magnitude of the shear that is required for stabilization. The quenching action of a flow shear on an instability of this type can be shown schematically as follows. Consider the ions whose interaction with the wave builds up the wave. These ions are concentrated in some "region of radial localization of the wave," whose radial extent is of the order of ρ_i. The ions which are located closer to the edges of this region undergo additional drift as a result of the radial gradient of the drift velocity. The motion of the ions in the wave system therefore appears to be altered compared to the motion that would exist in the absence of shear. Specifically, for example, there appears a Doppler shift between the frequency of the wave and the Larmor rotation. It is completely obvious that the change in the motion becomes significant when the additional drift velocity becomes comparable to the phase velocity of the wave, i.e., when (disregarding the cylindrical symmetry)

$$\nabla_r v_{dr} \rho_i k_\theta \approx \omega_{Bi} . \tag{1}$$

The "outermost" ions fall out of resonance with the wave and no longer pump the wave, which constitutes the stabilization effect.

A less simplified approach suggests that the required shear must depend on how strongly the threshold for the existence of the given mode is exceeded, i.e., the "margin of instability" of the mode. Therefore, if the relation (1) is used to estimate the critical

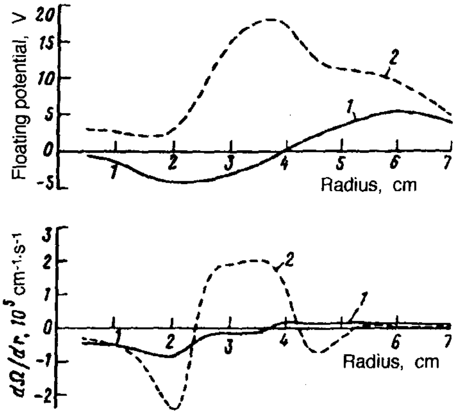

FIG. 2. Radial distribution of the plasma potential and shear of the angular velocity. *1* — Initial distribution; *2* — same but with a bias voltage of 40 V.

magnitude of the shear, we can assume that it is more correct to place on the right-hand side not the frequency of the oscillations but rather their growth rate, which is directly related to the distance from threshold. This softens the stabilization criterion, since the growth rate is usually less than the frequency.

It follows from the relation (1) that the critical magnitude of the gradient of the drift velocity is inversely proportional to the mass of the ions; i.e., the required gradient of the electric field is inversely proportional to the mass of the ions. For the impurity mode in PR-8, according to relation (1), the required gradient $\nabla_r E_r$ is of the order of 10 V/cm^2, which is achievable. For a hydrogen DCI, however, the field will have to be approximately 15 times stronger, and under the conditions of PR-8 (long plasma column with a limited margin of MHD stability) it would lead to the appearance of a centrifugal instability.

The experiment which we performed can be summarized as follows. At the stage of plasma decay, when a pronounced impurity mode is present, the potential profile $\varphi(r)$ in the section of the column is rapidly changed. A positive, square voltage pulse with a magnitude of up to 50 V is applied to the ring-shaped electrode at the cusp. The changes produced in this manner in the profile of the plasma potential (more accurately, the floating probe potential) and, correspondingly, the shear of the angular velocity $d\Omega/dr$ are shown in Fig. 2. The position of the electrode was chosen in such a way that the maximum of the shear would occur approximately in the region of greatest amplitude of unstable oscillations. The result of this action is shown in Fig. 3, which also shows the probe signal of the oscillations of the plasma potential. For greatest clarity, the signal was simplified by eliminating from it the spectrum of low (down to 100 kHz) and high (above 500 kHz) frequencies, which have no bearing on the instability being investigated. It is obvious that after the bias voltage is applied, the oscillations characteristic for DCI decay rapidly, and after the voltage is removed the instability is gradually restored.

Figure 4 shows the frequency spectra of a signal without and with bias voltages of

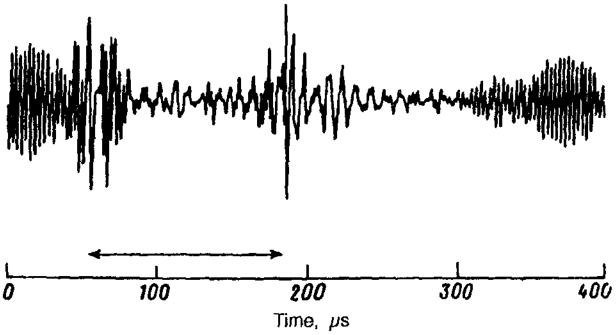

FIG. 3. Action of the shear on the unstable oscillations. The arrow marks the time interval at which the bias voltage was applied (at the ends of the interval the signal is distorted by noise).

two different magnitudes. It is obvious that when a sufficiently high bias voltage is applied, the frequency of about 320 kHz, which is associated with the instability and which is sharply pronounced in the first case, completely vanishes (more accurately, it decreases to the average noise level). Why is an appreciable Doppler shift of the frequency, produced as a result of imparting rotation to the plasma, not observed in the intermediate case (spectrum *2*)? The explanation is apparently that the main region of radial localization of the instability corresponds to the region of the maximum of the altered potential $\varphi(r)$, i.e., the region of small values of v_{dr}.

Figure 5 shows the "blocking curve" of the instability, i.e., the average amplitude of the oscillations remaining when the bias voltage is applied, as a function of the magnitude of the bias voltage applied to the electrode. As one can see, the action of the shear in this case is of a threshold type; i.e., up to a certain value of the applied voltage the instability seemingly does not feel this voltage, and above this value the instability quickly vanishes. However, the magnitude of the threshold bias voltage is not fixed once and for all, and it can be perceptibly shifted in one or another direction, even without strong changes in the experimental conditions. This is probably attributable to the fact that under different conditions the "margin of instability" of a given mode, which depends on many factors, is different — the greater this margin, the greater the magnitude of the shear that is required for stabilization.

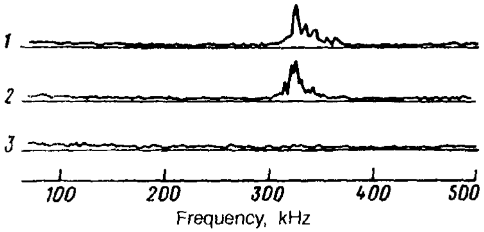

FIG. 4. Frequency spectra of noise: *1* — No bias voltage; *2* — with a bias voltage of 20 V; *3* — with a bias voltage exceeding 40 V.

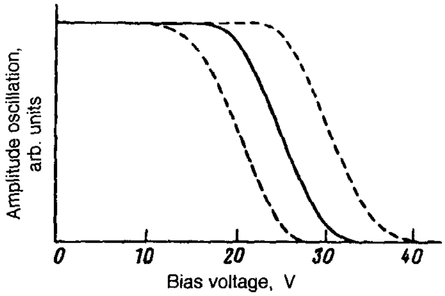

FIG. 5. Average amplitude of unstable oscillations as a function of the applied bias voltage.

In summary, the experiment described above demonstrates that the **E** × **B** flow shear effectively suppresses relatively low-frequency and long-wavelength DCI, which develops on impurity ions in the mirror confinement system. The magnitude of the shear which gives rise to the suppression approximately corresponds to relation (1). Of course, the result obtained is of interest not as a way toward fighting the DCI in open plasma confinement systems, for which there has been no need for a long time, but rather it is interesting as a step toward a detailed investigation of the stabilizing action of flow shear in all its diverse manifestations.

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