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Experimental study of the parallel velocity shear instability

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Abstract

The parallel velocity shear instability (PVSI) is experimentally investigated in a double-ended Q machine in which the shear in the ion flow is produced by suitable shaping of the axial magnetic field. Instability fluctuation levels approaching nearly 100% are often observed. © 1997 Elsevier Science B.V.

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The parallel velocity shear instability (PVSI), previously referred to as the Kelvin–Helmholtz instability, was first studied experimentally over 30 years ago [1]. This instability may arise when the ion streaming velocity along the magnetic field, $\boldsymbol{B}$, changes from one magnetic field line to another. D'Angelo showed that in an inhomogeneous plasma having equal ion and electron temperatures ($T_i \approx T_e$) the instability condition is

$$\frac{\partial v_{0z}}{\partial x} > 2^{1/2}\frac{c_i}{\ell_n}, \qquad (1)$$

where $\partial v_{0z}/\partial x$ is the variation of the field-aligned ion flow velocity, v_{0z}, with the coordinate, x, the direction perpendicular to $\boldsymbol{B}$, ℓ_n is the scale length of the density gradient in the x direction, and $c_i = (kT_i/m_i)^{1/2}$ is the ion thermal speed [2]. Thus, if the parallel ion velocity variation occurs over a distance comparable to that of the density gradient, according to Eq. (1) instability will occur if the velocity changes by an amount on the order of the ion acoustic speed. Then, subject to the assumptions discussed in Ref. [2], for the case of a homogeneous plasma ($\ell_n \to \infty$), Eq. (1) predicts that the presence of *any* shear gives rise to instability. Thus, this instability is expected to occur in a number of situations, and in fact it has been invoked to explain plasma fluctuations observed in various geophysical and astrophysical settings, e.g., the earth's polar cusp [3] and comet tails [4]. This instability has also been discussed in connection with turbulence observed at the edge of tokamaks [5].

In the early laboratory work on the PVSI, several different experimental arrangements were used to produce a relative drift between adjacent layers of the plasma in a double-ended Q machine [1]. In one of these configurations, the so-called "ring + disk" setup, the resulting oscillations were localized in the region of strongest velocity shear, had a frequency generally in the range of 1–4 kHz, and propagated primarily as an $m = 1$ mode with $\lambda_{\parallel} \gg \lambda_{\perp}$, where $\parallel$ and $\perp$ refer to directions parallel and perpendicular to the

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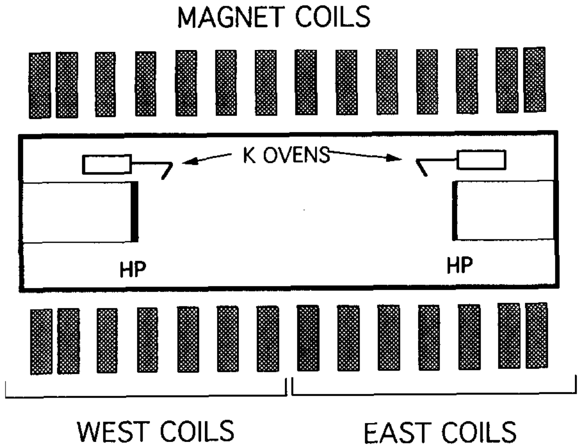

Fig. 1. Schematic diagram of the double-ended Q machine. The west and east magnet coil sets can be powered independently to produce various magnetic field configurations.

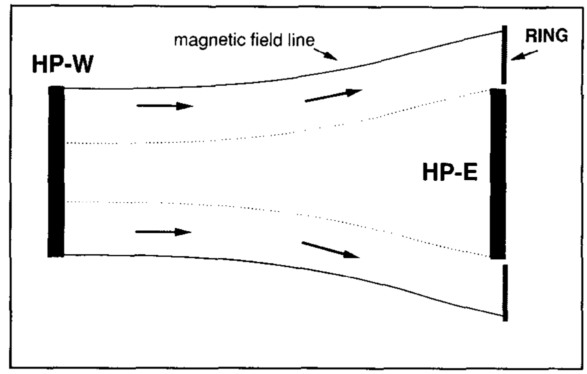

Fig. 2. Schematic diagram of the double-ended Q machine with a diverging magnetic field configuration. The solid lines represent field lines mapping from the edge of the west hot plate (HP-W) and the dotted lines those from the east hot plate (HP-E). A non-flowing plasma is produced in the region between the dotted lines, while a plasma flowing from west to east is produced in the outer region and is terminated on the floating ring.

magnetic field. This "ring + disk" setup was recently employed in our IQ-2 device to study the effects of negative ions on the PVSI [6] and also to investigate the effects of ion-neutral collisions on the PVSI [7]. All of these configurations used various biased electrodes either inserted into or surrounding the plasma column to produce the shear. We thought it would be worthwhile to investigate the PVSI using a different configuration that did not involve inserting electrodes into the plasma column. We expected that the results of this type of experiment would add confidence to those obtained using the " ring + disk" setup. Also, this new configuration, which is described below, resembles more closely some of the actual geophysical environments where parallel velocity shear is known to exist.

The experiments were performed in the Iowa double-ended Q machine (IQ-2) which produces a potassium (K^+) plasma ~ 6 cm in diameter and $\sim$160 cm in length. The schematic diagram of the device is shown in Fig. 1. The plasma is produced by surface ionization of potassium atoms from two atomic beam ovens on two hot ($\sim$2000-2500 K) tantalum plates. The plasma density is in the range of 10^9-10^{10} cm^{-3}, with electron and ion temperatures $T_e \approx T_i \approx 0.2$ eV.

The plasma is confined radially by an axial magnetic field produced by 14 solenoid coils arranged in two 7 coil sets (east and west coils). Under "normal" Q machine operation, with the same current in each coil, a uniform axial magnetic field is obtained with a strength up to 0.6 T. The east and west coils can also be powered independently (0-1000 A) to produce a magnetic field configuration with a variable field line geometry. Since both the electrons *and* the ions are strongly tied to the field lines, it is possible to produce a plasma column with an axially varying cross-section.

This feature was exploited to produce the parallel shear configuration shown schematically in Fig. 2. A few representative field lines which intersect the edges of the west and east hot plates are indicated. This magnetic geometry results in the formation of two distinct plasma regions - an outer annular region containing plasma produced only on the west hot plate and an inner region with plasma originating from both the west and east hot plates. Each hot plate/oven source produces a plasma with an ion flow directed away from the source due to the presence of an electron sheath with a voltage drop typically $\sim$2-3 V at each hot plate. By adjusting the hot plate and oven temperatures, it is possible, then to produce a nearly stationary plasma in the central region surrounded by an outer layer of plasma flowing from west to east. Thus, in the annular region near the dotted lines in Fig. 2 one expects a strong shear in the ion flow. The outer flowing plasma is terminated on a ring biased very close to the floating potential (≈ -2 V) to prevent current flow to the grounded end wall of the vacuum chamber.

The presence of a shear-driven instability was evi-

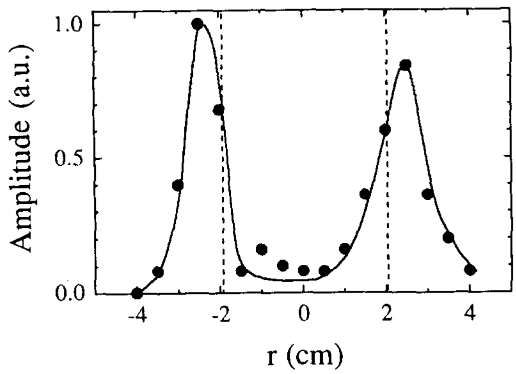

Fig. 3. Oscillation amplitude versus radial coordinate, r. The dotted lines correspond to those in Fig. 2. The maximum fluctuation amplitude corresponds to a $\delta n/n \approx e\delta\phi/kT_e \approx 0.7$. $I_W = 900$ A, $I_E = 200$ A.

denced by measurements of the radial profiles of the fluctuations in the floating potential of a Langmuir probe. For east and west coil currents of 200 A and 900 A, respectively, Fig. 3 shows the radial profile of the fluctuation amplitude roughly midway between the two hot plates. The dotted lines indicate the approximate locations of the magnetic field lines which map axially from the edges of the east hot plate (the dotted field lines in Fig. 2). The oscillation amplitude reaches a maximum in a cylindrically symmetric shell of about 1 cm thickness in the region where strong shear is expected to be present. The actual oscillation amplitudes, $\delta n/n \approx e\delta\phi/kT_e$, are typically quite high, $\sim$ 50–70%. Spectral analysis of these fluctuations revealed that the wave frequencies were in the range of 1–4 kHz.

Two additional measurements were made to establish the connection between the observed oscillations and the presence of shear. For a west coil current I_W = 900 A and several values of the east coil current ranging from 100 A to 900 A, radial profiles of the oscillation amplitude were obtained. Fig. 4 shows a plot of the maximum observed fluctuation amplitude versus the current in the east coils. The largest amplitudes were observed for $I_E < 300$ A. For $I_E > 800$ A the mode was apparently stabilized. As the east coil current is increased, the magnetic geometry is gradually restored back to the uniform field condition in which the outer region of flowing plasma disappears. Thus, both the flow *and the shear* are eliminated and the mode is stabilized.

It was also possible to reduce the shear by varying

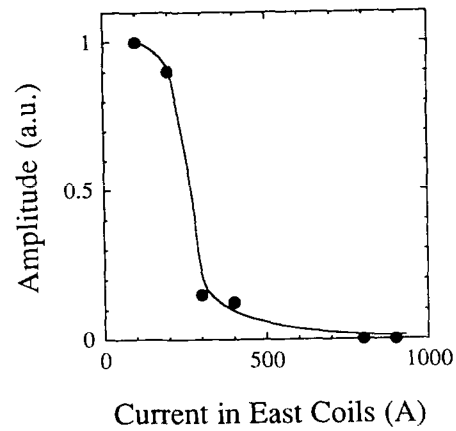

Fig. 4. The reduction in oscillation amplitude with increasing east coil current for a fixed $I_W = 900$ A.

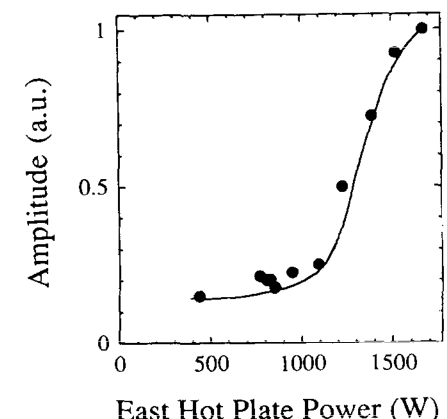

Fig. 5. Dependence of the oscillation amplitude on the east hot plate power. $I_W = 900$ A, $I_E = 200$ A.

the production of plasma from the east hot plate. This was accomplished by reducing the heating power on the east hot plate. As the power is lowered the amount of plasma streaming from the plate is also reduced. For fixed magnetic geometry ($I_E/I_W = 200/900$) and west hot plate power (2 kW), Fig. 5 shows the maximum fluctuation amplitude as a function of the east hot plate power. For this coil current ratio the magnetic field varies from about 0.57 T at the west hot plate to about 0.1 T at the east hot plate. The fluctuation amplitude decreases with decreasing east hot plate power. As the east hot plate power is reduced there is increasingly less and less westward flowing plasma in the central region of Fig. 2 to balance the eastward flow from the west hot plate. Thus, as the east plate power is reduced to zero, a nearly uniform plasma flow exists over the entire plasma cross-section, and the shear-driven mode is quenched. Note that this measurement establishes clearly that the *shear* is responsible for the instability and not simply the flow, since a *net* ion drift is still present as the east hot plate power is reduced.

Summarizing the experimental results we have found that: (i) A double-ended Q machine operated with a nonuniform magnetic field geometry can be used to generate parallel ion flow with shear in the direction perpendicular to $\boldsymbol{B}$. The velocity shear is created by the fact that there is an inner region of plasma with nearly no flow surrounded by an outer region of flowing plasma. The shear near the boundary of these two regions produces low frequency fluctuations with $\lambda_{\parallel} \gg \lambda_{\perp}$ that are localized in the shear layer. (ii) The instability was not observed under conditions of a uniform magnetic field in which a nearly stationary plasma with no shear is produced. (iii) The PVSI did not appear under conditions where the ion flow was present but without significant shear.

It is easily seen that under the conditions in which the results of Fig. 3 were obtained the instability condition, Eq. (1), was met. With $\partial v_{0z}/\partial x \approx \Delta v_{0z}/\ell_v$, where Δv_{0z} is the change in the ion flow speed over the shear layer and ℓ_v is the thickness of the shear layer, Eq. (1) can be re-written as $\Delta v_{0z}/\ell_v > 2^{1/2}c_i/\ell_n$. Then instability should occur for $\Delta v_{0z} > 2^{1/2}c_i(\ell_v/\ell_n)$. Typically $\ell_v \sim$ 2–3 ion gyro radii, whereas $\ell_n \sim$ 5–10 ion gyronradii. However, we can make the conservative assumption that $\ell_v \sim \ell_n$, so that for instability $\Delta v_{0z} > 2^{1/2}c_i \approx 10^5$ cm/s. For $T_i \approx 0.2$ eV, $c_i \approx 7 \times 10^4$ cm/s. The ion flow speed is determined by the acceleration of ions at the hot plate sheath. With a sheath drop, $V_s \approx 2$ V, we have $\Delta v_{0z} \approx v_{0z} \approx (2eV_s/m_i)^{1/2} \approx 3 \times 10^5$ cm/s, so that the shear should have been large enough to produce the instability.

It is very unlikely that the fluctuations we have observed are due to drift waves. A "drift wave scenario" would seem to be at odds with the type of results shown in both Fig. 4 *and* Fig. 5. Fig. 4 indicates that the instability disappears as the east coil current is increased. However, as I_E is increased, the plasma density gradient actually *steepens*, and if anything, one would have expected drift wave fluctuations to increase in amplitude. Likewise, a reduction of the east hot plate power (with the resulting decrease in oscillation amplitude shown in Fig. 5) would have actually favored the generation of drift waves. It is well known that drift waves are associated with the presence of ion sheaths at the hot plate which occur at low hot plate powers [8].

Finally, it seems appropriate to comment on the fact that the fluctuations seem to reach very high amplitudes ($\delta n/n$'s perhaps as large as 70% !). This experimental observation appears to be in line with a recent theoretical analysis by Daughton and Migliuolo [9] of the linear instability and eventual nonlinear saturation of electrostatic instabilities due to shear in a plasma flow parallel to the magnetic field. The important role of these modes for the transport of energy and momentum in various laboratory devices and geophysical environments is also discussed in Ref. [9]. Also, the results of three-dimensional modeling of the PVSI, recently reviewed by Ganguli [10], showed quite vividly that this instability can lead to substantial particle diffusion in the direction perpendicular to the magnetic field and a resulting reduction in the field-aligned flow.

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