MHD-stable confinement of a rotating plasma

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An MHD-stable plasma with a density of 10^{13} cm^{-3} and a rotation energy of 250 eV/ion has been produced experimentally in the SVIPP device.

According to the present understanding, a rotating plasma in an open axisymmetric confinement system can be stable if the density n increases with the radius.[1,2] The condition for centrifugal stabilization, $\partial n/\partial r > 0$, is compatible with energy insulation if the profiles of the density, $n(r)$, and the rotation velocity, $V(r)$, are such that the condition $\partial/\partial r\,(nV^2) < 0$ holds, while the condition $nV^2 = 0$ holds at the boundary. According to Ref. 3, MHD-stable profiles of this type do exist, and to actually achieve them is the goal of an experiment being carried out at the SVIPP device ("stabilization by rotation and the density profile"). The device is shown schematically in Fig. 1.

A dense plasma shell[4] is produced at the outer boundary ($r = 13$ cm) to form the required density profile. This shell maintains a profile with $\partial n/\partial r > 0$ at the edge of the region with $V \neq 0$, and it forms a transition layer between the rotating plasma and the liner: At the outer boundary of the shell, the condition $\partial n/\partial r < 0$ holds, but the condition $V = 0$ also holds.[1]

The plasma in the confinement volume rotates because of longitudinal particle fluxes, i.e., because of the electrical contact with end electrodes. Each electrode consists of ten metal rings separated by insulators. In the regimes that have been discussed, a potential $\varphi_0 = 10$ kV (1 kV per gap) is applied to the electrodes with respect to the liner. The magnetic field at the center is $H = 8$ kOe, and the mirror ratio is 3. After the shell injector is turned on (φ_0 and H are established beforehand), the confinement system is filled with plasma in about 1 ms. Figure 2 shows the density and

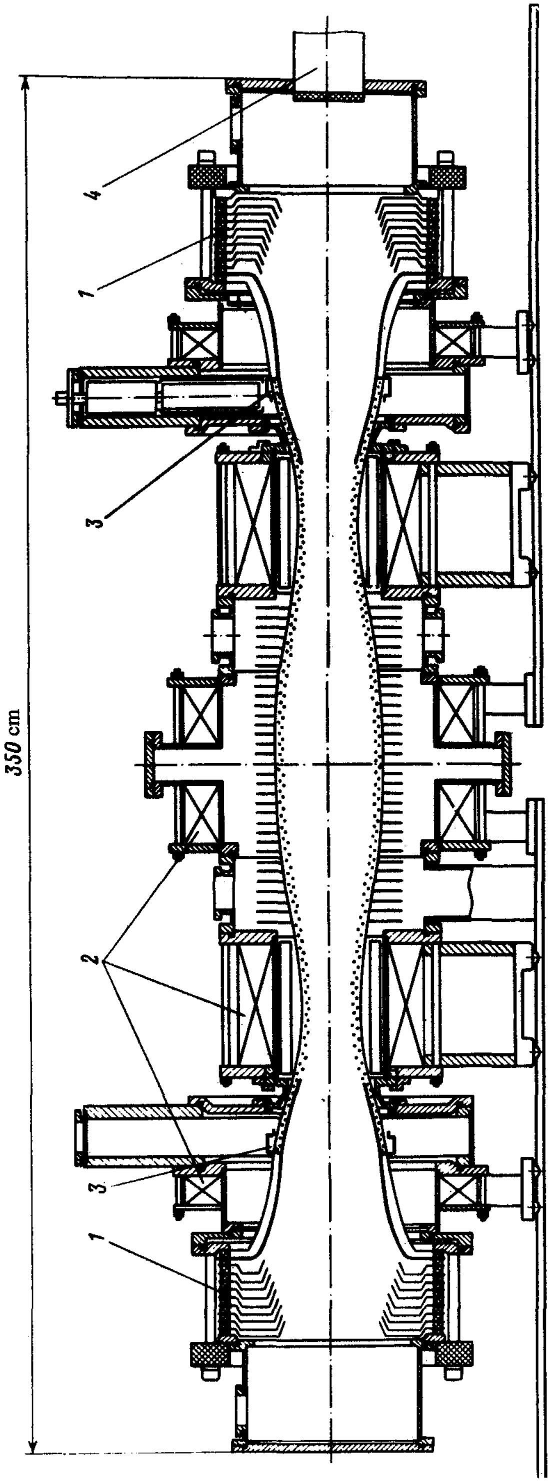

FIG. 1. 1—End electrodes; 2—magnetic field coils; 3—plasma-shell injectors; 4—gyrotron waveguide.

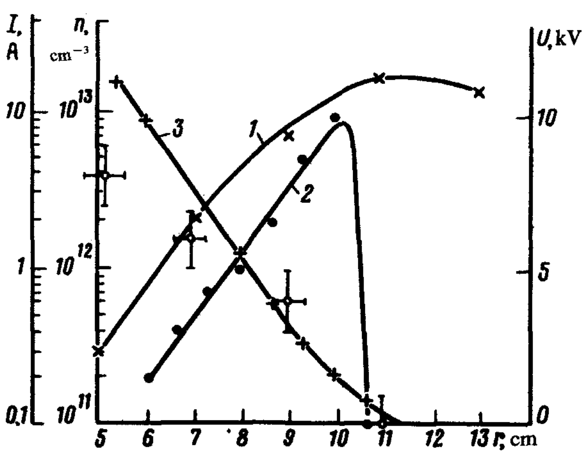

FIG. 2. Profiles of (1) the plasma density and (2, 3) the currents and potentials at the end electrodes. O—Plasma potential.

potential profiles, $n(r)$ and $\varphi(r)$, respectively, in the central plane. These profiles were constructed from measurements of the charge exchange of a He^0 beam.[5] The currents and potentials at the end electrodes corresponding to this regime are shown in Fig. 2, as projected along the lines of force to the central plane.

The electron temperature found from measurements of the Thomson scattering at $r = 10.5$ cm is 10–12 eV. From the spectrum of the charge-exchange atoms detected by a detector with a pulsed gas target,[6] we estimate the average energy of the ions in the rest frame of the plasma to be 200 eV. An estimate of the total energy in the plasma, confirmed by measurements of the diamagnetic signal, gives an energy lifetime $\tau_e \sim 0.1$ ms for the plasma, for the power deposition calculated from the data in Fig. 2. We thus conclude that the confinement system is free of at least the coarsest centrifugal instabilities, with a growth rate on the order of V/r.

To make a more precise confirmation, it would be necessary to eliminate the effect on the lifetime of those losses which reduce the value of τ_e even in a stable plasma: charge exchange, Coulomb scattering, and possible discharges in the electrode units.

"Tracer" particles make it possible to study the stability despite these loss mechanisms. Microwave heating of a plasma at the electron cyclotron resonance often produces a group of electrons with energies up to tens of keV, but with a low number density (see Ref. 7, for example). The lifetime of these electrons with respect to scattering into the loss cone is ~ 100 ms. A more rapid loss would be possible only if an instability occurred—a drift in the azimuthal electric fields—and would occur over roughly the same time as that required for the decay of the bulk of the plasma by this mechanism. On the other hand, it is easy to follow the fast electrons on the basis of the additional diamagnetism and the x-ray emission.

In the present experiments we use a gyrotron with $\lambda = 7.2$ mm, $P = 200$ kW, and $\tau = 1$–10 ms (Ref. 8). Under typical conditions, about 30 kW is absorbed in the plasma in a pulse $\tau = 4$ ms long, and electrons with energies up to 50 keV are produced. Their

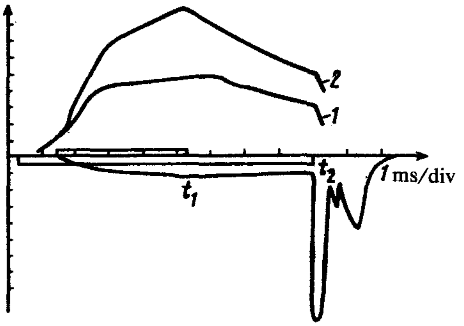

FIG. 3. 1—Diamagnetic signal of the plasma; 2—the same, with the gyrotron turned on; 3—x-ray emission from the liner. The gyrotron is turned off at t_1, and the plasma shell is turned off at t_2.

distribution over the plasma volume is determined from the x-ray emission from targets; for these measurements, small pellets are dumped into the plasma when the shell is turned on. The signal is roughly constant within the plasma ring, while it decays to zero near the axis ($r < 4$ cm). According to the oscilloscope traces in Fig. 3, the lifetime of the hot electrons is 5–7 ms, demonstrating the MHD stability of the plasma.

Turning off the plasma shell disrupts the stable regime. In Fig. 3, this event corresponds to a sharp decay of the diamagnetism—both that of the plasma itself and that of the fast electrons—and also to a burst in the x-ray emission from the side wall. The transition to the unstable state and the decay of the plasma take 30–50 ms. Photographs of the plasma emission taken from the end of the device with the help of an image converter at an exposure time of 1 μs reveal that the axial region becomes filled with an azimuthally inhomogeneous plasma stream during the decay (low-index azimuthal modes are clearly seen). The decay is accompanied by a spike in the current to the central rings of the end electrodes. At the same time, the rotation velocity decreases, and the confinement system rapidly becomes filled with gas as a result of recombination of the decaying plasma at the liner.

The rapid transition to the unstable state is evidence that the stabilization mechanism does not depend on contact with the ends (which is the governing effect in experiments with a low-density plasma[9]): Turning off the plasma shell could not by itself disrupt this contact in such a short time. All the experimental results can be interpreted in a natural way as evidence of a centrifugal stabilization.[1-3]

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