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STABILITY OF PLASMA CONFINED BY A COLD-GAS BLANKET

C. M. Braams
Association Euratom-FOM, FOM-Instituut voor Plasma-Fysica, Rijnhuizen, Jutphaas, The Netherlands
(Received 25 July 1966)

A steady-state plasma, confined by a cold-gas blanket in a toroidal magnetic field, is stable against magnetohydrodynamic instabilities. A ring whirl will help to define the equilibrium position, to stabilize against deviations from the steady-state, and to allow a poloidal field component.

Alfvén and Smårs[1] have advanced the idea that a thermonuclear plasma can be confined by a cold-gas blanket if the heat conduction in the ionized transition region is sufficiently reduced by a strong magnetic field. They have remarked that the gas blanket provides a barrier against impurities from the walls and that a plasma confined in this way is not subject to the same types of instabilities as a plasma confined by magnetic fields in vacuum. For a cylindrical plasma column with an axial magnetic field, they have computed a conduction loss which, by itself, would not be prohibitive for a large D-T reactor. Because of apparent advantages of systems with strong axial currents and azimuthal magnetic fields, in which the field is strongest and the pressure is lowest in the critical intermediate temperature zone, the Stockholm group have later concentrated on such pinch configurations.[2-6] Kink instabilities, however, then made it impossible to verify the calculations of heat losses through a quiescent blanket.

For temperatures up to 10^5 °K, information about heat conduction in magnetized plasma can be obtained from the studies of high-pressure arcs in axial magnetic fields, carried out by Wienecke et al. in Garching. Numerical computations[7] in which the heat transfer by ionization and recombination as well as radiative losses are also taken into account indicate that a strong magnetic field causes an important reduction of the power loss. Experiments[8] are in good agreement with those computations. This implies that the contribution from this temperature range to the integral of the heat conductivity, $\int_0^{T_{\max}} x dT$, is indeed small, as assumed by Alfvén, and also that instabilities do not play a dominant role in these experiments. It appears worthwhile, therefore, to reconsider the advantages of a gas blanket with an axial magnetic field. Before doing so, we will briefly point to some aspects of confinement by magnetic fields in vacuum.

The most violent instabilities of Z pinches, those of the kink and sausage types, are absent in systems with longitudinal magnetic fields produced by external coils. In these, the dominant instabilities are the magnetohydrodynamic exchange modes which, in turn, can be suppressed by minimum-B stabilization. In open systems, escape of particles along the magnetic field lines leads to deficiencies in the velocity distribution that can cause velocity-space instabilities. In this respect, closed systems have an advantage, but they can have no minimum B, at best "average-minimum B," the effectiveness of which, against interchange modes, has not yet been fully demonstrated. It is worth noting, therefore, that a simple torodial magnetic field combined with a gas blanket should be at least as good, with respect to the above-mentioned instabilities, as a toroidal average-minimum-B field in vacuum.

A crucial difference between magnetic insulation and magnetic confinement lies in the fact that a plasma in a magnetic field only behaves as a diamagnetic substance to the extent that its pressure is balanced by the field.[9] No magnetic energy is available for driving instabilities if the magnetic field is produced by external currents and is allowed to relax to its vacuum configuration. The plasma pressure must then be balanced by the cold gas, so that pressure gradients are also eliminated as a source of energy for instabilities.[10]

Not only can a gas blanket help to eliminate magnetohydrodynamic instabilities, but it also provides a means for introducing a sizable stabilizing gas dynamic energy term. Rotation of the gas will produce a centrifugal force field in which the hot gas has a position of minimum potential energy on the axis of rotation. In contrast, rotation of a plasma column in vacuum has a destabilizing influence.[11,12] A toroidal Z pinch in a ring whirl was considered by Shafranov,[13] who suggested that in this configuration the gas kinetic energy must exceed the magnetic energy for stability. In work on high-pressure arcs, centrifugal stabilization has been used extensively against thermal convection; it seems not to have been applied experimentally to magnetically driven disturbances.

Even if the model of a plasma column in pressure equilibrium with a gas blanket and immersed in a vacuum-type magnetic field contains no source of energy for hydromagnetic instabilities, there are several reasons why a positive stabilizing term may be desirable. During formation, heating, or compression of the plasma, there could be enough residual paramagnetism or diamagnetism to endanger equilibrium and stability. Furthermore, as shown by Wienecke,[14] Witkowski,[15] and Döbele, Wienecke, and Witkowski,[16] there is a weak diamagnetic effect even in the steady state, especially at low pressures, that is caused by the outward flow of plasma combined with the inward flow of neutral gas in the ionization-recombination region around 10 000°K. Finally, it would be very attractive, both for heating and for increasing the central density—which determines the thermonuclear yield—to allow a poloidal component of the magnetic field in excess of the Kruskal limit.[17] In keeping with Shafranov's argument,[13] one may expect the permissible longitudinal current to be greater with than without centrifugal stabilization. It is of interest, therefore, to note that for uniform angular velocity, the centrifugal energy is a fraction of the order of $(v_w/v_{th})^2$ of the thermal-energy content of the plasma. Here, v_w and v_{th} are the systematic and thermal velocities of the cold gas at the wall. If their ratio can be made to approach 1, the whirl should have a strong effect on the gross stability of the plasma column.

We conclude that a plasma in a ring vortex with a toroidal magnetic field is stable against magnetohydrodynamic and velocity-space instabilities. The permissible poloidal field component still remains to be investigated.

This work was performed under the EURATOM-FOM association agreement with financial support from ZWO and EURATOM. I thank Dr. L. Th. M. Ornstein, Dr. J. C. Terlouw, Dr. M. P. H. Weenink, and Dr. H. Wind for stimulating discussions.

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