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# ON THE STABILITY OF BOUNDARY LAYERS IN GAS MANTLE SYSTEMS

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1. Plasma-Neutral Gas Interaction Effects on the Stability of Drift Modes, Physica Scripta 15,1977, 318-324

2. On the Stability of Ballooning Modes in the Boundary Layers of a Gas Insulated Plasma, Royal Institute of Technology, Stockholm, TRITA-PFU-77-04, 1977, Revised edition 1978

3. On the Stability of Localized Drift Modes in the Boundary Layers of High Density Magnetically Confined Plasmas, Royal Institute of Technology, Stockholm, TRITA-PFU-77-07, 1977

4. Stability Properties of Cold Blanket Systems for Current Driven Modes, Royal Institute of Technology, Stockholm, TRITA-PFU-77-09, 1977

5. Non-Adiabatic Stability Analysis of Current and Magnetic Curvature Driven Modes in Cold Plasmas Penetrated by Neutral Gas, Royal Institute of Technology, Stockholm, TRITA-PFU-78-03, 1978

6. Stability Aspects of Plasmas Penetrated by Neutral Gas with Respect to Velocity Driven Modes, Royal Institute of Technology, Stockholm, TRITA-PFU-78-04, 1978

Paper 2 has been presented at the Workshop on Gas Blanket Research, Juthphaas 2-5 May 1977, Rijnhuizen Report 77-103 and at the Eighth European Conference on Controlled Fusion and Plasma Physics, 19-23 September 1977, Prague, Conference Proceedings I, p. 136.

Paper 4 has been presented at the Workshop on Plasma Transport and Theory, Varenna, 1-19 September, 1977. To be published by Euratom.

A summary of the results in Papers 1-4 has been presented in an invited paper at the Workshop on Fusion Fueling, Princeton, 1-3 November, 1977. Conference Proceedings published by ERDA, Conf-771129, March 1978, p. 67.

# ON THE STABILITY OF BOUNDARY LAYERS IN GAS MANTLE SYSTEMS

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## ABSTRACT

In this thesis a systematic investigation of the stability properties of the partially ionized boundary regions of gas mantle systems for a large class of dissipative magneto-hydrodynamic modes is presented.

In the boundary regions of gas mantle systems even very small concentration of neutrals will give rise to large pressure and density gradients. Consequently the stability properties of these regions become essential for the whole neutral gas mantle concept in particular since conventional stabilizing mechanisms associated with minimum-average-B and shear are expected to become less effective. The analysis treats three dimensional electrostatic as well as electromagnetic perturbations. Stability criteria are derived using generalized algebraic stability theorems by Routh and Horwitz or alternatively the Nyquist technique.

We conclude that in the partially ionized boundary regions of gas mantle systems several strong stabilizing mechanisms arise due to coupling between various dissipative effects in certain parameter regions. The presence of neutral gas strongly enhances the stabilizing effects in a dual fashion. First in an indirect way by cooling the edge region and second in a direct way by enhancing viscous and heat conduction effects. It has, however, to be pointed out that exceptions from this general picture may be found. The stabilizing influence of neutral gas on a large class of electrostatic as well as electromagnetic modes in the boundary regions of gas blanket systems is contrary to what has been found in low density weakly ionized plasmas. In these latter cases presence of neutral gas has even been found to be responsible for the onset of entirely new classes of instabilities. Thus there is no universal stabilizing or destabilizing effect associated with plasma-neutral gas interaction effects.

In 1960 Alfvén and Smårs suggested insulation of a thermonuclear plasma by a high density neutral gas (1). This approach should have certain advantages as compared to insulation by a magnetic field in an ultra high vacuum region, provided the thermal heat conduction losses could be kept at a tolerable level. Alfvén and Smårs showed that this is indeed the case if a strong magnetic field is applied. It was also shown that a high plasma temperature could be reached when the input power exceeded a certain critical, quite moderate value. Alfvén and Smårs further proposed that the presence of a surrounding dense neutral gas may have a stabilizing effect on certain plasma instabilities.

In this first approach to the gas blanket concept, a pressure balance between the plasma and neutral gas was postulated. However, later investigations have shown that a well defined diamagnetic partially ionized boundary layer has to separate the blanket from the plasma, and that the pressure in the plasma interior largely exceeds that of the blanket (2-4). Further, according to studies of the neutral gas penetration process into the plasma, such a separation was found to exist only when the product of ion density and plasma dimension exceeds a certain critical value (3,4). Below this value the hot plasma interior also becomes subject to charge exchange losses from penetrating neutrals. Furthermore, there also exists an upper limit on this product due to power balance constraints (5). If the heat supply from the thermonuclear core due to heat conduction cannot balance the power losses due to ionization, heating and radiation, a steady state is not possible. The extension of possible parameter ranges due to additional heat supply,for example ohmic and radio frequency heating as well as reduction due to impurity radiation and other losses, have to be further analysed.

One of the main advantages of the proposed type of system is that they possibly offer the simplest means of producing a very clean plasma. One of the main obstacles to overcome before a fusion reactor can be realized is associated with the influx of impurities and the resulting large radiation losses (6). Several proposals to reduce the impurity influx have been made such as the use of divertors, plasma rotation, selective extraction by high frequency heating and gas blankets. The last mentioned scheme together with an optimal choice of wall material, is probably the simplest means of reducing the impurity influx. The neutral gas parameters have to be chosen such that, first, the temperature in the boundary regions is well below the sputtering threshold and, second, the mean free path for fast charge exchange neutrals coming from the hot central core is less than the blanket dimensions. In this case the cool boundary regions will prevent hot plasma from interacting with material walls as well as efficiently absorb hot charge exchange neutral particles, thus reducing the sputtering rate.

Another advantage of gas blanket systems is that the surrounding neutral gas could act as a fuel reservoir, provided the transport processes are such that deuterium and tritium can diffuse into the hot central core at an appropriate rate and at the same time the "ashes" of the thermonuclear reactions, i.e. helium, can diffuse outwards (7).

The global MHD stability of gas blanket systems has been investigated by several authors (8,9). The general picture for the specific models investigated is that the stability limits for modes localized to central parts are unchanged as compared to a vacuum insulated plasma. However, the characteristic growth rates decrease, in particular when the density of the surrounding neutral gas is much larger than the ion density. For modes localized to the boundary regions the picture is somewhat different. In these regions even a very small concentration of neutral gas may have a substantial influence on the pressure balance (10). Thus large pressure and density gradients will arise across the boundary region in gas insulated plasmas. Consequently the stability properties of these regions become essential for the whole neutral gas blanket concept, in particular since conventional stabilizing mechanisms associated with minimum-average-B and shear are expected to become less effective here. In this thesis a systematic investigation of the stability properties of the boundary region of gas blanket systems for a large class of resistive MHD modes is presented.

In paper 2 are discussed the stability properties for electromagnetic modes driven by unfavourable magnetic curvature and pressure gradients, i.e. flute and ballooning modes. A previous investigation by Lehnert (11) of the flute stability is thus generalized, taking into account electromagnetic effects. As discussed by Lehnert (11) minimum-average-B stabilization is probably reduced in the cool boundary region due to insufficient magnetic-line tying. Consequently curvature driven modes necessarily have a finite extension along the lines of force and therefore electromagnetic effects have to be considered. Furthermore the coupling between plasma and neutral gas, which is essential in determining the stability properties, is generalized including neutral thermal effects. It is shown that, although the plasma neutral gas coupling is modified, the stability properties remain unchanged at least for incompressible modes which are of main interest. A general dispersion relation for localized electromagnetic modes is derived. Using the Nyquist technique, the stability criteria are found. It is shown that a joint viscous-resistive pressure effect introduces a strong stabilizing effect for mode propagation perpendicular to the lines of force, in agreement with earlier investigations by Lehnert. However, this effect is reduced, but not cancelled, by the so called Nernst effect. For modes propagating along the lines of force, an additional stabilizing resistive-resistive pressure effect is introduced, not previously considered to the authors knowledge. This effect also arises due to a coupling between dissipative mechanisms. In this case coupling between particle diffusion perpendicular to the line of force and finite resistivity parallel to the magnetic field. In plasmas with a high concentration of neutrals the particle diffusion effect is also enhanced due to ion-neutral collisions. Due to the joint action of all effects mentioned, the conclusion is that complete stabilization of ballooning modes can be achieved under rather general conditions in the boundary layers of gas-insulated plasmas.

Instabilities driven by the diamagnetic drift motion are discussed in papers 1 and 3. We have only considered collisional or dissipative drift modes since collisionless or universal drift modes and trapped particle modes are likely to be unimportant in the boundary regions, due to the high collisionality. Drift modes are typically destabilized by dissipative processes such as particle collisions and wave-particle resonances along the lines of force. These effects drive the electron and ion motions out of phase and the particles can then give up energy to growing waves. For typical gas mantle data, the dominant dissipative effect parallel to the lines of force is associated with Coulomb collisions, which thus provides the necessary mechanism for the onset of drift modes in this case. Electron-neutral collisions can typically be ignored. This is in contrast to certain low-density weakly ionized plasmas, such as the positive column of a low-pressure arc, where for instance electron neutral collisions are much more important. Here drift modes can actually be destabilized by the presence of neutral gas in this latter case (12, 13). This is contrary to the situation in the high density plasmas typical of gas mantle systems where neutral gas effects usually correspond to stabilizing effects. In paper 1 we consider non-localized electrostatic modes using the two-fluid approximation, including finite ion gyro radius effects in the ion pressure tensor. It is shown that the most difficult modes to stabilize propagate in the direction of the electron diamagnetic drift velocity, in agreement with previous investigations by Chen (14). Furthermore it is shown that finite ion gyro radius effects, plasma-neutral gas interaction and ion viscosity modify the behaviour of drift modes and introduce stabilizing effects. The effect of shear is also considered. It is concluded that shear has only a weak influence on these types of modes, primarily because of the small localization region of the modes being considered. The stabilizing effect may be further reduced due to collisional effects rendering ion Landau damping ineffective. The analysis in paper 1 was restricted to non-localized perturbations and cases where density gradient effects are more important than temperature gradient effects. In paper 3 this analysis is extended to include localized perturbations and an arbitrary ratio between the density and temperature scale lengths. Using the Nyquist technique, or alternatively a generalized version of Routh and Hurwitz's theorem, a stability criterion is derived from the dispersion relation. As has previously been discussed, drift modes are characterized by a finite extension along the lines of force. In the limit where the parallel wavelength goes to infinity the final stability criterion does not agree with the stability criterion derived for flute like perturbations. This paradox is discussed and resolved. Furthermore it is shown that the driving source for drift modes is considerably reduced due to the finite ion gyro radius and particularly viscous effects. In addition, joint viscous-resistive pressure and resistive-resistive pressure effects, discussed in connection with flute and ballooning modes, also introduce stabilizing effects for these types of instabilities.

The stability problem of systems with induced currents along the lines of force is being reported in paper 4. Previous investigations of similar problems, including plasma neutral gas interaction effects, have mainly been concerned with low density weakly ionized plasmas. In these cases the ion-neutral collision rate was large enough for the ions to be regarded as unmagnetized. Kadomtsev and Nedospasov (15) showed that plasma-neutral gas interaction effects play a crucial role for the onset of low-frequency kink-like modes. However, as shown in paper 4,current-driven modes in dense partially ionized boundary regions are typically stabilized by plasma-neutral gas interaction effects. We discuss pure electromagnetic kink-like modes driven by the torque arising from a transverse current density gradient and magnetic field perturbations. Using a suitable transformation,the final dispersion relation is transformed into a third order real polynomial. The final stability criterion is found by using a theorem by Hurwitz. It is shown that a joint viscous-magnetic diffusion effect, not previously considered, introduces a stabilizing effect in addition to the universal stabilizing effect associated with the bending of the lines of force. In order to find the most difficult modes to stabilize, we optimize the final stability criterion with respect to the wavenumber parallel and perpendicular to the lines of force. From a simple steady-state model we obtain expressions for the concentration of neutrals and the boundary layer thickness. We can thus derive a closed expression for the critical current density gradient as a function of ion density, magnetic field strength and temperature. It turns out that there exists a critical ion density above which the system is stable. This critical density typically increases with increasing magnetic field strength. Furthermore the possible ranges for stable operation are extended for decreasing temperature. We also consider electrostatic "rippling" type modes driven by the combined effect of a transverse resistivity gradient and a longitudinal current. Using the steady-state model being developed,closed expressions for the critical current are presented.

In paper 5 we investigate the relevance of the adiabatic approximation used in the previous papers 1-4.

We restrict the investigation to electrostatic magnetic curvature and current driven modes. The general theory presented involves solving the heat balance equation for the combined plasma-neutral gas system. Thus heat conduction, ionization and ohmic heating effects are explicitly considered while recombination effects are neglected. Recombination type instabilities are typically of relevance only in very low temperature plasmas where the recombination rate is high (16). In the general theory presented new branches in the dispersion characteristics are introduced. Furthermore it is shown that heat conduction typically introduces a stabilizing effect whereas ionization and ohmic heating can introduce either stabilizing or destabilizing effects depending on which parameter ranges are considered. Generally speaking, ionization type instabilities (17) only occur at neutral densities much higher than what is expected in the partially ionized boundary region of gas blanket systems. For the specific steady state models considered in paper 5, it is concluded that the general theory typically predicts similar or more favourable stability properties than the adiabatic theory for cases when the density scale length is less than or of the same order as the temperature scale length. Estimates of threshold quantities agree in order-of-magnitude estimates. For cases when the density scale length is much larger than the temperature scale length, it is concluded that the general theory predicts much less favourable stability properties, i.e. the adiabatic theory grossly overestimates the stabilizing effects. The reason for this is being discussed in detail in paper 5.

Instabilities driven by mass motions perpendicular or parallel to the lines of force are reported in paper 6. These types of instabilities are probably of no importance in a future thermonuclear gas mantle reactor. However in gas mantle model experiments such as in certain rotating plasma devices these investigations could be of importance. Previously Hoh (18) has shown that the presence of neutral gas in systems with transverse mass motion can give rise to instabilities. These instabilities arise due to the neutral drag force on the ions. This implies that the ion drift motion, perpendicular to the lines of force and the electric field perturbations, will lag somewhat behind the electron drift motion. This gives rise to a charge separation effect which tend to amplify the perturbations. This effect is, however, only important when the ion-neutral collision frequency is much higher than the ion gyro frequency. Many dense rotating plasma experiments are performed in parameter ranges where the ion neutral collision frequency is expected to be much less than the ion gyro frequency. In these cases charge separation effects due to neutral gas friction effects associated with the ion drift motion parallel to the electric field perturbations are more important (19). Instabilities driven by this type of effect are considered in paper 6. It is shown that neutral gas effects give rise to destabilizing as well as stabilizing effects for this mode. Furthermore we also consider modes of the Kelvin-Helmholz type (20) associated with a sheared mass flow. These types of modes arise independently of the presence of neutral gas or not. Closed expressions for threshold sheared and shearless mass flows are presented.

We conclude that, in the partially ionized boundary regions of gas mantle systems, several strong stabilizing mechanisms arise due to coupling between various dissipative effects in certain parameter regions. The presence of neutral gas typically strongly enhances the stabilizing effects in a dual fashion. First, in an indirect way by cooling the edge region and second, in a direct way by enhancing viscous and heat conduction effects. It must, however, be pointed out that exceptions from this general picture may be found.

The stabilizing influence of neutral gas on a large class of electrostatic as well as electromagnetic modes in the boundary regions of high density gas blanket systems is contrary to what has been found in low density weakly ionized plasmas. In these latter cases , the presence of neutral gas has even been found to be responsible for the onset of entirely new classes of instabilities. Thus there is no universal stabilizing or destabilizing effect associated with plasma-neutral gas interaction.

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Key words: Gas mantle systems, MHD-stability, plasma-neutral gas interaction, dissipative effects, resistivity, viscosity, heat conduction.