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FEEDBACK STABILIZATION OF PLASMA INSTABILITIES

(Rückkopplungsstabilisierung von Plasmainstabilitäten)

von

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Feedback stabilization

If the amplitude of a perturbation of the plasma grows, it is unstable. The growth of the perturbations of different parameters of the plasma (density, electric field, magnetic field, temperature, geometric characteristics etc.) can be detected. The detected signals can be amplified, the phase of the signals can be shifted and the transformed signals can be fed back to the plasma (Fig. 0.1). As result an essential change in the amplitude of the perturbations occurs. A corresponding choice of the amplification and phase shifting of the signals leads to a suppression of the instabilities. This way to suppress the instabilities is called feedback stabilization.

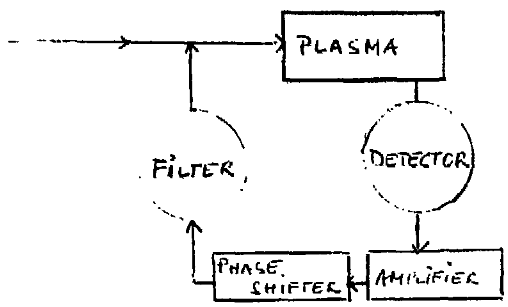

Fig. 0.1

The use of feedback control techniques is a new and promising area in plasma physics. It could be applied for the suppression of various instabilities.

The whole process of stabilization can be devided in three phases:

1) The detection of the dangerous signals. The sensing process requires, that the spatial patterns or modes be determined by electrodes, probes, light output, radiation or some other sensing scheme.

2) The amplification and transformation of the detected signals. There are used linear and nonlinear amplification processes. The corresponding phase shift must be made for each mode to get a resulting signal, which is able to suppress the detected perturbation. The frequency of the resulting signals is nearly the same as of the detected perturbation.

3) The feedback of the signals to the plasma. The coupling of energy into the particular modes can be made by probes, microwave signals or whatever technique ones`ingenuity suggests. Therefore in the literature on feedback stabilization a large spreading of different experimental methods and of corresponding theoratical interpretations exists. Each experimental method requires its own theoretical model and a common general theoretical model does not exist (only for some special instabilities). Only some common properties of the models give us the possibility to classify them in different groups. Such a classification will tried in this review.

1. Theory of the feedback stabilization

1.1. General theoretical model for electrostatic instabilities.

The general theory of linear feedback suppression of electrostatic instabilities has been given by Taylor and Lashmore Davies (1970, 1970+) and developed further by Sen (1973), Richards, Emmert and Grubb (1974) and Uckan and Kammash (1975).

If in a plasma electrostatic instabilities exist, a growth of the perturbation of the intensity of electric field can be put in evidence. Local growing charge densities appear, which can be deteced. We assume, that the perturbation of the electric potential at r=r' is ϕ (r'). An experimental system senses this potential and after transformation (amplification, phase shifting) it reintroduces a signal into the plasma at r=r'. The dependence of the form of the reintroduced signal from the detected perturbation is determined by the parameters of the feedback circuit. Taylor and Lashmore Davies (1970) introduced a response function in the form

$$g(\omega)\; G(r'', r') \tag{1.1}$$

which describes the effect of the feedback circuit. It was assumed, that the feedback circuit introduces into the plasma a supplementary electric charge, which compensates the charge density of the perturbation. The "external" charge density was determined by the reponse of the feedback circuit to the detected potential in the vicintity of r=r'. It can be expressed by the reponse function (1.1) in the form

$$\rho_{ex}(r'') = g(\omega) \int G(r'', r')\, \phi(r')\, dr' \tag{1.2}$$

In the absence of feedback the response of the plasma to an electric potential ϕ (r) $e^{i\omega t}$ can be represented by a generalized conductivity tensor $\varkappa_\omega$ (r,r') such that the current density is

$$j_\omega(r) = \int \varkappa_\omega(r, r')\, E_\omega(r')\, dr' \tag{1.3}$$

This leads to the dispersion relation:

$$\nabla \int dr'\, \epsilon_\omega(r, r')\, \nabla \phi(r') \;(\tag{1.4}$$

where

$$\hat{\epsilon}_\omega(r, r') = \delta(r - r') - \frac{4\pi}{i\omega} \varkappa_\omega(r, r') \tag{1.5}$$

Equation (2) determines the oscillation frequencies and the stability of the system through the eigenvalue ω in the absence of feedback. In the presence of feedback the created supplementary charge density (1.2) must be taken into consideration. Using the Maxwell equation div $\vec{D} = \varrho_{ext}$ we get instead of (1.4) the dispersion equation

$$\nabla \int dr' \varepsilon_\omega (r, r') \nabla \phi (r') + g(\omega) \int dr' G(r, r') \phi(r') = 0 \tag{1.6}$$

Before the effect of the feedback can be discussed it is important to distinguish two different types of instability which can arise from eq (1.4). The first type involves only a single mode of oscillation, which may have positive or negative energy. Growth of this instability is accompanied by an exchange of energy between the oscillation and the plasma medium, e.g. by dissipation. The second type of instability involves two modes of oscillations, one of positive and the other of negative energy. These oscillation become degenerate at the threshold of instability, which can be regarded as the exchange of energy between the two oscillations without any net transfer to the plasma medium. Following Hasegawa (1968) the first instability is named dissipative and the second reactive.

In the case of <u>dissipative instabilities</u> the tensor $\varepsilon_\omega(r, r')$ was assumed to have an hermitian (ε_h) and a small antihermitian part (ε_a)

$$\varepsilon = \varepsilon_h + \varepsilon_a \tag{1.7}$$

The <u>suppressor term</u> $g(\omega)$ was considered to be small compared to ε_h and the effect of the feedback on the real and imaginary parts of $\omega = \omega_0 + i\gamma_0$ were found to be the following

$$\omega = \omega_0 + kg \cos\theta \tag{1.7}$$

$$\gamma = \gamma_0 + kg \sin\theta \tag{1.8}$$

where $g = |g(\omega_0)|$; $\theta = \arg g(\omega_0)$, i.e. phase angle (1.9)

and
$$k = \frac{\iint \phi^*(r) G(r, r') \phi(r') \, dr \, dr'}{\iint \nabla \phi^*(r) \frac{\partial}{\partial \omega} \varepsilon_h (r, r') \Big|_{\omega = \omega_0} \nabla \phi(r') \, dr \, dr'} \tag{1.10}$$

where k is real due to the properies of ε_h and G.

Equations (1.7) and (1.8) show that the effect of the feedback may be to suppress or enhance instabilities according to the phase difference θ which is introduced between sensor and suppressor elements; a stable system may be rendered unstable and vice versa. The condition for stabilization is:

$$-\operatorname{Im} g(\omega_{0}) = -g \sin\theta > \gamma_{0}/k \qquad (1.11)$$

that is, the amplification must be greater than a critical value and the phase must be in one half of the phase plane for a positive energy wave and the opposite half for a negative energy wave.

The reactive instability does not depend on dissipation, therefore can be neglected and from (1.6) the dispersion relation

$$(\omega-\omega_{c})^{2} = -\gamma_{c}^{2} + g(\omega)\,k \qquad (1.12)$$

results, where now

$$k = \frac{2\iint \phi^{*}(r)\,G(r,r')\,\phi(r')\,dr\,dr'}{\iint \nabla\phi^{*}(r)\,\frac{\partial^{2}}{\partial\omega^{2}}\,\varepsilon_{h}(r,r')\Big|_{\omega=\omega_{c}} \nabla\phi(r')\,dr\,dr'} \qquad (1.13)$$

ω_{c} is the oscillation frequency at threshold and γ_{c} growth rate without feedback.

From eq (1.12) the conditions for stability are:

$$\operatorname{Re} g(\omega_{c}) > \gamma_{c}^{2}/k \qquad (1.14)$$

$$\operatorname{Im} g(\omega_{c}) = 0 \qquad (1.15)$$

Therefore we have again the result that the amplification must be greater than some critical value but this time any phase difference other than zero produces instability.

The theory of Taylor and Lashmore Davies was extended by Richards, Emmert and Grubb (1974) to include dissipative effects in reactive instabilities as well as the effect of frequency dependence of the phase shift of the feedback system. They determined the stability regions for different special cases. The theory is in agreement with the experiments, which they performed on the flute instability in magnetic mirrors and it shows, that the dissipation has the effect of providing an allowable range for the feedback phase. Feedback stabilization of multimode oscillations has been developed by Sen (1973) and applied to multimode weak dissipative and reactive electrostatic plasma instabilities. The amplitude and phase requirements of the feedback structure are obtained from the usual single mode stabilization technique. The response function of the feedback circuit (1.1) was obtained in analytical and graphical form for the critical values of the onset of the instability.

The general theory of simultaneous feedback stabilization of multimode oscillations in a collisionless magnetized plasma was developed for reactive and dissipative instabilities by Uckan and Kammash (1975).

In the absence of feedback the dispersion relation for electrostatic instabilities in a plasma (1.4) can be written as

$$\varepsilon(\omega,\vec{k}) = 0 \tag{1.16}$$

where ω and $\vec{k}$ are the frequency and the wave vector of the perturbation and $\varepsilon(\omega,\vec{k})$ is the Fourier transform of the dielectric function for longitudinal waves. In order to obtain the corresponding dispersion relation in the presence of the feedback the Fourier transform of (1.6) must be calculated. It was written by Kammash and Uckan (1975) in the form

$$\varepsilon(\omega,\vec{k}) = -F(\omega) \cdot G(\omega,\vec{k}) \tag{1.17}$$

where $F(\omega)$ and $G(\omega,\vec{k})$ are functions determined by the characteristics of the plasma and by the type of feedback controle. $F(\omega)$ is the feedback transfer function. It depends only from the type of the instability. For flute-like drift-cyclotron instabilities it was proposed by Uckan and Kammash (1975) the dependence

$$F = \frac{1+\tau_1\omega}{1+\tau_2\omega} F_0 \tag{1.18}$$

where τ_1 and τ_2 are time constants and F_0 is also constant.
For MHD - instabilities the dependence

$$F = \frac{\omega(1+\tau_1\omega)}{(1+\tau_2\omega)(1+\tau_3\omega)} F_0 \tag{1.19}$$

was chosen (τ_1, τ_2 and τ_3 are time constants).
The choise (1.18) and (1.19) of F gives the correct frequency dependence in the feedback loop for stable operation. In this case the stability will not be disturbed by any phase error or small time delay.
Starting from (1.17) stability conditions for dissipative and reactive instabilities result. In the case of dissipative instabilities the dielectric function has an hermitian and an antihermitian part.

$$\varepsilon(\omega,\vec{k}) = \varepsilon_h(\omega,\vec{k}) + \varepsilon_a(\omega,\vec{k}) \tag{1.20}$$

where

$$|\varepsilon_a| << |\varepsilon_h| \tag{1.21}$$

If we expand $\varepsilon(\omega,\vec{k})$ into a Taylor series about the eigenfrequencies ω_{q_k} we obtain the frequency displacement $\Delta\omega_{q_k}$ due to the feedback from (1.17) and (1.16) in the form

$$\Delta\omega_q = -F(\omega_q)\, G(\omega_q,\vec{k}) \Big/ \frac{\partial\epsilon_h}{\partial\omega}\Big|_{\omega=\omega_q} \qquad (1.22)$$

The real and imaginary parts of the frequency and growth rate are

$$\omega_r = \omega_{rq} + Re\left[-F(\omega_q)\, G(\omega_q,\vec{k}_q) \Big/ \frac{\partial\epsilon_h}{\partial\omega_q}\right] \qquad (1.23)$$

$$\gamma = \gamma_q + Im\left[-F(\omega_q)\, G(\omega_q,\vec{k}_q) \Big/ \frac{\partial\epsilon_h}{\partial\omega_q}\right] \qquad (1.24)$$

where $\omega_{rq}+i\gamma_q=\omega_q$ corresponds to the eigenfrequencies in absence of feedback. Therefore the stabilization occurs if $\gamma<0$ that is, if

$$Im\left[F(\omega_q)\, G(\omega_q,\vec{k}_q) \Big/ \frac{\partial\epsilon_h}{\partial\omega_q}\right] > \gamma_q \qquad (1.25)$$

for all q values.
Since $\gamma_q << \omega_{rq}$ the feedback transfer function near the q-th mode can be put in the form

$$F(\omega_q) \cong F(\omega_{rq}) = |F_q|\, e^{i\theta_q} \qquad (1.26)$$

where $|F_q|$ and θ_q are the gain and phase of the feedback system near the q-th mode, respectively. In view of this, conditions for the gain and phase result from (1.25) in the form

$$\pi < \theta_q + \arg\left[-G(\omega_{rq},\vec{k}_q) \Big/ \frac{\partial\epsilon_h}{\partial\omega_{rq}}\right] < 2\pi \qquad (1.27)$$

$$|F_q| > \gamma_q \Big/ Im\left[e^{i\theta_q} G(\omega_{rq},\vec{k}_q) \Big/ \frac{\partial\epsilon_h}{\partial\omega_{rq}}\right] \qquad (1.28)$$

In the case of reactive instabilities the dielectric function is hermitian. With a weak feedback assumption, we can apply perturbation theory to this case too, i.e. we expend $\epsilon(\omega,\vec{k})$ about the oscillation frequency and introduce in (1.17). Since $\partial\epsilon/\partial\omega|_{\omega_q}=0$ for reactive instabilities, the frequency displacement, $\Delta\omega_q$, due to feedback from ω_{rq} can be given by

$$(\Delta\omega_q)^2 + \gamma_q^2 = -2F(\omega_{rq})\, G(\omega_{rq},\vec{k}_q) \Big/ \frac{\partial^2\epsilon}{\partial\omega_{rq}^2} \qquad (1.29)$$

The necessary condition for stability corresponds to $\Delta\omega_q=0$, therefore

$$Re\left[-2F(\omega_{rq})\, G(\omega_{rq},\vec{k}_q) \quad \frac{\partial^2\epsilon}{\partial\omega_{rq}^2}\right] > \gamma_q^2 \qquad (1.30)$$

$$Im\left[2F(\omega_{rq})\, G(\omega_{rq},\vec{k}_q) \Big/ \frac{\partial^2\epsilon}{\partial\omega_{rq}^2}\right] = 0 \qquad (1.31)$$

The influence of dissipation on the reactive instabilities was also taken into acount by Uckan and Kammash through the antihermitian part $\epsilon_a(\omega_q,\vec{k})$ of the dielectric function. For the phase θ_q and for the gain $|F_q|$ they got instead of (1.30) and of (1.31) the stability conditions:

$$|F_q| \geq \frac{\delta_q^2 + 2A\delta_q}{2} \left| G(\omega_{rq}, \vec{k}_q) \Big/ \frac{\partial^2 \varepsilon_h}{\partial \omega_{rq}^2} \right| \qquad (1.32)$$

$$\theta_q = -\arg\left[2G(\omega_{rq}, \vec{k}_q) \Big/ \frac{\partial^2 \varepsilon_h}{\partial \omega_{rq}^2} \right] - \tan^{-1}\left\{ \frac{(1+2A/\delta_q)^{1/2}}{1+A/\delta_q} \right\} \qquad (1.33)$$

where

$$A = \frac{\partial \varepsilon'' / \partial \omega_{rq}}{\partial^2 \varepsilon_h / \partial \omega_{rq}^2}$$

The form of the function $G(\omega_{rq}, \vec{k}_h)$ depends from the structure of the feedback system. It is possible to chose the feedback circuit in such a manner, that the stability conditions for all possible eigenfrequencies should be satisfied.

A problem, similar to the feedback stabilization of the electrostatic plasmainstabilities was studied by Arsenin and Chuyanov (1968++). They analyse the possibility of suppression of drift beam instability of a monoenergetic electron beam by a feedback system. The electrostatic oscillations of the monoenergetic electron beam were considered assuming the beam placed in a cylindrical feedback radiosystem which excites outside the beam on electrostatic potential wave propagated at the same velocity as the potential fluctuations on the beam surface and with the amplitude proportional to that of the fluctuations. The conditions to suppress the drift beam instability are formulated.

1.2. Theoretical analysis of suppression of flute instabilities

The description and the analysis of the first experimental results on suppression of flute instability in an OGRA-II trap with fast neutral atom injection by means of a radio system measuring the electric field distribution of low frequency oscillations is given by Arsenin and Chuyanov (1967). In the space between plasma column and chamber wall a system of electrostatic transmitters, amplifiers and control electrodes are arranged in such a way that the field fluctuations are amplified and fed to the electrodes which damp the fluctuations. The theoretical analysis leads to stability conditions.

The possibilities if using the feedback system for suppressing flute instability were studied theoretically by Arsenin and Chuyanov (1968++). There a simple model was studied the stability of an infinitely long tenous plasma cylinder ($\beta \ll 1$). The nonhomogeneous plasma had a radius a and was directed along an external homogeneous magnetic field B_0. The flute perturbation had the form of

$$\psi = \varphi(r) \exp(im\theta - i\omega t)$$

where θ is the azimuthal angle and m is the azimuthal wave number. The effect of curvature was considered by introducing a radial gravity which resulted in an ion azimuthal drift of frequency ω^*. The effect of the feedback system on the plasma was included by considering the boundary condition on a surface of radius b which surrounded the plasma.

$$\varphi(b) = G\,\varphi(a) \tag{1.34}$$

The coefficient G is determined by the feedback system, and, in general, it can be complex and dependent upon the frequency. Equation (1.34) implies that the wave on the surface surrounding the plasma has the same phase velocity as that in the plasma.

The case of a grounded metallic wall corresponds to G=0. In this case the plasma is stable as long as $\omega_{oi}^2 \leq \omega_{Bi}\,\omega^*$. Here ω_{oi} is equal to the ion plasma frequency, ω_{Bi} is the ion cyclotron frequency. It was shown, that in the case of a plasma with a sharp boundary it is possible to increase the instability threshold. In the case of G= const the oscillation frequencies are given by

$$\omega^{\pm} = \frac{m\omega^*}{2} \pm \sqrt{\frac{m\,\omega^{*2}}{4} + \frac{|m|\,\omega_{oi}^2\,\omega^*}{2\omega_{Bi}\dfrac{G-(b/a)^{|m|}}{(b/a)^{|m|}-(a/b)^{|m|}} - \dfrac{\omega_{oi}^2}{\omega_{Bi}}}} \tag{1.35}$$

Thus, it is apparent that for a given density the oscillationsare stable if

$$G > \left(\frac{b}{a}\right)^{|m|} + \frac{\omega_{oi}^2}{2\omega_{Bi}}\left[\left(\frac{b}{a}\right)^{|m|} - \left(\frac{a}{b}\right)^{|m|}\right] \tag{1.36}$$

$$G < \left(\frac{b}{a}\right)^{|m|} - \frac{2\omega_{oi}^2}{|m|\,\omega_{Bi}\,\omega^*}\left[\left(\frac{b}{a}\right)^{|m|} - \left(\frac{a}{b}\right)^{|m|}\right] \tag{1.37}$$

A more thorough analysis will show that the appearance of the stability region when $G < C$ results from the unreal assumption about the plasma density distribution. Therefore the stabilization condition considered below will be $G > C$.

If the feedback system operates with a phase shift, that is G is complex, then there is an additional imaginary frequency. If condition (1.36) is satisfied and Im G/Re G<< 1, then the condition for reducing the oscillations has the form

$$\omega \, \mathrm{Im}\, G > 0 \qquad (1.38)$$

Conditions given above were deduced for stability relate to a plasma with sharp boundaries with a perturbation having the form of a surface wave. For a blurred boundary oscillations exist which are localized inside the plasma and insensitive to boundary conditions. However the lowest density thresholds correspond to the large scale modes, that is $|m| = 1$, for $\psi \cong r$ and $r > a$, in which case the stabilization criterion agrees with eq. (1.36) for any radial density distribution $n(r)$

The explicit form of condition (1.38) depends on the structure of the experimental system. In general the following effects give rise to the imaginary part of G:

1. the time of delay in the equipment and cable. For this

$$\mathrm{Im}\, G = \omega \Delta t \, \mathrm{Re}\, G$$

2. the shift in azimuth between the probe and the control electrode. For this $\mathrm{Im}\, G = (\theta_{pr} - \theta_{el}) |m| \, \mathrm{Re}\, G = \Delta\theta |m| \, \mathrm{Re}\, G$

3. the phase shift in the amplifier

$$\mathrm{Im}\, G \approx \frac{\omega^2 - \omega_{cr}^2}{\omega \, \omega_u} \mathrm{Re}\, G$$

Here $\omega_{cr}^2 = \omega_u \omega_l$, where ω_u and ω_l are the upper and lower boundaries of the amplifier band width.

Combining all these phase shifts, eq (1.38) takes the form

$$\omega^2 \Delta t + \omega |m| \Delta\theta + \frac{\omega^2 - \omega_{cr}^2}{\omega_u} > 0 \qquad (1.39)$$

This relation was generalized by Arsenin, Zhiltsov and Chuyanov (1969) for the case of a rotating plasma (with the frequency $\Omega = \frac{c\phi}{a^2 B_0}$, where ϕ is the potential on the azis). The following conditions was obtained instead (1.39)

$$\omega(\omega + \Omega)\Delta t + (\omega + \Omega)|m| \Delta\theta + \frac{(\omega^2 - \omega_{cr}^2)(\omega + \Omega)}{\omega \, \omega_u} > 0 \qquad (1.40)$$

This relation is qualitatively with the experiment in agreement (Arsenin, Zhiltsov, Chuyanov, 1969).

Chuyanov (1970) studied the feedback stabilization of the flute instability of a plasma with the aid of controlled electron beams. The electron beam intensity was modified in accordance with the fluctuations of the potential on the corresponding field line. A cold plasma with density variations perpendicular to the magnetic field lines was considered. A similar problem was considered by Arsenin (1970). He studied the possibility of the suppression of flute instability of a collisionless plasma cylinder in a simple mirror field using feedback-electron source intensity proportional to perturbation. In an other paper of Arsenin (1969) the possibility to control the perturbations outside the plasma and to mix two spatial modes, which can be excited independently in a free plasma is considered. An other method for feedback stabilization is proposed by Arsenin and Chuyanov (1976). They use the"natural"flow of charged particles in the neighborhood of the probes, which is connected with the collisional loses at the probes, to stabilize the plasma. They formulate the dispersion relation and the condition for the variation of the potential at the surface of the probe. The influence of the number of control electrodes on the stabilization of the flute instability is studied by Arsenin, Dement'eva and Kostomarov (1971). They considered a plasma cylinder with ion and electron densities constant over the cross section, placed in an external uniform magnetic field. Weak field inhomogeneties are simulated by a radial gravity causing an azimuthal ion drift. A dispersion relation is derived for the flute oscillations in the presence of the feedback. Stabilization is shown to be possible up to concentrations higher than the instability threshold for the mode $|m| = 1$ in the absence of feedback, but lower than the threshold for the mode $|m| = 2$. An analysies of the influence of the finite size of the enforcer electrodes on the feedback control of the plasma flutes was made by Crowley (1971). The experiments, related by Zhiltsov, Likhtenshtejn, Panov, Kosarev, Chuyanov and Shcherbakov (1975) showed, that the nonlinear effects (drop in the phase velocities of unstable waves and the reduction of the interaction with the confined fast ions) are essential in stabilization. It was also proposed, to replace cond. (1.34) with a dependence of the form [illegible] .

1.3. Rayleigh-Taylor instability

Melcher and Warren (1966) studied the feedback control of a Rayleigh -

Taylor instability in the case of a highly conducting interface stressed by a perpendicular electric field. The interface can be instable either because of gravity or the electric field. The theoretical calculations were made using the electromechanical fluid equations. The eigenfunctions and conditions of stability were determined. A proportional potential was fed back to the segmented electrode which imposed the quiscent electric field.

A theoretical description of the feedback stabilization of flute instability in a gravitational field is given by Arsenin and Chuyanov (1968+) in the case, when the boundary potential is controlled by signals derived from perturbations in the continuum. In the calculations boundary conditions where used, which considered the existence of the feedback. The authors introduced a corresponding gain function of the feedback and determined the conditions for the feedback gain and for the phase shift.

1.4 Feedback stabilization of hydromagnetic continua

In the case of the MHD - instabilities of a plasma coluumn the possibility appears to use a feedback method based on controlling the magnetic field outside the plasma. Such a control is automatically realized by the tokamak experiments, since the copper shell is a highly satisfactory feedback control device. For a certain extension of the tokamak operations it is, however, convenient to remove the copper shell. External feedback of the equilibrium position is then a natural substitute. Such possibilities to stabilize the MHD modes were studied by Pavlovskiy and Samoilenko (1967); Arsenin and Chuyanov (1968); Arsenin (1970+); Selezov (1970); Furth and Rutherford (1970); Melcher (1970); Millner and Parker (1970); Clark and Dory (1970); Ribe and Rosenbluth (1970); Wang (1970); Arsenin (1972); Lowder and Thomassen (1973); Hugill (1974) and Keller. Pochelon and Bachmann (1975, 1976).

Pavlovskiy and Samoilenko (1967) studied the possibility to realize distributed control systems for feedback plasma stabilization. They considered the case of a conducting shell, for example for a plasma column, a cylinder of high conductivity material, which supports a h.f. current shifted by 180^{0} with respect to a current of equal amplitude flowing in the plasma.

The long wave length kink instability was treated as an example and the stability criterion was formulated. Arsenin and Chuyanov (1968) studied the feedback stabilization of an incompressible, perfectly conducting current carrying plasma current. Arsenin (1970+) considers the case of the helical modes of the MHD instability of a current carrying plasma filament by means of a feedback system and formulates the stability conditions.

Selezov (1970) considers a system, where an infinite MHD-flow is separated from a nonconducting medium at rest by an elastic plate of constant thickness and infinite size. It is shown, that at a certain critical velocity of the flow unstable traveling waves will be excited in the system. It is shown that the introduction of a controlling magnetic field may improve the stability of the system, i.e., raise the critical velocity Melcher (1970) describes three types of analytical models: piecewise continuous, discrete coupled modes and coupled wavetrains. The corresponding experimental arangements are given in the paper. The specific stability regimes for m = 1 modes are determined. A discussion of difficulties in stabilizing interchange modes is given and a nonlinear form of the feedback obviating these difficulties is suggested. This nonlinear feedback is studied by Millner and Parker (1970). A constant corrective force of arbitary strength is applied to the plasma for such a time, as the local average of the surface displacement is positive. The authors show that linear feedback can not stabilize modes for which the perturbation amplitude is constant along the lines of the external magnetic field. The nonlinear stabilization is studied using an energy principle.

The Kruskal-Shafranov modes of a cylindrical plasma are examined by Clarke and Dory (1970) with respect to possible active feedback stabilization. They show that this method is possible in principle, but presents great practical difficulties. Similar results were obtained by Furth and Rutherford (1970) for the tokamaks. They show that the interchange instabilities, against which linear magnetic feedback is ineffective, are fortunately stabilized by the minimum-average-B- property of the tokamak. A possibility for feedback stabilization of a high-β sharp- bounded plasma column with helical fields was described by Ribe and Rosenbluth (1970). Wang (1970) studies the feedback stabilization of suface instabilities. An explicit form of feedback for linear pinch with uniform axial static magnetic field is given. Linearized MHD-equations were used. Stability diagrams for m = 0,1,2 modes are given. A detailed theoretical analysis of the suppression of screw hydrodynamic instability of current carrying plasma column by feedback systems is given by Arsenin

(1972). The influence of different currents in the metallic shell on the stability of plasma column was exanined. It was proposed to use currents in external conductors to produce at the plasma surface an additional magnetic pressure proportional to the displacement of the boundary which would cause the boundary to the equilibrium position. The stabilization conditions are formulated for different current distributions in the plasma column and in the stabilizing system. It was assumed that the longwavelength ($|k|a \ll 1$) radial perturbations have the form

$$\xi_r = \xi_{m,k}(t)\left(\frac{r}{a}\right)^{|m|-1}\exp(im\theta - ikz)$$

and satisfy the linearized MHD-equation

$$\ddot{\xi}_{m,r} - \Omega^2\left[\frac{2m}{|m|}\alpha(\alpha m - kah_i)\cdot(\alpha m - kah_i)^2 + h_i(1-\alpha^2)\cdot\chi(m - kah_e)^2\right]\xi_{m,k} = 0 \qquad (1.41)$$

where $\Omega = \frac{B_I}{\sqrt{4\pi\rho}\,a}$; ρ is the density of the plasma; a the radius of the plasma column; $B_I = \frac{2I}{ca}$; I is the total axial current, α denotes the part of the axial current, which is uniformly distributed over the cross section; $h_i B_I$ is the magnetic field intensity in the plasma; $h_e B_e$ the magnetic field between the plasma and the metallic shell and $\chi = -\frac{|m|}{a}\frac{\psi}{\partial\psi/\partial r}\Big|_{r=a}$; where ψ is the potential of the magnetic field of the perturbation outside de plasma $(\vec{B}_{ext} = \nabla\psi)$. The quantity χ is determined by the boundary conditions at the jacket at $r = b$, and therefore he depends from the used feedback system connected to the jacket.

It can have the form

$$\chi \sim (m - kah_e)^{-1} \qquad (1.42)$$

discussed by Morozov and Solov'ev (1964), or

$$\chi \sim (m - kah_e) \qquad (1.43)$$

described by Arsenin and Chuyanov (1968), or

$$\chi = \mathrm{const} \qquad (1.44)$$

used by Arsenin (1970+).

Studying the plasma column with distributed current ($\alpha = 1$, $h_i = h_e$) and the case of surface currents ($\alpha = 0$) Arsenin (1972) analises different possibilities to choose the function χ and deduces the corresponding conditions for stability. He confirmes, that there are possibile feed-back systems, which extend the domains of stability and formulates the corresponding stability conditions. A more general theoretical treatment of the feedback stabilization of the m = 2 and m = 3 MHD instabilities has been given by Lowder and Thomassen (1973) and complected by Hugill (1974). The possibility to stabilize the MHD m = 1 mode with a feedback system was confirmed experimentally.

1.5 Cyclotron oscillations

A special feedback radiosystem controlled by perturbed fields outside the plasma was proposed by Arsenin (1968) to damp the cyclotron oscillations. The method is described theoretically for a plasma cylinder in a metallic tube. The conditions for stabilization were determined. The method was verified experimentally in OGRA II experiments.

In another paper Arsenin (1970) studied the cyclotron waves in a rarefied plasma sorounded by a surface of finite conductivity or a surface with potential controlled feedback. He shows that such a surface can have a stabilizing effect. The conditions for feedback stabilization with a control of the fields outside the plasma are also formulated.
Kitao (1971) studied the feedback stabilization of density-gradient-driven drift-cyclotron instabilities by the use of a feedback source term in the Vlasov equation, assuming the discrete control probe to be a distributed source. The conditions for feedback stabilization were determined. It was shown, that optimal stabilization is possible by a phase shift from 0^{0} to 90^{0}.

1.6 Drift waves

Furth and Rutherford (1969) present theory of the stabilization of drift waves by modulated electron sources. The dispersion relation was deduced and discussed for the strongly collisional and the weakly collisional case and conditions for stabilization of drift waves were given. A theoretical study of the feedback stabilization of the finite amplitude density gradient drift wave in the Q-machines was made by Blau and Wong (1969). They show, that the time derivative of the perturbation intensity can be expressed as a unique function F (I) of the intensity itself, so that time no longer appears explicitely. The coefficients of the polynomial approximation of F (I) are measured experimentally and related to the growth and nonlinear saturation rates of drift instabilities.

1.7 Mulitmode two-stream instability

Chervin and Sen (1973) used a three-fluid theory for the study of the feedback stabilization of a multimode two-stream instability in a finite one-dimensional plasma. They considered a model which corresponds to a three stream plasma (with one static stream). They formulate the dispersion relation and the stability condition in the presence of the feedback. Two different feedback schemes are studied: a boundary control feedback scheme, with the creation of an electric field at the boundary, using a dependence of the detected electric field in th form

$$E(\omega, x=0) - E(\omega, x=L) = G(\omega)E\left(\omega, x=\frac{L}{2}\right) \tag{1.45}$$

and an internal feedback scheme, creating in the interior of the plasma an electric charge density of

$$\rho = -e\,k\,n(t, x) \tag{1.46}$$

The most promising feedback schemes involve sensing the total density perturbation and feeding back an appropriate charge. It is shown that by proper choice of feedback parameters in a single feedback loop, all unstable modes can be stabilized without destabilizing any modes which were previously stable.

1.8 Mikroinstabilities

Clarke (1969) studies the feedback stabilization of microinstabilities of mirror machins by feedback. He shows, that in agreement with the DCX - 2 experiments a coupling appears between a gyrofrequency instability and a normally stable ∇B drift wave. This coupling produces a new instability near the drift frequency and can lead to cross-field particle transport. This effect should occur in minimum - B geometries. The calculations were made in drift approximation using a parabolic model for the ion density and the dispersion relation was formulated.

1.9 Suppression of dissioative trapped-particle instabilities by neutral beam injection.

In a recent paper Sen and Sundaram (1976) studied the possibility of feedback suppression of trapped-particle instabilities of the magnetic type by modulated neutral-beam injection. The neutral beam acted both as a particle source and a momentum source. The main conclusions of the theoretical analysis can be summarized as follows:

The authors find that the dissipative trapped-ion instability can be

suppressed by a positive feedback at 180^0 phase with marginal gain $\sim \varepsilon^2 \omega_e^{*2}/\nu_e (1+R_T)^2$, where is the ratio of minor to major radius (inverse aspect ratio) ($= r/R$), ν_e stands for electron collision frequency, $R_T = T_e/T_i$ and $\omega_e^* = \frac{n q c T_e}{e B_\theta r} \frac{1}{n_e} \frac{dn_e}{dr}$.
(Here we used the notations, q for the safety factor ($= 2\pi/\iota(r)$), $\iota(r)$ the rotational transform angle, n the mode number to the toroidal direction, n_e the plasma density. Similarly the trapped-electron instability (for both limits $\omega_e^* <$ or $> \nu_e/\varepsilon$) can be quenched by negative feedback with zero phase and marginal gains of ν/ε or $\varepsilon \omega_e^{*2}/\nu_e$ according to wether $\omega_e^* <$ or $> \nu/\varepsilon$. We notice that both of these dessipative instabilities can be elimiminated simultaneously by negative feedback at -90^0 phase shift and a gain higher than the maximum thresholds.

The basic stabilization mechanismus appear to be density smoothing and deenergization of waves. Physically these mechanismus can be interpreted as follows: In the former case, the growing flute-type density perturbations are smoothed out by the replenishment of neutral-beam-injected plasma while, in the latter situation, the momentum of the neutral beam exerts pressure on the region where plasma is moving out rapidly and hence it de-energizes the growing waves. However the latter mechanismus is less effective in systems where the natural growth are large ($\gamma \sim \omega$).

2. Experiments on feedback stabilization

In the earliest feedback experiment reported Arsenin, Zhiltsov, Likhtenshtein and Chuyanov (1968) They stabilized the ion-cyclotron instability (a long symmetric mode). The antisymmetric mode has been also stabilized later by Zhiltsov, Likhtenshtein and Panov (1970). Church, Chuyanov, Murphy, Petravic, Sweetman and Thompson (1969) reported about the Phoenix II experiments on feedback stabilization of ion cyclotron instabilities. Two methods were used: microwave heating and transit time heating. In the first case the second and third harmonics could be suppressed, in the second case the first three harmonics could completely be quenched. Experiments on stabilization of flute instability were also made by Church et al. It has been shown that stabilization of the flute instability can be effective at densities of 10^9 cm^{-3}. Other experiments show a contrary effect. Kretschmer, Boeschoten and Demeter (1968) showed that the Alfven and ion cyclotron waves are made unstable in a hollow cathode arc of density $n_e \sim 10^{14}\,cm^{-3}$ by a feedback mechanism which is associated with electron flow across the anode sheath and the azimuthal magnetic field produced by the arc current. Experiments on stabilization of electron-cyclotron waves were reported by Haste (1970).

The theory on feedback stabilization of electrostatic instabilities seems to be supported by the experimental results. The dissipative type of instability seems to be relatively easily stabilized by a small amount of feedback over a wide range of phase. It has been shown in a series of experiments done by Keen and Aldridge (1969); Simonen, Chu and Hendel (1969); Parker and Thomassen (1969); Hendel, Chu, Perkins and Simonen (1970); Keen (1970); Wong, Baker and Booth (1970), Lindgran and Birdsall (1970) Hendel and Chu (1973) and Keen and Stott (1973). Most of these experiments study the dissipative drift instabilities, whereas the stabilization of the reactive type demand for agreement with theory [eq. (1.15) or eq. (1.22)] severe restrictions on the phase of the feedback. Stabilization of such instabilities is reported by Chuyanov and Murphy (1972) in the OGRA - II and PHOENIX - II. The effects of the feedback system on plasma losses coused by the flute instability has been studied and a correlation between plasma losses and the amplitude and frequency of the instability has been obtained. It was concluded that plasma losses can be controlled, to certain extent, by a simple feedback system. The experiments show the dependence of the flute instability threshold on the gain for a fixed probe position and also on the probe position for a fixed gain. The threshold is seen to rise with increasing gain and the optimum position of the probe coinsides with the maximum gradient of the density.

Mase and Tsukishima (1972) reported about the experimental results of the feedback control of an electrostatic wave which is self-excited in a mercury positive column. The experiments were made with a 5 cm diameter and 60 cm long glass discharge tube. The plasma parameters were $n_e = 1.4 \times 10^{16}\,cm^{-3}$ and $T_e = 3\,eV$. An external feedback was used succesfully. The theoretical treatment is given by the authors in an other paper (Tukishima, Mas 1972). They investigate first the structure of the internal feedback in a homogeneous plasma and show that it can be represented by a diagram similar to that of electronic feedback amplifier. The possibility of application of the proposed theory on the external feedback is described. There is a good agreement

with the experiment.
Experiments on stabilization of the flute instability were first reported by Arsenin, Zhiltsov and Chuyanov (1968) on OGRA-II operating as a simple mirror. These results were extended by Chuyanov (1969) on Phoenix II at higher densities. The potential at the edge of the plasma was detected, amplified and delayed, and fed back with a corresponding phase to the control electrodes. The control of the flute instabilities gave the possibility to increase the densities by a factor of 3-4,5.
Zhiltsov, Likhtenshtejn, Panov, Kosarev, Chuyanov, Shcherbakov (1975) reported about the use of multi-element feedback system by the stabilization of the unstable hydrodynamic flute oscillations in the OGRA III. An electrostatic, 12-electrode feedback system was created to stabilize the flute instability. It suppresses the lower space modes of this instability. By using it the authors were able to raise the threshold density of the onset of less 10-fold and observe excitation and stabilitation of the higher modes of the flute instability. Three branches of flute oscillations were detected and their change under the influence of feedback was studied.
In a comprehensive review on the problems related to plasma confinement in adiabatic trapes Ioffe and Kadomtsev (1971) describe the possibilities of feedback stabilization of flute instability. Experiments with OGRA- I, Alice and Phoenix are reported.

Prater (1971) showed experimentally that a flute instability which travels in the plasma in the direction of the ∇B drift can be stabilized in a magnetic mirror with a pair of suppressor electrodes mounted outsides of the mirror.
Zrnič and Hendricks (1970) report on experiments concerning the stabilization of the Rayleigh-Taylor instability by a two-station a.c. magnetic feedback system. In another paper Zrnič , Hendricks and Crowley (1970) studied a simple model of Rayleigh-Taylor instability on a fluid pendulum and its stabilization under the influence of magnetic fields with and without feedback. An experiment is described which was performed in order to study the possibilities of stabilizing the first sinusoidal mode of a one-dimensional Rayleigh-Taylor instability. The experimental results are supported the MHD theory.
An $l = 0$ MHD feedback experiment to control the $m = 1$ instability on a plasma column subject to $l = 1$ helical fields is being under-

taken by Gribble, Burnett and Harder (1972) (Scylla-IV-3-experiments). Brown et al. (1971) reported experiments carried out with a device called COMPLEX in which a current-free magnetized plasma could be produced, with independently variable density and electron temperature. The plasma density fluctuations could be significantly reduced with the help of a feedback control system, which was connected with the plasma upstream and downstream photomultipliers and the Langmuir probe.

Keller, Pochelon and Bachmann (1975, 1975$^+$, 1976) obtained a suppression of the m = 1 growing mode of a screw pinch by feedback stabilization. The transverse field produced by l = 1 windings was automatically controlled by the magnetically detected plasma motion, in order to create a restoring force for both displacement coordinates. A theoretical analysis of different control methods is given by Keller (1973). He describes the possibilities of optical and magnetic detection and the possible coupling between the probe and the feedback control windings. Two different schemas of the possible experimental systems are given. Experiments on the suppression of m = 1 modes using HCN laser to probe the interior of the plasma are reported by Chen, Jassby and Marhic (1972).

Succesful results were recently reported about feedback stabilization of the up/down position of the plasma in tokamaks. Stable tokamak discharges could be achieved with an aspect ratio lower than 2,5 and a safety factor at the adge equal to 4 at the Erasmus tokamak of the École Royale Militaire - Brussels (Bhatnagar, Bosia, Messiaen, Paithankar, Piret, Vandenplas, Weynants 1976). Similar results were reported concerning the experiments on JIPP T -II (hybrid stellarator-tokamak system) from Fujita, Fujiwara, Hamada, Itoh, Kadota, Kawahata, Kuroda,Matsuoka, Matsuura, Miyahara, Miyamoto, Ohkubo, Tananashi, Terashima and Toi (1976). Experiments on feedback control of the plasma position in resistive shell configuration were carried out. The vertical magnetic field was feedback-controlled and the horizontal one was preprogrammed. A stable tokamak plasma could be successfully obtained by feedback control of the vertical magnetic field if the vertical displacement of plasma ring is suppressed within a certain value by the pre - programmed horizontal field. The safety factor was kept larger than 3. It was realized a current duration in the plasma twenty times

as large as the skin time of the resistive shell.
Collisionless drift waves have been explored extensively on Q-machines by Hendel, Chu and Politzer (1968); Rowberg and Wong (1970) and Wong, Baker and Booth (1970) and the possibility to reach stability was shown. The results are summarized by Thomassen (1971). It is shown, that in any case with increasing gain an unstable $m = 2$ mode was suppressed, while an $m = 1$ mode was destabilized. But there are experimental possibilities permitting suppression of the $m = 2$ without exciting the $m = 1$ mode. Lindgren and Birdsall (1970) simultaneously suppressed the $M = 2,3$ and 4 modes of the collisionless dirft instability using frequency filters on the pickup probes to achieve three independent feedback loops.
A great variety of experimental arangements were used by several authors. One of the more interesting coupling schemes used for the drift instability, has been reported independently by Hendel, Chu, Perkins and Simonen (1970) and Wong, Baker and Booth (1970, 1970^{+}). It consists of a microwave source, tuned to the upper hybrid frequency and modulated by the drift wave to be suppressed. On transmitting the modulated wave into a region of the plasma of increasing density there is complet absorption of the wave at the upper hybrid. This gives a possibility to apply an efficient method of interaction with ion modes without probes, by means of collisionless coupling between resonant electron modes. The collisionless nature of the nonlinear interaction between electron and ion modes is emphasized leading to the feasibility of feedback stabilization in hot collisionless fusion plasmas. (Wong, Baker and Booth 1970^{+}). A similar effect appers in the presence of collisions too. (Hendel, Chu, Perkins, Simonen 1970). A beam modulation was used to suppress the electron plasma waves and the acoustical waves by Tsuru, Itakura and Kojina (1973). A basically different method was used by Chen and Furth (1969). They use neutral-beam injection to provide feedback controlled volume sources of particle and momentum density. The perturbations were sensed by optical or microwave beams.
As a simple illustration the stabilization of resistive drift waves was discussed. A possibility to use the proposed method for the feedback stabilization of trapped particle instabilities was studied by Sundaram and Sen (1975).
Feedback stabilization of drift oscillations in plasmas with higher

densities than tose obtainable in OGRA-II are reported by Taylor and Lashmore Davies (1970).

Keen and Aldridge (1969^{+}) report on their experiments on suppression of drift type instabilities. The experiments were performed with an argon hollow-cathode arc discharge with $T_e \sim 5\,eV$, $n \sim 10^{15}\,m^{-3}$, axial field $\sim 1\,kG$. The instability frequencies were in most cases between 5 and 8 k Hz, the axial wavelengths were longer than the apparatus, the azimuthal mode number was m = 1. Ion density fluctuations were detected by means of an ion biased probe. The feedback loop consisted of a wideband amplifier with variable gain, a phase-shifter capable of phase shift up to 450^{o}, and a system of power amplifiers and similar phase shifters so that power could be applied to up to four plate electrodes arranged at the edge of the plasma. Stabilization was best, when only one plate was used and consequently a mixture of modes was applied to the plasma.

Kitakawa and Tanaka (1971) report on the feedback control of collisional drift instability by a modulated microwave source.

Keen and Fletcher (1970) stabilized an ion-sound wave using an electron cyclotron resonant structure to heat locally the electrons and to modulate the electron temperature. Light fluctuations picked up with a photodiode were amplified and fed to the structure. Similar waves were observed at the Innsbruck-Q-machine and stabilized (Sandu, Rasmussen, Schrittwieser 1977) Edge oscillations in a Q-machine have been suppressed by Mueller, Corbin and Palmer (1970) and by Chu, Hendel, Jasby and Simonen (1970). Ionization waves were controlled by Garscadden and Bletzinger (1970) and ballooning-type drift modes (see Cap 1976) were suppressed in a toroidal stellarator by Hartman, Henden and Munger (1970) Kelvin Helmholtz instabilities were stabilized by Hendel and Chu (1970). In departure from the usual active feedback system Lindman (1970) has proposed a passiv wall instabilized scheme, and an experiment by Carlyle (1970) lends support to the idea.

A possibility to control the operating temperature of a steady-state fusion reactor using feedback stabilization method by means of injection rate of fuel injection energy and radiation loss is investigated by Ohta, Yamato and Mori (1971). The feedback stabilization methods can be applied to the semiconductors too. Corresponding experiments were reported by Anker-Johnson, Fossum and Wong (1970).

3. Nonlinear interpretation of the feedback stabilization.

In an experiment on a hollow cathode arc, Keen and Aldridge (1969) stabilized "drift-like" waves. To explain the results Keen (1970) used the fact that a number of plasma instabilities behave in a manner described by the classical Van der Pol oscilator:

$$\frac{d^2 n_1}{dt^2} - (\alpha - 3\beta n_1^2)\frac{dn_1}{dt} + \omega_0^2 n_1 + G\,\omega_0^2\, n_1(\tau) = 0 \qquad (3.1)$$

This equation contains the last term $G\omega_0^2 n_1(\tau)$ which describes the feedback and depends on the delay time τ (related with the phase shift). A detailed analysis of this theoretical model was made in connection to the feedback stabilization of the ion-sound instability (Keen 1970+). The connection with the dynamic stabilization was studied in an other paper by Keen and Fletcher (1969).

Successful experiments on feedback stabilization of collisional drift waves in various gaseous plasmas $(n \sim 10^{11} - 10^{12}\,cm^{-3}, T_e \sim 5\,eV)$ have been performed by Keen and Stott (1973). The results have been interpreted on the basis of eq. (3.1). The predicted variation of the instability amplitude and its frequency as a function of the gain and phase angle are in agreement with the experiments.

In order to show that the ion sound instability can be stabilized by a remote feedback technique, Keen and Fletcher (1971) carried out theoretical as well as experimental investigations. In the latter a remote source of energy at the electron cyclotron resonance frequency was used to suppress the instability. The low frequency instability was sensed remotely by a photodiode detector or an electrostatic probe outside the glass vessel; the signal which was proportional to the density or potential fluctuations, was fed back to modulate the energy source. This modulated source caused local heating of the plasma electrons where by the electron temperature was modulated. If it was of correct amplitude and phase, the feedback signal damped the m=0 ion sound instability which was used to demonstrate the technique. A nonlinear theory was developed in order to show how the amplitude and the frequency of the instability should change as the fractional modulation, the electron temperature, and the phase shift were varied in the feedback loop.

The nonlinear effects in the plasma are supported by many other experiments. E.g. the appearance of beat frequency waves is a consequence of the nonlinear theory (Keen, Fletcher 1969). It is confirmed experimentally by Moresco and Zilli (1976).

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