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PHYSICS OF OPEN TRAPS

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НОВОСИБИРСК

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A B S T R A C T

In the present paper, the basic physical problems determining the fusion prospects of the open traps are considered. Main attention is paid to the possibility of a scalable modelling of the anomalous transverse transport in long solenoids (which are a necessary component of most of the types of open traps), and to the problem of the MHD stability of axisymmetric ambipolar traps. The experimental device for studying the transverse transport in a long solenoid, based on the concept of a gas-dynamic trap, is discribed. Various axisymmetric MHD - stabilizers for ambipolar traps are considered, including the recently suggested stabilizer in the form of a "fat" mirror machine. Such a stabilizer is shown to provide the suppression of large-scale flute perturbations in the framework of a "natural" geometry of open traps.

INTRODUCTION

The chances to create a commercially attractive fusion reactor based on the ambipolar trap (Dimov, Zakaidakov, Kishinevski, 1976; Fowler and Logan, 1977) will be determined by answering to the following main questions:

1. To what an extent is the effective ion collision frequency in the plugs close to a Coulomb one?
2. How large is the anomalous transverse transport (associated, for instance, with a drift turbulence) in a long central cell?
3. Is it possible to find a simpler, in comparison with presently used, configurations of MHD-stabilizers (in particular, axisymmetric ones)?

The first question is the most important one: if the scattering is 10-20 times faster than a Coulomb one, then the power required to sustain plasma in the end cells will become unacceptably high. This question hasn't yet been answered clearly in an experimental way: the plasma parameters in the present-day devices are such that the charge exchange losses and/or the ion deceleration by an electron drag are usually dominant. Unfortunately, to predict the behaviour of a plasma in reactor-scale devices, it's impossible to rely also upon the theoretical results, since at present there is no complete theory of a turbulence excited by the "velocity space" microinstabilities. So, regarding the first question, we have to restrict ourselves by the notice that the situation with the enhanced scattering is at present somewhat uncertain and, to clarify it, we will have probably to wait till the new experimental machines, like MFTF-B, will enter the region of plasma parameters where the Coulomb scattering will be dominant.

As far as the second question is concerned, the recent experiments (Simonen and co-workers, 1985) definitely indicate the existence of a certain anomalous transport. However, it is not quite clear whether the source of losses is some kind of "universal" instabilities connected with the radial gradient of plasma parameters, or the losses are induced by nonaxisymmetric electric fields arising because of the asymmetry of the end cells. For this reason, it would be desirable to set up a special experiment on the study of the transverse transport under the conditions not complicated by the presence of the non-axisymmetric elements in the system. One such possibility is described in the next section, dealing with the so-called gas-dynamic trap (Mirnon,Ryutov;1979).The MHD stability of a plasma in the gas-dynamic trap is provided within a frame of an axisymmetric magnetic configuration, the source of stabilization being a plasma outflowing from the trap. The gas-dynamic trap is of interest also in the respect that it is absolutely insensitive to the velocity-space microinstabilities and for this reason makes a backup for the ambipolar traps in the case if the anomalies in the ion scattering in the end cells will be indeed unacceptably large.

The possible answers to the third of the above formulated questions are discussed in the last section of the paper where the axisymmetric MHD-stabilizers for ambipolar traps are considered[1].

THE DEVICE FOR STUDYING THE TRANSVERSE TRANSPORT IN A LONG SOLENOID

This Section describes the scheme of the experiment directed towards the study of the transverse plasma losses in a long solenoid. The experiment is being prepared at the Novosibirsk Institute of Nuclear Physics under the guidance of Dr. G.V.Roslyakov and is based on the use of a gas-dynamic trap.

General Characteristics of the Gas-Dynamic Trap (GDT)

The GDT is an axisymmetric mirror machine with a high mirror ratio $R \gg 1$ and a length L satisfying the condition

$$L \gtrsim \lambda_{ii} \frac{\ln R}{R} \qquad (1)$$

where λ_{ii} is the ion free path length. Under the condition (1), the plasma lifetime in GDT is determined by a simple gas-dynamic estimate corresponding to the time of gas leakage from a vessel with a small hole:

[1] As the plasma density in the expanders of the ambipolar traps is small, the simple stabilization mechanism working in gas-dynamic trap is unapplicable for them.

$$\tau \sim \frac{RL}{s} \qquad (2)$$

where s is the sound velocity in the plasma. It is important that the estimate (2) is insensitive to the plasma microinstabilities.

One more advantage of the GDT is that it can ensure the MHD plasma stability even for the axisymmetric geometry. This possibility is associated with the fact that, under the condition (2), the plasma density just beyond the mirror throats is about the same as inside the trap. As a consequance, when calculating the buoyancy force exerted to the flute by the surrounding plasma, it is necessary to take into account not only the contribution from the inner part of the trap, which by itself is usually destabilizing, but also the contribution from the expanders, where the field lines have a favorable curvature (Fig. 1), and which is, respectively, stabilizing. In this respect, the GDT differs considerably from the usual short ($L \ll \lambda_{ii}\ln R/R$) mirror trap, in which the plasma density beyond the mirror is low in terms of the parameter L/λ_{ii} as compared with the plasma density inside the trap so that only the inner region of the trap makes a contribution to the stability criterion.

This stabilization mechanism was first discussed by Mirnov and Ryutov (1979, 1980). In order to obtain a qualitative picture of stabilization, they used the criterion derived by Rosenbluth and Longmire (1957) (the version for a plasma with a sharp boundary):

$$\int \frac{dz}{B^2 r} \frac{d^2 r}{dz^2} (p_{\parallel} + p_{\perp}) > 0. \qquad (3)$$

Here $p_{\parallel}$ and $p_{\perp}$ are the density of the longitudinal and transverse momentum flux (with plasma flow included):

$$p_{\parallel} = p + \rho v^2, \quad p_{\perp} = p, \qquad (4)$$

where p, ρ and v are the hydrodynamic pressure, the density and the velocity of the plasma, respectively. The remaining symbols in (3) are as follows: $r = r(z)$ is the distance from the boundary field line to the axis and $B = B(z)$ is the magnetic field strength at the axis (the paraxial approximation is used).

In the region beyond the mirror, the pressure drops rapidly so that one can assume that there

$$p_{\parallel} + p_{\perp} \approx \rho v^2 = q \frac{B}{B_{max}} \cdot v, \qquad (5)$$

where q is the mass flux in the mirror (at $B = B_{max}$), i.e. stabilization is directly related to the plasma flow. The velocity v changes in the expander insignificantly; roughly it may be assumed to be constant. Bearing in mind that, in the paraxial approximation, r is proportional to $1/\sqrt{B}$ we obtain that the contribution to the stability criterion (3) from the expander region is proportional to

$$\int \frac{dz}{\sqrt{B}} \frac{d^2}{dz^2} \frac{1}{\sqrt{B}} \qquad (6)$$

If B decreases rapidly enough in the expander region,

$$B \sim z^{-\alpha}, \quad \alpha > 2 \qquad (7)$$

(z is counted from the mirror), the integral (6) is positive, and the main contribution to it comes from the region of weak magnetic field near the plasma absorber. At sufficiently large expansion rate (defined as B_{max}/B_{ex}) the stabilizing contribution is very large.

The limitations on the maximum expansion rate are connected, first, with the fact that at $\alpha > 2$ and large z's the paraxial approximation is violated and, second, with the fact that the "dynamic pressure" ρv^2 of a plasma flow decreases slower than the magnetic pressure $B^2/8\pi$ and at too large expansion rates becomes larger than $B^2/8\pi$, leading to the "stretching" of the field lines and disappearance of the stabilizing effect. However, calculations made by Nagorny, Ryutov and Stupakov (1984) and Mirnov, Nagorny and Ryutov (1984) show that the stability margin can be made large enough.

Experimental Device

The gas-dynamic trap, because of its axial symmetry, can be a basis of a relatively simple experimental device for studying the anomalous transverse plasma losses in a long solenoid in the conditions where all the obscuring effects caused by the presence of non-axisymmetric elements are absent. The possible parameters of the experiment are listed in Table 1, and the scheme of the experiment is shown in Fig.2.

TABLE 1 Parameters of the Experiment

Initial plasma density	$4 \cdot 10^{13}$ cm^{-3}
Temperature of heated plasma	150 eV
Mirror-to-mirror length	7 m
Plasma radius	11 cm
Expander length	1,8 m
Mirror field	16 T
Mirror ratio	80
Injection energy	20 keV
Trapped injection current	250 A
Duration of the injection pulse	0,25 ms
Density decay time	4 ms
Plasma β in the solenoid	10%

The plasma with the temperature $T \sim 10$ eV and density up to $5 \cdot 10^{13}$ cm^{-3} will be injected from the plasma gun through one of the mirrors, which "opens" during the gun pulse. After that, for 0,25 ms the neutral hydrogen beams with an energy of about 20 keV will be injected. These beams will be decelerated by electrons for about 0,25 ms, thereby transferring the energy to the plasma. The obtained warm plasma will flow out of the system during several milliseconds, simultaneously expanding over the radius (because of the transverse diffusion). This will enable to evaluate the diffusion coefficient in various regimes.

The plasma temperature and density in the device can easily be reduced to 30 eV and 10^{13} cm^{-3} respectively; the magnetic field on the uniform section can be reduced by a factor of two. Since all these changes can be done independently, the basic dimensionless parameters of the system

$$N = \frac{a}{r}, \quad \beta = \frac{8\pi p}{B^2}, \quad \Delta\psi = \frac{r_{ii} L}{a^2} \qquad (8)$$

may be varied in broad intervals.

Open traps (including the gas-dynamic one) are distinguished from the other systems with magnetic confinement by a relatively small value of the parameter N (N = 10÷30 for a mirror reactor, and N = 150÷200 for a reactor-tokamak); in addition, most of the schemes of open traps have a long, L = (100÷500)·a, section of a homogeneous magnetic field. Both circumstances can have strong influence on the excitation of drift instabilities causing the transverse plasma diffusion. The described experimental device offers favourable possibilities of studying the anomalous transport in the long solenoid under the conditions not obscured by the axial asymmetry of the system. First, as the device allows to vary N in the range from 10 to 30, one can pass through the threshold of high-frequency drift instabilities ($N \sim 20$, see Mikhailovskii, 1971). Second, the value of $L/a \sim 50$ is quite sufficient for a complete manifestation of low-frequency drift instabilities. Third, the device makes it possible to pass through the range of the β values from 0 to 40%; this is quite sufficient to clarify a possible role of the finite plasma pressure in the stabilization of drift instabilities. Fourth, a lowering of the temperature down to 40-50 eV and simultaneous increase of N up to 30-40 permits one to analyse an influence of the collisions on low-frequency drift instabilities.

MHD STABILITY OF AXISYMMETRIC AMBIPOLAR TRAPS

In principle, it is known a number of different methods providing the stabilization of flute perturbations in axisymmetric ambipolar traps. Some of them are oriented to the use of purely magneto-hydrodynamic effects, while the others are based on the stabilization methods making use of the finite Larmor radius (FLR) effects or those similar to them. We will start our consideration with the first group of methods.

Magneto-Hydrodynamic Methods of Stabilization

The first MHD-stable axisymmetric mirror trap was suggested by Andreoletti (1963) and Furth (1963). One of its version is demonstrated in Fig. 3 (in combination with the ambipolar trap). In contrast to the conventional mirror machine, where the magnetic field has minimum in the longitudinal direction and maximum in the trasverse one, the Andreoletti-Furth mirror has an absolute minimum of B. The points of the minimum constitute a circle with the centre on the magnetic axis.

The dashed line in Fig. 3 denotes the field line limiting the connecting plasma from the axis' side. This plasma has to provide an electric contact between the plasma of the stabilizer

and that of the plug. Because of the presence of the null of the magnetic field on the stabilizer axis, there is no connecting plasma near the axis of the stabilizer and, hence, the MHD stability in the corresponding region of the plug is provided by a flat (over the radius) profile of pressure.

Unfortunately, the recent numerical calculations have shown that the depth of the magnetic well created by the Andreoletti-Furth stabilizer is very small for realistic geometries. Additional problems are associated with a small thickness of the plasma in the ring cusp: this makes the plasma in this region to be quite susceptible to microinstabilities.

To deepen the magnetic well, G.I.Dimov (1982) has suggested a stabilizer in the form of a cusp (Fig. 4). Near the null of the magnetic field the adiabatic ion confinement breaks down. In order to avoid too fast ion losses from this region, an additional (external) plug is included into the system. It functions well if the plasma density in the vicinity of null is small enough. The admissible rate of density decrease is determined (at a constant ion temperature) by the relation

$$n \sim U^{-5/3} \qquad (9)$$

where

$$U = \int \frac{dl}{B} \qquad (10)$$

(integration is made along the field line between the axial and ring cusps). At the point $B = 0$ the density can thus be several times lower than far from this point. The non-adiabatic losses through the ring cusp are assumed to be also suppressed by ambipolar effects.

A more sophisticated system based on the using of the elements of the cusp is discussed by Logan (1980).

Arsenin (1983) has suggested a stabilizer with the alternating sign of the curvature of the field lines (Fig. 5). There is a hot plasma in the regions A and C of the stabilizer; in region B there is a tenious connecting plasma. The plasma in the stabilizer is hollow. Choosing correctly the pressures in regions A and C, one can achieve a sufficient stability margin of the system as a whole. The disadvantages of the Arsenin stabilizer consist in the necessity to accurately match the parameters of the plasma in different parts of the stabilizer and in a relatively small thickness of the plasma.

The purely MHD stabilization mechanisms can work in the framework of paraxial systems as well, if the population of fast sloshing ions is created in them with the turning points in the region of favourable curvature of the field lines. Such a mechanism of stabilization has been discussed many years ago by Kesner and has been analysed in detail by Hinton and Rosenbluth (1982). Unfortunately, as has been shown in the paper of these two authors, a considerable stabilizing effect apprears only at a small angular width of the distribution function of sloshing ions, and, to provide so small width, a very high injection energy (tens of MeV) is required.

Stabilization Methods Based on FLR Effects

The other methods of stabilization of ambipolar traps are based, to a greater or lesser extent, on the use of the FLR effects or those analogous to them. Timofeev (1979) points out that the inertia of a flute is large because of the large length of the central cell, and the growth rate of flute instability of the system as a whole is small as compared with the frequency of centrifugal and gradient drift of fast ions in the end cells. As a result of the action of the effects similar to the FLR ones (but not identical to them!), not only the high azimuthal modes but also the m = 1 mode are stabilized. The approach suggested by A.V.Timofeev seems to be promising but at present there is no clear idea of the possible role of the negative energy oscillations which can exist in the systems with a fast drift of ions.

In the papers by Arsenin (1979, 1982) only the m = 1 mode is suggested to be stabilized using the MHD methods, while the higher modes are assumed to be stabilized using the FLR effects. One of the possibilities (see Arsenin, 1979) consists in inserting additional winding or a current-carrying rod inside the plasma (Fig. 6); another one is to use the end cells of the shape shown in Fig. 7.

Kesner (1984) has suggested to place a conducting shell near the plasma to achieve the stability of the m = 1 mode (Fig.8). If the plasma is of a finite pressure and its extent along the device axis is small (strong anisotropy), the image currents appear in the shell when the plasma shifts as a whole. An interaction of the plasma currents with the image ones gives rise to the restoring force. However, because the effect is proportional to β^2, it takes place only at high plasma pressure.

Logan (1981) has suggested a stabilizer which is similar to Andreoletti-Furth one but has no absolute minimum B (Fig.9). This stabilizer can serve simultaneously as the thermal barrier. The plasma in the system is hollow. The outer boundary is stabilized by the effect of favourable curvature of the field lines; as for the inner boundary, the population of hot electrons is assumed to be created on the inner field lines to stabilize it (see Fig. 9). The hot electrons should act in the same manner as the fast electrons in EBT. One more possibility of stabilizing the inner boundary is to cause the central cell plasma in the vicinity of the inner boundary to rotate slowly. In this case, because of an outward growth of density, the centrifugal stabilizing effect occurs (Panasyuk, Tsel'nik; 1975), which is proportional to the length of the central cell. If the central cell is long, the required rate of rotation might be low.

A certain disadvantage of the systems shown in Figs.6 and 9 is a relatively small thickness of the plasma in the ring cusp region and the presence of a "hole" in the plasma.

Stabilizer in the Form of a "Fat" Mirror Machine

One more scheme of the stabilizer has recently been suggested by Ryutov and Stupakov (1985). The scheme has two advantages: first, it is based on the "traditional" geometry of the open traps, without the elements of the cusp; second, the plasma in it doesn't have to be hollow. The stabilizer is a "fat" nonparaxial mirror machine, i.e. the mirror machine in which the transverse plasma size is comparable with the mirror-to-mirror length.

To have an idea of the potentialities of a "fat" stabilizer, we consider a simple model in which: i) the plasma in the end cell is assumed to be an isotropic gas with the specific heat ratio $\gamma = 5/3$, and, ii) the mirror ratio in the stabilizer is assumed to be very large (this allows the parameters of the plasma in the stabilizer and in the central cell to be regarded as independent of each other). Let's first consider how such a stabilizer affects the global m = 1 mode, assuming that the flute oscillations with $m \geq 2$ are stabilized by the FLR effect in a long central cell.

Let us find now the perturbation of the potential energy in the end cell for a global flute displacement. According to the said above, we will assume that the structure of the eigenfunction, determining the plasma displacement, is given by the requirement of elimination of the FLR effects in the long central cell. This requirement corresponds to the perturbation of the potential of the form

$$\psi = \text{const} \sqrt{\Phi} \cos\varphi \qquad (11)$$

where Φ is the magnetic flux inside a given magnetic surface and φ is the azimuthal angle. With the displacement caused by the perturbation (11),

$$\vec{\xi}_\perp = \text{const} \frac{[\vec{B}, \nabla\psi]}{B^2}, \qquad (12)$$

substituted into the standard expression for the potential energy (see, e.g., Mikhailovskii, 1971), we obtain

$$\delta W = A \int \Phi \left[\frac{dp}{d\Phi} \frac{dU}{d\Phi} + \gamma \frac{p}{U} \left(\frac{dU}{d\Phi} \right)^2 \right] d\Phi \qquad (13)$$

where U is determined by the formula (10) in which the integration should be performed between the mirrors, and $A > 0$ is a normalization constant insignificant for further analysis.

If the transverse size of the plasma is small in comparison with the characteristic scale of the magnetic field variation, the second term in the square brackets may be neglected and the plasma proves to be unstable in a universal way, regardless to the pressure profile $p(\Phi)$. The last term, playing a stabilizing role, becomes substantial on the distances from the axis, which are comparable with the length of the end cell.

Any radial pressure distribution may be composed of the delta-functions of the form

$$p = p_0(\Phi_0)\delta(\Phi - \Phi_0) \qquad (14)$$

Since the expression (13) is linear with respect to p, to prove the existence the stable pressure profiles it is sufficient to verify that $\delta W > 0$ at least at one position of the pressure peak of the form (14). Substituting eq.(14) into eq.(13) and integrating by parts in the first term of (13), we find

$$\delta W = Ap_0 \left[\gamma \frac{\Phi}{U} \cdot \left(\frac{dU}{d\Phi} \right)^2 - \frac{d}{d\Phi} \left(\Phi \cdot \frac{dU}{d\Phi} \right) \right] \equiv Ap_0 F(\Phi) .$$

At small Φ, as $dU/d\Phi$ is positive, the function $F(\Phi)$ is negative. At large Φ the confinement region is usually limited by a separatrix passing through the zero point (zero points) of the magnetic field (as an illustration, Fig.10 shows the field lines of the magnetic field obtained by the superposition of the field of two point-like mirror coils located at points A and B and the longitudinal uniform field whose intensity is equal to 6% of the field intensity of two point-like coils at point O). One can show that the function $F(\Phi)$ is also negative (tends to $-\infty$) at the outer boundary of the confinement region, at $\Phi \to \Phi_s$ where Φ_s is the magnetic flux inside the separatrix. Thus, stable states can exist only at intermediate values of Φ, in some annular region. It is interesting that if such a region ("stability ring") exists, then any pressure distribution inside it is stable with respect to the global mode.

For the magnetic field shown in Fig.10, the plot of the function $F(\Phi)$ is presented in Fig. 11a. As is seen from the Fig.11a the "stability ring", indeed, exists in this case. The plots of the functions $U(\Phi)$ and $B_0(\Phi)$ (B_0 is the field in the equatorial plane of the stabilizer) are illustrated in Fig. 11b.

Producing the plasma in the "stability ring", we shall provide a certain margin of the MHD stability allowing some amount of the plasma to be placed in the paraxial region of the stabilizer as well. For the magnetic configuration depicted in Fig.10, the numerical calculations (made by I.A.Kotelnikov) show that for the distributions of the pressure of the form

$$p = p_a \cdot \begin{cases} (U/U_a)^{-\nu} & \Phi < \Phi^* \\ 0, & \Phi > \Phi^* \end{cases}$$

where Φ^* is the magnetic flux corresponding to the outer boundary of the stability ring and the index "a" is referred to the values of p and U on the magnetic axis, the stability occurs at $\nu < 0.87$ (the limiting pressure profile corresponding to $\nu = 0.87$ is demonstrated in Fig. 11b).

Thus, the most dangerous "global" mode of flute oscillations in an ambipolar trap can be stabilized using simple axisymmetric end cells; acceptable are the pressure profiles with a maximum on the axis.

The fact that the function $F(\Phi)$ attains positive (corresponding to the stability) values in the "stability ring" raises hope for that in the system under consideration not only the global mode $m = 1$, $n = 0$ (n is the number of a radial normal mode) but also a few next modes of flute oscillations can be stabilized. To elucidate this question, one should consider the equation for the eigenfunction $\psi(\Phi)$. For an ambipolar trap with a long central solenoid, this equation has the form

$$\frac{1}{\rho_c}(\rho_c \Phi \psi')' - \frac{m^2\psi}{4} - \frac{m^2B^2}{2\omega^2\rho_c L_c}\psi\cdot\left(\frac{\gamma}{U}U'^2p+U'p'\right)=0 \qquad (15)$$

Here and below the dash indicates the differentiation with respect to Φ, and ω is the frequency of oscillations. When deriving this equation, the central solenoid (its length is denoted by L_c, the magnetic field intensity and the plasma density on the uniform section by B_c and ρ_c, respectively) is assumed to give a main contribution to the inertia of the flute, while the "fat" stabilizers - to the driving force (so that U should be calculated only for the stabilizers).

Assuming, for simplicity, that ρ_c = const and making the substitution $\chi = \psi/\sqrt{\Phi}$, it is possible to reduce Eq.(15) to the Schroedinger equation

$$\chi'' - V(\Phi)\chi = 0 \qquad (16)$$

(corresponding to the energy $E = 0$), in which the "potential energy" $V(\Phi)$ is determined by the formula

$$V(\Phi) = \frac{m^2-1}{4\Phi^2} - \frac{m^2B^2}{2\omega^2\rho_c L_c}\left(\frac{\gamma}{U}U'^2p + U'p'\right) \qquad (17)$$

The eigenfrequencies are found from the condition of successive appearance of the zero-energy levels in the potential (17) dependent on the frequency ω as on the parameter.

If the special measures on the creation of the "stability ring" are taken, then the instability of the global mode occurs; the characteristic instability growth rate can be estimated, by the order of magnetude, from the relation

$$\omega^2 \sim -\Gamma^2 = \frac{p_s}{L_s L_c \rho_c}$$

where L_s and p_s are the length of the stabilizer and the characteristic pressure in it, respectively. In this case, for the smoothly decreasing pressure profile (Fig. 12a), the potential energy $V(\Phi)$ has a broad and deep negative minimum (Fig. 12b). At $|\omega| \sim \Gamma$ the potential well of this shape "comprises" not only the solenoid for $m = 1$, $n = 0$ but also the solutions for $m = 1$, $n \neq 0$, i.e. a lot of modes are unstable simultaneously with a growth rate $\sim\Gamma$.

If there is the strongly expressed "stability ring" in the system, i.e. in the expression for $V(\Phi)$ the term $\gamma U'^2p/U$ is considerably larger than the term $U'p'$ everywhere, except the narrow region near the point of vanishing p, then the minimum of $V(\Phi)$ becomes narrow and shallow (Fig. 12c). In such a potential well there are no levels with $E = 0$ at $|\omega| \sim \Gamma$ and $m = 1$. For the levels to appear, one should reduce $|\omega|$ to the values $\sim\Gamma\Delta/L_s$, where $\Delta \ll L_s$ is the width of the potential well, or to increase m to the values $\sim\Delta/L_s$. In this case, the depth of the potential well near the point of vanishing p becomes sufficient for the appearance of a level with $E = 0$ in it. The characteristic space scale of the appropriate eigenfunction is Δ, the preturbations decreasing exponentially towards the axis of the system.

Thus, we conclude that in the non-paraxial mirror only the flute instabilities whose scale is small in comparison with plasma radius and which are localized near the outer plasma boundary, remain unstable if the magnetic field profile is chosen correctly. One can expect that the corresponding residual MHD activity will not lead to too fast transverse losses of the plasma; in addition, high modes should be stabilized by the FLR effect.

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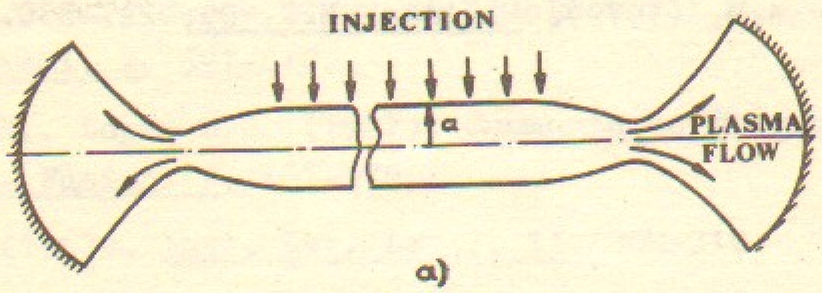
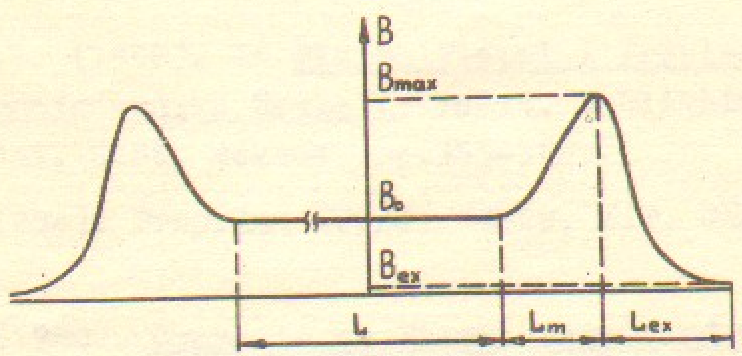


a)



b)

Fig. 1. Gas-dynamic trap: a) shape of magnetic field lines; b) distribution of the magnetic field intensity along the z axis (the ratio B_{max}/B_o is not in scale; B_{ex} is magnetic field intensity at the surface of the expander).

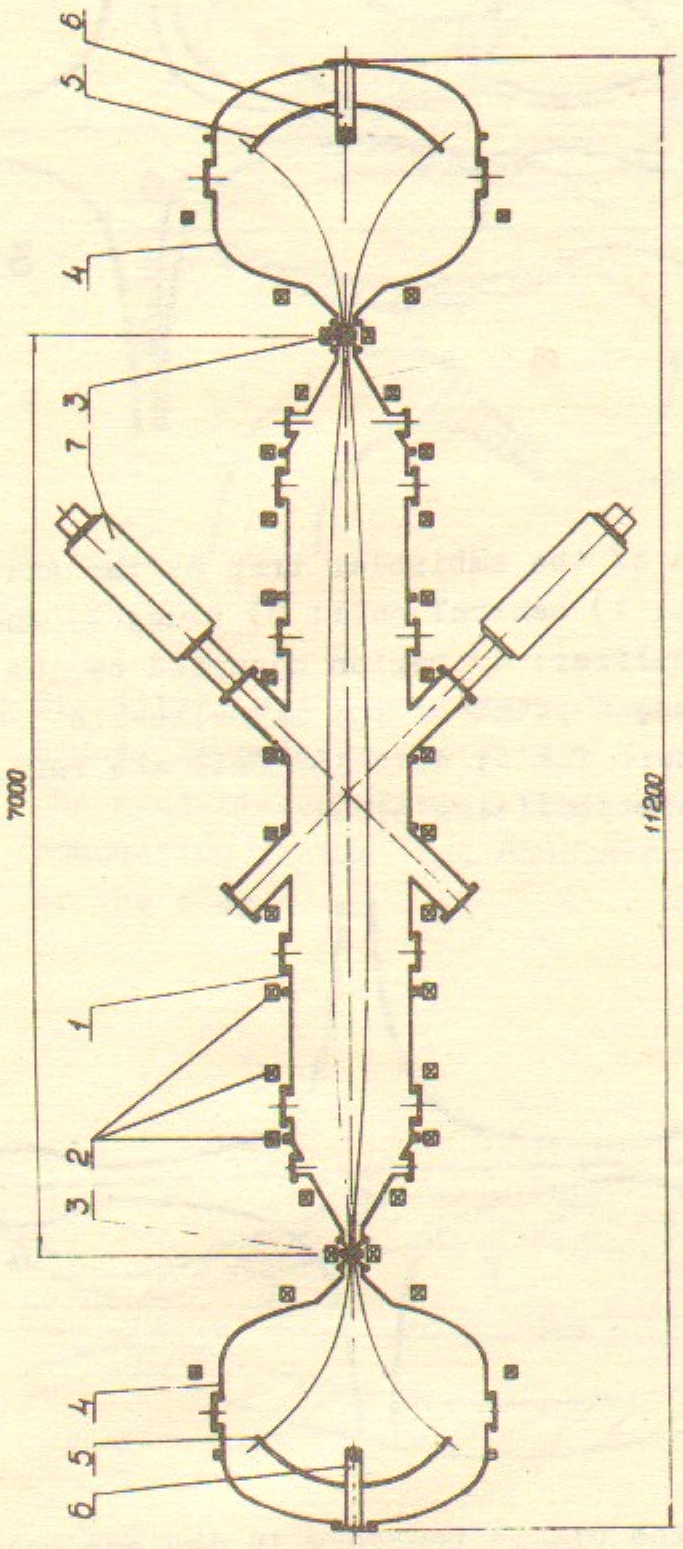


Fig. 2. Experimental model of a gas-dynamic trap: 1) central vacuum chamber; 2) coils of a solenoidal magnetic field; 3) mirror coils; 4) vacuum chambers of the expanders; 5) plasma receivers; 6) plasma guns; 7) atomic injectors. The sizes are given in millimeters.

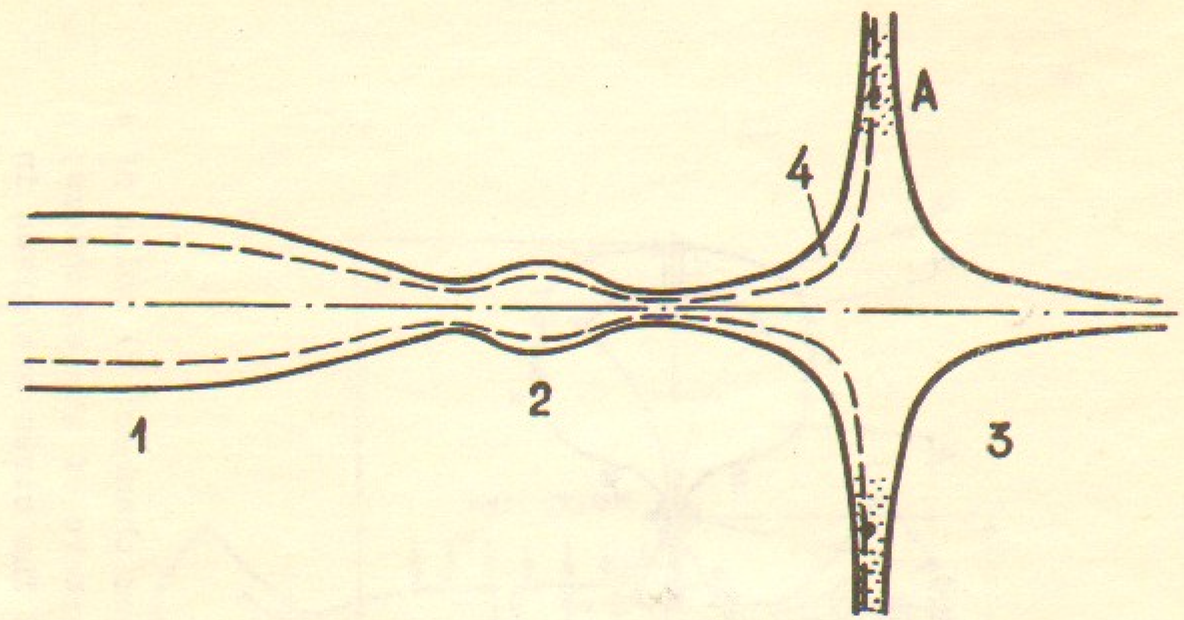


Fig. 3. Stabilization of the ambipolar trap by the Andreoletti-Furth trap; 1) central cell; 2) plug; 3) Andreoletti-Furth stabilizer; 4) region occupied by the connecting plasma; A-point of the magnetic-field minimum, O -point of zero field; dots indicate the region occupied by the stabilizing plasma.

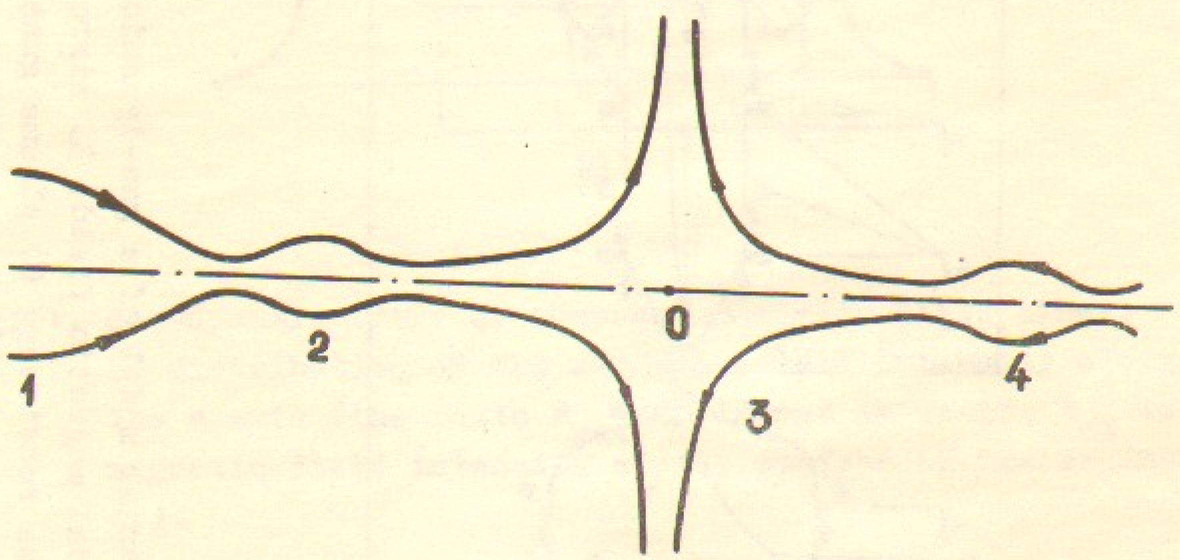


Fig. 4. The shape of the plasma boundary in the ambipolar trap with a cusp stabilizer. The direction of the field lines is indicated by arrows. 1) central cell; 2) plug; 3) cusp stabilizer (0 stands for the zero point); 4) auxiliary plug.

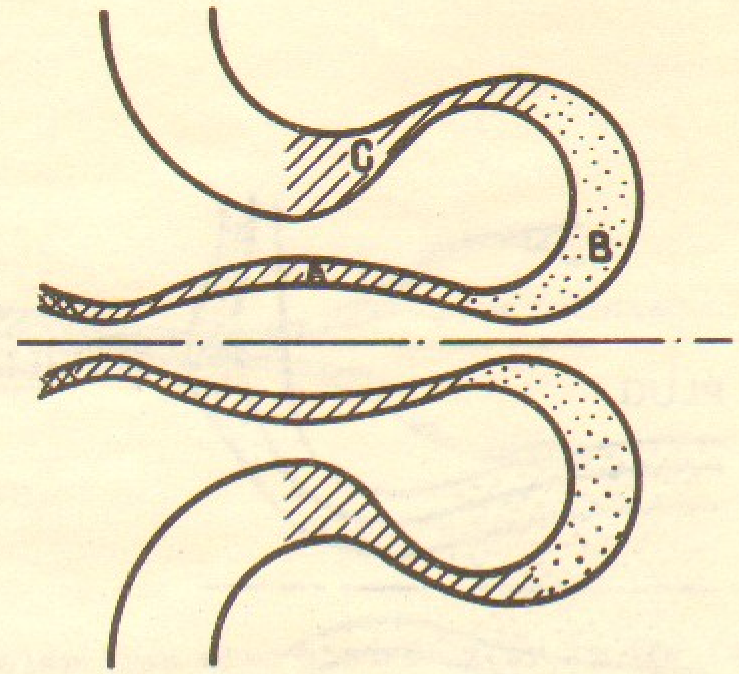


Fig. 5. Stabilizer with the alternating curvature of field lines. Dashed are the region A and C occupied by the stabilizing plasma, the points indicate the connecting plasma (B), double-dashed is the plasma of the plug.

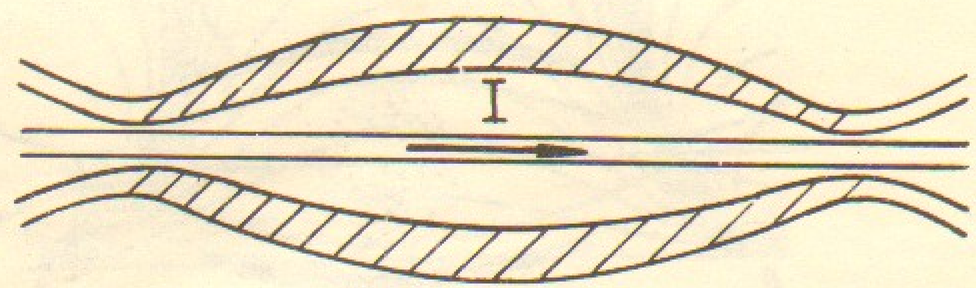


Fig. 6. Stabilization of the m = 1 mode in the paraxial mirror machine by the current-carrying rod. The plasma region is shaded.

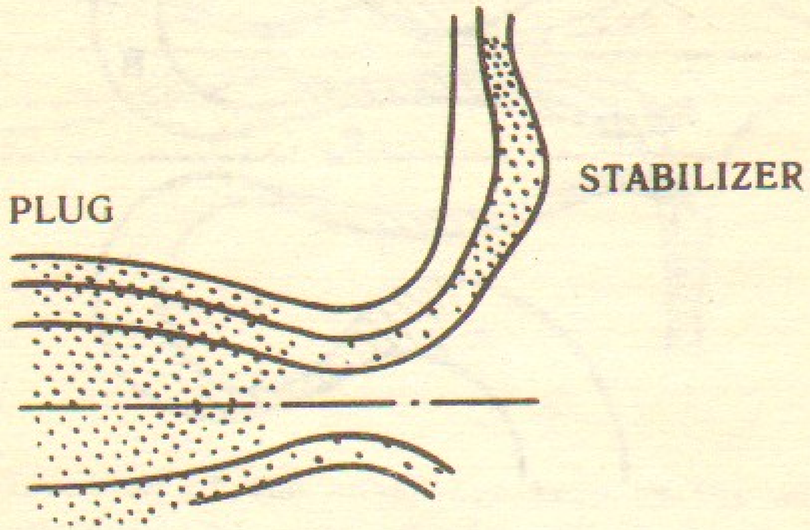


Fig. 7. Stabilization of the m = 1 mode using the system with a maximum of B outside the plasma.

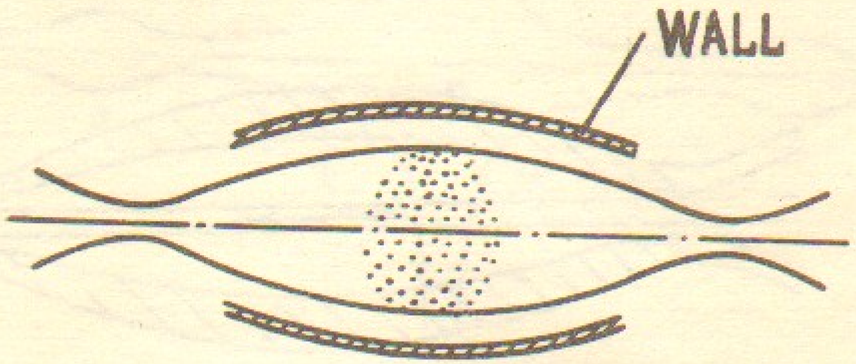


Fig. 8. Stabilization of the m = 1 mode by conducting walls.

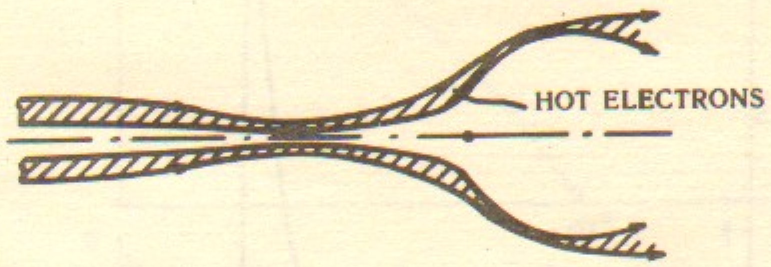


Fig. 9. Ambipolar trap with a stabilizer in the form of non-symmetric semi-cusp. The region occupied by plasma is dashed. O stands for the zero field.

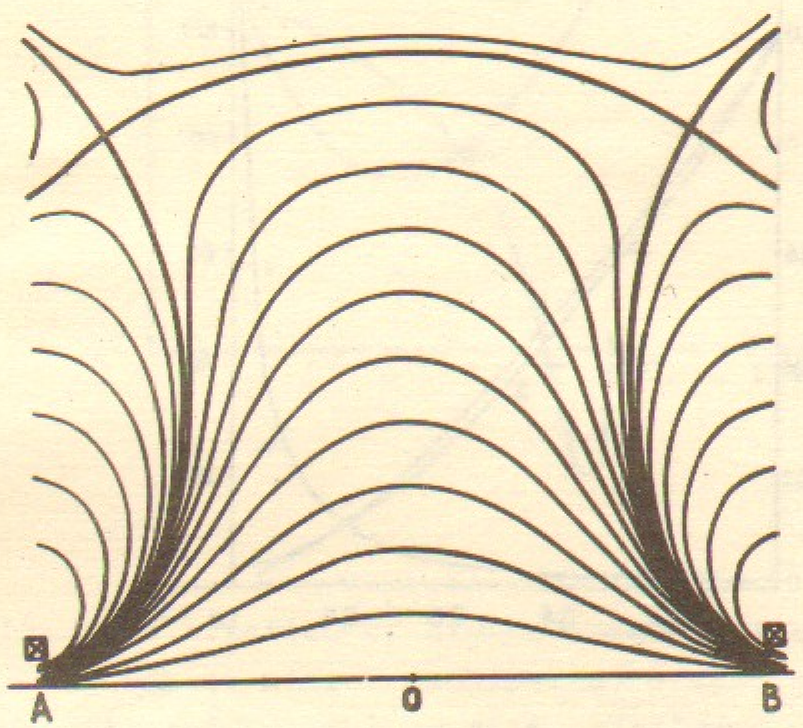


Fig.10. Field lines in the non-paraxial stabilizer. The "stability ring" zone is dashed.

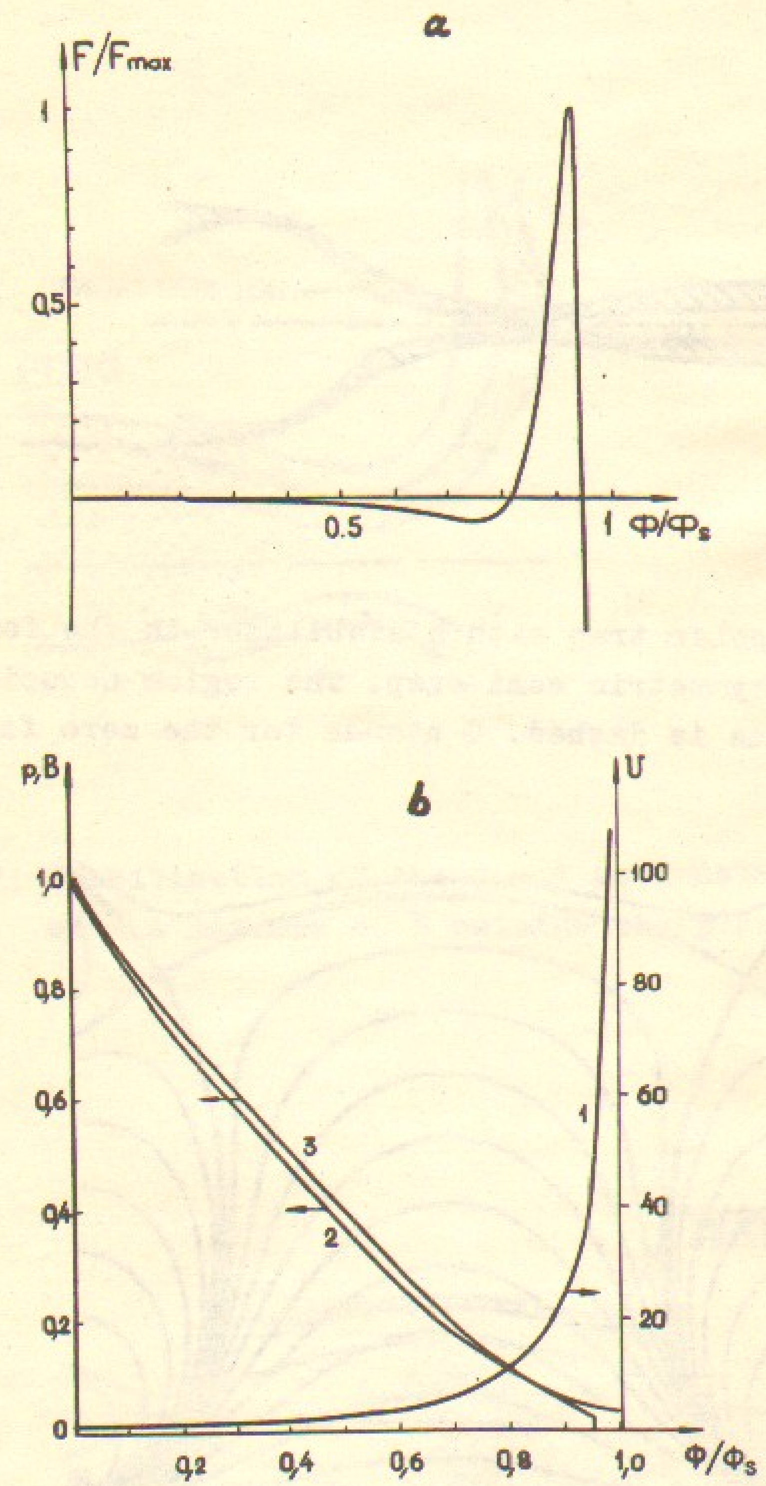


Fig. 11. Some properties of the magnetic field demonstrated in Fig.10: a) plot of the function $F(\Phi)$ normalized to its maximum value; b) plots of the dependences $U(\Phi)$ (curve 1), $B_o(\Phi)$ (curve 2) and $p(\Phi)$ (curve 3) for the same field (all the quantities are normalized to their values on the axis).

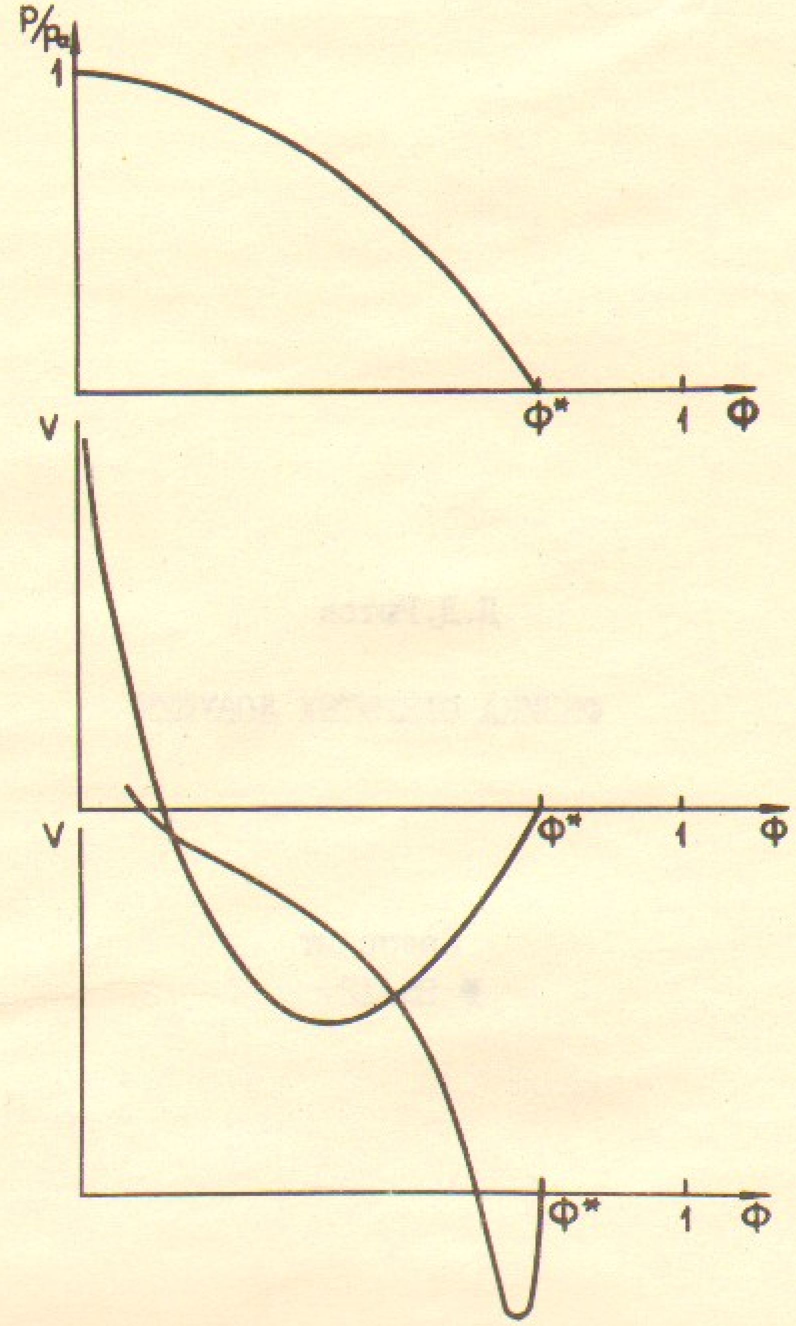


Fig. 12. Stabilization of higher modes in the non-paraxial mirror machine: a) pressure profile $p(\Phi)$; the condition $|p'|/p < U'/U$ is assumed to be valid; b) "potential energy" $V(\Phi)$ in the absence of the stability ring at $|\omega| \sim \Gamma$; c) "potential energy" $V(\Phi)$ in the presence of a strogly pronounced "stability ring" at $|\omega| \sim \Gamma$.

Д.Д.Рютов

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