ИНСТИТУТ ЯДЕРНОЙ ФИЗИКИ
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D.D.Ryutov

MAGNETIC MIRRORS

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I. INTRODUCTION

Mirror devices offer a number of important potential advantages with respect to the closed systems: $\beta \sim 1$ can be easily achieved in them; they allow the stationary operation, are less sensitive to the impurity problem and, finally, are more simple from the engineering point of view. All this justifies the current attitude to mirrors as to the second (after tokamaks) most probable way to magnetic fusion.

Ambipolar traps, which have been suggested by Dimov and coworkers/1/ and Fowler and Logan/2/, are the leader in mirror research. They extend the line of "classical" mirrors being in progress over the past two decades. Because of this long history as well as of their present firm position in the field of CTR, it isn't quite certain that they should be referred to as the "unconventional", or "alternative" classes of thermonualear devices. In view of this, in what follows, we shall discuss, mainly, the other systems which have more reasons to be considered as unconventional ones, viz.: rotating plasma devices, cusps, and multimirror systems. The discussion will be based, for the most part, on the results obtained at the Institute of Nuclear Physics (INP).

The position of these unconventional schemes in the programme of mirror studies is determined, first of all, by the fact that, unlikely the tokamak situation, the scale of extrapolation of today's experimental ambipolar traps to the ambipolar reactor is still very large and on the way to the final goal some serious obstacles may be met. Of those that can be foreseen right now, the most dangerous are the velocity space microinstabilities in the end cells (see Section 2). Therefore, the other versions of open systems should be evaluated, first of all, basing on the extent to which they are free from this weak point. In particular, the three types of traps mentioned above are quite insensitive, by their very principle, to the velocity space microinstability.

The significance of alternative schemes of mirror devices also consists in the fact that some of them do not make it necessary to employ complicated and expensive techniques, necessary for ambipolar reactor, for example, neutral injectors with the energy of hundreds keVs and complex vacuum systems.

And, finally, the third point that determines the importance of studies on alternative open-trap schemes is that they are a potential source of new ideas allowing the refinement of the most developed open trap - the ambipolar one (in particular, this is relevant to cusps).

The presentation is arranged as follows. In the first part of Section 2 the restrictions on the level of microfluctuations in the end cells of the ambipolar trap are discussed in some detail, while in the second part we describe a recently discovered phenomenon that could be of some general interest to plasma physics - the formation of potential jumps in a smoothly varying magnetic field. Section 3 is concerned with the status of research on rotating plasma devices (centrifugal traps). Section 4 is devoted to the problems of cusps with electrostatic plugging. The questions which concern the physics of multimirror dense-plasma systems are discussed in Section 5. Note again that the basis of our discussion are the results obtained at the INP.

2. SOME PHYSICAL ASPECTS OF AMBIPOLAR TRAPS

The significance of the problem of microinstabilities for ambipolar traps arises from the fact that, according to simple physical considerations an admissible level of plasma microfluctuations is strictly limited: in the case of a thermonuclear reactor, the contribution of microfluctuations to ion scattering becomes comparable with that of Coulomb collisions already at

$$W/nT \sim 10^{-8} \div 10^{-9} \qquad (1)$$

(W is the energy density of fluctuations).

It is worth noting that the present-day ambipolar reactor designs have been based on the assumption that the losses

of particles in the end cells are purely Coulomb. In connection with somewhat frightening character of the estimate (1), it seems reasonable to try to take into account, at least phenomenologically, a possible role of microturbulence. For example, this can be done by introducing a certain effective scattering frequency ν_{eff} instead of purely Coulomb scattering frequency ν_c:

$$\nu_{eff} = A\nu_c$$

with $A > 1$. Seemingly, the value $A = 10$ will be fatal for reactor, but it would be interesting to evaluate at what level of microfluctuations the reactor can still survive.

Microinstabilities can also strongly affect the functioning of "thermal barriers" suggested in Livermore in 1979/3/. Here, beam-type instabilities produced by sloshing ions distribution (rather than the loss-cone ones) are most dangerous/4/.

We would like to mention here one recently discovered effect which, having no direct relation to the microinstabilities and other key questions of operation capability of "thermal barriers", is of noticeable general interest as a concrete example of realization of Alfven's idea/5/ on sheaths formation in a plasma. We mean the phenomenon of formation of Debye sheaths in the throats of a barrier cell, which has been discovered by Pekker/6/ (and later studied in more details by Cohen/7/).

The potential jump arises in the case of a strong depletion of the distribution function in the region of the trapped ions (i.e., in the situation typical for thermal barriers). This conclusion is supported by the following arguments. The s-dependence of the electrostatic potential*, in the absence of jumps, is defined from the condition of plasma quasineutrality:

$$\exp\frac{e\varphi}{T_e} = \frac{n_i(\varphi, B)}{n_{io}} \qquad (2)$$

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* s is the distance along a magnetic field line.

where φ is the electrostatic potential counted from its value in the central cell, n_i is the ion density, n_{io} is the ion density in the central cell, B is the magnetic field strength dependent on s in the known manner. The electron distribution function is regarded as the Boltzmann one. B-dependence of n_i is connected with anisotropy of the ion distribution in the barrier cell. The effect proves to be most striking in the case when there are no trapped ions at all/6/. Equation (2), as it is seen from Fig. 1 taken from the paper by Pekker, has no solutions at $B < B_{max}$ for the values of φ which are close to zero.

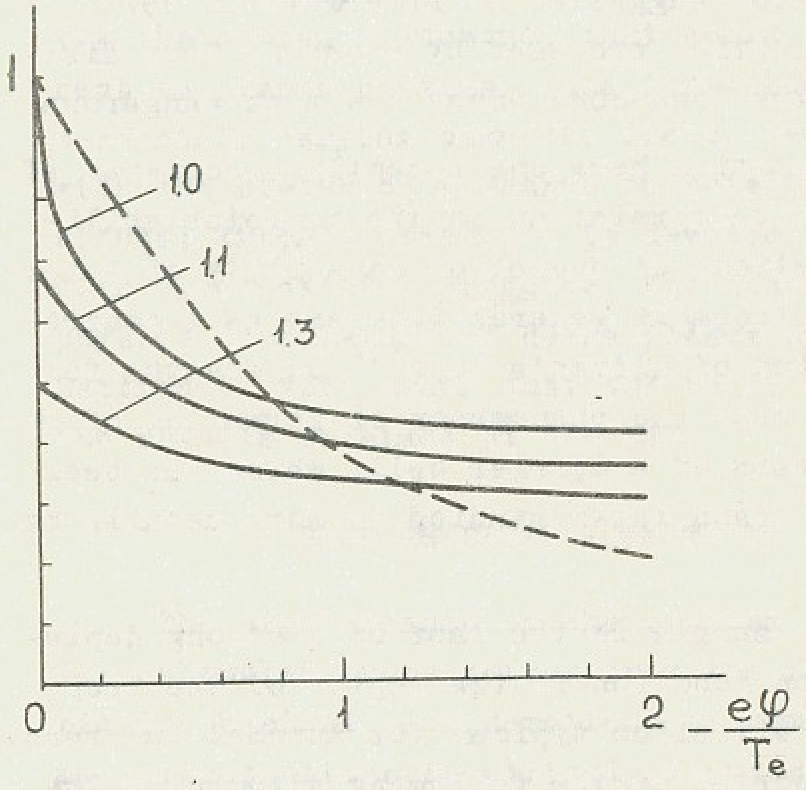

Fig. 1. Plot of the left-hand side (dotted line) and the right-hand side (solid lines) of Eq. 2 as a function of $e\varphi/T_e$ for $T_e = T_i$. The numerical parameter at the solid curves indicates the corresponding value of B_{max}/B.

This fact points to the presence of a potential jump in the mirror throat so that the dependence φ (s) acquires, as a whole, the form demonstrated in Fig. 2.

The study, carried out by Cohen/7/, has shown that with the appearance of trapped ions, the jump shifts to the center of a barrier cell and its value decreases, until it disappears at some critical density of trapped ions.

As has recently been established by Pekker/8/, the presence of potential jump can result in a very fast ion scattering. Pekker has analysed the case when the trapped ions are absent, and the magnetic field is non-axisymmentric (has the Ying-Yang geometry). In this case, the potential jump is situated at the surface constituted by the points where $\partial B/\partial s = 0$. The magnetic field lines intersect this surface (which is close to a plane perpendicular to magnetic axis) at the angle $\sim r/L$ (where r is the transverse plasma size, L is the scale of longitudinal magnetic field inhomogeneity) to the normal. As the thickness of the jump (approximately the Debye radius r_D) under the typical conditions is small compared to ion Larmor radius r_L, the ion magnetic moment μ changes, at each crossing of the jump, by the value $\Delta\mu \sim r/L$. One can verify that the successive changes of μ are uncorrelated with each other, that eventually points to the presence of scattering. The effective scattering time τ is of the order of $t_{\parallel}\cdot(\mu/\Delta\mu)^2 \sim t_{\parallel}\cdot(L/r)^2$, where $t_{\parallel} \sim L/v_{Ti}$ is the ion bounce period in the barrier cell; numerically, τ is by many orders of magnitude smaller than the Coulomb scattering time.

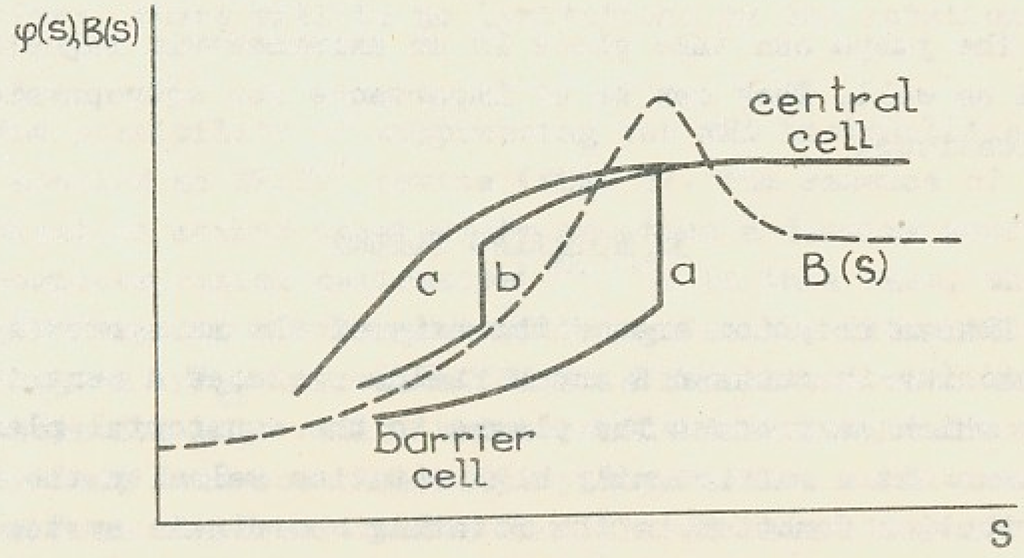

Fig. 2. The typical dependence of φ on s near the transition between the barrier cell and the central cell: a - no trapped ions in the barrier cell; b - - intermediate amount of trapped ions; c - large amount of trapped ions.

From the physical point of view, so rapid scattering will lead to an immediate appearance of trapped ions whose number grows till the disappearance of this jump. Actually, the presence of this "self-treatment" effect means that, in real systems, only the distribution functions, which do not result in the formation of jumps, can be met.

The jumps can take place in an axisymmetric magnetic field as well. They can be of importance for astrophysical applications.

3. ROTATING PLASMA

Plasma rotation around the axis of the axisymmetric mirror machine in crossed E and B fields produces a centrifugal force which compresses the plasma to the equatorial plane of the trap. At a sufficiently high rotation velocity the ion distribution function in the rotating coordinate system becomes nearly isotropic, that leads to eliminating the danger of velocity-space microinstabilities. The main difficulties in realizing this scheme of plasma confinement consist in the necessity to overcome the so-called "Alfven limit" in the velocity of plasma rotation (just for this reason the HOMOPOLAR and IXION devices have failed), and also in the necessity to provide the MHD stability of a rotating plasma.

At present, the first difficulty may be considered as surmounted: in 1976-1979 the rotation velocity V of $5 \cdot 10^7$ cm/s was achieved at the PSP-IM device with a plasma density of 10^{13} cm^{-3} (see Ref. /9/). The duration of such a state of plasma constituted 5 ms and was determined by the time of propagation of the gas, puffed by a pulsed valve, through the chamber volume*.

The whole totality of the facts points out that the effect of criticial velocity is determined by the near-electrode phenomena for the case of sufficiently dense plasma. In particular, in order to attain a high rotation velocity, it is necessary to provide the conditions under which the power density on the electrode surface were not higher than some limiting value at any stage of discharge.

In a stable plasma with a low concentration of neutrals (as should be the case in a thermonuclear reactor), the flows to the walls, which cause gas desorption and evaporation, are small. Thus, if the electric strength of insulators will be sufficient, there will be no limitations on the rotation velocity.

The possibility of suppressing the MHD instabilities is being studied at SVIPP* device (Fig. 3). The essence of the stabilization method consists in creating a density profile with positive radial derivative /10, 11/. In this case, the centrifugal force is a strong stabilizing factor, with stability improving as V/V_{ti} increases. This is consistent with the requirements for this ratio, which result from longitudinal confinement and loss-cone instability suppression conditions. It follows from simple estimates that the MHD stability is possible already at small $\partial n/\partial r$. To create the conditions with $\partial n/\partial r > 0$ in the region of fast rotation, the flow of cold plasma is arranged near the outer wall, and the hot plasma should be produced due to diffusion from this flow. As the estimates show, the density and electric field profiles, close to the required ones can be obtained in this way.

In the near-wall region, occupied by the flow, $\partial n/\partial r < 0$, and the MHD stability is provided by that the plasma is not confined in the flow and passes through the mirrors, so that there is the average min B along the flow.

The more careful analysis of MHD instability, made in Ref. /12/, has not revealed any additional obstacles for this scheme.

Experiments have been started at the PSP-2 device on testing the other scheme of stabilization of the flute instability which is based on the contact of the plasma with special end electrodes located beyond the mirrors (Fig. 4). The esti-

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* In the previous experiments performed at the HOMOPOLAR-5 device at $n \sim 10^{13}$ cm^{-3}, the same rotation velocity was attained only for 20 μs, and then the breakdown occured.

* SVIPP stands for Russian "stabilization by rotation and density profile".

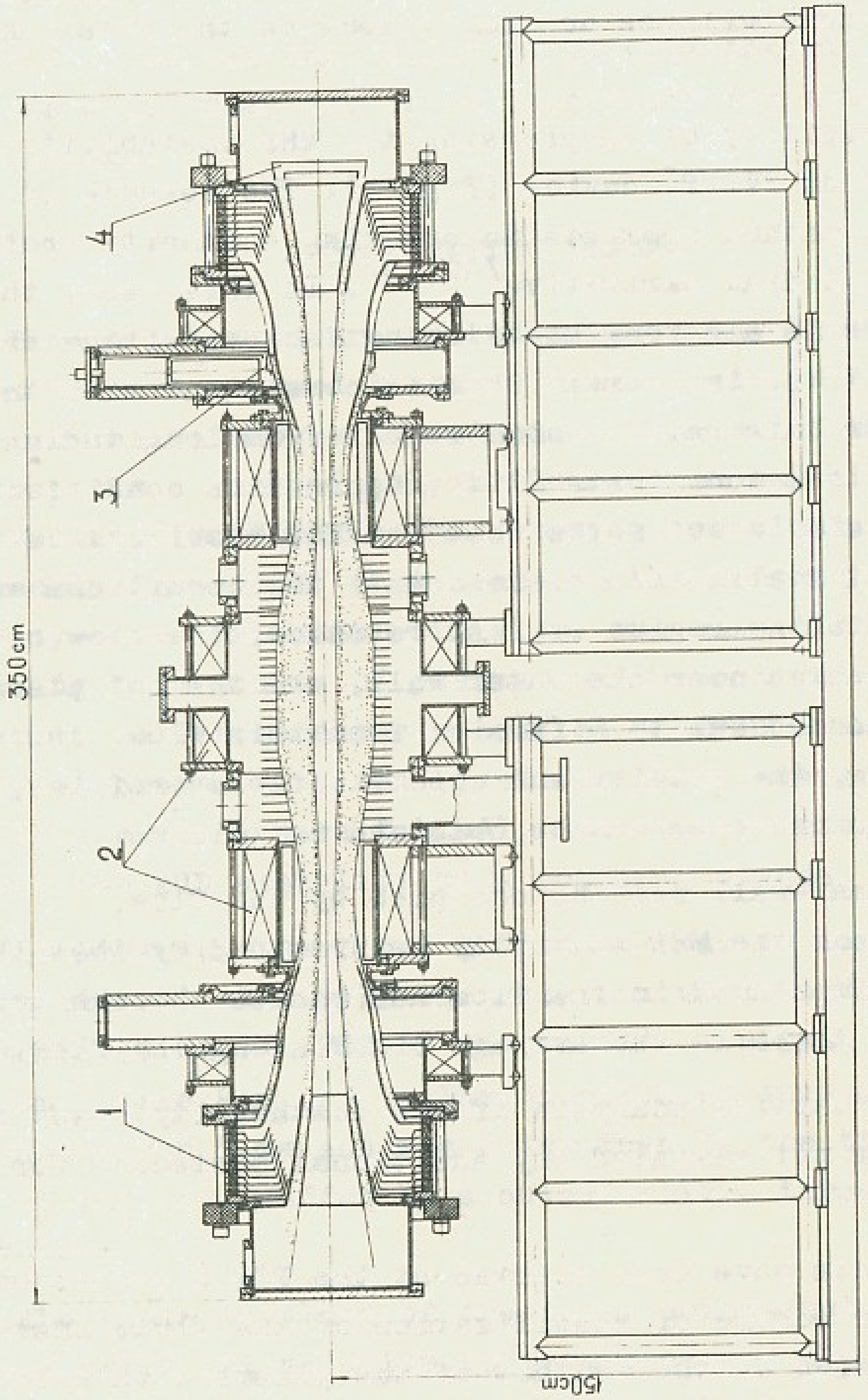

Fig. 3. The schematic of SVIPP-1 device: 1 - insulator, 2 - magnetic coils, 3 (4) - source of external (internal) plasma jet; B_{max} = 20 kGs; B_{min} = 7 kGs.

mates show that the plasma of such a kind can be stable if the conditions cited below are satisfied simultaneously:

- some definite electric-field profile must be sustained in the plasma (for parabolic n(r), it is quite enough if E(r) decreases by 25-50% along the radius);

- longitudinal electron current from the plasma must exceed some criticial value, which is dictated by the geometry of the device/13, 14/.

The above conditions have been taken into account at the PSP-2 device. This device was put into operation in 1981. Its parameters are the following: magnetic field (in the centre) is up to 30 kGs, mirror ratio is 2.5; plasma diameter is 100 cm; distance between mirrors is 160 cm; the energy of ion rotation is of the order of 100 keV, the expected ion temperature is $20 \div 40$ keV; the expected plasma density at the magnetic field values indicated above is $(2 \div 5) \cdot 10^{13}$ cm^{-3}; the value of the total electric potential at the end faces of the devices is equal to 10^6V.

Under the conditions of discharge cleaning of the walls, the potentials achieved are 200 kV in a quasistationary regime (with discharge plasma density $10^{10} \div 10^{11}$ cm^{-3}).

Some indications that the chosen method of stabilization is effective (at least with respect to the highest azimuthal modes) are presented in the paper/15/, describing the experiments at smaller device PSP-02 (rotation velocity $8 \cdot 10^7$ cm/s, $n \sim 10^{12}$ cm^{-3}).

4. CUSPS

The idea of the cusp with electrostatic pligging of slits was suggested by Lavrent'ev (Kharkov) in the early 60 s. The device is schematically shown in Fig. 5. Between electrodes A and B (C and D), a large potential difference (a few plasma temperatures) is applied. The sign of this difference is indicated at the figure. If the transverse slit size is small compared to the Debye radius,

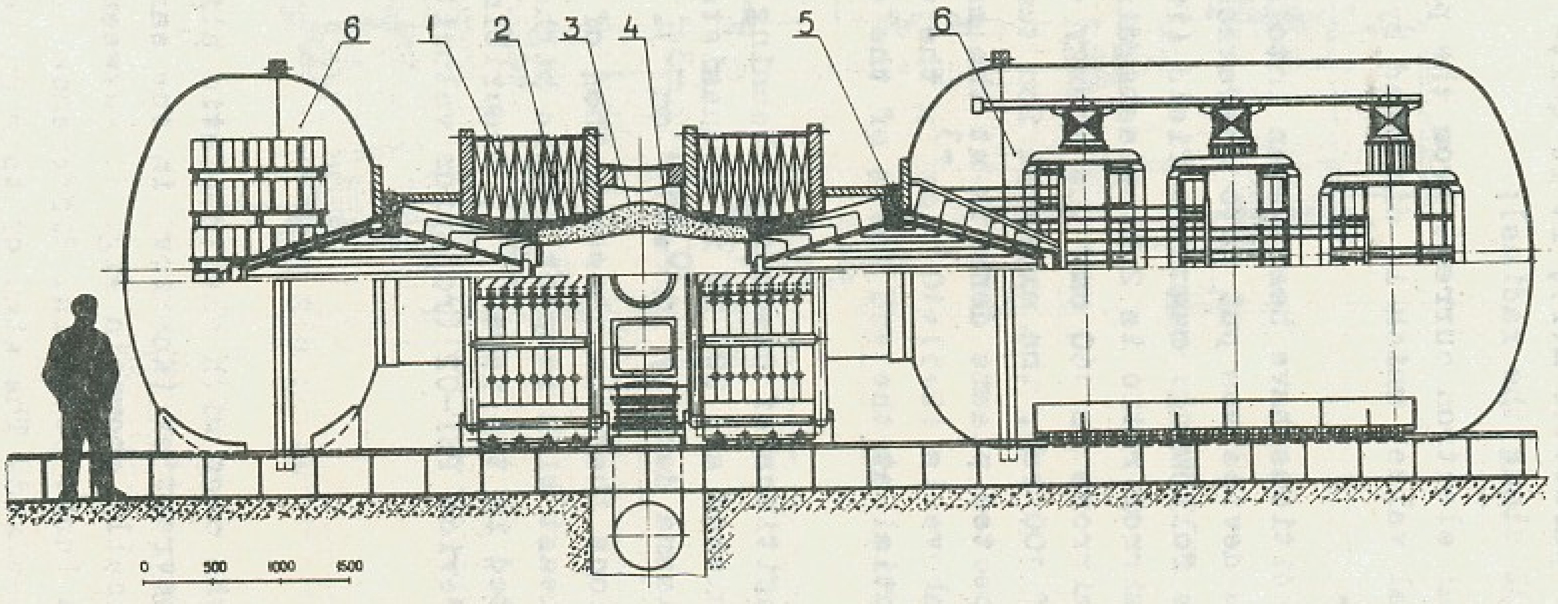

Fig. 4. PSP-2 device: 1 - magnetic field coils, 2 - vacuum chamber, 3,4 - liners, 5 - end electrodes, 6 - H.V. power supply system. Main parameters: magnetic field 72 kGs (in mirrors); mirror ratio 2.5; electric field 100 kV/cm; radial potential difference 1 MV.

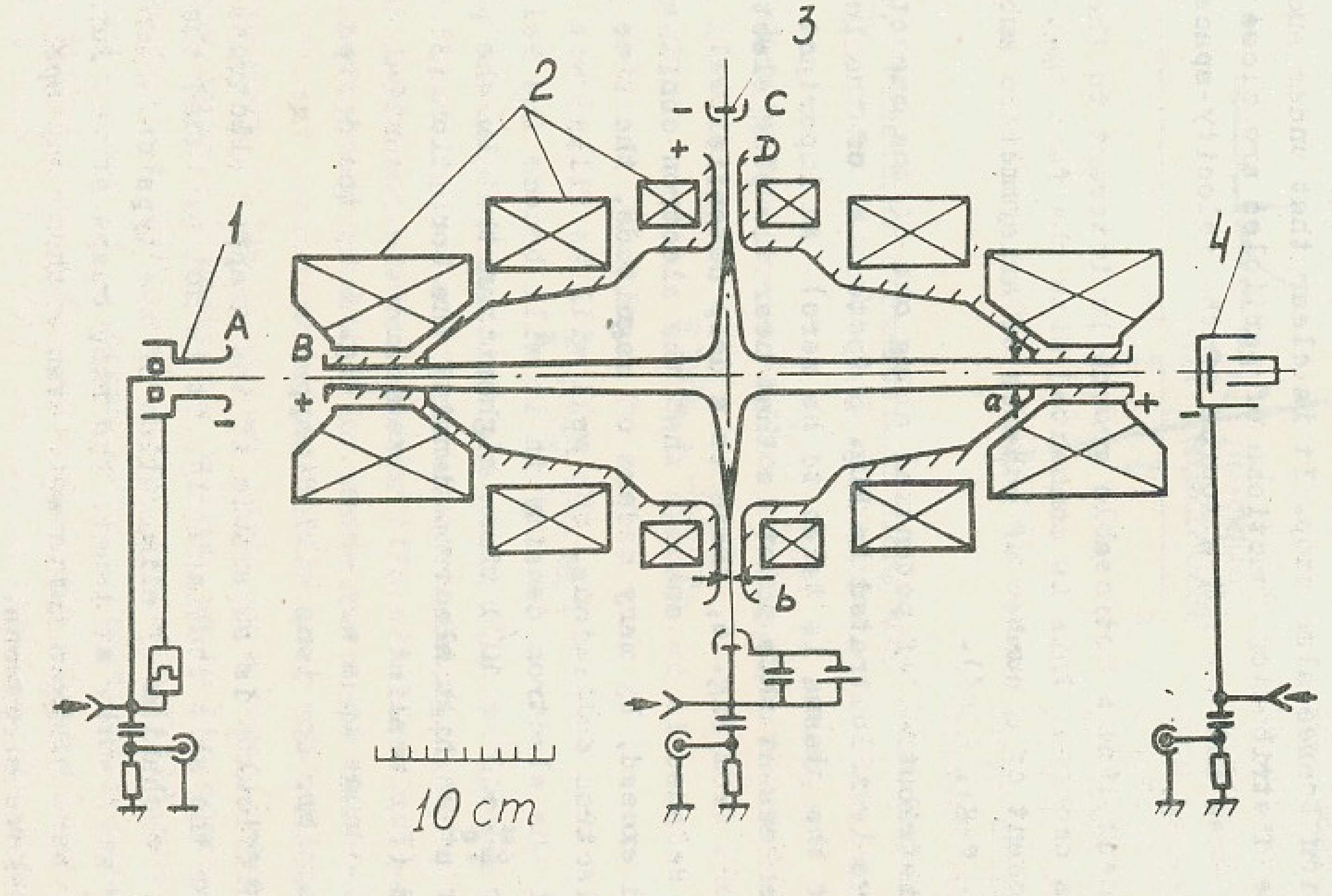

Fig. 5. JUPITER-1M device: 1,4 - point cusp plugging electrodes; 2 - magnetic system; 3 - ring cusp plugging electrode.

$$a, b \ll r_D \qquad (3)$$

(for notations, see Fig. 5), the electrons cannot leave the system; as for the ions, they will escape from the plasma until the internal plasma regions are charged to a negative potential such that ion losses also stop. It is clear that under such conditions the distribution functions of particles are close to Maxwellian ones and are not a source of the velocity-space microinstabilities.

In recent time a noticeable growth in interest to the cusps physics has occured. This is connected with the fact that they are a component of a number of schemes of axisymmetric ambipolar traps (see, e.g., /16/).

The distribution of potential along one of the magnetic fields lines is illustrated in Fig. 6 (potential of the internal part of the plasma is taken to be zero). An important question that arises at this point is that near the plug electrodes, as it follows from Fig. 6, there is a deep potential well for electrons. Because it is assumed that the electron confinement time should exceed, by many orders of magnitude, the time of electron-electron collisions, the well will be filled with electrons until the electron density in it will become the Boltzmann factor (exp $\frac{e\varphi}{T_e} \sim 10^3 \div 10^4$) times higher than that in the plasma centre. But at so high electron density the condition (3) will be violated (for realistic slit sizes) and the potential distribution will change in a way shown in Fig. 6 by the dotted line, i.e. the barriers for ions will disappear.

This difficulty is superable if the trapped electrons are removed from the slit continuously. It is not excluded that some "natural" mechanism of elimination of the type of diocotron instability will work. At least, the ring cusps at the Jupiter devices/17/ were plugged quite well even without any special measures to remove electrons.

The parameters of the plasma produced at "JUPITER IM" were the following: density $n = 10^{12}$ cm^{-3}, $T_e = 100$ eV, $T_i = 50$ eV, lifetime $\tau = 1$ ms (at the magnetic field strength $B_R = 17$ kGs in the ring cusp and $B_p = 56$ kGs in the point cusp). The geometrical sizes of the device are: the distance ℓ from the center to the point cusp is 20 cm, the ring cusp radius R is 10 cm, plasma thickness in the ring cusp is $b = 1.5 \cdot 10^{-3}$ cm, point cusp diameter is $a = 0.6$ cm. So large difference between the values of a and b is due to the fact that they are related to each other by the magnetic flux conservation condition:

$$\pi R b B_R = \frac{\pi a^2}{4} B_P$$

i.e.

$$\frac{b}{a} = \frac{a}{4R} \frac{B_p}{B_R} \ll 1$$

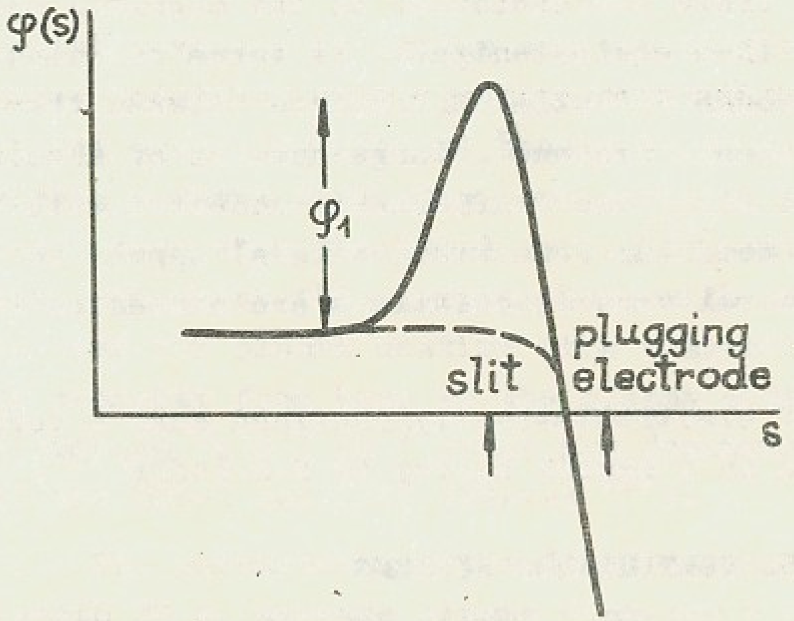

Fig. 6. Potential distribution along the field line near the plugging electrode.

It is easy to see that the condition (3) is not satisfied in the point cusp, i.e. their electrostatic plugging is impossible. Indeed, the experiments/17/ have shown that switching off the plugging potential in the point cusps causes only an insignificant reduction in the lifetime of the plasma (a similar procedure in the ring cusp leads to a fast plasma decay). Then one paradox immediately arises: as in the confinement region there is a point with a zero magnetic field and the adiabatic invariance of μ breaks, the lifetime of plasma should be not higher than a few tens of flight times of ions across the trap (see Ref. /18/), while, in reality, the lifetime of plasma proves to be a few tens times higher.

One of the possible explanations of this paradox was suggested by the author of the present paper and attributes the unexpectedly long confinement time to the presence, in the plasma, of an electric field perpendicular to the magnetic one (magnetic surfaces are then equipotential). It turns out that in the case of large enough potential difference between the internal and external plasma regions*, large domains of absolute particle confinement (i.e. the confinement connected with the energy and canonic momentum conservation laws) appear in the velocity space. The relevant calculations are presented in the Appendix.

Another version of electrostatically confined cusp - toroidal one - is discussed in a recent survey by M.S.Ioffe/19/.

5. MULTIMIRROR SYSTEMS

In multimirror systems the plasma with free path length λ, which is smaller than the device length L, is effectively confined. Plasma confinement under such conditions is not sensitive to the velocity space microinstabilities. In the plasma with moderate density, the condition $\lambda \ll L$ can be satisfied only if the device is rather long (of the order of 500-600 m). Nevertheless, if the magnetic system of the device is based on the modular principle, i.e. is composed from simple identical elements, the large length doesn't seem to be unexceptable/20/. In such a multimirror-trap scheme one can use the neutral injection technique for plasma production and heating.

The other version of multimirror reactor - with high plasma density ($n \sim 10^{17}$ cm^{-3}) - is developed at the INP/21/. Within the frames of this version, the transverse plasma confinement is assumed to be provided by a corrugated metal wall, while the magnetic field is used only to suppress the transverse thermal conductivity. On one hand, this enable one to guarantee the MHD-stability of plasma even in the axisymmetric system and, on the other hand, to weaken the requirements for the magnetic field strength (to operate in the conditions when $\beta \gg 1$). The multimirror reactor of such a kind must be a pulsed machine.

The above approach seems attractive because it makes it possible to use some simple and inexpensive techniques in the future thermonuclear reactor. However, at the level of experimental devices, it causes serious difficulties, since for adequate modelling of the wall confinement at $\beta \gg 1$, an energy of the order 100 kJ÷1 MJ should be transferred to the plasma within a short time. The corresponding possibility will at last occur when the GOL-3 device/22/ will be ready for operation, in which the electron beam with an energy of 1 MJ will be used for plasma heating (the possibility of effective energy transfer from beam to the plasma with a density in the $3\cdot10^{14}$ cm^{-3}÷10^{16} cm^{-3} range was demonstrated in the experiments at the GOL-1 and INAR devices/23/).

The parameters of the GOL-3 device are the following: length 20 m, average plasma diameter 6 cm, average magnetic field 60 kGs, mirror ratio 2, number of cells 30; plasma temperature and density 1 keV and 10^{17} cm^{-3}, respectively. The main purpose of experiments at the GOL-3 will be to clarify the similarity laws for wall confinement of plasma with $\beta > 1$.

In recent time several suggestions have been offered which allow one to increase substantially the longitudinal lifetime in multimirror devices. In particular, one should mention the method of heavy impurity admixture. The purpose of seeding plasma with impurities is to increase Z_{eff} with the corresponding decrease of the free path length λ and of the rate of longitudinal diffusion (note that in the multimirror trap the longitudinal plasma expansion occurs in a diffusive manner with a diffusion coefficient $D \backsim \lambda \backsim Z_{eff}^{-2}$). The limitation on the density of impurities is connected with the growth of bremsstrahlung radiation. In the case of uniform, over the length, introduction of impurities (analysed in Ref. /24/), this limitation proves to be fairly severe and the increase in time of the longitudinal confinement (and in the energy enhancement coefficient Q) is determined only by a factor of about 1.5.

However, one can introduce impurities non-uniformly over the length, adding them only into the regions of maximum density gradient where they have most influence on the diffusion rate. For the pulsed thermonuclear reactor the corresponding analysis has been made in Ref. /25/ on the basis of one-dimensional numerical calculations. The initial plasma parameters (ini-

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* The potential difference of the order of a few T_e/e is typical for the open traps.

tial energy content and temperature), Z of impurities, their relative content, and the spatial distribution have been varied over broad intervals.

The value of energy enhancement Q of the thermonuclear reactor as a function of the relative density of impurities is shown in Fig. 7.

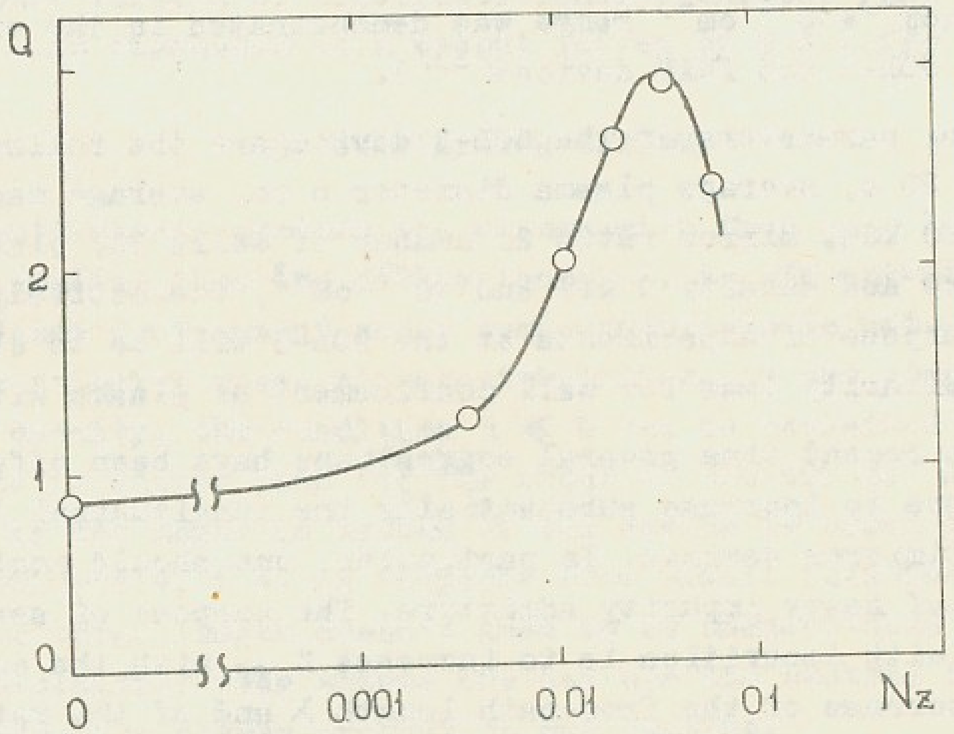

Fig. 7. Plot of plasma enhancement coefficient Q vs. relative density of impurities. $W_o = 10$ MJ/cm^2, $T_o = 8$ keV, Z = 10.

The plot corresponds to the initial energy content in the plasma $W_o = 10$ MJ/cm^2 and to an initial temperature of 8 keV. The impurities with Z = 10 (neon) are added into two symmetric regions near maximum density gradient of hydrogen, each constituting approximately 0.1 of the total plasma length. The density of impurities is measured in terms of $N_z \equiv n_z^{max}/n^{max}$ where n_z^{max} and n^{max} are the maximum initial densities of impurities and main plasma (attained not at the same point!). The maximum effect is observed at the density of impurities

about 3-7%.

The diagram, summarizing the results of numerical simulation, is drawn in Fig. 8, where the plasma enhancement of the reactor is presented vs. the atomic number of the impurity atoms.

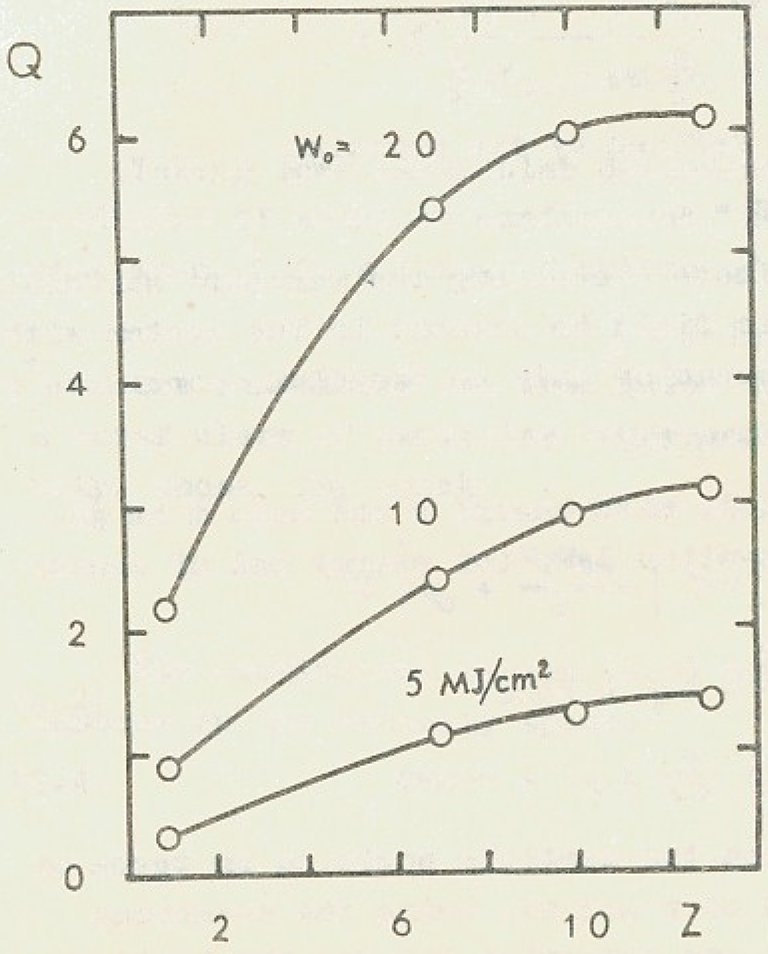

Fig. 8. Enhancement coefficient Q vs. atomic number of impurities for various values of the initial plasma energy content W_o.

The initial energy content W_o in the plasma in MJ/cm^2 is taken as a parameter for the curves. All remaining parameters are optimized for each point. It follows from the figure that, first, there is no sense in using the admixture with $Z > 10 \div 15$ because of the growth of losses connected with bremsstrahlung and, second, adding of admixture with $Z \simeq 10$ permits one to increase the nuclear energy release by 3÷5 times at the same initial energy content in the plasma.

In the pulsed reactor, the required distribution of impurity can be achieved by means of pulsed puffing of the impurity.

The non-uniform distribution of impurity can also be realized in the stationary multimirror reactor mentioned above. To do this, the injection of heavy atoms ahould be concentrated at the desired place.

APPENDIX

Considering a low-β plasma, we use a vacuum presentation of the cusp magnetic field:

$$B_z = -Gz, \quad B_r = \frac{Gr}{2},$$

where G is some constant. The vector-potential of this field has only one (ψ) component

$$A_\psi = \frac{G}{2} rz$$

The magnetic surfaces are defined by the equation

$$r^2 z = q$$

where q is the flux coordinate (labelling the magnetic surface). We assume that the electric field is present in the system with electrostatic potential depending only on the flux coordinate[*]:

$$\varphi = \varphi(q)$$

The motion of a particle with charge e and mass m is governed by two exact conservation laws (of energy and of canonical momentum):

$$\frac{mv^2}{2} + e\varphi = \text{const} \qquad (A.1)$$

$$r\left(V_\psi + \frac{e}{mc} A_\psi\right) = \text{const} \qquad (A.2)$$

It is convenient to describe the particle position in terms of q and z variables (instead of r and z). Using the notations $\chi = 2e\varphi/m$, $\alpha = eG/2mc$ and subscript "0" for the initial values of particle velocity and position, we can rewrite Eqs. (A.1) and (A.2) in the form:

$$v^2 + \chi(q) = v_0^2 + \chi(q_0) \qquad (A.3)$$

$$z = \frac{q v_{\psi o}^2}{\left[r_0 v_{\psi o} + \alpha(q_0 - q)\right]^2} \qquad (A.4)$$

We are going to find the class of initial conditions for which the particles can't leave the device through the point cusp[*]. As follows from (A.3), at a given q,

$$v_\psi^2 < v_0^2 + \chi(q_0) - \chi(q)$$

Then, from (A.4), it follows a strict inequality which defines the maximum distance along z-axis that can be reached by the particle for some given q:

$$z < \frac{q\left[v_0^2 + \chi(q_0) - \chi(q)\right]}{\left[r_0 v_{\psi o} + \alpha(q_0 - q)\right]^2} \qquad (A.5)$$

Taking some particular dependence $\chi(q)$, one can find the condition of absolute confinement. Let's consider a particular case when χ is a linear function of $|q|$[**]:

$$\chi = c\,|q|$$

One can easily see from (A.5) that, indeed, there exists a broad class of particles whose motion along z is finite, namely, those, for which

$$c\left|q_0 + \frac{r_0 v_{\psi o}}{\alpha}\right| > v_0^2 + c\,|q_0| \qquad (A.6)$$

The confinement region (A.6) consists, in general, of two spheres in the velocity space.

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[*] Note that, since the potential φ is produced by the plasma charges, it is not necessary that it should satisfy the Laplace equation.

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[*] The ring cusp is assumed to be electrostatically plugged.

[**] It is clear that φ should be an even function of Z. For this reason we write here an absolute value of q.

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