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ИНСТИТУТ ЯДЕРНОЙ ФИЗИКИ СО АН СССР

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EXPERIMENTAL MHD STABILITY LIMIT IN THE GAS-DYNAMIC TRAP

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ABSTRACT

This paper summarizes the results of extensive experimental investigations of a plasma MHD stability in GDT, which have been carried out over past 3 years at Novosibirsk. The objective of the experiments reported was to give experimental evidence of plasma stability in GDT and compare the conditions,under which it would be achieved, with the theoretical predictions. It was found that, theoretical predictions generally agree with the measurements with only one notable exception,namely the limit in the mirror ratio for the plasma stability. This observation is discussed in detail in the present paper.

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1. INTRODUCTION

The Gas Dynamic Trap (GDT) is an axisymmetric mirror device with a large mirror ratio R and a length - l considerably exceeding the effective ion mean free path of scattering into the loss cone [1].

The main advantage of the trap is that it can provide a plasma MHD stability even for an axisymmetric geometry. MHD stability can be achieved because of the fact that plasma density and the momentum flux in the expander region just, beyond the mirror throats with a favorable curvature of field lines, are large enough to balance the destabilizing contribution between the mirrors of the trap. This contrasts with conventional mirror machines that have a nearly collisionless plasma, for which the pressure as well as the momentum flux in this region are obviously negligible, so that MHD stability is not obtained for axisymmetric geometry.

The objective of the experiments was to give experimental evidence of plasma stability in GDT and to compare the conditions, under which it can be achieved, with the theoretical predictions. In particular, the MHD stability limit of warm plasma confinement in GDT is also a critical point for the start-up physics of prospective upgraded devices with more dense and hot plasmas .

Fig. 1 shows schematically the GDT layout. Magnetic field at the midplane was varied from 1.5 to 2 kG. The stainless steel vacuum chamber of 11 m long and of 0.5 m in radius was evacuated to base pressure $\simeq 10^{-6}$ Torr.

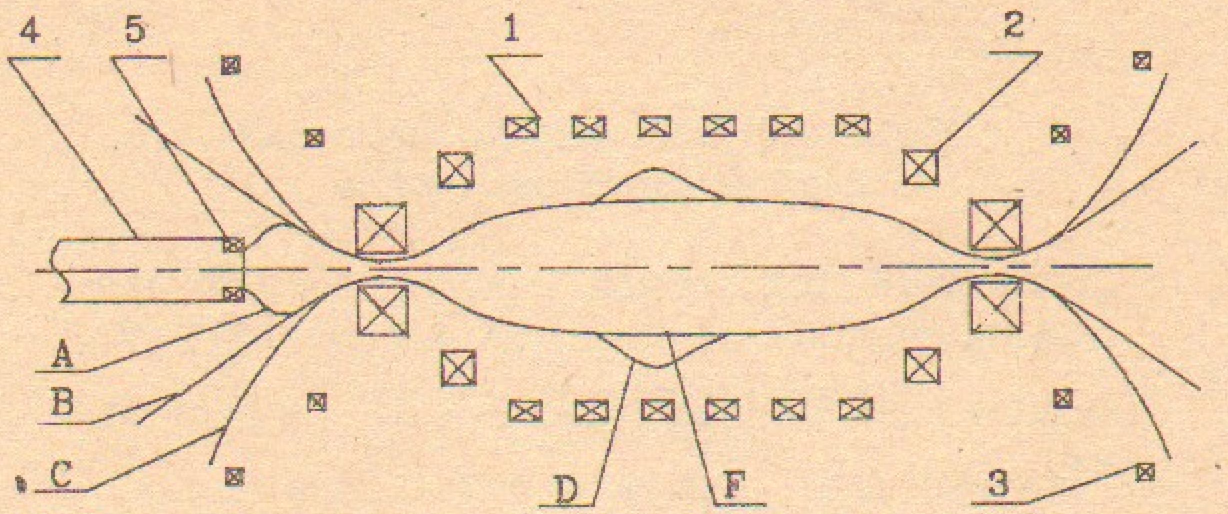

Fig. 1. The GDT layout: *1* - solenoid coils; *2* - mirrors; *3* - expander coils; *4* - plasma gun; *5* - plasma gun solenoid.

Fied line geometry:
A - plasma gun solenoid switched on; B - plasma gun solenoid and expander coil switched off; C - plasma gun solenoid. switched off, expander coils switched on; D - perturbed field lines geometry; F - optimal configuration.

The curvature of the field lines in the region outside the mirrors, where the plasma stream leaking out the trap expands, is controlled by switching on the coils with current opposite to those in the central cell coils (see Fig. 1). These coils are energized with independent supplies.

Both mirror coils are composed of two parts inserted one into another. The outer one is supplied in series with central cell coils, whereas the inner coils are powered independently and produce a field of up to 100 kG. These coils provide a variable mirror ratio ranging from 12.5 to 100.

The warm plasma under investigation is produced in the trap by a plasma source - a hydrogen fed washer stack gun located in one of the end tanks. In Fig. 1 magnetic lines of force are also shown for various regimes of operation.

2. SUMMARY OF THEORY

A stability analysis has been carried out with the Rosenbluth - Longmire pressure-weighted curvature criterion [2]. For a collisional tandem-mirror open trap with 5 to 10

ion-ion mean-free paths between mirrors and the good curvature within the mirror cell this stability criterion quantitatively agreed with experiments [3]. A criterion modification applicable to the gas-dynamic trap was considered in [4]. According to [2, 4] the condition for stability against the curvature-driven flute modes can be represented in the following form:

$$W = \int \frac{\kappa \; (P_\perp + P_\parallel) dl}{r \; H^2} \geq 0 \tag{1}$$

where the normal curvature is κ, the components of pressure tensor are given by $P_\perp$ and $P_\parallel$. An integration is performed along a line with radius $r(l)$ and magnetic field H. Inside the trap $P_\parallel$ and $P_\perp$ should be taken equal one to another. In the expanders $P_\parallel$ is being substituted by $P+\rho \upsilon^2$.

It was found convenient to divide integral (1) into two different parts: the first (W_1) is being extended along a line inside the trap and the other (W_2) in the expanders. For the central cell filled with an isotropic plasma integral W_1 is obviously negative. It is also convenient to express the condition for stability, which is equivalent to (1), in terms of the "safety factor" Q defined as an absolute value of the ratio of contribution made by expanders (W_2) to that from the central (W_1) cell (we assume W_2 being positive). In order that a plasma may be stable against flute modes the safety factor Q should exceed unity. Further we will use the fact that for GDT the Q value is obviously inversely proportional to the mirror ratio (it changes as a plasma pressure in the expanders). For large scale flute modes criterion (1) should be somewhat modified to take into account the spatial structure of perturbations.

As it obviously follows from (1) the regions with a small magnetic field make the greatest contributions to the stability integral. Therefore, the estimation of the safety factor is very sensitive to the choice of the upper limit to this integral that corresponds to spatial points in expanders. In practice, the integration is performed till one of the two imposed limitations is broken. The first condition consisted in that the ion Larmor radius should be small compared to the local curvature radius $(\rho\cdot\kappa) \le (\rho\cdot\kappa)_c$. The second limitation imposed is that the plasma beta should be smaller than unity. Both of these limitations are imposed by the theory and, if violated, make the theoretical predictions rather unreliable. The part of a flux line where these limitations are violated should presumably be considered as region that doesn't make any contribution to the stability criterion.

3. STABLE AND UNSTABLE REGIMES OF CONFINEMENT IN THE GDT

A warm plasma was injected into the trap during 3 ms. Plasma parameters inside the trap depended upon the discharge current and gas feed rate .The density was varied from 1.5 10^{13} cm^{-3} up to 7 10^{13} cm^{-3}, the temperature - from 5 to 15 eV, the plasma radius was ~ 6.5 cm [5]. For all regimes of operation the ion mean free path was substantially smaller than either the total machine length or the distance between the the mirrors .

During the gun operation for any cases, neither MHD instability or substantial transverse plasma losses occurred probably due to line-tying. After the plasma gun was turned off the plasma behavior became sensitive to the curvature of field lines in the expanders.

As has been reported previously [5, 6, 7], when the curvature of the field lines in expanders was favorable and the safety factor for the large scale modes with $m \approx 1$ was calculated to be about 5, a stable regime of the plasma confinement was observed.

The plasma lifetime (which was about 2.5 ms) was in a good agreement with the calculated flow rate through the mirrors. Running the machine without energizing the coils in expanders made the curvature of the field lines there

negligible. Under these conditions during plasma decay there was observed flutes growth which resulted in precipitous plasma losses within approximately 5 time scales for the large scale modes.

The theoretical predictions are generally consistent with the experimental observations with only one notable exception, namely the Q factor, which measurements will be discussed in more detail in the next section.

4. EXPERIMENTS ON THE SAFETY FACTOR MEASUREMENTS IN GDT

Additional efforts were made to quantitatively verify the agreement of the calculated Q value with the experimentall one. Experimentally, two different approaches were used to measure this value. Both used a controllable change of the contribution to stability criterion (1) coming from a certain region occupied by a plasma. During these changes the MHD stability limit, corresponding to Q=1, was reached and then after rather simple calculations it was possible to evaluate Q for initial undisturbed conditions .

As we have mentioned before the contribution made by the expanders is proportional to R^{-1}. One can then change this contribution by varying the current in the inner mirror coils. Varying the mirror field in this way caused negligible field changes in the central cell and the expanders of the order of $\delta H \approx 10^{-3}$ H.

Another approach to measure Q was to change the unfavorable contribution of the central cell in an easy controllable manner. We changed the magnitude of the field locally in the central cell using an additional coil placed near the midplane. Simulation runs were carried out to obtain integral (1) over central part of the trap for a certain current in this coil. If energized, this coil, reduces the safety factor right up to the stability limit, when Q=1. In Fig. 1 one can see a schematic of field lines for this case.

We discuss the experimental results obtained by making use of both the approaches. The plasma lifetime vs the mirror ratio ranging from R=12.5 to 75 is plotted in Fig. 2. We observed the expected linear relationship, corrected slightly for the mirror ratio dependence of the lifetime, within the interval R≤35, as indicated in the figure.

Whenever we exceeded the mirror ratio of 35, the plasma lifetime was found out to decrease due to the instability drive and enhanced transverse losses. For such mirror ratios the MHD activity of a plasma was observed and it can be interpreted as a transition through interchange instability threshold that is attributed to reducing of the expander's favorable contribution to stability criterion (1). An analysis of the data represented in the Fig. 2 indicates that in our operating regime with R=25 the value of the Q factor would be estimated as 1.5-2. The distortions of a plasma radial profile were observed at mirror ratio of 50 by making use of special neutral beam diagnostic [8]. The radial profiles taken during the plasma unstable decay are shown in Fig. 3. This observation also confirms that plasma became unstable for large mirror ratios. Approximately the same value of the safety factor was also inferred from the data obtained at the shots when we changed the configuration of the field lines inside the trap with the additional coil (see also Fig. 4).

5. DISCUSSION

The major success of GDT-experiments in terms of physical base has been the absence of the flute-like modes in the trap as predicted by theory [1]. At the same time throughout the measurement of stability limit with respect to the mirror ratio, we have observed the Q factor to be approximately 20% of the theoretically predicted one. The data taken for unstable regimes show that the driven perturbations have the form of flutes elongated throughout the trap (estimation of $k_\parallel$ gives it to be less then 10^{-3}). The azimuthal spectrum of unstable oscillations was dominated by the modes with $m \approx 1$.

The exact reason for the Q reduction is at present unknown. One of the possible reasons may be an uncertainty in parameter (κρ)ç that defines the upper limit of integration in Eg. 1. As it was mentioned above a value of the safety factor is very sensitive to this limit. On the other hand, this may be a result of some processes in expanders, which alter the plasma flow and are not still taken into account by the theory. While we observed the stability limit, insufficient measurements were made to determine parameters of the plasma flow inside the expanders. This led to additional experimental efforts to determine the characteristics of plasma flow here. The evaluation of integral (1) over expanders requires the data on components of pressure tensor in all points along the field lines, which represents an extremely complicated problem. Therefore, using simple diagnostics we have tried to find out the differences between the plasma flow regime and the theoretical one.

The measurements with the Faraday caps and probes have shown that at least up to the magnetic field $H \geq 10^{-2} H_{max}$ the density of plasma flow changes in accordance with the flux conservation law, namely j/H = const. This means that neither significant ion losses nor significant deviations of ions from the field lines occurred. The measurements of the electron temperature just beyond the mirror throat have indicated it to be much smaller then that inside the trap. Hence, the regime of the plasma flow should be very close to an adiabatic one, when the longitudinal heat transport may be neglected. According to our simulation runs the regime with $T_e \simeq 5$ eV should be also nearly adiabatic. To identify the regime of flow in expanders we have tried to use data on the potential distribution along field lines, the latter being rather sensitive to plasma parameters. Besides that, the potential drop between the mirror throat and end wall is also interesting to know. This enables one to evaluate the ion momentum flux in the near-end-wall regions where the magnetic field is small and from which the contribution to stability is therefore large.

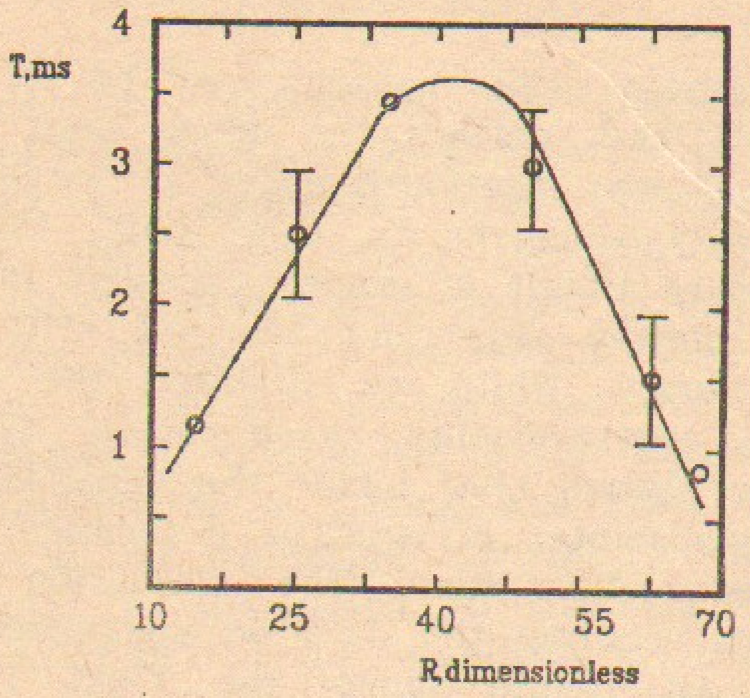

Fig. 2. Plasma lifetime vs. mirror ratio.

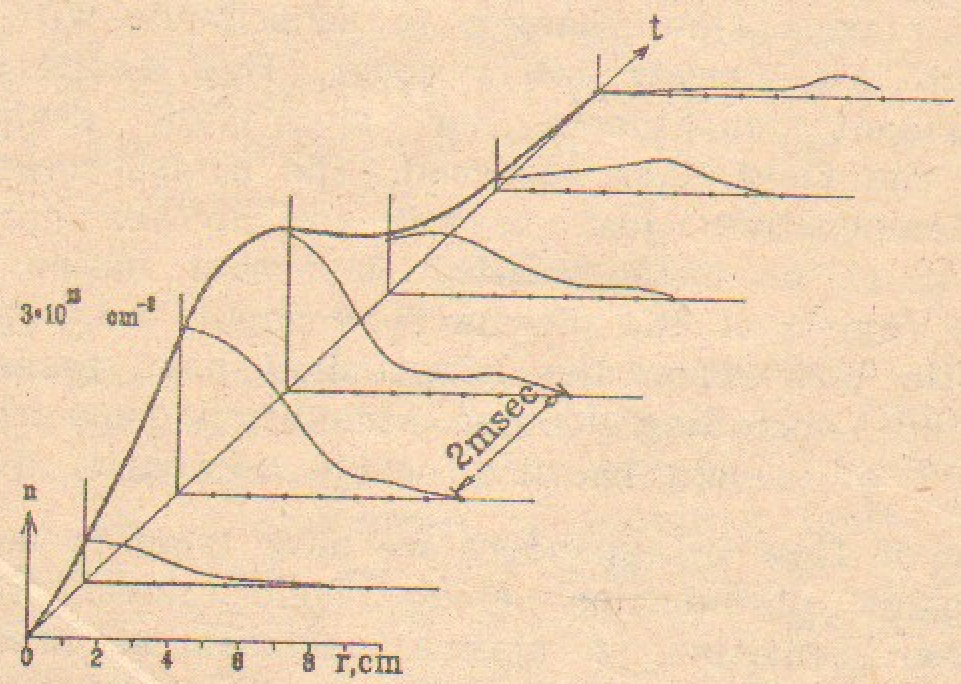

Fig. 3. Density profile during the decay at mirror ratio R = 50.

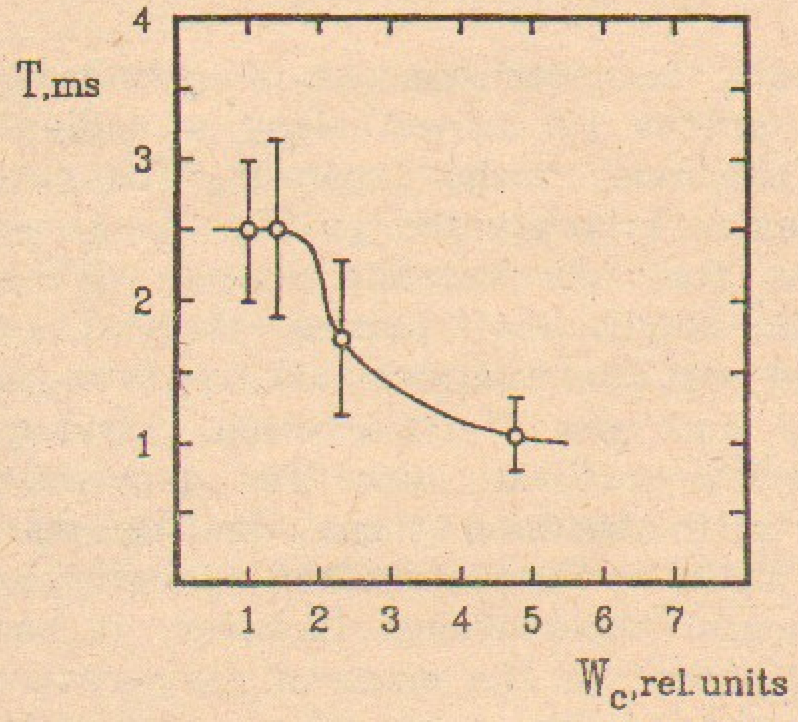

Fig. 4. Plasma lifetime vs. unfavourable conribution from central cell.

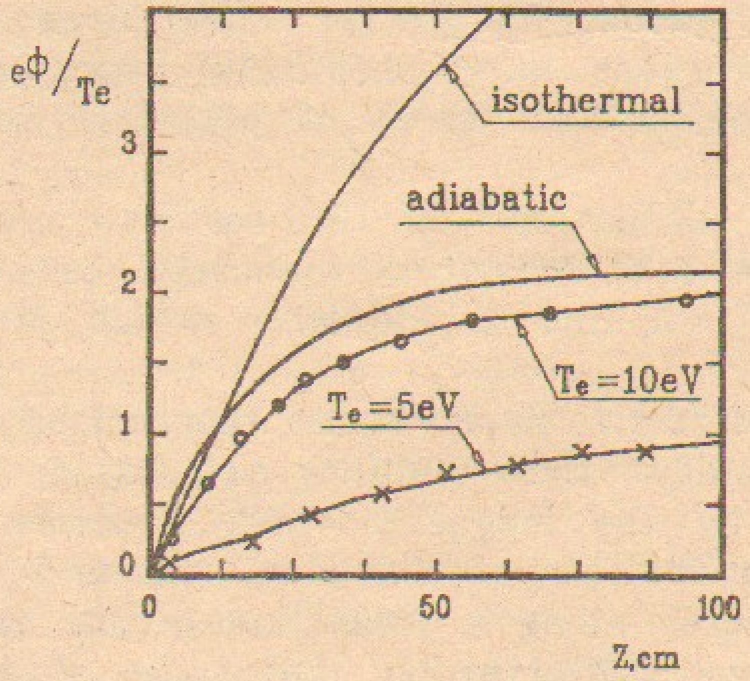

Fig. 5. Potential drop from mirror throat in expander.

We have done the measurements of potential by making use of emissive probes [9] moved along a radius inside the trap and along the axis in the expander. The potential profile in the expander is presented in Fig. 5. Also shown are potential profiles for two opposite limits with an infinite and a negligible longitudinal plasma thermal conductivity. We have carried out calculations taking into account the plasma viscosity and the finite thermal conductivity, and found the calculated potential curve for experimental conditions to be lying in between these limiting curves. Apparently, neither model for potential distribution uniquely fits the experimental observations. However, it has been observed that an increase in the electron temperature to 10 eV provides a potential profile approaching that calculated for the adiabatic regime. This is the reason to hope that a further temperature increase will produce a plasma flow with parameters within the domain where the results of our simulation runs prove applicable. The safety factor has been obtained by use of isothermal as well as adiabatic approximations. It's calculated value is found to be only slightly different (about 25 %) for these opposite regimes. A considerable decrease in Q should be expected from the fact that the experimental curves of potential are lying under the adiabatic one.

An exact calculation of Q for our experimental conditions ($T_e \simeq 5eV$) requires the data on the density profile along a field line in expander which is at present not available.

Additional effects have been theoretically predicted [10, 11] to modify the stability condition from that determined only by the magnetic field structure. They are connected with a finite resistivity of the end plates. The electron temperatures along a field line in the expander are at present unknown. Nevertheless the shape of experimental potential curves indicates it to be substantially smaller than that given by the adiabatic model of flow for the same spatial points. If this is the case, the theory [11] predicts a value of the safety factor which is much smaller compared to the calculated one without taking into account the end wall conductivity.

The stability criterion which has been formulated in terms of the pressure-weighted curvature, obviously needs to be additionally verified in experiments. Apparently, the problem of the quantitative fit of the safety factor obtained from Fig. 1 is inherent not only to GDT. Thus, notwithstanding this stabilization criterion has been qualitatively checked in ambipolar trap experiments [3, 12], in [12] a considerable difference between MHD stability limit and that theoretically predicted has been noted.

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