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MEASUREMENTS OF PLASMA EQUILIBRIUM RESPONSE TO EXTERNAL MULTIPOLE MAGNETIC FIELDS IN AN AXISYMMETRIC MIRROR

BudkerINP 95-4

НОВОСИБИРСК

Measurements of plasma equilibrium response to external multipole magnetic fields in an axisymmetric mirror.

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Abstract

The paper is devoted to the experimental investigation of the plasma equilibrium response to externally applied non-axisymmetric disturbances of the main magnetic field. The results are presented for dipole and quadrupole disturbances applied inside the expander end cell. Comparison of the experimental data with estimates made on the basis of MHD-theory is given. Reasonable agreement with the theory for dipole disturbances was observed.

1 Introduction

During the last decade, a few versions of the MHD-stable, fully axisymmetric magnetic mirrors have been proposed and extensively studied, both experimentally and theoretically [1, 2, 3, 4]. Axial symmetry of the magnetic field of these systems, evidently being beneficial itself for the magnets design, provides also a number of advantages which realize in improved plasma confinement. At the same time, residual disturbances of the symmetry, that nevertheless inevitably remain, may be hazardous to these systems resulting in enhanced radial transport [5] and, for the most extreme cases, even in lost of the equilibrium. In the gas-dynamic trap (GDT)[6], the studies related to this problem were initiated by experimental observations of the plasma behavior during its decay in various configurations of the magnetic field. It was found that the plasma relaxation into an equilibrium state exhibited significant role of non-axisymmetric disturbances of the magnetic field. This gave raise to experimental efforts to elucidate the role of these effects and, if possible, to find the ways of their control and use for the diagnostic purposes.

Here we present a comparison between the experimentally measured response of the plasma equilibrium to the disturbances and the results of its analytical and numerical modelling. The paper is organized as follows. Section 2 describes the experimental setup and initial observations indicating existence of the disturbances. Measurements of the plasma equilibrium response to controlled dipole and quadrupole disturbances of the main magnetic field are presented in section 3. Section 4 contains a comparison of the experimental results with theoretical predictions, stressing the application of the data to measurement of stability properties of the plasma.

2 Experimental setup

The GDT experiment [6, 7, 8] consists of a solenoidal 7 m long central cell which is bounded on each end by an axisymmetric minimum-$|B|$ anchor cell. Axisymmetric magnetic field has a strength of 0.15–0.22 T at the midplane and up to 16 T at magnetic mirrors. The central cell field was produced by a set of coils installed on the vacuum chamber and connected in series, whereas the field in the mirrors can be additionally increased if a small radius mirror magnet was energized from independent power supply. The GDT experiment has several distinguishing features when compared to other axisymmetric magnetic mirrors. The most important of them is that the main plasma which contained in the central cell is assumed to be strongly collisional, so

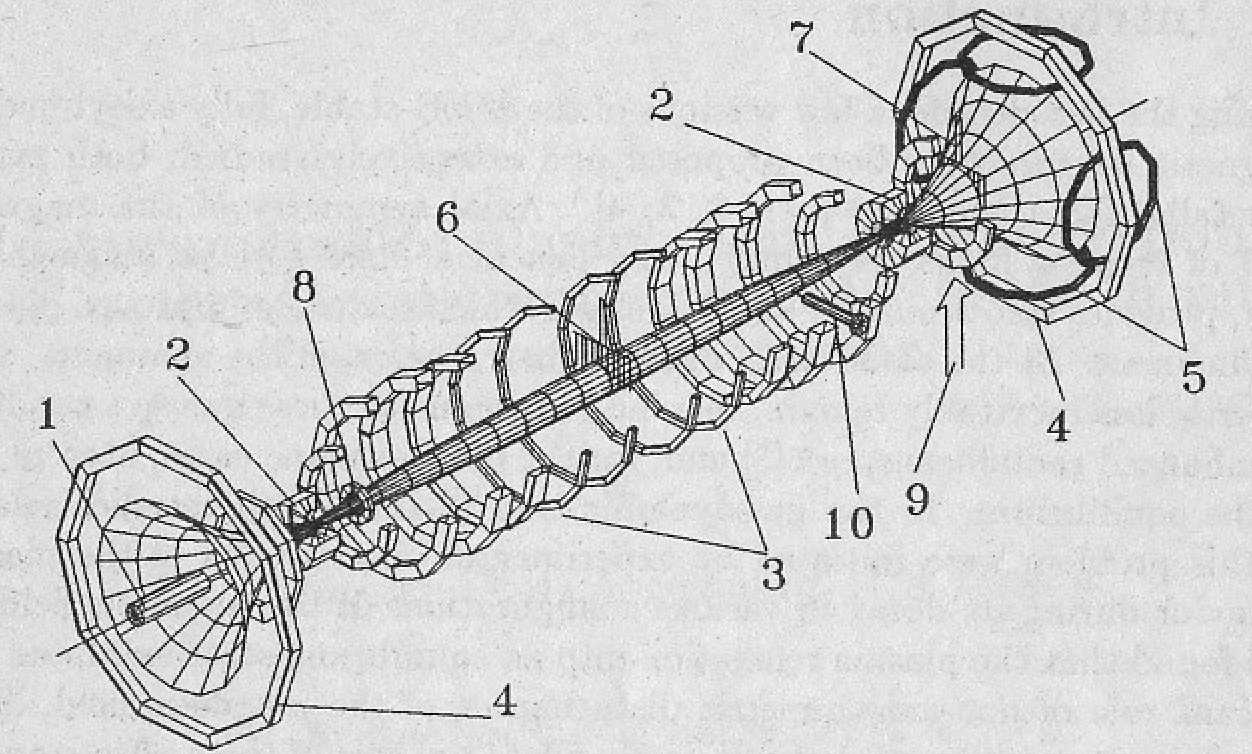

Figure 1: *Experimental layout and diagnostics.*
1 – plasma gun; 2 – mirror coils; 3 – central cell coils; 4 – expander coil; 5 – disturbing coils; 6,7 – linear probe array; 8 – azimuthal probe array; 9 – RF-interferometer; 10 – movable triple probe.

that the ion mean free path of scattering into the loss cone is small compared to the distance between the mirrors. Under these conditions, the regions of plasma expansion just beyond the mirrors, where the expanding field lines have a favorable curvature, can be served as rather effective MHD-anchors. The reason is that the collisional losses from the central cell are high enough to sustain relatively high density of the transient plasma outside the mirrors. By adjusting the magnetic field at the mirror throats, the plasma density inside these regions can be increased above a certain value, so that to make the pressure-weighted curvature averaged over the entire trap be favorable for MHD-stability. This stability has been successfully demonstrated in recent experiments on the GDT facility [8].

The experimental layout is schematically depicted in Fig.1. The plasma build-up in the trap was performed by a plasma gun located beyond the magnetic mirror in one of the end tanks. During the gun operation plasma remained macroscopically stable, within certain limits, even if the instability threshold defined by the pressure-weighted curvature criterion [9] has been exceeded. This phenomenon was attributed to the electric contact of the central cell plasma with the plasma inside the gun where it is supposed to

be highly conductive across the magnetic field. The peak plasma density reached during a typical shot for 3ms gun operation was $\sim 6 \times 10^{13} cm^{-3}$ with electron temperature 5–10 eV.

Systematic measurements of the plasma column offset and radial width were done by making use of linear probe arrays located in the central cell and inside the expander. Locations of the probes and other diagnostics used are shown in Fig.1. However, the first observations were made using an azimuthal array of probes that measured the plasma density at periphery. Calculations using a Gaussian model density profile which has been shifted from the axis to simulate what was seen by the probes have shown that the plasma centroid experienced significant movements during the decays. The accuracy of such a reconstruction is less in comparison with the accuracy of the plasma core data obtained with the linear arrays of probes. Nevertheless, this approach enabled us to trace the macroscopic plasma movements during the shots with reasonable credibility.

In stable decays, it was observed that the plasma column, after the gun being turned off, had a chaotic initial offset from the geometrical axis of the trap. Subsequently, during $\sim 300 - 500\mu$sec, the plasma involved to a position that turned out as being almost the same for different shots. The motion had a form of shifting into the final position that further remained unchanged during the decay (~2ms) or it appeared as a damping oscillation about this position. A few samples of trajectories of the plasma column center during the relaxation are shown in the Fig.2. Open circles indicate the initial positions of the plasma just before the decays, whereas the intermediate positions during the relaxation are shown by the solid ones. As it is easily seen, the final position of the plasma centroid was considerably shifted from the geometrical axis of the machine. We anticipate that the plasma offset observed in our experiments is provoked by uncontrollable dipole disturbances of the magnetic field.

Previously, in [10, 11], the influence of external non-axisymmetric disturbances of a plasma equilibrium in a long axisymmetric magnetic mirror was treated in approximation of the ideal MHD-theory. It was noted that multipole disturbances should cause perturbations of a pressure profile with a corresponding azimuthal number. Rough estimates based on this theory indicated that the transverse on-axis field of the order of a few gausses would be sufficient to explain the measured offset. Residual dipole disturbances of the main axisymmetric field may result from misalignments of the coils, existing of soft-iron-made parts near the device, etc. Because of the pulse character of the main magnetic field, screening currents in metallic structures of the walls of the building could also provide considerable contribution to

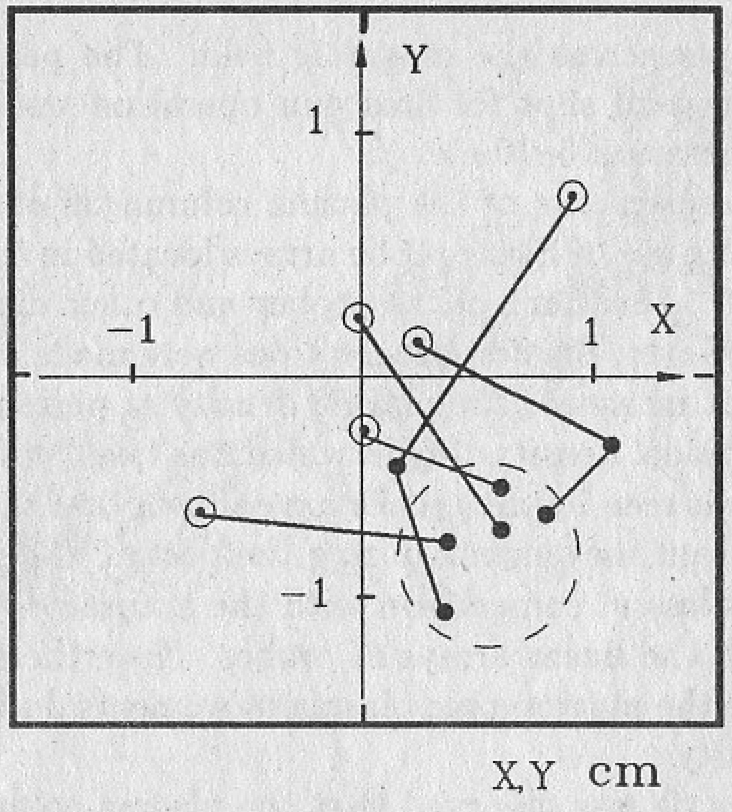

Figure 2: *Plasma centroid motion during stable decays.*

the distortions. Note that unstable decays also exhibited preferable direction of the motion of the plasma column after switching the gun current off. This observation could be also accounted to the existing disturbances of the symmetry.

Obviously, it is practically impossible to avoid completely distortions of the axisymmetric magnetic configuration. Hence, it seems very important to develop a reliable control system of a plasma equilibrium position and a shape which will be able to reduce these distortions to an acceptable level. Furthermore, this system, if complemented by a proper feed back loop could be capable of stabilizing large scale flute perturbations. Specifically, we studied the possibility to control the plasma equilibrium using the coils that produce small transverse magnetic fields in the regions of the plasma expansion beyond the mirrors. As it was first mentioned in [10], because of the fact that the main magnetic field here is quite small, the external field applied in these regions could alter the equilibrium to the maximum possible degree. Anticipating a brief summary of the theoretical results given in Discussion, note, that the theory predicts the plasma column offset in the case of a dipole perturbation to be determined by a pressure-weighted curvature of the field lines. It is then worth note that stability properties of the plasma can be judged quantitatively from the data on the plasma offset as a function of

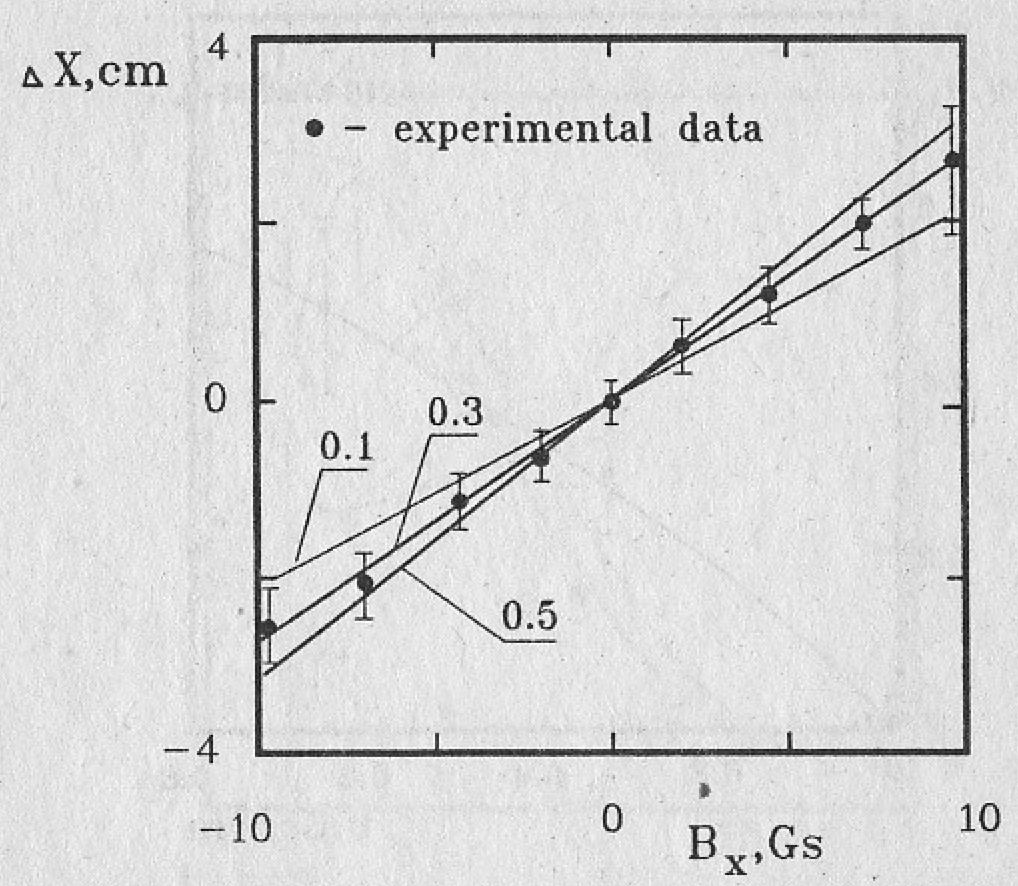

Figure 3: *Plasma offset vs amplitude of dipole disturbance*

amplitude of applied dipole perturbation. More elaborately, the measurements of the plasma off-axis shift under dipole disturbance which externally applied inside the expander, can provide one with the data on the stability properties of the high-m localized flute modes. This data can also be used in order to estimate stability boundary of large scale flute modes which, if driven unstable, can degrade the plasma lifetime.

3 Application of controlled disturbances

In our experiments, the dipole perturbations in the expander were produced by a pair of coils with inner radius of 0.84 M installed at the distance between them of 2.4 M (Fig.1). The magnetic field generated by the coils was practically homogeneous over the expander region occupied by the plasma. Fig.3 shows the shifts of the plasma centroid, measured from its non-disturbed equilibrium position, as a function of transverse field amplitudes in the expander.

Quadrupole perturbations in the expander were generated by two pairs of coils of 0.5 m in diameter (Fig.1). The currents in opposite coils in each pairs were opposite to generate the additional field of the quadrupole symmetry.

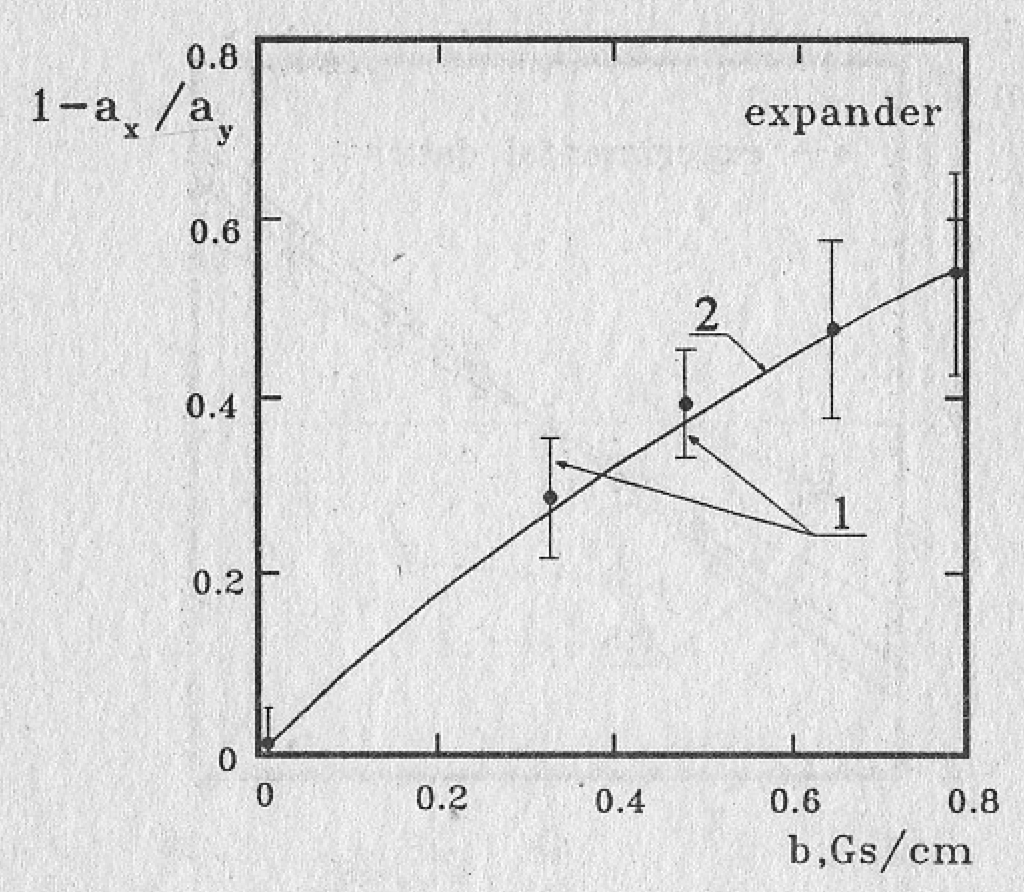

Figure 4: *Plasma ellipticity vs amplitude of quadrupole disturbance: 1 – experimental data; 2 – calculated for the adiabatic regime of flow and* $\kappa\rho_{crit} = 0.3$.

Referencing to conventional approach, we characterized on-axis amplitude of the perturbation by the quadrupole parameter b(z) appearing in the expression for the disturbed scalar potential $\delta\phi = (x^2 - y^2)b(z)$. Due to relatively small radius of the disturbing coils, this parameter significantly changed over the expander. Resulted ellipticity of the plasma column was measured by a linear array of the Langmiur probes located inside the central cell and by RF-interferometer (λ=8mm) which measured the linear plasma density along the diameter. The interferometer was situated just beyond the mirror throat in the expander. To deduce the ellipticity from the interferometric data, we have used the values of linear plasma density measured along the perpendicular diameters for subsequent shots in which the currents in the disturbing coils was changed so as one would expect 90° rotation of the ellipsoid around the z-axis. Fig.4 shows the measured ellipticity as a function of value of b(z) taken in the z-position of the center of the disturbing coils.

The majority of the data were taken when the magnetic field in the end tank was of the expander's configuration. During these experiments, the coils set that provided cusp configuration inside the end tank has been installed [12]. Thus we were able to choose the cusp or expander configuration for use

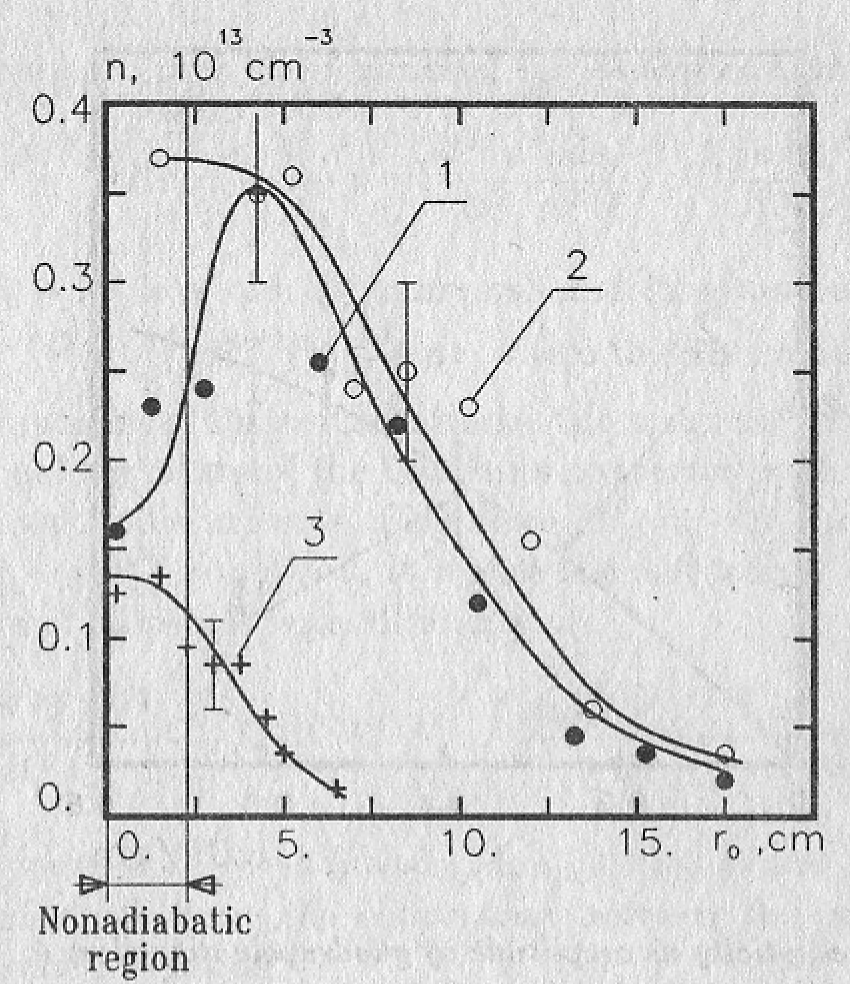

Figure 5: *Plasma density profiles in the cusp end cell: 1 – experimental data; 2 – calculated from the particle balance equations; 3 – experimental data in the outer cusp section.*

in certain series of shots by reconnecting outer and inner coils of the end tank. The plasma inside the cusp was fed by the collisional losses from the central cell. Its density was considerably higher in the adiabatic region as compared with the plasma in expander due to partial trapping between the local field maxima in the ring and point cusps. Typical density profile, measured by a movable triple probe in the cusp, is shown on Fig.5 as a function of the field line radius at the midplane. Also shown in the Fig.5 are the profiles calculated by equating the local losses near certain field line from the central cell which feed the cusp and those from the cusp end cell. In the calculations, we were taking into account temporal variation of the plasma density in the central cell during the build-up and subsequent decay. The axial density profile was assumed constant in accordance with the triple probe data. A distinct feature of the cusp-anchored gas-dynamic trap is the singularity of a specific volume of the flux tubes $\int \frac{dl}{B}$ near the axis. A theory that relevant

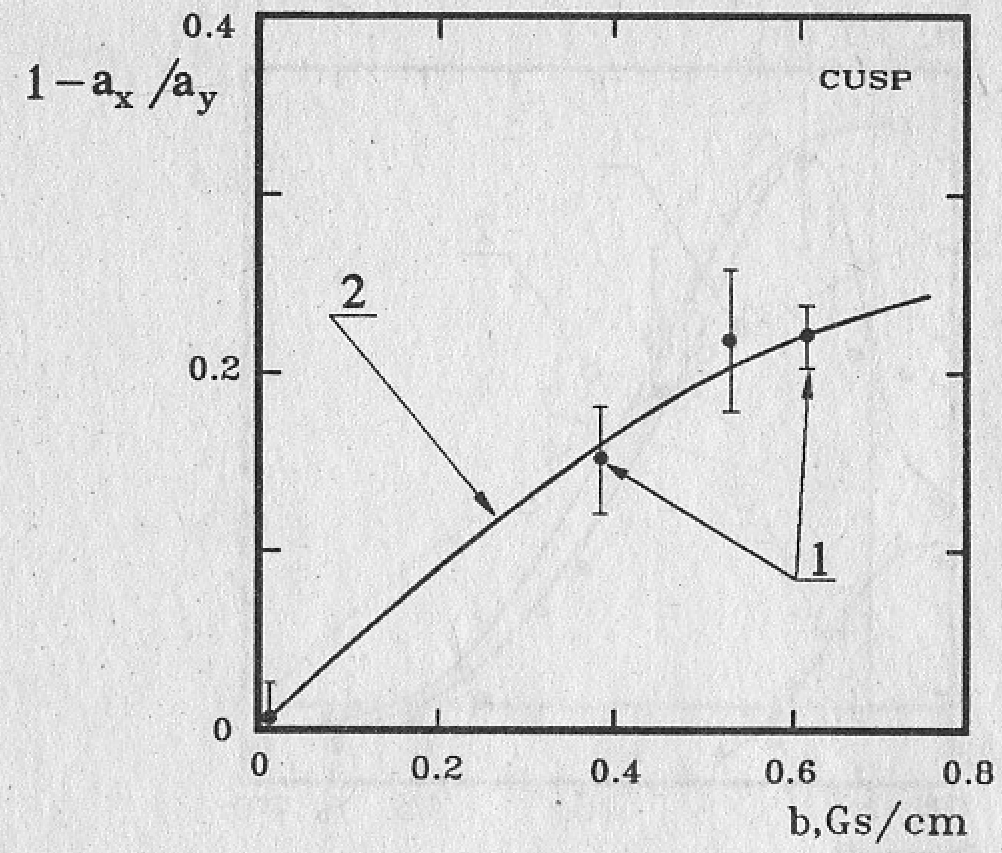

Figure 6: *Plasma ellipticity vs amplitude of quadrupole disturbance: 1 – experimental data; 2 – calculated curve.*

to this case [13] deduces the equilibrium response which is quite different as compare to that for trap with expander end cell. The measured ellipticity vs amplitude of the quadrupole disturbance in the cusp is presented in Fig.6. The data also show reasonable agreement with the MHD plasma model over a wide range of the amplitudes of the disturbances.

4 Discussion

A plasma equilibrium in an axisymmetric gas-dynamic trap with multipole external disturbances of the magnetic field was first discussed theoretically in [10]. The equilibrium was treated in an approximation of ideal magneto-hydrodynamics. To facilitate the discussion of our experimental results we display the main relationships following mainly to the results of [10, 11]. In the case of dipole disturbance, when a small $\delta H_x(z)$ transverse field is applied, the components of the magnetic field can be written in the form (using a long thin approximation) : $H_z = H(z)$, $H_x = \delta H_x(z) - \frac{x}{2}H'(z)$, where H(z) - is the unperturbed on-axis magnetic field. It follows from the results of [10] that, when mapped on the midplane, the surfaces of constant

plasma pressure are then to be enclosed circles shifted from the axis by:

$$\Delta x = \frac{1}{\sqrt{H_0}} \times \int \frac{d^2\delta x}{dz^2}\frac{\hat{p}ds}{H^{3/2}} \Big/\Big/ \int \frac{\hat{p}\kappa ds}{H^2 r} \qquad (1)$$

Here $\hat{p} = P_\perp + P_\parallel$ is a sum of transverse and longitudinal pressures, function $\delta x = R^{-1/2}(z)\int_{-\ell}^{\ell} R^{1/2}(z)\frac{\delta H_x}{H(z)}dz$, where the integrand comprises corresponding component of the perturbation of the magnetic field - δH_x, and $\frac{d^2\delta x}{dz^2}$ is an additional curvature of the field lines connected with the disturbance.

If a quadrupole disturbance of the form $\delta H_x = -2b(z)x$, $\delta H_y = +2b(z)y$, $\delta H_z = -(x^2 - y^2)\frac{db}{dz}$ is applied, it makes the surfaces of constant pressure take the form of ellipsoids with ellipticity of:

$$\int \frac{ds\hat{p}R^{1/2}E^{-1/2}}{H^2}\frac{d^2}{dz^2}R^{-1/2}E^{1/2} \Big/\Big/ \int \frac{ds\hat{p}R^{1/2}E^{1/2}}{H^2}\frac{d^2}{dz^2}R^{-1/2}E^{-1/2} \qquad (2)$$

where $E(z) = \exp(4\int_0^z \frac{b(z)}{H(z)}dz)$ and R-is a current mirror ratio. Integration in 1,2 is performed along the entire trap between the end walls which is considered to be insulating.

Equation 1 that defines the offset of the plasma column was somewhat rewritten as compared to that obtained in [10] using paraxial approximation. This allows to reduce it to the form where one can easily recognize in the denominator the pressure weighted curvature that enters the MHD-stability criterion [9] for localized flute modes with $m \gg 1$. Hence, the data represented in the Fig.3 can be regarded as a measurement of the averaged curvature. We compared the value of this parameter inferred in such a manner from the data on the equilibrium response with our previous measurements of the MHD-stability limits in the gas-dynamic trap [14]. To proceed with more detail comparison of both methods, note that the value of the integrals which enter 1,2 strongly depends on a choice of the limits of integration. These corresponds to the points near the end walls where the magnetic field significantly diminishes resulting in possible violation the approximations of MHD-theory. The upper limit of integration was fixed by a condition that at least either of two imposed limitations is broken: $\kappa\rho \leq \kappa\rho_{crit}, \beta \leq 1$. For the typical core plasma conditions of GDT, only the former limitation was practically violated. We kept track of these conditions just at the certain field line corresponding to a maximum of the pressure gradient because it is quite obvious that response of the plasma column is determined mainly by a region at the radial profile where pressure gradient has its maximum. According to this consideration, we have calculated the integrals for other radii canceling the integration at z-position where the limitations broken for the field line corresponding to this maximum. The value of $\kappa\rho_{crit}$ in the calculations was varied from 0.1 to 0.5.

Fig.3 shows the curves calculated with the assumption that the plasma parameters vary along the field lines in expander following to an adiabatical low. This assumption is consistent with our previous results presented in [14]. We found that the data given in Fig.3 can be well fitted by the curve calculated for $\kappa\rho_{crit}$=0.3. Sensitivity of the calculated shift to the limitation imposed on $\kappa\rho_{crit}$ is illustrated by the curves corresponding to $\kappa\rho_{crit}$=0.1 and 0.5. The choice of $\kappa\rho_{crit}$ =0.3 as a best fit is also supported by the measurements of the plasma ellipticity, the results of which are shown in Fig.6.

Doing as so, we tried to compare the pressure-weighted curvature of the field lines obtained from the experiments with the controlled disturbances of the magnetic field and that from the stability boundary. In fact, the comparison was made in terms of the position of the point on the field lines to which the integration could be performed. The position of this point was fixed by the limiting value of $\kappa\rho_{crit}$, which thus define upper limit in the stability integral. This approach suggests, of course, that parameters of the plasma flow in the expander are known (we assumed that they were correctly covered by either izothermal or adiabatic model of the flow [15]). A comparison to the experimental data on electrostatic potentials in expander show, that the adiabatic model is reasonably accurate only for the regimes with neutral beam heating in the central cell [14] when the electron temperature was higher than 10 eV whereas in these experiments it was about 5 eV. Nevertheless, the estimations of $\kappa\rho_{crit}$ obtained with both methods were found to be in reasonable agreement.

As it was already mentioned, our previous experiments on the MHD-stability limits in the gas-dynamic trap have shown that the expander's contribution to the stability criterion was considerably less than that calculated for $\kappa\rho_{crit}$=0.5. Present experiments also indicate that $\kappa\rho_{crit}$=0.3 is a more appropriate value to be used in agreement with our previous measurements of the stability boundary.

Finally, it worth to note of the role of finite Larmor radius effects [16] in the problem under consideration. In principle, one could expect strongly reduced response to quadrupole disturbance because these effects could prevent the plasma from being distorted with azimuthal numbers $m \geq 1$ [17]. However, our experiments did not reveal any influence of these effects on the plasma equilibrium response to the perturbations. In our case, this might be a consequence of rather low temperature of the plasma. Nevertheless, further

theoretical considerations are needed to provide a quantitative answer.

This research was supported in part by the U.S. Department of Energy under the Contract No.B192560 with the Lawrence Livermore National Laboratory.

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Изучение отклика плазмы на внешние мультипольные магнитные поля в аксиально-симметричном пробкотроне

Ответственный за выпуск С.Г. Попов
Работа поступила 16 января 1995 г.

Сдано в набор 20 января 1995 г.
Подписано в печать 20 января 1995 г.
Формат бумаги 60×90 1/16 Объем 0.7 печ.л., 0.6 уч.-изд.л.
Тираж 200 экз. Бесплатно. Заказ N° 4

Обработано на IBM PC и отпечатано на
ротапринте ИЯФ им. Г.И. Будкера СО РАН,
Новосибирск, 630090, пр. академика Лаврентьева, 11.