Experimental PseudoSymmetric Trap EPSILON

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Abstract. Within the framework of the conceptual project "Adaptive Plasma EXperiment" a trap with the closed magnetic field lines "Experimental Pseudo-Symmetric trap" is examined. The project APEX is directed at the theoretical and experimental development of physical foundations for stationary thermonuclear reactor on the basis of an alternative magnetic trap with tokamak-level confinement of high β plasma. The fundamental principle of magnetic field pseudosymmetry that should be satisfied for plasma to have tokamak-like confinement is discussed. The calculated in paraxial approximation examples of pseudosymmetric curvilinear elements with poloidal direction of B isolines are adduced. The EPSILON trap consisting of two straight axisymmetric mirrors linked by two curvilinear pseudosymmetric elements is considered. The plasma currents are short-circuited within the curvilinear element what increases the equilibrium β. The untraditional scheme of MHD stabilization of a trap with the closed field lines by the use of divertor inserted into axisymmetric mirror is analyzed. The experimental installation EPSILON-OME that is under construction for experimental check of divertor stabilization is discussed. The possibility of ECR plasma production in EPSILON-OME under conditions of high density and small magnetic field is examined.

1. Introduction

The concentration of intellectual and financial resources on Tokamak direction has allowed proving experimentally the feasibility of controlled fusion in the magnetic confinement systems (MCS). With a new acuteness a question to fundamental physics of magnetic confinement arises: - Is it possible, in principle, to improve essentially the properties of fusion reactor? The Kurchatov Institute conceptual project APEX is aimed on the development of the physical foundations for steady state fusion reactor based on an alternative type MCS capable of high β plasma confinement with a tokamak-like lifetime. The various stationary MCS with large β and without "superbanana" trajectories of the charged particles are examined. In the present paper the idea of linked mirrors is developed. It is well known, that plasma with large β can be obtained in mirrors, but the confinement time is small in comparison with tokamak scale. The obvious solution of a problem consists in closing of two mirrors by two curvilinear elements (CE) [1]. Many authors offered various variants of linked mirrors. The ELMO Bumpy Torus experiments are most known. The trap DRACON with short-circuited plasma currents was proposed in [2]. Now there are no experiments with linked mirrors. The physical reason of such situation consists in large plasma losses in all the proposed MCS. One of the basic APEX tasks is the clarification of the fundamental cause of large losses and development of methods on their elimination by tailoring geometry of MCS.

2. Principle of pseudosymmetry

The search for good MCS from the standpoint of steady state confinement of high-pressure fusion plasma is largely based on the analysis of the topography of the magnetic field strength B on an equilibrium magnetic surface (MS) [3-5]. The fast "superbanana" losses are eliminated if **all** $B=const$ contours on the MS encircle either the magnetic axis or the major axis of the torus. The former type of traps has been named poloidally pseudosymmetric (PP type), the latter – toroidally pseudosymmetric (TP type). The simplest example of PP trap is axisymmetric mirror. Tokamak is the simplest TP system. Two types of pseudosymmetry (PS) are topologically incompatible. The **principle of pseudosymmetry** could be pronounced

– the separate traps linked in a closed system must have *the same type* of pseudosymmetry. All linked mirrors proposed up to now contravene this principle. As a result the confinement is bad. In the most general form the condition of PS has a form [5]

$$\frac{[\mathbf{B}\nabla r]\nabla B}{\mathbf{B}\nabla B} = f\ , \tag{1}$$

here *f* is a bounded function, **B** is the magnetic field vector, and r is an arbitrary label of MS. The well-known relation determines the MS in a trap without the rotational transform

$$U = -\oint \frac{dl}{B} = const\,. \tag{2}$$

The choice of function *f* influences upon the plasma confinement through the change of magnetic field geometry. The choice *f=0*, known as isodynamic or orthogonality condition, makes the MCS ideal for plasma confinement, because the drift surfaces of **all** charged particles coincide with MS. The choice *f*=*f*(ρ), known as quasisymmetry condition in traps with rotational transform, provides for new stellarators the tokamak-like confinement. The traps with closed field lines allow the choice *f*=*f*(ρ,θ), where θ is the field line label. Such traps have the equal length of all field lines on MS and have been named isometric [3]. Isometry in 3D systems can exist only in the limited space. The PS condition implies merely that the function *f* should be bounded. In this case the unconfined superbanana drift orbits are eliminated [4]. The PS condition can be fulfilled throughout the trap. By the appropriate choice of the special magnetic flux coordinates the general condition (1) can be reduced to the behavior of the magnetic strength on the magnetic surface

$$\frac{\partial B}{\partial q} + f\,\frac{\partial B}{\partial z} = 0. \tag{3}$$

Here *ζ=const* is the surface of the magnetic potential in vacuum. Since the PS condition (3) refers to MS only, the layer optimization of MCS is possible. Actually, in order to obtain good plasma confined in a trap it may be enough to satisfy condition (3) only over the narrow boundary layer. Low radial transport inside this layer may play the role of a barrier that reduces the total losses. This possibility is discussed in [6].

2.1 Isometry in a trap with a flat axis in paraxial approximation

According to a PS principal the CE in linked mirrors should be of the same type as straight mirrors, i.e. of PP types. To demonstrate of existence of such CE without rotational transform we shall consider the isometry in a trap with a flat axis in paraxial approximation. In the isometric systems the lengths of the segments of the field lines on MS between **any** two contours *B=const* are equal. For the magnetic axis curvature *k* and for MS ellipsoidal cross-section ε=*a/b* (*a* in magnetic axis plane) we obtained equations

$$ka = C_1(ab)', \tag{4}$$

$$aa'' - bb'' = -0.5C_1^2(a^2b^2)'' - (2C_1a_1 + C_2)(ab)'. \tag{5}$$

Here $C_{1,2}$=*const* and prime denotes the derivative along the magnetic axis. The choice $C_1=C_2=0$ gives the known orthogonality condition for straight mirror. At $C_1\neq 0$ the relation for axis curvature (4) of isometric trap coincides with the expression obtained in [3]

$$k = const\,\frac{B_0'}{B_0^{3/2}}\exp\left(\frac{h}{2}\right), \tag{6}$$

here B_0 is the magnetic field on the axis; the MS ellipticity is equal to $e = \tanh h$. If *const* in relation (6) is replaced by a function, the PS condition is obtained. The change of curvature sign, i.e. zigzags of a magnetic axis, is a salient geometrical feature of PP CE. On *FIG.1* the PP curvilinear element calculated from paraxial expressions is shown. The gray-scale intensity indicates the B value. One can see that all B=const lines encircle the magnetic axis. There exist solutions for closed bumpy torus-like systems, too.

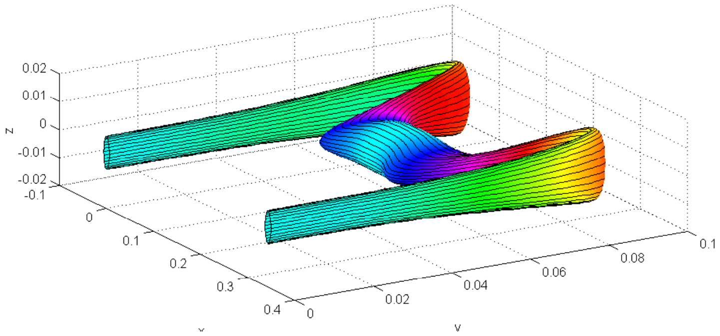

FIG.1. PP CE, color shows the B=const contours on MS.

3. MHD stabilization of a trap with closed field lines with the help of a magnetic divertor

The traps with the closed field lines (CL) are characterized by large longitudinal gradients of magnetic field. This circumstance as well as PS condition and large β makes the realization of MHD stabilization by average *minB* difficult [7]. However, the traps with CL have additional, though practically unexplored, opportunity for stabilization. It is known that for MHD flute-like stability in the case of CL the condition (7) should be satisfied [8].

$$-\nabla p \nabla U + \frac{\gamma p (\nabla U)^2}{|U|} \geq 0 \quad . \tag{7}$$

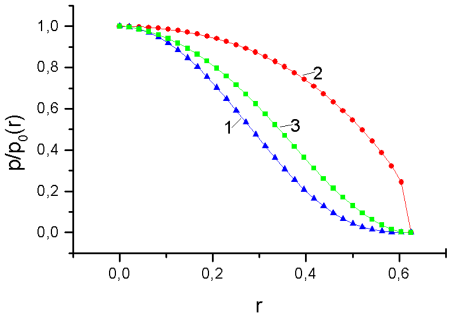

FIG. 2. Marginal stable pressure profiles, B=0 at r=0.62m; 1 - $p_\perp >> p_\|$ ($\int p_\perp dl$ is shown); 2 - $p_\perp = p_\|$; 3 – “mirror” distribution function.

Here p is pressure, γ=5/3 is the adiabatic exponent. If the U value has a minimum on some magnetic surface, the stability obviously takes place when the plasma pressure is concentrated near this surface (first term in (14) is positive). In a trap with toroidal divertor the quantity U has a minimum on the separatrix ($U \to -\infty$) due to formation of a ring with B = 0. In the situation of practical interest the maximum pressure is on the axis, instead of separatrix. The MHD stability is possible in this case too, but due to the second term (7). The marginally stable p profile is defined by equality in (14) and is characterized by p=0 on separatrix [9]

$$p = const \cdot \left(\oint \frac{dl}{B} \right)^{-g} . \tag{8}$$

The condition (7) is correct for plasma with finite pressure. Thus, if there is the equilibrium with pressure profile (8), it is stable against convective modes. This stabilization mechanism works due to "rough" effect of nonparaxiality. The nonparaxial stabilizing effect works and for axisymmetric mirrors, too. Such simple traps with divertor can be used as the components of the closed system, providing stability without violation of PP. The study of plasma stability in One Mirror Element (OME) with a divertor is the important step of the program on Experimental Pseudo-SymmetrIc cLOsed trap (EPSILON). In isolated mirror trap the pressure is anisotropic, $p_{\perp}>p_{\parallel}$. The anisotropy strengthens the stabilizing effect, since the large group of particles is located in the area with strong gradient of a magnetic field. On *FIG.2* the calculated marginal pressure profiles under EPSILON-OME experiment conditions for various distribution functions are shown. In accordance with results of [10], **all** MHD perturbations in axisymmetric trap with isotropic pressure are stable if condition (7) is satisfied and one-dimensional equation describing flute and ballooning perturbations has no more than one negative eigenvalue. The preliminary calculations show that the limiting β increases at increase of pressure on separatrix. For experimental study of this effect the additional plasma source is provided in divertor ring cusp of EPSILON-OME installation.

4. Experimental pseudosymmetric trap EPSILON

Within the framework of the project APEX a trap with the CL and with a flat axis EPSILON is examined theoretically. This trap consists of two axisymmetric mirrors with diverters and two PP CE. The diverters provide the MHD stability and the existence of omnigeneous equilibrium MS. The conforming to PS principle eliminates large "superbanana" losses. To obtain large β there are two possibilities: use of the rippled magnetic field all over the trap (as in ELMO bumpy torus) or only in special CE with the short circuited secondary currents (as in DRACON). In EPSILON the latter possibility is examined. The line closing in EPSILON is achieved by making MCS anti-symmetric about the median plane. The mirror symmetry and isometry can be used for short-circuiting of secondary currents in PP CE. Due to the fact that each cell of EPSILON trap possesses mirror confinement, it is possible to begin the experimental study of separate cells.

4.1 EPSILON-OME experiment

The experiment on isolated mirror EPSILON-OME has been chosen as the first step of APEX experimental program. The requirements of physical representative and maximal use of available equipment determined experimental parameters. The former requirement is ensured by stationary operation, attainability of high β in a large enough volume and possibility to verify the new scheme of MHD stabilization. The available equipment has determined the range of magnetic field and plasma parameters: magnetic field in the center 0.28T; mirror ratio 2.8; volume of confined plasma 1.25m^3; CW 0.5 MW ECR heating at frequency 7GHz; maximum β~0.15. Magnetic configuration of EPSILON-OME installation is shown on *FIG.3*. Twin divertor coils are pulled apart for better access of ECR power to the center of the trap. Such a configuration also permits to create a cusp trap on the separatrix near the ring B=0. Plasma production in this small trap will add the stabilizing effect to that of the divertor. The calculated marginally stable profiles are shown on *FIG.2*. It can be seen from the figure that profiles are monotonous and usual for experimental practice.

4.2 ECR heating at weak magnetic field

Weak magnetic field is characteristic of plasma systems with high plasma pressure. For rather weak magnetic field the plasma density exceeds density value determined by condition $w_{pe} = w$. So, the possibility of plasma production with the use of ECR in EPSILON-OME is under question. The analysis of electromagnetic waves penetration through the dense plasma to the ECR surface was done in [11]. Two systems of ECR plasma productions are designed.

The first system has the longitudinal near axis microwave input for dense plasma production. The second system has the transversal input for plasma production in the cusp region.

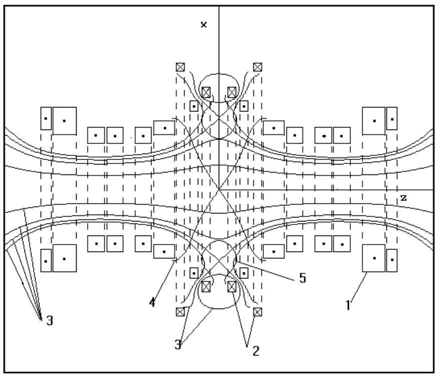

FIG.3 EPSILON-OME magnetic configuration: 1 – mirror coils, 2 – divertor coils with opposite current, 3 – field lines, 4 – fundamental ECR surfaces, 5 – second harmonic ECR surfaces.

5. Conclusion

Convergence of closed and opened systems may lead to the development of the stationary magnetic trap capable of high β plasma confinement with tokamak level of losses. Ideas of PP and divertor MHD stabilization give a new approach to the old idea of mirrors linking into a closed system. The first step of experimental activity is the construction of EPSILON-OME installation. The start of experiments is expected within two years. Numerous discussions with V.D. Shafranov had determining influence on our study. The work is partially supported by Russian Foundation for Basic Research, No. 00-15-96526, Program of support to scientific schools.

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