# Project EPSILON – the Way to Steady State High β Fusion Reactor

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**Abstract.** Pseudosymmetry (PS) principle being used for hot plasma confinement magnetic systems construction could provide realization of all the magnetic confinement potential. Namely: to realize hot plasma confinement at steady state operational mode with a "tokamak" confinement time level. The high β regime lets a possibility to think about advanced fuels (D- $^3$He, D-D).

It is proposed to check the main idea and preliminary theoretical examination experimentally in frame of EPSILON project – closed rippled magnetic trap without rotational transform and with poloidal PS. The EPSILON consists of two (or more) crimped mirror traps, closed with curvilinear elements. MGD stability and plasma cleaning are provided with axially symmetrical divertors displaced along the mirror traps with zero magnetic field at separatrix.

## 1. Introduction

The fusion parameters of magnetically confined hot plasma will be got in ITER – the first experimental thermonuclear reactor that is now prepared for construction. As the nearest goal of magnetic fusion development is coming near, next stage problems becomes actual. They are the problems of magnetic confinement system optimization from reactor technology point of view. Power reactor should have high power, technology and economic efficiency, be serviceable and meet safety and ecology demands. Because of the reason, world fusion development efforts along with the largest tokamak experiment realization should take aim at looking-for possible improvements of magnetic confinement systems. The improvements could be consisting in inherent steady state high β operation, technology simplification, efficiency increasing and possibility to use ecologically attractive fuels (D$^3$He).

## 2. Project EPSILON .

Unacceptable losses through mirrors turned out the main obstacle in the way of fusion reactor construction on base of mirror trap. Different schemes of the losses diminishing were proposed. One of those was an idea of few traps connection into closed system. One of the first such proposals was Kadomtsev's idea to close two crimped mirror traps by two toroidal magnetic elements with strong magnetic field [1]. We propose to realize that idea on base of last time conception of hot plasma magnetic confinement distinctive features. EPSILON consists of two or more mirror traps with divertors (Ordinary Magnetic Elements – OME), connected with the same number of CRELs (CuRve Elements)

### 2.1. Principle of Pseudosymmetry

Magnetic field geometry quality specifications are based on magnetic field module level lines topography (isomagnetics lines) at equilibrium magnetic surfaces [2]. Namely magnetic field geometry and charged particle drifts define as plasma confinement so pressure limitation on plasma equilibrium in magnetic trap. In axially symmetric systems with strait axis all Larmor centers of all charged particles don't leave a magnetic surface during its drift motion and,

consequently, any neoclassical losses are absent as well as secondary plasma current (high β is possible). In tokamak (unique closed symmetrical system with unipolar current) the generalized toroidal momentum conservation leads to motion of charged particles banana trajectory centers along magnetic surfaces. Because of that a neoclassical transverse diffusion and secondary Pfirsh – Shluter currents are arising and decrease significantly an equilibrium beta (in experiment the beta is usually limited by MHD instability at significantly smaller level). Experiments show a possibility of rather good confinement in tokamaks and stellarators at low β meanings. Steady state 3D magnetic systems (Stellarators, for instance) are, as a rule, characterized by increased losses because of "superbanana" drift trajectories presence (banana trajectories of banana centres).
The isomagnetic line topography analysis has shown that 3D situation isn't an obstacle for drift motion integrals existence in limited region of a plasma confinement. The traps with such regions were named quasisymmetrical ones. And what is more, it turned out that even without the drift motion integrals presence it is possible to eliminate the "superbanana" drift trajectories, which are defined reason in a magnetic system properties worsening. It is sufficient to provide longitudinal adiabatic invariant level lines for all particles be closed around magnetic axis or around axis of torus. The magnetic field level line topography at equilibrium magnetic surfaces have to be characterized by island absence, i.e. the isomagnetic lines should be closed around magnetic axis (as in mirror trap) or around torus axis (as in tokamak). Those demand have got name: *pseudosymmetry* condition. The prefix *pseudo* reflexes the fact that there is neither symmetry nor drift motion integrals [3].
There are two types of pseudosymmetry: poloidal and toroidal ones. Only the poloidal one provides high beta operation. It is very important to note that the two types of pseudosymmetry are topologically incompatible. To provide good confinement one should not make both of them at one magnetic surface. (Unfortunately that mistake was done almost systematically in previous proposals).

### 2.2. **EPSILON Physical Basement**

The project EPSILON fundamental positions are as follows:

1. Pseudo symmetrical geometry of a magnetic configuration;
2. Drift surfaces embedding;
3. Practical absence of rotational transform;
4. MHD stability is provided by a magnetic "hillock" instead of a magnetic "well";
5. High β in principle.

***Pseudo Symmetry*** (PS) of a magnetic configuration is necessary to get a "tokamak" level of plasma confinement. It means that "super banana" transverse losses are absent [4]. The problem is to provide the PS at the CRELs. The important point is: because of poloidal symmetry of the base solenoidal elements, the CREL's PS should be namely poloidal one [5]. In that case all the isomagnetic lines, $|\mathbf{B}| = B = \text{const}$ at equilibrium magnetic surfaces should enclose the magnetic axis. That is fulfilled automatically at axially symmetric parts of the system.
***Drift surfaces embedding.*** (DSE) The PS condition is necessary but not sufficient one for good plasma confinement. It should be supplemented with condition of DSE in which case contours of constant longitudinal magnetic invariant

$$J = \int \mathrm{v}_{||} dl \text{ , where } \mathrm{v}_{||} \text{ is longitudinal particle velocity,} \qquad (1)$$

enclose a magnetic axis and coincide in ideal case with equilibrium magnetic surfaces (quasi isodynamics, QID). Here . The integral (1) should be calculated along a magnetic line. In case of trapped particles it should be taken between points of reflection, $\mathrm{v}_{||} = 0$ and for the passing ones – along the whole closed contour. Failure to execute the QID condition gives additional loss. QID could be provided having the magnetic force lines length between any two isomagnetic lines on equilibrium magnetic surface independent on azimuth (isometry condition, IM) [1]. Unfortunately the IM can't be provided exactly in toroidally closed geometry [1]. But fortunately the IM is not necessary condition to provide the QID. It is sufficient to meet a weak IM condition, i.e. magnetic lines length equality between isomagnetic lines with the same magnetic field module value (the same mirror ratio).

In the EPSILON project QID for strongly passing particles is very important. As for such particles the integral in (1) should be taken along the whole closed trap, the QID will be provided if the magnetic field axis is shorter than all the other magnetic force lines. Equilibrium magnetic surface is defined with isolines of U

$$U(\Phi) = \oint \frac{dl}{B} = \text{const} \quad . \qquad (2)$$

So minimum of U should be achieved also at magnetic axis. Toroidal divertors with zero magnetic fields at separatrix promote substantially achievement of that goal. It is clear from (2) that $U \to \infty$ at the separatrix. The divertors keep the axial symmetry of the solenoids and don't spoil PS at high $\beta$ values.

***Rotational transform*** (RT) plays very contradictory role in plasma confinement. On the one hand it provides existence of real and topologically stable magnetic surface formed by one magnetic force line. Shear of the rotational transform is very strong MHD stabilizer. On the other hand the rotational transform excites lot of MHD instabilities and is a reason of $\beta$ value limitation. Project EPSILON does abandon in fact the rotational transform and use effects of plasma compressibility for MHD stabilization and possibility of significant $\beta$ value increasing. It is well known that magnetic field closing makes a magnetic surface topologically unstable. It seems that any disturbance of mirror surface (say, at installation assembling) or any transverse magnetic field appearance (like Earth magnetic field) should immediately "unwind" the force lines and plasma will flow along those to a wall. But in reality any such a kind disturbance generate unipolar longitudinal plasma current, which results small rotational transform that provides topological stabilization of magnetic surfaces. To control those currents and to compensate dynamically transverse parasitic magnetic fields it is foreseen to use special windings. So the EPSILON is the trap with low rotational transform. Next question is: whether the plasma compressibility stabilizing effect will be kept at presence of such rotational transform values? This problem was investigated theoretically and it was shown [3] that up to rotational transforms

$$\mu \sim \frac{\rho_i R}{a^2}, \qquad (3)$$

where $\rho_i$ - ion Larmour radius, a – plasma radius, R – characteristic toroidal radius, plasma compressibility stabilizing effect is kept. At so low rotational transforms force lines after one turning about the trap are shifted to distances less or comparable with ion Larmour radius. With $\beta$ increasing the system with low rotational transform becomes more close to system with a zero one.

***Divertors influencet.*** Analysis of a divertor system influence to particle confinement (in particular – to fusion products confinement) [9] and to plasma equilibrium [10,11] was done.

As for the collisionless transversal *particle losses*, those take place only from rather thin plasma layer (its thickness is of Larmour, $\rho$, radius order of value) displaced close to edge magnetic surface (of confinement region). The $\rho$ value near the field null should be estimated as the $\rho$ calculated for field value taken at a distance $\rho^* = \left(v_T / |\nabla \omega_c|\right)^{1/2}$ from field null. Here $v_T$ - is thermal velocity. Cyclotron frequency gradient, $\nabla \omega_c$, should be taken at a point B=0.

For fusion products $\rho$ is relatively large, but they are born rather far from the separatrix.

For some little fraction of passing particles the losses because of non adiabatic situation (it takes place also in layer with a thickness of $\rho$ order of value) can be important. That can occur if such a particle endures displacement from one magnetic surface to another during passing through a CREL. (Pitch angle variation itself is not dangerous under $\mu$ nonconservation in closed trap). It is relatively simple to find the $\Delta\mu$ value which is necessary for non adiabatic zone definition. It was done for different field models of trap with ring divertor and practical application of the obtained expressions was estimated.

*Plasma equilibrium* in mirror trap with a divertor was calculated in [11] on base of Grad – Shafranov equation at given currents in external coils and different plasma pressure profiles $p(\psi)$ ($\psi$ - flux coordinate) with $p$ was equal to zero at separatrix. Anisotropic plasma $(p_\perp \neq p_{||})$ equilibrium at that configuration was examined as well [11]. In that case besides of generalized Grad – Shafranov equation the longitudinal equilibrium equation (which binds $p_\perp$ and $p_{||}$) was taken into consideration. The result is: presence of a divertor don't prohibit from equilibrium achievement at $\beta \sim 1$, where the $\beta$ value should be accounted using plasma pressure and vacuum magnetic field in a divertor centre. It should be noted that because of unlimited rising of $U = \oint B^{-1} dl$ near the separatrix, the equilibrium isn't destroyed by CRELs influence.

***Plasma stability questions.*** MHD flute stability in traps of interest without average $\min B$ is provided because of strong magnetic field nonunuformity in the divertors. In MHD model with isotropic plasma pressure such a nonunuformity influence becomes apparent as plasma compressibility effect. The stability condition can be written as follows [12]

$$w_{MHD} = \nabla p \cdot \nabla U + \gamma p \frac{|\nabla U|^2}{U} \geq 0, \tag{4}$$

where $\gamma = 5/3$. Indifferently stable pressure profile is

$$p^* = p_0 \left( \frac{U}{U_0} \right)^{-\gamma}, \tag{5}$$

Index 0 means value at axis.

The stability condition has been got in MHD model for collisionless plasma is sufficient because a disturbance potential energy is not less than in that model. Cruscal – Oberman kinetic model allows profiles with more value of $|p'/p|$ than follows from (5). That was demonstrated for configuration with divertor in [13].

The condition of formula (4) don't limits $\beta$ value; it can be fulfilled at a finite pressure as well, when the value U is calculated with real equilibrium magnetic field **B** (specific kind of the indifferently stable pressure profile $p^*(\psi)$ generally speaking is dependent on $\beta$). $\beta$ limitation arises from balloon disturbances. The MHD model gives for a long system very low critical value of $\beta$. For instance, as it was shown in [14,15], if magnetic coils are symmetrical relatively some plane crossing toroidal magnetic system (such a symmetry provides closing magnetic force lines), then

$$\beta_{cr} \sim \pi^2 \frac{a}{|\bar{\kappa}| L^2}, \tag{6}$$

where a – plasma "minor radius", $\bar{\kappa}$ - characteristic force line curvature , $L$ - force line length. That critical value is defined by a most long "antisymmetric" balloon mode with two nulls of displacement $\xi$ (Fig.1.). If $L>>a$ that gives $\beta_{cr} << 1$ and $\beta_{cr}$ the less, the $L$ more.

However it is necessary take into account that while the mirror ratio in the divertor is high, most of particles in it are trapped. Those "feels" fields disturbances in the region of localization only and responds to the disturbance as to local flute one (with amplitude of disturbance in given divertor). While the field nonunuformity is high the trapped particles give strong positive (stabilizing) input into the disturbance potential energy. This kinetic effect can't be uncovered in MHD model). If there are many divertors displaced along the system periodically, with length of the period, l, then [14]

$$\beta_{cr} \sim \pi^2 \frac{a}{|\kappa|\, l^2}\,. \tag{7}$$

At $l << L$ estimation with the formula (4) gives much higher value than the MHD criteria (3). The limitation of (4) defined by a balloon mode with half length l in which the displacement should be equal to zero in each of divertors (see fig 2).

There is another possibility: balloon instability localized in a divertor itself, at its radial periphery (the mode which is antisymmetric relatively divertor equatorial plane). It is necessary to investigate its influence on critical $\beta$ value.

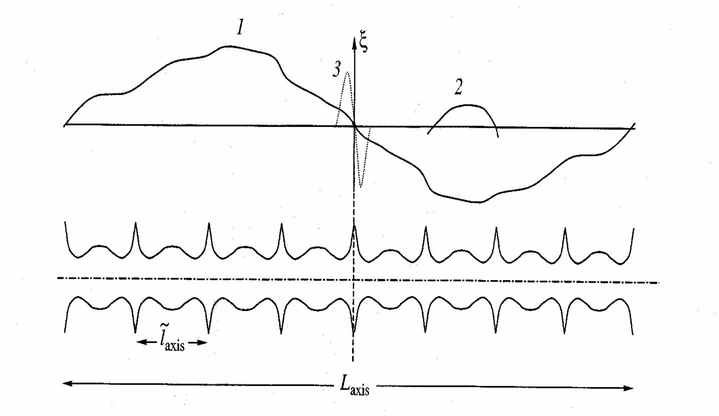

Fig.2. Displacement $\xi$ in balloon disturbance 1 – long wave disturbance which defines $\beta$ in MHD model; 2 – disturbance with zeros in each divertor, which defines $\beta$ with account of trapped particles; 3 – antisymmetric mode localized in divertor;

***Some problems of a high β***. High β could raise some problems. For instance we should meet the mentioned above QID conditions for passing particles. As it was demonstrated in [16], that at low average $<\beta>$ the QID conditions are realized with magnetic hill conditions. At high $<\beta>$ the QID can be provided with magnetic well. But there is some intermediate range of the parameter where the $J$ contours are fully destroyed that leads to high losses. So, high $<\beta>$ mode of operation should be achieved with some force crossing of that barrier.

## 3. Some about Reactor Perspective of the Closed Mirror

The main EPSILON scheme attractive inherent features from reactor conditions point of view are as follows:

***Steady state operational mode.*** Current drive is not necessary i.e. energy and momentum injection systems are not necessary as well.

***High β mode of operation*** provides more flexibility in reactor realization and exploitation. For D-T reactor, in particular, there is a possibility of significant specific power increasing at given magnetic field value. On the other hand it is possible to diminish magnetic field value at given specific power, if that defined by wall thermal load. β value variation is rather important for load regulation in power circuit.

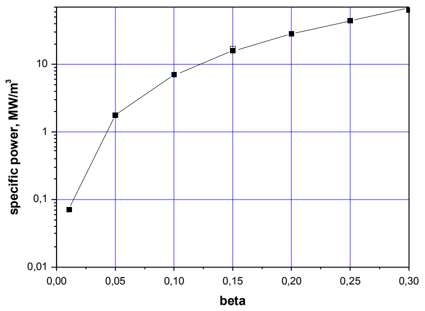

Fig.2 Specific power, MW/m$^3$, in D-T reactor at T=15 keV, as a function of β. It's increasing (limited by wall thermal load) lets to get more compact reactor. EPSILON geometry causes more uniform power flow to the first wall

Advanced fuel cycles (D-$^3$He and D-D catalyzed) can be considered for EPSILON type reactor in connection with high β operational mode. Potential advantages are rather known: radiation problems diminishing and, for D-$^3$He, energy efficiency increasing (if proper direct conversion devices will be developed). Fig. 3 and 4 demonstrate critical values of energy confinement time, $t_E$, and triple product, $nTt_E$, for those cycles, versus β value, which were got with "0 D" calculations by formulas being usually used for such estimations (see, for instance [17]). One could see that it is possible to hope to ignite D-$^3$He and D-D catalyzed reactors at β > 0,25-0,3.

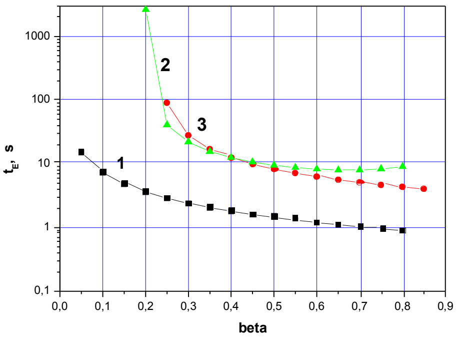

Fig.3. Critical confinement time $t_E$, [s], as function of β. 1) D-T,2) D-D cat.,3) D-$^3$He

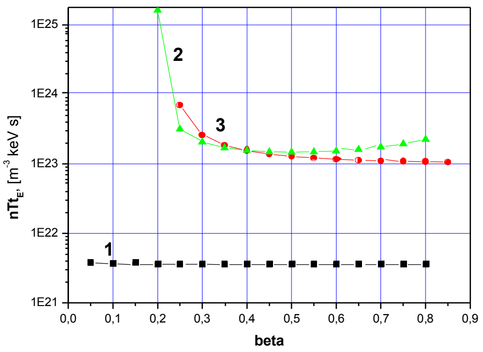

Fig.4. Critical triple product, $nt_ET$, [m$^{-3}$s keV] as function of β. 1) D-T,2) D-D cat.,3) D-$^3$He

***Magnetic system structure additivity.*** Each OME length can be prolonged without principal limitations that let increase reactor installed nuclear capacity.

## 4. Proof-of-Principle. Proposed EPSILON-M experiment

It is proposed to check the main statements of the project in frame of EPSILON-M experiment – closed rippled trap without rotational transform and with poloidal pseudosymmetry. It is combination of two axially symmetrical mirror traps closed by curved connectors . MHD stability and plasma cleaning will be provided with symmetrical toroidal divertors displaced along the mirror traps with zero magnetic field at separatrix.

Poloidal pseudosymmetry lets a unique possibility to divide the closed trap into separate elements that could be fabricated and investigated independently. In proposed project such elements are mirror traps and curved connectors.

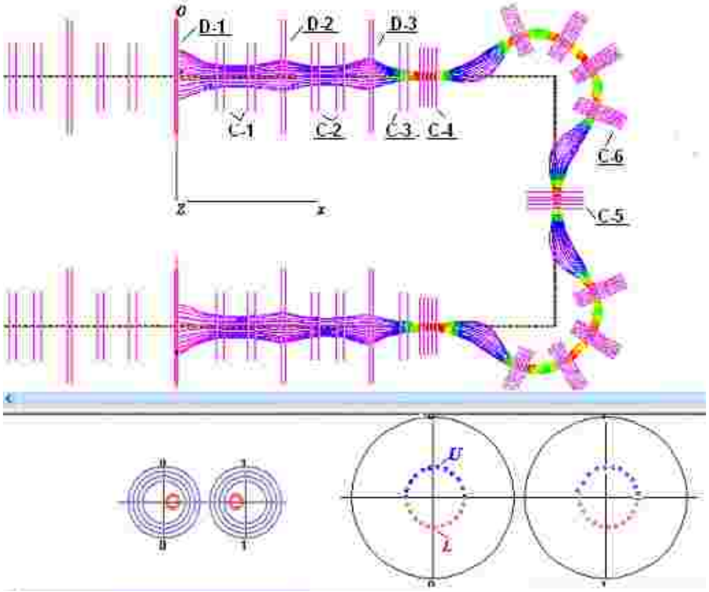

Fig.5. EPSILON-M magnetic configuration. D – divertor coils, C – solenoid coils

EPSILON-M magnetic configuration (Fig.5.) is arranged with water cooled copper coils of round form. The main axis rectangle dimensions are 1.6m x 5.2m. OMEs are displaced at long sides; the shorter ones are occupied by CRELs and matching coils C-5. Plasma heating methods: at CRELs – ECR; at OMEs – ICR and OXB scheme [18]. Mode of operation – steady state. Working gases – hydrogen, deuterium.

The EPSILON-M main parameters

| | | |
|---|---|---|
| 1 | Plasma volume, $m^3$ | 1.2 |
| 2 | Average plasma diameter in solenoids, $m^3$ | 0.3 |
| 3 | Maximal plasma density, $m^{-3}$ | $10^{19}$ |
| 4 | Plasma temperature, keV | 0.5 |
| 5 | Confinement time, s | 0.005 |
| 6 | Average $\beta$ in solenoids | 0.1 |
| 7 | Magnetic field in solenoids, T | 0.1 |
| 8 | Magnetic field in CRELs, T | 1 |
| 9 | Heating power, MW | 0,5 |

## 5. Conclusion

The proposed magnetic confinement system should provide mirror confinement of majority of plasma ions in practically axisymmetric mirror traps and confinement of significant part of passing particles. Plasma stability should be also provided by the divertor system.

Previous open trap experiments can be used for EPSILON development. In particular it is possible to use the ambipolar methods of particle and energy confinement which are well developed and checked. The CRELs have a service function of energy loss diminishing. They liquidate plasma contact with a wall along magnetic force lines and solve problem of electron temperature increasing in open traps. Because of high $\beta$ operational mode and specific structure the system can be attractive from its possible reactor perspective point of view.

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