PARTICLE DRIFT ORBIT TOPOLOGY IN PARAMAGNETIC PLASMAS OF SPHERICAL TRAPS.

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A big interest now is connected with investigations of plasma confinement in tokamaks with small aspect ratio – "spherical" tokamaks in which thermal/current magnetic energy ratio is $\beta_j \le 1$ (paramagnetic plasmas) and the ratio of current magnetic field value to toroidal field value is $B_j/B_0 \sim 1$. In this situation together with particle trajectories which are known from the standard neoclassical theory new trajectories arose as was found in Ref. [1].

In this paper for topology of all types of charged particle trajectories analysis the equation of motion in drift approximation is used [2]

$$\psi(\varepsilon,\theta) = J + \varsigma \frac{v_{\|}}{v}(1+\varepsilon\cos\theta) = J \pm \varsigma(1+\varepsilon\cos\theta)\sqrt{1-(1-G)b} \quad (1)$$

where G is Hamiltonian of drift equations which is connected with the normalized magnetic momentum, J is the canonical angular momentum, $\varepsilon = r/R$ is toroidicity, R – is the major tokamak radius, θ is the poloidal angle, $\psi(\varepsilon,\theta)$ is the poloidal magnetic flux, $b(\varepsilon,\theta)$ is normalized magnetic field, $\varsigma = 2\rho q/R$ is the small parameter of the drift approximation – normalized Larmor radius ρ, q is the safety factor.

With help of the model solution [3] ($dP/d\psi = \text{const}$ and $d\Phi^2/d\psi = \text{const}$, where P is plasma pressure and Φ is the poloidal current) of Grad-Shafranov equation the magnetic surfaces for the toroidal plasma column placed into the ideal conductive shell with circular cross-section were calculated

$$\psi = \varepsilon^2(1+\eta_1\varepsilon\cos\theta) - \eta_1\varepsilon\varepsilon_a^2\cos\theta \quad (2)$$

here $\varepsilon_a = 1/A$ is the inverse aspect ratio. In this case the dependence of the magnetic field module on plasma pressure and on the current magnetic field is

$$b(\varepsilon,\theta) = \frac{B}{B_0} = \frac{1}{1+\varepsilon\cos\theta}\sqrt{B_t^2 + B_\theta^2} \quad (3)$$

where $B_t^2 = 1 - \left(\frac{B_J}{B_0}\right)^2 (\beta_j - 1)(1 - \psi A^2)$, $B_\theta^2 = \left(\frac{B_J}{B_0}\right)^2 \varepsilon^2 A^2 (1 + \eta_2 \varepsilon \cos\theta)^2$,

$\eta_1 = (\beta_J + 1/4)$, $\eta_2 = 4(\beta_J - 1/2)/3$.

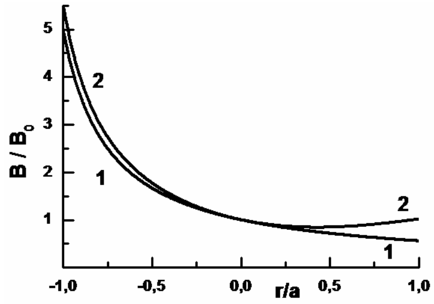

Fig.1.

In Fig.1 the dependences of the vacuum magnetic field amplitude (1) and the magnetic field amplitude for $\beta_j = 1$ and $B/B_0 = 1$ (2) are given. One can see that when $\beta_j = 1$ the magnetic field amplitude has minimum at $r/a \sim 0.2$. Here a is the minor tokamak radius. This minimum produces the trajectories which were found in [1]. It is convenient to represent the different types of trajectories on G-J phase plan [4] (Fig.2). On the same Figure one can see the discriminant curves for particles which crossed equatorial plan. These curves are calculated with help of equations

$$F = \psi - J \pm \varsigma V_{\|}(1 + x) = 0 \quad (4)$$

$$\partial F / \partial x = 0 \quad (5)$$

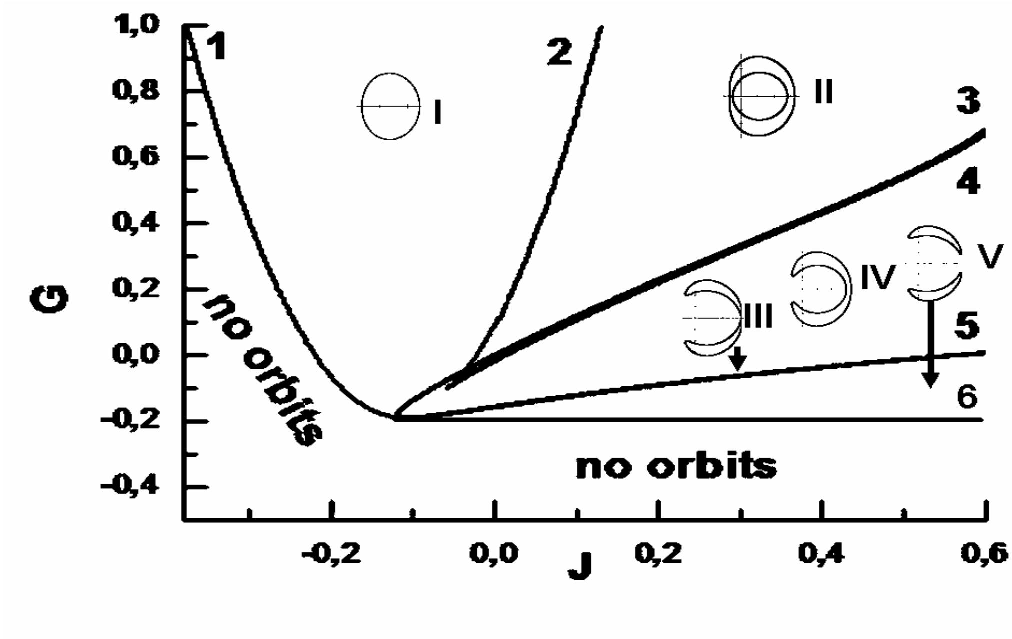

Fig.2.

Here $x = \varepsilon \cos\theta$. The curves are found for A=1.25, $\varsigma = 0.2$, $\beta_j = 1$ and $B/B_0 = 1$. In the same Figure the curves which are correspondent to conditions when parallel to magnetic field velocity is equal to zero at $\theta = 0$ (curve 5) and $\theta = \pi$ (curve 3). Curve 1 is the locus of co-passing stagnation orbits, 2 is the locus of counter-passing stagnation orbits, 4 is the locus of the banana pinch orbits, 5 is the locus of tear drop pinch orbits, 6 is the locus of tear-drop stagnation orbit. The curves which describe orbits with $V_{||}(\theta = 0) = 0$ and the locus of tear drop pinch orbits in the Figure scale are coincide. Curves 1 and 6 show the boundaries of orbit existence. In this Figure I is co-passing orbit, II are co- and counter passing orbits, III is tear drop pinch orbit, IV is banana orbit, V are tear drop orbits.

For rough estimation we will accept that radial transport mainly depends on trapped particles. Taking into account all calculated trajectories let us use the result of the random walk method

$$\chi \sim f_b \Delta\varepsilon^2 \nu_{eff} \quad (6)$$

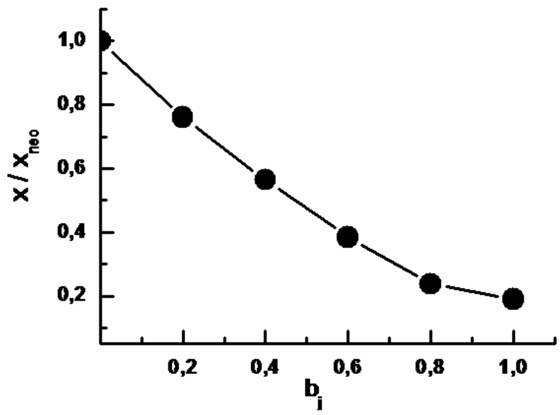

Fig.3.

where f_b is the fraction of trapped particles which are placed between curves 4 and 6 in Fig.2. For simplicity let us neglect by the f_b dependence on β_j and let us take as $\Delta\varepsilon$ the maximal excursion of orbit from magnetic surface ε_s. In Fig.3 one can see the normalized on the neoclassical value coefficient of radial diffusion as function of β_j for $\varepsilon_s = 0.6$. From this Figure one can see that when $\beta_j = 1$ in a spherical tokamak the radial diffusion coefficient can be less in 5 times in comparison with its neoclassical value.

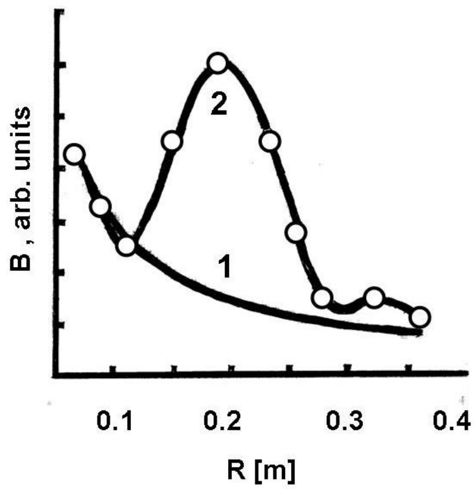

Fig.4.

Even more exotic orbits we found in the toroidal oblate field-reversed configuration. In Ref. [5] the results of investigations on TS-3 (Japan) trap with strong paramagnetic toroidal field are described. The toroidal magnetic field radial distribution on 61 μs of discharge time is given (curve 2). Curve 1 is vacuum toroidal magnetic field. One can see that radial dependence of the toroidal magnetic field is enough complex. This field has two minimum and two maximum. In such magnetic field amount of different types of article orbits is greater than in usual tokamak. The typical orbits one can see in Fig.5.

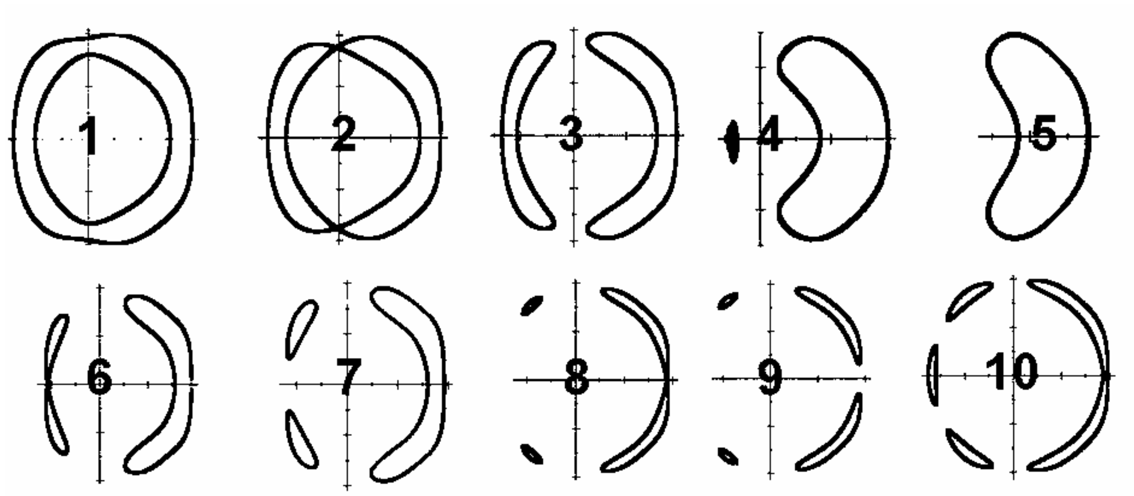

Fig.5

We named these orbits as follows. 1 is untrapped, 2 is vertical pinch, 3 and 4 are twins, 5 is banana, 6 are twins with reverse tear drop pinch, 7 is Trojan system, 8 is Trojan system with tear drop pinch, 9 and 10 are trapeze. It is need to mention that all orbits with the same number have the same values of G and J.

The estimation of the radial transport coefficient in this trap shows that transport in this case is strongly suppressed. Coefficient of radial diffusion is 20 times less than calculated with help of the neoclassical theory and is only 5 times greater than classical one.

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