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By analytical and computational consideration it is shown that the condition of quasi-isodynamicity for the configurations with poloidal direction of the contours of the magnetic field strength on the magnetic surfaces can be fulfilled with high enough accuracy for compact configuration. It is shown that for the configurations with toroidal direction of these contours the condition of quasi-isodynamicity is equivalent to the condition of quasi-symmetry, so that there is no the gap between these two conditions. The further optimization is required to stabilize the ballooning modes in the considered configuration.

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Key words:

helical plasma, fast particles confinement, pseudo-symmetry, quasi-isodynamicity

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M.I. Mikhailov, K. Yamazaki

I. Introduction

During last decades it was shown (see, e.g., [1-4]) that in spite of loss of symmetry in closed stellarators, it became possible to "restore" the fast particle confinement up to the level of the symmetric configurations by corresponding adjustment of the form of the magnetic surfaces and the surfaces B = constant. Such conditions as quasi-helical-symmetry [1], quasi-axi-symmetry [2] and quasi-isodynamicity [3] are now well known and used for stellarator optimization. Here the attempt is made to analyse the necessary and sufficient conditions for improvement of fast particles confinement, mainly for the configurations with poloidal direction of lines B = constant on magnetic surfaces. The radial electric field is not important for fast particle confinement and will not be taken into account here.

Usually, the passing particles are confined well, so here the reflected particles will be considered, only. Let's suppose that we would like to confine all reflected particles for a long time. The reflected particles can be subdivided on two types in according to the character of their drift motion. The particles of the first type are well trapped (it means that they are always trapped), so that the second adiabatic invariant, $J_{\parallel} = \int V_{\parallel} dl$, is conserved and it can be used to describe the trajectories of the "banana" centers. To improve the confinement of such particles one need to make contours of the second adiabatic invariant closed inside plasma column and in addition, tries to make $J_{\parallel}$ constant on the magnetic surfaces. If $J_{\parallel} = J_{\parallel}(s)$, the banana centers of trapped particles will drift along the magnetic surfaces.

The particles of the second type are barely reflected particles, so that they are trapped on one part of their trajectory and are passing on another part. The transition from trapped to passing is non-adiabatic process, thus, for such particles the second adiabatic invariant is not conserved. The character of drift motion of these particles is similar to "diffusive" one, even in collisionless regime. Thus, after some character time, τ_d, they will be escaped from the plasma column. One can try to increase this character time, τ_d, or to find the configuration in which such type of particle orbits will be absent. Here we will consider the last way.

Thus, our aim is to find the configuration in which there are no trapped-passing (or barely reflected) orbits so that the second adiabatic invariant is conserved for all reflected particles. In addition, we would like to have the contours of the second adiabatic invariant closed inside the plasma column for all reflected particles.

The condition of absence of trapped-passing or barely reflected orbits can be easily formulated as follows (in Ref. [5] it was named the condition of pseudo-symmetry):

$$B = B(s,\theta), \qquad B = B(s,\theta - N\zeta), \qquad B = B(s,\zeta), \qquad (1)$$

for axial, helical, and poloidal direction of lines B = constant on magnetic surfaces, respectively.

The pseudo-symmetry (ps) condition requires the magnetic field strength B to be a two-dimensional function in flux coordinates with straight magnetic field lines, s, θ, ζ. It is worth to note here that these coordinates are not necessary the magnetic (Boozer) ones. The lines B = constant on magnetic surfaces in ps configurations do not form the islands and can go in axial, helical or poloidal direction. In magnetic coordinates these lines are not straight, but still do not form the islands.

Two first cases can be called as toroidally pseudo-symmetric configurations.

The ps condition is necessary, but not sufficient for improved particles confinement. In ps configuration all trapped particles have adiabatic character of drift motion, so that the second adiabatic invariant contours show the banana center trajectories. But the fulfilment of ps condition does not guaranty that the contour of the second adiabatic invariant are closed inside the plasma column. If, for example, these lines cross the plasma column cross-section, it means that during adiabatic motion the particle will go very quickly from the plasma column (see, e.g. Ref. [6]). We can say that in non-optimized ps configuration the particle confinement can be much worse then in, for example, conventional stellarator. Thus, our aim is to study the possibility to close the contours of the second adiabatic invariant for all reflected particles inside the plasma column, at least in some internal part of the column.

Below we will suppose that ps condition is fulfilled and will use just the flux coordinates in which the magnetic field strength is two-dimensional function. Here the configurations without net toroidal current will be considered, only.

II. Analytical consideration of the expression for the second adiabatic invariant

Using the flux coordinates in which the magnetic field strength is two-dimensional function and the magnetic field lines are straight ones, from co- and contra-variant representation of the magnetic field,

$$\mathbf{B} = F\nabla\zeta + \nabla\varphi - \nu\nabla s = \nabla\Psi \times \nabla\zeta + \nabla\Phi \times \nabla\theta, \tag{2}$$

one can easily find the expression for the second adiabatic invariant. For the case of poloidal ps, when $B = B(s,\zeta)$, and for zero net toroidal current it has the follows form

$$J_{\parallel} = \int V_{\parallel} dl = \int \frac{\sqrt{B_{reflect} - B}}{B} F\left(1 + \frac{1}{F}\left.\frac{\partial\varphi}{\partial\zeta}\right|_{\mathbf{B}}\right) d\zeta. \tag{3}$$

Here $\left.\frac{\partial\varphi}{\partial\zeta}\right|_{\mathbf{B}} = \frac{\partial\varphi}{\partial\zeta} + \iota\frac{\partial\varphi}{\partial\theta}$. In eq.(3) only the function φ depends on poloidal coordinate.

As the function φ is a periodical one on poloidal and toroidal coordinates, the Fourier representation can be used for it. Because of linear dependence of $J_{\parallel}$ on φ, it is possible to consider the poloidal harmonics separately. For example, let's consider the first poloidal harmonic. For simplicity, lets treat here the case of stellarator symmetry. In this case the function φ can be represented as follows:

$$\varphi = A_1 \sin\theta + A_2 \cos\theta, \qquad A_1 = \sum_n \varphi_n \cos n\zeta, \qquad A_2 = \sum_n \varphi_n \sin n\zeta. \tag{4}$$

After the transformation $\theta = \theta_0 + \iota\zeta$, where θ_0 is a label of the magnetic field line, one can find for $(\partial\varphi/\partial\zeta)|_B$:

$$(\partial\varphi/\partial\zeta)|_B = \sin\theta_0(A_1\cos\iota\zeta - A_2\sin\iota\zeta)' + \cos\theta_0(A_1\sin\iota\zeta + A_2\cos\iota\zeta)' \tag{5}$$

Here prime denotes the derivative on ζ.

In case of stellarator symmetry considered here in used coordinates, B is even function of ζ. Let's consider that this value has only one maximum and one minimum on system period and that $\zeta = 0$ corresponds to minimum of B and that there is a maximum of B on $\zeta = \pi$. From (4) and (5) it is clear that the part of $(\partial\varphi/\partial\zeta)|_B$ that is proportional to $\sin\theta_0$ is odd one, so that it does not make input in integral (3). Thus, the quasi-isodynamicity condition, $J_\parallel = J_\parallel(a)$, puts no limitation on $(A_1\cos\iota\zeta - A_2\sin\iota\zeta)$, but it requires $(A_1\sin\iota\zeta + A_2\cos\iota\zeta)' = 0$. As for $\zeta = 0$ this function itself is equal to zero, we can formulate the qi condition as follows:

$$A_1\sin\iota\zeta + A_2\cos\iota\zeta = 0 \tag{6}$$

Here $A_1(\zeta)$ and $A_2(\zeta)$ are periodic functions.

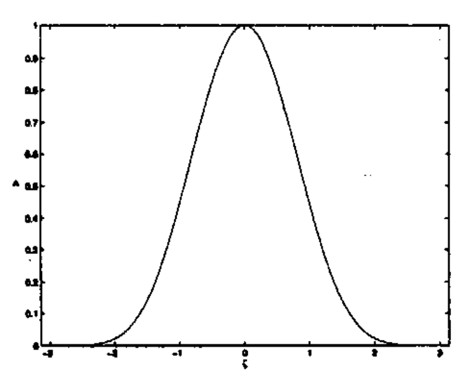


Fig. 1a. Results of test optimization on φ_n. The function $A_1(\zeta)$, optimized to quasi-isodynamicity is shown.

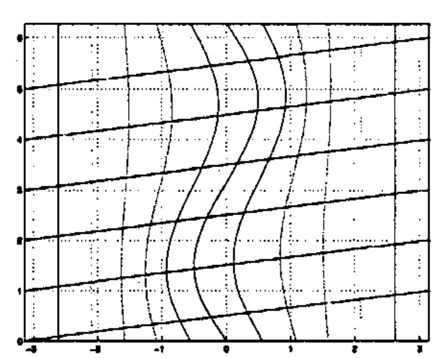


Fig. 1b. The magnetic field lines (straight lines) and contours of B in magnetic coordinates for the set of φ_n determined by minimization of left-side expression in (6).

The condition (6) can't be satisfied exactly (see, e.g. discussion in Ref. [7]). The radial dependence of $J_\parallel$ permits one to have closed contours of the second adiabatic invariant even for nonzero (but small enough) poloidal variation of this value. A simple test was made [7] to estimate the possible accuracy of the fulfilment of the condition (6). The minimization of the integral

$$\int_{-\pi}^{+\pi} (A_1 \sin \iota\zeta + A_2 \cos \iota\zeta)^2 \, d\zeta \qquad (7)$$

with respect to φ_n with the condition $A_1(0) = 1$ shows that for $-6 \le n \le 6$ the accuracy of the fulfilment of the condition (6) is of the order of 10^{-5} and the periodic function $A_1(\zeta)$ goes to zero for $\zeta = \pm\pi$. Fig.1 shows the function $A_1(\zeta)$ on the period and the contours of B in Boozer coordinates for this nearly quasi-isodynamic configuration. It is seen that the B contours have a cosine-like behaviour. The positions of the extrema move along the magnetic field lines and the amplitude gradually disappears with approaching $\zeta = \pm\pi$. It can be seen from the expression for φ in qi configuration:

$$\varphi = \sin\theta_0 (A_1 \cos \iota\zeta - A_2 \sin \iota\zeta) = A_1(\zeta) \sin\theta_0 / \cos \iota\zeta . \qquad (8)$$

Thus, it is important that the amplitude can be changed along the toroidal coordinate. If this amplitude is constant (see Fig 2a), it is impossible to satisfy the qi condition for nonzero amplitude and finite rotational transform. It is worth to remind that in the near-axis approximation for the case of toroidal ps the magnetic field strength has in Boozer coordinates the form $B = B_0(1 - C\cos(\theta_B + \lambda(\zeta_B)))$, with B_0 and C being the constants, so that the contours of B have the same form for all values of B (see Fig. 2b). The qi condition in non qs configuration can be fulfilled for infinite rotational transform, only.

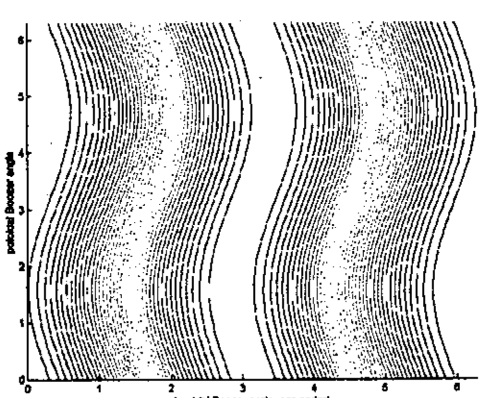


Fig.2a The contours of B in magnetic coordinates for *poloidally* ps configuration with the single toroidal harmonic in function φ.

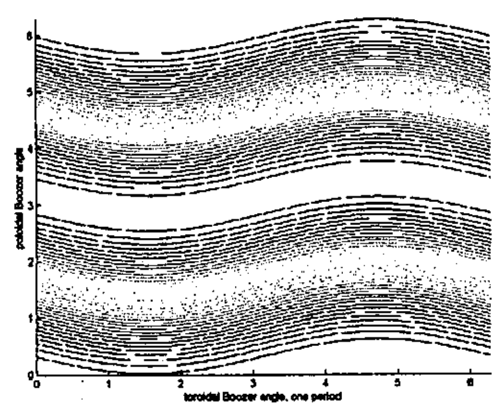


Fig.2b. The contours of B in magnetic coordinates for *toroidally* ps configuration with the single poloidal harmonic in function φ.

Thus, for toroidal direction of the contours of B in near-axis approximation there is no gap between the quasi-symmetry and quasi-isodynamicity. The difference between toroidal and poloidal cases reflects the difference in possible dependencies of the magnetic field strength on poloidal and toroidal Boozer coordinates: in near-axis approximation there is only first poloidal harmonic, m=1, in spectrum of B, while any arbitrary dependence on toroidal coordinate can be prescribed in B. Far enough from the magnetic axis the Fourier spectrum on poloidal coordinate became wider and in principle, one can expect the appearance of the gap between quasi-symmetry and quasi-isodynamicity, or omnigeneity, at least on one magnetic surface.

It is easy to see that the approach used here for the first poloidal harmonic can be used by the same manner for arbitrary poloidal mode number m.

In the following section the effects of fulfilment of qi condition on the secondary and the bootstrap currents will be discussed. For further consideration it is important that in qi configuration function $\varphi(\theta_0,\zeta)$ is even function of ζ. Because of the periodicity requirements this can be realised in the case, when $\varphi(\theta_0,\zeta)$ is equal to zero in the regions of maximal B, only. That means that in qi configuration in Boozer coordinates the lines B = constant should be straight near the maximum of B.

III. The effect of fulfilling of quasi-isodynamicity condition on the bootstrap and the Pfirsch-Schlueter currents

Secondary current

For considered here qi configurations with poloidal direction of lines B = constant the expression for divergence of perpendicular equilibrium current has the form:

$$\sqrt{g}\nabla\cdot\mathbf{j}_\perp = -p'\frac{\partial\varphi}{\partial\theta}\left(\frac{1}{B^2}\right)'_\zeta. \tag{9}$$

It is easy to see that in coordinates θ_0,ζ this value is odd on ζ. One can interpret this as that the nonzero divergence of the equilibrium perpendicular current leads to appearance of positive charges on one side of the magnetic field line and equal number of negative charges on another side (relative the position of minimal B), so that the secondary equilibrium currents should be closed inside the one period. It can be shown directly from the equation for $\alpha = \frac{\mathbf{jB}}{\mathbf{B}^2}$:

$$\left.\frac{\partial\alpha}{\partial\zeta}\right|_\mathbf{B} = p'(\Phi)\frac{\partial\varphi}{\partial\theta_0}(1/B^2)'_\zeta. \tag{10}$$

For considered above input from the first poloidal harmonic we can find explicit expression for secondary current:

$$\alpha = -\cos\theta_0\int_{-\pi}^{\zeta}p'(\Phi)\frac{A_1(\zeta)}{\cos\iota\zeta}(1/B^2)'_\zeta d\zeta, \tag{11}$$

so that $\alpha(\theta_0,-\pi)=\alpha(\theta_0,\pi)=0$, i.e. the secondary currents are closed inside plasma period. It is easy to check that for such α the net toroidal current is equal to zero,

$$< \mathbf{jB} >=< \alpha B^2 >= 0\,. \qquad (12)$$

The analytical consideration is partly confirmed by calculations of secondary currents coefficient for some optimized toward qi configurations. Fig.3a shows the dependence of maximal value of α on toroidal coordinate (minimum B is located in the beginning of period, maximal B is in the middle of period) for optimized toward qi N=6 configuration [4]. In Fig.3b the same is shown for N=2 configuration.

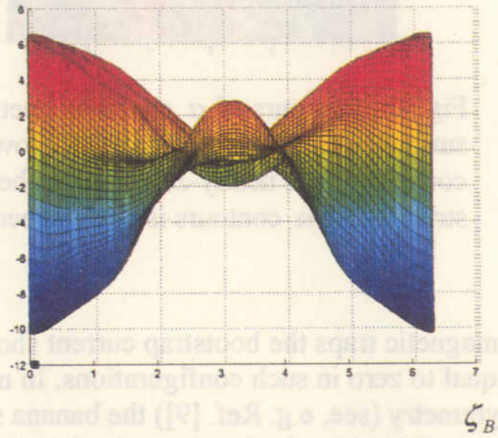


Fig. 3a. The dependence on toroidal Boozer coordinate of maximal on θ_B value of the secondary current coefficient α for N=6 qi configuration.

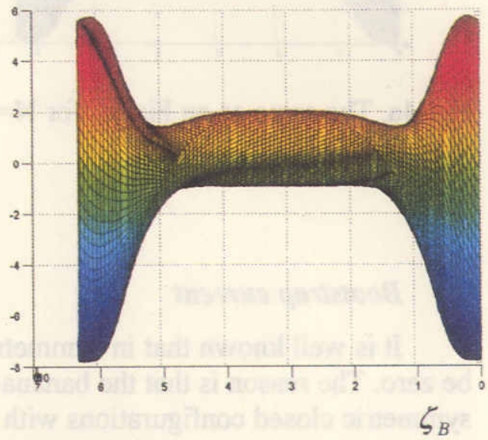


Fig. 3b. The same as on Fig.3a, for N=2 qi configuration.

One can hope that closed inside plasma period secondary currents should be small enough. This really takes place in N=6 and N=2 configurations. Nevertheless, it is not evident that such distribution of the secondary currents corresponds to its minimum. Fig.4a shows the dependence of maximal value of α on toroidal coordinate for near-qi N=9 [8]configuration, which is characterized by extremely low secondary currents and in addition, by very small toroidal effect.

It is seen from Figs. 4 that the lines $\alpha = 0$ have helical structure. In zero net toroidal current configurations the current density lines mainly are closed on itself after one turn around the magnetic axis. The form of these closed lines is roughly a closed circles with inclination that can be varied along the magnetic axis. The point on which $\alpha = 0$ corresponds to point in which vector of the current density is perpendicular to the magnetic field line. In N=2 configuration the lines of these points go in toroidal direction with almost the same poloidal position (no rotating), while in N=9 configuration these lines rotates around the magnetic axis. Thus, the secondary current here creates mainly the helical component of the magnetic field, so that the toroidal shift is very small, even for high enough plasma pressure.

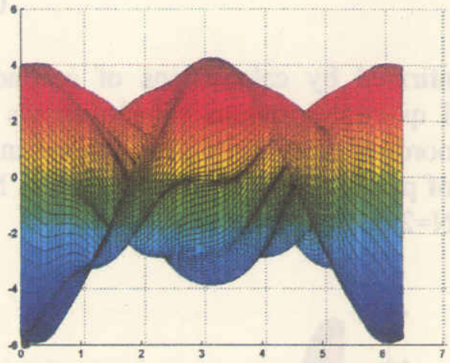


Fig. 4a. The same as on Fig.3a, for N=9 qi configuration.

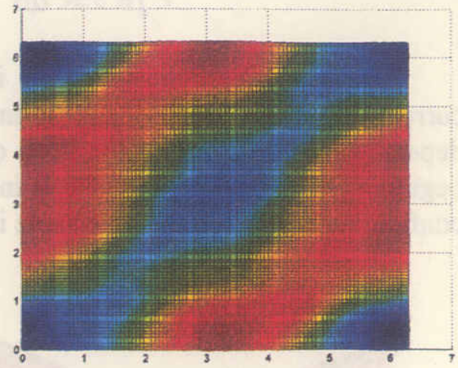


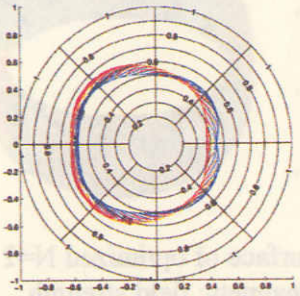
Fig. 4b. Contours of α on the magnetic surface in Boozer coordinates. Yellow colour corresponds to nearly-zero α. The helical structure of α contours is clearly seen.

Bootstrap current

It is well known that in symmetric open magnetic traps the bootstrap current should be zero. The reason is that the banana-size is equal to zero in such configurations. In non-symmetric closed configurations with mirror symmetry (see, e.g. Ref. [9]) the banana size is finite, but the conservation of mirror symmetry requires the bootstrap current to be equal to zero, too. Considered here configuration with poloidal direction of lines B = constant has significant bumpy-component of the magnetic field. These configurations are not the symmetric ones and do not poses the mirror symmetry. Nevertheless, some features of trapped particles drift motion permit to suggest that the value of bootstrap current here can be small. Figs. 5a,b show the projections of well trapped and barely reflected particles on plasma column cross-section. The colour here corresponds to the value of particle's parallel velocity. One can see that the position of red and blue colors relative each other is different for out-word and in-word parts, so that it is difficult to predict the direction of bootstrap currents. Really, one can show that in qi configurations with poloidal direction of lines B = constant on the magnetic surfaces the value of bootstrap current should be zero.

In $1/\nu$ regime there are some analytical equations for the bootstrap current coefficients (see, e.g. Refs. [10-13]):

$$
\begin{aligned}
&<\mathbf{jB}>=G_b\left(L_1\frac{dp}{d\Phi}+L_2\frac{dT}{d\Phi}\right),\\
&G_b(s)=\frac{1}{f_t}\left(<g_2>-\frac{3<B^2>}{4B_{\max}^2}\int_0^1\lambda\frac{<g_4>}{<g_1>}d\lambda\right), \qquad (13)\\
&g_1=\sqrt{(1-\lambda B/B_{\max})},\\
&\mathbf{B}\cdot\nabla(g_2/B^2)=\mathbf{B}\times\nabla\Phi\cdot\nabla B^{-2},\\
&\mathbf{B}\cdot\nabla(g_4/g_1)=\mathbf{B}\times\nabla\Phi\cdot\nabla g_1^{-1},\\
&g_2(B_{\max})=g_4(B_{\max})=0.
\end{aligned}
$$



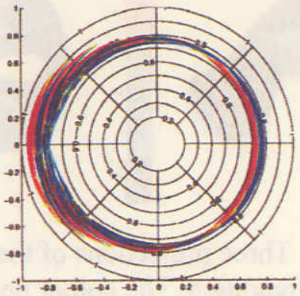


Fig.5a. The projection of the well trapped particle drift orbit. The colour is defined by particle's parallel velocity $V_{\|}$, so that the red colour corresponds to maximal positive $V_{\|}$, while the blue one means the maximal $V_{\|}$ in negative direction.

Fig. 5b. The same as on Fig.5a, but for barely reflected particle.

It is seen that the equations for g_2 and g_4 are very similar to that for α. Thus, for example, the equation for g_2 / B^2 can be expressed as follows:

$$\left.\frac{\partial(g_2 / B^2)}{\partial\zeta}\right|_{\mathrm{B}} = -\frac{\partial\varphi}{\partial\theta}(1/B^2)'_{\zeta}. \tag{14}$$

From comparison of this equation with eq. (10), taking into account eq. (12), one can find that $<(g_2 / B^2)B^2> = <g_2> = 0$. Just the same conclusion can be made for another coefficient, g_4. This analytical consideration is confirmed by calculation of the bootstrap current in W7X, and in qi configurations [14, 15].

IV. Some results of the computational optimization toward qi

While the condition of quasi-isodynamicity [3] was formulated after the computational design of Germany stellarator W7-X, in this configuration the quality of qi is used from deeply to moderately trapped particles. Some later the configurations that are nearly qi for all reflected particles were found by numerical optimization for N=6 [4] and N=9 [8]. From the viewpoint of reactor design the configurations with smaller number of periods could be more attractive if the acceptable value of average β could be achieved. Below some results are presented for N=2 configuration with aspect ratio about 4 and $<\beta> \approx 2.7\%$. Fig.7 shows the 3D views of optimized configuration. The character feature of this configuration is the large enough mirror ratio and large deviation of the magnetic axis from the plane.

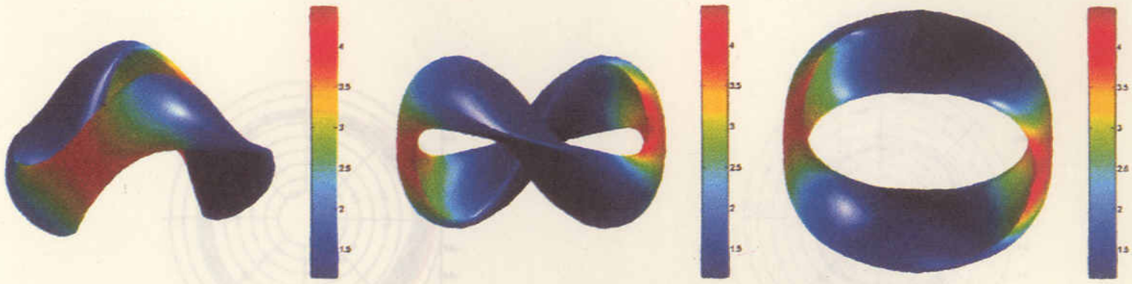


Fig.6. Three projections of the boundary magnetic surface of optimized N=2 configuration. The colour defines the value of the magnetic field strength.

Fig.7. shows the behaviour of lines B = constant on the magnetic surface that correspond to ½ of plasma minor radius for N=2 stellarator. It is seen that the configuration approaches the ps one with high accuracy.

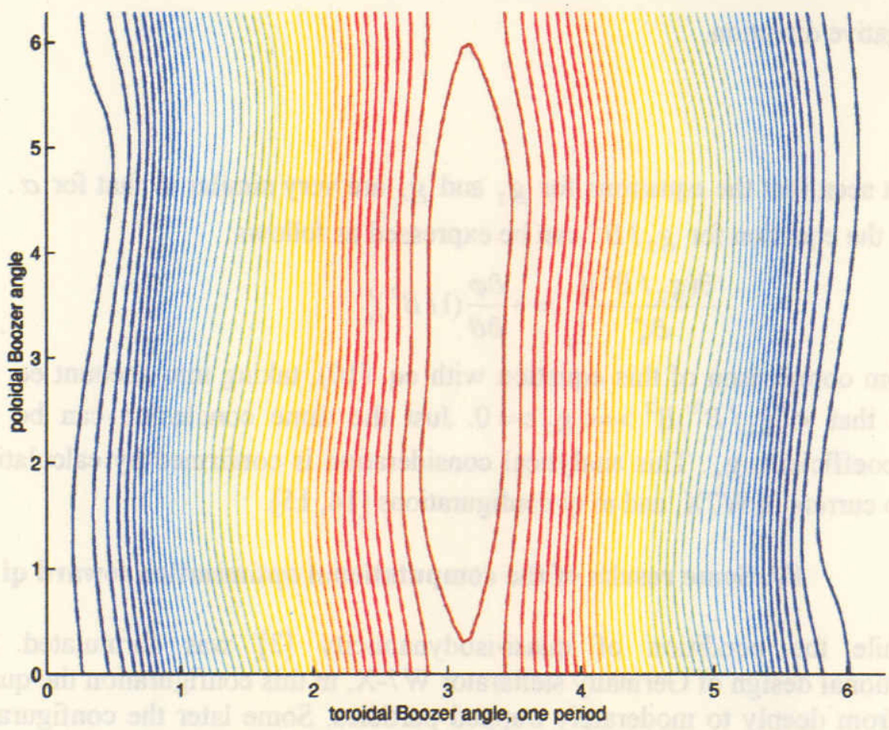


Fig. 7. The contours of the magnetic field strength on the magnetic surface that corresponds to ½ of minor plasma radius.

Fig. 8 shows the contours of the second adiabatic invariant for the set of values of $B_{reflect}$, from deeply trapped (top left) to barely reflected (bottom, right) particles. It is seen, that for internal part of the plasma volume these contours are closed inside the plasma column for all reflected particles. It is seen also, that the value of the second adiabatic invariant is maximal near the magnetic axis.

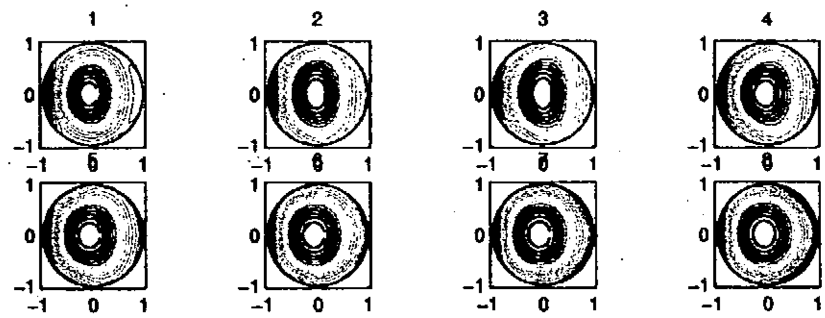


Fig. 8. The contours of the second adiabatic invariant for a set of increasing values of $B_{reflect}$.

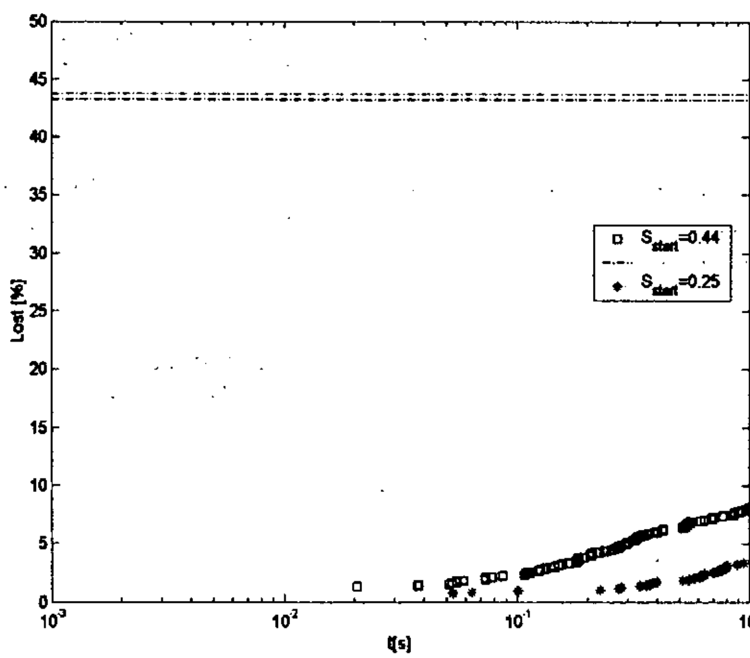


Fig. 9. Collisionless α-particle confinement in the optimized N=2 configuration as a function of time of flight. Particles are started at s = 0.25 (red) and s = 0.44 (blue), that correspond to ½ and 2/3 of plasma minor radius. The straight dashed lines show the fractions of reflected particles. Normalization: $B_0 = 5$T, plasma volume is 1000m^3, kinetic energy of α-particles is 3.5 MeV.

Fig.10 shows the cross-sections of the plasma column for beginning, ½ and ¼ of the period. The character feature of this configuration is a large enough deviation of the magnetic axis from the middle plane. It is seen also, that the shear of the rotational transform is small, so that low rational resonance magnetic surfaces are excluded from the plasma column.

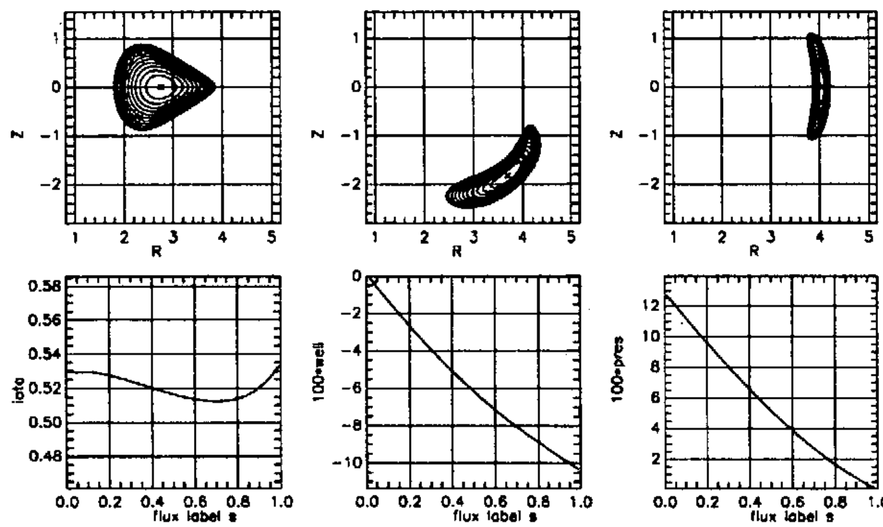


Fig.10. Three cross-sections (beginning, ¼ and ½ of period) of optimized N=2 configuration and radial profiles of rotational transform, magnetic well and plasma pressure.

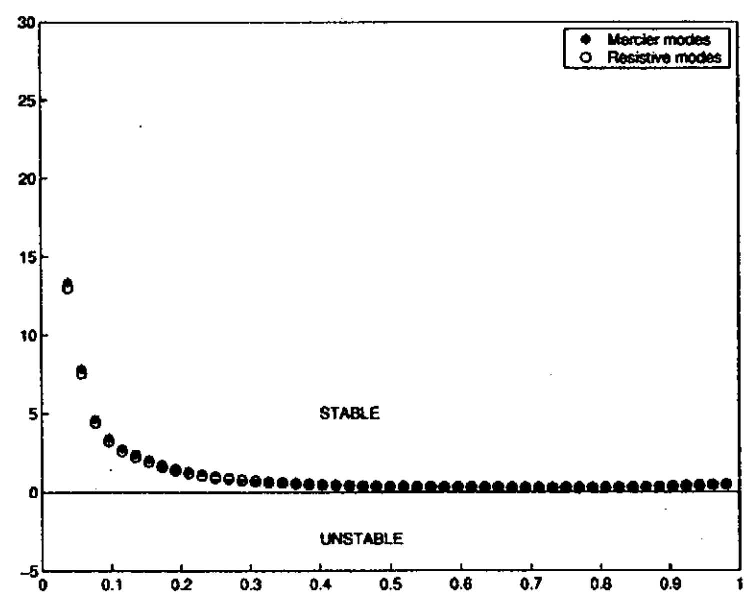


Fig.11. Mecier and resistive modes stability along the radial coordinate.

The optimization have shown that the requirements of improved particle confinement are not in contradiction with the conditions of the Mercier and resistive modes stability (see Fig.11).

IV. Conclusions

By analytical and computational consideration it is shown that the condition of quasi-isodynamicity for the configurations with poloidal direction of the contours of the magnetic field strength on the magnetic surfaces can be fulfilled with high enough accuracy for compact configuration. It is shown that for the configurations with toroidal direction of these contours the condition of quasi-isodynamicity is equivalent to the condition of quasi-symmetry, so that there is no the gap between these two conditions. The further optimization is required to stabilise the ballooning modes in the considered configuration.

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