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Quasi-Isodynamical Configurations without Transitional Particle Orbits

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Abstract

The possibility for collisionless confinement of all reflected particles in a stellarator with poloidal direction of the contours of B on the magnetic surfaces is investigated computationally. As a result, a configuration is found with $<\beta>\approx 5\%$ in which all reflected particles started at the inner half of the plasma have very long collisionless confinement time.

It is also shown that the requirement of good particle confinement is well compatible with the Mercier and resistive local-mode stability conditions.

Introduction

The investigations of the possibilities to improve the particle confinement have shown that approaching quasisymmetry leads to this goal for configurations with helical [1] and axial [2] directions of the contours of B on the magnetic surfaces. For the third possible direction of the contours of B on the magnetic surfaces, the poloidal one, the corresponding condition of quasisymmetry can not be satisfied in closed magnetic systems, in particular not in the linear approximation with respect to the distance from the magnetic axis. As was shown during the W7-X optimization (see, e.g. Ref. [3]) and more rigorously formulated in Ref. [4], the improvement of collisionless particle confinement in such systems can be achieved by optimization of the contours of the second adiabatic invariant $\mathcal{J} = \int v_{\|} dl$ to be constant on magnetic surfaces, *for deeply to moderately deeply trapped particles*. In Ref. [4] this condition was named quasi-isodynamicity. As was shown in Ref. [4], it can be fulfilled in configurations far from quasisymmetry. The barely reflected particles in those configurations are confined for a long time but eventually lost due to collisionless stochastic diffusion.

The possibility to fulfill the condition of quasi-isodynamicity for all reflected particles was studied analytically in Ref. [5]; the poloidal direction of the contours of B was considered in near-axis approximation. The main conclusion was that the condition $\mathcal{J} = \mathcal{J}(s)$ can not be fulfilled exactly for all reflected particles, but can be satisfied with any prescribed accuracy. In Ref. [6] the helical direction of the contours of B was considered for a model field strength; the method used can be applied to systems with poloidal direction of the contours of B, too.

In the present paper the possibility to collisionlessly confine all reflected particles for a long time is investigated numerically for the system with poloidal direction of the contours of B. Results are presented for a configuration with aspect ratio $A \approx 12$, six periods and finite plasma pressure, $<\beta>\approx 5\%$.

The choice of penalty functions

The optimization procedure was performed with the VMEC code [7] for the equilibrium computation and the JMC code [8] for obtaining the spectrum of B in magnetic coordinates. The orbit integration code in magnetic coordinates [9] was used as a diagnostic to check the quality of the optimized configuration.

To find a configuration with poloidally closed contours of B the condition of pseudosymmetry [10] as it was formulated in Ref. [11] was used for constructing the penalty function. This condition itself is not sufficient for good particle confinement [12], thus, in addition the requirement for the contours of $\mathcal{J}$ started at some prescribed magnetic surface to be closed inside the plasma column for all values of $B_{\rm ref}$, i.e for all reflected particles, was imposed. In the last stage of the optimization the requirements of Mercier and resistive local-mode stability were imposed, in addition. The results of the optimization were checked by direct calculation of the α-particles loss for a power plant-size configuration. In addition, the transport and stability properties of the optimized configuration were investigated with a suite of field line following codes [13,14].

Results of the optimization

A 3D view of the optimized configuration is shown in Fig. 1. The color here indicates the value of the magnetic field strength. The characteristic feature of this configuration is the nearly straight magnetic axis in the regions of the field strength extremes (two regions in one period). The contours of $\mathcal{J}$ are shown in Fig. 2 for increasing values of $B_{\rm ref}$, $B_{\rm ref} = B_{min} + i(B_{max} - B_{min})/7,\ i = 1...6$, in polar-coordinate representation $\sqrt{s}, \theta$ with s the flux label. The top left contours are near the minimal value of $B_{\rm ref}$ and the bottom right ones near the maximal one. The red color corresponds to maximal value of $\mathcal{J}$ showing the max-$\mathcal{J}$ property of this configuration. It is seen that – for all values of $B_{\rm ref}$ – contours of $\mathcal{J}$ started from inner half of the plasma column are closed inside the plasma. The direct check of α-particle confinement shows that using $\mathcal{J}$-optimization is adequate to reach the collisionless confinement goal. Fig. 3 shows the history of particles lost during a time of flight of 10 sec for particles started from 2/3 of minor plasma radius. There is no loss of particles started at 1/2 and smaller plasma radii.

Fig. 4 shows the radial dependence of the largest Fourier coefficients of the magnetic field strength. It is seen that the bumpy component here is larger than in the quasi-isodynamic configuration described in Ref. [4].

The results of Mercier and resistive local-mode stability in the optimized configuration calculated by the JMC code are shown in Fig. 5 for $<\beta>= 5\%$.

The optimized configuration was investigated by field line following codes, too (see, e.g. Ref. [13,14]). These calculations have confirmed the Mercier stability of the configuration. In addition, the Pfirsch-Schlüter factor (the ratio $< j_{||}^2 > / < j_{\perp}^2 >$) was calculated. It was shown that this factor is approximately 0.13-0.15, showing the significant reduction of the secondary current. Fig. 6 shows the radial dependence of the effective ripple determining the level of transport in the $1/\nu$ regime. It is worth to emphasize that in the optimization procedure only the requirement of the closedness of $\mathcal{J}$ contours was imposed. The further minimization of the effective ripple is possible, as it was seen during the optimization.

Conclusions

It is shown that using $\mathcal{J}$-optimization together with optimization toward pseudosymmetry (i.e using information about the magnetic field strength only, without direct calculation of particle drift motion) permits to find configurations with good collisionless particle confinement. It is also shown, that these criteria for confinement improvement are well compatible with the conditions of Mercier and resistive mode stability.

Acknowledgments

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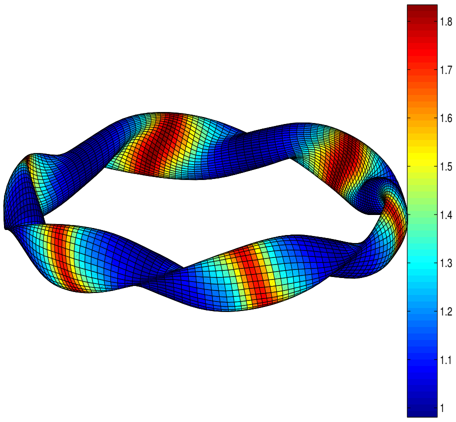

Fig. 1. Boundary magnetic surface of the optimized configuration also showing the magnetic topography. The colors define the range of the magnetic field strength (red – maximum, blue – minimum.

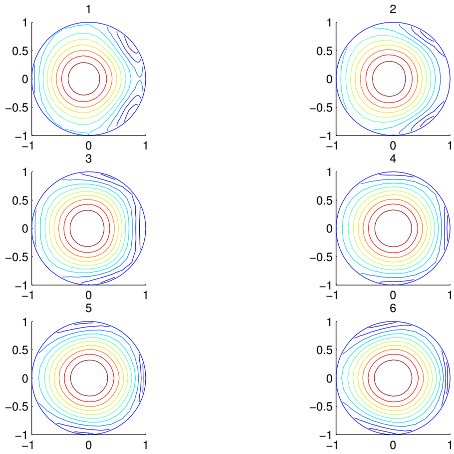

Fig. 2. $\mathcal{J}$ contours for increasing values of $B_{\rm ref}$ in polar-coordinate representation $\sqrt{s}, \theta$ with s being the flux label.

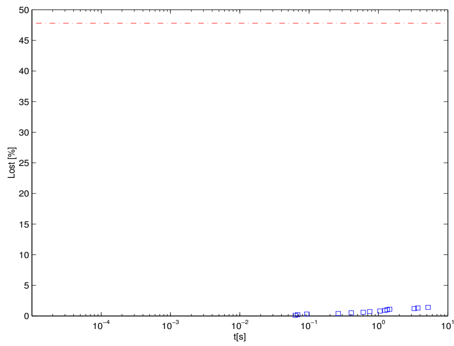

Fig. 3. Collisionless α-particle confinement in the optimized configuration as a function of the time of flight. One thousand particles are started at $s_{start} = 0.44$ (2/3 of the plasma radius); the dashed line shows the fraction of the reflected particles.

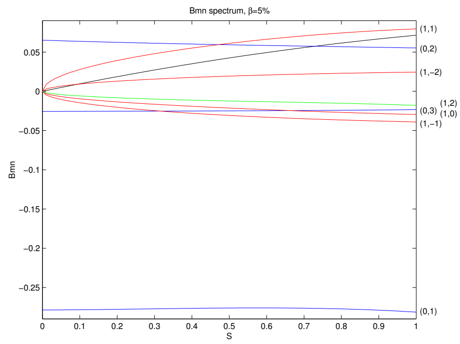

Fig. 4. Radial dependencies of few largest Fourier coefficients $B_{m,n}$ for optimized configuration. $B_{0,0}$ is shown by black line and is plotted in the form $B_{0,0}(s) - B_{0,0}(0)$, with $B_{0,0}(0) = 1$.

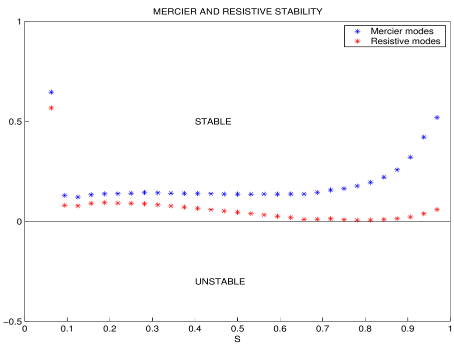

Fig. 5. Mercier and resistive modes stability along the radial coordinate.

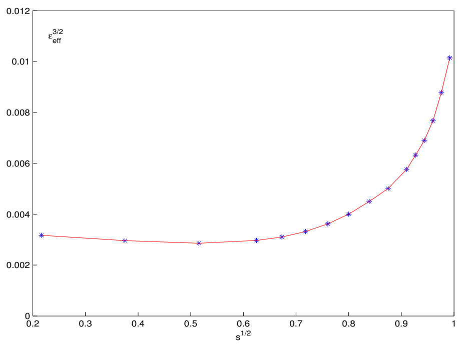

Fig. 6. Radial dependence of the "effective ripples" for optimized configuration.