Search for very-high-β MHD stable quasi-isodynamic configurations

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(Received October 12, 2007/ Accepted ?)

Quasi-isodynamic configurations offer the possibility of very good energetic particle confinement. They seem to offer the possibility of achieving very high plasma β, too.

Keywords: Plasma and Fusion Research, Stellarators, Quasi-isodynamicity, MHD stability, Very high plasma β

1 Introduction

Quasi-isodynamic [1] (*qi*) configurations have been previously found by computational optimization with high stability β limit, good neoclassical confinement properties and excellent fast particle collisionless confinement for configurations with poloidally closed contours of the strength of the magnetic field B [2,3]. It was shown analytically [3] that the secondary parallel current density in *qi* configurations remains contained within each plasma field period, namely, between the cross-sections with maximal magnetic field strength B. In the *qi* configurations considered earlier, the divergence of the current density perpendicular to the magnetic field lines changes sign only once along the magnetic field within one field period. From this it follows that the parallel current density cannot change sign along the magnetic field within one period. Thus, because of the vanishing net parallel current, the parallel current density exhibits a dipole component which impairs MHD stability at very high β in the *qi* situation considered here for configurations with shallow magnetic well in the associated vacuum magnetic field. The search for possible ways to diminish this current density in quasi-isodynamic configurations was the subject of [4].

For this search a two-staged approach had been taken. In a model investigation it was clarified that quasi-isodynamicity is compatible with vanishing dipole current density in a more elaborate structure of the topography of B exploiting the possibility of detailed toroidal design of B in 3d configurations; then a configurational investigation established a geometry realizing the essential features of this model and is seen in Fig. 1, Fig. 3 (left) and Fig. 4 (left).

In this work it is investigated whether MHD-stable equilibria of this type of configuration exist.

2 Current result at $\langle\beta\rangle \approx 0.2$

The configuration of Figs. 1 and 4 (left) had been obtained at zero β. It exhibits a significant magnetic hill so that one of the essential ingredients of its optimization towards high β has been the transition to a vacuum field magnetic well as a prerequisit for MHD stability. As seen from Fig. 1, the starting point of the optimization is characterized by a roughly hexagonal plasma shape, i.e. by as little curvature as compatible with the straight sections encompassing the maxima of B. Since a magnetic well necessitates plasma curvature and higher order poloidal shaping (triangularity, indentation, ...), it is plausible that the local plasma column curvature had to increase. This is seen in Fig. 2, but most clearly in Fig. 9 (while not prominent in Fig. 10). The subsequent achievement of high β is accompanied by two characteristic features. As in the initial condition, the Fourier components (in magnetic coordinates) of B and the volume element $\sqrt{g}$ corresponding to axisymmetric curvature are very small, simulating an aspect ratio of several hundred, see Fig. 5. Also, since the strong poloidal as well as toroidal shaping, see Fig. 4 (right), drives higher order Fourier components of $\sqrt{g}$, the optimization needed to exploit (and strictly observe) a window in rotational transform value, here chosen to be $\frac{6}{7} < \iota < \frac{6}{6}$. While introducing curvature is necessary for stability, see Fig. 6, ballooning instability will limit it. Preliminary evaluation of ballooning instability considering the local ballooning equation for symmetric ballooning at the four symmetry points of the field period and flux surface label $s \approx 0.3$ shows the abscence of strong-ballooning instability, see Fig. 7. This analysis needs to be completed following the procedure used in [3], in particular because of the gap in marginal β found there between local and non-local ballooning analysis. Some features observed in earlier stable configurations are prominent in the configuration obtained here, too: the triangular shape of the flux-surface cross-sections at the

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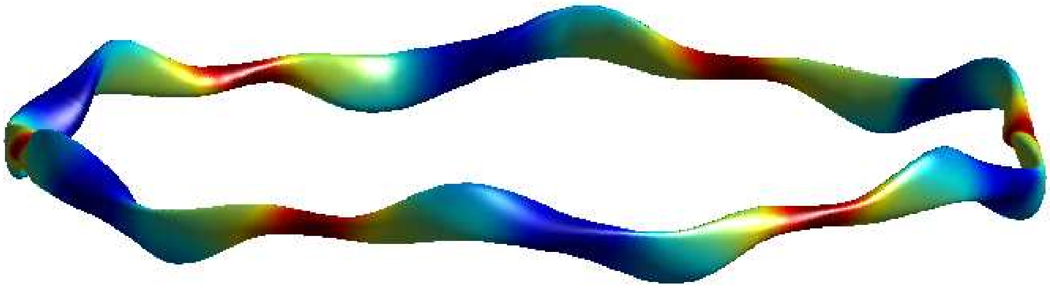

Fig. 1 Boundary magnetic surface showing the magnetic topography of [4].

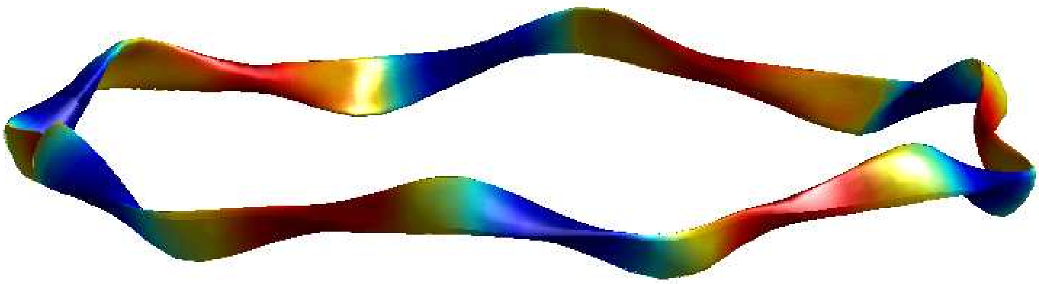

Fig. 2 Boundary magnetic surface showing the magnetic topography of the stable configuration.

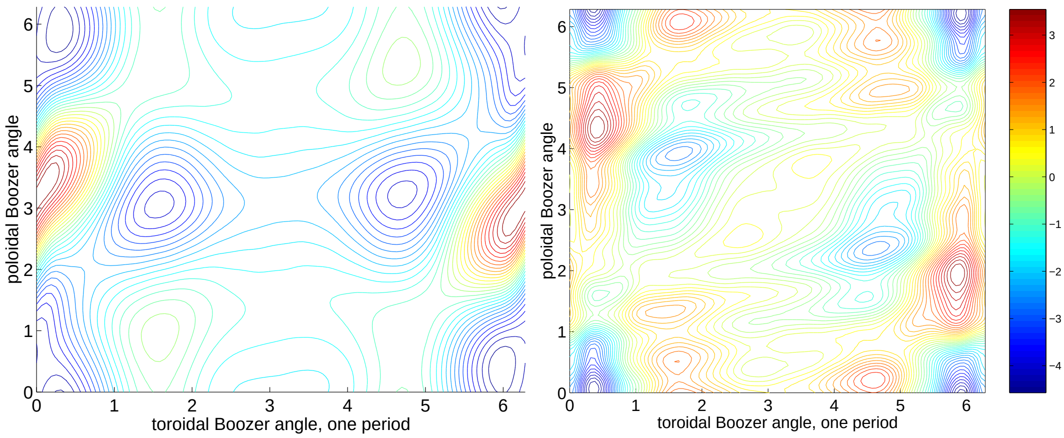

Fig. 3 *Left: the structure of the parallel current density ($j_{\|}/B$) of the configuration of Fig. 1 showing $j_{\|1,0} = 0$; Right: the structure of the parallel current density ($j_{\|}/B$) of the configuration of Fig. 2.*

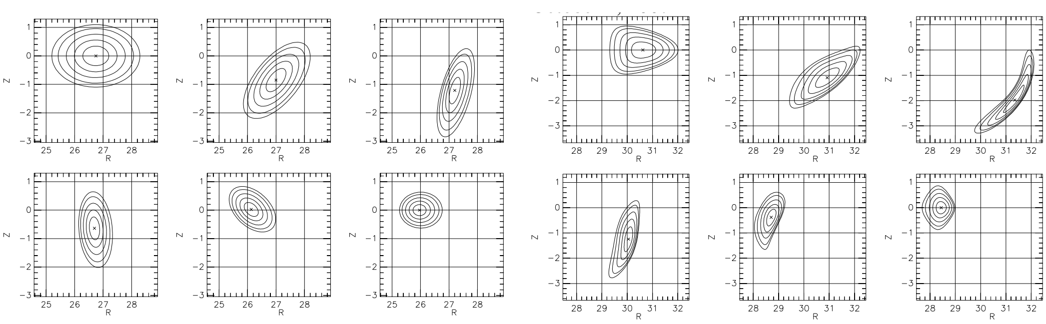

Fig. 4 *Cross sections of magnetic surfaces of the configurations in Figs. 1 and 2 along half a period beginning with the minimum of B and ending at the maximum of B.*

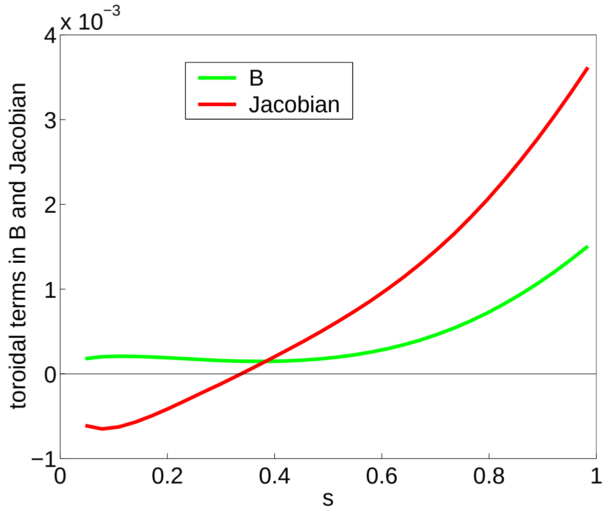

Fig. 5 Fourier coefficients of B and $\sqrt{g}$ in magnetic coordinates corresponding to toroidal curvature.

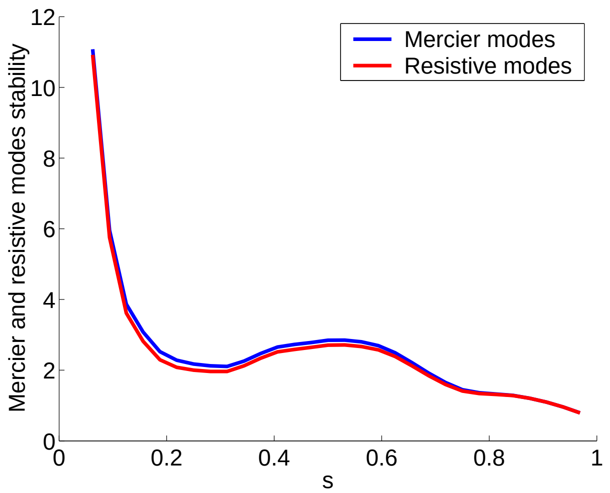

Fig. 6 Mercier and resistive-interchange stability.

minimum of B and indentation in the range of strongest curvature. It remains to be investigated whether the higher-order poloidal and toroidal shaping found, e.g. the quadrangularity at the maximum of B and in Fig. 4 (right), is really necessary to achieve MHD stability.

The neoclassical physics properties have not in detail been part of this high-β optimization; they should be benign in view of the contours of the second adiabatic invariant, see Fig. 8 (right), but their detailed investigation and, eventually, optimization remains to be done in order to complete this case study of a very-high-β configuration.

3 Summary

In the context of quasi-isodynamic stellarators with poloidally closed contours of the magnetic field strength it is investigated whether very-high-β MHD-stable equilibria exist. With a previously introduced new structure of

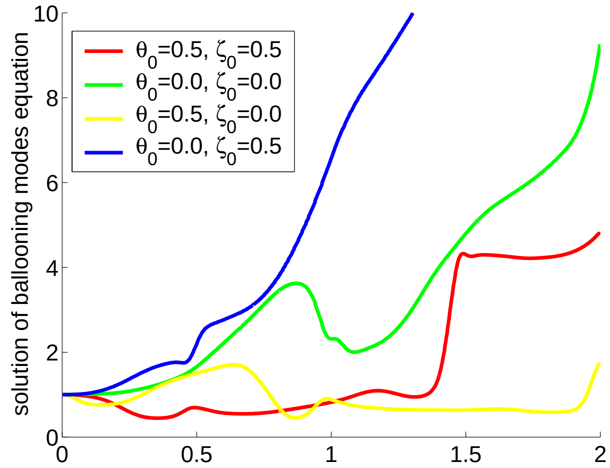

Fig. 7 Solutions of the ballooning equation along fieldlines covering two periods and passing through the four symmetry points on the flux surface at $s = 0.3$.

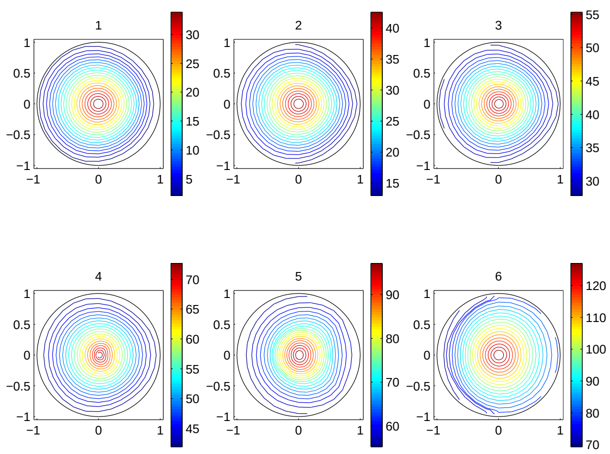

Fig. 8 Structure of $\mathcal{J}$ in the configuration obtained for different values of B, B_{ref}, at which trapped particles are reflected; 1 - near the minimum of B, 6 - near the maximum of B.

a period as a starting point equilibria are found which are Mercier, resistive-interchange and strong balooning (symmetric) stable at $\langle\beta\rangle \approx 0.2$. Further work will concern further MHD-stability analysis and the details of the neoclassical physics properties of this type of configuration.

4 Acknowledgment

Part of the computations of this work has been performed on the NIFS LHD Numerical Analysis Computer SX-8.

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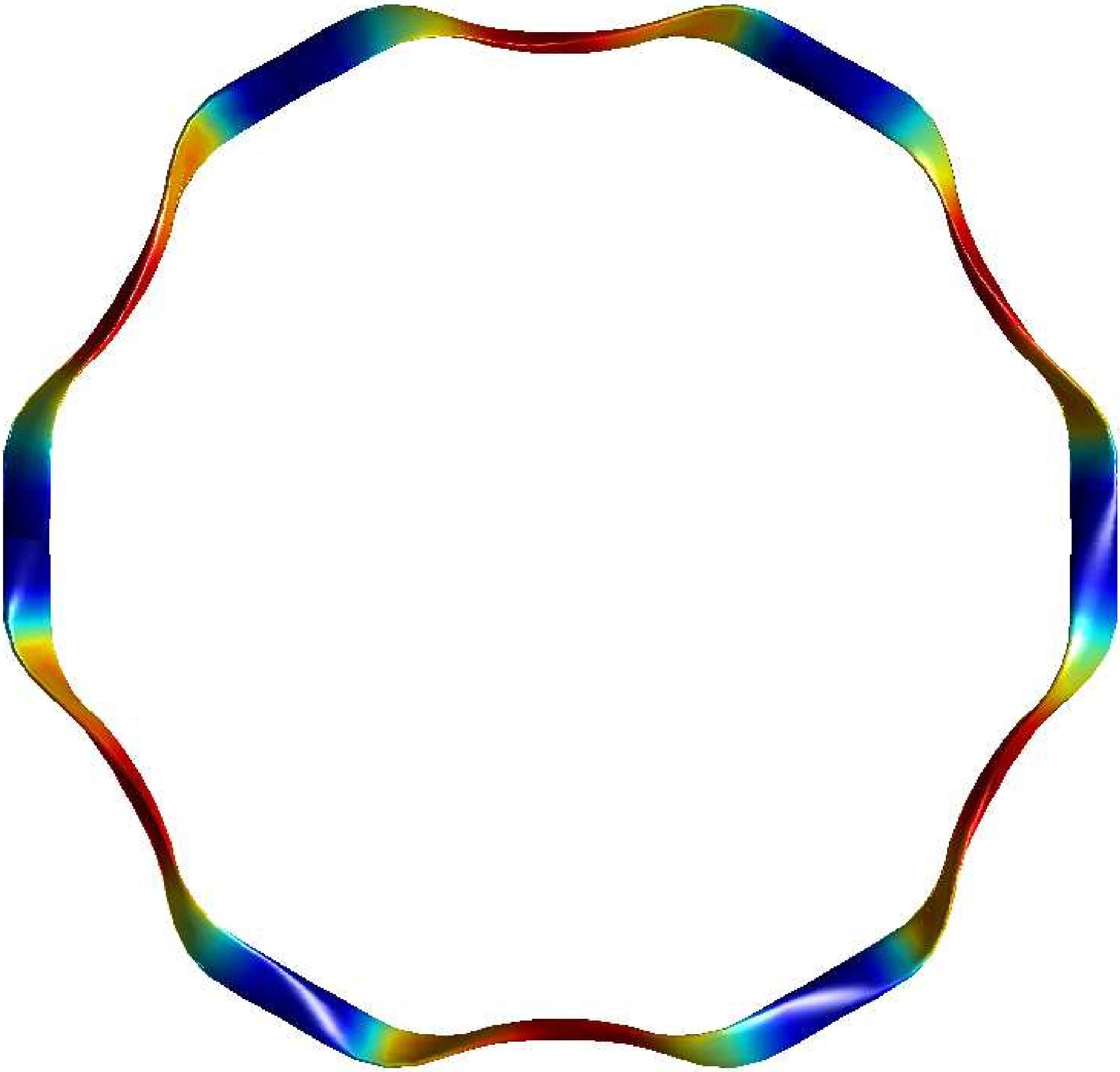

Fig. 9 Top view of the configuration shown in Fig. 2.

Fig. 10 Equatorial view of the configuration shown in Fig. 2.