Exploration of Configurational Space for Quasi-isodynamic Stellarators with Poloidally Closed Contours of the Magnetic Field Strength

V.R. Bovshuk [1], W.A. Cooper [2], M.I. Mikhailov [1 *], J. Nührenberg [3], V.D. Shafranov [1]

[1] *Russian Research Centre "Kurchatov Institute", Moscow, Russia*

[2] *Centre de Recherches en Physique des Plasmas, Association Euratom-Confédération Suisse, Ecole Polytechnique Fédérale de Lausanne, Switzerland*

[3] *IPP-Euratom Association, MPI für Plasmaphysik, 17491 Greifswald, Germany*

I. 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 such *qi* configurations remains contained within each plasma field period, namely, between the cross-sections with maximal magnetic field strength B. In those *qi* configurations, 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 and the compatibility of very high β with small neoclassical ripple. The latter was experienced in a previous study of a very-high-β case [4] with a sizable ripple; tests showed it to be unlikely that this ripple could be reduced by one order of magnitude. A reduction of the dipole component of the current density should make the magnetic structure more stiff with respect to changes in β so that the attainability of a small ripple should be less strongly coupled to the β value. Such a reduction should naturally occur in a sequence of configurations with proportional increases in toroidal aspect ratio and number of periods. This tendency was verified, will be exemplified in Sec. II, but is only relevant for understanding a very-large-aspect-ratio feature of the structure of stellarator configurational space.

The search for qualitatively different ways to diminish this current density in quasi-isodynamic configurations was the subject of [5]. For this search a two-staged approach had been taken. In

*email: mikhail@nfi.kiae.ru

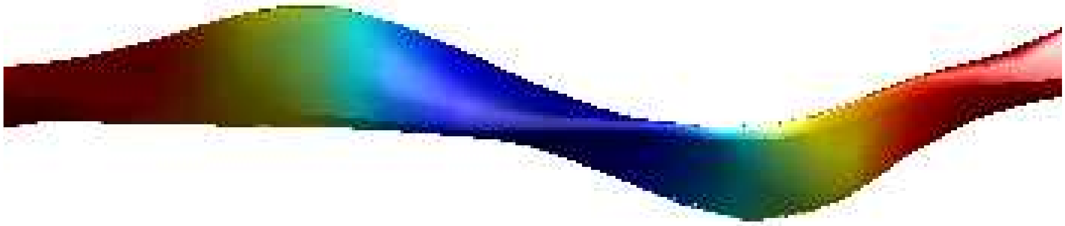

Figure 1: *Boundary magnetic surface showing the magnetic topography of [6]. The color varies from red (highest field strength) to blue (lowest field strength).*

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. These features are seen in Fig. 1

Preliminary optimizations searching for the existence of very-high-β MHD stable configurations within this configurational class were successful [6] so that further optimizations aimed at combined very-high-β MHD stability and small equivalent ripple and will be described in Sec. III.

II. Very-large-aspect-ratio configurations

Here, it is demonstrated that the origin of the difficulty in combining very high β and small equivalent neoclassical ripple in qi configurations is the influence of the toroidal aspect ratio. A quite extreme extrapolation of the configuration found in [3] is considered first: keeping the geometrical features of flux surface cross sections, increasing the aspect ratio of the period by about a factor of three, the number of periods to 36 (so that the toroidal aspect ratio is about 270) and the β value to $\langle\beta\rangle \approx 0.2$ re-optimization leads to a configuration which is stable with respect to the local ballooning analysis and exhibits a small equivalent ripple, $\delta \approx 5 \cdot 10^{-3}$. Because of the combination of very high β and very small curvature, a configuration of this type exhibits a special α-particle confinement feature. In the core, confinement becomes independent of the second adiabatic invariant because a toroidally closed surface of the strength of B encloses inner magnetic surfaces up to about a third of the plasma radius, see Fig. 2.

Second, a case interpolating between this asymptotically extreme one and the one in [3] is investigated: selecting $N = 18$ with $A \approx 90$ optimization at $\langle\beta\rangle \approx 0.2$ leads to a situation which is still unstable to asymmetric local ballooning modes, see Fig. 3, but, for the same plasma boundary becomes local-ballooning stable for $\langle\beta\rangle \approx 0.16$, so that it is an interesting case for

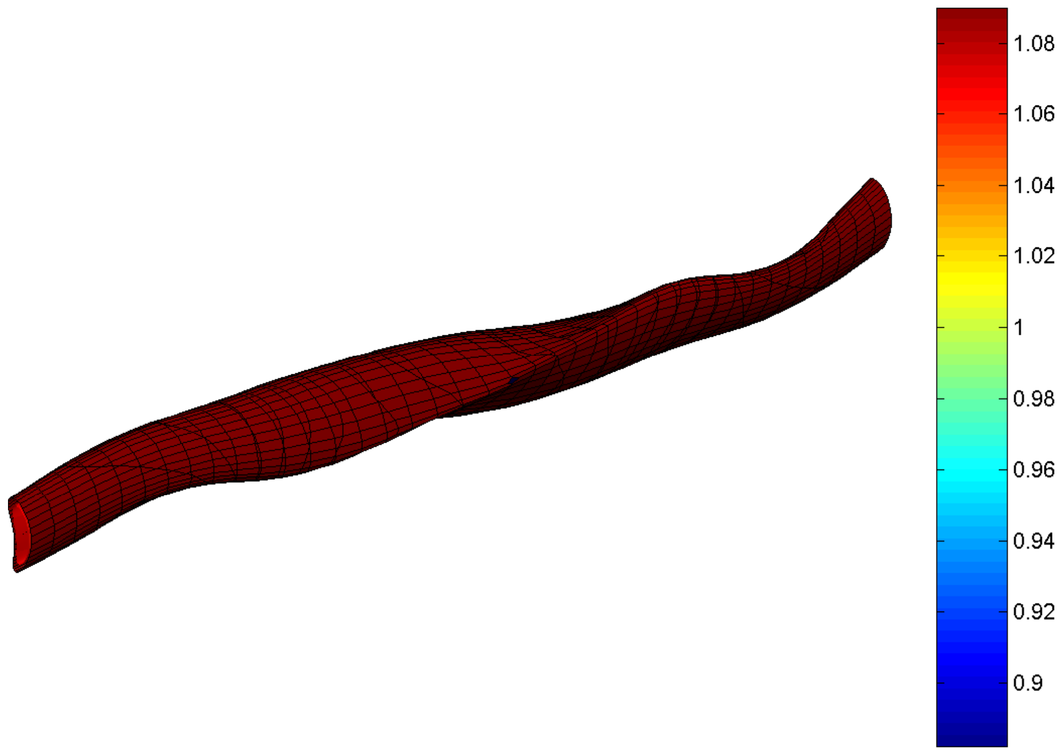

Figure 2: *Magnetic topography at very high β and aspect ratio: the toroidally closed surface $B \approx 1.08$ encloses inner magnetic surfaces (one of them shown at the left end of the period) up to about a third of the radius.*

nonlocal balloning analysis, see [3].

III. More elaborate geometry

A primary goal to be pursued in the new geometry [5, 6] has been to show the compatibility of very high β and small equivalent ripple. The associated optimization has been done with the following parameters. The number of periods of the configuration is $N_\mathrm{p} = 6$, the aspect ratio about 30 and its rotational transform per period about $\frac{1}{6}$; the β value has been chosen to be $\langle\beta\rangle \approx 0.2$. Whether a further increase of β would be meaningful depends on detailed further investigations of e.g. the behavior of energetic-particle collisionless confinement in view of the significant reduction of the strength of B in the core of the plasma.

The procedure of optimization has been analogous to [3] with two modifications. i) Preliminarily, the ballooning-stability requirement only concerned symmetric ballooning modes. ii) As in [5] as an additional constraint - for keeping the dipole component of the secondary current small - the requirement of a small $m = 1, n = 0$ component of $\sqrt{g}$ in magnetic coordinates.

Figures 4 to 8 give an overview on the configuration found. Since the strong poloidal as well as toroidal shaping drives higher order Fourier components of $\sqrt{g}$, the optimization really needed to exploit (and strictly observe) a window in rotational transform value, here chosen to be $\frac{6}{7} < \iota < \frac{6}{6}$. Some features observed in earlier stable configurations are prominent in the

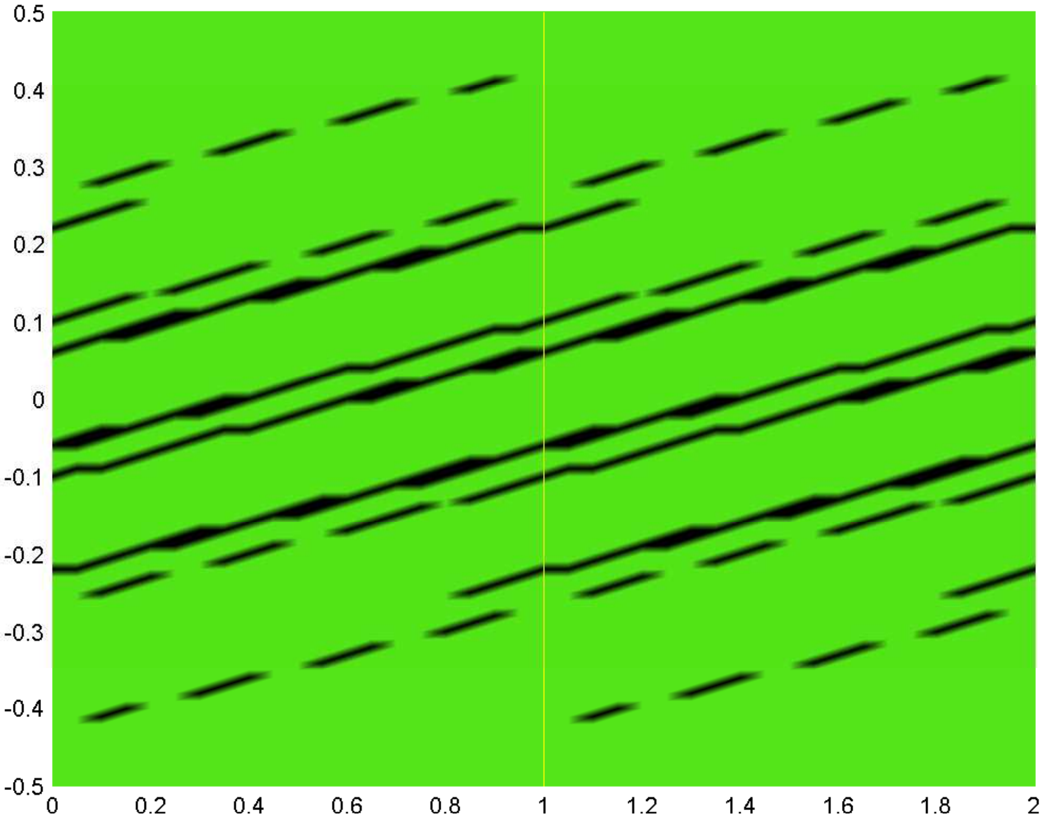

Figure 3: *Most unstable (dark blue) regions on a magnetic surface as obtained from the local-ballooning analysis. Shown are two periods out of 18.*

configuration obtained here, too: the triangular shape of the flux-surface cross-sections at the minimum of B and indentation in the range of strongest curvature.

The main new feature appearing as a result of optimization towards small neoclassical ripple is the formation of a secondary minimum of B in the region originally exhibiting the maximum of B. A tentative explanation may be that this region is uncurved because of the requirement of quasi-isodynamicity so that localization of reflected particles there does not increase the neoclassical ripple, see Fig. 8, which is of the order of 1% in the plasma core.

IV. Summary

In the context of quasi-isodynamic stellarators with poloidally closed contours of the magnetic field strength it is investigated whether very-high-β equilibria exibiting small neoclassical ripple exist. Within the structure of a period considered earlier [3], this has been verified at very large numbers of periods and aspect ratio at which these equilibria are MHD-ballooning stable. With a previously introduced new structure of a period as a starting point, such configurations are found at lower but still large aspect ratio. However they are ballooning unstable so that this configurational property still remains to be optimized.

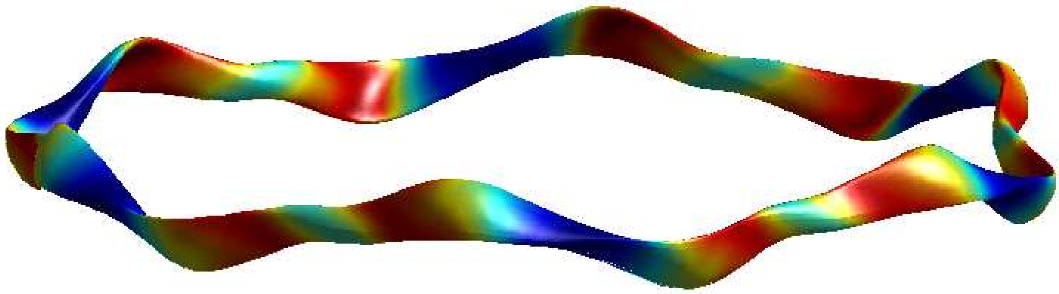

Figure 4: *Boundary magnetic surface showing the magnetic topography of a new configuration type.*

V. Acknowledgment

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

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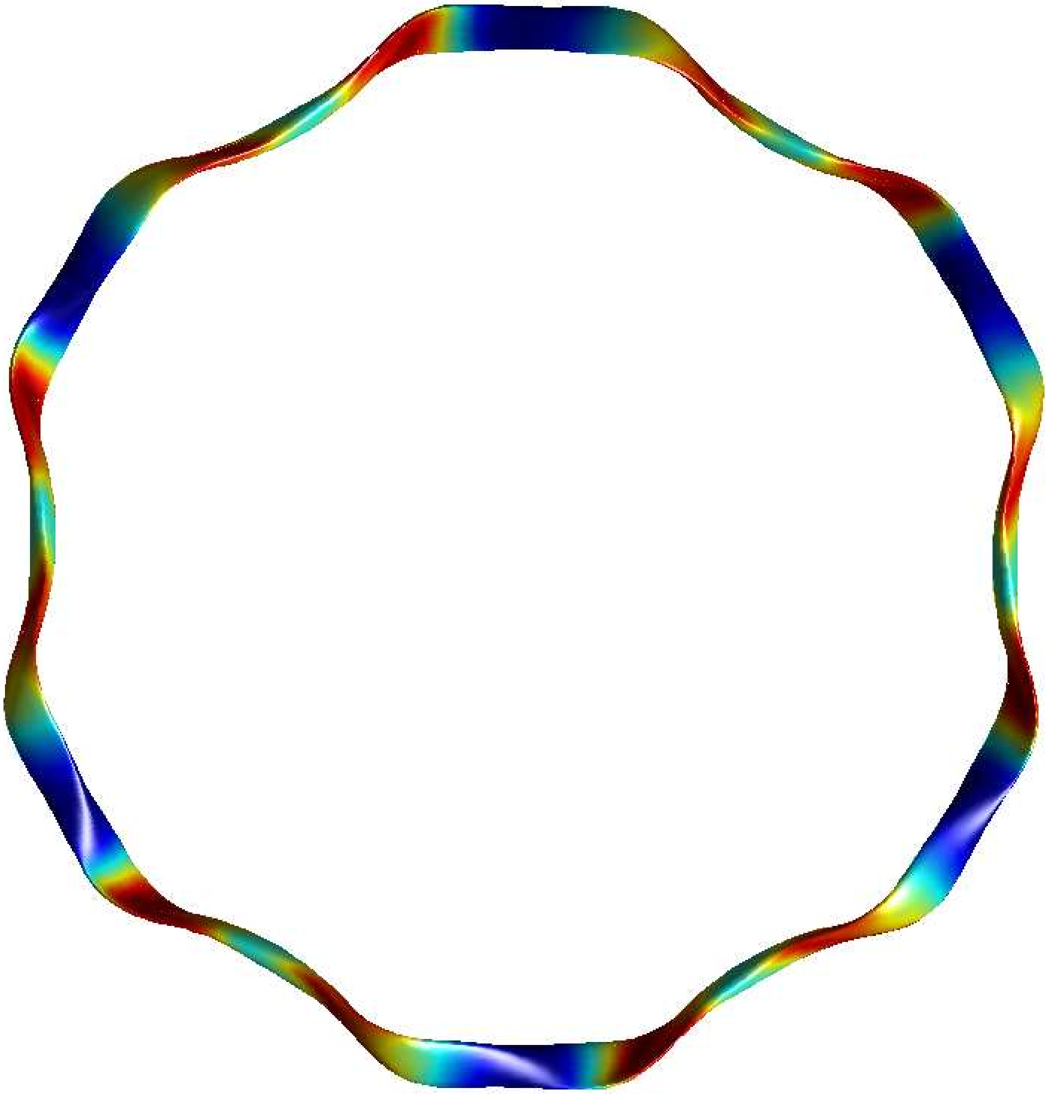

Figure 5: *Same as before, but top view.*

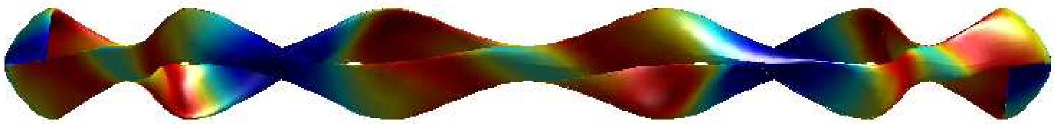

Figure 6: *Same as before, but side view.*

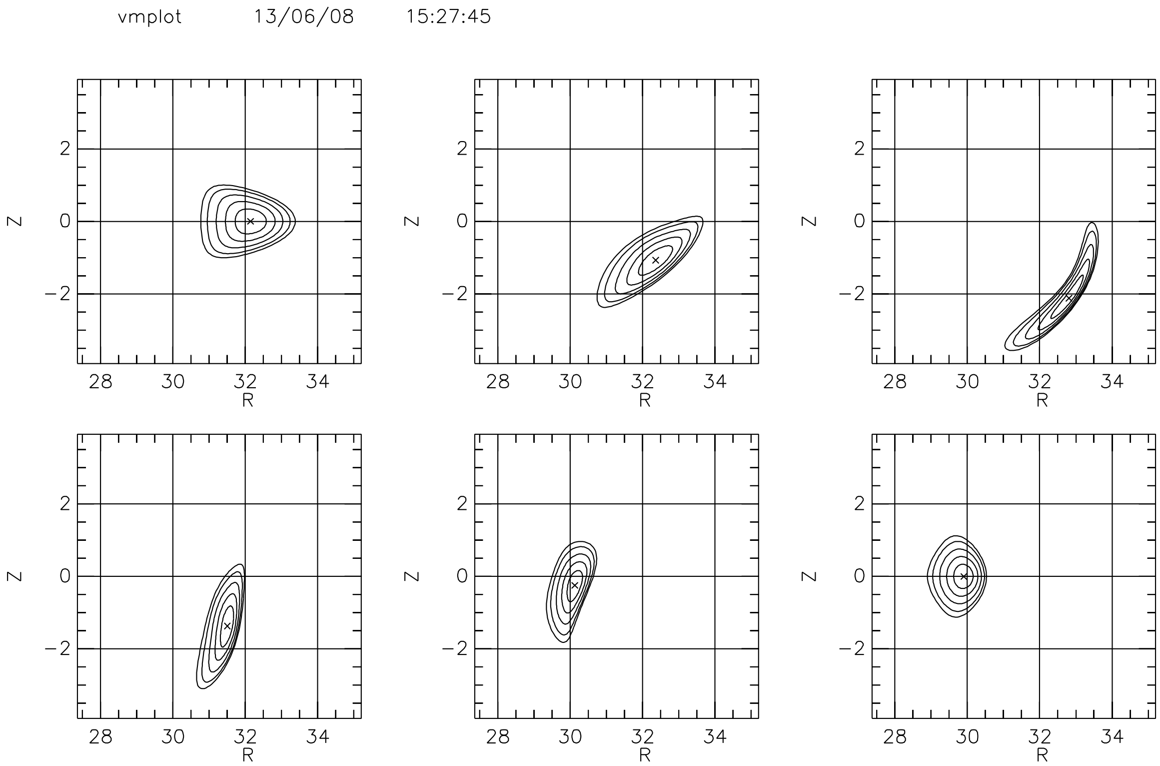

Figure 7: *Cross sections of magnetic surfaces of the configuration seen in along half a period beginning with the minimum of B and ending at the secondary minimum of B.*

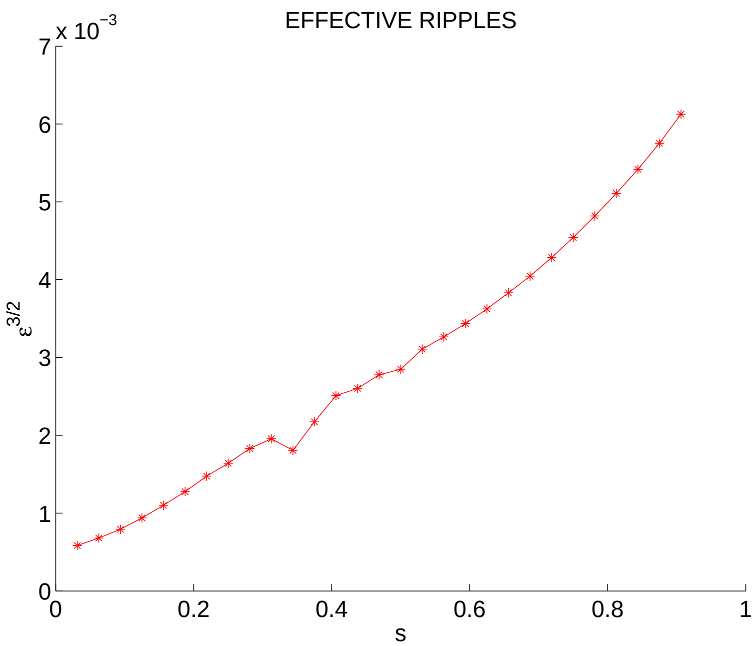

Figure 8: *Equivalent neoclassical ripple to the* $\frac{3}{2}$ *power vs. flux label.*