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Optimization of neoclassical transport in URAGAN-2M*

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Introduction

For planned optimization, the $1/\nu$ neoclassical transport is studied for the torsatron Uragan-2M (U-2M) [1]. For stellarators where the finite plasma pressure causes a weak influence on the equilibrium (e.g., U-2M) the effective ripple, ϵ_{eff}, can be calculated using the field line tracing code [2] (NEO code) in real space coordinates. Also, an optimizing procedure is carried out using the code [3] for optimizing stellarators with fixed coil design. In the optimization run the currents in the adjacent toroidal field coils are varied.

Basic parameters

The U-2M device (IPP, Kharkov) is an l=2 torsatron with an additional toroidal magnetic field (m_p=4, R_T=170 cm, m_p is the number of the field periods along the torus, R_T is the big radius of the torus). In the design phase of this device a big number of various studies were carried out, the results are summarized in [1]. At the same time, due to the flexibility of the device magnetic system further investigations of possibilities of improving the confinement properties are possible and desirable.
The additional toroidal magnetic field in U-2M is produced by a system of 16 toroidal field coils (TF coils) uniformly distributed in angle along the major circumference (4 coils in each field period). In accordance with [1] for the "standard" configuration, which is considered here, the mean current in such a coil is I_{TFC}=5/12 (in units of the helical coil current). In this case the parameter $k_\varphi = B_{th}/(B_{th} + B_{tt})$ is k_φ=0.375 (B_{th} and B_{tt} are the toroidal components of the magnetic field produced by helical and TF coils, respectively). For the so called "fat" configuration the mean current in a TF coil is approximately 9/14 (k_φ=7/25). The additional control parameter for improving the effective ripple is the difference of currents in adjacent TF coils [1, 4].
An important role in the formation of the torsatron magnetic configuration belongs to the vertical field coil (VF coil) system which produces the magnetic field compensating the vertical magnetic field of the helical coils to the necessary value. In the presented computations the VF coil system variant [5] is used which makes it possible to suppress significantly the island structure of the magnetic surfaces.
For the helical coils the magnetic field and its spatial derivatives are calculated on the basis of the Biot-Savart law modeling each helical coil by 24 current filaments distributed in two layers. The magnetic fields produced by the TF and VF coils are calculated using elliptic integrals (recalculating the fields obtained in the local coordinate systems of each coil to the general cylindrical coordinates).

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Optimization run and computations of effective ripple

In view of the results of [4] the currents in the TF coils are presented in a form $I_{TFC} \pm \Delta I$ with sign plus for the inner two coils in each field period and with sign minus for the outer two coils (further, ΔI is expressed in the units of the helical coil current). In [4] a decrease in the effective ripple was found in U-2M for certain values of $\Delta I > 0$ (and vice versa an increase in case of $\Delta I < 0$). Here the dependence of the effective ripple on ΔI is analyzed using methods which are valid (in contrast to [4]) over the entire magnetic configuration and allow in this case to obtain the quantitative evaluation of the effective ripple.
Optimization run [3] using the NEO code [2] for the $\epsilon_{\rm eff}^{3/2}$ computation is performed with varying the ΔI parameter. It should be noted that the computation of $\epsilon_{\rm eff}^{3/2}$ is more useful (as compared to $\epsilon_{\rm eff}$) since for the $1/\nu$ transport regime the transport coefficients are proportional directly to $\epsilon_{\rm eff}^{3/2}$. To assess the necessary interval of the ΔI variation, before the optimization run computations of the $\epsilon_{\rm eff}^{3/2}$ quantity are performed for the ΔI values of 0 and ±5/144. After that a more detailed assessment of the configuration confinement properties in case of $1/\nu$ regime is performed using the optimization procedure [3] for the ΔI interval of -0.1÷0.1.
In the procedure the total stored energy in the plasma volume is used as fitness parameter with an energy source, $Q(r) = \frac{Q_0}{r}\delta(r)$, which is localized at the magnetic axis. It is assumed that the temperature profile is defined by the heat conductivity equation

$$\frac{1}{r}\frac{\partial}{\partial r} r\kappa_\perp \frac{\partial T}{\partial r} + Q(r) = 0 \qquad (1)$$

with the boundary conditions $T(a)$=0 and $\lim\limits_{r\to 0}\left(r\frac{dT}{dr}\right) = 0$ (here a is the boundary of the plasma). So, the heat conductivity, $\kappa_\perp$, is proportional to $\epsilon_{\rm eff}^{3/2}T^{7/2}$, and computation of $\epsilon_{\rm eff}^{3/2}$ for sets of computed magnetic surfaces is an essential part of the optimization procedure. The normalized stored energy

$$\hat{W} = \int\limits_0^a dr\ r\hat{n}(r)\left(\int\limits_r^a \frac{dr'}{r'\epsilon_{\rm eff}^{3/2}(r')}\right)^{2/9} \qquad (2)$$

can be obtained by integrating the temperature profile resulting from (1) ($\hat{n}$ is a normalized plasma density).

Results

Fig. 1 shows cross-sections of magnetic surfaces used for the $\epsilon_{\rm eff}^{3/2}$ computations for ΔI =0 (in the φ=0 plane and after half of the field period). A circle with a radius of 34 cm shows the inner boundary of the vacuum chamber. Magnetic islands at ι=4/5 can be observed not far from the chamber boundary. Magnetic surfaces for ΔI=5/144 and ΔI=-5/144 (not shown here) differ from those in Fig. 1 mainly by the sizes of the outermost magnetic surfaces. For $\Delta I > 0$ ($\Delta I < 0$) these sizes are smaller (bigger) than those in Fig. 1. The positions of the islands for these cases only slightly differ from that for ΔI=0. In the case of ΔI=5/144 for the region outside the ι=4/5 islands the magnetic configuration has entirely a structure of island chains consisting of very big numbers of small islands.
The results of the computations of $\epsilon_{\rm eff}^{3/2}$ for ΔI=0, ±5/144, 0.035 and 0.0375 are presented in Fig. 2 (for the non-island magnetic surfaces) as functions of the mean radius r of a magnetic surface. The curves presented in Fig. 2 have gaps corresponding to the island surfaces.

Different total intervals in r correspond to different sizes of the outermost magnetic surfaces. Surfaces outside the islands are not fully inside the vacuum vessel and, therefore, suppressed for computations of the total stored energy (nevertheless $\epsilon_{\text{eff}}^{3/2}$ is shown for ΔI equal to 0 and -5/144 in Fig. 2). It follows from the results that for the small r for ΔI=5/144, 0.035 and 0.0375 the $\epsilon_{\text{eff}}^{3/2}$ value is smaller by order of one magnitude than that for ΔI=0. However, this difference decreases when approaching the islands and in the island vicinity it becomes small. For ΔI=-5/144 the $\epsilon_{\text{eff}}^{3/2}$ values are bigger than for ΔI=0. From the computations also follows that in the islands $\epsilon_{\text{eff}}^{3/2}$ reaches the values 0.2÷0.3 for all considered cases. The obtained results are in a qualitative agreement with results of [4] for rather small r/a (with a being the mean radius of the outermost magnetic surface). Note that the $\epsilon_{\text{eff}}^{3/2}$ values of 0.01÷0.1 which are characteristic for Fig. 2 from r approximatly 7cm to r corresponding to the appearance of the island are essentially bigger than those which are desirable from the viewpoint of the stellarator optimization [6].

The optimization results are presented in Fig. 3 in form of the normalized stored energy (2) as a function of ΔI. The results correspond to models of the particle density where constant and parabolic profiles are assumed. A maximum in the stored energy is seen for ΔI ≈0.035 that is rather close to the ΔI value 5/144 (≈0.03472) considered above.

Summary

Employing newly developed techniques [2, 3] which are based on an integration along magnetic field lines, the 1/ν transport coefficients are studied numerically for various configurations of U-2M. The magnetic field computed directly from the coil currents is used for the coefficient computations. From the results of the optimization procedure carried out with varying the currents in the adjacent toroidal field coils it follows that a maximum in the stored energy exists for a certain difference of these currents which is close to that corresponding to the decreased $\epsilon_{\text{eff}}^{3/2}$ value.

Preliminary results show a configuration with an enhanced total stored energy compared to the “standard” configuration. Very close to the “best” configuration another one with a poor energy content can be seen. This might be subject for further investigations. In calculated magnetic configurations magnetic islands are found corresponding to ι=4/5 not far from the vacuum chamber boundary (although the islands corresponding to ι=4/6 are essentially suppressed). In principle, the islands at ι=4/5 can be used for the island divertor.

References

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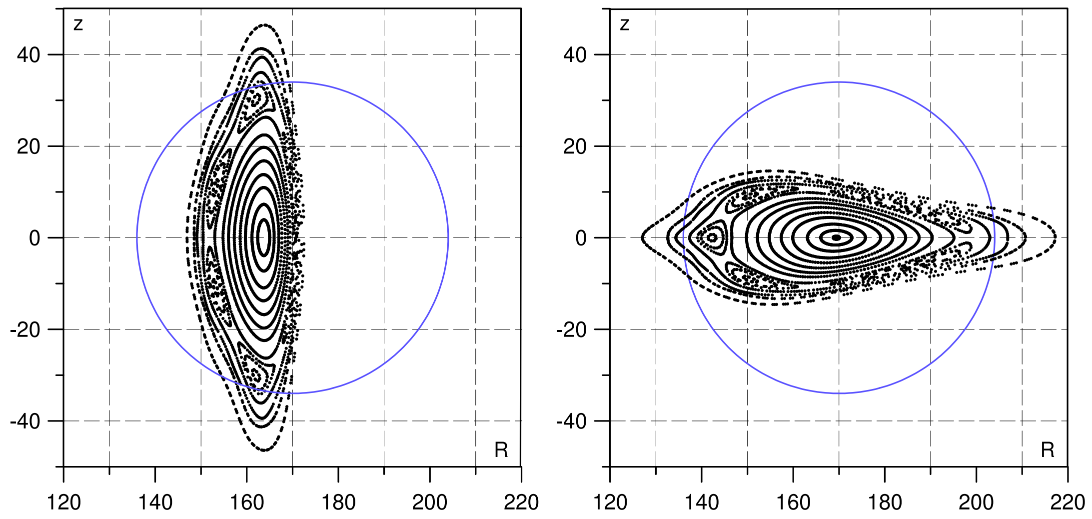

Fig.1. “Standard” configuration of U-2M for ΔI=0.

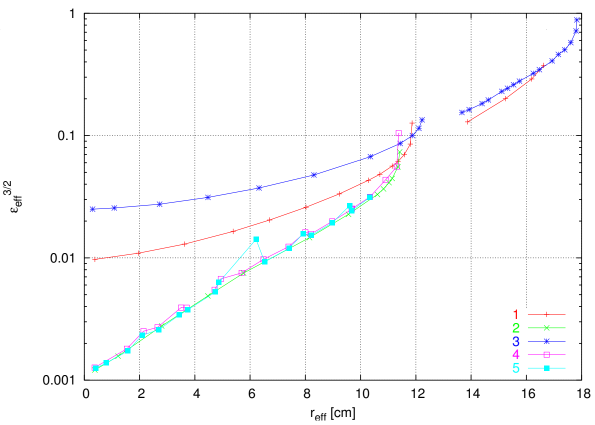

Fig.2. Parameters $\epsilon_{\rm eff}^{3/2}$ as functions of r for various ΔI; 1: ΔI=0; 2: ΔI=5/144; 3: ΔI=-5/144; 4: ΔI=0.035; 5: ΔI=0.0375 (gaps in curves correspond to the island surfaces).

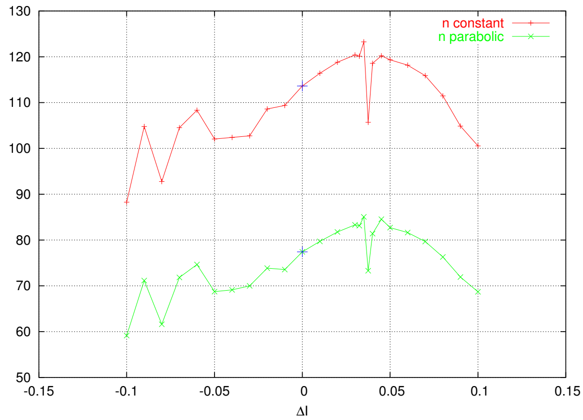

Fig.3. Normalized stored energy (in a. u.) (see Eq. (2)) vs. change of ΔI.