NEOCLASSICAL TRANSPORT FOR URAGAN-2M IN THE $1/\nu$ REGIME

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The $1/\nu$ neoclassical transport (effective ripple, ε_{eff}) is studied for the torsatron Uragan-2M (see in [1]. For stellarators where the finite plasma pressure causes a weak influence on the equilibrium ε_{eff} can be computed using field line tracing code [2] in real space coordinates. Also, an optimizing procedure is carried out using the code [3] for optimizing stellarators with fixed coil design. Besides, possibilities of improving the neoclassical transport by changing the resulting vertical magnetic field are considered.

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INTRODUCTION

The U-2M device (IPP, Kharkov) is an l=2 torsatron with an additional toroidal magnetic field (m_p=4, R_T=170cm, m_p is a 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 is 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 of 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). The additional control parameter for improving the effective ripple is the difference of currents in adjacent TF coils [1], [4].

An important role in formation of the torsatron magnetic configuration belongs to the vertical field coil (VF coil) system. 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).

COMPUTATIONS OF EFFECTIVE RIPPLE AND OPTIMIZATION RUN

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, ε_{eff}, was found in U-2M for certain values of ΔI>0 (and vice versa an increase in case of ΔI<0). Here the dependence of ε_{eff} 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 ε_{eff}.

Optimization run [3] using NEO code [2] for the $\varepsilon_{eff}^{3/2}$ computation is performed with varying the ΔI parameter. Note that computation of $\varepsilon_{eff}^{3/2}$ is more useful (as compared to ε_{eff}) since for the $1/\nu$ transport regime the transport coefficients are proportional directly to $\varepsilon_{eff}^{3/2}$. To assess the necessary interval of the ΔI variation, before the optimization run computations of $\varepsilon_{eff}^{3/2}$ are made 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 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, $Q(r)= Q_0\delta(r)/r$, 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 $\lim\limits_{r\to 0}(rdT/dr)$=0 (here a is the boundary of the plasma). So, the heat conductivity, $\kappa_\perp$, is proportional to $\varepsilon_{eff}^{3/2}T^{7/2}$, and computation of $\varepsilon_{eff}^{3/2}$ for sets of computed magnetic surfaces is an essential part of the optimization procedure. The normalized stored energy

$$\overline{W} = \int_0^a dr r\overline{n}(r)\left(\int_0^a \frac{dr'}{r'\varepsilon_{eff}^{3/2}(r')}\right)^{2/9} \qquad (2)$$

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

RESULTS

Fig.1 shows cross-sections of magnetic surfaces used for the $\varepsilon_{eff}^{3/2}$ 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 of ι=4/5 can be seen close to 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 ΔI>0 (ΔI<0) these sizes are smaller (bigger) than those in Fig.1. The position 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 $\varepsilon_{eff}^{3/2}$ 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 for the curves 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 $\varepsilon_{eff}^{3/2}$ is shown for ΔI equal to 0 and -5/144 in Fig.2).

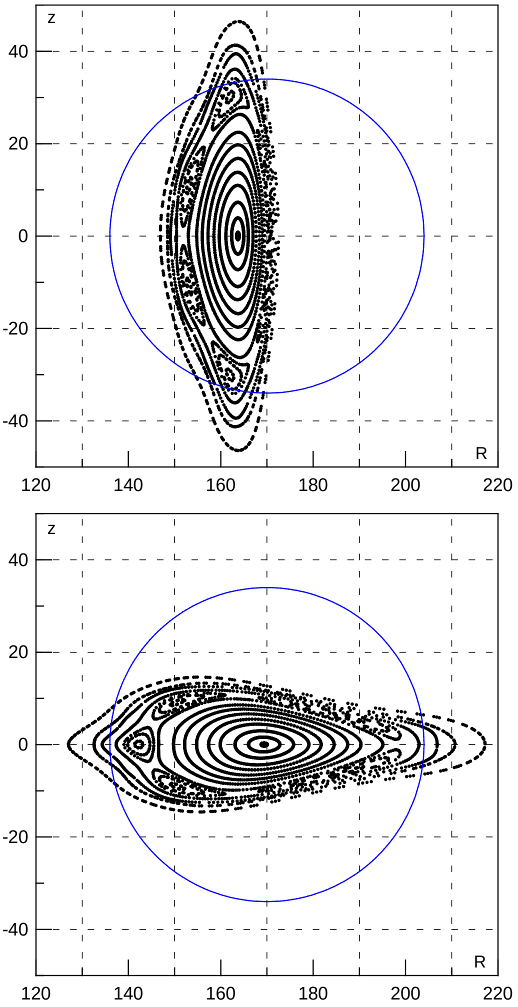

Fig. 1. "Standard" configuration of U-2M for ΔI=0

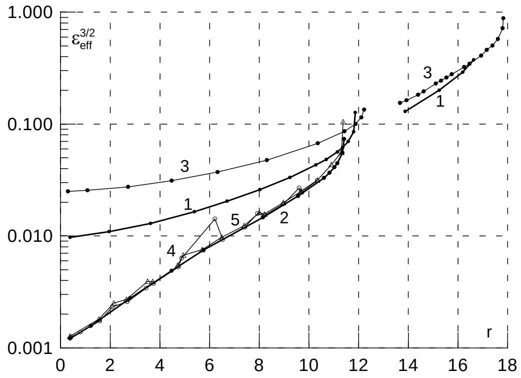

Fig.2. Parameters $\varepsilon_{eff}^{3/2}$ as functions of r for various ΔI;
1: ΔI=0; 2: ΔI=5/144; 3: ΔI=-5/144;
4 and 5 (thin lines): ΔI=0.035 and 0.0375, respectively
(gaps in curves correspond to the island surfaces)

It follows from the results that for the small r for ΔI=5/144, 0.035 and 0.0375 the $\varepsilon_{eff}^{3/2}$ value is smaller by one order of magnitude than that for ΔI=0. However, this difference decreases when approaching the islands and in the island vicinity becomes small. For ΔI=-5/144 the $\varepsilon_{eff}^{3/2}$ values are bigger than for ΔI=0. From the computations also follows that in the islands $\varepsilon_{eff}^{3/2}$ 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 $\varepsilon_{eff}^{3/2}$ values of 0.01÷0.1 which are characteristic for Fig.2 from r approximately 7 *cm* 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 the form of a normalized stored energy (2) as a function of ΔI. The results correspond to a model of the particle density where constant and parabolic profiles are assumed. A maximum in the stored energy is seen for $\Delta I \approx 0.035$ that is rather close to the ΔI value 5/144 considered above.

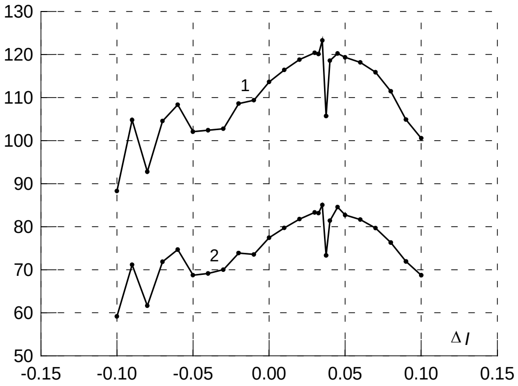

Fig.3. Normalized stored energy (in a. u.)
(see Eq.(2)) vs. change of ΔI;
1: n=const., 2: parabolic profile of n

The afore-presented results relate to the initial "standard" configuration which is well centered with respect to the vacuum chamber and is characterized by a resulting vertical magnetic field $B_\perp$ of $B_\perp/B_0 \approx 2.5\%$ value (B_0 is the mean toroidal magnetic field). Further, the calculations are performed for the changed value of $B_\perp$, namely, for $B_\perp$=0 and $B_\perp/B_0 \approx$-2.5% in case of ΔI=0 (the positive (negative) $B_\perp$ value corresponds to the somewhat un-compensated (over-compensated) vertical field of the helical coils). For these changes an additional homogeneous vertical magnetic field of the necessary value is used. Due to the changes in $B_\perp/B_0$ the magnetic axis turns out to be inward shifted with respect to its position for $B_\perp/B_0 \approx 2.5\%$. Fig.4 shows the magnetic surfaces corresponding to $B_\perp/B_0 \approx$-2.5%.

Computational results for $\varepsilon_{eff}^{3/2}$ corresponding to the new values of $B_\perp/B_0$ are presented in Fig.5 (curves 3 and 4) as functions of r/a with a being the mean radius of the outermost magnetic surface for $B_\perp/B_0 \approx 2.5\%$, ΔI=0. For comparison curves 1 and 2 in the figure show some results from Fig.2. Curve 5 shows the results corresponding to $B_\perp/B_0 \approx$-2.5% when the $B_\perp/B_0$ value is obtained by the corresponding increase in the currents of the VF coils but not by the additional homogeneous magnetic field.

It follows from Fig.5 that the inward-shifted magnetic configurations have markedly smaller values of $\varepsilon_{eff}^{3/2}$ than the configurations corresponding to $B_\perp/B_0$=2.5%. This can be explained by the fact that inward shifted stellarator configurations turn out to be rather close to the so called "σ-optimized" configurations (see, e.g., [7]).

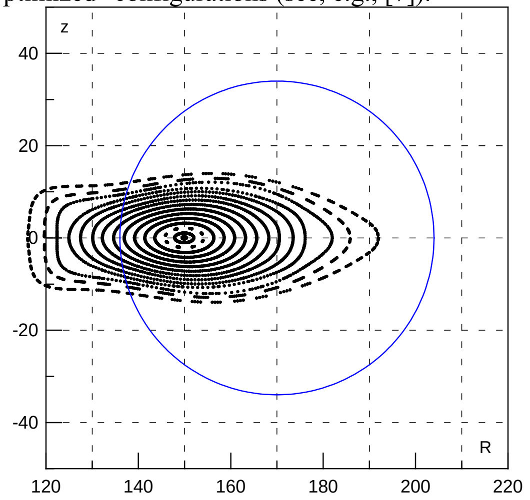

Fig. 4. "Inward-shifted" configuration of U-2M

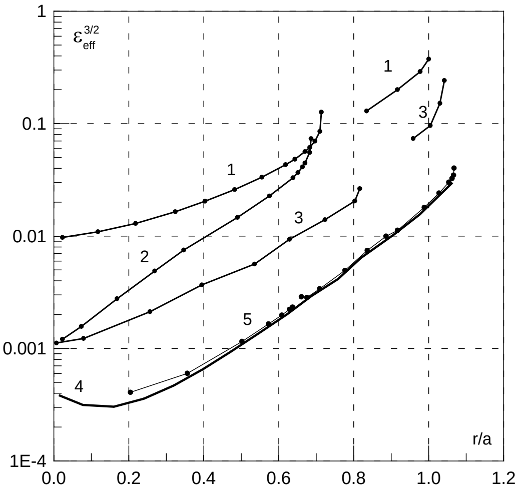

Fig. 5. Parameters $\varepsilon_{eff}^{3/2}$ as functions of r/a;
1: $\Delta I=0$, $B_\perp/B_0=2.5\%$; 2: $\Delta I=5/144$, $B_\perp/B_0=2.5\%$;
3: $B_\perp=0$, $\Delta I=0$; 4 and 5: $B_\perp/B_0= -2.5\%$, $\Delta I=0$

Because of the vacuum chamber and islands the confinement regions are smaller than it is seen from Figs.2 and 5. They can be characterized by the corresponding maximum values of r/a which equal $r/a\approx 0.82$ for $B_\perp/B_0=0$, $r/a\approx 0.47$ for $B_\perp/B_0=-2.5\%$; $r/a\approx 0.68$ for $B_\perp/B_0=2.5\%$, $\Delta I=5/144$.

CONCLUSIONS

The initial "standard" U-2M configuration is well centered with respect to the vacuum chamber. It is found that for this configuration the 1/ν transport is essentially bigger than that which is desirable from the viewpoint of the stellarator optimization [6]. Some improvement in this transport can be achieved by a certain difference of currents in adjacent TF coils. Markedly smaller 1/ν transport can be obtained by changing the resulting vertical magnetic field in a way which leads to an inward-shifted configuration. This way can be of interest although the inward-shifted stellarator configuration can posses a magnetic hill (instead of a magnetic well). From recent experimental results [8] for LHD follows that MHD stability as well as good transport properties can be obtained simultaneously in inward-shifted configurations with a magnetic hill.

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НЕОКЛАССИЧЕСКИЙ ПЕРЕНОС В РЕЖИМЕ 1/ν ДЛЯ УРАГАНА-2М

В.Н. Калюжный, С.В. Касилов, В. Кернбихлер, В.В. Немов, Б. Сейвальд

Изучен неоклассический перенос в режиме 1/ν («effective ripple», ε_{eff}) для торсатрона Ураган-2М [1]. Для стеллараторов, где конечное давление плазмы оказывает слабое влияние на равновесие, ε_{eff} может быть рассчитан с применением кода [2], использующего интегрирование вдоль магнитных силовых линий в реальных пространственных координатах. Применена также оптимизационная процедура, использующая код [3] для оптимизации стеллараторов с фиксированными катушками. Рассмотрены также возможности снижения коэффициентов неоклассического переноса путем изменения результирующего вертикального магнитного поля.

НЕОКЛАСИЧНИЙ ПЕРЕНОС В РЕЖИМІ 1/ν ДЛЯ УРАГАНА-2М

В.М. Калюжний, С.В. Касілов, В. Кернбіхлер, В.В. Нємов, Б. Сейвальд

Вивчено неокласичний перенос в режимі 1/ν («effective ripple», ε_{eff}) для торсатрону Ураган-2М [1]. Для стелараторів, де вплив кінцевого тиску плазми на рівновагу являється слабким , ε_{eff} може бути розраховано з застосуванням коду [2], що використовує інтегрування вздовж магнітних силових ліній в реальних просторових координатах. Застосовано також

оптимізаційну процедуру, яка використовує код [3] для оптимізації стелараторів з фіксованими котушками. Крім того, розглянуто можливості зниження коефіцієнтів неокласичного переносу шляхом змінювання результуючого вертикального магнітного поля.