Optimization of energy confinement in Uragan-2M[1]

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Abstract

In framework of optimization of the confinement properties of Uragan-2M (U-2M) [1] the normalized stored energy is analyzed for various configurations of this device in the $1/\nu$ transport regime. Using the NEO code [2] for computation of the heat conductivity, optimization runs [3] are carried out with an energy source which is localized at the magnetic axis. The additional vertical magnetic field is used as a varying parameter.

Introduction

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 various studies were carried out whose results are summarized in [1]. Due to the flexibility of the magnetic system of the device, further investigations of possibilities for an improvement of 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). The additional control parameter for improving the effective ripple is the difference of currents in adjacent TF coils [1,4].

The vertical field coil (VF coil) system plays an important role in formation of the magnetic configuration of the torsatron. The total vertical magnetic field is produced by the VF coils and the vertical magnetic field of the helical coils. The desired vertical magnetic field is reached by adjusting the current of the vertical field coils. These currents can also be used as control parameters.

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).

Optimization of energy confinement

In [3] an optimization procedure for the stored energy in the plasma had been worked out to analyze the confinement properties of the TJII device [5] for the $1/\nu$ regime. For the calculations of the heat conductivity, $\kappa_\perp$, the NEO code [2] was used. In [6] this procedure had been used for the corresponding computations in U-2M using

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the difference of currents in adjacent toroidal field coils as a varying parameter. Here the analogous computations are performed using the change in the resulting vertical magnetic field, $B_\perp$, as such a parameter. The interval of $B_\perp/B_0 \approx$ is $\approx$-2.5% to $\approx$2.5% (B_0 is the mean toroidal magnetic field). Figs. 1, 2 and 3 show examples of cross-sections of magnetic surfaces used for the following computations of the neoclassical transport which correspond to $B_\perp/B_0 \approx$2.5%, $B_\perp/B_0 \approx$0 and $B_\perp/B_0 \approx$-2.5%, respectively.

In the optimization procedure [3] 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 $\epsilon_{\text{eff}}^{3/2} T^{7/2}$, and computation of $\epsilon_{\text{eff}}^{3/2}$ for sets of computed magnetic surfaces is an essential part of the optimization procedure. The normalized stored energy

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

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

In view of the results [4] the currents in the TF coils of U-2M 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 (ΔI is expressed in the units of the helical coil current). The optimization run with varying the ΔI parameter within the interval of -0.1÷0.1 had been performed in [6] for 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 $B_\perp/B_0 \approx 2.5\%$. The corresponding magnetic surfaces for the case of ΔI=0 are presented in Fig. 1. The optimization results for the calculations [6] are presented in Fig. 4 in form of the 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. Note that surfaces outside the islands are not fully inside the vacuum vessel and, therefore, suppressed for computations of the total stored energy. The optimum value of ΔI correlates qualitatively with results of [4] where the effective ripple for U-2M was analyzed for rather small r/a (with r being the mean radius of a magnetic surface and a being the mean radius of the outermost magnetic surface).

Another way of improving the $1/\nu$ transport in stellarators with helical windings is connected to changes of the resulting vertical magnetic field in a way which leads to an inward-shifted configuration (see, e.g. in [7, 8]). Further, the calculations are performed for the changed value of $B_\perp$ in the interval from $B_\perp/B_0 \approx$-2.5% to $B_\perp/B_0 \approx$2.5% in case of ΔI=0 (the positive (negative) $B_\perp$ value corresponds to the somewhat under-compensated (over-compensated) vertical field of the helical coils).

For these changes the necessary $B_\perp/B_0$ value is obtained by the corresponding increase in the currents of the VF coils. Due to the changes in $B_\perp/B_0$ the magnetic axis turns out to be inward shifted with respect to its position for $B_\perp/B_0$=2.5%. Figs. 2 and 3 show the magnetic surfaces corresponding to the changes in $B_\perp$ obtained by increasing the currents of the VF coils for $B_\perp/B_0$=0 and $B_\perp/B_0$= -2.5%.

For the optimization calculations under these conditions the factor f_{VFC} connected with an additional vertical magnetic field is considered now as a varying parameter. This is a multiplying factor for the currents in the VF coils. It enters into the expression for the magnetic field of the VF coils in a way, that $B_\perp/B_0$=2.5% for f_{VFC}=1, $B_\perp/B_0$=0 for f_{VFC}=1.166 and $B_\perp/B_0$=-2.5% for f_{VFC}=1.332.

Two cases are carried out with varying this parameter within the interval of 1÷1.332. In the first case a limitation of the useful plasma volume by the vacuum chamber is taken into account. In the second case this limitation is ignored. The optimization results for the model with the constant particle density are presented in Fig. 5. An optimum value of the vertical magnetic field is found in the first case were a maximum in the stored energy is seen. This maximum is approximately 1.4 times bigger than the corresponding maximum in Fig. 4 where ΔI is the varying parameter. The optimum f_{VFC} corresponds to $B_\perp/B_0$ ≈0 and is determined by opposite roles of decreasing the neoclassical transport coefficients and increasing the limiting role of the vacuum chamber with increasing inward shift of the plasma. As it follows from the second case, when ignoring the limitation of the vacuum chamber, the maximum in the stored energy is still higher and is realized for f_{VFC} close to a value corresponding to $B_\perp$ ≈-2.5%.

Conclusions

The initial "standard" U-2M configuration is well centered with respect to the vacuum chamber. It is found that for this configuration the $1/\nu$ transport is essentially bigger than that which is desirable from the viewpoint of the stellarator optimization [9]. Some improvement in this transport can be achieved by a certain difference of currents in adjacent TF coils. Markedly smaller $1/\nu$ transport can be obtained by changing the resulting vertical magnetic field in a way which leads to an inward-shifted configuration. In U-2M, such a shift leads to a decreasing of the useful plasma volume because of a limitation role of the vacuum chamber. Nevertheless, due to a still bigger decrease of the $1/\nu$ transport the stored energy can increase as it follows from the obtained results. Inward-shifted stellarator configurations may be of interest although they can posses a magnetic hill (instead of a magnetic well). From the recent experimental results [8] for LHD it follows that the MHD stability and good transport properties are compatible in the inward-shifted configuration with a magnetic hill.

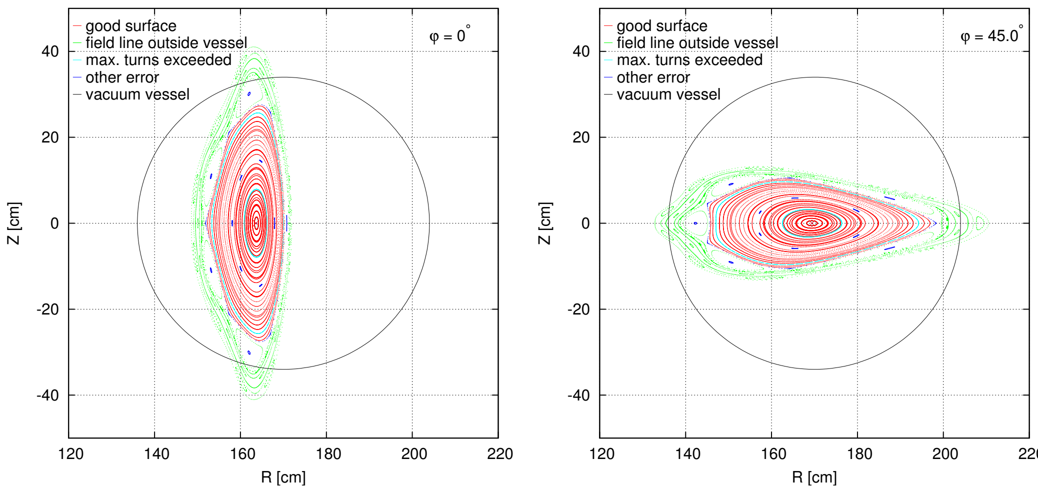

Fig.1. Cross sections for the "standard" configuration ($B_\perp/B_0 \approx$2.5%).

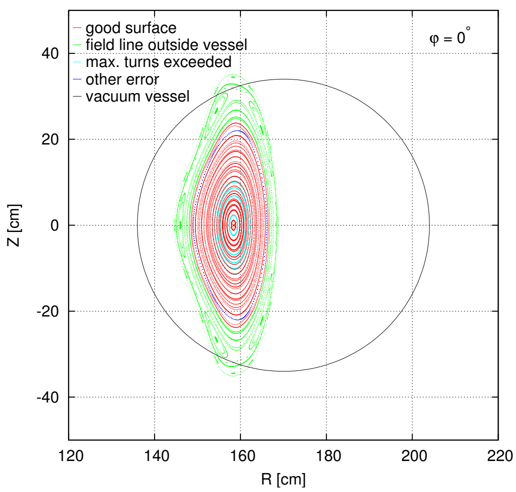

Fig.2. Cross section for $B_\perp/B_0$=0.

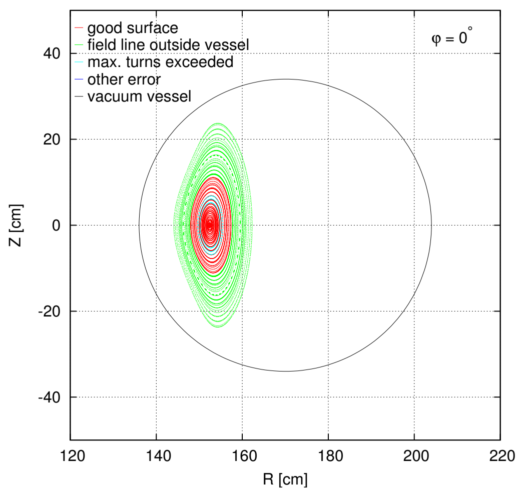

Fig.3. Cross section for $B_\perp/B_0 \approx$-2.5%.

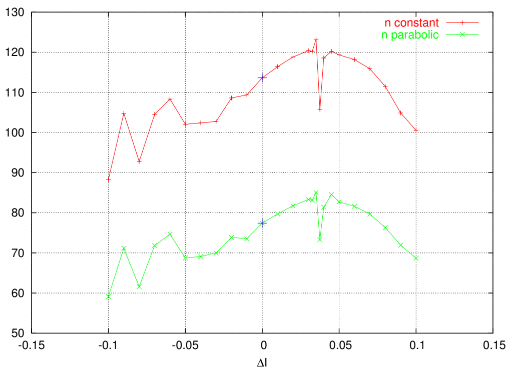

Fig.4. Normalized stored energy (in a.u.) vs. ΔI.

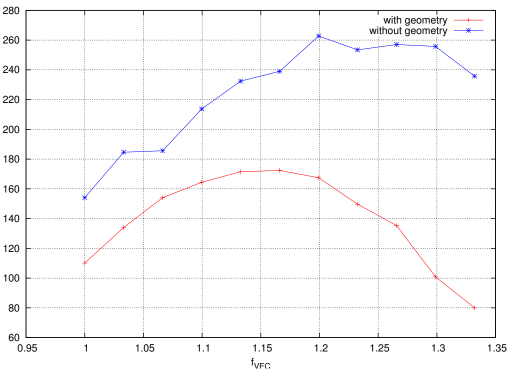

Fig.5. Normalized stored energy (in a.u.) vs. f_{VFC} (for a constant particle density profile).

References

[1] O. S.Pavlichenko for the U-2M group, *Plasma Phys. Control. Fusion*, **35**, B223-B230 (1993).

[2] V. V. Nemov, S. V. Kasilov, W. Kernbichler and M. F. Heyn, *Phys. Plasmas*, **6**, p 4622 (1999).

[3] B. Seiwald, V. V. Nemov, S. V. Kasilov, W. Kernbichler, Proc. of 29th EPS Conference on Plasma Phys. and Contr. Fusion, Montreux, 17-21 June 2002, ECA, 26B, P-4.099 (2002).

[4] C. D. Beidler, N. T. Besedin, V. E. Bykov, et al., Proc. of 13th IAEA Conf. on Nuclear Fusion, Washington, Vol.2, Vienna: IAEA, p.663 (1991).

[5] C. Alejaldre, J. Alonso, L. Almoguera, et al., *Plasma Phys. Control. Fusion*, **41**, pp. A539-A548 (1999).

[6] B. Seiwald, V. V. Nemov, V. N. Kalyuzhnyj, S. V. Kasilov, W. Kernbichler, Proc. of 31th EPS Conference on Plasma Phys., London, 28 June - 2 July 2004, ECA, 28G, P-5.118 (2004).

[7] M. F. .Heyn, et al., *Plasma Phys. Control. Fusion,* **43**, 1311 (2001).

[8] O. Motojima, et al., *Nucl. Fusion* **43**, 1674 (2003).

[9] G. Grieger, W. Lotz, P. Merkel, J. Nührenberg, J. Sapper, E. Strumberger, H. Wobig, the W7-X Team, R. Burhenn, V. Erckmann, U. Gasparino, L. Giannone, H. J. Hartfuss, R. Jaenicke, G. Kühner, H. Ringler, A. Weller, F. Wagner, and the W7-AS Team, *Phys. Fluids B*, **4**, 2081 (1992).