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Calculations of $1/\nu$ transport for Uragan-2M taking into account the influence of current-feeds and detachable joints of the helical winding*

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Introduction

For a numerical investigation of confinement properties of a specific stellarator an appropriate model of the corresponding coil system is necessary. This model is desirable to be as close as possible to the real coil system. In [1] the $1/\nu$ transport had been investigated in the "Uragan-2M" (U-2M) torsatron. The magnetic field produced by the helical winding and its necessary spatial derivatives are calculated in that work on the basis of the Biot-Savart law. However this model field is somewhat incomplete since the influence of the current-feeds and of the detachable joints of the helical winding was not taken into account. In other publications [2,3], computations of magnetic surfaces for U-2M have been performed taking into account these additional elements. However, the numerical code used there can not be directly applied to calculations of $1/\nu$ transport.

Here, the data base for the U-2M coils used in [2,3] is transformed to a new form which is valid for the already existing code for computations of **B** and its spatial derivatives. With this code, using the transformed data base, computations of the $1/\nu$ transport are made for some practically interesting magnetic configurations of U-2M. The obtained results are compared to results of previous works.

Basic model and parameters

In the model of the magnetic system of U-2M used in [2,3] the helical winding is split into a set of filamentary conductors. Each of the filaments is split into 200 short straight conductors. The Biot-Savart law is used for calculating the magnetic field of every such element as well as of the current feeds and of the detachable joints. The currents and respective coordinates of the above straight elements calculated by the code of [2,3] are written into a standard data file for calculations of magnetic fields of various stellarator devices (see, e.g., in [4]). Such a data base can be conveniently used for the data input into the already existing Biot-Savart code [1] for computations of **B** and its spatial derivatives.

Using the new data base, computations of the $1/\nu$ transport coefficients are made for U-2M parameters of practical interest for which the rotational transform, ι, is bigger than 1/3 (near the magnetic axis) and smaller than 1/2 (for the outer surfaces) (k_φ=0.31, see, in [1,3]). Note that the magnetic field and its spatial derivatives from the toroidal field coils as well as from

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the poloidal field coils are calculated using the complete elliptical integrals (as it has been done for the magnetic field in [2,3]).

Peculiarities of computations

Usually, the $1/\nu$ regime is characterized by the so called effective ripple (equivalent helical ripple), $\varepsilon_{\rm eff}$, (see, e.g., in [5]). The quantity $\varepsilon_{\rm eff}^{3/2}$ enters into neoclassical transport coefficients as a geometrical factor representing the influence of the magnetic field geometry. In [6] the field line integration technique is proposed for computations of $\varepsilon_{\rm eff}^{3/2}$ in arbitrary stellarator configurations using real space variables. This code is automatically taking into account all kinds of trapped particles. An important part of the numerical computation in the field line tracing code is the computation of $\nabla\psi$ with ψ being a magnetic surfaces label.

Because of the non-symmetric arrangement of the current feeds and of the detachable joints the stellarator symmetry of the resulting magnetic field of U-2M is violated and there exist no cross-sections of magnetic surfaces with an up-down symmetry. This complicates the determination of starting conditions for the computation of $\nabla\psi$. In such a case, a preliminary computation of the corresponding magnetic surface is necessary to find these conditions. The consequent calculation of $\nabla\psi$ is performed using an approach [7] which is based on simultaneous integration of close magnetic field lines. This differs from the $\nabla\psi$ calculations in [1,6], where the differential equations for $\nabla\psi$ are solved and where the starting values of $\nabla\psi$, $(\nabla\psi)_0$, are easily determined with high accuracy due to the presence of magnetic surface cross-sections with up-down symmetry. The advantage of the approach [7] is that it is less sensitive to a possible inaccuracy in the starting conditions.

According to [7], $\nabla\psi$ can be represented in cylindrical coordinates ρ,φ,z as

$$\nabla\psi = \lim_{\mathbf{r}_2(\varphi_0)\to\mathbf{r}_1(\varphi_0)} \frac{(\mathbf{r}_2(\varphi)-\mathbf{r}_1(\varphi))\times\mathbf{B}}{|(\mathbf{r}_2(\varphi_0)-\mathbf{r}_1(\varphi_0))\times\mathbf{B}(\varphi_0)|}. \tag{1}$$

Here, the curves $\mathbf{r}_1(\varphi)$ and $\mathbf{r}_2(\varphi)$ satisfy the field line equations $d\mathbf{r}/d\varphi = \rho\mathbf{B}/B_\varphi$ with starting points $\mathbf{r}_1(\varphi_0)$ and $\mathbf{r}_2(\varphi_0)$, respectively. The starting points are on the same magnetic surface and on the same meridian plane φ_0; $\mathbf{B}(\boldsymbol{\varphi_0})$ is $\mathbf{B}$ at the starting point $\mathbf{r}_1(\varphi_0)$. Following [7], to explain formula (1), let us consider in coordinates ψ, θ_0, φ the infinitesimal distance, $\mathbf{dr}$,

$$d\mathbf{r} = \mathbf{e_1}d\psi + \mathbf{e_2}d\theta_0 + \mathbf{e_3}d\varphi, \tag{2}$$

with

$$\mathbf{e_1} = \sqrt{g}(\nabla\theta_0\times\nabla\varphi),\ \mathbf{e_2} = \sqrt{g}(\nabla\varphi\times\nabla\psi),\ \mathbf{e_3} = \sqrt{g}(\nabla\psi\times\nabla\theta_0), \tag{3}$$

where $\sqrt{g} = 1/|(\nabla\psi\times\nabla\theta_0)\cdot\nabla\varphi|$. Here θ_0 is an angle-like variable which labels a field line on a magnetic surface and satisfies the Clebsch representation of $\mathbf{B}$, $\mathbf{B} = \nabla\psi\times\nabla\theta_0$. From this representation and (3) one finds

$$\nabla\psi = \mathbf{e_2}\times\mathbf{B}. \tag{4}$$

To obtain $\mathbf{e_2}$ let us consider a particular value of $d\mathbf{r}$ from (2), $d\mathbf{r}_{\theta_0}$, which corresponds to fixed ψ and φ, $d\mathbf{r}_{\theta_0} = \mathbf{e_2}d\theta_0$. Since $d\mathbf{r}_{\theta_0}$ corresponds to $\mathbf{r}_2(\varphi)-\mathbf{r}_1(\varphi)$ one obtains (1) from (4).

Results

In the preliminary computation of any magnetic surface, integration of the magnetic field line was made for a starting point $\mathbf{r}_1(\varphi_0)$ for an interval corresponding to 250 turns around the z axis. All intersections of this field line with the φ_0 plane are considered and the nearest one to $\mathbf{r}_1(\varphi_0)$ is chosen as $\mathbf{r}_2(\varphi_0)$. To find $\varepsilon_{\rm eff}^{3/2}$, simultaneous field line tracing computations of two field lines are performed with those two starting points, where $\nabla\psi$ is computed using (1).

Computations are made for two regimes of the vertical magnetic field. In the first regime, the currents in the vertical field coils fully correspond to those in [3]. Here, the magnetic surfaces are well centered with respect to the vacuum chamber (see Fig. 1). These surfaces are in good agreement with the corresponding results in [3]. In the second regime all the currents in the vertical field coils are increased with respect to the first regime with a factor 1.13. In this case the vertical magnetic field of the helical winding turns out to be fully compensated and the resulting vertical magnetic field is zero. In this regime the magnetic surfaces are inward shifted with respect to the vacuum chamber (see Fig. 2). The computational results for $\varepsilon_{\rm eff}^{3/2}$ for these two regimes are presented in Fig. 3 (curves 1 and 1f, resp.). Irregularities are seen for $17 < r_{\rm eff} < 19$ and $15 < r_{\rm eff} < 16$, respectively, which relate to island magnetic surfaces corresponding to $\iota = 2/5$ (ι is the rotational transform in units of 2π, $r_{\rm eff}$ is the effective radius of the magnetic surface). In the second regime, these island surfaces are outside of the chamber and they are not shown in Fig. 2.

Computations are also made for cases where current feeds and detachable joints are omitted in the considered model of the helical winding (curves 2 and 2f in Fig. 3). In these cases, the magnetic field has stellarator symmetry and islands corresponding to $\iota = 2/5$ are absent. In Fig. 3 corresponding results [1] are presented for comparison (curves 3 and 3f). It follows from Fig. 3 that for non-island surfaces $\varepsilon_{\rm eff}^{3/2}$ obtained in [1] is slightly higher than the values obtained now. This can be explained by a somewhat different laying of current filaments for the helical winding model in [1].

Summary

Two peculiarities can be pointed out in this study. First, the approach to the $\nabla\psi$ computation used in [1] was reconsidered. The reason is that stellarator symmetry of the resulting magnetic field of U-2M is violated because of the non-symmetric arrangement of the current feeds and detachable joints of the helical winding. Second, a preliminary computation of each magnetic surface is necessary to find the starting conditions for the computation of $\nabla\psi$. The lack of the stellarator symmetry leads to formation of new island surfaces for some rational values of the rotational transform. The obtained $\varepsilon_{\rm eff}^{3/2}$ values for such island surfaces can be markedly different from those for the non-island surfaces. For non-island magnetic surfaces the $\varepsilon_{\rm eff}^{3/2}$ values turn out to be sufficiently close to the corresponding results obtained in [1].

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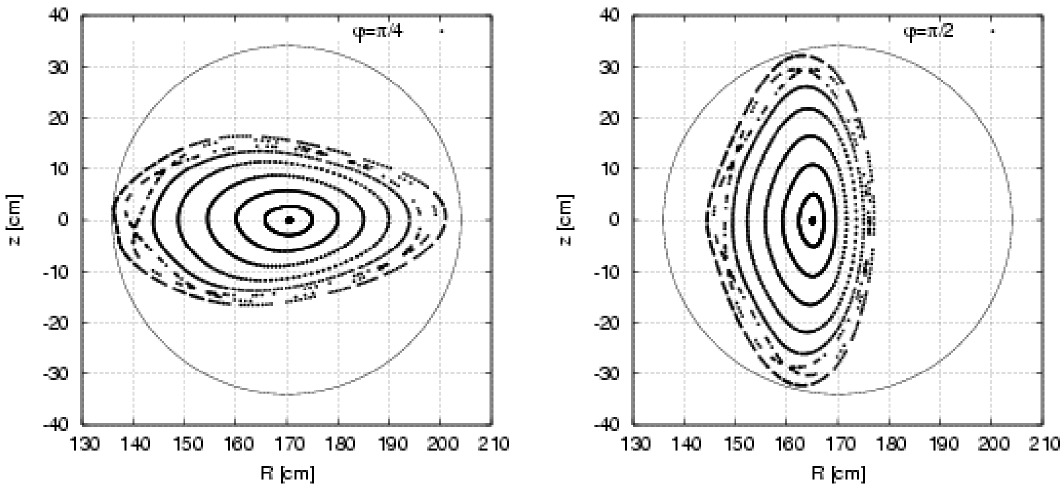

Fig.1. Magnetic surfaces of U-2M for k_φ=0.31 inside the vacuum chamber. A circle with a radius of 34 cm shows the inner boundary of the vacuum chamber. Island surfaces corresponding to ι=2/5 are present not far from the vacuum chamber.

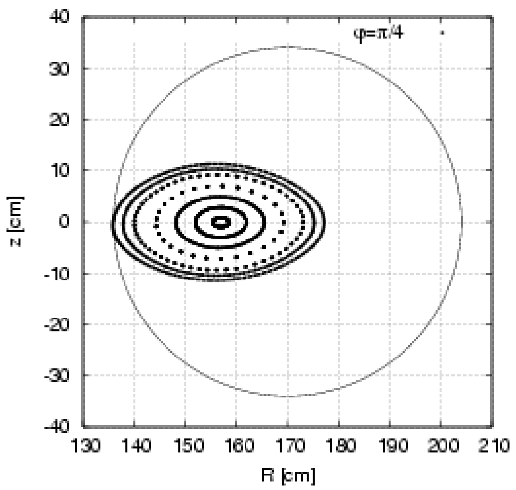

Fig.2. Magnetic surfaces of U-2M for k_φ=0.31 with full compensation of the vertical magnetic field originating from the helical winding.

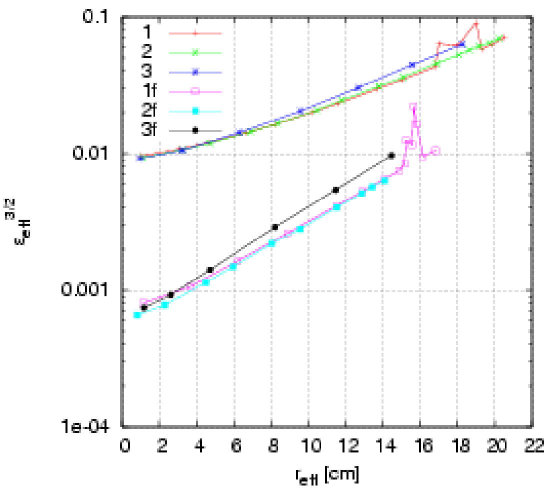

Fig.3. Parameter $\varepsilon_{\text{eff}}^{3/2}$ for U-2M with k_φ=0.31 for different models of the helical winding. 1 and 1f: helical winding model of [3]; 2 and 2f: without current feeds and detachable joints in the same model; 3 and 3f: helical winding model of [1]; (1, 2 and 3 - the magnetic surfaces are well centered with respect to the vacuum chamber; 1f, 2f and 3f - fully compensated vertical magnetic field of the helical winding).