Calculations of high energy particle losses for stellarators in real space coordinates *

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Introduction

In numerical studies of collisionless charged particle losses (in particular, α-particle losses) in stellarators the most consistent approach is realized in codes which perform a direct computation of particle losses using the guiding center drift equations to follow trapped particle orbits until such particles are lost. Such an approach has been realized, in particular, in [1] in which a huge sample of particles is followed with random starting points as well as random values of pitch angles on an initial magnetic surface. It should be noted that computations in [1] are performed in magnetic coordinates. A final conclusion about properties of the pertinent configuration can be only made when taking into account the influence of islands and stochastic regions which may exist in a real magnetic field and which can be analyzed only in real space coordinates. Therefore, for this study a code analogous to that of [1] is worked out for the case of a stellarator magnetic field given in real space coordinates. In this case calculations can be made in a magnetic field with three-dimensional inhomogeneity in presence of stochastic regions and island magnetic surfaces. This field can be calculated in real space from coil currents using the Biot-Savart law as well as from three-dimensional magneto-hydrodynamic (MHD) finite β equilibrium codes such as PIES or HINT. Calculations with this code are performed for the life time of α-particles in magnetic configurations of U-2M (Uragan-2M) and W7-X adapted to reactor plasma parameters.

Computational procedure and initial conditions

In the proposed approach a sample of 1000 particles (trapped plus untrapped) is followed with random starting points as well as random values of pitch angles on an initial magnetic surface. The guiding center drift equations are solved with help of the code used in [2]. Every particle orbit is followed until the particle reaches some limiting surface with the plasma confinement region inside it. In particular, the inner surface of the vacuum chamber as well as the boundary surface of the confinement region or outer boundary of the stochastic region can be used as such limiting surface. This surface is called "a virtual chamber". The particle is recorded as a lost particle when it reaches this virtual chamber. From the general sample of α-particles the sample of trapped particles gives the principal contribution to the collisionless particle losses. In the calculations all classes of trapped particles are taken into account, i.e., particles trapped not only within one magnetic field ripple but also trapped within several magnetic field ripples. The influence of an ambipolar radial electric field is not taken into account because it has only negligible effect on α-particle motion. As in [1], guiding center orbits are started at an aspect ratio A of ≈ 40 and ≈ 20, respectively.

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Calculations are performed for the life time of 3.5 MeV α-particles in a number of stellarator magnetic configurations of U-2M and W7-X. As a test case, calculations are carried out using the W7-AS configuration as an example. All the considered configurations are adapted to reactor plasma parameters: $a = 1.6$ m and $B = 5$ T (see in [1], a is the plasma average radius, B is the magnetic field). The magnetic field for W7-AS is calculated using decomposition in Dommaschk potentials [3].

For U-2M the magnetic field is calculated using the Biot-Savart law code with taking into account current-feeds and detachable joints of the helical winding [4]. Two different magnetic configurations of U-2M are considereded. For both configurations magnetic field parameters are chosen to provide magnetic surfaces which are well centered with respect to the vacuum chamber. For the first configuration the toroidal magnetic field is chosen in such a way that the rotational transform ι is within $1/3 < \iota < 1/2$ ($k_\varphi = 0.31$, see, in [4]). The second configuration ($k_\varphi = 0.295$) has a slightly larger toroidal magnetic field and ι within $0.31 < \iota < 0.383$. For this configuration the resonant magnetic surfaces with $\iota = 1/3$ are inside the confinement region. Under the influence of current-feeds and detachable joints the stellarator symmetry of the U-2M magnetic field is violated and considerable island magnetic surfaces arise in the central region of the magnetic configuration. For comparison, also calculations are performed where such an influence is neglected.

For W7-X a vacuum high mirror configuration obtained using the Biot-Savart law code (see, e.g. in [5]) as well as three-dimensional MHD finite β equilibrium high mirror configurations obtained with help of the HINT2 code ($\beta \approx 2\%$ and 4%, see, e.g., in [6]) are studied. Further, the configuration obtained using the Biot-Savart law code is defined as the case for $\beta = 0$. In some calculations the role of the stochastic region surrounding the confinement region is analyzed. To accelerate computations, the Lagrange polynomial interpolation of the magnetic field is applied for both last devices.

Computational results

The computational results for the life time of trapped α-particles are presented in Figs. 1 and 3 in form of plots for the collisionless evolution in time of trapped α-particle fractions. A decrease of these fractions corresponds to an increase of the corresponding losses.

Fig. 1 shows the computational results obtained for W7-AS and U-2M in case of particles started at magnetic surfaces corresponding to A$\approx$ 40. Here, the boundary surface of the confinement region is taken as a virtual chamber for W7-AS. For U-2M the virtual chamber coincides with the inner surface of the vacuum chamber. From the results for W7-AS follows that an essential part of trapped α-particles is lost with an approximate loss time of 10^{-4}s. These results are in a reasonable agreement with the corresponding results of [1] obtained in magnetic coordinates. The life time of α-particles for U-2M is somewhat smaller than for W7-AS. It is found that there is no essential difference in the results for both configurations of U-2M. Also, the presence of magnetic islands caused by a violation of the stellarator symmetry has no essential influence on the life time of α-particles.

Fig. 2 shows cross-sections of some surfaces which are important for computations in the magnetic field of W7-X. The figure contains the starting magnetic surfaces at aspect ratios ≈ 40 and ≈ 20 as well as the boundary magnetic surface of the confinement region and the outer boundary of the stochastic region surrounding the confinement region. The plots relate to the case of $\beta \approx 4\%$, however, the topology of the corresponding plots for the cases of $\beta \approx 2\%$ and $\beta = 0$ is the same.

The computational results obtained for W7-X for the cases of $\beta \approx$4% and β=0 are presented in Fig. 3. For every of these cases computations are performed for a virtual chamber determined by the boundary surface of the confinement region as well as by the outer boundary surface of the stochastic region. This allows one to assess the role of the stochastic regions of the magnetic field in confinement of the trapped α-particles. It is found that the difference in the results corresponding to both kinds of the virtual chamber is rather small. In particular, for $\beta \approx 4\%$, $A \approx 40$ the results practically coincide. This means that the confinement properties of the stochastic regions are insufficient. It is also found that independently of the choice of the virtual chamber, the cases with $\beta \approx 4\%$ are better than the cases with $\beta = 0$. Such an improvement correlates with the analogous results obtained for W7-X in [1] using magnetic coordinates. However, in Fig. 3 for $A \approx 20$ this improvement decreases to the end of the integration interval.

As it follows from the plots, during the time 0.1s the trapped α-particle fractions become approximately 1.6, 2.7, 3.2 and 3.6 times less than at the beginning of integration for the cases of ($\beta \approx 4\%$, $A \approx 40$), ($\beta = 0$, $A \approx 40$), ($\beta \approx 4\%$, $A \approx 20$) and ($\beta = 0$, $A \approx 20$), respectively. So, for finite β the life time of trapped α-particles found here for W7-X is somewhat smaller than it was obtained in magnetic coordinates in [1].

Computational results for the case of $\beta \approx 2\%$ are not presented in Fig. 3 to avoid overloading of the figure. If these results would be presented the corresponding plots would be located between the analogous plots for the case of $\beta \approx 4\%$ and for the case of $\beta = 0$.

Summary

In this analysis of α-particle confinement, the guiding center drift equations are solved with help of the code used in [2]. Calculations of the life time of 3.5 Mev α-particles in a number of stellarator magnetic configurations of U-2M and W7-X both adapted to reactor parameters are presented. For U-2M the magnetic field is calculated using the Biot-Savart law code taking into account current-feeds and detachable joints of the helical winding [4]. Under this influence considerable island magnetic surfaces arise in the central region of the magnetic configuration. Calculations are also performed without taking into account such an influence. From the results it follows that the presence of magnetic islands has no essential influence on the life time of α-particles in U-2M.

For W7-X a vacuum high mirror configuration obtained using the Biot-Savart law code (see, e.g. in [5]) as well as the three-dimensional MHD finite β equilibrium high mirror configurations obtained with help of the HINT2 code ($\beta \approx 2\%$ and 4%, see, e.g., in [6]) are studied. The role of the stochastic region surrounding the confinement region is also analyzed. From the results it follows that the cases with finite β confinement are better than cases with the vacuum magnetic field. It is also found that the confinement properties of the stochastic regions are insufficient. The life time of α-particles in W7-X is essentially better than in U-2M. However, for finite β this life time is somewhat smaller than it was obtained in magnetic coordinates in [1].

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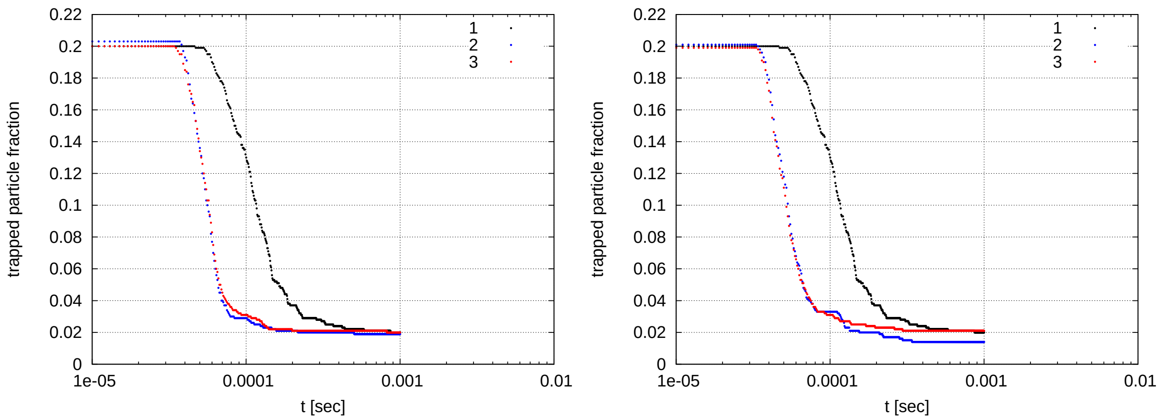

Fig. 1. Collisionless evolution of trapped α-particle fraction for W7AS and U2M adapted to reactor parameters. 1: W7AS (black points), 2: U2M with current feeds and detachable joints of the helical winding (blue points), 3: U2M without the influence of the indicated elements (red points) (stellarator symmetry, insignificant sizes of the magnetic islands). For U2M $k_\varphi = 0.295$ (left) and $k_\varphi = 0.310$ (right).

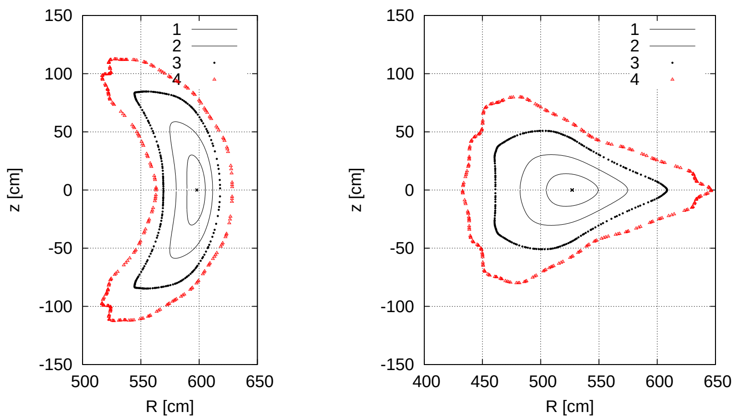

Fig. 2. Characteristic surfaces of W7-X for $\beta \approx 4\%$ (HINT2 code). Plots are numbered from the inside of the magnetic configuration. (1) and (2): (thin lines) magnetic surfaces from which particles are started (at aspect ratio $A \approx 40$ and $A \approx 20$, respectively), (3): (black points) boundary magnetic surface of the confinement region, (4): (red triangles) outer boundary of the stochastic region.

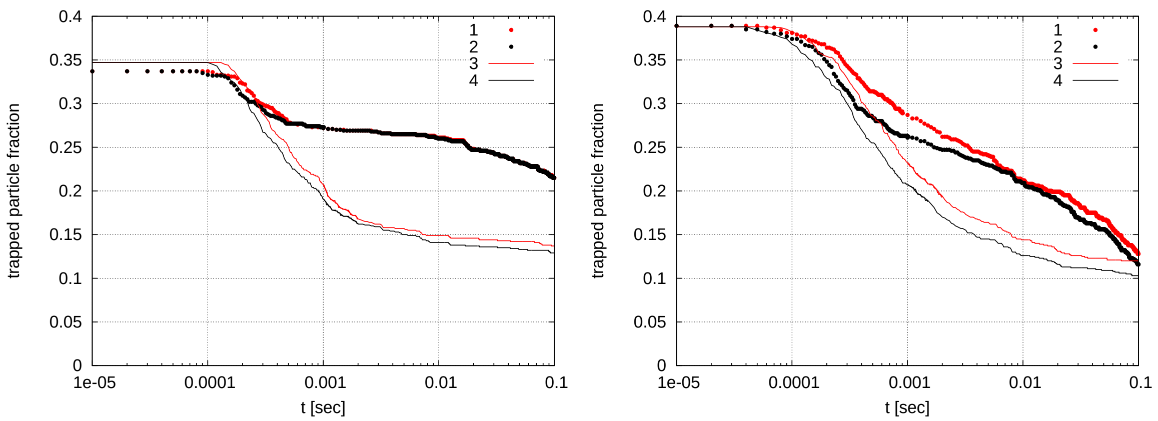

Fig. 3. Collisionless evolution of trapped α-particle fraction for W7-X adapted to reactor parameters. Particles are started at aspect ratios $A \approx 40$ (left) and $A \approx 20$ (right); 1 and 2 (upper pair of curves): magnetic field from the HINT2 code for $\beta \approx 4\%$, 3 and 4 (lower pair of curves): magnetic field from the Biot-Savart law code, $\beta = 0$; 1 and 3 (red) boundary surface of the stochastic region is taken as a virtual chamber, 2 and 4 (black) boundary surface of the confinement region is taken as a virtual chamber.