

Calculations of collisionless high-energy particle losses for heliotron/torsatron devices in real space coordinates *

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Introduction

For heliotron/torsatron devices the use of inward shifted configurations has been recommended in a number of references in order to reduce the neoclassical transport in the fusion-relevant long-mean-free-path regime. In particular, Refs. [1,2] discuss such a possibility for CHS and LHD. In the pertinent experiments an improvement of the neoclassical transport has been observed for inward shifted configurations. In Ref. [2] it was found that good MHD stability and favorable transport are compatible in inward shifted configurations.

Together with reduced neoclassical transport, the decrease of collisionless high-energy charged particle losses (in particular α -particle losses in a reactor plasma) is also important for stellarator type devices. Here, this question is considered in a numerical study of α -particle confinement in magnetic configurations corresponding to the heliotron/torsatron devices CHS, LHD and Uragan-3M [3] (U-3M). All these configurations are adapted to reactor plasma parameters using an average plasma radius of $a = 1.6$ m and a magnetic field of $B = 5$ T. Calculations are performed in real space magnetic fields for vacuum configurations. The code, which is described in Ref. [4], is applied for direct computations of particle losses solving the guiding center drift equations in real-space coordinates. This code allows one to analyze the particle confinement in magnetic fields with a three-dimensional inhomogeneity in presence of stochastic regions and magnetic islands.

Computational procedure and initial conditions

In the approach proposed in Ref. [4], a sample of 1000 particles (trapped plus passing) is followed. They are started at random points on an initial magnetic surface with random values of pitch angles. Every particle orbit is followed until the particle reaches the boundary surface of the confinement region where it is recorded as lost. 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. Calculations are performed for the life time of 3.5 MeV α -particles, which are started on magnetic surfaces corresponding to $r/a \approx 0.25$ and $r/a \approx 0.5$ with r being the magnetic surface average radius. The influence of an ambipolar radial electric field is not taken into account because it has only negligible effect on α -particle motion. To accelerate the computations, the Lagrange

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polynomial interpolation of the magnetic field is applied for CHS and LHD.

The CHS and LHD configurations are characteristic for $l = 2$ torsatron/heliotron devices with a rather large number of magnetic field periods along the torus (8 periods for CHS and 10 periods for LHD). As it is known, an optimization of the trapped particle confinement in such devices can be obtained by using an additional vertical magnetic field of appropriate value, thus creating a so-called “inward shifted configuration”. The properties of such a configuration are rather close to those for “ σ optimization” [5]. For CHS an optimized configuration of such a kind had been proposed in Ref. [1] (the drift-orbit-optimized CHS configuration) together with the standard CHS configuration. Improvement of neoclassical transport properties for LHD using the inward shifted configurations has been discussed and analyzed in Refs. [2,6]. Note, that good MHD stability and favorable transport are compatible in the inward shifted configuration of LHD [2].

In the present study of α -particle confinement in CHS and LHD the vacuum magnetic fields for both devices are calculated in the same way as in Refs. [7,8] where the neoclassical transport has been calculated for these devices using the code NEO [9] for standard as well as inward shifted configurations. For this purpose, the Biot-Savart law code is used for CHS and decompositions into toroidal harmonic functions containing the associated Legendre functions are used for LHD with decomposition coefficients, which are obtained by minimizing the magnetic field component that is normal to the boundary magnetic surfaces found from VMEC equilibria. With this, configurations with magnetic axis positions 3.75 m and 3.55 m (according to Refs. [6,8]) are determined as standard and inward shifted configurations, respectively, of LHD.

The U-3M device is an $l = 3$ torsatron with 9 helical field periods along the torus. A peculiarity of its standard configuration is that it is an outward shifted configuration for improving MHD stability properties. It is found in Ref. [3] that small errors in the U-3M magnetic system exist. They are equivalent to a small eccentricity in the vertical field coils. The corresponding perturbations of the U-3M magnetic field lead to appearance of large magnetic islands corresponding to $\iota = 1/4$ inside the confinement region. To demonstrate this phenomenon, Fig. 1 shows the corresponding magnetic surfaces for cases without and with the indicated perturbations.

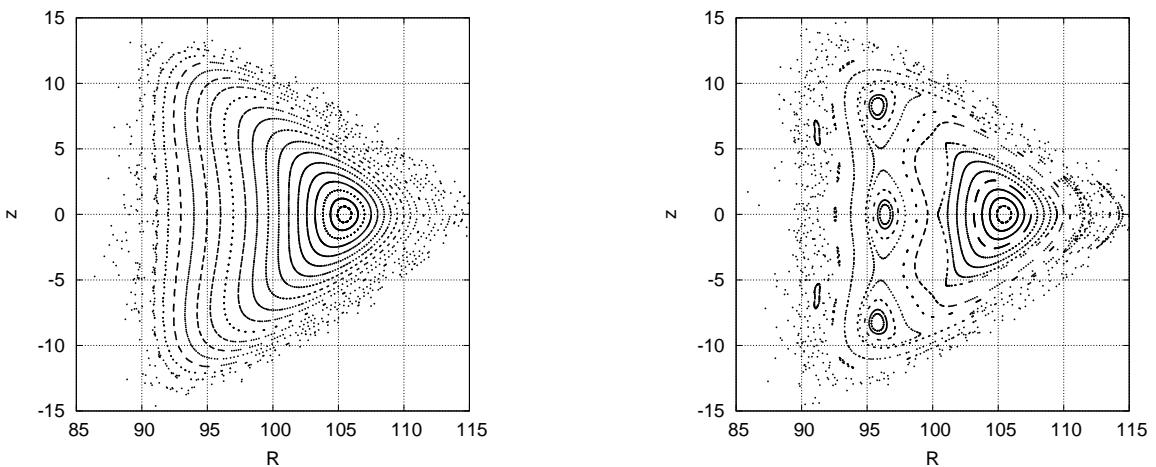


Fig. 1. Magnetic surfaces of the U-3M standard configuration without a small eccentricity in the vertical field coils (left) and with such eccentricity (right).

The magnetic field for the U-3M vacuum configurations is calculated using the helical winding field decomposition into the toroidal harmonic functions (with 33 harmonics) and using

complete elliptic integrals of the first and second kind for the field of the vertical field coils. This approach was also used in Ref. [10] for computation of the neoclassical transport in U-3M using the code NEO [9]. The inward shifted configuration of U-3M is obtained by a certain increase of currents in the vertical field coils (approximately by 10% as compared to the currents for the standard configuration). For this configuration the rotational transform, ι , changes from $\iota = 0.254$ in the center of the configuration to $\iota \approx 0.42$ near the boundary. When taking into account the indicated small eccentricity in the vertical field coils, small magnetic islands, which correspond to $\iota = 1/3$ are generated.

Computational results

The results are presented as plots of the collisionless time evolution of trapped α -particle fractions. A decrease in time corresponds to an increase of particle losses. For the CHS and LHD configurations the corresponding results are presented in Fig. 2. The results for the inward shifted configurations are marked with points whereas those for the standard configurations are presented just as lines. It can be seen that the number of trapped particles in inward shifted configurations is larger than those in standard configurations. For inward shifted configurations a delay of particle losses takes place as compared to the rate of losses in standard configurations. E.g., in LHD at $r/a \approx 0.5$ during the time 0.01 s about 8% of the particles (trapped plus passing) are lost in the inward shifted configuration ($0.44 - 0.36 = 0.08$) whereas for the standard configuration such losses constitute to 17% ($0.36 - 0.19 = 0.17$).

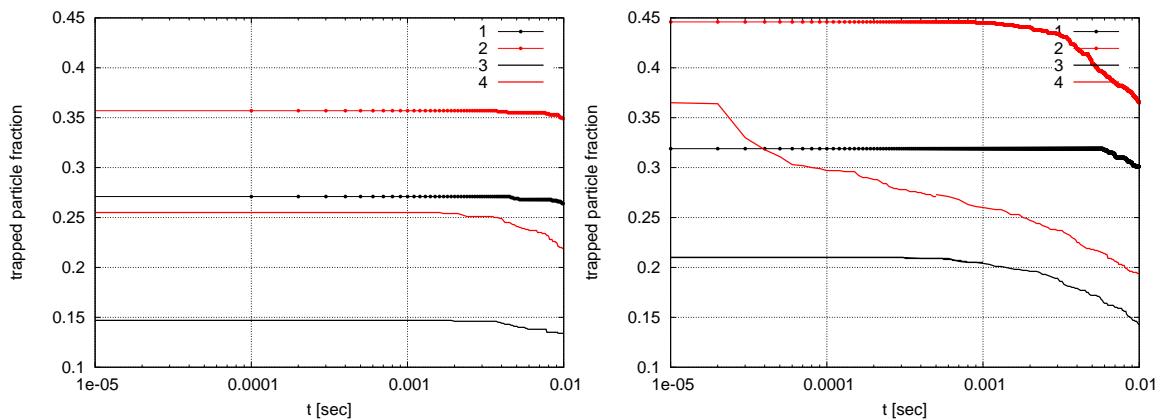


Fig. 2. Collisionless evolution of trapped α -particle fraction for CHS (left) and LHD (right) adapted to reactor parameters for inward shifted configurations (plots 1 and 2, with points) and standard configurations (plots 3 and 4, with lines). Particles are started on the magnetic surfaces corresponding to $r/a \approx 0.25$ (plots 1 and 3, black) and $r/a \approx 0.5$ (plots 2 and 4, red).

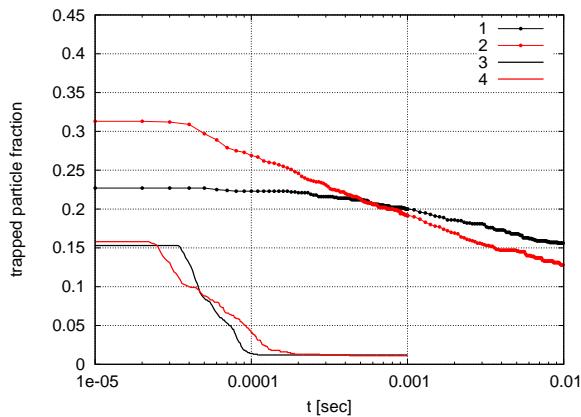


Fig. 3. Collisionless evolution of trapped α -particle fraction for U-3M adapted to reactor parameters for inward shifted configurations (plots 1 and 2, with points) and standard configurations (plots 3 and 4, with lines). Particles are started on the magnetic surfaces corresponding to $r/a \approx 0.25$ (plots 1 and 3, black) and $r/a \approx 0.5$ (plots 2 and 4, red).

For U-3M the collisionless time evolution of the trapped particle fraction is shown in Fig. 3. For both types of configurations, calculations are performed for both cases where island structures caused by a small eccentricity in the vertical field coils are either present or absent. Both cases show no noticeable difference in the results. For the standard configuration the approximate α -particle loss time is 10^{-4} s. The loss time is approximately the same for $r/a = 0.25$ and $r/a = 0.5$. From the comparison it follows that the life time of trapped particles for the standard configuration of U-3M is significantly smaller than that for the standard configurations of CHS and LHD. For the inward shifted U-3M configuration the rate of particle losses is markedly decreased. The loss time significantly increases and becomes approximately two orders of magnitude higher than for the standard configuration.

Summary

Comparative computations of collisionless high-energy particle losses are carried out for standard and inward shifted configurations of CHS, LHD and U-3M. The number of trapped particles in all inward shifted configurations is larger than the one in standard configurations. For inward shifted configurations a delay of collisionless particle losses takes place as compared to the rate of losses in standard configurations. Transformation to an inward-shifted configuration increases the trapped particle life time for all considered configurations. The life time of trapped particles in the standard configuration of U-3M is significantly smaller than that for the standard configurations of CHS and LHD. This can be explained by the fact that the standard configuration of U-3M is actually an outward shifted configuration and represents the opposite case of a “ σ -optimized” stellarator configuration. It is also found that for standard and inward-shifted configurations of U-3M the presence of magnetic islands caused by a small eccentricity of vertical field coils has no noticeable influence on the trapped particle life time.

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