

Calculations of confinement of high energy ions for a stellarator type trap DRAKON *

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Introduction

The equilibrium stellarator configuration DRAKON [1] consists of two rectilinear regions and two curvilinear elements (known as CREL), which close the magnetic system and whose parameters are chosen such as to keep the Pfirsch-Schlüter currents within the CREL and to prevent them from penetrating into the rectilinear sections. In order to improve the plasma confinement, the magnetic field in the CRELs is higher than the field in the rectilinear parts. So, in fact the rectilinear parts represent two mirror traps, which are closed by the CRELs. Fusion reactions in such a device can be realized in the mirror parts, which help to confine the hot ion component (tritium) with high perpendicular energy. The hot ions are assumed to be trapped in the magnetic mirror parts where fusion reactions take place with the cold background plasma ions (deuterium), which are confined by the CRELs and the mirror parts. In such a scenario good confinement of hot ions is important. It must be provided by mirror symmetry of the magnetic field in the mirror parts analogous to the axial symmetry of an open mirror trap. However, such a symmetry can be broken under the influence of CRELs.

In this work, a numerical study of high energy ion losses is carried out for the mirror parts of a specific model [2] of the DRAKON type trap. A recently developed technique [3] is applied for direct computations of particle losses solving the guiding center drift equations in real-space coordinates. The life time of high energy tritium ions with 70 keV is analyzed for a plasma with a minor radius of about 35 cm in the center of the mirror region.

Initial conditions and computational procedure

The magnetic system of the specific trap is formed by two solenoids with a finite number of current-carrying rings, which are distributed uniformly along the solenoid axis. Each of the two CRELs consists of three semi-tori whose planes have angles α of 120° between neighboring semi-tori [1]. In practice, more complicated CRELs may be required to provide MHD stability [4]. A general scheme of the magnetic system is shown in Fig. 1 where R is the semi-torus radius, a is the radius of the current-carrying ring, d is the distance between the ring centers along the solenoid axis, ℓ is the rectilinear section length, ℓ_1 is the length of the central part of the solenoid with a reduced ring current I_1 as compared to the current (I) in the other rings. The parameter d can be expressed through the total number of current-carrying rings, N , and the full length of the solenoid axis, ℓ_f , as $d = \ell_f / N$. The following parameters are used in the numerical study: $R_m = I/I_1 = 2$, $R = 100$ cm, $a = 40$ cm, $\ell_1 = \pi R / 2$, $B_0 = 4$ T (average magnetic field strength). Two values of ℓ are considered, namely $\ell = 2\pi R$ and $\ell = \pi R$. For those parameters the trap has nested magnetic surfaces with a rotational transform $\iota \approx 0.14$ (in units of 2π) and

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the radius of the confinement region is about 35 cm in the center of the mirror part.

In the approach proposed in Ref. [3] a sample of 1000 particles (trapped plus passing) is followed with random starting points on an initial magnetic surface as well as random values of pitch angles. Every particle orbit is followed until the particle reaches the loss boundary surface surrounding the confinement region. Here, only losses of trapped high energy ions in the mirror parts are studied.

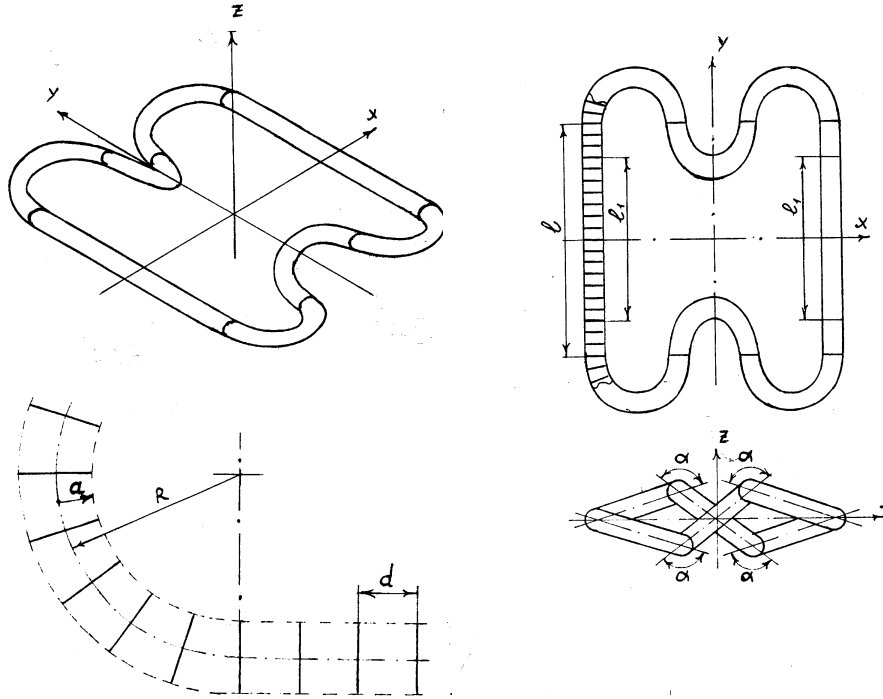


Fig. 1. A scheme of the DRAKON type trap.

Numerical computations are carried out in the real space magnetic field produced by the system of current carrying rings in two stages. First, a Cartesian system of coordinates is used (see Fig. 1) for computing B and for computing the starting points in the mirror region. Those are distributed over a part of the initial magnetic surface within a length of $3\ell/4$ (see Fig. 2). An initial magnetic surface is characterized by its minor radius r in the plane $y = 0$. Note that a tube with $r=38$ cm is considered as the loss boundary surface in this section.

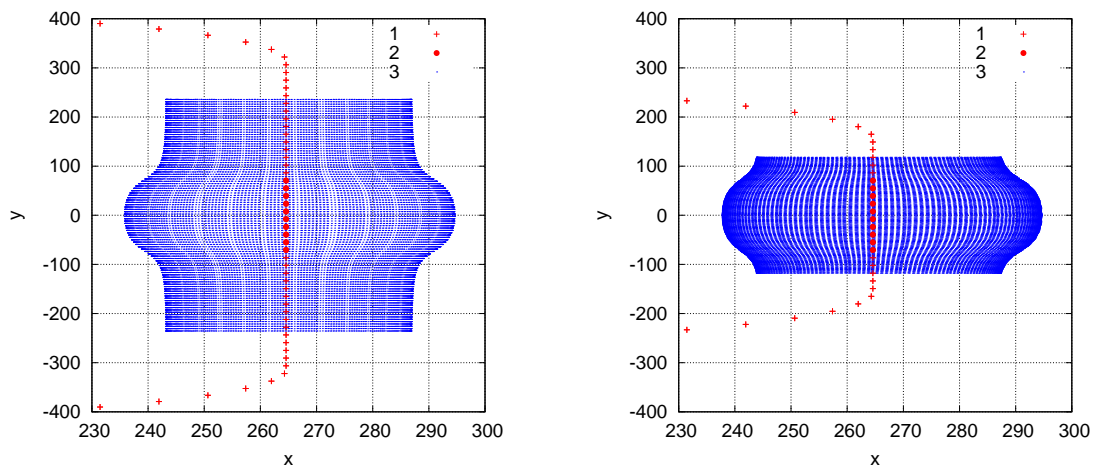


Fig. 2. Parts of initial magnetic surfaces $r=30$ cm (3) containing starting points for $\ell = 2\pi R$, $N = 200$ (left) and for $\ell = \pi R$ (right); (1): the solenoid axis, (2): part of this axis corresponding to section ℓ_1 .

At the second stage, local cylindrical coordinates associated with one of the rectilinear sections are used for computations of high energy ion losses performed for particle distributions presented in Fig. 2. A particle is considered also as lost if it leaves the rectilinear section due to its longitudinal motion along the magnetic field line. So, only those trapped particles being confined in the mirror parts are considered as confined. Note that in the random choice of starting points and corresponding pitch values a linear approximation is used for the dependence of the relative flux tube volume on the sequence of possible starting points. To accelerate the computation, the Lagrange polynomial interpolation of the magnetic field is applied. The influence of an ambipolar radial electric field is not taken into account.

One set of computations is done using a rectilinear section of length $\ell = 2\pi R$ and a total number of $N = 200$ rings. In this case, the number of rings N_1 in the section ℓ_1 with decreased ring current is 10. For comparison, also a case with $N = 400$ and $N_1 = 20$ is studied. For calculations with a shorter rectilinear section of $\ell = \pi R$ the distance between the ring centers is not changed, so N is reduced accordingly and N_1 is kept constant.

Computational results

Fig. 3 presents the collisionless time evolution of high energy trapped ion fractions, which characterize the trapped particle life time. A decrease of these fractions corresponds to an increase of losses. Characteristic parameters of the calculations are given in the figure caption.

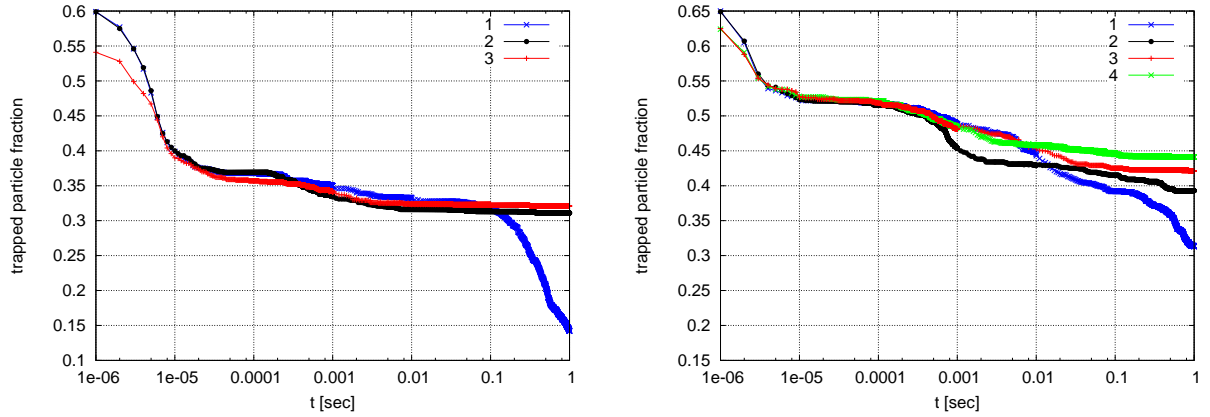


Fig. 3. Collisionless time evolution of the trapped high energy ion fractions in the mirror part for $\ell = 2\pi R$ (left) and $\ell = \pi R$ (right); 1: $r=30$ cm, $N_1=10$; 2: $r=30$ cm, $N_1=20$; 3: $r=20$ cm, $N_1=10$; 4: $r=20$ cm, $N_1=20$.

During a time of about 10^{-5} s a fast decrease of the trapped particle fraction takes place because particles with sufficiently large pitch values leave the rectilinear section due to their motion along the magnetic field lines. After this initial phase, the trapped particle drift across magnetic surfaces becomes the main reason for losses. These losses are delayed and a certain amount of trapped particles stays to be confined during the observation time. The losses for initial surfaces with $r=20$ cm are smaller than those for surfaces with $r=30$ cm. Losses are also smaller if a larger total number of current carrying rings is used.

The dependence of particle life time on particle trapping depth is also analyzed. As a result, boundary values of initial particle pitch values, $\lambda = v_{\parallel}/v$, are found where particles with smaller pitch values are confined. This boundary values depend on starting positions along y . Characteristic plots with results for $N_1 = 10$ and magnetic surfaces with $r=20$ cm and 30 cm are presented in Fig. 4. Results clearly show that for $r=20$ cm (Fig. 4, left) particles with small values of λ are not lost during the observation time of 1 s if their starting point in y is located within ± 90 cm (for $\ell = \pi R$) and ± 220 cm (for $\ell = 2\pi R$). At the center of these regions particles are confined if λ is smaller than 0.6 or 0.66, respectively. Note that the extension of ℓ_1 in y is ± 78.5 cm. For magnetic surfaces with $r=30$ cm (Fig. 4, right) the analogous confinement regions do not change notably for the short observation time of 0.01 s. For longer observation times these

regions decrease. With an increase of the total number of the current carrying rings to values corresponding to $N_1 = 20$ the λ -plots for magnetic surfaces with $r=30$ cm become very similar to those in Fig. 4, left.

So, outside the sections ℓ_1 regions exist, for which after initiating a particle with sufficiently small λ this particle is confined within the mirror part of the trap. The extension of these regions is increasing with an increased length of the rectilinear sections ℓ . From the obtained results follows the possibility for satisfactory confinement of high energy ions from neutral beam injection in the mirror part of DRAKON in the case of sufficiently small $|v_{\parallel}|$. The results can also be of interest for studies of plasma neutron sources based on stellarator type magnetic configurations.

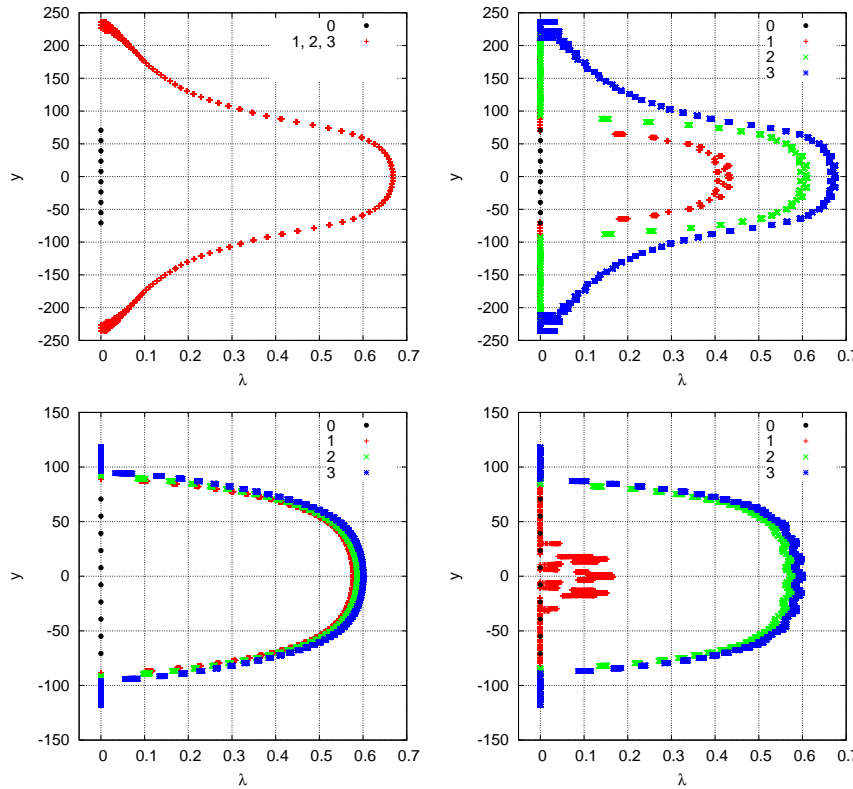


Fig. 4. Boundary values of initial particle pitch values, λ , for confined particles as function of the starting position along the rectilinear section for magnetic surfaces $r=20$ cm (left) and $r=30$ cm (right) for cases $\ell = 2\pi R$ (top) and $\ell = \pi R$ (bottom). Results relate to $N_1=10$ and observation times 1 s (1), 0.1 s (2) and 0.01 s (3); points (0) show rings with decreased current within section ℓ_1 .

Summary

For high energy ions of tritium with an energy of 70 keV comparative computations of collisionless losses in the mirror part of a specific design [2] of the DRAKON type trap are carried out. Two variants of the trap are considered with different lengths of the rectilinear sections (initial and shortened). Also the total number of current-carrying rings in the magnetic system is varied. The results show that high energy ions from neutral beam injection can be satisfactorily confined in the mirror part during $0.1 \div 1$ s if v_{\parallel} is chosen close to zero or if the value of $|v_{\parallel}|/v$ is smaller than a certain boundary value.

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