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Calculation of the Magnetic Field and Electron Trajectories in System of the DRAKON Type

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Abstract

The results of calculation of the magnetic structure and the electron trajectories in the plasma trap DRAKON are described. The optimum mirror ratio was obtained for electrons starting close to the system axis in KREL with magnetic mirrors. The electron ejection areas were calculated to create the plasma-beam discharge in DRAKON. It is found that the magnetic field lines and electron trajectories form the system of the enclosed toroidal surfaces having a round cross-section. Due to a symmetric change of the current distribution in the trap coils these surfaces are displaced but their form is kept.

Keywords:

nonplanar helical axis stellarator, electron drift, stellarator equilibrium

1. Introduction

The stellarator system DRAKON [1] consists of the separate equilibrium sections: two straight parts with an axisymmetric magnetic field are connected by two curvilinear elements (KRELs) with a nonuniform field. The equilibrium in the DRAKON magnetic system means both the electron drift compensation (in the single particle mode) and the diamagnetic current one (in the plasma mode) within KREL. The vacuum magnetic configuration was modeled using the system of the thin current coils. The solenoid current J was defined with a correspondence between the computational modeled magnetic field B and the magnetic field in the experimental design proposed by one of the authors [2]. The field from a single coil was calculated using the Biot-Savart formula. In the mathematical computing model the magnetic field lines and the electron trajectories are traced by the third-order Runge-Kutta adaptive step algorithm. The drift of an electron D relative to "its own" field line on the plane of a coil is determined as the distance between the "track" of the field line and the electron one.

2. KREL with Magnetic Mirrors

The geodesic KREL constructed in MEPhI consists of two periods of a 5-periodical geodesic torus (the geometrical axis is a geodesic curve on the surface of the basic torus with a major radius of 40 cm and a minor radius of 12 cm) [3]. It has been determined in experiments that the equilibrium part of this KREL device is equal 1.5 periods [4]. The computer model with 40 thin current coils (radius a=7.5 cm, step of coils d=0.6a) is modified to correspond the experimental unit "KREL with magnetic mirrors" designed recently. Since the equilibrium part is located between 4-th and 36-th coils the perpendiculars of 1–3rd and 37–40th coils are set up in parallel to 4th coil perpendicular and 36th respectively, so there are two straight parts at the ends of KREL. Moreover, the current J in 1–3rd and 37–40th coils is increased to create magnetic mirrors. Because the space axis is straightened at the ends, the

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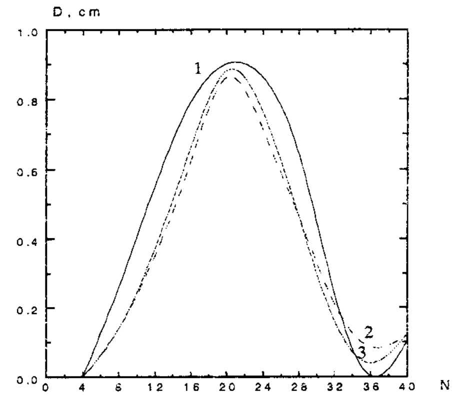

Fig. 1 Dependence of the electron drift on the number of coil N in geodesic KREL: 1) without the straightened end parts; 2) with one for the mirror ratio $R=0.9$; 3) for $R=R_{opt}$.

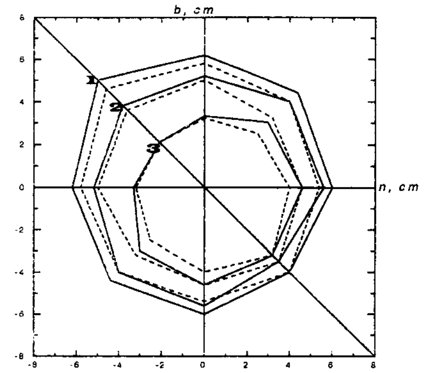

Fig. 2 Regions S_1 of the magnetic field lines (the solid lines) and S_2 of the electron trajectories (the dashed lines) closed within a trap for the mirror ratio: 1) $R=0.9$; 2) $R=1.6$; 3) $R=3.3$.

rotary transformation of magnetic field is suppressed and the residual electron drift Dr (electron drift at the end of the equilibrium part) is enhanced as shown in Fig. 1. The increases of Dr depend on the starting point of an electron. Starting close to the system axis the electrons with a characteristic Larmor radius $r_e=m_e v_e c/eB=0.09a$ ($-e$, m_e — electron charge and mass, c-light velocity, v_e-electron velocity for electron energy $U_e=800$ eV, $B=140$ Gs) have Dr from 0.016 to $0.09D_{max}$ (D_{max} is maximum of the electron drift at the center of KREL), $Dr_{max}=0.09D_{max}$ at $n=-0.1a$, $b=0$ of starting point, where n-normal and b-binormal with respect to the geometrical axis in the center of the initial coil. The increase of the current in the straightened part disturbs the magnetic structure of KREL by the additional magnetic flux of mirrors, so a part of field lines and electrons go away on the wall of the chamber. In Fig. 2 the regions S_1 of the magnetic field lines and S_2 of the electron trajectories closed within a trap are shown on the starting plate of 4-th coil (starting outside S_1 and S_2 field lines and electrons leave a trap). These areas are mainly shifted in the second quadrant (the magnetic field is weaker there) when the mirror ratio of the KREL magnetic mirrors R increase from 0.9 to R_{max} (on which electrons come to the wall). Figure 1 shows that there is the optimum value R_{opt} for minimum Dr, which depends on the starting point and the initial energy of an electron, for example, $R_{opt}=2$, $R_{max}=5.4$ on $r_e=0.09a$ ($U_e=800$ eV). For low energy electrons with $r_e=0.032a$ ($U_e=100$ eV, $B=140$ Gs) Dr varies from 0.032 to $0.098D_{max}$ ($Dr_{max}=0.09D_{max}$ for $n=0$, $b=0$ of starting point), $R_{opt}=1.5$, $R_{max}=5.9$. Hence to create the plasma-beam discharge in KREL for $r_e=(0.03-0.09)a$ a mirror ratio R has to be from 1.5 to 2.

3. The Magnetic Trap DRAKON

The first simple theoretical model of KREL "3/2-T" consists of three half-torus rotated relative to one another through 120° [5]. Computations of electron trajectories in the DRAKON system with KREL "3/2–T" were done for 50 keV electrons starting from the central coil of straight part (radius of coils $a_2=4$ cm, step of coils $d=0.2a_2$, current $J_2=600$A, $B_2=1$ kGs) close to the system axis ($r<0.1a_2$) and passing KREL ($a_1=2.4$ cm, $J_1=1800$ A, $B_1=3$ kGs) with compensation of their drift. Figure 3 shows that the calculated enclosed toroidal magnetic surfaces have a round cross-section and their axis is displaced from the geometrical one. The maximum of the axis displacement due to KREL's influence is placed at the center of the straight part (which length $L_s=6a_2$) and has the value $0.03a_2$. The electron trajectories as found form the system of enclosed toroidal surfaces, a cross-section of which is close to a round and their axis is displaced both from the magnetic axis and geometrical one. This displacement is in proportion to r_e.

In order to test stability in DRAKON relatively to the symmetric current perturbations in coils, the magnetic structure and the electron trajectories were calculated for two cases. In the first case to reduce the sag of the undisturbed magnetic field ($\Delta B/B=0.21-0.38$), which take place in the central region of KREL, the current of coils in both central half-torus is increased twice. Hence the number of the locked particles is reduced in this region. In the second case to produce a magnetic field strength at the end of the straight parts

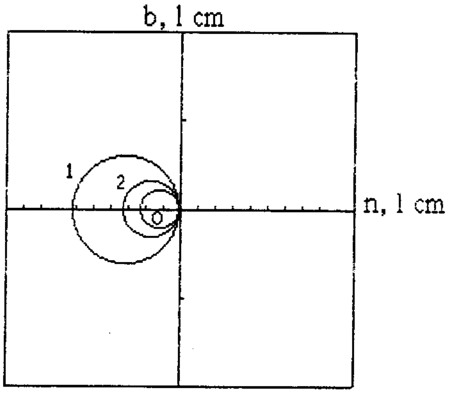

Fig. 3 Cross-sections of vacuum magnetic surfaces on the central plate of the straight part in DRAKON with the current increase 1) in the central half-torus; 2) plus in the straightened parts, and without one 0).

the current is increased 3 times there (in the region of 1−5th coils from both ends). Owing to this the magnetic fields in KREL and at the end of straight parts are the same. It makes an enhanced reflection of electrons from mirrors of the straight traps, so the number of passing to KRELs electrons is decreased twice, an angle of "loss cone" is reduced from 56° to 37° for starting from a geometrical axis electrons and from 51° to 34° for boundary electrons ($r=0.5\ a_2$) as was found in calculations. Figure 3 shows that the magnetic axis displacement increases for the first case compare to second one due to the perturbation of a magnetic field by added magnetic flux of the central half-torus, the increase of the current in the edge coils compensate this influence. The axis of electron toroidal surface is displaced also, but cross-section form of the surfaces is kept both for a magnetic field and electrons.

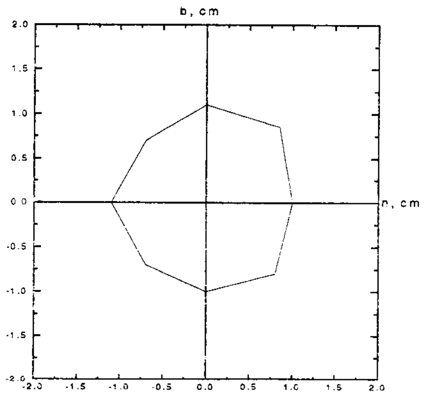

Fig. 4 Region S_3 of the electron trajectories closed within DRAKON.

In order to define the suitable area of the plasma-beam discharge in DRAKON the region S_3 of the electron trajectories closed within unit was calculated for starting from the central coil of the straight part electrons with $r_e=0.2a_2$ (Fig. 4). Starting outside S_3 ($r>0.25a_2$) electrons go away on the wall of the chamber during the first turn.

4. Conclusion

The calculation of magnetic structure and electron trajectories have shown that the magnetic fields of mirrors disturb the equilibrium part of the KREL and produce the residual electron drift. There is optimum value of the mirror ratio $R_{opt}=1.5-2$ for magnetic trap "KREL with mirrors". It was numerically demonstrated that the electrons started close to axis are shifted to azimuthal direction after one turn of the whole system and do not leave DRAKON system with KRELs "3/2-T", forming the system of enclosed toroidal surfaces with a round cross-section as well as the vacuum magnetic surfaces, which are stable relative to the perturbations of the current structure. The suitable areas for plasma-beam discharge were determined both for KREL with mirrors ($r<0.4\ a$) and DRAKON ($r<0.25\ a_2$).

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