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IMPURITY ION REMOVAL WITH THE USE OF DRIFT RESONANCE

A.A.Shishkin* and A.V.Zolotukhin**

****Institute of Plasma Physics, National Science Center "Kharkov Institute of Physics and Technology", Kharkov, 61108, Ukraine,***

***** Department of Physics and Technology, Kharkov "V.N.Karazin" National University, Kharkov, 61077, Ukraine***

Impurity ion removal in a toroidal magnetic trap with a helical field under time-dependent magnetic field perturbations is considered using guiding center equations. The ultimate goal is to find out ways to remove impurities from the confinement volume or to protect the confinement volume from impurity ion penetration in stellarator (torsatron) type traps.

1. Introduction

A principal physical problem for fusion magnetic traps (both modern devices and future reactors) is the presence of impurity ions which are produced from the interaction of plasma with the walls, limiters and divertor targets and their transport into the bulk plasma. In this paper, we propose a new method of impurity ion control by use of the drift resonance for passing particles. We focus on the study of one physical phenomenon, namely, the drift resonance of the impurity ions with time-dependent magnetic field perturbations. These perturbations with "wave numbers" m and n produce magnetic islands on rational magnetic surface with the rotational transform $\iota = m/n$. The islands change their radial position due to the dynamic control of the magnetic configuration during the plasma discharge. Passing resonant impurity ions with energy W and velocity pitch angle $V_{\|}/V$ in the presence of an electric field $\mathbf{E}$, form drift islands on the drift surface with the drift rotational transform $\iota^* = m/n$.

These drift islands are somewhat similar to the magnetic islands. Under the same time-dependent magnetic field the drift islands can also change their radial position. This means the drift islands move across the magnetic surfaces [1] and the impurity ion is therefore removed. If reversed, this method also provides the means of conveying impurity ions into the plasma. This method can be applied for diagnostic purposes in a plasma experiment.

Coulomb scattering and other dissipative processes can disrupt the drift resonance. We have found the conditions under which the drift resonance is conserved during particle motion. The role of the electric field in the plasma is also clarified.

Time-dependent magnetic field perturbations considered here can be produced with vertical field coils in the torsatron type trap. Small scale islands can be regulated by the control of currents in vertical field coils [2] or in additional coil systems designed to control magnetic field perturbation.

We should like to underscore that here we consider *slowly changing* magnetic fields. Magnetic field perturbations change with a characteristic period approximately equal to the drift island formation time. For the parameters chosen here this is about 1 second which is close to the typical length of the plasma discharge stellarator-type devices.

Very important conclusion is that impurity ion transport is selective in energy W and $V_{\|}/V$: the impurity ions are removed with drift island motion however bulk ion confinement is not distorted.

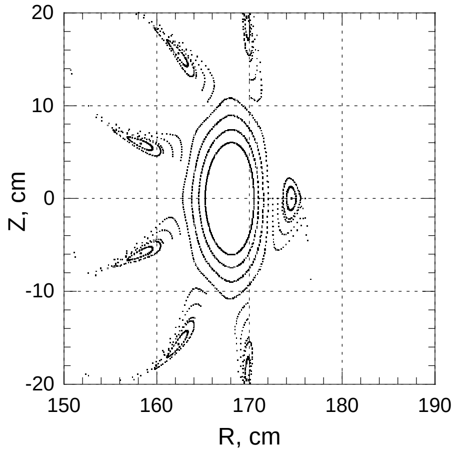
In our analysis the equations of particle motion in the guiding center drift approximation are used and Coulomb scattering is taken into account. This approach is described in details in [1,3]. The main magnetic field model and the magnetic field perturbations are taken here as in [1].

2. Magnetic configurations

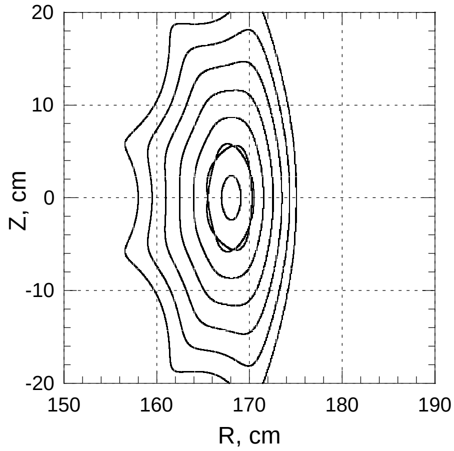
For our studies there were chosen two magnetic configurations with the parameters which are rather close to the Uragan 2M torsatron [2], namely, $l = 2$, $m = 4$, $B_0 = 2\,\mathrm{T}$, $R = 170\,\mathrm{cm}$, $a_h = 44.5\,\mathrm{cm}$. The main helical harmonic $\varepsilon_{2,4} = 0.2$, residual vertical field harmonic $\varepsilon_{1,0} = 0.0075$ and one of the satellite harmonics $\varepsilon_{1,4} = 0.003$ remain the same for both configurations. Other values of $\varepsilon_{n,m}$ are taken to get an island family at the magnetic surface with rational value of $\iota = 4/7$ but with different displacement from the magnetic axis. In the case considered here the magnetic rotational transform is $\iota_B = 0.532 + 0.146(r_0/a_h)^2$. This value of ι_B is close to the rational value $\iota = 4/7$. That is why it is reasonable to choose the magnetic perturbation with $m_p = 4, n_p = 7$. Namely this resonance will be used further but for the drift rotational transform, i.e. $\iota^* = 4/7$.

We consider two magnetic configurations: one of them has islands at the periphery and the other one has islands near the magnetic axis.

For the first configuration (Fig.1a) the $\varepsilon_{n,m}$ parameters are $\varepsilon_{3,4} = 0.0,\ \varepsilon_{7,4} = 0.18$. In this case the islands are placed at the periphery of the confinement volume. In the space between the closed magnetic surfaces and the islands the magnetic surfaces are destroyed.



a



b

Fig.1. Magnetic surfaces in configurations with the islands at the periphery of a plasma (a) and in the core of a plasma (b)

For the second configuration (Fig.1b) the parameters are $\varepsilon_{3,4} = -0.004$ $\varepsilon_{7,4} = -0.18$. For such a choice the islands are placed inside the confinement region.

3. Impurity ion removal from plasma core

Impurity ions in drift resonance with the magnetic field perturbation can be removed from the

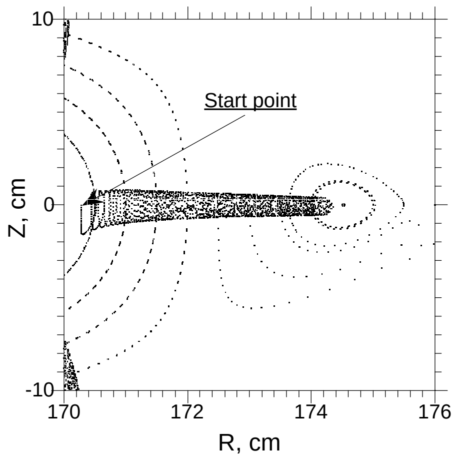


Fig.2. The removal of C^{+4} ion from the core of plasma due to variation of magnetic field parameters on the background of islands

plasma core by moving the drift island. One typical example is shown on Figure 2.

The changing of the magnetic field parameters in accordance with

$$\varepsilon_{n,m} = \varepsilon_{n,m,0} + \varepsilon_{n,m,1}\sin(\Omega_{n,m}t + \delta_{n,m})$$

under the values

$\varepsilon_{3,4,0} = -0.004$, $\delta_{3,4} = \pi$, $\varepsilon_{3,4,1} = -0.004$, $\Omega_{3,4} = 0.02875 rad/s$, $\varepsilon_{7,4,p,0} = -0.18$, $\varepsilon_{7,4,p,1} = -0.36$, $\Omega_{7,4} = 0.02875 rad/s$, $\delta_{7,4} = \pi$

causes the particle to drift out from the island family inside the confinement volume in the direction of the island family at the periphery of the plasma (Fig. 2). The characteristic time of the magnetic field variation ($2\pi/\Omega_{n,m}$) is comparable to somewhat larger than the time of the formation of the drift island [1]. The starting point coordinates are $r_0 = 0.28$ cm, $\vartheta_0 = 0$, $\varphi_0 = 0$, the energy $W = 20$ eV and the pitch velocity $V_{\|}/V$ =0.9. The time elapsed is 4.73 sec. The drift island is shown with the island family in the background.

The effect of Coulomb scattering on impurity ion removal from the plasma core. Collisions can be very important especially in the core of plasma. In Fig.3 the drift orbits of a test particle are shown assuming different values of the plasma density.

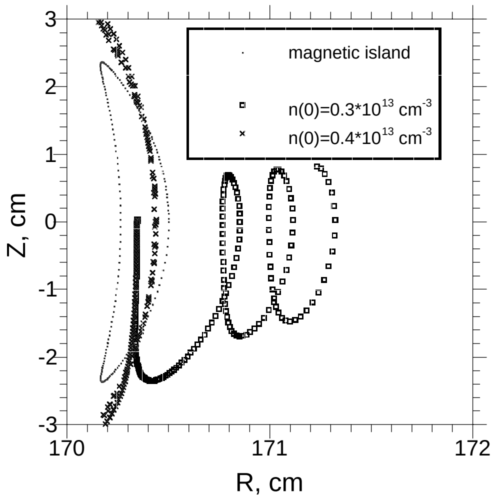


Fig.3. The effect of scattering on the drift resonance of C^{+4} ion in the core of plasma under the different values of the density $N(0)$

The particle remains on a resonant passing orbit when $N(0) < 0.4\times10^{13}\,\mathrm{cm}^{-3}$ (Fig.3). The drift resonance disrupts for $N(0) = 0.4\times10^{13}\,\mathrm{cm}^{-3}$. This disruption has a threshold feature because the motion of the drift island starts deep inside the plasma, where the density is highest (Fig.3). The drift trajectory of the impurity ion shown in Figs. 2, 3 is not the full trajectory but only the intersection points of the trajectory with the planes $\varphi = 2\pi\, i/m$ $(i = 0,1,2,...)$, a so-called Poincaré plot. In the case when $\iota^* = m_p/n_p$ there exist n_p drift islands in the vertical cross-section.

4. Removal of the impurity ion cloud

To understand what fraction of impurity ions are involved in the drift resonance and escape from the confinement volume, 40 ions are launched with the starting points as shown in Fig.4. Initially the particles are randomly distributed in the vicinity of the magnetic island and the velocity pitch values are randomly chosen in the range $0.8 < V_{\|}/V < 0.95$.

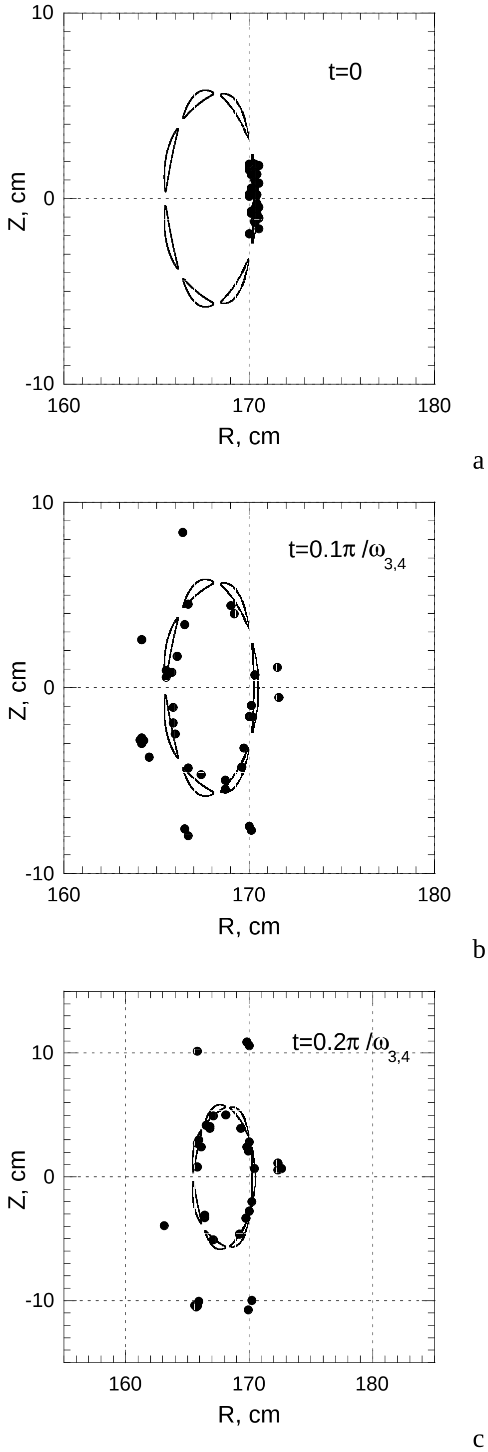


Fig.4. The cloud of impurity ions at different moments of time

The energy of impurity ion (C^{+4}) is equal to 20 eV. Figures 4b and 4c show the positions of the test impurity ions at the moments $t = 0.1\pi/\Omega_{3,4}$ and $t = 0.2\pi/\Omega_{3,4}$. The distribution of test particles at the final stage shows that near 40% of the launched particles follow the resonance trajectories and are removed. Other particles (~60% of launched particles) remain in the island region. Similar analysis out for impurity ions with the parameter $V_{\|}/V$ in the range of $0.7 \le V_{\|}/V \le 0.8$ has shown that the fraction of particles driven out by chosen magnetic perturbation decreases to 25% of launched particle number. It should be noted that initial position of ion cloud is not optimal for the removal: many particles are placed outside the island. For the practical tasks the more optimized approach is possible: to choose the island with other set of number *(m, n)* (smaller values), larger amplitude of the perturbation on order to increase the size of the islands and hence to place more impurity ions inside the island. High developed approaches to optimize divertor operation is to combine the natural magnetic configuration and externally induced magnetic perturbations. The examples of such configurations are the local island divertor in LHD [4], island structure magnetic configurations in stellarators Wendelstein 7-AS and TJ-II, the ergodic dynamic divertor for TEXTOR.

5. Conclusions

A slow variation of an auxiliary magnetic field (for instance, VF coil currents) in the magnetic trap (the thermonuclear device) can be used to remove impurity ion from the core of plasma due to motion of the drift island (for resonant passing particles). The additional coils can be applied to realize the proposed method [5]. The system of coils similar the local island divertor coils on LHD [4] can be used for the resonant pumping in/out of the particles on the heliotron / torsatron type devices [5].

This method of controlling impurity ion removal using islands can be applied to different systems with helical fields; an examples is the HELIAS configuration [6] with its natural 5 islands at the periphery of the confinement volume.

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