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Monte Carlo modelling of the transport in the stellarator periphery with magnetic islands

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Abstract

Two Monte Carlo methods have been developed to model the transport phenomena of impurities in the edge plasma of stellarators taking into account the complex magnetic field topology in the stellarator periphery: (i) a new version of the ERO code, where the sputtered impurity atoms are followed through successive states of ionization and recombination during their 3D motion in the whole plasma volume; (ii) a self-consistent set of hydrodynamic equations describing the dynamics of the plasma and the impurities, supplemented by a kinetic equation for the description of the neutral particles dynamics, is solved using Monte Carlo techniques. The magnetic island structure is described by the Chirikov–Taylor map technique. The corresponding effects are studied for different cross diffusion coefficients and impurity injection positions. The results show that the existence of magnetic islands significantly influences the transport in the stellarator periphery and that the injection of impurities into the magnetic island region leads to effective plasma cooling and lowering of the energy flux to the target.

Keywords: Monte Carlo modelling; Stellarator; Boundary plasma; Impurity

1. Introduction

In order to reduce the power load to divertor/limiter plates a substantial fraction of the power in fusion devices must be dissipated by line radiation of impurities localized in the boundary plasma. The magnetic island structure in stellarators, which can easily be controlled by changing the rotational transform ι is supposed to offer a particularly favorable possibility for such boundary cooling. Using fast reciprocating erosion probes impurities can be introduced locally into the magnetic islands. First studies were made with titanium injected into the edge plasma of the stellarator W7-AS (see [1]). In order to describe such experiments one has to distinguish three processes: the erosion of the solid probe, which acts as the impurity source; the transport of the sputtered impurities in the boundary and core region and their effect on the plasma (cooling). In Section 2.1 simple estimations are given in the frame of 1D models for steady-state conditions. Further, two Monte Carlo methods have been developed to model time-dependent the transport phenomena in the edge plasma of stellarators (Section 2.2 and Section 3): (i) a new version of the ERO code [2], where the magnetic field structure of the stellarator W7-AS was included (Section 2.2); (ii) a self-consistent two-dimensional model which is used to investigate the effect of impurities injected into magnetic islands on plasma cooling and on the energy flux to the divertor plates (Section 3).

2. Transport of impurities

2.1. Preliminary considerations

The erosion of a solid probe exposed in the plasma boundary is determined by physical sputtering and thermal sublimation. The eroded amount of a Ti probe exposed during 20 ms at a certain position (expressed as distance

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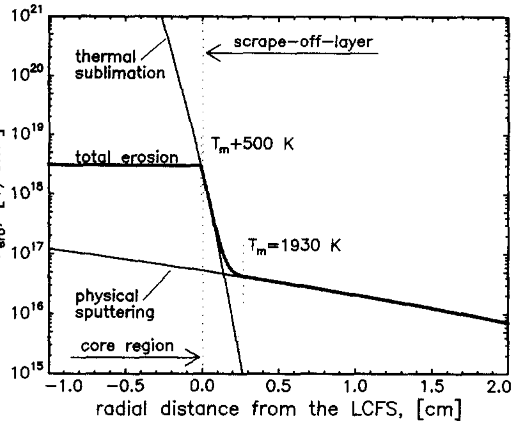

Fig. 1. Erosion of a Ti probe due to physical sputtering and thermal sublimation versus the distance from the LCFS.

from the last closed flux surface (LCFS)) has been calculated. The results are shown in Fig. 1 for the following parameters: electron temperature and density at the LCFS $T_e = 100$ eV and $n_e = 1 \cdot 10^{13}$ cm^{-3}, decay length of the plasma parameters $\lambda = 2$ cm, physical sputtering yield $Y_{D \to Ti} = 0.042 \cdot (1 - \exp(-(T_e - 5)/40))$ (T_e in eV), sublimation rate $\Gamma_{subl} = 2 \cdot 10^{30} \exp(-4.9/kT_s)$ (cm^{-2} s^{-1}), initial surface temperature $T_s = 293$ K. For these parameters the surface-temperature of the Ti probe reaches the melting temperature, $T_m = 1930$ K, at a position near the LCFS. The amount of eroded material increases by an order of magnitude owing to the starting evaporation of the probe. The maximum surface temperature is restricted (here $T_m + 500$ K) in the case of metals due to the simple fact that the melted material of a thin surface layer drops up. Whereas high impurity concentration in the scrape-off-layer (SOL) is desirable with respect to plasma boundary cooling, an increase of the core concentration should be avoided. The central impurity density n_I^{core} (ions/m^3) can be related to the influx rate of impurity neutrals Φ_{inj} (atoms/s) by using the model of Engelhardt and Feneberg [3] and its improvements [4–6]. By including further the effect of prompt redeposition and an anomalous drift velocity of the form $V^{drift}(r) = 4V^{drift}(r/a)(1 - (r/a))$ (a is the small plasma radius) one obtains:

$$n_I^{core} = \frac{(1 - P_{pr})\Phi_{inj}(r_{inj})\lambda_{gen}}{A_p D_\perp^{edge}} \exp\left\{ - \frac{2V^{drift}a}{3D_\perp^{core}} \right\} \quad (1)$$

where A_p is the plasma surface area, $D_\perp$ is the cross-field diffusion coefficient in the specified plasma region. In Eq. (1) an inward directed drift velocity gets a negative sign. $P_{pr} = \frac{1}{2}(\exp(-2\lambda_{iz}/\rho_z) + \exp(-\lambda_{iz}/(5\rho_z)))$ is the fraction of prompt redeposited atoms, where ρ_z is the gyration radius of the injected impurity atoms and λ_{iz} is the ionization length. This relation results from the theoretical model of Fussmann and calculations with the ERO code (see Ref. [7]). If the ionization occurs near the position of injection, r_{inj}, (due to the short ionization length of thermally sublimated Ti atoms) and inside the SOL, the parameter λ_{gen} can be defined as (see also Ref. [4]) $\lambda_{gen} = \lambda_{SOL} \exp(-(r_{inj} - a)/\lambda_{SOL})$, where $\lambda_{SOL} = \sqrt{D_\perp^{edge} L_c / v_{imp}}$, L_c is the shortest connection length to the limiter or divertor plate and v_{imp} is the average velocity of the impurity ions gained owing to friction with the streaming plasma flow. For the case of $r_{inj} < a$ the term $\lambda_{gen}/D_\perp^{edge}$ in Eq. (1) should be replaced by $(\lambda_{SOL}/D_\perp^{edge} + (a - r_{inj})/D_\perp^{core})$.

2.2. Results of the 3D Monte Carlo code ERO

The 3D Monte Carlo code ERO has been used to investigate the erosion of solid probes and the transport of the emitted atoms in the plasma of the stellarator W7-AS. The vector components of the magnetic field in each space point are calculated owing to the coil geometry and the currents. Plasma pressure effects on the magnetic field structure are not considered. The erosion of a fast reciprocating probe is calculated taking into account both physical sputtering and thermal sublimation as well as the motion of the probe in the plasma boundary with decaying plasma parameters. The non-stationary heat equation for cylindrical geometry (3D) is numerically solved. Thus, the erosion rate $\Phi_{inj}(r)$ as a function of the radius is determined. The sputtered atoms are followed through successive states of ionization and recombination during their 3D motion in the whole plasma (core and boundary) with given density and temperature fields. Their motion is determined by the Lorentz force (i.e., gyration is included) and by collisions with the plasma ions. The heating up, the friction and the

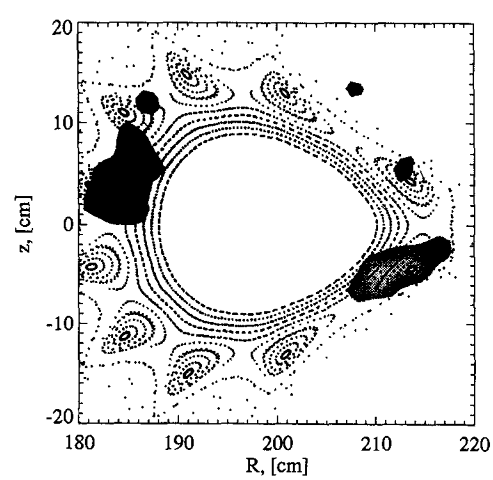

Fig. 2. Normalized Ti density distribution as calculated by the ERO code for the W7-AS magnetic field configuration ($\iota = 0.513$, presented as a Poincare plot – dashed-line contours) in the plane $\phi = 72°$.

parallel diffusion is described using the characteristic collision times; the cross diffusion by a constant value of the diffusion coefficient. The code gives as output the 3D spatial distributions of the various ionization states. This allows in principle a detailed comparison with experimental results which can be obtained by spectroscopical measurements. The effects of the magnetic field structure and of the cross diffusion have been studied for Ti as the injected material by varying the position of injection and the cross diffusion coefficient. A $\iota \simeq 5/10$ magnetic field configuration (five islands) has been chosen for the calculations. For demonstration, the calculated Ti density distribution in the $\phi = 72°$ plane is shown together with the Poincare plot of the magnetic field configuration in Fig. 2. The Ti atoms were injected at position $R = 201$ cm, $z = 13$ cm, $\phi = 0$ (inside one island) and $D_\perp = 0.1$ m^2/s has been taken. The ionized Ti atoms are moving around the torus and come back to the start point after two turns ($\iota \simeq 5/10$). They are kept inside this island owing to the low cross diffusion coefficient.

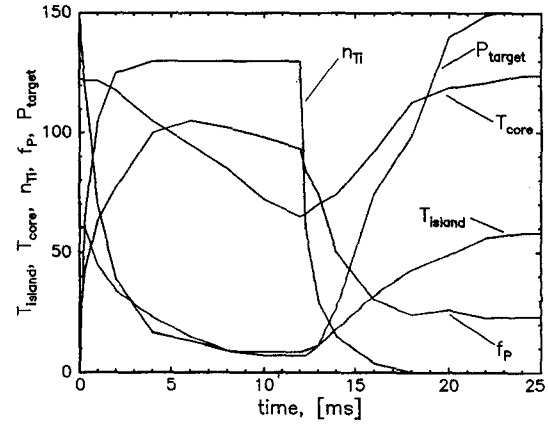

Fig. 4. Time evolution of the island temperature T_{island} (eV), the core plasma temperature T_{core} (eV), the Ti density maximum n_{Ti} (10^{10} cm^{-3}), the relation of the total power loss to the input power f_{p} (%) and the peak power load on the target P_{target} (10^2 W/m^2).

3. Plasma edge cooling by impurities

An approach to model the transport phenomena in the edge plasma with magnetic islands is to use the Chirikov–Taylor map technique [8] together with a simple Monte Carlo method [9]. In the frame of an improved model the influence of impurities on the particle and energy transport and the plasma cooling in edge plasmas was investigated in [10]. The dynamics of the plasma and the impurities is described by a self-consistent set of hydrodynamic equations, supplemented by a kinetic equation for the description of the neutral particles dynamics. The magnetic island structure is described by the Chirikov–Taylor map technique, and the impurities are treated in the frame of the average-ion model [11]. Ionization, excitation, charge exchange, neutral particle recycling at the target surface and radiative cooling of the edge plasma by impurity ions are taken into consideration.

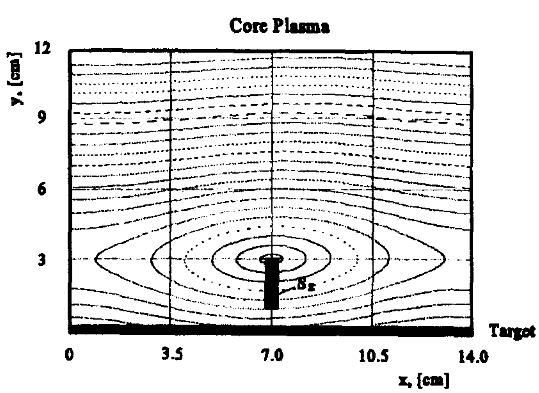

Fig. 3. Island structure described by the Chirikov–Taylor map technique and the region of impurity injection, S_z.

3.1. Model equations and computational method

The set of fluid equations has the form

$$\frac{\partial n_{\mathrm{i}}}{\partial t} = \mathrm{div}\left(D_\perp \vec{\nabla}_\perp n_{\mathrm{i}} - \vec{V}_{\mathrm{i}\parallel} n_{\mathrm{i}} \right) + n_{\mathrm{e}} n_0 k_{\mathrm{ion}}, \tag{2}$$

$$\frac{\partial n_z}{\partial t} = \mathrm{div}\left(D_\perp \vec{\nabla}_\perp n_z - \vec{V}_{z\parallel} n_z \right) + S_z(\vec{r}, t), \tag{3}$$

$$\frac{3}{2}\frac{\partial n_{\mathrm{e}} T_{\mathrm{e}}}{\partial t} = \mathrm{div}\left(\kappa_\parallel \vec{\nabla}_\parallel T_{\mathrm{e}} + \kappa_\perp \vec{\nabla}_\perp T_{\mathrm{e}} - \tfrac{5}{2}\vec{V}_{\mathrm{i}\parallel} n_{\mathrm{e}} T_{\mathrm{e}} \right) - n_{\mathrm{e}}\{ n_0 L_0 + n_0 k_{\mathrm{ion}} I_{\mathrm{ion}} + n_z L_z \}, \tag{4}$$

where $\vec{a}_\parallel$ and $\vec{a}_\perp$ are the components of the vector $\vec{a}$ parallel and perpendicular to $\vec{h} = \vec{B}/B$; n_{i}, n_z, V_{i}, V_z are the densities and velocities of the ions and the charge-averaged impurities, respectively; k_{ion} is the ionization rate coefficient, I_{ion} is the ionization potential, $D_\perp$ and $\kappa_\perp$ are the corresponding coefficients of the perpendicular anomalous plasma diffusion and heat conduction, $\kappa_\parallel \sim T_{\mathrm{e}}^{5/2}$ is the classical heat conduction coefficient, T_{e} is the electron temperature (assumed to be equal to the temperature of the other plasma components), S_z is a impurity source, n_{e} is given by $n_{\mathrm{e}} = n_{\mathrm{i}} + Zn_z$, L_0 describes the excitation and ionization of hydrogen atoms and L_z is the radiation function for the impurities. In order to complete the particle and energy balance, we use the kinetic equation for the distribution function of the hydrogen atoms $f_0(t, \vec{r}, \vec{v})$ and the closed box model for the particle balance: $\int (n_0 + n_i)\mathrm{d}\vec{r} = \mathrm{const.}$, $n_0 = \int f_0 \,\mathrm{d}\vec{v}$. The geometry of the problem and the impurity sources are shown in Fig. 3, where the magnetic island is described by the

Chirikov–Taylor map; x is the poloidal distances and $y = r_t - r$ with the target position r_t. The boundary conditions of the problem are given in [10]. The 2D transport on the poloidal cross-section consists of two physically separate parts: (i) the projection of the transport along the magnetic field line to our fixed cross-section, which describes the particle motion of the magnetic surface on the cross-section in the direction $\vec{h}_p = \vec{B}_p / B_p$, (ii) the isotropic part of the transport (across the magnetic field line). The corresponding random processes for the density and energy of the particles can be written as follows:

$$\Delta \vec{r}_n = \sqrt{2 D_\perp \Delta t}\, \vec{\xi}_{p\perp} + V_p \Delta t \vec{h}_p, \tag{5}$$

$$\Delta \vec{r}_e = \sqrt{2(\kappa_\perp / n_e) \Delta t}\, \vec{\xi}_{p\perp} + \sqrt{2(\kappa_p / n_e) \Delta t}\, \vec{\xi}_{p\|} + (5/2) V_p \Delta t \vec{h}_p, \tag{6}$$

where $V_p = V_\| \Delta l / L$, $\kappa_p = \kappa_\| (\Delta l / L)^2$; Δl is the distance between two neighboring Chirikov–Taylor points on the cross-section, and L is the distance along the magnetic field line between these points. Here is $V_\|$ the local ion sound velocity $c_s(T_e)$ with the sign determined randomly at the moment of particle birth, and $\xi_{p\mu}$ is a set of three random numbers ($\langle \xi_{p\mu} \rangle = 0$, $\langle \xi_{p\mu}, \xi_{p\nu} \rangle = \delta_{\mu,\nu}$).

3.2. Numerical results

The transport in the edge plasma is investigated assuming $D_\perp = 1.0$ m^2/s (0.5 m^2/s) outside (inside) the island region, $\kappa_\perp = 3 n_e D_\perp$, power input $P_{in} = 0.2$ MW and a island connection length $L = 30$ m. The impurity source localized near the O-point (see Fig. 1). with a strength $S_z = 4 \cdot 10^{19}/\text{m}^3\text{s}$ is switched on at $t = 0$ and switched off at $t = 12$ ms. The time evolution of the temperatures in the island and the core plasma, the impurity density maximum, the peak power load on the target surface and the relation of the total power loss to the input power is given in Fig. 4. After the impurity injection and after switching off the source all values change rapidly. The profiles of the temperature at $t = 0$, $t = 12$ ms, $t = 24$ ms and the impurity density at $t = 12$ ms are shown in Fig. 5.

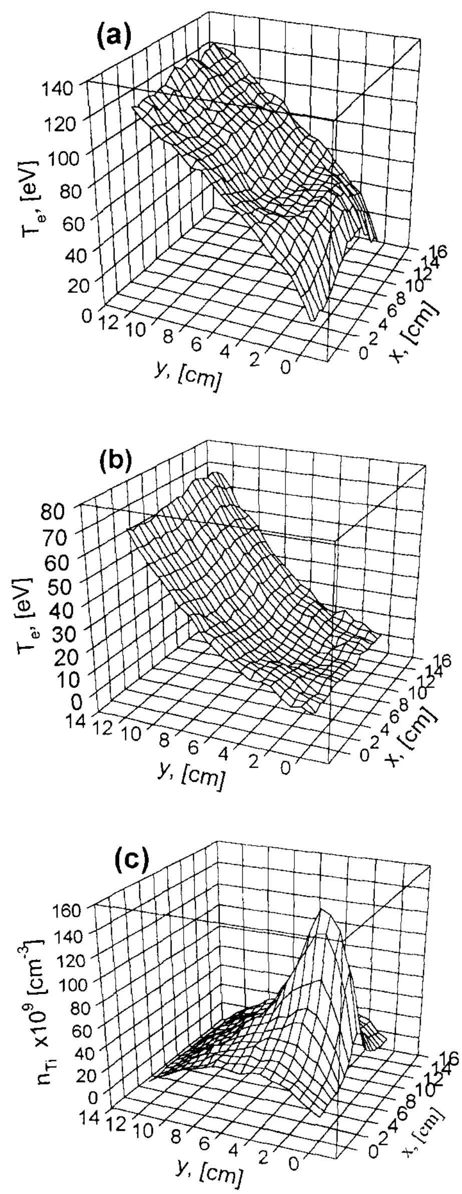

Fig. 5. Profiles of the temperature at $t = 0$ and $t = 24$ ms (a) at $t = 12$ ms (b) and the impurity density at $t = 12$ ms (c).

4. Conclusions

Impurity injection into the boundary plasma of stellarators offers the possibility of effective plasma cooling in this region. In order to minimize the central impurity concentration the source of neutrals $\Phi_{inj}(r_{inj})$ and the ionization of the neutral impurity atoms should be localized outside the core plasma by selecting appropriated plasma conditions (Section 2.1). In this paper two models are presented, which describe the transport of the injected impurities and their effects on the plasma parameters taking the complex magnetic field structure of stellerators into account. Using the ERO code 3D spatial distributions of the various ionization stages of the impurity ions can be calculated. It is shown, that Ti atoms injected into one islands remain there for longer time only if the cross diffusion coefficient is sufficient low ($D_\perp \leq 0.2$ m^2/s). For higher values cross diffusion dominates over the magnetic field structure. In the frame of a self-consistent two-dimensional model the effect of injected titanium impurities on the transport in the plasma edge is studied. The results show that the injection of impurities into the magnetic island region near the O-point in a time interval of 12 ms leads to perceptible plasma cooling and lowering of the energy flux to the target and after injection to a fast transition into the initial state. The efficiency of these effects increases with decreasing perpendicular diffusion coefficient inside the magnetic island. In order to confirm the concept of radiating islands, for which low cross diffusion inside the island and larger one outside is required, measurements of the cross field diffusion coefficient in the stellarator periphery are needed.

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