ENERGY AND PITCH-ANGLE DISTRIBUTION OF THE PROMPT LOSSES IN TOKAMAK WITH NON-CIRCULAR CROSS-SECTION

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Technique of calculation the pitch-angle, energy and poloidal distributions of the flux of charged fusion products lost to the first wall of axisymmetric tokamak due to first orbit loss mechanism is developed. Analytical model of the magnetic field used in this study takes into account Shafranov shift, elongation, triangularity and up-down asymmetry. Usage of the drift constant of motion space allows substantial reducing the computational efforts for simulation the lost particles flux at a given point of the first wall.

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INTRODUCTION

The first orbit (FO) loss is one of the conventional loss mechanisms of the charged fusion product (CFP). There are thorough review on theoretical study [1] and experimental research activities [2] of this loss mechanism. Analytical approaches for FO flux calculation were derived in [1, 3]. It should be noted that these models were provided for poloidal distributions of FO loss of CFPs in tokamak with circular cross-section. The numerical code presented in current study in addition to poloidal distributions allows also examination of pitch-angle and energy distributions of the FO loss in tokamaks with elliptic and triangular flux surfaces.

After the first experiments in TFTR [4], it became obvious that FO losses can be decreased significantly due to increasing the plasma current above $3\,MA$. Nevertheless, interest to these losses in this study is caused by necessity to develop common approach for simulation of FO loss signal in scintillator probe in order to distinguish contributions from the studied processes and from the FO losses. For example, the toroidal field ripple induced losses were observed in addition to the conventional FO losses of DD CFPs in JET [5].

Thus, the main aim of this study is to develop the theoretical approach for simulation spatial and velocity distributions of FO losses in order to model the scintillator probe signal of pure FO losses. This approach should cover variety of existing magnetic configurations, the magnetic field model should be flexible for predictive modeling, should maintain test particle simulations for crosscheck validation. Smooth, axially symmetric wall is assumed. The finite Larmor orbit width has been neglected yet, in order to introduce the main ideas of developed approach. Test particle simulations were carried out using the same magnetic configuration in order to provide a cross-check.

1. FLUX CALCULATION MODEL

In current study, magnetic configuration of tokamak is assumed to be axisymmetric with non-circular flux surfaces. The analytical model for such configurations is described in details in [6]. Using this model, it is also possible to carry out test particle simulations using the same numerical model of the magnetic configuration [7]. It is supposed that flux surfaces are determined by the parametric dependence of the cylindrical coordinates

$$R(\rho,\chi) = R_0 + \Delta(\rho) + \rho\cos(\chi), \tag{1}$$

$$Z(\rho,\chi) = Z_{ax} - k(\rho)\rho\sin(\chi)\left[1-\Lambda(\rho)\cos(\chi)\right]^{\alpha}, \tag{2}$$

where R and Z represent the spatial variables of the cylindrical coordinates $\{R,\varphi,Z\}$, ρ and χ represent variables of the new flux-like coordinates $\{\rho,\chi,\varphi\}$, $\Delta(\rho)$, $k(\rho)$, $\Lambda(\rho)$ are flux surface parameters: the Shafranov's shift, the elongation parameter and the triangularity parameter respectively, α is a flux surface model parameter, R_0 is a vacuum vessel major radius, Z_{ax} is a Z coordinate of the magnetic axis. The coordinate ρ is a flux surface label and its value is equal to distance between the magnetic axis and the flux surface in the equatorial midplane, and χ is the analog of poloidal angle. The angle φ is the toroidal angle, and its value and direction coincide in both coordinate systems $\{R,\varphi,Z\}$ and $\{\rho,\chi,\varphi\}$.

Commonly total flux of lost particles can be written as

$$\Gamma_{loss} = \int\limits_{LD} R_{fus}(\mathbf{r},\mathbf{v})\,d\mathbf{r}d\mathbf{v}, \tag{3}$$

where $R_{fus}(\mathbf{r},\mathbf{v})$ source of CFP particles; $\mathbf{r}$, $\mathbf{v}$ – radius vector and velocity vector respectively. The integration domain "*LD*" (Loss Domain) is defined by the full set of particle orbits, which intersects confinement boundary, e.g. last closed flux surface or vacuum vessel wall. Here we assume that particle is lost if its trajectory intersects plasma boundary $\rho = a_{pl}$.

Generally, the integration domain is six-dimensional. However, taking into account axial symmetry of the problem and using guiding center approximation, this domain becomes four-dimensional. Thus, the concrete set of four numbers defines only one specific orbit. Certainly, it is true if the effect of Coulomb collisions is neglected.

Diagnostic techniques, such as a scintillator probe or a Faraday cup, give a tip to choose the set of variables in the following way $\{a,\chi_a,\xi_a,V\}$, where a,χ_a define the position of the probe in the $\{\rho,\chi\}$ coordinates, and ξ_a,V describe the orbit parameters (pitch $\xi=V_{\parallel}/V$ and particle speed V, where $V_{\parallel}$ is the parallel particle velocity). Nevertheless, it is possible to derive the alternative representation of the lost particle flux in the terms of the variables $\{a,\chi_a,\xi_a,V\}$

$$\Gamma_{loss}=\int\limits_{LD}R_{fus}\sqrt{g}J_a 2\pi d\rho d\chi_a 2\pi V^2 d\xi_a dV \qquad (4)$$

where $\sqrt{g}$ Jacobian of coordinate system $\{\rho,\chi,\varphi\}$, J_a Jacobian of coordinates transition $\partial(\rho,\chi,\xi,V)/\partial(a,\chi_a,\xi_a,V)$ and it is supposed that source of CFP particles $R_{fus}(\rho,\xi_a,V)$ in real space depends only on flux label ρ and it is axially symmetric in velocity space regarding to the direction of magnetic field. First assumption is based on the thesis that R_{fus} depends only on plasma specie densities and temperatures, which are commonly supposed to be constant on the flux surface. The second one is a consequence of the fast phase mixing due to cyclotron gyration.

2. DRIFT ORBIT TOPOLOGY ANALYSIS

Taking into account the invariance of the magnetic moment and the toroidal angular momentum, the guiding center motion equations take the form

$$\left(1-\xi^2\right)R(\rho,\chi)=\left(1-\xi_a^2\right)R_a, \qquad (5)$$

$$\Psi(\rho)+C\xi R(\rho,\chi)=\Psi_a+C\xi_a R_a, \qquad (6)$$

where $R_a=R(a,\chi_a)$, $\Psi_a=\Psi(a)$ and $C=mV/e$. These equations implicitly define particle trajectory $\rho(\chi,\mathbf{c}_a)$ and pitch-angle variation along orbit $\xi(\chi,\mathbf{c}_a)$, where $\mathbf{c}_a=\{\chi_a,\xi_a,V\}$. Nevertheless, not only χ can be chosen as the independent parameter, it is also possible to consider ρ or ξ as independent variable.

In order to exclude the dependence on χ the equations (5) and (6) can be rewritten as

$$R(\rho,\mathbf{c}_a)=\left(B_\xi+D_\xi\right)/2C, \qquad (7)$$

$$\xi(\rho)=\left(B_\xi-D_\xi\right)/2A_\xi, \qquad (8)$$

where $A_\xi=\Psi(\rho)-\Psi(a)-C\xi_a R_a$, $B_\xi=\left(1-\xi_a^2\right)R_a C$ and $D_\xi=\sqrt{B_\xi^2+4A_\xi^2}$, these designations are made for convenience reasons.

Under given orbit parameters $\{a,\chi_a,\xi_a,V\}$, it is possible to reconstruct the guiding center trajectory for particle with speed V, which passes through point $\{a,\chi_a\}$ with pitch ξ_a. For this purpose, one can change ρ continuously and evaluate R from Eq. (7). Then using R and ρ it is possible to derive χ

$$\chi=\arccos\left\{\left[R(\rho)-R_0-\Delta(\rho)\right]/\rho\right\}. \qquad (9)$$

Finally, using Eq. (2) coordinate Z can be obtained.

Taking into account up-down symmetry of magnetic configuration, and supposing that point $\{a,\chi_a\}$ is the final point of trajectory, independent parameter ρ should be changed only in segment $[\rho_{\min},a]$, where $\rho_{\min}$ is value of variable ρ at the point of intersection of trajectory with equatorial midplane.

To find $\rho_{\min}$ one can derive the equation

$$C^2R^2(\rho_{\min},\chi_{\min})-A_\xi^2(\rho_{\min})+B_\xi CR(\rho_{\min},\chi_{\min})=0, \qquad (10)$$

where $\chi_{\min}=0$ for intersection point at the '*low field side*' and $\chi_{\min}=\pi$ for the '*high field side*'. Analysis of the drift orbit topology in a axisymmetric magnetic configuration is presented in [8, 9].

According to the provided drift orbit analysis it is now possible to localize roots of the Eq. (10) and to finish the definition of '*Loss domain*' in $\{a,\chi_a,\xi_a,V\}$. Thus the expression (4) for the loss particle flux can be written as

$$\Gamma_{loss}=2\pi\int\limits_{-\pi}^{\pi}d\chi_a\int\limits_0^\infty dV 2\pi V^2\int\limits_{-1}^{1}d\xi_a 2\int\limits_{\rho_{\min}}^{a}d\rho R_{fus}\sqrt{g}J_a, \qquad (11)$$

where $\sqrt{g}$ can be derived using [6], and J_a can be derived using expressions (7) and (8).

RESULTS AND CONCLUSIONS

Commonly, the scintillator probe is placed at the fixed point. This gives an opportunity to consider only flux at the given location $\{a,\chi_a\}$. Next point is that this probe data contains information about separate flux tubes with the given pitch and particle speed $\{\xi_a,V\}$, i.e. the signal from the certain channel of probe is in fact proportional only to value of the integral over ρ in (11). Thus for further study we will consider only monoenergetic flux $I(a,\chi_a,\xi_a,V)$ of the lost particles at point $\{a,\chi_a\}$ with pitch and velocity $\{\xi_a,V\}$

$$I=\int\limits_{\rho_{\min}}^{a}d\rho R_{fus}(\rho,\xi_a,V)\sqrt{g}J_a. \qquad (12)$$

The expression for metric coefficient J_a can be used

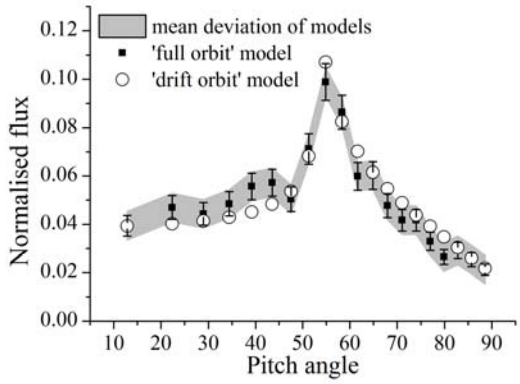
$$J_a=\frac{a\sin\chi_a}{\rho\sin\chi}\frac{1+\xi_a^2}{1-\xi_a^2}\frac{1}{\sqrt{1+4/G^2}}, \qquad (13)$$

where $G=B_\xi/A_\xi$. It is supposed integration along orbit in Eq.(12). Thus, the variable χ in Eq. (13) can be derived using Eq. (9).

To provide numerical integration in Eq. (12) it is used Gauss scheme with 32 points. This scheme doesn't require the evaluation of integrand at the integration domain ends. This feature of the scheme becomes very useful taking into account singularity of Eq. (13) at $\chi=0$ and $\chi=\pi$, which takes place for $\rho=\rho_{\min}$.

It is obvious that FLR effects play significant role in the CFP dynamics. However, to simplify the analysis of FO loss distributions in this paper we neglect the finite Larmor orbit width. Nevertheless, gyro-orbit simulation of 400000 test particles was carried out, in order to provide a cross-check. All parameters of magnetic configuration were the same as used for Eq. (12).

The results of this calculation are demonstrated in Figure. It is seen that distributions of both approaches are in reasonable agreement. For this calculation the source term was supposed monoenergetic.



Comparison of the pitch angle distribution of the lost CFP, which are calculated using "full orbit" and "drift orbit" models

In conclusion, we would like to summarize main results of the presented study. The earlier developed approach for poloidal distribution of prompt losses of CFP is extended to calculate pitch-angle and velocity distributions of the lost ions. The numerical code for simulation of the FO losses of CFP is developed for axisymmetric magnetic configuration of tokamak taking into account non-circular flux surfaces. Smooth axially symmetric 2D wall is assumed I this model. Cross-check of the newly upgraded approach against full orbit calculations shows good agreement.

The approach used in this paper gives an opportunity to decrease calculation efforts for simulating the experimental data from scintillator probe, or other point probe. Results of the test numerical simulation agree with earlier conducted calculations [1, 3] and experimental data [4, 5].

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РАСПРЕДЕЛЕНИЯ ПО ЭНЕРГИИ И ПИТЧ-УГЛУ ПРЯМЫХ ДРЕЙФОВЫХ ПОТЕРЬ В ТОКАМАКЕ С НЕКРУГЛЫМ СЕЧЕНИЕМ

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Разработан метод для расчета распределений по питч-углу, энергии и полоидальному углу потока заряженных продуктов синтеза, теряемых на первой стенке осесимметричного токамака вследствие мгновенных потерь (МП). Используемая в этом исследовании аналитическая модель магнитного поля учитывает шафрановский сдвиг, эллиптичность, треугольность и асимметрию «верх-низ». Использование пространства инвариантов движения дает возможность значительно уменьшить вычислительные усилия при моделировании потока теряемых частиц в заданную точку на первой стенке.

РОЗПОДІЛИ ПО ЕНЕРГІЇ ТА ПІТЧ-КУТУ ПРЯМИХ ДРЕЙФОВИХ ВТРАТ В ТОКАМАЦІ З НЕКРУГЛИМ ПЕРЕРІЗОМ

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Розроблено метод обчислення розподілів по пітч-куту, енергії та полоїдальному куту потоку заряджених продуктів синтезу, які втрачаються на першій стінці осесиметричного токамака внаслідок миттєвих втрат (МВ). Аналітична модель магнітного поля, яка використовується в цьому дослідженні, враховує шафранівський зсув, еліптичність, трикутність та асиметрію «верх-низ». Використання простору інваріантів руху дає можливість значно зменшити обчислювальні зусилля при моделюванні потоку частинок, що втрачаються, в задану точку на першій стінці.