SINGLE PARTICLE SIMULATION IN THE VICINITY OF SEPARATRIX UNDER TOKAMAK X-POINT SWEEPING

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The removal efficiency of the divertor X-point sweeping regimes is considered on the base of the numerical simulation of the tungsten ion motion in the gyroorbit approximation. The dependence of the loss particle fraction from the kinetic energy and initial position is studied. The results of the analysis show that the appropriate choice of the modulation law of the divertor current gives an opportunity to decrease heat load of the plasma facing components.
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1. INTRODUCTION AND MOTIVATION

A lot of experimental investigations on tokamaks are devoted to decreasing of the heat load on plasma facing components in the divertor region and impurity transport control at the plasma edge. The interest to this problem is caused by attempts to model fusion reactor scenarios on nowadays fusion devices [1,2].

It was shown on tokamak DIII-D that it is possible to lower peak heat flux on the divertor plates by a factor 3 [3] using X-point sweeping. Besides that this technique is intensively used at torsatrons for sweeping not only X-points but the magnetic axis too [4,5].

The MHD consideration [6] of same method gives an opportunity to analyze particle and energy flows in plasma volume except the close vicinity of the separatrix because in mentioned region the effects of finite Larmor radius become considerable.

In this paper a simple analytical model is proposed for analyzing the efficiency of the controlling the impurity ions with the divertor configuration under X-point sweeping. This approach is based on the single particle gyro-orbits simulation. The effect of vertical sweeping of the magnetic rib is considered for toroidal geometry. The simplicity of magnetic configuration is provided by authors' wish to select the effect of X-point on plasma transport at the edge.

The simplest toroidal configuration with rotational transform and X-point sweeping is described in the Section 2. Results of the numerical simulation of the tungsten ion motion are presented in the Section 3. The principal conclusions are summarized in the Section 4.

2. MODEL OF THE MAGNETIC FIELD

The following analytic expressions are used for modeling the tokamak like magnetic configuration with X-point:

- main confinement field

$$\mathbf{B}^{(0)} = \frac{B_0 R_0}{R_0 - r\cos\vartheta}\left\{0, \frac{r}{R_0}\iota(r), 1\right\}; \qquad (1)$$

- additional magnetic field which leads to X-point formation

$$\mathbf{B}^{(X)} = b^{(X)}\{-\sin(\vartheta-\vartheta_c), r/r_c - \cos(\vartheta-\vartheta_c), 0\}, \quad (2)$$

where

$$b^{(X)} = \frac{2I(t)}{c}\frac{(R_0 - r_c\cos\vartheta_c)r_c}{(R_0 - r\cos\vartheta)(r^2 + r_c^2 - 2rr_c\cos(\vartheta-\vartheta_c))},$$

$\{r,\vartheta,\varphi\}$ are the quasitoroidal coordinates, B_0 is the magnetic field value on the circular axis of the torus, $\iota(r)$ is the rotational transform angle, R_0 is the major radius of the torus, $\{r_c,\vartheta_c\}$ are the coordinates of the divertor coil, c is the light velocity in vacuum, $I(t)$ is the value of the divertor coil current, t is time. For further simulations we will use three modulations of this current:

- *"unmodulated"*

$$I(t) = I_0, \qquad (3a)$$

- *"positive" modulation*

$$I(t) = I_0 - \Delta I + \Delta I\cdot((t/T) - \mathrm{int}(t/T)), \qquad (3b)$$

- *"negative" modulation*

$$I(t) = I_0 - \Delta I\cdot((t/T) - \mathrm{int}(t/T)), \qquad (3c)$$

where I_0 is the constant, ΔI is the amplitude of modulation, T is the period of modulation, int(x) is the function which gives the integer part of x. These modulations are presented in Fig.1.

For magnetic field configuration presented with Eqs.(1) and (2) the magnetic flux function is obtained from equation $(\mathbf{B}\nabla\Psi) = 0$ as the following expression

$$\Psi = \int B_0 r\iota(r)dr + (2I(t)/c)\ln\left(r_c^2 + r^2 - 2rr_c\cos(\vartheta-\vartheta_c)\right). \qquad (4)$$

This function Ψ can be normalized

$$\Psi_N(r,\vartheta) = \frac{\Psi(r,\vartheta) - \Psi(r_O,\vartheta_O)}{\Psi(r_X,\vartheta_X) - \Psi(r_O,\vartheta_O)}, \qquad (5)$$

where $\{r_O,\vartheta_O\}$ and $\{r_X,\vartheta_X\}$ are coordinates of the O-point and X-point, respectively. This normalization leads to the following: Ψ_N is equal '1' at the separatrix, and '0' at the magnetic axis.

3. NUMERICAL SIMULATION OF THE TUNGSTEN ION MOTION

To analyze the efficiency of the different X-point sweeping regimes the numerical simulation of the ion trajectories was carried out. In calculations, 800 test particles (tungsten ions W^{+1}) were distributed in the vicinity of the separatrix at 10 flux surfaces in 8 s at each surface. The value of Ψ_N for these positions varies in the range 0,9 – 0,99 with step 0,01. The initial space distribution of test particles is presented in Fig.2. For each test particle initial velocities were chosen randomly from the Maxwellian distribution with the temperature 100 eV. This temperature is usually considered as the temperature of the plasma edge. It should be noted that for different modulations of the divertor current the set of particle parameters remains invariable.

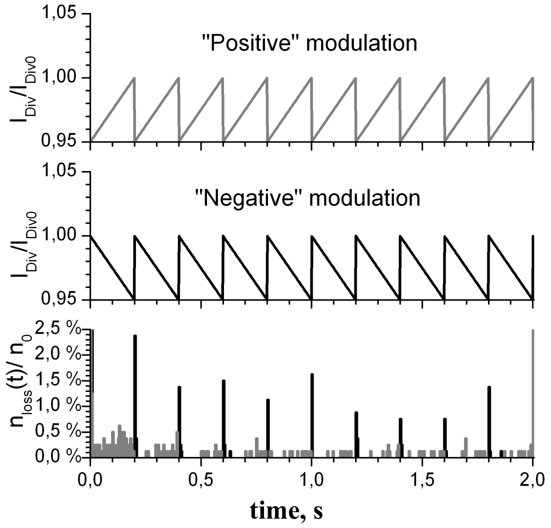


Fig.1. The divertor current modulation regimes and the dependence from time of the loss particle fraction relatively to initial quantity

The numerical calculation shows that 111 particles are lost during the first 10 ms for any of suggested modulations. Then during next 2 s particles aren't lost in "unmodulated" case and for modulated cases nearly 100 particles are lost in addition to mentioned. This shows that due to small modulation of divertor current it is possible to increase the removal of impurity ions from the plasma edge by a factor 2. The time evolution of these losses is presented on Fig.1 (n_0 is the initial quantity of test particles). It can be seen that "positive" modulation is more favorable because under this modulation particle flow is prolonged in contrary to "negative" modulation case when flow is presented by rare peaks at the beginning of each modulation period.

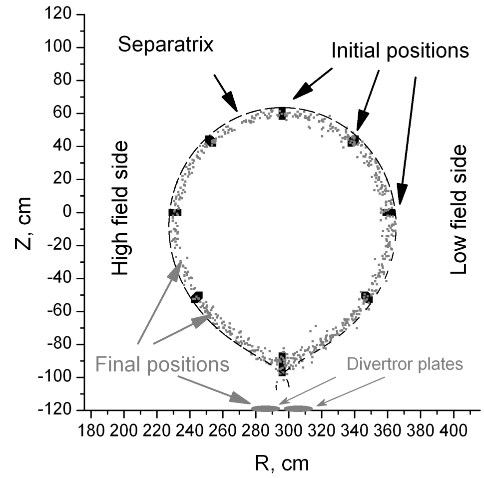


Fig.2. The initial and final spatial distribution of test particles (W^{+1}) in vertical cross section of the torus

The fraction of lost particle from each chosen flux surface (Fig.3) and the energy range (Fig.4) are presented ($n_0(\Psi_N)$ and $n_0(W)$ are the initial quantity at given surface Ψ_N and the given energy range near W).

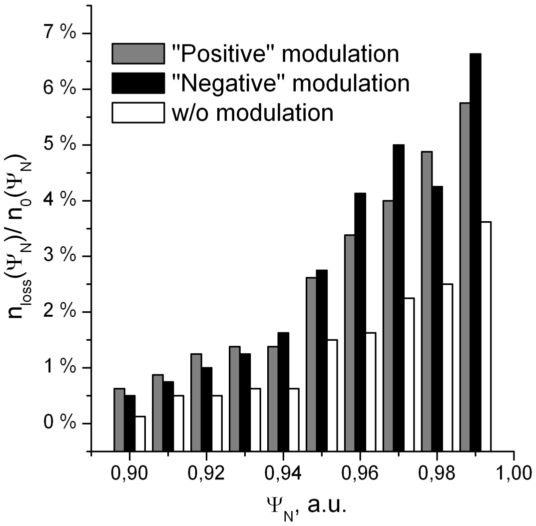


Fig.3. The dependence from magnetic flux label (Ψ_N) of the lost particle fraction relatively to initial quantity at given surface

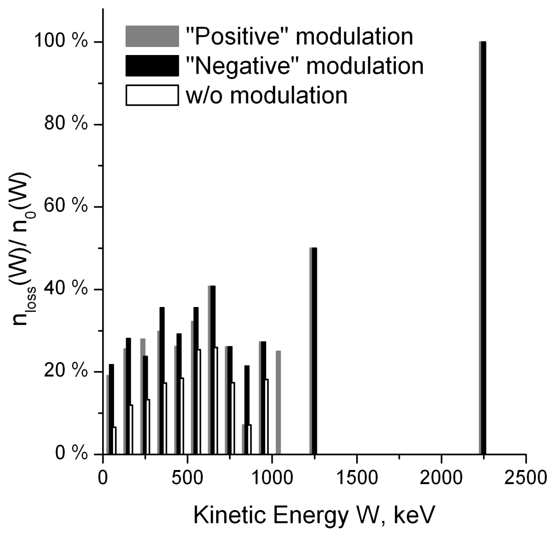
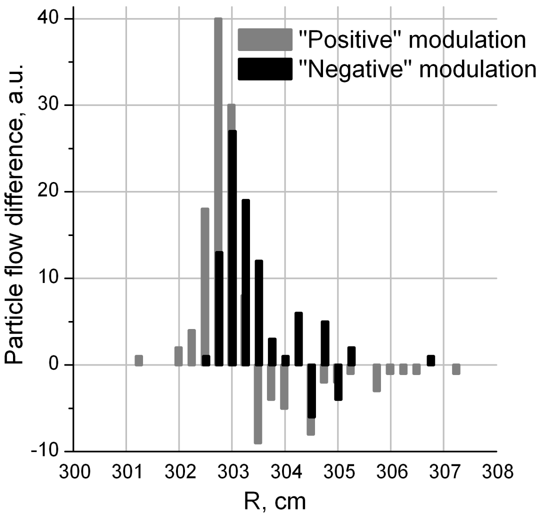


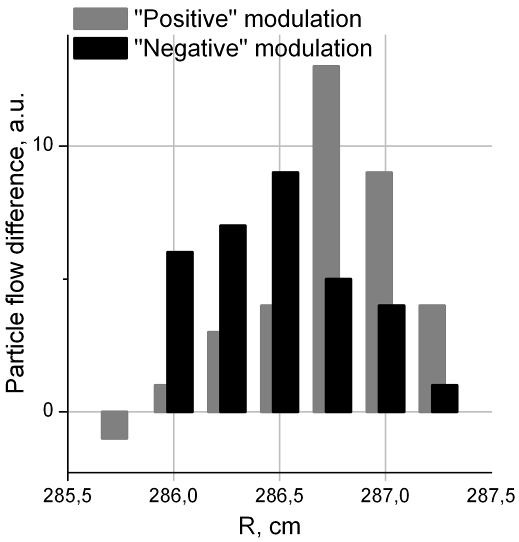
Fig.4. The lost particle fraction

It can be seen that losses under modulation from different surfaces (energy intervals) are nearly proportional to those which take place in "unmodulated" case.

On Fig.5 the deposition of lost test particles on imaginary divertor plates (see Fig.2) is presented as difference between flow under modulation and flow without modulation. It is seen that modulation leads to increasing of the particle flow on these plates. Besides that small redistribution of load occurs on low field side plate (Fig.5a): at the region from R=303–306 cm flow is decreased and at the region R=301–303 cm is increased in comparison with the "unmodulated" case. The same picture is seen in Fig.5b. However, it should be noted that in "positive" modulation case the losses are prolonged and that's why are less destructive then in "unmodulated" case and under "negative " modulation.



a



b

Fig.5. The difference between modulated and unmodulated cases of test particle deposition on the imaginary divertor plate a) at the low field side and b) at the high field side

4. CONCLUSIONS

From the carried out analysis it is seen that regime with “positive” modulation of divertor current has several advantages:

- increased the impurity ion removal;
- this increased flow is rather moderate and prolonged;
- the region of ion deposition is widen.

The right choice of the modulation law of the divertor current gives an opportunity to decrease heat load of the plasma facing components under the increased impurity removal.

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МОДЕЛИРОВАНИЕ ДВИЖЕНИЯ ЧАСТИЦЫ ВБЛИЗИ СЕПАРАТРИСЫ ПРИ РАСКАЧИВАНИИ Х-ТОЧКИ ТОКАМАКА

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Эффективность различных режимов раскачивания Х-точки рассмотрена на основании результатов моделирования движения иона вольфрама при учёте конечного радиуса Лармоворской орбиты. Изучена зависимость доли потерянных частиц от кинетической энергии и начального положения. Результаты анализа показывают, что при правильном выборе закона модуляции тока в диверторных проводниках возможно уменьшить тепловую нагрузку на материальную часть дивертора.

МОДЕЛЮВАННЯ РУХУ ЧАСТИНКИ ПОБЛИЗУ СЕПАРАТРИСИ ПРИ РОЗГОЙДУВАННІ Х-ТОЧКИ ТОКАМАКА

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Ефективність різних режимів розгойдування Х-точки розглянуто на основі результатів моделювання руху іону вольфраму при врахуванні кінцевої величини радіуса Ларморівської орбіти. Вивчено залежність долі втрачених частинок від кінетичної енергії та початкового положення. Результати аналізу вказують на те, що при належному виборі закону модуляції струму в диверторних провідниках можливо зменшити теплове навантаження на матеріальну частину дивертора.