https://doi.org/10.46813/2023-143-013

ON THE PHYSICAL PARAMETERS OF THE STELLARATOR – SOURCE OF NEUTRONS WITH NEOCLASSICAL LOSSES, TAKING INTO ACCOUNT RECYCLING AND BOHM LOSSES

V.A. Rudakov

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

E-mail: rudakov@kipt.kharkov.ua

The results of calculations of the physical parameters of the stellarator used as a neutron source for initiating nuclear reactions in a blanket of a hybrid reactor are presented. The calculations were carried out assuming the implementation of neoclassical transport processes, taking into account recycling and Bohm losses. The crushing effect of Bohm diffusion on the results of neutron yields is shown.

PACS: 52.55.Hc, 52.55.Rk, 52.55.Dj

INTRODUCTION

The results of a comparison of the theory of plasma confinement and experiments on stellarators give grounds for the possibility of predicting the expected parameters of plasma in experimental facilities of the next generation, in particular, in systems that can be used to create a neutron source. The transport coefficients in the neoclassical theory are functions of local plasma parameters, which make it possible to obtain their spatial distributions by solving a system of equations such as diffusion and heat conduction. Similar solutions were made in works on the calculation of plasma parameters in various versions of the stellarator reactor: experimental [1], demonstration [2] and power [3], in which it was shown that, under certain assumptions about the methods of filling fuel and heating the plasma, the reactor a stellarator with comparable dimensions can have energy characteristics similar to the corresponding types of tokamak reactor.

In this work, we study the possibility of creating a neutron source based on a stellarator system designed to initiate nuclear reactions in a blanket of a hybrid reactor. The stellarator was calculated, the linear dimensions of which were increased by a factor of one and a half compared with the dimensions of the LHD experimental setup. The size of the large radius of the toroidal chamber is taken equal to R = 6 m, the small radius of the plasma a =1 m, the radius of the first wall of the vacuum chamber a_c =1.1 m This increase makes the parameters of the stellarator comparable with existing experimental facilities such as tokamak. The magnetic field confining the plasma is assumed to be B = 5 T. In this case, the scale of the system turns out to be sufficient to accommodate a multiplying blanket around the plasma. When performing the work, a numerical code was used, which makes it possible to take into account not only neoclassical plasma diffusion losses, but also losses caused by other mechanisms, the presence of which is inevitable in thermonuclear installations. In this case, an attempt was made to take into accountthe influence of a certain proportion of Bohmian losses and recycling.

1. FEATURES OF THE NUMERICAL CODE

When performing this work, the spatio-temporal numerical code was upgraded, which was previously used to calculate the parameters of reactors in [1-3]. In these works, neoclassic was taken as the main mechanism of losses. At the same time, plasma losses in the reactor are not limited to one neoclassic and associated losses in the form of radiation. A significant contribution to such losses can be made by various instabilities, for example, drift instability. In [4] the possibility of explaining, observed in a number of experiments on Bohm diffusion stellarators, in particular, on the "C" stellarator [5], was shown for the first time by the development of drift-dissipative instability. The Bohm diffusion coefficient has the form (1):

$$D_B = \mathrm{ck}T/16 \text{ eV}. \quad (1)$$

Subsequently, a Bohm-like dependence of the diffusion coefficient was also revealed on some other stellarators, although its value was smaller, sometimes by tens of times [6]. Another inevitable transfer mechanism that should also be considered is recycling. In a thermonuclear reactor, it is proposed to use a divertor to remove particles lost from the plasma from the chamber. However, the operation of the divertor should not be considered ideal. Part of the plasma lost from the containment volume will interact with the chamber walls and return to the plasma in the form of neutral atoms. When upgrading the numerical code, these loss mechanisms were taken into account.

The calculation model is based on the system of equations given in [2, 3] to describe the spatiotemporal behavior of plasma in a stellarator reactor, which was supplemented by an equation for neutral atoms, and the equations for plasma diffusion and thermal conductivity of ions take into account the transfer coefficients associated with Bohm diffusion. As a plasma source, in addition to the pellet injection model, a source is used that takes into account the influx of charged particles by ionization of neutral atoms. As a result, the system of equations took the form:

$$\frac{3}{2}\mathrm{N}\frac{\partial T_{\mathrm{e}}}{\partial t}=-\frac{1}{r}\frac{\partial}{\partial r}r\Pi_{\mathrm{e}}+\frac{K_f N^2\langle\sigma v\rangle}{4}E_\alpha+Q_{he}-Q_{\mathrm{ei}}-Q_{\mathrm{b}}-Q_{\mathrm{c}}+Q_{\mathrm{E}}, \quad (2)$$

$$\frac{3}{2}n\frac{\partial T_i}{\partial t}=-\frac{1}{r}\frac{\partial}{\partial r}r\Pi_i+Q_{ei}+Q_{hi}-Q_E, \quad (3)$$

$$\frac{\partial n}{\partial t}=-\frac{1}{r}\frac{\partial}{\partial r}rS_e+S_\delta, \quad (4)$$

$$\frac{\partial n_a}{\partial t}=-\frac{1}{r}\frac{\partial}{\partial r}rS_a-S_\delta. \quad (5)$$

The first two equations describe the space-time behavior of the electron (2) and ion (3) temperatures. The next two are the diffusion equations for plasma (4) and neutral particles (5). The first term on the right side of the equation for electrons takes into account the neoclassical thermal conductivity, while in the equation for ions it is the sum of the neoclassical and Bohmian thermal conductivities. The remaining terms on the right-hand sides of equations (2) and (3) denote, respectively, the energy release due to the dissipation of thermonuclear α-particles, the collisional heat exchange between ions and electrons, the power of additional heating of electrons and ions, the heat exchange between the components due to the ambipolar electric field, the power of the bremsstrahlung and cyclotron radiation.

The flow of neutral atoms was chosen as $S_a = -n_a v_{T0}/\pi$, where v_{T0} is their thermal velocity. In this case, the source of charged particles was determined by the expression: $S_\delta = n_a n<\sigma v>$. The diffuse plasma flow consists of the sum of neoclassical and Bohmian diffusion. The magnitude of the ambipolar electric field is calculated from the equality of the electron and ion diffusion fluxes $S_e = S_i$ at each step of the space-time grid. The system of equations (2)-(5) is supplemented with initial and boundary conditions. The total number of charged and neutral particles in the plasma and chamber volume is kept constant. In this case, the density of neutrals in the volume outside the plasma is determined by the balance of fluxes of charged particles and neutral atoms at the plasma boundary.

Various models of plasma heating by external sources are used: only heating of electrons, only of ions, or simultaneous heating of two components. It is assumed that the specific heating power is proportional to the plasma density: $Q_h = k_h n$. In this case, the total heating power is determined by the integral over the plasma volume: $P_{hj}=\oint Q_{hj}dv$, where the index j means ions or electrons. Equation for density (3) contains on the right side, in addition to the diffusion term, a term with a particle source, by means of which the maintenance of the plasma density at an approximately constant level is modeled.

The maximum neoclassical losses in a stellarator are located in the region where the effective collision frequency $\nu_{\mathrm{eff}} = \nu_j/\varepsilon_{\mathrm{eff}}$ is close to the doubled plasma rotation frequency in a radial electric field ω_E [7]. Here νj is the frequency of Coulomb collisions of ions or electrons;$\varepsilon_{\mathrm{eff}}$ is the effective amplitude of helical magnetic field corrugations. According to [7], if $\varepsilon_{\mathrm{eff}}$ turns out to be greater than the amplitude of the inhomogeneity of the toroidal magnetic field ε_t, then the diffusion coefficient to the left of the maximum is proportional to the square root of ν_j, and in the case of the reverse inequality ($\varepsilon_{\mathrm{eff}}<\varepsilon_t$), diffusion increases linearly with frequency $-D \propto \nu_j^{-1}$.

In this work, as well as in [8], the calculations were performed for the case of a reactor with small ripples of the helical magnetic field, when the inequality $\varepsilon_{\mathrm{eff}}<\varepsilon_t$ is satisfied. The values of the plasma density were assumed to be large enough to carry out the transfer mode for both components $D \propto \nu_j^{-1}$. In this case, the plasma and heat fluxes for the electronic component have the form:

$$S_{\mathrm{e}}=-0.2\frac{\mathrm{n_e}\varepsilon_{\mathrm{t}}\sqrt{\varepsilon_h}\nu_e \mathrm{c}^2 T_{\mathrm{e}}^{\,2}}{e^2B^2r^2\omega_E^2}\left(\frac{n'}{n}+\frac{e\Phi'}{T_e}+\frac{1}{2}\frac{T_e'}{T_e}\right), \quad (6)$$

$$\Pi_{\mathrm{e}}=0.4\frac{n_{\mathrm{e}}\varepsilon_{\mathrm{t}}\sqrt{\varepsilon_h}\nu_e c^2 T_{\mathrm{e}}^{\,3}}{e^2B^2r^2\omega_E^2}\left(\frac{n'}{n}+\frac{e\Phi'}{T_e}+\frac{3}{2}\frac{T_e'}{T_e}\right). \quad (7)$$

Similar fluxes for ions look the same, but their magnitude is (M/m)½ times larger and the sign of the potential gradient is reversed. The diffusion equation for plasma and neutral deuterium and tritium atoms contains, in addition to diffusion terms, a source and sink term that takes into account the ionization of atoms. Equal amounts of deuterium and tritium were assumed in the reactor. The density was maintained at a constant level by injection of fuel pellets and by ionization of neutral atoms entering the plasma by recycling. The contribution of other elementary processes was neglected due to their smallness. The value of the radial electric field was found from the equality of the ionic and electron neoclassical diffusion fluxes at each node of the spatial grid along the small radius of the plasma.

In most cases, a dome-shaped model of fuel pellet ablation was used in the work: $\delta n = n_\delta(1+x^4/\Delta^4-2x^2/\Delta^2)$, where Δ is the half-width of the evaporation region, which was equal to 0.5, 0.75, and 1 in different calculations. The size of the pellet varied within 1…2 % of the total number of particles in the reactor plasma. When the number of particles in the plasma decreased below 0.99, the next pellet was thrown into the plasma. In this case, the energy costs for heating the injected particles were taken into account, and the energy losses for tablet evaporation and ionization of atoms were neglected due to their smallness.

2. CALCULATION RESULTS

To ensure the plasma parameters, the diffusion regime of which corresponds to expressions (6) and (7), it was assumed that the setup would operate with a sufficiently high plasma density. Calculations have shown that to satisfy such conditions it is necessary to have plasma with a density of the order of 10^{20} m^{-3}. In specific calculations, average plasma densities of 1.9, 2, and

$2.1 \cdot 10^{20}$ m^{-3} were used. At such values of the plasma density, in almost all calculations for plasma ions and electrons, the loss regime was fulfilled with the dependences of the transfer coefficients $D_j \propto v_j^{-1}$. In various calculations, heating powers from 10 to 20 MW were used, the absorption of which was assumed to be proportional to the plasma density.

The calculations showed a significant dependence of the plasma parameters of the neutron source on even a relatively small fraction of Bohm losses, which were taken into account in the diffusion and thermal conductivity coefficients of the ions. The value of the Bohm diffusion fraction was determined by the multiplier k_b in the transfer coefficients. Fig. 1 shows the time dependences of the thermonuclear radiation power in the absence of Bohm losses and for their different values.

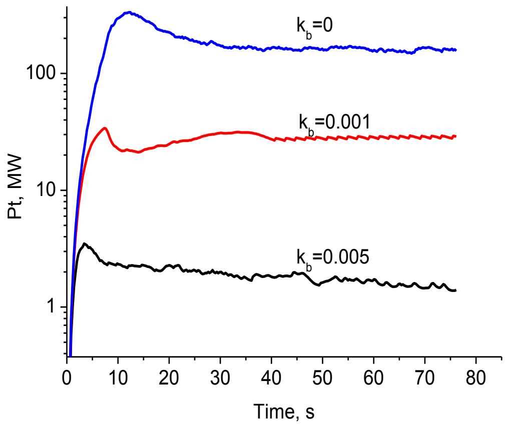

Fig. 1. Time dependences of the power of the neutron source at variousBohm diffusion levels.
$n = 2 \cdot 10^{20}$ m^{-3}, P_h =20 MW, k_h = 0.25, Δ =1

Fig. 2 illustrates the behavior of the average temperatures of ions and electrons for the cases k_b = 0 and 0.005. The two-hundredth fraction of the Bohm diffusion coefficient leads to a threefold decrease in the plasma temperature, which reduces the thermonuclear power by almost two orders of magnitude, which means a corresponding decrease in the neutron flux.

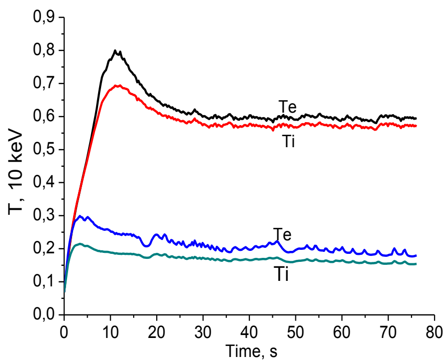

Fig. 2. Time dependences of temperature at various Bohm diffusion levels: $n = 2 \cdot 10^{20}$ m^{-3}, P_h=20 MW, k_h = 0.25, Δ =1, k_b = 0 and 0.005

The following figures Figs. 3-5 shows the spatial profiles of the plasma density, the temperature of ions and electrons, and the ambipolar electric field. The plasma density profiles are shown for two values of the half-width of the pellet injection region – Δ = 1 and 0.75. With a narrower fuel pellet injection region, a more compact plasma column is formed with a rapid decrease in density outside the injection region. A steep plasma gradient forms at the edge of the injection region.

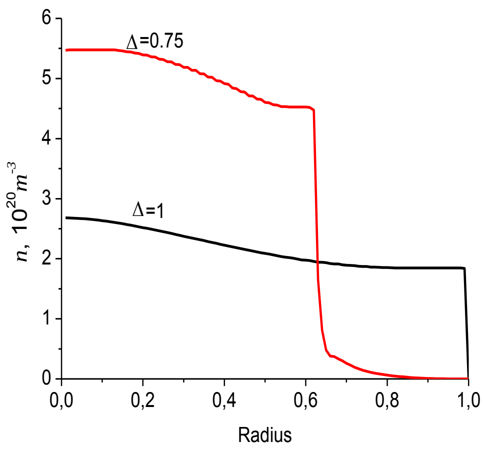

Fig. 3. Spatial distributions of plasma density for two half-widths of the pellet evaporation region:
$n = 2 \cdot 10^{20}$ m^{-3}, P_h=20 MW, k_h = 0.25, Δ =1 and 0.75

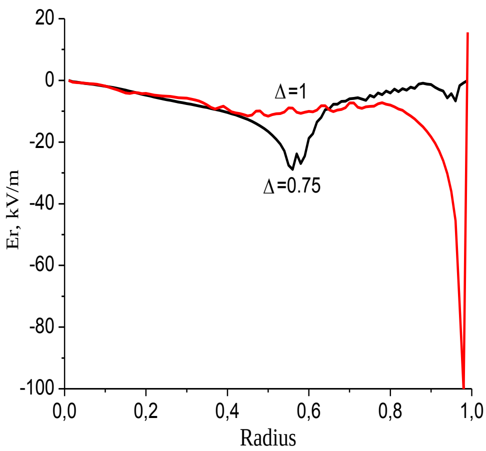

Fig. 4. Spatial distributions of the ambipolar electric field for two half-widths of the pellet evaporation region: $n = 2 \cdot 10^{20}$ m^{-3}, P_h=20 MW, k_h=0.25, Δ =1 and 0.75, k_b=0.005

In publication [9], an analysis of the effect of recycling on the physical parameters of the stellarator reactor was carried out. It has been shown that accounting for recycling reduces the synthesis capacity by about 20%. Calculations of the neutron source parameters showed that the main mechanism affecting plasma losses is Bohm diffusion. Fig. 6 shows the behavior of the fusion power for the cases k_h=0.25 and 0 with the Bohm coefficient k_b=0.005. Against the background of the action of the Bohmian transfer mechanism, the influence of recycling is insignificant.

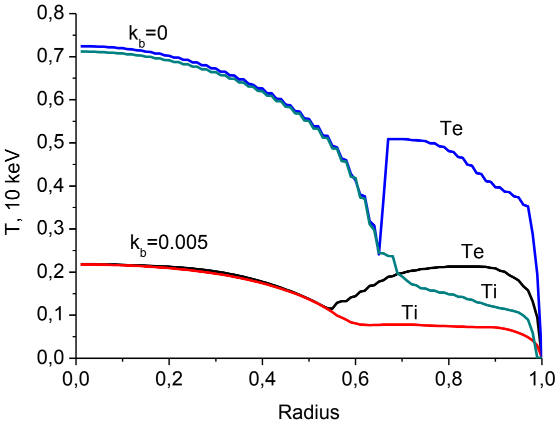

Fig. 5. Spatial distributions of the ion and electron temperatures: $n = 2\cdot10^{20}\ m^{-3}$, $P_h = 20$ MW, $k_h = 0.25$, $\Delta = 0.75$

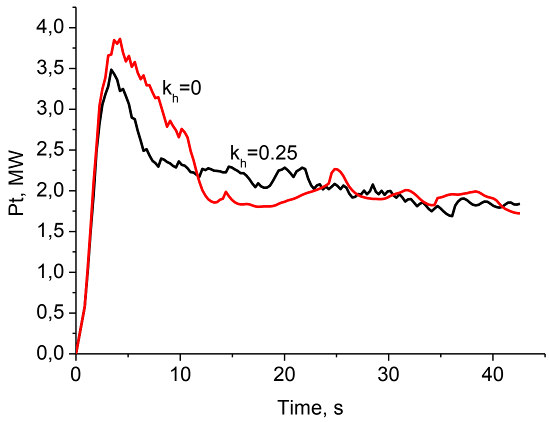

Fig. 6. Time dependences of the synthesis power at two values of the recycling share: $n = 2\cdot10^{20}\ m^{-3}$, $P_h = 20$ MW, $k_h = 0$ and 0.25, $\Delta = 1$, $k_b = 0.005$

CONCLUSIONS

Calculations of the physical parameters of the stellarator used as a neutron source showed a significant effect of anomalous losses in the form of Bohm diffusion, the insignificant presence of which leads to a multiple decrease in the neutron flux. Implementation of a neutron source using a stellarator will require measures to suppress such a loss mechanism.

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Article received 22.12.2022

ПРО ФІЗИЧНІ ПАРАМЕТРИ СТЕЛАРАТОРА – ДЖЕРЕЛА НЕЙТРОНІВ ПРИ НЕОКЛАСИЧНИХ ВТРАТАХ З ОБЛІКОМ РЕЦИКЛІНГУ ТА БОМІВСЬКИХ ВТРАТ

В.А. Рудаков

Наведено результати розрахунків фізичних параметрів стеларатора, що використовується як джерело нейтронів для ініціювання ядерних реакцій в бланкеті гібридного реактора. Розрахунки проводилися у припущенні реалізації неокласичних транспортних процесів з урахуванням рециклінгу та бомівських втрат. Показано руйнівну дію бомівської дифузії на результати виходу нейтронів.