ABOUT PHYSICAL PARAMETERS OF EXPERIMENTAL REACTOR- STELLARATOR IN THE CONDITIONS OF AMBIPOLARITY OF NEOCLASSICAL TRANSPORT FLUXES

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Parameters of an experimental stellarator reactor operating under conditions of ambipolarity of neoclassical transport fluxes are calculated with the use of a space-time numerical code. Dimensions of the system and the confinement magnetic field are taken the same as in the ITER tokamak reactor. The paper shows a possibility of engineering development of an experimental stellarator reactor with parameters comparable to these of an experimental tokamak reactor.

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INTRODUCTION

Successful results of investigations at tokamaks were used as a base for development of an experimental ITER tokamak reactor [1]. The ITER project implementation will allow one to carry out investigations on the plasma with characteristics corresponding to a full-scale fusion reactor and to solve engineering problems concerned with construction and exploitation of many systems providing the reactor operation.

Similarly, investigations at the experimental stellarator rector will be a necessary stage of works aimed to solving the problems of controlled thermonuclear fusion with the use of such a system. Despite attractive features which allow steady-state operation of a stellarator, investigations with such traps are limited because of the high plasma losses predicted by the neoclassical theory.

Investigations with the purpose of stellarator optimization have demonstrated that it is possible to reduce the neoclassical losses by decreasing the helical magnetic field ripple ε_h [2]. Solutions of the system of equations determining the plasma loss-energy balance under ambipolarity conditions have shown that the plasma confinement can be much improved under conditions of fuel injection into the plasma center [3].

The present paper considers the process of starting and sustaining of the steady-state fusion burn in the experimental stellarator-reactor having plasma parameters and magnetic characteristics corresponding to the design objectives of the ITER reactor.

SYSTEM OF EQUATIONS

A system of equations which is a combination of the heat conduction equations for electrons and ions and the diffusion equations has been solved. The system describes the time-space plasma behavior in the 1D space case under the assumption of the minor plasma radius averaged over magnetic surface.

$$\frac{3}{2}N\frac{\partial T_e}{\partial t}=-\frac{1}{r}\frac{\partial}{\partial r}r\Pi_e+\frac{K_f N^2\langle\sigma v\rangle}{4}E_\alpha+Q_{he}-Q_{ei}-Q_b-Q_c+Q_E, \quad (1)$$

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

$$\frac{\partial N}{\partial t}=-\frac{1}{r}\frac{\partial}{\partial r}rS_j+S_\delta. \quad (3)$$

Here Π_i, Π_e, S_i and S_e are the heat fluxes and fluxes of ion and electron particles corresponding to the electron transfer mode $1/\nu$ and to the square root of ion collision frequency [4], E_α − α − particle energy; Q_{ei} − collision heat exchange; Q_b – bremsstrahlung; Q_c – cyclotron radiation; Q_{hj} – external source heating. Here and below the index j marks a particle type. The content of deuterium and tritium in the reactor plasma was taken equal. The coefficient K_f=0.95 determines the α− particle energy part transferred to electrons. It has been supposed that the most part of cyclotron radiation is absorbed in the plasma and the power loss is only 5 %.

In calculations it has been assumed that the specific heating power is proportional to the plasma density. The ambipolar electric field influence on the plasma particle energy was taken into account by $Q_E=-S_j\cdot E_r$. The term with a source S_δ in the right side of equation (3) provide the plasma density maintenance at a level close to the constant one.

To the system of equations (1)-(3) added were boundary and initial conditions in which the spatial derivatives of density, temperature and potential are equal to zero in the plasma center, and the values of these parameters at the boundary are equal to the low constant values. The electric field was determined from the equation of balance between ion and electric fluxes at every step of numerical code spatial grid. In all cases the solution was corresponding to the left (ion) root giving the negative values of E_r.

CALCULATION RESULTS

In the paper, similarly to the case of ITER reactor, the tore radius R=6.2 m, minor radius a-2 m, confinement field B_0=5.3 T.

Plasma losses substantially depend on the quantity ε_h, the value of which at the plasma boundary is taken equal to 0.06, as in [3], that approximately corresponds to its value in the LHD facility where the magnetic configuration center position is located at the radius R=3.53 m [2].

The injection of fuel pellets has been simulated by the expression $\delta n = n_p(1 - x/\Delta)$, which determines their throwing into the plasma center from the half-width evaporation region Δ. The expenditure of energy for injected particle heating is taken into account.

Fig. 1 shows the reactor fusion power behavior during the plasma heating with 40 MW power. In this case the energy input to plasma ions and electrons was 20 MW. The fusion power reached approximately 600 MW with heating power conservation. If the heating power decreases to 10 MW, then the steady-state burn is set with a fusion power of about 440 MW. The full heating stopping leads to the reaction damping.

Fig. 2 and 3 illustrate the spatial distribution of the plasma density and ambipolar electric field for three values of half-width ablation region (Δ=0.5; 0.75 and 1). Maximum values of the plasma density and the deepest field minimum E_r are formed at minimal values of ablation region Δ=0.5. A phenomenon of the deepest minimum E_r has been found in experiments and is confirmed by calculations for the facility W7-AS [5].

To the small width Δ the peak values of the reactor heat power are corresponding (Fig. 4). Spatial distributions of ion and electron temperature are shown in Fig. 5. Their significant difference in the peripheral region is because of the ambipolar field influence. As a result there is a notable discrepancy between the average values of Te and Ti (Fig. 6). The increase of the average plasma density value from $7 \cdot 10^{19}$ to $8 \cdot 10^{19}$m^{-3} leads to the heat power increase almost by a factor of 1.5 (Fig. 7). In this case the steady-state burn mode was sustained by the additional heating power of 10 MW shared equally between ions and electrons.

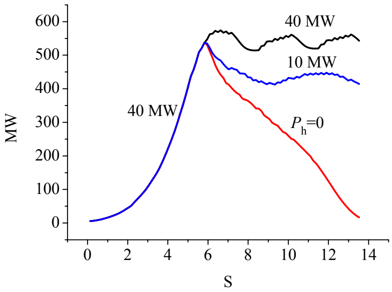

Fig. 1. Reactor heat power in the process of ignition with a plasma heating power of 40 MW, $N=0.7 \cdot 10^{20}$ m^{-3}, Δ=0.5

Besides the additional heating powers, in the plasma the α– particle energy is absorbed that makes a one fifth part of the reactor heat power. And a half power is lost as a result of bremsstrahlung and cyclotron radiation. Note, that the bremsstrahlung is calculated under the assumption that Z = 1 that is possible only in the case of ideal operation of a divertor.

RESULTS AND DISCUSSION

Some variants of stellarator reactor parameters are given in the Table in comparison with the ITER reactor parameters. The investigation results show that the stellarator reactor may have fusion energy release modes similar to those which have been planned in the ITER reactor. An important condition in principle is the necessary fuel injection directly into the plasma center. Thus the spatial distributions with sharply peaked profiles of parameters can be realized. The design quantity β in the plasma center reaches 25 % that can make a problem in providing the stability of such modes. The calculations have shown that a significant part of the plasma heat energy is taken away with bremsstrahlung and cyclotron radiation despite the assumption about the high reflection power of the first wall and minimum value of the plasma charge Z. Implementation of the above-mentioned conditions can be realized with appropriate designs of the first wall and plasma divertor.

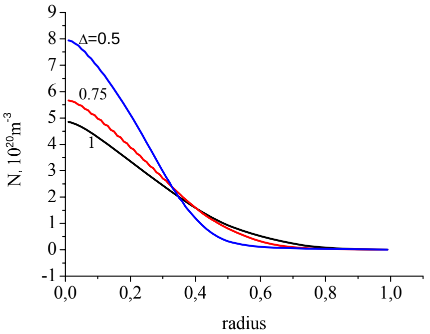

Fig. 2. Spatial distributions of the plasma density for different pellet evaporation widths: Δ=0.5; 0.75; 1. *$N=0.7 \cdot 10^{20}$ m^{-3}, P_h=40 MW*

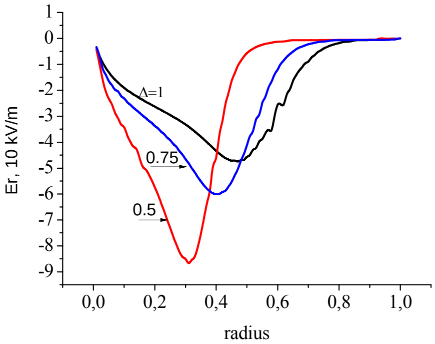

Fig. 3. Spatial distributions of E_r for different pellet ablation widths: Δ=0.5; 0.75; 1. $N=0.7 \cdot 10^{20}$ m^{-3}, P_h=40 MW

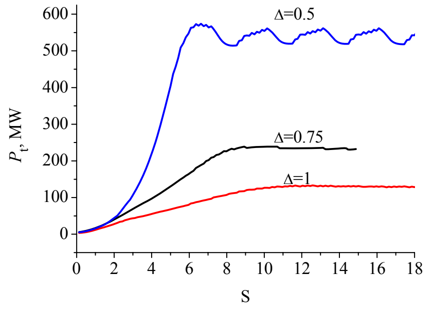

Fig. 4. Reactor thermal power in the process of ignition for different pellet evaporation widths: Δ=0.5; 0.75; 1. $N=0.7 \cdot 10^{20}$ m^{-3}, P_h=40 MW

The investigation results obtained enable to conclude that an experimental stellarator rector can have characteristics comparable with these of an experimental tokamak reactor.

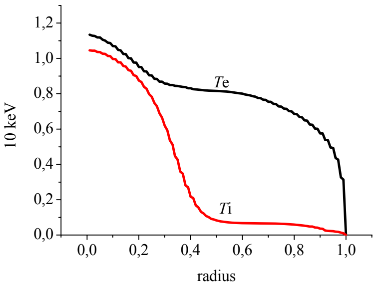

Fig. 5. Spatial distribution of the plasma temperature in the steady-state burn mode: $\Delta=0.5$, $N=0.7\cdot10^{20}$ m^{-3}, $P_h=40$ MW

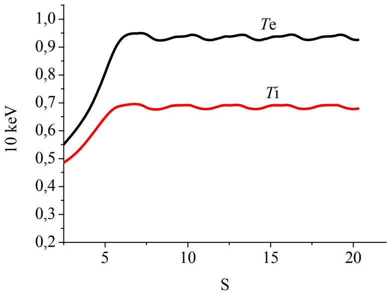

Fig. 6. Temperature of ions and electrons in the process of ignition and after transition into the steady-state burn mode: $\Delta=0.5$, $N=0.7\cdot10^{20}$ m^{-3}, $P_h=20+20$ MW

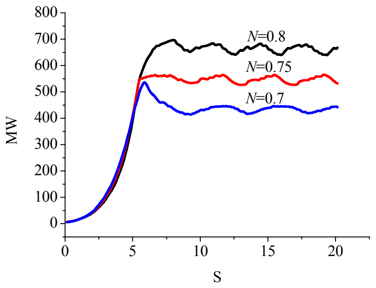

Fig. 7. Reactor thermal power in the process of ignition for different values of the plasma density: $P_h=40$ M, $\Delta=0.5$, $N=0.7$; 0.75; $0.8\cdot10^{20}$ m^{-3}

Table of reactor parameters

	ERSt-1	ERSt-2	ERSt-3	ITER
Confinement magnetic field – B, T	5.3	5.3	5.3	5.3
Major tore radius – R, m	6.2	6.2	6.2	6.2
Minor radius – a, m	2	2	2	2
Average density – $<N>$, $10^{20}/m^3$	0.7	0.7	0.8	0.8…1.0
Electron temperature – Te, кeV	9.3	9	9	8.9
Ion temperature – Ti, кeV	6.8	6.7	7	8.1
Helical ripple at the boundary – ε_{hmax}	0.06	0.06	0.06	0
Total heat power – P_t, MW	540	510	660	500
Load on the first wall – Q_w, MW/m^2	0.68	0.64	0.82	0.6
Plasma pressure – $<\beta>$, %	1.6	1.55	1.83	2.2
Energy lifetime – τ_E, s	1.1	1.09	1.08	2.1
Particle confinement time – τ_n, s	1,8	2.8	2.5	-
Additional heating power, MW	40	30	40	40

REFERENCES

1. O. Mitarai and K. Muraoka. Ignition analyses with ITER89P and ITER93HP scaling for burn control and diagnostics in ITER-ID // *Plasma Phys. Control. Fusion.* 1998, v. 40, p. 1349-1372.

2. S. Murakami, A. Wakasa, H. Maaβberg, C.D. Beidler, H. Yamada, K.Y. Watanabe. LHD Experimental Group Neoclassical Transport Optimization of LHD // *Nucl. Fusion.* 2002, v. 42, p. L19-L22.

3. V.A. Rudakov On parameters of stellarator reactor under conditions of ambipolarity of neoclassic transport fluxes // *Visnyk Kharkivs'kogo Natsionalnogo Universytetu. Seriya fizychna "Yadra, chastynky, polya".* 2012, N2/54/, p. 15-23 (in Russian),

4. L.M. Kovrizhnykh. The Energy Confinement Time in Stellarators// *Nucl. Fusion*. 1984, v. 24, p. 435.

5. Y. Turkin, C.D. Beidler, H. Maaβberg, et al. Neoclassical transport simulations for stellarators // *Physics of Plasmas*. 2011, v. 18, p. 022505.

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О ФИЗИЧЕСКИХ ПАРАМЕТРАХ ЭКСПЕРИМЕНТАЛЬНОГО РЕАКТОРА-СТЕЛЛАРАТОРА В УСЛОВИЯХ АМБИПОЛЯРНОСТИ НЕОКЛАССИЧЕСКИХ ТРАНСПОРТНЫХ ПОТОКОВ

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С использованием пространственно-временного численного кода рассчитаны параметры экспериментального реактора-стелларатора в условиях амбиполярности неоклассических транспортных потоков. Размеры системы и удерживающее магнитное поле приняты такими же, как и в реакторе-токамаке ITER. Показана возможность создания экспериментального реактора-стелларатора с характеристиками, сопоставимыми с характеристиками экспериментального реактора-токамака.

ПРО ФІЗИЧНІ ПАРАМЕТРИ ЕКСПЕРИМЕНТАЛЬНОГО РЕАКТОРА-СТЕЛАРАТОРА В УМОВАХ АМБІПОЛЯРНОСТІ НЕОКЛАСИЧНИХ ТРАНСПОРТНИХ ПОТОКІВ

В.А. Рудаков

З використанням просторово-часового чисельного коду розраховано параметри експериментального реактора-стеларатора в умовах амбіполярності неокласичних транспортних потоків. Розміри системи і утримуюче магнітне поле прийняті такими ж, як і в реакторі-токамаці ITER. Показана можливість створення експериментального реактора-стеларатора з характеристиками, порівнянними з характеристиками експериментального реактора-токамака.