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ON THE PHYSICAL PARAMETERS OF A NEUTRON SOURCE – STELLARATOR WITH A CONVENTIONAL HELICAL MAGNETIC FIELD DESIGN

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The results of calculations of physical parameters of the neutron source based on the model of a stellarator with a traditional helical winding are presented. The LHD stellarator, the dimensions of which are increased one and a half times, is taken as a basis for the design. The parameters of the source operating under conditions of high plasma density, when the electron collision frequency always corresponds to the dependence $D_e \propto \nu^{-1}$ are studied. It is shown that fusion powers of the order of one hundred MW are achievable at the plasma heating powers planned for the ITER.

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INTRODUCTION

In one act of DT-fusion 17.5 MeV of energy is released with the birth of α-particle and neutron, and one fission of a nucleus of a heavy element by a thermonuclear neutron gives about 200 MeV. At the same time, neutrons born as a result of nuclear fission can cause new fissions. The number of such fissions is determined by the multiplication factor *Km*, which at $K_m < 1$ according to [1] is equal to: $\eta = 1/(1{-}K_m)/\nu_f$, where ν_f is the number of neutrons born in one act of fission. In the case of $K_m > 1$ the reactor enters the uncontrolled chain reaction mode. Thus, when, for example, the breeding system provides the number of fission acts per one external neutron $\eta = 10$, the power of the reactor can increase many times compared to the power of the fusion neutron source. As a result, a fusion device with a fusion power of about one or several tens of MW is sufficient to create a power reactor of gigawatt capacity. In contrast to a traditional reactor based on nuclear fission, where the multiplication factor is equal to one, in such a reactor at $K_m < 1$ there is no possibility of an uncontrolled chain reaction.

The combination of fusion and nuclear fission reactions in a single device defined the name of such systems by the word – hybrid. Hybrid fusion reactors have been considered as energy sources practically since the beginning of research on the problem of controlled fusion.

The incident with the nuclear reactor in Chernobyl extinguished interests in hybrid systems for some time and intensified work in the direction of creating pure fusion reactors, in particular, the ITER project. However, the prospect of solving the energy problem with the help of pure fusion reactors remains rather remote, so in recent years there has been renewed interest in the development of hybrid systems [2], the creation of which takes real shape due to the fact that modern thermonuclear facilities have achieved a fusion power of 10 MW [3, 4].

So far, hybrid fusion reactor designs have been predominantly developed with tokamaks in mind. One of the disadvantages of tokamaks is the impossibility of maintaining a stationary thermonuclear reaction in the system. This creates certain technical problems when creating a stationary power source on their basis. The above problem is removed in a stellarator, in which it is possible to maintain a stationary fusion reaction. At the same time, experimental studies of thermonuclear plasma in stellarators have not yet reached the level of studies on tokamaks, although the features in plasma confinement obtained in experiments fit approximately into the same regularities that are indicated in tokamaks [5].

The results of comparison of the theory of plasma confinement and experiments on stellarators give grounds for the possibility of predicting the expected plasma parameters in the next generation experimental facilities, in particular, in systems that can be used to create a neutron source. Transfer coefficients in neoclassical theory are functions of local plasma parameters, which allow us to obtain their spatial distributions by solving a system of diffusion and heat conduction type equations. Such solutions were performed in the works on the calculation of plasma parameters in different versions of the stellarator reactor: experimental [6], demonstration [7], and power [8], in which it was shown that, under certain assumptions about the methods of fuel filling and plasma heating, the stellarator reactor with comparable dimensions can have energy characteristics similar to the corresponding types of the tokamak reactor.

The possibility of creating a neutron source based on a stellarator system was investigated by the author of this publication in [9,10]. In [9], a neutron source whose magnetic system is similar to the LHD stellarator with dimensions increased by a factor of one and a half was considered. In calculations of the plasma parameters, it was assumed that they are neoclassical, corresponding to the collision regime in which the dependence $D_i \propto \nu^{1/2}$ and for electrons $D_e \propto \nu^{-1}$.

It is shown that in optimal cases at moderate heating power consumption such a source can give neutron fluxes from several to tens of MW of thermonuclear power. In [10], a variant of a neutron source whose magnetic system design is similar to that of the W-10X stellarator was considered. The peculiarity of such a design is the small values of the corrugations of the helical magnetic field. In this case, the plasma losses corresponded to the collision frequencies at which the diffusion fluxes of plasma ions and electrons were in the $D_{i,e} \propto \nu^{-1}$. In addition, the influence of recycling and anomalous losses was taken into account. As a result, it was shown that acceptable neutron fluxes can be obtained at a sufficiently small fraction of anomalous diffusion in the total plasma losses.

In the present publication, the parameters of the neutron source whose magnetic system design corresponds to the LHD stellarator were calculated, but in contrast to the plasma confinement mode considered in [9], it was considered that the diffusion losses of the ionic component in can be both in the $D_i \propto \nu^{1/2}$, so in depending on $D_i \propto \nu^{-1}$. In this case, the transfer mode can be different at different radii of the plasma cord.

In the calculations, an analogue of the LHD stellarator design is adopted, the linear dimensions of which are increased by one and a half times. Such an increase makes the parameters of the stellarator comparable to the existing tokamak-type experimental facilities. At the same time, the scale of the system is sufficient to accommodate the propagating blanket around the plasma.

NUMERICAL MODEL

Numerical calculations and studies were carried out by using the numerical code used in publications [9, 10]. The numerical model is based on a physical model described by a system of four equations that allow us to solve a one-dimensional space-time problem of heating, plasma confinement in a thermonuclear trap, and control the process of neutron production due to the fusion of deuterium and tritium nuclei.

The solved system of equations [10] consisted of two heat conduction equations for plasma ions and electrons, which, in addition to the diffusion terms, took into account the energy release in electrons as a result of dissipation of thermonuclear alpha particles, plasma heating by external sources, collision and due to the ambipolar electric field heat exchange between plasma components, as well as cyclotron and braking losses.

The next two equations were the plasma diffusion equation and the equation for the flux of neutral particles. The flux of neutral atoms was chosen as $S_a = -n_a \upsilon_{T0}/\pi$, where υ_{T0} is their thermal velocity, n_a is the density of neutral atoms. In this case, the source of charged particles was ionization $S_\delta = n_a n \langle\sigma\upsilon\rangle_i$.

The maximum of neoclassical losses in the stellarator is in the region where the effective collision frequency $\nu_{eff} = \nu_j/\varepsilon_{eff}$ turns out to be near the doubled rotational frequency of the plasma in the radial electric field ω_E [11]. Here ν_j is the Coulomb collision frequency of the plasma ions or electrons; ε_{eff} is the effective amplitude of the ripples of the helical magnetic field. In the considered problem, it was assumed that at effective collision frequency less than $2\omega_E$ the ion losses corresponded to the dependence $D \propto \nu_j^{1/2}$. At higher collision frequencies ($\nu_{eff} > 2\omega_E$), the diffusion fluxes of ions and electrons decrease with increasing collision frequency. In this problem, we calculated processes with high plasma density, at which the effective collision frequencies of both plasma components in most cases were greater than $2\omega_E$.

The diffusion equations for plasma and neutral atoms of deuterium and tritium, in addition to the diffusion terms, contain a term that takes into account ionization of atoms as a source and a sink. The deuterium and tritium contents in the reactor were assumed to be equal. Density maintenance at a constant level was provided 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 its smallness. The value of the radial electric field was found from the equality of ion and electron neoclassical diffusion fluxes at each node of the spatial grid along the small radius of the plasma.

Various models of plasma heating by external sources were used in the calculations: separate heating of electrons, ions, or simultaneous heating of two components. It was also assumed that the specific heating power is proportional to the plasma density. Different fuel pellet ablation models were used in different calculations. The size of the pellet varied between 1 and 2 percent of the total number of particles in the reactor plasma. When the number of particles in the plasma decreased below 0.99, another pellet was thrown into the plasma. At the same time, the energy consumption for heating of injected particles was taken into account, and energy losses for tablet evaporation and ionization of atoms were neglected due to their smallness.

A stellarator with a large radius R = 6 m, a small plasma radius r_p = 1 m, and a magnetic field B_0 = 5 T. Tesla was taken as initial parameters for numerical calculations. The radius of the first wall of the vacuum chamber r_w = 1.1 m. The helical inhomogeneity of the magnetic field was modeled by the expression $\varepsilon_h = 0.01+0.05x^{0.87}$, which approximately corresponds to the radial dependence of ε_h in the LHD setup. Sufficiently high plasma densities ($\langle n\rangle = (1.5\ldots2)\cdot10^{20}\,\mathrm{m}^{-3}$) were chosen for the calculations. At the same time, the electron and ion diffusion coefficients over most of the plasma radius corresponded to the dependences $D \propto \nu_j^{-1}$.

CALCULATION RESULTS

The LHD stellarator has already been considered as a basis for the design of a neutron source [9]. In this work, the operating modes of the source with relatively low plasma densities were considered. The transport losses corresponded to the dependences $D \propto \nu_j^{1/2}$ for both plasma components. At the same time, fusion powers at the level of one tens of MW were obtained. In the present work, in order to optimize the transport losses, the plasma densities were increased, which led to higher plasma temperatures and higher fusion powers and, consequently, to an increase in neutron fluxes.

Figs 1 and 2 illustrate the time dependences of fusion power and ion and electron temperatures during plasma heating when plasma ions and electrons are heated with the same power levels of 18 and 20 MW. The average over the plasma cord cross-section value of the plasma density in these calculations was equal to $1.5 \cdot 10^{20}$ m^{-3}. The thermonuclear power of the source depends significantly on the plasma heating power.

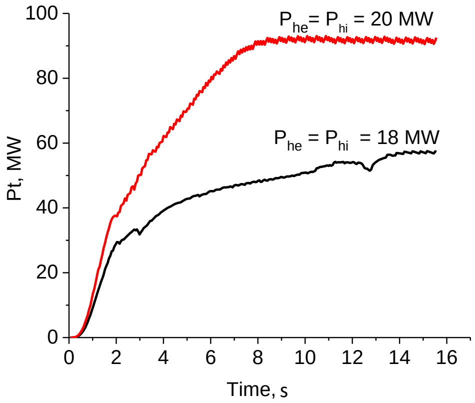

Fig. 1. Time dependences of the fusion power of the neutron source at two values of heating power 40 and 36 MW, <n>=1.5·10^{20} m^{-3}

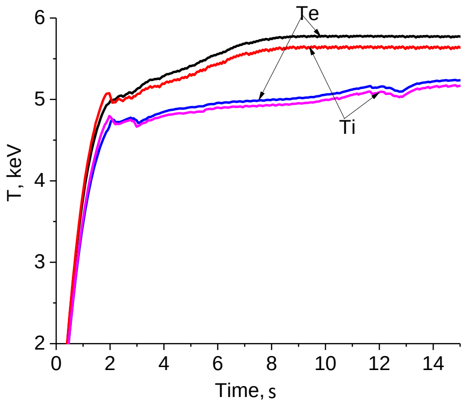

Fig. 2. Time dependences of the average plasma temperature at two values of heating power 40 and 36 MW, <n>=1.5·10^{20} m^{-3}

The average temperature values of ions and electrons do not differ much. Their spatial profiles as a function of the plasma radius averaged over the magnetic surface are shown in Fig. 3. The difference in temperatures is manifested mainly in the boundary region, where the low plasma density does not provide intensive heat exchange.

Fig. 4 shows the dependences of the effective ion collision frequency and the plasma rotation frequency in an ambipolar electric field. The ion collision frequency is significantly larger than ω_E, indicating diffusion losses of both plasma components, which correspond to the dependence $D \propto \nu^{-1}$ practically over the entire cross section of the plasma cord.

The thermonuclear power of the neutron source and the plasma density profiles depend significantly not only on the heating power but also on the method of *fuel* supply. Fig. 5 shows the radial distributions of plasma density for two variants of fuel pellet vaporization. The profile peaked to the center corresponds to the variant of tablet vaporization in the center of the plasma, and a flatter profile is formed when fuel is injected in the middle of the plasma radius. Note also that the fusion power is significantly higher when the fuel is injected into the center of the plasma.

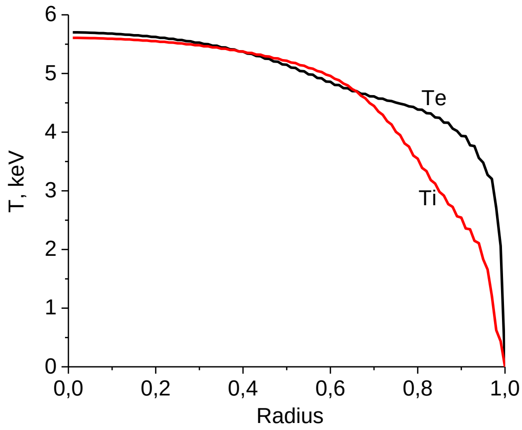

Fig. 3. Radial temperature profiles of plasma electrons and ions Phe=Phi=18 MW, <n>=1.5·10^{20} m^{-3}

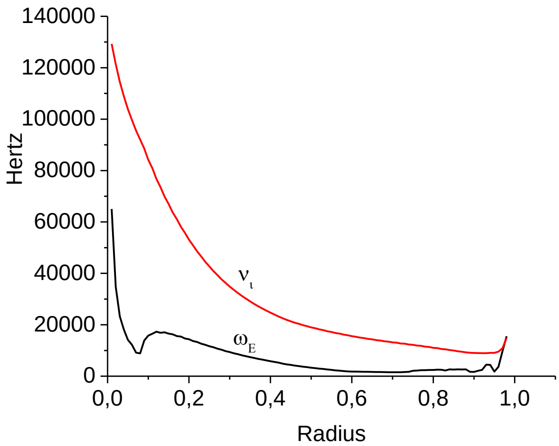

Fig. 4. Radial profiles of the plasma rotation frequency in the radial electric field and the effective ion collision frequency. Phe=Phi=18 MW, <n>=1.5·10^{20} m^{-3}

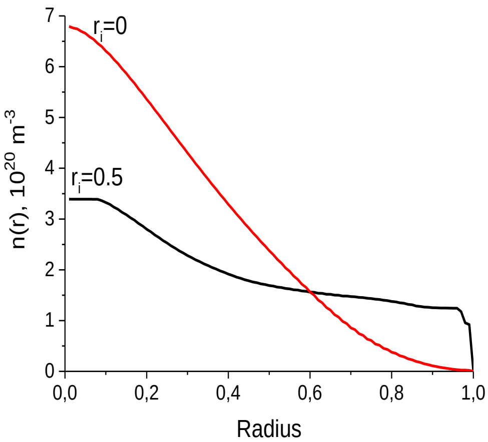

Fig. 5. Radial profiles of plasma density for two variants of fuel injection into the plasma, <n>=1.5·10^{20} m^{-3}

The ambipolar electric field plays an essential role in the transport processes, equalizing the values of electron and ion diffusion fluxes. Fig. 6 shows its typical radial distributions. Its magnitudes indicate the realization of the ionic neoclassical root of diffusion. Its depth at the maximum is about 35 kV/m, which corresponds to the gradient combination in the neoclassical ion diffusion flux.

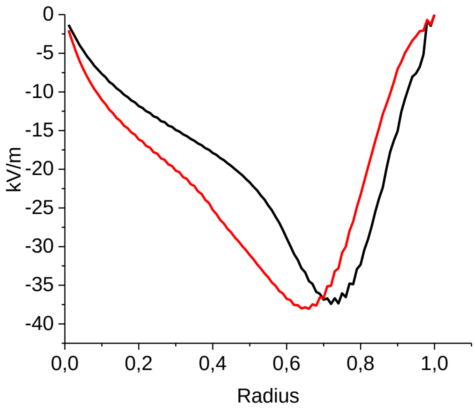

Fig. 6. Radial profiles of the ambipolar electric field at two plasma heating powers of 40 and 36 MW

CONCLUSIONS

The results of calculations of physical parameters of the neutron source based on the design of a stellarator with a conventional helical coil and dimensions close to the ITER tokamak show that it is possible to obtain neutron fluxes whose power can reach hundreds of megawatts. Under conditions of neoclassical transport processes, the obtained neutron fluxes can be varied in a wide range by changing the modes of fuel supply and power values of plasma heating sources.

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ПРО ФІЗИЧНІ ПАРАМЕТРИ ДЖЕРЕЛА НЕЙТРОНІВ – СТЕЛАРАТОРА З ТРАДИЦІЙНОЮ ГВИНТОВОЮ КОНСТРУКЦІЄЮ МАГНІТНОГО ПОЛЯ

В.А. Рудаков

Наведено результати розрахунків фізичних параметрів джерела нейтронів, заснованого на моделі стеларатора з традиційною гвинтовою обмоткою. За основу конструкції взято стеларатор LHD, розміри якого збільшено в півтора рази. Вивчено параметри джерела, що працює в умовах високої щільності плазми, коли частота зіткнень електронів завжди відповідає залежності $D_e \propto \nu^{-1}$. Показано, що при запланованих для ІТЕР потужностях нагріву плазми досяжні потужності синтезу порядку однієї сотні мегаватт.