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ON PHYSICAL PARAMETERS OF THE DEMONSTRATION STELLARATOR-REACTOR OPERATING IN THE MODE OF SELF-SUPPORTED THERMONUCLEAR REACTION

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With the use of a one-dimensional spatial-temporal numerical code under conditions of ambipolarity of neoclassical transport fluxes the regimes of the self-supported DT-fusion reaction in a reactor-stellarator are calculated. Cases of heating both ion and electron plasma components are considered. It is shown that powers of heating of plasma of scale 25 MW can be sufficient for excitation in reactor of the steady-state self-supported burning. Technical and physical parameters of such reactor correspond to characteristics of a demonstration reactor.
KEY WORDS: reactor-stellarator, ambipolar electric field, neoclassics, transport fluxes, plasma heating, power balance

ПРО ФІЗИЧНІ ПАРАМЕТРИ ДЕМОНСТРАЦІЙНОГО РЕАКТОРА-СТЕЛАРАТОРА, ЯКИЙ ДІЄ В РЕЖИМІ ТЕРМОЯДЕРНОЇ РЕАКЦІЇ ІЗ САМОПІДТРИМАННЯМ

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Із використанням одновимірного просторово-часового чисельного коду в умовах амбіполярності неокласичних транспортних потоків розраховані режими підпалу реакції DT-синтезу, що самопідтримується в реакторі-стелараторі. Окремо розглянуті випадки нагрівання іонного і електронного компонентів плазми. Показано, що потужності нагрівання плазми масштабу 25 МВт може бути достатньо для виведення реактора в режим стійкого горіння, що сам підтримується. Технічні та фізичні параметри такого реактора відповідають характеристикам демонстраційного реактора.
КЛЮЧОВІ СЛОВА: реактор-стеларатор, амбіполярне електричне поле, неокласика, транспортні потоки, нагрівання плазми, енергетичний баланс

О ФИЗИЧЕСКИХ ПАРАМЕТРАХ ДЕМОНСТРАЦИОННОГО РЕАКТОРА-СТЕЛЛАРАТОРА, РАБОТАЮЩЕГО В РЕЖИМЕ САМОПОДДЕРЖИВАЮЩЕЙСЯ ТЕРМОЯДЕРНОЙ РЕАКЦИИ

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С использованием одномерного пространственно-временного численного кода в условиях амбиполярности неоклассических транспортных потоков рассчитаны режимы поджига самоподдерживающейся реакции DT-синтеза в реакторе-стеллараторе. Рассмотрены случаи нагрева как ионного, так и электронного компонентов плазмы. Показано, что мощности нагрева плазмы масштаба 25 МВт может быть достаточно для вывода реактора в режим устойчивого самоподдерживающегося горения. Технические и физические параметры такого реактора соответствуют характеристикам демонстрационного реактора.
КЛЮЧЕВЫЕ СЛОВА: реактор-стелларатор, амбиполярное электрическое поле, неоклассика, транспортные потоки, энергетический баланс

Possibility of steady-state fusion reaction ignition and absence of global plasma disruptions, characteristic for tokamaks, can be considered as main properties of a stellarator determining its potentiality as a base for a fusion reactor. A stellarator possesses also some important features such as:

- Vacuum magnetic configuration providing the steady-state plasma confinement in the processes of burn phase and operating mode start-up and change;
- No pulsed thermal and power loads onto the first wall and equipment decreasing the device operating life;
- Lowering of design requirements to superconducting magnetic field systems and plasma heating systems;
- Possibility of divertor developing on the base of a natural magnetic field configuration.

Disadvantages of a classical stellarator include the complexity of a magnetic system including a toroidal field system and a helical field system. The problem was somewhat simplified by the torsatron idea, namely, to use unidirectional helical currents for creation of toroidal confining and helical magnetic fields, that was first suggested in [1] and subsequently developed in [2]. It turned out that it is possible to obtain longitudinal and helical magnetic fields using a solely system of unidirectional helical currents. A further research into simplification of the stellarator magnetic system resulted in different ideas on the modular system construction [3-6]. A modularity of the construction substantially simplifies the fabrication and maintenance of the system.

High plasma losses caused by the helical and toroidal magnetic field nonuniformity influence on the charged particle drift motion, first predicted in [7], until recent times were one of the main obstacles in developing the fusion stellarator-reactor. Therefore, earlier fusion reactor studies led to large device sizes compared to similar projects on the base of a tokamak system. A prototype reactor developed in the USSR [8] had a major torus radius R=36 m and the minor plasma radius a=1.8 m. In the German project of a HSR reactor the major torus radius was equal to 22 m for the case of a five-field-period (M=5) and to 18 m in the M=4 variant [9,10]. The Japan projects of Force-Free Helical Reactors, (FFHR), based on the LHD experimental facility in different variants give a major radius R in the 10 – 20 m range [11].

In further investigations [12-14] the plasma losses under conditions characteristic for a fusion reactor were studied in more detail. An important peculiarity of these investigations was to learn about the role of an ambipolar electric field in the transport processes. The ambipolar electric field establishes the equality of ion and electron diffusion fluxes with conservation of plasma quasi-neutrality. It has been established that there are three electric field values permitting the equality of ion and electron diffusion fluxes [4], two of them being stable. It seems that the fusion modes permitting to realize a positive sign of radial electric field [14] (electron root) are more preferable.

The fusion plasma is characterized by the relatively low frequencies of Coulomb collisions at which the transport coefficients are strongly dependent on the amplitude of magnetic field ripples ε_h produced by helical harmonics. A high plasma loss level in the traditional stellarators because of a relatively high value of ε_h has stimulated the research of magnetic configurations providing confinement properties close to these of tokamaks. These properties can be reached by a special choice of a magnetic field harmonic composition when the effective helical field ripple is appreciably decreasing. Such configurations are referred to as quasi-symmetric ones. Therefore, in recent years the designing and building of new stellarator-type fusion facilities (e.g. NCSX, W7-X and CHS) is carried out with taking into account the idea of quasi-symmetry. When designing such magnetic systems high requirements are set up for accuracy in fabrication of magnetic field coils having a complicated spatial configuration that make their production difficult. Therefore the period of W7-X construction was prolonged in time and the NCSX facility creation was stopped. Besides, the magnetic systems with a LHD-type continuous helical winding and the modular version having similar properties allows one to obtain the field with sufficiently low values of helical ripples [6,15].

At forecasting the parameters of reactors and large-scale experimental facilities it is necessary to take into account the existing correspondence between the losses predicted by the neoclassical theory and losses observed in experiments using operating facilities. Paper [16] analyses the data of comparison between the experimental results and the neoclassical theory for three stellarators: LHD, W7-AS и TJ-II. The electric field values were calculated by the DKES code using the plasma density and plasma temperature distributions experimentally observed. In the case of ECR plasma heating the electron root is realized with a low plasma density ($n<3\cdot10^{19}$m^{-3}) and the ion root – with $n>4\cdot10^{19}$m^{-3} [17]. For the central region of plasma column certain accordance between the neoclassical theory and experiment was obtained in the facilities LHD and TJ-II [18, 19].

Design works on stellarator-reactors are carried out practically in all the scientific centers where the plasma confinement in the stellarator systems is studied: Helias in Germany [10,20], series of FFHR reactors in Japan [11], ARIES–CS compact reactor project in the USA [21]. In this works one uses numerical codes considering the neoclassical transport (sometimes in combination with an anomalous one) and the ambipolar electrical field. The scalings obtained from analysis of experiments at fusion facilities are taken into account too. Although, there are many projects, it is difficult to find now these in which the steady-state fusion reaction can be realized as a result of a self-consistent solution from the coupled diffusion and heat conduction equations with given sources. In particular, the DKES code [22] is frequently used in which the spatial electric field distribution and other parameters are calculated from the given plasma density and temperature profiles. Only the transport TOTAL_P code realizes self-consistent solutions, which have been developed by T. Amano and K. Yamazaki, can be mentioned according to the available information [10]. One of the first results of this code application was density decreasing observed in the central plasma region under conditions of the reaction sustaining by fuel pellet injection.

In the previous author's paper [23] the one-dimensional space numerical code has been applied in which the system of heat conduction equations for ions and electrons, as well as, the diffusion equations with given initial and boundary conditions was used. The initial conditions were chosen so that the transition to the self-sustaining steady-state burn could occur without additional plasma heating sources. The LHD device was used as an analog for the structural model. The ambipolar electric field has been calculated from the condition of equality between the diffusion fluxes of electrons and ions. As a result, the system was self-consistently evolving to the steady state sustained by the fuel pellet injection model. It has been shown that using the fuel injection into the plasma column center it is possible to reach the self-sustaining steady-state burn in the comparatively compact reactor with major radius R=10 m, minor plasma radius a=2 m and magnetic field B=5 T. The results obtained were used to study in more detail the demonstration experiment feasibilities.

It is obvious that a necessary stage of R&D works on the problem of controlled nuclear fusion is the creation of the demonstration stellarator-reactor in order to demonstrate the self-sustaining fusion reaction of deuterium and tritium nuclei with expending costs as minimum as possible. The problem posed is not to realize an economically profitable project suitable for commercial use. Major R&D issues specific to the compact reactor include the following: the fact of demonstration of fusion burn modes and development of control methods for them. In solving this problem the technical feasibilities for the project realization and its cost are very important. In particular, the engineering factors such as sizes, magnetic field values and plasma heating source powers, as well as, structural materials and design requirements should be within the limits of realizability. Then the reactor cost is proportional to its volume. In other words, the smaller is the reactor volume the lower is its cost.

The purpose of the presented work was to reach the self-sustained burn in the reactor having sizes as small as possible with conservation of acceptable magnetic field values using low plasma heating source powers as far as possible. In the work the author uses a set of equations described in [23] with thermal neoclassical transport coefficients. There the heat conduction equation includes additionally a term taking into account the energy exchange between ion and electron plasma components due to the radial electric field action. The nonzero plasma heating sources are used too.

SYSTEM OF EQUATIONS AND NUMERICAL MODEL

The system of equations being solved includes two heat conduction equations (for electrons and ions) and the diffusion equation describing the spatial-time behavior of plasma in the stellarator-reactor. A one-dimensional space dependence of plasma parameters on the average minor plasma radius is assumed. The system of equations differs from that of [23] as the heat conduction equations for electrons (1) and ions (2) contain an additional term taking into account the particle energy change as a result of their radial motion in the electric field.

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

$$\frac{3}{2}N\frac{\partial T_i}{\partial t}=-\frac{1}{r}\frac{\partial}{\partial r}r\Pi_i+Q_{ei}+Q_{hi}-Q_{\mathrm{E}}\,, \tag{2}$$

$$\frac{\partial N}{\partial t}=-\frac{1}{r}\frac{\partial}{\partial r}rS_j+S_\delta\,. \tag{3}$$

The third equation in the system is the diffusion equation. The first term in the right-hand side of electron heat conduction equation (1) determines the temperature change provoked by the heat flux corresponding to the transport mode 1/ν in the neoclassical theory [13]. The second term in the right side describes the heating of electrons produced during the fusion by α– particles with the energy E_α=3.52 MeV. An equal deuterium and tritium content in the reactor plasma is assumed. The coefficient K_f determines the energy fraction given to electrons. It is considered that 95% of energy and α–particles goes for plasma heating, therefore in the calculations we have taken K_f =0.95. The next terms in the right-hand side of equation (1) are: Q_{he} - heating from external sources; Q_{ei} - heat exchange with ions as a result of Coulomb collisions; Q_b - bremsstrahlung; Q_c - cyclotron radiation; Q_{E} - particle energy change in the electric field due to their radial motion. When these reactor parameters are used the cyclotron radiation can transport a significant part of energy and, at the same time, it is well reflected from the chamber wall, therefore in the calculations its reflection coefficient is taken equal to 0.95. As a result, the main part of cyclotron radiation remains in the plasma and only 5% of power is absorbed by the reactor walls.

For numerical simulation we used different models of plasma heating by external sources: only the electron heating, only the ion heating or simultaneous heating of two components. It has been supposed that the specific heating power is proportional to the plasma density: $Q_{hj}=k_{hj}N$, where the subscript j denotes electrons or ions depending on the equation. The total heating power was determined by the integral through the plasma volume: $P_{hj}=\oint_V Q_{hj}dv$.

The ambipolar electric field effect on the plasma particle energy is taken into account by the quantity $Q_{\mathrm{E}}=-S_j E_r$ under conditions when the diffusion fluxes of electrons and ions are equal: S_e=S_i.

In [23] and in this paper the heat fluxes and diffusion particle fluxes determined in [13] were used. The plasma electrons were assumed to be in the regime when the diffusion coefficient had the inverse dependence on the collision frequency and the ion diffusion follows the dependence $\sqrt{\nu}$. The right-hand side of density equation (3) contains the diffusion term and the term with the source S_δ with which the plasma density has been maintained at an approximately constant level. Diffusion losses have been compensated by the model of fuel pellet injection. As is shown in earlier studies [23] from the point of view of plasma confinement the fuel injection into the central plasma column region is optimum.

The system of equations (1 - 3) was supplemented with boundary and initial conditions. It has been assumed that the spatial derivatives of density, temperature and potential in the plasma column center are equal to zero.

$$T'_{j,x=0}=0, N'_{x=0}=0\ ,\ \Phi'_{x=0}=0,\ T_{,x=1}=\delta_T, N_{x=1}=\delta_n \tag{4}$$

and the initial conditions satisfy the expressions:

$$T_{j,t=0} = T_{j,0}(1-x^n)+\delta_T, N_{j,t=0} = N_0(1-x^n)+\delta_n, \tag{5}$$

where the subscript j denotes a particle sort, x is the current plasma radius normalized to unity. In most calculations the exponent n at x in the initial conditions was taken equal to 2. The constants δ_n and δ_T determine the values of plasma density and temperature at the plasma column boundary. In these calculations they were taken equal to zero.

The electric field has been determined from the equation of equality between the ion and electron fluxes, $S_e = S_i$, at each step of space grid in the numerical code. Note, that in the general case there are three roots of the equation under consideration [14]. The calculations show that in different sections of the plasma radius there are the solutions with one and three roots simultaneously that complicates the choice of a solution which can be realized in the reactor. In [23] and in this paper it has been assumed that in all cases the electric field corresponds to the left (ion) root giving its negative values. Such a choice is not optimum from the point of view of reactor confinement properties. The more suitable might be the regime in which the electric field positive values are realized [14] (electron root), however, such solutions exist not always unlike the left (ion) root. It is logical to suppose that the reactor transition into the regime with a positive sign of ambipolar electric field will not lead to termination of the self-sustaining reaction and its power can be regulated by changing the corresponding parameters, for example, by the plasma density choice.

CALCULATION RESULTS

The present work similarly to [23] uses as a base the reactor concept providing the confining magnetic field B_0 equal to 5 T with a minor plasma radius a=2 m. The value of helical magnetic field ripple amplitude at the plasma edge ε_h has been taken 0.06. In the LHD stellarator the effective ripple at the plasma edge is 0.05 if the magnetic axis is shifted on the radius R = 3.53 m [15]. In [23] the self-sustaining burn regime has been set by the self-consistent evolution of plasma parameter profiles from the given initial conditions. The steady-state burning was successfully obtained in the reactor with R – 10 m by the fuel injection into the center of plasma column.

Here also the fuel pellet injection was simulated by the expression $\delta n = n_p(1 - r/\Delta)$ that corresponds to their "throwing" into the center of plasma having the evaporation region half-width Δ. The value Δ has been taken equal to the half plasma radius a. The fuel pellet mass contained 1% of the particle number in the reactor volume. The next fuel pellet is injected into the plasma when its density is less by 0.99 than the given value. In this case the energy losses on heating the injected particles are taken into account, and the energy losses on the pellet evaporation and atom ionization are neglected as they are comparatively small.

Unlike [23] here the fusion reaction ignition has been performed by the plasma heating starting from the relatively low temperatures. Following the results of [23] firstly the calculations have been carried out for parameters of the reactor with a major plasma radius R = 10 m. A total power of plasma heating used was varying from 20 to 80 MW. External heating sources were shut down after reaching the given fusion reaction power, then the steady-state burn was set with self-consistent spatial distributions of density, temperature and electric potential. In the case with a given average value of the plasma density independently on the initial distributions of rest parameters, the reactor reaches the ignition regime characterized by the same shape of spatial distribution of parameters and the same total fusion power.

In the process of heating and evolutionary alteration of parameters the shape of their distributions undergoes appreciable changes. Fig.1 shows the initial density and temperatures distributions with mean values $\langle N_0\rangle = 7\cdot10^{19}$ m^{-3} and $\langle T_{e0}\rangle$ = 1keV, $\langle T_{i0}\rangle$ =1.5 keV, as well as, the ambipolar electric field distribution found from the equality of electron and ion diffusion fluxes, the initial conditions being given. The high gradient and the value of the ambipolar electric field are observed at the plasma boundary. A maximum negative electric field value is 60 kV/m at relatively low electron and ion temperature values.

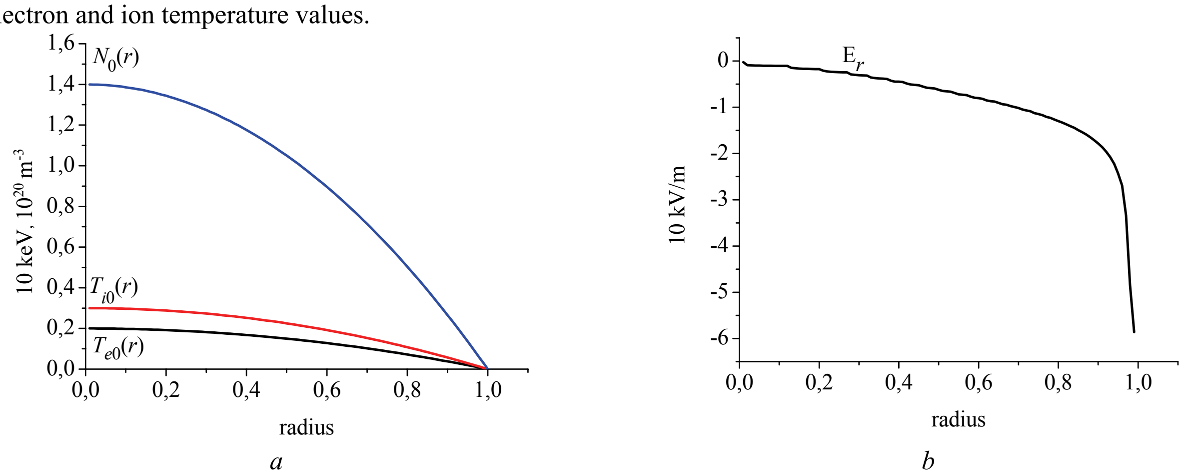


Fig.1 Initial distributions of plasma parameters
a – density, temperatures of ions and electrons, *b* – ambipolar electric field. R=10 m, a=2, B_0=5 T.

The Fig. 2 shows the behavior in time of the reactor fusion power and average values of electron and ion temperatures in the process of heating with subsequent transition to the self-sustaining burn regime. In the case under consideration the ion heating has been carried out (P_h = 40 MW). After reaching the thermal fusion power of 800 MW the heating source was shut down and the system evolved to the steady-state regime with a power of about 900 MW. It should be noted that this regime may be named as steady only conditionally because it is easy to see a slight variation with time in the temperature of both components and in the total reactor power too. Are these variations a consequence of in-reactor processes or the cause is related with the numerical code instability? It is yet not clear. Only one argument argues for internal processes: similar solutions are repeated independently on the initial conditions and heating power. By conserving the same average value of the plasma density the solutions give the same thermal power value in the steady-state burn regime.

Note also that unlike the results of [23] the reactor thermal power is significantly lower (in that case with R=10 m and $<N>=6.4\cdot10^{19}$ m^{-3} the steady-state burn was started at P_t= 1500 MW) that is a consequence of the lower ion temperature. The difference between the ion and electron temperature values is also appreciably larger then in the case published earlier. The causes of the difference will be explained below.

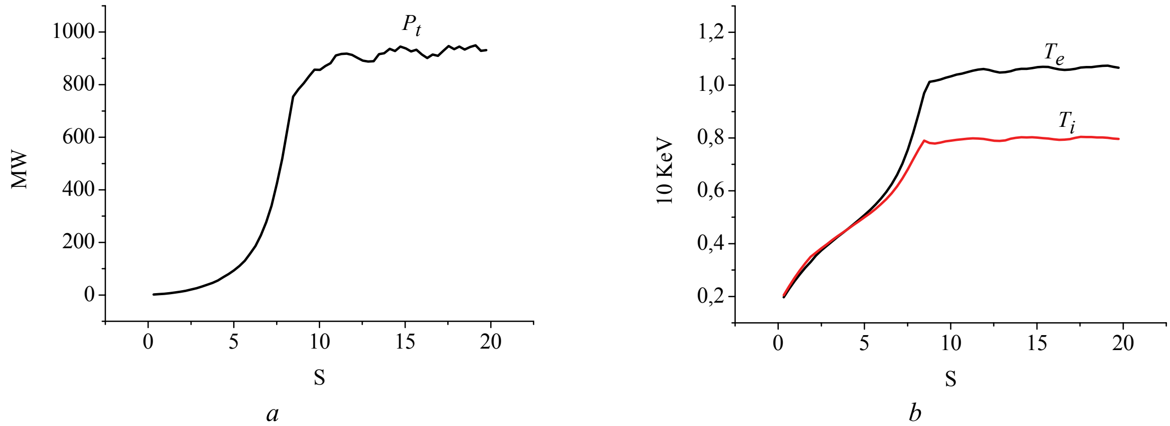


Fig. 2. Ignition process and reactor transition into the steady-state burn regime
a – reactor thermal power in time, *b* – variation of electron and ion temperatures. R=10 m, a=2 , B_0=5 T, $<N>=7\cdot10^{19}$ m^{-3}, ion heating P_h = 40 MW up to P_t =800 MW

Fig.3 illustrates the spatial distribution of the density, electric field, ion and electron temperatures of the plasma for the case of the steady-state burn. In the internal half of plasma column the plasma density considerably increases to N=6 10^{20} m^{-3} in the center. In the external radius section the plasma density decreases almost by two orders of magnitude as compared with the center of plasma. The electrical field behavior is the same as described in [23] – decreasing from zero in the center of plasma to 80 kV/m in the region of radius middle with a subsequent sharp rise to the close-to- zero values at the plasma boundary. The phenomenon of a deep minimum of radial electric field is revealed in experiments and is confirmed by calculations in installation W7-AS [16].

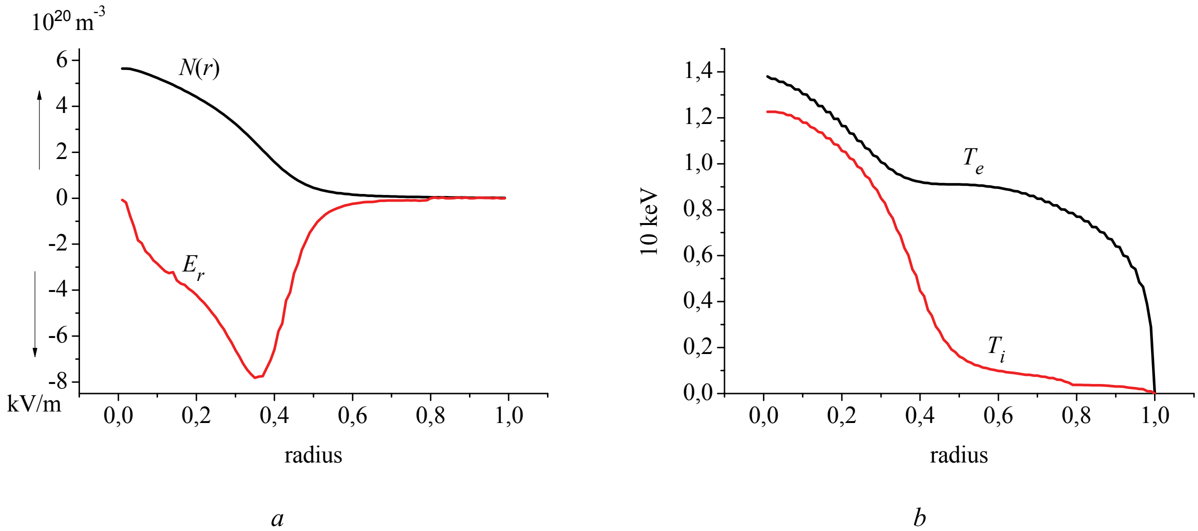
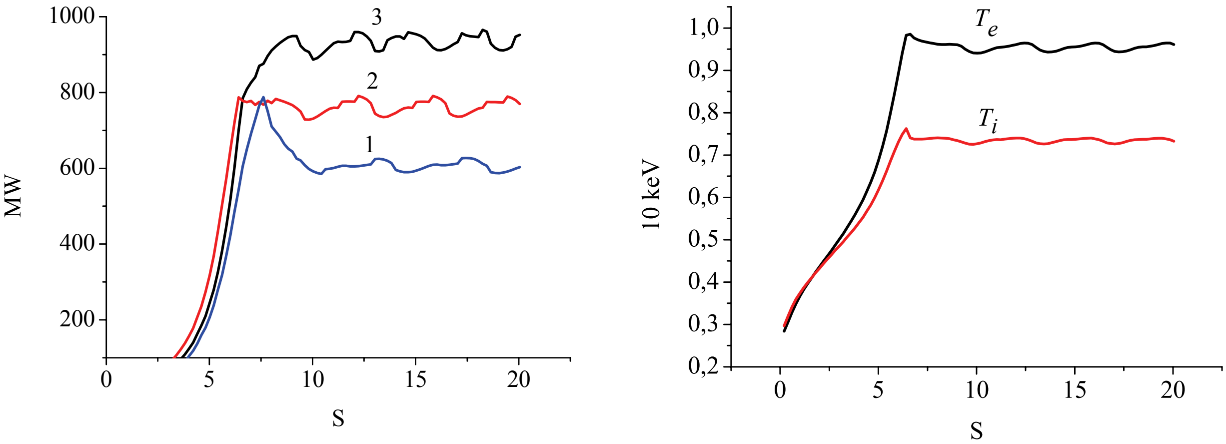


Fig.3. Spatial distribution of parameters in the steady-state burn regime
a – densities of plasma and electric field, *b* – ion and electron temperatures. R=10 m, a=2 m, B_0=5 T, $<N>=7\cdot10^{19}$ m^{-3}, ion heating P_h = 40 MW up to P_t =800 MW, t = 19.75 s.

The profiles of ion and electron temperatures are very different from these obtained in [23]. In the external half of plasma radius the ion temperature behaves similarly to the plasma density profile decreasing with a sharp gradient in the middle radius section. In the external half of plasma the electron temperature has a convex profile with a much larger value than that of ions. The difference in the spatial temperature distributions is caused by the electron-ions interaction with the radial electric field: ions, overcoming the positive potential, give up their energy to the field, and electrons, moving radially, on the contrary, take away the energy from the field. As a result, the average ion temperature is appreciably lower than the average electron temperature that leads to the thermal reactor power lowering.

The calculations confirmed that the self-sustaining reaction can be reached not only for the case with a major radius R = 10 m, but also in the reactor with R = 8 m by conserving the confining magnetic field values and minor plasma radius: B_0=5 T, a=2 m. The Fig.4 represents the fusion power variation in time in the process of ion component heating with P_h = 40 MW for three values of the average plasma density: $<N>$=0.7..; 0.75… and $0.8{\cdot}10^{20}$ m^{-3}. The figure also shows the temperature behavior in time for the case $<N>=0.75{\cdot}10^{20}$ m^{-3}. In all the cases the heating source has been shut down after reaching the fusion power of 800 MW. In the case of the plasma density $<N> = 0.8{\cdot}10^{20}$ m^{-3} the fusion power increase continues up to the level of 900 MW. When $<N> = 0.75{\cdot}10^{20}$ m^{-3}, the reactor power decreases and reaches the steady-state level of about 780 MW. An appreciable power decreasing is observed when the plasma density decreases to $<N> = 0.7{\cdot}10^{20}$ m^{-3}. In this case the thermal reactor power reaches the level of 600 MW.

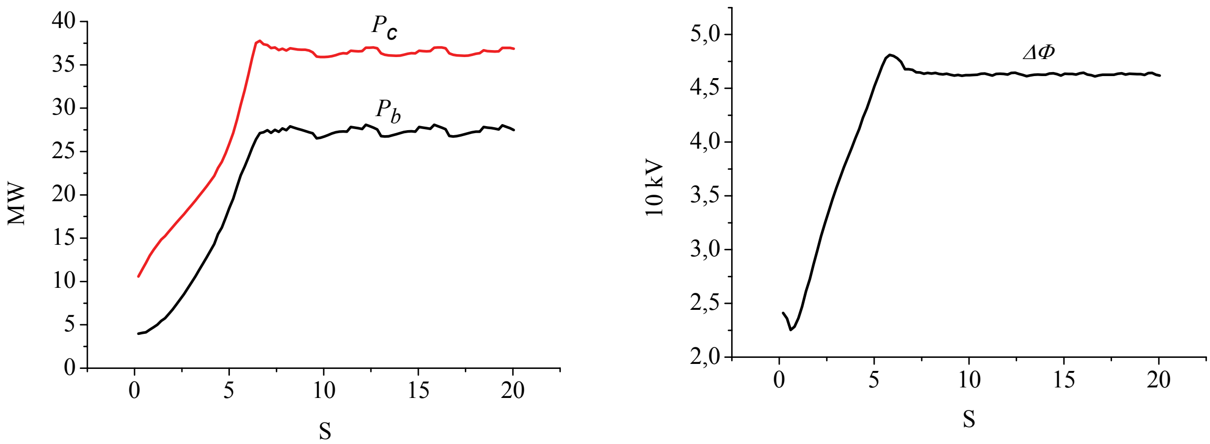


a *b*

Fig. 4. Ignition process and reactor transition into the steady-state burn regime

a – thermal reactor power in time:1 - $<N> = 7{\cdot}10^{19}$, 2 - $<N> = 7{,}5{\cdot}10^{19}$, 3 - $<N> = 8{\cdot}10^{19}$ m^{-3}; *b* – variation of electron and ion temperatures $<N> = 7.5{\cdot}10^{19}$ m^{-3}, R=8 m, a=2 m, B_0=5 T, P_{hi} = 40 MW up to P_t =800 MW.

In the case of R = 8 m the spatial distributions of plasma density, electric field, temperatures, electrons and ions are similar to the distributions given in Fig.3 for the reactor with the major radius R = 10 m. The Fig. 5 illustrates the behavior in time of the bremsstrahlung and cyclotron radiation powers in the process of plasma heating and reactor transition into the steady-state burn regime. The figure shows also the change in time of the electric potential difference between the center and the edge of the plasma for the average density $<N> = 7.5{\cdot}10^{19}$ m^{-3} and the plasma heating power P_h = 40 MW. After the reactor transition into the steady-state burn regime (t > 5 s) the potential, as well as, the rest plasma parameters are not changing.



a *b*

Fig. 5. Ignition process and reactor transition into the steady-state burn regime:

a – cyclotron radiation power - P_c and bremsstrahlung power – P_b in time ; *b* – behavior of the electric potential difference - $\Delta\Phi$ between the center and edge of the plasma. $<N> = 7.5{\cdot}10^{19}$ m^{-3}. R=8 m, a=2 m , B_0=5 T, P_{hi} = 40 MW up to P_t =800 MW.

In the reactor with a power of 800 MW no more than 160 MW is released due to the α– particle energy absorption in the plasma. As a result of bremsstrahlung and cyclotron radiations the power losses are 65 MW that makes more than one third of all the power lost by the plasma. But, in the problem the impurity losses are not taken into account and, in particular, one should consider the loss increase provoked by the bremsstrahlung due to the presence in the plasma of some fraction of α– particles. Besides, in the problem it is assumed that only 5% of cyclotron irradiation is taken up by the first reactor wall, and the rest 95% are absorbed in the plasma. An appreciable decrease in the coefficient of cyclotron radiation can complicate the problem of obtaining steady-state burn regimes.

The energy loss increasing along the bremsstrahlung channel due to the α– particle presence in the plasma will be evaluated using the following considerations. Denote the α– particle lifetime in the plasma by the symbol τ_α. A number of α– particles produced in the process of fusion in time τ_α is easily determined using the division of the total reactor power by the energy of one fusion event with the multiplication by the α– particle confinement time

$$N_\alpha = P_t \tau_\alpha / E_f, \tag{6}$$

where E_f is the energy released as a result of one fusion event. And the relative α– particle fraction is the result of number N_α division by the total number of plasma ions. Such an evaluation for the reactor with R = 8 m, average density $\langle N\rangle = 7.5\cdot10^{19}$ m^{-3} and thermal power P_t=800 MW gives for the α– particle fraction

$$\eta_\alpha = N_\alpha \tau_\alpha / \langle N\rangle V = 6.2\cdot10^{-3}\ \tau_\alpha,$$

where V is the plasma volume. It may be assumed that the order of α– particle diffusion is comparable with the main diffusion order. If the particle lifetime is approximately 3 s, a possible fraction of α– particles will be about 2% and their influence on the bremsstrahlung loss value will be, probably, insignificant.

The Fig. 6 presents the spatial distribution of the specific fusion power P_f and the quantity β determining the ratio of gas-kinetic and magnetic pressures. Also, in the figure shown is the time dependence of the pellet number that allows one to determine the particle loss rate and. consequently, to determine their confinement time. Note the high level of the quantity β in the plasma center (about 25%) despite a relatively low level of its average value. The dependences under consideration are the result of relatively sharp plasma density and temperature profiles. The same spatial distributions of β and specific fusion power were observed in [23] too.

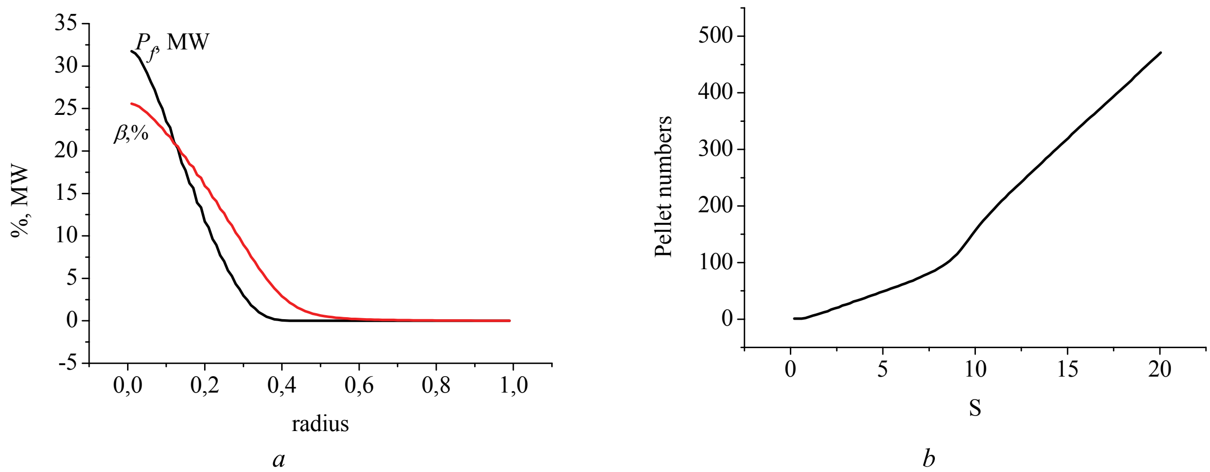
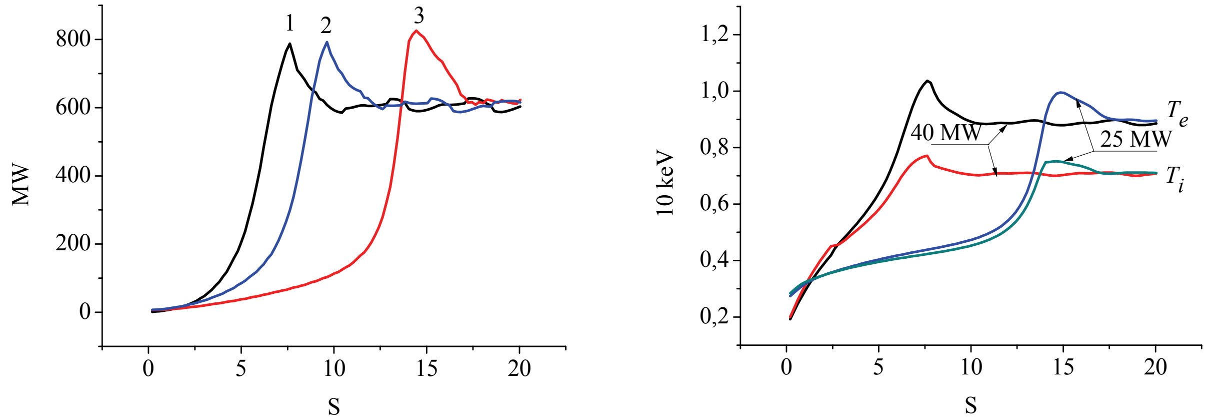


Fig. 6. Spatial distributions of specific fusion power and β values, and the time dependence of the pellet number
a – specific fusion power - P_f and quantity β in percents; *b* – increase of the pellet number in time. $\langle N\rangle = 7.5\cdot10^{19}$ m^{-3}. R=8 m, a=2 m, B_0=5 T, P_{hi} = 40 MW up to P_t =800 MW

The Fig. 2-6 illustrate the ignition and steady-state burn regimes in the stellarator-reactor for the heating power P_h = 40 MW. The calculations for other heating powers have shown that the self-sustaining fusion reaction can be reached with lower fusion powers. The Fig. 7 shows the fusion power behavior in the process of plasma heating using three power values from three heating sources - 40, 30 and 25 MW, as well as, the ion and electron temperature variations in time by injecting 40 and 25 MW into the plasma.

The use of a 40 MW heating power allows one to reach a 800 MW thermal fusion power in 7.5 s after the heating startup, and then the reactor turns into the steady-state regime of the self-sustaining reaction. In the case of 25 MW heating power the reactor reaches the 800 MW power level approximately in 14 s after the heating startup. When lower powers have been used, the reactor transition into the self-sustaining burn regime was not achieved. Note that independently on the P_h value, having other parameters conserved, the reactor goes to the fusion power level with like distributions of spatial density, electric field and plasma component temperatures.



a *b*

Fig. 7. Time dependences of the total thermal reactor power and of the plasma temperature calculated for different values of plasma heating power - P_h; *a* – thermal power behavior: 1- P_{hi} = 40 MW, 2 - 30 MW, 3 – 25 MW; *b* – time dependence of the temperature for two values of P_{hi} – 40 and 25 MW. Ion heating up to 800 MW with subsequent shut down of the heating source. $<N> = 7\cdot10^{19}$ m^{-3}, R=8 m, a=2 m, B_0=5 T.

DISCUSSION AND CONCLUSION

The table presents the result of reactor parameter calculations for two values of the major torus radius R = 10 m and R = 8 m, and the parameters of the demonstration reactor of the DEMO-C tokamak are given too [24]. The minor plasma radius, magnetic field and amplitude of helical magnetic field distortion in all the stellarator-reactor variants were unchangeable. The average plasma density for the case R = 10 m was taken equal to $7\cdot10^{19}$ m^{-3}, and for R = 8 m the density was changing from $7\cdot10^{19}$ to $8\cdot10^{19}$ m^{3}. All the rest parameters are the consequence of the self-consistent solution of the system of equations (1-3) with a given initial and boundary conditions determined by expressions (4, 5).

Table

Reactor parameters

	RSt-1	DSt-2	DSt-3	DSt-4	DEMO-C [24]
Confining magnetic field –B, T	5	5	5	5	7.7
Major torus radius – R, m	10	8	8	8	7.8
Minor plasma radius – a, m	2	2	2	2	1.5
Mean density – $<N>$,10^{20}/m^3	0.7	0.7	0.75	0.8	1.55
Electron temperature – T_e, keV	10.7	8.8	9.5	10.1	21
Ion temperature – T_i , keV	8	7.1	7.3	7.6	23
Helical ripple at the plasma boundary–ε_{hmax}	0.06	0.06	0.06	0.06	0
Total thermal power – P_t, MW	920	600	780	900	2400
Load onto the wall – Q_W, MW/m^2	1.15	0.94	1.22	1.4	2.5/3.4
Plasma pressure – $<\beta>$, %	2.1	1.7	2.2	2.26	4.6
Energy confinement time – τ_E, s	1.33	1.4	1.24	1.16	2.1
Particle confinement time – τ_n, s	3.1	3.3	2.8	2.44	[1)]

Note a distinct difference in the reactor temperature and power from the results of [23] for the variant of a reactor with a major radius R = 10 m. Consideration of the radial electric field has led to the appearance of a significant difference in the ion and electron temperatures in the external plasma region. The average ion temperature was approximately by 2 keV lower as compared to the electron temperature. As a result, the reactor power was decreased. Nevertheless, the regime of self-sustaining burn was conserved.

In the tokamak reactor the major radius is sufficiently close to the torus radius dimension of the stellarator-reactor in the variant with R=8 m. The minor plasma radius in the tokamak is distinctly less (a=1.5 m against 2 m in the stellarator), however, its decrease is compensated by the significant increase of the magnetic field induction from 5 T to 7.7 T. The paper [24] does not contain information how have been obtained the plasma-physical parameters of the demonstration tokamak reactor. Note that the plasma temperature and density values in the tokamak reactor are several times higher than the corresponding values in the stellarator-reactor. As a result, the average value of β in the tokamak reactor is more than twice higher than in the stellarator-reactor despite the higher value of the confining magnetic field.

[1] The time of particle confinement is unknown.

Taking into account that the plasma temperature and density distributions have a maximum in the center of plasma, the local values of β here can reach several tens of percents and, consequently, there is a problem of a steady-state operation in such regimes. The local values of β for the case of the stellarator-reactor are shown in Fig.6 where β_{max}=25%. So, the problem of β values is common for both reactor types.

The present work shows a possibility for the reactor to reach a self-sustaining burn regime using a comparatively low (25 MW) power of the heating sources. Note, that in the DEMO-C project it is planned to use the plasma heating sources with a power up to 110 MW [24]. And at the same time the reactor in any case will not operate in the regime of self-sustaining reaction. Also here is shown the opportunity to control the reactor power by varying the plasma density. When the average plasma density is changing from $7\cdot10^{19}$ m^3 to $8\cdot10^{20}$ m^{-3} the reactor power increases by a factor of 1.5. At the same time, the fusion reaction ignition in the stellarator-reactor occurs with a much lower value of the confining magnetic field and, consequently, under conditions being less stressed in the view of engineering problems. And so, the demonstration stellarator-reactor seems more preferred than the tokamak reactor.

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