УДК 621.039.623

EFFECT OF COLD ALPHA-PARTICLE REMOVAL AND FUELING SCENARIOS ON POWER AND PARTICLE BALANCE IN FUSION PLASMA

A.V. Eremin[1], A.A. Shishkin[1,2]
[1]*Kharkiv V.N. Karazin National University, Kharkiv-77, UKRAINE,*
[2]*Institute of Plasma Physics, National Science Center "Kharkiv Institute of Physics and Technology", Kharkiv-108, UKRAINE*
Received July 20, 2007

Evolution in time of the plasma density, temperature and thermal alpha-particle density is considered under modeling of the helium ash removal. It is shown that slow changing in time of the helium ash density can be used for the operation path changing in fusion DT plasma. There is considered also the effect of different scenarios of fueling rates on the plasma operation path and steady state parameters. The temporal evolutions of the operating point during the ignition access and ignited operation phases are analyzed analytically and numerically. The main target of the study is the optimization of the plasma operation scenario in future fusion reactors including ITER.
KEY WORDS: fusion plasma, ignition and confinement, alpha-particles, time evolution, alpha-particle removal, fuel rates scenarios, ITER

Achieving the fusion power in Joint European Torus (JET) tokamak in the operation with the deuterium and tritium mixture plasma and the possible next step in the controlled fusion device International Tokamak Experimental Reactor (ITER) stimulate the further study of the fusion plasma in a toroidal magnetic trap of the reactor scale. Among many problems there is an unsolved problem about the role of helium ash in power and particle balance of fusion plasma [1-2]. The effect of the removal of the helium ash on the achieving of the steady state and plasma parameters in steady state is considered. The removal of helium ash taking into account the rule of the helium ash confinement time changing during the plasma discharge is modeled. The confinement time τ_E is supposed to be not constant but is a harmonic function of the time.

SYSTEM OF THE BALANCE EQUATIONS

Initial equations

The following set of equations is used to describe the temporal evolution of plasma parameters averaged over the volume: density of deuterium ions $\overline{n}_D(x)$, density of tritium ions $\overline{n}_T(x)$, density of thermal alpha-particles $\overline{n}_\alpha(x)$, plasma energy $\overline{W}(x)$ and density of the impurity ions $\overline{n}_Z(x)$ with the charge number Z:

$$\frac{d\overline{n}_D(x)}{dt} = S_D - \overline{n}_D(x)\overline{n}_T(x)\langle\sigma\upsilon\rangle_{DT}(x) - \frac{\overline{n}_D(x)}{\tau_p}, \tag{1}$$

$$\frac{d\overline{n}_T(x)}{dt} = S_T - \overline{n}_D(x)\overline{n}_T(x)\langle\sigma\upsilon\rangle_{DT}(x) - \frac{\overline{n}_T(x)}{\tau_p}, \tag{2}$$

$$\frac{d\overline{n}_\alpha(x)}{dt} = \overline{n}_D(x)\overline{n}_T(x)\langle\sigma\upsilon\rangle_{DT}(x) - \frac{\overline{n}_\alpha(x)}{\tau_\alpha}, \tag{3}$$

$$\frac{d\overline{W}(x)}{dt} = \frac{P_{ext}}{V} + P_{oh} + P_\alpha - P_{loss} - P_{brems} - P_{sync}, \tag{4}$$

$$\frac{d\overline{n}_Z(x)}{dt} = S_{imp\,Z} - S_{Z-1}\overline{n}_{Z-1} - (\alpha_Z + S_Z)\overline{n}_Z(x) + \alpha_{Z+1}\overline{n}_{Z+1} - \frac{\overline{n}_Z(x)}{\tau_Z}. \tag{5}$$

Here $x = \dfrac{r}{a_{pl}}$ is the dimensionless radial variable and a_{pl} is the plasma radius, bars denote the averaging over the volume; S_D and S_T are the source terms which give us the fuel rates, τ_α, τ_p and τ_Z are the particle life times: the deuterium and tritium (τ_p), thermal alpha-particle (τ_α) and impurity ion (τ_Z). P_{ext} is the external heating power, V is the plasma volume, P_{oh} is the density of ohmic heating power, P_α is the power density released in the form of charged particles, P_{loss} is the plasma conduction loss power density, P_{brems} is the bremsstrahlung power density, P_{sync} is the power density of the synchrotron radiation; S_{impZ} is the impurity ion source, α_{Z-1} and α_Z are the recombination rates,

S_{Z-1} and S_Z are the ionization rates. Here only one specie of impurity ions is taken into account but the system of equations can be generalized to the case of several species of impurities.

Transformations of the equations of plasma density, plasma temperature, t hermal alpha-particle and impurity ion density

Plasma Density

If the plasma density $\overline{n}_e(x)$ is induced as

$$\overline{n}_e(x) = \overline{n}_D(x) + \overline{n}_T(x) + 2\overline{n}_\alpha(x) + Z\overline{n}_Z(x), \tag{6}$$

then the equation of the evolution of the plasma density after the substituting of (1)-(3) takes the following form

$$\frac{d\overline{n}_e(x)}{dt} = S_{DT} - \frac{\overline{n}_D(x) + \overline{n}_T(x)}{\tau_p} - 2\frac{\overline{n}_\alpha(x)}{\tau_\alpha} + Z\frac{d\overline{n}_Z(x)}{dt}, \tag{7}$$

where $S_{DT}=S_D+S_T$.

Density of thermal alpha-particles

If the plasma energy density is taken in the form

$$\overline{W}(x) = \frac{3}{2}\left[\overline{n}_e(x)\overline{T}_e(x) + \left(\overline{n}_D(x) + \overline{n}_T(x) + \overline{n}_\alpha(x)\right)\overline{T}_i(x) + \overline{n}_Z(x)\overline{T}_Z(x)\right], \tag{8}$$

then the derivative in time becomes

$$\begin{aligned}\frac{d\overline{W}(x)}{dt} = \frac{3}{2}\overline{T}_i(x)&\left[\left(1+\frac{1}{\gamma_e}\right)\frac{d\overline{n}_e(x)}{dt} - \frac{d\overline{n}_\alpha(x)}{dt} + \left(\frac{1}{\gamma_Z} - Z\right)\frac{d\overline{n}_Z(x)}{dt}\right] \\ &+ \frac{3}{2}\frac{d\overline{T}_i(x)}{dt}\left(\left(1+\frac{1}{\gamma_e}\right)\overline{n}_e(x) - \overline{n}_\alpha(x) + \left(\frac{1}{\gamma_Z} - Z\right)\overline{n}_Z(x)\right),\end{aligned} \tag{9}$$

where $\gamma_e = \frac{\overline{T}_i(x)}{\overline{T}_e(x)}$ and $\gamma_Z = \frac{\overline{T}_i(x)}{\overline{T}_Z(x)}$. If the following parameters are induced

$$f_D = \frac{\overline{n}_D(x)}{\overline{n}_e(x)}, \qquad f_T = \frac{\overline{n}_T(x)}{\overline{n}_e(x)}, \quad f_\alpha = \frac{\overline{n}_\alpha(x)}{\overline{n}_e(x)}, \quad f_Z = \frac{\overline{n}_Z(x)}{\overline{n}_e(x)}, \tag{10}$$

then the equation for the evolution of the plasma temperature takes the following form

$$\begin{aligned}\frac{d\overline{T}_i(x)}{dt} = &\frac{1}{\frac{3}{2}\left(1+\frac{1}{\gamma_e} + f_Z(\frac{1}{\gamma_Z} - Z) - f_\alpha\right)\overline{n}_e(x)}\left(\frac{P_{ext}}{V} + P_{oh} + P_\alpha - P_{loss} - P_{brems} - P_{sync}\right) - \\ &- \frac{\overline{T}_i}{\frac{3}{2}\left(1+\frac{1}{\gamma_e} + f_Z(\frac{1}{\gamma_Z} - Z) - f_\alpha\right)\overline{n}_e(x)}\left[(1+\frac{1}{\gamma_e})\frac{d\overline{n}_e(x)}{dt} + (\frac{1}{\gamma_Z} - Z)\frac{d\overline{n}_Z}{dt} - \frac{d\overline{n}_\alpha(x)}{dt}\right].\end{aligned} \tag{11}$$

About the plasma parameter profiles assumption

The plasma parameter profiles after averaging over the radial coordinate are assumed [1, 2] as

$$\overline{T}_i(x) = \frac{T_i(0)}{1+\alpha_T}, \; \overline{n}_e(x) = \frac{n_e(0)}{1+\alpha_n}, \; \overline{n}_\alpha(x) = \frac{n_\alpha(0)}{1+\alpha_n}. \tag{12}$$

In our further calculations we use profile parameters $\alpha_n = 0.5$ and $\alpha_T = 1$.

System of equations for the plasma parameters evolution in the center of confinement volume

Under the assumptions about the profiles the equations for the plasma parameters $n_e(0)$, $T_i(0)$, and the thermal alpha-particle fraction $f_\alpha(0)$ in the center of confinement volume transform to the following form

$$\frac{dn_e(0)}{dt} = S_{DT}(1+\alpha_n) - n_e(0)\left(\frac{f_D(0) + f_T(0)}{\tau_p} + 2\frac{f_\alpha(0)}{\tau_\alpha}\right) + Z\frac{d\overline{n}_Z(x)}{dt}(1+\alpha_n), \tag{13}$$

$$\frac{df_\alpha(0)}{dt} = n_e(0)\frac{f_D(0)f_T(0)}{1+\alpha_n}\langle\sigma\upsilon\rangle_{DT} - f_\alpha(0)\left(\frac{1}{\tau_\alpha}+\frac{1}{n_e}\frac{dn_e(0)}{dt}\right), \tag{14}$$

$$\frac{dT_i(0)}{dt} = \frac{(1+\alpha_n)(1+\alpha_T)}{\frac{3}{2}\left(1+\frac{1}{\gamma_e}+f_Z(\frac{1}{\gamma_Z}-Z)-f_\alpha(0)\right)n_e(0)}\left(\frac{P_{ext}}{V}+P_{oh}+P_\alpha-P_{loss}-P_{brems}-P_{sync}\right)-$$
$$-\frac{T_i(0)}{\left(1+\frac{1}{\gamma_e}+f_Z(\frac{1}{\gamma_Z}-Z)-f_\alpha(0)\right)n_e(0)}\left[(1+\frac{1}{\gamma})\frac{dn_e(0)}{dt}-\frac{df_\alpha(0)}{dt}+(\frac{1}{\gamma_Z}-Z)(1+\alpha_n)\frac{d\overline{n}_Z(x)}{dt}\right], \tag{15}$$

Equation (6) transforms into the following one:

$$\overline{f}_D(x)+\overline{f}_T(x)+2\overline{f}_\alpha(x)+Z\overline{f}_Z(x)=1. \tag{16}$$

Now it is possible to compare this system of equations (13) – (15) with the analogous system of the evolution equations in [1]. The difference is as the follows. We take into account impurities density $\overline{n}_Z$ in the charge neutrality condition, which implies to Z_{eff}, alpha particles fraction. The fraction $f_\alpha(0)$ enters in the different way, which leads to different view of the plasma energy balance equation. This is the consequence of the different form of $\overline{W}$ taken here. We take the contribution of thermal alpha-particles into account in (8). We do not multiply the derivative $\frac{df_\alpha}{dt}$ by the coefficient 2; the magnitude $f_\alpha(0)$ is present in the denominator of the expressions in the right hand side of the equation (15) for the evolution of the plasma temperature T_i. If there is the removal of thermal alpha particles (in this case $\frac{df_\alpha}{dt}<0$), then their contribution should lead to decrease of the temperature T_i. However at the same time decrease of f_α should cause the increase of the T_i, because of its presence in the denominator. So we can conclude that there are two competitive mechanisms and it is necessary to find the "operating windows" within which the removal of thermal alpha particles is favorable for the achieving the ignition boundary.

In the following calculations we omit the terms proportional to $\frac{d\overline{n}_Z}{dt}$. Impurity ion density enters as parameter in bremsstrahlung power (see Eq. 21). In our calculations we take f_Z equal to 1%.

MODELS OF FUSION PRODUCT RATE, RADIATION AND TRANSPORT LOSSES

For the further analysis we chose the following models for alpha-particle power input and the radiation and transport losses.

The reaction rate is used in the following form [2]:

$$\langle\sigma\upsilon\rangle_{DT} = 2.57\cdot10^{-18}\frac{1}{T^{2/3}U^{5/6}}\exp\left(-\frac{19.98\ U^{\frac{1}{3}}}{T^{1/3}}\right)\ [\frac{m^3}{\sec}], \tag{17}$$

where

$$U = 1-T_i(0.02507+T_i(0.00258-0.0000619T_i))/(1+T_i(0.066+0.00812T_i)). \tag{18}$$

There is used also the following expression for thermal reaction rate [3]:

$$\langle\sigma\upsilon\rangle_{DT} = 3.68\cdot10^{-18}\frac{1}{T^{2/3}}\exp\left(-\frac{19.94}{T^{1/3}}\right)\ [\frac{m^3}{\sec}], \tag{19}$$

where temperature T is measured in [keV]. The plot of $<\sigma\upsilon>_{DT}$ versus of ion temperature is shown in Fig. 1. Curve (1) is calculated accordingly to Eq. (17), curve (2) is calculated accordingly to Eq. (19). We can see the difference between these two plots, which implies to density dependence on temperature shown below. In smaller temperatures region we have greater values of fusion product rate for U dependent type of $<\sigma\upsilon>_{DT}$. But with temperature increasing we get less rapidly growth law of thermal reaction rate for DT fusion. For temperature values about 30 keV we get equal values of thermal reaction rate coefficients for both $<\sigma\upsilon>_{DT}$ dependences, no matter with or without taking into account function $U(T)$. We have to note that increasing ion temperature from 10keV to 30keV we get strong growing of thermal reaction rate. As a result of it we can get more than 10 times increase of fusion product densities, which leads to proportional increasing of fusion energy released in DT reaction.

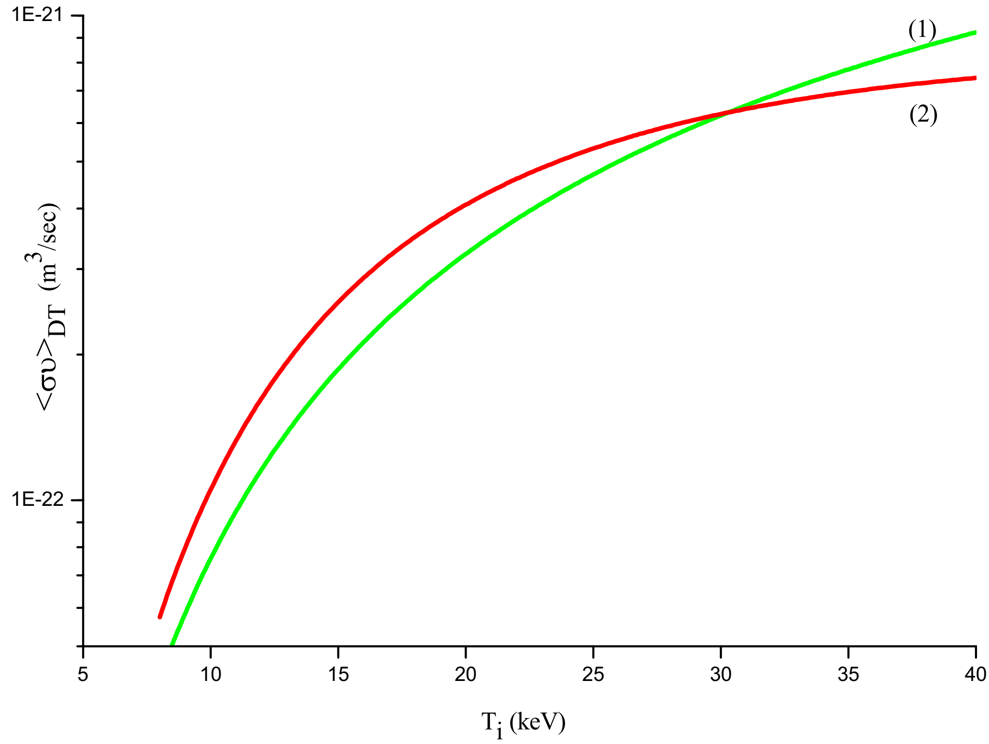


Fig. 1. Reaction rate $<\sigma\upsilon>_{DT}$ as a function of ion temperature T_i : (1) - U(T) = 1, (2) - U(T)

Let's make some estimation for energies releasing and outgoing from plasma volume during ignition and ignited operation. We will have alpha heating power due to fusion reactions in plasma volume. It basically depends on plasma density and reaction rate $<\sigma\upsilon>_{DT}$. Bremsstrahlung energy losses due plasma electrons collisions with ions mainly depend on plasma density and effective charge number. Plasma conduction losses power depend on temperature and has a strong inversely dependence on effective energy confinement time. $P_{incoming}$ is the sum of all incoming powers, like fusion power, auxiliary heating power.

Alpha-particle power is calculated according to the following expression:

$$P_\alpha = 5.6 \cdot 10^{-13} n(0)^2 \; f_D f_T \langle \sigma\upsilon \rangle_{DT} \;\; [\frac{W}{m^3}], \tag{20}$$

bremsstrahlung power P_{brems} is given as following:

$$P_{brems} = 5.4 \cdot 10^{-37} Z_{eff} n(0)^2 \, \sqrt{T_e(0)} \;\; [\frac{W}{m^3}], \tag{21}$$

here we calculate effective charge state as follows

$$Z_{eff} = \frac{1}{n(0)} \sum\nolimits_Z n_Z(0) Z^2 , \tag{22}$$

the plasma conduction loss power P_{loss} is given as following:

$$P_{loss} = \frac{3}{2} \cdot 1.6 \cdot 10^{-19} n(0) T(0) (1 + f_D + f_T) / \tau_E \;\; [\frac{W}{m^3}], \tag{23}$$

where temperature $T_{i,e}(0)$ is measured in units [keV], density $n(0)$ in [m^{-3}].

Thermal reaction rate $<\sigma\upsilon>_{DT}$ is a key parameter which defines fusion power density released in high temperature DT plasma. There is a minimum on U(T) function, as a result of which we have inflection on alpha particles energy dependence curve.

Here we can see simple dependence between effective energy confinement time and conductive losses in fusion plasma. The greater τ_E we have, the smaller conductive losses power density in plasma. As a result of it we get better confinement of energy in fusion plasma volume.

Bremsstrahlung losses from plasma are more than twenty times smaller than conductive losses in non dusty plasma with effective charge number up to 5. But with increasing of effective charge number, means presence of heavy, high charge state impurity in plasma, we will get rapid increase of bremsstrahlung power density.

We have second power dependence of effective charge number on bremsstrahlung power losses, means that introduction impurities with Z about 10 leads to about hundred times increasing of bremsstrahlung power losses.

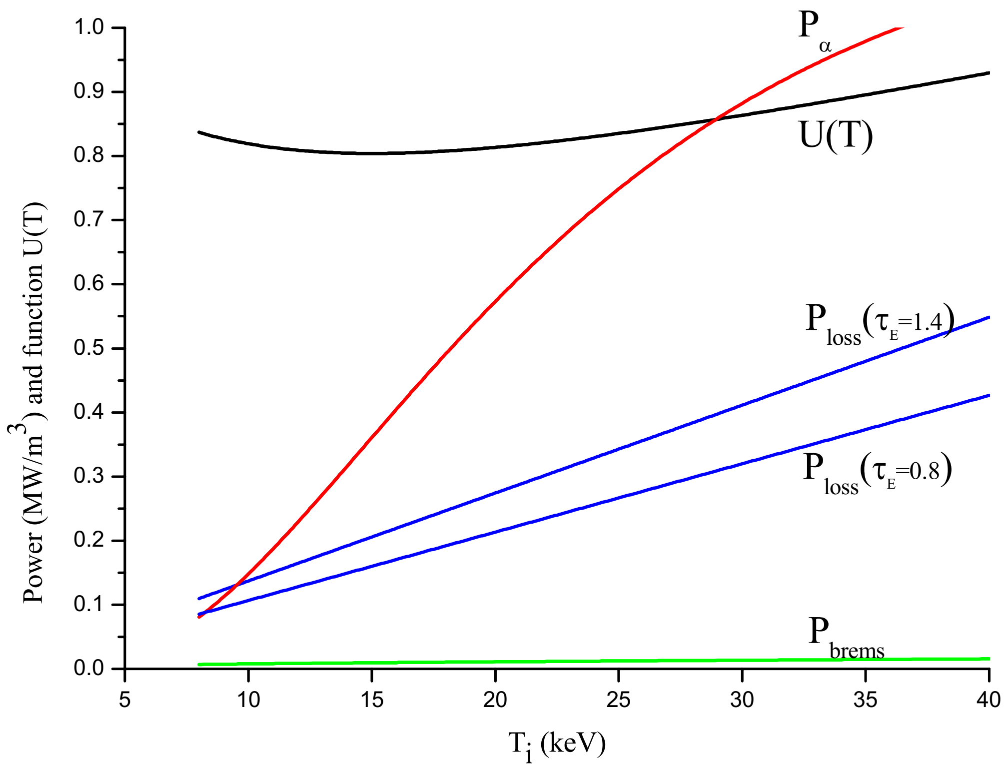


Fig. 2. Alpha heating power (P_α), function U(T) and power losses: bremsstrahlung losses (P_{brems}) and conduction losses (P_{loss}) for two different values of energy confinement time τ_E

Confinement time τ_E can be estimated by ITER98P scaling

$$\tau_E^{\mathrm{ITER98P}} = 0.0365 * M^{0.2} I_p^{0.97} R^{1.93} (a/R)^{0.23} k^{0.67}_{elongation} (n_0 \cdot 10^{-19})^{0.41} B_t^{0.08} P_{heat}^{-0.63}, \tag{24}$$

where M is measured in atom mass units, plasma current I_p - in MA, major plasma radius R - in meters, $k_{elongation}$ - plasma elongation, plasma density n in m^{-3}, magnetic field in Tesla, P_{heat} external heating in MW. In our calculations we take τ_E equal to 1.8 sec [1].

The next expression for energy confinement time is used for investigation of temporal evolution with time dependent law for helium ash removal [7]:

$$\tau_\alpha = 0.75 + \frac{0.4}{\pi} \sum_{j=2n}^{\infty} \frac{j}{j^2 - 1} \sin j\omega t, \tag{25}$$

where ω=0.27.

STEADY STATE EQUATIONS

There are three equations which describe the steady state:

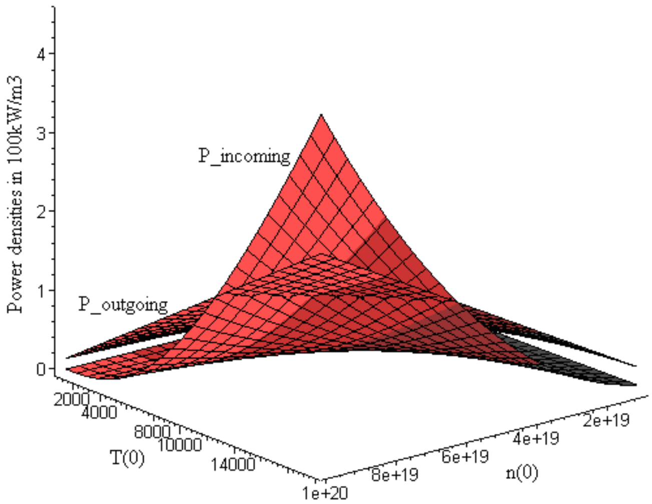
$$S_{DT}(1+\alpha_n) - n_e(0)\left(\frac{f_D(0)+f_T(0)}{\tau_p} - 2\frac{f_\alpha(0)}{\tau_\alpha} \right) + Z\frac{d\overline{n}_Z(x)}{dt}(1+\alpha_n) = 0, \tag{26}$$

$$n_e(0)\frac{f_D(0) f_T(0)}{1+\alpha_n}\langle \sigma \upsilon \rangle_{DT} - \frac{f_\alpha(0)}{\tau_\alpha} = 0, \tag{27}$$

$$\frac{P_{ext}}{V} + P_{oh} + P_\alpha - P_{loss} - P_{brems} - P_{sync} = 0. \tag{28}$$

If the right hand side of the equation (4) is put equal to zero then the equation of the plasma ignition (28) is obtained. This equation set give the dependence of plasma density $n_e(0)$ versus plasma temperature $T_i(0)$.

$P_{outgoing}$ respectively is the sum of all energies outgoing from plasma volume, such as bremsstrahlung power losses, conduction losses, synchrotron losses. If we take into account the alpha-particle power P_α, the plasma conduction loss power P_{loss}, the bremsstrahlung power P_{brems}, then plasma operation contour takes the form shown in Fig. 3. Here we neglect the synchrotron radiation power P_{sync}. These curves are usually named as plasma operation contour (POPCON) [1, 2, 4, 5]. The plots in Fig. 3 are given for the external heating power P_{ext} and the ohmic heating power P_{oh} equal zero. That planes crossing in n-T view show us plasma operation contour (POPCON).



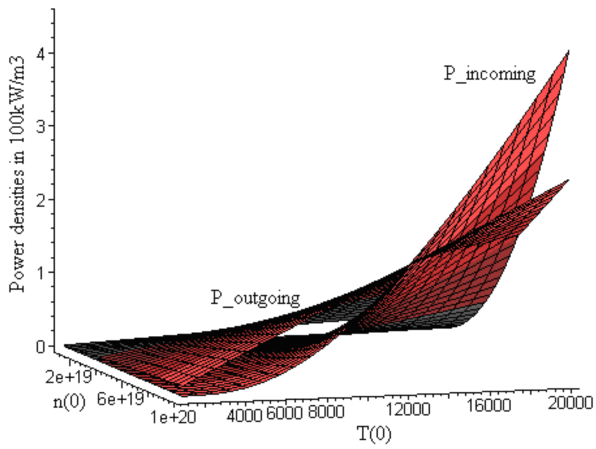


Fig. 3. Dependence of incoming and outgoing power densities (100kW\m^3) in plasma on temperature and plasma density

In Fig. 4 the fraction of cold helium ash is taken as a parameter and we see the difference in the ignition boundary under the different f_α values. The smaller f_α the easier ignition is obtainable.

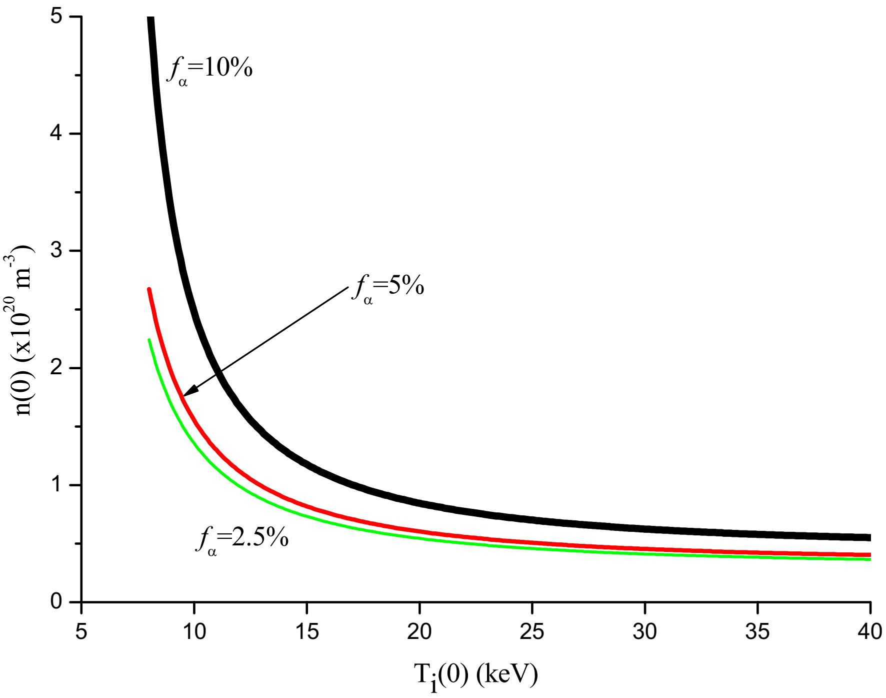


Fig. 4. Plasma density dependence on temperature for different helium ash fractions, for plasma operation contour

IGNITION BOUNDARY AND PLASMA OPERATION PATHS WITHOUT AND UNDER THE ALPHA-PARTICLE REMOVAL

In present paper, we obtain dependence of plasma ignition boundary from plasma parameters: density, temperature, fraction of alpha-particles, and operation path (plasma parameters $n_e(0)$ and $T_i(0)$ evolution in time) for different ignition regimes. The careful control of the plasma density by fuelling S_{DT} is necessary. Real time measurements of plasma density and ion temperature during the heating phase are needed to get the desirable operating point on the n-T plane (POPCON). The thermally stable ignition regime can be reached by control of alpha particles fraction f_α and plasma ion temperature T_i. If the helium ash confinement time changes, then the helium ash density and plasma density changes together. Without diagnostics which plasma parameters, like helium ash fraction or energy confinement time, are changed during ignition and ignited operation it's easier to operate plasma ignition path by the feedback control of heating power and fuelling of deuterium and tritium by monitoring fusion power. It also possible to control the ignition process by changing Z_{eff} in plasma, by injection of impurity pellet, leading to increasing bremsstrahlung power losses P_{brems} and slower plasma temperature increasing during ignition.

Let's take a look on plasma operation path with and without helium ash removal. Figures 5 (a, c) and 6 (a, c) present temporal evolution of plasma density (in 10^{20} m^{-3}), alpha ash fraction f_α (in tens of percents) and plasma temperature T_i (tens of keV) for different fueling scenarios. Figures 5 (b, d) and 6 (b, d) correspondingly present temporal evolution of the same plasma parameters when the alpha ash removal is present in operation volume.

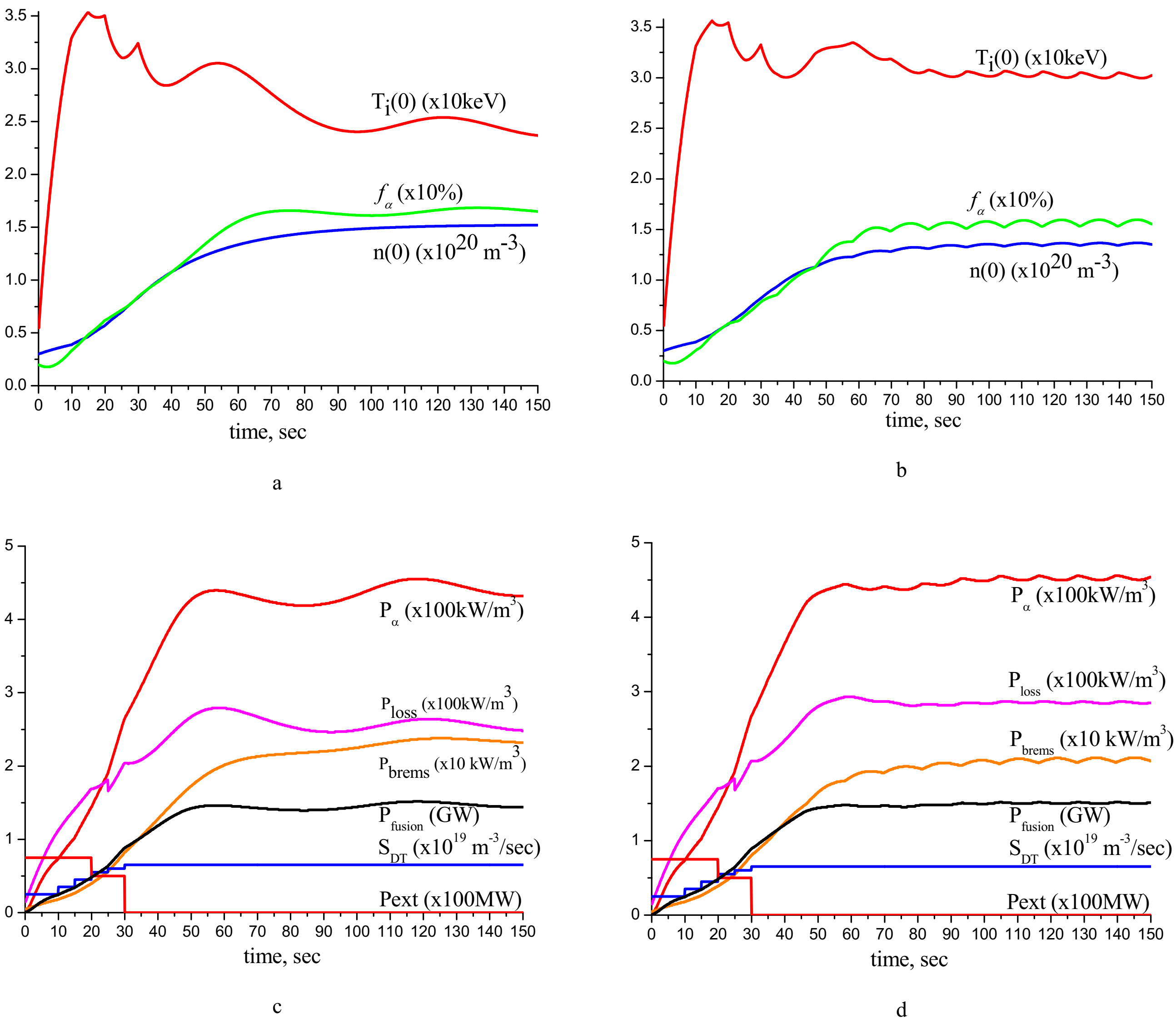
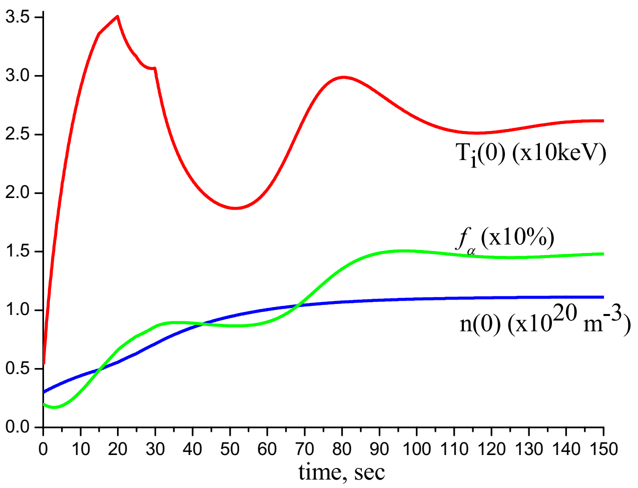


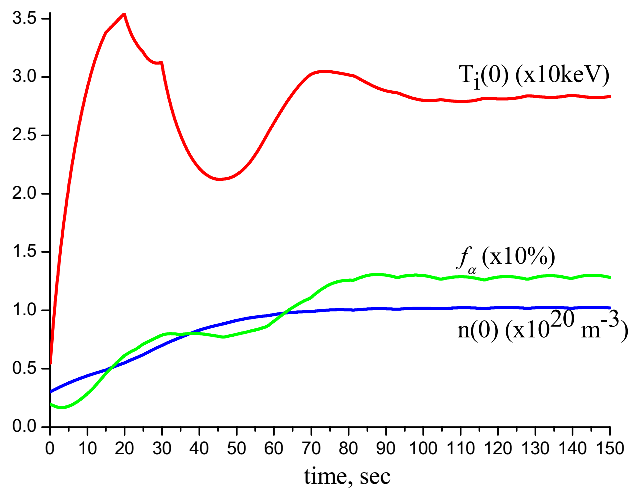
Fig. 5. Plasma parameters evolution in time:
a - (n, f_{alpha}, T_i) without removal of helium ash, b - (n, f_{alpha}, T_i) with removal of helium ash, c - (P_{alpha}, P_{loss}, P_{brems}, P_{fusion}, S_{DT}, P_{ext}) without removal of helium ash, d - (P_{alpha}, P_{loss}, P_{brems}, P_{fusion}, S_{DT}, P_{ext}) with removal of helium ash

We can easily manage plasma parameters by so called feedback control, means we can measure fusion power density and based on it change source fueling density, auxiliary heating power density, alpha ash removal rate [7]. In that way we can move operation path to get ignition at different values of plasma parameters. By such feedback control it is possible to get ignition at low plasma density values but with high temperature, or get ignition in high density plasma with lower temperature values.

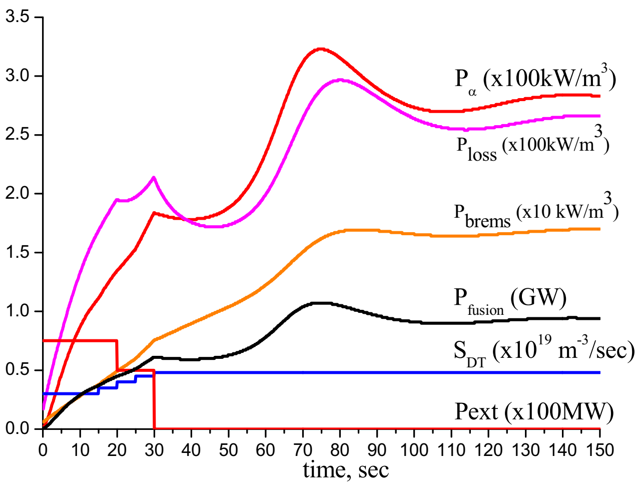
Second series of plasma operation graphs present simulation results for fueling and input power scenarios differs from first series. Basically the difference can be noted in next: for the second series we have lower D+T fueling rate. Auxiliary heating powers in both series are equal. It has strong influence to the destination plasma parameters. Due to this we have steady state temperature for the first fueling scenario about 5keV higher than for the second one.



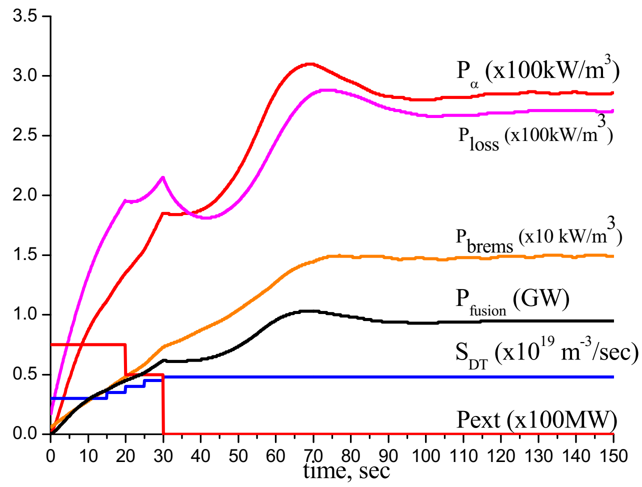
a



b



c



d

Fig. 6. Plasma parameters evolution in time:
a - (n, f_{alpha}, T_i) without removal of helium ash, b - (n, f_{alpha}, T_i) with removal of helium ash, c - (P_{alpha}, P_{loss}, P_{brems}, P_{fusion}, S_{DT}, P_{ext}) without removal of helium ash, d - (P_{alpha}, P_{loss}, P_{brems}, P_{fusion}, S_{DT}, P_{ext}) with removal of helium ash

The operation paths (plasma density versus plasma temperature) on the background of the POPCON (Fig. 7) show us the consequence of the stages of the plasma heating and density increase due to fuel coming and heating. It is easy to note that operation paths with and without helium ash removal reach ignition region in different ways. Removal of helium ash from ignition volume causes the operation path position are placed on n-T plane at smaller values of plasma density and temperature. It means that we need less external power and can operate at lower densities region, and so we can use simpler fuel and power injection system, magnetic confinement system, easier plasma operation.

There are two competitive mechanisms which implies on plasma temperature evolution in time – alpha heating power due to energy released in fusion reactions and power losses from plasma, mainly affected by plasma conduction losses and bremsstrahlung losses. To get the steady state we need to reach region where sum of losses from plasma is approximately equal to energy released in plasma due the fusion processes. From the beginning till ignition phase we input some external power P_{ext} by the NBI or ICRF sources to reach self-ignited operation, when the energy for fusion reaction obtained from alpha particles released as a result of D+T fusion reactions. We should like to emphasis that one needs strictly controlled source of fuel particles, deuterium and tritium. The fueling profile has a great influence on resulting parameters of the steady state regime, released fusion power, density of plasma and temperature in steady state. The operating point moves to the higher temperature side in the ignition regime due to alpha heating, and to the lower temperature side out-side the ignition regime due to cooling. While the operating point approaches the final point slowly with the increase in the plasma density from the higher temperature side after switching off the heating power, the ignition boundary also shifts up with the increase in the helium ash density fraction.

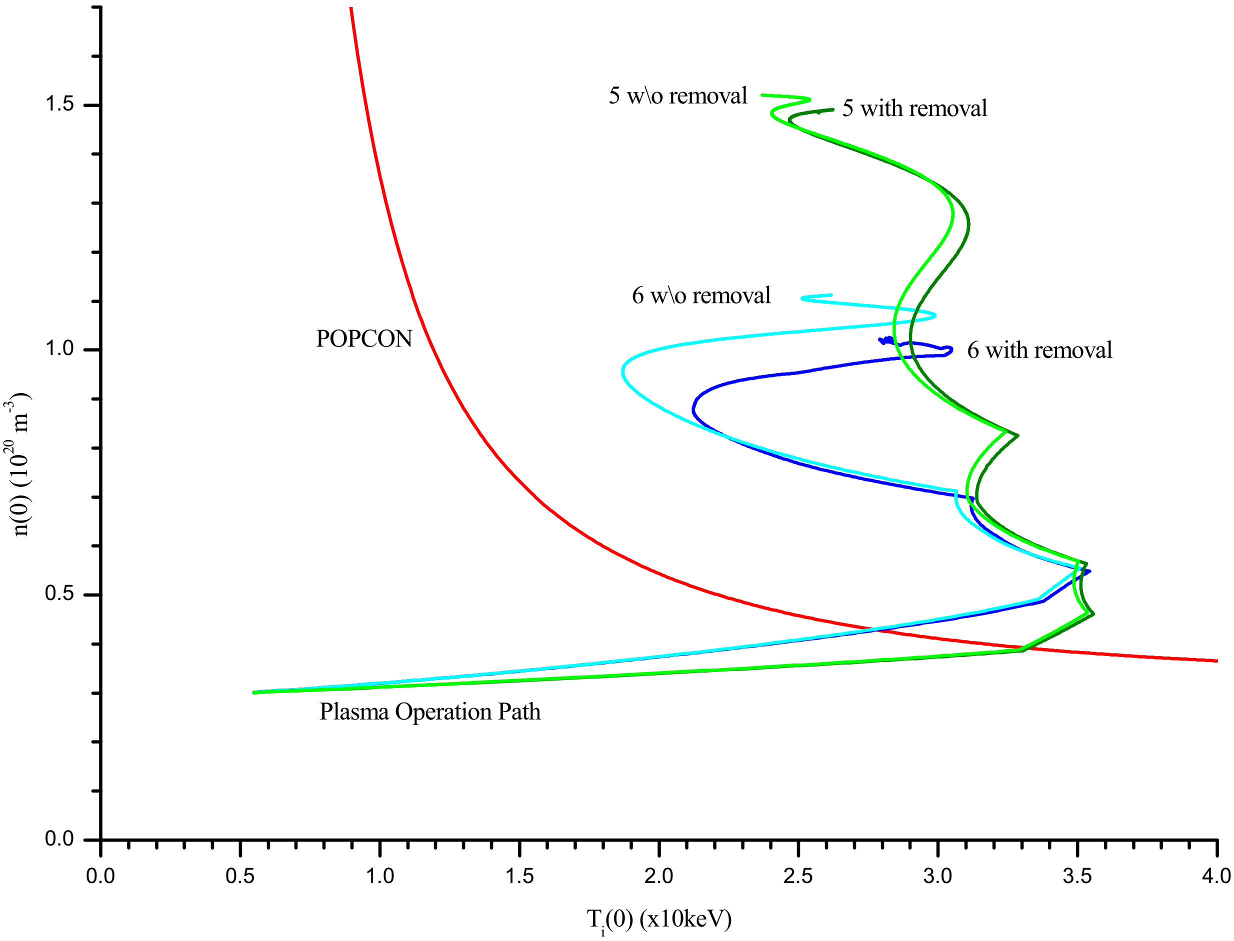


Fig. 7. The operation path (plasma density versus plasma temperature) on the background of the POPCON

DISCUSSION

The system of balance equations in this paper is derived to describe the plasma steady state and plasma operation path with an emphasis on the impurity and helium ash dynamics. It differs from the analogical system in paper [1] in some points. Here the impurity ion density is taken into account; the plasma energy is taken as the sum of energy contained in deuterium, tritium ions and thermal alpha particles. As one can see here the difference in the final system of equations appears. Here only one approach to model the removal of helium ash is considered, namely the change of the confinement time τ_α in time [7]. Other models are also possible. Particularly, the description of the plasma particle and power balance not only in time but in space also. However, the other approaches take much more computer time. That is why it is very useful to study different mechanisms separately and then choose the more advanced scenarios and check them with more complicated codes such as 3D numerical codes. The real technique to remove helium ash in reactor systems, particularly helical field magnetic traps, is proposed in some papers [6, 7] and literature cited therein.

CONCLUSIONS

1. The effect of the removal of helium ash on the plasma parameters is demonstrated here. One can see some reduction of the bremsstrahlung losses and that in the steady state the plasma parameters are more stable in time under the removal of the helium ash. The fusion power is more "flat", i.e. more "equalized" in time (it does not change in time so strongly).

2. The effect of the change of the fuel source S_{DT} in time on the plasma parameters in the steady state is found here. We should notice that in the case of the smaller fuel rate (Fig. 6.) the steady state is established on the level of the lower value of the helium ash (approximately 12 % (Fig. 6. a, c) instead of 15 % (Fig. 6. b, d). The fusion power is some smaller, namely $P_{fusion} \approx 1$ GW in the case of the smaller fuel rate (Fig. 5) in comparison with the $P_{fusion} \approx 1.5$ GW in the previous case (Fig. 6)

3. Plasma operation paths (temporal evolution of plasma parameters) $n_e(0)$ and $T(0)$ on the background of POPCON line (Fig. 7) can distinguish noticeably under the different scenarios of fueling. Plasma operation path marked as "6 with removal" in Fig. 7 leads to lower value of temperature $T(0)$ and plasma density $n_e(0)$ under the desired value of the output fusion power P_{fusion}.

ACKNOWLEDGMENTS

This work is partly supported in the framework of the Science and Technology Center in Ukraine, Project No.3685. Authors express their gratitude to Professor I.O. Girka, Doctor I.V. Pavlenko and Professor V.D. Yegorenkov for useful discussions and comments.

REFERENCES

1. Mitarai O. and Muraoka K. Ignition analysis for burn control and diagnostic developments in ITER // Nuclear Fusion. – 1997. –Vol.37, №11. – P. 1523-1539.
2. Beidler C. D., Harmeyer E., Kisslinger J., Ott I., Rau F., Wobig H. Studies of a Stellarator Reactor of the Helias Type: The Power Balance // Max-Planck-Institut fur Plasmaphysik, Report IPP 2/318, June 1993.
3. Bosch H. S., Hale G. M. Improved Formulas for Fusion Cross-Sections and Thermal Reactivities // Nuclear Fusion. – 1992. – Vol.32, №4. – P. 611-631.
4. Perez-Navarro A. Dynamics studies for stellarator reactors. In: Proceedings of the 6th Workshop on WENDELSTEIN 7-X and Helias Reactors // Max-Planck-Institut fur Plasmaphysik, Report IPP 2/331, 1996. – P. 222-226.
5. Mitarai O. and Sudo S. Ignition Characteristics in D-T Helical Reactors // National Institute for Fusion Science, Research Report NIFS – 283, June 1994.
6. Motojima O. and Shishkin A. A. Drift island motion in helical plasma and its use for ash removal and high-energy ion injection // Plasma Physics and Controlled Fusion. – 1999. – Vol.41. – P. 227-242.
7. Shishkin A.A. Estafette of drift resonance, stochasticity and control of particle in a toroidal magnetic trap // Nuclear Fusion. – 2002. – Vol.42. – P. 344-353.

ВЛИЯНИЕ УДАЛЕНИЯ ХОЛОДНЫХ АЛЬФА-ЧАСТИЦ И СЦЕНАРИЕВ ПОДАЧИ ТОПЛИВА НА БАЛАНС ЭНЕРГИИ И ЧАСТИЦ В ТЕРМОЯДЕРНОЙ ПЛАЗМЕ

А.В. Ерёмин[1], А.А. Шишкин[1,2]

[1]*Харьковский национальный университет им. В.Н. Каразина,*
Харьков-77, Украина,
[1]*Институт физики плазмы, ННЦ «Харьковский физико-технический институт»,*
Харьков-108, Украина

В работе рассмотрена эволюция во времени плотности плазмы, температуры и доли тепловых альфа-частиц при моделировании удаления холодных альфа-частиц. Показано, что медленное изменение во времени плотности холодных частиц может быть использовано для управления путем поджига в термоядерной дейтериево-тритиевой плазме. Также рассмотрено влияние различных сценариев ввода топлива на режимы горения плазмы и на параметры в стационарном состоянии. Проведен численный и аналитический анализ эволюции параметров плазмы во времени, влияние на положение рабочей точки на пути достижения горения и непосредственно фазы горения. Основной задачей исследования является оптимизация сценариев поджига и горения плазмы в будущих термоядерных реакторах, включая ITER.

КЛЮЧЕВЫЕ СЛОВА: термоядерная плазма, поджиг и удержание, альфа-частицы, временная эволюция, удаление альфа-частиц, сценарии ввода топлива, ITER