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D+D FUSION PRODUCTS YIELD IN TORSATRON LARGE HELICAL DEVICE

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In the present paper we study the possibility to obtain fusion products and control of fusion products amount in operating torsatron device, particularly Large Helical Device. The study is carried out on the base of the particle and power balance equations where the evolution of plasma parameters in time is being followed also. Access of the ignition and the steady operation for different fueling schemes is studied. There were developed the fueling scenarios which provide the amount of fusion products distinguished two orders magnitude amount. It is shown that varying the fueling rates (the source term in the balance equations) makes it possible to control the fusion product amounts two orders of the magnitude.

KEY WORDS: fusion plasma, ignition, confinement, time evolution, tritium removal, fuel rates scenarios

Removal of the fusion products in the fusion plasma can be helpful for the operation of the fusion reactor [1], particularly the plasma parameters in the steady state are more stable, and the bremsstrahlung losses are smaller. The principal question is the following: is it possible to realize the removal of fusion products from the confinement volume with the suitable techniques? There are the practical proposals, how it is possible to do with the use of the drift resonances of the fusion products [2-3], especially on the Large Helical Device in experiments with D+D [4]. In the paper [4] it is shown that with the use of the drift resonances the tritium ions with the birth energy (W=1.01MeV) can be extracted. The aim of this research work is to analyze the conditions under which it is possible to obtain the fusion products on the Large Helical Device and propose the parameters of such experiment, particularly the scenario of injection of the fuel for D+D fusion. Such experiment could check the possibility of the selective removal of the fusion products with the use of the drift resonances of the particle.

MOTIVATION OF STUDY

When we say the drift resonances we mean the resonance between the particles with the drift twisting angle $\iota^* = m/n$ and the magnetic field perturbation $\vec{b} = B_0\{b_{n,m}(r)\sin(n\vartheta - m\phi, b_{n,m}(r)\cos(n\vartheta - m\phi, 0\}$, which can lead to the escape of the particles from the confinement volume. In Large Helical Device there are exist the Local Island Diverter (LID) coils [5] which can be used for the organization of the necessary drift resonances. However, it is necessary to understand under what plasma parameters the fusion products can appear in the Large Helical Device. To answer this question in this paper we study the balance of particles and energy and follow the evolution in time of the plasma parameters and achieving the plasma steady state and the fraction of the fusion products.

We study the fusion plasma processes in Large Helical Device:

$$D+D \rightarrow \begin{array}{l} T(1.01\ MeV)+p(3.3\ MeV) \\ \\ {}^3He(0.82\ MeV)+n(2.45\ MeV). \end{array} \qquad (1)$$

There are two channels for the reaction with almost equal probability. There is a possible secondary reaction of D plasma with D+D fusion products T (1.01 MeV) and $_3$He (0.82 MeV) with higher fusion rate

$$\begin{array}{lll} D+T & \rightarrow & {}_4He(3.5MeV)+n(14.1MeV) \\ & & \\ D+{}_3He & \rightarrow & {}_4He(3.6MeV)+p(14.7MeV). \end{array} \qquad (2)$$

In our numerical model we take into account primary and secondary reactions. In the secondary reaction process we neglect difference in products energies and assume that we have one reaction with the same reaction rate and products with averaged energies.

BALANCE EQUATIONS SET

Initial equations

The following set of equations is used to describe the temporal evolution of plasma parameters: density of source deuterium plasma ions $\overline{n}_D(x)$, density of thermal fusion products $\overline{n}_{T,{}_3He}(x)$ (T and $_3$He), plasma energy $\overline{W}(x)$:

$$\frac{d\bar{n}_D(x)}{dt} = S_D - \bar{n}_D^{2}(x) < \overline{\sigma \upsilon} >_{DD(p,n)} - \frac{\bar{n}_D(x)}{\tau_D} - \bar{n}_D(x)\bar{n}_{T,{}_3He}(x) < \overline{\sigma \upsilon} >_{D-T,{}_3He}, \qquad (3)$$

$$\frac{d\bar{n}_{T,{}_3He}(x)}{dt} = \bar{n}_D^{2}(x) < \overline{\sigma \upsilon} >_{DD} - \bar{n}_D(x)\bar{n}_{T,{}_3He}(x) < \overline{\sigma \upsilon} >_{D-T,{}_3He} - \frac{\bar{n}_{T,{}_3He}(x)}{\tau_{T,{}_3He}}, \qquad (4)$$

$$\frac{d\bar{W}(x)}{dt} = \frac{P_{ext}}{V} + P_D - P_{brems} - \frac{3}{2}\frac{\bar{n}_D(x)\bar{T}_D(x)}{\tau_E}. \qquad (5)$$

Here $x = r / a_{pl}$ is the dimensionless radial variable and a_{pl} is the plasma radius, bars denote the averaging over the volume; S_D is the source term which gives us the fuel rate; τ_D is the deuterium confinement time, $\tau_{D,3He}$ is the D and ${}_3He$ fusion product confinement time, τ_E is a energy confinement time. We assume that P_{ext} is the external heating power, V is the plasma volume, P_D is the power density released in the form of charged particles, P_{loss} is the plasma conduction loss power density ($P_{loss} = \frac{3}{2}\frac{\bar{n}_D(x)\bar{T}_D(x)}{\tau_E}$), P_{brems} is the bremsstrahlung power density. All three heating schemes are taken into account as $P_{ext}=P_{ICRF}+P_{ECH}+P_{NBI}$ with time dependence written about below.

We use the evolution equations set (3)-(5) as it is described in [1, 6].

DEVICE AND PLASMA PARAMETERS

Large Helical Device is one of the largest operating magnetic plasma confinement devices with a major radius which can be varied from 3.42 to 4.1 m, a minor radius which averages 60 cm and a plasma volume on the order of 30 m^3 [6,7]. Large Helical Device is well equipped with a variety of plasma heating methods: neutral beam injection (NBI) – 3 beam lines, 150-180 keV negative ion, ~10 MW total; ion cyclotron resonance heating (ICRH) – 6 antenna, ~2.7 MW total; electron cyclotron resonance heating (ECRH) 84 and 168GHz, ~2.1 MW total. The flexible combination of these heating sources has enabled several notable achievements in Large Helical Device: peak electron and ion temperatures exceeding 10 keV and 12.5 keV, respectively, the formation of an electron internal transport barrier, averaged beta of ~3.2% and a stored energy of 1.16 MJ and a long pulse duration exceeding 120 s. In addition line-averaged electron densities up to $1.6x10^{20}$ m^{-3} have been achieved and confinement time scaling which rivals ELMy H-mode tokamaks has been demonstrated [7, 8].

Heating source	Input power	Duration	Density	Plasma temperature
ECH	50kW	120s	$0.3x10^{18}$ /m^{-3}	T_e ~ 0.65 keV
NBI	600 kW	80s	$16x10^{18}$ /m^{-3}	T_i ~ 1.5 keV
NBI	100 kW	110s	$10x10^{18}$ /m^{-3}	T_i ~ 0.35 keV
ICH	350 kW	120s	$8x10^{18}$ /m^{-3}	T_e ~ T_i ~ 1.3 keV
ICH	520 kW	150s	$6x10^{18}$ /m^{-3}	T_e ~ T_i ~ 2 keV

Table. Machine & Plasma parameters used in this Analysis (for Large Helical Device long pulse, shot #53776)

Plasma Volume	30 m^{-3}
Major Radius	3.9 m
Minor Radius	0.6 m
Magnetic Field	2.75 T
Operation Time	1905 sec
Ion Temperature	2.0 keV
Electron Temperature	1.3 ÷ 1.7 keV
Averaged electron density	7 ÷ 8 $x10^{18}$ m^{-3}
Input total power	680 kW
ICRF power (steady state injection)	520 kW
ECH power (steady state injection)	100 kW
NBI power (25sec pulse at intervals)	60 kW (averaged for one duty cycle)
Total input energy	1.3 GJ

MODELS OF FUSION PRODUCT RATE, RADIATION AND TRANSPORT LOSSES

The reaction rate for DD fusion reaction is used in the following form [9]:

$$\left\langle \overline{\sigma\upsilon} \right\rangle_{DD} = 2.33 \cdot 10^{-14} \frac{1}{T^{2/3}} \exp\left(-\frac{18.76}{T^{1/3}} \right) \qquad [\frac{m^3}{\sec}], \tag{6}$$

where temperature T is measured in [keV]. The plots of $<\sigma\upsilon>_{DD}$ and $<\sigma\upsilon>_{DT}$ versus of ion temperature is shown in Fig. 1. It is easy to see that we have more than two orders difference at our working temperatures about 10keV in Large Helical Device in Deuterium - Deuterium reaction rates versus Deuterium-Tritium reaction rates. The particular effect is really important in our observation, because we have intensive birth of Tritium during thermonuclear reacting, as the D+D fusion product. But with temperature increasing we get less rapidly growth law of thermal reaction rate for DD fusion. We have to note that increasing temperature from 1keV to 10keV we get strong growing of thermal reaction rate, it consist the four order of magnitude growth. But with further temperature growth from 10keV up to 50keV we have not such result in thermal reaction rate, it is only increases in ten times. 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 DD reaction.

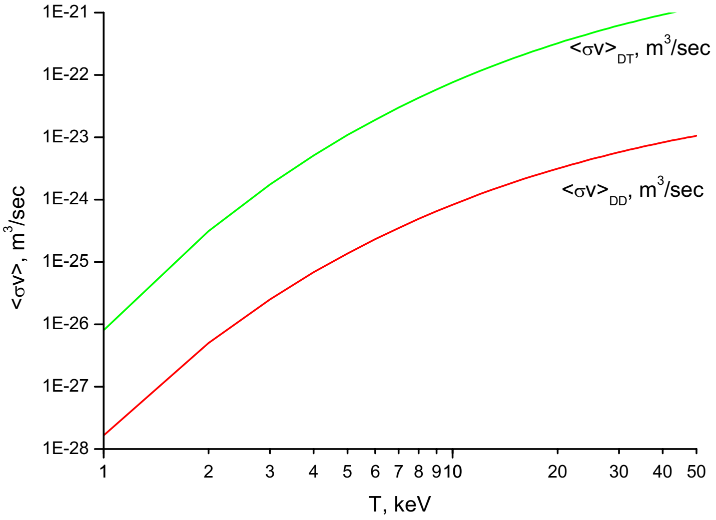


Fig. 1. Reaction rate $<\sigma\upsilon>_{DD}$ and $<\sigma\upsilon>_{DT}$ as a function of ion temperature

Let's make some estimation for energies releasing and outgoing from plasma volume during ignition and ignited operation. We have particles heating power due to fusion reactions in plasma volume. It basically depends on plasma density and reaction rate $\left\langle \overline{\sigma\upsilon} \right\rangle_{DD}$. 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.

Power releasing in form of charged particles due to fusion processes in plasma is calculated according to the following expression:

$$P_D = 3.3 \cdot 10^{-13} n_D^2 \left\langle \overline{\sigma\upsilon} \right\rangle_{DD} \qquad [\frac{W}{m^3}], \tag{7}$$

bremsstrahlung power P_{brems} is given as following:

$$P_{brems} = 5.4 \cdot 10^{-37} Z_{eff} n(0)^2 \sqrt{T_e(0)} \qquad [\frac{W}{m^3}], \tag{8}$$

here we calculate effective charge state as follows

$$Z_{eff} = \frac{1}{n(0)} \sum\nolimits_Z n_Z(0) Z^2 , \tag{9}$$

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

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

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

Thermal reaction rate $<\sigma\upsilon>_{DD}$ is a key parameter which defines fusion power density released in high temperature fusion plasma. We have to note, that looking on Fig. 2 one can obtain that it's much easier to get steady ignited operation in lower temperatures region for DD plasma. The reason of it is very rapid increasing of conduction power density losses in confinement volume on temperature. But power releasing due fusion processes in plasma many times smaller than losses, because thermal reaction rate for DD reaction is too small in reachable temperature region.

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. At the present time on Large Helical Device it is possible to get energy confinement time up to τ_E =0.36 sec.

Bremsstrahlung losses from plasma are more than twenty times smaller than conductive losses in 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 strong dependence of bremsstrahlung power losses on effective charge number, means that introduction impurities with Z about 10 leads to about hundred times increasing of bremsstrahlung power losses.

Energy confinement time τ_E is about 1 sec demonstrates desirable level of power losses. Due to different dependencies of incoming and outgoing powers from plasma we have to understand that we need to find such operation region, where we have optimal values of each dependence.

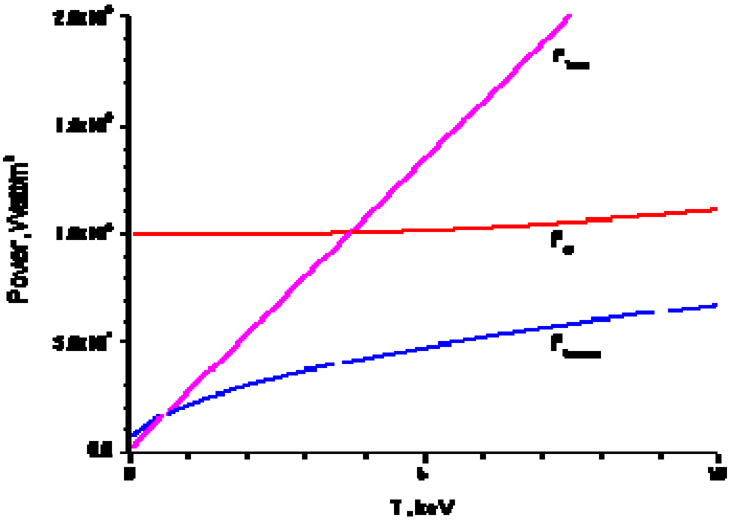


Fig. 2. Fusion heating density power (P_D=$P_{Dfusion}$+P_{ext}), bremsstrahlung power density losses (P_{brems}) and conduction power density losses (P_{loss}) for τ_E=1 sec, P_{ext}=3MW

Confinement time τ_E is estimated by international ISS95 stellarator scaling [10]:

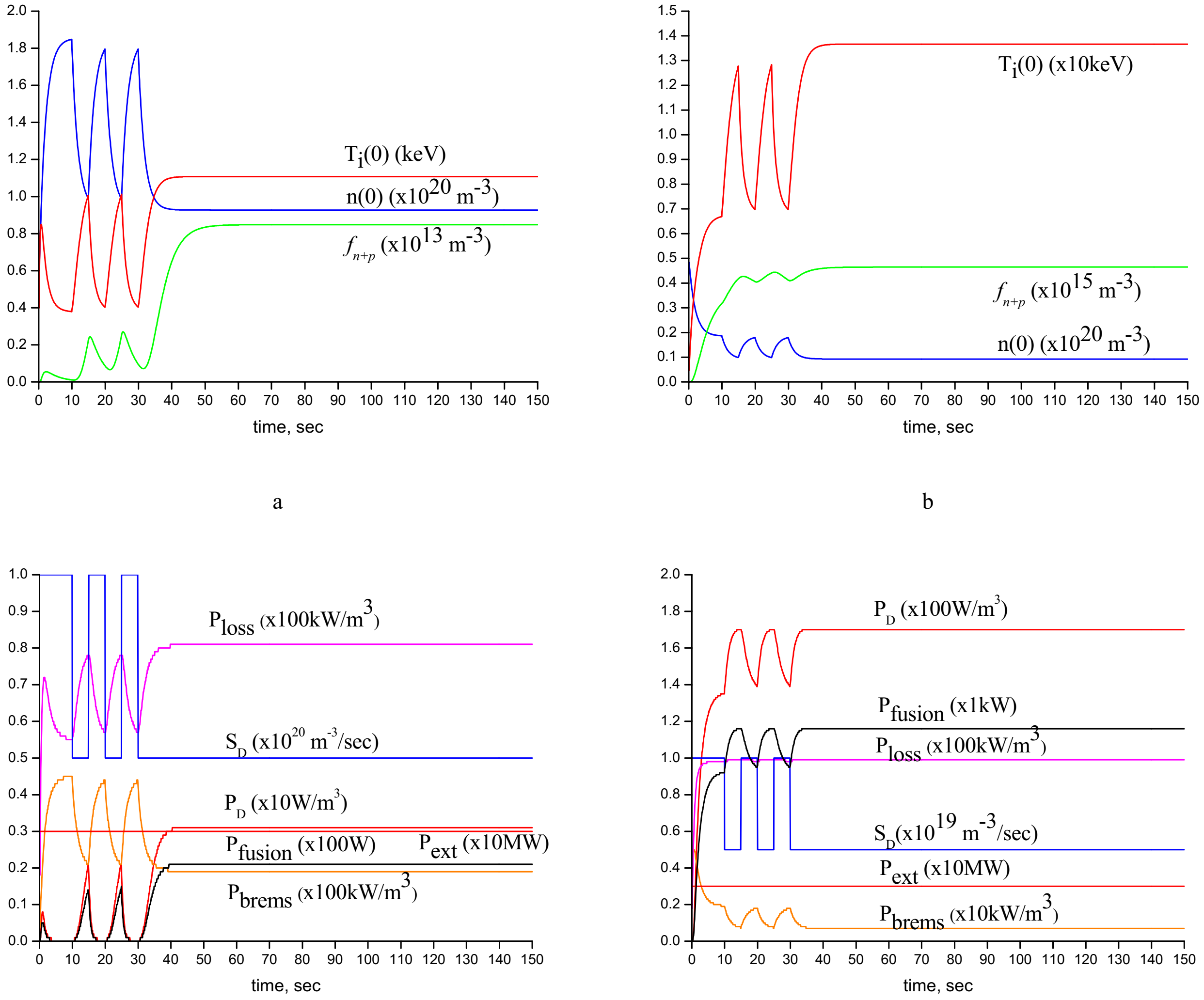
$$\tau_E^{ISS95} = 0.079\cdot a^{2.21}R^{0.65}P_{heat}^{-0.59}(n_0\cdot 10^{-19})^{0.51}B_t^{0.83}\varsigma_{2/3}^{0.4}, \quad (11)$$

where major plasma radius R - in [m], plasma density n in [m^{-3}], magnetic field in [T], P_{heat} external heating in [MW]. In our following calculations we take τ_E equal to 0.36 sec [10]. For particle confinement time we assume the following ratios: $\tau_D = \tau_{T,He} = 10\ \tau_E$ [11].

PLASMA PARAMETER EVOLUTION UNDER DIFFERENT FUELING SCENARIOS

Numerical calculations for different fueling and power injection scenarios are goaled to obtain optimal regions of plasma operation. The influence of different fueling scenarios on steady state parameters is studied. We model plasma parameters evolution (plasma density, temperature, fusion products rate) with different fueling scenarios products removal. Steady state operation under the different density fueling and power injection schemes is investigated.

We observe fusion DD plasma operation for 150 sec, which is long enough for steady state operation establishment. In previous investigations it was shown, that steady state establishes at such period stay stable in future. Thus, such period of plasma observation is enough indicative. It is not too simplify model, but on the other hand, not result in significant growth of numerical solution time of the time evolution equations set. In our model we consider that fuel goes to confinement volume by the periodic injection of deuterium pellets in plasma. In our model the uniform distribution of injected particles and heating power in the plasma center and periphery is considered. Thus at the numerical decision of the time evolution equation set of the plasma parameters we do not consider differences in profiles of the fuel density and temperatures, due to their non-uniform receipt in various regions of plasma. We consider that distribution of injected fuel and power is isotropic over the total plasma volume. The results of the numerical calculation of the above-stated equations set of the plasma time evolution is given on the following figures. On the first graph (Fig. 3 a, b) of each series of modeling temperature T_i (0) in [keV], density of the basic plasma n (0) in terms of [m^{-3}], and also density of fusion products f_{n+p} (T and $_3$He), formed as a result of thermonuclear reaction between D+D, are represented. On the second series of each graph the initial plasma parameters - injected density of source fuel ions S_D in units [m^{-3}sec^{-1}], power of external heating of plasma P_{ext} in [W] are given. On the same second figures in each series (Fig. 3, c, d) the results received during numerical modeling for all power densities allocated in plasma: thermonuclear fusion P_D, density of energy leaving plasma due to bremsstrahlung losses P_{brems} in [W/m^3], plasma conductivity losses P_{loss} in [W/m^3], the total thermonuclear power allocated in all volume of experimental device P_{fusion} in [W] are given.



a b

c d

Fig. 3. Plasma parameters evolution in time in Large Helical Device D+D fusion reaction:
a - (n, f_{alpha}, T_i) for P_{ext}=3MW and fueling power density S_D=0.5x10^{20} m^{-3}sec^{-1} with steady state operation, b - (n, f_{alpha}, T_i) for P_{ext}=3MW and fueling power density S_D=0.5x10^{19} m^{-3}sec^{-1} with steady state operation, c - (P_D, P_{loss}, P_{brems}, P_{fusion}, S_D, P_{ext}) for S_D=0.5x10^{20} m^{-3}sec^{-1}, d - (P_D, P_{loss}, P_{brems}, P_{fusion}, S_D, P_{ext}) for S_D=0.5x10^{19} m^{-3}sec^{-1}. (S_D, P_{ext} is a steady state values)

Let's examine behavior of plasma at initial parameters and structure of input power and fuel in the case corresponding to graphs on Fig. 3. Our purpose in this case is to reach the basic plasma density high enough, the higher ratio of D+D fusion products in plasma, and temperature of the basic plasma up to 10keV. For this purpose we use high density of particles input in plasma S_D= 1x10^{19} m^{-3}sec^{-1} , and power density entered into plasma of the order 3 MW/sec. Such input of initial parameters enables us to not lead up loss in plasma to a level when they considerably exceed a positive effect given due to the contribution of energy of fusion products and power injected from the outside. Smooth escalating of input of density up to 1x10^{19} m^{-3}sec^{-1} at the initial stage of ignition at constant power of external heating allows to receive the significant jump of plasma temperature in time at the initial stage of ignition, due to a high ratio of energy on plasma volume unit.

We would like to note that the input of fuel particles (source term S_D) in the shape of “steps in time” (Fig.3 c, d) gives us opportunity to not too rapid decrease of plasma energy per density unit. As a result of such source particles injection scheme we get lower parameters and more effective heating, optimum ratio for incoming and outgoing powers from experimental device.

CONCLUSIONS

It is shown, that we can get fusion products with density $f_{np}=0.8\text{x}10^{13}$ m^{-3} for next operating parameters: 3MW external heating power, source fueling density $S_D=0.5\text{x}10^{20}$ $\text{m}^{-3}\text{sec}^{-1}$, ion's temperature T=1.1keV, plasma density $n=1\text{x}10^{20}$ m^{-3} on Large Helical Device.

For another fueling and heating scheme (source fueling density $S_D=0.5\text{x}10^{19}$ $\text{m}^{-3}\text{sec}^{-1}$, ion temperature T=13keV, plasma density $n=1\text{x}10^{19}$ m^{-3}) fusion products density $f_{np}=0.4\text{x}10^{15}$ m^{-3} is obtained. Such results is obtained for steady state plasma operation regime and observed on 150 sec period. Now days there is a technical possibility to inject 3MW heating power in to confinement volume on Large Helical Device.

As it is shown in our paper [4] it is possible to realize the fusion products removal under the fusion D+D reaction on the Large Helical Device. Selective removal of fusion products (tritium T or helium $_3$He ions) can be carried out with the use of drift resonances. The drift resonances for the passing particles with the drift twisting angle $\iota^*=1/1$ and closed values ($\iota^*=12/10$) can be excited with the use of the Local Island Divertor (LID) coils that creates the island divertor configuration in the Large Helical Device.

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ВЫХОД ПРОДУКТОВ СИНТЕЗА D+D В ТОРСАТРОНЕ LHD

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В этой работе нами рассмотрена возможность получения продуктов синтеза и управления их количеством на современной установке торсатронного типа на примере Large Helical Device (LHD). Изучение проблемы проведено на основании уравнений баланса энергии и частиц с одновременным рассмотрением временной эволюции параметров плазмы. Изучены процессы достижения горения и работа в стационарном режиме для различных сценариев подачи топлива в экспериментальную установку. Разработаны такие сценарии подачи топлива в систему удержания, которые позволяют достигать превышения плотности продуктов синтеза на два порядка при равных затратах внешней мощности нагрева. Показано, что, изменяя закон подачи топлива в систему (исходные параметры в уравнениях баланса), можно управлять количеством образующихся продуктов синтеза в пределах двух порядков.

КЛЮЧЕВЫЕ СЛОВА: термоядерная плазма, сценарии поджига, удержание, эволюция параметров плазмы, удаление трития, сценарии подачи топлива.