ISSN 1063-7788, Physics of Atomic Nuclei, 2020, Vol. 83, No. 10, pp. 1391–1395. © Pleiades Publishing, Ltd., 2020.
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Estimation of the Parameters of a Fusion Neutron Source Based on Deuterium Plasma

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Received November 7, 2017; revised December 12, 2017; accepted December 18, 2017

Abstract—Sources of fusion neutrons with an energy of about 10 MeV can be a driver in hybrid fusion–fission reactor. They can be used for the disposal of radioactive wastes involved in the closure of the nuclear fuel cycle. Currently, the projects of such systems rely on the use of the D–T reaction and the production of tritium in the blanket. In terms of availability of fuel components, the D–D reaction is attractive. The energy of the neutrons produced in the D–D reaction directly is not high enough, but fast neutrons of 14 MeV are produced by the burning of the tritium produced in the D–D reactions. The possibilities of using a D–D plasma confined in a magnetic trap to generate fast neutrons are analyzed. To increase the reaction rate, a powerful heating by injection of neutral deuterium atoms is considered. Under such conditions, a significant population of fast deuterons is maintained. The requirements on the parameters of the plasma and the magnetic trap are discussed to present the possible concept of a fusion neutron source based on deuterium plasma.

Keywords: fusion plasma, deuterium, fast neutrons, neutral beam injection heating

DOI: 10.1134/S1063778820100233

1. INTRODUCTION

At present, the concept of neutron fusion sources for hybrid fusion–fission systems with a subcritical blanket is being actively discussed [1–3]. A hybrid fusion–fission system is a reactor in which the fusion plasma is a neutron source surrounded by a blanket containing fertile isotopes (^{238}U, ^{232}Th) or transuranic elements. As a result of the interaction of fusion neutrons with the blanket filling, energy and fissile nuclear fuel (^{239}Pu, ^{233}U) are produced, and radioactive waste is also utilized (transmuted). The existing projects of neutron sources with magnetic plasma confinement are focused on the use of the D–T reaction and the production of tritium in the blanket [1–3]. As a rule, a tokamak is considered as a confinement system. Systems based on open traps [4, 5] and other magnetic configurations [6, 7] were analyzed.

In this work, the possibility of obtaining a neutron yield from deuterium plasma without external tritium feeding is considered.

Deuterium as an energy resource is attractive primarily for its availability. However, the D–D reaction rate is more than an order of magnitude lower than the D–T reaction rate; therefore, obtaining a positive energy yield from the deuterium plasma, which does not contain tritium, is hardly considered at present.

In the deuterium plasma, the following reactions are possible:

$$\mathrm{D} + \mathrm{D} \to n(2.45\ \mathrm{MeV}) + {}^3\mathrm{He}(0.817\ \mathrm{MeV}), \quad (1)$$

$$\mathrm{D} + \mathrm{D} \to p\,(3.02\ \mathrm{MeV}) + T\ (1.01\ \mathrm{MeV}), \quad (2)$$

$$\mathrm{D} + \mathrm{T} \to n\,(14.1\ \mathrm{MeV}) + {}^4\mathrm{He}(3.5\ \mathrm{MeV}), \quad (3)$$

$$\mathrm{D} + {}^3\mathrm{He} \to p(14.68\ \mathrm{MeV}) + {}^4\mathrm{He}(3.67\ \mathrm{MeV}). \quad (4)$$

Neutrons with a relatively low energy of 2.45 MeV are produced in reaction (1). Neutrons with the energy of 5 MeV and higher are of greatest interest for hybrid systems. If tritium produced in reaction (2) has time to react with deuterium, then the release of D–T neutrons with the energy of 14.1 MeV (reaction (3)) becomes noticeable. This is possible if the tritium confinement time in the trap is long enough. If, in addition to tritium, helium-3, which is formed in reaction (1), has time to burn, then such a thermonuclear fuel cycle is called fully catalyzed. Owing to the differences in cross sections and rates of D–T and D–^{3}He reactions, a situation is possible when a significant part of tritium has time to burn, and helium-3, on the contrary, has time to leave the trap almost completely, without having time to react with deuterium.

Here we consider the approximation corresponding to the so-called semi-catalyzed D–D cycle, in which tritium produced in the D–D reaction is completely burned, and all of helium-3 leaves the trap. In such a thermonuclear cycle, the energy yield in neutrons is $P_n/P_{fus} \approx 0.67$, and in this case, D–T neutrons account for the fraction of $P_{n14}/P_{fus} \approx 0.55$. The high fraction of fast neutrons makes such a thermonuclear cycle without an external tritium source attractive and potentially interesting from the point of view of a neutron source. No need for tritium handling is a very significant advantage of such a neutron source over a neutron source requiring tritium breeding.

The total efficiency of the hybrid fusion–fission system is [3]

$$\begin{aligned}\eta_{net} &= P_{net}/P_{fus} \\ &= \eta_e(\alpha_n M + 1 - \alpha_n + 1/Q) - 1/(\eta_d Q),\end{aligned} \tag{5}$$

where P_{net} is the output (electrical) power, P_{fus} is the fusion power, M is the blanket gain, $\alpha_n = P_n/P_{fus}$ is the fraction of the fusion energy yield in neutrons, Q is the plasma power gain, η_e is the efficiency of the conversion of heat into electricity, and η_d is the efficiency of the external heating system (driver).

In the case of the D–T reaction, $\alpha_n = 0.8$. We assume that $\eta_e \approx 0.35$. Modern systems for neutral beam injection (NBI) heating and electron cyclotron resonance (ECR) heating have the efficiency of $\eta_d \approx 0.4$. In this case, the fusion neutron source with $Q = 1$ and the blanket gain of $M = 25$–50 provides the efficiency of $\eta_{net} \sim 10$. For the deuterium plasma without the external tritium source, the system with $Q \approx 0.3$ and $M \approx 80$ may have the efficiency of $\eta_{net} \approx 10$.

It is possible to maintain a significant population of epithermal (fast) ions at $Q < 1$ by means of the powerful injection of fast atoms. The fusion reaction rate with the participation of fast particles is much higher than that in the case of the Maxwellian plasma. The high density of energy release makes the system relatively compact.

2. BALANCE OF ENERGY AND PARTICLES

To estimate the limiting efficiency of fusion reactions in the deuterium plasma heated by injection of fast atoms, the stationary energy balance is considered in the form

$$P_{inj} + P_{fus} - P_n = P_{rad} + \frac{W_{th}}{\tau_E}, \tag{6}$$

where $W_{th} = \frac{3}{2}\left(\sum_i n_{i,th} k_B T_i + n_e k_B T_e\right) V$ is the energy of the thermal components, k_B is the Boltzmann constant, $n_{i,th}$ is the thermal ion density, n_e is the electron density, T_i is the ion temperature, T_e is the electron temperature, V is the plasma volume, P_{inj} is the absorbed injection power, P_n is the power in neutrons, P_{rad} is the radiation loss power, and τ_E is the energy confinement time of thermal components.

Note that we neglect the losses of fast deuterons during deceleration. The fusion power for reactions involving only thermal components is calculated using the formulas from [8]. For reactions with the participation of fast components, the reaction cross sections [8] averaged over the approximate velocity distribution function of fast particles are used.

Radiation losses include bremsstrahlung and cyclotron radiation. At high temperatures, the bremsstrahlung is calculated according to [9]. For cyclotron losses, a modified Trubnikov formula is used [10]. The reflection coefficient of cyclotron radiation by the wall is taken to be $R_w = 0.85$. Note that, in regimes with powerful injection and an increased fusion reaction rate, the losses associated with bremsstrahlung are small. The effect of cyclotron losses is noticeable at high temperatures.

We consider the balance of particles. Two populations can be distinguished—thermal and fast. Thermal ions (further denoted by the subscript *th*) can appear in plasma upon evaporation of introduced solid grains, upon ionization of cold gas, and also as a result of deceleration and thermalization (relaxation) of the injected beam of fast particles. The source of fast ions (the subscript *f*) is proportional to the injection power. The balance of thermal and fast ions of the kind *i* can be expressed by the equations [11, 12]

$$\frac{n_{i,th}}{\tau_p} = \frac{n_{i,f}}{\tau_f} + (dn/dt)_0 = \frac{n_{i,f}}{C_{inj}\tau_f}, \tag{7}$$

$$\frac{n_{i,f}}{\tau_f} = \frac{P_{inj}}{VE_0} - \frac{n_{i,f}}{\tau_L}. \tag{8}$$

Here $(dn/dt)_0$ is the thermal ion source not associated with injection; the source of injected particles is $(dn/dt)_{inj} = P_{inj}/(VE_0)$; E_0 is the injection energy; τ_p is the confinement time of thermal ions; τ_f is the relaxation time of the fast particle beam; τ_L is the time of losses of fast particles; the parameter C_{inj} takes into account the ratio of thermal ion sources;

$$C_{inj} = \left[1 + \frac{(dn/dt)_0}{n_{i,f}/\tau_f}\right]^{-1}. \tag{9}$$

If the thermal population is formed only owing to the thermalization of fast ions, then $C_{inj} = 1$. The value $C_{inj} \approx 0$ corresponds to regimes with a negligible content of fast particles. Here we consider the case $C_{inj} = 1$.

The electron density satisfies the quasineutrality condition

$$n_e = \sum_i Z_i(n_{i,th} + n_{i,f}), \tag{10}$$

where Z_i is the ion charge ($Z_i = 1$ for the plasma containing hydrogen isotopes).

The power gain in the plasma is

$$Q = P_{fus}/P_{inj}. \qquad (11)$$

The relaxation time of the population of fast ions corresponding to the distribution function [13] is

$$\tau_f \approx \frac{1}{3}\tau_s \ln[(E_0/E_c)^{3/2} + 1], \qquad (12)$$

where E_0 is the initial energy of particles (injection energy) and E_c is the critical energy (corresponding to the equality of the slow-down rates on electrons and thermal ions).

The thermalization of fast ions occurs largely as a result of collisions with electrons; therefore, the temperature of thermal ions is assumed to be approximately equal to the electron temperature: $T_i = T_e = T$.

Equations (6)–(8) produce the relations

$$\frac{\tau_f}{\tau_E} = \frac{2E_0}{3k_B T_e}\left[1 + (1-\alpha_n)Q - \frac{P_{rad}}{P_{inj}}\right] - \frac{2K_\tau}{C_{inj}}, \qquad (13)$$

$$\frac{n_{i,f}}{n_{i,th}} = \frac{2E_0}{3k_B T_e}\frac{C_{inj}}{K_\tau}\left[1 + (1-\alpha_n)Q - \frac{P_{rad}}{P_{inj}}\right] - 2, \qquad (14)$$

where $K_\tau = \tau_p/\tau_E$ is the ratio of the confinement times of particles and energy for thermal components.

The dimensions and density of the plasma should correspond to the beam attenuation length [14]

$$l \approx \frac{5.5\times10^{17}E_0}{n_e A_0}, \qquad (15)$$

where l is measured in meters, E_0 is the injection energy in kiloelectron-volts, n_e is the electron density in m^{-3}, and A_0 is the atomic number of the injected particle (for deuterium, $A_0 = 2$).

For complete trapping of the beam in the plasma and uniform heating of the plasma column, the relation $l \approx 2a$ should hold.

3. CALCULATION RESULTS

The analysis showed that stationary regimes are possible at temperatures limited by the maximum value

$$T_{\max} \approx \frac{C_{inj}}{3K_\tau}\frac{E_0}{k_B}. \qquad (16)$$

At $T > T_{\max}$, the stationary regime is not possible at a noticeable content of fast particles. If the confinement time of thermal components is large, then the accumulation of the thermal population leads to the disappearance of the effect of fast particles.

The main parameters specified in the calculations were the energy of injected deuterons E_0, the ratio of the plasma pressure to magnetic pressure β, and the radius of the plasma column a. The temperature of thermal components T was varied; in this case, the required energy confinement time of thermal components τ_E was determined from the balance of energy. The relative content of fast particles $n_{i,f}/n_{i,th}$, ion and electron densities $n_i = n_{i,th} + n_{i,f}$ and n_e, (vacuum) magnetic field induction B_0 necessary for the plasma confinement, energy gain in the plasma Q, neutron energy flow J_n from the plasma, and other parameters were determined in calculations.

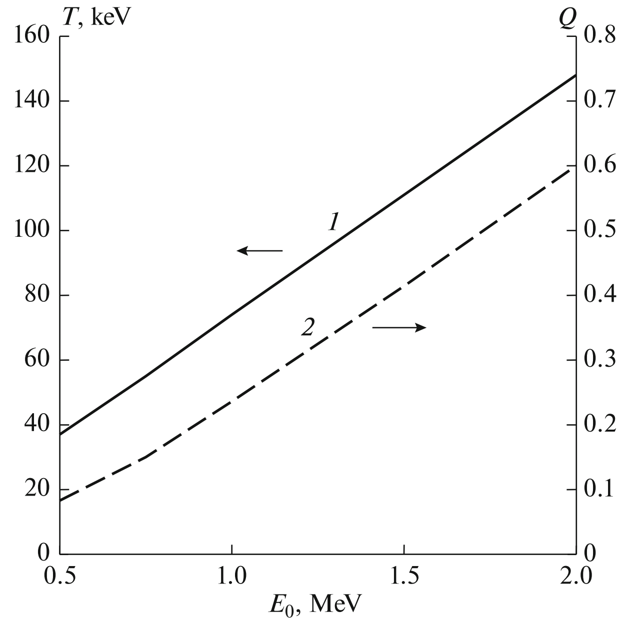

Fig. 1. Temperature of thermal components of the plasma (*1*) and power gain (*2*) as a function of the injection energy at $n_{i,f} = n_{i,th}$.

The calculation results are presented in Figs. 1–3 for regimes in which the density of fast ions is equal to the density of thermal ones ($n_{i,f} = n_{i,th}$).

The temperature increases with the increase in the energy confinement time of thermal components τ_E; in the case, Q also increases, and the fraction of fast particles decreases. The power gain in the plasma Q depends on the injection energy E_0 and temperature of thermal components T. The T and Q values in Fig. 1 correspond to regimes in which $n_{i,f} = n_{i,th}$ is achieved.

Figure 2 shows the corresponding confinement time values of thermal components and also the times of ion-ion collisions for thermal ions. Figure 3 shows the vacuum magnetic field induction B_0 and neutron energy flow from the plasma J_n. Data in Figs. 2 and 3 correspond to the fixed density $n_i = n_e = 1.4\times10^{20}$ m^{-3}. Since the plasma size a is associated with the injection energy and the plasma density by relation (15), at the indicated density, the plasma column radius is $a = 1$ m for $E_0 = 500$ keV, $a = 2$ m for $E_0 = 1$ MeV, etc. The increase in the required energy confinement time of

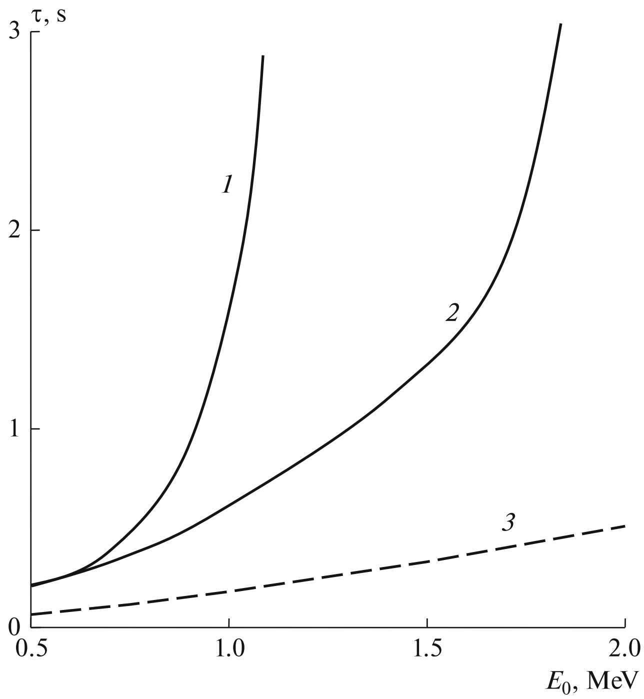

Fig. 2. Required energy confinement time of thermal components at $\beta = 0.1$ (*1*) and $\beta = 0.5$ (*2*); the time of ion-ion collisions (3); $n_{i,f} = n_{i,th}$; $n_i = n_e = 1.4 \times 10^{20}$ m^{-3}.

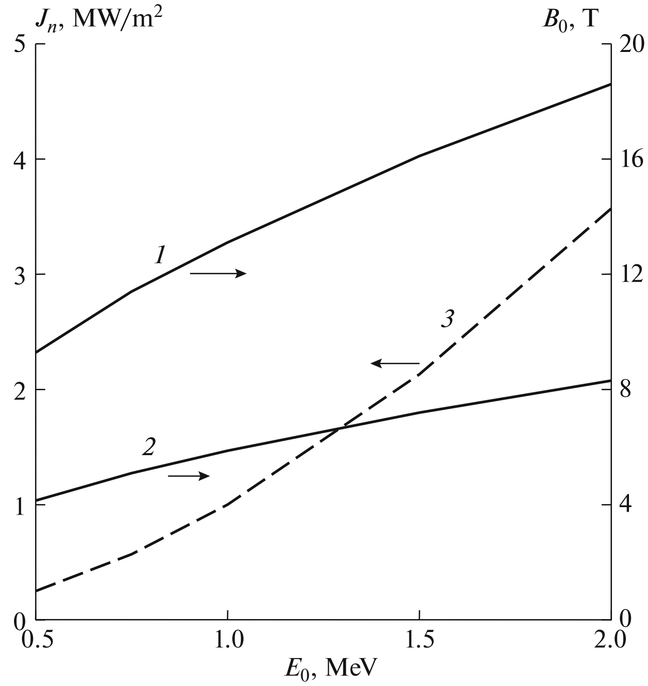

Fig. 3. Vacuum magnetic field induction at $\beta = 0.1$ (*1*) and $\beta = 0.5$ (*2*); neutron energy flow from the plasma (*3*); $n_{i,f} = n_{i,th}$; $n_i = n_e = 1.4 \times 10^{20}$ m^{-3}.

thermal components τ_E at the decrease in β is explained by cyclotron losses. At high β, they are relatively small because of the diamagnetic weakening of the magnetic field in the plasma. The effect of cyclotron losses becomes significant at high temperatures ($T_e > 50$ keV) achieved at injection energies of $E_0 >$ 750 keV.

We also note that, at $E_0 > 1$ MeV, the neutron flow $J_n > 1$ MW/m^2, which is unfavorable from the point of view of the resource of the first wall. The gain at $E_0 =$ 1 MeV is only $Q = 0.2$.

4. CONCLUSIONS

As a result of the analysis, the requirements for the parameters of the system that uses the deuterium plasma heated by powerful neutral beam injection to obtain fast neutrons were determined. It is possible to say that the tokamak is not suitable for these purposes because of the low β, and a system with $\beta \sim 0.5$ or higher is required. An open trap, for example, could potentially be considered. Its main advantage is its simplicity of the design. The confinement of thermal components improves with increasing temperature in an open trap. Despite the presence of a loss cone, fast ions are well confined owing to the relatively weak angular Coulomb scattering. The estimates showed that the scattering time of fast ions is an order of magnitude longer than the relaxation time of the beam. On the other hand, the required energy confinement time of thermal components is about an order of magnitude larger than the time of ion-ion collisions, which is not easy to implement in an open trap. Among the traps with closed magnetic field lines, one can note the field-reversed configuration (FRC), in which $\beta \sim 1$. The issues of obtaining high temperatures (~100 keV) and injection of ions with energies of 1 MeV and higher, of course, require further analysis, since now it is difficult to say whether there are fundamental physical limitations for the implementation of the required parameters in such systems.

CONFLICT OF INTEREST

The authors declare that they have no conflicts of interest.

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Translated by L. Mosina