Deuterium-lithium plasma as a source of fusion neutrons

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Abstract. The concepts of deuterium-tritium (D–T) fusion neutron source are currently developed for hybrid fusion–fission systems and the waste transmutation ones. The need to use tritium technologies is a deterrent factor in this promising direction of energy production. Potential possibilities of using systems that do not require tritium developments are of a significant interest. A deuterium-deuterium (D–D) reaction is considered for the use in demonstration fusion neutron sources. The product of this reaction is tritium, which will burn in the plasma with the emission of fast neutrons. D–D reaction is significantly slower then D–T reaction. Present study shows an increase in neutron yield using a powerful injection of the beam of deuterium atoms. The reactions of the deuterium with lithium isotopes are considered. In some of these reactions, fast neutrons can be obtained. The results of the calculation of the neutron yield from the deuterium lithium plasma are discussed. The estimates of the parameters needed for the realization of a source of fusion neutrons are presented.

1. Introduction
Development of powerful sources of fast (~ 10 MeV) neutrons on the basis of nuclear fusion reactions is a promising direction of future energy production systems. Such systems have the potential to solve the problems of radioactive waste utilization, nuclear fuel cycle circuit. They can be considered as a drivers of a hybrid fusion–fission reactors for nuclear power generation and nuclear fuel production. Projects of fusion neutron sources are usually based on D–T reaction that requires development of tritium breeding technologies. The reaction of deuterium with lithium is considered for accelerator-driven systems [1, 2].

D–D reaction is apparently attractive from the point of view of availability of primary deuterium fuel. There are two channels of this reaction:

\[ \text{D} + \text{D} \rightarrow n \text{ (2.45 MeV)} + ^3\text{He} \text{ (0.817 MeV)}, \]

\[ \text{D} + \text{D} \rightarrow p \text{ (3.02 MeV)} + \text{T} \text{ (1.01 MeV)}. \]

Energy of D–D neutrons is not high enough for the fusion–fission applications since the typical transmutation thresholds are about 5 MeV. D–D plasma can be a source of neutrons with energy 14 MeV which are produced as a result of burn of the tritium produced in the reaction (2). D–T fusion reactivity is high and therefore much of the tritium will burn before it will be lost from the trap. Estimates showed tritium rate burning is higher than 70% [3, 4]. Note, that for systems based on D–D reactions plasma power gain reaches a value of \( Q > 1 \) only if the ratio of the plasma pressure to the magnetic pressure \( \beta \approx 0.5 \) and higher [5]. So, for deuterium-based fusion high-pressure plasma
systems should be considered: open mirror trap, field reversed configuration, and perhaps a spherical tokamak [6–9]. Small amount of lithium can improve the energy balance of D–D-based plasma, because lithium can react with deuterium. A number of such reactions produce neutrons. Intense neutral beams of fast atoms can be used to increase the reaction rate [10, 11].

2. D–D fusion cycle with lithium doping

The following additional fusion reactions are possible in a deuterium plasma with some amount of lithium [12]:

\[
\begin{align*}
 D + ^6\text{Li} &\rightarrow p + ^4\text{He} + 2.257 \text{ MeV}, \\
 D + ^6\text{Li} &\rightarrow p (4.397 \text{ MeV}) + ^7\text{Li} (0.628 \text{ MeV}), \\
 D + ^7\text{Li} &\rightarrow n (2.958 \text{ MeV}) + ^7\text{Be} (0.423 \text{ MeV}), \\
 D + ^6\text{Li} &\rightarrow n (~0.66 \text{ MeV}) + ^4\text{He} + ^4\text{He} + 1.794 \text{ MeV}, \\
 D + ^7\text{Li} &\rightarrow ^4\text{He} + ^4\text{He} + 22.371 \text{ MeV}, \\
 D + ^7\text{Li} &\rightarrow n + ^4\text{He} + ^4\text{He} + 15.121 \text{ MeV}.
\end{align*}
\]

In figure 1, fusion reactivity parameters are presented for reactions (1)–(8) for a Maxwellian plasma.

Consider fusion cycle, wherein the tritium produced in the reaction (2) and (3) is burned by reaction with deuterium:

\[
 D + T \rightarrow n (14.1 \text{ MeV}) + ^4\text{He} (3.5 \text{ MeV}).
\]

In principle other products of reactions (1)–(6) may also take part in secondary reactions, for example:
The cross section of D–T reaction greatly exceeds the other reactions therefore we assume that tritium may burn completely before leaving the trap, the other products leave the trap without taking part in secondary reactions.

Reaction (8) has two channels. At high energies of the colliding nuclei the direct interaction of nucleons is dominant mechanism accompanied by the birth of neutrons with energy about 14 MeV \cite{13}. At moderate energies in fusion plasma the compound nucleus channel is more probable \cite{14}. In this case, estimate neutron energy about 5 MeV.

In the analysis we use the plasma energy balance equation (per unit volume)

\[ P_{aux} + P_{fus} = P_n + P_{rad} + \frac{W_{th}}{\tau_E}, \]

where \( W_{th} = \frac{3}{2} \left( \sum_i n_i k_B T_i + n_e k_B T_e \right) \) is the thermal energy; \( k_B \) is the Boltzmann constant; \( n_i \) and \( n_e \) are ion and electron densities; \( T_i \) and \( T_e \) are ion and electron temperatures (it is assumed that \( T_e = T_i = T \)); \( P_{aux} \) is absorbed power of external heating; \( P_{fus} \) is fusion power; \( P_n \) is neutron power; \( P_{rad} \) is radiation loss power (at high \( \beta \) only bremsstrahlung considered \cite{6}); \( \tau_E \) is thermal energy confinement time.

Figures 2 and 3 show the results of calculations for D–\( ^6 \)Li and D–\( ^7 \)Li mixtures. Figure 2a shows the values of the Lawson parameter \( L = n \tau \), where \( n \) is total density of all plasma components, \( \tau = \tau_E \) is thermal energy confinement time. In figure 2b, triple parameter \( LT = n \tau T \) is presented. These Lawson parameter and triple parameter \( LT = n \tau T \) correspond to the regime with \( Q = P_{fus}/P_{aux} = 1 \). Figure 3 shows the yields of neutrons for D–\( ^6 \)Li and D–\( ^7 \)Li mixtures as a function of the plasma temperature. The reasonable lithium fraction is \( x_{Li} = 0.3–0.4 \). Lawson parameter is \( n \tau \sim 2 \cdot 10^{22} \, m^{-3} \cdot s \) at \( T \sim 100 \, keV \). In this case, the 14 MeV neutron yield is about 50% in D–\( ^6 \)Li mixture, and 35% in D–\( ^7 \)Li mixture.

**Figure 2.** Lawson parameter \( n \tau \) (a) and parameter \( n \tau T \) (b) for D–\( ^6 \)Li (solid) and D–\( ^7 \)Li (dashed) for different lithium to deuterium density ratios: 1 – \( x_{Li} \) = 0, 2 – 0.1, 3 – 0.2, 4 – 0.35, 5 – 0.4.
Figure 3. Neutron yield from $^6$Li ($x_{Li} = 0.35$) (a) and $^7$Li ($x_{Li} = 0.4$) (b) mixtures with complete tritium burn: 1 – neutrons of all energies total, 2 – 14 MeV neutrons total, 3 – 14 MeV neutrons resulting from the burn of tritium from reaction (2), 4 – 14 MeV neutrons resulting from the burn of tritium from reaction (3), 5 – 2.45 MeV neutrons from reaction (1), 6 – 2.958 MeV neutrons from reaction (5), 7 – neutrons (~ 0.66 MeV) from reaction (6), 8 – neutrons (~ 5 MeV) from reaction (8).

3. Conclusions
Analysis showed that deuterium plasma without an external source of tritium can potentially be used to generate fast neutrons. Small lithium dopant improves the performances of the fusion cycle. Further improvement can be achieved via a powerful neutral beam injection [15]. In the case of lithium coated reactor first wall, its erosion doesn’t cause negative effects. It is difficult to say about details of a particular type of magnetic trap for deuterium–lithium fusion system. The neutron source based on open mirror trap could potentially be considered for the presented fusion fuel cycles.

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