Limiting energy gain in deuterium plasma at powerful injection heating

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Abstract. The possibility of neutron production in deuterium plasma (with no external tritium breeding) is considered for the case of high ratio of fast particles. High amount of fast deuterons is sustained by a powerful injection of neutral beams. In this case, fusion reactivity is essentially higher that the reactivity in the Maxwellian plasma. The reactivity is calculated by taking into account non-equilibrium velocity distribution function of fast deuterons. Plasma power gain $Q \sim 0.5$ can be achieved at electron temperature of approximately 100 keV and deuteron injection energy of approximately 2 MeV. To realize such a scheme for this type of fusion fuel, the plasma pressure should be approximately equal to the magnetic pressure.

1. Introduction

Sources of fusion neutrons with an energy of 14 MeV can be the drivers in a hybrid fusion–fission reactor. In addition, they can be used for the disposal of radioactive wastes and can be involved in the closure of the nuclear fuel cycle [1, 2].

In present work, we consider the possibility of obtaining a neutron yield from deuterium plasma without an external tritium source. Deuterium as an energy resource is attractive due to its availability. However, the rate of D–D reactions is more than an order of magnitude lower than the rate of the D–T reaction. Therefore, currently, obtaining a positive energy yield from deuterium plasma with no tritium is practically not considered. In our study, a strong neutral beam injection (NBI) heating is assumed to increase the reaction rate. Under such conditions, significant population of fast particles is maintained.

In deuterium plasma, the following fusion reactions are possible:

\begin{align}
D + D &\rightarrow p \ (3.02 \text{ MeV}) + T \ (1.01 \text{ MeV}), \\
D + D &\rightarrow n \ (2.45 \text{ MeV}) + ^{3}\text{He} \ (0.817 \text{ MeV}), \\
D + T &\rightarrow n \ (14.1 \text{ MeV}) + ^{4}\text{He} \ (3.5 \text{ MeV}), \\
D + ^{3}\text{He} &\rightarrow p \ (14.68 \text{ MeV}) + ^{4}\text{He} \ (3.67 \text{ MeV}).
\end{align}

Fusion neutrons originating from the D–T reaction (3) with energies of approximately 14 MeV are of particular interest. The blanket technology for tritium breeding has certain difficulties. Therefore, it is reasonable to consider the possibility of producing fast fusion neutrons in plasma based on the available deuterium. The energy of neutrons produced in the reaction (2) is not sufficient for fission of...
fertile isotopes. Reaction (1) produces tritium that can effectively react with deuterium, which produces 14 MeV neutrons [3–6]. The yield of fast 14 MeV neutrons can be more than 50% of the total fusion power $P_{fus}$. Due to low reactivity of Maxwellian D–D plasma, the requirements for the magnetic trap are very stringent, particularly due to the large proportion of radiation losses [7, 8]. The possible solution for this problem is to increase the reaction rate in the plasma with a significant population of fast (epithermal) particles. In the present work, we consider regimes with $Q \sim 0.5$ in deuterium plasma that is heated by a powerful NBI of fast deuterium atoms.

2. Theoretical background
The analysis is based on the model [9–11] of energy and particle balance for the NBI-heated plasma by taking into account the velocity distribution function of injected fast particles [12, 13].

In the stationary regime, energy and particle balances are expressed using the following equations:

$$P_{fus} + P_{nj} = P_n + P_{rad} + \frac{W_{th}}{\tau_E},$$

(5)

$$n_{i,th} = \frac{n_{i,f}}{\tau_p},$$

(6)

$$\frac{n_{i,f}}{\tau_f} = \frac{P_{nj}}{E_0},$$

(7)

where $P_{fus}$ is the fusion power, $P_{nj}$ is the NBI heating power (absorbed), $P_n$ is the neutron power, $P_{rad}$ is the radiation loss power, $W_{th} = \frac{3}{2} (n_{i,th} k_B T_i + n_e k_B T_e)$ is the thermal energy, $k_B$ is the Boltzmann constant, $n_{i,th}$ is the thermal ion density, $n_{i,f}$ is the fast ion density, $n_e$ is the electron density, $T_i$ is the ion temperature, $T_e$ is the electron temperature, $\tau_E$ is the energy confinement time for the thermal components, $\tau_p$ is the thermal particle confinement time, $\tau_f$ is the beam relaxation time, $E_0$ is the injection energy.

For high-pressure plasma ($\beta = plasma pressure/magnetic pressure \sim 1$), radiation losses consist primarily of bremsstrahlung, and they can be calculated using the formulas in [14]. Synchrotron losses can be calculated using the formula in [15]. It is assumed, that $T_e = T_i = T$, and $\tau_p = 3 \tau_E$.

Two limiting cases are considered to estimate the fast particle reactivity. In the first case, the distribution function is uniform in the velocity space at $v < v_0$, where $v_0$ is the initial velocity of deuterium nuclei. In the second case, monoenergetic distribution is used ($v = v_0$ for all deuterons).

In the case of uniform distribution, the fast reactivity is $<\sigma v> = \int_0^{v_0} \sigma(v)v^3 dv$. Monoenergetic approximation is acceptable if the particle confinement time is less than the time of beam relaxation. In this case, fast deuteron reactivity is $<\sigma v> = \sigma(v_0)v_0$. Note that under monoenergetic and uniform approximations, the reactivity depends only on the injection energy, and it is independent of the plasma temperature. Figure 1 shows fusion reactivity that involves fast particles. The fast particle reactivity is approximately one order higher than the reactivity in a Maxwellian plasma. For example, at a typical temperature of Maxwellian plasma of $T = 100$ keV, the D–D reactivity is $<\sigma v> = 0.2 \cdot 10^{-22}$ m$^3$/s. For the injection energy of $E_0 = 2$ MeV, the fast reactivity is $<\sigma v> = 1.0 \cdot 10^{-22}$ m$^3$/s. In Figure 1, one can see the difference of approximately 30% between uniform and monoenergetic approximations. Note that for the conditions under consideration, the injection energy of $\sim 1$ MeV is close to the critical energy (at which the beam–electron and beam–ion slow-down rates are compared), while the velocity distribution function varies slightly. Therefore, for the estimates, we use a homogeneous approximation.
Plasma size and density correspond to the length of the beam attenuation [16]

\[ l = \frac{5.5 \times 10^{17} E_0}{n_e A_0} \]  

(9)

where \( l \) is the length of the beam attenuation in meters, \( E_0 \) is injection energy in keV, \( n_e \) is electron density in m\(^{-3}\), and \( A_0 \) is the atomic number of the injected particle (\( A_0 = 2 \) for deuterium).

For a complete capture of the beam in the plasma and for a heating penetration into the plasma column, the relation \( l = 2a \) is assumed.

### 3. Results of calculations

For the calculations, the main input parameters are: energy of injected deuterons \( E_0 \), the ratio \( \beta \) of plasma pressure to magnetic pressure, radius \( a \) of the plasma column. Thermal component temperature \( T \) was varied. Required energy confinement time \( \tau_E \) was defined from the energy balance equation. The following parameters were calculated: the fast to thermal ion density ratio \( n_{f_i} / n_{th_i} \), ion density \( n_i = n_{i,th} + n_{i,f} \); electron density \( n_e \); magnetic field induction \( B_0 \) (vacuum value) required for the confinement at given \( \beta \); plasma power gain factor \( Q \); neutron energy flux from the plasma \( J_n \); and other parameters.

In Figures 2–4, the calculation results are presented for regimes when fast ion density is equal to thermal ion density (\( n_{i,f} = n_{i,th} \)). If energy confinement time \( \tau_E \) increases, temperature and \( Q \) increase, too, but fast ion ratio decreases.

**Figure 2.** Temperature of thermal components (solid) and plasma power amplification factor (dashed) at \( n_{i,f} = n_{i,th} \) versus injection energy: 1 – \( \beta = 0.1 \), 2 – \( \beta = 0.5 \).

**Figure 3.** Required confinement time for thermal component (solid) and ion-ion collision time (dashed) at \( n_{i,f} = n_{i,th} \) versus injection energy: 1 – \( \beta = 0.1 \), 2 – \( \beta = 0.5 \).
In Figure 3, the corresponding values of thermal energy confinement time are presented. Ion-ion collision time values are shown. In Figure 4, magnetic field induction $B_0$ and neutron energy flux $J_n$ are presented. The data in Figures 2–4 correspond to fixed density $n_i = n_e \approx 1.4 \times 10^{20} \, \text{m}^{-3}$. Because plasma radius $a$ is defined by the equation (9), it is $a = 1$ m at $E_0 = 500$ keV, $a = 2$ m at $E_0 = 1$ MeV, etc. The increase of the required thermal energy confinement time $\tau_E$ with $\beta$ decreasing is connected with synchrotron losses. At high $\beta$, synchrotron losses are relatively small due to plasma diamagnetism. The influence of synchrotron losses is sufficient at high temperatures ($T_e > 50$ keV), which can be archived at injection energy $E_0 > 750$ keV.

Note that at $E_0 > 1$ MeV, the neutron flux $J_n > 1$ MW/m$^2$, which is unfavorable from the point of view of the first wall durability. The power gain at $E_0 = 1$ MeV is $Q = 0.2$.

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Figure 4. Neutron energy flux from the plasma (solid) and vacuum magnetic field induction (dashed) at $n_{i,f} = n_{i,th}$ versus injection energy: 1 – $\beta = 0.1$, 2 – $\beta = 0.5$. 