Simulations of fusion neutron source based on the axially symmetric mirror trap for the thorium hybrid reactor

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Abstract. The axially symmetric open mirror trap is considered as a neutron source for the hybrid thorium reactor. Plasma parameters are optimized in order to achieve the maximum neutron yield in the volume surrounded by the subcritical fuel assembly while meeting the stability criteria. For plasma consisting of equal amounts of deuterium and tritium isotopes, in the fuel assembly region, the neutron yield was found to be \(0.6 \times 10^{17}\) n/s at an input power of 20 MW, and it will increase to \(2.6 \times 10^{17}\) n/s if the input power increases two times. In optimal regimes, the plasma parameters were close to those achieved in experiments at the GDT facility.

1. Introduction

Over the past few years, the project for the high-temperature gas-cooled thorium reactor has been considered in Tomsk Polytechnic University\textsuperscript{[1]}. As the further development of this project, the hybrid reactor is proposed with the subcritical fuel assembly (SFA) and the axially symmetric mirror trap as a neutron source\textsuperscript{[2]}. In this study, the plasma parameters in the open mirror trap are simulated. The goal of this study is to select a configuration that provides the maximum neutron yield in the SFA region.

The mirror trap configuration is described in detail in\textsuperscript{[2]}. It has some distinctive features. The mirror trap is an axially symmetric system confining two ion components named the warm and the fast ions. For the warm ions, the temperature is relatively low and the collision rate is high, so the ion distribution function is close to the Maxwellian one. The population of fast ions is formed mainly due to the charge-exchange collisions between the warm ions and the fast neutrals provided by the injected atomic beams. The main channel of the particle and energy losses is the "longitudinal loss" channel formed by the plasma flowing along the magnetic field through the magnetic mirrors. The energy is introduced into the system by injecting the atomic beams with the individual atom energies from several tens to hundreds keVs. The angle between the injector and facility axes is 30°; it is chosen as a compromise between the desire to improve the plasma parameters and the need to comply with the engineering restrictions. To maintain the material balance, the so-called "gas puffing" is used. The gas jets at room temperature are injected into the plasma column, where they are ionized, thus, increasing the warm ion density. In this paper, we mainly consider the configurations with the deuterium-tritium plasma, in which the inputted power and the gas puffing flows are shared between two equal isotopic portions. The main cell is located between the magnetic mirrors with a magnetic field of 15–20 T and is divided into two parts. In the first part, the magnetic field is almost uniform, and it is used for confining the warm component and injecting the atomic beams. The second part is
inside the SFA. The magnetic field here is approximately twice as high as that in the first part, and smoothly increases towards the magnetic mirrors, ensuring the almost uniform neutron yield along the facility axis. The geometric characteristics of the SFA were chosen similarly to those in [2]: the length of the neutron emission region is 3 m, and the plasma column radius is 10 cm.

The neutron source configurations considered in this paper, as well as the restrictions imposed on the plasma parameters, are described in Section 2. The simulation results are presented in Section 3. The brief conclusions are formulated in Section 4.

2. Formulation of the problem
Six neutron source configurations were studied in this work. The magnetic field profile and the injection power $P_{\text{inj}}$ were fixed for each configuration, while the injection energy (the energy of particles in the heating beams) $E_{\text{inj}}$ and the puffed gas flow $J_{\text{gas}}$ were varied. The DOL code [3] was used for simulating the main plasma parameters, including the neutron yield. However, the DOL code does not take into account the development of instabilities. Therefore, the stability criteria formulation and verification are the essential parts of this work. The calculations that do not meet the stability criteria were discarded, since the development of instabilities would lead to the considerable degradation of the neutron yield, as compared to that obtained using the DOL code.

The following types of instabilities were taken into account, when formulating the stability criteria. The most dangerous hydrodynamic instability for the mirror traps is the flute-like mode. However, according to [4], there are several methods for suppressing this mode without considerably modifying the facility. For this reason, in this paper, this issue is considered to be resolved. A number of instabilities occur at high plasma pressures, such as the ballooning and mirror modes. The GDT facility has demonstrated [4] the stable plasma confinement at a relative pressure of $\beta_v = 0.55$. The condition $\beta_v < 0.5$ is used to ensure the stable plasma confinement and to exclude the development of the high-beta modes. Looking ahead, we note that this condition was not violated in all the configurations under consideration. The kinetic instabilities can develop, if the distribution function considerably differs from the Maxwellian one. To stabilize the warm component, we used the estimation criterion $\tau_{\text{kin}} / \tau_{\text{gd}} \leq 1$, where $\tau_{\text{kin}}$ and $\tau_{\text{gd}}$ are the confinement times of the warm ions calculated for the classical mirror trap and for the trap with the gas-dynamic plasma confinement, respectively. We note that the classical mirror trap (the case of $\tau_{\text{kin}} / \tau_{\text{gd}} >> 1$) is subjected to the development of a number of kinetic instabilities. The stability conditions for the fast ions were considered according to [5]. The sufficiently high density of the warm ions is required to stabilize the DCLC mode: $n_w / n_f \geq 0.1$, where $n_w$ and $n_f$ are the densities of the warm and fast ions, respectively. And to stabilize the double-humped instability, the warm ion temperature $T_w$ should not be too low as compared to the fast ion energy: $T_w / E_{\text{inj}} \geq 0.01$.

Figure 1. The magnetic field $B$ distributions along the $z$ axis of the facility for different configurations. Beam injection is performed at the point $z = 0$ m. The SFA is located in the coordinate ranges of $6 \, m < z < 9 \, m$ and $4 \, m < z < 7 \, m$ for the $v1$–$v2$ and $v3$–$v6$ configurations, respectively.
The magnetic field profiles in the main cell used in the calculations are shown on Fig. 1. In the first four configurations, the injection power was $P_{\text{inj}} = 20 \text{ MW}$ and the magnetic field in the magnetic mirrors was $15 \text{ T}$. For the v1 configuration, the field was chosen the same as in [2]. Two modifications of the v1 configuration are considered: the field between the magnetic mirrors was increased twice (the v2 and v4 configurations), and the cell length (in the region of the beam injection) was reduced twice (the v3 and v4 configurations). In the v5 and v6 configurations, the injection power was increased to 30 and 40 MW, respectively. In these configurations, the field profile was the same as in the v3 configuration, except for the field in the magnetic mirrors, which was slightly increased to 20 T. A series of calculations were performed for each configuration, among which the configurations that meet the stability conditions were selected. Among these options, the optimal one was chosen with the maximum neutron yield in the SFA region.

3. Results and discussion

At first, the results of calculations for the v1–v4 configurations were compared in order to estimate the effect of the magnetic field profile. A twofold increase in the field leads to a decrease in all the parameters: the neutron yield decreases two times, the ion temperature drops 2-3 times, and the plasma density decreases 1.5–2 times. For this reason, the v2 and v4 configurations were found to be less efficient. The comparison of the v1 and v3 configurations demonstrates that, at the same collision rates $\tau_{\text{kin}} / \tau_{\text{gd}} \approx 1$, in the shorter device, the neutron yield is 20–25% higher. Therefore, the v1 configuration was excluded from further consideration. Further reduction of the cell length (in the region of the beam injection), as compared to the v3 configuration, is still possible, but it may meet difficulties due to the finite sizes of the injector vessels and the magnetic system coils. In the second stage, the v3, v5 and v6 configurations with the similar magnetic field profiles and the gradually increasing heating powers were considered in detail together with the additional v3DD configuration for the pure deuterium plasma. The optimal calculated parameters for these configurations are shown in Table 1.

**Table 1.** The optimal calculated parameters for different configurations. The parameters for deuterium and tritium are separated by a slash.

| Configurations: | v3 | v5 | v6 | v3DD |
|-----------------|----|----|----|------|
| Plasma isotopic composition | 50% D + 50% T | 100% D |
| Total injected power, MW | 20 | 30 | 40 | 20 |
| Injection energy (energy of single atom), keV | 50 | 70 | 70 | 40 |
| Gas puffing (for each isotope), eq. kA | 2  | 2.5 | 3.2 | 4 |
| Electron temperature, keV | 0.57 | 0.74 | 0.77 | 0.54 |
| Ion temperature, keV | 0.41/0.40 | 0.65/0.63 | 0.72/0.70 | 0.46 |
| Fast ions density in the SFA region, $10^{13} \text{ cm}^{-3}$ | 3.6/5.0 | 4.7/6.4 | 5.5/7.5 | 7.7 |
| Warm ions density in the SFA region, $10^{13} \text{ cm}^{-3}$ | 0.7/0.9 | 1.4/1.8 | 1.8/2.3 | 1.9 |
| Maximum relative pressure $\beta$ | 0.1 | 0.18 | 0.22 | 0.08 |
| Captured fraction of the heating beams | 0.89/0.94 | 0.93/0.96 | 0.95/0.98 | 0.91 |
| Neutron yield in the SFA region, n/s | $0.62 \times 10^{17}$ | $1.8 \times 10^{17}$ | $2.6 \times 10^{17}$ | $3.9 \times 10^{14}$ |
| Total neutron yield, n/s | $1.4 \times 10^{17}$ | $3.9 \times 10^{17}$ | $5.6 \times 10^{17}$ | $8.7 \times 10^{14}$ |

Time evolution of the plasma parameters has a distinctive feature that may be important for the neutron balance of the subcritical fuel assembly. In the initial stage of the discharge, the electron temperature increases faster than that of the warm ions. As a result, the neutron production rate becomes stationary in approximately 0.1 s. In this case, the maximum neutron yield is achieved in 35 ms after the beginning of injection, and this maximum exceeds the stationary neutron production rate.
by 8%. After the plasma heating is switched off, the neutron production rate drops much faster: during the first 2.5 ms, it drops approximately twice, and during the next 5 ms, it decreases another 20 times.

4. Conclusions
The mirror trap configuration with deuterium-tritium plasma appropriate for using as a neutron source for the hybrid thorium reactor is considered in the paper. It is shown that a neutron yield of \(1.4 \times 10^{17}\) n/s can be achieved inside the subcritical fuel assembly at a plasma heating power of 20 MW. This is approximately 45% of the total amount of neutrons produced in plasma. The neutron yield will increase up to \(5.6 \times 10^{17}\) n/s, if the heating power is increased up to 40 MW. The neutron production rate reaches the stationary value in 0.1 s after the injection is switched on; and after it is switched off, it drops much faster. We note that the optimal plasma parameters are quite close to those achieved in experiments at the GDT facility in the BINP SB RAS [5].

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