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The regime of the improved confinement with deuterium pellet injected into plasmas of tokamak T-10 with W and Li limiters

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Abstract. In this paper, we present the first, after replacing a graphite limiter with a tungsten limiter, experimental results of the regimes of improved plasma confinement in the T-10 tokamak when injecting deuterium pellets. Comparison with the results of previous experiments with a graphite limiter shows the preservation of the improved confinement effect. Preliminary results of the experiments on the change in poloidal angle of injection of pellets allow us to say that with the central injection, the maximum effect of improved confinement is observed.

1. Experimental data and results

Studies of plasma scenarios on improved energy confinement and particle confinement during the injection of deuterium pellets in the T-10 tokamak have been performed for a long time [1]. The main purpose of these experiments is to study the regimes with improved plasma confinement. The T-10 tokamak limiter has a circular cross-section, main radius of 1.5 m, radius of unmovable circular limiter of 0.33 m, radius of movable limiter of 0.2–0.3 m, toroidal magnetic field $B_t \leq 5$ T. Before the experimental campaign of 2015–2016, the circular and movable limiters, which were made from graphite, were replaced with tungsten. As a result, it became possible to investigate the effect of impurities, their amount and distribution, on the characteristics of the regime of improved confinement when injecting deuterium pellets.

In the experiments, a modified multi-barrel pellet injector (MPI-8) from the Pelin firm was used. After the modification, MPI-8 allows to inject up to eight pellets per discharge (up to five pellets with a diameter of 1.0 mm and up to three pellets with a diameter of 0.7 mm) with a pellet velocity of 0.5–0.8 km/s.

In the analyzed shots with pellet injection, the plasma current was 270 kA, the toroidal magnetic field was 2.42 T, and the power of additional electron cyclotron heating was 0.85–1.5 MW. Similar to the earlier experiments with a graphite diaphragm [1–3], the injection of deuterium pellets during additional microwave heating in the experiments with a tungsten limiter, the plasma confinement was improved despite a much higher level of impurity content than with a graphite limiter. The change in the level of impurities after the replacement of graphite limiter with tungsten is described in detail in [4]. As can be seen from Table 1, when pellets are injected during electron cyclotron heating, the...
ratios of the experimental energy confinement time to the scaling ITER IPB98 (y, 2) are increased by 1.5 times, e.g., to increase the $H_H$ factor.

$$\tau_{E,ib}^{IPB(y,2)} = H_H 0.0562 I_p^{0.98} B_T^{0.15} P^{-0.69} M^{0.41} R^{1.97} \varepsilon^{0.19} 1^{0.58} 0^{0.78}$$

(in s, MA, T, MW, $10^{19}$ m$^{-3}$ and m, respectively). Effective elongation is defined as $k_a = S_c / \pi a^2$, where $S_c$ is the plasma cross-section area. The same $H_H$ factor increase was also observed with a graphite limiter where internal and external transport barriers were observed [3]. The experimental energy confinement time was determined from diamagnetic measurements.

**Table 1.** Change of the $H_H$ factor by scaling ITER IPB98 (y, 2) when pellets are injected for various limiter materials

| Limiter      | $H_H$ factor before pellets | $H_H$ factor after pellets | $H_H_{pel} / H_H_{ECRH}$ |
|--------------|----------------------------|----------------------------|--------------------------|
| C limiter    | 0.7                        | $\geq 1$                    | $\geq 1.5$               |
| W limiter    | 0.53                       | $\geq 0.8$                 | $\geq 1.5$               |

Improvement of the energy confinement is also demonstrated by other plasma characteristics. Thus, the loop voltage after pellet injection remained approximately at the same level as before the injection despite the density increase (see Figure 1). The vertical dashed lines in Figure 1 indicate the times of pellet injection.

Unlike the graphite limiter, with tungsten, we cannot confidently say about the presence of an internal transport barrier. However, in the ratio of the electron temperature profile after the injection of the first pellet to the temperature profile before the injection (Figure 2, 1-st pellet), there are regions with a high gradient. For all subsequent pellets, the corresponding profile ratio has a similar dependency (Figure 2, 2-nd pellet). This dependence is typical for internal transport barriers, the formation of which was demonstrated in experiments with a graphite limiter [1–3].

**Figure 1.** Average density along the central chord $n_e$ and loop voltage $U_0$ at tungsten limiter.

**Figure 2.** Ratio of the electron temperature profiles during the additional heating at tungsten limiter.

To check the efficiency of the chord system of pellet injection, several discharges with different poloidal injection angles were carried out. Schematically, the chord system of injection is shown in Figure 3. A preliminary analysis of these discharges makes it possible to say that the central injection leads to the greatest effect of improving confinement, because in that case, the $H_H$ factor has the maximal increase (see Table 2).
Figure 3. Pellet injection scheme at different angles.

2. Summary
Experiments with the conditions where the tokamak chamber is equipped with a tungsten limiter show that, despite the higher level of impurities than with a graphite limiter, the injection of pellets nevertheless leads to an improved confinement. Because the $H_H$ factor with a graphite diaphragm increases by the same amount and transport barriers are observed, it can be assumed that even with a tungsten limiter, external transport barriers are formed.

Experiments to change the poloidal angle of pellet injection show that the greatest increase of the ratio of the experimental confinement time to the calculated value is observed with the central injection of pellets.

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