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Co- and counter-pellet-injection in T-10 tokamak

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Abstract. The article presents the results of experimental studies and modelling of chord pellet injection in the T-10 tokamak plasmas. The deviation of pellets at different angles up to the peripheral injection does not result in their substantial degradation for speeds of approximately 600 m/s. The concepts of co- and counter-pellet-injection relative to the direction of rotation of the tokamak plasma are introduced. With an increase of the angle of pellet deviation, a substantial increase in the front duration and in the decay of bursts of radiation intensity of the deuterium Dα atom line was observed experimentally, and the simulations demonstrate an increase in the amplitude of the occurring radial electric field.

1. Introduction

Many phenomena in the high-temperature plasma, which is created and confined in tokamaks, are associated with the processes that take place at the edge of the plasma column near the last closed magnetic surface. Pellet injection is an active diagnostics, which substantially disturbs the plasma. It is one of the opportunities to study and change the confinement mode and transient processes due to the formation of strong gradients of density and temperature. Therefore, it is advisable to consider how to obtain the maximum density and temperature gradients, which preferably should be formed at a given radius of plasmas. It is necessary to choose the conditions and parameters both of the plasma and pellet injection to prevent the disruption of plasma discharge in the tokamak.

To achieve the maximum gradient, it is necessary to ensure long-term evaporation of pellets near magnetic surface of the selected target. At the edge, this can be done by reducing the velocity of injected pellets. Such experiments have been previously carried out [1, 2]. At a lower velocity, the pellet will evaporate at the edge of the plasma column and will not penetrate into the inner plasma regions. However, the reduction of pellet velocity decreases the stability of injection parameters and the precision of its synchronization with other systems that control processes in the tokamak plasma.

In this study, to solve the problem, instead of changing the speed of the particulates, it is proposed to change the direction of injection from radial to chord direction. In this case, the pellet will evaporate over longer-term near the magnetic surface that the injection direction is tangent to. Then, the maximum gradient forming region is pre-set not only at the edge of the plasma, but also in the interior of the plasma column. The minimum achievable radius for creating disturbances in this case can be calculated via the pellet evaporation scaling by taking into account changes in the plasma parameters along the chord direction of the injection. Compared with the central injection, for the chord injection, less pellet material will be deposited in the areas external to the area of maximum gradient, which increases the effectiveness of injection.

One of the tasks of this work was the technical implementation of the chord pellet injection and comparison of results of the chord injection with previous results of the central injection along the plasma radius [1–3].

Important parameters of the plasma at the last closed magnetic surface are the radial electric field, plasma rotation speed, and the shear. The moving pellet in the case of a central injection has no toroidal and poloidal velocity projections. During the evaporation and equalization of the background plasma temperature and particles in a cloud of evaporated pellet, a part of the energy of the toroidal and poloidal rotation transfers to the evaporated material. Due to this effect, the pellet "decelerates" plasma rotation differently at different radii. At the same time, the strong gradients give rise to the radial electric field, which significantly affects the shear of poloidal rotation [1].

In the case of chord pellet injection, one can distinguish between two types of injection geometry. In one case, pellet velocity is directed in the direction of plasma rotation, and the initial pellet impulse will provide a positive correction to the momentum of plasma rotation at the outer radii, and, in another case, the correction will be negative. The option of pellet injection in the same direction as the rotation of plasma we will name a co-pellet-injection, and injection in the direction opposite to the rotation of plasma - a counter-pellet-injection.

2. Experiment

For the experiments using co- and counter-pellet-injection, the chord injection system was developed at SPbPU, which allows to scan all directions from the central injection to injection at a tangent to the plasma column. The system was installed in the port that connects the pellet injector to the T-10 tokamak. The geometry of the non-central injection is shown in Figure 1. One of the objectives of this study was to show the possibility of deviation of accelerated deuterium pellets without their destruction. In addition, it was necessary to perform the deviation of pellets not at a fixed angle, but be able to smoothly change it from shot to shot, and thereby to scan a specific range of angles.

A modified multibarrel pellet injector (MPI-8, PELIN production) is used at the T-10 tokamak [4]. After modification, the MPI-8 device allows to inject up to five pellets of 1 mm in diameter and up to three - 0.7 mm in diameter per discharge with the range of pellet velocities of 500–800 m/s. Pellets are frozen inside the barrels according to the in situ technology. In this case, an 8-barrel injector is capable of injecting all pellets in a single discharge with an arbitrary delay.

The location of systems and diagnostics on the T-10 tokamak is shown in Figure 1. The fuel pellet injector is located in section "C" with a multi-channel microwave interferometer near the antenna of the diagnostics of the electron temperature, which monitors the change in intensity of the second harmonic of the electron cyclotron emission (ECE). Each section of the T-10 tokamak is equipped with gyrotrons for additional plasma heating. The SXR diagnostics is shifted by 90° in the toroidal direction relative to the pellet injection section. It is also possible to compare the results of deuterium injection and impurity pellet injection, which is performed in section "B", shifted by 90° relative to the deuterium injection device.

In May of 2016, the first experiments were carried out on the injection of up to 5 pellets in one discharge in regimes with additional plasma heating and using a chord pellet injection system. In addition to the central injection without pellet deviation, injection was performed with a deviation of 7.5° in the middle of a minor radius and 12.75° in the peripheral region of plasma. In these experiments, the direction of plasma current and toroidal field corresponds to the counter-clockwise rotation when viewing the T-10 tokamak from the top, as on the plan view in Figure 1. As the pellets are deflected up, for a given current direction, the experimental geometry corresponds to the counter-pellet-injection. Table 1 summarizes the main parameters of the injected pellets, which are considered in the article.

The experiments have shown that in the case of a deviation of the pellet injection angle from the central one, a fraction of destroyed pellets somewhat increases. However, in general, they have successfully passed through the chord pellet injection system and were deflected by a predetermined angle. During the plasma discharge, the chord injection system remains still, and the injection angle is fixed. During the time between the discharges, the angle of deflection can be changed to any given value of the operating range of the chord injection system.

Table 1. Parameters of the pellets that are injected at different deviation angles

Shot number	Deviation angle	Velocity v, m/s	Mass m, mg
68508	0°	671	0.35
68510	12.75°	685	0.36
68511	7.5°	662	0.38

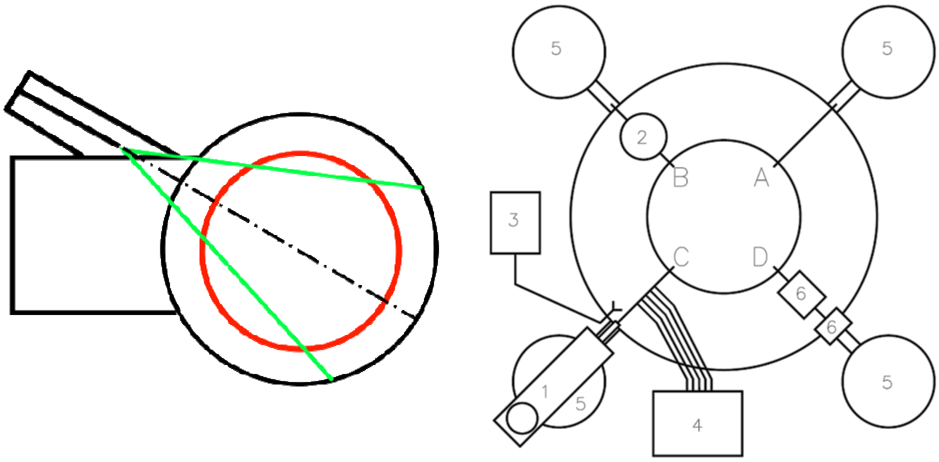


Figure 1. Scheme of the experiment on the T-10 tokamak.

The left drawing illustrates cross-section C with an installed chord pellet injection system. The dash-dot line corresponds to the case of central pellet injection. Solid green lines indicate a sector of available directions of the chord pellet injection.

The right scheme is a plan view of the T-10 tokamak. A, B, C, D are letters assigned to cross-sections with a set of ports in each of them, where 1 is the hydrogen pellet injector, 2 is the impurity pellet injector, 3 is the electron temperature diagnostics of plasma, 4 is the microwave interferometer, 5 are the gyrotrons, and 6 is the SXR diagnostics of plasma.

Figure 2 shows the plots of emission intensity of the Dα line of deuterium atoms for different angles of the counter-injection of deuterium pellets. Their comparison shows an increase in duration both of the rise time and the fall time of pulses with an increase of the angle of deviation of the injected pellets. For this dependence, there is still no definitive explanation and reproduction in the simulation results. Presumably, the observed delay in the formation of pulse Dα emission, in the case of deviation of injected pellets, is caused by longer evaporation time in the plasma peripheral layers, which are rapidly depleted in electrons with enough energy to evaporate the pellet material. This leads to a slower heating of the cloud of evaporated material and a stronger displacement of current to the central region of plasma, which considerably slows down the relaxation of peripheral regions after the injection.

3. Modeling

To analyze the experimental results, a comparative modeling of the central and chord injection should be performed. In the case of a chord injection, it is necessary to consider the two-dimensional geometry of the pellet trajectory and change the transport equation by incorporating the corrections, which are usually not taken into account when modeling the central injection.

To analyze the experimental results, modeling of the evolution of plasma was undertaken using the ASTRA code [5]. In this model, we considered a system of transport equations (1), where ρ is the effective minor radius, t is the time, V is the volume of plasma, $V' = \partial V/\partial\rho$, B_0 is the magnetic field at the center of plasma, Γ_e and Γ_i are the electron and ions fluxes, respectively; q_i and q_e are the corresponding heat fluxes, n_e and n_i are the density of electrons and ions, respectively; S_e, P_e and P_i are the terms that take into account the sources of electrons, electron and ion heat sources, respectively; $\sigma_{||}$ is the conductivity of the plasma in a direction parallel to the magnetic field; $J = I/R_0B_0$, where R_0 is the major radius of the tokamak vacuum chamber, I is the plasma current; $G = V'/(4\pi^2) \langle(\nabla\rho/r)^2\rangle$; j_{BS} and j_{CD} are the averaged density of bootstrap current and current drive, respectively.

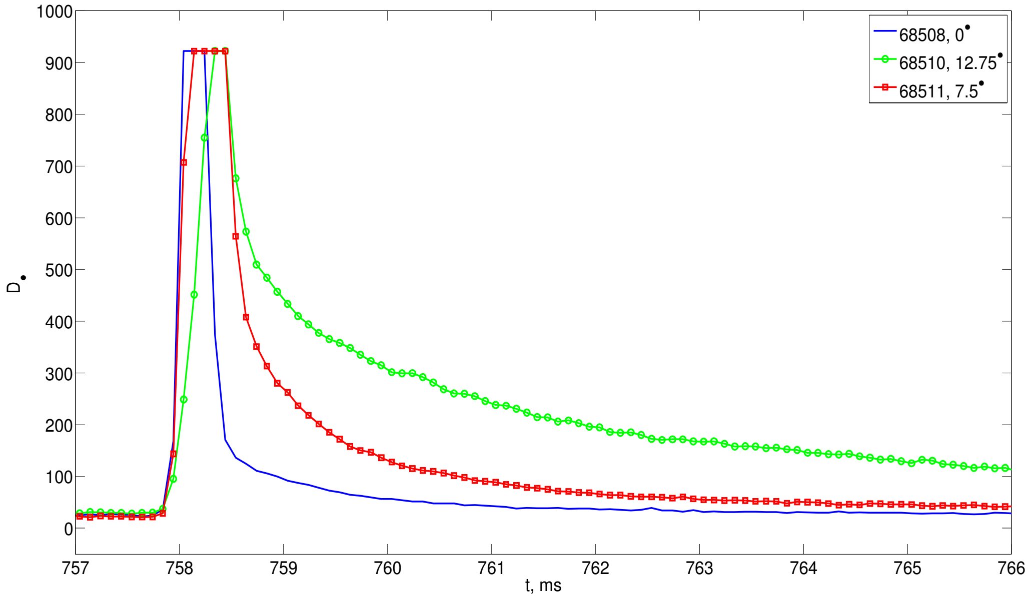
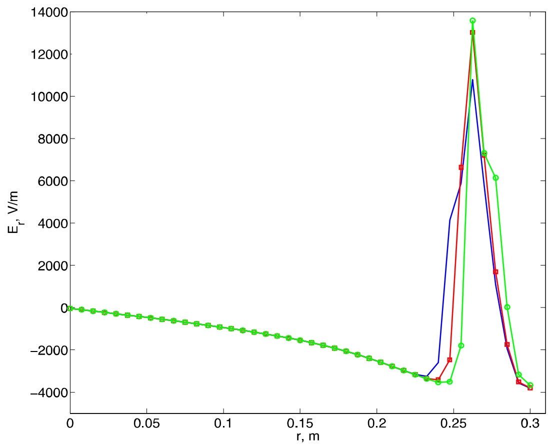


Figure 2. Spikes of the Dα line emission intensity after the pellet injection for 3 different pellet injection directions. Blue continuous line corresponds to 0° (central pellet injection), red line with squares - 7.5° deviation of the pellet trajectory, and green line with rhombs - 12.5° deviation (almost tangential injection).

$$
\begin{aligned}
&\frac{1}{V'}\left(\frac{\partial}{\partial t}-\frac{\dot{B}_0}{2B_0}\frac{\partial}{\partial\rho}\rho\right)(V'n_e)+\frac{1}{V'}\frac{\partial}{\partial\rho}\Gamma_e=S_e,\\
&\frac{3}{2}(V')^{-5/3}\left(\frac{\partial}{\partial t}-\frac{\dot{B}_0}{2B_0}\frac{\partial}{\partial\rho}\rho\right)\left[(V')^{-5/3}n_eT_e\right]+\frac{1}{V'}\frac{\partial}{\partial\rho}\left(q_e+\frac{5}{2}T_e\Gamma_e\right)=P_e,\\
&\frac{3}{2}(V')^{-5/3}\left(\frac{\partial}{\partial t}-\frac{\dot{B}_0}{2B_0}\frac{\partial}{\partial\rho}\rho\right)\left[(V')^{-5/3}n_iT_i\right]+\frac{1}{V'}\frac{\partial}{\partial\rho}\left(q_i+\frac{5}{2}T_i\Gamma_i\right)=P_i,\\
&\sigma_{\parallel}\left(\frac{\partial\psi}{\partial\rho}-\frac{\rho\dot{B}_0}{2B_0}\frac{\partial\psi}{\partial\rho}\right)=\frac{JR_0}{\mu_0\rho}\frac{\partial}{\partial\rho}\left(\frac{G_2}{J}\frac{\partial\psi}{\partial\rho}\right)-\frac{V'}{2\pi\rho}(j_{BS}+j_{CD})
\end{aligned}
\tag{1}
$$

The matrix of transport coefficients is given as (2). Expressions for the transport coefficients: α_i - neoclassical corrections that are small for the T-10 tokamak, r - minor radius, τ_h - on time of gyrotron, $\theta(\tau_h)$ - Heaviside function.

Figure 3 shows that the radial electric field E_r in case of injection without deviation is less than the simulation results for the maximum and average deviation. Since the evaporation takes place closer to the plasma edge for the injection with deviation, the radial electric field is also shifted to the periphery.



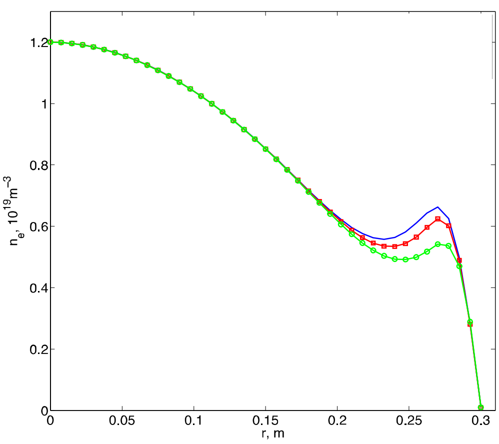


Figure 3. Results of modelling radial electric field (left plot) and electron density (right plot) in the case of chord pellet injections with different deviations from the axis of the central injection. Colors, symbols and lines are the same as in Figure 2.

$$
\begin{pmatrix} D_n & 0 & 0 & C_n \\ 0 & \chi_e & 0 & C_e \\ 0 & 0 & \chi_i & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix}
\quad \text{where} \quad
\begin{aligned}
&D_n = 1+6(1-r^2)^{5/2}+\alpha_1\\
&\chi_e = 1+8(1-r^2)^4+2\theta(\tau_h)+\alpha_4\\
&\chi_i = 2+8(1-r^2)^5\\
&C_n=\alpha_2 \qquad C_e=\alpha_4
\end{aligned}
\tag{2}
$$

4. Conclusions

The possibility of increasing density and temperature gradients of tokamak plasma as a result of chord injection of pellets has been experimentally demonstrated. It is shown that the change in the pellet injection angle makes it possible to create perturbations in the density and temperature of the plasma at the desired radius of the plasma. It was determined that in the case of chord pellet injection, the direction of rotation of the plasma should be taken into account. To denote two different variants of the combination of the direction of injection and rotation of the plasma, the terms "co-" and "counter-pellet-injection" are introduced, and the possibility of their application was realized. In the first case, the projection of pellet velocity on the plane, which is tangent to the plasma, coincides with the direction of rotation of the plasma, while in the second - they are opposite.

The chord pellet injection system was developed at the Peter the Great St. Petersburg Polytechnic University and installed on the T-10 tokamak. It allows to deviate accelerated pellets just before they hit the plasma. The system covers the entire range of angles from the center to the peripheral injection in both sides of the axis of the injector in a vertical cross section the T-10 tokamak. The first experiments have demonstrated the technical feasibility of a controlled deviation of the accelerated pellets without their substantial destruction at velocities of more than 600 m/s.

One of the observed differences in injection along different chords was an increase in the duration of the rise and fall times of intensity of the Dα line emission of deuterium atoms in comparison with central injection. Presumably, this is, firstly, due to greater depletion of the magnetic surface with primary electrons, which are spent evaporating the pellet material and, secondly, the displacement of plasma current in the central region of plasma.

The results of the experiments were modeled using the ASTRA code. The calculation of deposition of pellet material is performed by scaling for the evaporation rate [6] based on the actual weight of the pellet and taking into account the two-dimensional nature of its trajectory in the injection section. Simulations have shown the occurrence of a more intense radial electrical field in the case of chord injection compared with central injection.

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