Study of thermal quench of discharge using a massive gas injection into the plasma of T-10 tokamak

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Abstract. The report presents the results of simulations of plasma disruption in the T-10 tokamak using the ASTRA code, including discharges with a disruption being initiated by the massive gas injection (MGI). This study focuses on the development phase of thermal quench, and the effect of different channels of heat loss during quench evolution is examined. It is shown that the initial phase of the slow phase of thermal quench can be described by the selection of sources and transport coefficients.

1. Introduction

The design and putting into operation of increasingly powerful tokamaks creates a problem of preventing major plasma disruptions and controlled quench of discharge. It should be noted that the physics of the processes that occur during a disruption depends more on the geometry of tokamak magnetic system and the plasma confinement regimes implemented there than on the amount of stored energy in the plasma discharge. This makes it possible to perform preliminary studies on this subject using small and medium tokamaks with less risk of damage, because they have a lower plasma energy content.

To study the various scenarios of initiation and evolution of plasma disruption and suppression of the runaway electron beams, it is necessary to use a variety of active systems that affect plasma in order to test various scenarios of controlled quench of the plasma discharge. At the T-10 tokamak, it is possible to use the following active systems: firstly, it is the main control system for executing control programs for the plasma current, magnetic fields and operation of piezoelectric valves for the working gas injection, and secondly, stationary and movable (positionable) pulsed gas valves, impurity pellet injector (the latter is now equipped with a chord pellet injection system), as well as an electron cyclotron resonance plasma heating (ECRH) system, movable and lithium limiters [1]. It should be noted that the unique systems of movable MGI valve [2] and chord pellet injection allow to study disruption parameters as a function of gas source position relative to the plasma edge and the impact parameter of pellet injection, respectively, and compare the scenarios of co- and counter-pellet-injection (“co-” means injection along the direction of plasma rotation, “counter-“ corresponds to injection in the opposite direction against the direction of plasma rotation).

On the Tore Supra tokamak with a limiter, the injection of approximately 0.1 moles of helium was carried out for 4 ms in the experiments on quenching of ohmic plasma discharge with a current of up to 1.2 MA [3]. This amount of helium was calculated numerically based on experimental results of the
FTU tokamak [4] using an assumption that impurity injection into steady-state plasma should suppress and during thermal quench reduce the generation of runaway electron beams.

The decrease in runaway electron current to the wall was observed using the response of HXR detectors. The HXR emission increases simultaneously with the appearance of photo-neutrons, which are produced when runaway electrons reach the first wall of the facility. It is observed that in discharges with helium injection, the number of runaway electrons, which reached the plasma-facing elements of the facility, is less (by 2-3 orders of magnitude) than in experiments with plasma disruptions without MGI [3].

In addition to massive helium injection, experiments with an ordinary argon injection were performed at the Tore Supra tokamak. With the massive helium injection, smaller eddy currents formed, and the plasma current decreased slower than in the case of argon injection, which led to lower loads on the constructional elements of the facility during disruptions. Based on the results of experiments on the Tore Supra tokamak, it has been demonstrated that the massive helium injection does not produce plasma pollution, and cleaning of the first wall of the device became easier [3].

2. Experiment

For the numerical modeling of plasma thermal quench, which is caused by the impurity injection, a discharge #66640 with a thermal and current quench in the T-10 tokamak with a limiter was chosen.

In this experiment, the injection of argon at a pressure of 3 bar was carried out using a gas valve (Figure 1), which is located 30 mm from the last closed magnetic surface, at the time of 834 ms from the beginning of discharge.

Prior to the injection of argon impurity, a steady-state ohmic operating mode of the tokamak was achieved with an average electron concentration of $2.5 \times 10^{19} \text{ m}^{-3}$, a current in the plasma of $I = 250 \text{ kA}$, and an average loop voltage of $U = 1.0 \text{ V}$. When argon was injected, the plasma periphery cooled, the current was displaced to the central part, and the electrical conductivity of plasma decreased. The ionization of impurity led to an increase in the average electron density and subsequent plasma discharge disruption because of exceeding the plasma density limit.

The electron density profile before the injection, the characteristics of the T-10 tokamak and experimentally measured plasma parameters were taken as the initial data for modeling. The initial electron temperature profile was chosen to be parabolic and normalized to correspond with the value of loop voltage $U = 1.0 \text{ V}$.

![Figure 1. T-10 tokamak scheme (top view and cross section B): 1 – hydrogen pellet injector, 2 – impurity pellet injector, 3 – electron temperature diagnostics, 4 – microwave interferometer, 5 – gyrotrons, 6 – SXR diagnostics, 7 – movable gas valve for MGI.](image)
In Figures 2 and 3, solid lines represent the experimental responses of electron temperature to the chord passing through the radius of plasma discharge $r = 0.21$ m and loop voltage, respectively. They represent the early slow phase of the thermal quench. In the T-10 tokamak, this phase lasts for 100-200 $\mu$s. The outer regions of plasma cool down, and the effective charge of plasma and radiation losses increase during this time. In the non-central regions of plasma, the electrical conductivity decreases, which leads to the increase in loop voltage and the displacement of current into the central part of the plasma discharge. In the simulation, it was expected to obtain a qualitatively similar evolution of the corresponding values after the impurity injection.

3. Modeling
Numerical study on the influence of injected impurities on the plasma parameters of the tokamak during the first stage of thermal quench was carried out using the ASTRA code [5], which numerically solves the system of transport equations (1) for the electron density $n_e$, electron temperature $T_e$, ion temperature $T_i$ and poloidal flux $\theta$.

The first equation describes the balance of electrons (the number of particles conservation law), the second and third equations describe the energy balance (the energy conservation law) for electrons and ions, and the fourth equation describes Ohm's law for a plasma discharge. The system (1) is complemented by the appropriate initial and boundary conditions of the first kind [5]. In the system (1), $\rho$ is the effective minor radius; $t$ is the time; $V$ is the volume of plasma; $V' = \frac{\partial V}{\partial \rho}$, $B_0$ and $B_0'$ are the magnetic field and its time derivative at the center of the plasma discharge, respectively; $I_e$ and $I_i$ are the electron and ion fluxes, respectively; $q_e$ and $q_i$ are the corresponding heat fluxes; $n_e$ and $n_i$ are the electron and ion concentrations, respectively; $S_e$, $P_e$ and $P_i$ are the terms that take into
account electron sources, electron and ion heating sources, respectively; $\sigma_i$ is the conductivity of plasma in the direction parallel to the magnetic field; $J = I/(R_0 \cdot B_0)$, where $R_0$ is the radius of the tokamak vacuum chamber, $I$ is the plasma current; $j_{bo}$ and $j_{cd}$ are the averaged bootstrap current densities due to the electron cyclotron resonance heating of plasma, and the current caused by external sources, respectively; $G_2 = \left\langle (\nabla \rho / r)^2 \right\rangle \cdot V' (4\pi)^2$.

$$\frac{1}{V'} \left( \frac{\partial}{\partial t} - \frac{\dot{B}_0}{2B_0} \frac{\partial}{\partial \rho} \right) \left( V' \dot{n}_e \right) + \frac{1}{V'} \frac{\partial}{\partial \rho} \Gamma_e = S_e,$$

$$\frac{3}{2} \left( V' \right)^\gamma \left( \frac{\partial}{\partial t} - \frac{\dot{B}_0}{2B_0} \frac{\partial}{\partial \rho} \right) \left[ \left( V' \right)^\gamma n_{Te} \right] + \frac{1}{V'} \frac{\partial}{\partial \rho} \left( q_e + \frac{5}{2} T_e \Gamma_e \right) = P_e,$$

$$\frac{3}{2} \left( V' \right)^\gamma \left( \frac{\partial}{\partial t} - \frac{\dot{B}_0}{2B_0} \frac{\partial}{\partial \rho} \right) \left[ \left( V' \right)^\gamma n_{Ti} \right] + \frac{1}{V'} \frac{\partial}{\partial \rho} \left( q_i + \frac{5}{2} T_i \Gamma_i \right) = P_i,$$

$$\sigma_i \left( \frac{\partial \psi}{\partial \rho} - \frac{\rho \dot{B}_0}{2B_0} \frac{\partial \psi}{\partial \rho} \right) = J R_0 \frac{\partial}{\mu_0 \rho \frac{\partial}{\partial \rho}} \left( \frac{G_2 \frac{\partial \psi}{\partial \rho}}{J} \right) - \frac{V'}{2\pi \rho} \left( j_{bs} + j_{cd} \right)$$

The injection of gas (argon) was included in the system (1) via $S_{imp}, P_{rad}$ and $P_{Br}$ in the sources $S_e$ and $P_e$:

$$S_e = S_{ion} - S_{rec} + S_{imp},$$

$$P_e = P_{oh} - P_{el} - P_N^{e} - P_{rad} - P_{Br},$$

where, $P_{oh}$ is the ohmic heating power; $P_{el}$ and $P_N^{e}$ describe the energy exchange due to the interaction of electrons with ions and neutral particles, respectively; $P_{rad}$ is the power radiated due to impurity injection; $P_{Br}$ is bremsstrahlung; $S_{ion}$ and $S_{rec}$ describe the processes of ionization and recombination, respectively; $S_{imp}$ is the ionization/recombination of the injected impurity atoms.

The formulas for $S_{ion}, S_{rec}, P_{oh}, P_{el}$ and $P_N^{e}$ were originally built in the ASTRA code [5]. However, for calculating $S_{imp}, P_{rad}$ and $P_{Br}$, the appropriate subroutines were developed according to the following expressions:

1) $S_{imp} = n_{imp} \cdot \partial <Z_{imp} \cdot (\nabla \rho / \rho) \cdot \partial > / \partial t = n_{imp} \cdot \partial <Z_{imp} \cdot (\nabla \rho / \rho) \cdot \partial T_e / \partial t > / \partial t$, where the derivative $\partial <Z_{imp} \cdot (\nabla \rho / \rho) \cdot \partial T_e / \partial t >$ was calculated using the average-ion model [6, 7];

2) $P_{rad} = n_{imp} \cdot L_2$, where $[P_{rad}] = erg \cdot cm^{-3} \cdot s^{-1}$, $[n_{imp}] = cm^{-3}$ [7];

3) $P_{Br} = 5.35 \cdot 10^{18} \cdot Z_{eff} \cdot n_{imp} \cdot T_{e}^{1.7}$, where $[P_{Br}] = W \cdot m^{-2} \cdot [T_e] = keV$ [8].

According to [5], the ASTRA code can include up to three auxiliary transport equations:

$$\frac{\partial}{\partial t} \left( V' f_j \right) = \frac{\partial}{\partial \rho} \left[ V' (\nabla \rho)^2 \left( D_j \frac{\partial f_j}{\partial \rho} - u_j f_j \right) \right] + V' S_j, \quad j = 1, 2, 3$$

with the appropriate initial and boundary conditions. The first of these equations was used to describe the influence of impurity density $n_{imp}$ on transport processes, i.e., $f_i = n_{imp}$. Then, index 1 corresponds to the quantities that describe the impurity behavior. This allowed us to determine for the impurity its sources $S_i$, diffusion coefficient $D_i$ and pinch velocity $u_i$, and to simulate the evolution of concentration of argon particles after injection. Similar to [6], the values of $D_i$ and $u_i$ were set as for the electrons, and source $S_i$ was set to 0. The condition of the third type (conservation of the number of impurity particles in the plasma volume) was chosen as the boundary condition for the impurity:

$$\left. \left( - D_i \frac{\partial f_i}{\partial \rho} + u_i f_i \right) \right|_{\rho = \rho_i} = 0$$

As a result of the simulation, plots of the electron temperature at the radius of plasma discharge $r = 0.21 \text{ m}$ and loop voltage were obtained, which qualitatively coincide with the plots of the real
discharge #66640 in the T-10 tokamak with a limiter (Figures 2 and 3). Figure 4 demonstrates the profiles of electron temperature, which were obtained as a result of modeling the disruption using the ASTRA code. From Figure 4, it is clear that after the compression of plasma into the central regions, plasma mixing does not occur, therefore. This physical phenomenon, which is an essential part of the second stage of a disruption, cannot be described using the model that was discussed in this article.

4. Conclusions
The report presents the results of a numerical simulation of a discharge disruption in the T-10 tokamak using the ASTRA code, including discharges with the initiation of a discharge disruption using a massive pulsed gas injection. The main attention is paid to the phase of the evolution of thermal plasma quench and the effect of various heat loss channels during it. It is shown that the initial slow phase of the development of thermal plasma quench can be described by selecting sources of impurity and transport coefficients. The comparison of the results of modeling with the experiment demonstrates that the proposed approach of taking into account the injected gas in the ASTRA code by solving the auxiliary transport equation allows to qualitatively simulate the evolution of plasma parameters during the first stage of a thermal quench, which is caused by the impurity injection.

Acknowledgments
The authors are thankful to the staff of the T-10 tokamak for the provided data and support. The work was carried out with the partial support from the State Corporation ROSATOM, contract No.H.4x.241.9B.17.1011.

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