Influence of Plasma Opacity on Current Decay after Disruptions in Tokamaks

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Abstract. Current decays after disruptions as well as after noble gas injections in tokamak are examined. The thermal balance is supposed to be determined by Ohmic heating and radiative losses. Zero dimensional model for radiation losses and temperature distribution over minor radius is used. Plasma current evolution is simulated with DIMRUN and DINA codes. As it is shown, the cooled plasmas at the stage of current decay are opaque for radiation in lines giving the main impact into total thermal losses. Impurity distribution over ionization states is calculated from the time-dependent set of differential equations. The opacity effects are found to be most important for simulation of JET disruption experiments with beryllium seeded plasmas. Using the coronal model for radiation one can find jumps in temperature and extremely short decay times. If one takes into account opacity effects, the calculated current decays smoothly in agreement with JET experiments. The decay times are also close to the experimental values. Current decay in argon seeded and carbon seeded plasmas for ITER parameters are simulated. The temperature after thermal quench is shown to be twice higher in comparison with the coronal model. The effect for carbon is significantly higher. The smooth time dependence of the toroidal current for argon seeded plasmas is demonstrated in contrast to the behavior in carbon seeded ones.

1. Introduction.

One of the most important problems for conventional tokamaks as well as for ITER is the problem of disruptions. In order to mitigate disruption consequences pellet or noble gas injections have been proposed and are examined intensively [1-5] .At the first stage of the experiment the penetration of the jet into plasma core without any significant MHD activity has been observed. Magnetic perturbations rise rapidly after jet arrival to the some critical internal magnetic surface. The MHD instability causes the thermal quench. The instability mixes the central plasma region and brings the noble gas ions into the plasma center in a short time. Strong radiation and following plasma cooling is typical for the third stage. The similar situation takes a place during current decays in disruptions when plasmas are saturated by wall material ions. First two stages were simulated in [6-8].

The third stage is simulated in the present paper. It has been investigated in Ref. [2] with zero-dimensional code KPRAD. The thermal balance is supposed to be determined by Ohmic heating and radiative losses,

$$P_{Ohm} = Q_{rad} \tag{1}$$

Plasma was assumed to be transparent for resonant radiation in lines. One can see (Ref. [2]) that the simulated electron density as well as the radiated power exceeds the DIII-D experimental data by factor 2 or more at the stage of current decay. However, the KPRAD model describes the temperature evolution at least qualitatively for argon seeded plasmas. The situation occurs to be significantly different when we try to use the similar model in order to simulate the current decay in JET disruption experiments [9] for beryllium and carbon seeded plasmas. We cannot get even the qualitative coincidence if we suppose the plasmas transparent for line radiation. As an example, radiation losses from beryllium seeded optically thin plasmas and Ohmic heating power are shown in Fig. 1. The solutions of Eq. (1) are determined by the intersections of two curves. After the fast thermal quench the solution is related to the highest root at the right branch. The temperature falls down with the current decrease and achieves the minimum of loss curve. Then, the solution must jump to the left branch. Hence, one may observe the jump in the current value. However, no jumps are observed in experiments. Moreover, the current decay time simulated is significantly lower than the experimental one.

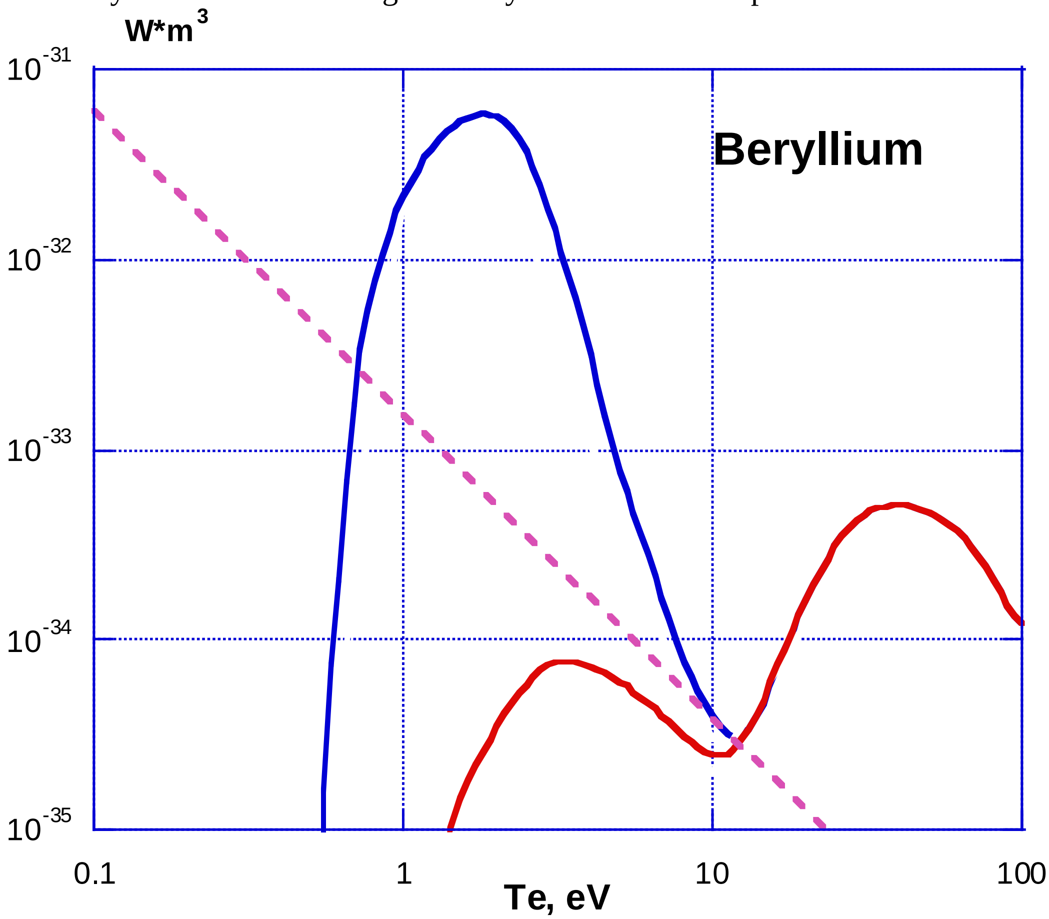

FIG.1. Specific radiation losses and specific Ohmic power (dashed line) for beryllium seeded plasmas. Solid blue line is respected to the ignorance of opacity effects, solid red line shows results with opacity effects ($n_e = 10^{21}\ m^{-3}$).

The reason of such a discrepancy is the optical opacity of impurity seeded plasmas. For example, let us estimate the opacity effect for the bright line $\lambda = 0.977 \cdot 10^{-7}\ m$ from the spectrum of the carbon ion CIII (ion charge z=3).

The absorption coefficient in a center of the resonance line is given by the expression [10]

$$\kappa_0 \approx \pi n_I \left(\frac{\lambda}{2\pi}\right)^2 \frac{\gamma}{\gamma + \Gamma}. \qquad (2)$$

Here n_I is the impurity density, E_{tr} is the transition energy, $\gamma = \frac{\Delta E_{nat}}{E_{tr}}$ is the relative natural line broadening, $\Gamma = \frac{\Delta E_{ext}}{E_{tr}}$ is the external one, $l_0 = \kappa_0^{-1}$ is the mean free path of the resonant photon. The plasma is optically thin if $l_0 / a << 1$, where a is a characteristic plasma size. The ratio of the radiation decay time to the de-excitation by electron impact β is the other important parameter [10].

$$\beta \approx 2.7 \cdot 10^{-13} \frac{n_e}{E_{tr}^{7/2}} \sqrt{x}\left(1 - xe^x Ei(x)\right), \; x = E_{tr} / T_e \qquad (3)$$

Radiation is trapped in the plasma volume if $\delta = \frac{a}{l_0} \frac{\beta}{1+\beta} >> 1$. The condition $\delta = 1$ separates the regions of volume and surface radiations.

The parameter δ is calculated for carbon plasmas with the electron temperature $T_e = 1\, eV$, electron density $n_e = 10^{20}\, m^{-3}$ and carbon ion density $n_C = 10^{20}\, m^{-3}$, and $a = 1\, m$, which are typical for the current decay stage. The external broadening is supposed to be Doppler one. Under these conditions one can find $\delta = 18.3$. Hence, the plasma is opaque at least for the line chosen.

2. Mathematical model.

The current decay stage is simulated. The energy balance is supposed to be determined by Ohmic heating and radiative losses similar to KPRAD model. It is described by Eq. (1). The temperature is supposed to be uniform across the plasma channel. The model for radiation losses is described in details in Ref. [8]. Neither coronal nor local thermodynamic equilibria are supposed. Resonant photon trapping inside the plasma volume as well as the excitation from ionization states is taken into account. The temperature is calculated as a solution of Eq. (1) with Ohmic heating at the left under the assumption of the uniform distribution over plasma channel. The current density is calculated with DIMRUN code for JET [11] and DINA code for ITER [12] as a function of time.

3. Simulation of disruptions in JET.

Current decay after disruption in JET with the wall covered by beryllium is simulated. Taking into account opacity effects one can find the radiation loss curve takes the shape (Fig. 1, red line) significantly different than the shape shown in Fig. 1 (blue line). One can see that the solution of Eq. (1) decreases continuously with the current decay in contrast to the previous case. The calculation results for current decay time as a function of the beryllium density is shown in Fig. 2. The initial current value and electron density are assumed to be equal *3 MA* and $10^{19}\ m^{-3}$ respectively. Experimental current decay time $\tau_{L/R}$ is found [9] to be inside the interval *170 – 100 ms* for wide range of Be concentrations, $2 \cdot 10^{19}\ m^{-3} < n_{Be} < 1 \cdot 10^{20}\, m^{-3}$ for one stage current decay. The shortest current decay time is approximately equal to $10\, ms$ for the Beryllium densities more than

$5 \cdot 10^{20} m^{-3}$. One can see that experimental and computed results are in a good coincidence only if the opacity effects are taken into account.

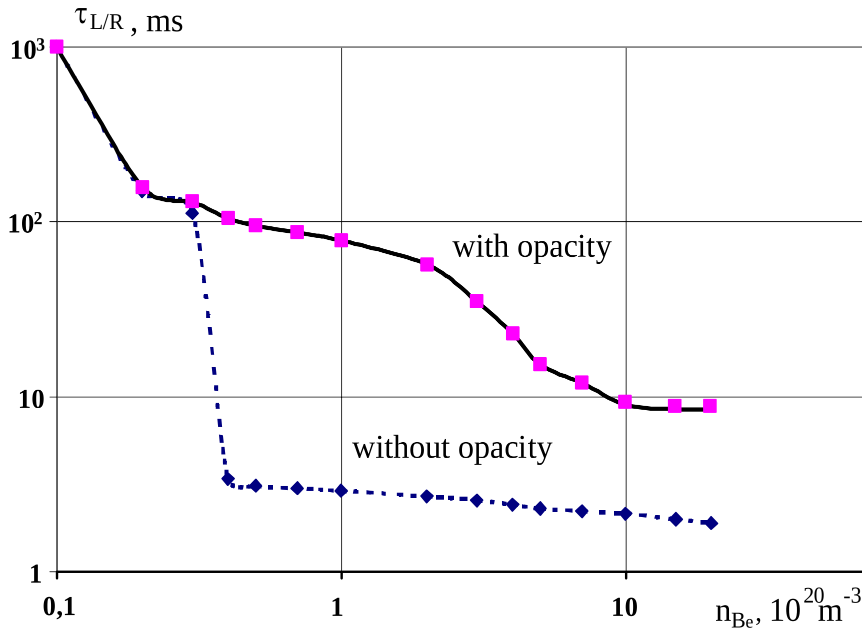

FIG. 2. Current decay time as a function of beryllium concentration

4. ITER simulations.

How one can see from the previous paragraph, our model is verified successfully with JET experiments and may be applied for ITER predictions. The current decay after disruption in ITER is simulated for both carbon and argon seeded plasmas. The initial current and electron density are chosen to be equal to *15 MA* and $8 \cdot 10^{19}\ m^{-3}$ respectively. The right and left hand sides of Eq. (1) for carbon seeded plasmas with different impurity densities are shown in Fig. 3. The distributions over ionization states are calculated with the set of differential equations. Neither coronal nor local thermodynamic equilibrium is supposed. The calculations show that the difference between current radiation losses and equilibrium (taking into account opacity effects) ones is not significant.

One can see that the difference in radiation losses with and without opacity effects is significant for $T_e < 10\, eV$. For the carbon density around $2 \cdot 10^{19}\ m^{-3}$ the heating curve is practically parallel to the radiation curve for $8\, eV < T_e < 20\, eV$ and the total toroidal current $I \approx 5\, MA$. Hence, the solution is expected to be very sensitive to small current variations. Evolutions of the electron temperature, total toroidal current and halo currents are shown in Figs. 4.

First, ignoring opacity effects one underestimates the temperature significantly. Second, the non-monotonic temperature behavior is related to the sensitivity mentioned above. The total toroidal current falls down slowly. After reaching the minimum at the loss curve ($t \approx 17\, ms$) the solution jumps to the left branch of the curve (Fig. 3). The total current continues to decrease but the current channel shrinking causes the increase of

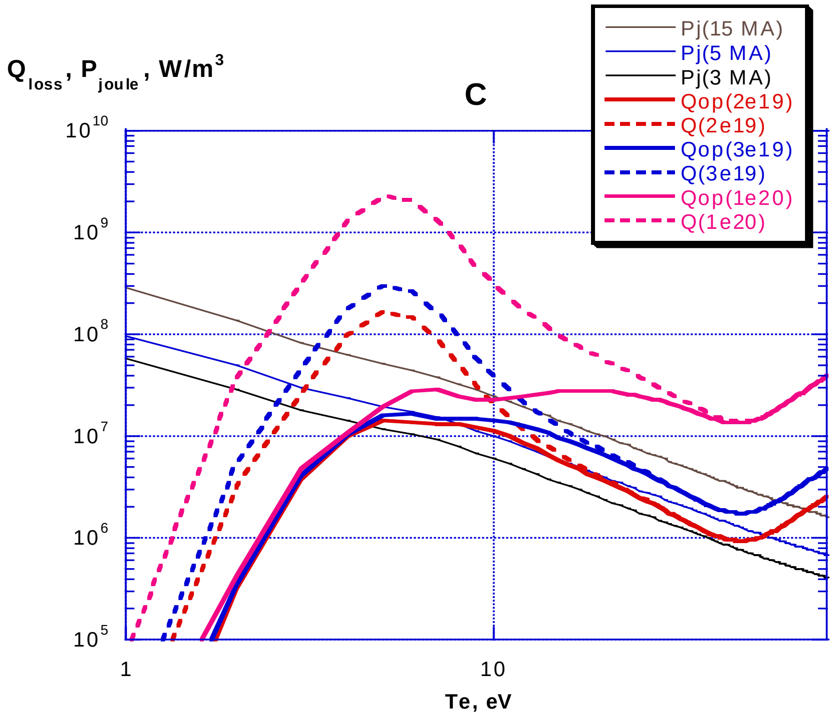

FIG. 3. Specific Ohmic heating and radiation losses for Carbon seeded plasmas. Dashed lines show the results obtained for transparent plasmas. Solid lines are related to results obtained when opacity effects are taken into consideration. Carbon densities are shown in brackets.

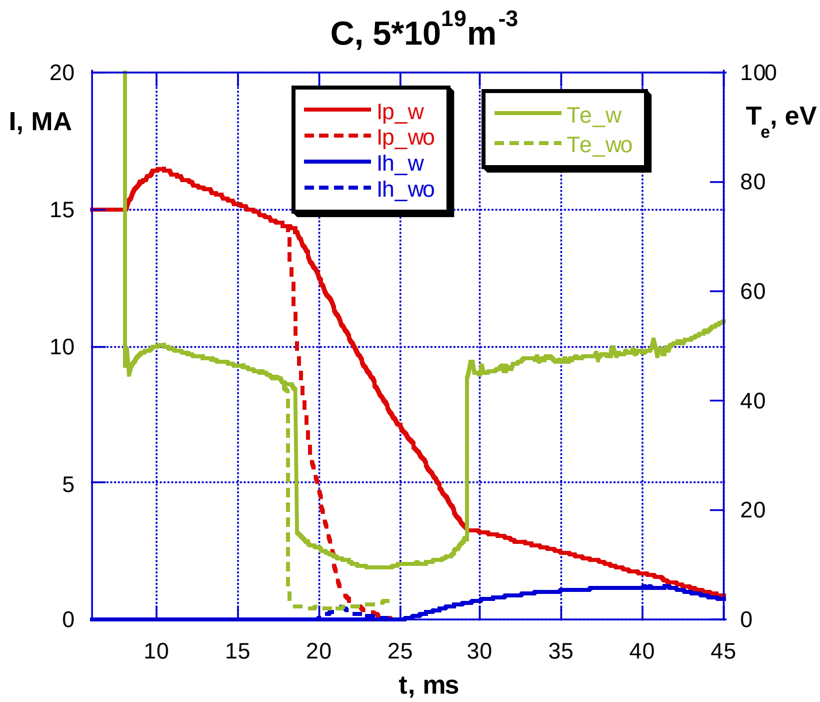

FIG. 4. Evolution of the electron temperature (green lines), total toroidal currents (red lines) and halo currents (blue lines) with opacity effects (solid lines) and without them (dashed lines).

$n_C = 5 \cdot 10^{19}\ m^{-3}$.

current density and of the heating respectively. Hence, the temperature achieves the upper point of the loss curve and jumps to the right branch of the curve ($t \approx 28 ms$). As a consequence, there are two typical current decay times.

In total, ignoring opacity effects one underestimates the electron temperature and the current decay time by factor 5 or even more. Taking into account opacity effects calculated halo current appears significantly later. Its maximum is significantly higher.

Also the current decay after argon jet injection is simulated. Heating and loss curves for argon are shown in Fig. 5. For ITER parameters the opacity effects don't change the solutions of Eq. (1) qualitatively, however, the expected temperature may be increased by factor 2.

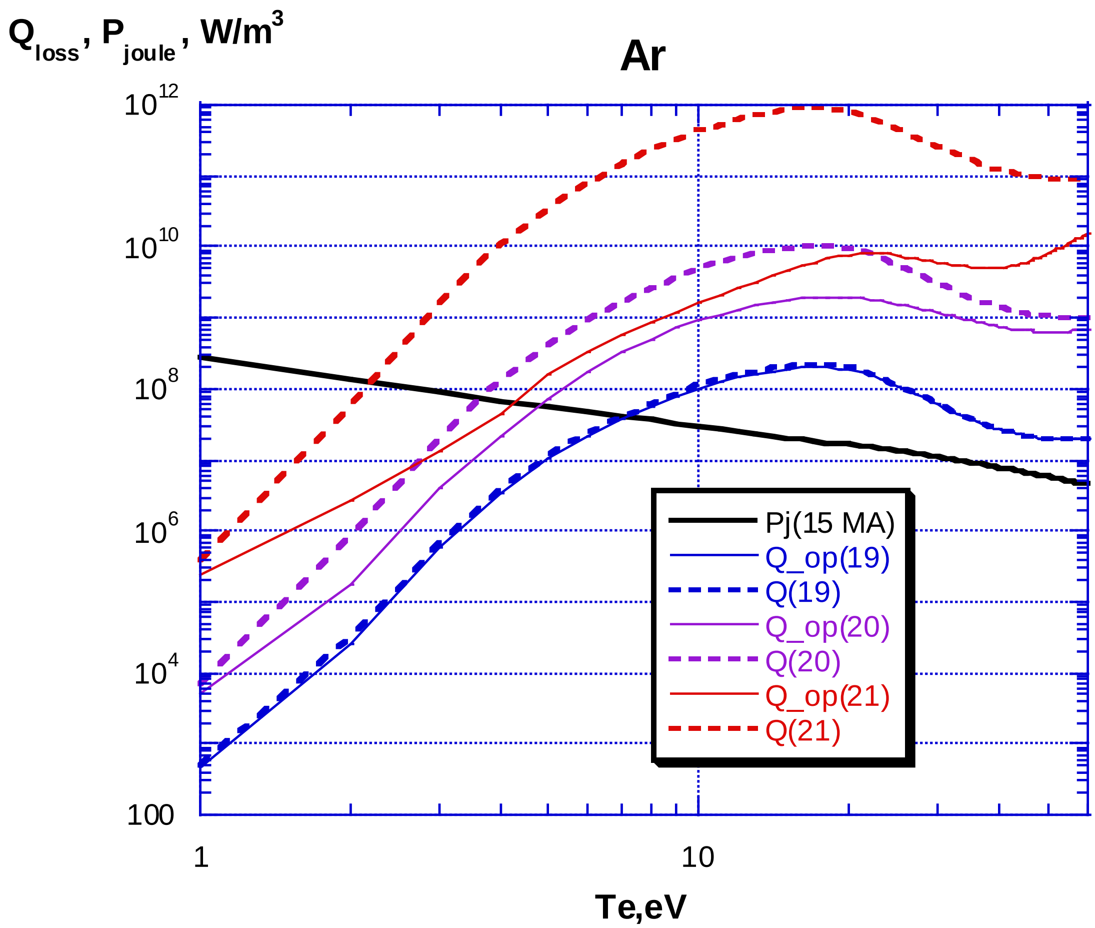

FIG. 5. The same as in FIG. 3 but for argon.

One can see that there is only unique intersection of the heating curve corresponding to the initial current and any loss curve. Hence, temperature "jumps" are expected neither for transparent plasmas nor for opacity effects. The influence of opacity in argon seeded plasmas is expected to be not so important as for carbon or beryllium seeded ones. The time evolutions of the electron temperature, total toroidal current and halo current are shown in Fig 6. The continuous impurity injection during *5 ms* is

supposed. The argon concentration rises from $2\cdot10^{19}\,m^{-3}$ to $1.2\cdot10^{20}\,m^{-3}$. One can see that the temperature calculated taking into account opacity effects is approximately twice higher than the temperature calculated under the assumption of transparency. The influence of opacity on the current decay time and halo currents is not important.
The comparison of Fig. 6 and Fig. 4 shows that the current decay time and halo current both are significantly lower (by factor 4-5) in argon seeded plasmas than in carbon seeded ones. Present simulations show that the noble gas injection successfully mitigate the disruption events in ITER.

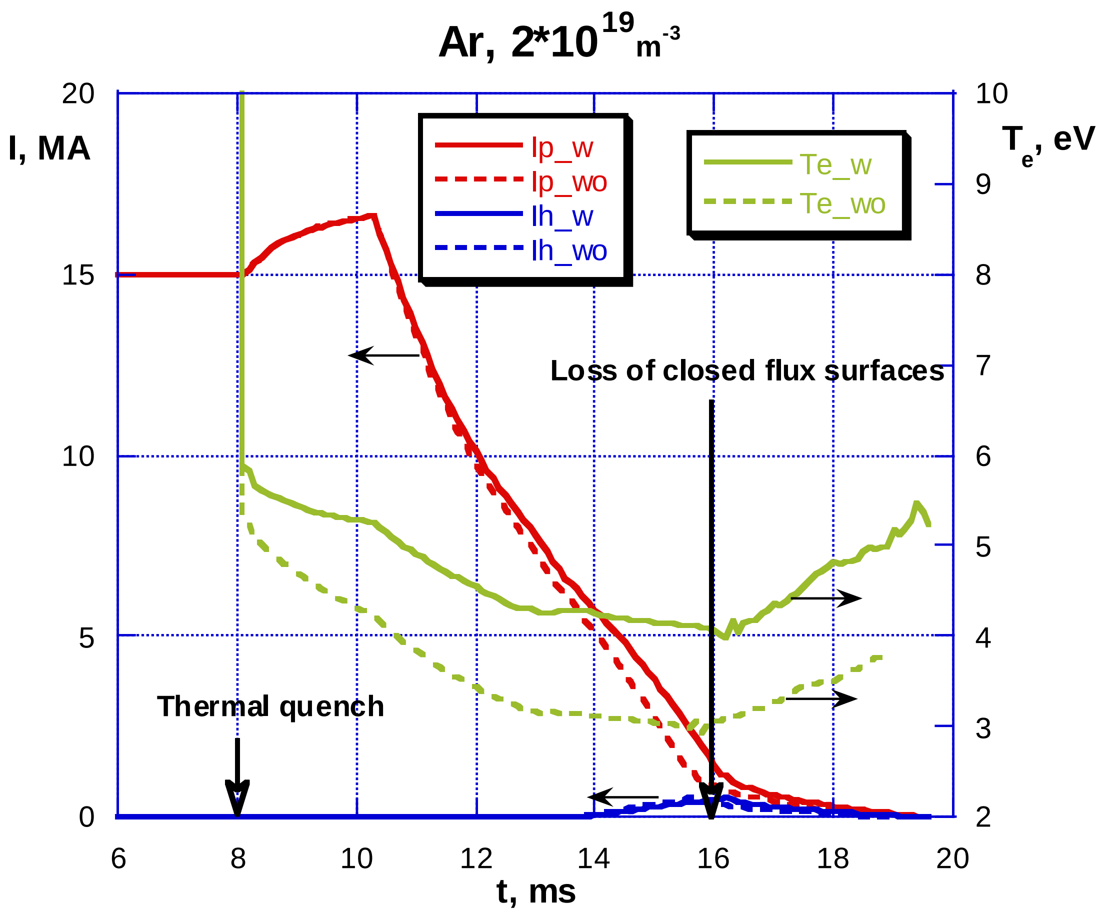

FIG. 6 The same as in FIG. 4 but for argon.

5. Summary.

- The optical thickness for impurity radiation in lines and opacity effects are shown to be important at the stage of current decay after disruptions and noble gas injection in tokamaks.
- The model proposed is verified by the comparison with JET experiments. The good coincidence of simulated and experimental results for the current decay time in JET is achieved in contrast to the results obtained under the assumptions of optical transparency.

- ITER simulations show that the temperature as well as halo current is underestimated significantly under the assumption of optical transparency of carbon seeded plasmas at the stage of the plasma current decay.
- The opacity effects are not so important for argon seeded plasmas.
- If the argon massive jet is injected the current decay time and halo current both are significantly smaller than in disruptions. Hence, the injection may mitigate disruption consequences successfully in ITER.

6. Acknowledgement

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