Multiplet effects in radiation losses during discharge quenching by intense argon injection in ITER

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1. Introduction. One of conditions of the experimental tokamak reactor ITER's safe operation is the possibility of disruption instability mitigation by massive injection of inert gases, in particular, of argon and neon. Impurity radiation from the plasma periphery will allow to "reradiate" the considerable part of plasma thermal energy and to reduce the energy flux on the divertor plates. Numerical modeling of Ar or Ne massive gas injection (MGI) in the ITER 15 MA Q ~ 10 baseline scenario at the quasi-stationary stage of discharge (flat-top of the current) was carried out in [1]. For modeling of main plasma parameters, the ASTRA transport code [2] was used, integrated with the ZIMPUR code [3], which describes the dynamics of charge states, radiation losses and transport of impurities (radiation losses were simulated in [1] for optically thin coronal plasma). For calculation of the gas outflow from the MGI system into the main chamber, the phenomenological model [4] was used.

Here we present the results of assessment of the following effects for scenario simulated in [1]: (i) line radiation imprisonment effects, using the "escape probability" model; (ii) the non-coronal effects caused by collisional quenching; (iii) the fine structure of levels with account of multiplet splitting. This task is stimulated by the results [5] where the impact of plasma opacity effects on the disruption mitigation by the MGI in tokamaks was shown (only the first two effects were taken into account there).

2. Analysis of modeling results for argon radiation power during MGI. Here for illustration we consider radiation of two argon ions – Ar^{+15} and Ar^{+3}, which have spectral lines of high intensity and could be used for plasma diagnostics. We estimate the above-mentioned effects on the radiation of these ions at two stages of discharge with MGI: before and after thermal quench (TQ).

We use the "escape probability" model of line radiation escape from plasma (see, e.g., surveys [6, 7]) and the simplified non-coronal radiative-collisional model to assess the opacity effects. The correction to the local values of radiation loss power from the strongest lines may be evaluated, for small and moderate deviations from the coronal limit $P_{\mathrm{rad}}^{(\mathrm{coronal})}(\mathbf{r})$, with the following factor:

$$P_{\mathrm{rad}}(\mathbf{r}) = \sum_i \left(P_{\mathrm{rad}}^{(\mathrm{coronal})}(\mathbf{r})\right)_i \left(\frac{\bar{T}(\mathbf{r})}{\beta(\mathbf{r}) + \bar{T}(\mathbf{r})}\right)_i, \qquad (1)$$

where summation goes over strongest radiative transitions, $\beta(\mathbf{r})$ is the quenching factor, namely the ratio of the rate of the de-excitation by the electron impact to the rate of spontaneous radiative decay of the excited state, $\bar{T}(\mathbf{r})$ is so called "escape probability" of photons, i.e. the angle-averaged probability of the photon escape (without any acts of absorption/reradiation) from the plasma volume from the given point $\mathbf{r}$. For the inhomogeneous plasma of volume V one has

$$\bar{T}(\mathbf{r}) = \frac{1}{4\pi}\int_{(4\pi)} d\Omega_{\mathbf{n}} \int_0^{\infty} d\omega\, P(\omega, \mathbf{r}) \exp\left\{-\int_0^{r_b(\mathbf{n},\mathbf{r})} k(\omega, \mathbf{r}' + \mathbf{r})\mathbf{n}d\mathbf{r}'\right\}. \qquad (2)$$

Here $P(\omega, \mathbf{r})$ is (normalized over frequency ω) spectral line shape of photon emission by excited atom at the point $\mathbf{r}$, $k(\omega, \mathbf{r})$ is the coefficient of absorption of photon by non-excited atoms atom at the point $\mathbf{r}$ (the inverse mean-free-pass length of photons). The $\mathbf{r}_b(\mathbf{n}, \mathbf{r})$ is the coordinate of the point on the media boundary, at which the line drawn from the point $\mathbf{r}$ in the direction of unity vector $\mathbf{n}$ crosses the media boundary.

For the Ar^{+15} ion at time moments 9.0, 10.01 and 11.06 ms (before thermal quench [1]) the calculations were performed for the transition $3p \rightarrow 2s$:

$\{1s^2 3p^1\ (^2P) \rightarrow 1s^2 2s^1\ (^2S)\}$, $\Delta E = 527.93$ eV, $g_1 = 9$, $g_0 = 4$, $\tau = (1/1.44e{+}12)$ s, (3)

where g_1 and g_0 are the statistical weights of the upper and lower energy level, τ is lifetime of the excited state with respect to spontaneous radiative decay, ΔE is the transition energy. At time moments 11,16, 11,51, 11,91 and 12,31 ms (after thermal quench) the calculations were performed for the transition $2p \rightarrow 2s$:

$\{1s^2 2p^1\ (^2P) \rightarrow 1s^2 2s^1\ (^2S)\}$: $\Delta E = 32$ eV, $g_1 = 3$, $g_0 = 1$, $\tau = (1/1.17e{+}9)$ s. (4)

For the Ar^{+3} ion in the temperature range of our interest, 1 eV < T_e < 10 eV, the following spectral lines dominate in the power losses of this ion:

$\{3s3p^4\ (^2S) \rightarrow 3s^2 3p^3\ (^2P^\circ)\}$ ($3p \rightarrow 3s$), λ= 702.867 Å, $\Delta E = 17.6$ eV, (5)

$\{3s^2 3p^2(^3P)3d\ (^2D) \rightarrow 3s^2 3p^3\ (^2P^\circ)\}$, ($3d \rightarrow 3p$), λ= 532.718 Å, $\Delta E = 23.3$ eV. (6)

The quenching factor $\beta(\mathbf{r})$ is defined as

$$\beta(\mathbf{r}) = \tau n_{\mathrm{e}}(\mathbf{r}) \langle v\sigma_{10}\rangle(\mathbf{r}), \qquad (7)$$

where $n_0(\mathbf{r})$ is the density of atoms/ions at the ground state, $\langle v\sigma_{10}\rangle(\mathbf{r})$ is the electron impact de-excitation rate.

For the optical thickness Θ of the plasma layer with depth L and for the radiative transition frequency ω_0 one has

$$\Theta = \int_0^L k(\omega_0, x)dx. \qquad (8)$$

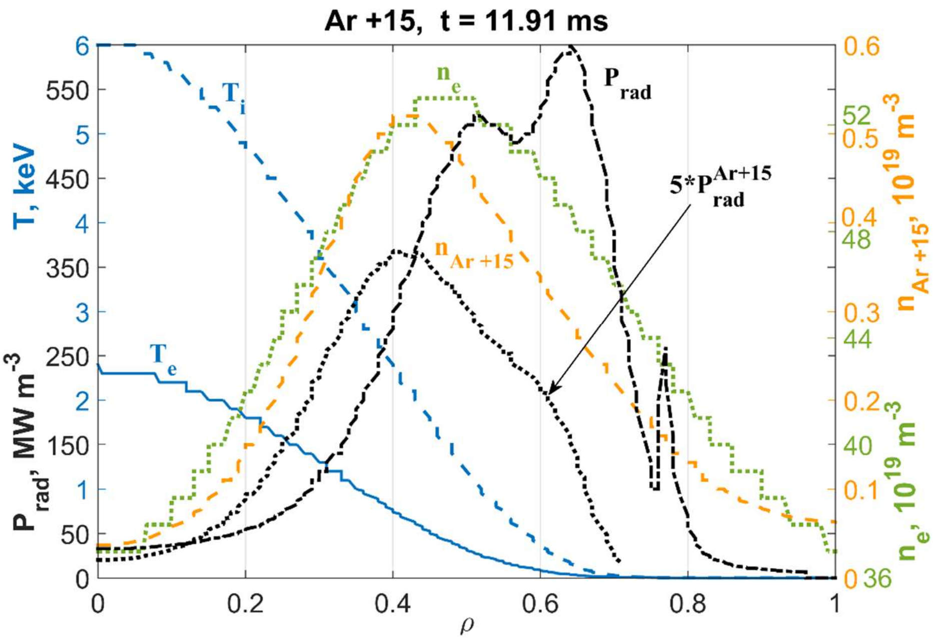

Figure 1. Spatial profiles of plasma parameters at time t = 11.91 ms: electron (solid blue) and ion (dashed blue) temperatures, electron density (green), argon ion Ar^{+15} density (orange), total radiation loss power by ZIMPUR (dash-dot black), radiation loss power $P_{\mathrm{rad}}^{\mathrm{Ar+15}}$ for Ar^{+15} (dotted black). The optical thickness Θ over the path along major radius for line 2p → 2s (4) is Θ ≈ 1.75.

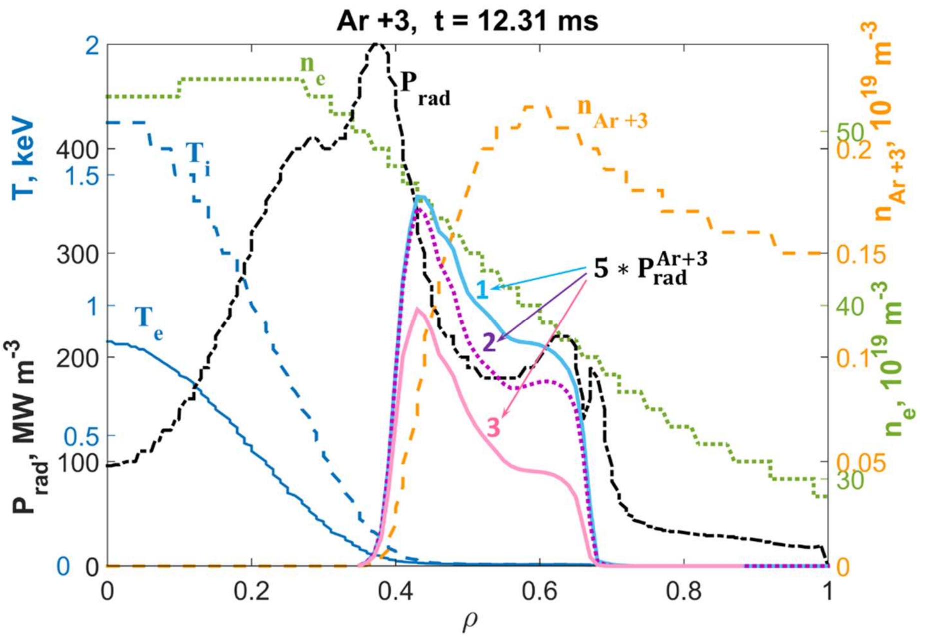

Figure 2. The same as in Fig. 1, but for time t = 12.31 ms and for ion Ar^{+3}, orange curve displays Ar^{+3} density. The optical thickness Θ over the path along major radius for lines (5) and (6) is: $\Theta_{532} \approx 16.30$, $\Theta_{702} \approx 6.88$. There is also shown the following comparison of radiation power losses: curve 1 - local emissivity in the lines (5) and (6), calculated with account of the exact structure of atomic energy levels and the respective coronal limit of radiative-collisional model without opacity effect; curve 2 – the same but for the simplified radiative collisional model with the opacity effect described by Eq. (1); curve 3 – total emissivity of Ar^{+3} ion in the coronal limit for the approximate structure of atomic energy levels, used in the ZIMPUR code. One can see that opacity effect gives the corrections ~ 25-30%.

Spatial profiles of power losses of argon ions are shown, together with other parameters of plasma at the different time moments: Fig. 1 is for Ar^{+15} at 11.91 ms after injection start; Fig. 2 is for Ar^{+3} at 12.31 ms after injection start.

The results of calculations performed show that in the ITER discharge quenching scenario simulated in [1] the plasma opacity effects are small for the radiation of intense argon lines, which could be interesting for plasma diagnostics. Despite the optical thickness of plasma on these transitions isn't small, the smallness of the excitation quenching factor allows photons to leave quickly plasma volume without noticeable reduction of respective radiation loss power.

At the stage of impurity stirring the radiation losses of Ar^{+3} in the area with electron temperature $T_e \leq 5$ eV become noticeable in the significant part of the whole plasma volume. At this stage the strong effect of the opacity on the discharge evolution appears that was predicted in [5] (cf. Fig. 12 in [5]) without account of the fine structure of atomic levels.

3. Conclusions. The radiation losses calculation with account of two effects, namely (i) radiation imprisonment and (ii) non-coronal radiative-collisional model, in the model of the excited levels, averaged over multiplets, gives, presumably, an upper bound for estimation of the impact of opacity effects upon discharge quenching by the impurity injection. The opacity on the strong lines of the argon ions Ar^{+3} and Ar^{+15} which could be used for plasma diagnostics, has no significant effect on the full radiation power losses of plasma in the discharge quenching scenario simulated in [1]. However, for comparison with [5] a more detailed analysis is needed.

The most significant effect appears to be the multiplet splitting, which provides the increase of radiative losses, e.g., by a factor of ~2 for low ionized atoms at low temperatures, because the resolution of the fine structure of atomic levels for Δn=0 transitions leads to contribution of lower excitation energy than that in the model of multiplet-average radiative transitions.

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