Modelling of lithium transport and its influence on the edge plasma parameters in T-15MD tokamak

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Abstract. A possible application of a lithium emitter-collector scheme to the T-15MD tokamak is considered. 2D simulations with the SOLPS4.3 code package indicate that the outer midplane is the optimal position for the lithium emitter. In the magnetic configuration analysed, lithium deposition is primarily localized in the upper outer divertor. Lithium radiation enhancement due to non-coronal effects for the case studied is about a factor of 6. However, although much higher than normally observed for higher Z impurities (such as neon), this enhancement is clearly insufficient to provide significant energy dissipation, unless the lithium inventory in the edge becomes close to the deuterium one.

1. Introduction
Power exhaust, high erosion of the plasma facing components (PFC) caused by the extreme heat fluxes and probable PFC melting during the transient events, such as Type I ELMs and disruptions, are among the main challenges ITER and future tokamak-reactors will face [1]. One of the possible solutions for a steady-state tokamak-reactor or a fusion neutron source (FNS) is employing a liquid metal as the divertor material (for an overview of the different concepts proposed see [2] and references therein). The main advantages of the liquid metal concept are self-healing and virtual invulnerability to the neutron damage. One of the most mature and extensively used among the lithium technologies proposed is a capillary porous system (CPS) filled with liquid lithium [3]. In Russia, such systems have been successfully tested and routinely used on T-11M and T-10 tokamaks [4]. Now, with construction of new T-15MD tokamak at the “Kurchatov Institute” [5], a possible application of an emitter-collector lithium CPS limiter system similar to the one used on T-11M tokamak [6] should be analysed.

The first critical issue here is choosing the appropriate position for the lithium emitter that would provide as wide as possible distribution of lithium throughout the scrape-off layer (SOL). Uniform lithium distribution is important for both lithiation (wall covering with the lithium films) and maximisation of the lithium radiation power. Equally significant is determination of the location(s), where the lithium eroded from the emitter would migrate and where the most efficient position for the lithium collector would be. Enhancement of the lithium radiation due to non-coronal effects is often considered by the authors of lithium limiter/divertor concepts capable of making otherwise weak lithium radiation an efficient dissipation mechanism [7,8]. Therefore, evaluating the degree of the lithium radiation increase compared to its coronal level for the T-15MD plasma is another important objective. To answer these questions, we simulate lithium migration in the T-15MD geometry with the SOLPS4.3 code package [9].
2. Simulation setup
The SOLPS4.3 [9] code package consists of a 2D multi-fluid MHD code B2, which describes the transport of the energy and particles (both the main plasma and impurities) in the charged components of the plasma, coupled via the source terms to the 3D kinetic Monte-Carlo code EIRENE [10] that describes the neutral transport. In modelling, the effective rates of different atomic processes involving lithium impurity, such as electron impact ionization, recombination and electron impact excitation, must be taken into account. The data for these rates have been taken from the ADAS database [11] and approximated with the parametric fits used in the B2 and EIRENE codes. The maximum deviation of the resulting fits from the original ADAS data is within 20%.

The real geometry of the T15-MD chamber is used. The magnetic configuration considered for the first years of operation is an asymmetric double null with the upper X-point situated rather far from the inner separatrix. Therefore, the upper divertor is much less loaded compared to the “main”, lower one. Up to 23 MW of the auxiliary heating power is planned for T-15MD in future [5]. In our modelling we simulate the deuterium edge plasma with the power coming from the core plasma across the separatrix, \( Q_{\text{SOL}} = 6 \text{ MW} \), which is roughly equivalent to (for example) \( Q_{\text{SOL}} = 12 \text{ MW} \) with 50% of this power reradiated by some seeded impurity. In simulations without lithium, the total amount of deuterium nuclei (both ions and neutrals), \( N_D^{\text{edge}} \), is chosen as the second control parameter determining the edge plasma equilibrium [12]. \( N_D^{\text{edge}} \) is taken equal to \( 6 \times 10^{20} \) particles, which corresponds to the onset of divertor detachment in pure deuterium plasma with the \( Q_{\text{SOL}} \) value selected.

Lithiation of the main chamber impedes the deuterium recycling. Following [13], we decrease the recycling coefficient from 1 to 0.93 for the cases with lithium injection. Changing the recycling coefficient affects the plasma solution significantly. The plasma density near the targets decreases noticeably. Consequently, the plasma temperature and the peak heat loads increase and the resulting divertor plasma state is now further away from detachment.

The lithium limiter is modelled with a toroidally-symmetric lithium atom source with the puffing rate of \( \Gamma_{\text{puff}}^{\text{Li}} = 5 \times 10^{20} \) particles per second. Comparing the lithium influx chosen with the high performance FTU lithium limiter erosion rate calculated with the ERO code (see [14] for the details) one can see that \( \Gamma_{\text{puff}}^{\text{Li}} \) used corresponds to the toroidal ring limiter of a roughly 1 cm width, which seems reasonable. For obvious reasons, it is much easier to insert any kind of movable limiter from the low field side (LFS) of the chamber. Therefore we limit our study to three possible limiter positions – inside the lower outer divertor, inside the upper outer divertor and at the outer midplane (OMP). The recycling coefficient for lithium is set to 0 – i.e., the lithium ions and atoms stick to the wall as soon as they hit it.

3. Modelling results and discussion
The resulting lithium density distribution in the edge of T-15MD is shown in Figure 1 for the three lithium limiter positions examined. The low ionization potential of the neutral lithium (5.4 eV) results in a very short ionization length in the dense SOL and divertor plasmas. Hence, the lithium atoms can hardly penetrate to the main chamber SOL even through the cold plasma of the upper outer divertor, leave along the highly loaded “main”, lower outer divertor. However, at the OMP, the distance the lithium neutrals need to fly to get inside the inner separatrix is very short compared to the divertor limiter positions. This results in a very wide lithium distribution, even if we do not allow for the re-erosion of lithium deposited on the main chamber walls. For this reason, in what follows, we limit ourselves to the most interesting case of the lithium limiter situated at the OMP.

To find the best possible position of the lithium collector, we compare the lithium deposition rate along the first wall with the rate of lithium erosion by the deuterium ions (we neglect lithium self-sputtering for now). For the modelled case of a rather high deuterium density, the energy of the impinging deuterium ions lies within the 10-50 eV range (allowing for the sheath acceleration). In this range, the lithium sputtering yield, \( Y_{\text{Li}}^{\text{scatt}} \), calculated with the TRIM code [15], can be roughly
approximated with a linear function. If we take into account that only 1/3 of the sputtered lithium leaves the surface as a neutral (and 2/3 leaving it as ions are immediately returned back to the surface by the sheath electric field), this function increases from 0.001 for the 10 eV deuterium ions to 0.01 for the 50 eV ions. Another factor that influences the lithium sputtering yield even more than the impinging deuterium ion energy is the surface temperature. To take the surface temperature into account we, following [16], calculate the total sputtering yield

$$\gamma_{\text{Li,S}} = \gamma_{\text{Li,therm}}^{\text{Li,S}} + \gamma_{\text{Li,coll}}^{\text{Li,S}}$$

where

$$\gamma_{\text{Li,therm}}^{\text{Li,S}} = \frac{0.016}{k(T_s + 350)^{1/2}} \exp \left[ -\frac{U}{k(T_s + 350)} \right]$$

Here $k$ is the Boltzmann constant, $U = 1.59$ eV is the lithium sublimation energy and $T_s$ is the surface temperature. What is left now is to estimate $T_s$. The T-15MD first wall and divertor will be made of the carbon fiber composite (CFC) and the pulse duration will be several (<10) seconds. Hence, for a crude estimate of the surface temperature we can use the well-known solution for the semi-infinite target:

$$T_s = (\pi \rho C_p \kappa)^{1/2} \int_0^\tau q_w (t - t')^{1/2} \, dt$$

Here $\rho$, $\kappa$ and $C_p$ are the CFC density, thermal conductivity and thermal capacity, respectively, and $q_w$ is the heat flux to the target surface. To obtain the zero-order estimate for $T_s$, we assume that the heat flux to the divertor targets equals the stationary heat load (calculated in our simulations) and lasts for $\tau_{\text{pulse}} = 1$ s.

Figure 1. Density distribution of lithium (atoms and ions together) in the edge of T-15MD tokamak; the lithium limiter is situated (from left to right) at the lower outer divertor, at the upper outer divertor and at the outer midplane.

In Figure 2 the resulting lithium deposition profile is given. The boundary cells of the computational domain are stretched along the horizontal axis (we “go” along the main chamber wall from the lower private flux region (PFR) to the lower inner target (LIT), then to the upper inner target (UIT), etc., until the circle closes). The dashed red curve indicates $\gamma_{\text{Li,S}}^{\text{Li,L}}$ cut off at the value of 10 roughly corresponding to the surface temperature of 500 °C. For given conditions, the sputtering yield above this value renders lithium deposition impossible. The solid blue curve shows the resulting lithium deposition rate (in the units of $10^{20}$ particles per second). It is clear from Figure 2 that the optimal position for the lithium collector is the outer (from the X-point to the shadow of the first wall) part of the upper outer divertor target. The reason for this is simple. Both the lower inner and lower outer divertors are highly loaded, therefore $\gamma_{\text{Li,L}}^{\text{Li,L}}$ there is high and most of the lithium deposited there will be sputtered by the deuterium ions (note that we do not take into account evaporation and self sputtering that will make lithium deposition there even less probable). Because the lithium limiter is
situated at the OMP, it is much easier for the lithium ions to get into the upper outer divertor compared to the upper inner one. Finally, the upper divertors are much cooler than the lower ones due to the asymmetry of the present magnetic configuration. This makes the upper outer divertor the ideal place for lithium to stick.

For given $\Gamma_{\text{Li puff}}$ and the lithium limiter situated at the OMP, the resulting lithium inventory in the edge is about ~3% of the deuterium one. The lithium radiation is localized in a thin layer close to the inner separatrix, which agrees well with the existing experimental data [7] and 2D simulations [13]. Non-coronal effects for lithium are indeed significant. Close to the inner separatrix, the lithium radiation power is 10 to 30 times higher than the coronal one (see Figure 3). Overall, the increase of the radiation over the coronal one calculated for the same plasma profiles is approximately a factor of 6. This enhancement is much stronger than for the impurities conventionally used for the power exhaust, such as nitrogen or neon. For instance, the neon radiation enhancement due to the non-coronal effects rarely exceeds 20%. However, even the non-coronal effects cannot bring lithium on par with the conventional impurities with respect to the radiation power. It is negligible compared even to the deuterium radiation. For the particular case considered, the simulated lithium radiates approximately 170 kW, whereas the total deuterium radiation power is about 1.6 MW. Hence, significant dissipation through the lithium radiation channel would only be possible if the lithium inventory in the edge is of the same order as the deuterium one. This is hardly acceptable because of the core plasma contamination.

Figure 2. Lithium deposition rate (solid blue curve) and lithium sputtering yield by deuterium ions (red dashed curve) plotted along the computational domain boundary.

Figure 3. Ratio of calculated lithium radiation power to its coronal value, calculated based on the computed lithium distribution and background plasma profiles.

4. Conclusions
Simulations of lithium migration in the edge plasma of T-15MD tokamak have been performed with the SOLPS4.3 code package. For this purpose, the effective rates of different lithium atomic processes taken from the ADAS database were incorporated into the code. The simulations show that the lithium emitter positioned at the outer midplane provides a wide lithium distribution throughout the SOL and is optimal for wall lithiation and maximization of the lithium radiation. The emitted lithium is deposited mainly at the upper outer divertor and should be collected there. The non-coronal radiation enhances the lithium radiation significantly, by approximately a factor of 6. However, this enhancement is still insufficient for efficient energy dissipation with lithium radiation, unless the lithium inventory in the edge is of the same order as the deuterium one. This would result in a
significant core plasma contamination. Therefore, seeding the edge plasma with higher Z impurity is still required for the power exhaust during operation with the lithium emitter-collector system.

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