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Integrated core-SOL-divertor modelling for DTT tokamak with liquid metal divertor targets

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Abstract

The I-DTT tokamak has been analyzed by means of the integrated core-SOL-divertor modelling with COREDIV code when either lithium or tin are used as liquid divertor target materials. It has been found that the solution (operating scenario) is determined by the LM divertor properties, leading to the requirements that the heat load to the liquid target is reduced below a threshold value. The threshold is determined by the limits to the plasma contamination by the evaporated material. In the case of the Li target, the limit is found to be ~ 8 MW/m^2 and is achieved by strong Li radiation in the divertor (vapor shielding). It appears, that there is a low density limit, and plasma solution is only achievable if the plasma density is high enough. The low density operation might be recovered if Kr seeding is applied. For the the liquid tin divertor, the heat load threshold is much lower than for Li due to stronger limits on the tolerable impurity concentration. Since Sn radiates predominantly in the core, the power crossing the separatrix is well below the P$_{LH}$ threshold. It appears that Ne seeding does not solve the H-mode operation problem, however Li seeding might be the solution.

Keywords: Liquid metal divertors, tokamaks, plasma modelling

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1. Introduction and Physical Model

The prospect of using liquid metal (LM) targets as alternatives to the conventional solid ones in the divertor of a tokamak reactor is continuously gaining interest in the last years[1]. At present lithium and tin are among the most promising candidates and the performance of the two elements as plasma facing materials is under investigation [1, 2, 3]. The use of liquid targets in the divertor is foreseen in the projected Italian Divertor Test Tokamak (I-DTT) [4, 5], one main mission of which is to study the power and particle exhaust issues in DEMO relevant conditions.

In this paper, the possible operational space for the I-DTT device is analyzed for the standard single null divertor configuration by means of the integrated COREDIV code simulations when either lithium or tin are used as liquid target materials.The targets are modelled as a thin liquid metal layer superimposed on a tungsten substrate that faces the plasma while its bottom is kept at a fixed temperature. The calculated evaporation rate together with sputtering gives the total impurity source strength. The details of the evaporation model are presented in Ref.[6]. The impurities originating from the sputtering and vaporization processes are expected to modify plasma characteristics significantly both in the bulk and in the scrape-off layer (SOL). Therefore, the simulations are performed with the COREDIV code which self-consistently solves radial 1D energy and particle transport equations of plasma and impurities in the core region and 2D multifluid transport in the SOL. As this work forms a follow-up of our previous efforts, the detailed description of the transport model can be found in Refs. [5, 7, 8] and details of the model are skipped here. In the core, the 1D radial transport equations for bulk ions, for each ionization state of impurity ions and for the electron and ion temperatures are solved, whereas in the SOL, the 2D fluid Braginskii like equations are solved in the simplified slab geometry but taking into account plasma recycling in the divertor region and sputtering, evaporation and prompt re-deposition processes at the target plates.

Four different scenarios have been considered in our simulations corresponding to different volume averaged densities: the reference one, two lower, and one higher, respectively n_e=1.8, 1.0, 1.5, 2.3×10$^{20}m^{-3}$ with a correspondent density at the separatrix n_{es}= 6.0, 3.3, 5.0,

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$7.5{\times}10^{19}m^{-3}$. The macroscopic parameters, plasma current, magnetic field, confinement factor and auxiliary power, are respectively: $I_p = 6.0$ MA, $B_T = 6.0$ T, $H_{98} = 1$, $P_{aux} = 45$ MW have been kept constant. We have chosen the highest predicted heating power in order to investigate the exhaust power problem in conditions that are as close as possible to the conditions expected in a reactor.

2. Simulations of Liquid Lithium Divertor

The influx of impurities released from the LM divertor might affect plasma performance in numerous ways and the effect depends strongly on the impurity type. For fusion reactor, the acceptable core impurity level is determined by dilution and radiation losses. For lithium (Li), with low nuclear charge ($Z = 3$), dilution is the dominant constraint. Since I-DTT does not rely on fusion power, plasma dilution might not be as dangerous as for the reactor but it can have also a detrimental effect on confinement, which is not however included in the COREDIV modelling.

Table 1: plasma parameters for different plasma scenarios and Li divertor

$n_e[\times 10^{20}m^{-3}]$	2.3	1.8	1.5	1.0
c_{Li} [%]	7.3	8.1	8.3	NoS
Z_{eff}	1.46	1.51	1.53	NoS
P_{plate} [MW]	15.5	15.5	15.5	NoS
P_{sep} [MW]	41.7	42.5	43.1	NoS
P_{rad} [MW]	30.2	30.1	30.	NoS
P^{max}_{plate} [MW/m^2]	8	8	8	NoS
$\Gamma_{Li}[\times 10^{23}s^{-1}]$	6.7	7.6	8.1	NoS
T^{max}_{surf} [^{o}C]	765	766	766	NoS

Some plasma parameters are shown for different scenarios in the Table 1. Simulations are performed assuming the following LM divertor parameters: Li layer width $d_{Li} = 1$mm, tungsten base width $d_W = 10$mm, coolant temperature T_0=200 ^{o}C and the angle between magnetic field and the target surface is set to $\alpha_{plate} = 2^o$. Simulations show that in the case of Li target, there is a low density limit for the accessible scenarios which is related to the plasma dilution due to strong influx of evaporated Li atoms and consequently there is no solution (NoS) for the low density scenario ($n_e = 10^{20}m^{-3}$). It can be seen that for DTT device maximum Li concentration in the core is $c_{Li} \lesssim 8.3$ % corresponding to $Z_{eff} \lesssim 1.53$ and lithium influx of the order of $\Gamma_{Li} \lesssim 8 \times 10^{23}s^{-1}$. It should be stressed that the solution in terms of the global plasma parameters like power to the plate P_{plate}, power crossing separatrix P_{sep}, total radiated power P_{rad} is independent of the plasma density. Surprisingly, the local LM divertor surface parameters like maximum power flux at the liquid target P^{max}_{plate} and the maximum target surface temperature T^{max}_{surf} do not depend on the plasma density. That results can be explained by self-consistency between Li production (due to evaporation) and the power losses in the edge (SOL) plasma by radiation of Li ions. It comes out from the Fig.1, that the Li (as well Sn) evaporation rate is a very steep function of the power flux density at the target. Since the Li concentration in the plasma is limited (dilution or radiative collapse), the Li evaporation has to be limited otherwise there is no solution (no plasma scenario). In our case $\Gamma_{Li} < 10^{24}s^{-1}$ and consequently the power density must be smaller than ~ 8 MW/m^2 (the power density is calculated as projection of the parallel heat flux on the target surface with $\alpha_{plate} = 2^o$) corresponding to the liquid surface temperature $T^{max}_{surf} \sim 765\,^o$C. The reduction of the power is achieved by strong Li radiation in the SOL (vapor shield). In other words the solution (plasma scenario) is defined by the LM divertor properties corresponding to the maximum allowed power flux at the target (or surface temperature). For the considered DTT scenarios the heat load to the target exceeds the DEMO limit (5 MW/m^2) and it might be necessary to further reduce the power to the target. Since in the case of Li, the radiation cooling is concentrated in the divertor region, the power crossing the separatrix is well above the power threshold for the L-H transition (≤ 25 MW) and therefore there is a place for additional radiating impurity in the core. With seeding, the effect of the low density limit discussed above might also be mitigated. Calculations have been performed for all 3 scenarios assuming krypton (Kr) seeing and the results are presented in the Fig.2. First, it can be seen that the low density operation ($n_e = 10^{20}m^{-3}$) is recovered if the Kr seeding level is high enough $\Gamma_{Kr} > 10^{20}s^{-1}$ ($c_{Kr} > 0.35$ %). However, the seeding does not reduce significantly the power to the target (f_{rad} is only slightly increased) and

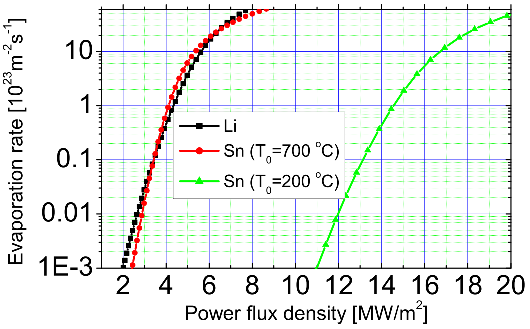

Figure 1: Evaporation rate for Li and Sn

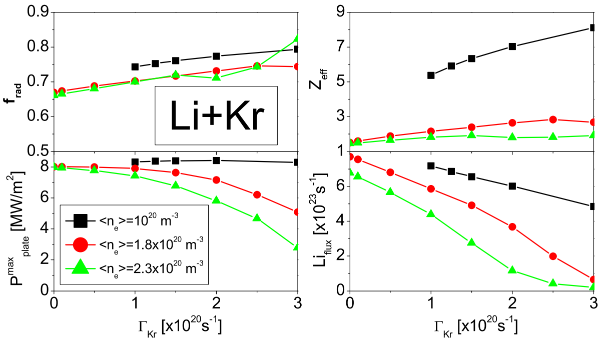

Figure 2: Plasma parameters vs. Kr seeding

for scenarios with medium and low density strongly increases plasma contamination (Z_{eff} level). The reason for almost constant radiation is such that Li radiation in the SOL is replaced by Kr radiation (in the core) with seeding in such a way that overall losses are kept constant in order to limit the heat load to the liquid target to the threshold value. We should note, that the reduction of the heat load to the target and the Li influx depend on the plasma density (with seeding) and it is the most efficient for higher densities. It should be stressed that for the considered, rather high heating power, lithium production is mostly due to evaporation process. Sputtering starts to be important only at high seeding levels (c_{Kr} > 0.1 %) and high plasma densities when the heat flux to the target is mitigated by krypton and hydrogen radiation. Regarding the question of divertor operation, it appears that achievement of detached or even semi-detached conditions in the divertor might be difficult even in the case of high density plasmas. In the Fig.3, we plot the plasma densities and temperatures at the target strike point position for the medium (open symbols) and high (full symbols) density scenarios. It is apparent that at low seeding levels mostly ionization of lithium contributes to the electron density and in spite of relatively high density ($n_e \sim 1.5 \times 10^{21} m^{-3}$) detachment can not develop. Only for the highest seeding levels semi-detached operation seems to be possibly, however at this conditions the power crossing the separatix might approach the L-H threshold.

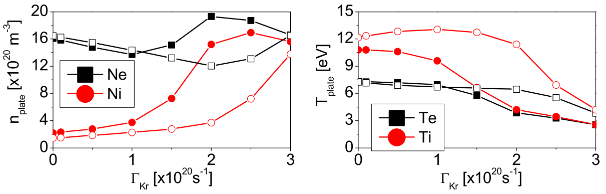

Figure 3: Plasma parameters vs. Kr seeding

3. Simulations of Liquid Tin Divertor

In the case of tin (Sn) divertor the effect of the impurity on the plasma performance is to large extent similar to the Li case as it can be seen in the Table 2 where some plasma parameters are shown for different scenarios. Simulations were performed assuming the Sn divertor parameters such to have similar evaporation rate as for Li case (see Fig.1): Sn layer width d_{Sn} = 2mm, tungsten base width d_W = 25mm, coolant temperature T$_0$=700 ^{o}C.

Table 2: plasma parameters for different plasma scenarios and Sn divertor

$n_e[\times10^{20}m^{-3}]$	2.3	1.8	1.5	1.0
c_{Sn} [%]	0.04	0.07	0.1	0.27
Z_{eff}	1.54	2.03	2.66	5.62
P_{plate} [MW]	5.3	5.0	4.71	3.93
P_{sep} [MW]	14.8	13.7	12.9	10.7
P_{LH} [MW]	24.2	20.4	18.0	13.6
P_{rad} [MW]	39.	39.6	40.0	41.4
P^{max}_{plate} [MW/m^2]	2.56	2.55	2.53	2.34
T_e^{plate} [eV]	1.77	1.87	1.95	2.44
$\Gamma_{Sn}[\times10^{21}s^{-1}]$	2.8	3.0	3.17	4.21
T^{max}_{surf} [^{o}C]	1339	1336	1330	1284

First of all, there is a very strong coupling between core and edge regions which in principle determines the operational regime of the device. The point is that the Sn production in the divertor (mostly due to evaporation) strongly affects the energy balance in the core and due to self-regulating mechanism determines in turn the release of Sn atoms from LM divertor targets. Since the allowed Sn influx in case of tin is almost 2 orders of magnitude smaller than for Li (higher Sn concentrations would lead to the radiative collapse) the conditions in the divertor are such that the heat flux density to the target stays at the threshold value ($\sim$ 2.5 MW/m^2, $T^{max}_{surf} \sim$ 1330 ^{o}C), which is much lower than in the Li case. Such strong power reduction can be achieved only by large radiation fractions (f_{rad} > 85%) leading to semi-detached conditions in the divertor.

However, since Sn as high Z impurity radiates effectively in the core region, the power crossing the separatrix is reduced to the levels well below the L-H power threshold, meaning that H mode operation might be difficult with tin divertor. A possible way to improve the situation would be to replace the Sn core radiation by radiation of low Z seeded impurity in the SOL region. Neon seems to be the natural candidate and we have performed investigations of the influence of Ne seeding on the H-mode operation window for all plasma scenarios. It appeared however, that Ne seeding could not recover the H-mode operation since neon is not able to reduce effectively the Sn production, both by evaporation and sputtering. It is illustrated for the reference case ($n_e \sim 1.8 \times 10^{21} m^{-3}$) in the Fig.4, where it can be seen that with increased Ne influx, the evaporation flux is reduced but simultaneously the sputtered flux due to Ne impurity increases and the total tin release from the target is only slightly reduced. Consequently, the core radiation remains high. We have tested also the effect of the Li seeding and the results are somehow optimistic, since the H-mode operation can be recovered for sufficiently high seeding levels ($\Gamma_{Li}^{puff} > 4 \times 10^{22} s^{-1}$) as can be seen in Fig.5.

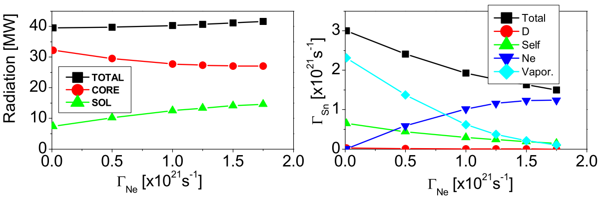

Figure 4: Sn production and radiations vs. Ne seeding

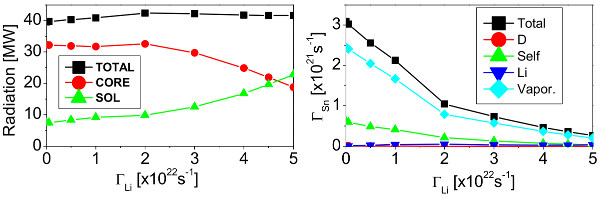

Figure 5: Sn production and radiations vs. Li seeding

All our results presented up to now assume that n_{es}/n_e=1/3. However, if operation with higher edge densities is possible than the operation in the H-mode would be much easier due to increase screening efficiency of the SOL and consequently reduced core radiation as illustrated in the Fig.6, where the reference case is compared to the situation with higher $n_{es} = 7.5 \times 10^{19} m^{-3}$. Another possible solution to the problems with the H-mode operation would be the change of the liquid tin divertor settings. For example, if the divertor settings are such that the evaporation rate is strongly reduced (d_{Sn} = 2mm, d_W = 10mm, T_0=200 ^{o}C, see Fig.1) corresponding to the power threshold value of ($\sim$ 11 MW/m^2 , $T_{surf}^{max} \sim 1300\,^o$C), than the divertor operation moves from the evaporation dominated regime to the sputtering dominated Sn production regime leading to reduced core Sn contamination as can be seen in the Fig.6.

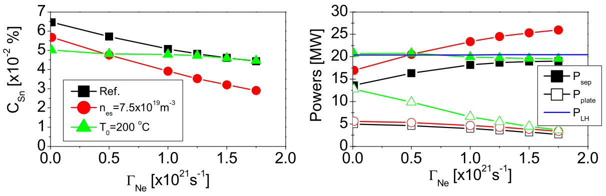

Figure 6: Sn concentrations and powers vs. Ne seeding

4. Conclusions

The behavior of the plasma parameters of the I-DTT tokamak has been analyzed for the standard divertor single null configuration by means of the integrated core-SOL-divertor modelling with COREDIV code when either lithium or tin are used as liquid target materials. It has been found that for LM divertors, in case of high power operation, the solution (operating scenario) is determined by the LM divertor properties, leading to the situation that the heat load to the liquid target is reduced below a threshold value. The threshold is determined by the requirement that the plasma contamination by the evaporated material is tolerable from the tokamak operation point of view (dilution or radiative collapse). In the case of Li target, the limit is set to $\sim$ 8 MW/m^2 and is achieved by strong Li radiation in the divertor (vapor shielding). It appears, that there is a low density limit, and plasma solution is only achievable if the plasma density is high enough ($n_e > 10^{20} m^{-3}$. The low density operation might be recovered if Kr seeding is applied.

For the tin liquid divertor, the heat load threshold is much lower than for Li (at least for the considered Sn divertor parameters) due to stronger limits on the tolerable impurity concentration. Consequently, radiation fractions are even larger (> 85%) and since Sn radiates predominantly in the core, the power crossing the separatrix is well below the P_{LH} threshold. It appears that Ne seeding does not solve the H-mode operation problem, however Li seeding might be the solution. In addition it has been found, that operation with higher edge plasma densities or change of the tin liquid divertor operation point from evaporation to sputtering regime might alleviate difficulties with the H-mode operation.

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[1] T.W. Morgan et al., Nuclear Materials and Energy, V. 12 (2017), pp. 210-215
[2] G. Mazzitelli et al., Journal of Nuclear Materials V. 463 (2015) 1152-1155
[3] G. Mazzitelli et al. ”First experimental results of heat loads on tin liquid limiter on FTU”, presented at 5th ISLA Conf. Moscow, 25-27 September 2017
[4] F. Crisantiet al., Fusion Engineering and Design, V. 124, Nov. 2017, pp. 288-298
[5] R.Zagórski et al., Fusion Engineering and Design, V. 122, Nov. 2017, pp. 313-321
[6] M.Poradziński et al., Fusion Engineering and Design, V. 122, Nov. 2017, pp. 248-251
[7] R.Zagórski, et al., Nucl. Fusion, 53, 073030 (2013)
[8] R.Zagórski, et al. Contrib.Plasma Phys.**54(4-6)**, 442 (2014)