

Assessment of Scrape-Off Layer and divertor plasma conditions in JT-60SA with tungsten wall and nitrogen injection

G. Rubino^{a,*}, G. Calabrò^a, M. Wischmeier^b

^a Department of Economics, Engineering, Society and Business Organization (DEIm), University of Tuscia, Largo dell'Università snc, Viterbo, 01100, Italy

^b Max Planck Institute for Plasma Physics, Boltzmannstr. 2, 85748 Garching, Germany

ARTICLE INFO

Keywords:

SOLPS-ITER

JT-60SA Scenario 3

High radiating scenario

W wall

Nitrogen

ABSTRACT

The possibility to safely operate tokamaks strongly depends on the capability to protect the divertor targets from excessive power load and erosion. Here, we will present a study of the JT-60SA Scenario 3 with a W wall to identify possible criticality in the transition from C to W wall. The assessment of the SOL and divertor plasma conditions is made with the SOLPS-ITER code suite. The simulation results show that safe operations are mainly limited by T_e . In addition, the analysis of the balance equations highlights the importance of the impurity injection. It represents the main mechanism to drive the decrease in power load onto the outer target (P_{OT}) by impurity radiation and to achieve detachment via the collisions between D^+ ions and D_2 molecules.

1. Introduction

The feasibility to operate future tokamaks is strictly related to the technological limit imposed by the divertor material. In order to get sustainable power loads on the target plates and to limit its erosion, a large part of the power needs to be radiated, e.g. by the injection of external impurity. The achievement of stable high radiating scenarios in tokamaks with metallic walls has been extensively studied and demonstrated in present machines as JET or ASDEX Upgrade [1]. One of the mission of JT-60SA, the largest superconducting tokamak that will operate before ITER [2], is to explore the feasibility of the integrated scenarios where a high performing plasma core is coupled with a high radiative divertor. The power exhaust study is split in two different research phases: the first one with C as plasma facing component, while in the second one the transition to a fully metallic wall made of W is forecast [3].

In this work we will show the analysis of the Scrape-Off Layer and divertor conditions in JT-60SA equipped with a fully W wall. We have taken into account the Scenario 3, the vertical Lower Single Null inductive high density and high collisionality scenario [3]. In this scenario, the separatrix hits the vertical targets both on inner and outer plates. The strike points are located close to the corners and the geometry is characterized by a closed shape. The SOL plasma has been simulated by means of the 2D edge code SOLPS-ITER, where the plasma is described by a set of Braginskii like transport equations coupled with the Monte Carlo code EIRENE for the neutral dynamics [4]. The assessment of the conditions able to ensure safe operations is

discussed by considering the engineering limits in steady state defined by $P_{OT} < 10 \text{ MW/m}^2$ and $T_e = 5 \text{ eV}$. P_{OT} has been set lower than the technological limit $P_{OT} = 15 \text{ MW/m}^2$ found in [5] for the W coated CFC block in order to precautionary take into account the longer pulse length $t = 60 \text{ s}$ compared to the $t = 5 \text{ s}$ of the experimental tests. Previous studies performed with SONIC [6] and COREDIV [7,8] have shown the possibility to define a wide range of operational windows both in case of Ar and Ne injection.

This paper is organized as follows: in Section 2, an overview of the JT-60SA Scenario 3 and the SOLPS-ITER setup is presented. The results of the simulations in terms of general trends are discussed in Section 3, where we also analyze the physical mechanisms able to lead to a detachment of the plasma from the outer target plates. In Section 4, the operational window in terms of Deuterium and impurity puffing rates is defined. Conclusions are summarized in Section 5.

2. SOLPS-ITER setup and scenario overview

The main geometry and plasma parameters of the JT-60SA Scenario 3 are given in Table 1. It is characterized by a relative high density and a moderate auxiliary power level compared to other scenarios [3]. Taking into account core radiation as given in [8], the input power in the simulations is set to $P_{in} = 20 \text{ MW}$. To reach the high radiation fraction needed to fulfill the $P_{OT} < 10 \text{ MW/m}^2$ and $T_e < 5 \text{ eV}$ constraints, N seeding is considered in the study due to its well established divertor cooling performance in metallic devices as JET [9]

* Corresponding author.

E-mail address: giulio.rubino@enea.it (G. Rubino).

<https://doi.org/10.1016/j.nme.2020.100895>

Received 31 July 2020; Received in revised form 1 December 2020; Accepted 18 December 2020

Available online 30 December 2020

2352-1791/© 2020 The Authors.

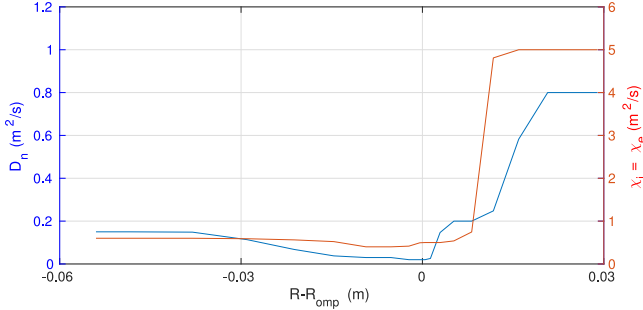
Published by Elsevier Ltd.

This is an open access article under the CC BY-NC-ND license

(<http://creativecommons.org/licenses/by-nc-nd/4.0/>).

Table 1Main plasma parameters of the Scenario 3 of JT-60SA [3] and JET experiment 85419 at $t = 18$ s.

	B_T [T]	I_p [MA]	R [m]	r [m]	k_x —	δ —	q_{95} —	$\langle n_e \rangle$ [10^{19} m^{-3}]	P_{aux} [MW]	P_{in} [MW]	$\lambda_{q,Eich}$ [mm]
JT-60SA	2.25	5.5	2.96	1.18	1.86	0.4	3	10	30	20	1.4
JET	2.7	2.5	3	0.9	1.72	0.4	3.2	7	18	12.5	1.7

**Fig. 1.** Radial midplane profiles of the diffusion coefficients D (blue) and $\chi_i = \chi_e$ (red) used in JT-60SA simulations. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

and ASDEX Upgrade [10]. This choice is also related to the similar radiative features of N compared to C. Therefore, N is particularly suited to perform a preliminary analysis of the transition from C to W wall. Crossfield drifts are not included in these simulations. As shown in [11,12], the actual conditions of the HFS divertor and, in particular, the appearance of the high density HFS region cannot be reproduced in simulations without drifts. Therefore, we have focused the analysis on the LFS divertor.

A diffusive ansatz has been assumed for the cross-field transport described by the perpendicular particle and the heat diffusion coefficients D and $\chi_{i,e}$, respectively. A spatially varying shape in the radial direction has been set to simulate the H-mode operation. Considering the machine size similarity in terms of major radius R (Table 1), the “calibration” of the coefficients has been performed on a JET experiment as close as possible to the considered scenario in JT-60SA. The main constraints used to select the JET experiment are: magnetic configuration (Lower Single Null), strike points position (both on vertical targets), δ , N injection, P_{aux} . A stationary nitrogen seeded 2.7 T, 2.5 MA H-mode high triangularity plasma belonging to the M13-14 experimental campaign [9,13] has been selected. The main parameters are given in Table 1 and compared with the ones of JT-60SA. We can note the similarity in terms of plasma shape, i.e. $\delta = 0.4$ in both cases and close values of κ . In terms of geometry, both equilibria have strike points on the vertical target albeit in JT-60SA they are located close to the corners. A lower power level is available in JET. The decay length $\lambda_{q,Eich}$ extrapolated with the Eich scaling [14] are quite close to the one of JT-60SA, showing the similarity from the exhaust point of view. The SOLPS-ITER results of JET in terms of n_e and T_e midplane profiles well fit the HRTS and reflectometry data. D and $\chi_{i,e}$ profiles are used in JT-60SA simulations although a rescaling of a factor 2 is needed to approach the extrapolated $\lambda_{q,Eich}$. The radial profiles of the transport coefficients in the main SOL are shown in Fig. 1, while constant values of $D = 0.8 \text{ m}^2/\text{s}$ and $\chi_i = \chi_e = 1 \text{ m}^2/\text{s}$ are used below the X-point.

3. Assessment of safe operational SOL conditions

The assessment of the plasma conditions and the hierarchy of the physics processes that ensure safe operations is a crucial point in the analysis of the transition to a fully metallic wall in JT-60SA. A scan in N content is performed. The amount of both D and N is determined by imposing Dirichlet boundary conditions on the core side, i.e. by imposing a fixed density n_{D^+} and n_{N^+} . The latter spans in the range $1/100 \div 1/10 \text{ n}_{D^+}$.

General trends. Fig. 2 shows the results in terms of general trends of $n_{e,sep}$ (2a), $P_{max,OT}$ (2b), $T_{e,OT}$ (2c) and f_{rad} (2d) as a function of Z_{eff} measured on the separatrix at the equatorial plane. Due to the high inner-outer asymmetry, most of the power is diverted toward the outer divertor chamber with a ratio of $Inn/Out = 1/2$ in attached conditions. As a result, the inner divertor conditions are less critical than the outer one and are not shown. Firstly, we see that $n_e < 1/2 n_{GW}$, where $n_{GW} = 1.26 \times 10^{20} \text{ m}^{-3}$. Therefore, it remains in an allowable region of operation throughout the scan. The thermal load on target plates does not represent a major concern, since a low amount of N ($Z_{eff,sep} = 1.66$) is sufficient to radiated enough power ($f_{rad} = 30\%$) to have a maximum load $P_{max,OT} < P_{OT} = 10 \text{ MW/m}^2$. However, the plasma is still attached, T_e on target is high and represents the most stringent constrain. At the strike point position, i.e. where the separatrix hits the target, a reduction in $T_{e,SP}$ is observed (blue squares) because of the recycling of the Deuterium molecules in the direction of the separatrix in the V-shaped/corner geometry [15]. This effect is limited to a region close to the strike point itself and a shift of the $T_{e,max,OT}$ occurs. Therefore, $T_{e,max,OT}$ (red diamonds) is more representative of the target conditions than $T_{e,SP}$. By increasing in $Z_{eff,sep}$, a reduction in $T_{e,max,OT}$ and a more pronounced shift in the far SOL occur, as can be seen in Fig. 3 where $T_{e,OT}$ and $\Gamma_{D,OT}$ profiles are shown for both low (solid line) and high (dashed line) Z_{eff} . As a results, we can reach safe operations where $T_e < 5 \text{ eV}$ in the region of high particle fluxes. This condition corresponds to $f_{rad} > 50\%$ and a $Z_{eff,sep} > 2.37$. In this case, the plasma starts to detach from the wall. A deep detachment and a X-point radiation is achieved for $f_{rad} > 70\%$ and $Z_{eff,sep} = 3.1$.

In order to define a detachment condition we consider a reduction in $I_{div,max}$ by 80% (red line), as in [16]. The trend in terms of detachment achievement is clearly visible in Figs. 2e and 2f, where $I_{div,peak}$ and pressure drop are shown. We can note a first fall of both quantities that corresponds to the attainment of the power limit. This reduction is related to the geometrical effect. In order to get the desired I_{div} decrement and to detach the plasma from the wall, we need $Z_{eff} > 2$, that is the last two points in the scan. These trends confirm the previous observation and are further confirmed by the movement of the ionization front toward the X-point (not shown here).

Evaluation of physical drivers. In order to identify the most relevant terms in the equations, an analysis of the energy and pressure balance is performed. Considering a steady state condition, the global balance for total internal energy and pressure on a certain region of the domain read as:

$$[A_x q_x]_{down} - [A_x q_x]_{up} = \int_{up}^{down} S_{en,tot} h_x A_x dx; \quad (1a)$$

$$\left[\frac{B_\theta}{B} A_x \left(p + m_i n_e v_\parallel^2 \right) \right]_{down} - \left[\frac{B_\theta}{B} A_x \left(p + m_i n_e v_\parallel^2 \right) \right]_{up} = \int_{up}^{down} S_{mom,tot} h_x A_x dx. \quad (1b)$$

The LHSs represent the energy and momentum flux (i.e. total pressure) at the boundary of the selected region. The RHSs are the corresponding integrated sources. These terms take also into account the sources computed by EIRENE.

The analysis of the total internal energy balance in the outer divertor chamber is shown in Fig. 4. The considered domain also extends into the private flux region (PFR), in order to show the related heat diffusion. On the top, the fluxes across the divertor entrance and on the outer target are shown for 3 different cases: attached plasma ($Z_{eff,sep} =$

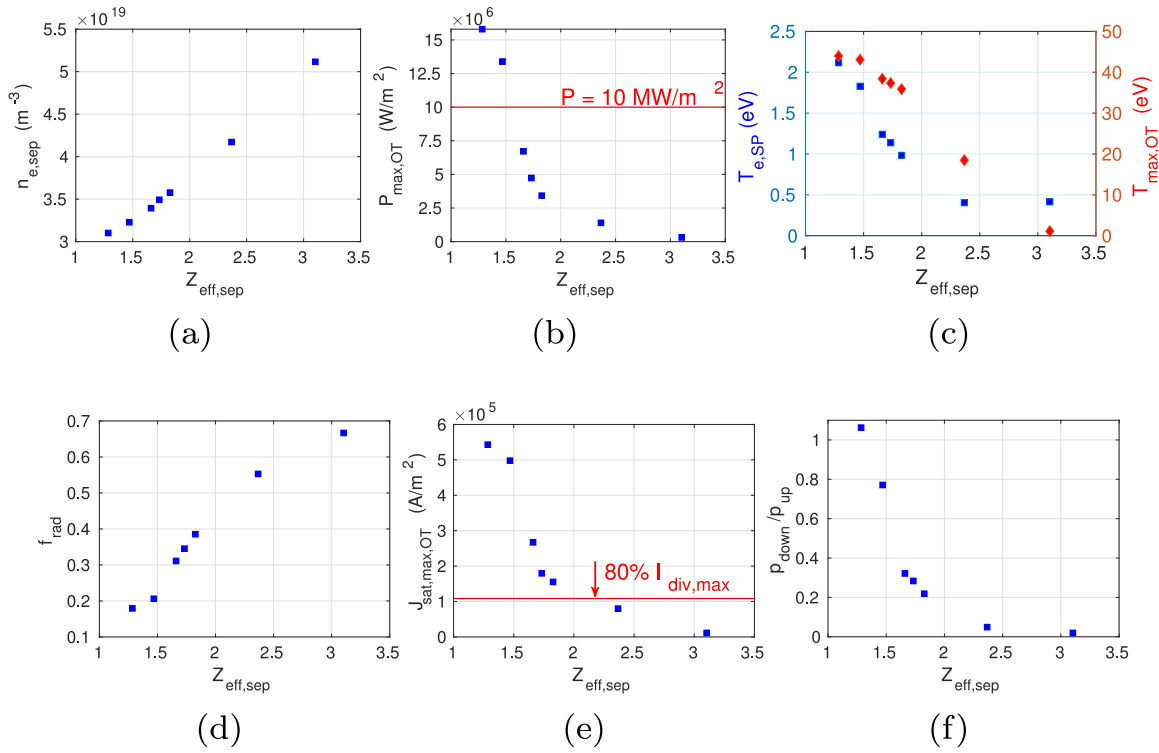


Fig. 2. SOLPS-ITER N scan prediction of $n_{e,sep}$ (a), $P_{max,OT}$ (b), $T_{e,OT}$ (c), f_{rad} (d), $I_{div,max,OT}$ (e), p_{down}/p_{up} (f) as a function of $Z_{eff,sep}$ in JT-60SA. In (b) and (e) the horizontal red line represents the power limit $P_{OT} = 10 \text{ MW/m}^2$ and the $80\% I_{div}$ reduction, respectively. In (c) the blue dots are $T_{e,SP}$ while the red diamonds are $T_{e,max,OT}$. In (f) p_{down}/p_{up} refers to the total pressure (static + dynamic) ratio. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

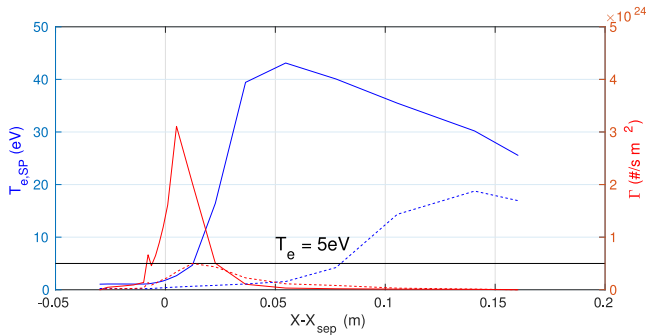


Fig. 3. Outer target profiles of T_e (blue) and Γ_D (red) as a function of the distance from the separatrix. Solid lines refer low $Z_{eff} = 1.66$ while dashed line to high $Z_{eff} = 2.37$. The horizontal black line indicates the $T_e = 5 \text{ eV}$ limit. The strike point position, that is at the separatrix, is identified by $X - X_{SP} = 0$. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

1.47), onset of detachment ($Z_{eff,sep} = 2.37$) and deep detachment ($Z_{eff,sep} = 3.1$). In the first case, the upstream internal energy flux (mainly electron conduction) is reduced on the target plate because of the synergy between the radial diffusion in the PFR and the geometrical effect, i.e. the atom-plasma processes. However, these effects are not enough to reduce P_{OT} and T_e to an allowable level. A radiation by impurity is then necessary. By increasing the N content, there is a flattening of the perpendicular power flux profile while keeping the upstream fluxes almost unchanged. This reduction is mainly driven by an increase in the impurity radiation, while the D contribution is $P_{rad,D} \approx 15\% P_{rad,tot}$. In case of deep detachment and X-point radiation, most of the power is radiated by the impurity and a very small part can reach the target plates. The other source terms are negligible.

Fig. 5 shows the pressure balance by considering the SOL from the outboard equatorial plane up to outer target. In this case, the PFR is not taken into account since we are mainly interested in the pressure drop in the SOL from the separatrix outward. As we can see, in case of an attached plasma the pressure is preserved along the flux tubes (**Fig. (a)**), except a drop near the separatrix due to the collisions between D^+ ions and D atoms. By approaching the detachment condition, T_e decreases along the outer target plates and the peak shifts in the far SOL. As a consequence, the contribution of the collision between D^+ and D_2 molecules increases and allows a loss of momentum in a layer close to the target, where a $p_{drop} > 90\%$ is observed. Instead, the other sinks of momentum play a marginal role. When a X-point radiation condition is achieved, a break-up of the momentum balance is observed due the N ionization front shift above the X-point.

4. Operational window

In order to take into account more realistic cases, the assessment of the operational window satisfying the technological limits has been performed by varying Γ_D and Γ_N . The gas puff are the main lower and the outer divertor ports for D and N, respectively. The pump is located below the divertor cassette and simulated by considering an albedo $\alpha = 0.94$.

Fig. 6 shows the results of the SOLPS-ITER in terms $n_{e,sep}$ in the range of scanned puffing rates. The operational window is delimited by the T_e limit, i.e. it represents the most stringent constrain. On the contrary, P_{max} condition is fulfilled for all plasma conditions, except a small region in the left bottom corner. A wide operational window can be defined for upstream density in a neighborhood of the nominal value $n_{e,sep} = 3 \times 10^{19} \text{ m}^{-3}$ and with $f_{rad} > 50\%$. In these conditions, we have $3 < Z_{eff,sep} < 4$.

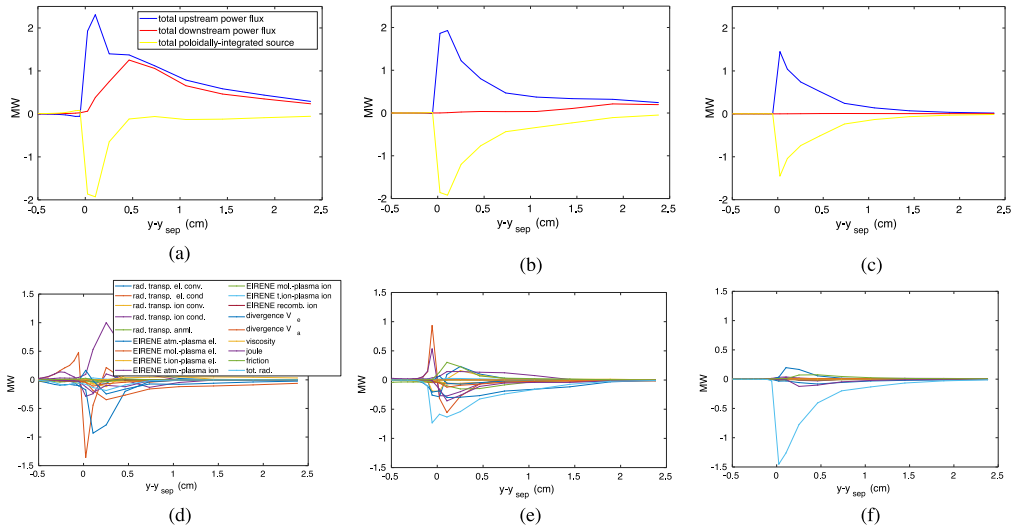


Fig. 4. Global internal energy balance for the SOLPS-ITER simulations of JT-60SA in the outer divertor chamber. On the top the fluxes (divertor entrance in blue and target in red) and the integrated source (yellow), while on the bottom the decomposition of the source as a function of the radial position. On the left $Z_{eff,sep} = 1.47$ (attached case), in the center to $Z_{eff,sep} = 2.37$ (onset of detachment) and on the right $Z_{eff,sep} = 3.1$ (deep detachment). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

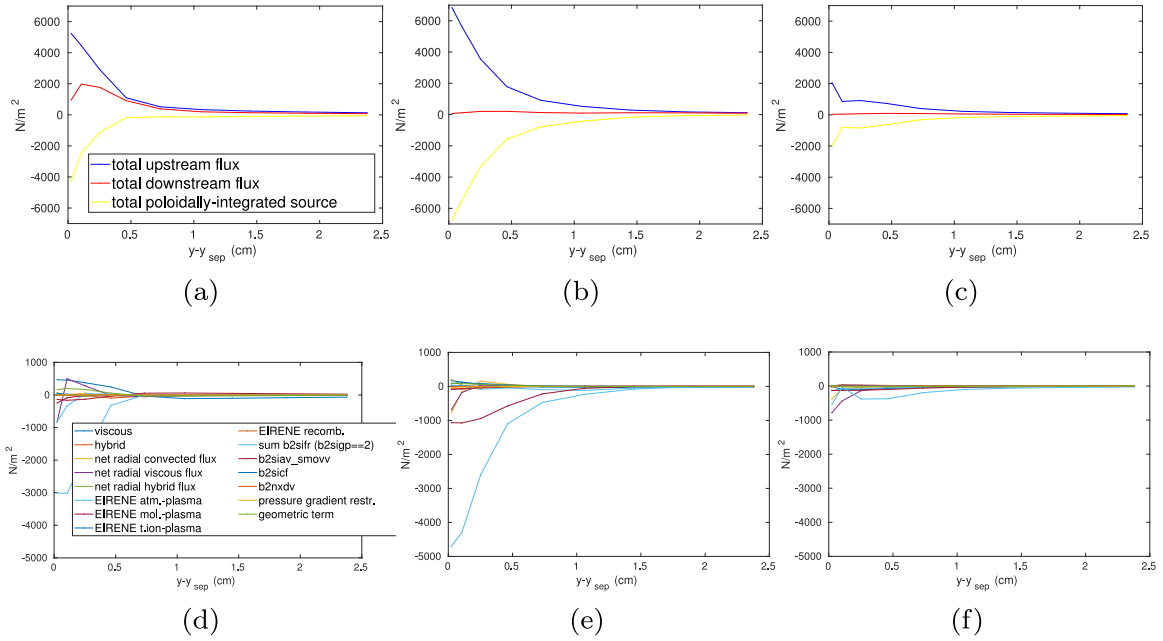


Fig. 5. Global pressure balance for the SOLPS-ITER simulations of JT-60SA in the SOL between the equatorial plane and the outer target. On the top the fluxes (OMP in blue and target in red) and the integrated source (yellow) and on the bottom the decomposition of the source as a function of the radial position. On the left $Z_{eff,sep} = 1.47$ (attached case), in the center to $Z_{eff,sep} = 2.37$ (onset of detachment) and on the right $Z_{eff,sep} = 3.1$ (deep detachment). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

5. Conclusions

The assessment of the SOL and divertor conditions in JT-60SA scenario 3 in the transition to W wall shows that T_e , i.e. the erosion, represents the most critical point. This condition limits the possible operation of the machine and require that at least half of the power must be radiated. A high radiative fraction is necessary to achieve detachment, i.e. $f_{rad} > 70\%$. In addition, the SOLPS-ITER simulations suggest that manageable values of power density are foreseen onto the outer target plate, even in case of low f_{rad} and low Z_{eff} . The analysis

of the energy and momentum balances highlights the key role played by the impurity injection. The impurity radiation is the main mechanism leading to a reduction in the P_{OT} and to reach temperatures able to trigger detachment. Furthermore, the loss of momentum caused by the collision between D_2 molecule and D^+ represents the main driver for the detachment onset, while the contribution of other physical processes is negligible.

As final remark, we have to note that the effects of drifts are not taken into account in this study. An important effect can be played by them and it is essential to include this contribution in future studies.

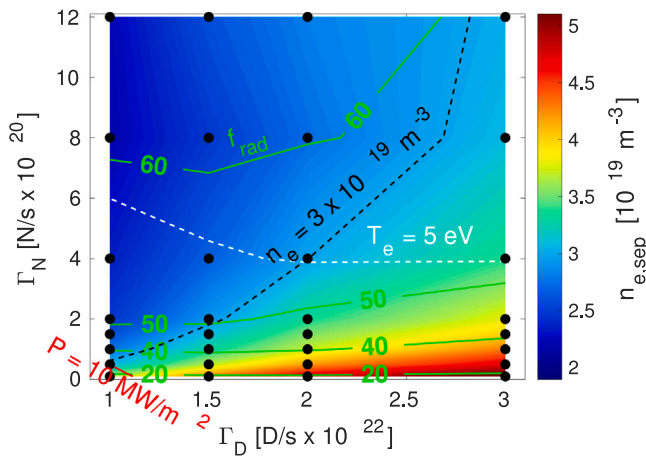


Fig. 6. Operational window showing contour of $n_{e,sep}$ for JT-60SA Scenario 3. Contour levels at $n_{e,sep} = 3 \times 10^{19} \text{ m}^{-3}$, $P = 10 \text{ MW/m}^2$ and $T_e = 5 \text{ eV}$ are respectively shown in black, red and white. Green lines represent contour lines for f_{rad} . (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

CRediT authorship contribution statement

G. Rubino: Conceptualization, Methodology, Investigation, Writing - original draft, Software. **G. Calabrò:** Supervision, Project administration, Writing - review & editing. **M. Wischmeier:** Supervision, Project administration, Writing - review & editing, Investigation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

This work has been carried out within the framework of the EU-ROfusion Consortium and has received funding from the Euratom research and training programme 2014–2018 and 2019–2020 under grant agreement No. 633053. The views and opinions expressed herein do not necessarily reflect those of the European Commission. One of the authors (G. Rubino) gratefully acknowledges D. J. Moulton for the numerical tool used to perform the energy and momentum balance analysis.

References

- [1] M. Bernert, et al., Power exhaust by SOL and pedestal radiation at ASDEX upgrade and JET, Nucl. Mater. Energy 12 (2017) 111–118, <http://dx.doi.org/10.1016/j.nme.2016.12.029>, URL <http://www.sciencedirect.com/science/article/pii/S2352179116302174>, Proceedings of the 22nd International Conference on Plasma Surface Interactions 2016, 22nd PSI.
- [2] G. Giruzzi, et al., Advances in the physics studies for the JT-60sa tokamak exploitation and research plan, Plasma Phys. Control. Fusion 62 (1) (2019) 014009, <http://dx.doi.org/10.1088/1361-6587/ab4771>.
- [3] J.-S.R. Unit, JT-60SA Research Plan. Research Objectives and Strategy. Version 4.0, Tech. rep., 2018, URL http://www.jt60sa.org/pdfs/JT-60SA_Res_Plan.pdf.
- [4] S. Wiesen, et al., The new SOLPS-ITER code package, J. Nucl. Mater. 463 (2015) 480–484, <http://dx.doi.org/10.1016/j.jnucmat.2014.10.012>, URL <http://www.sciencedirect.com/science/article/pii/S0022311514006965>, PLASMA-SURFACE INTERACTIONS 21.
- [5] M. Fukumoto, et al., High heat flux testing of mm thick tungsten coatings on carbon-fiber composites for the JT-60sa tokamak, Phys. Scr. T170 (2017) 014029, <http://dx.doi.org/10.1088/1402-4896/aa8c54>.
- [6] H. Kawashima, et al., Simulation of radiative divertor plasmas by ar seeding with the full W-wall in JT-60sa, Contrib. Plasma Phys. 56 (6–8) (2016) 778–783, <http://dx.doi.org/10.1002/ctpp.201610045>, URL <https://onlinelibrary.wiley.com/doi/pdf/10.1002/ctpp.201610045>, <https://onlinelibrary.wiley.com/doi/abs/10.1002/ctpp.201610045>.
- [7] K. Gałazka, et al., Numerical analyses of JT-60sa tokamak with tungsten divertor by COREDIV code, Plasma Phys. Control. Fusion 59 (4) (2017) 045011, <http://dx.doi.org/10.1088/1361-6587/aa5c58>.
- [8] R. Zagórski, et al., Numerical analyses of baseline JT-60sa design concepts with the COREDIV code, Nucl. Fusion 57 (6) (2017) 066035, <http://dx.doi.org/10.1088/1741-4326/aa6602>.
- [9] C. Giroud, et al., Progress at JET in integrating ITER-relevant core and edge plasmas within the constraints of an ITER-like wall, Plasma Phys. Control. Fusion 57 (3) (2015) 035004, <http://dx.doi.org/10.1088/0741-3335/57/3/035004>.
- [10] A. Kallenbach, et al., Divertor power load feedback with nitrogen seeding in ASDEX upgrade, Plasma Phys. Control. Fusion 52 (5) (2010) 055002, <http://dx.doi.org/10.1088/0741-3335/52/5/055002>.
- [11] F. Reimold, et al., The high field side high density region in SOLPS-modeling of nitrogen-seeded H-modes in ASDEX upgrade, Nucl. Mater. Energy 12 (2017) 193–199, <http://dx.doi.org/10.1016/j.nme.2017.01.010>, URL <http://www.sciencedirect.com/science/article/pii/S235217911630059X>, Proceedings of the 22nd International Conference on Plasma Surface Interactions 2016, 22nd PSI.
- [12] V. Rozhansky, et al., Contribution of $E \times B$ drifts and parallel currents to divertor asymmetries, Nucl. Fusion 52 (10) (2012) 103017, <http://dx.doi.org/10.1088/0029-5515/52/10/103017>.
- [13] G. Rubino, et al., Study of nitrogen seeded plasma in JET in preparation of JT-60sa, 2019, URL <http://ocs.ciemat.es/EPS2019PAP/pdf/P5.1039.pdf>.
- [14] T. Eich, et al., Inter-ELM power decay length for JET and ASDEX upgrade: Measurement and comparison with heuristic drift-based model, Phys. Rev. Lett. 107 (2011) 215001, <http://dx.doi.org/10.1103/PhysRevLett.107.215001>.
- [15] A. Loarte, Effects of divertor geometry on tokamak plasmas, Plasma Phys. Control. Fusion 43 (6) (2001) R183–R224, <http://dx.doi.org/10.1088/0741-3335/43/6/201>.
- [16] A. Kukushkin, et al., Consequences of a reduction of the upstream power SOL width in ITER, J. Nucl. Mater. 438 (2013) S203 – S207, <http://dx.doi.org/10.1016/j.jnucmat.2013.01.027>, URL <http://www.sciencedirect.com/science/article/pii/S0022311513000354>, Proceedings of the 20th International Conference on Plasma-Surface Interactions in Controlled Fusion Devices.