Nuclear Materials and Energy 43 (2025) 101939

Contents lists available at ScienceDirect

Nuclear Materials and Energy

journal homepage: www.elsevier.com/locate/nme

Exhaust assessment of a European Volumetric Neutron Source (EU-VNS) using SOLPS-ITER

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ARTICLE INFO

Keywords:
Neutron source
Power exhaust
Modelling
SOLPS-ITER
Tokamak
Impurity seeding

ABSTRACT

EUROfusion considers a volumetric neutron source (EU-VNS) to generate a neutron wall load of about $0.5\,MW/m^2$ to qualify tritium breeding blankets early in support of EU-DEMO that mitigates the risk of a late testing for required nuclear technology. The envisaged small-scale $R = 2.5\,m$ D-beam/T-target driven fusion device ($P_{fus} \approx 30\,MW$) must exhaust helium particles and dissipate sufficient energy from the large auxiliary power required ($P_{aux} \approx 50\,MW$) entering in large parts the edge. A SOLPS-ITER assessment indicates that with argon seeding a finite divertor operational window exists allowing to avoid core dilution by helium and to reduce the peak heat-flux density below $10\,MW/m^2$. It is shown that an extra constraint of $Z_{eff} < 2-3$, required to sustain good core performance to produce the required amount of fusion neutrons, can also be met if the Greenwald-fraction $f_{GW} \approx 0.5$ is maintained with total T-throughputs at about half the ITER value. It is reasoned that for a EU-VNS design study the exhaust operational window can be enlarged by choosing other seeding species like Krypton, refining the balance between pellet- to gas-fuelling, and integrated core-edge modelling.

1. Introduction

The current strategy for EU-DEMO tritium breeding blanket R&D requires input from ITER Test-Blanket Modules (ITER-TBMs). Although the a design value for neutron fluence in ITER is at least one order of magnitude lower compared to what would be required to qualify a breeding blanket engineering design for EU-DEMO [1] the ITER-TBM will still provide relevant input towards an engineering scaling. With the recent delays seen in the ITER research plan however, de-risking actions are required for the process of nuclear qualification for the EU-DEMO blanket. One option is to devise a volumetric neutron source (VNS) and a European feasibility study for a tokamak-based VNS is currently undertaken [2]. In this study a testing facility of medium-size ($R \approx 2.5\,\text{m}$ with large-aspect ratio $A = R/a \approx 4.6$), metal wall and D-T beam-target driven fusion power is proposed. Key requirement is a high machine availability with bulk tritium plasma producing fusion neutrons predominantly by beam target reactions from D neutral beam injection (NBI). Hence, the EU-VNS would also generate relevant neutron fluence towards the EU-DEMO breeding blanket design requirements and thus could bridge a critical engineering gap.

For EU-VNS the expected $P_{edge}/R \approx 20$, requires an optimized divertor shape and the possibility of regular replacement of the metallic divertor components during down-times of the device. In order to manage the heat load at the strike lines, a significant fraction of power entering the edge must be redistributed on the entire vessel surface by line-radiation of seeded impurities. To stabilize the plasma and to achieve large neutron wall loads however, the core impurity content must not exceed an upper limit of $Z_{eff} < 2-3$, a value that has been estimated by METIS calculations to find the EU-VNS design point. At the required fusion power $P_{fus} \approx 30\,\text{MW}$ about $2.5\cdot10^{19}$ Helium particles per second will be produced which must be removed in the divertor by active pumping in order to avoid additional dilution.

In this contribution the results of a conceptional assessment of the operational space for power and particle exhaust in a possible EU-VNS

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https://doi.org/10.1016/j.nme.2025.101939
Received 17 June 2024; Received in revised form 7 April 2025; Accepted 18 April 2025
Available online 9 May 2025

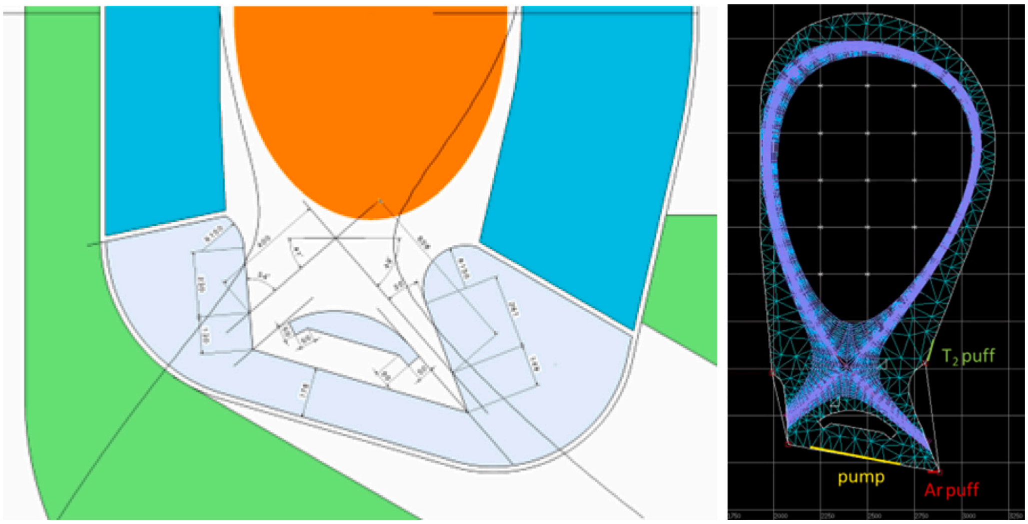

Fig. 1. Left: EU-VNS divertor shape for the conceptual study including a dome; Right: SOLPS-ITER simulation grid (84 × 36 quadrilateral cells) and EIRENE neutral triangular mesh, and depicted locations of T_2-gas puff, Ar-puff and pumping surface.

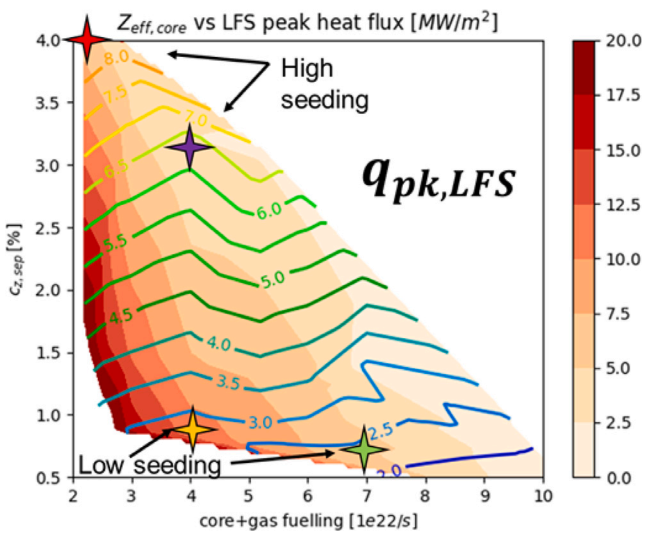

Fig. 2. Overview of operational space of the simulated EU-VNS T+He+Ar database in terms of Z_{eff} (solid lines) vs. $q_{pk,LFS}$ (coloured contour-plot), as function of total T-throughput ($\Phi_{T,gas}+\Phi_{T,core}$) and averaged separatrix impurity concentration $c_{z,sep}$. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

are demonstrated. Starting with a brief summary on the EU-VNS physics basis in Section 2, the results from SOLPS-ITER modelling to find the divertor operational space for a detached EU-VNS divertor scenario using by Argon (Ar) seeding are discussed in Section 3. Section 4 concludes the paper and gives an outlook on further aspects of possible extensions of the work.

2. EU-VNS physics basis and design point

EU-VNS is a device that should be producing 14 MeV neutrons at a peak neutron wall load of at least NWL $= 0.8 \cdot P_{fus}/S \approx 0.5\,\mathrm{MW/m^2}$ (with the plasma surface $S = 4\pi^2 aR\sqrt{(1+\kappa)/2}$) that allows a demonstration of nuclear qualification of breeding blanket concepts. In order to keep the machine compact a small EU-VNS is required to rely on beam-target fusion reactions. The recent JET 2023 DTE3 campaign record discharge [3] is an example for such a plasma, but the calculated NWL is, comparably, too small by a factor 5–10. The neutral beams are also employed to drive the plasma current as there is not enough space in the radial build to accommodate a large central solenoid. The proposed concept of EU-VNS, consequently, has to have a large amount of auxiliary power being installed. The neutron rate is (at zeroth order) independent on the plasma density in a beam-target configuration: $P_{fus} \propto n_e \tau_s P_{beam}/E_{beam}$ with beam stopping time $\tau_s \propto T_e^{3/2}/Z_b^2 n_e$, with Z_b the nuclear charge number of the beam particles (e.g. $Z_b = 1$ for deuterons). Hence, for given beam configuration and power, the NWL scales as

Table 1
EU-VNS design point derived by METIS/ASTRA.

R	B_t	I_p	A	κ	P_{NBI}	P_{ECH}	P_{fus}	P_{edge}
2.53 m	5.4 T	1.75 MA	4.6	1.5	42.5 MW	10 MW	29.0 MW	53.3 MW

$$\mathrm{NWL} \propto \frac{A}{R^2}\frac{P_{beam}}{E_{beam}}\frac{T_e^{3/2}}{Z_b^2} \tag{1}$$

and thus additional electron cyclotron heating is required to increase T_e in the core. To overcome MHD stability, EU-VNS relies on fast-particle stabilization with

$$\beta_N \propto \frac{P_{beam}}{R^3} A^3 \frac{q}{B^2 n_e}\frac{T_e^{3/2}}{Z_b^2}. \tag{2}$$

A reasonably low value for $Z_b \propto Z_{eff} < 2$–3 is required for EU-VNS, because of (i) keeping the slowing down time of the beams long enough, so to keep P_{fus} high, and (ii) avoid a too large loop voltage $V_{loop} < 1\,\mathrm{mV}$ as otherwise the current drive from NBI may not be sufficient to maintain long enough pulse length. The machine design point as such is thus a result of balancing NWL performance (NWL $\approx 0.5\,\mathrm{MW/m^2}$) and stability prescribed by $\beta_N \leq 3.5\%\,\mathrm{Tm/MA}$ (assuming fast particle stabilization, derived by a MARS-K simulation), and the parameters to optimize for EU-VNS are essentially the aspect ratio A and magnetic field strength B_t. The remaining free parameter is the major radius R which is assumed to be as small as possible, since we want to minimize the plasma surface – i.e. maximize the NWL. The found minimum R is compatible with the radial build constraints (i.e. enough space for toroidal field coils and neutron shielding).

With these constraints, the METIS and ASTRA codes have been employed to identify a EU-VNS design point as given in Table 1 requiring a critical level of $Z_{eff} < 2$–3.

From the Martin scaling [4] EU-VNS design point scenario sits well inside the H-mode operational space (with $P_{LH} \approx 11\,\mathrm{MW}$). The high-density and high-power conditions suggest that EU-VNS will operate

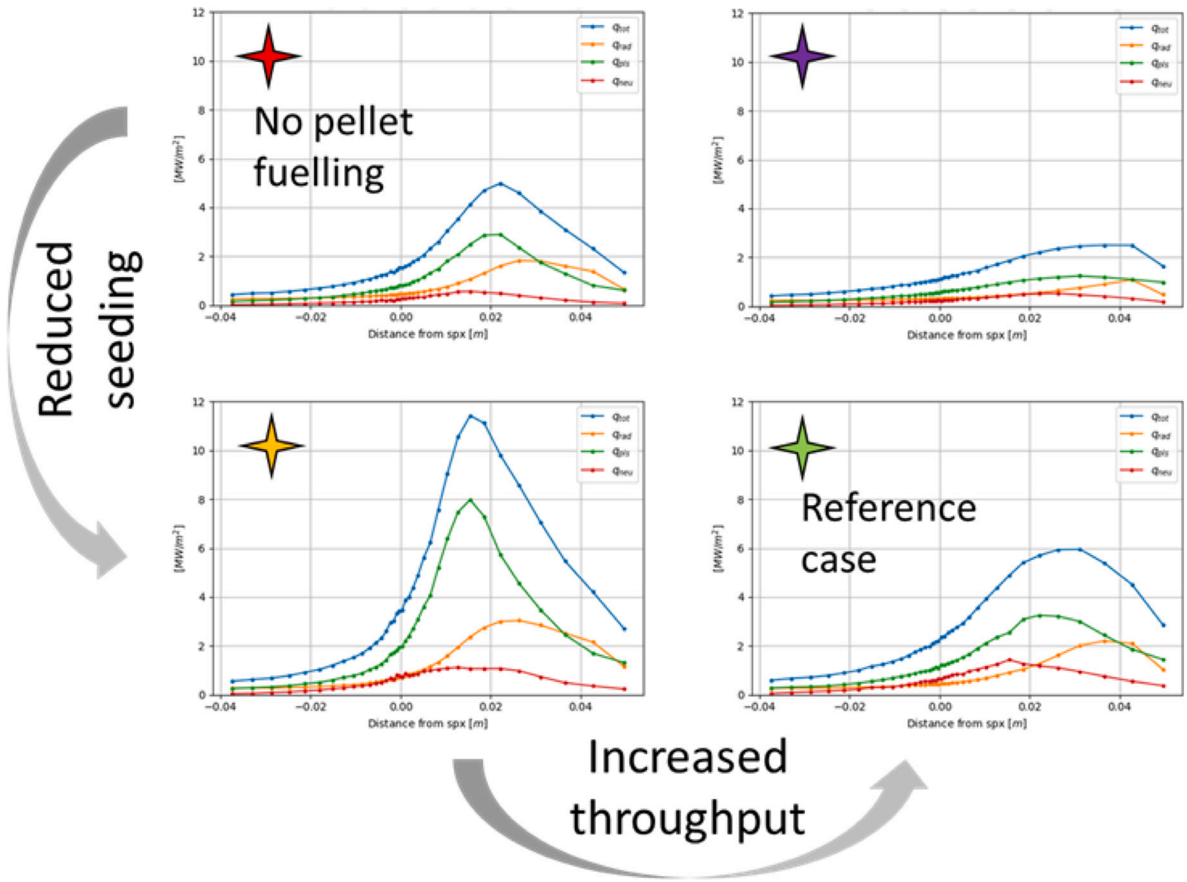

Fig. 3. Outboard target heat-flux density profiles (total q_{tot} in blue, consisting of q_{rad}, q_{pls} and q_{neu} for the components of radiative, plasma and neutral load, respectively) - the coloured symbols depict the corresponding operational points in Fig. 2. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

likely in a small-ELM/type-III ELM regime and detailed MHD stability analysis is still ongoing by the time of writing of this paper. In the presented work we focus on steady-state conditions without any transients in the plasma edge. ELM driven erosion fluxes from the main-wall by enhanced (ELM-driven) fluxes will be discussed elsewhere.

3. Divertor conceptual design point with SOLPS-ITER: T+He+Ar

3.1. SOLPS-ITER model setup

SOLPS-ITER [5,6] was setup for T+He+Ar plasma species simulations for the EU-VNS divertor conceptual study (Fig. 1). The EIRENE neutral kinetics model is employed using the standard hydrogenic atomic and molecular physics model as described in [7,8] (assuming mass scaling for the tritium atomic rates). The impurity model employs the ADAS database. The radial anomalous diffusion is assumed to be flat everywhere with coefficients $D_{\perp} = 1\,\mathrm{m}^2/\mathrm{s}$ for all ion species, and $\chi_e = 1\,\mathrm{m}^2/\mathrm{s}$ and $\chi_i = 0.75\,\mathrm{m}^2/\mathrm{s}$ for electron and ion radial heat conductivity, respectively. These coefficients result into a radial heat decay length at the outer mid-plane of about $\lambda_q \approx 3$ mm in the near-SOL close to the separatrix. No parallel flux-limits and neither SOL currents nor drift flows were assumed in the model.

For the conditions at the core-side (i.e. pedestal top) the power entering the edge $P_{edge} = 50\,\mathrm{MW}$ was assumed to be equally shared between electrons and ions. The He-particle influx from the fusion product is resulting in $\Gamma_{\mathrm{He}^{2+},core} = 2.5 \cdot 10^{19}\,\mathrm{s}^{-1}$. The pump in the divertor private flux region (PFZ) is adjusted to a pumping speed ($S_{pump} \approx 20\,\mathrm{m}^3/s$) to ensure sufficient He pumping and to keep the He concentration at about 1% at the core boundary. Conditions for ionized Ar ions were assumed to be zero influx at the core boundary. To stabilize the Ar content in the simulation (i.e. to avoid slow numerical oscillations especially at low Ar concentrations) a feedback scheme for a floating but constant average of Ar-ion density at the core boundary was employed.[1]

Given this model setup as the basis, the particle throughputs for the T-content (in terms of pellet-like content core fuelling rates and molecular gas fuelling) and Ar content (purely seeded from the divertor region) have been scanned: $\Gamma_{T^+,core} = 0.25–5 \cdot 10^{22}\,\mathrm{s}^{-1}$ (log-scan), $\Gamma_{T_2,gas} = 2–5 \cdot 10^{22}\,\mathrm{s}^{-1}$ (only 2 values) and $\Gamma_{\mathrm{Ar},gas} = 1–5 \cdot 10^{20}\,\mathrm{s}^{-1}$ (log-scan) - all rates in atomic units. The results of the database of converged simulations (about 30) are presented in the following by means of linearly interpolating the operational space covered by the scans.

3.2. Results and discussion

A finite window for the divertor operational space has been found for the EU-VNS in detached conditions at reasonably low $q_{pk,LFS} < 10\,\mathrm{MW/m}^2$ induced by Ar seeding. Fig. 2 summarizes the simulation map results in terms of $Z_{eff,core}$ at the pedestal top vs. peak heat-flux density $q_{pk,LFS}$ at the outboard divertor target (low-field side, LFS). It is observed that both, Ar-seeding and T-fuelling (from core and gas) facilitate a reduction of $q_{pk,LFS}$. For the high seeding cases however (exemplary displayed as red and purple symbols in Fig. 2) the

[1] Note: SOLPS-ITER's boundary condition model for the core boundary should be set to BCCON = 13.

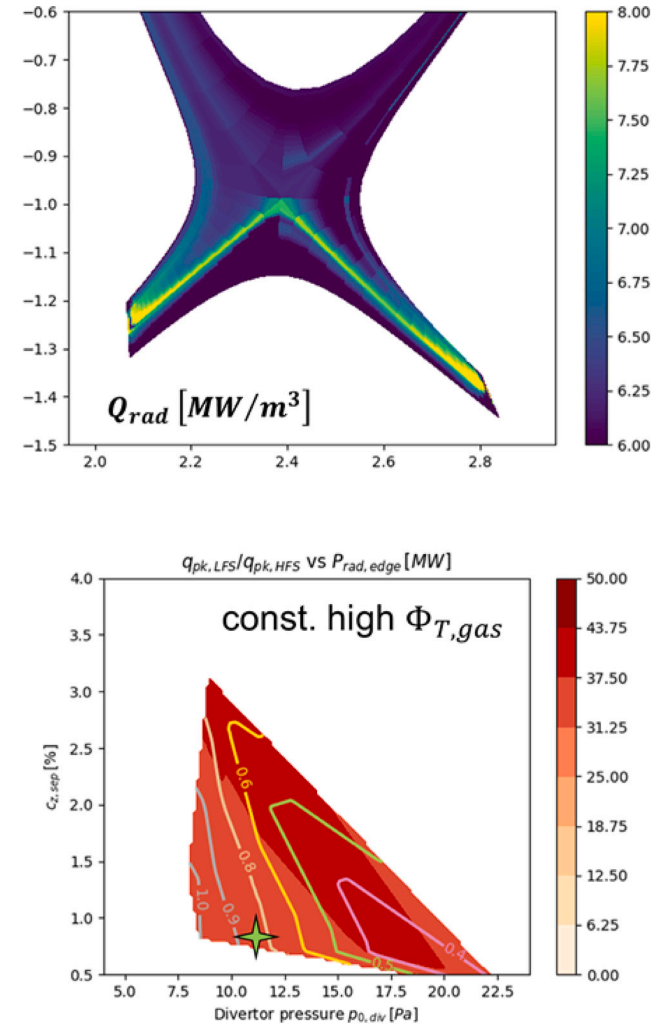

Fig. 4. Left: radiative power loss density in the EU-VNS divertor reference case (green symbol, right figure); Right: asymmetry of inboard to outboard peak heat-fluxes $q_{pk,LFS}/q_{pk,HFS}$ (coloured solid lines) and total radiated power P_{rad} (coloured contour) with varying $c_{z,sep}$ and $p_{0,div}$. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

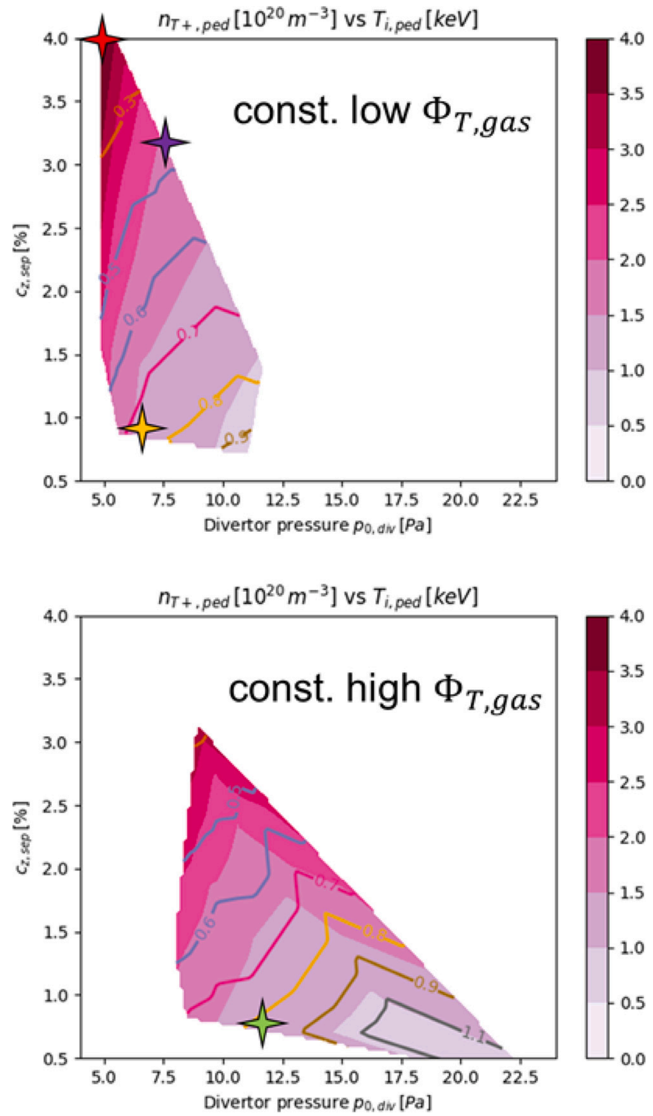

Fig. 5. Comparing the operational space for $n_{T^+,ped}$ (solid lines) and $T_{i,ped}$ (contour plot) vs. $c_{z,sep}$ and $p_{0,div}$, for low and high T-gas throughput $\Phi_{T,gas}$. The ASTRA/METIS conditions for the pedestal top ($n_{T^+,ped} = 0.5 \cdot 10^{20}\,\mathrm{m}^{-3}$ and $T_{i,ped} = 2\,\mathrm{keV}$) can only be met at low $p_{0,div}$. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

requirement of keeping Z_{eff} below the required level is not achieved, although in these cases the resulting heat-flux can be depressed into a strongly pronounced detached regime. Only with significant higher T-fuelling at lower Ar-seeding a $Z_{eff} \approx 2.5$ is achievable that would be compatible to the core plasma performance requirements. The total T-throughput Φ_T for such a scenario is significant (i.e. $\Phi_T = 4\text{–}7 \cdot 10^{22}\,\mathrm{s}^{-1}$, and thus close to the expected ITER T-throughput $\Phi_{T,ITER} \approx 10^{23}\,\mathrm{s}^{-1}$). In the following the simulation case with the best performance in terms of $Z_{eff} < 2.5$ and $q_{pk,LFS} = 6\,\mathrm{MW/m}^2$ is named as *reference case* (bottom right case in Fig. 2, green symbol).

Fig. 3 displays for the four marked cases in the operational space diagram (Fig. 2) the corresponding LFS heat-flux density profiles. It is obvious that by carefully balancing Φ_T and Ar seeding rate (i.e. $c_{z,sep}$) the heat-flux can be optimized. The LFS heat-flux profiles (and the individual fractions for neutral, plasma and radiation loads) are very similar for the no-pellet fuelling case with high seeding (red case) to the balanced reference case with lower seeding (Z_{eff}) but significant higher Φ_T.

Fig. 4 (right) shows that for the reference case the outboard target receives a lower q_{pk} compared to the inboard side. This trend increases up to $q_{pk,LFS} \approx 0.5 q_{pk,HFS}$ towards larger divertor neutral pressures $p_{0,div}$. This is likely to be related to the localized Ar source in the LFS region (c.f. Fig. 1). To achieve the required level of dissipation in the SOL, a radiative fraction of up to $P_{rad}/P_{edge} \approx 60\%\text{–}80\%$ is sufficient, mainly in the SOL and divertor, not requiring an X-point radiating regime.

This is featured by the good compression of Ar, $\eta_{\mathrm{Ar}} = n_{\mathrm{Ar},LFS}/n_{\mathrm{Ar},sep}$. For the reference case compression is remarkably high ($\eta_{\mathrm{Ar}} \approx 15$, not displayed) at reasonably high neutral divertor pressures ($p_{0,div} \approx 11\,\mathrm{Pa}$), the corresponding enrichment factor for this case is $\eta_{\mathrm{Ar}}/\eta_T \approx 1.5$. This seems is sufficient to keep Z_{eff} low in the upstream region close to the separatrix. The compression in the model is enhanced also by increase of $p_{0,div}$ that linearly increases with the T-gas throughput $\Phi_{T,gas}$. Earlier assessments to employ Neon as seeding gas caused always a too low compression and further assessments of Ne for EU-VNS were abandoned.

Enhancing the ratio of T-gas fuelling to T-core fuelling (pellets) $\Phi_{T,gas}/\Phi_{T,core}$ apparently opens up a larger operational space in the Z_{eff} vs. q_{pk} domain. At the same time however, the ASTRA/METIS predictions for the required top-pedestal conditions are $n_{T^+,ped} = 0.5 \cdot 10^{20}\,\mathrm{m}^{-3}$ and $T_{i,ped} = 2\,\mathrm{keV}$ have to be met. Fig. 5 shows that these conditions can roughly be achieved (assuming the given transport parameters employed in SOLPS-ITER) at moderate $p_{0,div} \approx 6–8$ Pa at lower $\Phi_{T,gas}$, and only at the expense of larger $q_{pk,LFS}$ (yellow symbol in Figs. 2 and 5). Combining this with the constraint $Z_{eff} < 2–3$ this would require additional heating in the edge, or, stronger T-fuelling from the core as the latter is more efficient to reduce Z_{eff} than pure gas-fuelling. A second option would be to allow for another impurity species (like krypton) that is even more efficient in reducing plasma pressure in the upstream/core region of the plasmas compared to Ar to reduce the divertor heat loads further.

4. Conclusions and outlook

It is suggested by SOLPS-ITER modelling that a finite operational window exists for the EU-VNS divertor configuration proposed with argon seeding in order to reduce the peak heat-load density at target plates to values safely below $10\,\mathrm{MW/m^2}$ (steady) despite the compact geometry of the VNS divertor. The compression of argon in the divertor is enough avoiding large amounts of core radiation. A significant fraction of T-particle throughput is to be delivered by pellets in order to enlarge the operating space with respect to the core performance requirement $Z_{eff} < 2–3$. The tritium density is high but within the Greenwald limit ($\bar{n}_T \approx 1.1 \cdot 10^{20}\,\mathrm{m^{-3}} < n_{GW} \approx 1.8 \cdot 10^{20}\,\mathrm{m^{-3}}$) and hence there is room to optimize the overall scenario further. Integrated modelling (core & edge) is required to resolve uncertainties in the assumed transport model and to self-consistently achieve ASTRA predicted top-pedestal conditions in combination with a working exhaust concept and expected total particle throughput requirements.

As a next step, further simulations employing other radiating impurity species like krypton to enlarge the operational space with respect to Z_{eff} vs. q_{pk} correlations are underway and will be presented elsewhere. Also, an assessment of the heat loads (plasma, neutral and radiation) in remote regions (divertor dome and reflector plates) is currently being pursued to identify critical heat-fluxes as upper engineering limits.

In all presented simulations, the diffusive coefficient for radial transport was adjusted to match a radial heat decay parameter $\lambda_q \approx 3$ mm. To what extent this assumption can be hold is questionable and requires at least a sensitivity study employing SOLPS-ITER. Taking a standard H-mode scaling for λ_q from Eich et al. [9] one would expect a lower value for EU-VNS machine parameters $\lambda_q^{Eich} = 0.63 \cdot B_p^{-1.19} \approx 1.23$ mm. However, the shaping of the EU-VNS design point seems to be large enough to reach a quasi-continuous exhaust regime (QCE, c.f. [10]) for which the access parameter is defined as $S_p = \kappa^{2.2}\,(1+\delta)^{0.9} = 2.44$ for EU-VNS (with the assumed triangularity $\delta = 0$). The QCE window opens up from $S_p > 3$ and allowing for a finite $\delta > 1.17$ would possibly place EU-VNS into an ASDEX-Upgrade type QCE regime, for which the dependence $\lambda_{QCE,AUG} = 6.75 \cdot p_{e,sep} + 2.43$ mm was identified [11]. Using the separatrix conditions from the presented SOLPS-ITER results for the VNS reference case (i.e. $n_{e,sep} = 0.5 \cdot 10^{20}\,\mathrm{m^{-3}}$ and $T_{e,sep} = 200\,\mathrm{eV}$) one would derive a $\lambda_q^{QCE,VNS} \approx 13$ mm, a value that is probably too optimistic.

For a EU-VNS divertor design phase to be pursued in succession of this conceptual study, a higher fidelity model should include the impact of drifts provided the scaling of the latter inversely systems size ($\rho^* = \rho/R$). It is expected that the combined force of $\mathbf{E}\times\mathbf{B}$ and ion ∇B drift will cause a redistribution of impurities from the outboard to the inboard divertor and thus reduces the LFS radiation losses. However, at such large values of $P_{edge}/R \approx 20$ in EU-VNS (c.f. ASDEX-Upgrade $P_{edge}/R \approx 12$) the formation of a high-field side high-density region (HFSHD) might occur [12], reducing the level of expected impurity concentrations in terms of Z_{eff} to possibly lower levels as the HFSHD region leads to inverted radial n_e profiles outside the inboard separatrix and consequently to increased core fuelling due to diffusion.

CRediT authorship contribution statement

S. Wiesen: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Formal analysis, Conceptualization. **Ch. Bachmann:** Project administration, Conceptualization. **M. Siccinio:** Writing – review & editing, Supervision, Software, Methodology, Formal analysis, Data curation, Conceptualization. **J. Boscary:** Formal analysis. **C. Bourdelle:** Conceptualization. **M. Coleman:** Conceptualization. **G. Federici:** Funding acquisition, Conceptualization. **F. Maviglia:** Data curation, Conceptualization. **R. Neu:** Writing – review & editing, Conceptualization.

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.

Acknowledgements

This work has been carried out within the framework of the EUROfusion Consortium, funded by the European Union via the Euratom Research and Training Programme (Grant Agreement No 101052200 — EUROfusion). Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Commission. Neither the European Union nor the European Commission can be held responsible for them.

Data availability

Data will be made available on request.

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