CONFERENCE PRE-PRINT

EXHAUST OPERATIONAL SPACE ASSESSMENT FOR THE EUROPEAN VOLUMETRIC NEUTRON SOURCE (EU-VNS)

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Abstract

The SOLPS-ITER edge plasma numerical model is employed to predict the exhaust operational space in a small-scale tokamak device currently being investigated as the proposed European Volumetric Neutron Source (EU-VNS) with large power-to-size ratio of P/R ~ 20 MW/m. Previous work is extended by the allowing krypton seeding to dissipate and redistribute heat. The found finite operational space is limited by both, engineering limits for the peak heat-flux expected at the divertor plasma facing components < 10MW/m^2, and at the same time requiring a low enough effective charge Z_{eff} in the core region to avoid dilution of the main plasma and thus shortening of slowing times of the beam-target driven fusion process in EU-VNS. It is demonstrated that with krypton the operational space can be larger than with argon seeding and at the same time the amount of tritium throughput can be halved compared to the original argon study. Still being large in terms of absolute values for the required total T-throughput rate of the order 3-4 10^{22} T/s, pellet fuelling is deemed to be as efficient to fuel both the core density and the separatrix density at the same time. As a consequence, a positive correlation is found between the krypton enrichment in the divertor and the increase of upstream density effectively fuelled by pellets. It is demonstrated that the value of Z_{eff} can be minimised to a value of ~ 1.5 keeping the divertor heat loads within limits. This value of Z_{eff}, and the observation of the required Greenwald fraction of 50% to achieve this, is also compatible with the predictions of the core plasma conditions for the current EU-VNS design point from ASTRA/METIS.

1. INTRODUCTION

The current strategy for EU-DEMO tritium breeding blanket R&D requires input from ITER Test-Blanket Modules. With the delays seen in the ITER research plan, 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 [1,2].

In a previous work on assessing the EU-VNS Ar was chosen as main radiating species in [3] employing a SOLPS-ITER simulation setup [4,5] for a T+He+Ar plasma exhaust scenario. In a rapid concept study using a first design point for EU-VNS, it was possible to show the existence of a limited operational space to achieve sufficient power mitigation in the edge. But the consequences were significant, i.e. requiring strong fuelling also with pellets, at a level of throughput of the order of ITER values, i.e. very high and thus costly. In addition, the minimum level found for Z_{eff} ~ 2.5 with Ar seeding only was also not optimal and at the verge of being not acceptable in terms of beam slowing down times. As a result, the T+He+Ar plasma scenario for the previous design point with a large power-to-size ratios P/R = 20 MW/m^2 is of a lesser use also in view of the limited degree-of-freedom to control the integrated core/edge EU-VNS scenario.

In this contribution the result of a new conceptional assessment of the operational space for power and particle exhaust in a possible EU-VNS are demonstrated when Ar is replaced by Kr to test further the sensitivity of the exhaust operational space on seeding species. In addition, and compared to the previous study in 2024, the EU-VNS design point has been modified to optimize the shape and fusion power of the device for both, the engineering aspect and also to optimise the fusion neutron wall load (which is in the end the figure-of-merit chosen allowing an efficient testing of a breeding blanket in EU-VNS). Table 1 summarises the main features of this new design point compared to the previous one. The testing facility is of medium-size (R ≈ 2.7m with large aspect ratio A = R/a ≈ 4.25), metal wall. Still the requirement of this device is a high machine availability with bulk tritium plasma producing fusion neutrons predominantly by beam target reactions from D neutral beam injection (NBI). In order to manage the heat load at the strike lines at the expected level of $P_{edge}/R \approx 20$, 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 NWL $\propto P_{beam}T^{3/2}A/E_{beam}R^2 Z_b^2$ (c.f. [3]), the core impurity effective charge must in the best case not exceed an upper limit of $Z_{eff} < 2$. At the required fusion power $P_{fus} \approx 38$MW (mainly from D-T beam-target fusion and larger than in the previous design point) about $1.4 \cdot 10^{19}$ Helium particles per second will be produced which must be removed in the divertor by active pumping in order to avoid additional dilution.

TABLE 1 EU-VNS design point derived by METIS/ASTRA for the previous design point, Wiesen et al. (2024) [3], and the new optimized one employed for the presented work.

	R[m]	**B_t[T]**	**I_p[MA]**	**A**	**κ**	**δ**	**P_{NBI}[MW]**	**P_{ECH}[MW]**	**P_{fus}[MW]**	**P_{edge}[MW]**
2024	2.53	5.4	1.75	4.6	1.5	0	42.5	10.0	29.0	53.3
2025	2.67	5.6	2.54	4.25	1.6	0.23	42.5	8.0	38.22	55.62

In the following, section 2 revisits the SOLPS-ITER numerical setup to model the T+He+Kr EU-VNS edge plasma for the new design point in comparison to the previous work in [3]. Section 3 describes the models results in detail in view of the achievable operational space in terms of Z_{eff} and peak heat-fluxes q_{pk} at the targets. Finally, section 4 discusses and summarizes the conceptual study on exhaust for EU-VNS up to now. It should be noted that a detailed and integrated study of the actual EU-VNS divertor design is not part of this current work. By the time of writing the decision to select a final design point of EU-VNS w.r.t. engineering details including a uncertainty study is still pending. In case of a positive decision, this work can be extended towards a fully integrated and detailed engineering design study of EU-VNS.

2. SOLPS-ITER MODEL DESCRIPTION

As in described in [3] the new model setup of SOLPS-ITER is very similar to the previous. The condition at the core-side (i.e. pedestal top) is a fixed level of power entering the edge P_{edge} = 55.62 MW and is thus assumed is about 10% higher compared to the previous design point, again equally shared between electrons and ions. The

He-particle influx from the fusion product assuming the 25% higher fusion power is resulting in $\Gamma_{He2+,core} = 1.4 \cdot 10^{19}\ s^{-1}$. The pump in the divertor private flux region (PFZ) is located as before at the divertor bottom and adjusted with a pumping speed ($S_{pump} \approx 20m^3/s$) to ensure sufficient He pumping and to keep the He concentration at about 1% at the core boundary (this is a free parameter, in the end the pumping speed at the engineering level will be chosen to reduce the He content to keep it at a reasonably low level).

The radial anomalous diffusion is assumed to be spatially flat everywhere with constant coefficients for radial particle diffusion and viscosity ($D_\perp = \eta_\perp = 1m^2/s$) and heat conductivities (χ_i=0.75m2/s, χ_e=1.0m^2/s) resulting into a radial heat decay length at the outer mid-plane of about $\lambda_q \approx 3mm$ in the near-SOL close to the separatrix. At the core boundary side and in addition to the (fusion product driven) He^{2+} particles a constant particle flow is assumed for T^+ (a constant pellet-type flux that is also scanned in this study). The boundary conditions towards the wall are assumed of fixed decay length of 3 cm. In the parallel direction no flux limiting factors are applied in the simulation. At the targets standard Bohm sheath conditions are assumed. Contrary to the work of [3], SOL currents are turned on in the simulation and the potential equation is being solved in SOLPS-ITER including current heating in the SOL. Plasma drift flows are not yet included by the time of writing of this paper.

To map out the exhaust operational space, the particle throughputs for the T-content (in terms of pellet-type core fuelling rates and fuelling via molecular gas flows) and Kr content (purely seeded from the divertor region) are scanned. Figure 1 depicts the fuelling, seeding and pumping locations in the SOLPS-ITER simulation grid. The grid itself consists of 84 x 36 quadrilateral cells for the plasma covering partly the confined region near the separatrix. This is required as it is suggested already in the previous work that significant line-radiation from impurities must take place inside the separatrix in order to reduce the upstream pressure leading to more benign plasma exhaust towards the divertor. This needs to be compatible with an upper limit for the allowable impurity concentration near the core to avoid shortening of beam slowing down times and core dilution as described in [3].

SOLPS-ITER has been used in the narrow-grid mode for which the space between the outermost modelled plasma grid boundary is filled up with a triangular mesh for the neutrals only, the latter covering also the sub-divertor structure around the dome in EU-VNS. The atomic and molecular physics model is very similar to the standard ITER design model [6] and includes neutral-neutral interactions leading to non-homogenous neutral pressure distributions (gradients) in the sub-divertor towards the pump at molecular pressures exceeding a few Pascals.

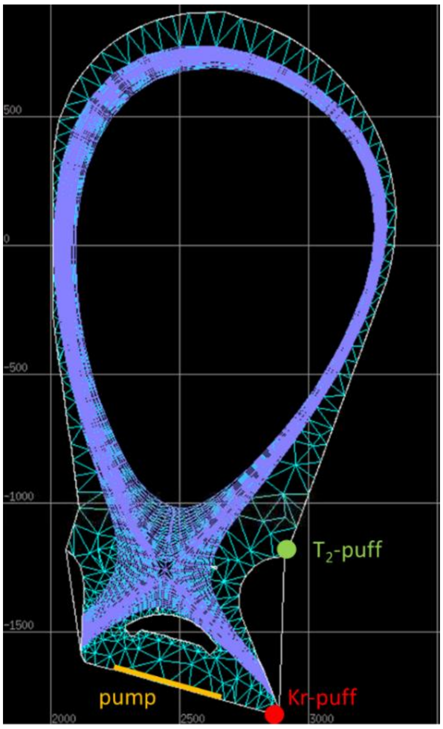


FIG. 1 SOLPS-ITER simulation grid (84 × 36 quadrilateral cells) and EIRENE neutral triangular mesh, and depicted locations of T_2-gas puff, Kr-puff and pumping surface.

3. SIMULATION RESULTS

This section summarises the SOLPS-ITER results for the scan of T-particle throughput and Kr seeding rate scan. Fig. 2 displays the grand result of the study demonstrating that there exists a finite operational space of EU-VNS staying within the limitations of critical $Z_{eff} < 2$ and the maximum peak heat-flux $q_{pk,LFS}$ at the low-field side (LFS) divertor target plate (< 10 MW/m^2). Compared to the previous study with Ar in [3] the Kr case provides a larger operational space, allowing also lower values of total T-particle throughputs $\Phi_{T,total} = \Phi_{T,core} + \Phi_{T,core}$ (about a factor of 2 lower compared to the Ar case).

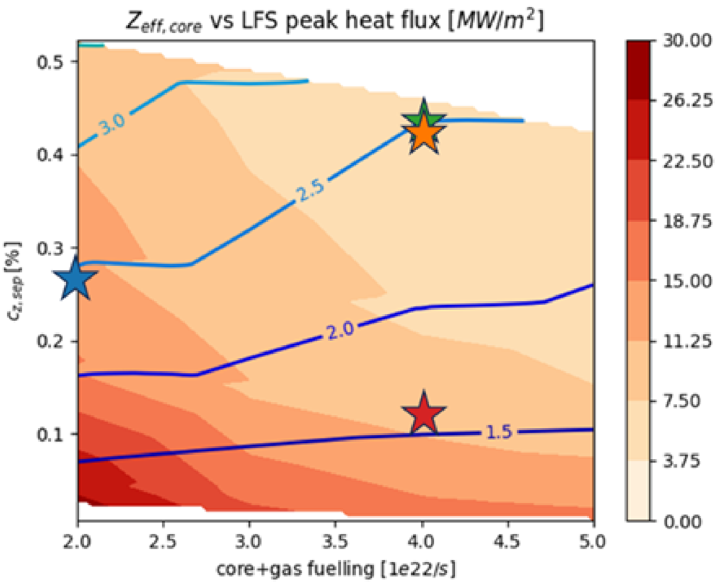


FIG. 2 Overview of operational space of the simulated EU-VNS T+He+Kr database in terms of Z_{eff}(solid lines) vs. $q_{pk,LFS}$ (coloured contour plot, note: the colour scale is different from [Wiesen2025]) and dependence on total T-throughput $\Phi_{T,gas} + \Phi_{T,core}$and averaged separatrix impurity density $c_{z,sep}$. The symbols correspond to the 4 cases in the figures 6 & 7: case I blue, case II orange, case III green, case IV red.

Similarly, figure 3 displays the operational space for $Z_{eff} < 2$ and $q_{pk,LFS}$ as a function of separatrix and core/pedestal densities and temperatures. The required densities to achieve significant power dissipation to stay within the limit $q_{pk,LFS} < 10MW/m^2$is achievable at medium levels of Greenwald fractions f_{GW}. In fact the boundary lies pretty much at the f_{GW} ~ 50% level expected from the ASTRA core model predictions (vertical dashed line in figure 3 r.h.s), and at the same time at a reasonable level of $Z_{eff} < 1.5 - 2$ is observed which is quite an acceptable (and better than for the Ar case). Notably, $T_{e,sep}$ stays roughly the same for the whole throughput and seeding scan, whereas the (ion) temperature at the core side $T_{i,core}$varies significantly between 1.0-1.7 keV depending on the level of Z_{eff}.

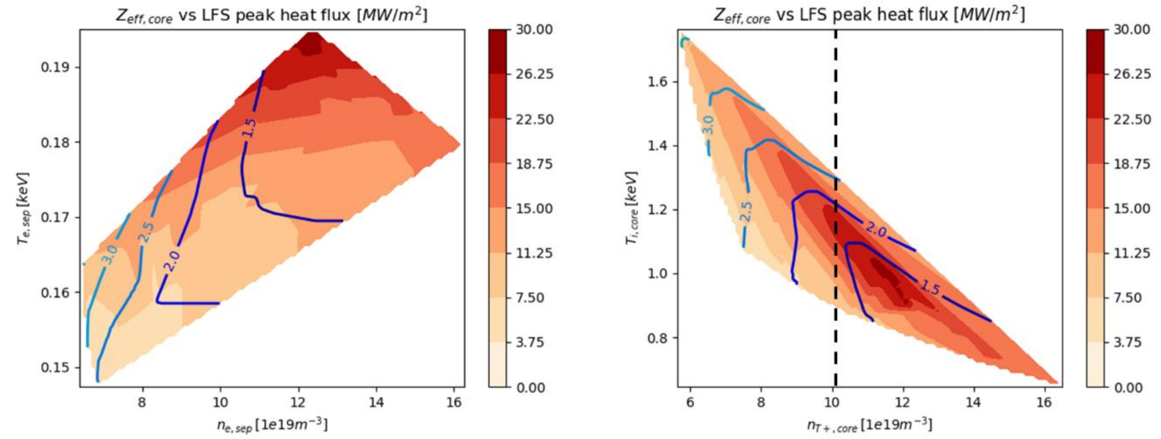


FIG. 3 Operational space in terms of separatrix density $n_{e,sep}$ and temperature $T_{e,sep}$ (left) and the same as function of core (pedestal) tritium ion density $n_{T+,core}$ and temperature $T_{i,core}$ (right). Solid lines again Z_{eff}. The vertical dashed line depicts the rough level of line-averaged density expected from ASTRA/METIS simulation for the EU-VNS design point (corresponding to a Greenwald fraction of f_{GW}~50%).

Krypton seems to be the better choice for the EU-VNS exhaust scheme as at the same time it allows for a reduction of power flows into the SOL (by achieving stable conditions with significant radiation inside the separatrix, c.f. figure 4, left). At the same time the Kr-impurity enrichment in the (LFS) outer divertor (OD) expressed as,

$$\frac{\eta_{Kr}}{\eta_T} = \frac{n_{Kr,OD}/n_{Kr,sep}}{n_{T,OD}/n_{T,sep}}$$

correlates positively, almost linearly, with the divertor neutral pressure $p_{0,div}$ and/or upstream density $n_{e,sep}$ (c.f. figure 4, right). As a result, Kr is very efficient to reduce the plasma pressure in both regions inside the separatrix and in the divertor, correlated with density. This result is very useful when considering integrated control of impurity content vs heat exhaust.

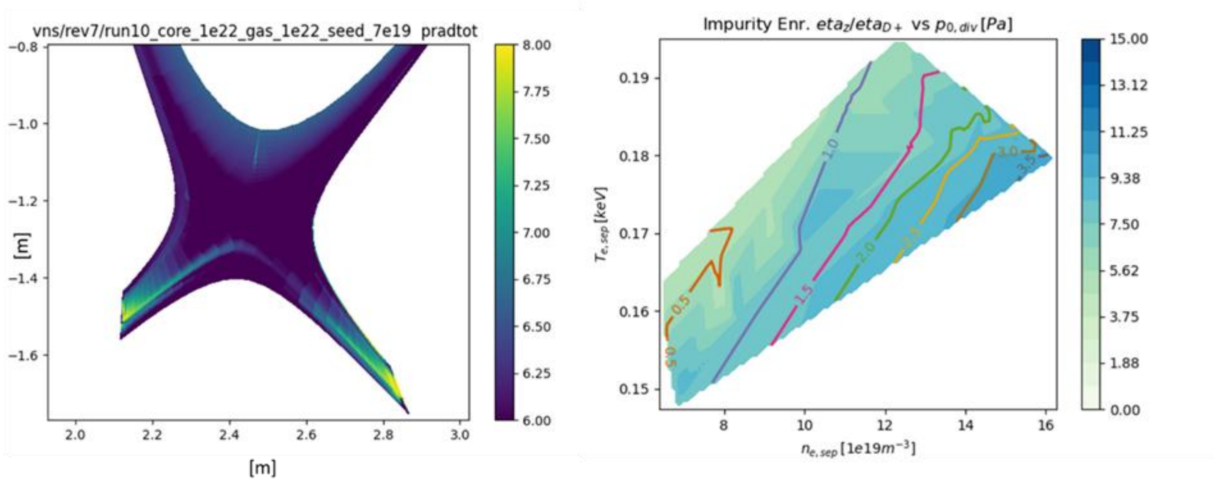


FIG. 4 Left: Kr radiation profiles in the EU-VNS reference case IV. Right: Kr impurity enrichment (solid lines) in the divertor (right) vs neutral pressure $p_{0,div}$ [Pa] in the divertor.

In addition, the neutral confinement in the divertor is also very efficient that seems to be correlating with the impurity enrichment (c.f. figure 5, l.h.s for molecular pressure distribution). The neutrals and impurities act on the LFS very efficiently leading to a slightly inverted asymmetric power ratio $q_{pk,LFS}/q_{pk,HFS}$ between the inner and the outer target for the highest levels of $p_{0,div}$.

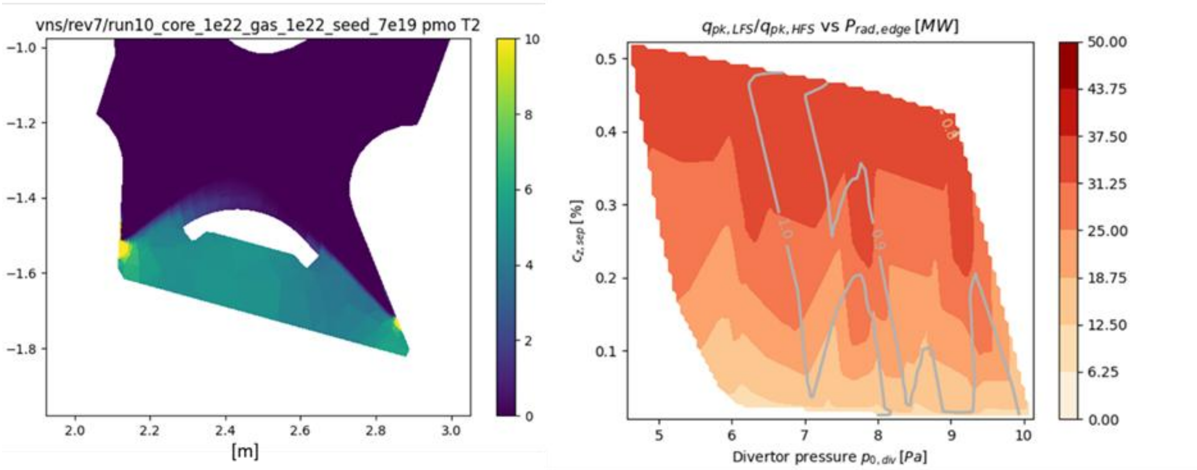
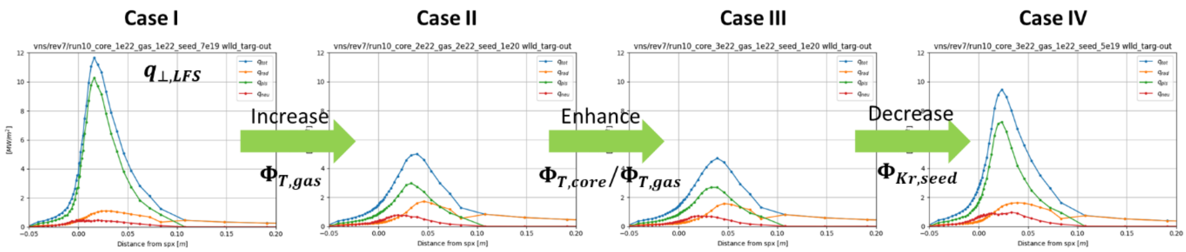


FIG. 5 Left: neutral (molecular) tritium pressure distribution $p_{0,div}$ [Pa] in EU-VNS for case IV; Right: in/out ratio of the peak heat fluxes $q_{pk,LFS}/q_{pk,HFS}$ vs total radiated power in the edge $P_{rad,edge}$, here as function of the averaged neutral pressure in the divertor $p_{0,div}$.

Figure 6 (and table within) summarizes exemplarily for a subset of reference cases the forward optimization attempts to minimize $Z_{eff} < 2$ and moderating peak heat-fluxes q_{pk} and symmetry at both LFS and HFS at the same time. The positive correlations of power dissipation with Kr in the core region and divertor with neutral pressure and upstream density is helpful here. In the best case as shown in the figure a value of Z_{eff}~1.6 could be achieved with a symmetric power sharing between inner and outer target < 10 MW/m^2. It needs to be noted that in order to achieve this, as in the previous work with Ar in [3], significant levels of fueling through pellets from the core is required. SOLPS-ITER in this work is assuming a constant flux coming for the core and transients from pellet ablation process are disregarded here.



Case No.	$\Phi_{T,core}$ [1/s]	$\Phi_{T,gas}$ [1/s]	$\Phi_{Kr,seed}$ [1/s]	Z_{eff}	$\langle c_{z,sep} \rangle$ [%]	$\langle p_{0,div} \rangle$ [Pa]	$q_{pk,HFS}$ [MW/m^2]	$q_{pk,LFS}$ [MW/m^2]
I	1e22	1e22	7e19	2.52	0.28	4.9	11.61	9.50
II	2e22	2e22	1e20	2.74	0.46	7.8	5.00	6.13
III	3e22	1e22	1e20	2.51	0.44	7.6	4.70	6.05
IV	3e22	1e22	5e19	1.64	0.12	7.9	9.46	9.50

FIG. 6 Comparison of the T+He+Kr cases, optimized towards lowering Z_{eff} even further but staying within the target heat-flux requirements. Pellet fuelling is more efficient to keep Z_{eff} down also for the T+He+Kr case, but the achievable low levels of $Z_{eff} < 2$ are more compatible with core plasma performance requirements

Lastly, figure 7 depicts radial profiles at the outer mid-plane (OMP) for cases I-IV. Whereas at the separatrix the temperatures for electrons and ions are quite robust and saturate at levels $T_{e,sep} \sim 150\ eV$ and $T_{i,sep} \sim 350 - 400 eV\ eV$, respectively. At the core side (top-pedestal region) temperatures vary significantly, e.g. for the ions by 50% and somewhat less strong for the electron temperature. To what extent the variation of ion temperature gradient in the edge impacts stability and transport in the edge is to be assessed in the near future (and such a task is now being pursued by a team of experts, E. Bray et al.).
For the densities it is observed that for the subset of cases (including the optimum case IV with low Z_{eff}) the required density stays well within the Greenwald fraction as discussed already above. The density gradients do

change only in a very limited way leading to a strong correlation between n_{core} and $n_{e,sep}$. Contrary to the Ar case in [3] pellet fueling is important to bring up the core density in order to lower Z_{eff} but the separatrix densities are fueled similarly well, leading to the positive correlation of impurity enrichment η_{Kr}/η_{T+} in the divertor region already mentioned above.

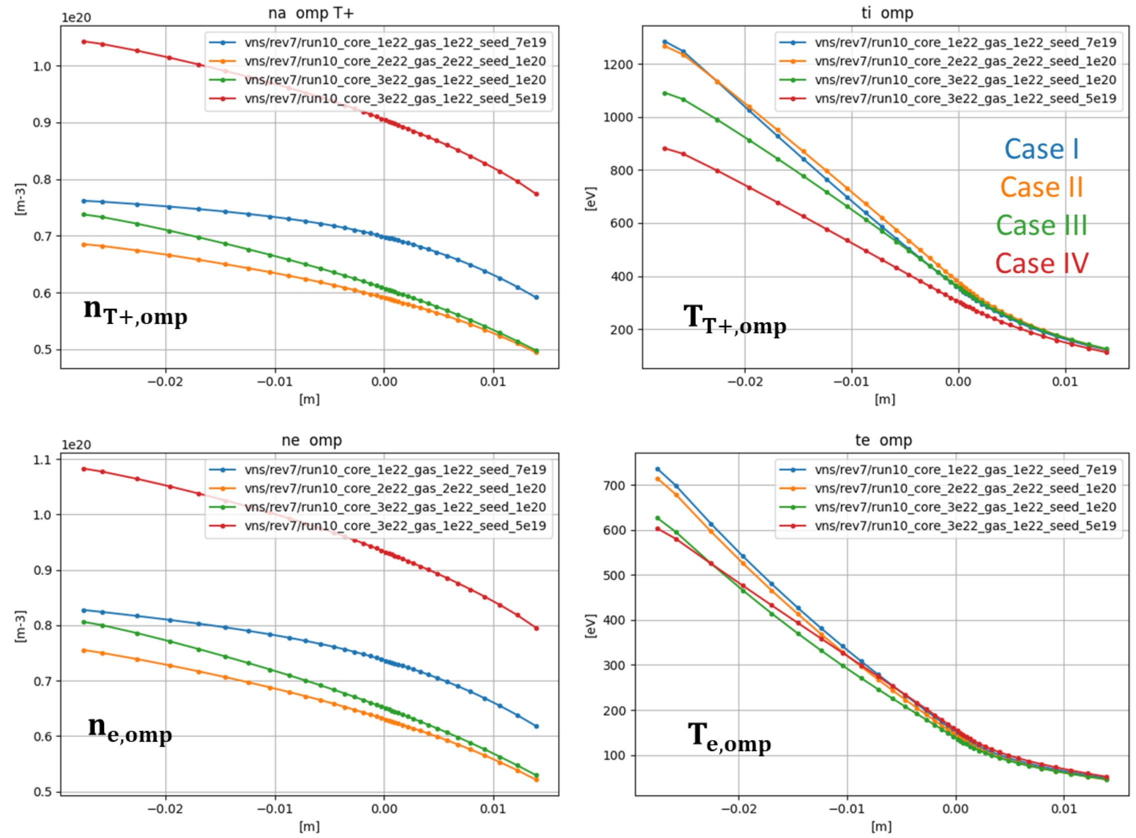


FIG. 7 Outer mid-plane profiles of ion density and temperatur (top) and for the electrons (bottom) for the subset of cases I-IV (c.f. figure 6)

4. CONCLUSION

The new SOLPS-ITER modelling results demonstrate and compared to previous work in [3] that the operational window found with Kr seeding can be even larger for the revised EU-VNS design point at 25% larger fusion power with only a slightly modified divertor configuration. The peak heat-load density at target plates have values safely below 10MW/m^2 (steady) despite the compact geometry of the VNS divertor (c.f. fig. 2). EU-VNS is assumed to have a narrow and hot near-SOL region being very opaque to gas fuelling through the SOL and as in the previous work pellet fuelling is required to increase the top-pedestal / core density. Fuelling by pellets in the T+He+Kr case is again very efficient compared to pure gas puffing and Z_{eff} can now be reduced closer to even more acceptable levels ~ 1.5 compared to the previous Ar cases in [3]. A positive correlation between Kr enrichment in the divertor and the level of neutral pressure and upstream density is enabled by pellet fuelling from the core side feeding also the separatrix efficiently. The tritium density required to minimise Z_{eff} is in line with the METIS/ASTRA design point calculations ($\langle n_T \rangle \approx 1.1 \cdot 10^{20}$m^{-3} i.e. around 50% f_{GW}). The required total T-throughput is still large ($\Phi_{T,gas} + \Phi_{T,core} \sim 3 \cdot 10^{22}$s^{-1}) but a factor of 2 lower compared to the previous T+He+Ar case in [3]. Integrated core-edge modelling is required to resolve uncertainties in the assumed transport model and to self-consistently achieve ASTRA predicted top-pedestal conditions resonating on the change of ion temperature gradients observed in the presented SOLPS-ITER simulations.

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.

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