ASSESSMENT OF ALTERNATIVE DIVERTOR CONFIGURATIONS AS AN EXHAUST SOLUTION FOR DEMO

H. REIMERDES[1*], R. AMBROSINO[2], P. INNOCENTE[3], A. CASTALDO[2], P. CHMIELEWSKI[4], G. DI GIRONIMO[2], S. MERRIMAN[5], V. PERICOLI-RIDOLFINI[4], L. AHO-MANTILLA[6], R. ALBANESE[2], H. BUFFERAND[7], G. CALABRO[8], G. CIRAOLO[7], D. COSTER[9], N. FEDORCZAK[7], S. HA[5], R. KEMBLETON[5], K. LACKNER[9], V.P. LOSCHIAVO[2], T. LUNT[9], D. MARZULLO[2], R. MAURIZIO[1], F. MILITELLO[5], G. RAMOGIDA[10], F. SUBBA[11], S. VAROUTIS[12], R. ZAGÓRSKI[4] AND H. ZOHM[9]

[1]Ecole Polytechnique Fédérale de Lausanne (EPFL), Swiss Plasma Center (SPC), Lausanne, Switzerland
[2]Consorzio CREATE, Universita' degli Studi di Napoli Federico II, Naples, Italy
[3]Consorzio RFX, Padova, Italy
[4]Institute for Plasma Physics and Laser Microfusion (IPPLM), Warsaw, Poland
[5]CCFE, Culham Science Centre, Abingdon, UK
[6]VTT Technical Research Center of Finland, VTT, Finland
[7]IRFM, CEA Cadarache, St. Paul-lez-Durance, France
[8]University of Tuscia, Viterbo, Italy
[9]Max-Planck Institute for Plasma Physics, Garching, Germany
[10]ENEA, Frascati, Italy
[11]Dipartimento Energia, Politecnico di Torino, Turin, Italy
[12]KIT, Karlsruhe, Germany

[*]Email: holger.reimerdes@epfl.ch

Abstract

The European roadmap for fusion energy has identified plasma exhaust as a major challenge towards the realisation of magnetic confinement fusion. To mitigate the risk that the single null divertor (SND) with a high radiation fraction in the scrape-of-layer (SOL) adopted for ITER will not extrapolate to a DEMO reactor, the EUROfusion consortium is assessing potential benefits and engineering challenges of alternative divertor configurations. A range of alternative configurations that could be readily adopted in a DEMO design has been identified. They include the X divertor (XD), the Super-X divertor (SXD), the Snowflake divertor (SFD) and the double null divertor (DND). The flux flaring towards the divertor target of the XD is limited by the minimum grazing angle at the target. The characteristic increase of the target radius in the SXD is a trade-off with the increased TF coil volume, but, ultimately, also limited by forces onto coils. Engineering constraints also limit XD and SXD characteristics to the outer divertor leg with a solution for the inner leg requiring up-down symmetric configurations. Capital cost increases with respect to a SND configuration are largest for SXD and SFD, which require both significantly more poloidal field coil conductors and in the case of the SXD also more toroidal field coil conductors. Boundary models with increasing degrees of complexity have been used to predict the beneficial effect of the alternative configurations on exhaust performance. Desired effects are an easier access to detachment, which is deemed to be necessary to obtain tolerable plasma parameters at the divertor targets, and a reluctance of the detachment front to displace along the divertor leg. While all alternative configurations should decrease the power that must be radiated in the outer divertor target, only the DND and possibly the SFD also ease the radiation requirements in the inner divertor. These decreases of the radiation requirements are however expected to be small making the ability of alternative divertors to increase divertor radiation without excessive core performance degradation their main advantage. Initial 2D fluid modeling of argon seeding in XD and SFD configurations indicate such advantages over the SND, while results for SXD and DND are still pending. Additional improvements, expected from increased turbulence in the low poloidal field region of the SFD also remain to be verified. A more precise comparison with the SND as well as absolute quantitative predictions for all configurations requires more complete physics models that are currently only being developed.

1. INTRODUCTION

The European roadmap for fusion energy [1,2] has identified a reliable solution for heat and particle exhaust as one of the main challenges towards the realisation of magnetic confinement fusion. Since power exhaust scales unfavourably with the size of the device, a reactor based on the tokamak concept must likely harness an even greater heat flux than ITER. Simultaneously, the higher particle and neutron fluences impose more stringent constraints on the plasma facing components and the admissible erosion. In the current European baseline scenario for a DEMO reactor, which foresees a single null magnetic configuration, this must be achieved by an even greater radiative power exhaust [3]. However, it is, as discussed in Section 2, uncertain whether greater divertor radiation is compatible with the energy confinement required in a reactor [4,5] and whether transients can be sufficiently suppressed to avoid any damage of the divertor targets. To mitigate the risk that the baseline scenario adopted for

ITER will not extrapolate to DEMO, the EUROfusion consortium is assessing the potential benefits and the engineering challenges of alternative divertor configurations as an exhaust solution for DEMO.

Several decades of divertor research have resulted in many configurations and concepts that may be considered as alternatives to the conventional divertor [6]. Among these configurations, a reduced set of basic geometry variations and corresponding divertor concepts that rely on the same physics basis as the baseline solution and can readily be adopted in a DEMO design is identified, and the underlying physics mechanisms described in Section 3. Alternative concepts generally increase the complexity of the device and their realization may exceed available technological capabilities. The extent of the geometric variations that could be attainable using only modest extrapolations of currently available technologies is evaluated in Section 4. While the range of achieved geometric variations may not be optimal, they are indicative of the achievable variations within the given constraints. Divertor models with increasing degrees of sophistication are then used in Section 5 to project the geometric variations into divertor performance improvements. To decrease the effect of systematic errors, these are compared to predictions for the baseline solution. The conclusions of the assessment are presented in Section 6.

2. THE PLASMA EXHAUST CHALLENGE

The EU roadmap foresees a demonstration fusion power plant (DEMO) that will follow ITER with the capability of generating several hundred MW of net electricity [23]. Aiming at a net electric power output of 500 MW with a conventional aspect ratio (*A*=3.1) tokamak the system code PROCESS is used to identify the main reactor parameters. Assuming a maximum magnetic field at the location of the toroidal field coils of 11.9 T limited by excessive forces onto the coils, an H-mode confinement factor H_{98}=1.1, a density that exceeds the Greenwald density by 20% and a normalized beta β_{N}=2.6 results in a device with a major radius of 8.8 m, an on-axis magnetic field of 5.8 T and a plasma current of 20.3 MA, Table 1. Correcting for core brems- and synchroton radiation losses the plasma is heated with P_{heat}=300 MW.

TABLE 1. PROCESS scenario for a A=3.1 reactor with P_{elec}^{net}*=500 MW*

R_0	8.8 m
κ_{95}	1.55
B_0	5.8 T
I_{P}	20.3 MA
$\langle n_{\mathrm{e}} \rangle$	8.7x10^{19}m^{-3}
P_{fus}	2000 MW
P_{α}	400 MW
P_{aux}	50 MW
P_{heat}	300 MW
$P_{\mathrm{rad}}^{\mathrm{core}}$	150 MW
P_{sep}	150 MW

The empiric scaling of the L-H threshold [34] requires that at least 135 MW of the heating power cross the LCFS in the plasma channel to access H-mode confinement. The L-H threshold together with a 10% margin sets the minimum P_{sep}=150 MW that must be exhausted in the divertor, with the remaining 150 MW exhausted by line radiation in the closed field line region, Table 1. In addition to removing power, the divertor must also exhaust 7x10^{20} He atoms/s that are generated in the fusion reactions. In the baseline scenario [3] the plasma exhaust relies on an extrapolation of the ITER solution [36] characterised by high divertor radiation obtained through impurity seeding and operation in a highly detached divertor regime, while maintaining a high neutral pressure in the pump ducts.

An empiric scaling [25] and a heuristic model [35] of the scrape off layer (SOL) width λ_{q} in attached scenarios predict values of approximately 1.0 mm for the outboard midplane of the considered reactor scenario, Table 1. Assuming a typical 1:2 power distribution between the inner and outer divertor the expected upstream parallel heat flux towards the outer divertor is $q_{\parallel,\mathrm{u}}$=6 GW/m^2. Such a high heat flux must be reconciled with technological solutions for the target, which impose limits most notably on the maximum heat flux onto the target surface and on the maximum electron temperature at the target.

The heat flux onto the target is limited to prevent excessive temperatures of any target component, which may cause melting or embrittlement but also radiation creep depending on the chosen materials. A typical value for the maximum heat flux onto the surface of a target made of reactor relevant materials is 10 MW/m^2 [37].

Fortunately, the grazing angle between magnetic field lines and the target surface, γ_{t}, is small, which reduces the component of the parallel heat flux that is perpendicular to the target surface,

$$q_{\perp,\mathrm{t}} = q_{\parallel,\mathrm{t}} \sin\gamma_{\mathrm{t}} \quad . \tag{1}$$

The value of γ_{t} can be reduced by decreasing the poloidal field at the target and, hence, increasing the poloidal flux expansion $f_{\mathrm{x,t}}$ and by tilting the target in the poloidal direction with respect to the separatrix. However, the need to assemble the divertor targets out of small building blocks leads to toroidal gaps and leading edges that must be shielded. Such shielding is typically achieved through chamfering of the target surface, which, together with manufacturing tolerances, impose a minimum value for γ_{t}. A similar constraint arises also from the need to control the position of the strike line. The ITER design resulted for example in γ_{t}~3° (+1° bevel of the mono-blocks) [22]. The chamfering of the target surface also reduces the maximum heat flux perpendicular to a toroidally symmetric target surface, $q_{\perp,\mathrm{t}}^{\max}$, with respect to the maximum heat flux capability of the target. Assuming a maximum heat removal at the target of $q_{\perp,\mathrm{t}}^{\max}$=5 MW/m^2 and a minimum angle of γ_{t}=1.5° the maximum parallel heat flux at the target is $q_{\|,\mathrm{t}}^{\max}$=200 MW/m^2. Even assuming that divertor broadening reduces the unmitigated peak heat flux by a factor of three (to 2 GW/m^2), at least 1.8 GW/m^2 corresponding to 90% of the power crossing the LCFS must be dissipated along field lines in the divertor. Such a large dissipation must be achieved through deliberate seeding of impurities in the divertor, with argon (Ar) having been identified as a possible species [23]. Achieving such a level of radiative power exhaust will, however, require an increase of the seed impurity concentration in the divertor over today's devices as well as ITER [4,5], which may not be compatible with core performance. Leakage of seed impurities from the divertor into the plasma core must be sufficiently small to avoid excessive core radiation as well as excessive fusion fuel dilution. The exact limits depend on the scenario. In the reference scenario the core radiation arising from divertor impurity seeding must be less than 150 MW and compatible with H_{98}=1.1 and the additional dilution of the fusion fuel must not reduce the alpha heating below 400 MW.

An additional limit is introduced by sputtering of the target material [24], which increases with the electron temperature at the target, $T_{\mathrm{e,t}}$. The sputtering has to be sufficiently low to avoid a reduction of the lifetime of the divertor and to avoid an intolerable influx of heavy impurities that would degrade core performance. With tungsten (W) being the most promising material for the divertor target armor, the maximum value of $T_{\mathrm{e,t}}$ is set by sputtering of W through impact of seed impurity ions to values below 5 eV.

The value of $T_{\mathrm{e,t}}$ is closely linked with the heat transfer through the plasma sheath at the target,

$$q_{\parallel,\mathrm{t}} \approx \gamma_{\mathrm{sheath}} \sqrt{\frac{k_{\mathrm{B}} T_{\mathrm{e,t}}}{2 m_{\mathrm{i}}}}\, p_{\mathrm{t}} \quad , \tag{2}$$

where p_{t} is the plasma pressure at the target and the potential energy of the ions neglected. As the upstream pressure is poised to increase with the higher heat flux and longer connection length in a reactor compared to today's devices and ITER, obtaining the same values for $q_{\parallel,\mathrm{t}}$ and $T_{\mathrm{e,t}}$ requires a larger pressure loss along SOL field lines. Since the pressure loss increases with lower $T_{\mathrm{e,t}}$ [38] DEMO must operate at lower $T_{\mathrm{e,t}}$ than today's devices. The lower value of $T_{\mathrm{e,t}}$ raises the concern that the operating regime is not stable as well as that the neutral pressure in the divertor and, hence, in the pump ducts may drop. Note that while decreasing γ_{t} helps establishing a tolerable target heat flux, the resulting larger tolerable parallel heat flux magnifies the challenge to decrease $T_{\mathrm{e,t}}$ to tolerable values.

Plasma exhaust in ITER represents a significant step towards DEMO and experiments in ITER will ultimately test whether the conventional single null divertor (SND) with a high radiation fraction in the SOL will extrapolate to a reactor. To mitigate the risk that the baseline will not extrapolate to DEMO, the potential benefits and the engineering challenges of alternative divertor configurations are assessed.

3. ALTERNATIVE DIVERTOR CONFIGURATIONS

To avoid significant delays in the European effort to design a DEMO reactor [7,8], the assessment only considers alternative configurations that rely on the same core physics, including H-mode confinement and detached divertor operation, as the baseline scenario. The considered configurations include a X, Super-X, Snowflake and Double-Null divertor, all of which have already been realised experimentally. Key aspects of these configurations also apply to other concepts, such as long-legged, tightly baffled, divertors, the X-point target divertor and the tripod divertor.

3.1. X divertor

The X divertor (XD) concept [9] relies on a flaring of the poloidal flux towards the target with two main consequences for the plasma exhaust. Firstly, a larger flux expansion at the target, $f_{\mathrm{x,t}}$, increases the wetted area, albeit by decreasing the grazing angle of field lines at the target, γ_{t}. While the same increase can be obtained by a poloidal tilt of the target, it is suggested that a higher flux expansion facilitates the control of the strike point location possibly providing a lower grazing angle at the target [10]. Secondly, flaring reduces the interaction area of neutrals towards the X-point thereby introducing a mechanism that keeps the neutral interaction region with close to the target [6]. This may increase the operational range where the detachment front, and hence the region of high neutral pressure, remains close to the target decreasing demands on the detachment control system. In addition, increasing $f_{\mathrm{x,t}}$ increases the connection length, $L_{\parallel}$, which should lower the detachment threshold. A beneficial effect on the detachment threshold beyond the increase of $L_{\parallel}$ is supported by fluid modelling using the SOLPS code [42].

The XD was realised well before the formulation of the divertor concept in ASDEX [43]. The plasma exhaust behaviour of the XD configuration was subsequently compared to the SND in TCV [44, 45] and DIII-D [42], but the comparison only showed a negligible or small beneficial effect.

3.2. Super-X divertor

The Super-X divertor (SXD) concept [11] extends the XD concept to toroidal flux flaring by increasing the major radius of the target, R_{t}. The increase of R_{t} increases the wetted area even for a constant grazing angle of the field line at the target. This decreases the peak heat flux that must be mitigated and lowers the detachment threshold. The increase of the major radius along the field lines also results in an inverse gradient in the parallel heat flux, which should stabilise the radiation-condensation instability and, hence the movement of the radiation front along the divertor leg and, thereby increasing the detachment window [12]. The increase of the target radius in the SXD can be combined with an increase of the poloidal flux expansion, as planned in MAST-upgrade [13], or even with an additional null point along the divertor leg as proposed in the X-point target divertor concept [14]. The decrease of the poloidal field would significantly increase the connection length and, thereby further reduce the detachment threshold. An increase in R_{t} usually comes with a longer divertor leg, L_{p}, which should adjust the balance between parallel and cross-field transport and result in a broader width of the power carry channel, λ_{q}. An increase of R_{t} should also facilitate the shielding of high heat flux components from neutron irradiation, increasing the choice and capabilities in the materials that can be used. A beneficial effect has also been seen in fluid simulations using the UEDGE [46] as well as the SOLPS code [47].

Significant variations of the outer target radius were experimentally obtained in DIII-D [26] and TCV [45], but in both experiments variations of the target geometry appear to mask the effect of R_{t}.

3.3. Snowflake divertor (SFD)

The snowflake divertor concept [15, 17] is based on a second order null point, where divertor coils simultaneously cancel the poloidal field, B_{p}, and its gradients, ∇B_{p}, and which leads to a characteristic hexagonal symmetry of the separatrix. In the vicinity of a second order null, B_{p} is lower than in a conventional X-point, which increases connection length and SOL volume. This increase is largest closest to the separatrix, where the unmitigated heat flux is highest. An increased $L_{\parallel}$, is expected to facilitate access to detachment. It is furthermore hypothesised that the decrease of the poloidal field increases turbulent cross-field transport or even macroscopic magneto-hydrodynamic instabilities [16, 48] that broaden λ_{q}, thereby further facilitating access to detachment. In a SFD, the poloidal flux is re-concentrated towards the target. Following the reasoning for the XD, Section 2.1, this may enhance the movement of a detachment front towards the null-region. It is, therefore, likely that the operating regime of a SFD reactor will resemble X-point radiators [49]. In such a regime, the SFD may have a smaller impact on core confinement than a SND with the low B_{p} region extending further into the region of closed field lines, where it may support higher poloidal gradients.

Due to inevitable deviations from the exact current distribution in the plasma, the poloidal field coils and passive structures, a real snowflake configuration features two nearby X-points with only one "primary" X-point with a non-zero ∇B_{p} determining the separatrix. Depending on the location of the secondary X-point in the private or common flux region one distinguishes snowflake-plus (SFD+) and snowflake-minus (SFD-) configurations. An increased distance generally increases ∇B_{p} at the primary X-point, which weakens the main advantages of the SFD, and leads to a set of proximity conditions [50,17]. The placement of the secondary null in the SOL of the outer divertor, often referred to as a low-field side (LFS) SFD-, may however even be desirable as it can decrease the peak parallel heat fluxes where it is most needed [18,19].

The SFD configuration was realized in TCV [51], NSTX [52] and DIII-D [53], but experimental observations are difficult to extrapolate to a reactor as the geometric modifications of the SOL depend strongly on the ratio of λ_{q} and the device dimensions, e.g. R_0 [54].

3.4. Double null divertor

The double null divertor (DND) is an up-down symmetric configuration with first order X-points at the top and bottom and corresponding divertors. As the transport across the LCFS has a strong ballooning character, heat and particles are predominantly exhausted to the outer targets, which have a larger R_{t} and, hence lower peak heat fluxes at the targets. The DND is, therefore, foremost a solution for the inner divertor leg. An additional advantage is an extremely quiescent and narrow inner SOL [20], with strongly reduced heat flux onto the inner wall that reduces the required breeding blanket armour. It may also facilitate HFS RF coupling [14].

Double-null configurations have been realized in many diverted tokamaks starting with T-12 [55]. The ability to control the power distribution between the upper and lower targets by magnetic balance is well documented (e.g. in MAST [56]).

It may also be necessary to extend the DND concept to alternative configurations, if they cannot protect the inner divertor target. This may be the case for realisable XD and SXD implementations in DEMO, discussed in Section 3.2, or for configurations that intrinsically favour the outer divertor such as possibly LFS SFD- variants.

4. REALISATION IN A DEMO SIZE DEVICE

Any of the assessed alternative configurations, discussed in Section 2, will increase the complexity of the magnetic configuration and, thereby, the engineering challenge and cost of a power plant. This assessment includes a study of whether the divertor concepts may be realised in a DEMO that uses presently available technologies and identifies limits to attainable geometric variations [21]. A key technology is conventional superconductors, which require dedicated winding facilities and exclude interlinked coils. The assessment, therefore, requires that the poloidal field (PF) coils must be located outside the toroidal field (TF) coils. A maximum magnetic field at the conductor is set to 12.5 T and the current density in the coils limited to 12.5 MA/m^2. Vertical forces onto a single PF coil must not exceed 450 MN and onto the entire central solenoid (CS) 300 MN. The maximum separation force in the CS must not exceed 350 MN. All configurations are conceived with 18 TF coils that are sized to limit the TF ripple to 0.6%. Each divertor target is tilted in the poloidal plane for separatrix field lines to form a grazing angle of γ_t =1.5° in toroidally symmetric configurations. The tilt direction is chosen to ‘close’ the divertor. While the assumed constraints may not be absolutely correct they characterise the orders of magnitude of the feasible.

The resulting reference and alternative configurations are described in Section 4.1 and 4.2, respectively and are referred to as “2017” configurations. A lowest order estimation of the cost increase of the alternatives with respect to the reference configuration, based on the increased mass of the superconductors is given in Section 4.3. A revision based in the evolving EU baseline, which most notably included a reduction of the number of TF coils from 18 to 16, has resulted in “2018” configurations discussed in Section 4.4. The “2018” configurations are also basis for a first investigation of possible repercussions for remote handling of the divertor and blanket modules in Section 4.5, which may affect availability and, thereby, the price of electricity. A rigorous ordering of the cost increases is not possible and further possibly important constraints and cost drivers are listed in Section 4.6.

4.1. Conventional single null reference configuration

A SND configuration that meets the scenario parameters used in the system code, Table 1, is obtained using 6 PF coils and a central solenoid consisting of 5 individually powered segments, Fig. 1. The TF coils enclose a volume of 7175 m^3, that is 3.5 times the plasma volume, and the forces onto the PF coils remain well below the limits. The parallel connection lengths from the outboard midplane to the inner and outer targets, evaluated on the flux surface with an upstream separatrix distance $dR_{\mathrm{u,sep}}$=1 mm, are 215 m and 125 m, respectively. Moderate flux expansions of 5.7 and 3.8 at the inner and outer targets allow for a ‘closed’ divertor target configuration with the poloidal angle between separatrix and the target, β_{t}, of only 28° and 20°, respectively.

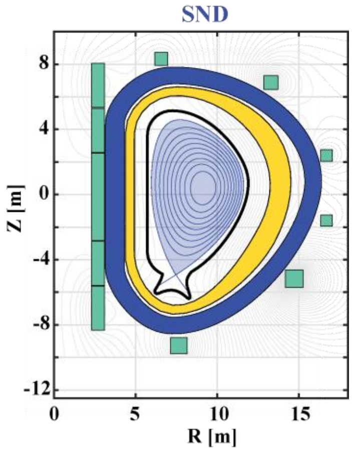

Figure 1. *Reference configuration with a Single-Null divertor (SND) (adapted from Fig. 1 in [16]). The 2D description consists of an equilibrium (light blue), a first wall including divertor target (black), a vacuum vessel (yellow), toroidal field coils (dark blue) and poloidal field coils (green).*

4.2. Alternative configurations

Alternative configurations with the same plasma and low order shape parameters are realised by iterating between the CREATE-NL code to place PF coils and calculate equilibria and the NOVA code to place first wall, vacuum vessel and TF coils [21]. The first wall maintains a minimum distance of 22.5 cm to the separatrix. The vacuum vessel allows space for breeding blankets and includes space for additional neutron shielding. The coil placement is optimised to meet the constraints described above and maximise the flat top flux swing. While the range of achieved geometric variations may not be optimal, they should be indicative of the achievable variations under the given constraints.

4.2.1 X divertor

The XD configuration can only be realised with poloidal flux flaring at the outer leg, Fig. 2(a) and Table 2, as space constraints prohibit coils that may flare the flux at the inner target. The flux swing for the XD is significantly reduced and achieving 75% of the flux swing of the SND requires a highly segmented CS. The flux flaring towards the outer divertor target is limited by the smallest value of γ_{t}. To maximise the flux expansion at the target, $f_{\mathrm{x,t}}$, the target is placed at nearly 90° with respect to the separatrix. The obtained ratio of the flux expansion at the target and its minimum value along the divertor leg of $f_{\mathrm{x,t}}/f_{\mathrm{x}}^{\mathrm{min}}$ = 1.3 quantifies the flaring and is the result of a trade-off with a longer divertor leg and a larger TF coil volume that in the assessed configuration is only marginally larger than for the SND, Table 2. Increasing the leg length and/or relaxing the constraint on γ_{t} could lead to a stronger flaring. This would, however, require a detailed study of expected manufacturing tolerances and configuration control capabilities. Flaring could also be increased, if additional poloidal field coils inside the TF coils could be considered. The increase of the outer leg length and the larger flux expansion have a significant effect on $L_{\parallel}$ to the outer target, almost doubling with respect to the SND.

4.2.2 Super-X divertor

The SXD configuration can only be realised with an increase in the target radius of the outer target, Fig. 2(b) and Table 2. The obtained target radius corresponds to 1.5 times the X-point radius. The increase in R_{t} is a trade-off with the TF coil volume that increases by more than 25% with respect to the SND, but ultimately by forces onto PF coils. The use of “external coils”-only prohibits additional poloidal flux flaring along the outer divertor leg. In the realised configuration, the connection length to the outer target increases by ~75% with respect to the SND and is almost as large as for the XD. The poloidal tilt of the outer target is strong with β_{t}=12°, since $f_{\mathrm{x,t}}$ is small, leading to an extremely ‘closed’ outer target configuration, Table 2.

4.2.3 Snowflake divertor

The SFD configuration can been achieved, within all constraints, with a marginal increase of the TF coil volume with respect to the SND, Fig. 2(c) and Table 2. Similarly to the XD, the flux swing is significantly reduced and achieving 75% of the flux swing of the SND requires an equally segmented CS. The assessed equilibrium has a SFD-plus topology with the two X-points being separated by 20 cm, leading to a 25 fold decrease in $|\nabla B_{\mathrm{p,xpt}}|$ with respect to the SND. The connection length to the inner and outer targets evaluated on the flux surface with $dR_{\mathrm{u,sep}}$=1 mm increases by factors of 2.2 and 2.8, respectively. In addition to the SFD+ a range of SFD-configurations is generated. The exact location of the secondary X-point with respect to the primary Z-point has negligible effects on the coil currents.

4.2.4 Double-null divertor

A DND configuration is realised with a marginal increase of the TF coil volume and a small reduction of the flux swing, Fig. 2(d) and Table 2. The connection length to the outer targets is similar to the outer target of the SND.

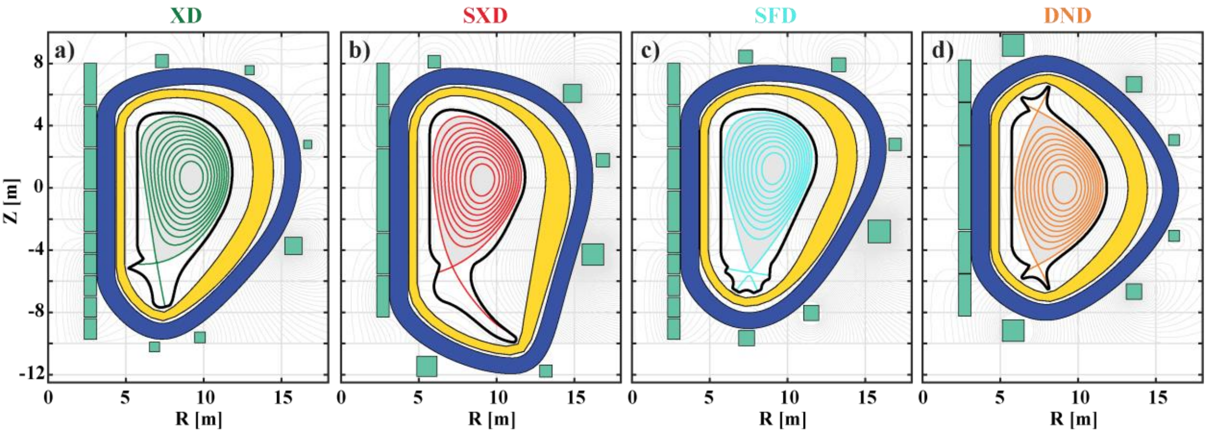

Figure 2. *"2017" DEMO configurations featuring (a) a XD, (b) SXD, (c) SFD and (d) DND (adapted from Fig. 1 in [16]).*

TABLE 2. Parameters used to estimate the costs and evaluate geometric variations of the "2017" reference SND, Section 3.1, and the corresponding assessed alternative configurations, Section 3.2. An extended version of the table can be found in [16].

		SND		**XD**		**SXD**		**SFD(+)**		**DND**	
Cost	V_{TF}/V_{plasma}	3.50		3.61		4.42		3.57		3.60	
	L_{TF} [m]	43.9		45.9		50.5		45.1		44.4	
	$\sum R_{PF} I_{PF}^{max}$ [m·MA·turns]	690		665		1016		970		744	
	Flux swing [Vs]	240		185		200		180		220	
Geometry	$\lvert\nabla B_{p,xpt}\rvert$ [T/m]	0.43		0.32		0.29		0.016		0.56	
		inner	outer	inner	outer	inner	outer	inner	outer	inner	outer
	R_t [m]	6.54	8.29	5.64	7.54	6.22	10.8	6.10	8.86	6.61	8.14
	L_p [m]	18.1	8.5	17.7	10.8	17.7	13.1	18.1	9.5	-	8.3
	$L_{\|\|}(dR_u = 1mm)$ [m]	215	125	237	236	238	217	464	344	-	104
	β_t [Deg.]	28	21	33	89	53	12	72	83	26	13

4.3. Comparison of the costs

For constant core parameters all alternative configurations increase the complexity and costs of a DEMO reactor over a device based on the SND. Main capital cost drivers are the superconductors used for the TF and the PF coils. Comparing the length of the required superconductor strand can, therefore, be used as a lowest order indication of the cost increases.

As the cross-sectional area of the TF coil winding pack is independent of the TF coil shape, the length of the required TF coil conductor strand is proportional to the poloidal circumference of each TF coil, L_{TF}. While XD, SFD and DND can be designed with similar TF coil volume, V_{TF}, and L_{TF} as the SND configuration, Table 2, the SXD increases L_{TF} and, hence, the costs of the TF coils by approximately 15%, Fig. 3.

The length of the PF coil conductors increases with the radius of each coil and the maximum current in each coil. As the PF coil currents change during the discharge the maxima are not necessarily simultaneously obtained. Using the maximum current at the start or the end of the current flattop (SOF and EOF) indicates that the SXD and SFD configurations require 50% and 40% more PF coil conductors, respectively, Fig. 3.

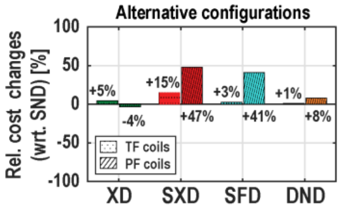

Figure 3. *Comparison of the lowest order cost estimates for TF and PF coils in alternative configurations with the SND configuration. The estimates are based on the required conductor lengths stated in Table 2.*

4.4. Adaptation to a new baseline design

To evaluate the implications of changes in the baseline design the reference configuration described in Section 3.2 as well as all assessed alternatives described in Section 3.3 were revised to consider changes in the reference parameters of the EU DEMO baseline design [39]. The changes comprise most notably a reduction of the number of TF coils from 18 to 16 and a reduction of the magnetic field from 5.8 T to 4.9 T, while meeting all of the above described constraints. To keep the same net electric power output, the plasma elongation κ_{95} is increased from 1.55 to 1.65 and β_{N} from 2.6 to 2.9. The changes in the specifications result in a plasma with a somewhat larger major radius of R_0 =8.9 m and a somewhat lower plasma current of I_{P} =19.1 MA. The resulting "2018" configurations are shown in Fig. 4.

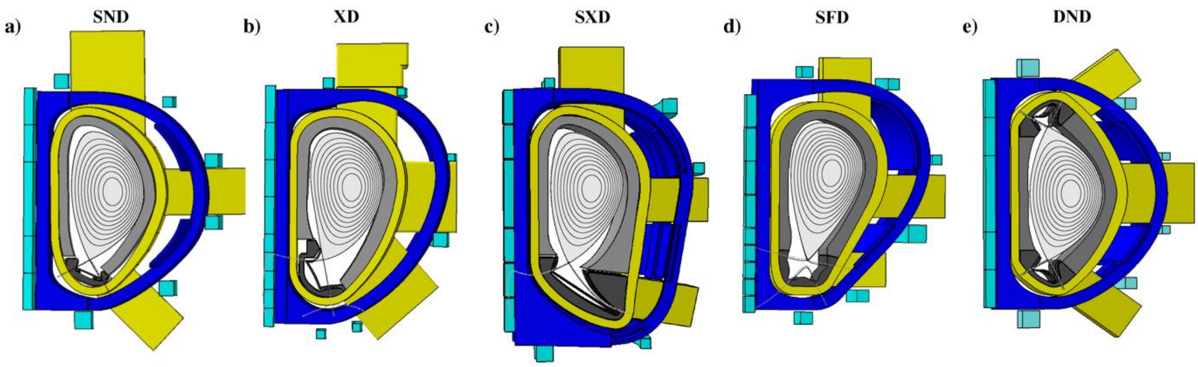

Figure 4. *"2018" DEMO configurations featuring (a) a SND, (b) XD, (c) SXD, (d) SFD and (e) DND. The descriptions include 3D models of the blanket (light grey), the divertor modules (dark grey), a vacuum vessel including ports (yellow), toroidal field coils (blue) and poloidal field coils (green).*

The revised plasma parameters lead to an approximately 15% larger plasma volume in all configurations. Due to the reduction of the number of TF coils the volume they encompass grows 10-15% more than the plasma volume. This increase does, however, not affect the conclusion on the increased cost of the alternative configurations relative to the baseline. The revision of the configurations has also only led to minor changes of geometric parameters that are deemed to affect the exhaust performance (e.g. the connection length, flux flaring or target radii).

4.5. Remote handling aspects

Remote handling of in-vessel components such as the required periodic replacement of blanket modules and divertor cassettes will affect the availability of a reactor and, hence, the price of electricity and should, therefore, be included in the costs of alternative divertor configurations. To identify potential implications of the alternative configurations on the remote handling 3D models of the devices based on the "2018" configuration, introduced in Section 4.4, have been developed [39]. In addition to detailed models of the divertor cassettes that meet the interface and space requirements determined in the DEMO baseline activity [40], the "2018" configurations also include the first wall, a vacuum vessel with ports, discrete TF coils, their inter-coil structure and PF coils. Critical issues identified in the 3D analysis fed back into the 2D description of the configurations.

The SND configuration, Fig. 4(a), features a divertor port, which is inclined by 45° with respect to the horizontal plane. Access to the blanket modules is provided via a top port and a vertical maintenance scheme [41].

The XD configuration, Fig. 4(b), has similar access to the divertor as the SND, but requires larger divertor cassettes, which complicates remote handling. As for the SND access to the blanket modules is provided via a top port and a vertical maintenance scheme.

The SXD configuration, Fig. 4(c), may feature a divertor port that has only a 10° with respect to the horizontal plane and whose dimensions are limited by the outer intercoil structure required to cope with higher electromagnetic loads expected in this configuration. The divertor cassette is even larger than the XD cassette further complicated remote access. Access to the blanket is provided via a top port and a vertical maintenance scheme.

The divertor coils of the SFD configuration, Fig. 4(d), restrict access to the divertor. A smaller port, which also competes with intercoil structure, offers horizontal access that is further complicated by the large SFD cassettes with four targets. Access to the blanket is provided via a top port.

The DND configuration, Fig. 4(e), features up-down symmetric divertor ports for divertor access that is similar to the baseline configuration. Access to the blanket must be provided by equatorial ports, which complicates both blanket segmentation and, consequently, remote handling operations.

4.6. Outstanding issues and next steps

Clearly, further constraints that will also have an impact upon the achievable geometric variations of the divertor configurations exist. A range of outstanding issues is identified and will be addressed in next steps.

(1) The structural integrity of the proposed TF coils, which presently deviate from typical D shaped coils, must be investigated and the coil shape adapted as necessary.

(2) The controllability of the vertical position and of the divertor configuration including the grazing angle of the field lines at the targets and the strike point location must be verified.

(3) The impact of the possible port locations and divertor module geometry on the costs of remote maintenance must be quantified.

(4) The potential benefits of additional PF coils based on copper conductors that could be placed inside the TF coils should be assessed.

5. PREDICTION OF THE DIVERTOR PERFORMANCE

A range of boundary models with varying degrees of complexity have been used to predict the effects of the alternative configurations on exhaust performance. Desired effects include an easier access to detachment, which is deemed necessary to obtain acceptable conditions at the plasma-wall interface in the divertor. This will have to be achieved largely through an increase of divertor radiation while avoiding excessive core confinement degradation. Once detachment is achieved the cold front should be reluctant to move along the divertor leg as it may lead to excessive core confinement degradation and a decrease of the neutral pressure in the pump ducts. The operating parameter range between detaching the divertor and the cold front reaching the X-point is commonly referred to as the detachment window and characterises the ability to handle transients. The alternative configurations are assessed through a comparison to the baseline solution. Such a comparison reduces the effect of systematic errors, which inevitably affect absolute predictions.

In order to evaluate the power exhaust performance of alternative divertors several figures of merit are proposed. Avoiding excessive target erosion and operating in a detached regime, both, require that the electron temperature at the target is sufficiently low, with $T_{\mathrm{e,t}}^{\mathrm{max}}$=5 eV being here used as a typical number [24]. In addition, the peak heat flux must not exceed the heat removal capacity of the target, with $q_{\perp,\mathrm{t}}^{\mathrm{max}}$=5 MW/m^2 being a typical value expected for high heat flux components exposed to the high neutron fluence in the DEMO divertor. This value includes already a penalty due to 3D effects such as gaps and target misalignments.

(1) *Required radiation fraction:* The key concern in any extrapolation to DEMO is the required increase in the radiation fraction outside the LCFS, i.e. in the divertor, $f_{\mathrm{rad,div}}$, and alternative configurations can be evaluated by their ability to decrease the required radiation fraction, $f_{\mathrm{rad,div}}^{\mathrm{req}} = f_{\mathrm{rad,div}} \mid T_{\mathrm{e,t}} \leq 5\mathrm{eV} \wedge q_{\perp,\mathrm{t}} \leq 5\mathrm{MW/m^2}$. Decreasing $f_{\mathrm{rad,div}}^{\mathrm{req}}$ correspondingly increases the tolerable residual power that can be exhausted at the divertor target, $P_{\mathrm{res}}^{\mathrm{tol}} = \left(1 - f_{\mathrm{rad,div}}^{\mathrm{req}}\right)P_{\mathrm{sep}}$. This first metric, therefore, quantifies the ability to exhaust more power at the target.

(2) *Required impurity concentration:* In addition to decreasing $f_{\mathrm{rad,div}}^{\mathrm{req}}$ alternative configurations can also reduce the impurity concentration required to achieve a desired radiation fraction and, hence, tolerable target temperatures. Since the key concern is excessive core radiation and fuel dilution, it is ultimately the ability to reduce the seed impurity (e.g. Ar) concentrations required to cool the divertor, $c_{\mathrm{z}}^{\mathrm{req}} = c_{\mathrm{z}} \mid T_{\mathrm{e,t}} \leq 5\mathrm{eV} \wedge q_{\perp,\mathrm{t}} \leq 5\mathrm{MW/m^2}$ that determines the power exhaust performance.

It is expected that lowering $f_{\mathrm{rad,div}}^{\mathrm{req}}$ and, ultimately, $c_{\mathrm{z}}^{\mathrm{req}}$ would correspondingly increase the operating range to lower separatrix density, which would, for example be advantageous in increasing current drive efficiencies.

5.1. Required radiation fraction

5.1.1 Extended 2-point model

The extended 2-point model can be used to relate upstream to target parameters [26,27]. To assess the ability to access detachment pressure losses along field lines are neglected. Assuming equal electron and ion temperatures and conductive transport only the heat flux at the target is [27],

$$q_{||,\mathrm{t}} = \left(1 - f_{\mathrm{rad,div}}\right) \frac{B_{\mathrm{tot,t}}}{B_{\mathrm{tot,u}}} q_{||,\mathrm{u}} \approx \left(1 - f_{\mathrm{rad,div}}\right) \frac{R_{\mathrm{u}}}{R_{\mathrm{t}}} q_{||,\mathrm{u}} \quad . \tag{1}$$

For the investigated configurations the error introduced by approximating the ratios of the total magnetic fields with the inverse of the major radii is lower than 1%. The heat flux at the target can, therefore, be reduced by increasing the target radius R_{t}. The tolerable residual power fraction $P_{\mathrm{res}}^{\mathrm{tol}} \propto 1 - f_{\mathrm{rad,div}}^{\mathrm{req}}$ to reduce the heat flux below $q_{||,\mathrm{t}}^{\mathrm{max}}$, therefore, increases with R_{t}. Among the assessed configuration only the SXD promises a significant advantage with R_{t} of the outer divertor and the corresponding $P_{\mathrm{res}}^{\mathrm{tol}}$ increasing by ~30% with respect to the SND, Table 3. However, since the DND configuration deviates power from an inner to an outer target the corresponding R_{t} and $P_{\mathrm{res}}^{\mathrm{tol}}$ increase by 28% with respect to the inner target of the SND.

An increase in connection length only helps to cool the divertor to tolerable electron temperatures. With [27],

$$T_{\mathrm{e,t}} \propto \left(1 - f_{\mathrm{rad,div}}\right)^2 / \left(L_{\parallel}^{4/7} R_{\mathrm{t}}^2\right) \quad , \tag{2}$$

the residual tolerable power fraction $1 - f_{\mathrm{rad,div}}^{\mathrm{req}}$ to cool the divertor below $T_{\mathrm{e,t}}^{\mathrm{max}}$ scales as $\propto L_{\parallel}^{2/7} R_{\mathrm{t}}$. The tolerable residual power of the SXD should, thereby increase by more than 50% over the SND with the advantages of the SFDs only being slightly lower, Table 3. The advantage of the DND is severely decreased as $L_{\parallel}$ to an outer target of the DND is much shorter than to an inner target of the SND.

TABLE 3. Extended 2-point model predictions for the residual power in alternative configurations for tolerable conditions at the outer target compared to the SND. The fraction of P_{sep} exhausted in the outer divertor is assumed to be independent of the divertor configuration.

		XD	SXD	SFD(+)	SFD(-)[1]	DND
$P_{\mathrm{res}}^{\mathrm{tol}}/P_{\mathrm{res}}^{\mathrm{tol,SND}}$ for $q_{||,\mathrm{t}} \le q_{||,\mathrm{t}}^{\mathrm{max}}$	$R_{\mathrm{t}}/R_{\mathrm{t}}^{\mathrm{SND}}$	0.91	1.30	1.07	0.81	0.98
$P_{\mathrm{res}}^{\mathrm{tol}}/P_{\mathrm{res}}^{\mathrm{tol,SND}}$ for $T_{\mathrm{e,t}} \le T_{\mathrm{e,t}}^{\mathrm{max}}$	$\left(L_{\parallel}^{2/7} R_{\mathrm{t}}\right)/\left({L_{\parallel}^{\mathrm{SND}}}^{2/7} R_{\mathrm{t}}^{\mathrm{SND}}\right)$	1.09	1.53	1.43	1.45	0.93

Changes in the divertor configuration may affect the in-out power sharing. Recent power sharing measurements in attached TCV plasmas with various divertor configurations [28] are qualitatively consistent with a power sharing arising from the simultaneous application of the 2-point model to inner and outer divertor [29], which predicts,

$$\frac{P_{\mathrm{in}}}{P_{\mathrm{out}}} = \frac{\mathcal{L}_{\parallel,\mathrm{out}}}{\mathcal{L}_{\parallel,\mathrm{in}}} \quad , \tag{3}$$

where $\mathcal{L}_{\parallel} \equiv \int_{\mathrm{upstream}}^{\mathrm{target}} R_0/R(s)\, ds$ is a weighted connection length. Considering the changes in the power sharing due to the changes in the divertor configuration in the predictions for $P_{\mathrm{res}}^{\mathrm{tol}}$ is advantageous for all outer targets, albeit at the expense of the inner targets, Table 4. The redistribution of the challenge from the outer to the inner divertor is particularly large for XD and SFD(-) configuration and the smallest for the SFD(+). As the inner divertor in the SND usually represents the smaller challenge some redistribution may be acceptable or even desirable, e.g. to detach the inner and outer divertors at the same time.

TABLE 4. Extended 2-point model predictions with variable power sharing for the residual power in alternative configurations for tolerable conditions at the inner and outer targets compared to the SND.

	XD		SXD		SFD(+)		SFD(-)[1]		DND	
	in	out	in	out	in	out	in	out	top	bot
$P_{\mathrm{res}}^{\mathrm{tol}}/P_{\mathrm{res}}^{\mathrm{tol,SND}}$ for $q_{||,\mathrm{t}} \le q_{||,\mathrm{t}}^{\mathrm{max}}$	0.64	1.14	0.76	1.54	0.84	1.16	0.58	1.26	0.88	1.29
$P_{\mathrm{res}}^{\mathrm{tol}}/P_{\mathrm{res}}^{\mathrm{tol,SND}}$ for $T_{\mathrm{e,t}} \le T_{\mathrm{e,t}}^{\mathrm{max}}$	0.66	1.37	0.79	1.80	1.05	1.55	0.68	2.25	0.71	1.22

[1] The SFD(-) has a X-point separation of $dR_{\mathrm{u,X2}}$=1 mm.

5.1.2 *2D fluid models*

A systematic study of the alternative configurations and the SND reference is carried out using the divertor transport codes TECXY and SOLEDGE2D-Eirene. These codes use ad-hoc cross-field diffusivities $D_{\perp,\mathrm{e/i}}$ = 0.42 m^2/s and $\chi_{\perp,\mathrm{e/i}}$ = 0.18 m^2/s, which were chosen to result in an upstream SOL width of approximately 3 mm for the single-null configuration and in attached conditions. This is significantly larger than the expected value (see Section 2) resulting in optimistic absolute numbers. The interpretation of the simulation will thus continue to focus on the relative performance with respect to the reference scenario.

Since simulations of DEMO-size configurations with medium-Z impurity, such as argon (Ar) are computationally expensive, the power crossing the separatrix is reduced with respect to the nominal value as a proxy for an increasing radiation fraction, $P_{\mathrm{sep}}^{\mathrm{sim}} = \left(1 - f_{\mathrm{rad,div}}\right) P_{\mathrm{sep}}$. All scans are performed with a fixed separatrix density (at the stagnation point), $n_{\mathrm{e,sep}}$ = 2.5x10^{19}m^{-3}, corresponding to ~30% of $\langle n_{\mathrm{e}} \rangle$ of the reference scenario, Section 2.

In most cases the requirement on $T_{\mathrm{e,t}}$ is found to be more severe than the requirement on $q_{\perp,\mathrm{t}}$. Since $q_{\perp,\mathrm{t}}$ depends strongly on γ_{t}, this may change if the constraint on γ_{t} turned out to be overly optimistic. The ability to meet either requirement is, therefore, discussed separately.

5.1.2.1 TECXY

The TECXY code [30] can treat diverted geometries with a single X-point and was recently extended to include the private flux region in the computational domain. The code simplifies the target geometry by assuming a perpendicular incidence of the flux surfaces. It also uses an analytic model for neutral particles. The perpendicular heat flux at the target is deduced from the grazing angle of the field line and the calculated parallel heat flux, $q_{\perp,\mathrm{t}} = q_{||,\mathrm{t}}^{\mathrm{TECXY}} \tan \gamma_{\mathrm{t}}$. The model enhances the 2-point model by coupling flux tubes and assuming realistic spatial gradients and connection lengths. The TECXY simulations, thereby, add the effect of the divertor geometry on the competition between parallel and perpendicular transport. Its applicability is limited once the interaction with neutrals becomes significant. It is applied to the SND, XD and SXD configurations described in Section 3.1 and 3.2. In addition, it is applied to a SFD(+) with a somewhat larger separation of the X-points than the SFD configuration described in Section 3.2, limiting the extent of the considered PFR to the region between primary and secondary X-point.

The TECXY code has been used to vary the power crossing the separatrix. For the nominal value of P_{sep}=150 MW, and without impurity seeding, the peak target temperatures and heat fluxes are not tolerable for all configurations. Reducing P_{sep} reduces $q_{\perp,\mathrm{t}}$, Fig. 5(a,b), and $T_{\mathrm{e,t}}$, Fig. 6(a,b), at both targets. Linear interpolation and in some cases extrapolation yields estimates of $P_{\mathrm{sep}}^{\mathrm{tol}}$ for both requirements.

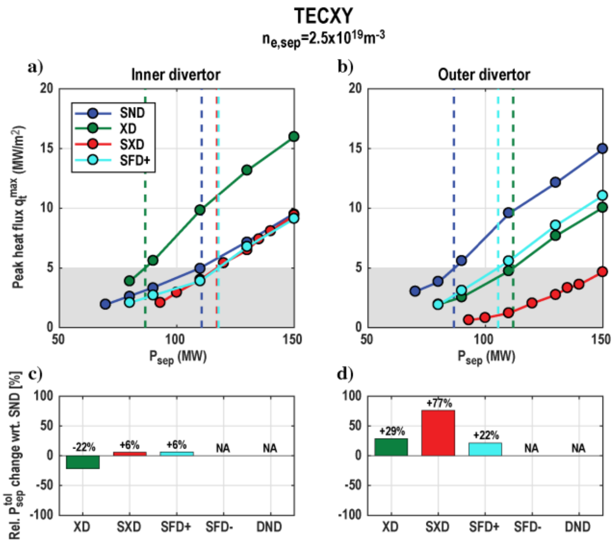

Figure 5. *(a,b) Peak heat flux onto the targets $q_{\perp,t}$ resulting from TECXY calculations of pure deuterium and varying the power that crosses the separatrix in various configurations. The shaded regions indicate acceptable $q_{\perp,t}$ and the dashed line the interpolated tolerable P_{sep}. (c,d) Relative change of P_{sep}^{tol} with respect to the SND configuration.*

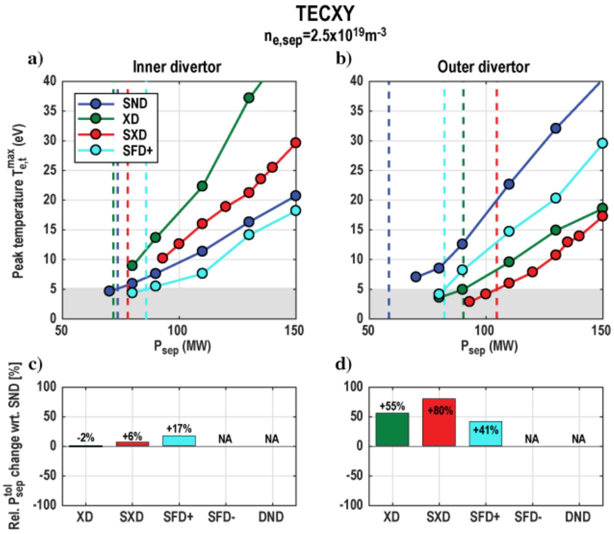

Figure 6. *(a,b) Peak electron temperatures at the targets* $T_{e,t}$ *resulting from TECXY calculations of pure deuterium and varying the power that crosses the separatrix in various configurations. The shaded regions indicate acceptable* $T_{e,t}$ *and the dashed line the interpolated (and in some cases extrapolated) tolerable* P_{sep}*. (c,d) Relative change of* P_{sep}^{tol} *with respect to the SND configuration.*

As expected from the 2-point model, Sect. 4.1, all alternative configurations increase $P_{\mathrm{sep}}^{\mathrm{tol}}$ at the outer target for both criteria with the increase being largest for the SXD, Figs. 5(d) and 6(d). The expected decreases of $P_{\mathrm{sep}}^{\mathrm{tol}}$ at the inner target, however, only persists for the XD configuration. As expected the SFD leads to the largest $P_{\mathrm{sep}}^{\mathrm{tol}}$ at the inner target, Figs. 5(c) and 6(c). The beneficial effects of all alternatives are greater for the requirement on $T_{\mathrm{e,t}}$ than for the requirement on $q_{\perp,\mathrm{t}}$.

According to the TECXY simulations the SXD configuration yields a larger beneficial effect for the outer target than XD and SFD(+), while the SFD(+) promises beneficial effects for both targets.

5.1.2.2 SOLEDGE2D

Experiments and modelling have shown that the poloidal tilt of the target has a large effect on the detachment dynamics including the onset of detachment. This is caused by the reflection of recycling neutral into the SOL and the trapping of neutrals near the target. The realism of the simulation is, therefore, improved with the SOLEDGE2D code [31], which includes the target tilt and a kinetic treatment of neutrals through coupling with EIRENE [32]. In addition to the improved treatment of neutrals SOLEDGE2D can also simulate divertors with multiple X-points including SFD-plus, SFD-minus and DND configurations.

The SOLEDGE2D-Eirene code has been used to vary the power crossing the separatrix [33]. As in the TECXY simulations reducing P_{sep} generally reduces $q_{\perp,\mathrm{t}}$, Fig. 7(a,b), and $T_{\mathrm{e,t}}$, Fig. 8(a,b), at both targets.

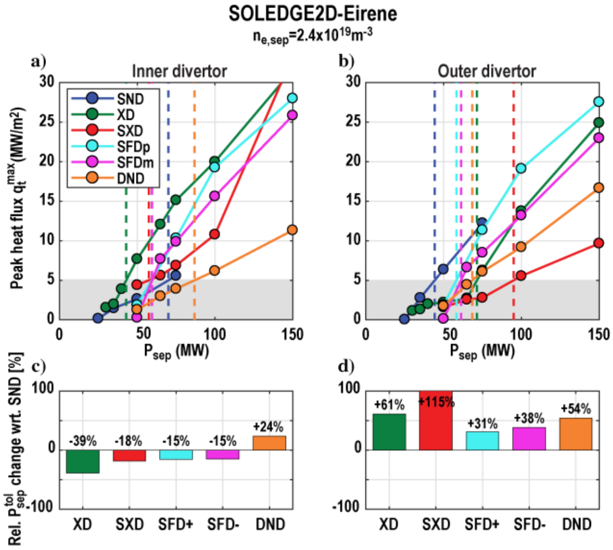

Figure 7. *(a,b) Peak heat flux onto the targets $q_{\perp,t}$ resulting from SOLEDGE2D calculations of pure deuterium and varying the power that crosses the separatrix in various configurations. The shaded regions indicate acceptable $q_{\perp,t}$ and the dashed line the interpolated tolerable P_{sep}. (c,d) Relative change of P_{sep}^{tol} with respect to the SND configuration.*

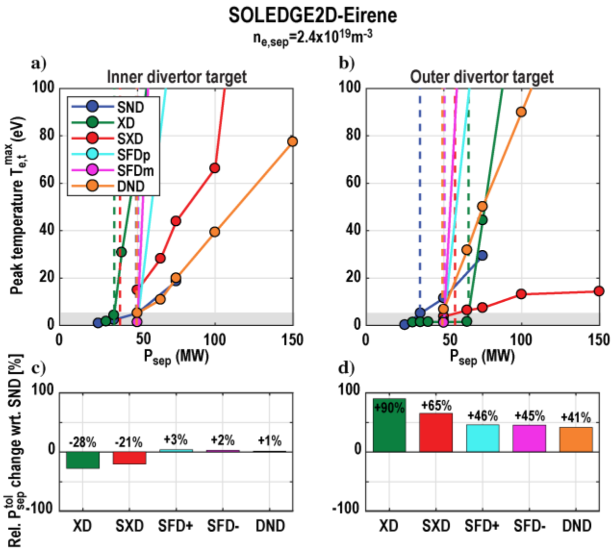

Figure 8. *(a,b) Peak electron temperatures at the targets $T_{e,t}$ resulting from SOLEDGE2D calculations of pure deuterium and varying the power that crosses the separatrix in various configurations. The shaded region indicates acceptable $T_{e,t}$ and the dashed line the interpolated (and in some cases extrapolated) tolerable P_{sep}. (c,d) Relative change of P_{sep}^{tol} with respect to the SND configuration.*

All alternative configurations increase $P_{\mathrm{sep}}^{\mathrm{tol}}$ at the outer target, Figs. 7(d) and 8(d). Absolute values, however, differ significantly from the TECXY predictions, Section 4.2.1. In particular, the in-out asymmetry in XD, SXD and SFD+ is stronger. The SFD- shows similar performance to the SFD+. The DND is predicted to have advantageous performance of the outer target and no repercussions for the inner target that becomes a second outer target.

5.1.3 Comparison of the models

The relative changes of the estimates for the tolerable residual power, which is used as a proxy for the required radiation fraction, obtained from various physics models discussed in Sections 4.1.1 and 4.1.2 are summarised in Fig. 9. The considered physics models increase in complexity with the SOLEDGE2D-Eirene representing the most complete set of effects. There is a general trend towards increasing the tolerable residual power by up to a factor of two, albeit in the cases of XD and SXD at the expense of the conditions at the inner target, presumably due to changes in the in-out power sharing. The beneficial effect of all alternative configurations except for the DND on the temperature is larger than the effect on the peak heat flux, presumably due to longer connection lengths. However, each additional effect can, to a somewhat lesser degree, still modify the advantage or disadvantage.

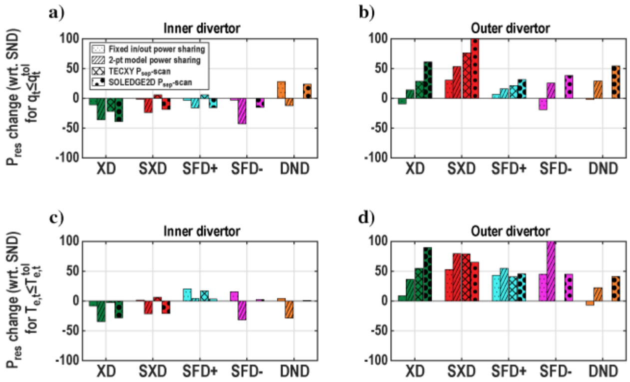

Figure 9. *Comparison of the tolerable residual power for acceptable target heat flux (a,b) and target electron temperature (c,d) in alternative configurations with the SND configurations using physics models of increasing complexity.*

As the required divertor radiation fraction $f_{\mathrm{rad,div}}^{\mathrm{req}}$ is high, a large relative increase of $P_{\mathrm{res}}^{\mathrm{tol}}$ is needed for a significant reduction of the required divertor radiation $P_{\mathrm{rad,div}}^{\mathrm{req}}$ as,

$$\frac{\Delta P_{\mathrm{rad}}^{\mathrm{req}}}{P_{\mathrm{rad}}^{\mathrm{req}}} = -\frac{1-f_{\mathrm{rad,div}}^{\mathrm{req}}}{f_{\mathrm{rad,div}}^{\mathrm{req}}} \frac{\Delta P_{\mathrm{res}}^{\mathrm{tol}}}{P_{\mathrm{res}}^{\mathrm{tol}}} \quad . \tag{4}$$

With $f_{\mathrm{rad,div}}^{\mathrm{req}}$ of the baseline scenario expected to be as high as 90% (as discussed in Section 2) an increase of $P_{\mathrm{res}}^{\mathrm{tol}}$ by a factor of 2, decreases $P_{\mathrm{rad,div}}^{\mathrm{req}}$ according to Eq. (4) by only ~10%. The improved exhaust performance expected from the physics effects discussed so far is, therefore, likely not sufficient to justify the increased costs. Alternative configurations must, therefore, be largely based on their ability to increase the divertor radiation without detrimental effects on core performance.

5.2. Required impurity concentration

The TECXY code has also been used to simulate Ar seeding. The calculations are carried out for the nominal separatrix density, $n_{\mathrm{e,sep}}$ = 2.5x10^{19}m^{-3}, and power crossing the LCFS, P_{sep}=150 MW. Increasing the seeding rate increases the impurity concentration as well as the divertor radiation and reduces $q_{\perp,\mathrm{t}}$, Fig. 10(a,b), and $T_{\mathrm{e,t}}$, Fig. 10(c,d), at both targets. The simulations are stopped when the electron temperature at the target decrease below 3 eV, where the physics model of the code is no longer applicable. In the case of the SXD, which has the lowest target temperatures without seeding, Section 5.1.2.1, this happens already for negligible seeding rates.

The effective charge of the plasma at the separatrix, $Z_{\mathrm{eff,sep}}$, is used as a measure for the detrimental effect on the core performance. Both simulated alternatives, XD and SFD+, require a lower $Z_{\mathrm{eff,sep}}$ to obtain tolerable conditions at the outer target, Fig.10(c,d). The calculations for the SND fail well before tolerable conditions are reached and no credible estimated of $Z_{\mathrm{eff,sep}}^{\mathrm{req}}$ can be obtained. The better performance of the outer divertor of XD and SFD compared to the SND is nevertheless qualitative consistent and, hence, expected from the discussion of $P_{\mathrm{res}}^{\mathrm{tol}}$, Section 5.1. At the inner target the SFD+ performs similarly to the SND, whereas the simulations of the XD result in a higher $Z_{\mathrm{eff,sep}}^{\mathrm{req}}$, Fig.10(a,b), again consistent with the discussion of $P_{\mathrm{res}}^{\mathrm{tol}}$, Section 5.1, and understood as a consequence of the redistribution of exhaust power from the outer to the inner divertor.

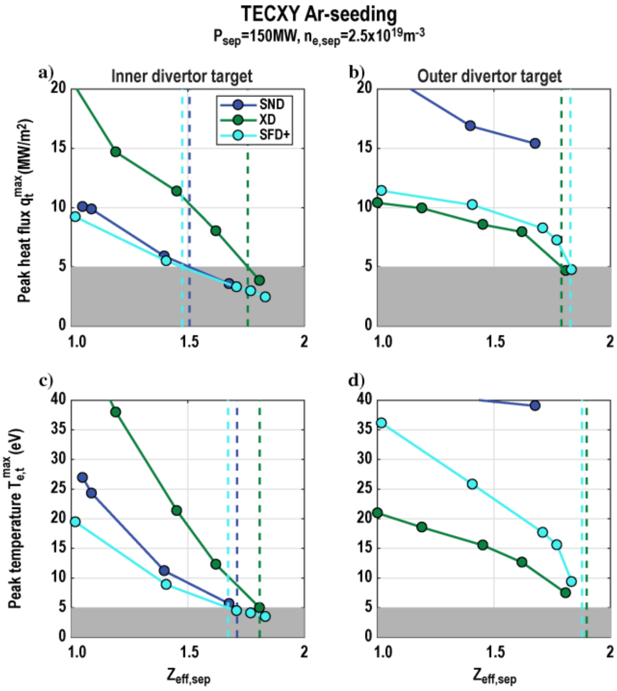

Figure 10. *(a,b) Peak heat flux onto the targets* $q_{\perp,t}$ *and (c,d) peak electron temperatures at the targets* $T_{e,t}$ *resulting from TECXY calculations of Ar seeding in various configurations. The shaded regions indicate acceptable* $q_{\perp,t}$ *and* $T_{e,t}$ *and the dashed line the interpolated tolerable* $Z_{eff,sep}$.

In addition to decreasing the required radiation fraction better divertor performance would also be obtained by increasing the divertor radiation for the same impurity concentration. The simulations yield that XD and SFD+, both achieve the same $P_{\mathrm{rad,div}}$ at a lower $Z_{\mathrm{eff,sep}}$, Fig. 11. To radiate 60 MW outside the LCFS, TECXY predicts that the XD and SFD+ require a ~20% lower $Z_{\mathrm{eff,sep}}$ than the SND. A more consequential comparison will, however, require the extension of the SND calculations towards acceptable conditions at both targets.

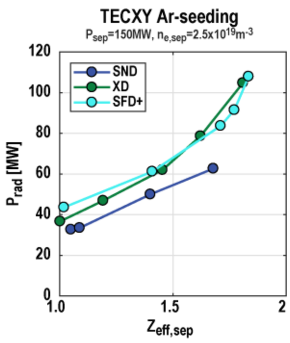

Figure 11. *Predicted dependence of the radiated power on the effective charge number at the separatrix.*

5.3. Outstanding issues and next steps

The divertor simulations have, to date, only been able to partially evaluate the proposed figures of merit. In particular a complete analysis of $f_{\mathrm{rad,div}}^{\mathrm{req}}$ and increasing $P_{\mathrm{rad,div}}$ to address the figure of merit (2) is still outstanding. The simulations have also not yet addressed the width of the detachment window, which characterises the ability of an exhaust solution to handle transients and which is expected to be a key advantage of the XD and SXD configuration. The assessment must, finally, also address the coupling of the radiative divertor to the core.

One of the main outstanding elements in the assessment remains the inclusion of predictive models for the cross-field transport. While the inclusion of drifts is, in principle, possible and faces mainly numerical challenges, the physics basis of the turbulent cross-field transport remains to be established.

6. CONCLUSION

Obtaining tolerable conditions at the divertor targets in DEMO will require a higher fraction of power that is dissipated in the divertor volume as well as a greater pressure drop along magnetic field lines in the SOL than necessary in today's devices. Since it is not certain that the required high radiative power exhaust is compatible with the simultaneously required core performance, alternative magnetic configurations to the conventional single-null divertor are assessed. The assessment is limited to alternative divertor concepts that rely on the same technologies and are compatible with the same core scenario envisaged for the current baseline DEMO.

DEMO configurations with XD, SXD, SFD and DND plasma exhaust solutions that rely exclusively on PF coils outside the TF coils have been developed. The PF coils meet constraints on forces, current densities and magnetic fields that are compatible with existing technologies. The main encountered limitations are that XD and SXD features can only be applied to the outer divertor. In addition, the flux flaring at the outer target of the XD is limited by the minimum grazing angle of field lines at the target and the major radius of the outer target of the SXD by coil forces. SFD and DND can be fully implemented, but may be affected by control limitations. A possible reduction of the flux swing can be largely eliminated by a greater segmentation of the CS. Capital cost drivers are larger TF coils in the case of the SXD, with approximately 15% higher TF coil costs than the SND baseline, and larger PF coils in the case of SXD and SFD, with approximately 50% higher PF coil costs. In addition, alternative configurations will complicate the remote maintenance of the divertor cassettes and blanket modules, but a quantification of the complexity increases in terms of cost increases remains to be established.

Performance improvements are expected with regard to a lower divertor radiation fraction required to obtain acceptable conditions at the target, $f_{\mathrm{rad,div}}^{\mathrm{req}}$, and a higher radiation fraction achieved with the same impurity concentration. All alternative configurations reduce the radiation fraction required for acceptable conditions at the outer target, but XD and SXD achieve this partially on the expense of less favourable conditions at the inner target. However, the overall high values of $f_{\mathrm{rad,div}}^{\mathrm{req}}$ entail that the expected increases of the tolerable residual power of up to a factor of two only translate into modes reductions of $f_{\mathrm{rad,div}}^{\mathrm{req}}$ of the order of 10%. The main advantage of alternative configurations must therefore be their ability to increase the divertor radiation without degrading core performance. First fluid simulations of Ar seeding in a subset of the assessed configurations indicate advantages of the XD and SFD configurations to radiate more power at the same impurity concentration. A quantitative comparison requires further optimization of the target geometry including baffling as well as the inclusion of an improved and self-consistent model for turbulent transport.

The assessment has, to date, only addressed the lowest order engineering constraints and most main physics aspects. It has not encountered any show stoppers, but identifies key limitations of XD and SXD. Within these limitations it nevertheless confirms advantageous exhaust performance of all assessed alternative configurations. A quantitative cost-benefit calculation, however, requires a more detailed engineering analysis and further physics model development and validation.

ACKNOWLEDGEMENTS

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