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Abstract

A comparison between different alternative divertor configurations, in terms of benefits and additional complexity is carried out for the European DEMO. A synergetic approach between different aspects of the problem, including physics and engineering, provides new insight on the capabilities of the new divertors to handle the exhausted power without compromising performance or machine design. Five different configurations are examined and compared with the baseline single null. It is found that the X-divertor and the Super-X provide some margin in terms of physics, tied with their longer connection length. For example, for the same amount of impurity concentration, these two configurations allow an upstream separatrix density 50% lower than the single null. Double null and Snowflaxe minus configurations, on the other hand, did not show significant improvement with respect to the single null. Engineering difficulties, however, make the applicability of the alternative configurations difficult for reactors. Improvements in the toroidal field coil design can be achieved with more D-shaped designs and with more rigid intercoil structures. Active control of plasma displacements requires unacceptable levels of power if performed with only external coils but become manageable if internal coils are employed. Neutronics studies do not show major differences between the different configurations. Finally, a hybrid single null/super-X design is proposed as a compromise between the potentially improved physics and the engineering complexity.

INTRODUCTION

The uncertainties surrounding the physics of plasma exhaust and its centrality in reactor design require a thorough evaluation of promising alternatives as a precautionary measure to avoid delays in DEMO [1], if the ITER solution for the divertor [2] could not extrapolate to reactor relevant machines. With alternative configuration we define any divertor solution that cannot be qualified by ITER. As a risk mitigation strategy, EUROfusion has worked on understanding the physics and engineering of new exhaust configurations for reactor relevant devices and DEMO in particular [3,4]. The objective is to provide a physics and engineering assessment of the usefulness and feasibility of alternative divertor configurations for DEMO by December 2023. In this contribution, we review the physics and engineering work carried out within EUROfusion's work package DTT1/ADC on the subject, showing with a quantitative assessment that alternative configurations provide a larger operating space than the single null according to multifluid simulations (in particular, lower Argon seeding levels and core concentration; lower separatrix density for comparable divertor protection; greater resilience to high power operations), but also highlighting the many engineering challenges that these configurations entail.

The primary activity of this work was to deliver integrated results through a "loop" where physics and the engineering concepts for sufficiently well-developed alternative designs are synergistically iterated and optimized. This was done by using multiple approaches spanning from predictive physics simulations of the alternative divertor configurations (ADCs) to investigations of the structural response of the toroidal field coils, of the controllability of the plasma, of the pumping efficiency and of the neutronic irradiation, thus providing a comprehensive overview of the problem, see *Fig. 1*.

It is important to note that this was a preliminary comparative analysis. Preliminary because while the tools used were state of the art, a number of simplifications were taken to provide an answer within reasonable time – yet all the approximations were chosen making sure not to leave out dominant effects. Comparative because the emphasis was not on the absolute values given by the calculations but rather on the trends observed and the differences between a configuration and another. Here it is important to remark that we tried to make comparisons as fair as possible by enforcing standards and documenting all the analysis properly.

Five configurations were analysed and compared to the baseline single null divertor (SND) [1]. These were the double null divertor (DND), the X-divertor (XD) [5], the Super-X divertor (SXD) [6], the Snowflake divertor (SFD) [7]. In addition, also a hybrid SND/SXD solution was examined as a compromise between the two. It is important to note that these labels are not representative of an exact design or fixed constraints as what matters in ADCs are their features, which, if properly designed, could lead to benefits on the machine operations. Hence, we present here a specific incarnation of the configurations above, and therefore generalizations might be unwise (e.g. if one of *our* ADCs is bad, it does not mean that that ADC is bad if implemented with a different design).

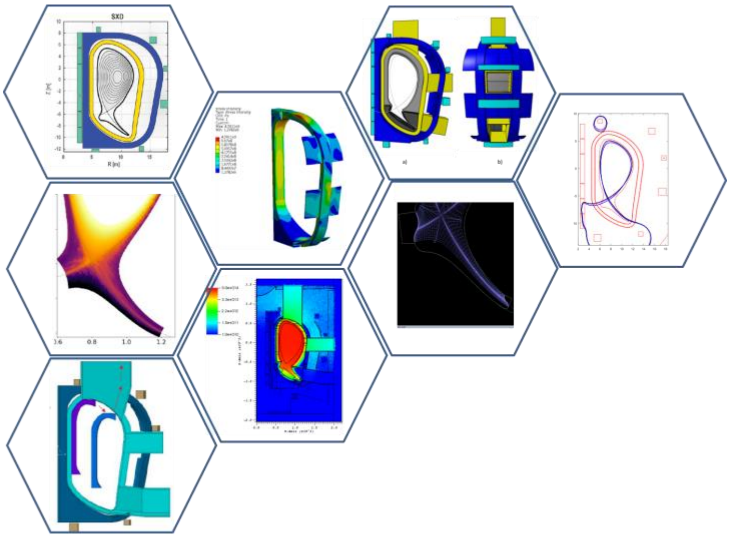

Fig. 1. Examples of the physics and engineering activities carried out in the WP-DTT1/ADC project.

1. CONSTRAINTS AND EQUILIBRIUM

The ADC solutions identified are constrained by a number of engineering requirements on the plasma geometry, on the forces on the coils and on the general layout of the machine. In particular, we fixed the plasma the current, I_p = 19.07MA, β_p = 1.141 and the internal inductance l_i = 0.8. At flat-top, we imposed, R ≅8.9m, A ≅ 3.1, k_{95} ≅ 1.65, δ_{95} ≅ 0.33, V_p ≅ 2466 m^3, which are the major radius, aspect ratio, elongation, triangularity, and plasma volume respectively. The poloidal field coil (PF) cross-sections was determined assuming a current density limit of 12.5MA/m^2. The magnetic field at the PF coils and central solenoid (CS) could not exceed 12.5 T. The maximum vertical force on a single PF could not exceed 450 MN and 300 MN on the CS stack, which was further constrained by a maximum separation force not exceeding 350 MN. In addition, in case of two or more PF coils positioned closer than 3m poloidally, the total vertical force from the PF coils on the supports could not exceed 450MN. The toroidal field (TF) coil cage consisted of 16 coils shaped to keep ripple below 0.6% without ferritic inserts. Finally, we assumed a minimum grazing angle at the divertor plates of 1.5 degrees.

In all the configurations discussed, these constraints are always satisfied using six PF coils external to the TF coil cage. With respect to the SND, a number of modifications were implemented. In particular, for the XD and SFD the bottom part of the TF coils was deformed to bring the divertor PF coils in specific positions to ensure flux expansion and a second order null, respectively; for the SXD the bottom outer part of the TF coil was stretched outward to allow for an outer strike point at large major radii; for the DND an up/down symmetrization of the coils was needed. An optimization was carried out to generate an equilibrium for each configuration with acceptable forces on the coils and satisfactory magnetic topology features (flux expansion, connection length, position of the outer strike point, or of the secondary X-point, depending on the configuration). Next the configuration was processed in order to generate a suitable TF coil, vacuum vessel and first wall, the latter compatible with the given impinging angle at the target, and intercoil structures. This also provided the electromagnetic loads on the coils, and a full structural analysis of the system was carried out with ANSYS. This procedure was iterative and required a few steps to converge to acceptable conditions. More details are available in [8].

2. PHYSICS OF THE ALTERNATIVE CONFIGURATIONS

From the physics point of view, the preliminary results presented in [3] were extended by using the SOLPS code, with initial results and the detailed numerical set up described in [4,9,10]. The simulations were organised in matrix scans, systematically performing hundreds of runs for each configuration, changing fuelling, seeding and power levels. In order to be able to carry out such a large investigation, a number of simplifications were necessary. No drift effects were present, the neutral model in the code used a fluid approximation and the argon impurities were bundled in three charge states (fully stripped, neutral and everything in between). While the neutral approach is justified by the large collisionality in the boundary plasma, its formulation does not include potentially important effects such as molecular reactions. For this reason, the value of our results resides in the possibility of comparing the configurations on the same ground and in the trends they reveal, rather than the absolute numbers they generate.

Operating spaces were identified by imposing constraints on the target loads and core physics: maximum heat load at the target smaller than 10MW/m^2, maximum temperature on the divertor targets smaller than 5eV, maximum Greenwald fraction at the separatrix smaller than 0.6, maximum separatrix Argon concentration less than 2%. With this approach, it was shown that configurations like the SXD or the XD provide a margin of roughly a factor two with respect to the SND, see *Fig. 2*. This means, for example, that in order to achieve acceptable divertor conditions and the same separatrix density, 50% less Argon concentration is needed in the SXD and XD than the SND. Alternatively, with the same Ar concentration, the two ADCs have n_{sep} 50% lower than the SND. Importantly, the results suggested that a higher power margin was possible at least for the SXD, as acceptable divertor conditions were obtained when doubling the power crossing the separatrix from 150MW to 300MW (this was not possible for the SND). These results are summarised in *Fig. 3* and are attributed to the fact that the ADCs have longer outer connection lengths, allowing for a more efficient use of Ar as a radiator. The longer connection length, indeed, increases the value of the upstream temperature and pressure (for a constant density), which in turn reduces the amount of Ar required for a given energy density flux drop (see the Langyel model described in [11] for generic applications and in [10] for the specific ADC ones).

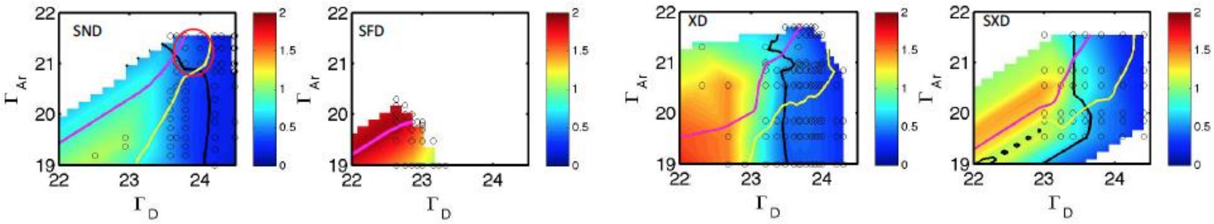

Fig. 2. Comparison of the operating space in the seeding, Γ_{Ar}, and fueling, Γ_D, space (axes in log10 scale, expressed in particles per second). The colorplots represent the He concentration (in %), the small circles individual simulations and the curves the operational space boundary (black is the temperature/heat flux limit, yellow the Greenwald fraction and purple the separatrix Ar concentration). The red circle approximately shows the operating space for the SND for reference.

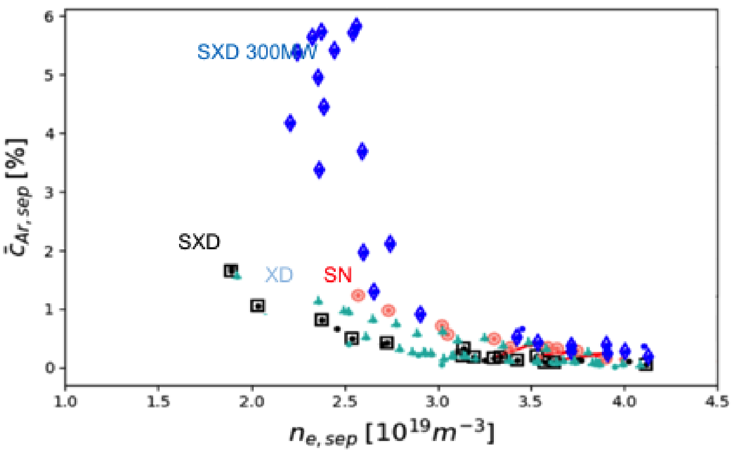

Fig. 3. Comparison of the SND, SXD (both at the nominal 150MW and at 300MW) and XD configurations in their respective operating spaces (each point represents a simulation with different Γ_{Ar} and Γ_D, the 300MW case goes to $c_{Ar,sep}$>2% only for clarity). The horizontal and vertical axes represent the separatrix density and the separatrix argon concentration.

Snowflake simulations were carried out in the SFD minus configuration, in which the secondary X-point is located at the low field side in the main SOL. A concern is that the loads in the SFD minus are sensitive to variations of the position of the secondary strike point. Indeed, no acceptable solution could be found at P_{SOL}=150MW for upstream separations of δr_{sep}=1mm and δr_{sep}=10mm. In both cases, the target temperature peaked at several hundreds of eV and the problematic strike point moved from SP4 to SP1-SP2 (the strike points are counted counter-clockwise, with SP1 the innermost and SP4 the outermost) as the separation increased. This suggests that the operating window for the SFD minus is relatively narrow and fine control of secondary X-point is mandatory. It is unclear, however, if the negative results were due to the moderate Argon seeding level of the simulations, as higher levels could not produce numerically stable runs (this, at the very least, shows that SFD simulations for DEMO scale devices are challenging). The problem of the controllability of the secondary X-point is potentially shared also by the DND which also relies on the good alignment of the separatrixes. In any case, the ideal connected DND configuration we investigated showed similar performance to the SND and a tendency to develop up/down asymmetries despite the absence of drifts. These asymmetries, present in low and intermediate Argon seeding levels, lead to a heat flux up to 50 times higher in the lower divertor than in the upper divertor. If this behaviour is confirmed in more sophisticated simulations, it might well reduce the benefits of the configuration.

One of the biggest uncertainties of associated with the multifluid calculations is the arbitrary choice of the perpendicular transport, which is imposed through constant diffusion coefficients in such a way that the upstream heat flux decay length is equal to 3mm. Turbulence simulations in 3D were carried out to gain insight on the effective transport in the ADCs, but it was necessary to reduce the scale of the device while maintaining the shape, in order to make the calculations numerically feasible. Preliminary results showed that filamentary structures are quite different in different ADC configurations, suggesting a strong effect of the geometry on their physics. Overall, longer connection length designs such as the SXD and XD displayed a broader target pressure profile as a result of this. However, the simulations had a simplified physics model, not including neutral or impurity physics. Perhaps more importantly, there was clear evidence of a poloidal variation of the transport mechanisms, with, for example, visibly elongated structures in the SXD outer divertor leg and convective cell formations at the X-point of the SFD [12].

The SOLPS calculations were also used as an input to pumping studies, which were carried out with the DIVGAS code [13], using a Monte Carlo technique to treat atomic and molecular dynamics in the private flux region and in the sub-divertor structures. Due to the uncertainties in the calculations of the input pressure, the value of the results obtained is only in the comparison between the configurations. It was observed that pumping of Helium can be problematic in all the configurations as, according to the calculation, the required extraction rate is beyond current technological capabilities. In general, the SXD performs better than the SND and the latter better than the XD, possibly because of the larger surface area and incoming particle flux. No SFD assessment was possible due to the fact that no converged SOLPS run in the operating space was identified.

3. ENGINEERING OF THE ALTERNATIVE CONFIGURATIONS

From the engineering point of view, structural calculations were performed with finite element methods and showed that typically, including ADC features comes at the cost of increasing stresses in the TF coils. All the configurations are generally more challenging than the baseline and present criticalities but, in some cases, these are comparable with those in the SND (at least the simplified version used in our analysis). A discussion of the stress concentrations and problematic areas observed in the TF coils of the configurations examined was presented in [4]. A more recent assessment was done on newly designed configurations which incorporate remote handling considerations and an improved port design. In general, stresses in the TF coils is caused by hoop forces due to the magnetic pressure and out of plane forces driven by the interaction of the poloidal currents flowing in the TF coils and the poloidal magnetic field generated by the PF coils (the two are not aligned and generate forces in the toroidal direction). The hoop stresses can be minimized by adopting a D-shape, which can be optimized to be bending free (only tension stresses). The out of plane forces can be counteracted by increasing the rigidity of the TF coil cage, for example reinforcing the intercoil structures.

As a consequence, a morphing procedure [14] was applied to gradually deform the existing ADC configurations towards a more D-shaped design. This led to an increase of the radial size of the TF coils, which took the PF coils further out. Additionally, the intercoil structures were strengthened by implementing a box design, which helped mitigating the effect of the out of plane forces. The combined effect of these solutions led to a visible reduction in the stress levels of both the SXD and SFD configuration, taking the former close to pass when a Von Mises yield criterion is applied. In *Fig. 4*, we show a comparison between the original and the improved designs. The maximum stress level is 500MPa and in the outer limb of the TF coil and 660MPa in the inner (with our color scale red areas are above 500MPa and are therefore problematic for the outer limb).

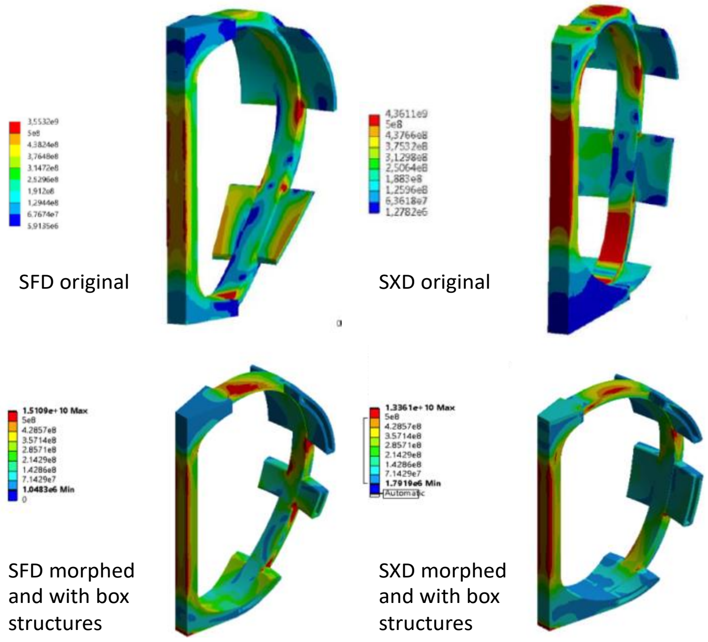

Fig. 4. Comparison between the stress maps of the original SXD and SFD designs (upper row) and after D-shape morphing and use of box intercoil structures. Note the different color scale for the lower limits. In the red areas the stress level is beyond the acceptable limits.

Control of the ADCs is particularly critical due to a number of factors. The first is that our preliminary designs were not optimized, and passive structures were rather far from the plasma, thus making them less stable. As a consequence, changes in the plasma equilibrium, induced by variations of the internal inductance, l_i, and β_{pol} of the order of 10%-15%, can lead to displacements of the plasma centroid and/or the separatrix of the order of 10-20cm, roughly an order of magnitude larger than the SND's. Also, ADC features typically lead to poloidal field coils farther away from the plasma, thus making control with only external coils very challenging. This conspires to generate power requests for the control system that are very large and often unacceptable. In particular, the start of ramp down phase is the most critical, with power requests for the control system of the order or larger than 1GW for all the ADCs and around 350MW for the SND. Active stabilization was designed with stringent and conservative constraints: 1) it employed only existing external coils (the four outermost); 2) the voltage required to return the plasma to its original state was assumed to be 10 times larger than the minimum voltage V_0 that can stop at $t \rightarrow \infty$ the vertical instability resulting from the assume displacement; 3) the displacement was instantaneous, and the control system started acting only when it reached its nominal value.

In order to mitigate the control problem three different solutions were investigated. Optimization of the PF coil position was carried out to reduce the distance between the plasma centroid and the magnetic axis (balancing); toroidally continuous stabilizing plates were introduced in the machine design; port compatible internal PF coils were introduced for vertical stabilization. The first two approaches led to moderate improvements in the maximum displacements. The SXD saw a reduction of the centroid displacement by almost a factor three (from 11cm to 4cm), while the improvement for the SFD and XD was more marginal and closer to a 40% reduction (e.g., from 14cm to 10cm for the SFD). On the other hand, small internal control coils could bring the power requests from hundreds of MW down to 10-20MW in the worst-case scenario (typically around 1-2MW), thus making control feasible. Of course, the presence of internal coils brings a number of engineering complexities that will have to be weighed in the overall machine integration and might not be possible. Note, however, that also for the SND the power requests without internal coils would be very large and of the order of several hundreds of MW in critical phases like the start of ramp down. Finally, an associated concern is that the potential benefits of some configurations rely on precise positioning of the secondary X-points (DND and SFD – ideal and minus), and if this cannot be continually and reliably ensured such benefits might be lost, as we have seen in the previous section.

Finally, a neutronics analysis performed on the SND, XD and SXD configurations was performed using the MCNP6 code and was reported in detail in [15]. We will therefore report here only the main results. First of all, in order to properly describe the neutronics loads, it was necessary to extend the machine design up to the bio-shield, as shown for the SXD in *Fig. 5*.

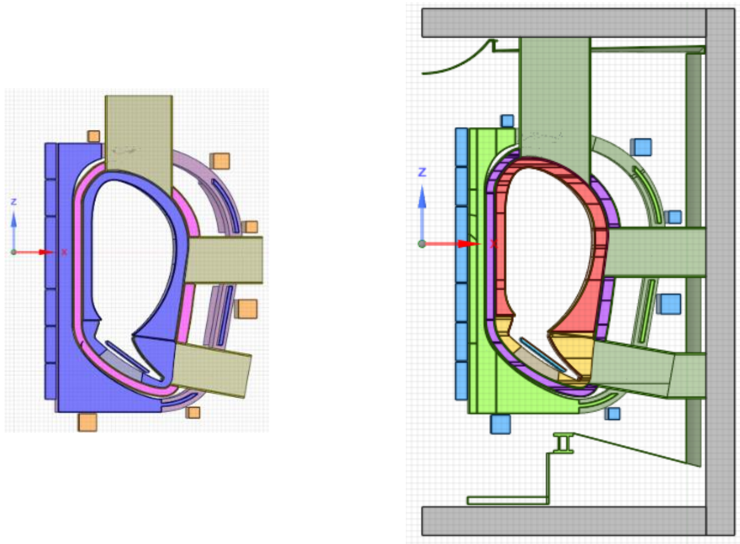

Fig. 5. Comparison between the original 3D build of the SXD and the extended one for neutronics studies (including the bio-shield and port extensions)

The results show that only relatively minor differences exist between the ADCs and the baseline SND and, importantly, that the tritium breeding ratio is basically unaffected by the different designs (1.15 for the SND and 1.13 for the SXD and XD). Damages to the structures, measured in displacements per atoms per full power year (DPA/FPY) and helium formation (which is a concern where re-wielding might occur) do not show particular criticalities in any of the configurations examined. It is worth noting that in our calculations both the baseline and the ADCs have an excessive nuclear heating in the TF coils, well above the limit imposed on the cryogenic superconducting coils. The SXD has a marginally better response close to the lower port due to the amount of material in the divertor region, but it still fails both at the midplane and near the upper port (the other configurations are concerning everywhere in the TF coil's outer limb. It is entirely possible that improved calculations with more refined models will show that the heating is within limits, so the value of the calculation is in the relative comparison between baseline and ADCs. At any rate, adjusting the port wall thickness or improving the shielding provided by the vacuum vessel might be beneficial.

4. HYBRID SND/SXD

Based on the experience with the standard ADCs investigated in the project, it was deemed useful to explore solutions with milder ADC features, in the hope to make their engineering compatible with the constraints, while still retaining beneficial physics mechanisms. It was therefore chosen to produce a hybrid SND/SXD configuration, shown in *Fig. 6*. The new configuration was designed to have a toroidal flux expansion exactly in between the SND and the SXD (Rt/Rx=1.3 for the hybrid while it was 1.45 for the SXD and 1.11 for the SND). This automatically changed and increased the poloidal flux expansion which is fx,t=3.13, compared with 2.4 for the SXD and 3.5 for the SND, so that the two effects compensated. The parallel connection length to the outer target is for the hybrid closer to the SXD than the SND (~155m instead of ~100m in the SND and ~175m for the SXD at 3mm from the separatrix), which is a positive aspect of this configuration.

Two new equilibria and associated engineering configurations were generated for the hybrid solution. One had standard vacuum vessel shaping with an additional passive stabilizing plate compatible with the breading blanket and the second had an optimized vacuum vessel following the curvature of the FW to bring passive structures closer to the plasma. Considering the challenging control issues experienced in the baseline and ADCs, both geometries have been equipped with 2 in vessel coils for active control purposes.

As shown in *Fig. 6*, the operating space of the hybrid is marginally smaller than the SXD but significantly larger than the SND. The fact that the Hybrid operating space is closer to the SXD than the SND might be a confirmation of the role of the connection length. In addition, the simulations show that the physics follows a continuum, and increasing $L_{//}$ does widen the margin. Finally, hybrid simulations were carried out with 300MW crossing the separatrix but no solution with acceptable divertor and core conditions was found (i.e. the operating space closed, like for the SND), although in some cases the simulations were close to pass.

The structural calculations, performed with the stress intensity criterion, still show problematic points in regions of the outer limb of the coil, which suggests that this preliminary design still requires improvements (a working point should exist assuming that the SND and the SXD have one). It is possible, for example, that moving the PF4 and PF6 outward would be beneficial as this could lead to more D-shaped profiles. The analysis of the power needed by the control system to return the plasma to its original position after displacements was done only for the case with internal coils, giving results aligned with the SND (10-20MW in the worst-case scenario of 15cm displacement in the start of ramp down phase and much smaller in all the other cases).

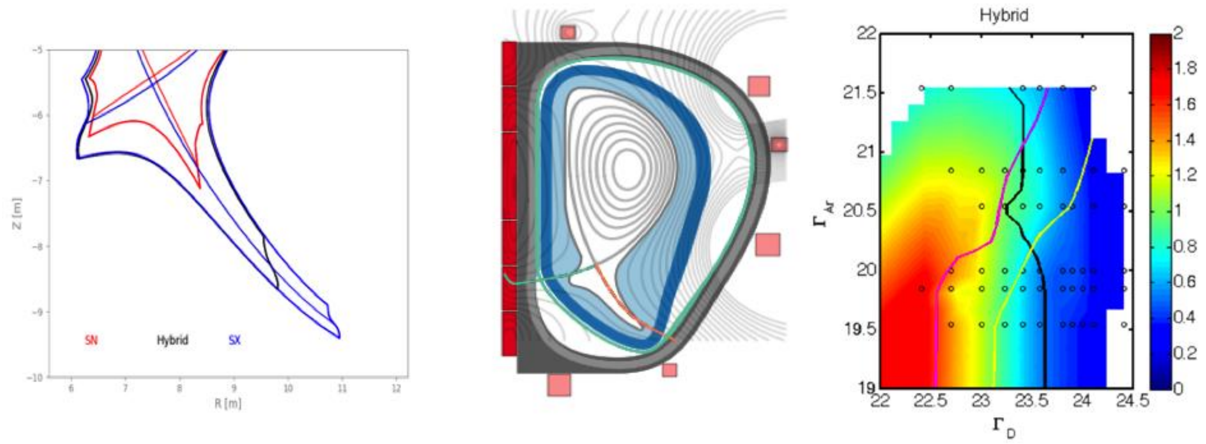

Fig. 6. (left) comparison between the SND, Hybrid and SXD divertor equilibria. (middle) Full hybrid 2D cross section. (right) Comparison between the SND, hybrid and SND operating space. The meaning of symbols and curves is the same as in Fig. 3.

5. CONCLUSIONS

The results reported here provide a comprehensive overview of the current knowledge of the physics and engineering of the alternative divertor configurations for reactor scale machines. The conclusions of this work are multifaceted. Our physics studies suggest potential benefits associated with longer outer connection length (XD and SXD). This would consist in an increased margin with respect to fluctuations in the plasma parameters (density, impurity concentration, power). However, configurations relying on a secondary X-point (DND and SFD ideal and minus) do not seem to perform better than the SND, at least at this stage of the analysis. The engineering of the ADCs is necessarily costlier than that of the baseline and it shares several of its criticalities, often in a more acute way. In particular, TF coil stresses and power requirements for control with external coils are systematically equal or higher than the baseline (in certain cases much higher). Other areas like the passive vertical stability, the neutronic irradiation and the tritium breeding ratio are nearly identical in all divertor configurations considered (including the baseline).

However, large uncertainties still surround the problem, despite the significant progress achieved in the last few years. Because of this, ensuring as much margin as possible in both the physics and engineering is important, so that potentially negative surprises could be mitigated, while maintaining an aggressive timeline for reactor design. Remaining as close as possible to solutions that we currently judge the most reliable is also probably sensible. This would imply designing solutions around the baseline, making relatively small changes that can provide more margin. In this category could fall the hybrid SND/SXD, but also attempts to maximize the poloidal flux expansion at the target (quasi-XD), potentially SFD plus designs if the secondary X-point can be sufficiently controllable. Obviously, not all these options are equally mature, and we have focused our attention only on the first.

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