An Assessment of Alternative Divertors for the European DEMO

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Introduction and Motivation

The scale of DEMO, in terms of size, power and complexity, poses unique challenges to exhaust physics. The large energy reservoir requires care in designing exhaust systems, especially in the presence of the large uncertainties that still remain in the physics and in the controllability of the transients. It is not clear the ITER solution will extrapolate to DEMO, hence building margin is essential.

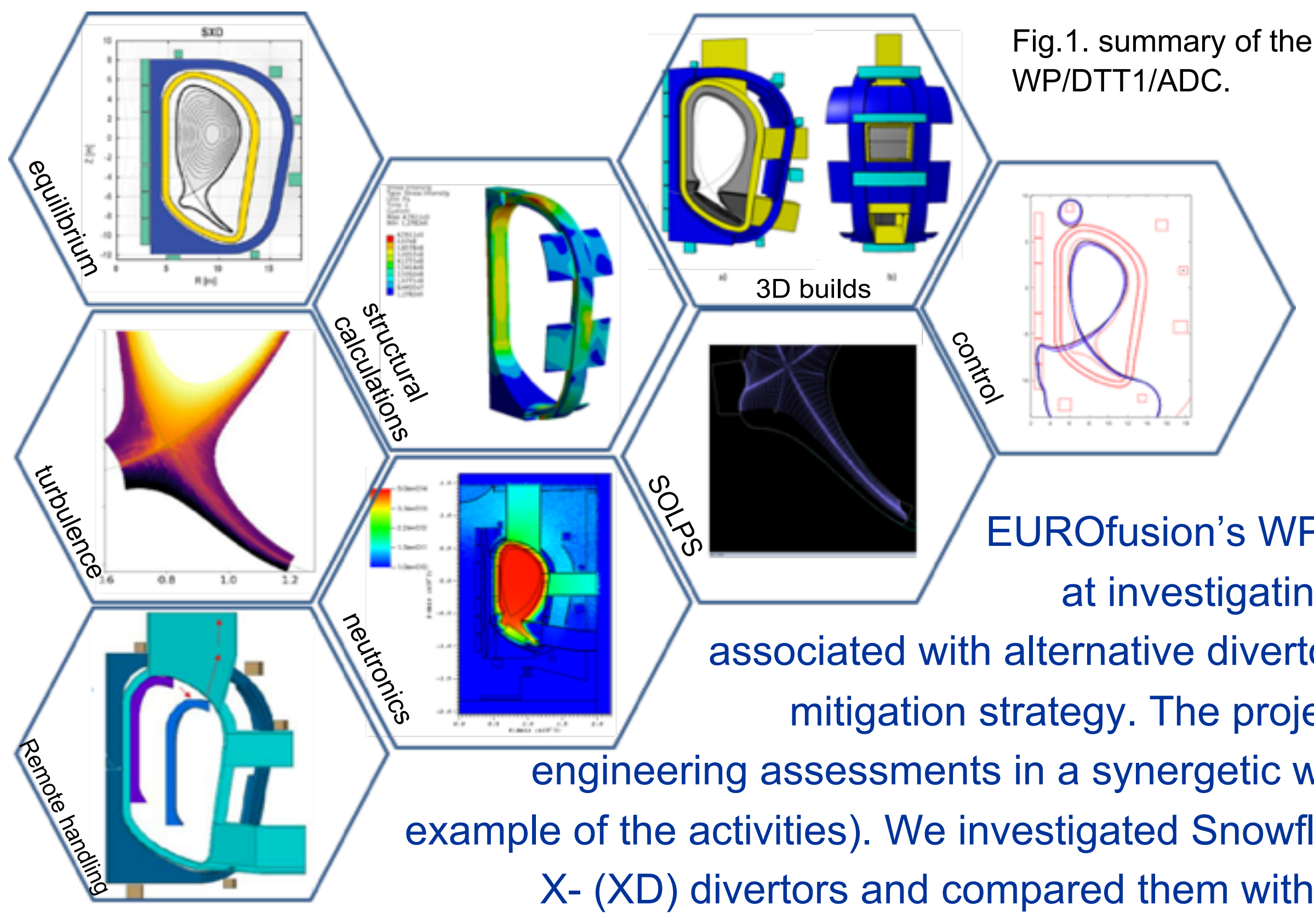


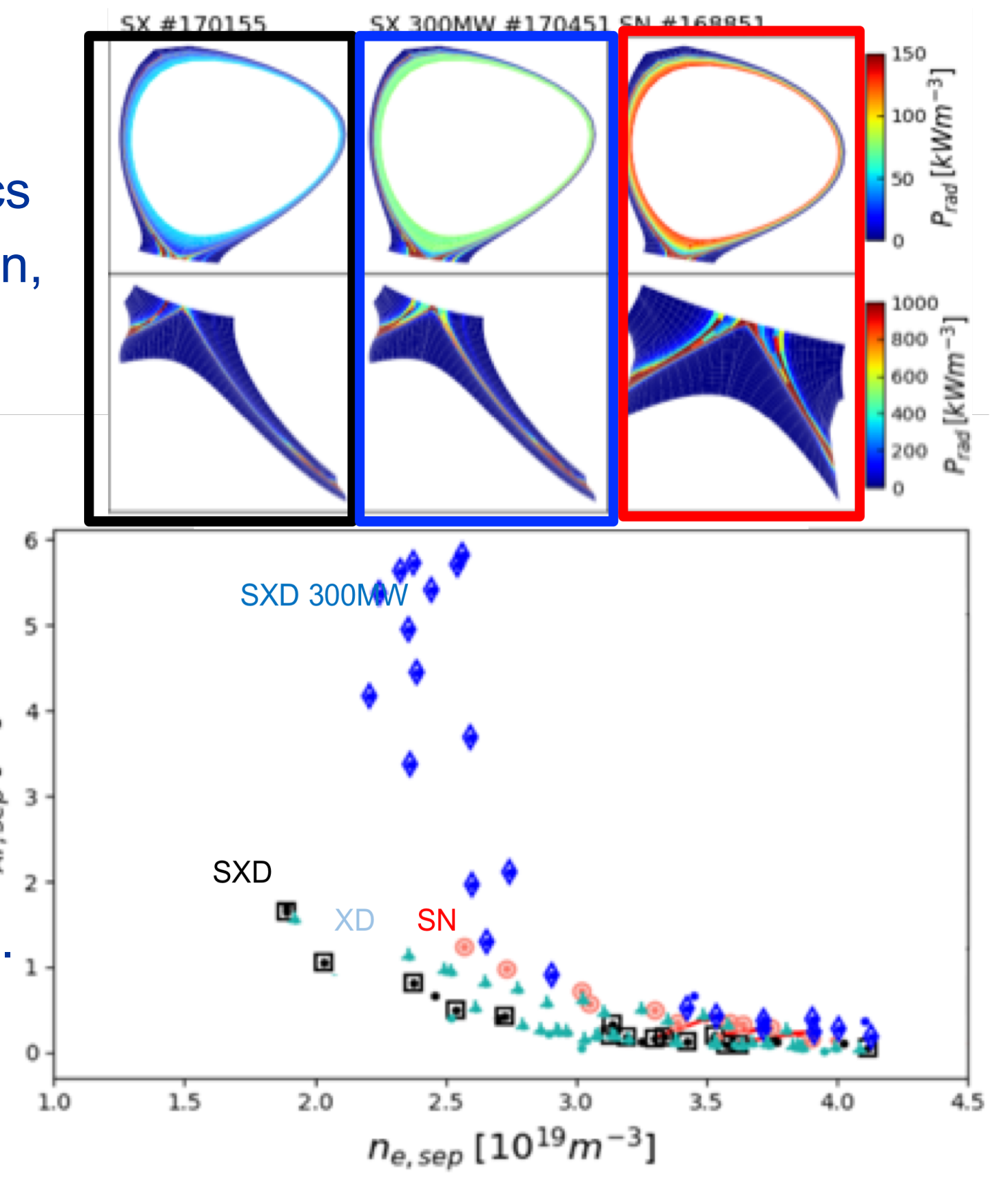
Fig.1. summary of the different activities carried out in WP/DTT1/ADC.

EUROfusion's WP/DTT1/ADC project was aimed at investigating the benefits and complexities associated with alternative divertor configurations, as a potential mitigation strategy. The project addressed both physics and engineering assessments in a synergetic way (see figure on the left for an example of the activities). We investigated Snowflake, (SFD) Super-X (SXD) and X- (XD) divertors and compared them with the baseline single null (SND).

Physics

All the configurations were studied with SOLPS-ITER in a controlled and standardized way. Large scans could only be done with fluid neutrals. We therefore lack molecular physics and a have a simplified treatment including bundling of Argon, lack of T and no drifts. We find that the XD and SXD have more margin than the SND, as they have acceptable core (Ar concentration < 1%, purple line, Greenwald fraction<0.6, yellow line) and target (T_t<5eV and P<10MW/m^2, black line) conditions for a wider range of fueling and seeding levels (x and y axes in Fig.2, in log scale and particle per second)

Fig.3. Line radiation patterns for different configurations and sepearatrix density as a function of the separatrix Ar concentration.



The reason for the increased performance is the better capability of long connection length configurations to radiate. The SND shows large radiation in the main SOL and core, while the SXD and XD require less Ar concentration:

$$c_z \propto \frac{q_{\parallel u}}{n_{eu}^2 L_{\parallel}}$$

From the Langyel model, required Ar concentration c_Z scales inversely with $L_{//}$

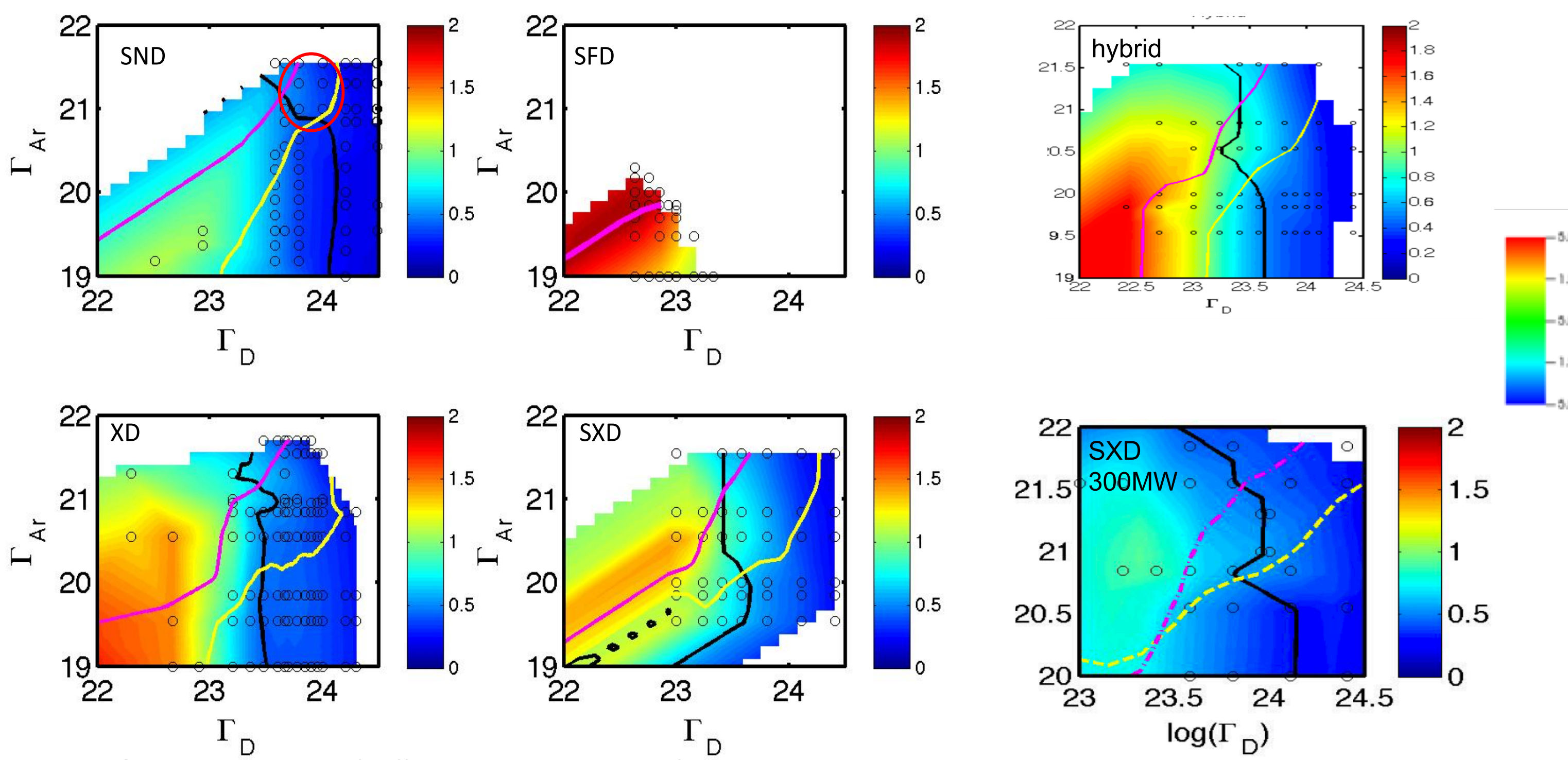


Fig.2. Operating space of different alternative configurations. The colourplot shows the He concentration at the separatrix in % (explanation of the other symbols is in the text). Each circle represents a different saturated simulation

Engineering

Structural calculations based on finite element calculations of stresses in the toroidal field coils were carried out. Both hoop and out of plane forces lead to excessive stresses, beyond the acceptable limits. New configurations closer to D-shape (morphing) and box intercoil structures to increase rigidity improve the designs of both the SFD and SXD (see Fig 4).

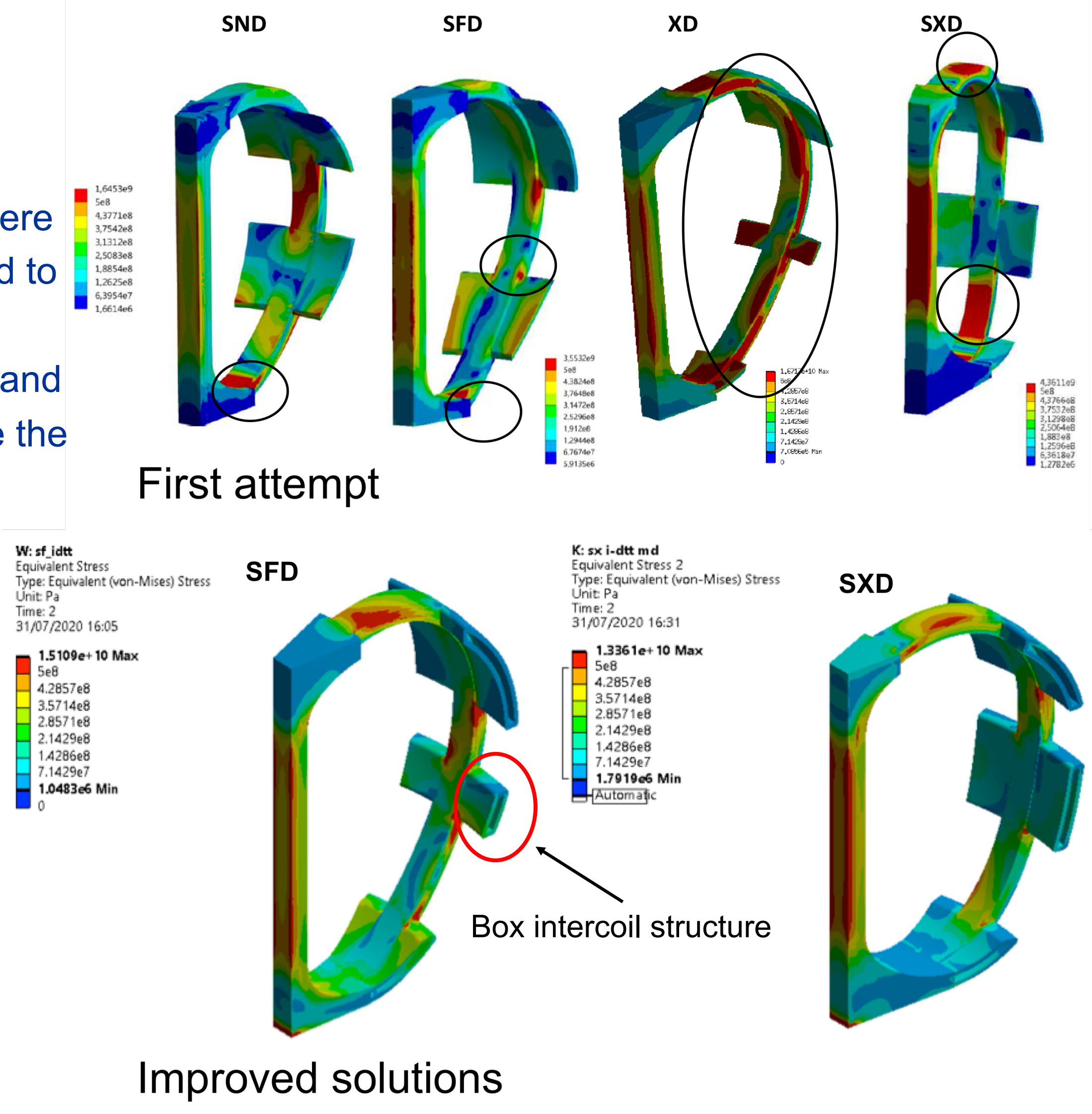
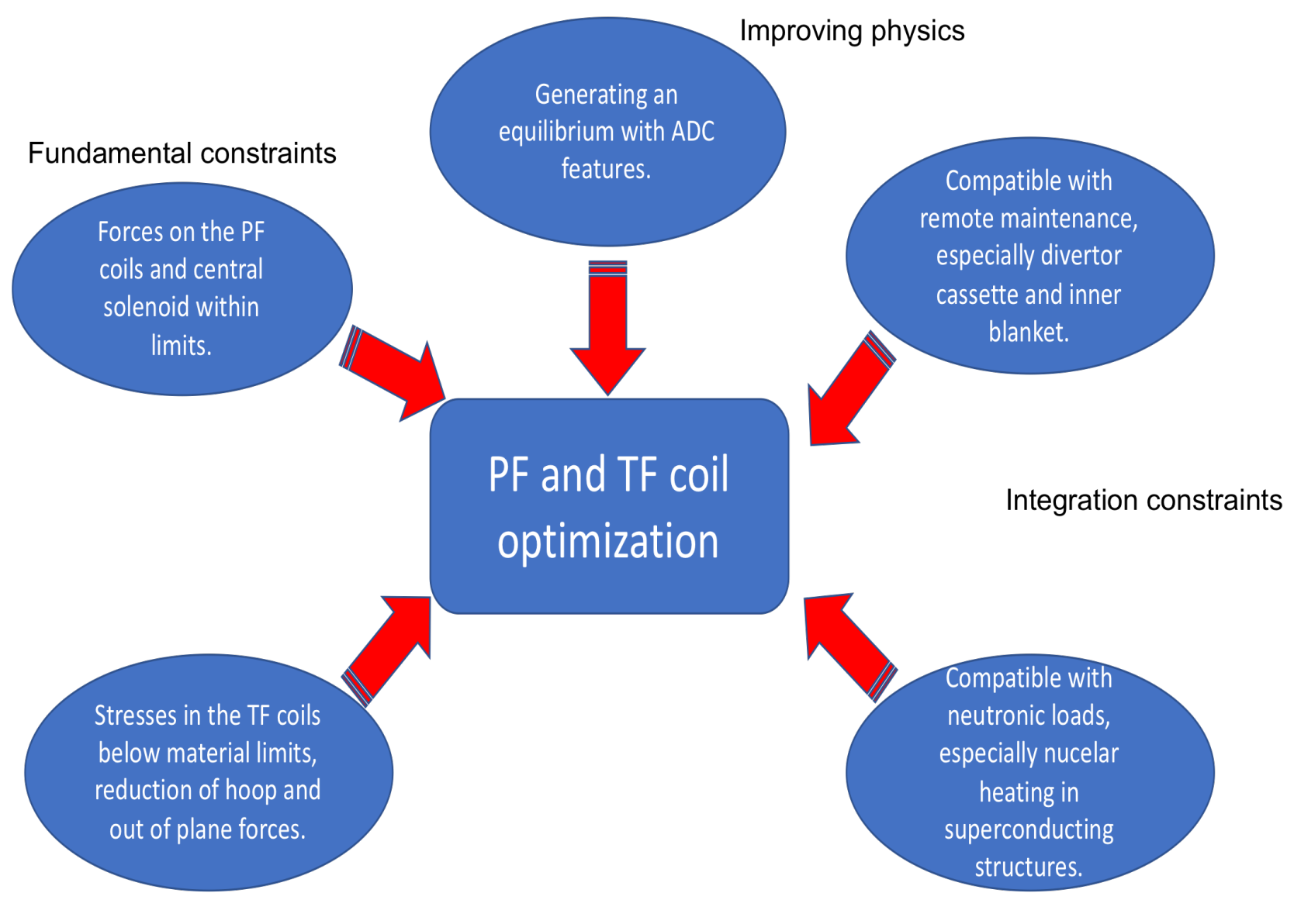


Fig.4. Stress maps for the initial and final TF coil configurations.



Improving physics

Fundamental constraints

Generating an equilibrium with ADC features.

Forces on the PF coils and central solenoid within limits.

Compatible with remote maintenance, especially divertor cassette and inner blanket.

PF and TF coil optimization

Integration constraints

Stresses in the TF coils below material limits, reduction of hoop and out of plane forces.

Compatible with neutronic loads, especially nucelar heating in superconducting structures.

Structural constraints

Fig.5. Coil optimization procedure.

Optimization of the coil shape and position is a complex problem which requires attacking the problems from different directions, see Fig. 5. This was done in an integrated way in the framework of the project.

We also investigated the sensitivity of each configuration to equilibrium perturbations and the ability of the control system to bring the plasma back. Using only external coils, the power requested in the SND is already of the order of 350MW, and getting worse for alternative configurations, as shown in the table to the right. Alternative configurations show a larger sensitivity to equilibrium perturbations with displacements of the plasma centroid of the order of 10-20cm (a few cm for the SND). This is due to the larger distance of the plasma from passively stabilizing structures and the External control coils. Solutions introducing plasma shape optimization and toroidally continuous stabilizing plates were considered. While this led to some improvement, control becomes feasible only when internal coils are considered.

Only external PF control coils

Configuration	Scenario snapshot	Power request [MW] VDE 5cm (With SP/without SP)	Power request [MW] VDE 10cm (With SP/without SP)	Power request [MW] VDE 15cm (With SP/without SP)
SXD	FT	126/196	505/783	>1000
	FT_li1	195/345	780/>1000	>1000
	SRD	914/>1000	>1000	>1000
XD	FT	38/45	152/180	342/407
	FT_li1	32/38	129/154	291/348
	SRD	278/362	>1000	>1000
SFD	FT	25/26	100/105	226/237

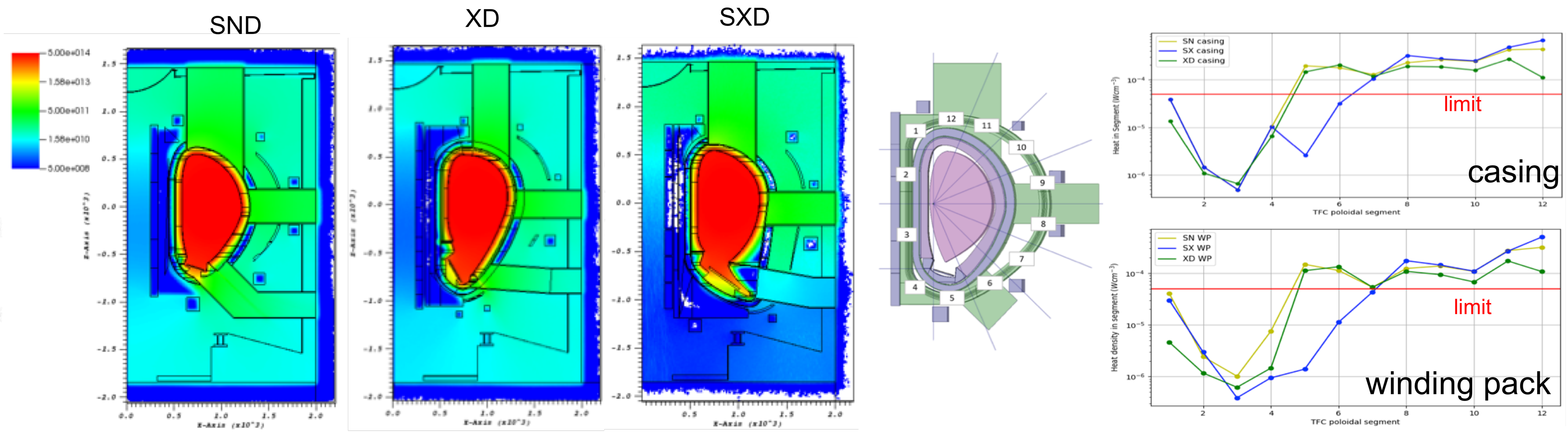
No morphing and hence simpler problem

Configurations		Scenario snapshot	Power request [MW] VDE 5cm	Power request [MW] VDE 10cm	Power request [MW] VDE 15cm
SXD	With Stability plate	FT	0.9	3.6	8.1
		FT_li1	1.1	4.4	9.9
		SRD	2.0	8.1	18.2
	Without Stability plate	FT	1.1	4.2	9.5
		FT_li1	1.3	5.1	11.6
		SRD	2.4	9.5	21.9
XD	With Stability plate	FT	0.6	2.5	5.6
		FT_li1	0.5	2.1	4.8
		SRD	1.5	6.1	13.6
	Without Stability plate	FT	0.7	2.7	6.2
		FT_li1	0.6	2.3	5.3
		SRD	1.7	6.7	15.1
SFD	With Stability plate	FT	0.7	2.6	5.9
	Without Stability plate	FT	0.5	2.0	4.5

With internal PF control coils

Finally, neutronics studies were carried out. They showed a similar behavior between the baseline and alternative configurations in terms of divertor heating, He formation and Tritium breeding. Comparative analysis of the nuclear heating in the TF coils showed that the SND and XD perform in a similar way while the SXD provides better shielding in the lower part of the machine, where the divertor is.

Fig.6. Neutron irradiation maps for different configurations (left) and detailed nuclear heating profiles in the TF coils' casing and winding pack.



Conclusions

An extensive comparison between the baseline SND configuration and a number of alternative divertor options has been performed, here showing some of the highlights. Simulations that extrapolate the behavior of the exhausted plasma suggest that an increased margin is possible in configurations with a longer connection length. In other words, SXD and XD can operate with less Ar or more power crossing the separatrix than the SND. Simple estimates based on the Langyel model seem to confirm this observations. Alternative designs lead to significant engineering complexity, especially when it comes to TF coil design and control. The latter is particularly problematic unless internal coils are introduced in the design.

Assuming that the SND will have a suitable engineering design, moderate modifications in the divertor could lead to additional physics margin and an incremental complexity. With this philosophy, a hybrid SND/SXD solution was developed with the major radius of the outer strike point halfway between the original SND and SXD. This led to better physics than the SND (see Fig 2) and less complex engineering than the SXD. Exploring the continuum of the solutions could therefore be beneficial.

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