EUROfusion

Assessing Alternative Divertors for DEMO strategy and first results

Fulvio Militello on behalf of the WP-DTT1/ADC team

This work has been carried out within the framework of the EUROfusion Consortium and has received funding from the Euratom research and training programme 2014-2018 under grant agreement No 633053. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

WP-ADC team

Aho-Mantila L., Ambrosino R., Body T., Bufferand H., Calabro’ G., Ciraolo G., Coster D., Di Gironimo G., Fanelli P., Fedorczak N., Giacomin M., Herrmann A., Innocente P., Kembleton R., Lunt T., Marzullo D., Merriman S., Moulton D., Nielsen A., Omotani J., Ramogida G., Reimerdes H., Reinhart M., Ricci P., Riva F., Stegmeir A., Subba F., Suttrop W., Tamain P., Teschke M., Thrysoe A., Treutterer W., Varoutis S., Wensing M., Wischmeier M., Xiang L.Y.

CCFE CULHAM CENTRE FOR FUSION ENERGY

IPP Max-Planck-Institut für Plasmaphysik

DTU Technical University of Denmark

cea

ENEA

CONSORZIO RFX Ricerca Formazione Innovazione

UNIVERSITÀ DEGLI STUDI DELLA Tuscia

create

VTT

KIT Karlsruher Institut für Technologie

EPFL ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

SWISS PLASMA CENTER

POLITECNICO DI TORINO

Introduction to the Work Package

- EUROfusion recognizes the complexity of the divertor challenge and the need for back-up solutions.
- The assumption (true or not) is that the ITER solution will not extrapolate to DEMO.
- The objective of WP-DTT1/ADC is to provide an **assessment** of the usefulness and feasibility of alternative divertor configurations for EU-DEMO by December 2023.

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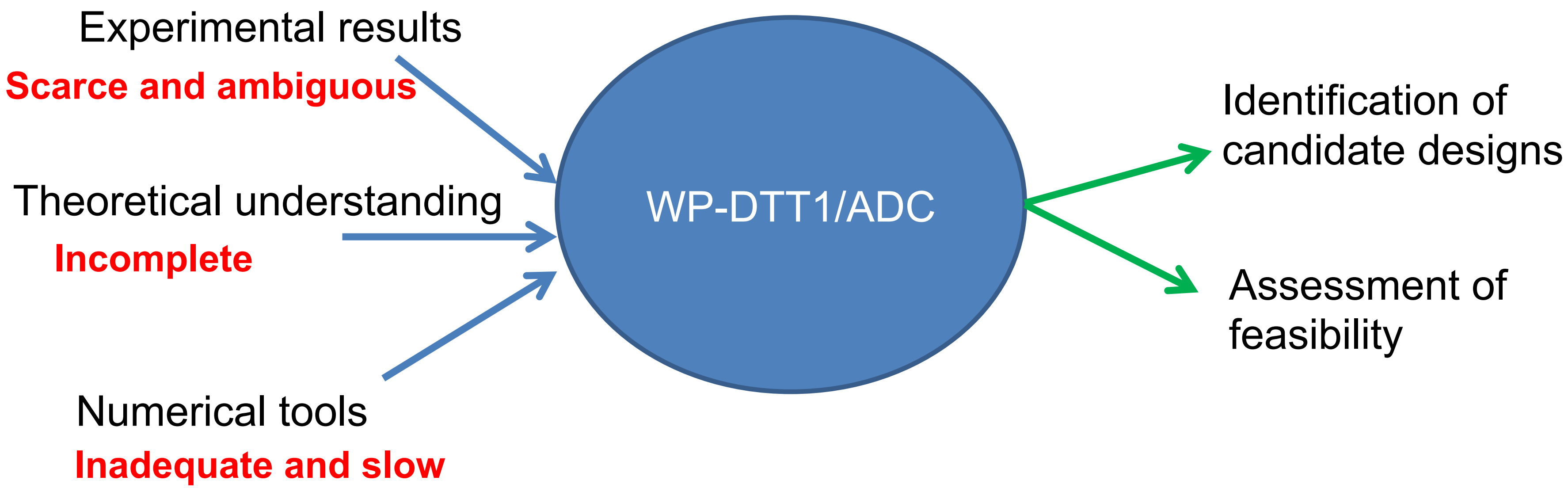

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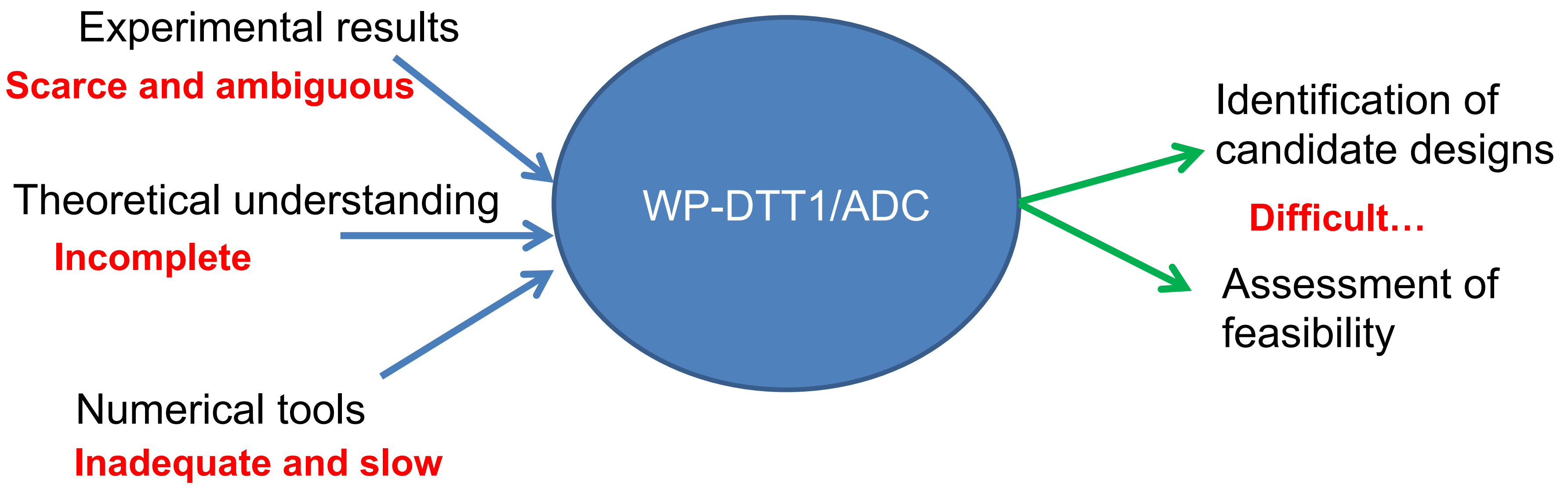
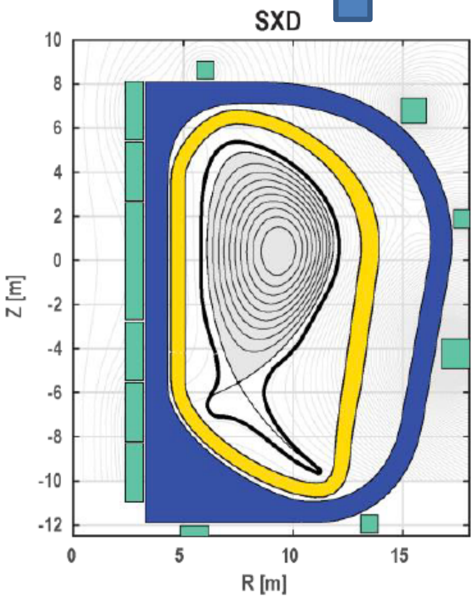
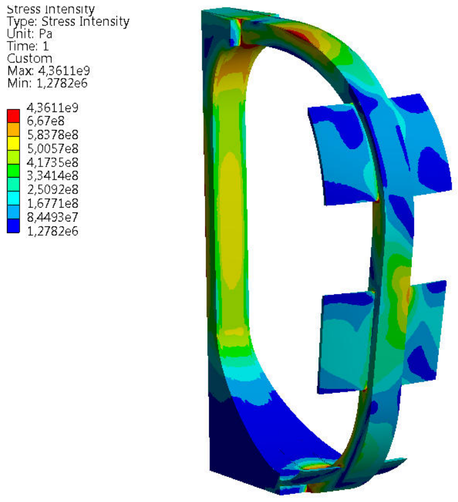
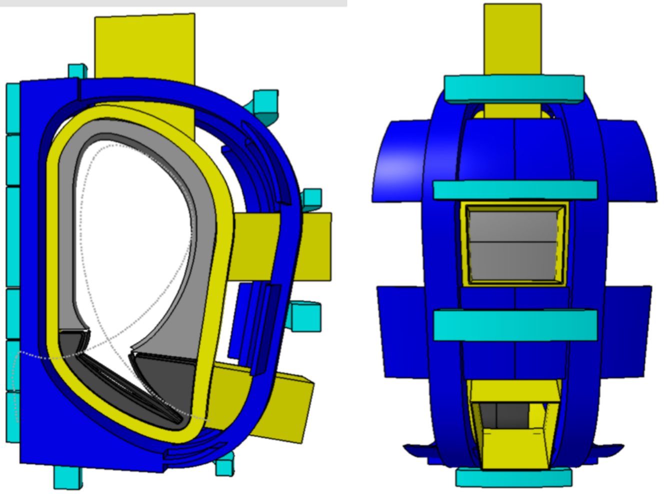


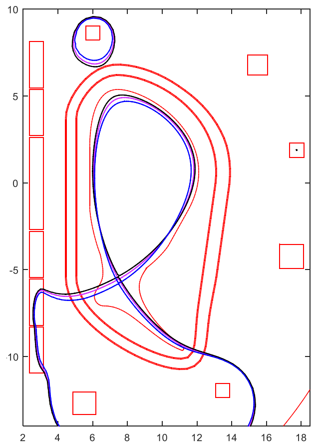
Multidisciplinary continuous improvement

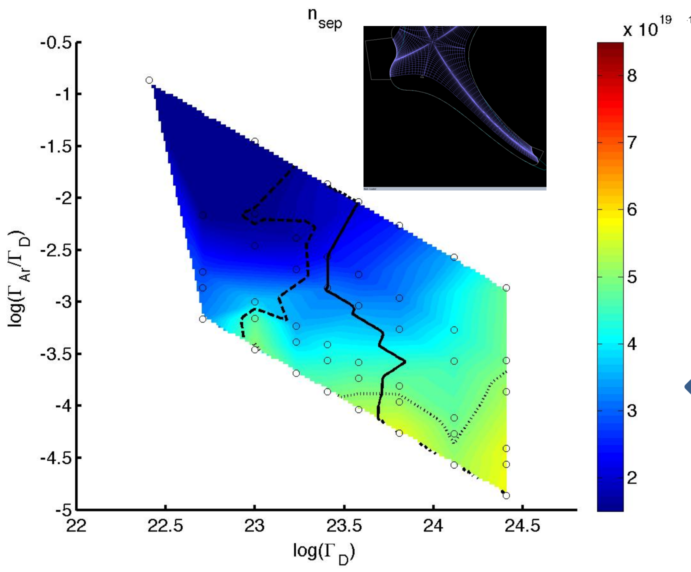


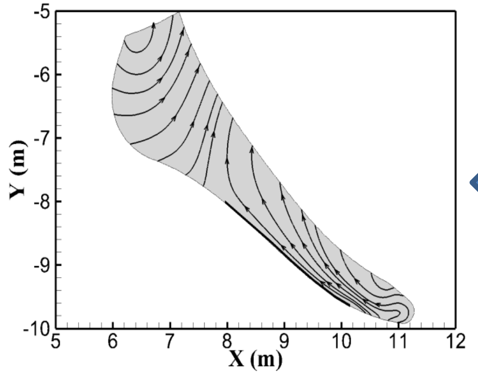


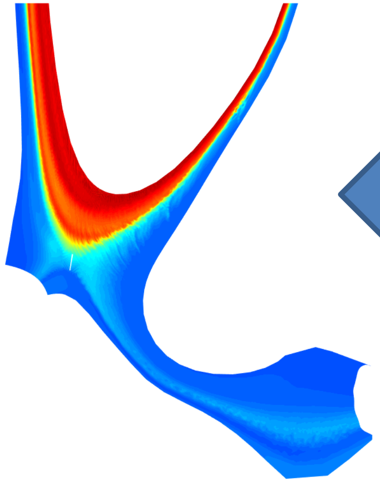


a) b)









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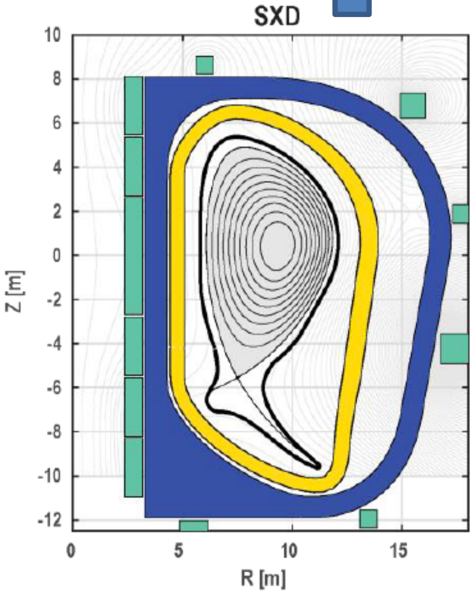
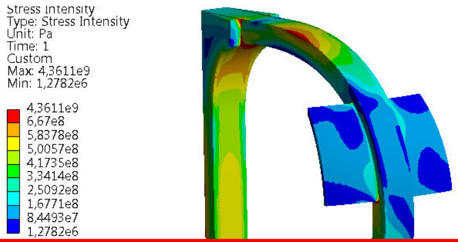
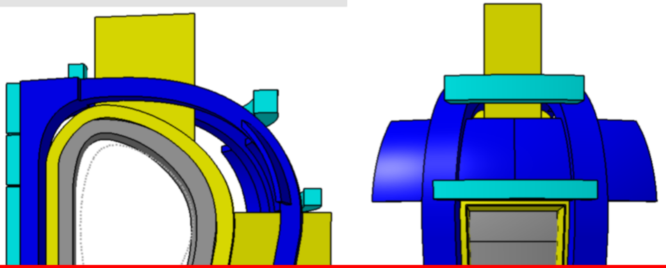
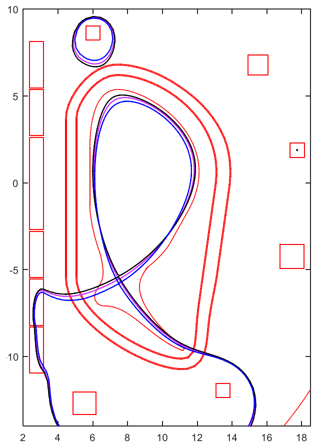
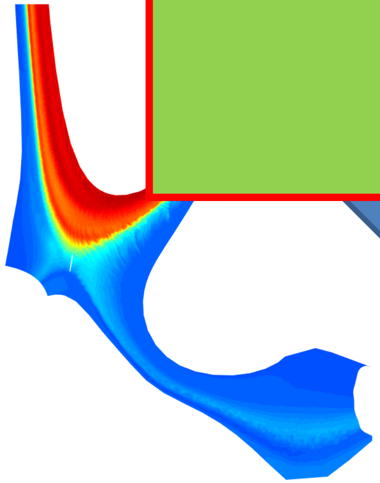


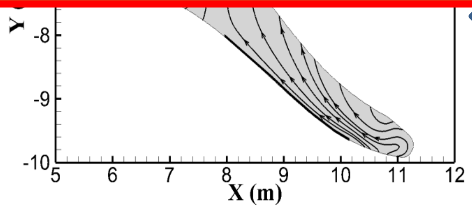


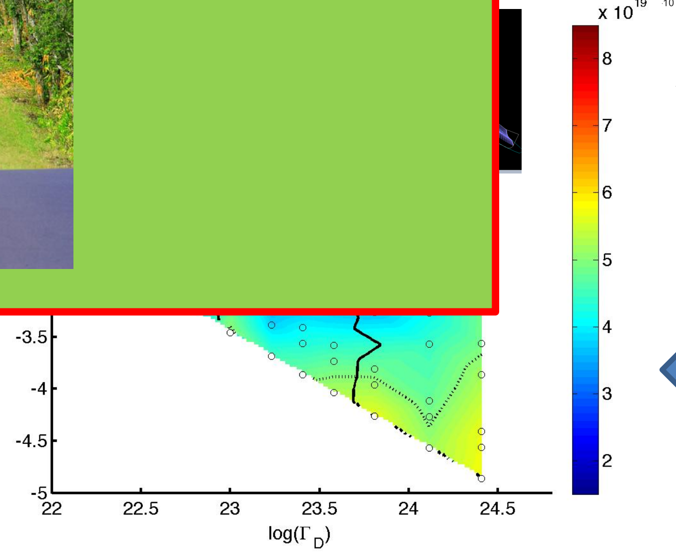




These initial results are aimed at identifying the criticalities, not at providing final conclusions

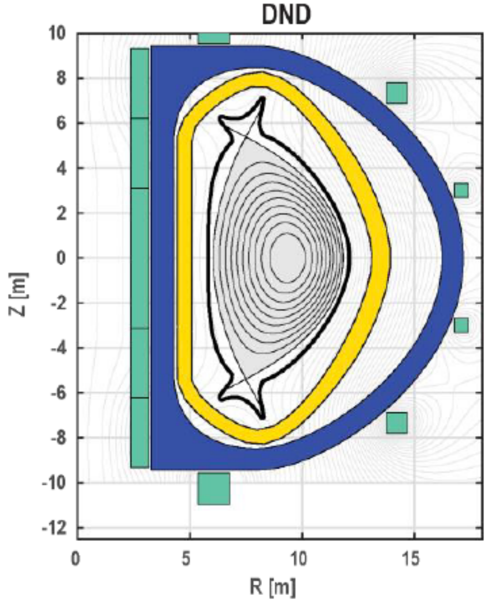


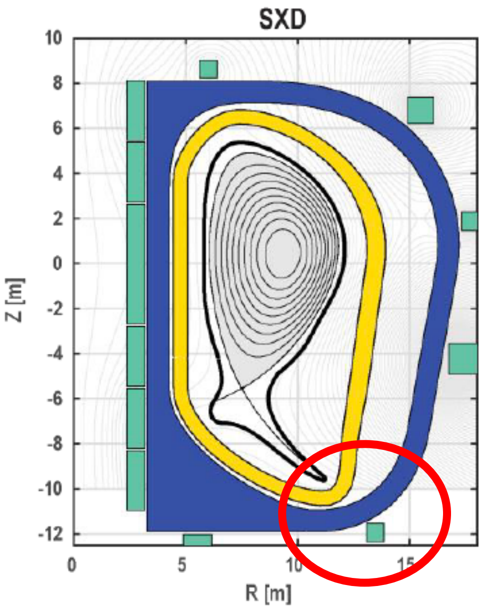


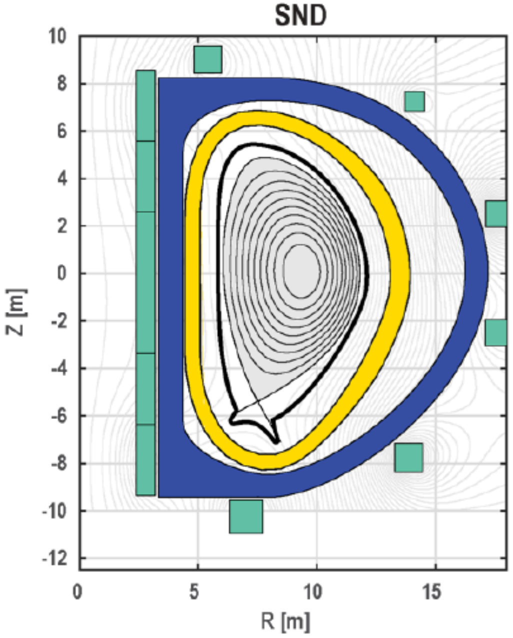


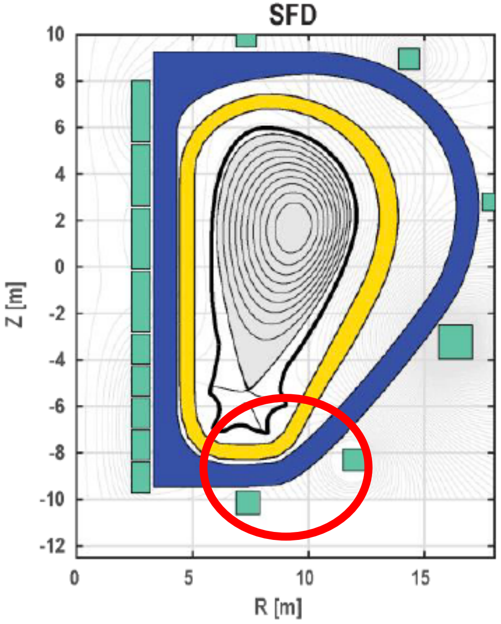
Equilibria

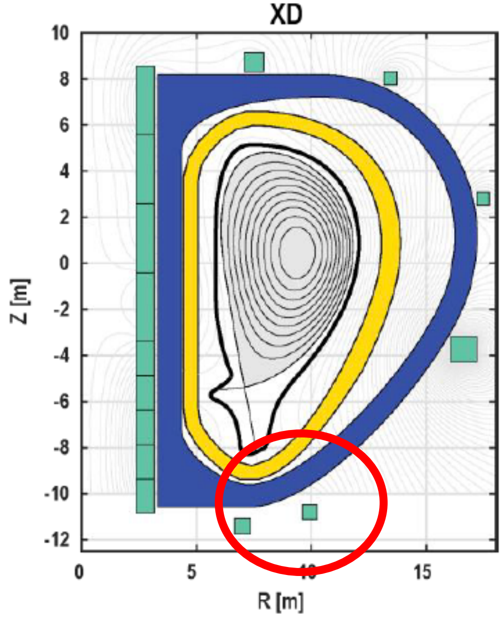
- All the equilibria are realized with 6 external coils.
- Lorentz forces on coils within mechanical constraints. Ripple within 0.6%.
- Unusual shape of the TF coils to accommodate needs of alternative configurations.







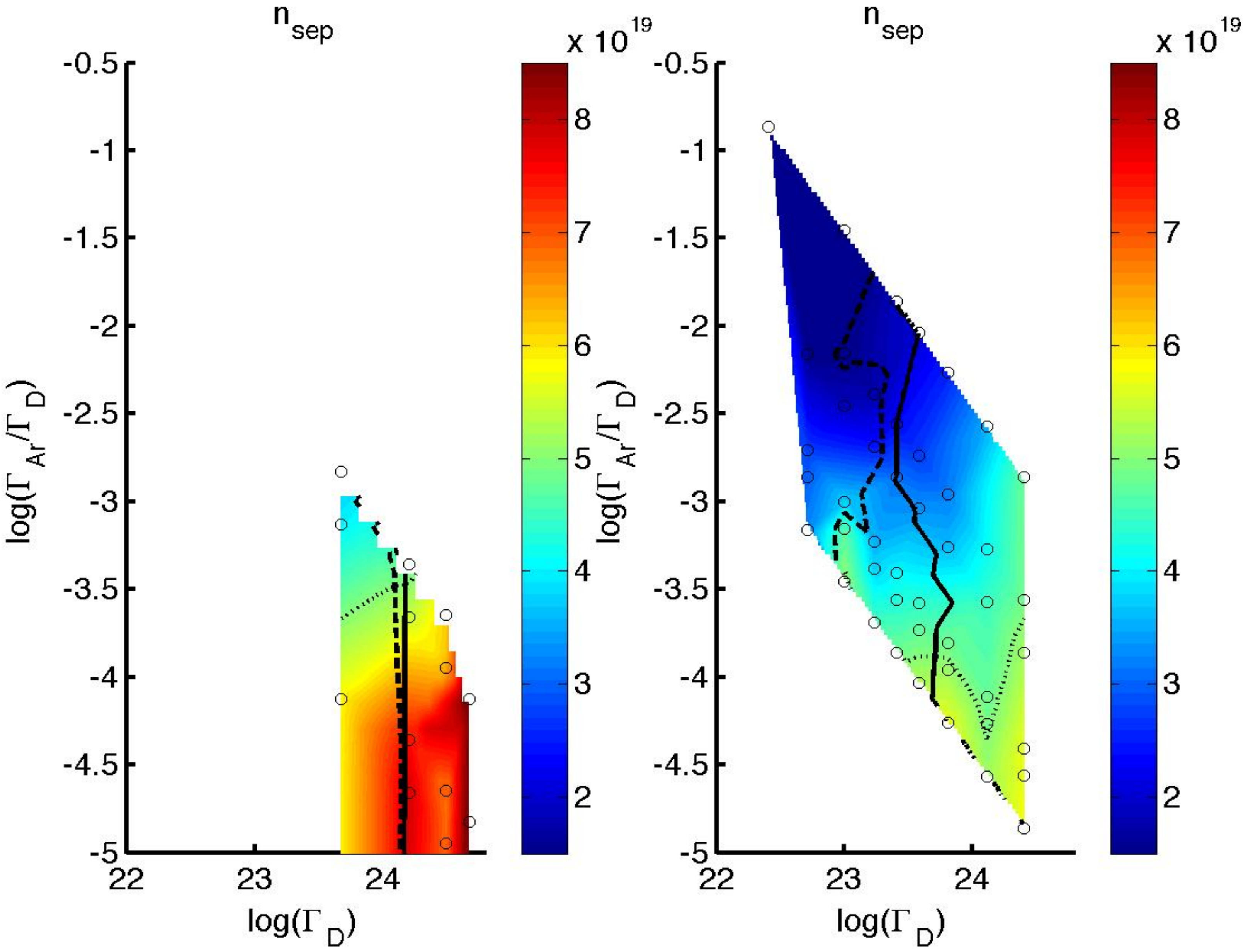




Multifluid calculations

- Multifluid calculations were carried out with SOLPS-ITER.
- D, He and Ar included, fluid neutrals and no drifts (for now).
- All configurations investigated, only SN and SXD at sufficient level of maturity.

- “Matrix” scans were used to investigate the response of the different geometries to similar conditions.
- SXD (potential) benefits:
  - Lower n_{sep} for same Ar concentration;
  - Bigger window gives possibility to increase the power crossing the separatrix (and hence reduce core radiation)?



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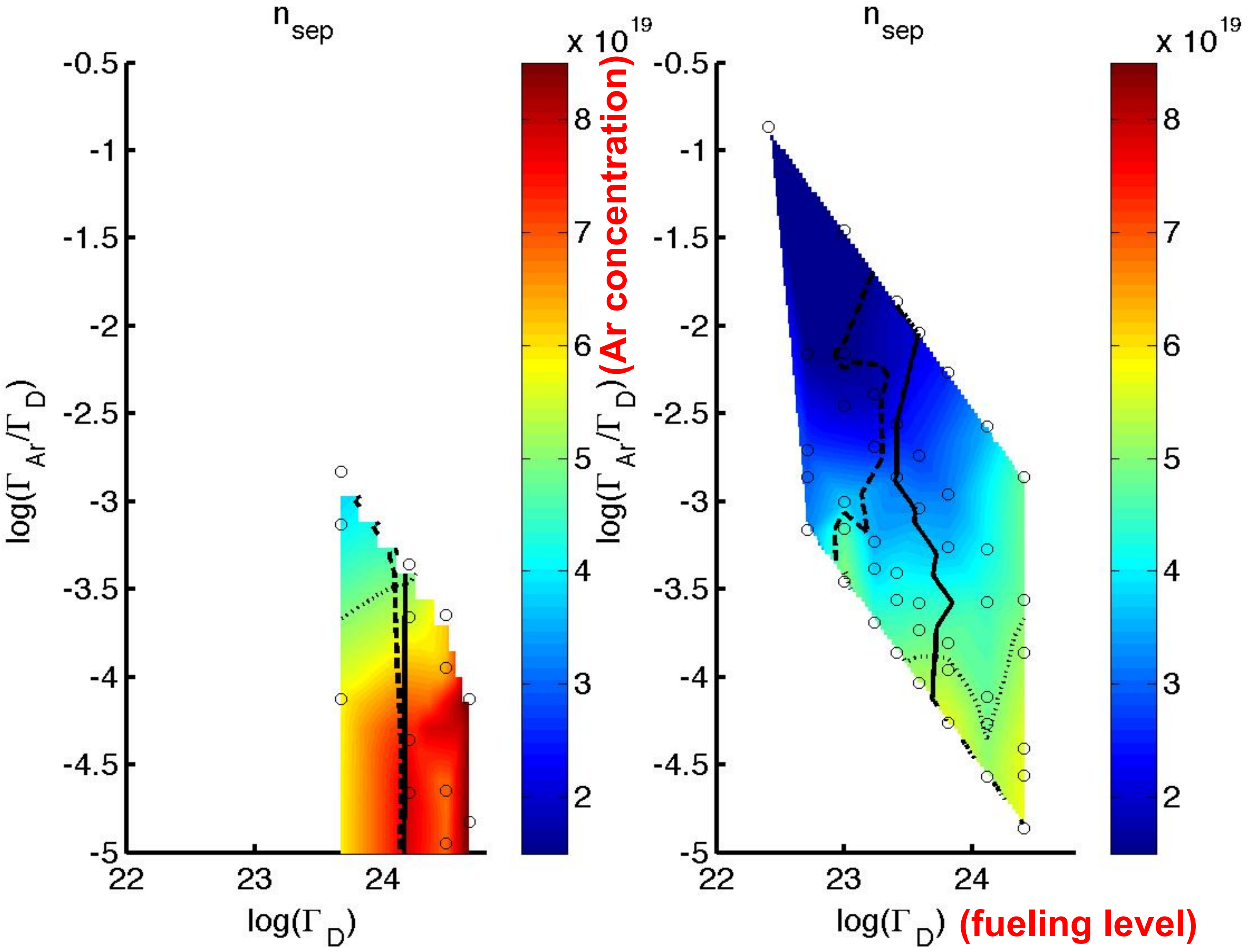

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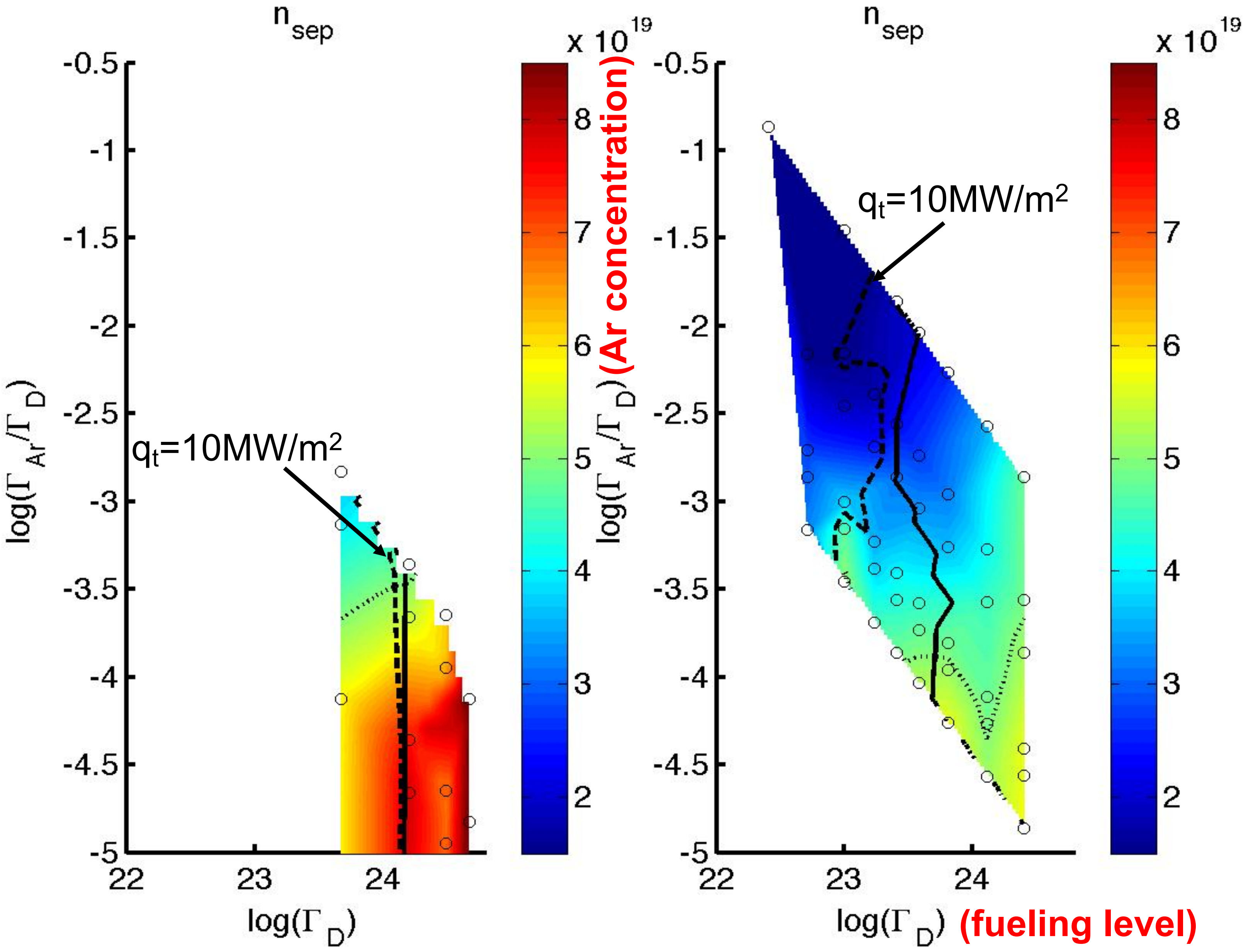

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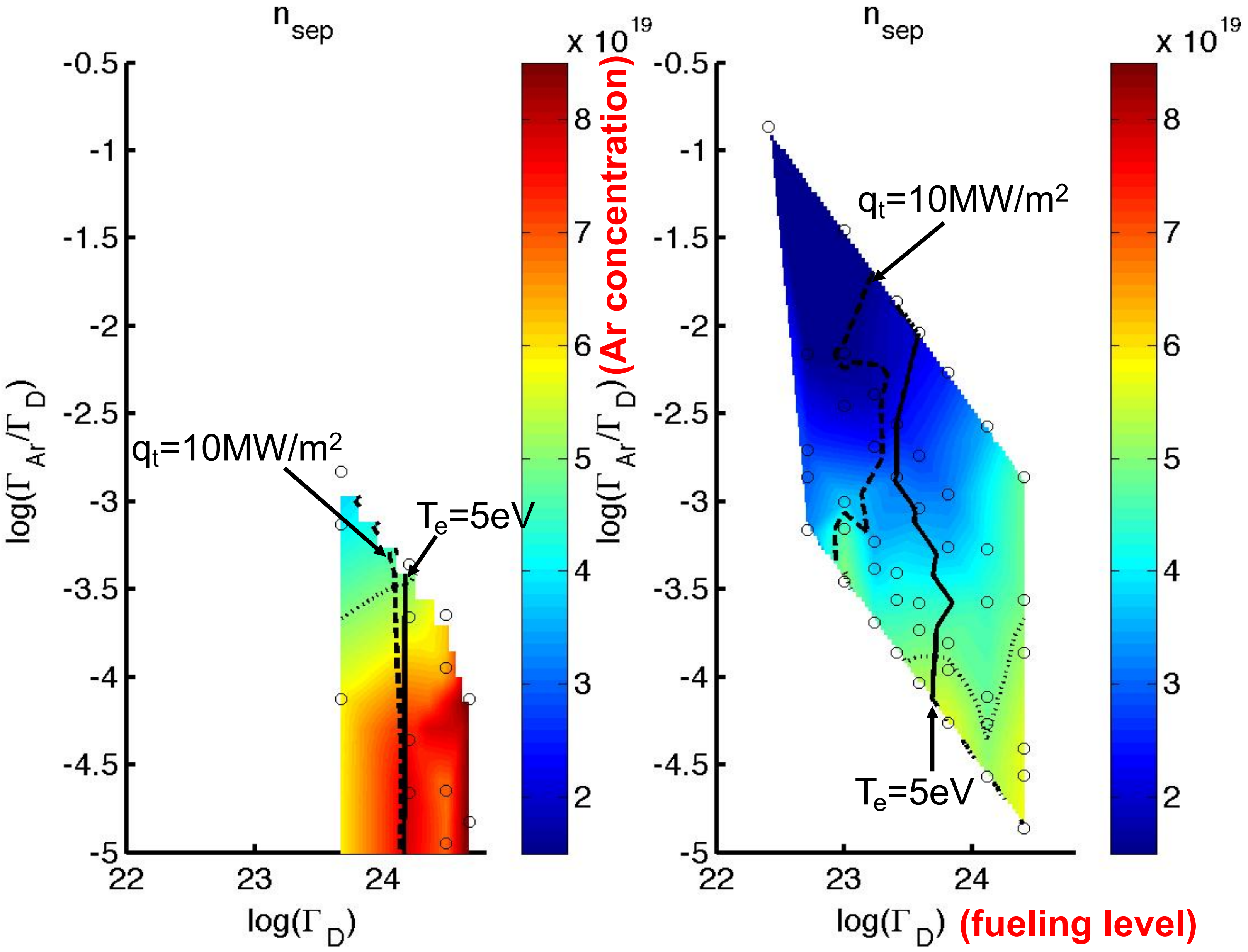

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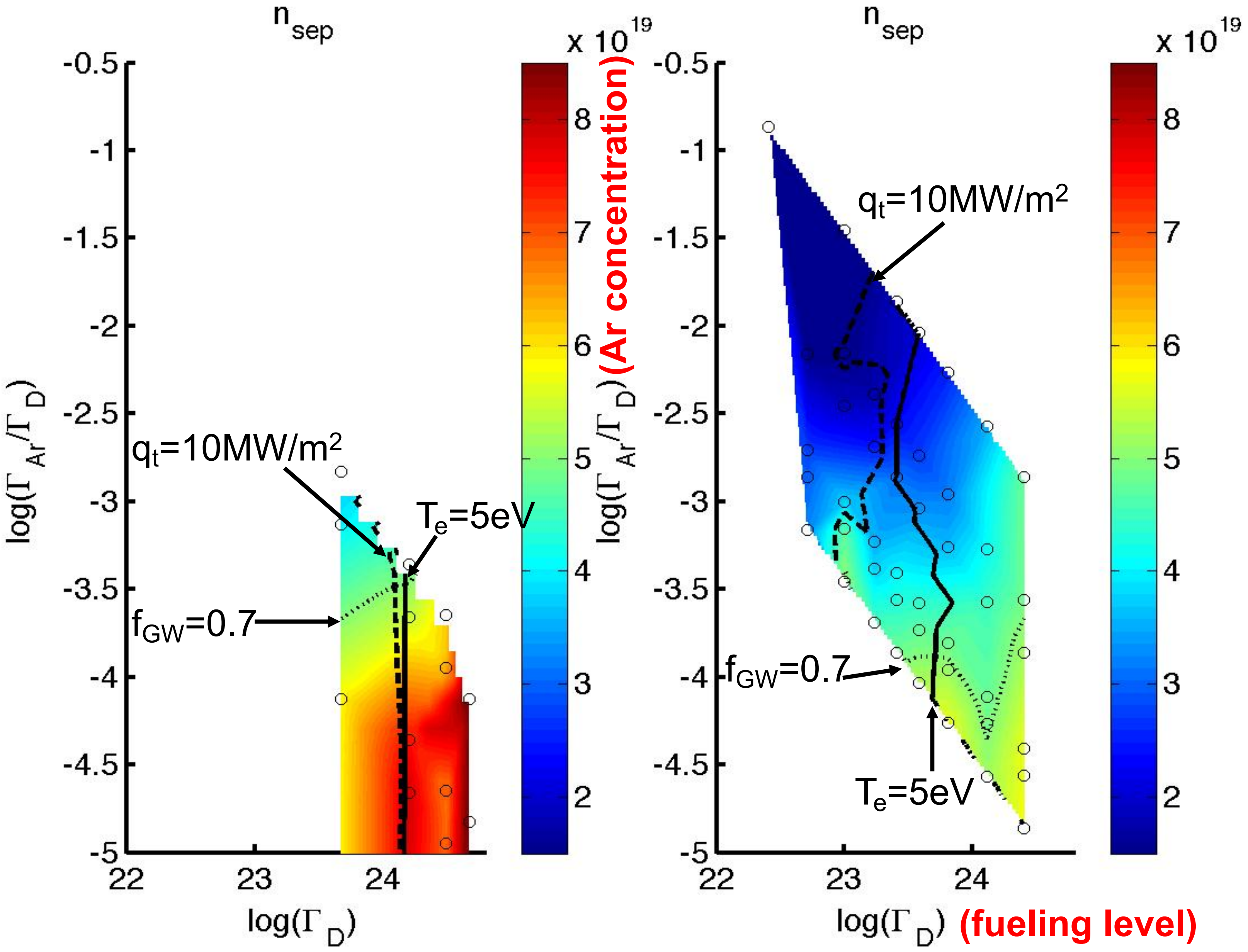

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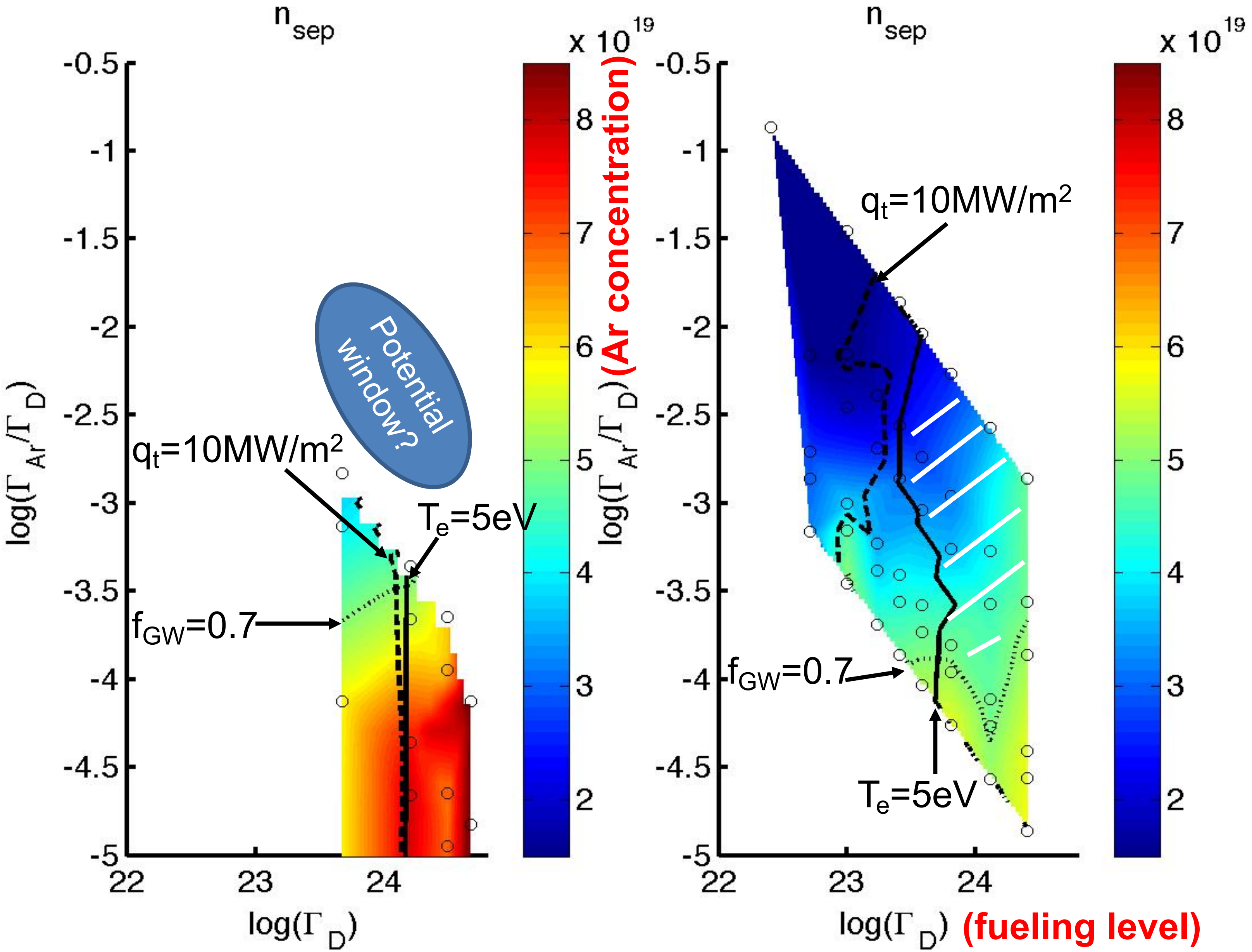

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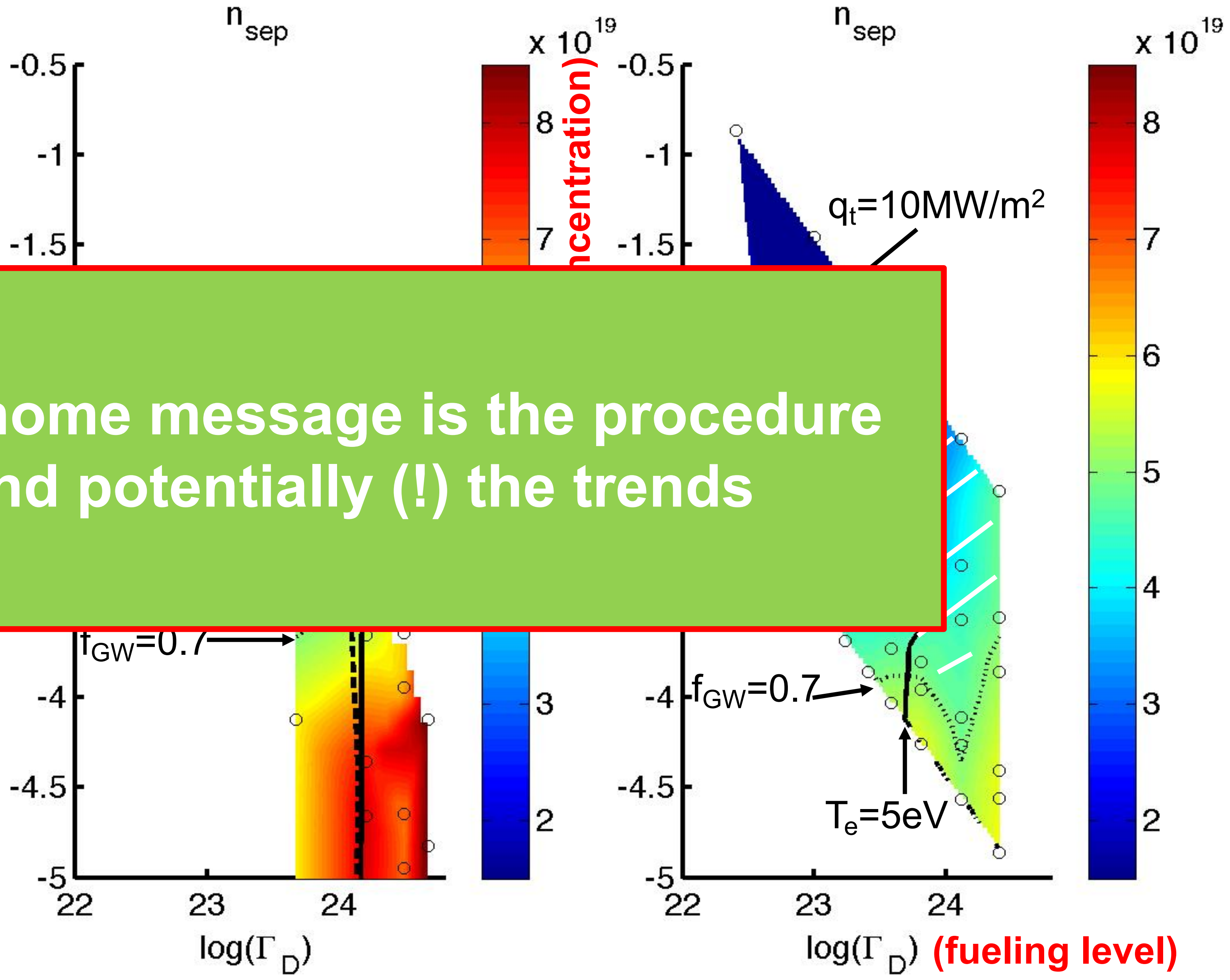
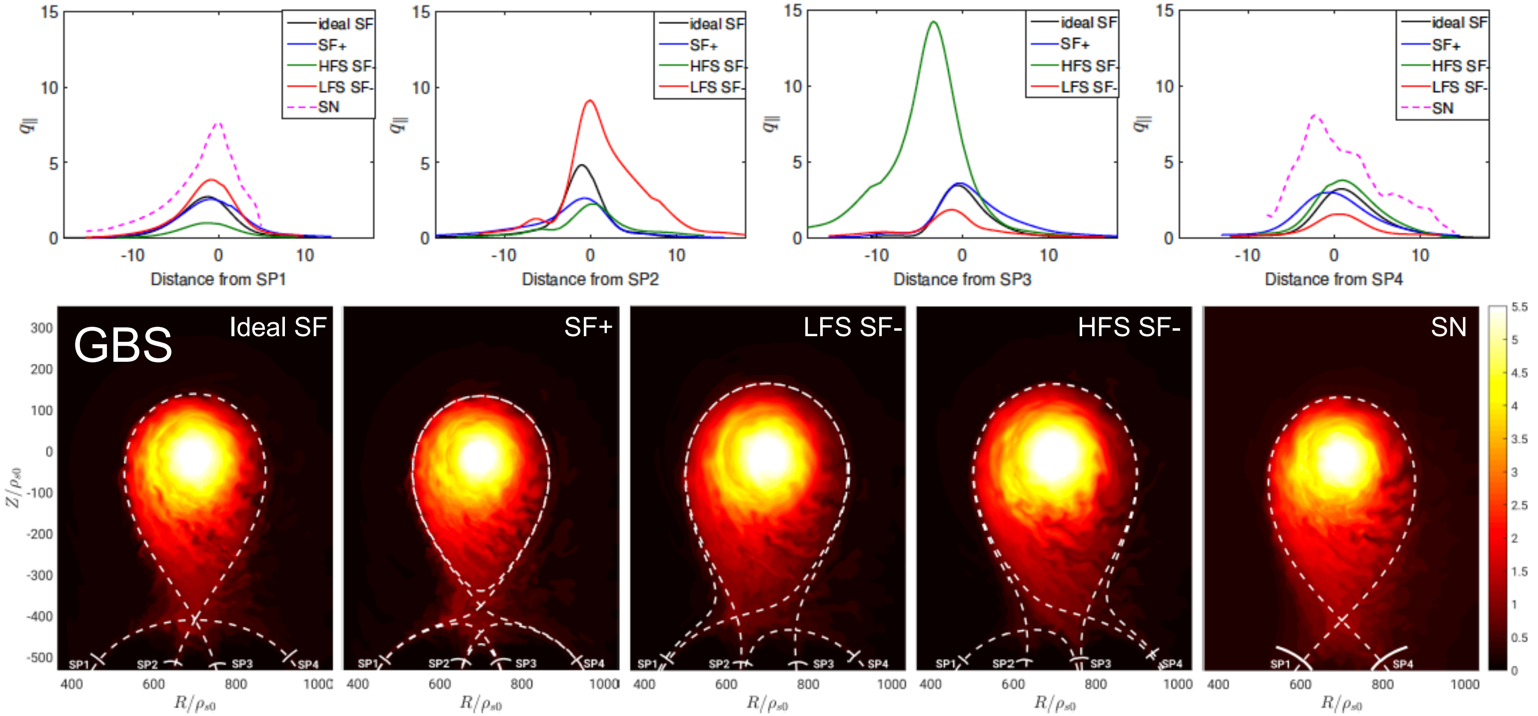


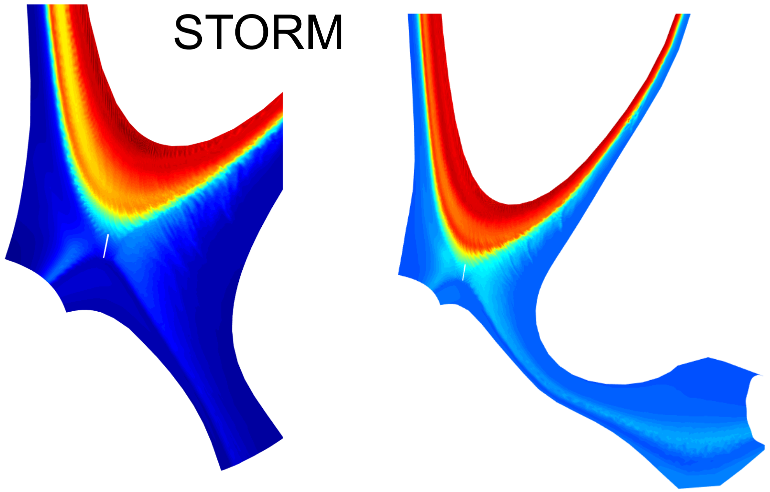
Take home message is the procedure and potentially (!) the trends

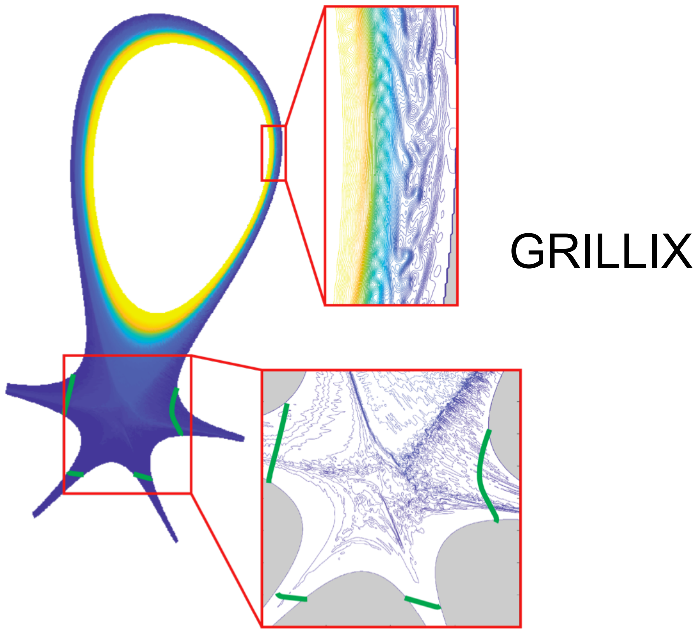
Turbulence

- First 3D turbulence simulations of alternative divertor configurations ever produced.
- Sandbox approach for the moment.
- SFD: drift induced electrostatic recirculating cell re-distributing the flux.
- SXD: stronger turbulence in the divertor leg.



Giacomin et al. (submitted to NF 2019)

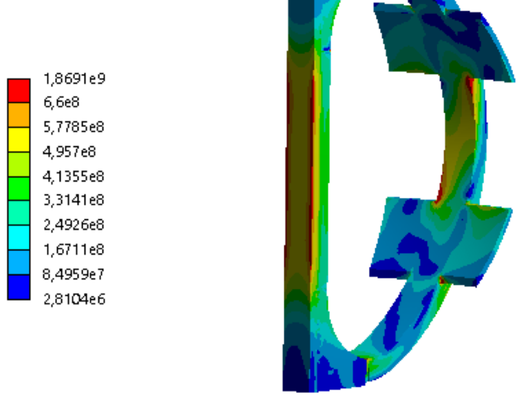




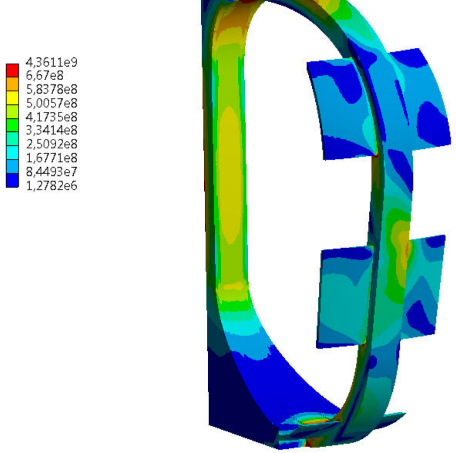
TF structural calculations

- Structural calculations were carried out to assess potential failure of the TF coils.
- Stress linearization used to assess the failure points.
- All configurations fail, but stress concentration can be probably removed in most cases.
- Intercoil structures and fillets not yet optimized. Room for improvement.

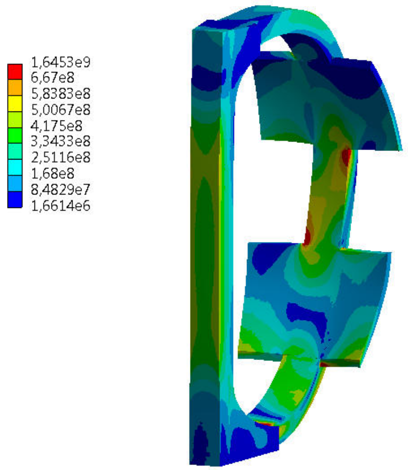
DND



SXD



SN



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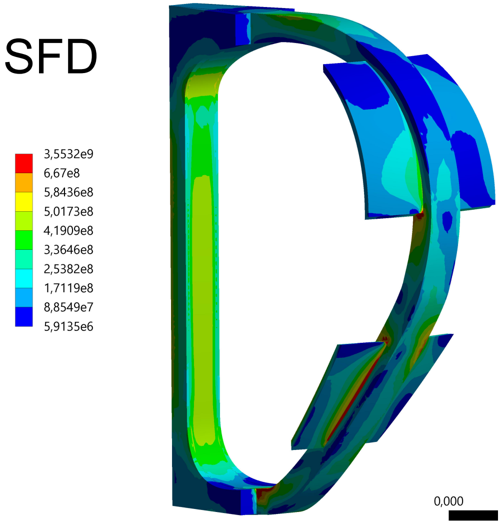
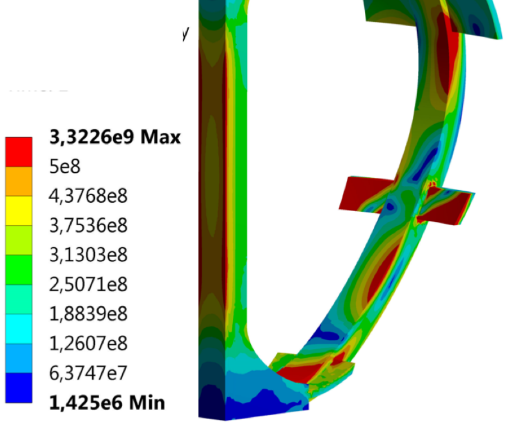


XD



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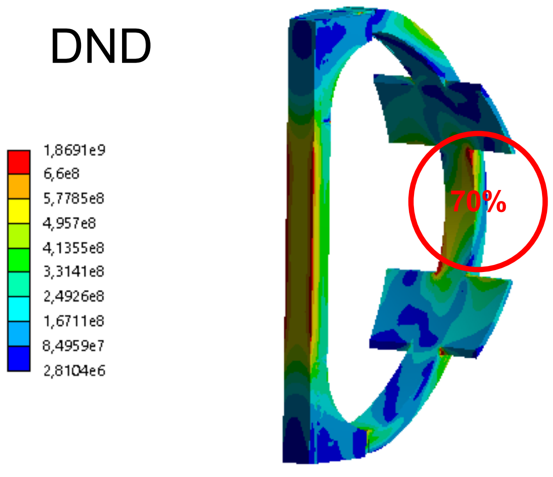

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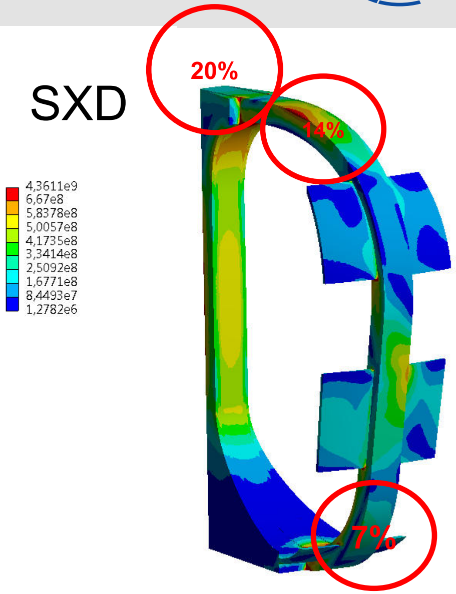

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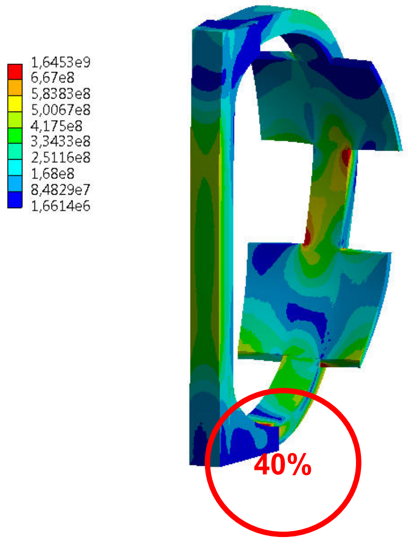

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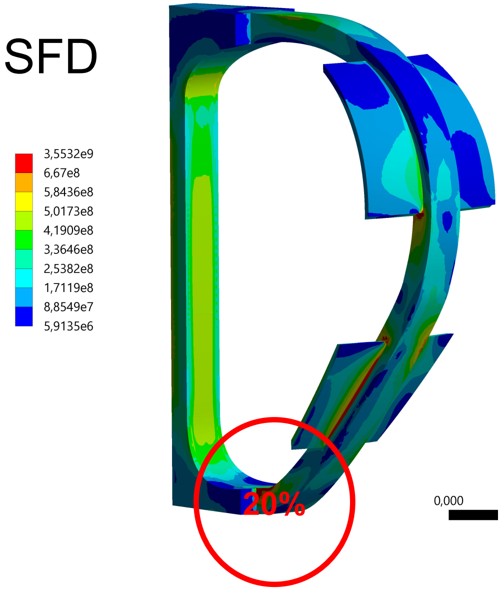

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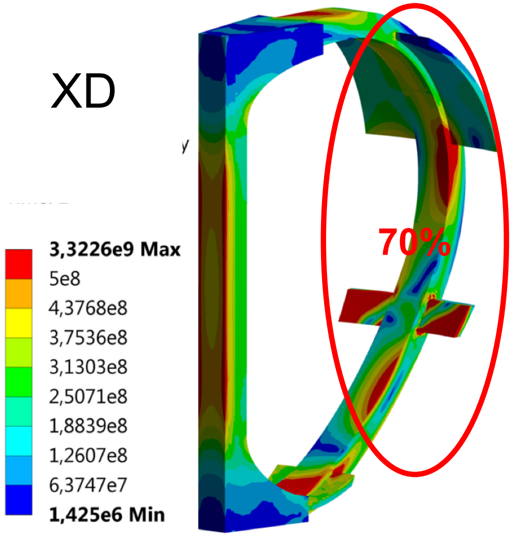

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- Out of plane forces can count for ~30% of the total in critical points

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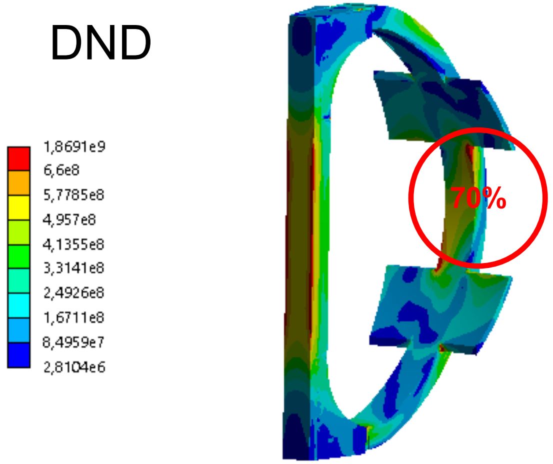

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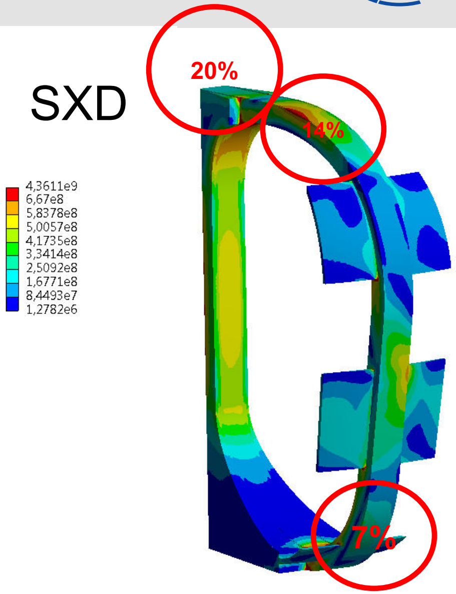
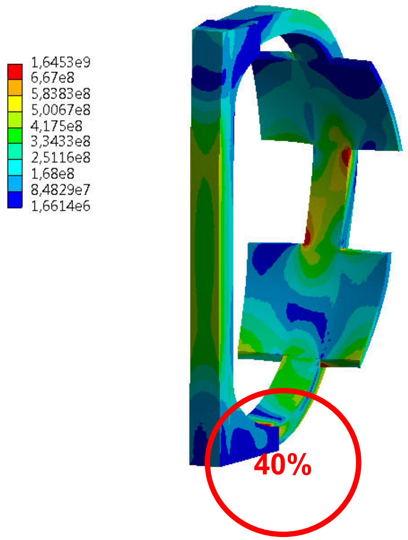
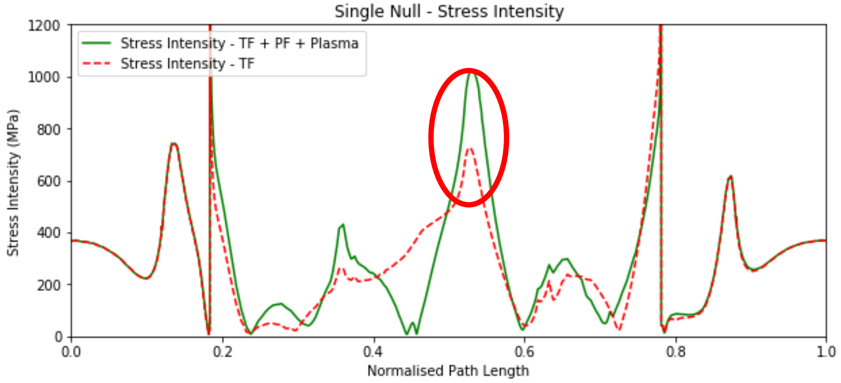


SN





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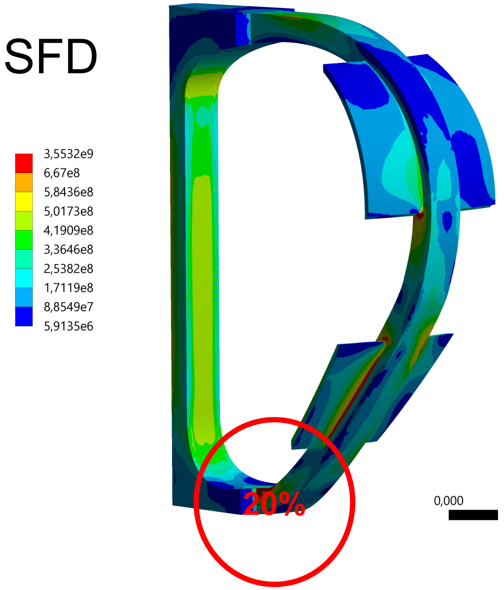

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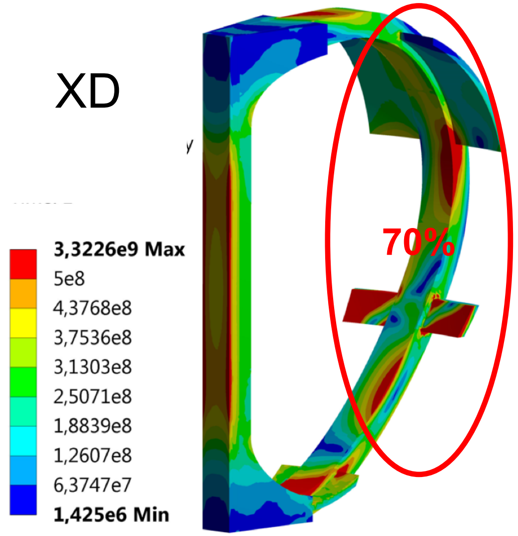

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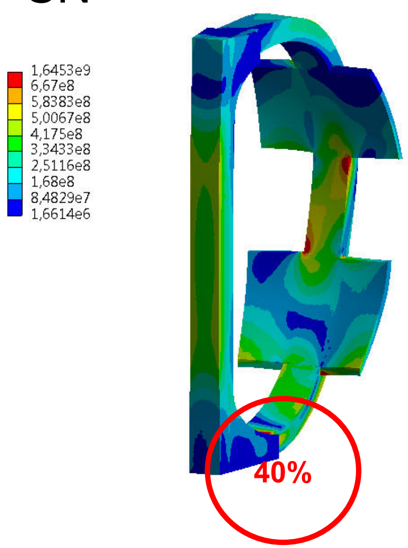
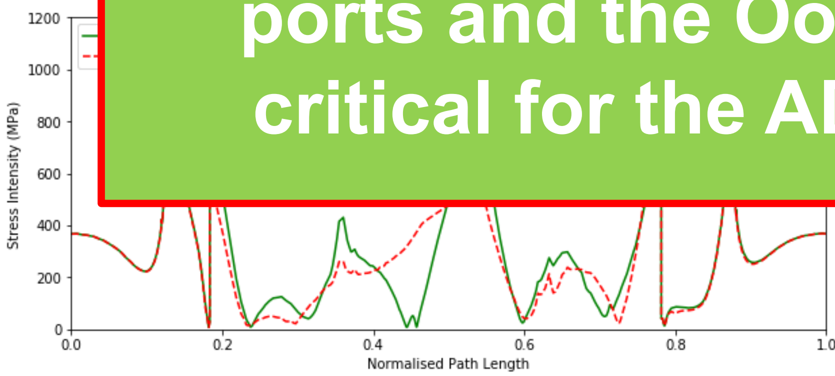
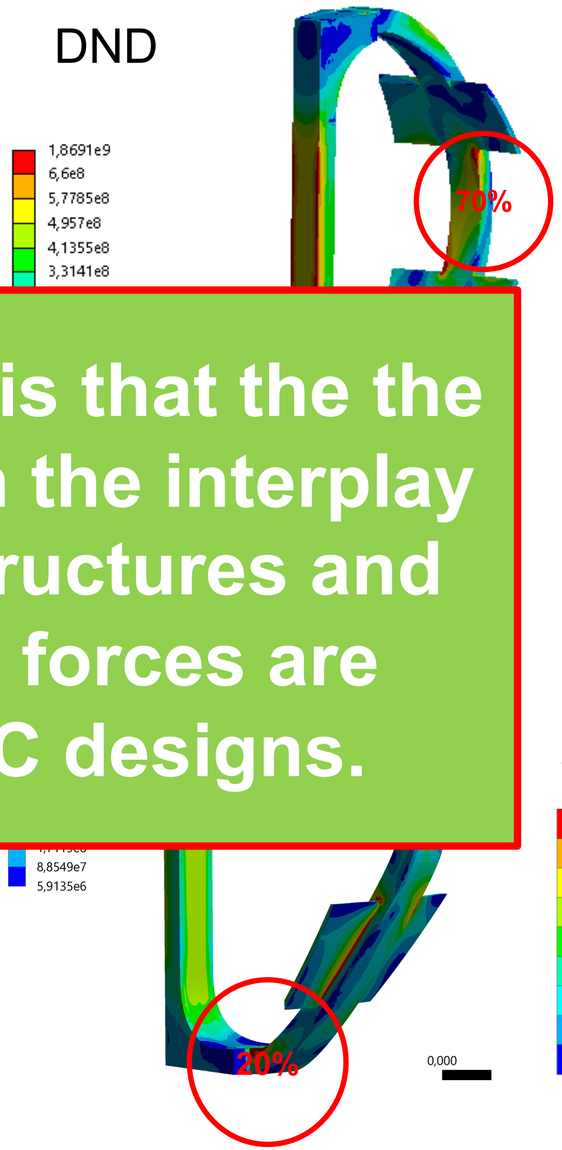
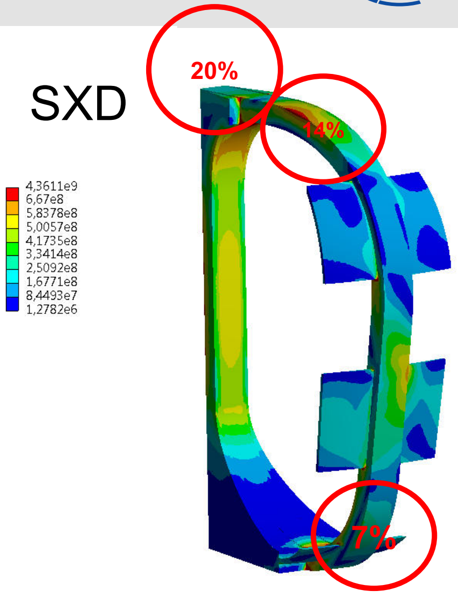
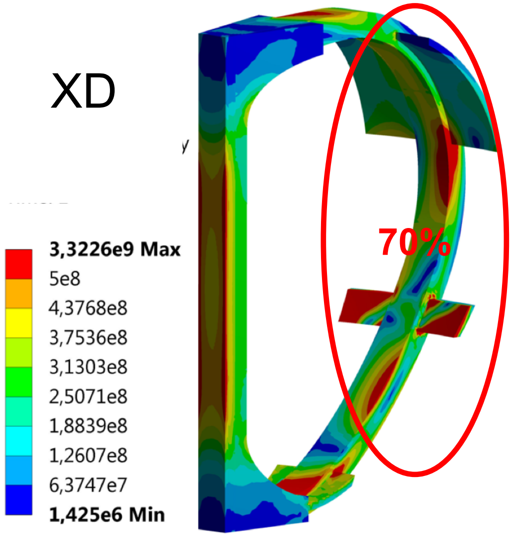
Take home message is that the the outer TF section with the interplay between intercoil structures and ports and the OoP forces are critical for the ADC designs.





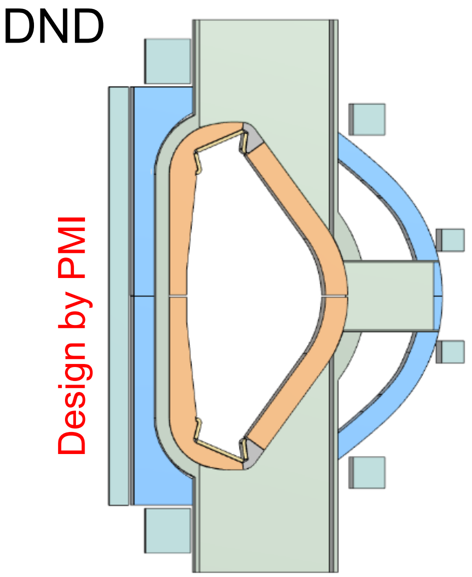


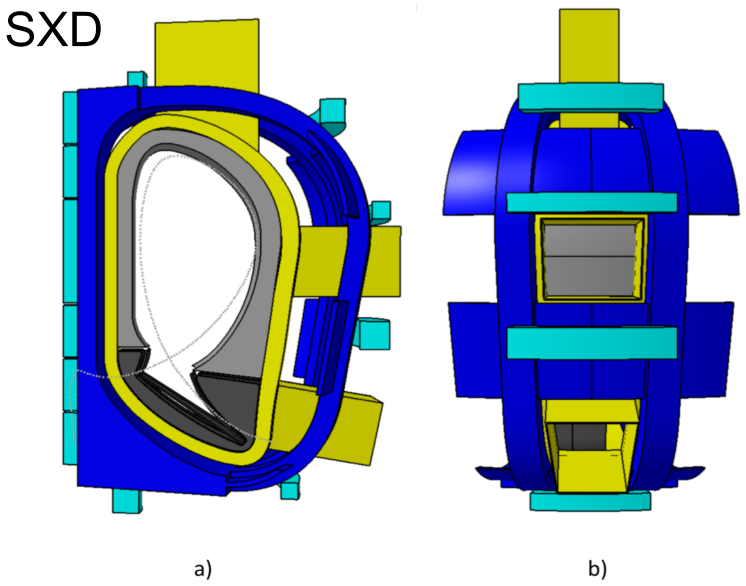


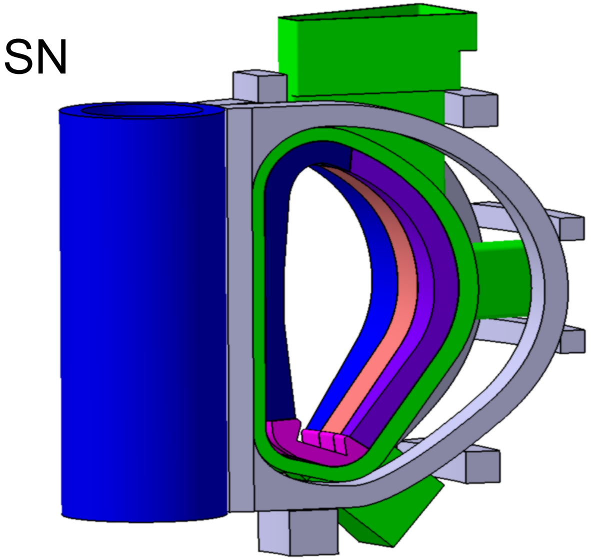


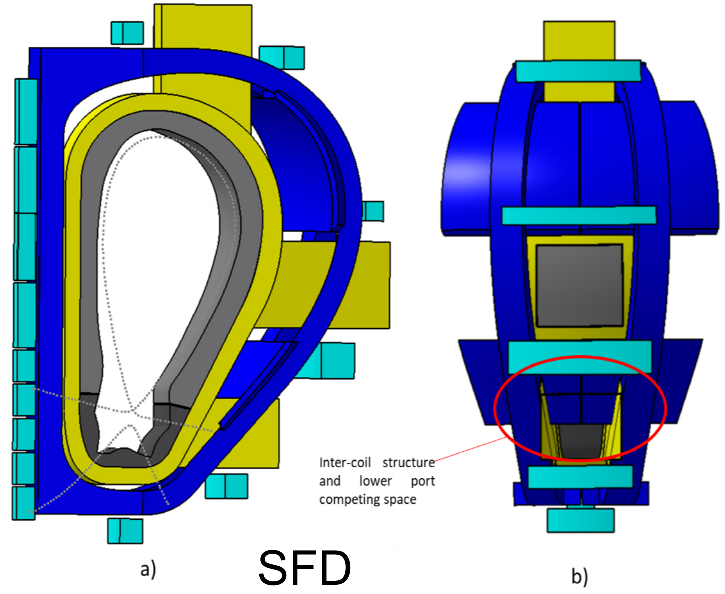
3D builds

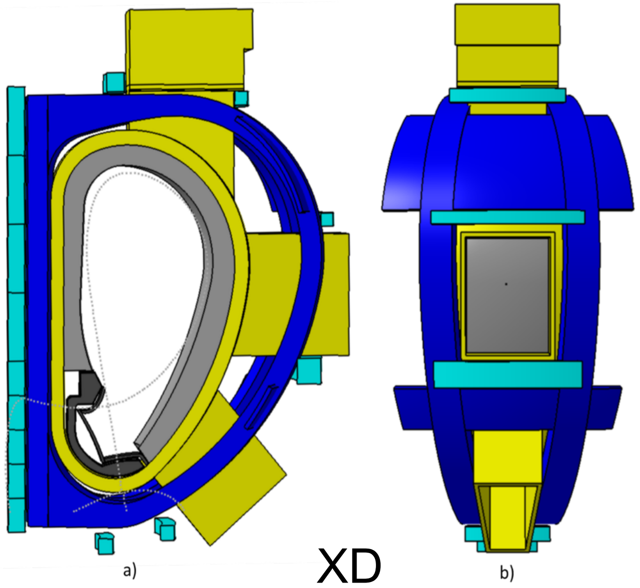
- 3D builds were generated to assess maintenance feasibility.
- Intercoils structures help with passive stabilization.
- SFD lower intercoil structures obstruct port.











Marzullo et al., ISFNt (2019)

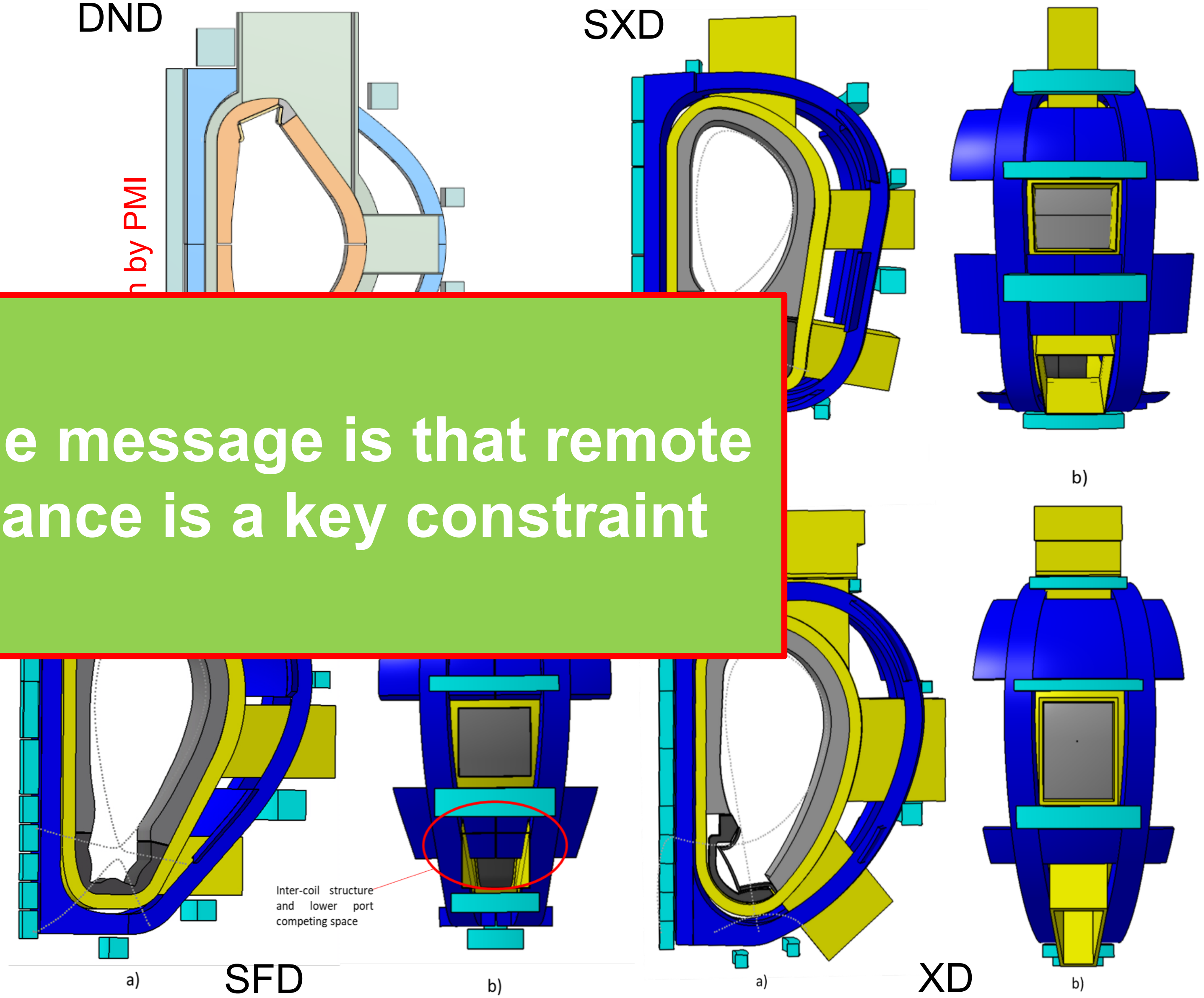
3D builds

- 3D builds were generated to assess maintenance feasibility.
- Intercoils structures help with passive stabilization.
- SFD lower intercoil struct
obstruct port.

Take home message is that remote maintenance is a key constraint

DND

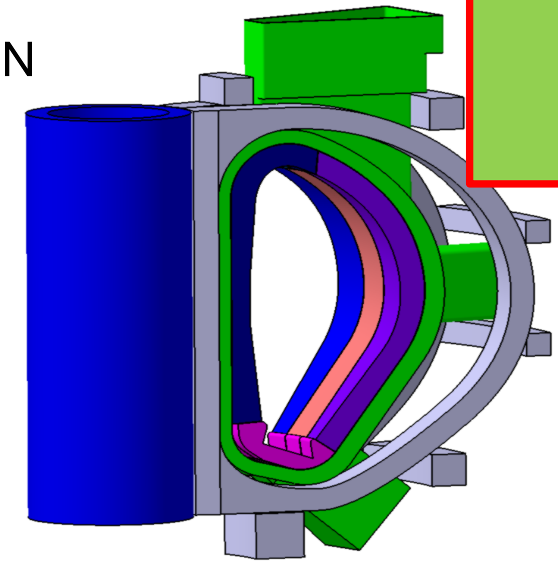
SXD



SFD

XD

SN



Control

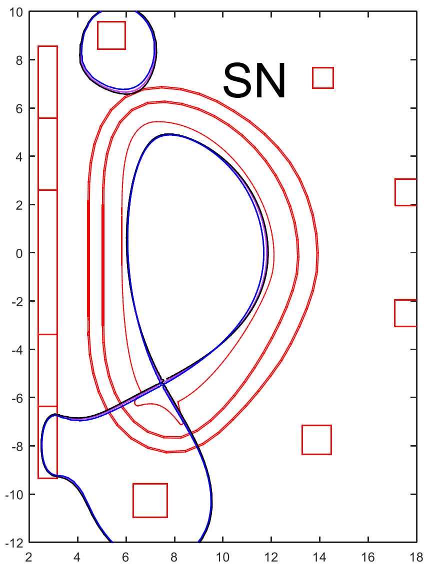
- A minor disruption and a big ELM were simulated imposing:

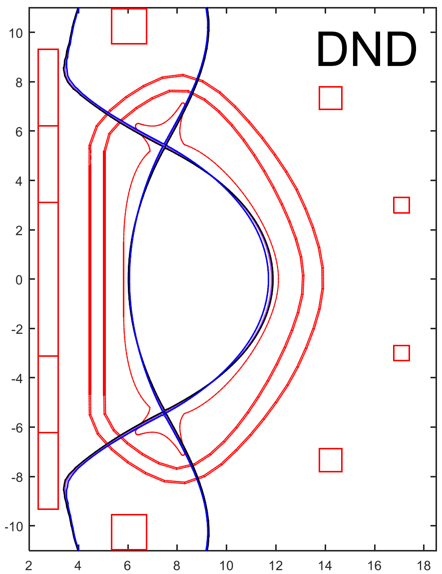
Minor disruption

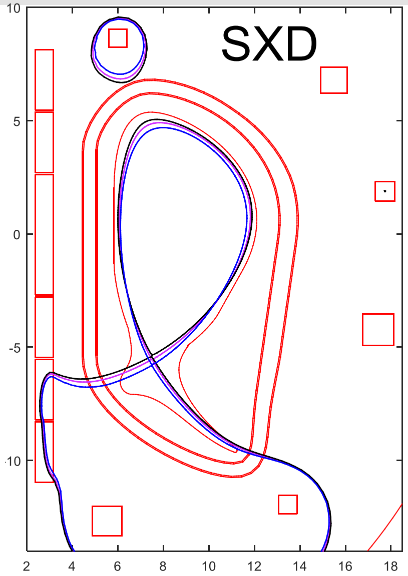
$$\Delta L_i = -0.1, \Delta\beta_{pol} = -0.1$$

Big ELM

$$\Delta L_i = 0.1, \Delta\beta_{pol} = -0.1$$

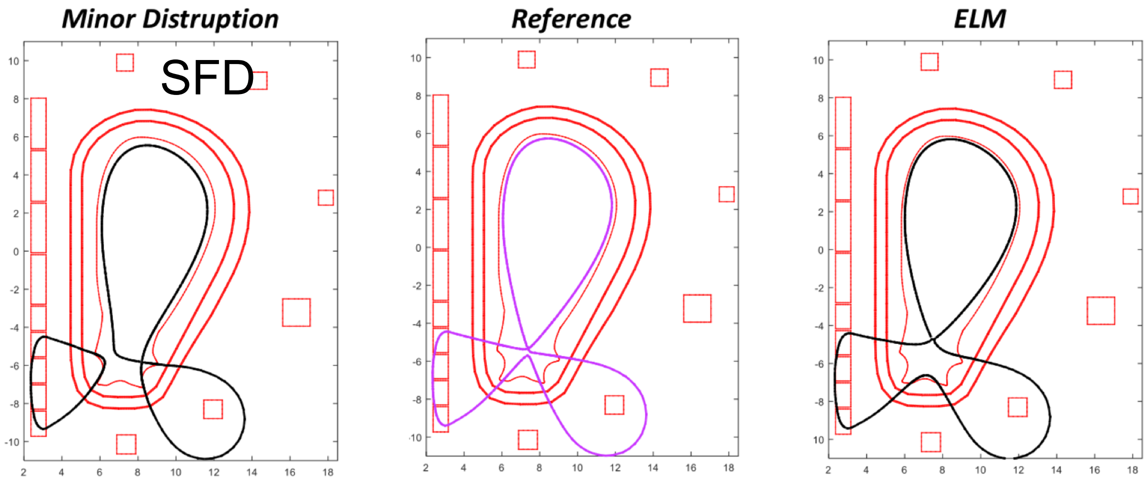


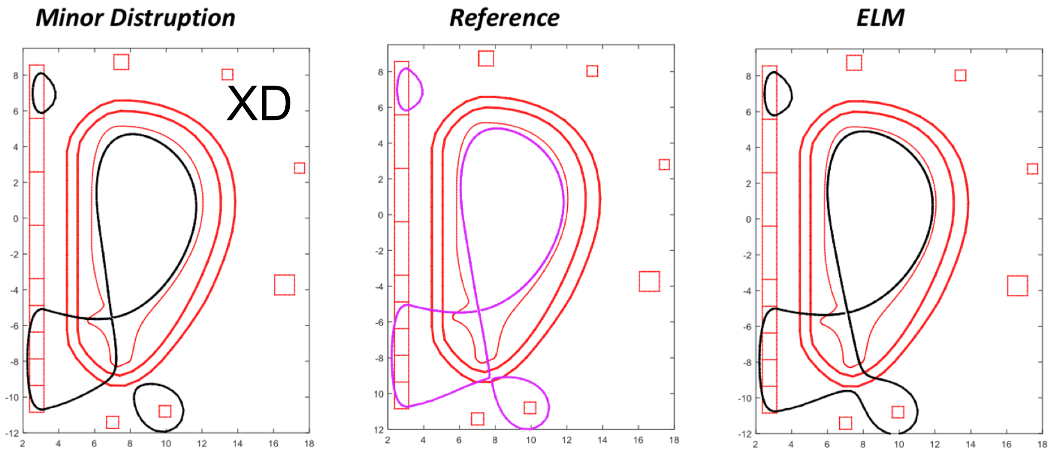




asymmetric perturbations not yet considered

Shape variation might be a problem, especially for upper wall (ΔZ~25cm)





Pronounced shape and topological variations

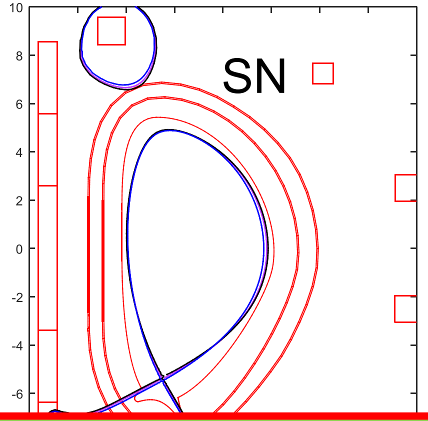
Strike point sweeps on the plate, but f_x remains constant.

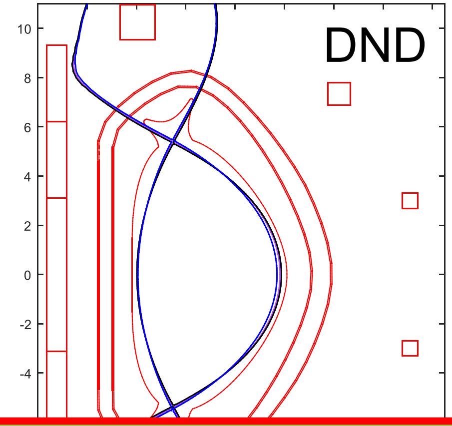
Control

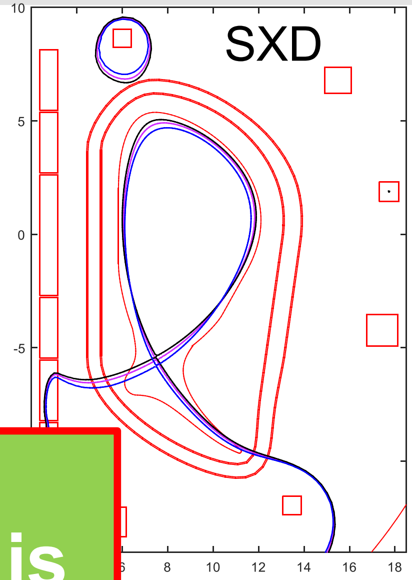
- A minor disruption and a big ELM were simulated imposing:

Minor disruption
$$\Delta L_i = -0.1, \Delta\beta_{pol} = -0.1$$

Big ELM
$$\Delta L_i = 0.1, \Delta\beta_{pol} = -0.1$$







Take home message is that control is difficult for all ADC configurations

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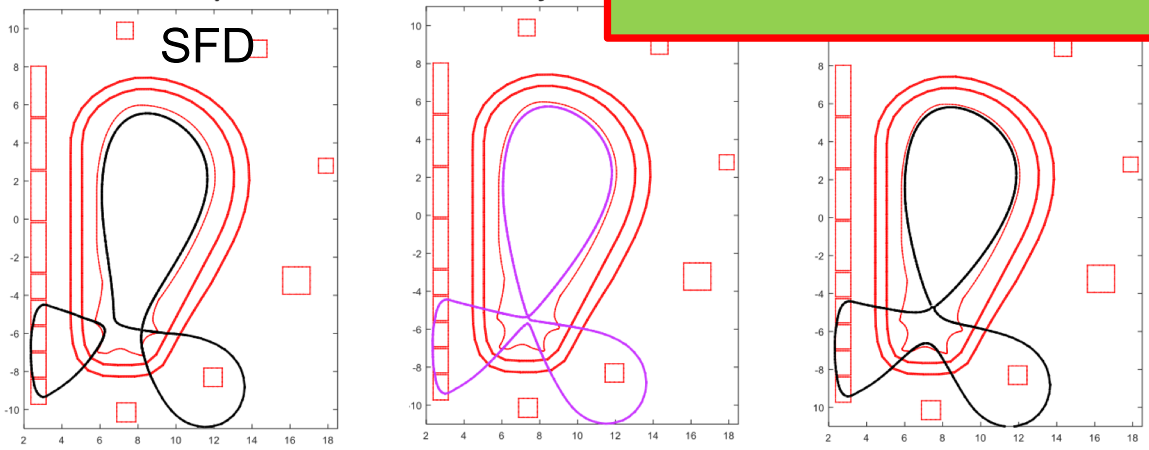
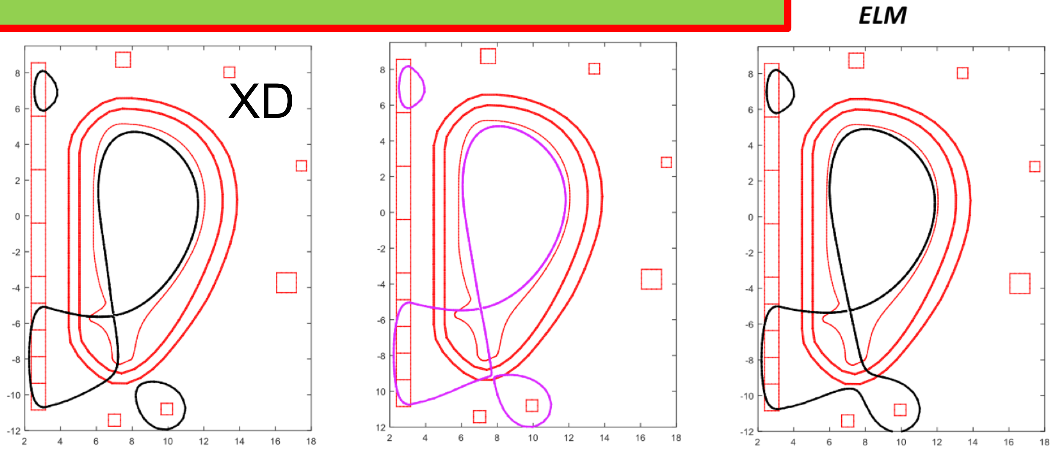




Pronounced shape and topological variations

Strike point sweeps on the plate, but f_x remains constant.

Summary and Conclusions

- **A broad overview of the benefits and challenges of the alternative configurations is ongoing.**
- **Take home messages:**
  - **physics procedure and potentially (!) the trends established;**
  - **interplay between intercoil structures and ports is crucial;**
  - **outer TF section and OoP forces are critical for the ADC designs;**
  - **remote maintenance is a key constraint;**
  - **control is difficult for all ADC configurations.**
- **Options:**
  - **Exploit the continuity between SN/SXD/XD.**
  - **Optimize the supporting engineering structures when possible.**
- **Conclusions:**
  - **For the SN the physics is challenging but the engineering is appealing;**
  - **For the ADCs the physics is appealing but the engineering is challenging;**
  - **<u>There is no magic bullet</u>**

- Backup slides

The "looping away" strategy

- For a reliable assessment, four loops are envisaged between now and December 2023:

Base

2018-19

Base with internal coils

2019-20

Hybrid or novel

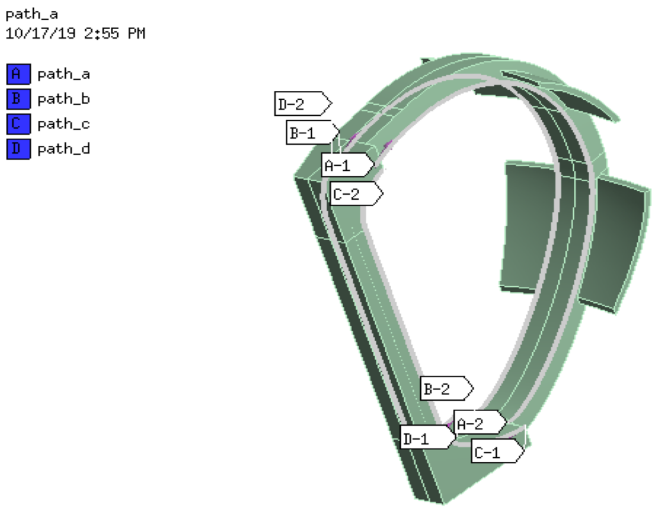
2020-21

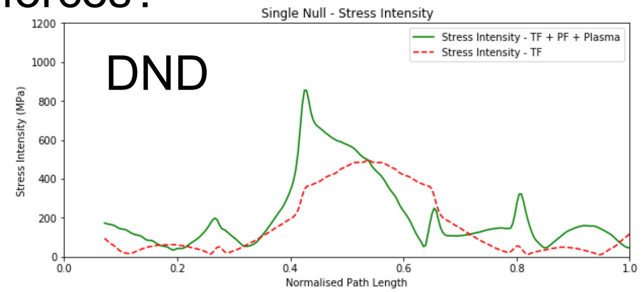
Optimized

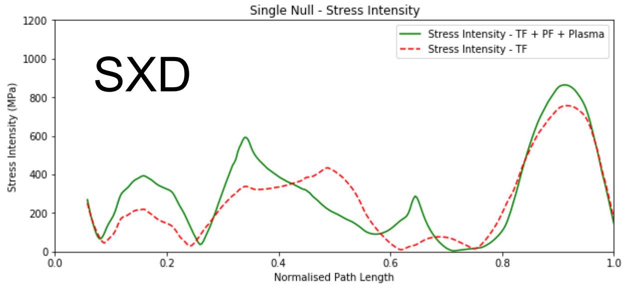
2022-23

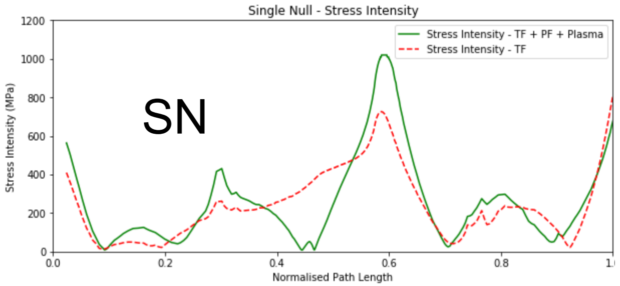
Out of plane forces and fatigue

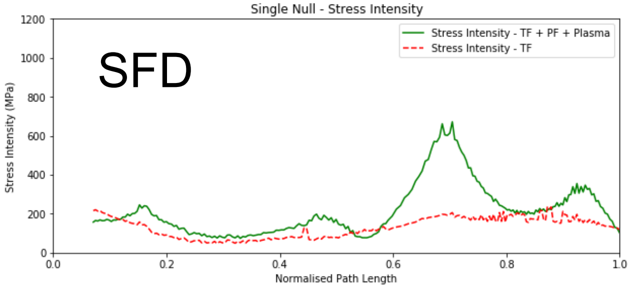
- Hoop forces not enough to induce failure per se most of the time (some exceptions in SXD and XD).
- Out of plane forces can count for ~30% of the total in critical points, thus inducing failure.
- Princeton D-shape not essential. Increasing rigidity with inter-coil structures can help.
- In DEMO, PF and plasma currents will be pulsed. Fatigue from OoP forces?

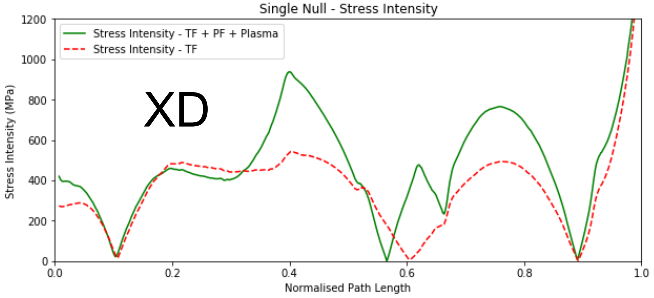




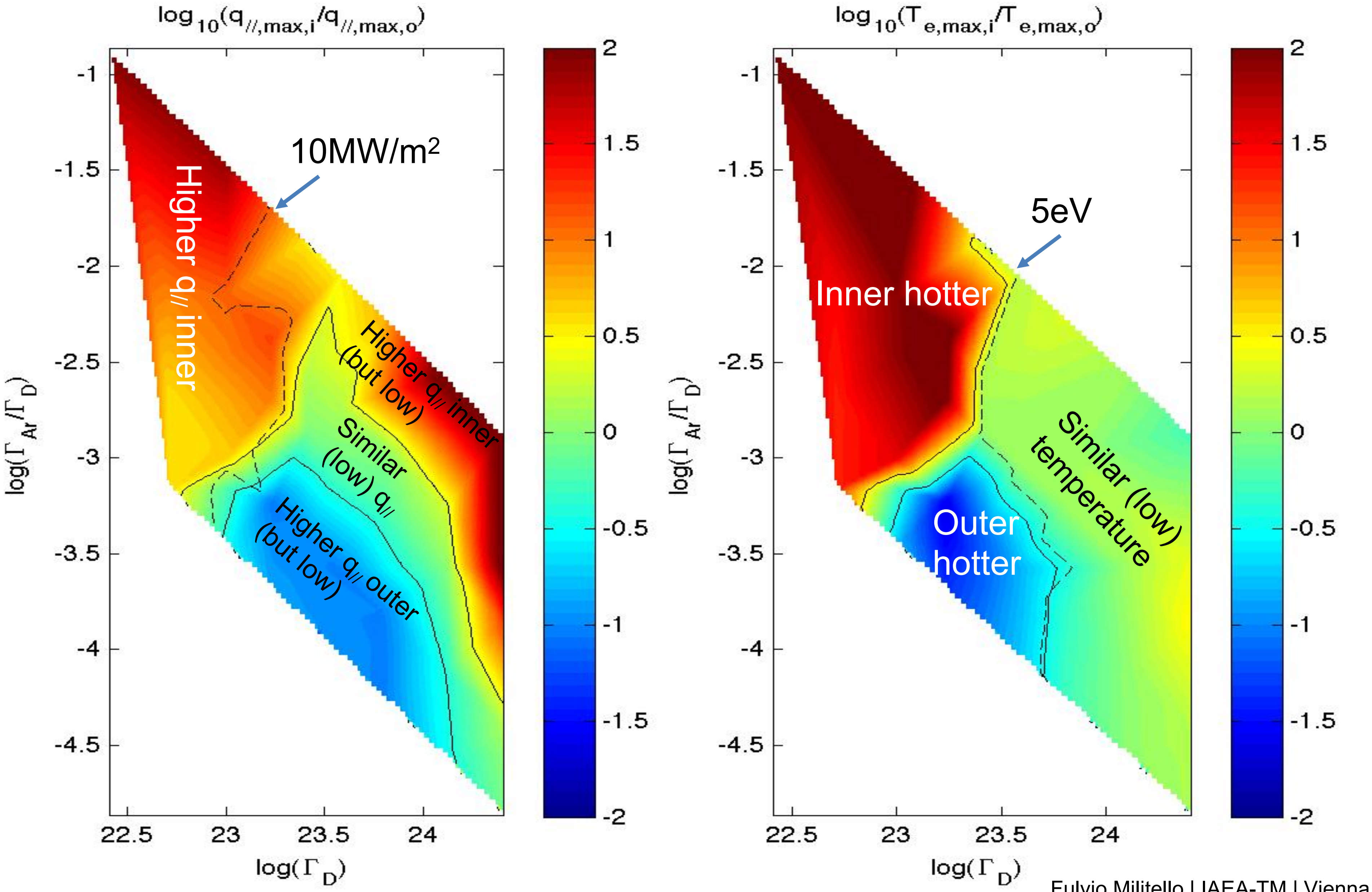








In/out asymmetry in SXD



ADC features

		SND	XD	SXD	SFD	DND
Shape	Elongation $k_{95\%}$	1.65	1.65	1.65	1.65	1.65
	Trinagularity $\delta_{95\%}$	0.33	0.29	0.33	0.24	0.33
	Volume V_{pl} $[m^3]$	2360	2365	2340	2360	2350
	V_{TF}/V_{pl}	3.87	4.02	4.85	4.04	4.15
X-point	R_{xpt} [m]	7.51	7.08	7.50	7.42	7.48
	Gradient $\lvert\nabla B_{p,xpt}\rvert$ [T/m]	0.387	0.227	0.247	0.032	0.378
	Vsol (ρ=1mm) [m]	6.40	8.71	8.51	22.7	4.75
	Vsol (ρ =3mm) [m]	17.2	23.4	22.8	46.5	12.6

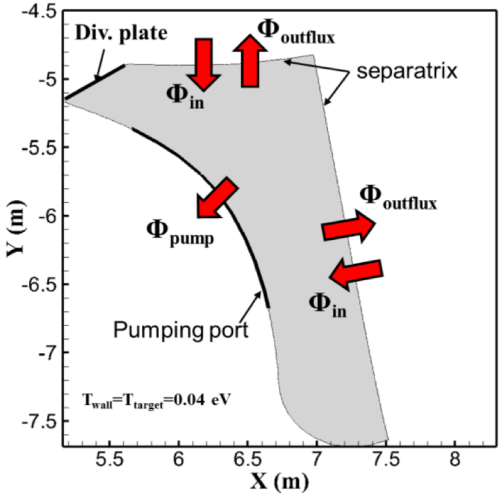
		SN		XD		SXD		SFD		DND
Targets		in	out	in	out	in	out	in	out	up
	L_p [m]	19.3	8.8	18.6	11.1	19.1	12.9	19.3	10.5	8.9
	$L_\parallel$(ρ =1mm) [m]	209	118	234	230	251	201	499	415	114
	$L_\parallel$(ρ =3mm) [m]	191	100	205	202	223	174	348	260	96
	$f_{x,t}/f_{x,min}$	1	1	1	1.29	1	1	1	1	1
	$f_{x,t}$	6.4	3.5	7.8	13.6	8.30	2.42	13.28	10.3	3.38
	R_t/R_x	0.87	1.11	0.83	1.07	0.83	1.45	0.78	1.21	1.10
	g_t [Deg.]	1.50	1.56	1.52	1.49	1.51	1.57	1.50	1.55	1.50
	b_t [Deg.]	27.1	15.3	34.5	75.1	38.7	11.1	88.5	53.1	14.3

Pumping

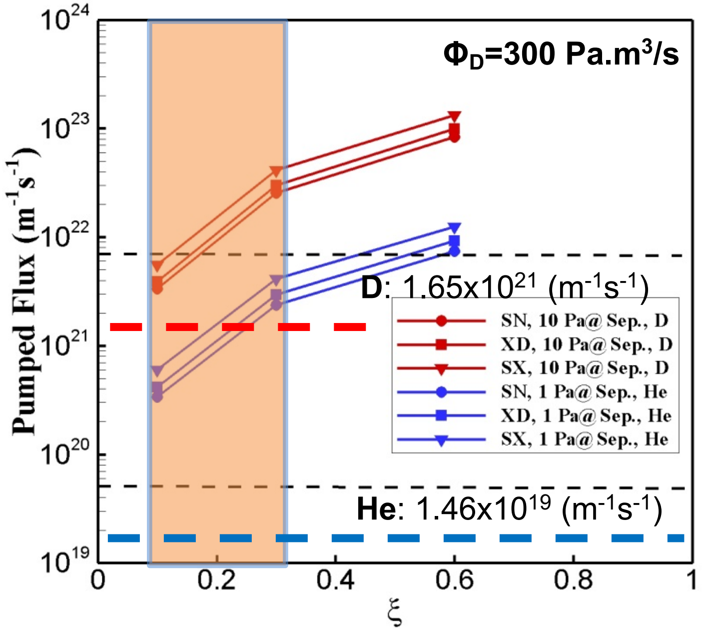
- Kinetic Monte Carlo simulations (DIVGAS) were performed to assess pumping performance in different geometries assuming given incoming flux.
- Within a realisitc range of capture coefficient ξ, Helium removal is feasible.
- The XD divertor compared with the reference SN case allows for higher neutral compression in the PFR, thus facilitating pumping. For the case of SX divertor this effect is even more pronounced

ξ =probability that the particle is pumped at the pump

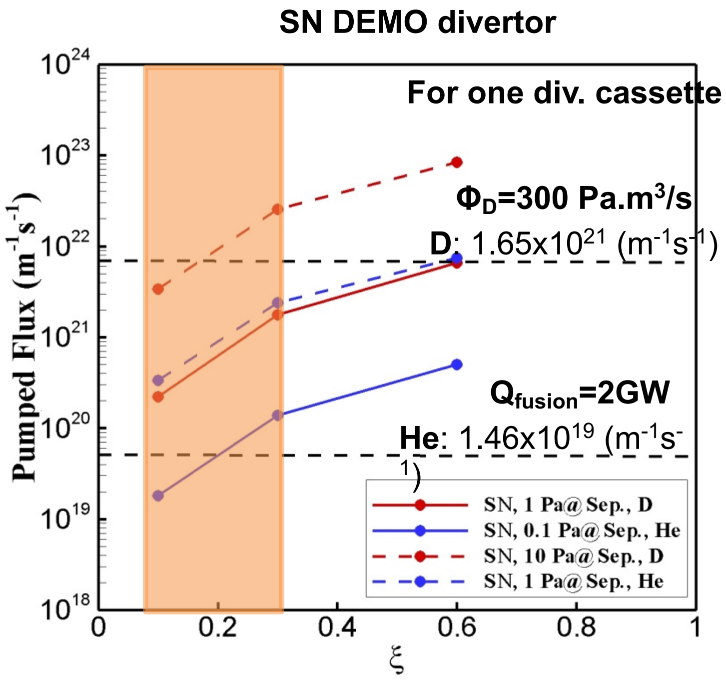
(Pumped flux in molecules per second per toroidal length)

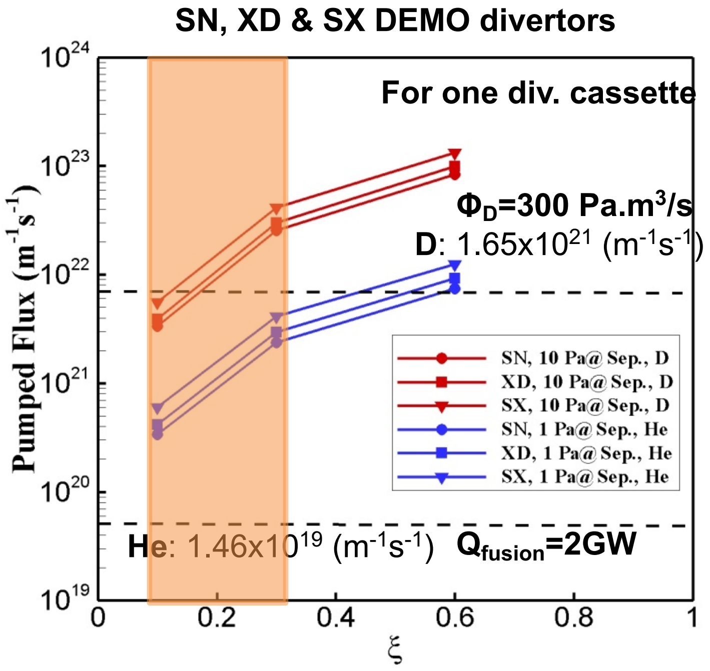


SN, XD & SX DEMO divertors



Pumping





- Higher neutral pressure and gas collisionality at PFR, allow for imrpoved helium removal. More specific, within a realisitc range of capture coefficient ξ, helium removal is feasible, whereas the fuel gas pumping can be realized at ξ above 0.2, assuming that the fuel particle throughput is 300 Pa.m^3/s.

- The simulations show that the design of the pumping system is crucial and challenging in order to satisfy the particle exhaust requirements.

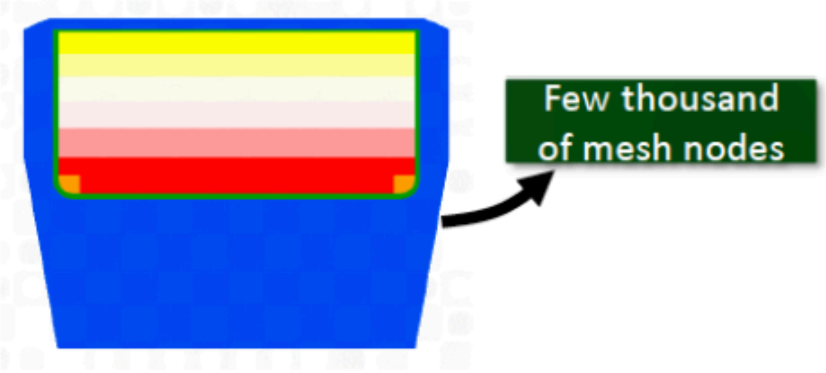
- The XD divertor compared with the reference SN case allows for higher neutral compression in the PFR, thus facilitating pumping. For the case of SX divertor this effect is even more pronounced.

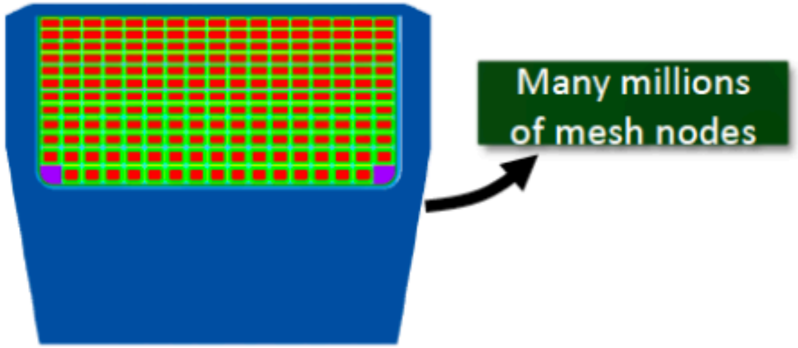
For more details please visit Poster #11, Y. Igitkhanov (6th Nov 2019, Session III)

Specifications of the equilibrium

- plasma current profile parameters:
  - Plasma current $I_{pl} = 19.07MA$
  - poloidal beta $\beta_p = 1.141$
  - internal inductance $l_i = 0.8$
  - Two different values of the flux on the plasma boundary with a constant plasma current $I_{pl} = 19.07MA$ shall be considered: at Start of Flat Top (SOF) and End of Flat Top (EOF)
- flat-top plasma shape parameters
  - $R \cong 8.938m$
  - $AR \cong 3.1$
  - $k_{95} \cong 1.65$
  - $\delta_{95} \cong 0.33$
  - $V_{pl} \cong 2466\ m^3$
- ***PF coil current***
- Poloidal coils cross-sections shall be determined assuming a current density limit of 12.5MA / m^2
- ***Magnetic field***
- The maximum field at the location of the PF and CS coils shall not exceed 12.5T
- ***Vertical Forces***
- Maximum vertical force on a single PF shall not exceed 450 MN
- Maximum vertical force on the CS stack shall not exceed 300 MN
- Maximum separation force in the CS stack shall not exceed 350 MN
- In case of two or more PF coils positioned close to each other: over a 3m poloidal length, the total vertical force from the poloidal coils on the supports shall not exceed 450MN
- ***TF coils***
- A 16 TF coil cage shaped to keep ripple below 0.6%
- Presence of TF shells not up-down symmetric
- ***Divertor***
- Distance between the divertor plates and the X-point region <1m
- Minimum grazing angle 1.5deg

- Simplified assumptions on internal structure of the winding pack.
- Correctness of the approach checked by WP-MAG.
- EM forces calculated on 9 filaments – convergence studies assessed it is ok.
- 1) calculate the principal stresses;
- 2) linearize them through the thickness of the component by splitting the actual stress/position function into a peak (maximum), a membrane (average) and a bending component (linear fit corresponding to the equivalent torque);
- 3) application of Tresca criterion on the membrane with failure limit of 660 MPa and on the membrane + bending with failure limit of 870 MPa.





aged variant of the 316LN steel alloy