Design process of the DTT divertor cryopumps –
An engineering view on particle exhaust modelling

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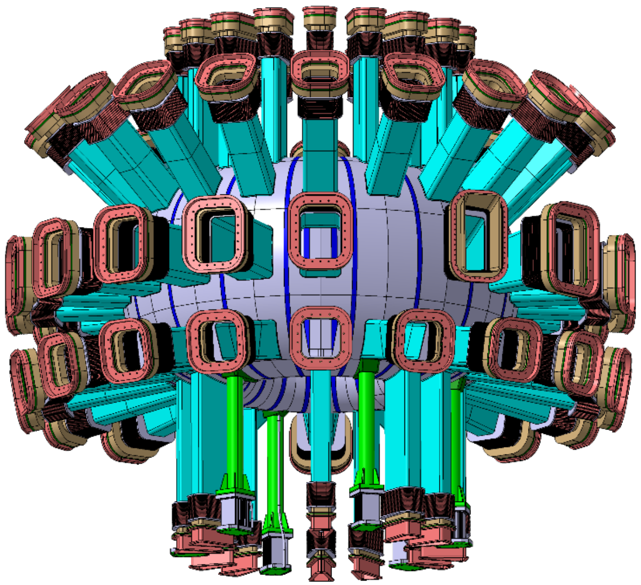
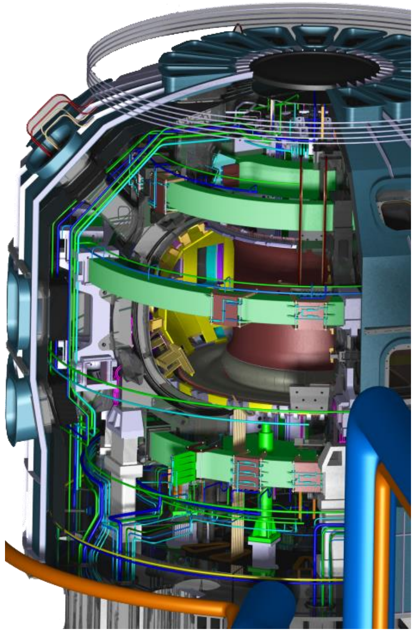
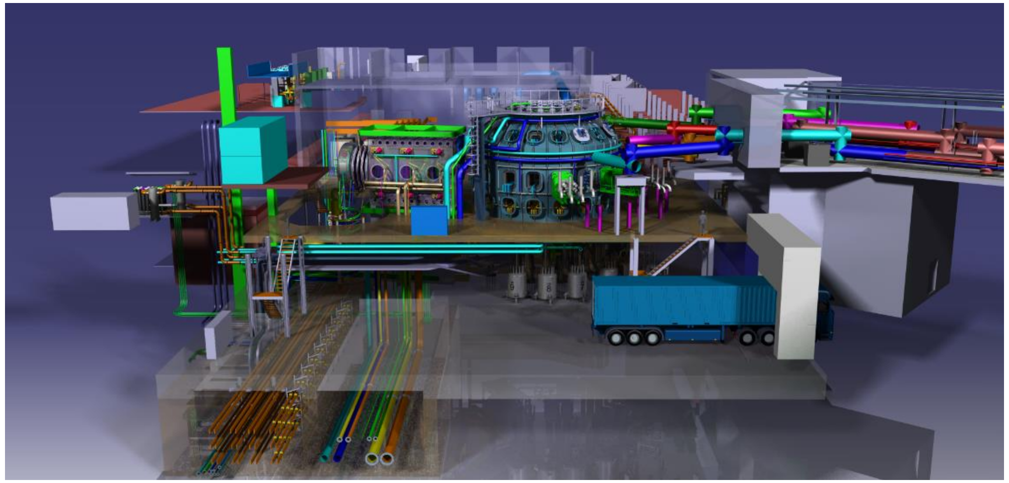
The Divertor Tokamak Test Facility (DTT)

- DTT is a new superconducting tokamak under construction in Italy (ENEA Frascati), organized under the DTT Consortium
- Main scientific goals are to address the key divertor related questions in the EUROfusion roadmap:
  - Investigate energy and particle exhaust challenge in integrated scenario (plasma/divertor/materials)
- EUROfusion with its work package WP DIV is co-funding the provision of the first divertor (PFC and cassettes) and its vacuum pumping system







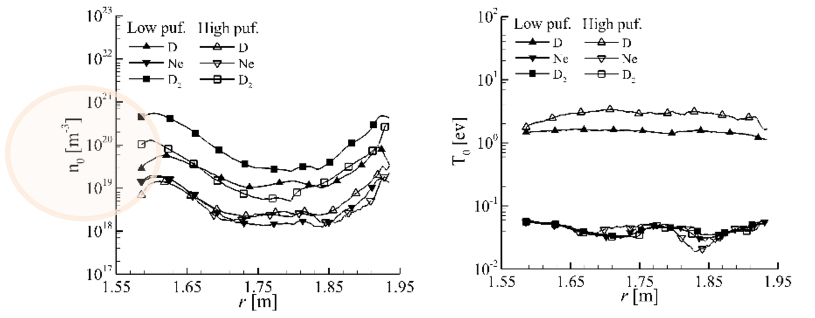
2D Pre-assessment of pumping port space: Plasma

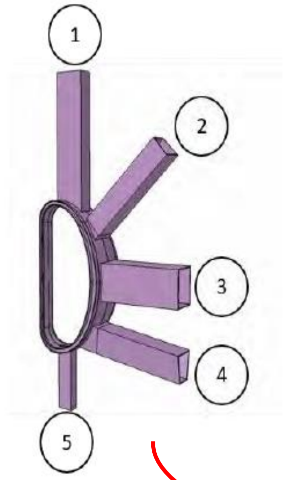
L. Balbinot et al., Development of DTT SN divertor scenario, Nuclear Mat. Energy (2021)

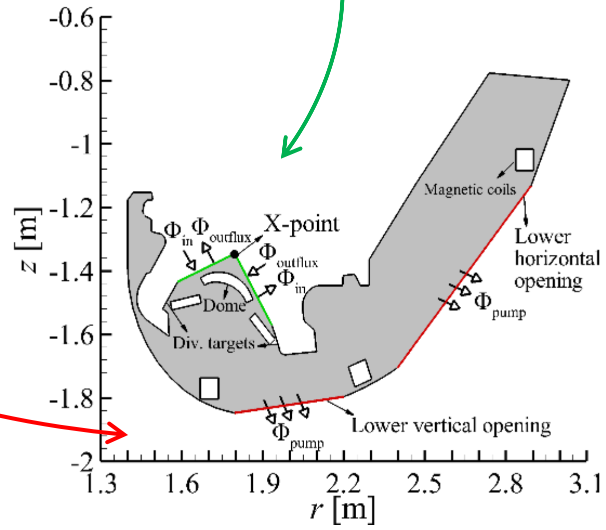
- Based on a representative plasma scenario established in *preliminary exploration studies with an ITER-like divertor* :
  - Maximum additional power (45 MW)
  - Fully detached, impurity seeding with Ne
  - Target density: $n_{e,sep}=8 \cdot 10^{19}/m^3$ ($0.7\ n_G$)
  - Two core fueling flow rates:

    $\Gamma_D=1.5 \cdot 10^{22}$ D/s, $\Gamma_{Ne}=1.2 \cdot 10^{20}$ Ne/s (low rate, 29 Pam³/s D_2)

    $\Gamma_D=5.3 \cdot 10^{22}$ D/s, $\Gamma_{Ne}=1.5 \cdot 10^{21}$ Ne/s (high rate, 103 Pam³/s D_2)
- Density and temperature distribution along the inner and outer separatrix legs (calculated with SolEdge2D-EIRENE) coupled as boundary conditions for the neutral gas computational domain (calculated in 2D with the DIVGAS code)
- Pumped flux expressed by dimensionless capture coefficient ξ: $S_{eff} = \xi * A * \bar{v}/4$





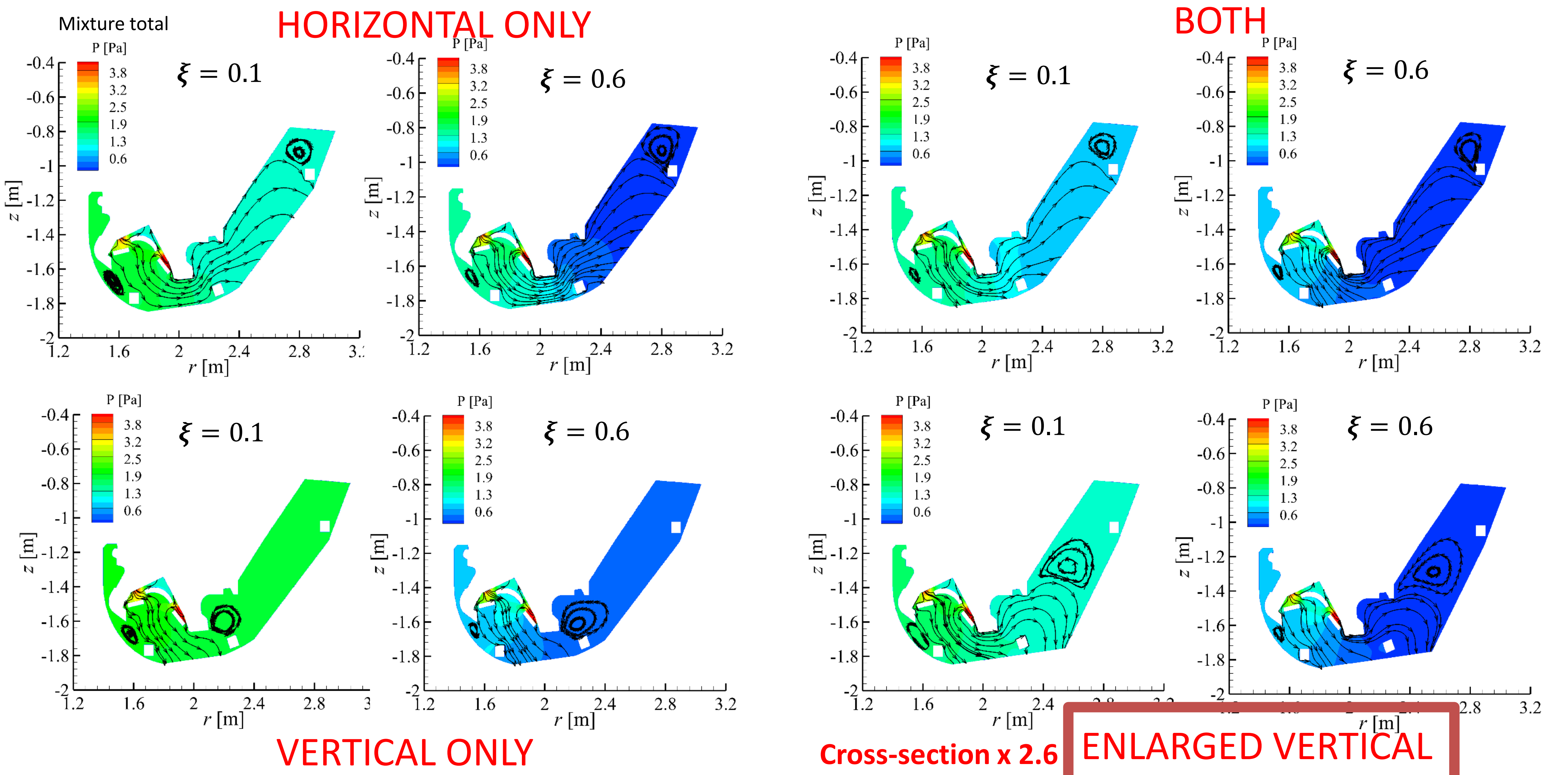


Comparison of port configs

2D Pre-assessment of pumping port space: Results

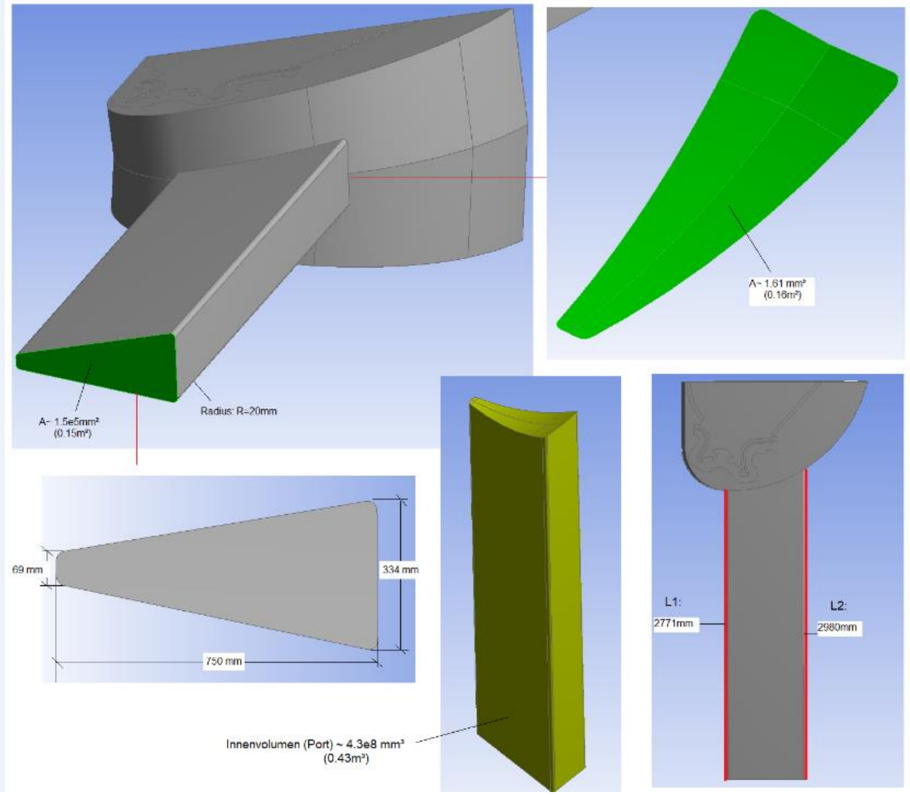
Divertor pressure map at high flow rate scenario

Chr. Tantos et al., DSMC simulations of neutral gas flow in the DTT particle exhaust system, Nuclear Fusion (2022)



Now geometry given – but which pump technology?

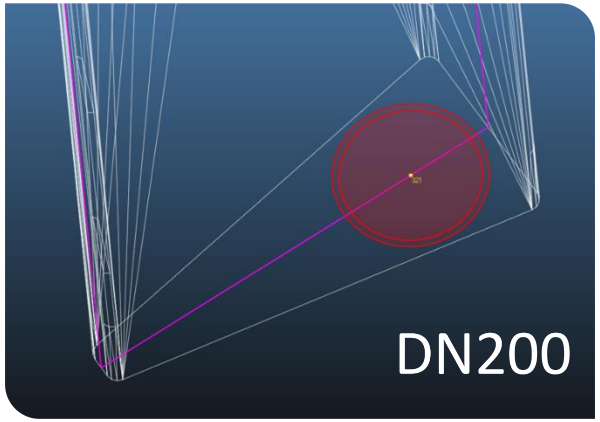
- Updated charge based on the pre-assessment results: Develop a pumping system solely based on the enlarged lower vertical ports (Port # 5).
- Target is: nine (max 10) of these ports.
- DIVGAS allows to unfold the throughput Throughput=pressure x pumping speed.
- At the found pump port inlet pressure of 1 Pa, this translates in a required pumping speed of 11.8 m³/s/port, i.e. a capture coefficient of $\xi = 0.23$
- A conservative assessment (free molecular flow using MOLFLOW+ code) was done on two candidate divertor pumping technologies: cryogenic pumping vs NEG pumping (non-evaporable getter).



Attached pumping

Deuterium

Sticking factor at outlet [-]	Capture coefficient ξ [-]	Eff. Pumping speed [m³/s]
0.2	0.086	4.17
0.3	0.101	4.91
1.0	0.135	6.52

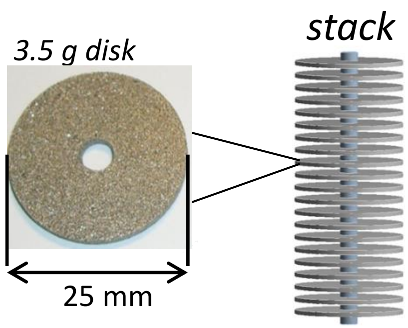


Sticking factor at outlet [-]	Capture coefficient ξ [-]	Eff. Pumping speed [m³/s]
0.2	0.007	0.35
0.3	0.011	0.52
1.0	0.031	1.49

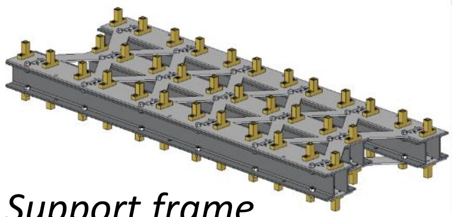
$$S_{\mathrm{eff}} = \xi * A * \bar{v}/4$$

Insufficient pumping speed → in-port solution necessary.

NEG optimisation



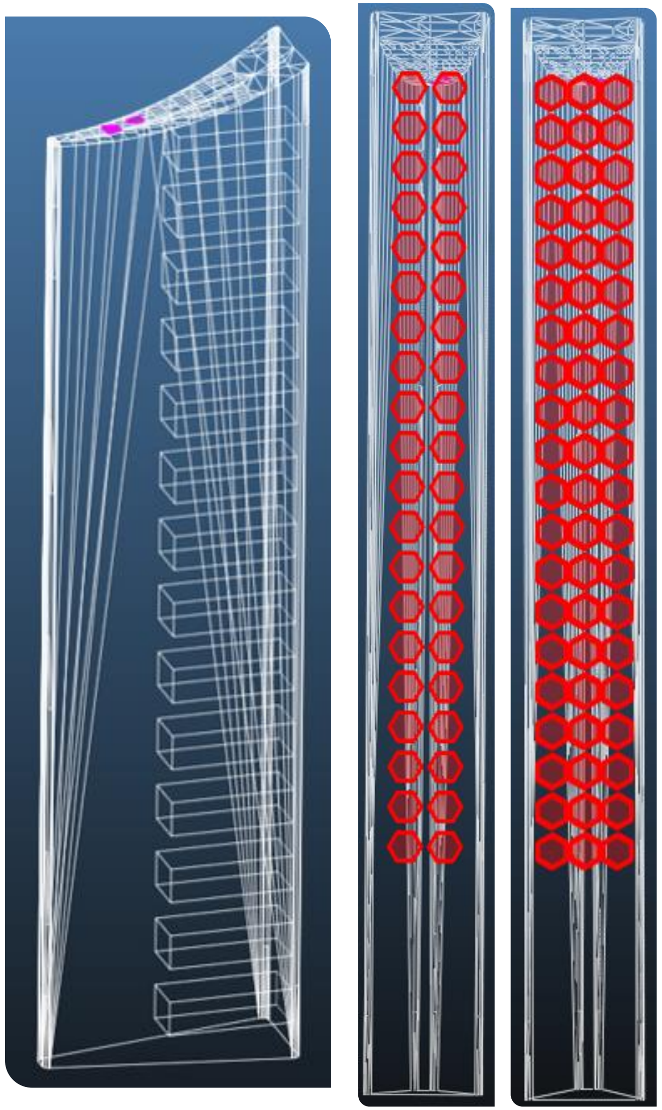
getter cartridge



Support frame

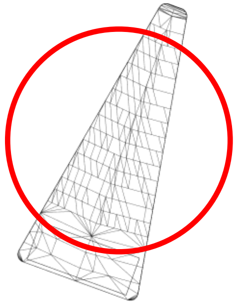
Example New material ZaO (SAES Getters), Characterized for NBI vacuum pumping

In-situ NEG
Downside:
Needs extra pumping system for the noble gases



Integral ξ=0.18.........0.21...0.23

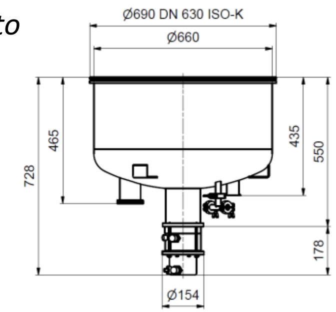
Idea for attached noble gas pumping system:

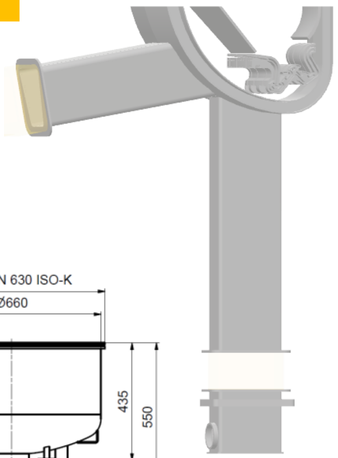


DIFFICULT

20 m³/s Ne,
Sticking ~0.3,

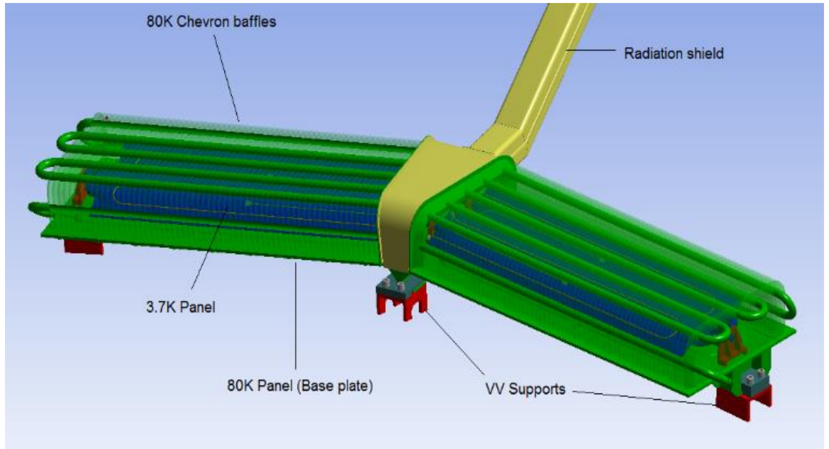
Eventually with additional water cooled baffle to shield against warm NEG





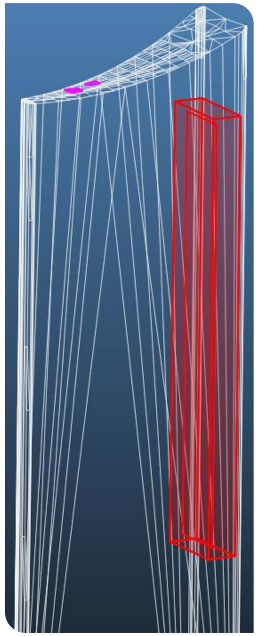
Cryo optimisation

In-situ Cryo
Downside: needs cryoplant



Example: JT-60SA customized cryopump

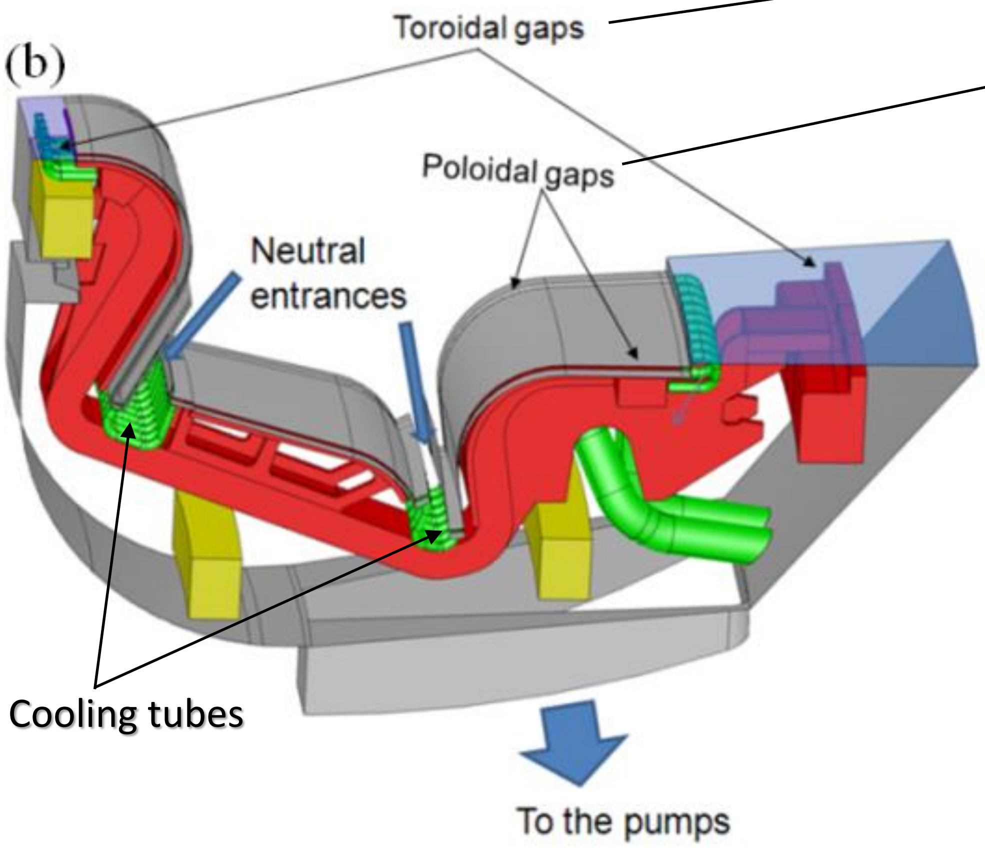
4.2 K Cryopanel: sticking probability=95%, 80 K baffle: transmission probability 30%

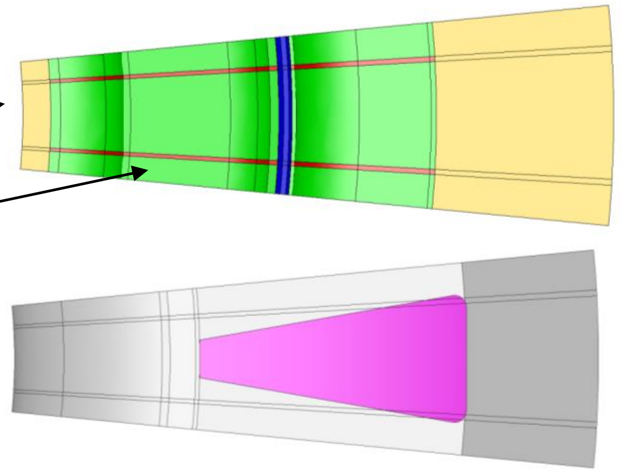


WORKS

- 1 Panel 1440x270mm
- capture coefficient = 24.3%
- S_{eff}= 11.8 m³/s
- 2 Panel 1440x150
- capture coefficient = 26.0%
- S_{eff}= 12.6 m³/s
- 2 long Panel 2100x150
- capture coefficient = 29,0% ✔
- S_{eff}= 14.2 m³/s
- Capacity:
- ~ 550s total pulse time at full throughput. ✔
- Heat load:
- Fits to ~ JT-60SA sized cryoplant w/o < 4K operation ✔

New DTT divertor - Pumping still fine?





- **Neutral entrance:** where the particles are injected based on the provided plasma data
- Toroidal gaps
- Poloidal gaps between the cassettes
- Cooling tubes
- **Pink surface:** Pumping opening, where the neutrals are pumped (0.01<ξ<0.3)
- Updated 2D plasma scenario (partially detached):

  $\Gamma_D = 8.4 \cdot 10^{22}$ D/s, $\Gamma_{Ne} = 1 \cdot 10^{21}$ Ne/s (160 Pam^3/s D_2)

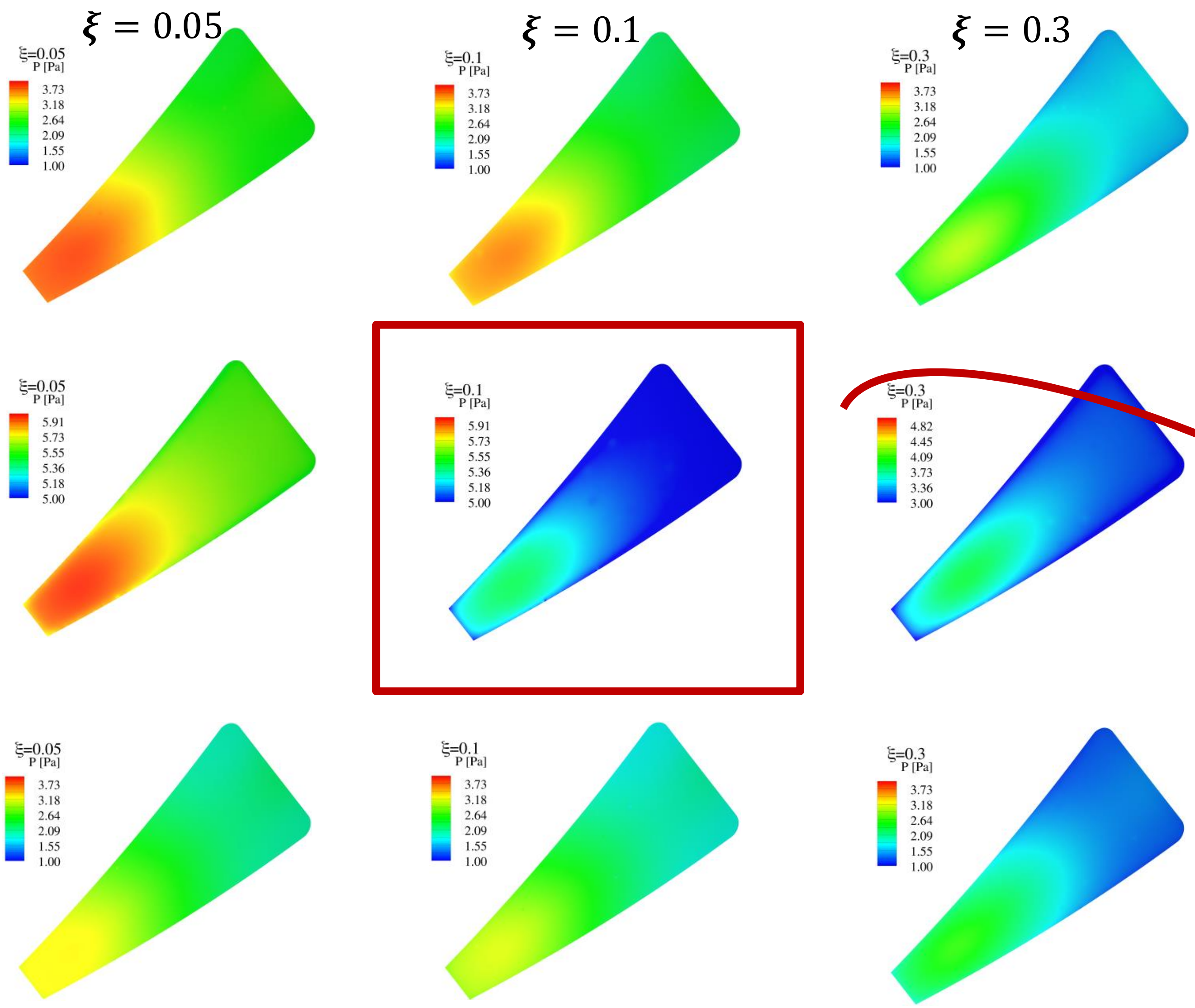
3D assessment

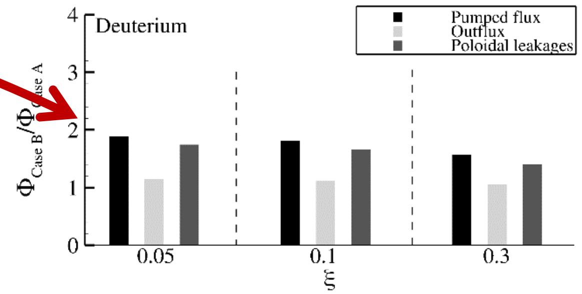
Chr. Tantos et al., 3D DSMC simulations 3D DSMC simulations of neutral gas flow in the DTT particle exhaust, submitted to Nuclear Fusion (2023)

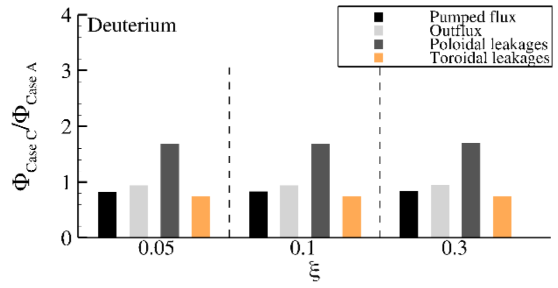
Case 1: basic scenario (incl. toroidal and poloidal leakages)

Case 2: Toroidal leakages closed

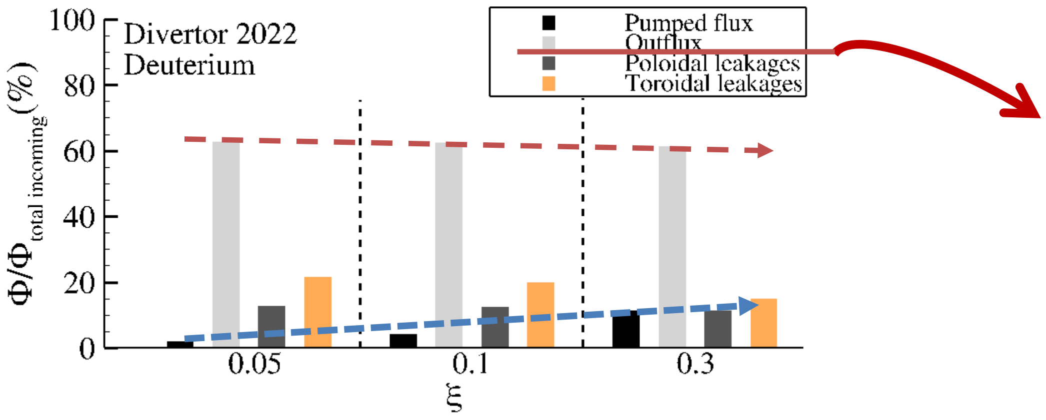
Case 3: Widened poloidal gaps between the cassettes: 10 mm → 20 mm





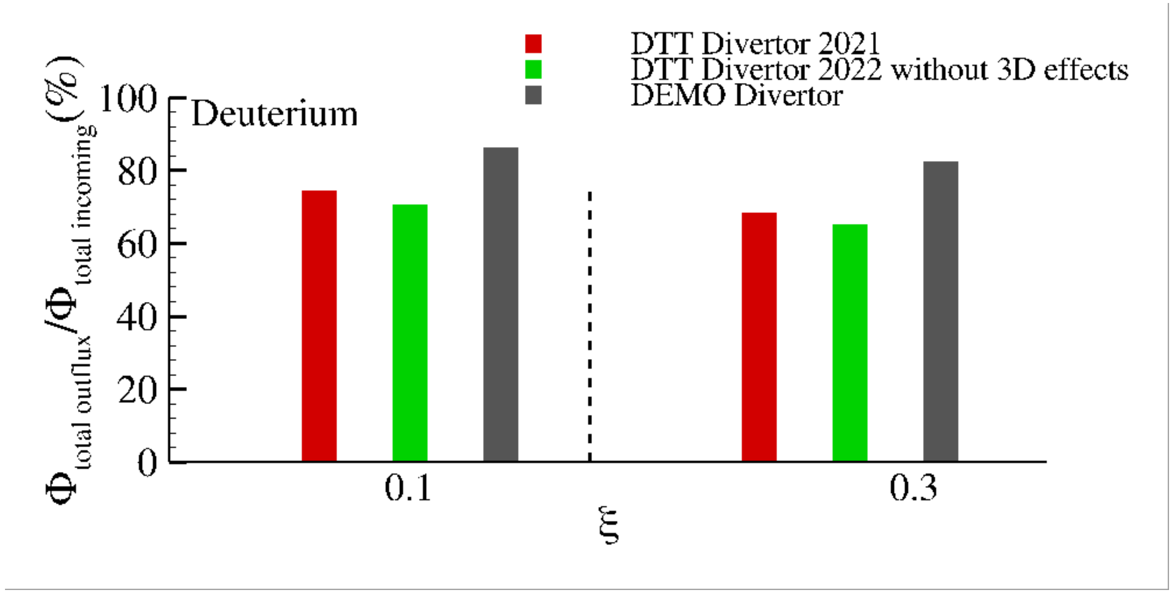


Divertor openness and 3D effects

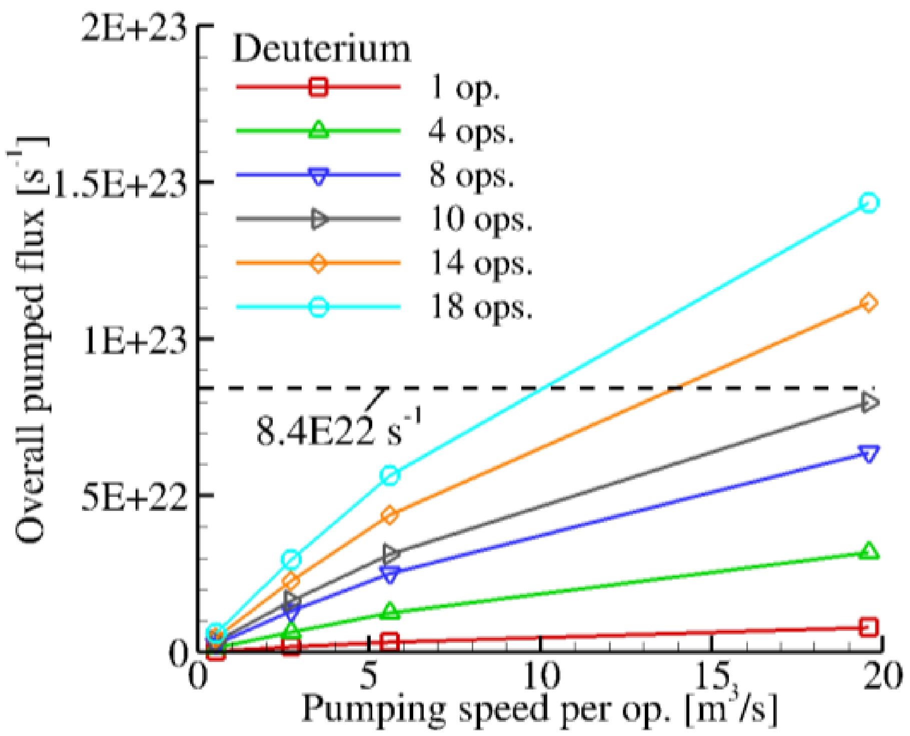


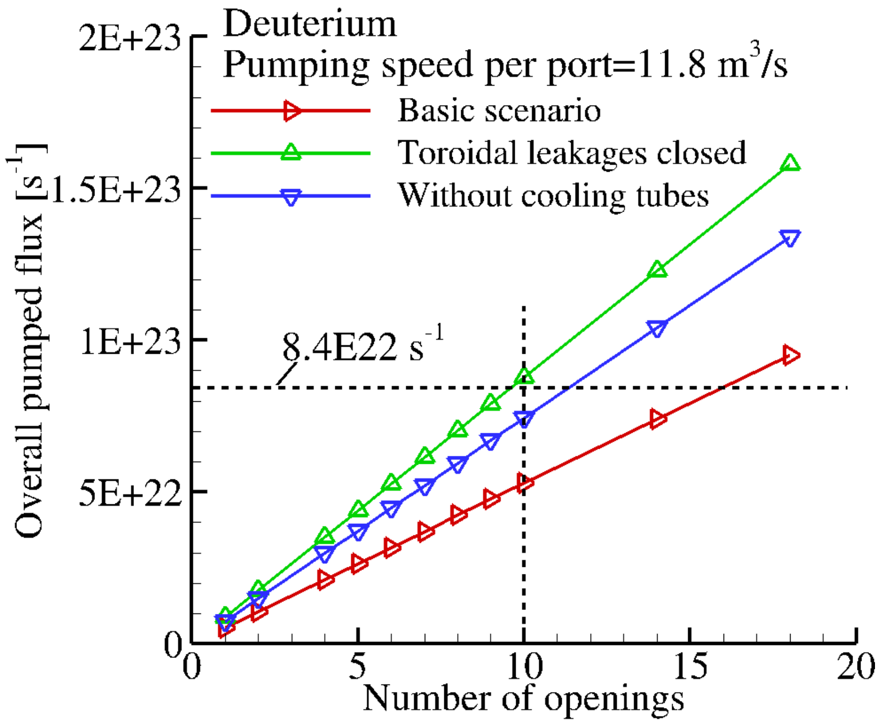
- The loss of particles from the divertor is dominated by the backreflection through the neutral entrance (´outflux´).
- If we eliminate both 3 D leakages, we see that, in this regard, the new divertor behaves a bit better than the 2021.

- Still, from the view of particle exhaust, the outflux is much higher than the pumped flux.
- But this is typical for a fusion divertor, as a comparison with DEMO shows.



Particle exhaust conclusions

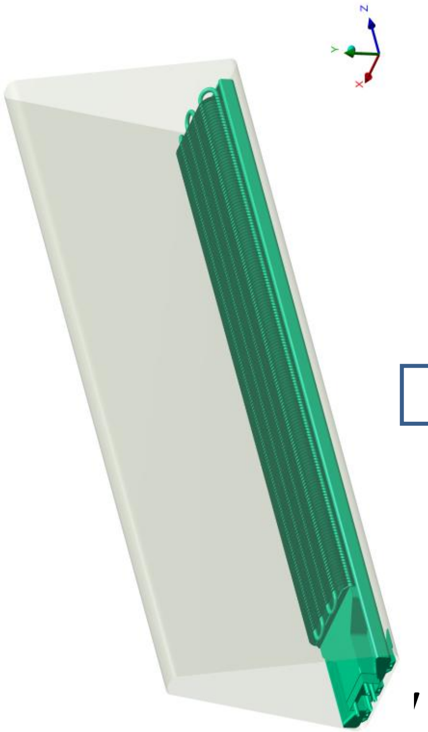


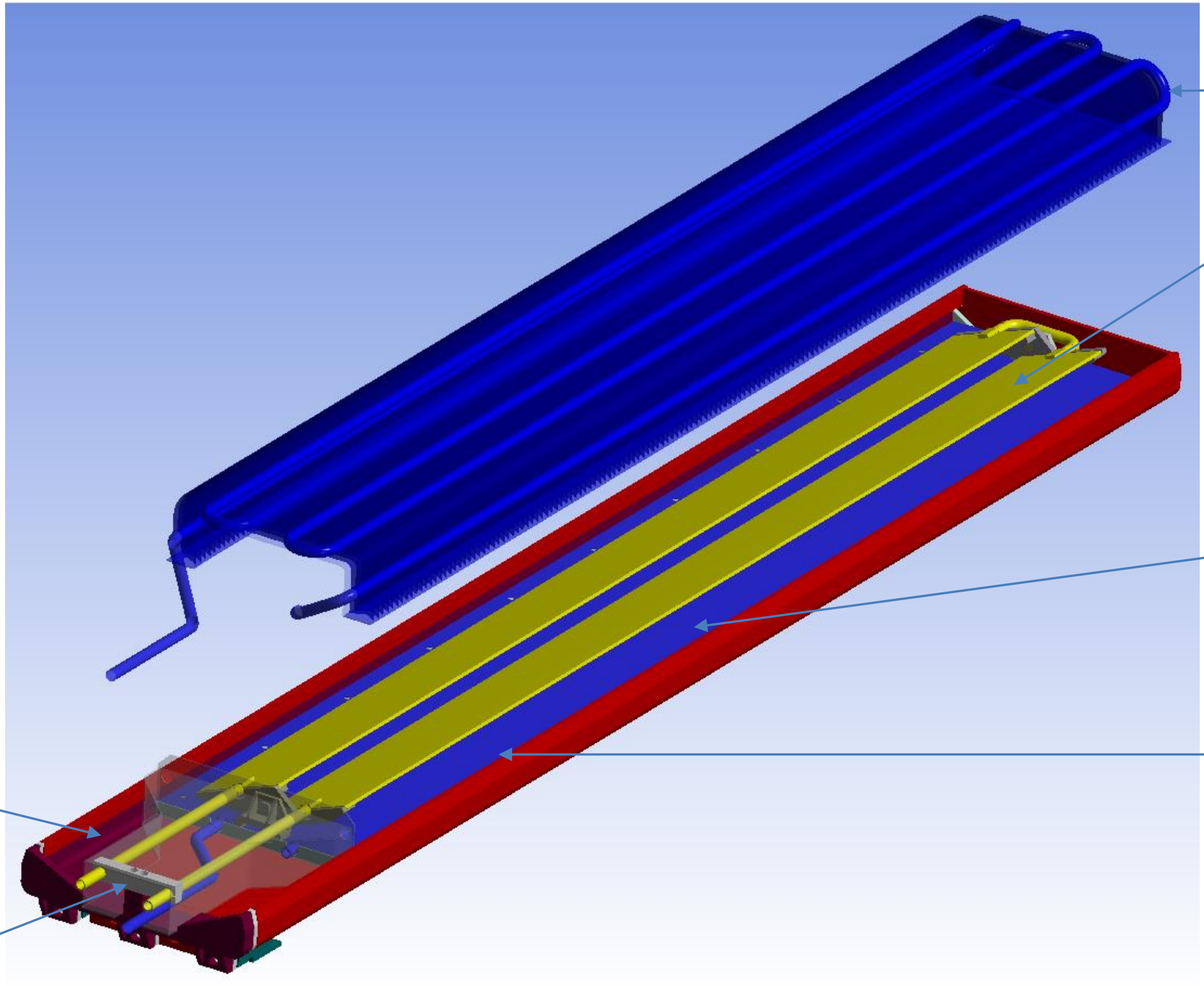


Variation of ξ under 3D conditions showed an improved pumping situation. The requested pumping speed is provided at a lower ξ than was found for the 2D calculations - Now: $\xi = 0.19$

The DTT Single Null divertor can be operated with the reference plasma scenario when being pumped with cryopumps located in 9…10 lower vertical ports, if the toroidal leaks are closed as much as possible.

Cryopump design





80K-Chevrons (deep drawn) 25 kg

4.5K-Panel (hydroformed, charcoal coated) 12 kg
20° inclined
1566x110 → 0.7 m² pumping surface

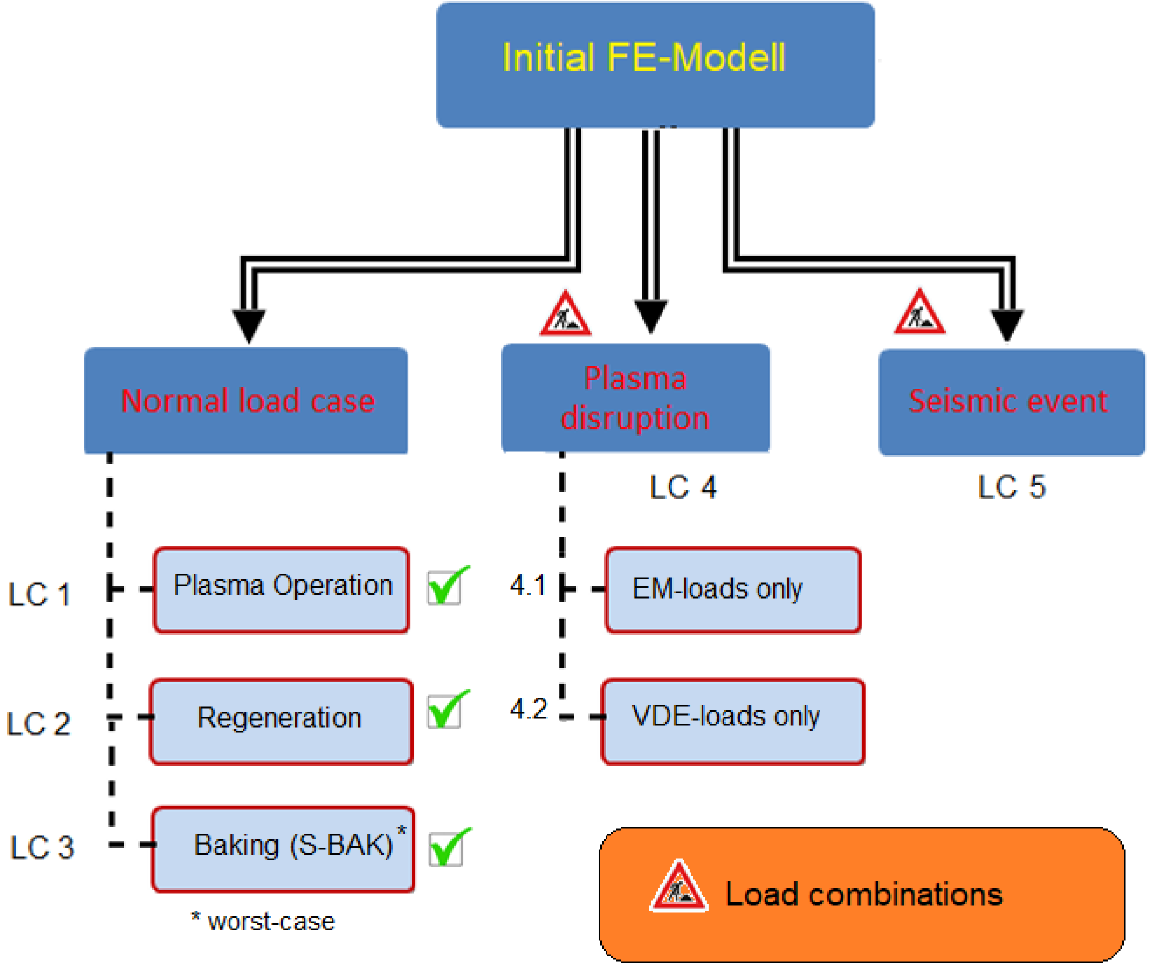
80K-Baseplate (hydroformed) 15 kg

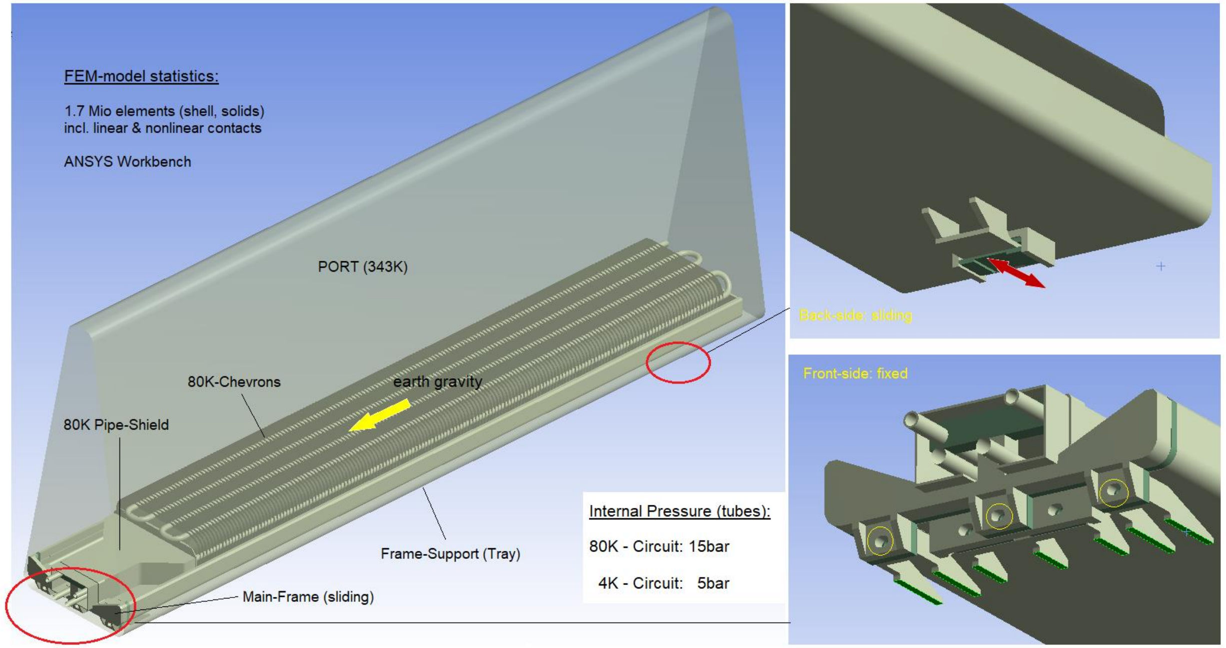
Frame-Tray (outside, red) 28 kg

Main-frame 16 kg

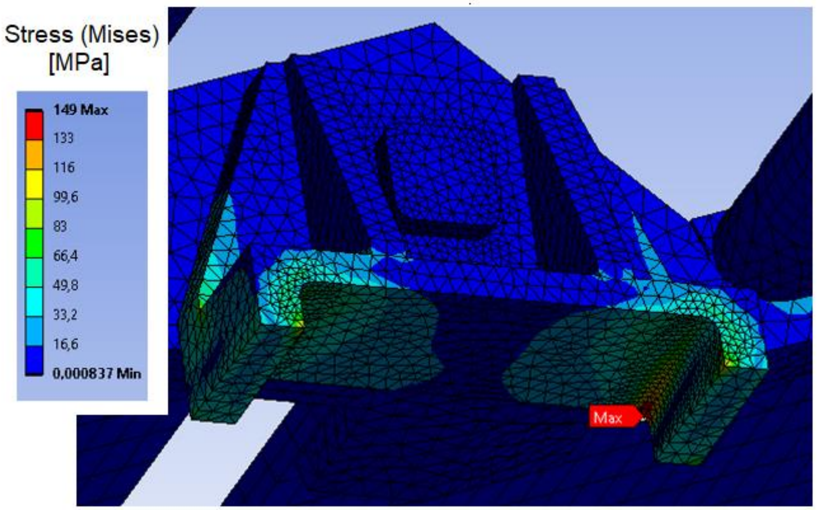
Insulations (Torlon)

Thermomechanical assessment ongoing

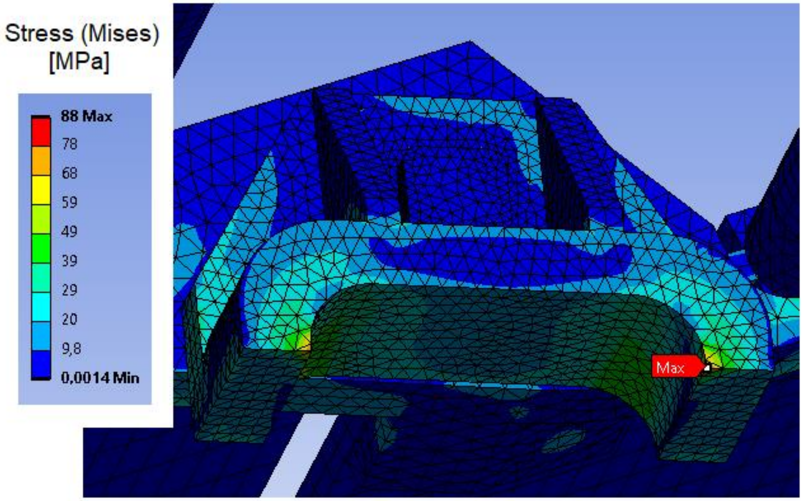




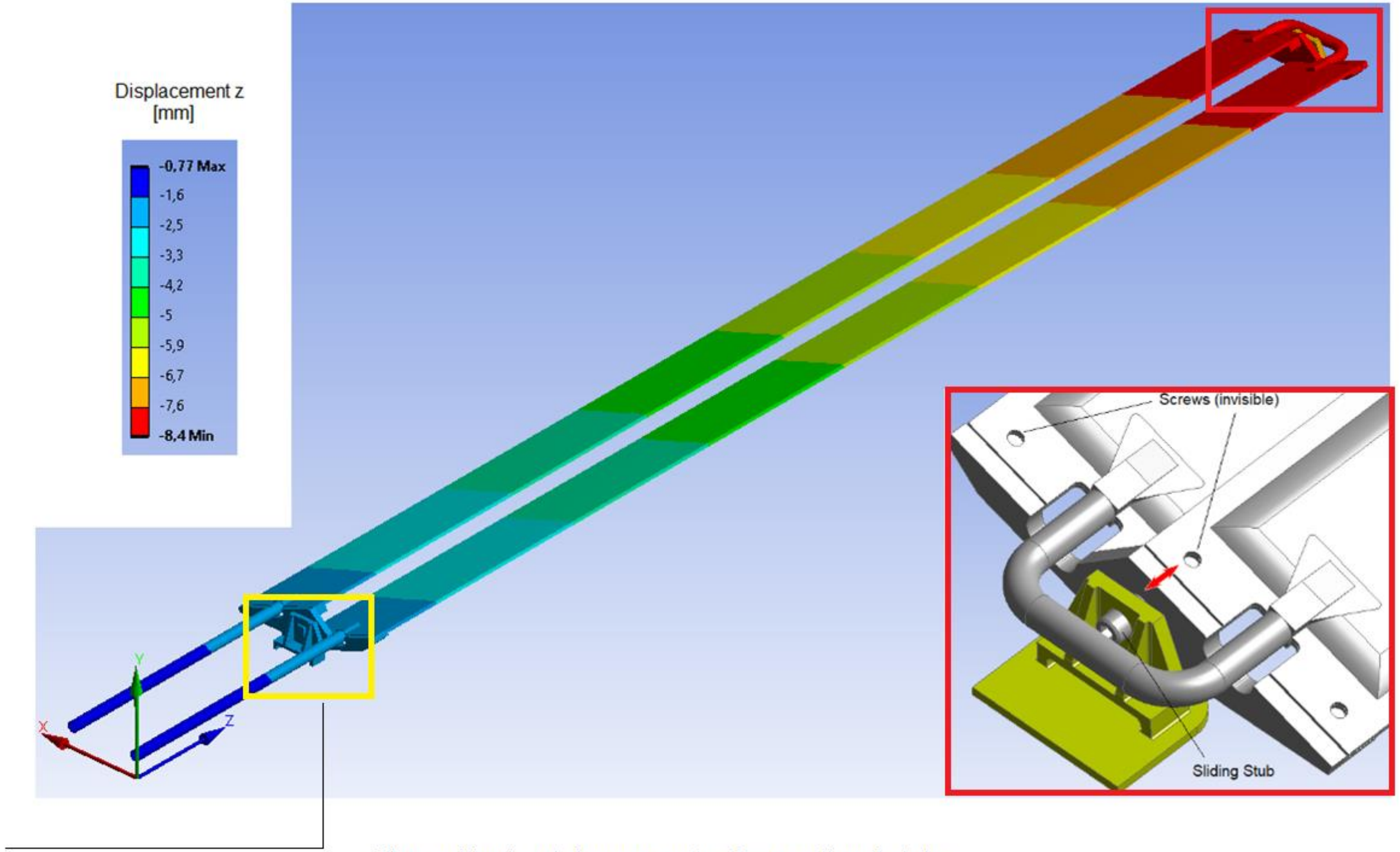
Iterative FEM design optimization



Higher max. stress @ 4K supports - old design



Lower max. stress @ 4K supports - improved design



Thermal horizontal movements @ operational state

Exemplary results

Load case "Operation"

Assembly	Max. stress [MPa]	Temperature [K]	Stress Limit [MPa]*	Safety factor
Frame-Tray	36	288	260	7,2
80K-Shield	132	175	360	2,7
Frame	91	208	355	3,9
80K-Chevrons	168	95	310	1,8
80K-Baseplate	85	90	310	3,6
4.5K Panels	149	53	350	2,3
Fixations (Port)	142	318	250	1,8

Load case "Regeneration"

Assembly	Max. stress [MPa]	Temperature [K]	Stress Limit [MPa]*	Safety factor
Frame-Tray	29	290	260	9,0
80K-Shield	108	180	290	2,7
Frame	88	210	355	4,0
80K-Chevrons	134	114	305	2,3
80K-Baseplate	77	110	305	4,0
4.5K Panels	64	100	310	4,8
Fixations (Port)	105	310	250	2,4

Load case "S-Baking"

Assembly	Max. stress [MPa]	Temperature [K]	Stress Limit [MPa]*	Safety factor
Frame-Support	30	438 (PORT)	180	6,0
80K-Shield	29			6,2
Frame	154			1,2
80K-Chevrons	30			6,0
80K-Baseplate	15			12,0
4.5K Panels	8			22,0
Fixations (Port)	24			7,5

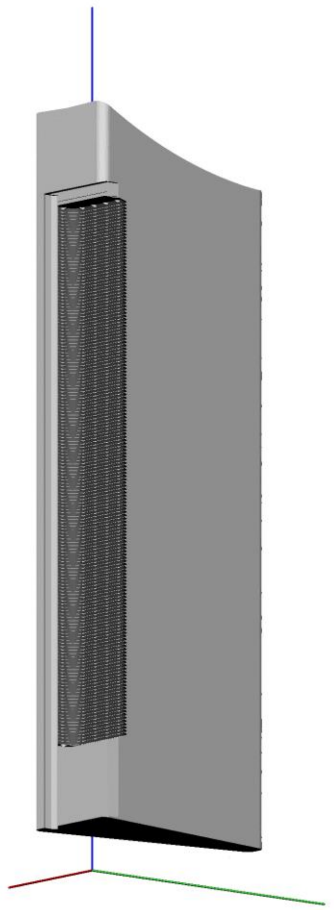
* 1.0% Yield stress is allowed for austenitic stainless steels according to pressure vessel standard EN13445-3
In cases of temperatures below 180K no verified data for 1.0% limit are available - 0.2% values were used.

Heat loads on one cryopump unit

Heat loads	Value
Radiation to the 80 K system	356 W
Radiation to the 4 K system	1.2 W
Gas cooling and adsorption	5.6 W

Collisional modelling of the flow in the pump duct

- With a detailed CAD model of the cryopump being available, one can extend the 3D simulations by integrating the complete port with pump.
- The Knudsen number in the pump duct is found to be in transitional flow (Kn~0.05 at the entrance).
- This flow regime will further help pumping, compared to the conservative collision-free case.
- It will also be calculated how (sorbed amount over time) the pumping surface gets saturated by incoming particles, as a function of the port height.
- The model is under work.

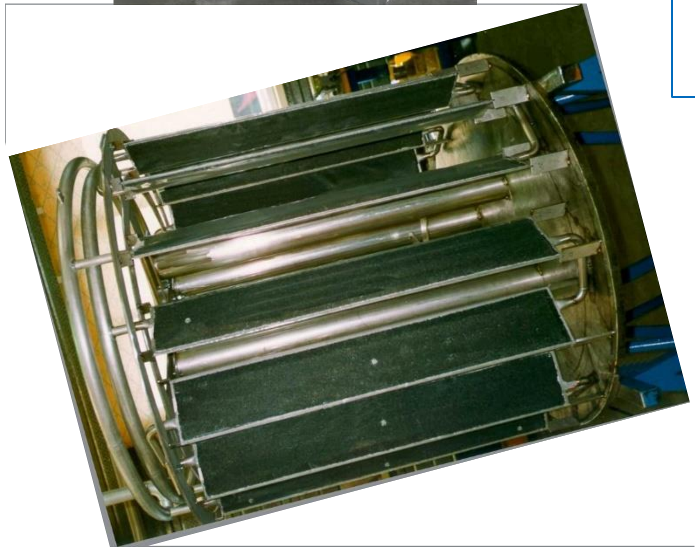


Red: Higher collisionality regime
Green: Lower collisionality regime

Other cryopumps with similar elements

iter

china eu india japan korea russia usa



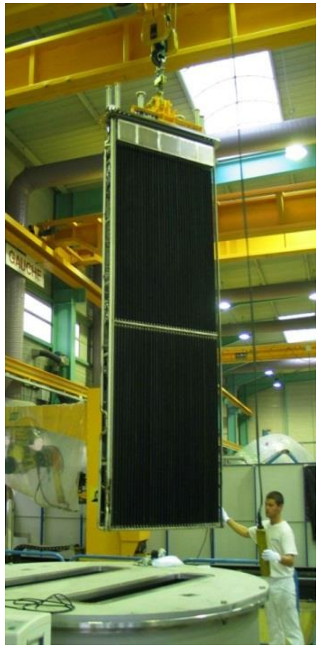
- Hydroformed components for pumping surfaces and thermal shields in different channel designs
- ~ 11 m² coated area (both sides coated)
- Supplied by GHe at 4K and 80 K, respectively
- ~ 70 m³/s pumping speed

- 3 identical panels in a row
- ~ 0.5 m² coated area (both sides coated)
- Supplied by LHe at 4K
- Actively heatable by attached heaters
- Operated under tritium
- 6.5 m³/s pumping speed

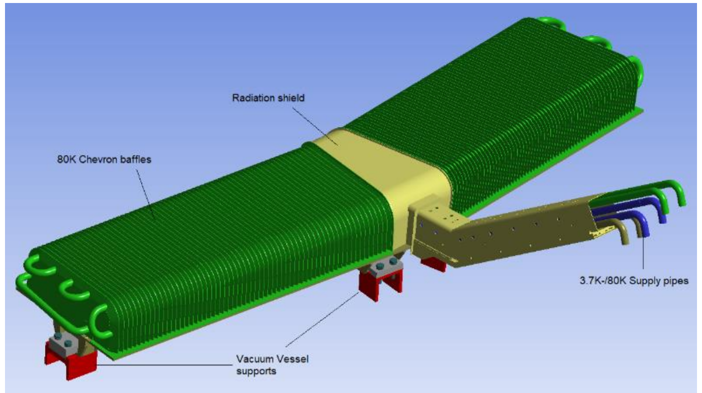
JET

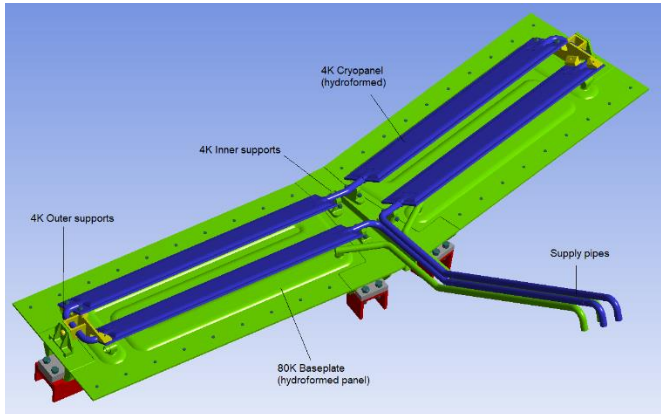
The MANITU and JT-60SA cryopumps

Max-Planck-Institut für Plasmaphysik



- ~ 12 m² coated area (both sides coated)
- Supplied by LHe at 4K and LN at 80 K
- Equipped with electric heaters
- ~ 350 m³/s pumping speed
- Same technology is being used for the AUG upper divertor upgrade.





- ~ 0.4 m² coated area (both sides coated)
- Supplied by 3.8 K He
- Equipped with electric heaters
- ~ 12 m³/s pumping speed
- 9 identical of such cryopumps

Summary

- The performance requirements of the DTT divertor pumping system have been extracted in a self-consistent way from the chosen reference plasma scenario.
- It was shown that these requirements can be fulfilled if the foreseen duct cross-section is enlarged.
- Recommendations were given for how to improve the divertor in terms of 3D particle exhaust; the feature with the strongest influence was the closure of the toroidal gaps.
- A high-performance pump system is then necessary, for which NEG pump technology was compared against cryopump technology. It was decided to go for a charcoal coated cryosorption pump.
- The design of the cryopump features design elements which are known from other cryopumps for fusion, which is expected to reduce manufacturing risk.
- Once the mechanical load assessment is over (mid 2024), the design can be finalized and the technical spec for manufacturing be elaborated (end 2024).

thank you!

This work was performed within the 7h cycle of MARCONI-FUSION HPC (project TOK-KIT) and also partially on the HoreKa supercomputer (project ngdsim) funded by the Ministry of Science, Research and the Arts 505 Baden-Württemberg and by the Federal Ministry of Education and Research.