VNS status, 20-Jan-2026

VNS overview and in-vessel configuration

C. Bachmann

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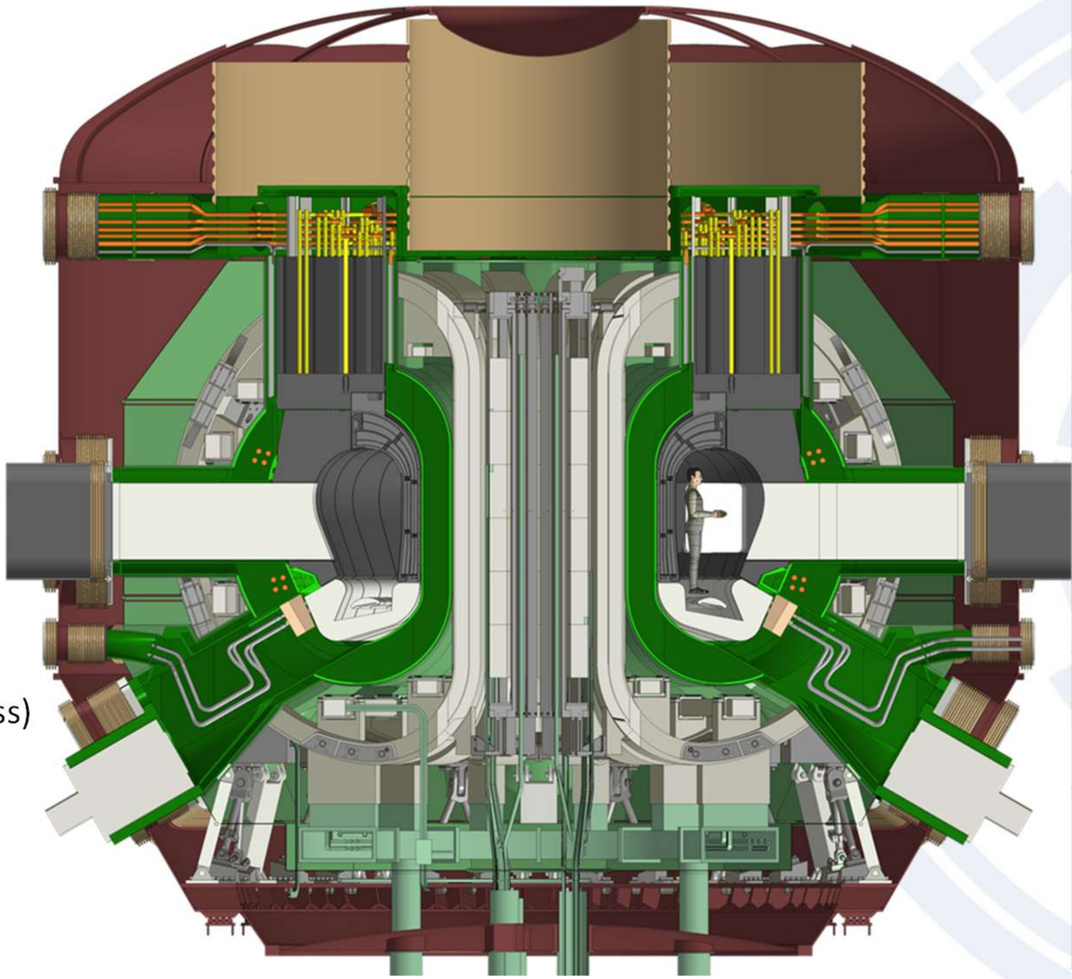
Status of VNS reference design point, R = 2.67m, B_0 = 5.6 T

References:

- 2D geometry: 2SF8KE
- 3D basic geometry: 2RHAD6
- METIS run + CREATE equilibria: 2S9DWS

Central design and integration team:

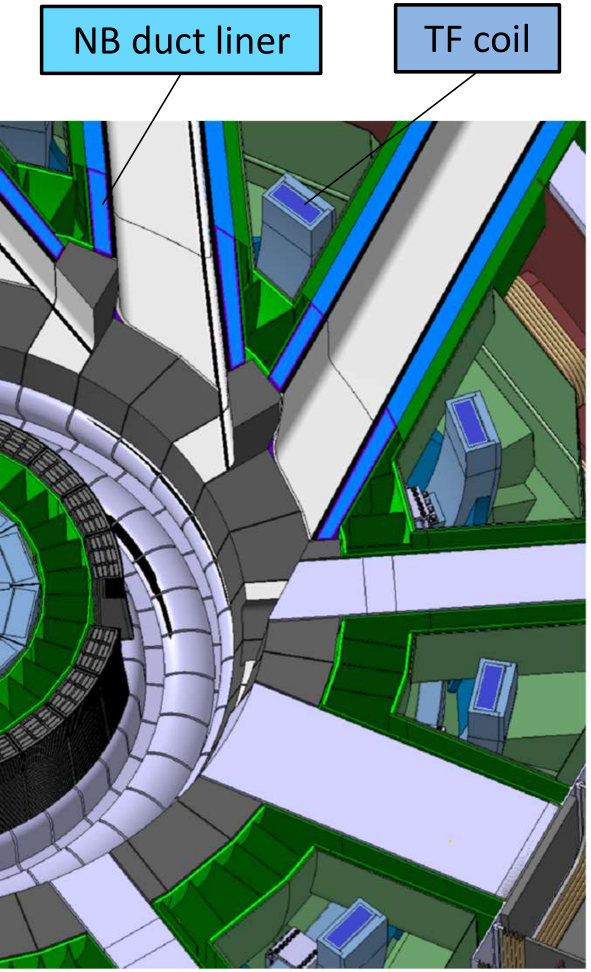
- Proj. manag. (K. Marcinkiewicz)
- Physics (F. Maviglia, C. Bourdelle)
- Magnets (L. Giannini)
- In-vessel components + cooling systems (I. Moscato)
- Vacuum and fuel cycle (T. Härtl)
- Plasma heating & diagnostics, electrical systems (T. Franke)
- Building and plant systems (C. Gliss)
- Safety (S. Rossanvallon)
- RH tools (R. Mozzillo)
- Neutronics (P. Pereslavtsev)
- CAD office (S. Renard)
- EM analysis (I. Maione)

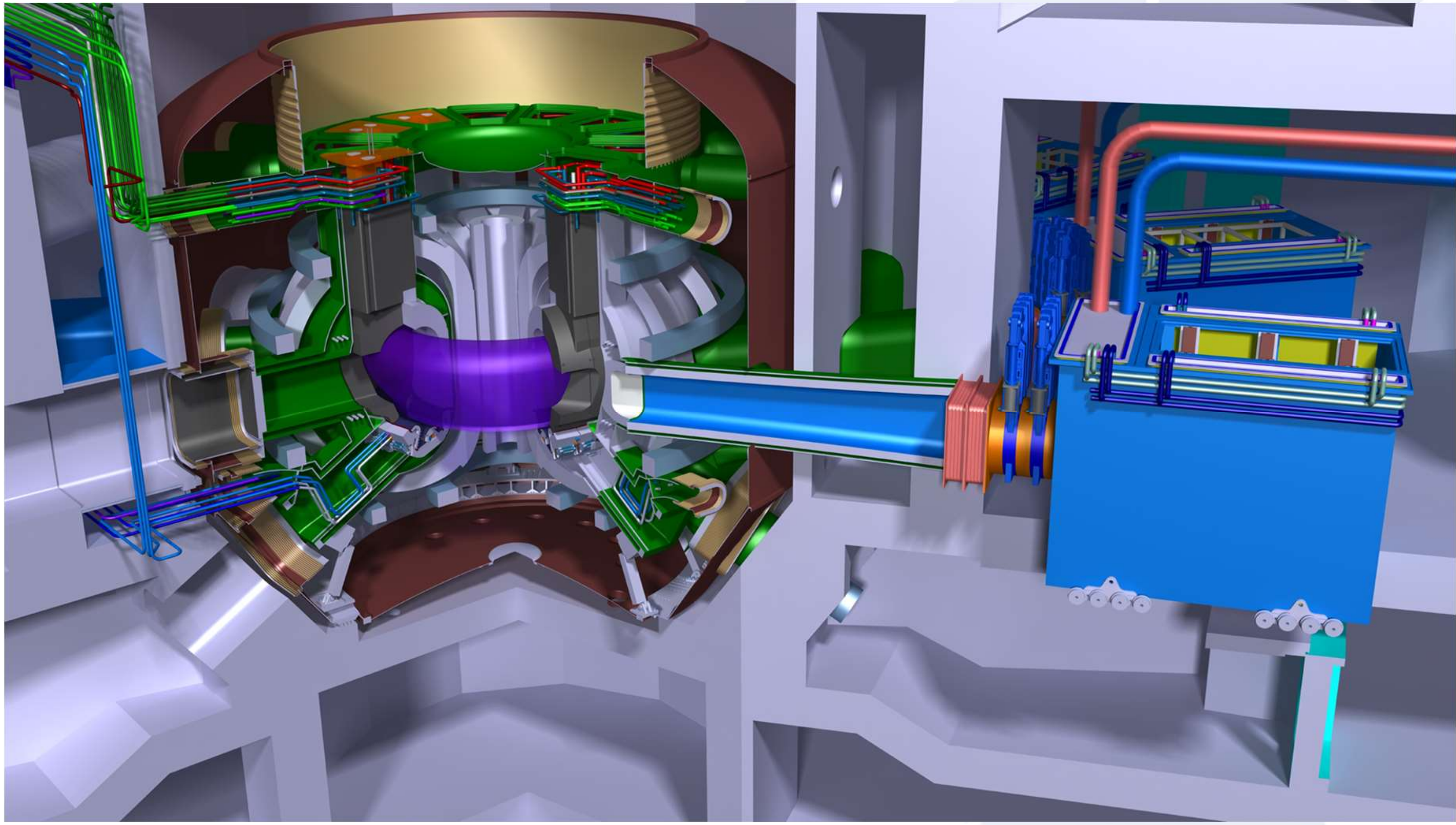


Pulse	Steady-state
R_0	2.67 m
a	64 cm
B_0 / B_{max}	5.6 / 13.2 T
P_{fus}	37.9 MW
P_{NB}, P_{EC}	42 / 8 MW
NWL peak	0.50 MW/m²
dpa_{peak}	3.6 dpa/fpy
k_{100}	1.55
β_N [Tm/MA]	2.76 %
q_{95}/Pl. Current	3.02/2.5 MA
T consumption	2.1 kg / fpy
Electricity cons. - NB - EC - **Total**	 118.5 MW 20 MW **161.5 MW**

NB configuration, 3 · 14 MW, 120 keV

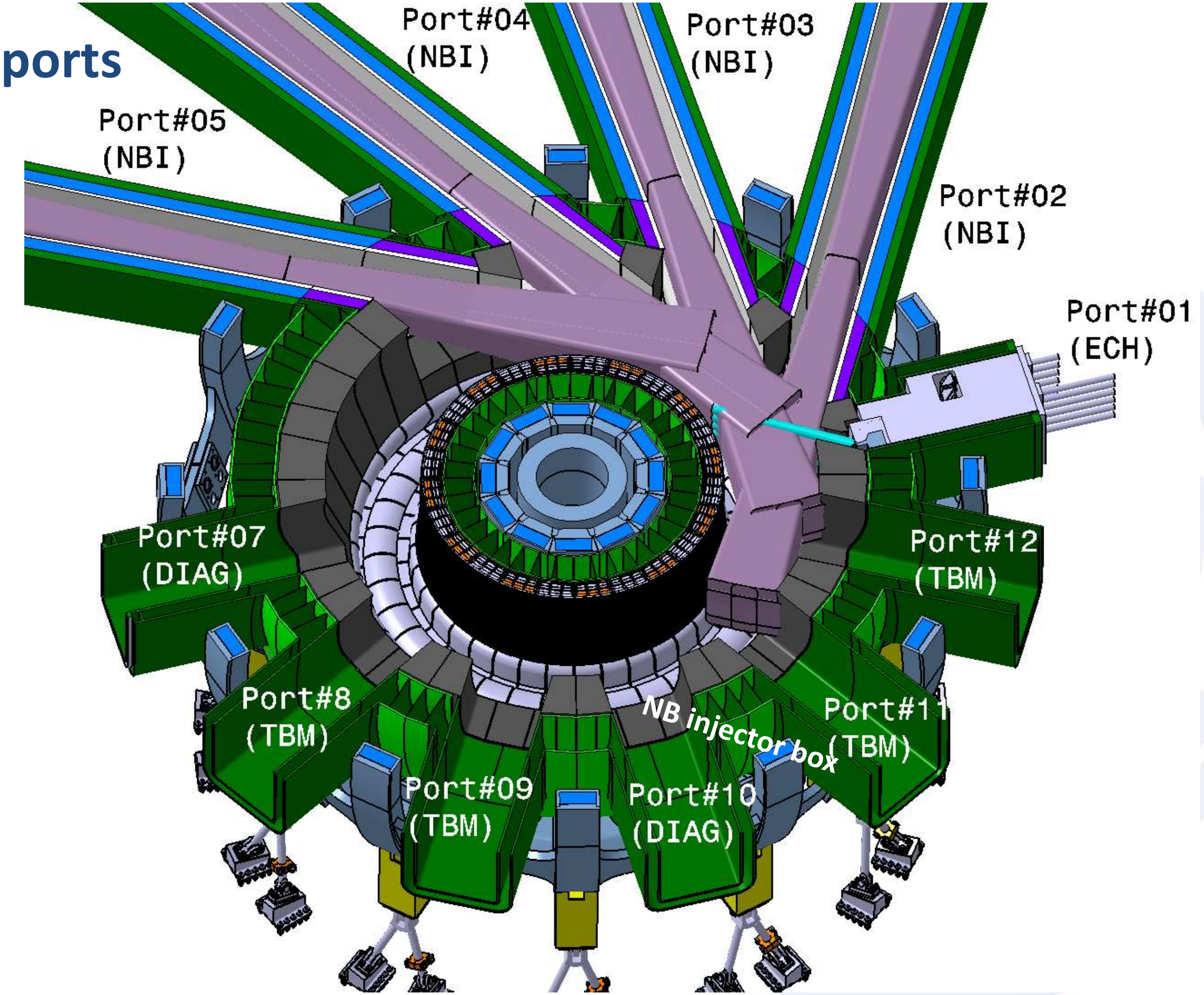
12 TF coils allow the integration of an ITER-like NB duct in-between TF coils.





Allocation of systems to ports

Port	Upper	Equatorial	Lower
#1	Blanket RH	EC	Divertor RH
#2	Blanket RH	NBI	Pumping
#3	Blanket RH	NBI	Pumping
#4	Blanket RH	NBI	Divertor RH
#5	Blanket RH	NBI	Pumping
#6	Blanket RH	blocked	Pumping
#7	Blanket RH	Diagn.	Divertor RH
#8	Blanket RH	TBM	Pumping
#9	Blanket RH	TBM	Pumping
#10	Blanket RH	Diagn.	Divertor RH
#11	Blanket RH	TBM	Pumping
#12	Blanket RH	TBM	Pumping



VV + in-vessel components

Steels for VV and in-vessel components

Tentative choices:

VV	Divertor	Shield blankets	Test blankets / TBMs		
316L(N)	316Ti	316Ti	EUROFER (tbd)		
50 – ~60°C, 11 bar	~50°C, 20 bar	~50°C, 10 bar	PWR	or	gas

Stainless steel @ T<200°C – 316L(N) or 316Ti:

long-term activation due to Nickel

→ VV (316L(N)): safety-class component, up to 2.75 dpa with moderate qualification program e.g., for weldments

→ Divertor cassette / shield blanket (316Ti): non-safety-class, possibly non-PED component, up to 20-40 dpa, with moderate qualification program.

EUROFER: **@ T>350°C:** 40-50 dpa

@ T<350°C (PWR water-cooling): up to 20 dpa

Difficult manufacturing (post-weld heat treatment required), difficult design due to high pressure coolant

→ Outboard test blanket

→ TBM

Vacuum vessel

Design:

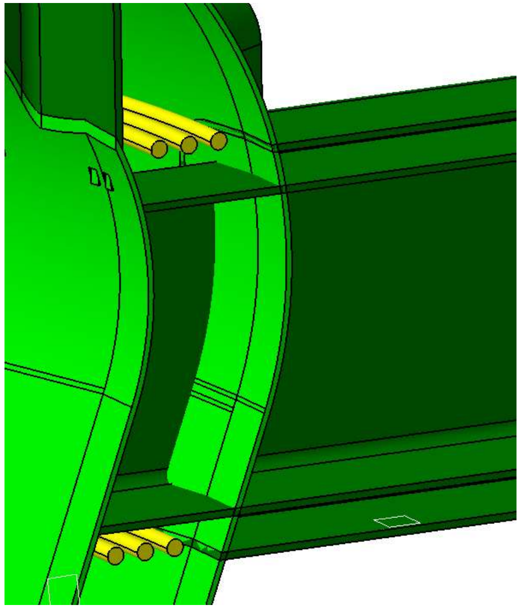
- Double-wall structure: 316(L)N
- Shell thickness: 30 mm
- n-shielding plates: 304, B_4C, tungsten

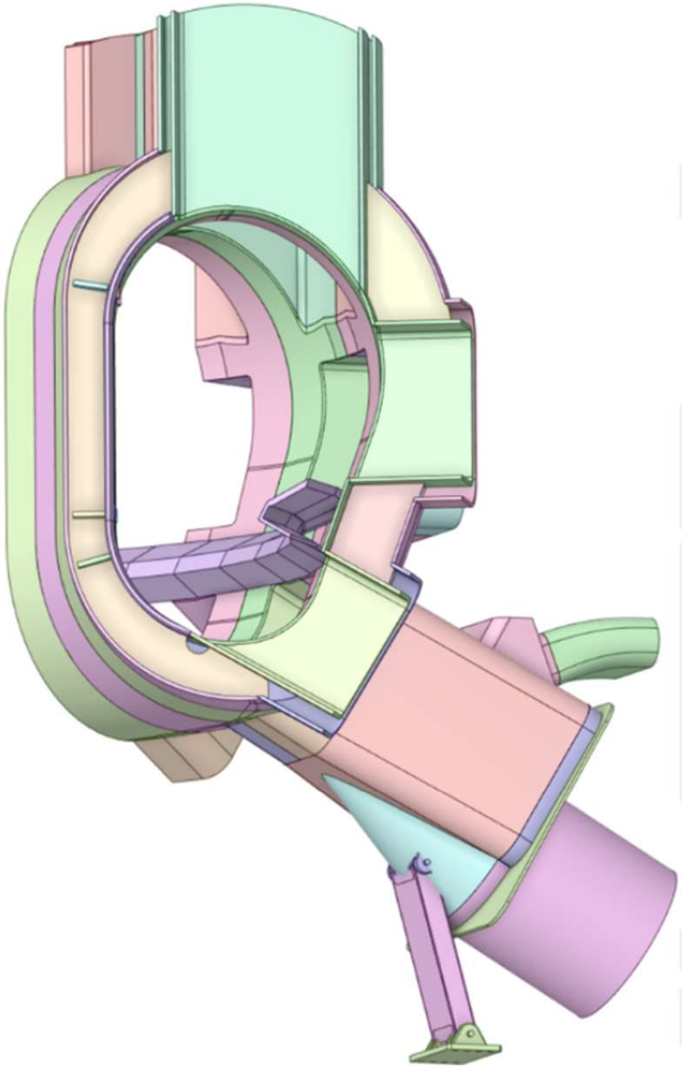
Operation:

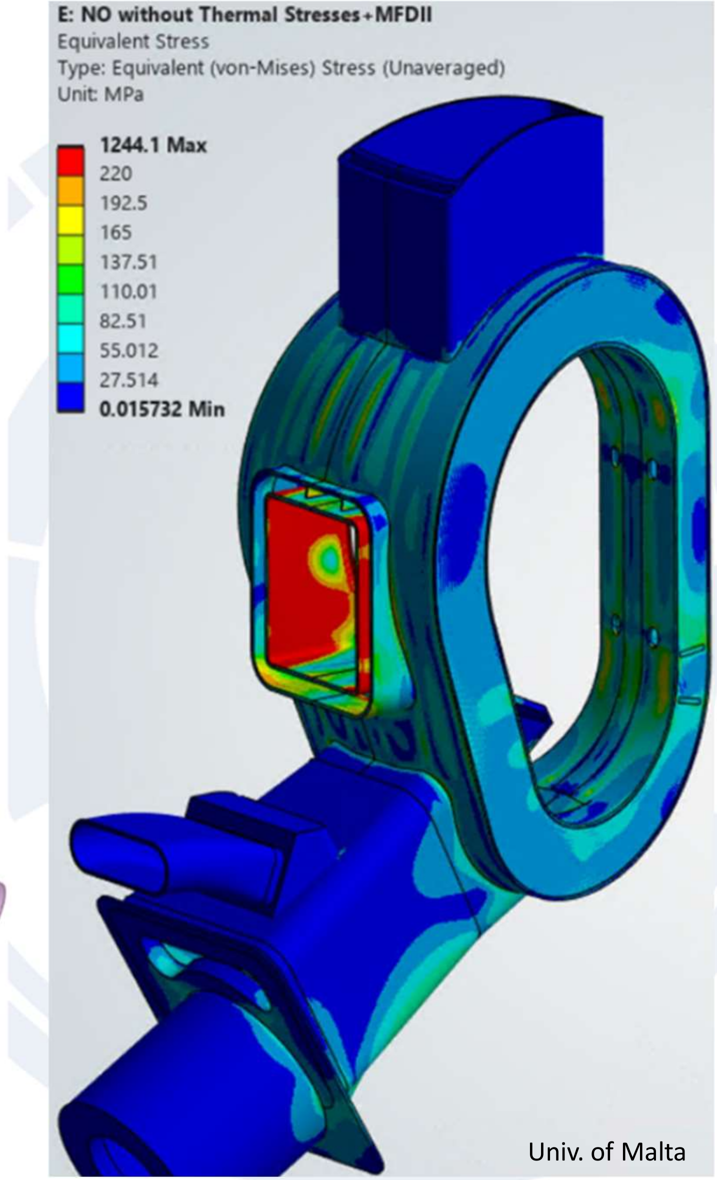
- Coolant: liquid water
- Operation: 50°C @ 11 bar
- Baking: 150°C @ 17 bar

Intra-VV coils:

- Active VS





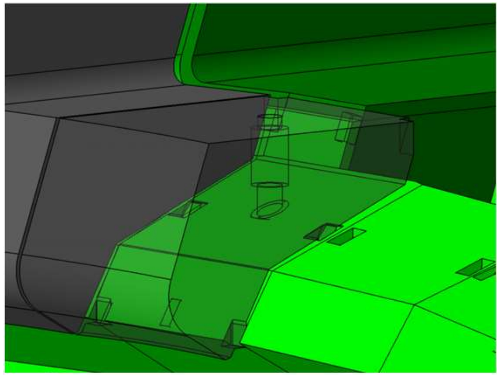


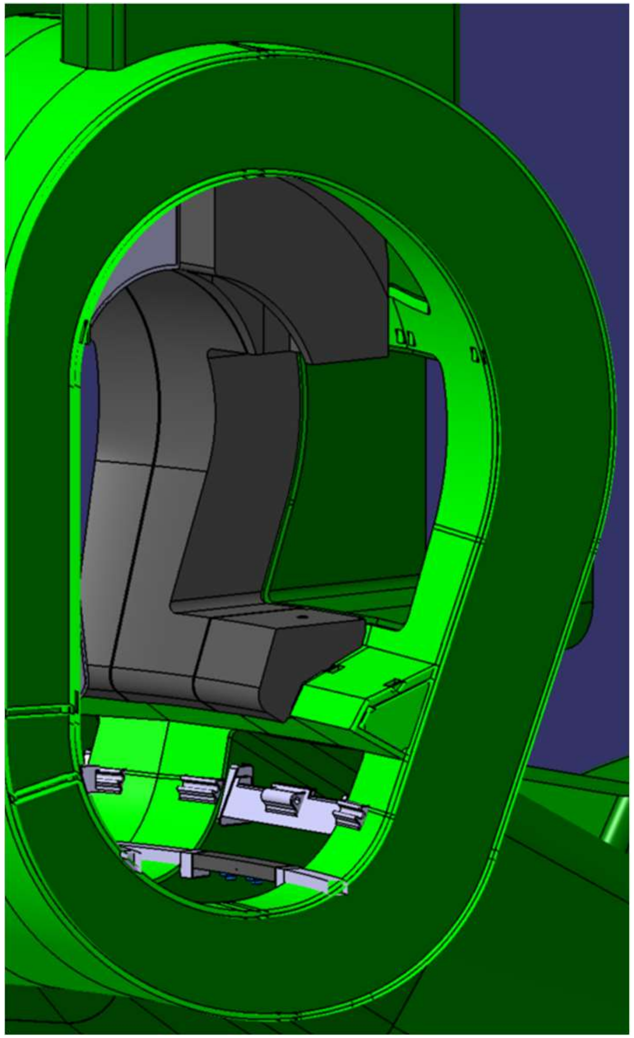
Outboard blanket integration

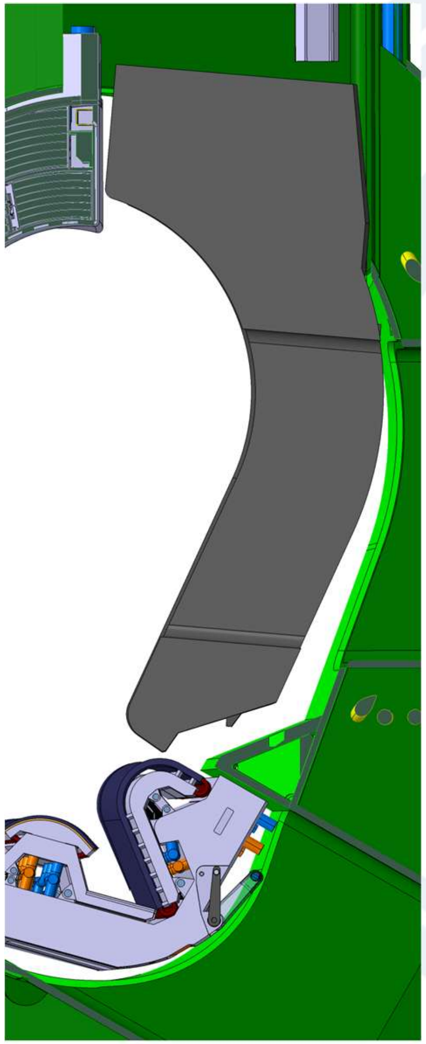
Triangular support allows the removal of the outboard segments while the divertor remains in-situ.

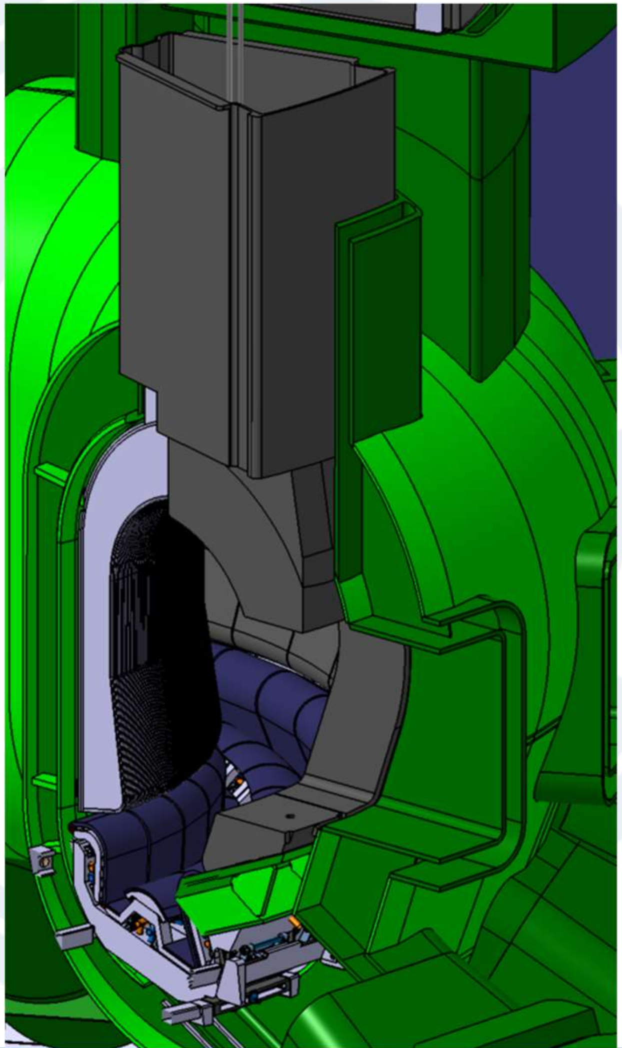
Some outboard segments are divided:

- Lower part is attached to triangular support.
- Upper part is part of the upper port shield plug.



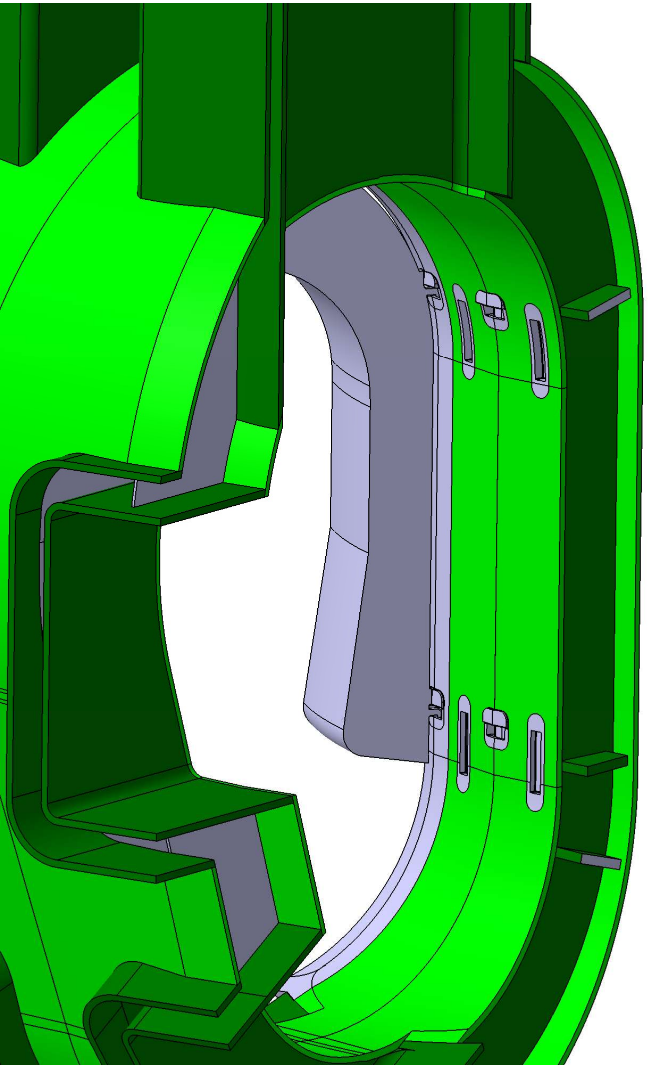


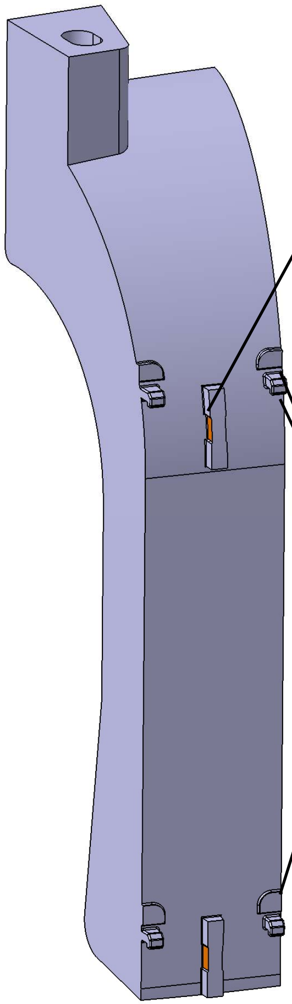




Inboard blanket support structures

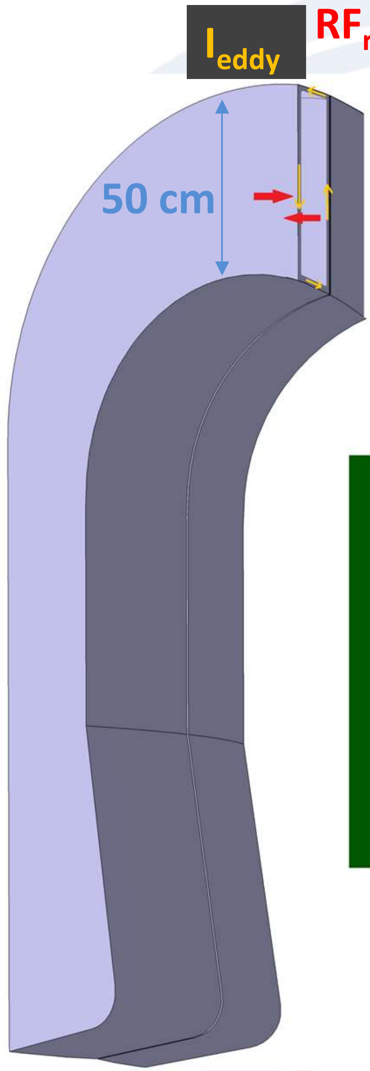
LT Calcoli

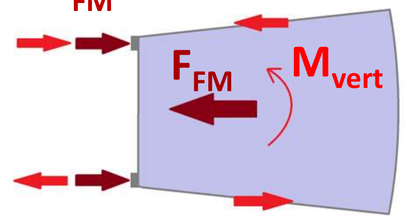


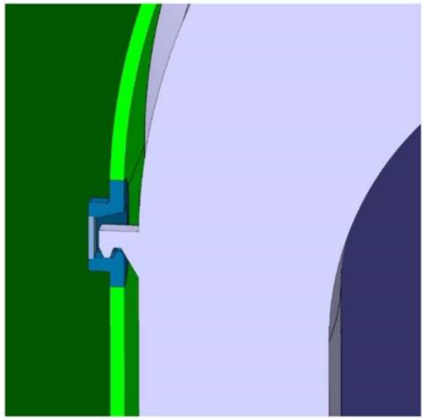


Toroidal shear key with MultiLAM electrical connector

Radial supports:
- Compression pads
- Tension hooks

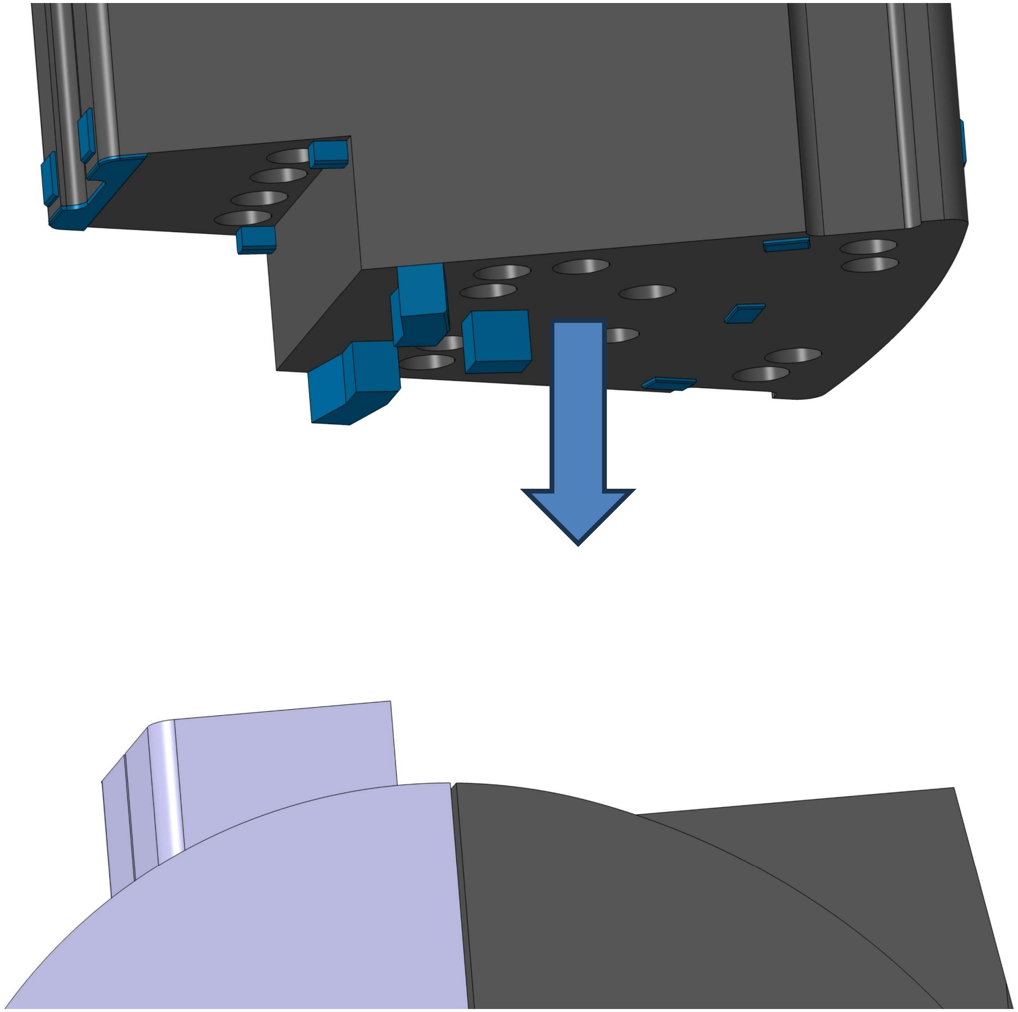


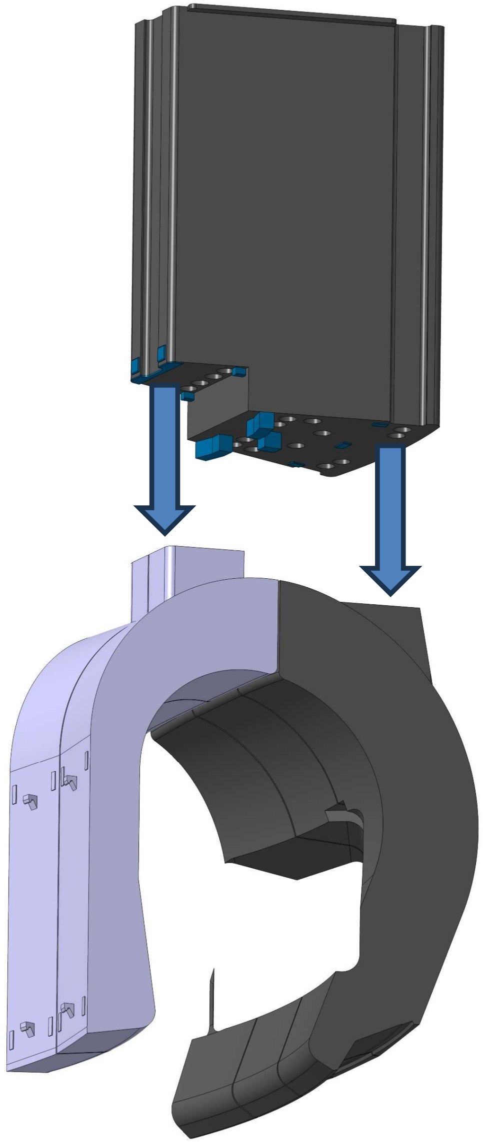




Blanket attachments – use of upper port plug

- Upper port plug blocks the upward movement of all five segments in one sector.
- Vertical gap allows thermal expansion (~1.5 mm inboard blanket, 3.5 mm outboard blanket).
- Off-centered vertical support reactions can be compensated on other supports.

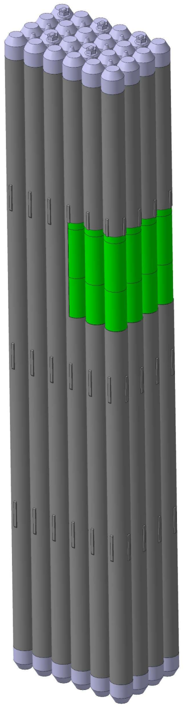


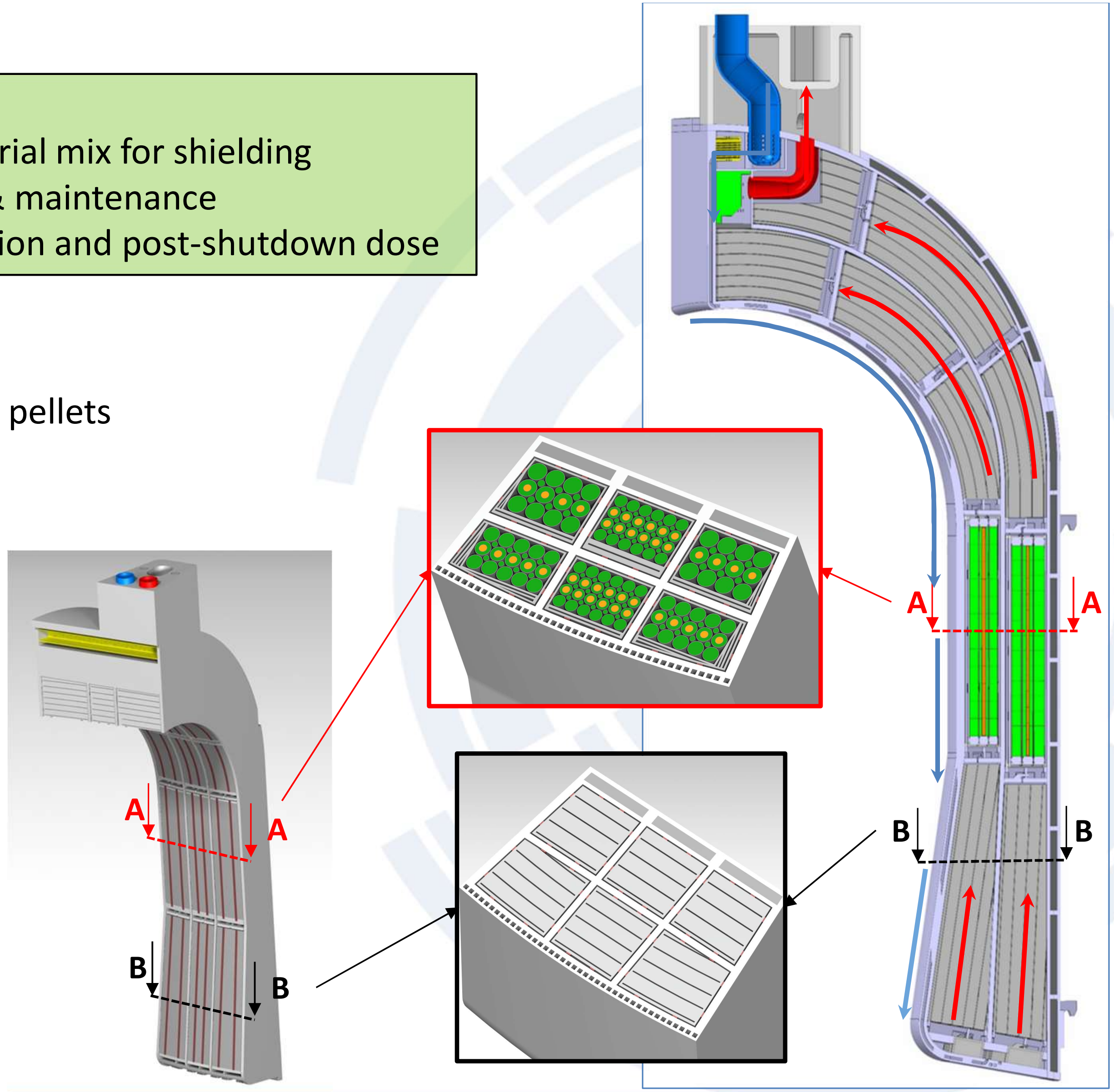


Shield blanket

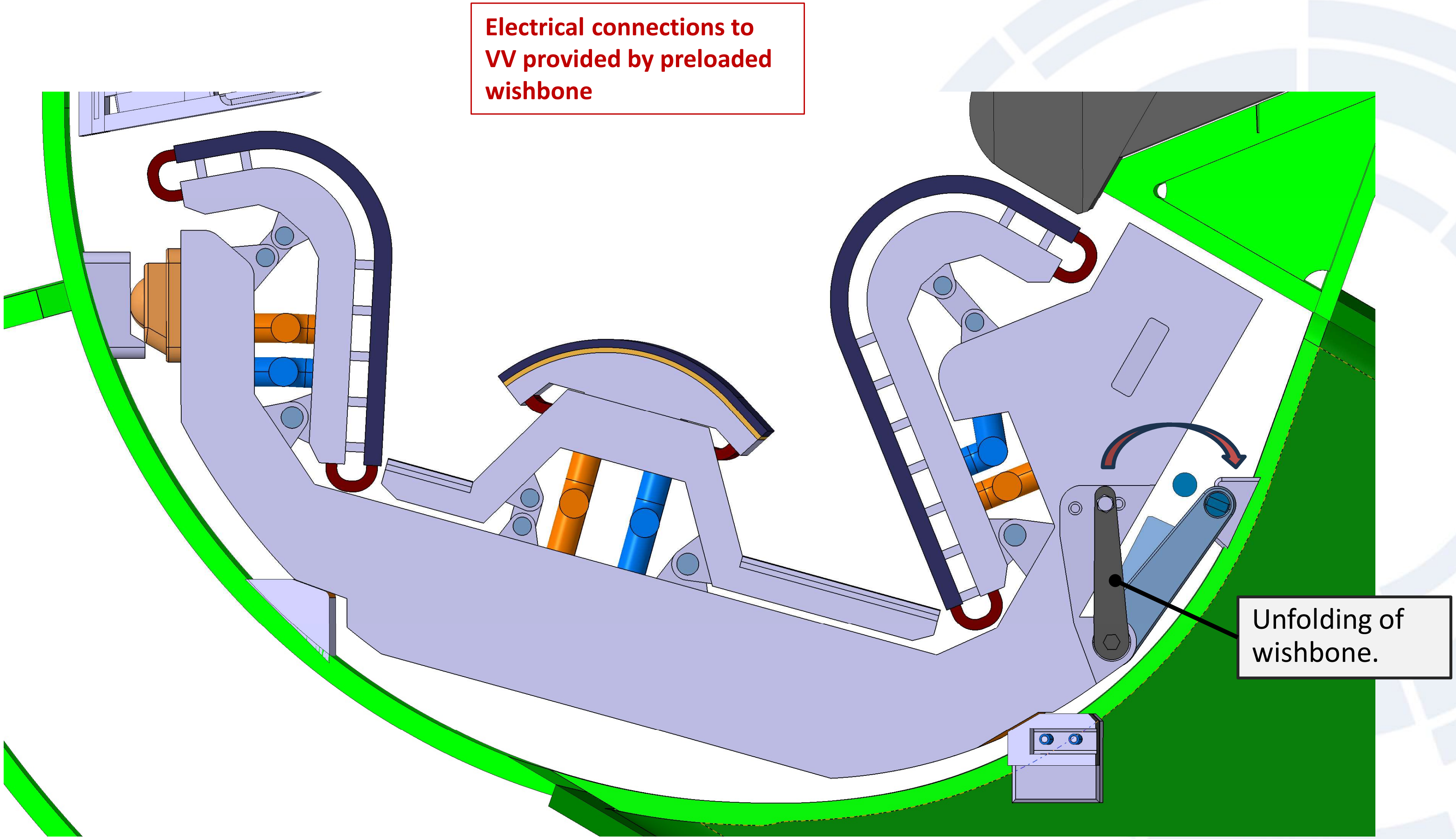
- Welded box, HIPed FW, 316Ti
- Water 50-70 °C @ 10 bar
- Tungsten wall
- Flat top heat flux on FW: <**0.15 MW/m²**
- Start-up heat flux up to 0.3 MW/m² for < 4 s
- TiH_2 or B_4C could be inserted within hollow tungsten pellets

Design goal:
- Optimize material mix for shielding performance & maintenance
- Reduce activation and post-shutdown dose



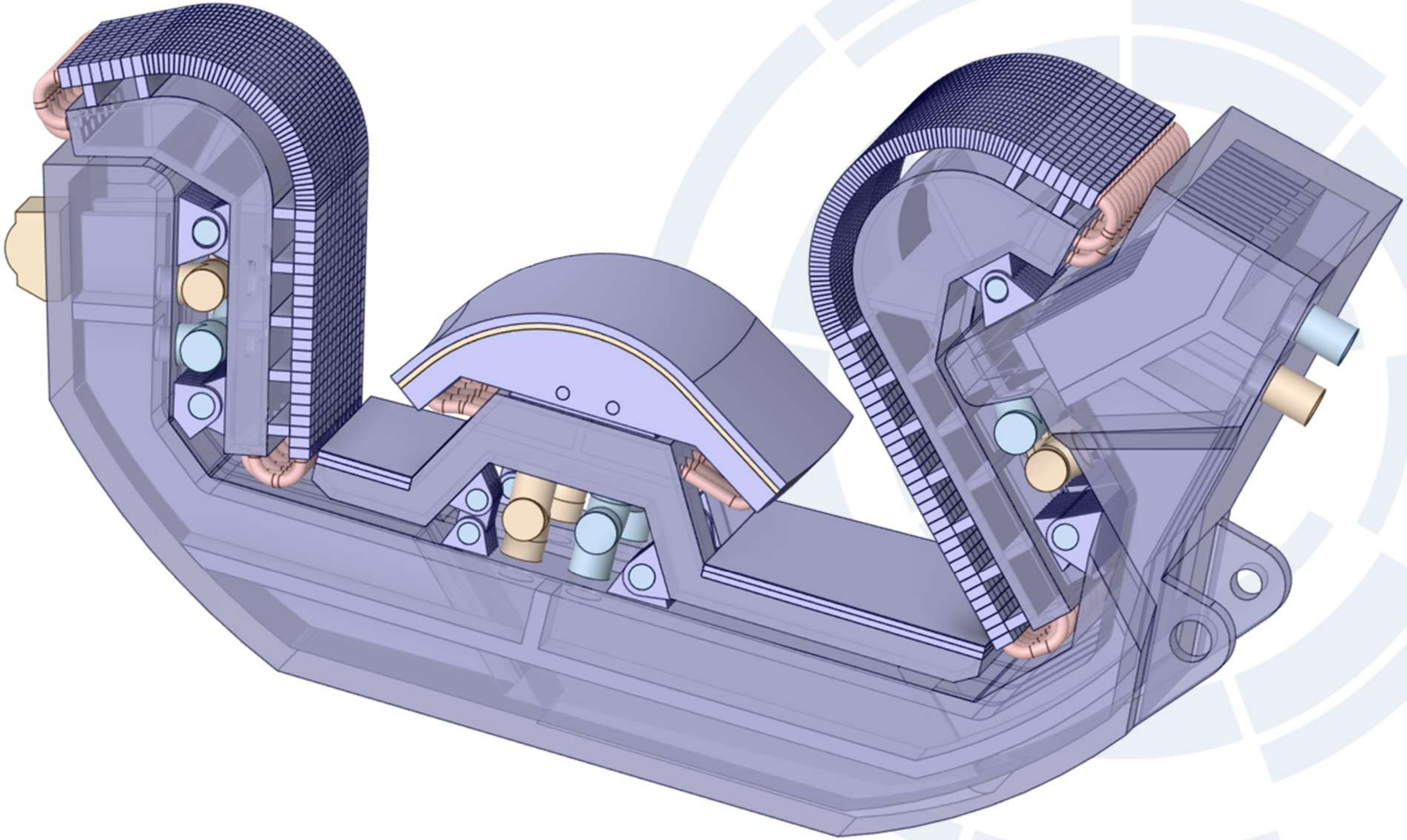


Divertor mechanical attachments



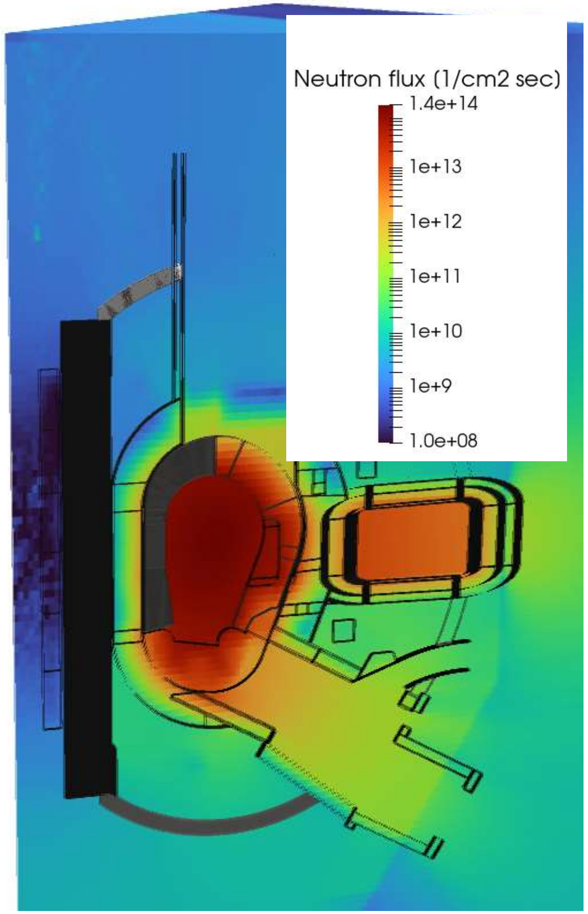
VNS Divertor – general design

- ITER-like
- Cassette body made of box-welded structures (316Ti).
- W-monoblocks for the Vertical Targets.
- Hypervapotron-cooled dome.
- T_{in}=50°C, p_{in}=35 bar.
- Tot. weight: 1.5 ton



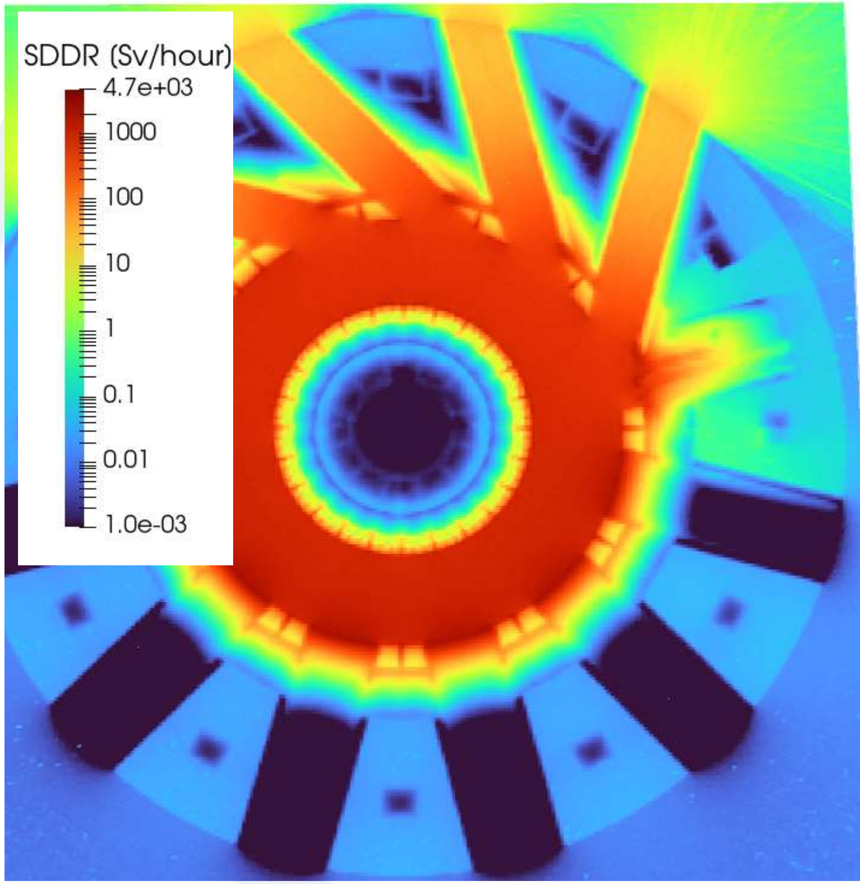
Radiation shielding

Operation



- TF coil on inboard side: expected peak dose ca. 20 MGy < 50 MGy
- Lower port radiation structures so far insufficient
- Significant radiation streaming through NB ports → radiation shielding structures

After 12 days



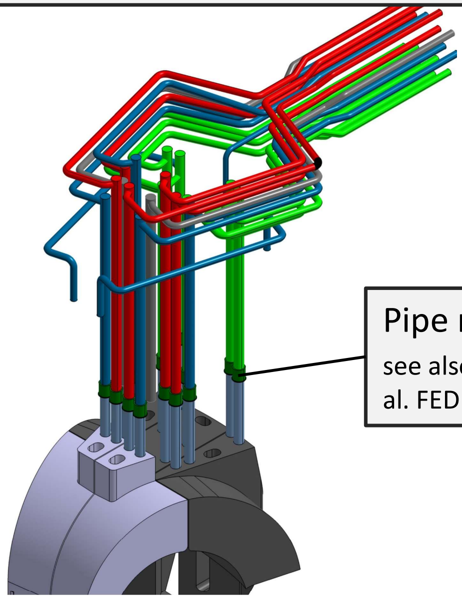
In-vessel component cooling pipes

<u>Blanket cooling pipes:</u>

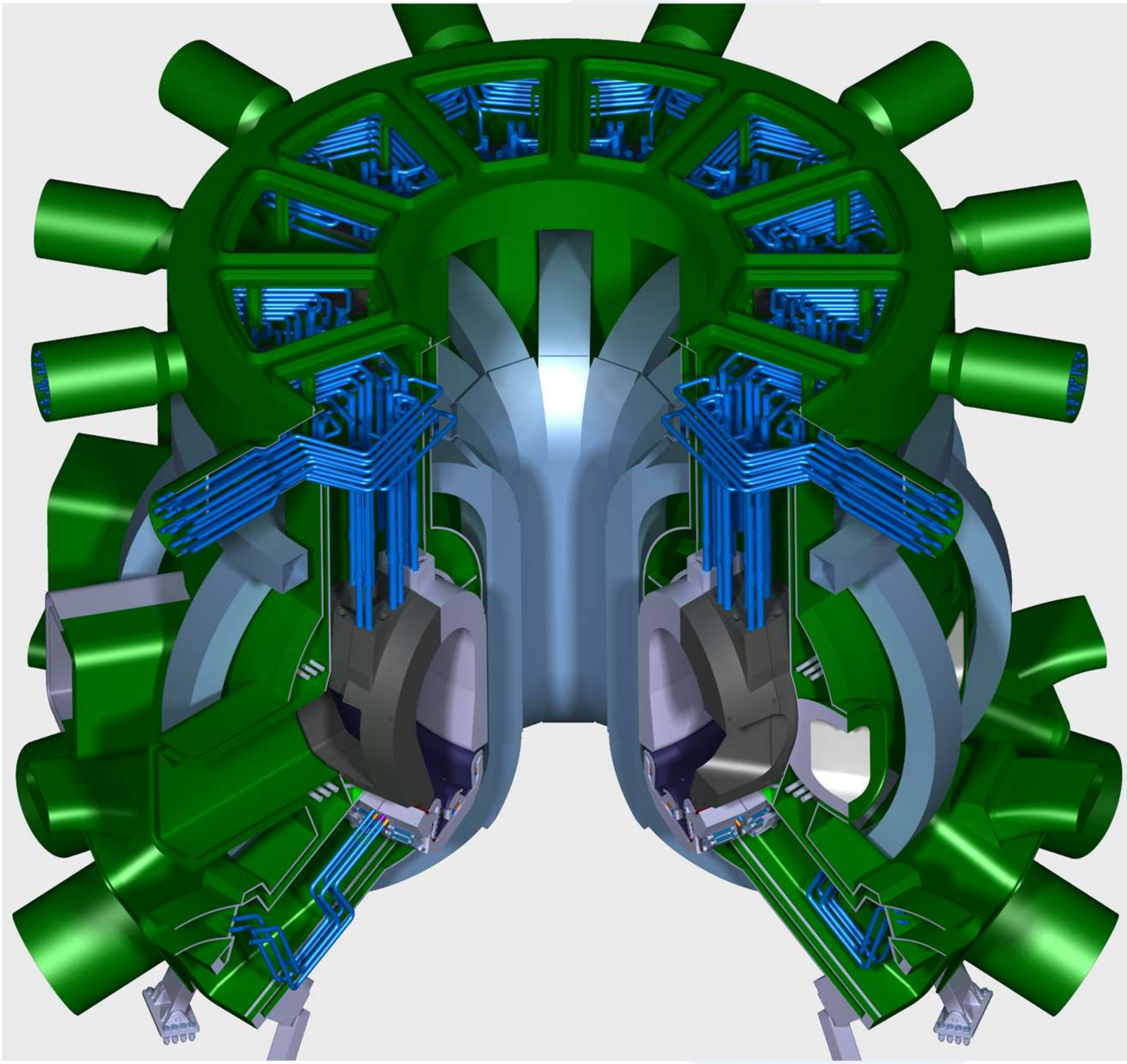
- All 16 + 2 pipes of one sector are routed through an upper port horizontal annex.
- Rewelding location behind blanket within port.
- Vertical access with in-bore tools after pipe cap removal.

<u>Divertor cooling pipes:</u>

- 6 cooling pipes in each of the 12 lower ports.
- Rewelding location behind divertor within port.

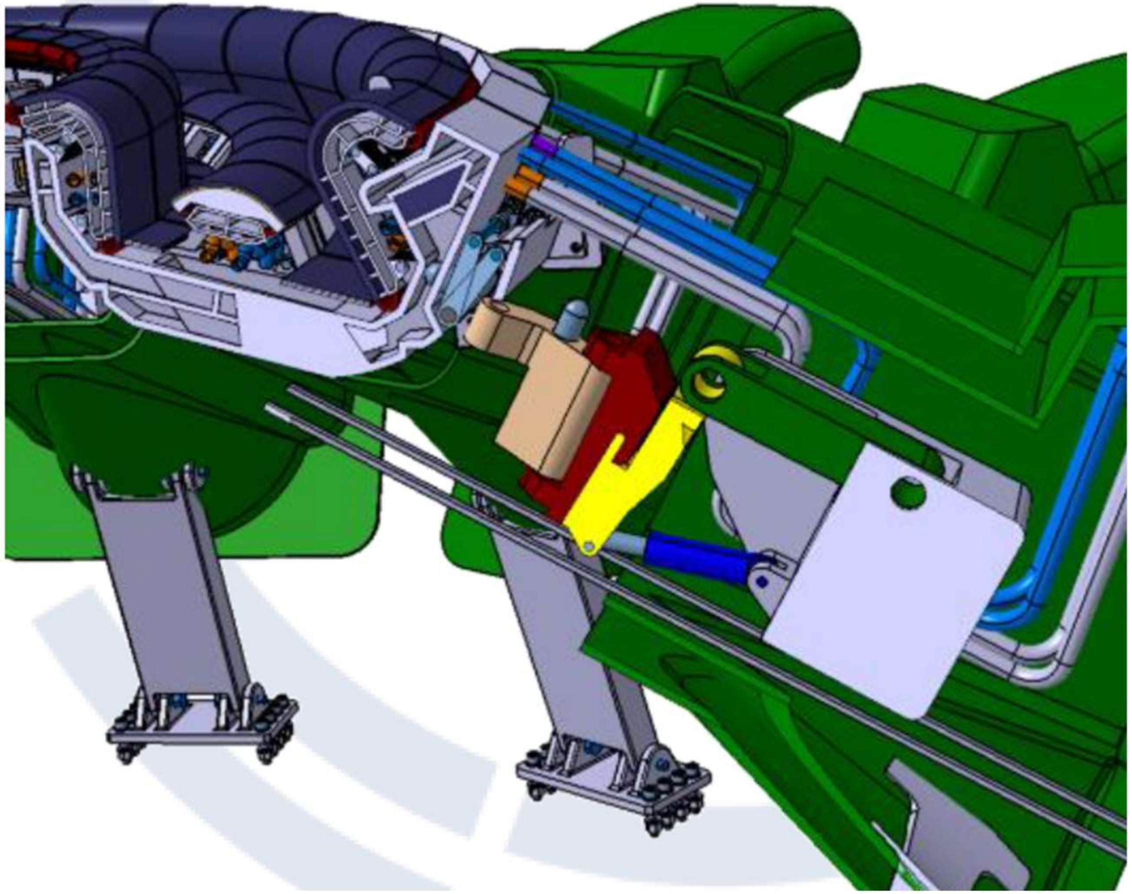


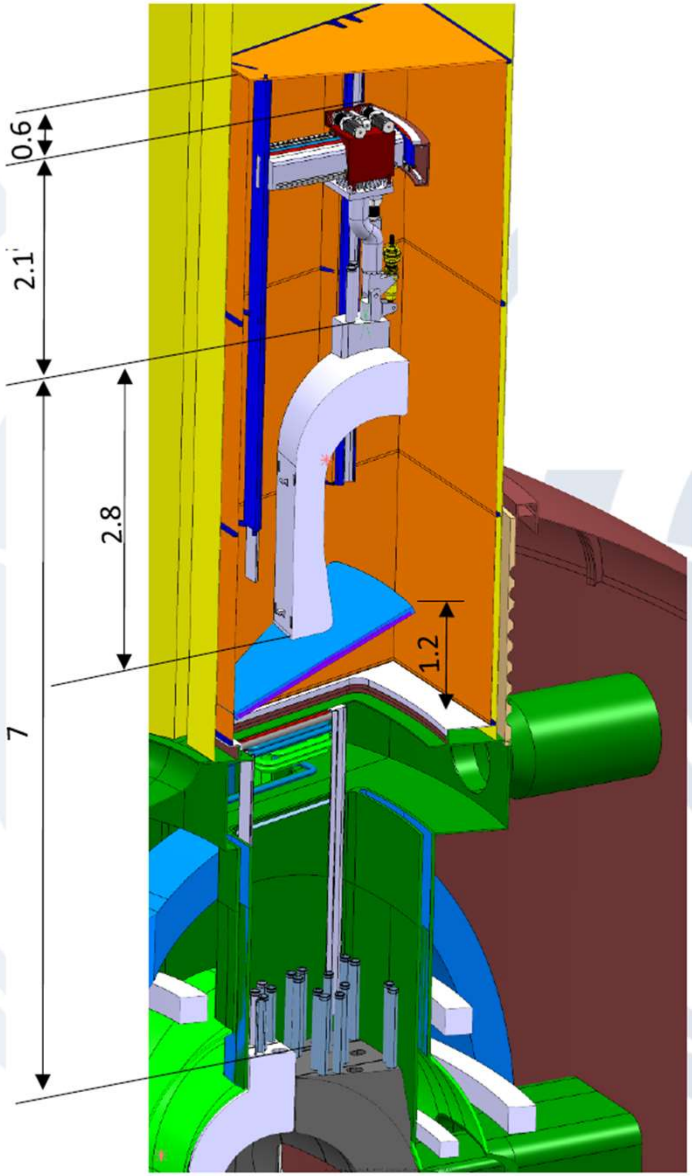
Pipe rewelding
see also [Mozzillo, Rocco, et al. FED 202 (2024): 114311]



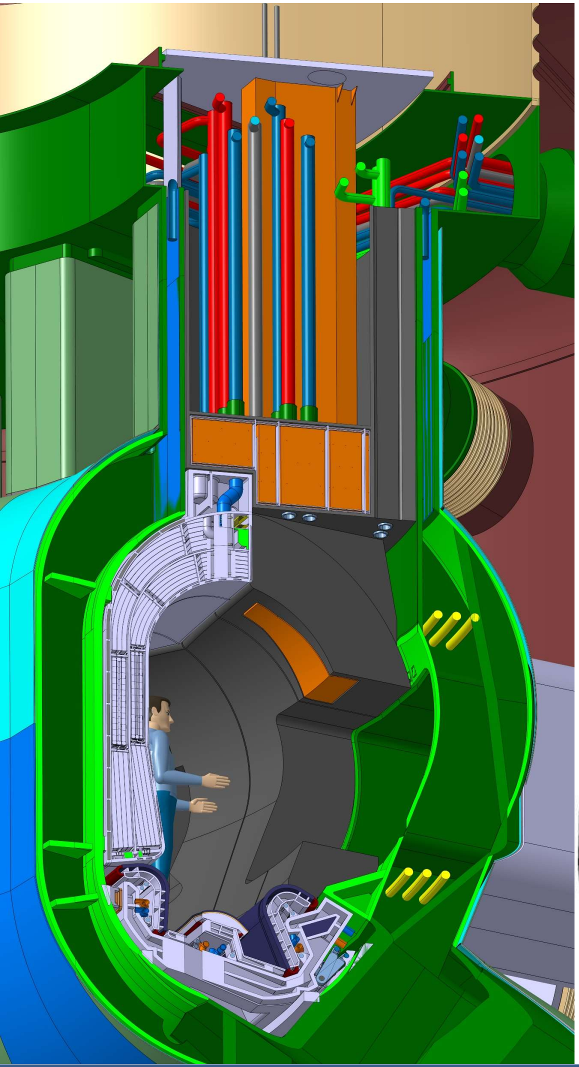
In-vessel RH

- 4 lower RH ports for divertor RH
- 12 upper vertical ports for blanket RH
- All cooling pipes are accessible

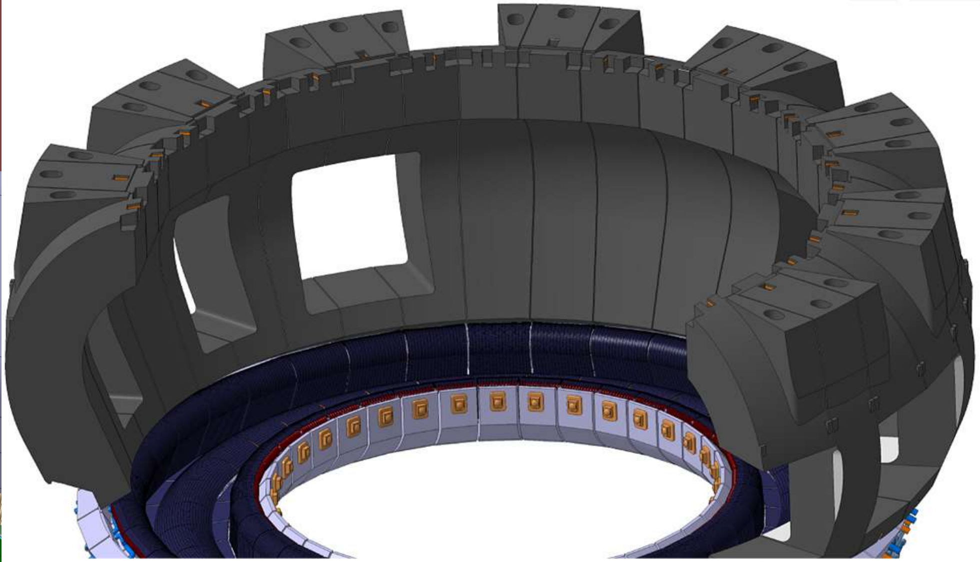


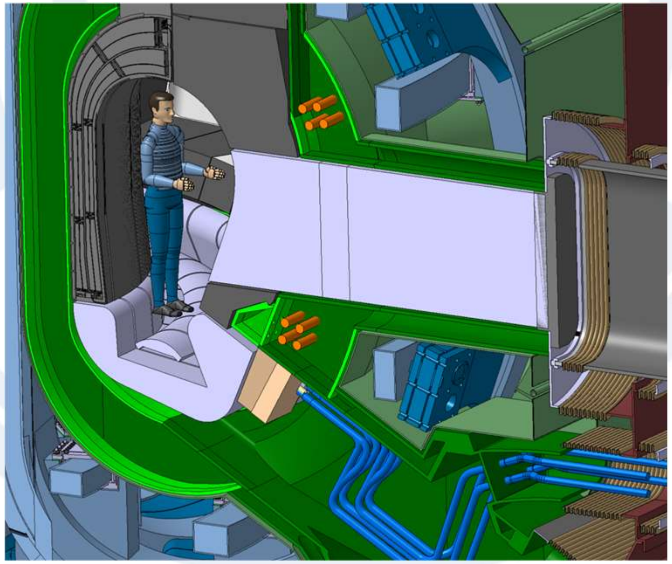


Test blanket installation options



	FW surface	Purpose	Installations
4 TBM port plugs	4 · 1.2 m²	Testing	Local auxiliary systems, Instrumentation
Few upper port plugs	0.2 × 0.5m = 0.1 m²	Testing	Connected to "global" cooling system Possibly local purge gas system, tbd. Instrumentation
up to 20 outboard segments	up to 20 · ≈1.2 m²	Qualification	Connected to "global" cooling and purge gas systems No instrumentation





Auxiliary systems

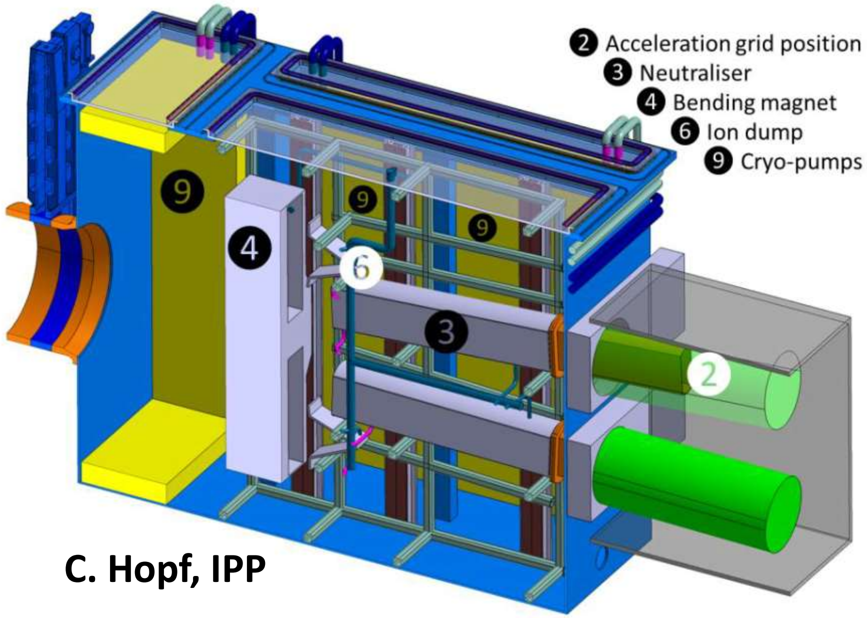
Plasma heating systems

NBI concept:

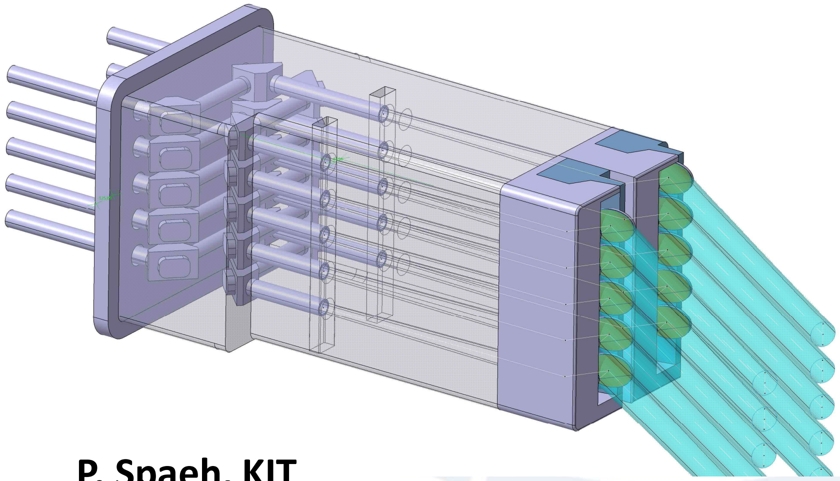
- *AUG-based NBIs*
- *3 NBIs in operation, 1 NBI in cryopump regeneration mode*
- *3 × 14 = 42 MW (to the plasma)*

EC launcher initial concept:

- *2 rows of each 5 steerable antennas*
- *Up to 10 MW to the plasma*



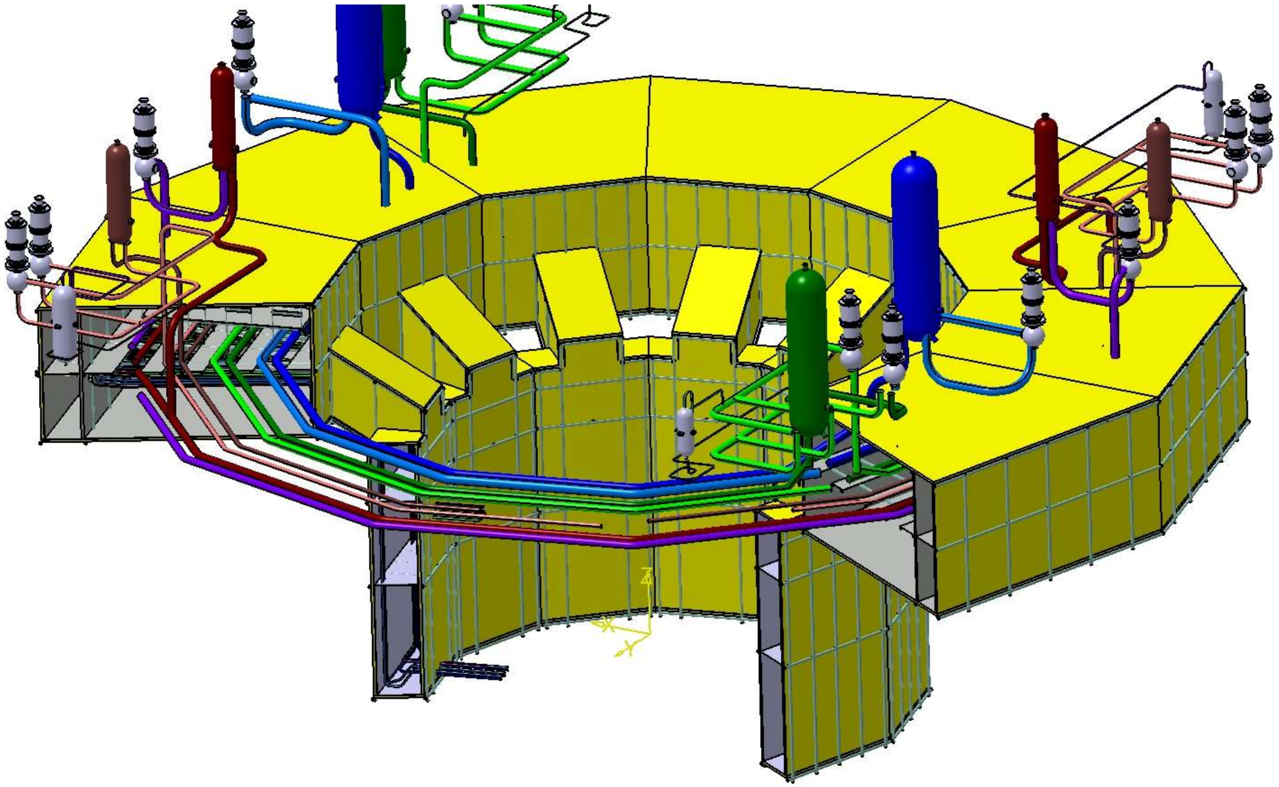
C. Hopf, IPP



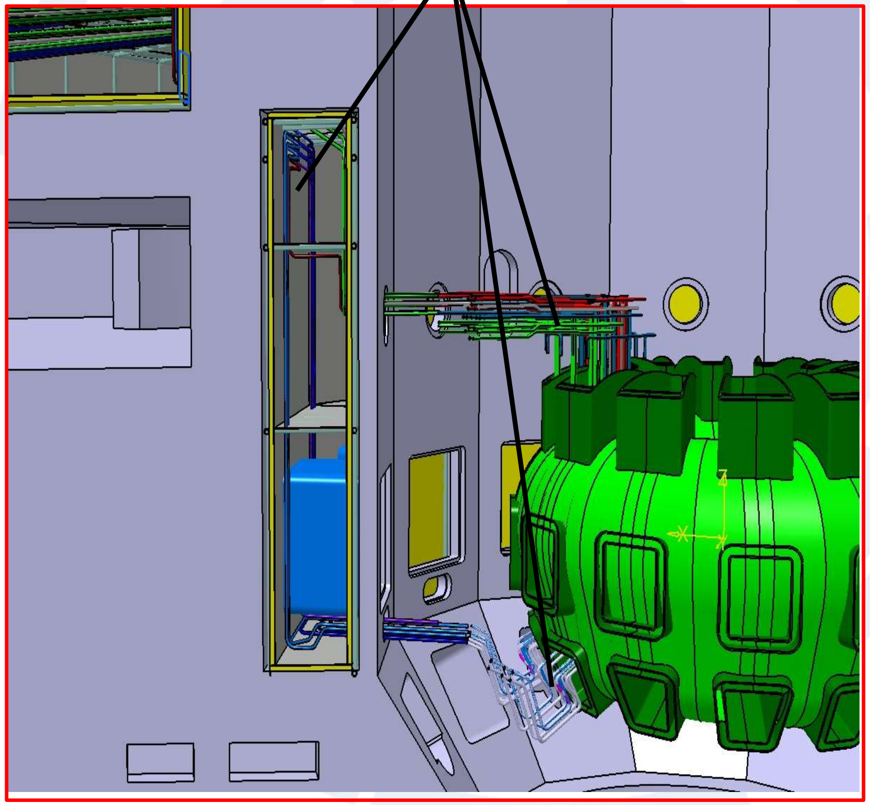
P. Spaeh, KIT

Tokamak cooling systems

Feeder and headers cabinet:
- 100 mm thermal insulation blanketing
- 10 mm steel plates as thermal shield for protection of concrete from gammas.
- Man-access for inspection and repair

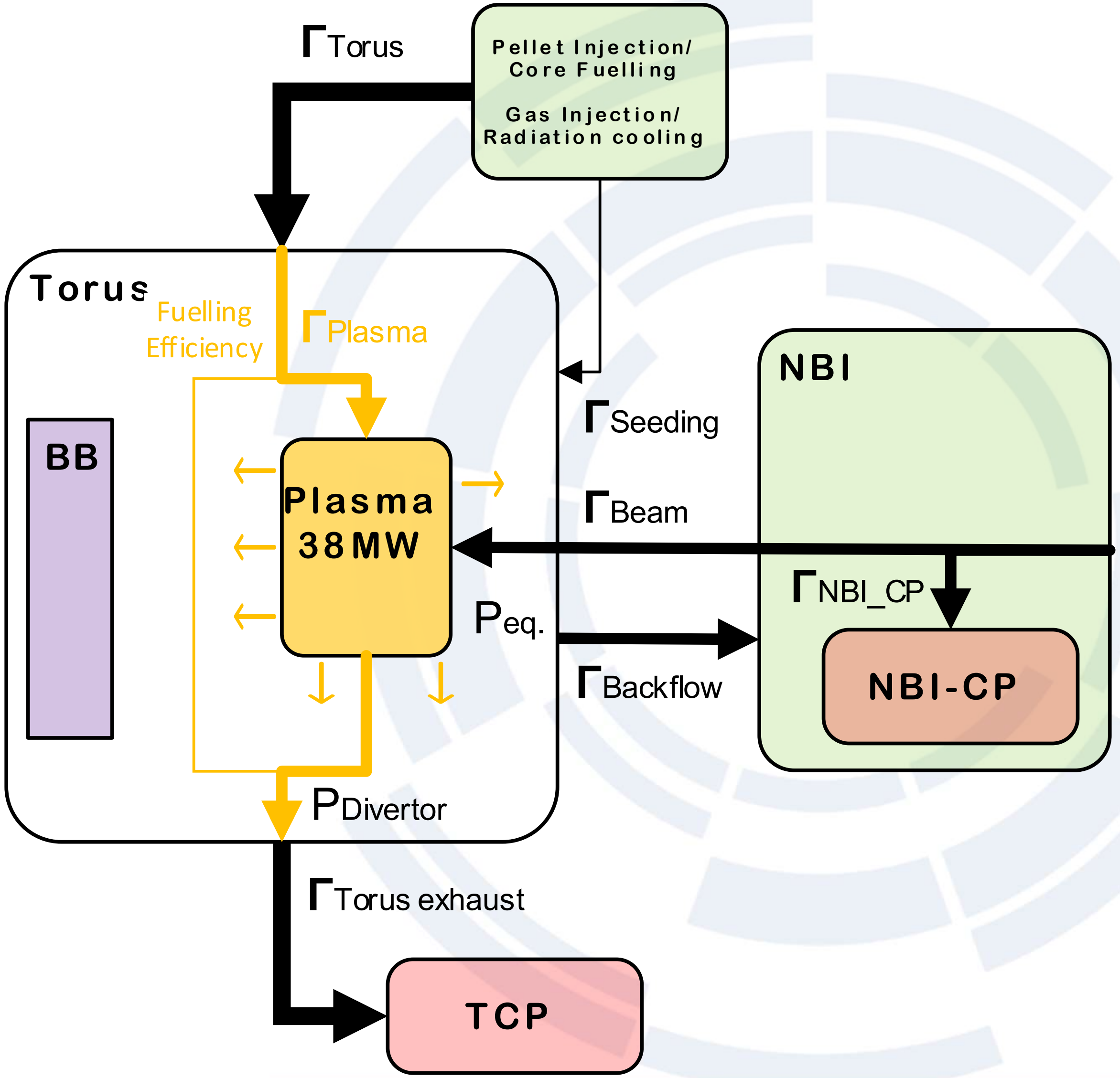


- Pipes exit the machine at the upper port and the the lower port levels.
- Intra-Bioshield routing towards upper pipe chase



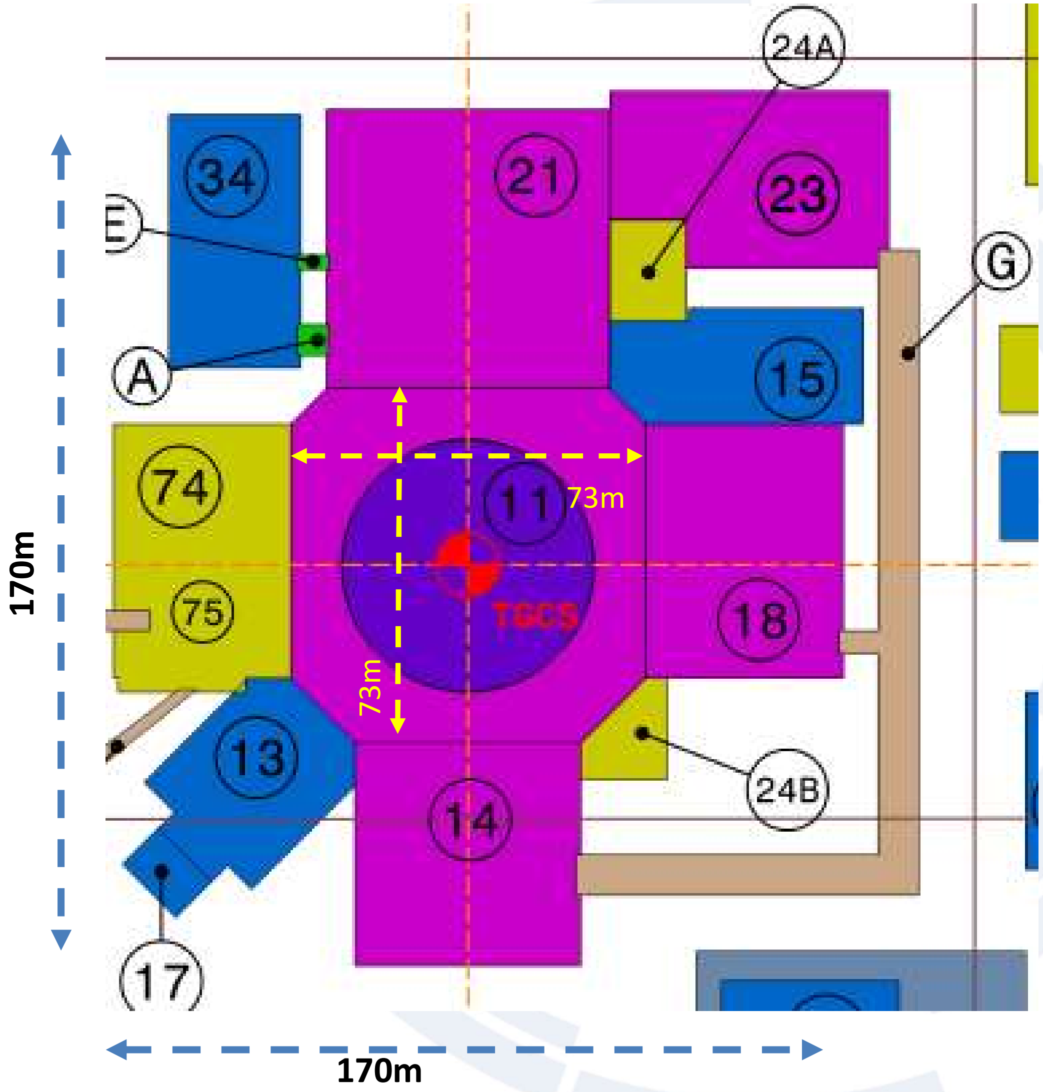
Fuel cycle (outdated, 2024 design point)

	Unit	D-Beam on T-plasma
Beam Energy	[keV]	12
Composition D/T	[%]	95/5
Composition D/T	[%]	5/95
NWL	[MW/m2]	**0.48**
P_fus	[MW]	**29**
ISS throughput	[atoms/s]	4.45E+22
T in ISS throughput	[atoms/s]	2.92E+22
Torus Cryo-Pumps	[g]	85
NBI Cryo-Pumps	[g]	19
Pellet Injector	[g]	23
1st confinement	[g]	**127**
ISS	[g]	386
Total	[g]	**513**



Site and nuclear buildings

11: Tokamak building
14: Tritium plant
18: Chem. vol. control
74: Diagnostic bd.
21: Hot cells
13: Assembly
15: Gyrotron building



Site:
- ca. 450m × 450m
- 4 large nuclear buildings, e.g. 70m × 70m
- ~165 MW of steady-state electric power supply

Nuclear license:
- Nuclear facility without risk of accidents requiring the evacuation of the public.
- On-site tritium inventory: ca. 500 g.
- Radwaste: ~2,000 tons low and intermediate level waste to be stored on site.

Tokamak Assembly

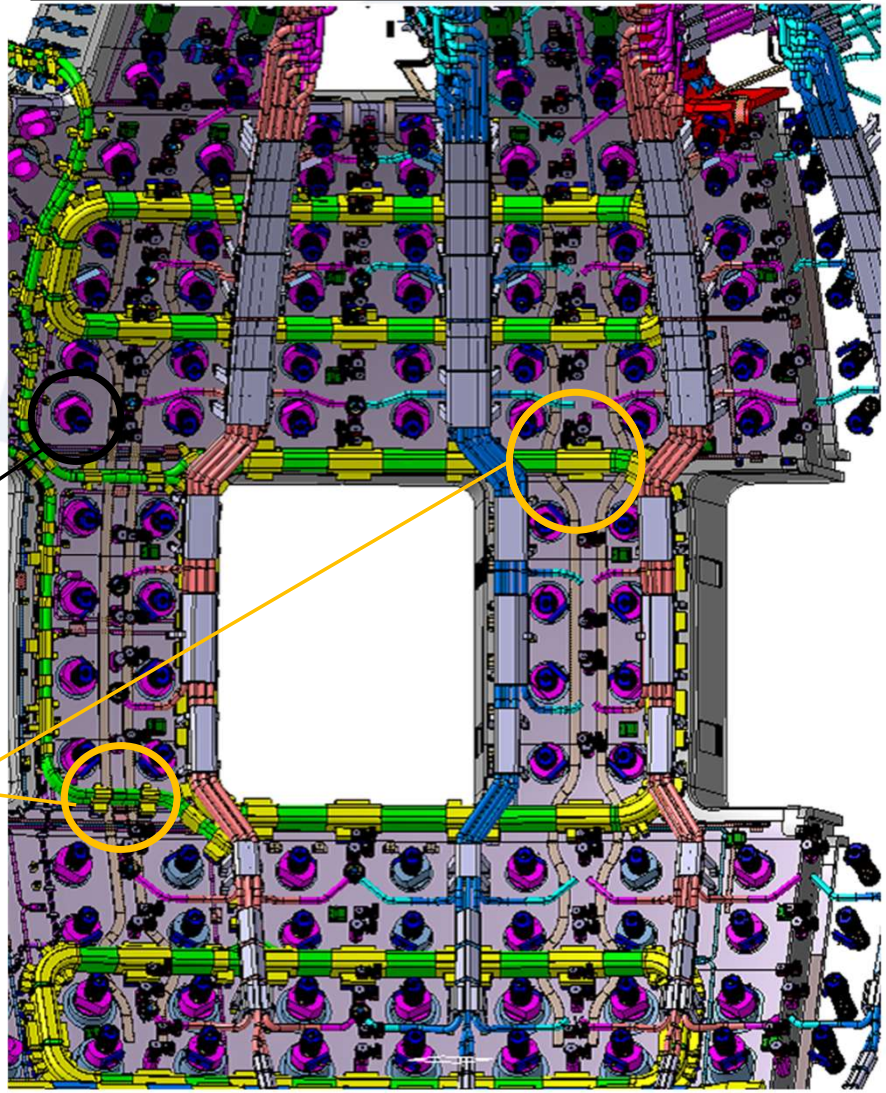
Assembly – design targets

Limited space in tokamak pit → <u>360° torus pre-assembly</u>

Reduce complexity of in-vessel systems integration:

- Minimize in-vessel coolant manifolds
- Avoid in-vessel coils
- Reduce mechanical attachment structures

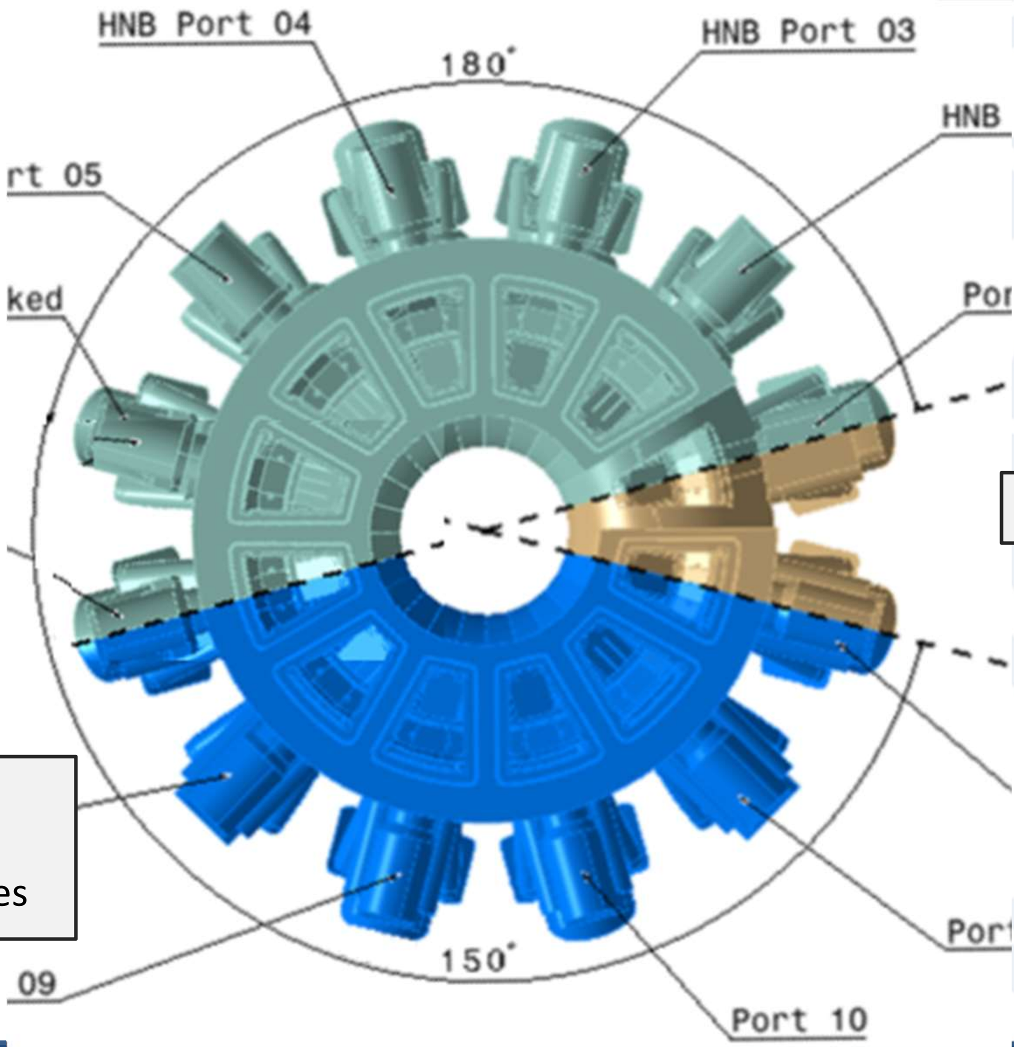
ITER VV outboard side, courtesy A. Martin (IO)



Avoid cable looms crossing in-vessel coils or manifolds

Assembly – 3 VV sectors

180° sector including all NB ports



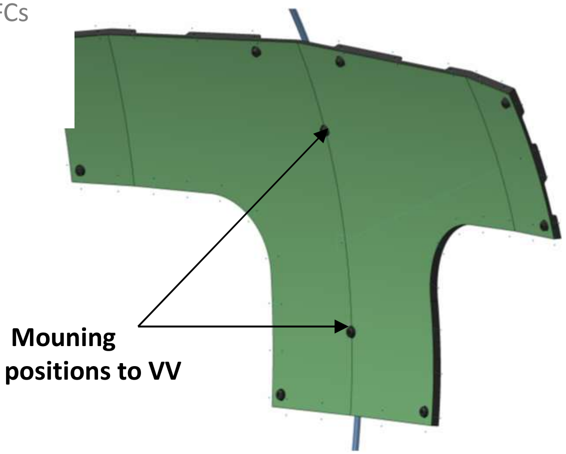
30° final sector

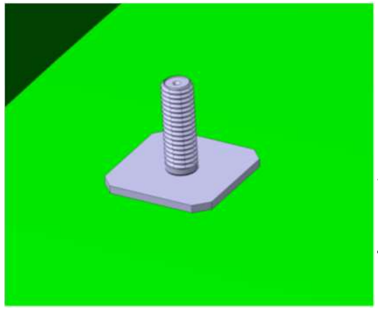
150° sector including equatorial port with intra-VV coils feed lines

Assembly hall: Mounting of VV thermal shield to 330° VV

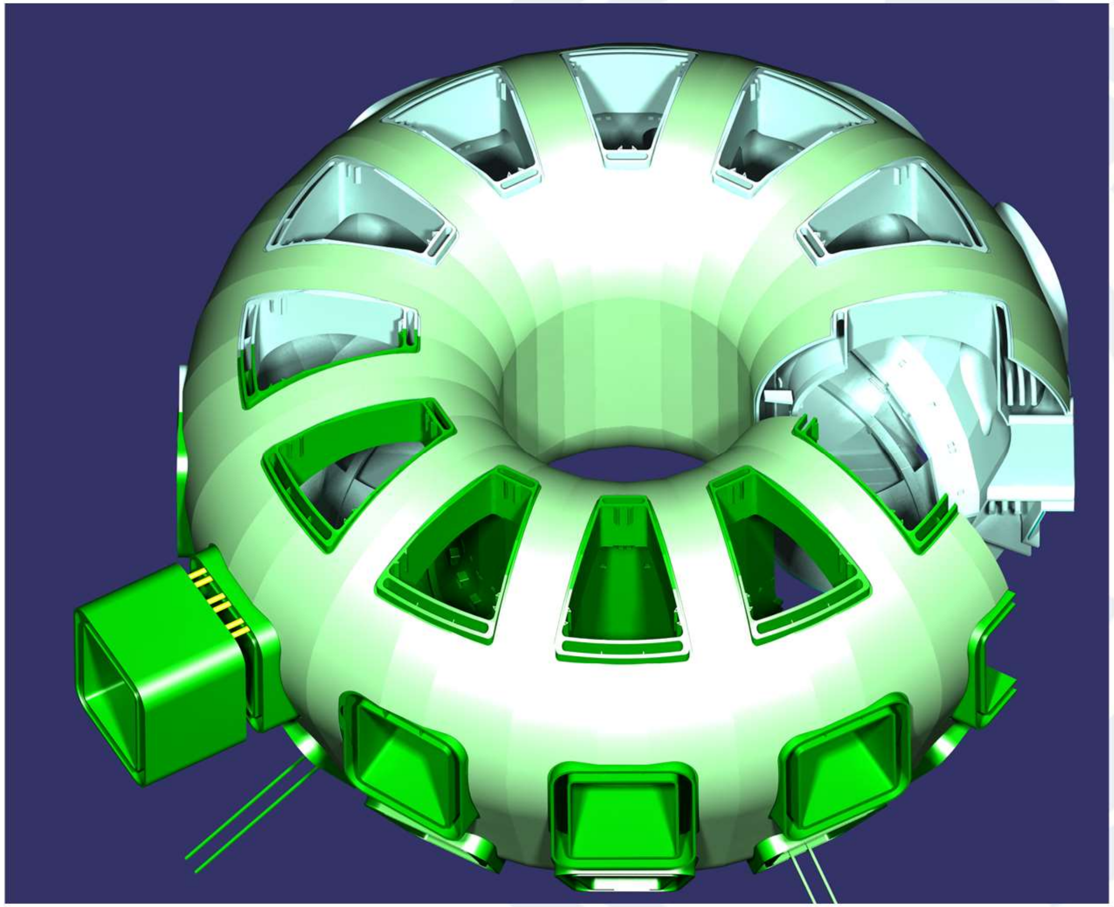
VV thermal shield panels mounted to VV

VV thermal shield panels are riveted together





Welded buffer plate with M8 press studs replace stud welding to facilitate checking the weld seam.



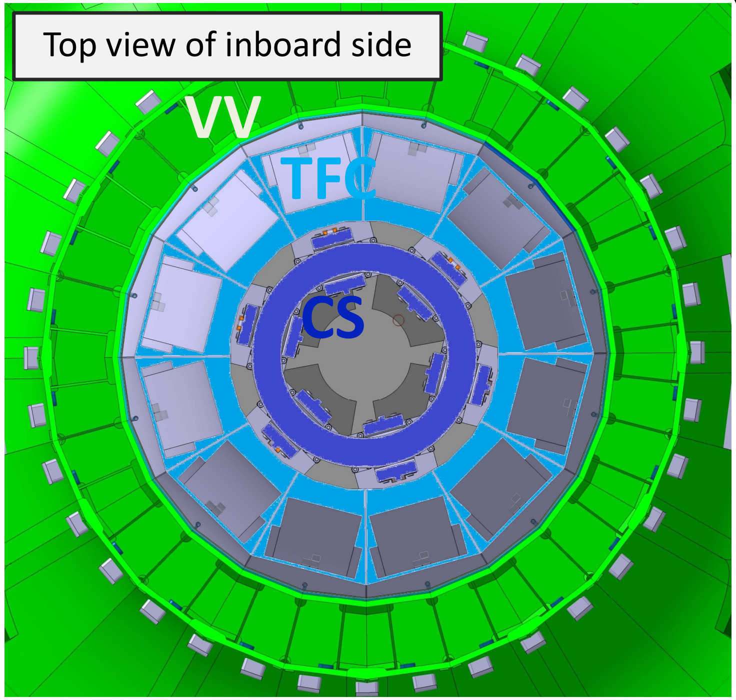
Assembly hall: Mounting of VV thermal shield to 330° VV – inboard side

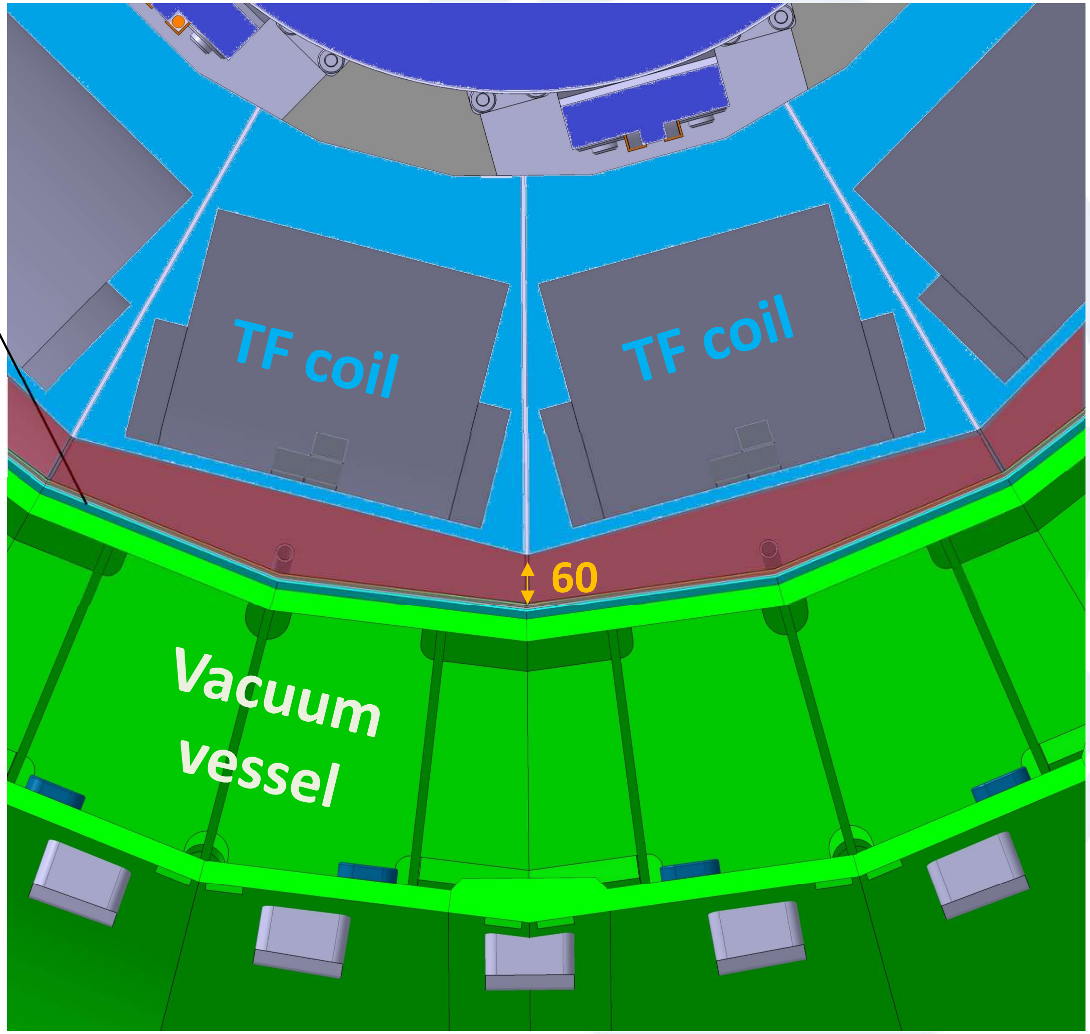
Factory: VV sector fabrication
Assembly hall: 150° + 180°
Assembly hall: 1 equatorial port
Assembly hall: VV Thermal shield
Assembly hall: 11 TF coils
Assembly hall: Preparation last sector
Assembly hall: Installation last sector
Assembly hall: Lower ports + lower PFCs
Tokamak pit: Cryostat
Tokamak pit: 360° tokamak lift
Tokamak pit: Equa. ports + upper
Tokamak pit: Upper ports
Tokamak pit: Cryostat top lid

TF coils are not present during assembly of VV TS

VV thermal shield with two MLIs

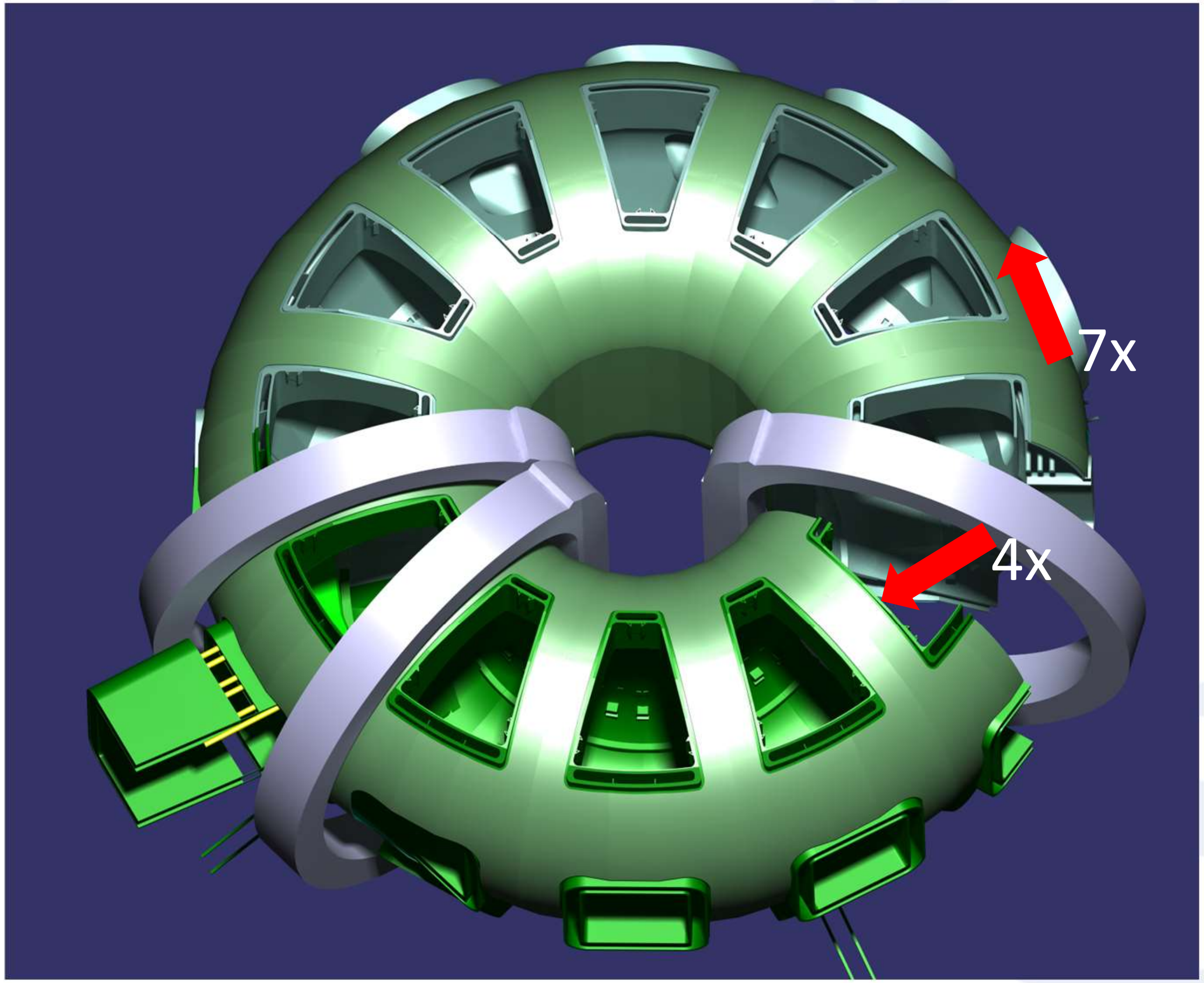
Top view of inboard side





Assembly hall: Assembly of 11 TF coils

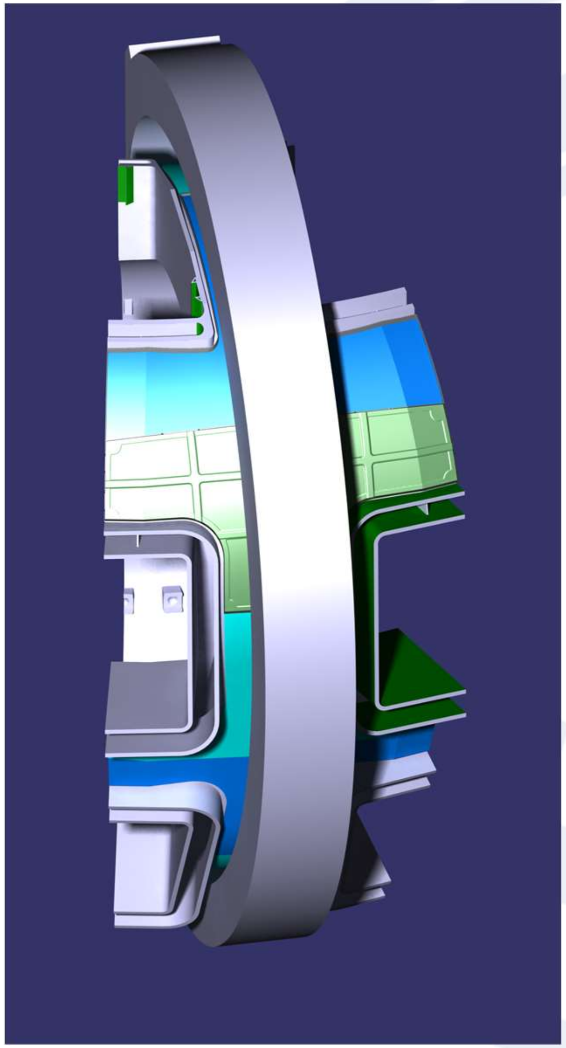
Polar crane used to assemble 11 TF coils (JT60-SA- like)



Assembly hall: Preparation of (last) 30° VV sector

Factory: VV sector fabrication
Assembly hall: 150° + 180°
Assembly hall: 1 equatorial port
Assembly hall: VV Thermal shield
Assembly hall: 11 TF coils
Assembly hall: Preparation last sector
Assembly hall: Installation last sector
Assembly hall: Lower ports + lower PFCs
Tokamak pit: Cryostat
Tokamak pit: 360° tokamak lift
Tokamak pit: Equa. ports + upper PFCs
Tokamak pit: Upper ports
Tokamak pit: Cryostat top lid

- 30° pieces of intra-VV coils conductors inside VV double-wall structure
- Assembly of VVTS
- Assembly of TF coil



Assembly hall: Torus completion / last sector assembly

Factory: VV sector fabrication
Assembly hall: 150° + 180°
Assembly hall: 1 equatorial port
Assembly hall: VV Thermal shield
Assembly hall: 11 TF coils
Assembly hall: Preparation last sector
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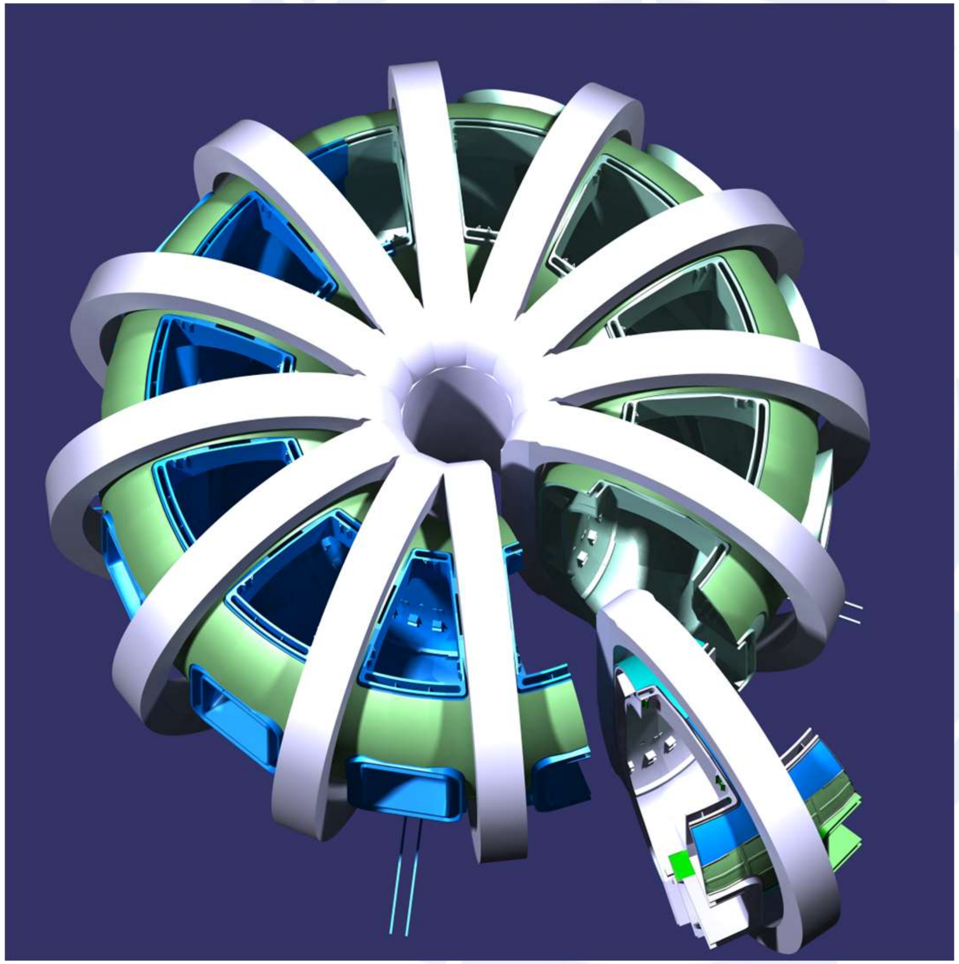
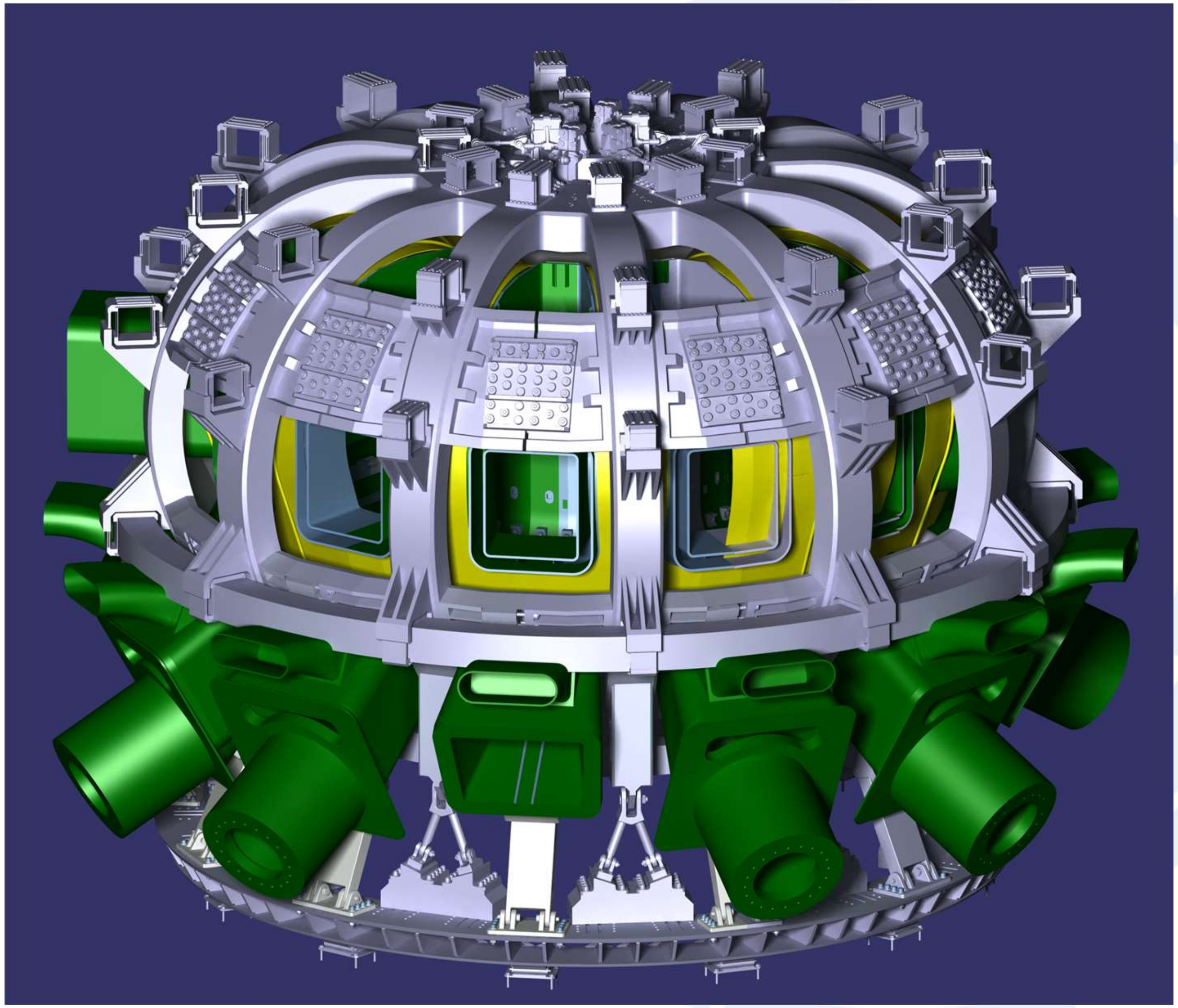


Assembly hall: Lower ports

Factory: VV sector fabrication
Assembly hall: 150° + 180°
Assembly hall: 1 equatorial port
Assembly hall: VV Thermal shield
Assembly hall: 11 TF coils
Assembly hall: Preparation last sector
Assembly hall: Installation last sector
Assembly hall: Lower ports + lower PFCs
Tokamak pit: Cryostat
Tokamak pit: 360° tokamak lift
Tokamak pit: Equa. ports + upper PFCs
Tokamak pit: Upper ports
Tokamak pit: Cryostat top lid

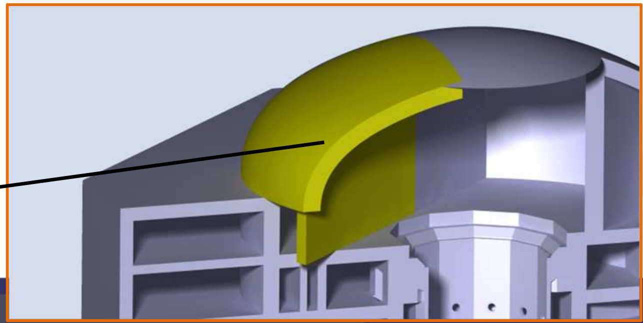
- Installation of PF4
- Welding of lower port extensions
- Assembly of gravity supports to VV and TF coils and to cryostat pedestal ring
- Installation PF5 & PF6

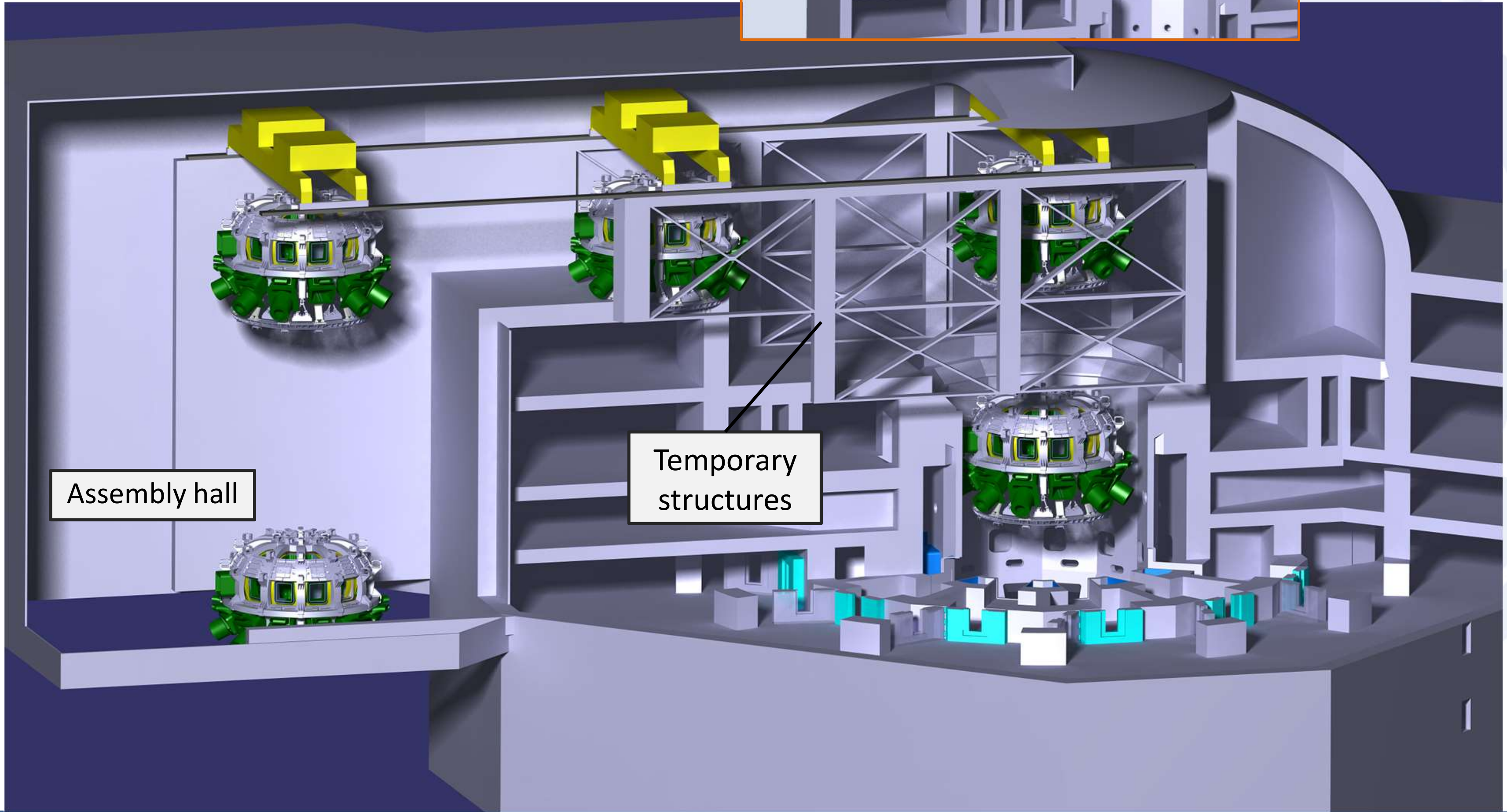


Tokamak pit: 360° tokamak lift

Factory: VV sector fabrication
Assembly hall: 150° + 180°
Assembly hall: 1 equatorial port
Assembly hall: VV Thermal shield
Assembly hall: 11 TF coils
Assembly hall: Preparation last sector
Assembly hall: Installation last sector
Assembly hall: Lower ports + lower PFCs
Tokamak pit: Cryostat
Tokamak pit: 360° tokamak lift
Tokamak pit: Equa. ports + upper PFCs
Tokamak pit: Upper ports
Tokamak pit: Cryostat top lid

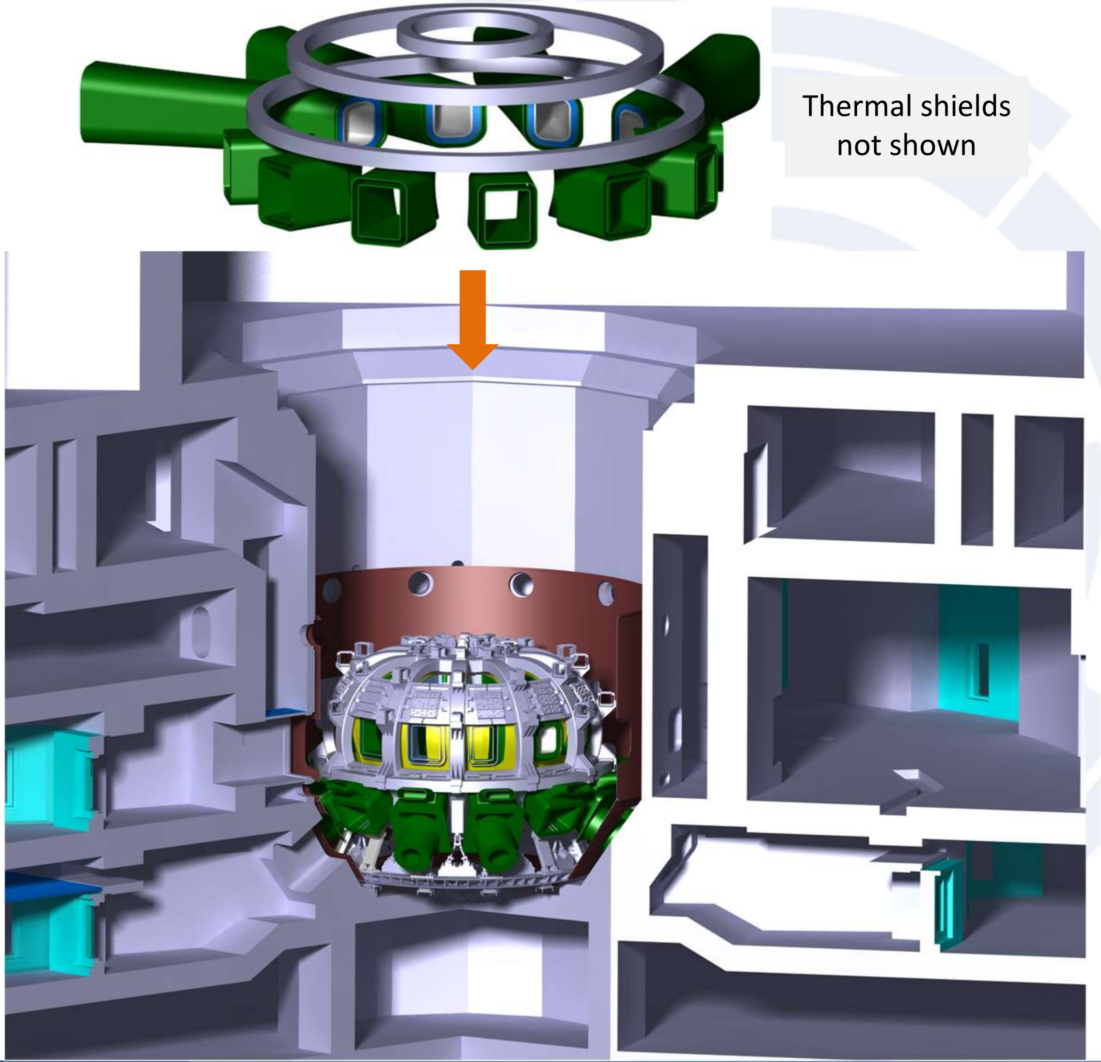
- m = 1,500 tons
- Ø 15m, H=8m
- Lifted on pedestal ring





Tokamak pit: Equatorial ports with therm. shields + upper PF coils

- Welding of equatorial port extensions
- Installation of equatorial port thermal shields
- Assembly of PF1, PF2, and PF3

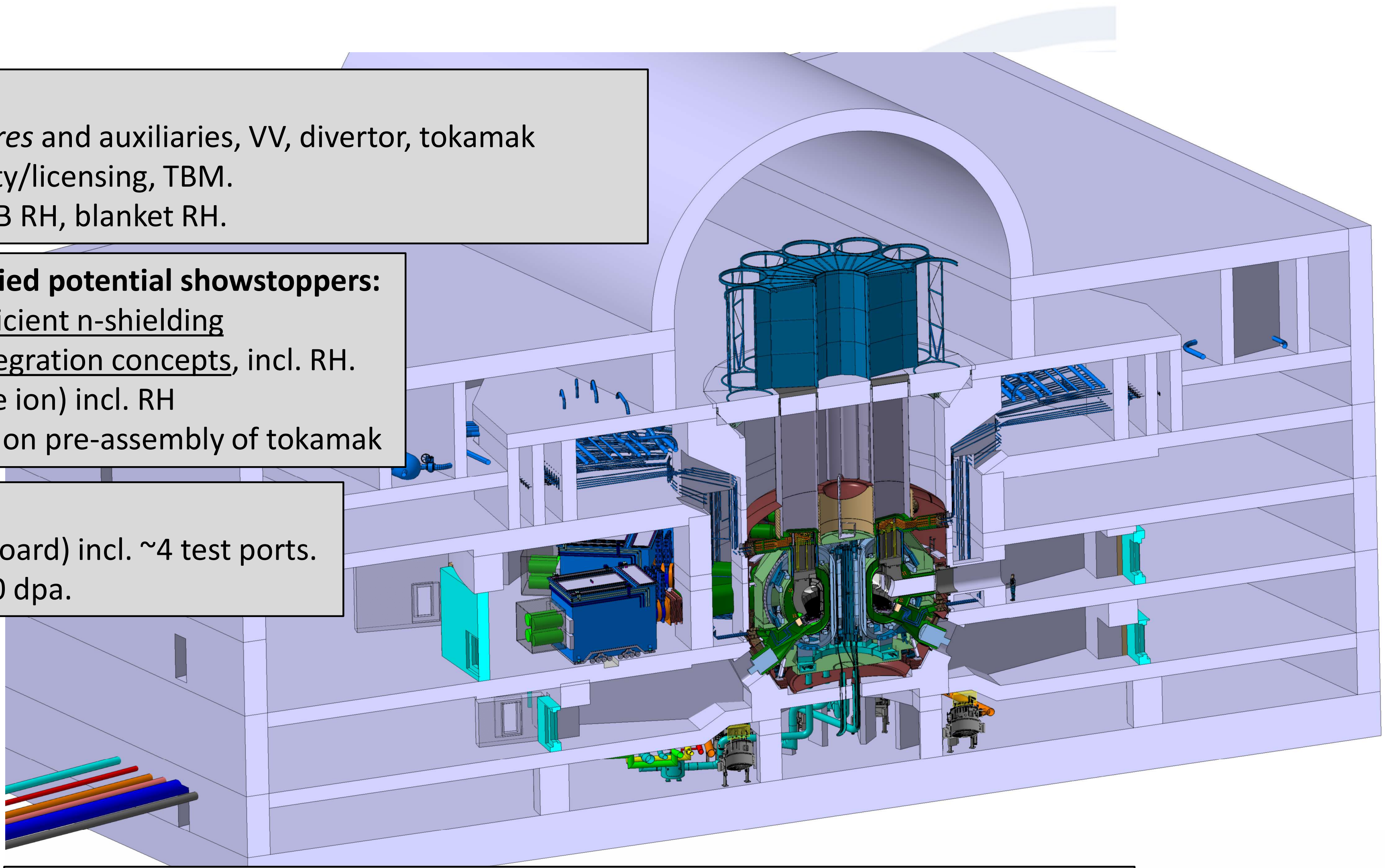


Summary

VNS technologies:
- <u>ITER-like:</u> Magnet *structures* and auxiliaries, VV, divertor, tokamak cooling, T-fuel cycle, safety/licensing, TBM.
- <u>New:</u> Steady-state NBI, NB RH, blanket RH.

Concepts for initially identified potential showstoppers:
- <u>Tokamak design with sufficient n-shielding</u>
- <u>In-vessel components integration concepts</u>, incl. RH.
- <u>NBI</u> (steady-state, positive ion) incl. RH
- <u>Tokamak assembly</u> based on pre-assembly of tokamak

Testing opportunities:
- ~25 m² testing area (outboard) incl. ~4 test ports.
- 14 full power years to ~50 dpa.



Design is constantly on-going for improvement and further substantiation

Relevant publications (incomplete list)

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3. 2024: Giannini, L., et al. "Conceptual design studies on the magnet system for the Volumetric Neutron Source (VNS)." IEEE Transactions on Applied Superconductivity (2024).
4. 2024: Giannini, L., et al. "Optimization of Poloidal Coil System for the Volumetric Neutron Source (VNS) Fusion Reactor." IEEE Transactions on Applied Superconductivity (2024).
5. 2024: Sorgente, Donato, et al. "Overview of in-bore pipe cutting and welding tools for the maintenance of CFETR and EU-DEMO", Fusion Engineering and Design 203 (2024): 114478
6. 2025: Haertl, T., et al. "Vacuum pumping concept for quasi-continuous NBI operation at a steady state fusion machine." 33rd Symposium on Fusion Technology (SOFT 2024). 2024.
7. 2025: Boscary, J., et al. "Divertor conceptual design of the European Volumetric Neutron Source." Fusion Engineering and Design 212 (2025): 114861.
8. 2025: Maione, Ivan Alessio, et al. "Electromagnetic design optimization of the inboard shielding blanket for the volumetric neutron source." FED217 (2025): 115122.
9. 2025: Wiesen, S., et al. "Exhaust assessment of a European Volumetric Neutron Source (EU-VNS) using SOLPS-ITER." Nuclear Materials and Energy (2025): 101939.
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11. 2025: Claps, Vincenzo, et al. "Development of an In-Bore welding tool prototype for DEMO's in-vessel pipes." Fusion Engineering and Design 217 (2025): 115166.
12. 2025: Bachmann, C., et al. "Engineering concept of the VNS-a beam-driven tokamak for component testing." Fusion Engineering and Design (2025): 114796.
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14. 2025: Mozzillo, Rocco, et al. "Remote maintenance strategy of the volumetric neutron source shielding blanket." Fusion Engineering and Design 218 (2025): 115226.
15. 2026: Aiello, G., et al. "Screening of suitable and testable structural materials for a volumetric neutron source." Fusion Engineering and Design 222 (2026): 115460