Overview of COMPASS-U Design

Design status: end of 2020

EUROPEAN UNION
European Structural and Investment Funds
Operational Programme Research,
Development and Education

MINISTRY OF EDUCATION,
YOUTH AND SPORTS

Outline

- **COMPASS Upgrade mission**
- **Design requirements, plasma scenarios**
- **Design of individual tokamak systems**
  - Cryostat
  - Support structure
  - TF coils
  - PF coils + central solenoid
  - Vacuum vessel
  - Plasma facing components
  - Cryogenics
  - NBI
  - ECRH
  - Power supply system
- **Neutronics**

COMPASS-U mission

GOAL: ***Compact flexible device with set of unique parameters relevant to next step devices***

- *Closed divertor with high plasma and neutral density, high opacity, high PB/R, high power fluxes*
- *High magnetic field, access to advanced confinement modes*
- *Hot first wall, full recycling regime, possibility to study liquid metals*

1) Conventional divertors

- Experimental demonstration of detached operation at ITER/DEMO relevant power fluxes

2) Edge plasma physics and confinement related activities

- Enhanced confinement modes (QH-mode, I-mode, negative triangularity)
- Low torque operation
- Disruption and RE physics (avoidance, mitigation, prediction, loads, etc.)
- Validation of theoretical models

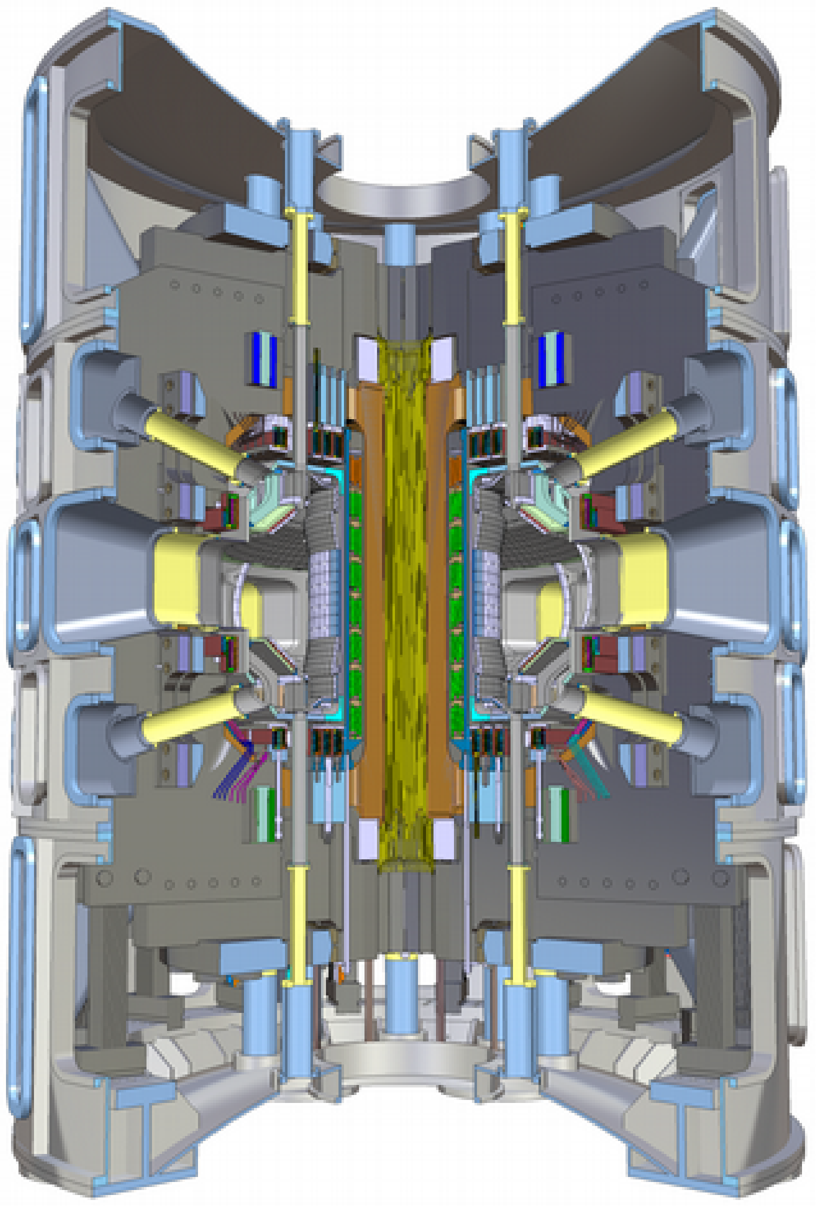
3) Test of advanced PFC materials in the divertor with quick response time

4) Test of liquid metals divertor concepts, hot wall operation

- Effect of liquid metals on machine performance, comparison of heat flux handling with solid/liquid metals divertor.

5) Advanced divertor concepts

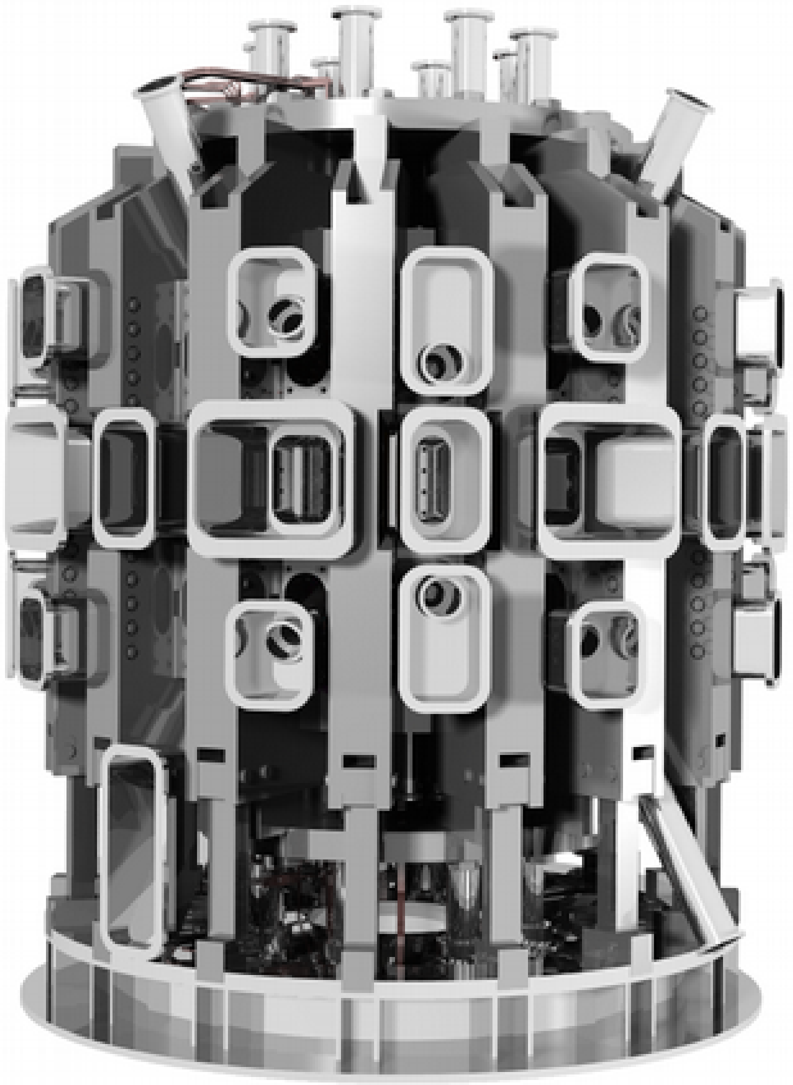
- Experimental demonstration of the snowflake configuration in a high density divertor; direct comparison with a conventional divertor



Design overview

Main design requirements

- Toroidal magnetic field $B_t = 5$ T
- Plasma current $I_p = 2$ MA
- Major radius R = 0.894 m
- Minor radius a = 0.27 m
- Aspect ratio A = 3.3
- Triangularity δ = 0.3-0.6
- Elongation κ = 1.8
- Enough space for different divertors
- Plasma shapes
  - single lower null, neg. triangularity with limited parameters (Phase 1-2)
  - double null (Phase 2-3)
  - snowflake, negative triangularity (Phase 3-4)
- Heating power
  - Phase 1 $P_{NBI} >= 3$ MW, $P_{ECRH} = 1$ MW (P*B/R ~ 25)
  - Phase 2 up to $P_{NBI} = 8$ MW, $P_{ECRH} = 10$ MW (P*B/R ~ 100)
- Vacuum vessel operation temperature up to 500°C (min. 300°C)



Plasma scenarios

- **Full time evolution of different plasma scenarios** modelled using METIS + FIESTA
- Example of scenarios:

#		Bt [T]	Ip [MA]	q95	κ	δ	flat-top length [s]
2	SND	1.25	0.4	3	1.8	0.5	4-11
3	SND	2.5	0.8	3	1.8	0.5	3-9
5	SND	5	1.6	3	1.8	0.5	1-3
6.4	SND	5	2	2.5	1.8	0.5	1-3
6.5	SND, low triangularity	5	2	2.5	1.8	0.3	1-3
6.6	SND, high triangularity	5	2	2.5	1.8	0.6	1-3
7	Double null	5	2	2.2	1.8	0.5	1-3
11	SND, negative triangularity	5	1	2.8	1.4	-0.2	

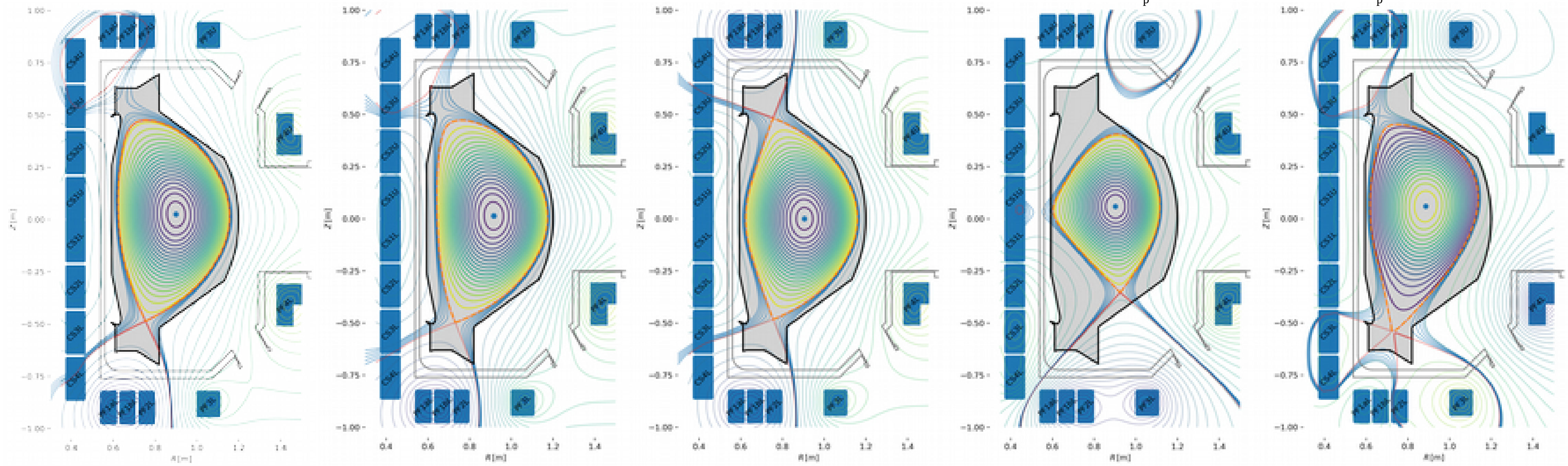
Scenario 6.4 — $\kappa = 1.8, \delta = 0.5$

Scenario 6.6 — $\kappa = 1.8, \delta = 0.6$

Scenario 7.4 — $\kappa = 1.8, \delta = 0.5$

Scenario 11.0 — $\kappa = 1.4, \delta = -0.2, I_p = 1$ MA

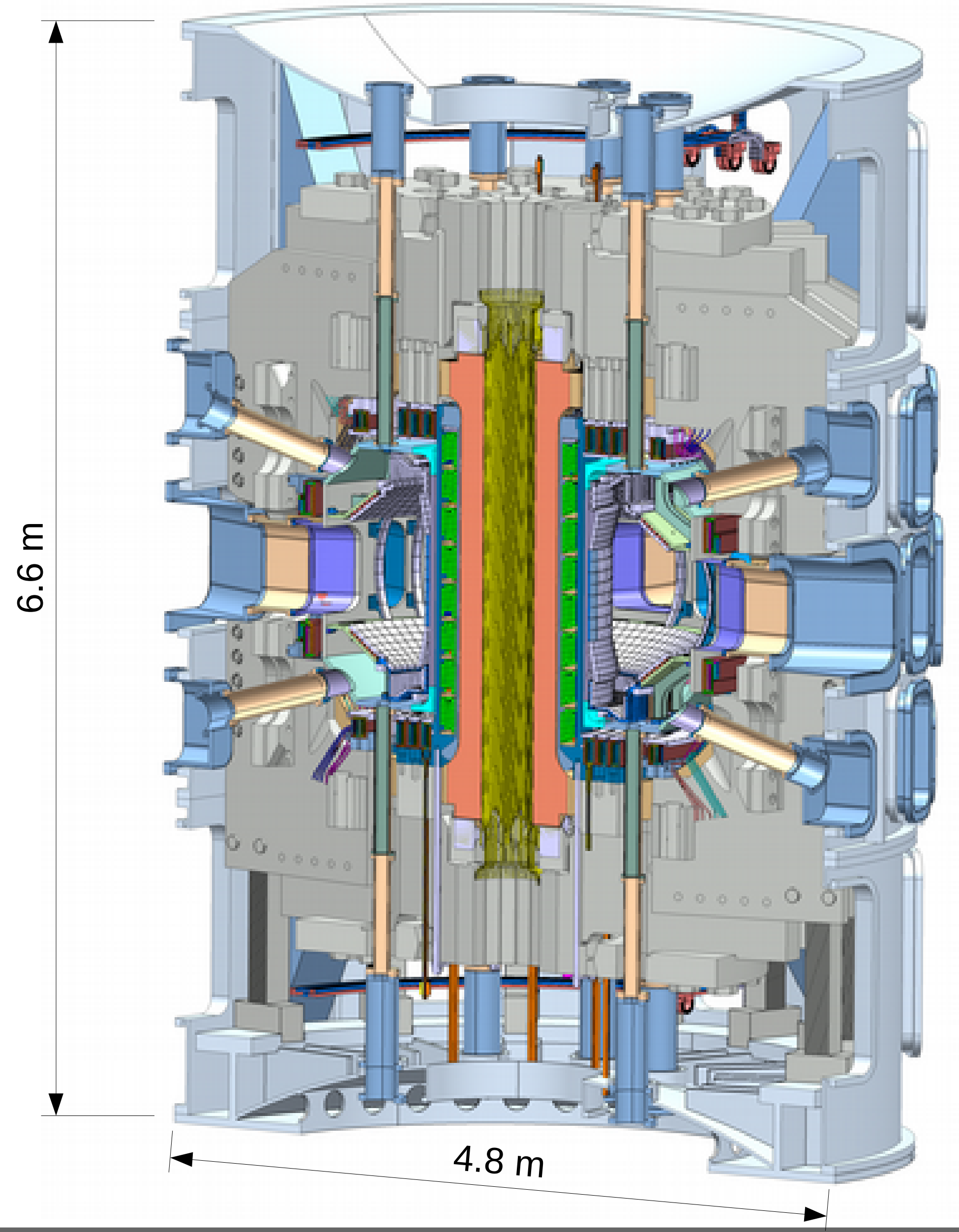
Snowflake — $I_p = 1.5$ MA



Design overview

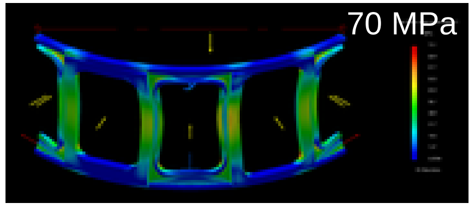
Main design features

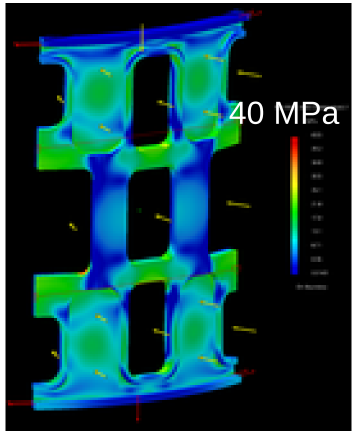
- **Metalic first wall** (Inconel, W-coated Inconel, W)
- Up to 35 mm thick **Inconel 625 vacuum vessel**
- **Hot first wall and vacuum vessel** operation (300-500°C, gaseous He or CO_2)
- **Vacuum vessel thermaly insulated by multilayer insulation** (MLI)
- **OFHC copper coils cooled to 80K** (gaseous He)
- **Central solenoid** (8 segments) and **PF coils** (4+4) **inside the TF**
- **Dismountable TF coils** (sliding and bolted joints)
- **Massive stainless steel support structure**
- **Stainless steel cryostat**
- **Vacuum vessel human access via large midplane ports**
- **Overal dimensions** ~6.6x4.8 m, weight ~300 t

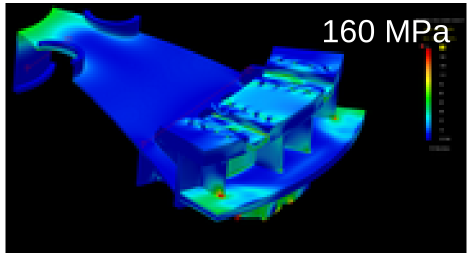


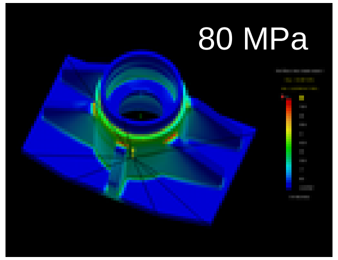
Cryostat

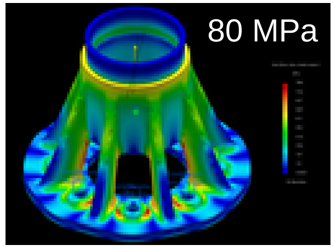
- **Stainless steel cryostat** (AISI 304)
- **Volume ~100 m^3**, weight ~50 t
- Tokamak is placed on top of the cryostat base
- 8 massive steel supports attached to the **0.8 m thick steel-reinforced concrete slab** of the experimental hall
- Multilayer thermal insulation on the inner surface
- Mechanical stress from the atmospheric pressure and disruptions was checked to be within acceptable limits

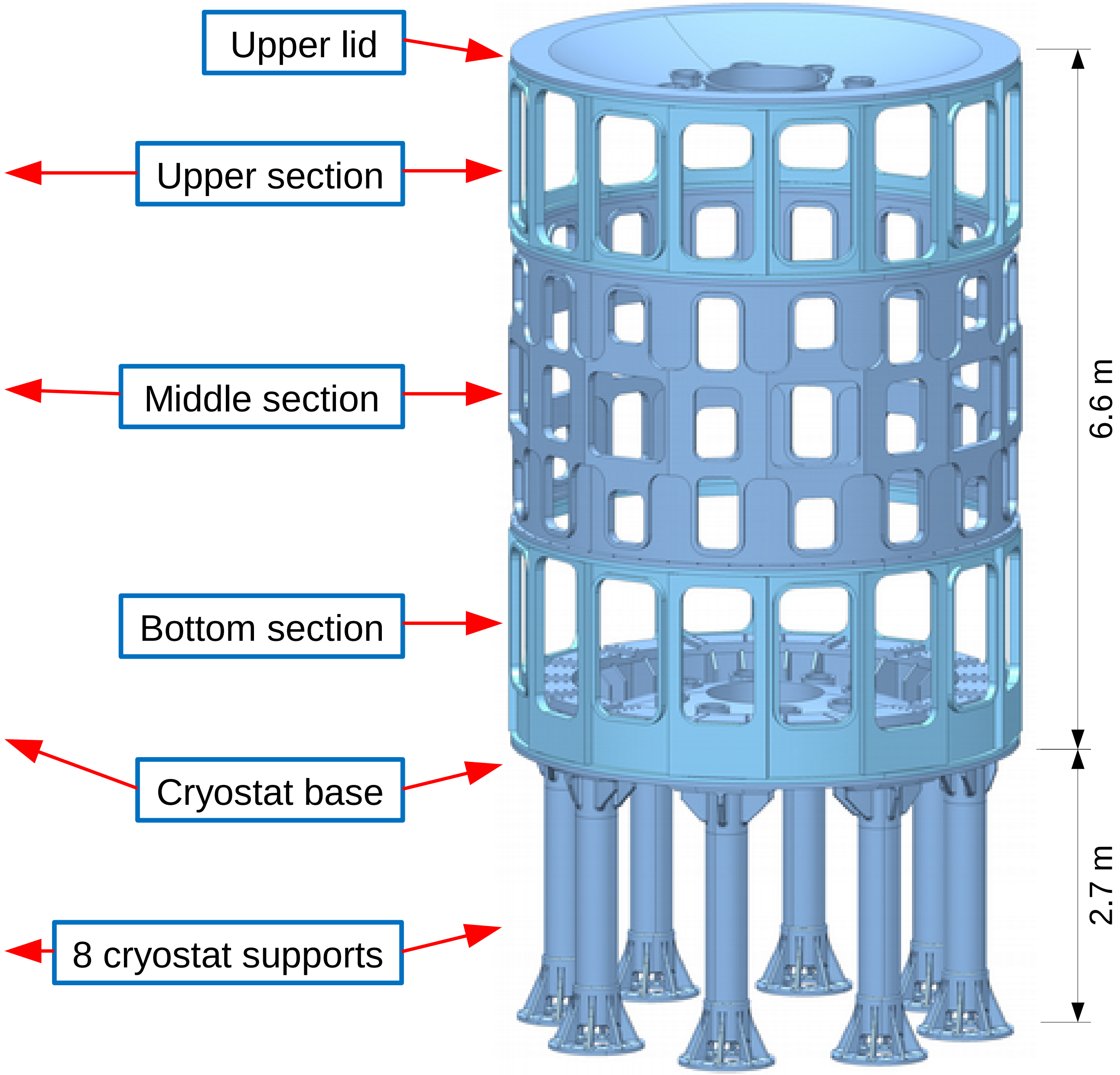






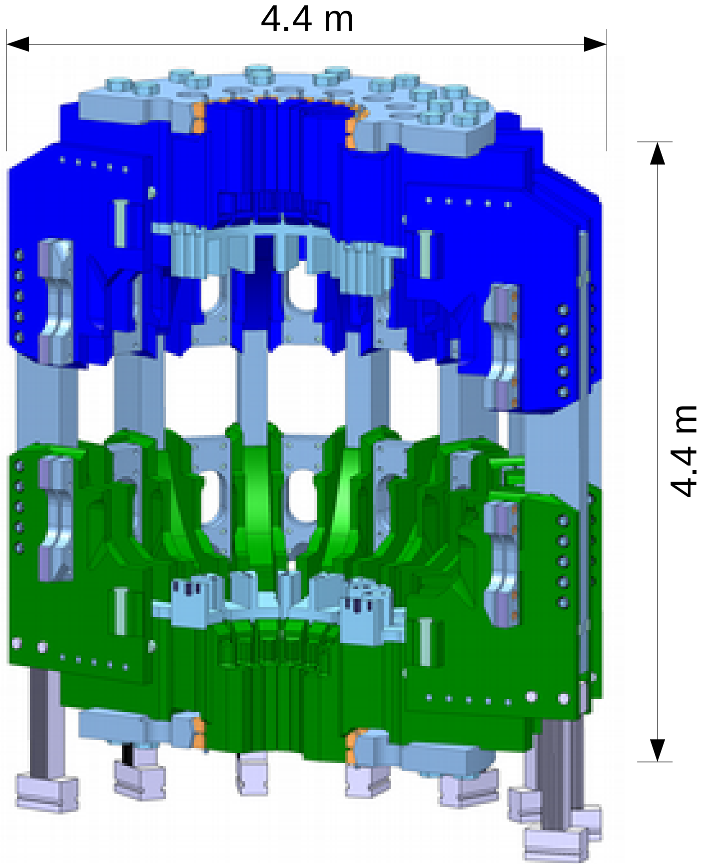


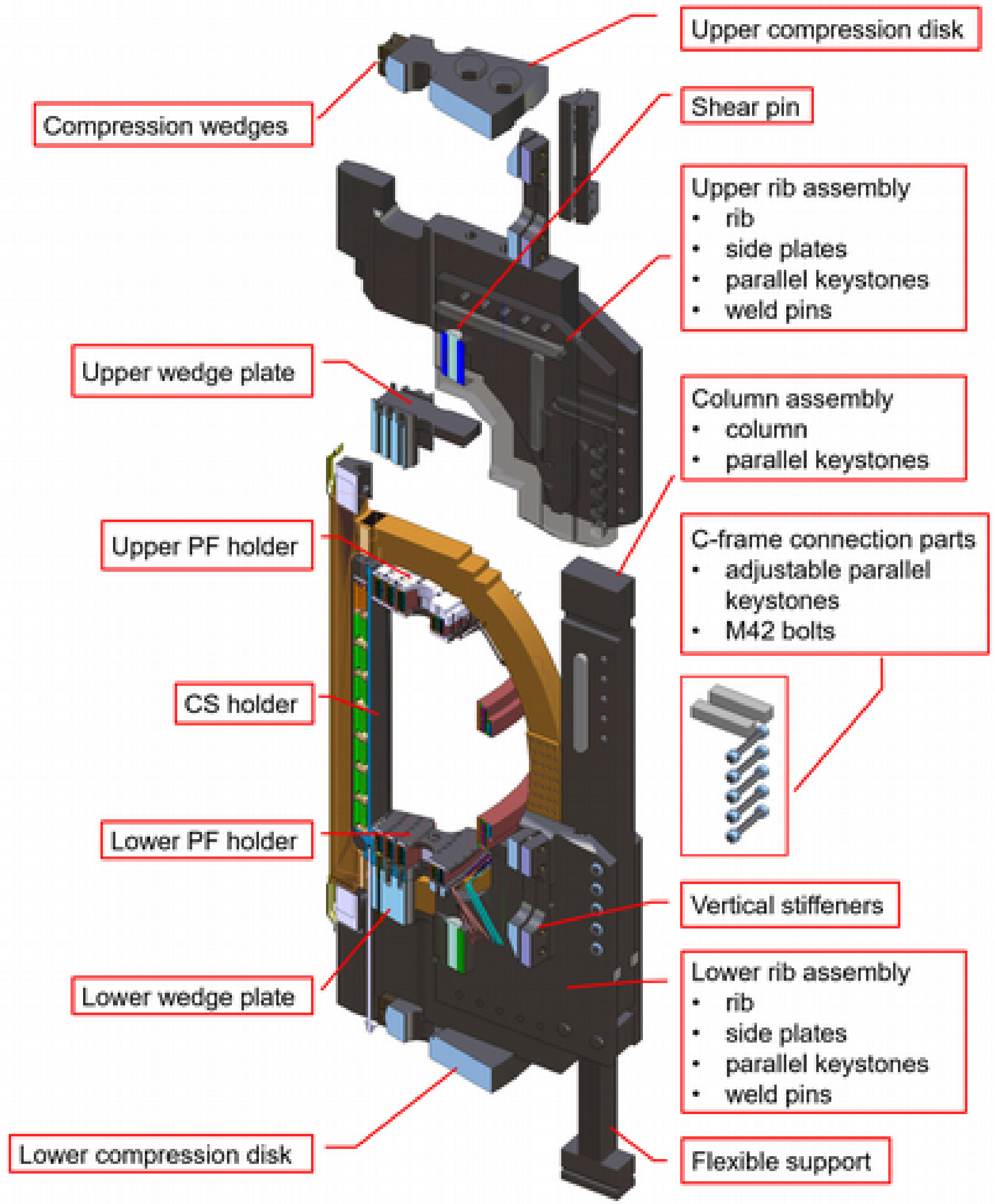




Support structure

- Material SS 304(L)N or 316(L)N
- Overall dimensions: height ~4.4 m, diameter ~4.4 m, total weight ~190 t
- 16 C-frames + flexible supports
- Cooled to 80 K, SS pipes welded to machined grooves, gaseous He
- **Cool-down in ~1 week time**, vertical contraction ~14 mm
- Vertical disassembly possible

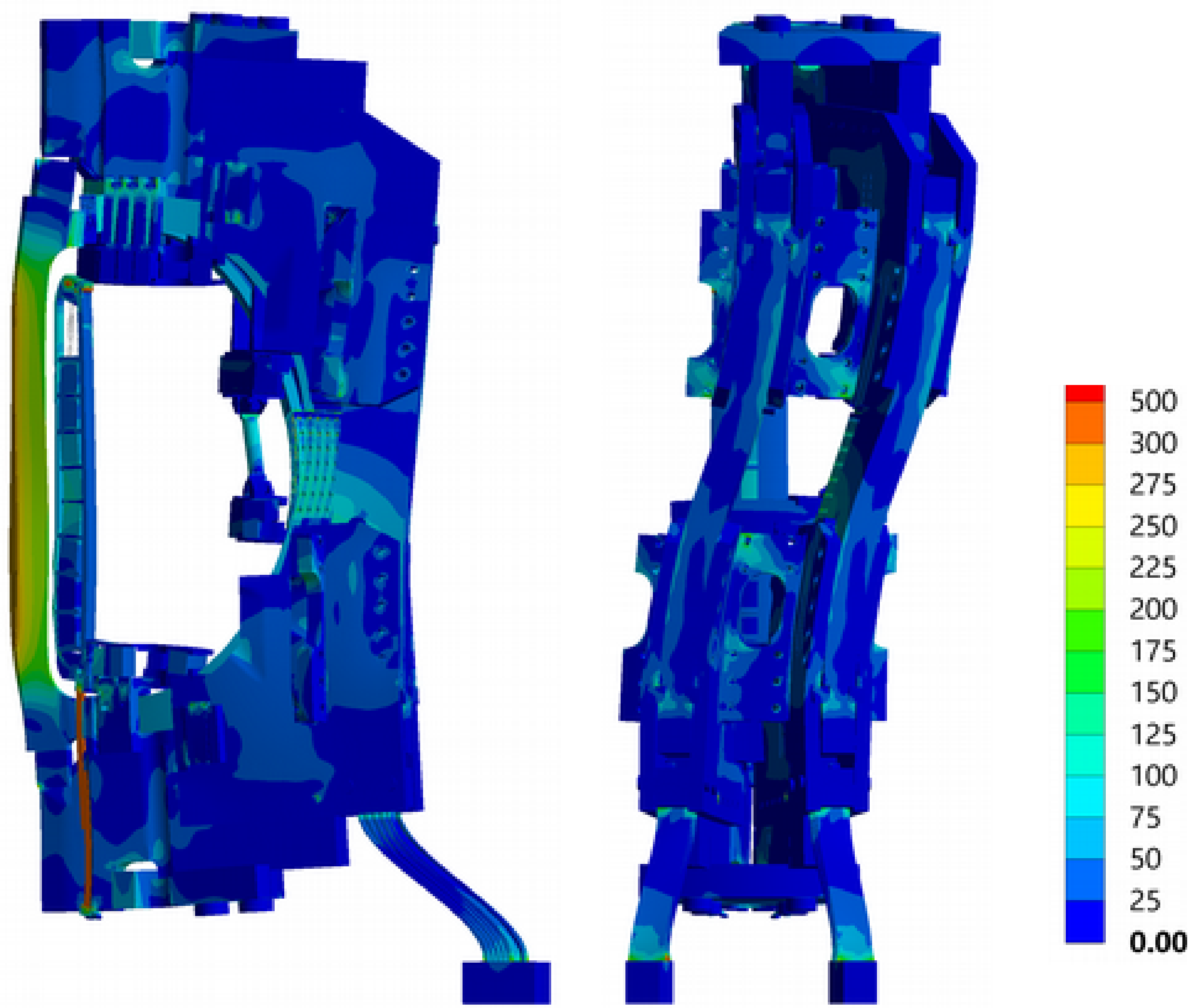




Support structure

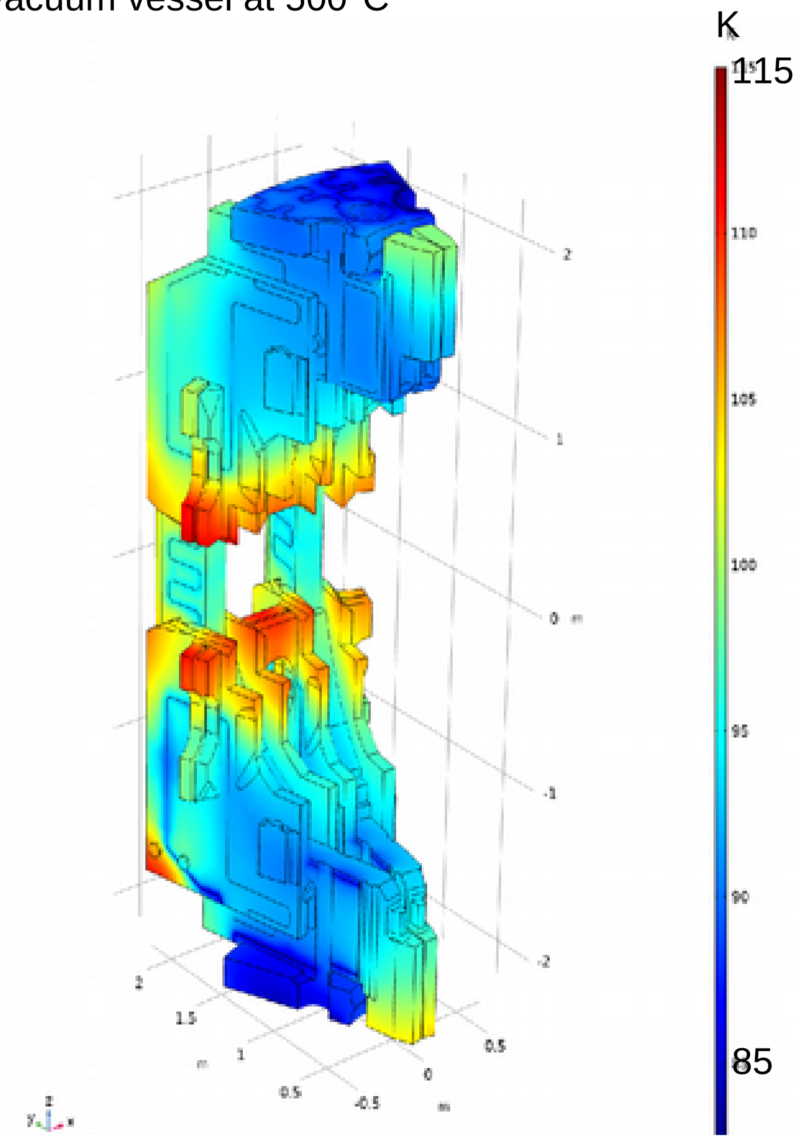
Von Mises stress in the support structure and TF coil [Mpa]

- Electromagnetic forces + thermal conditions (cooled support structure and coils).
- Deformation scale 100.



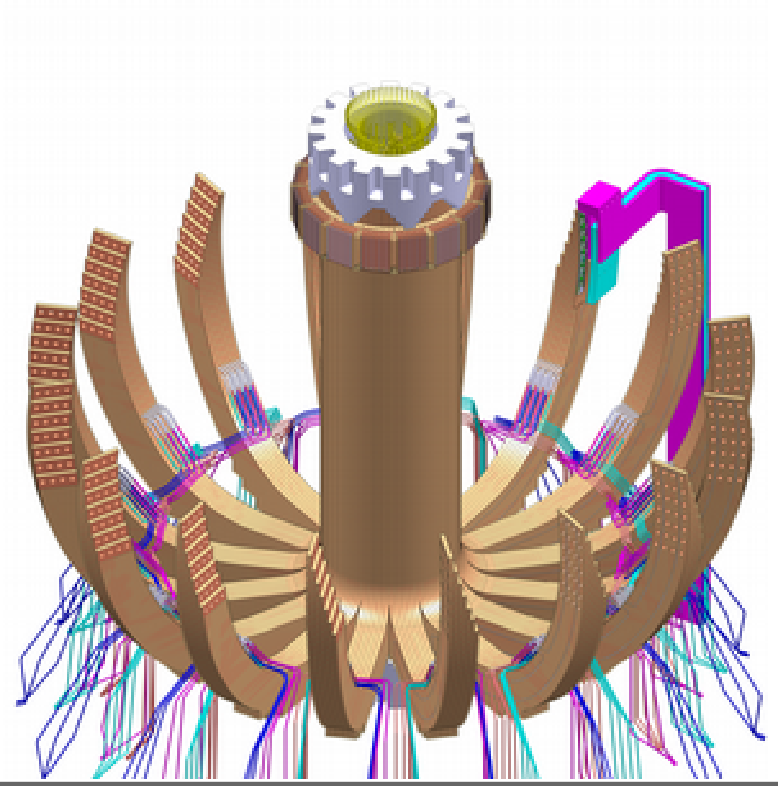
Temperature distribution after 1 week cool-down

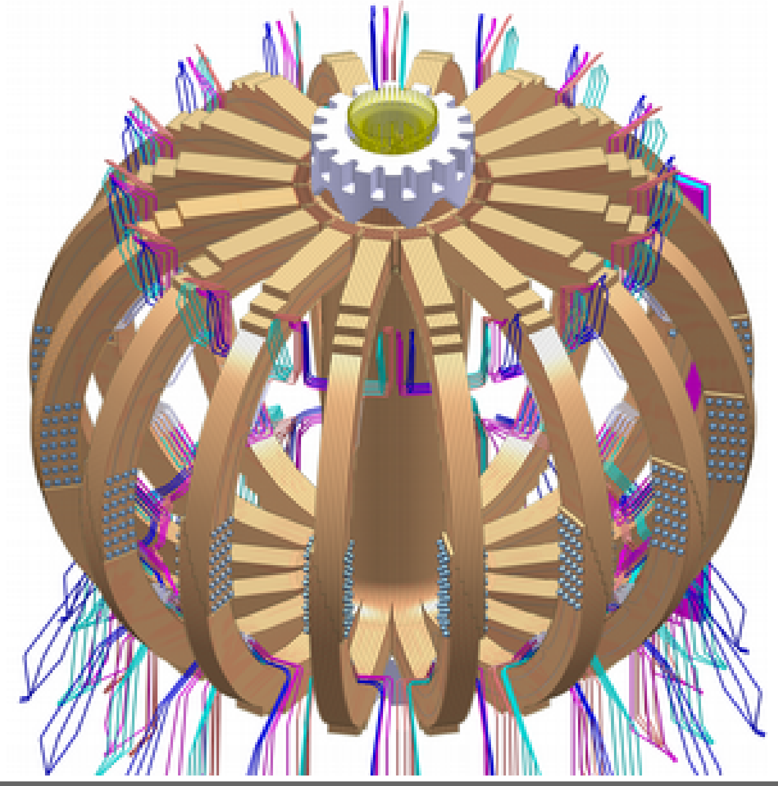
- Vacuum vessel at 500°C

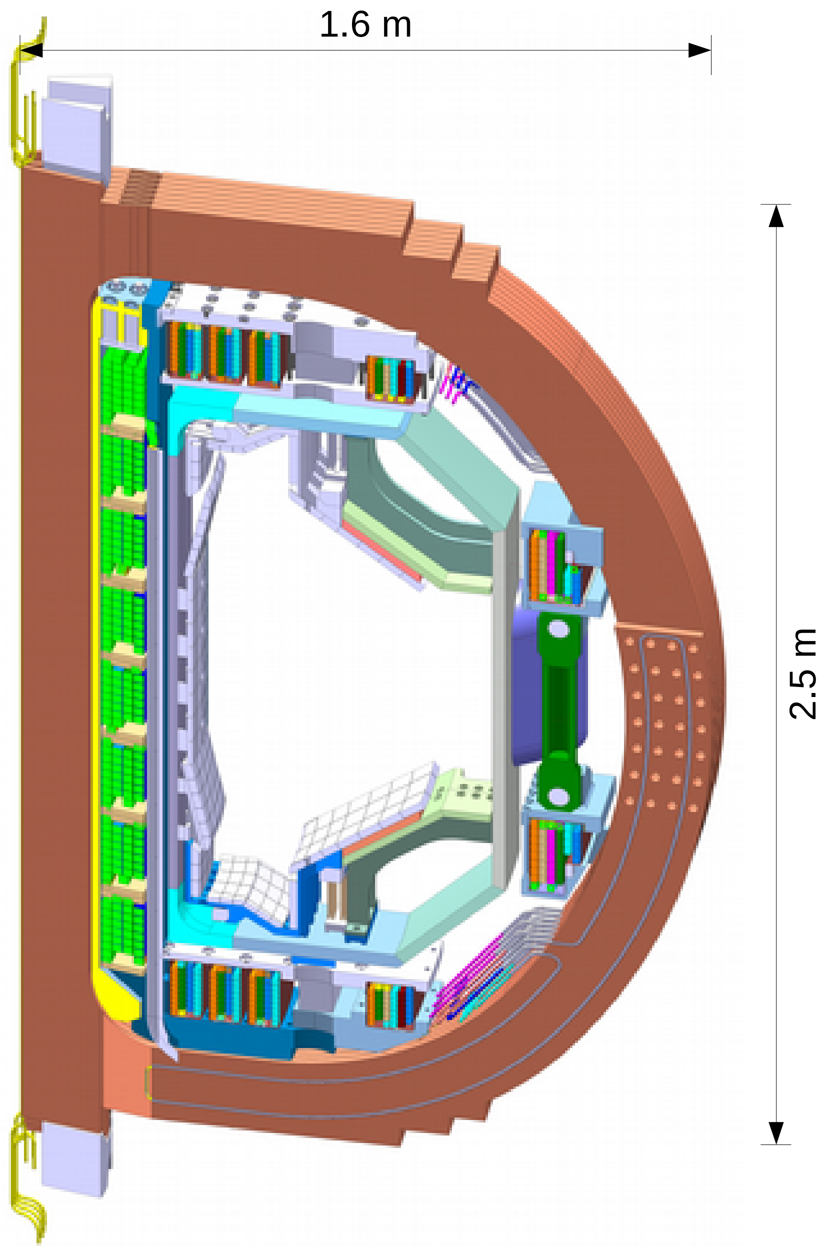


Toroidal field coils

- **16 coils**, **7 turns** each
- TF core + 16 upper limbs
- **16 sliding + 16 bolted joints**, turn-to-turn transition in the OMP bolted joint
- **200 kA** for **5 T** @ **R=0.894 m**
- TF ripple at separatrix **δ < 0.5 %**
- Material candidates **CuAg0.1** and **CuZr0.1**
- Cooled down to 80 K, gaseous coolant (He), Cu cooling pipes soldered to machined grooves



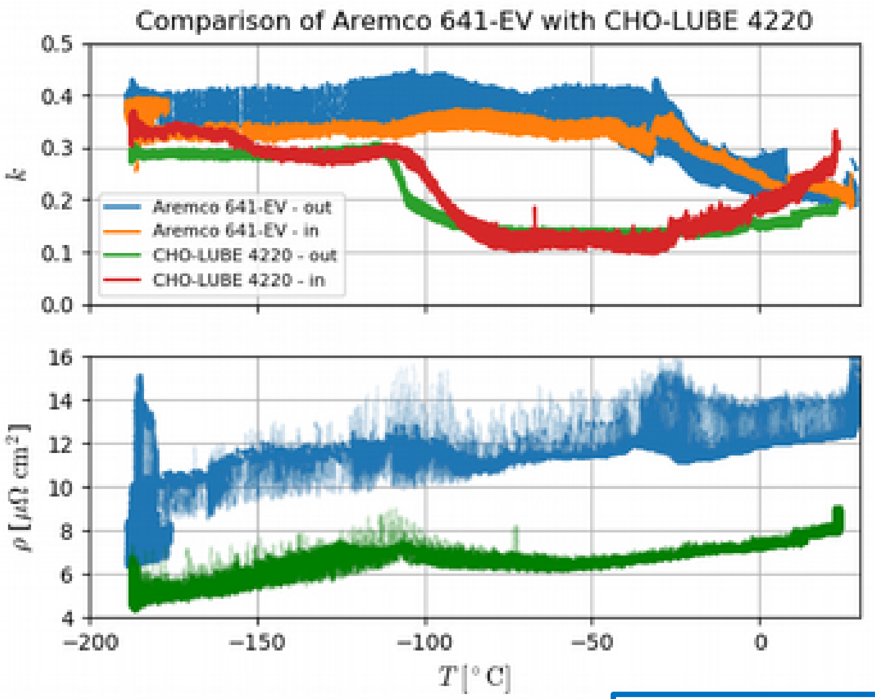


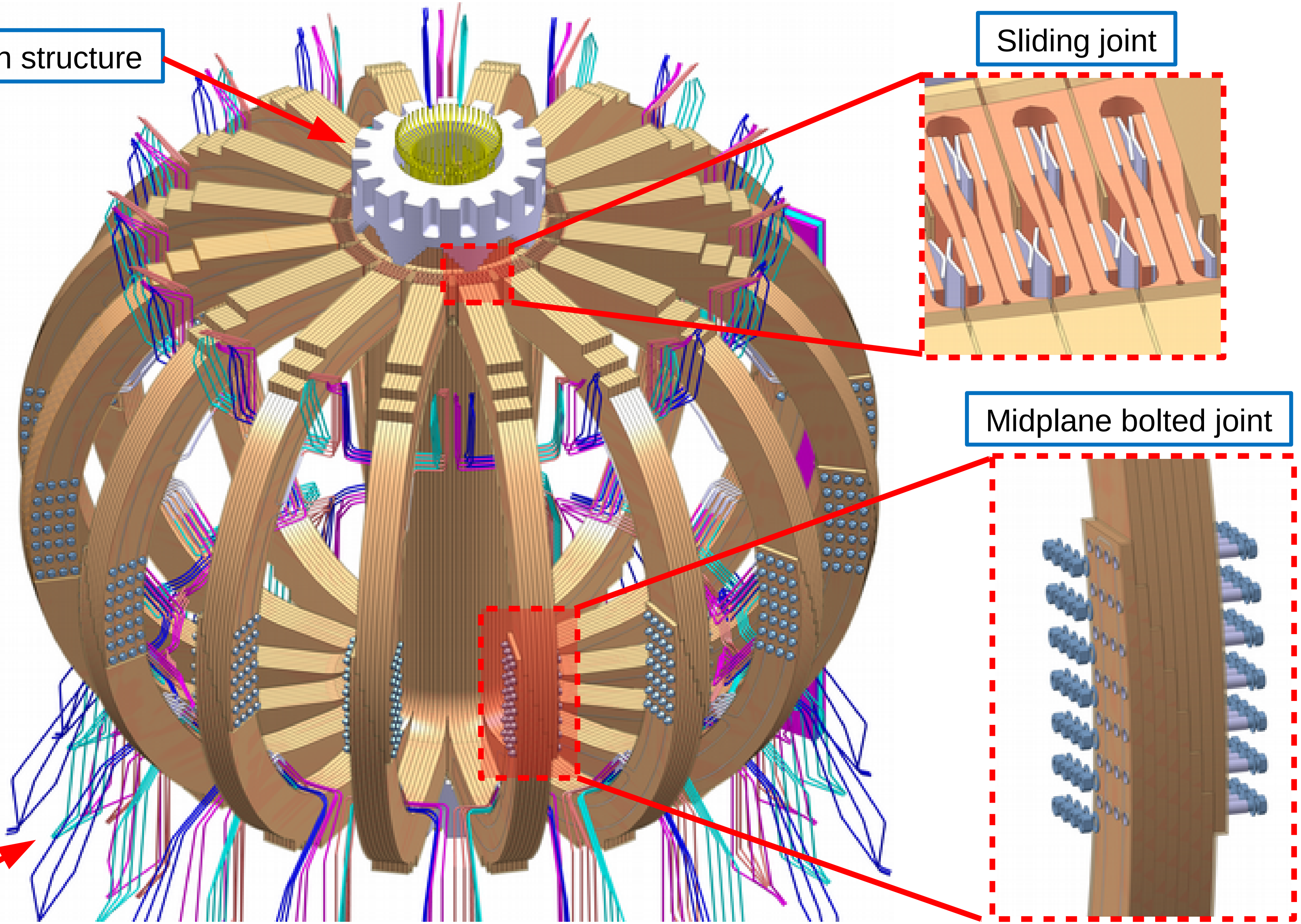


Toroidal field coils
joints

Toroidal field coils joints

- Sliding joint based on Alcator C-mod and MAST experience
- **3 s flat-top @ 5 T** expected with CuAg0.1 and 0.2 μΩ joint resistance
- TF temperature increase: ~several tens of K
- Testing of sliding joint properties is ongoing

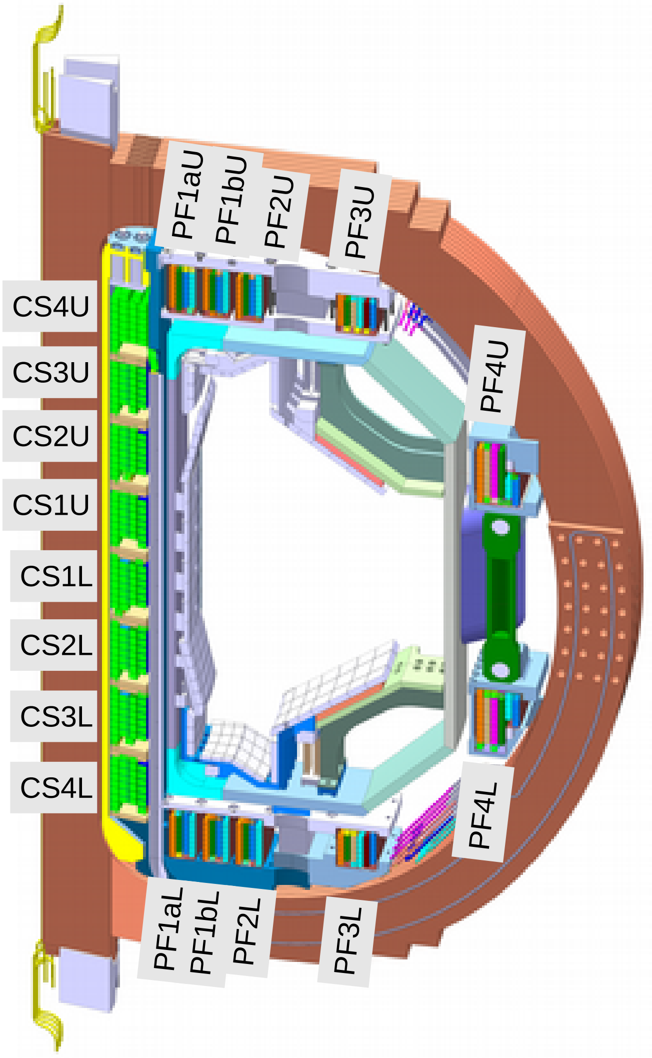


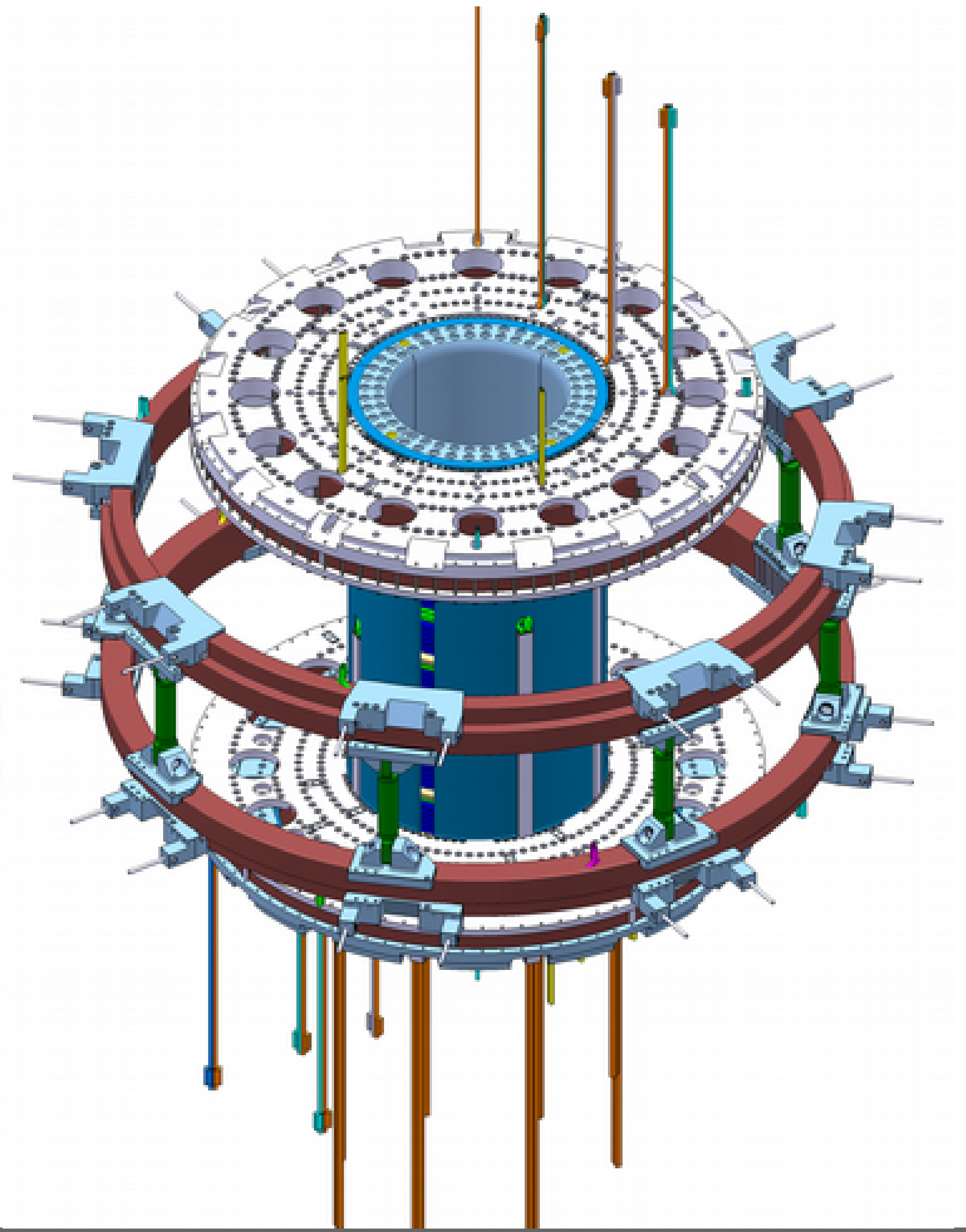


Poloidal field coils

- **8 identical CS coils**, **4+4 PF coils**
- 1 power supply per pair of CS coils => 14 PS in total.
- Hollow conductor - material **CuAg0.1** (C10700), half or full hard
- **Cooling down to 80 K** by gaseous coolant (He, H2)
- Conductor Insulation: 1 mm S2 glass tape + kapton
- Inter-layer insulation: 0.6 mm S2 glass tape
- Ground insulation: 3 mm S2 glass tape
- **Vacuum pressure impregnation** using epoxy resin

name, qty.	Current range [kA]	Conductor w x h [mm]	D [m]	turns	winding length [m]	cooling segments
8x CS	**± 50**	24 x 21	**0.8**	29	90	1
2x PF1a	**± 25**	15 x 15	**1.2**	32	120	2
2x PF1b	**± 25**	15 x 15	**1.3**	32	137	2
2x PF2	**± 25**	15 x 15	**1.5**	32	155	2
2x PF3	**± 25**	15 x 15	**2.1**	36	233	3
2x PF4	**± 30**	17 x 20	**2.9**	40	360	5



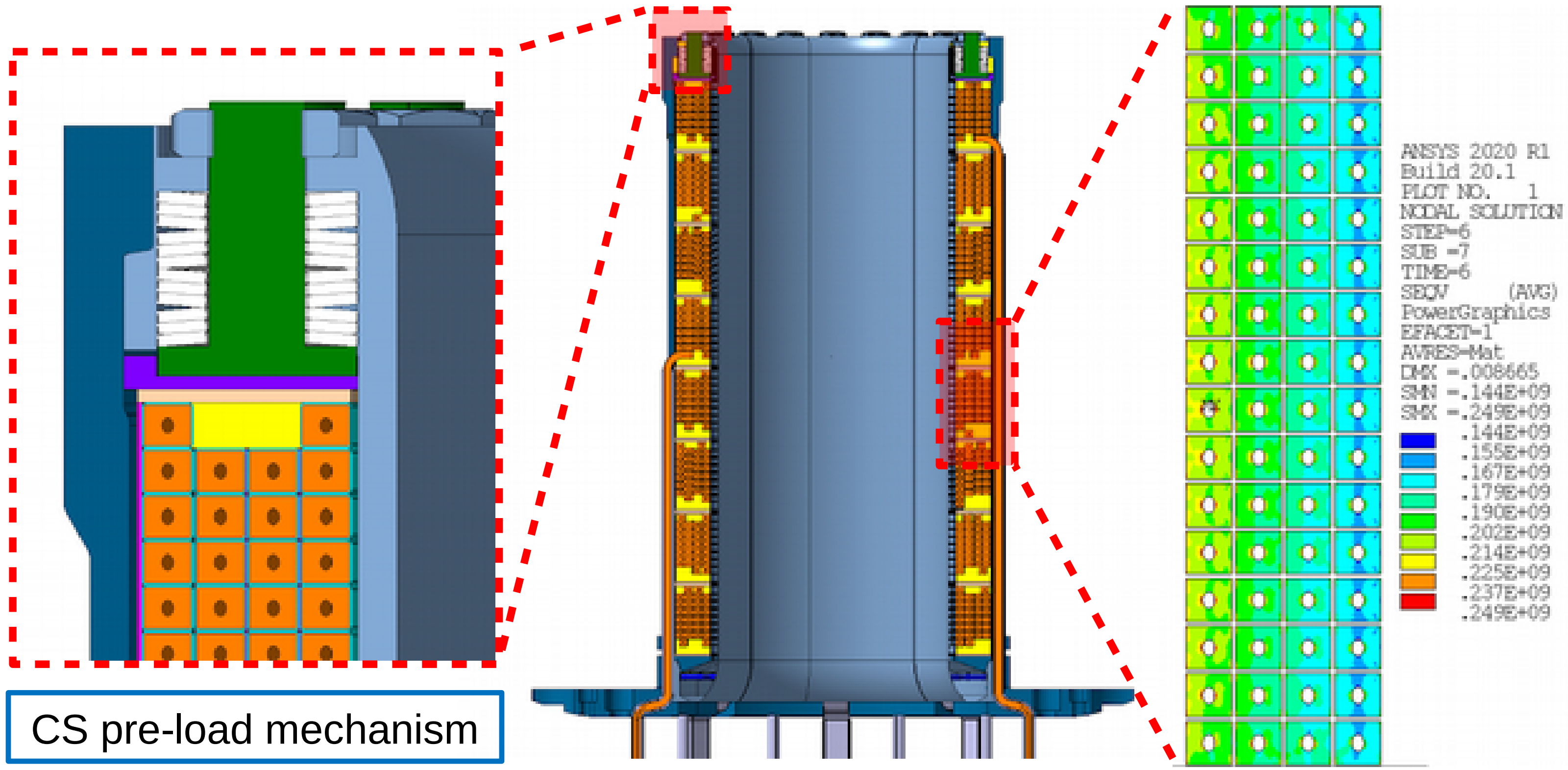


Poloidal field coils

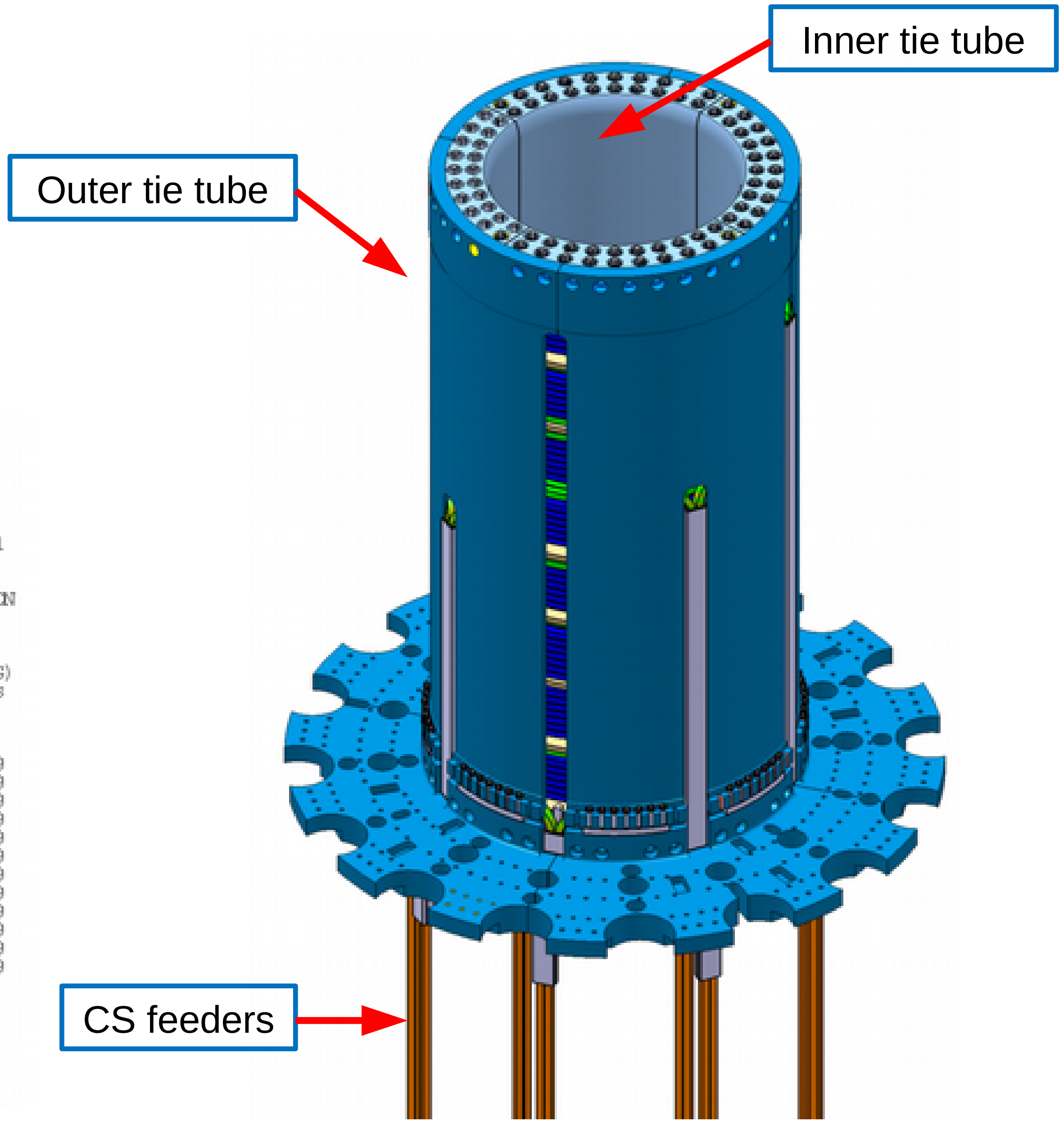
Central solenoid

Central solenoid pre-load

- CS is placed inside of **inner and outer tie tubes (Nitronic)**
- Outer tie tube is fixed to the lower TF wedge plate
- **20 stacks of heavy duty Belleville washers**
- **~several MN pre-load**, ~1 cm working range

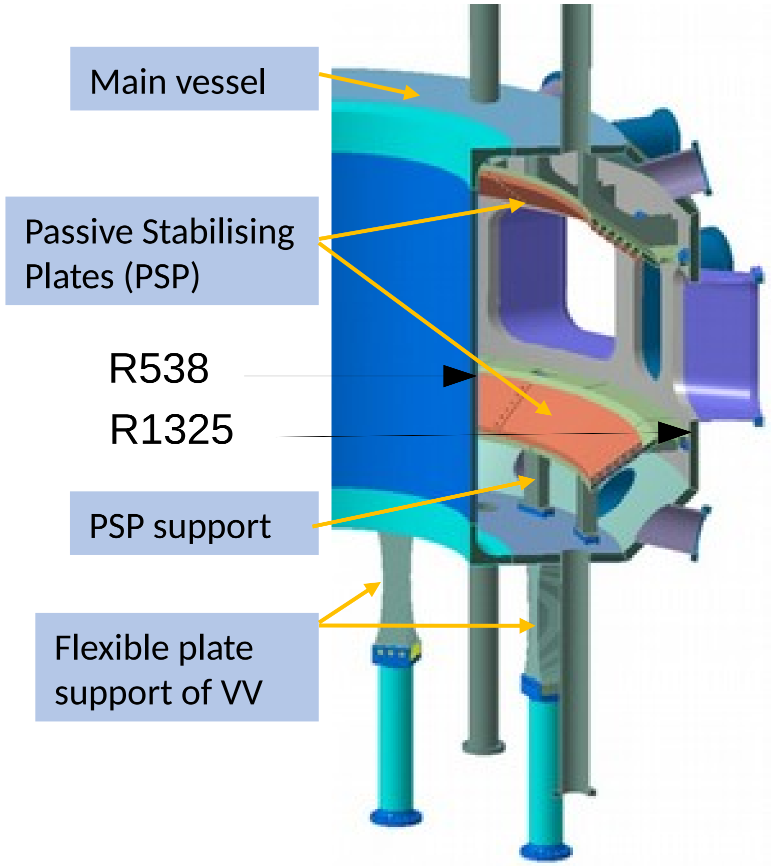


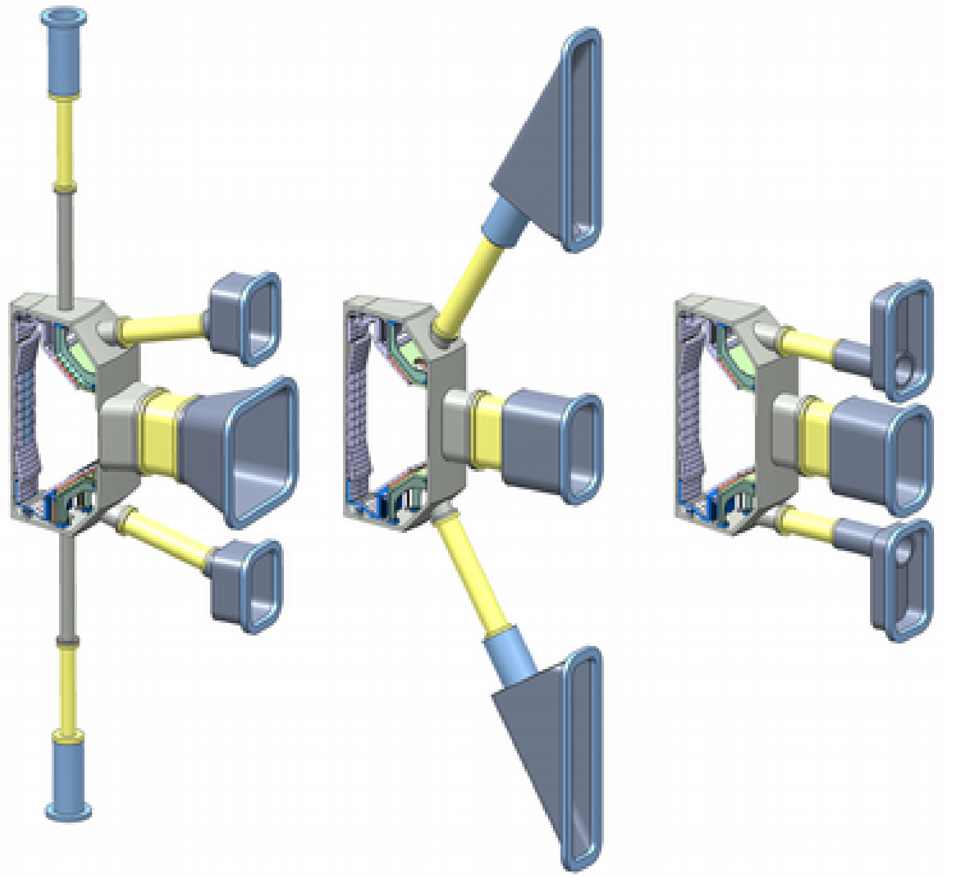
CS pre-load mechanism



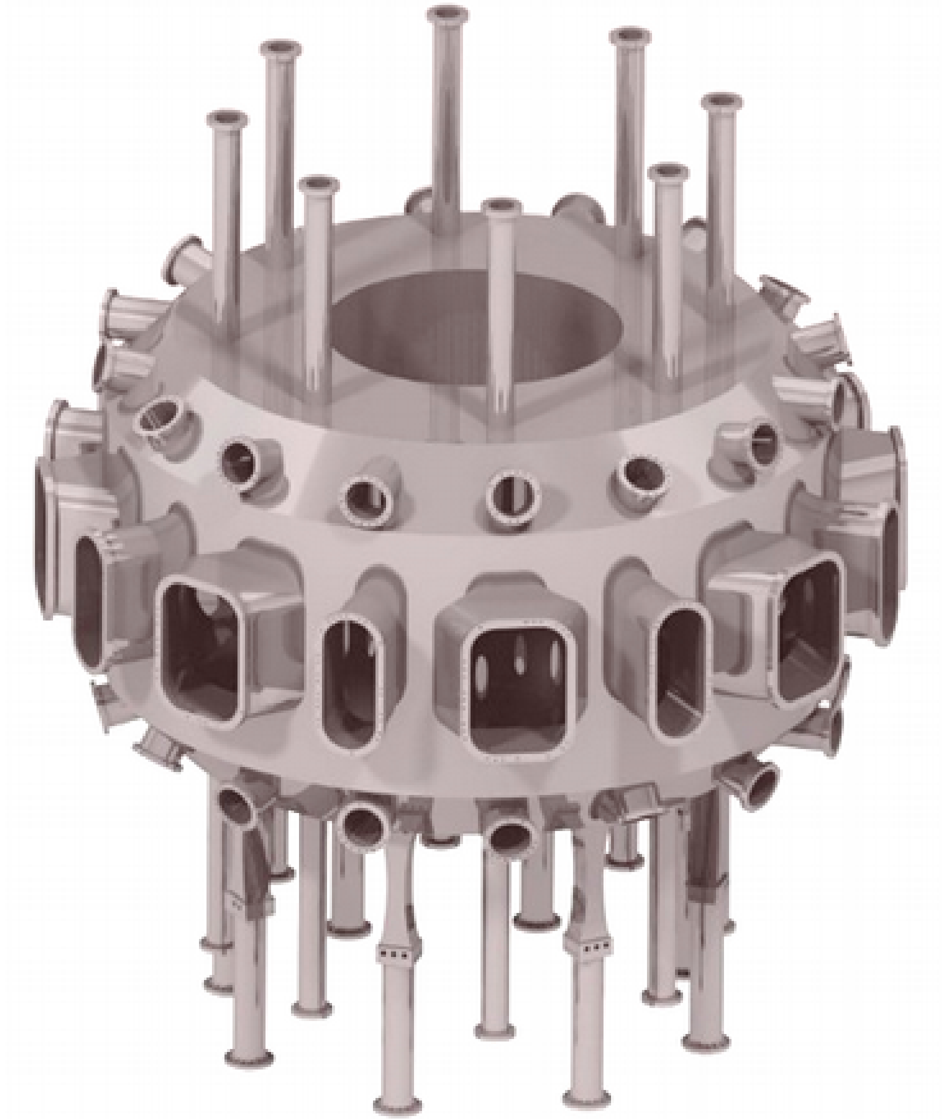
Vacuum vessel

- Material: **Inconel 625**
- 23 mm thick inner tube, 35 mm top, bottom and 30 mm LFS parts
- total weight: ~9 t (including PSP)
- 8 flexible Inconel 625 supports from bottom – connected to the lower compression disk of the support structure



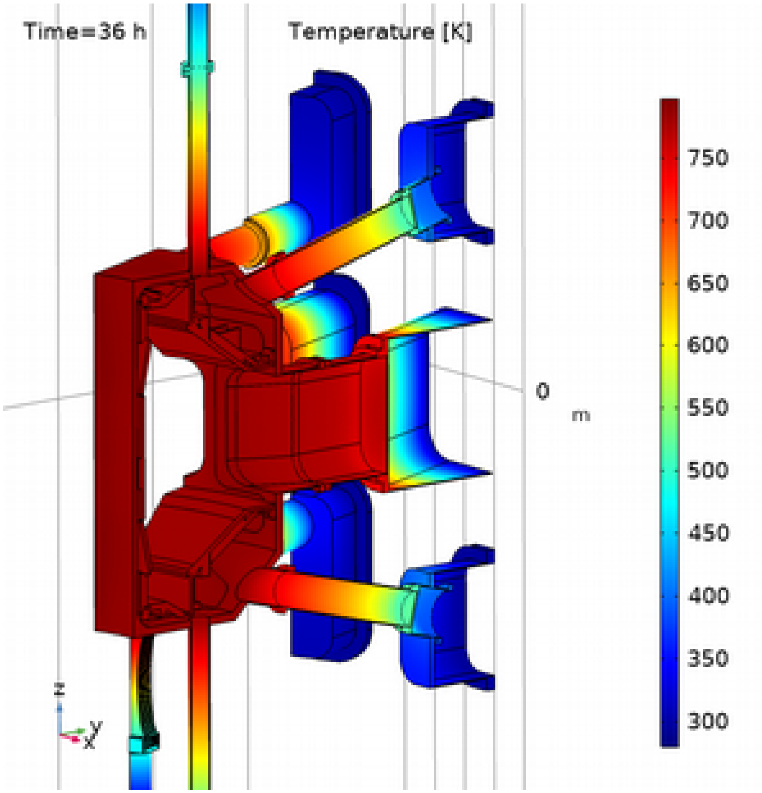


2 types of midplane ports, 3 types of divertor ports

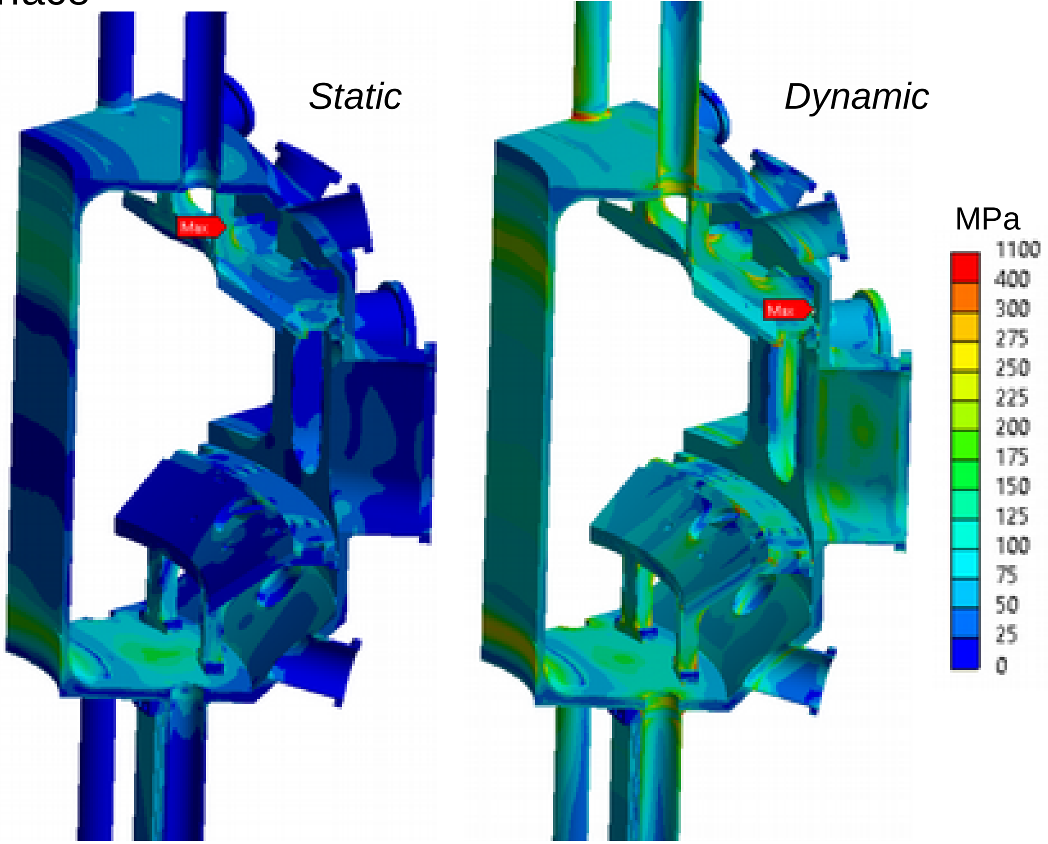


Vacuum vessel
heating

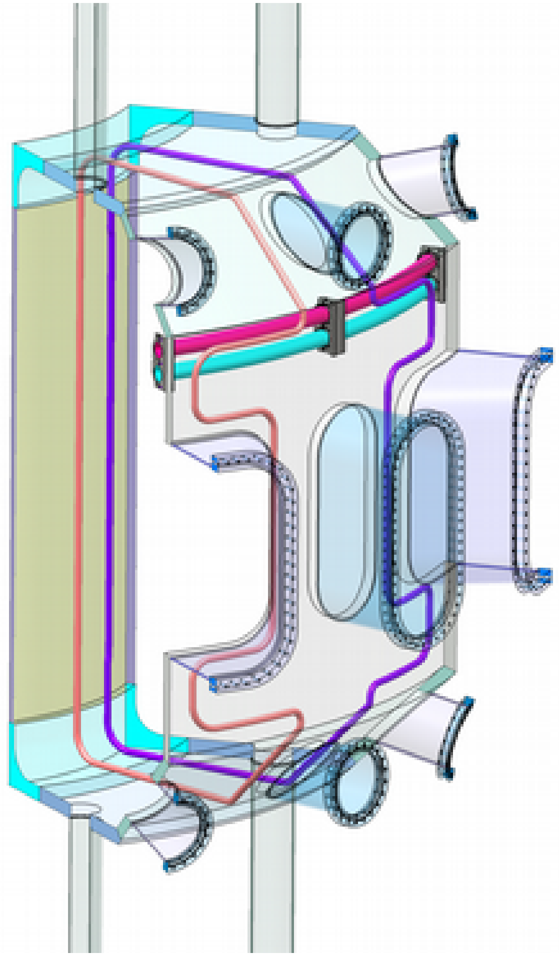
- Heating of VV up to 500 °C in ~24 h => **heating power~40 kW**
- Removal of deposited energy from plasma discharge (max. 40 MJ) in 20 min. => **cooling power ~33 kW**
- **Inconel 625 pipes welded on inside of VV**, OD 16 mm, 2 mm wall
- Gaseous medium (He or CO_2)
- PFC heated mainly by radiation
- 20 mm **MLI thermal insulation** at the outer surface



Temperature distribution at the vacuum vessel and port extensions.



Von Mises stress in the vacuum vessel and PSP.


Vacuum vessel heating pipe routing.

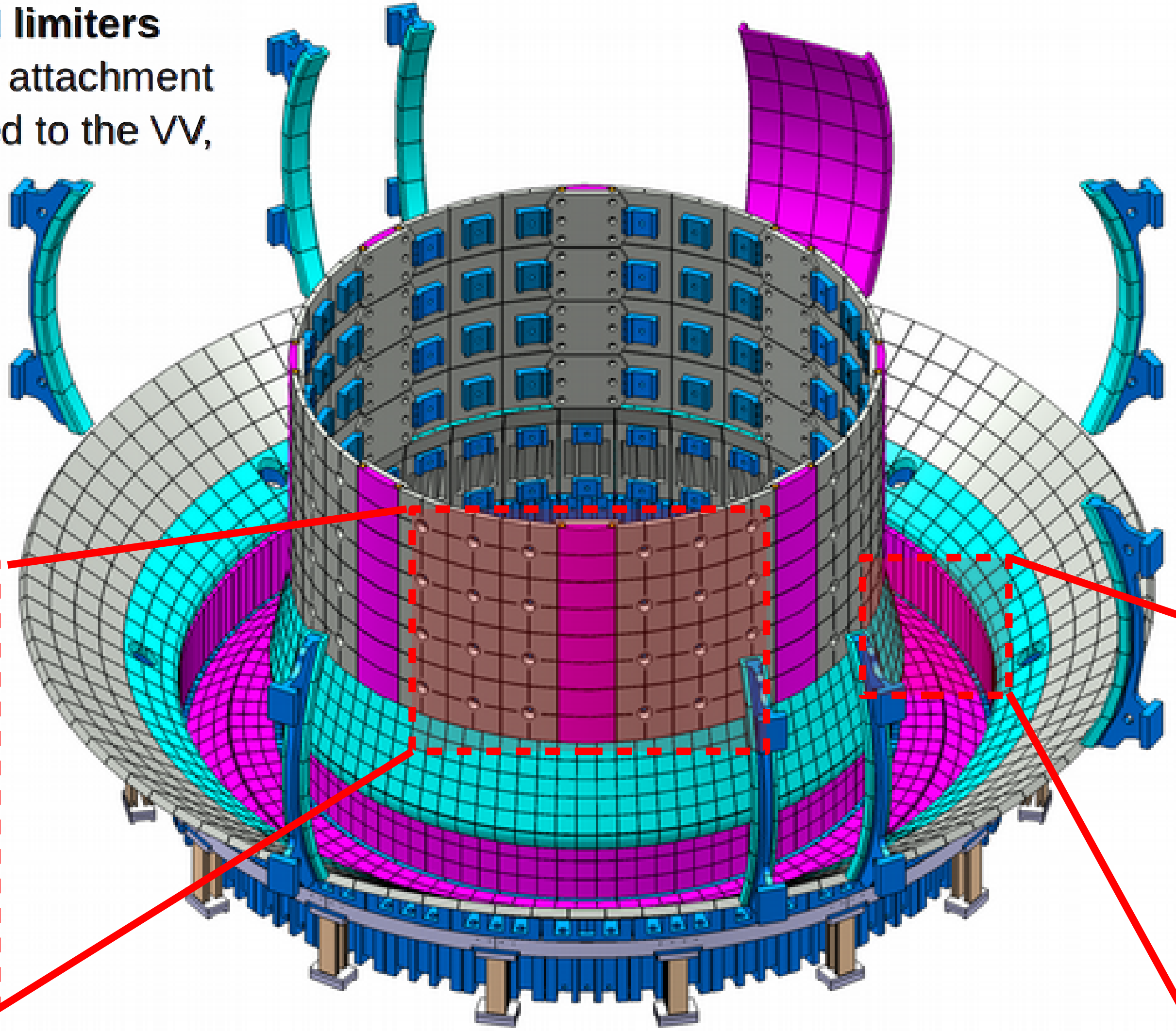
Plasma Facing Components

Inner wall limiters

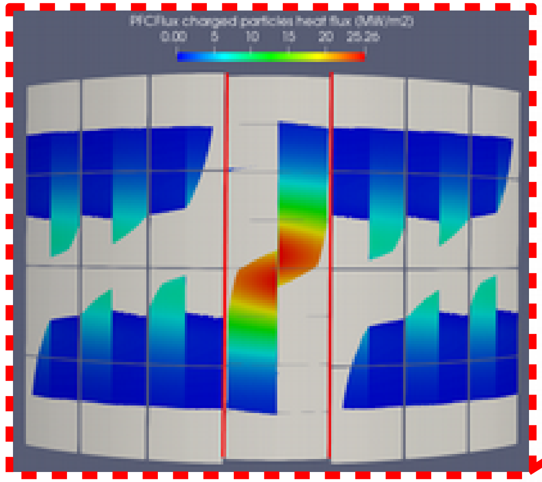
- Plasma start-up and termination (~0.4 s)
- tungsten tiles forming **8 guard limiters**
- Inconel 718 tiles with frontside attachment
- Inconel 625 **U-brackets** welded to the VV, precisely machined surface

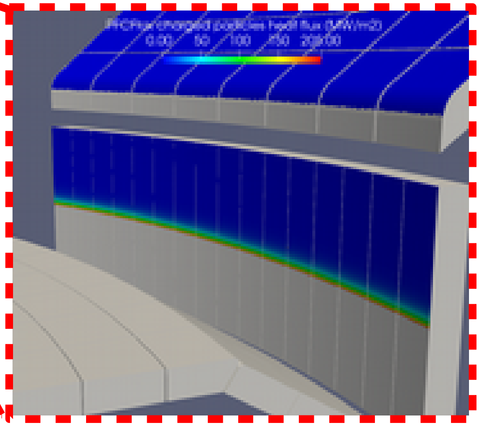
Divertor

- Heat loads in divertor up to ~100 MW/m^2
  => heat dissipation required
  (detachment, strike point sweeping)
  => designed for **20 MW/m^2, 2-3 s**
- **32 cassettes** bolted to toroidally continuous outer ring held by 16 flexible supports
- PFC tiles bolted from the cassette back side
- tungsten tiles in the divertor
- W-coated Inconel possibly on divertor baffles



Heat flux distribution during plasma ramp-down



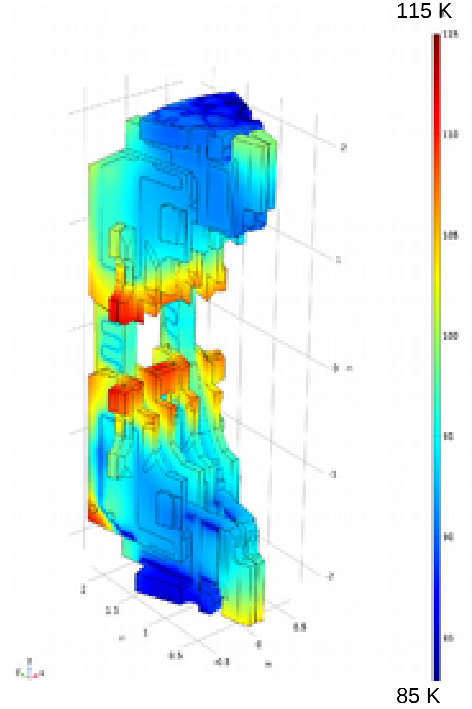


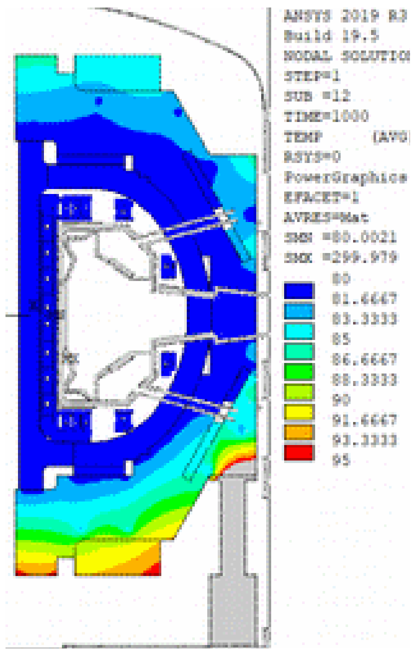
Heat flux distribution in the divertor

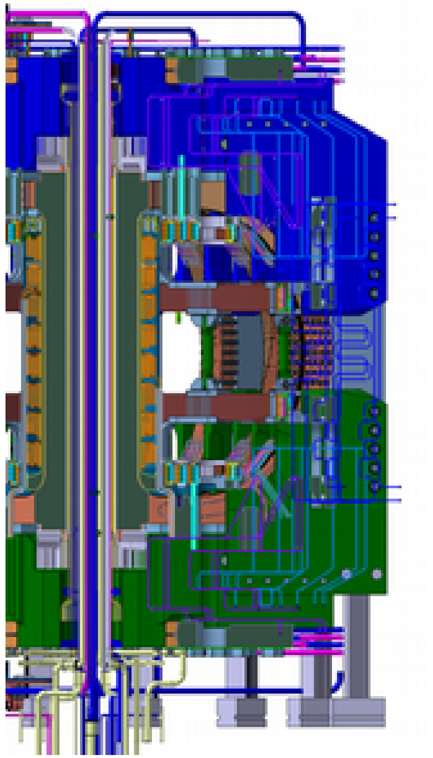
Cryogenics

Cryogenics overview

- **Cooldown after a discharge in <60 min**
  - TF coils ~250 MJ, PF coils ~50 MJ
    => required cooling power ~100 kW
- **Multiple closed gaseous helium loops**
  - **CS** - high pressure (p_{base} 60 bar, Δp 4 bar, $\dot{m}$ 80 g/s)
  - **PF** - medium pressure (p_{base} 20 bar, Δp 1 bar, $\dot{m}$ 160 g/s)
  - **TF** - low pressure (p_{base} 20 bar, Δp 0.1 bar, $\dot{m}$ 800 g/s)
- Main cold source – **liquid nitrogen heat exchanger**
  - Cycle cooler (Brayton, J-T, G-M, ...) for subcooling under 80 K



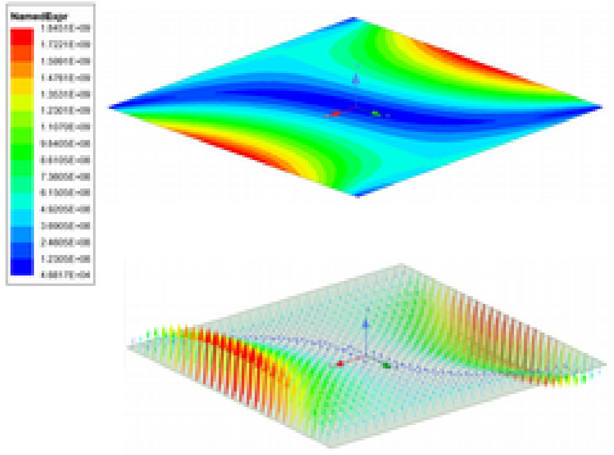


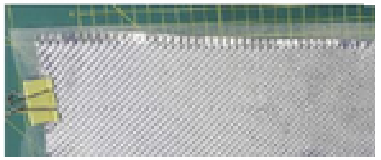


Multilayer insulation

- 10-20 mm space available, **30-40 layers attached to VV**
- **Glass fiber spacer** needed because of high temperature VV
- **Metalic** (SS, Au, Cu, Al, Ti) **reflector**
- Insulation cuts needed because of **eddy currents** (mainly during disruptions)
- **In-house MLI** experiments in progress, different metals and mounting schemes
- Investigation of force effects via FEM simulations initiated

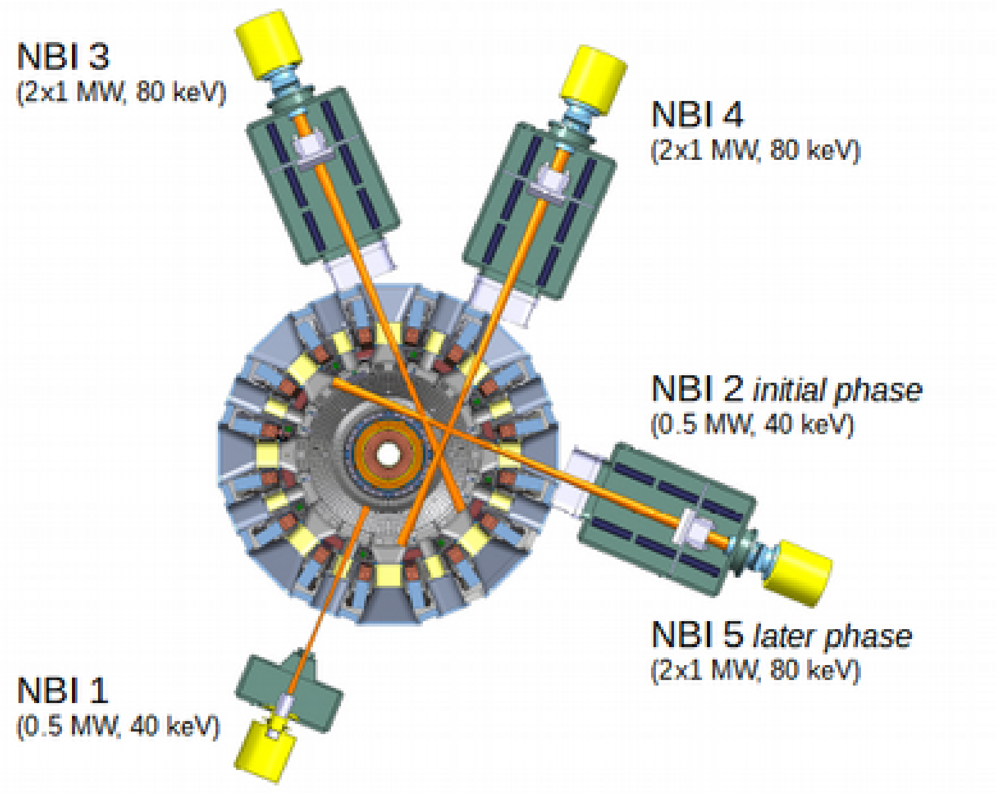
Body force density [N/m³]



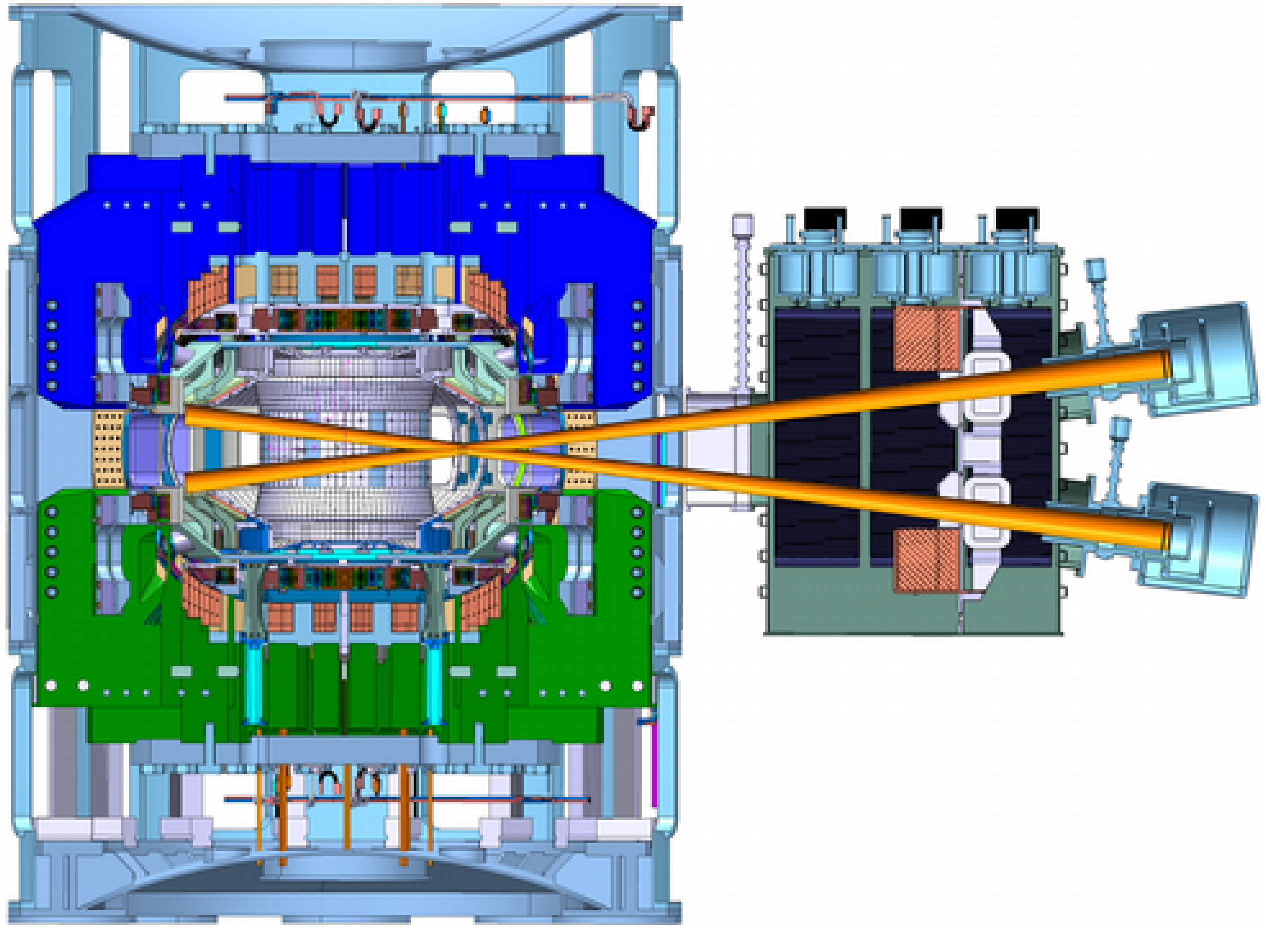


NBI

- **3-4 MW NBI @ 80 keV**, organized in 2 x 2 MW units
- 2 ion RF sources above each other **inclined by ~7°** from horizontal plane
- 1st unit is about to be delivered by BINP Novosibirsk (will be installed on COMPASS)
- Aiming between magnetic axis and HFS wall - **tangency radius R<0.65 m**
- COMPASS 0.3 MW @ 40 keV NBI will be used for diagnostic purposes



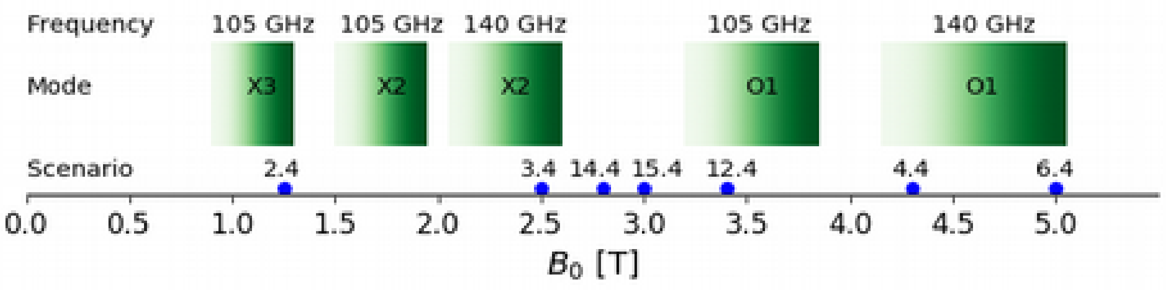
Top view of NBI distribution.



ECRH for different COMPASS-U scenarios

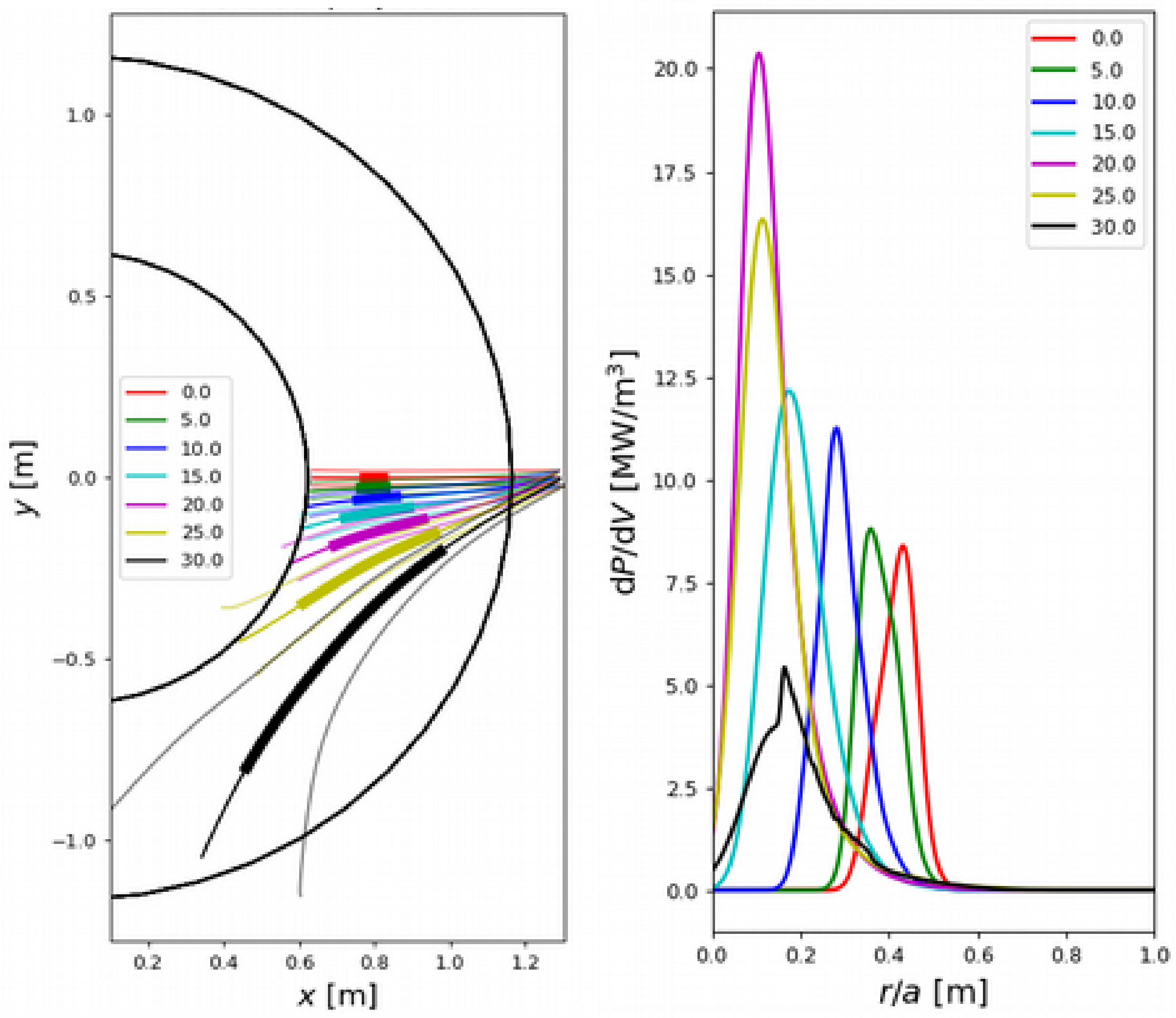
- Deposition on-axis is achieved for B_t 1-2.5 and 5 T
- Toroidal steering needed for B_t 3-4 T
- Simulations in TORBEAM + ASTRA ongoing

scenario	B_t [T]	n_{co} [m^{-3}]	Operation mode	f [GHz]
2	1.25	0.9×10^{20}	X3	105
3	2.5	1.2×10^{20}	X2	140
12	3.4	1.4×10^{20}	O1, toroidal steering	105
4	4.3	2.4×10^{20}	O1, toroidal steering	140
6	5	2.4×10^{20}	O1	140



Components specification

- Gyrotrons: dual freq. 105-140 GHz, 1MW, 3-5s pulse length
- Waveguides: 63.5 mm diameter, total length < ~30 m
- Launchers: large equatorial port, steering mirrors



Scenario 12.4 (3.4 T), 105 GHz, O-mode
Optimal injec. 20°, full abs. at ρ<0.3

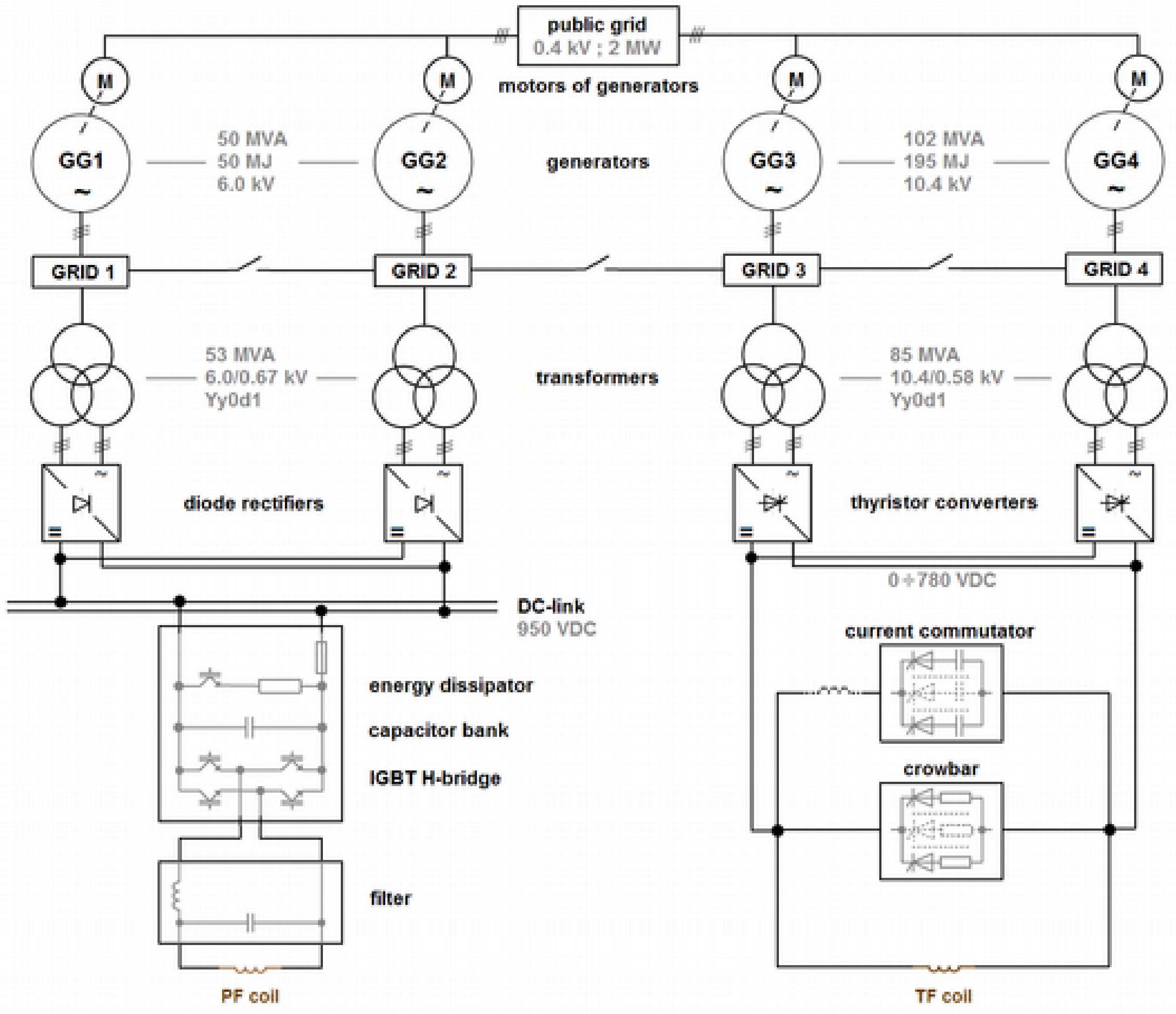
Power supply system

Power Supply System

- Existing flywheel generators (50 MVA, 50 MJ each)
- Two new flywheel generators (106 MVA, 195 MJ each)
- PF coils:
  - 85 MW, 90 MJ from flywheel
  - IGBT H-bridges
- TF coils:
  - 140 MW, 340 MJ
  - thyristor converters
- Auxiliary heating + reserve: 38 MW, 60 MJ
- In total: **263 MW, 490 MJ**

Status

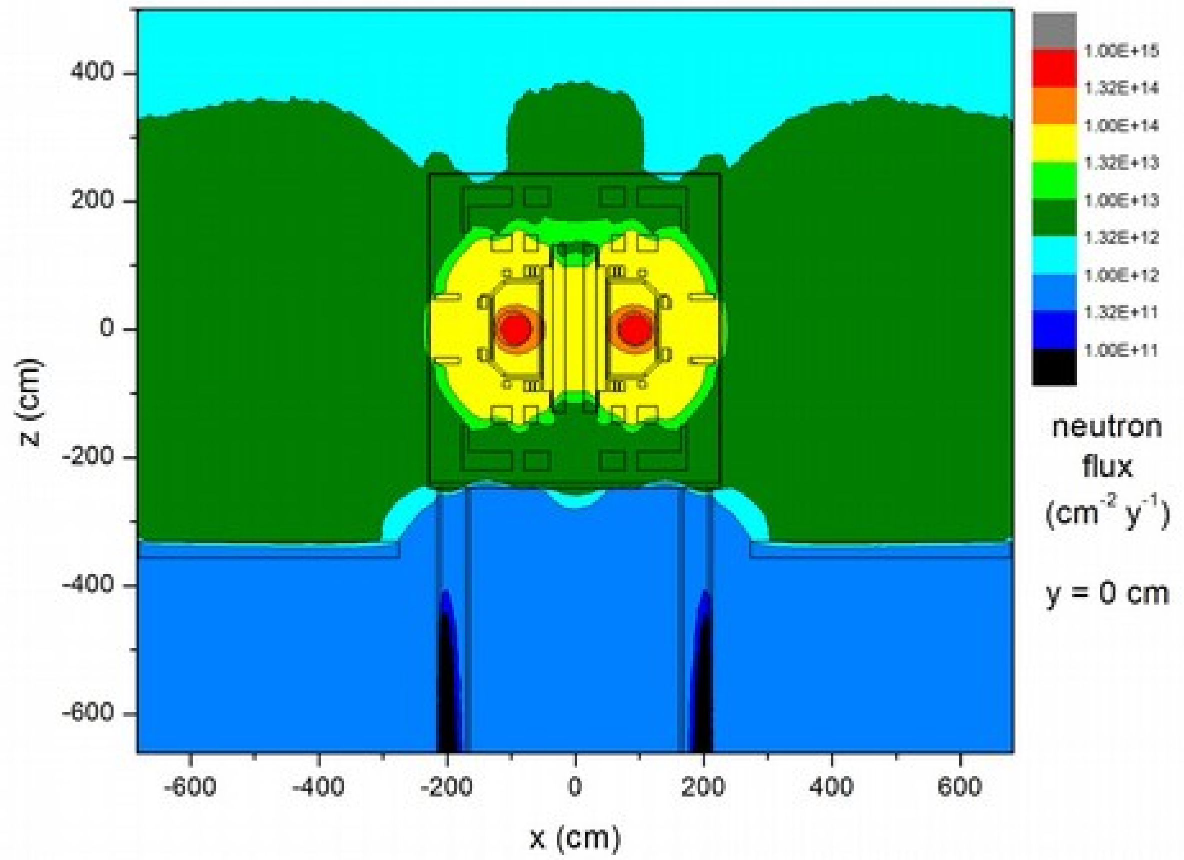
- FDR completed in February 2019
- Contract signed in February 2020



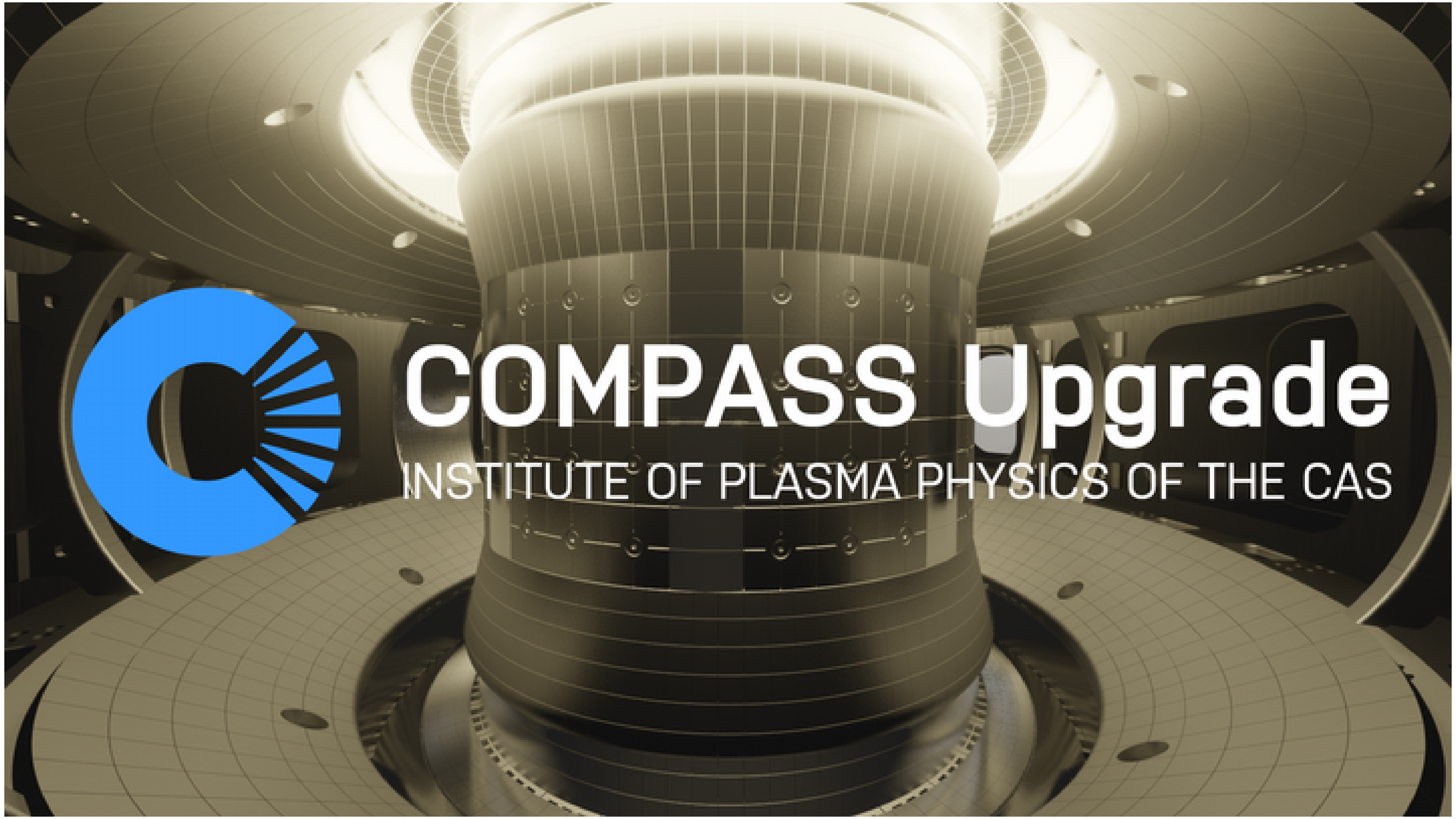
Schematic overview of the power supply system.

Neutronics

- The majority of ionizing radiation will come from **beam-target produced neutrons** during NBI operation.
- The expected neutron rate **1×10^{14} to 1.8×10^{15} neutrons/s** (4 MW NBI)
  => yearly production of 3×10^{18} neutrons for the expected scenario distribution.
- **Monte Carlo simulations** were carried out with the MCNP code to calculate both the neutron and gamma fields inside the experimental hall (IFJ PAN, Poland)



Summary & Outlook



https://youtu.be/oGfg0A5EsSE