COMPASS-U Design Overview

Design status spring 2021

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

MINISTRY OF EDUCATION,
YOUTH AND SPORTS

COMPASS Upgrade overview

Main design requirements

Toroidal magnetic field	B_t = 5 T
Plasma current	I_p = 2 MA
Major radius	R_g = 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

Metallic first wall

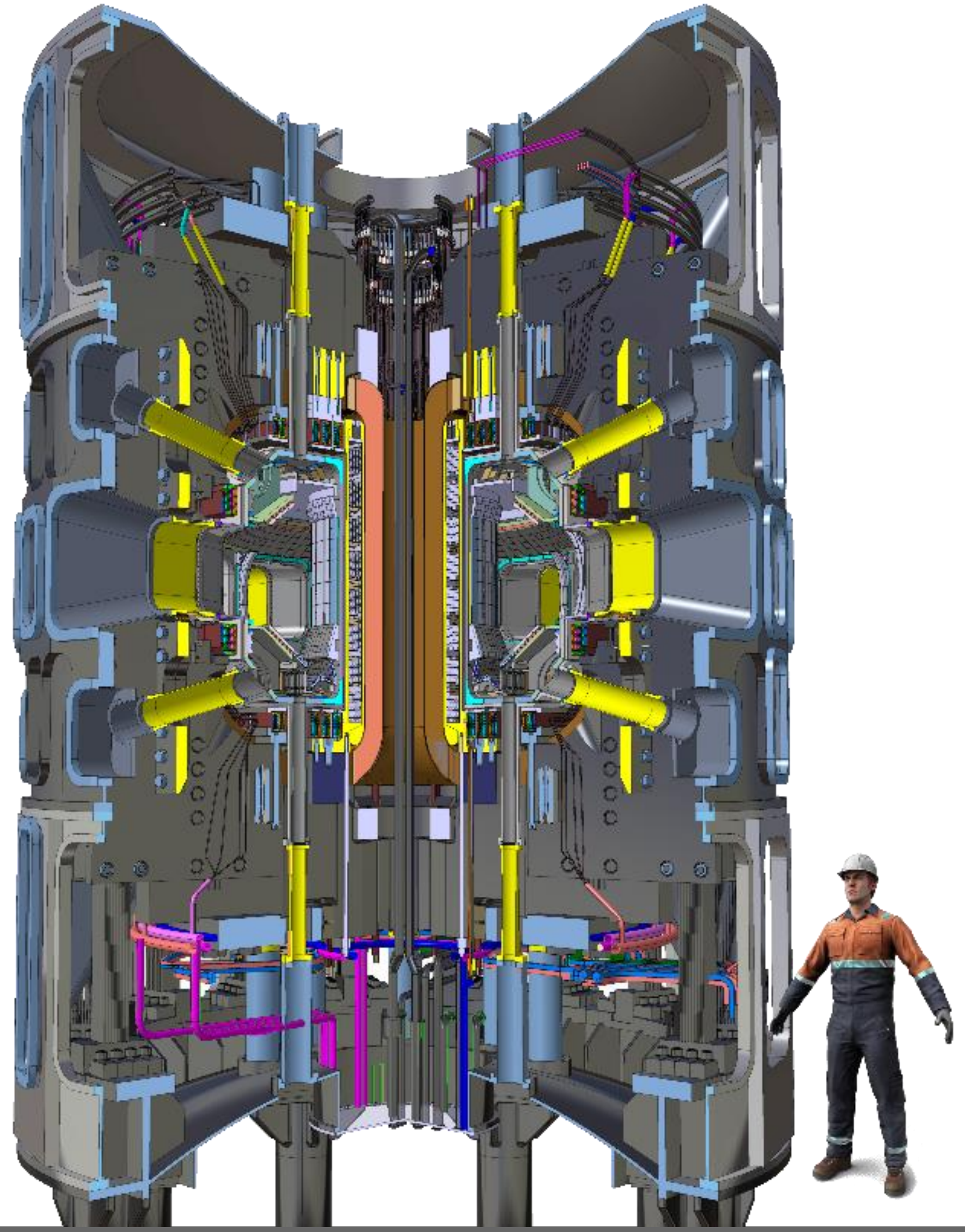
Vacuum vessel operation temperature up to 300°C (goal 500°C)

Plasma shapes

- single lower null, neg. triangularity with limited parameters (Phase 1-2)
- double null (Phase 2-3)
- snowflake, negative triangularity (Phase 3-4)

Plasma heating power

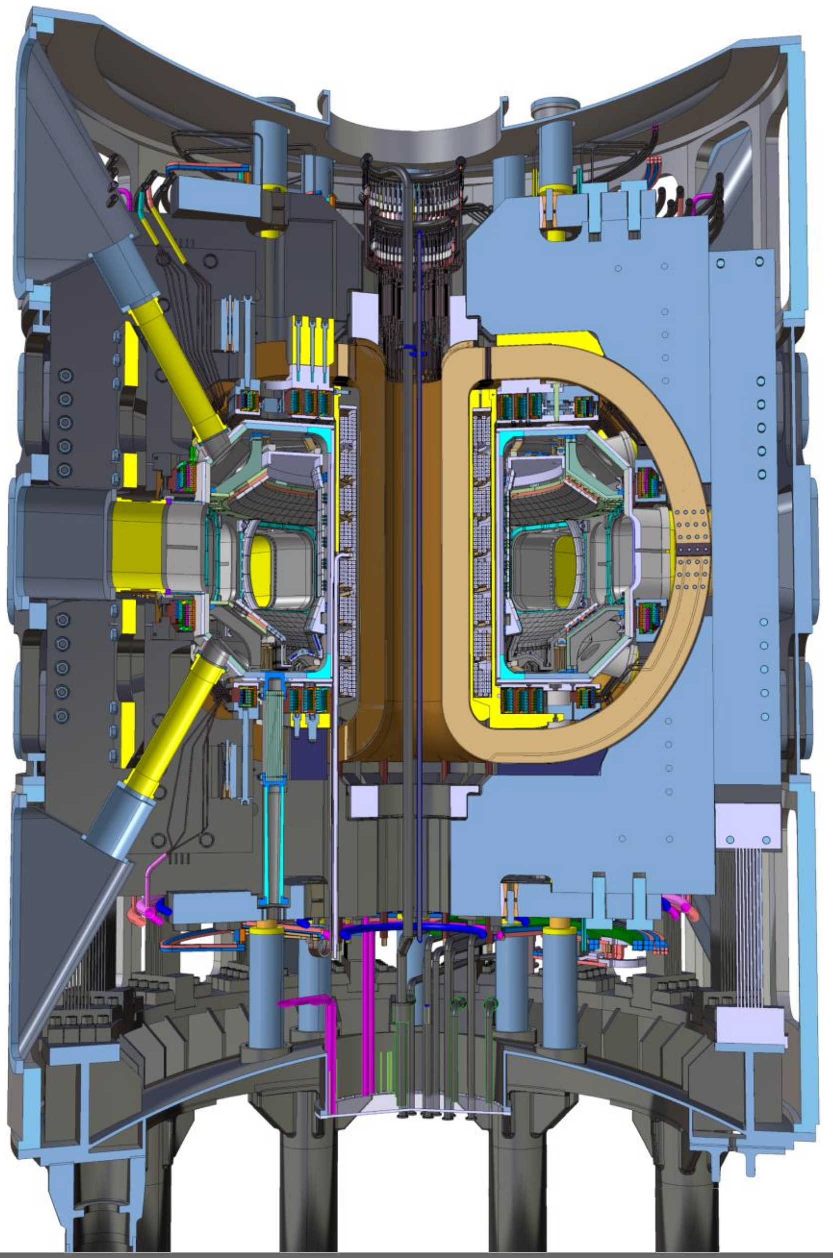
- Phase 1 P_{NBI} >= 3 MW, P_{ECRH} = 1 MW (P*B/R ~ 25)
- Phase 2 up to P_{NBI} = 8 MW, P_{ECRH} = 10 MW (P*B/R ~ 100)



Design overview

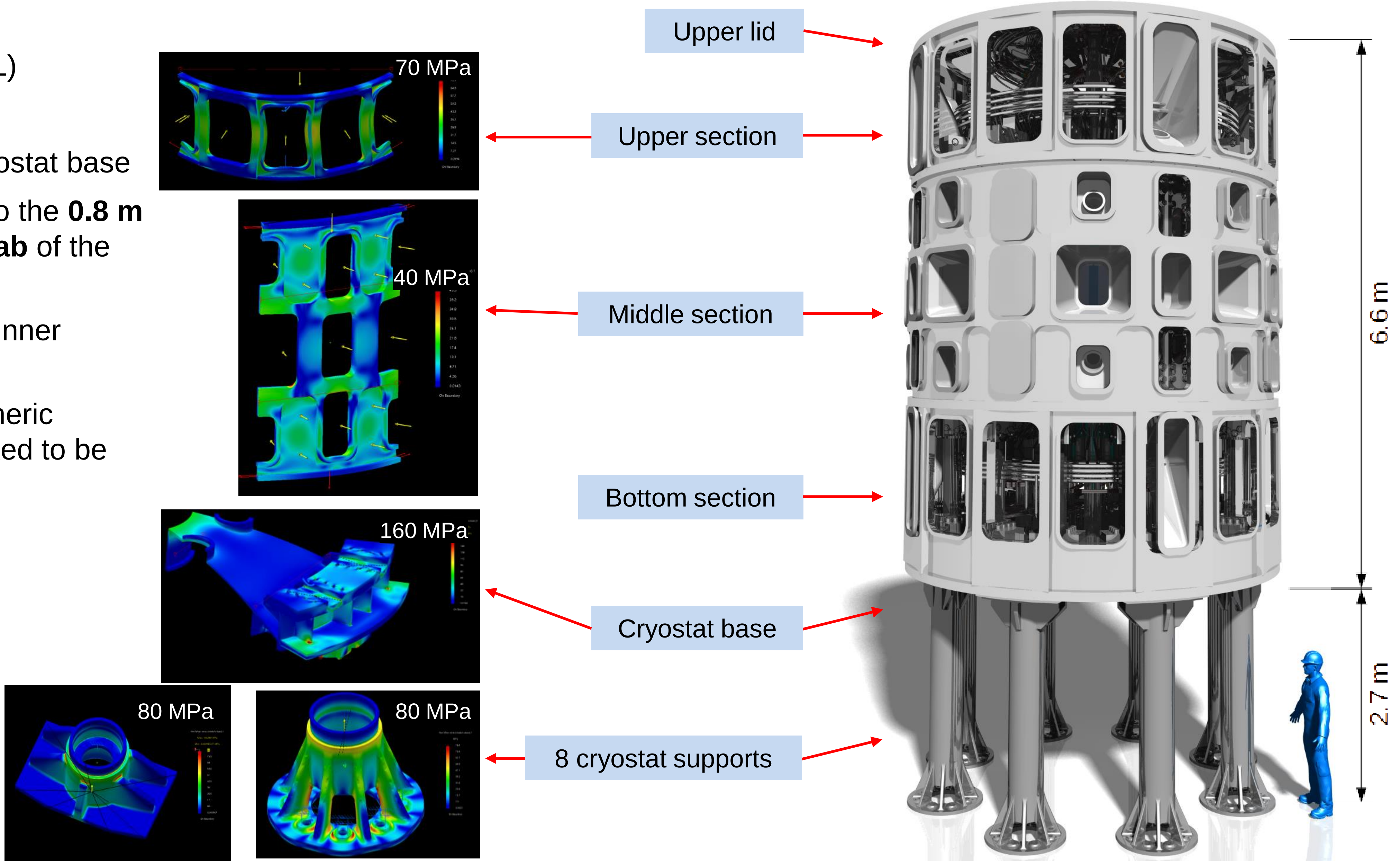
Main design features

- **Metallic 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 thermally insulated by **multilayer insulation** (MLI) or **microporous insulation**
- **CuAg0.1 (OF) 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** (AISI 316LN) **support structure**
- **Stainless steel** (AISI 304L) **cryostat**
- **Vacuum vessel human access via large midplane ports**
- **Overall dimensions** ~6.6x4.8 m, weight ~300 t



Cryostat

- **Stainless steel cryostat** (AISI 304L)
- **Volume ~100 m** , 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



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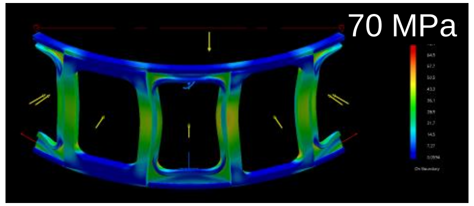
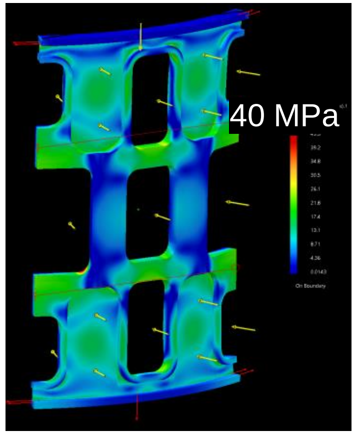
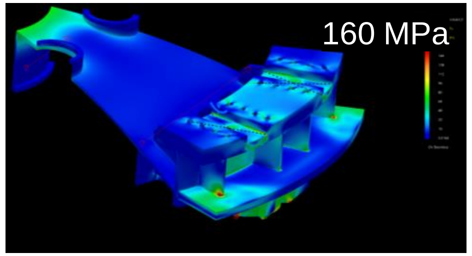
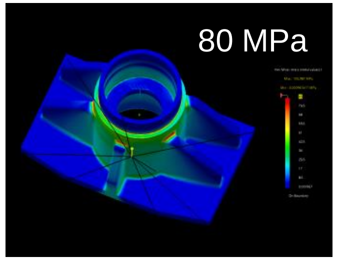
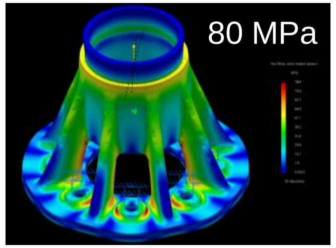
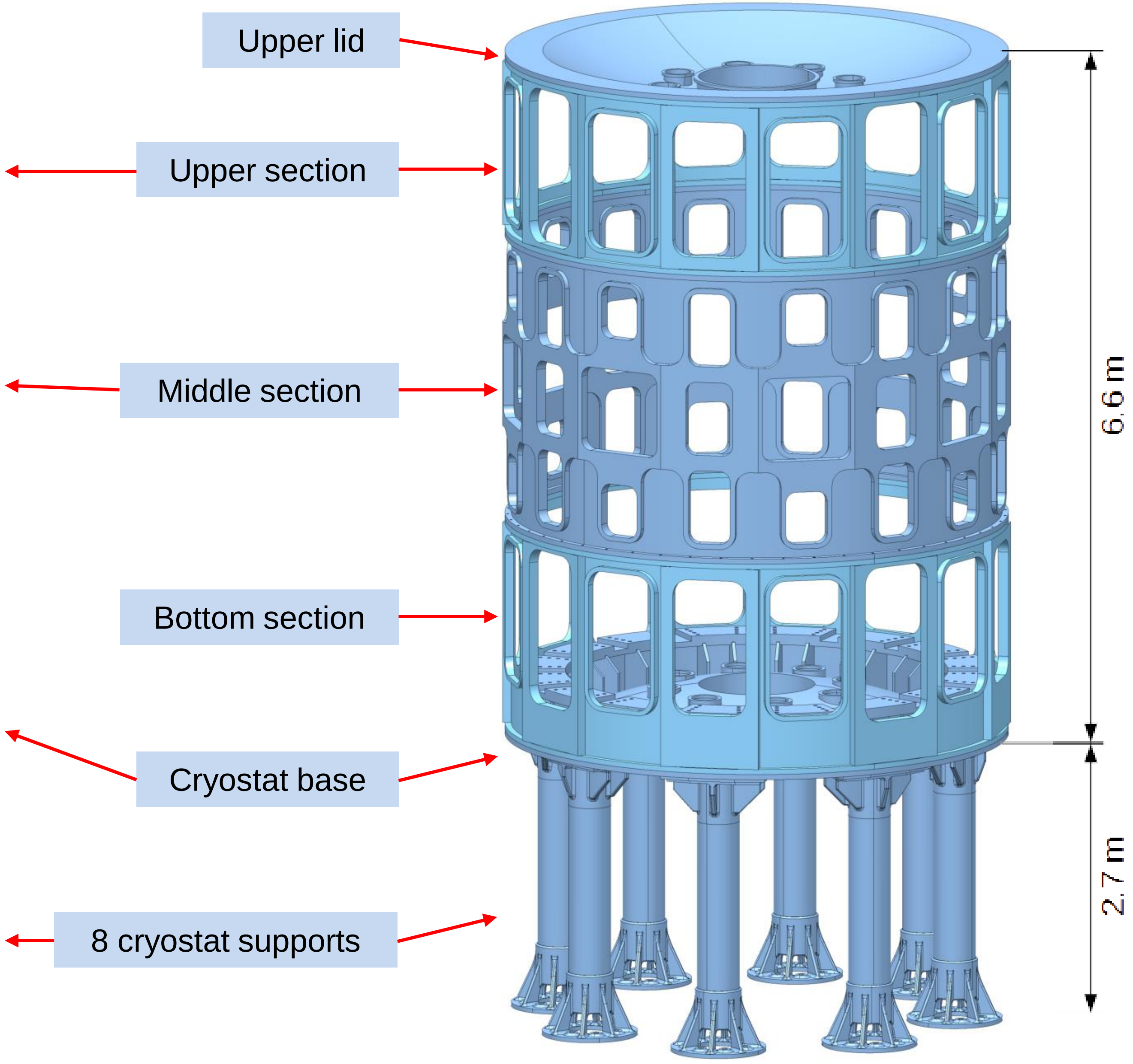






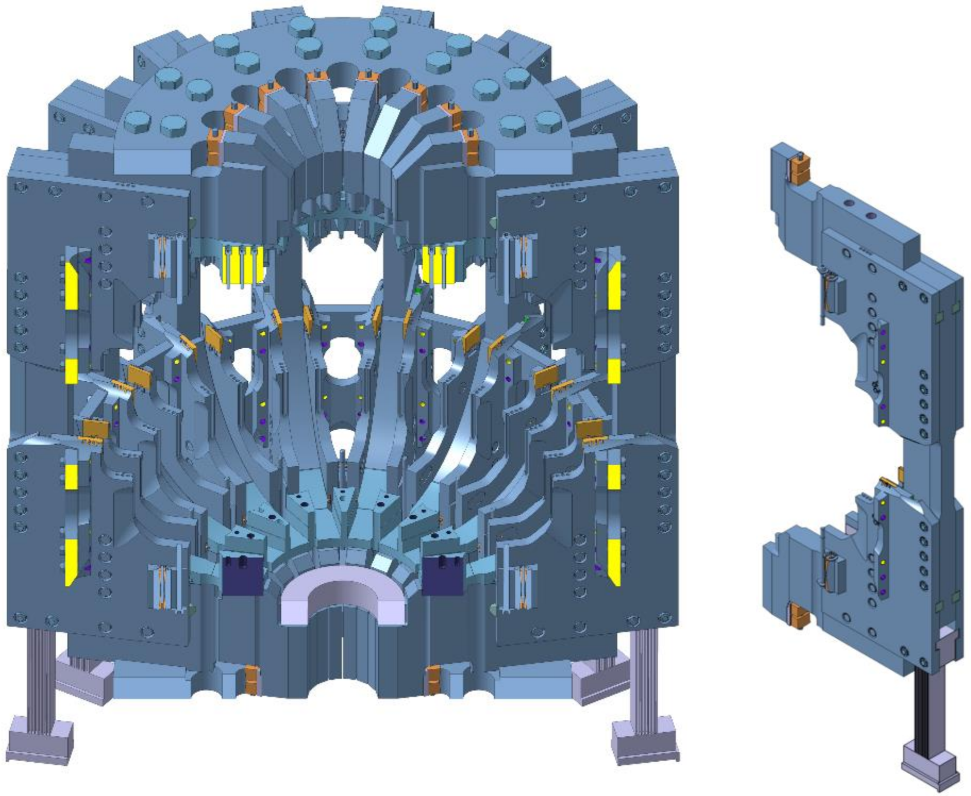


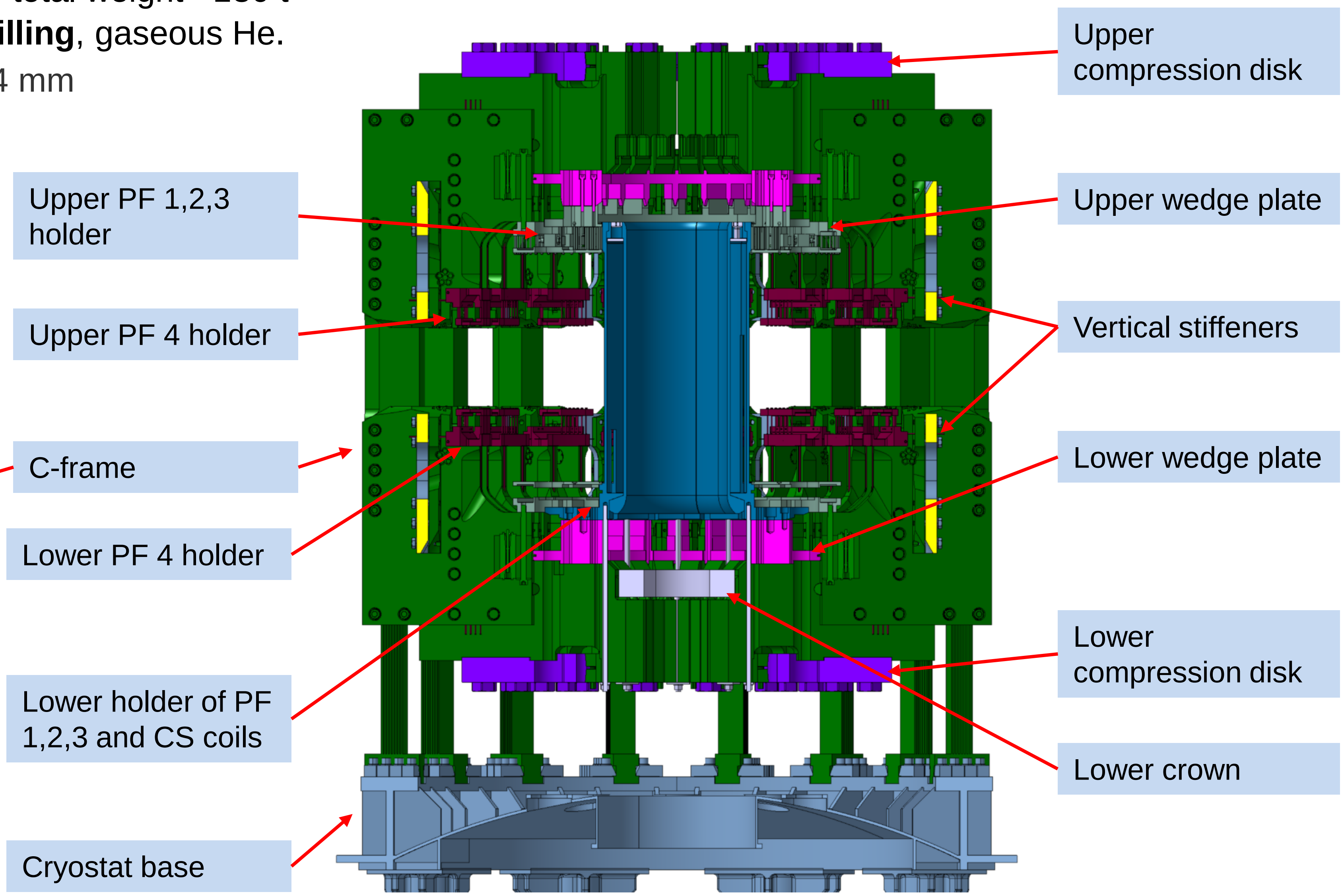




Support structure

- **Material AISI 316LN**, 16 C-frames + flexible supports
- Overall dimensions: height ~4.4 m, diameter ~4.4 m, total weight ~180 t
- Cooled to 80 K, **cooling channels done by deep drilling**, gaseous He.
- **Cool-down in ~1 week time**, vertical contraction ~14 mm
- Vertical disassembly possible





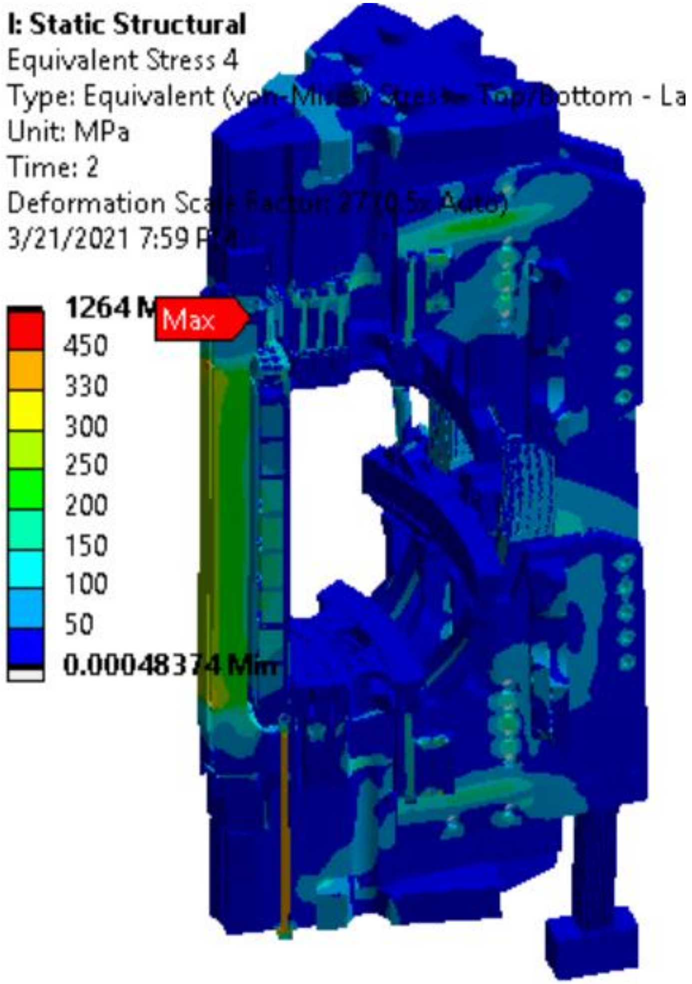
Support structure
FEM analysis

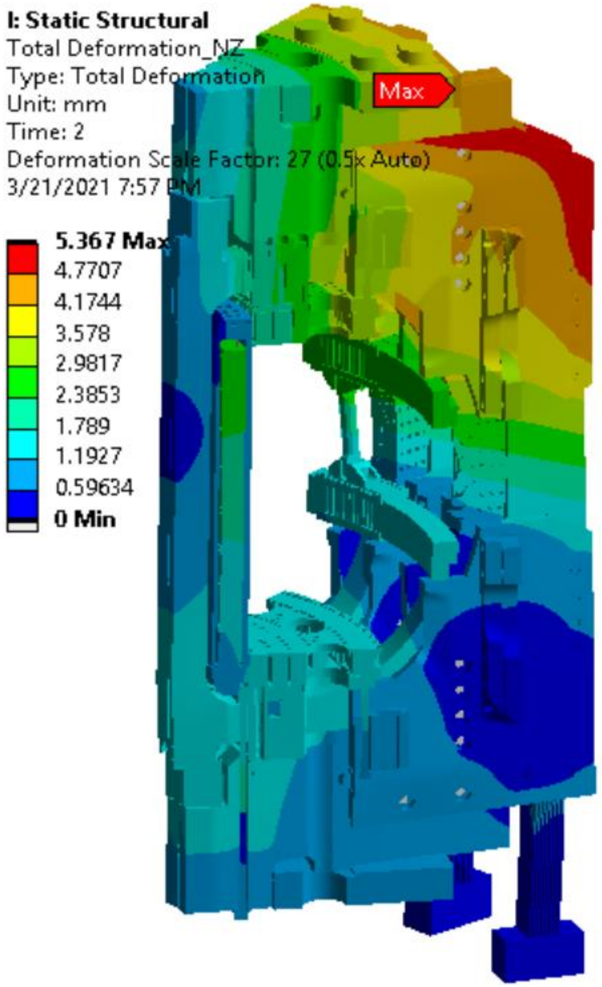
Von Mises stress [MPa] **Deformation** [mm]

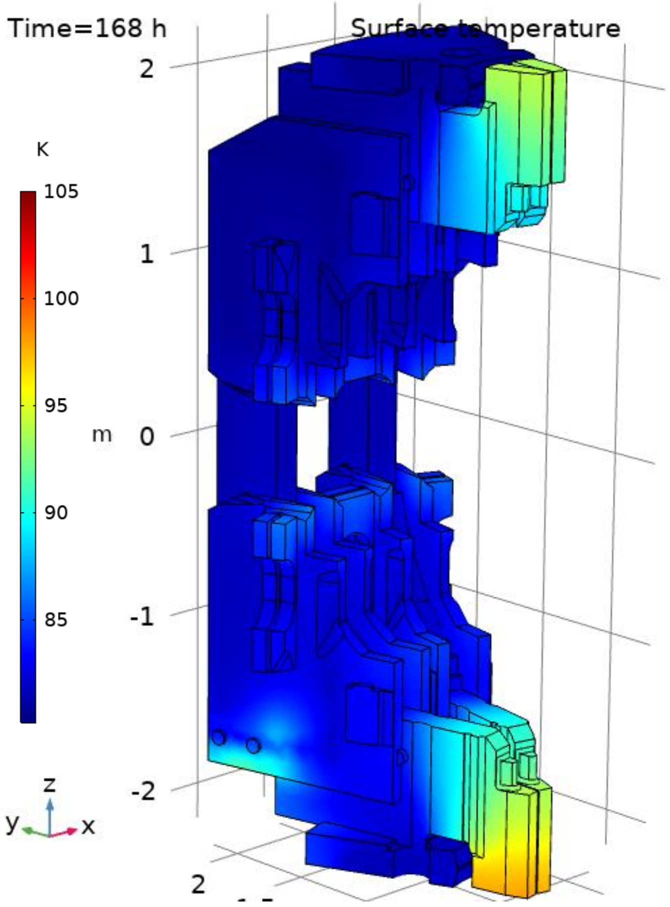
- New worst case scenario defined (5 T, after 2 MA disruption)
- Mutual displacement in TF sliding joint < 0.5 mm

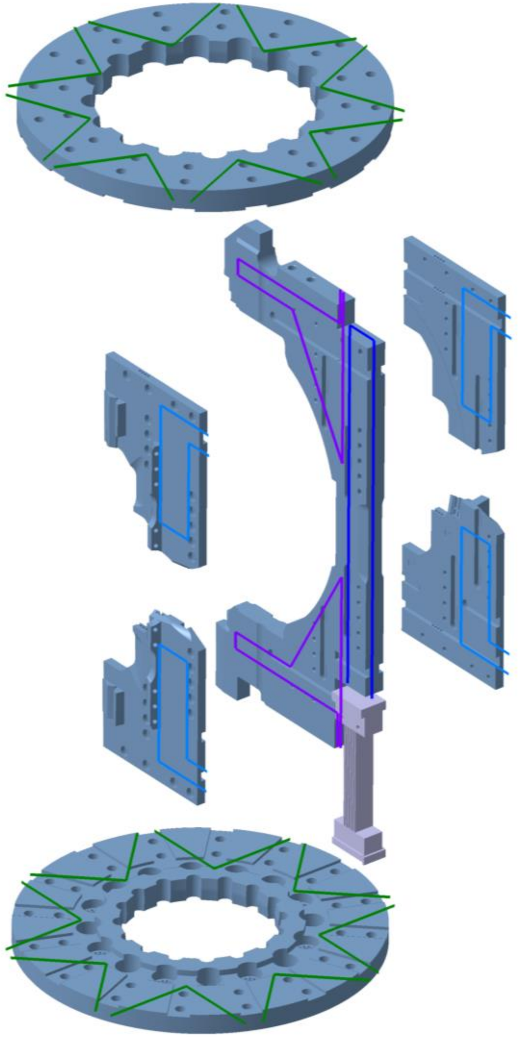
Temperature distribution [K]

- After 1 week cool-down
- Vacuum vessel at 500°C



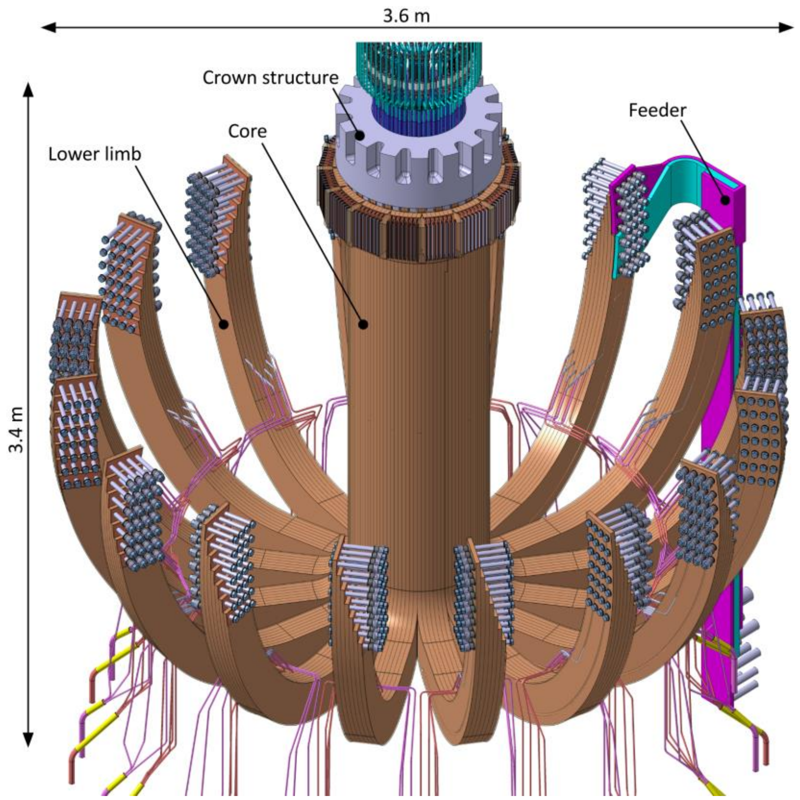


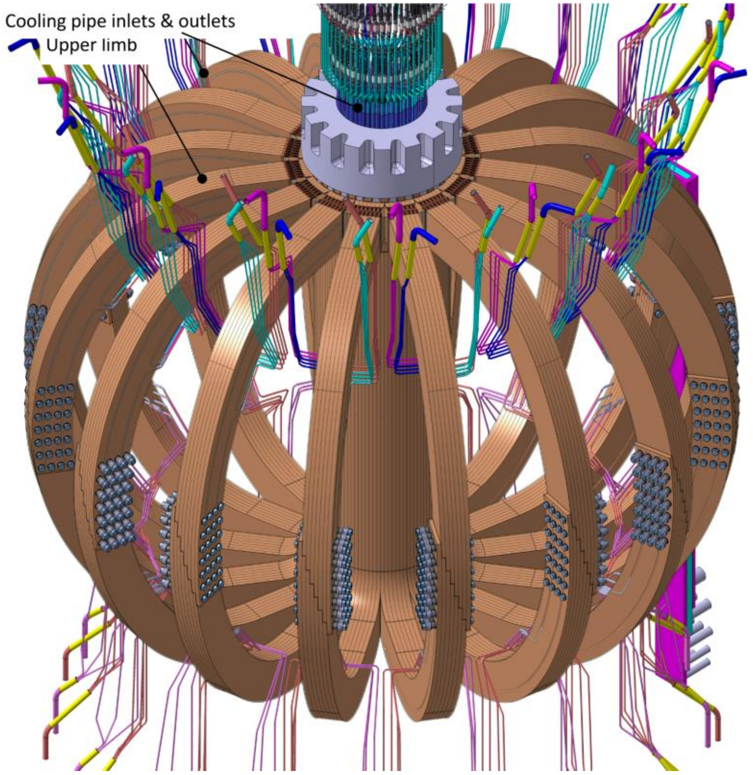


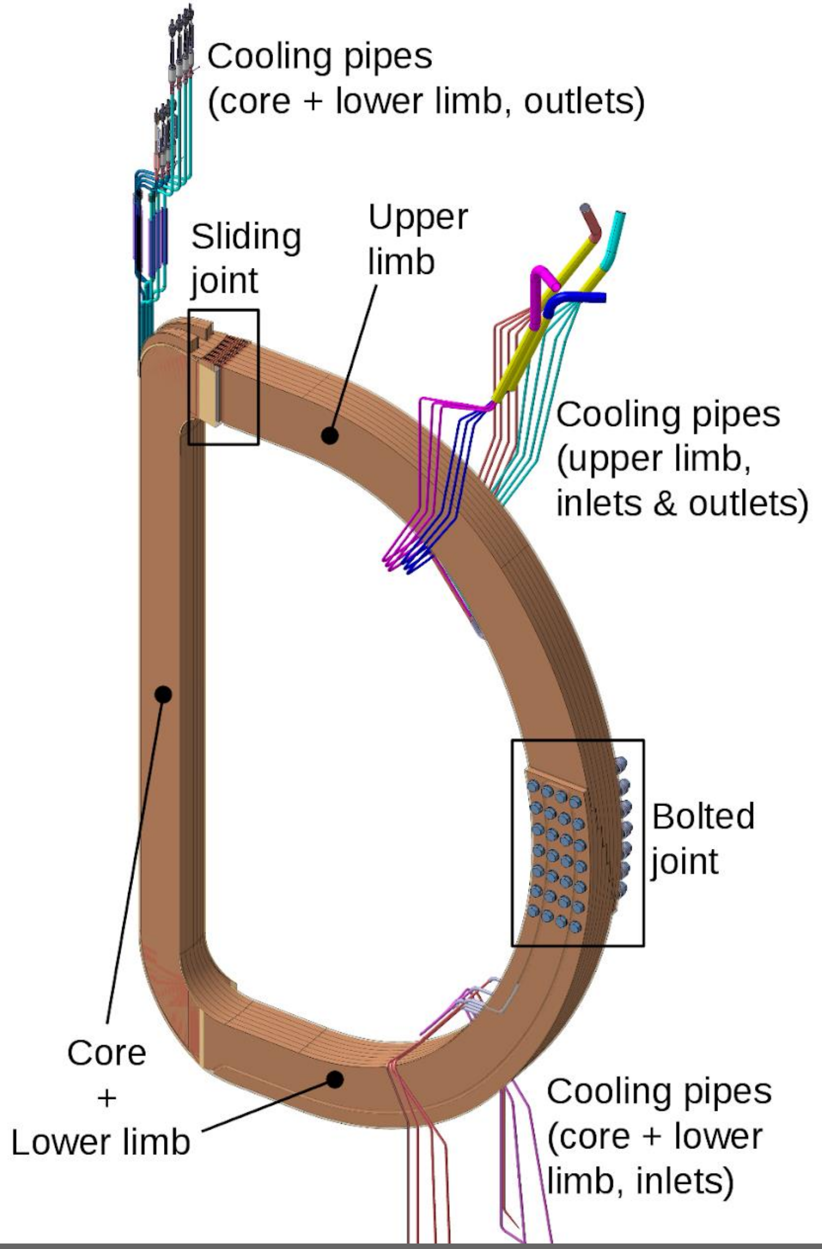


Toroidal field coils

- Material full hard **CuAg0.1 (OF)**, **16 bundles**, **7 turns** each
- TF core + 16 upper limbs connected via bolted and sliding joints
- **200 kA** for **5 T** @ **R=0.894 m**, TF ripple at separatrix **δ < 0.5 %**
- Cooled down to 80 K, gaseous He, Cu cooling pipes soldered to machined grooves



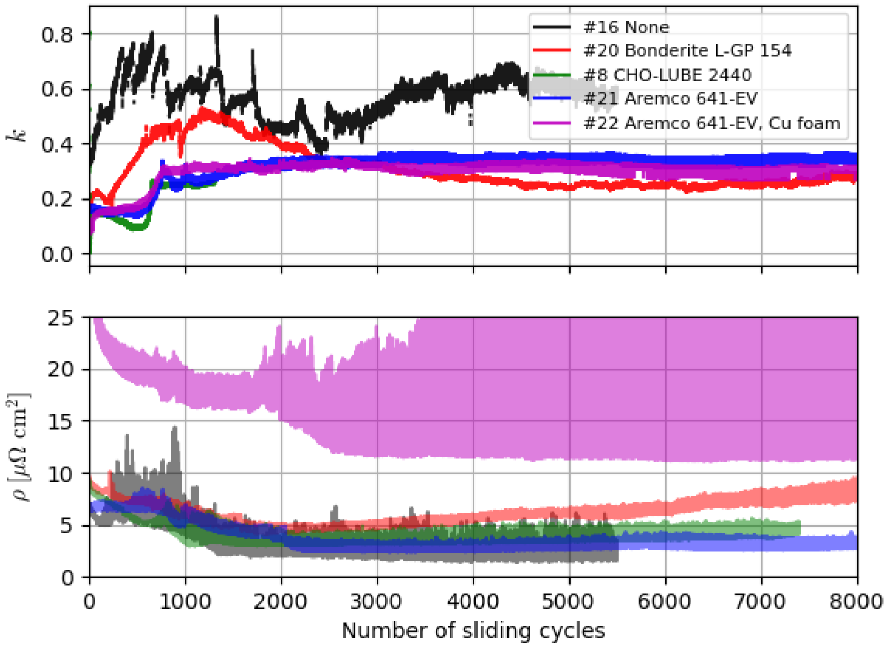




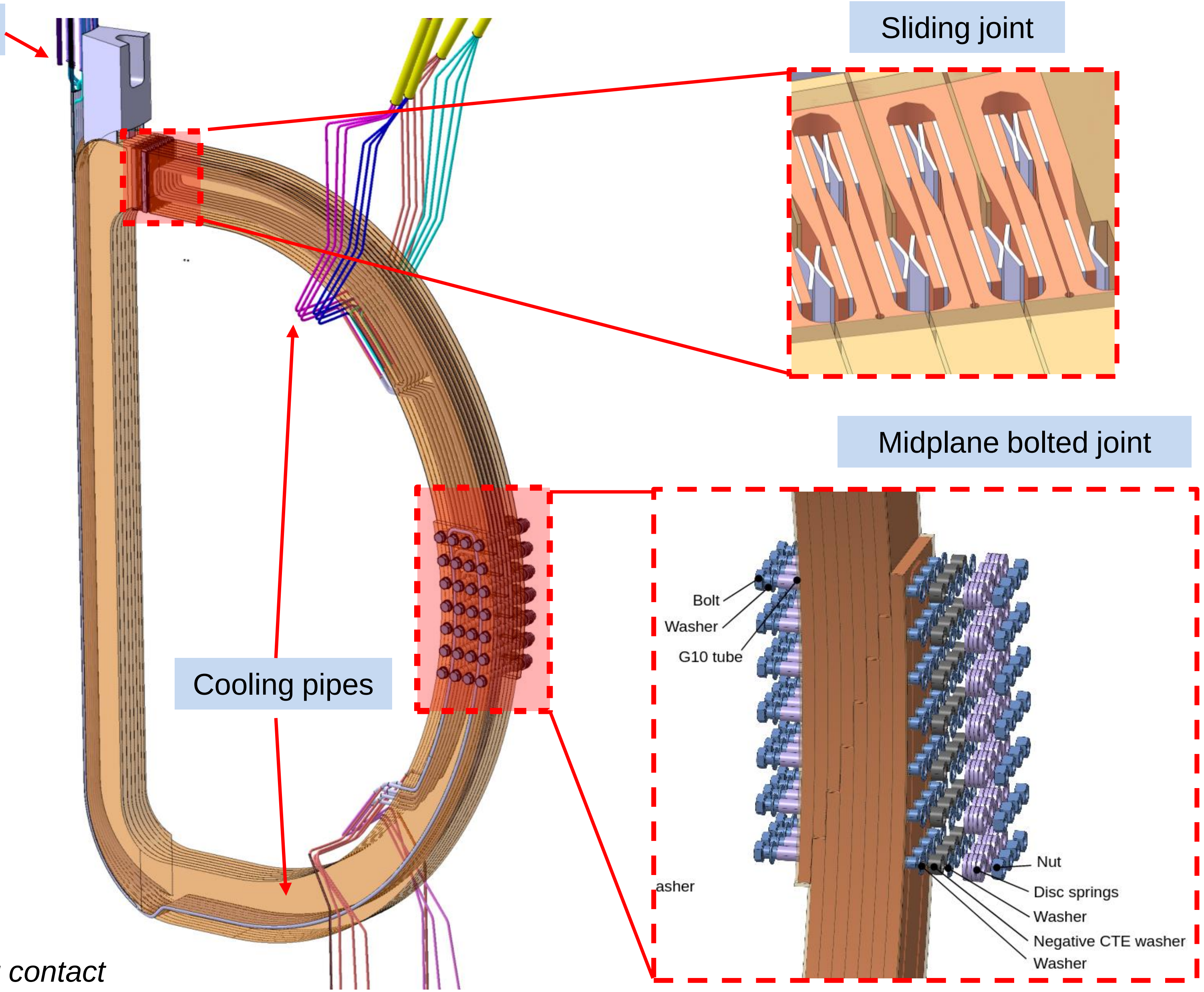
Toroidal field coils
joints

Toroidal field coils joints

- Sliding joint based on Alcator C-mod and MAST experience
- **Testing of sliding joint** properties under vacuum, cryogenic temperatures and high current density is successfully ongoing (1.7 kA/cm^2 tested)
- **~3 s flat-top @ 5 T** expected with CuAg0.1 and <0.5 μΩ joint resistance
- **Negative CTE washers** planned for the bolted joints



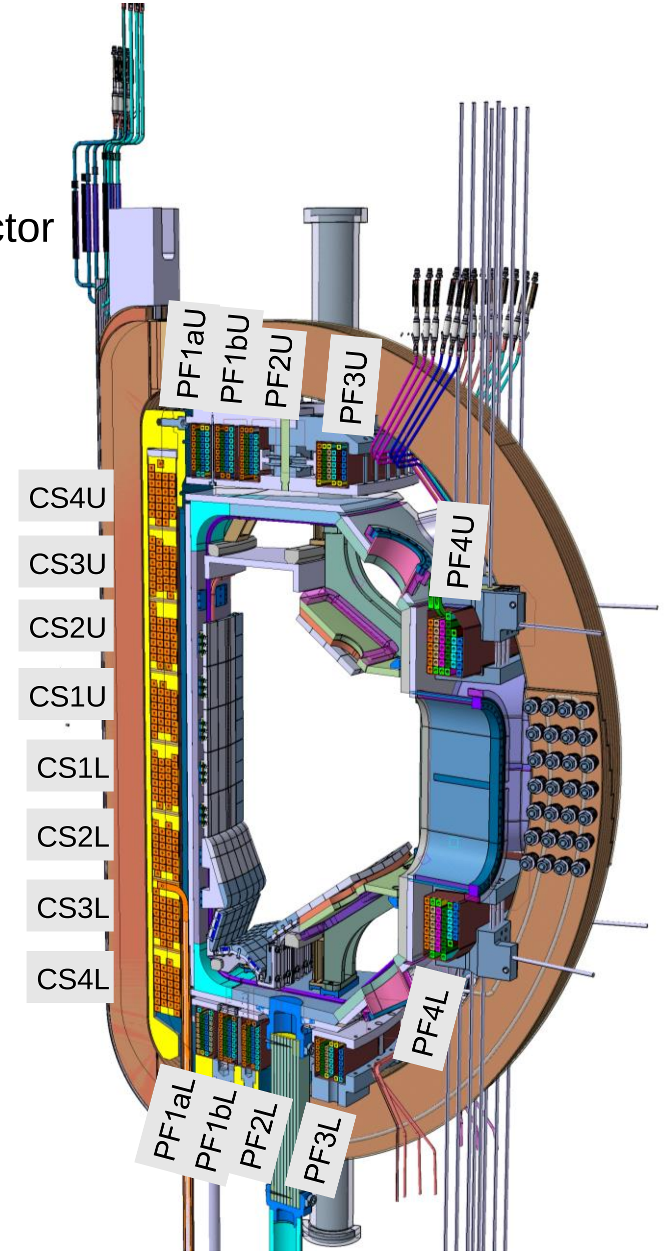
Testing samples of sliding contact

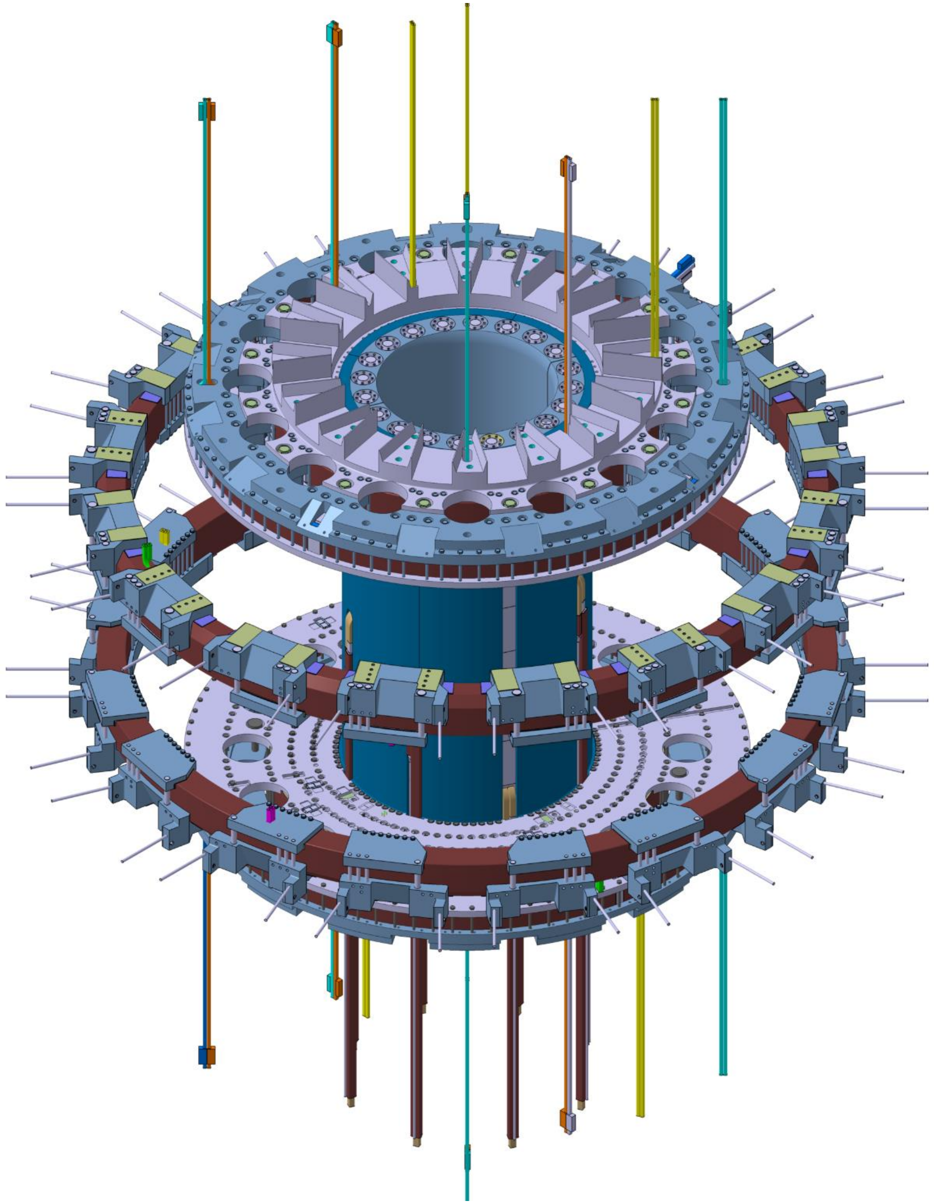


Poloidal field coils

- **8 identical CS coils**, **4+4 (5+5) PF coils**
- 1 power supply per pair of CS coils => 14 PS in total.
- **Cooling down to 80 K** by gaseous coolant (He, H_2)
- Material **CuAg0.1** (C10700), half or full hard hollow conductor
- Conductor Insulation: 1 mm S2 glass tape + kapton
- Inter-layer insulation (CS): 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

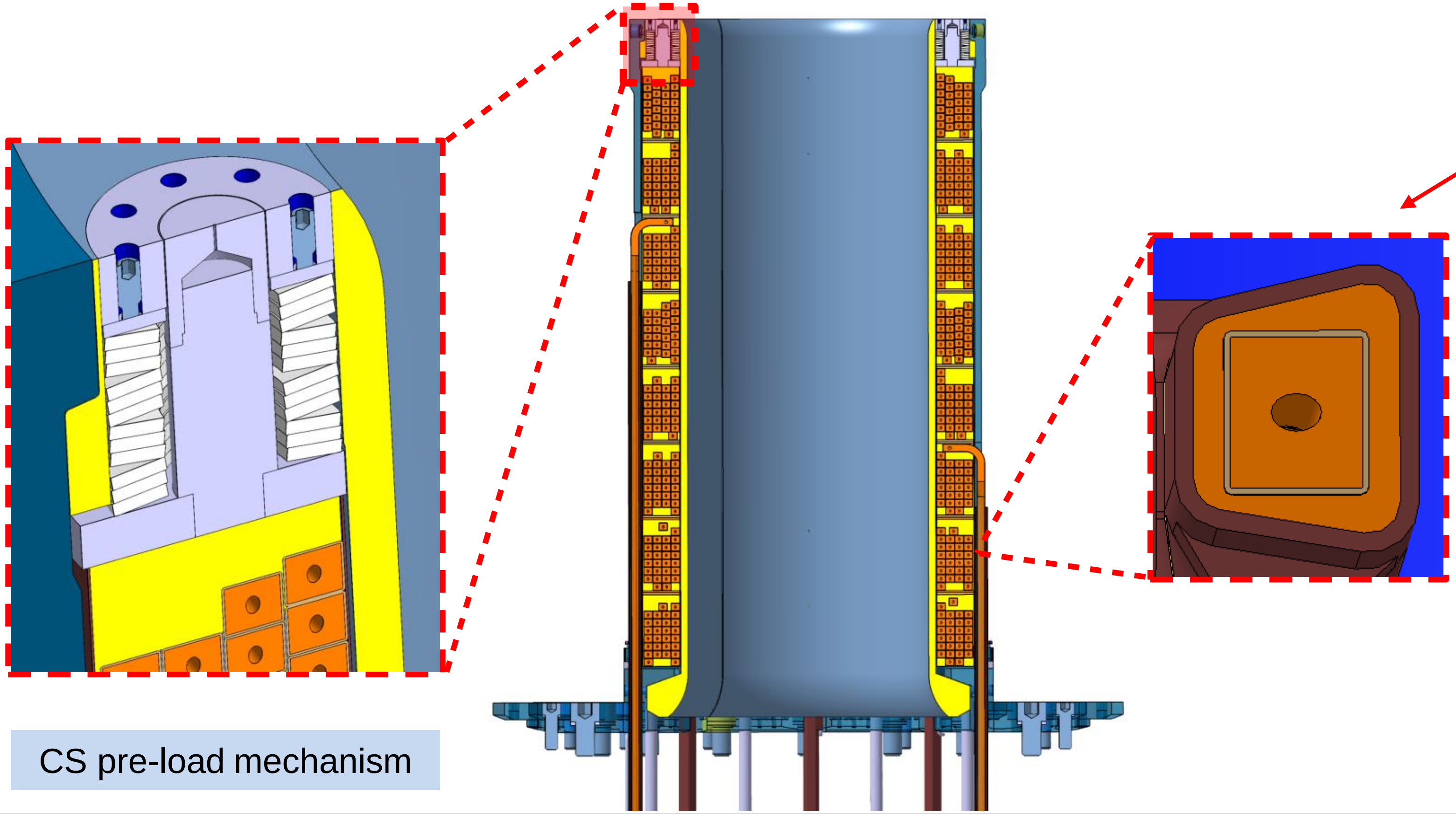


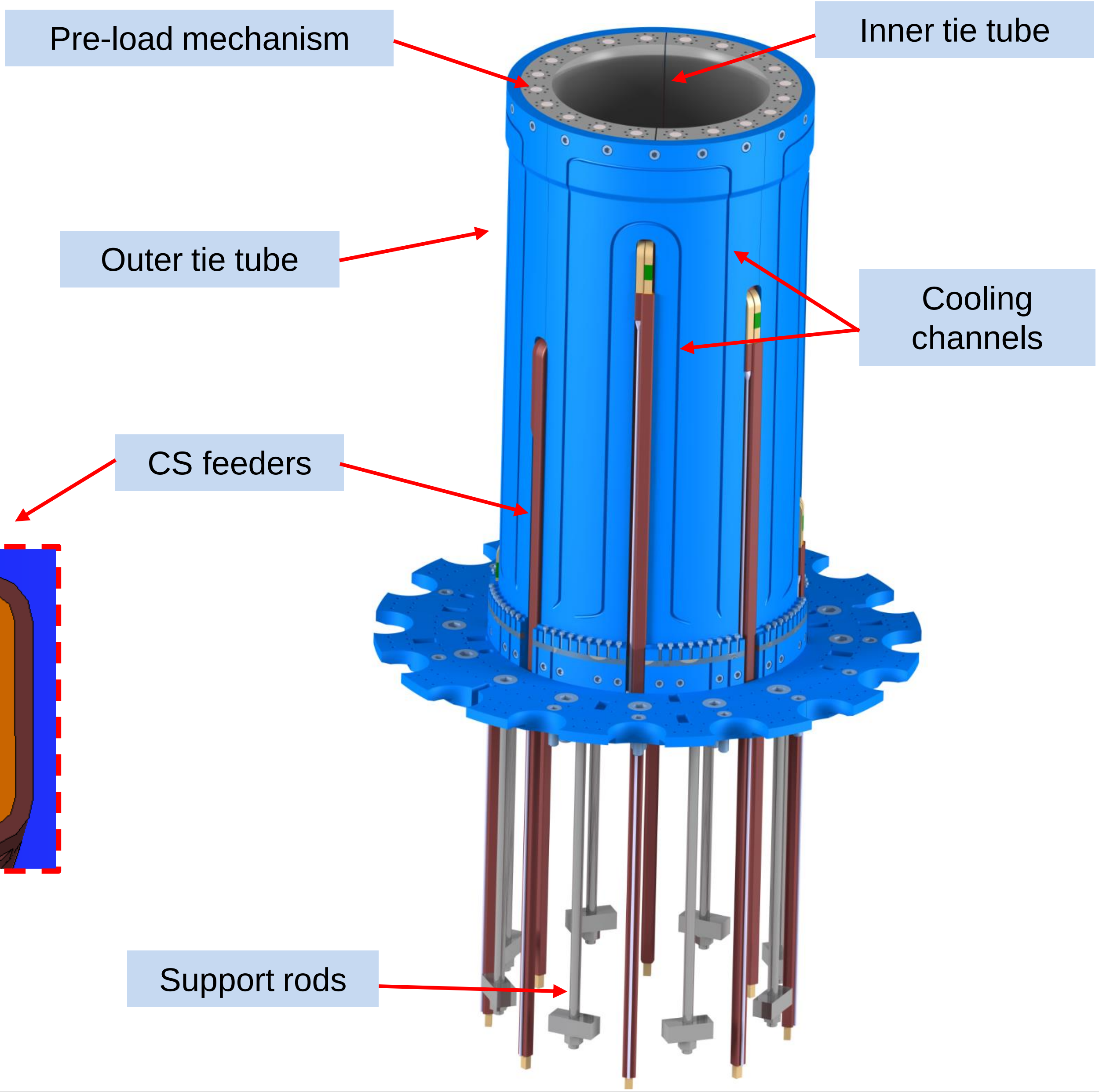


Poloidal field coils

Central solenoid

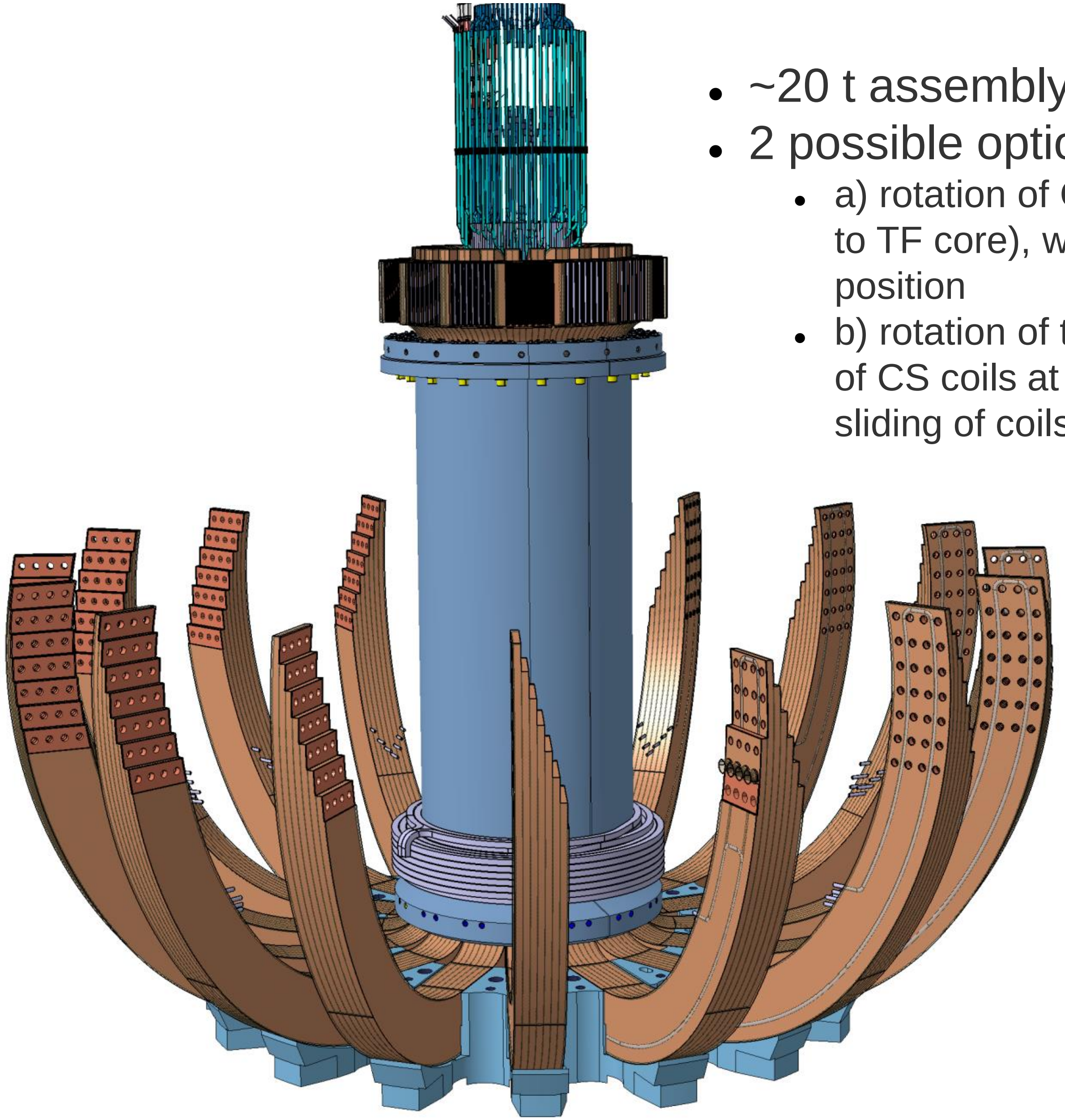
- CS is placed inside of **inner and outer tie tubes** (AISI 316LN or Nitronic)
- Conductor crossection increased to **24x21 mm**
- 20 stacks of Belleville washers (OD 100 mm) compressed by **Superbolt tensioner provide ~5 MN pre-load** of CS, ~1 cm working range
- CS feeders modified to **coaxial**, 8 rods holding CS vertically
- Cooling channels in outer tie tube



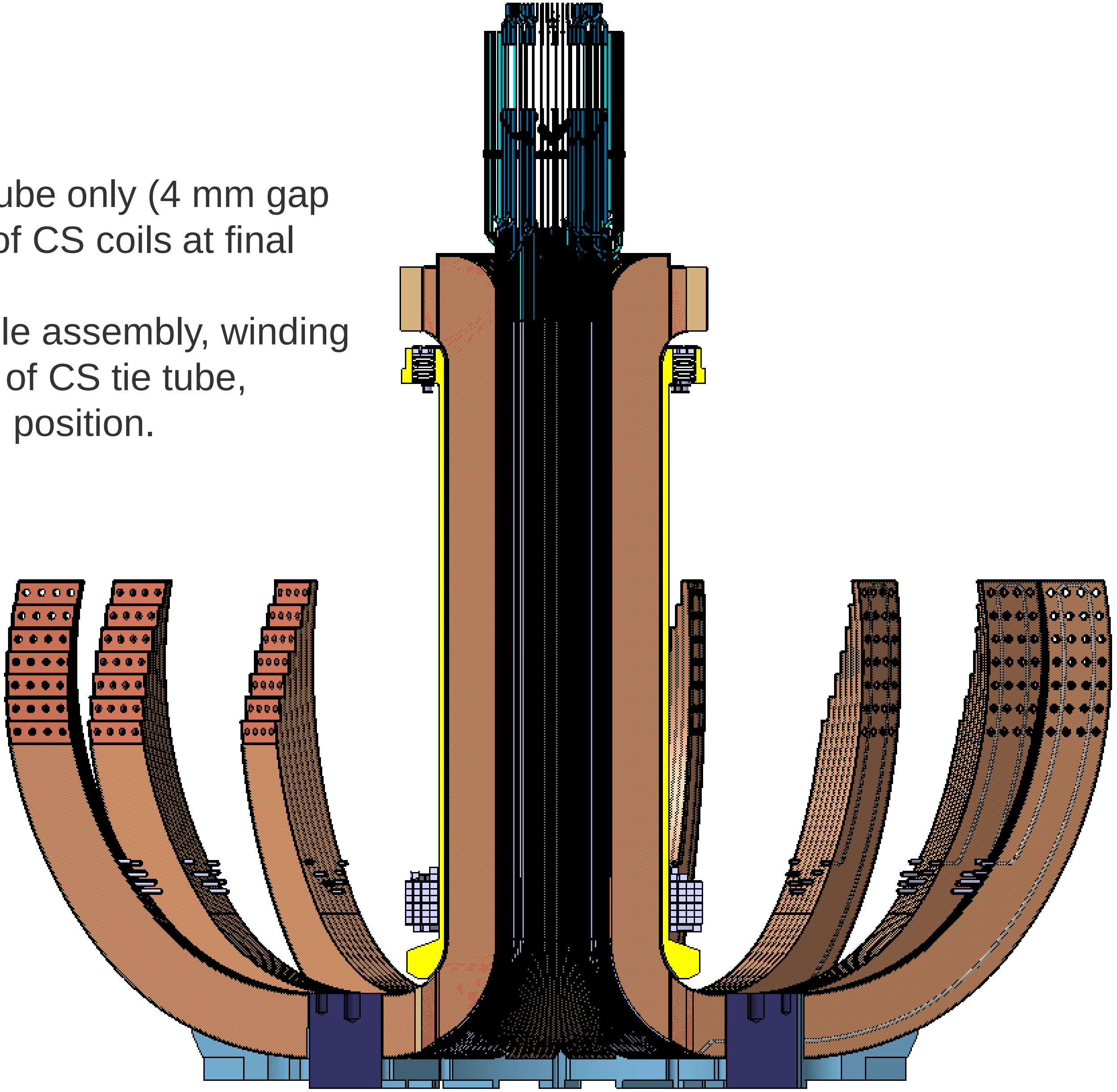


Poloidal field coils

Central solenoid winding

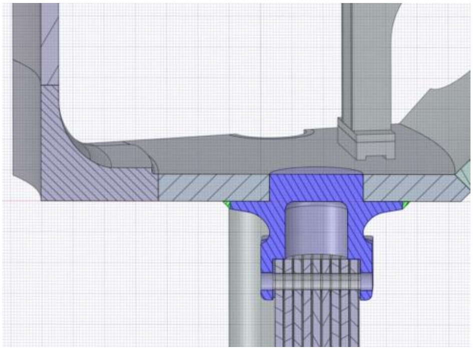


- ~20 t assembly
- 2 possible options:
  - a) rotation of CS tie tube only (4 mm gap to TF core), winding of CS coils at final position
  - b) rotation of the whole assembly, winding of CS coils at the top of CS tie tube, sliding of coils to final position.

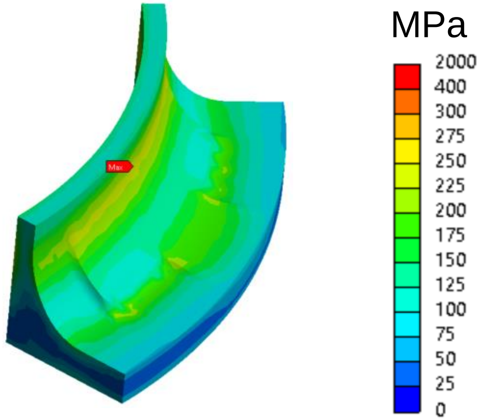


Vacuum vessel

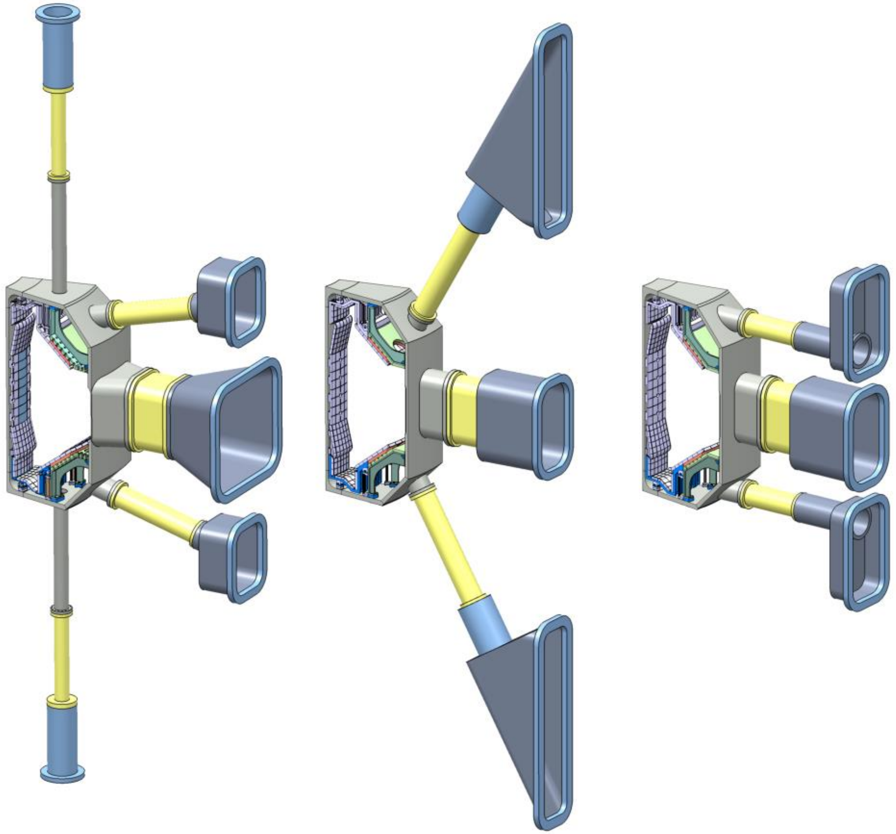
- Material: **Inconel 625,** 23 mm thick inner tube, 35 mm top, bottom and 30 mm LFS parts
- Total weight: ~9 t (including PSP)
- 8 flexible Inconel 625 supports– connected to the lower compression disk of the support structure



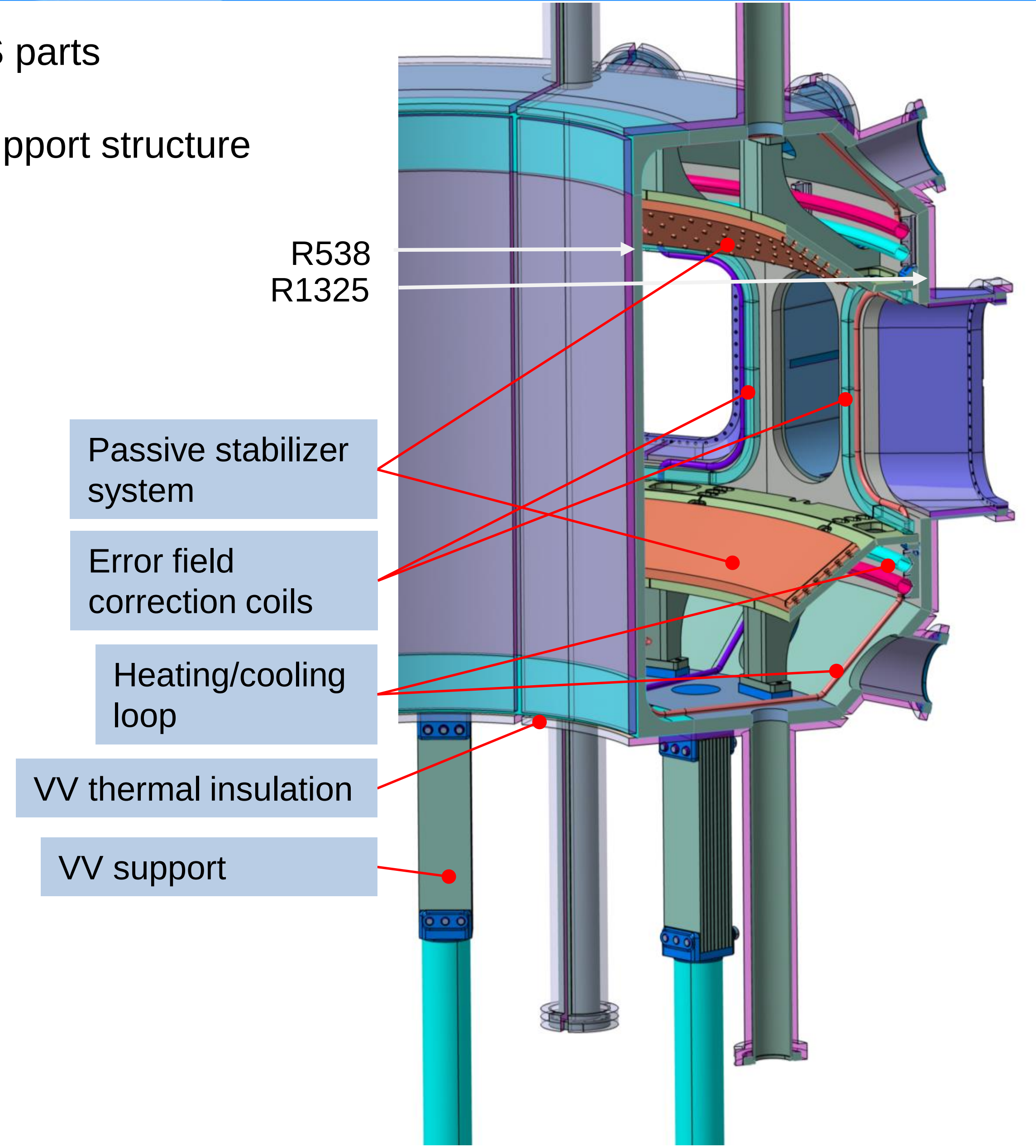
Connection of VV support.



Reinforced inner corner

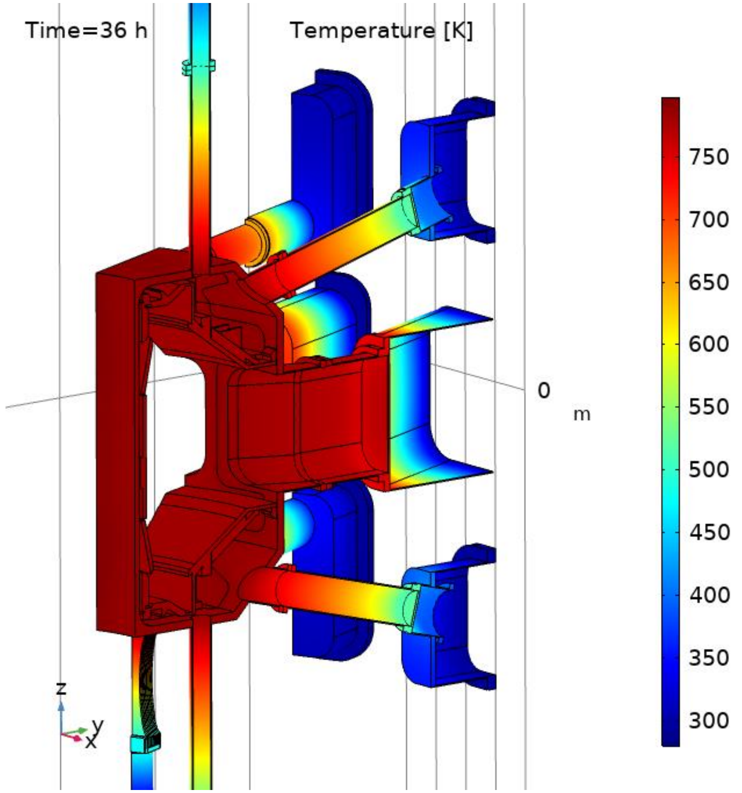


2 types of midplane ports, 3 types of divertor ports

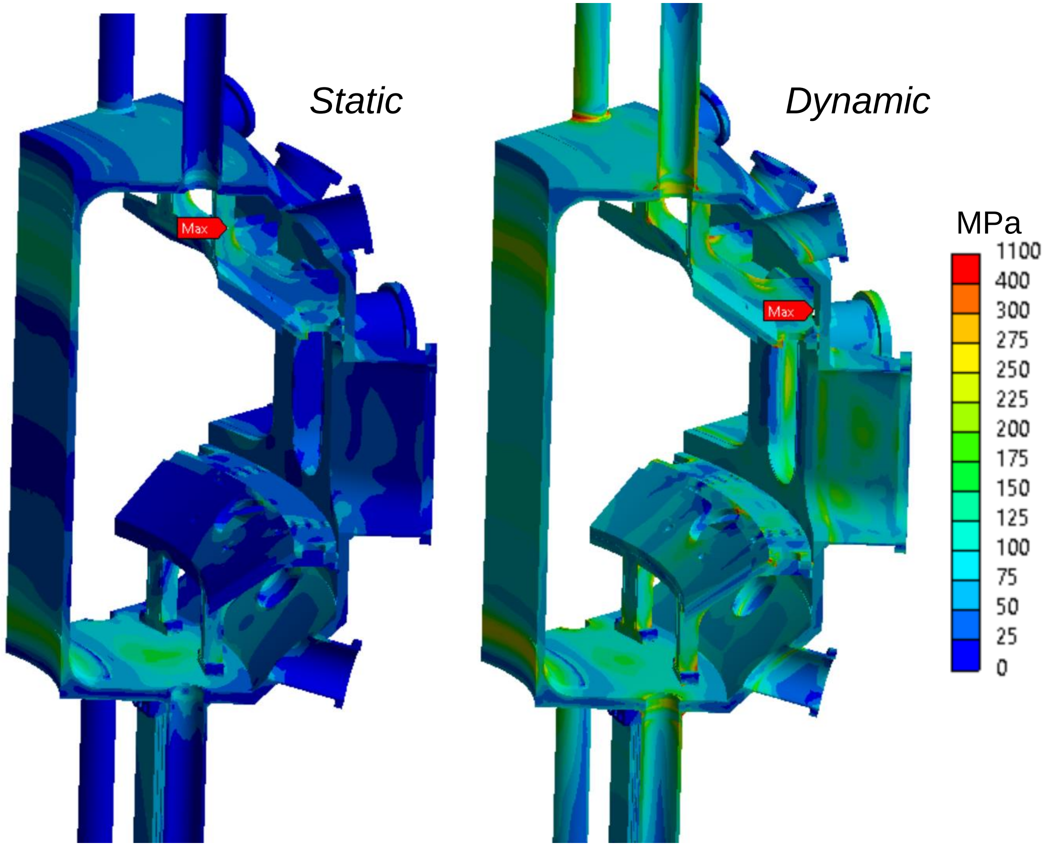


Vacuum vessel
Heating & FEM analysis

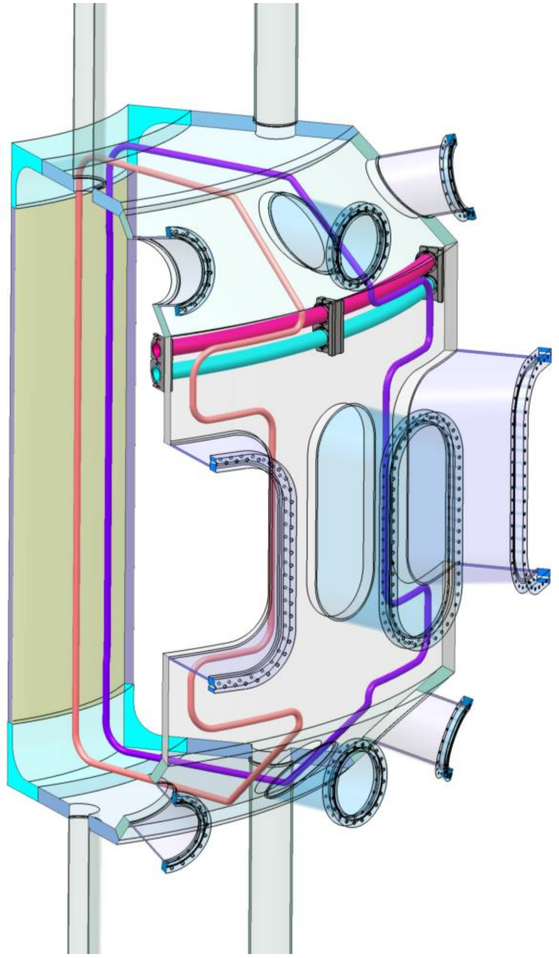
- Heating of VV up to 500 °C in ~24 h => **heating power~40 kW**
- Removal of deposited energy from plasma discharge (max. 40 MJ) in 20 min. => **cooling power ~33 kW**
- **Inconel 625 pipes welded on inside of VV**, OD 16 mm, 2 mm wall. Gaseous medium (He or CO_2)
- PFC heated mainly by radiation
-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



Temperature distribution at the vacuum vessel and port extensions.

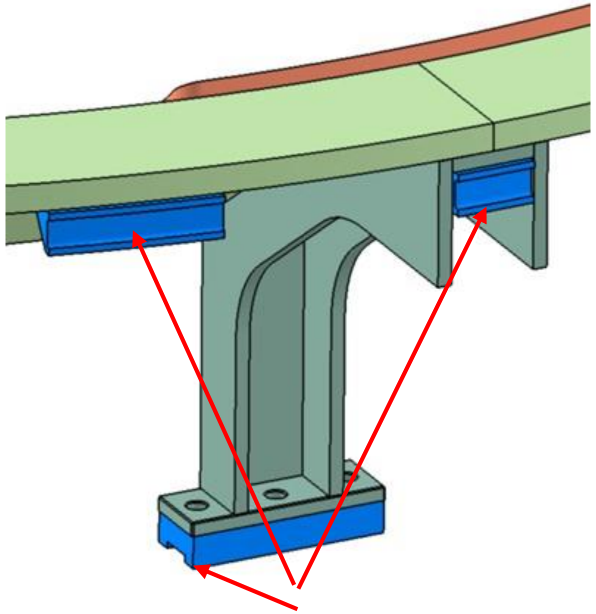


Von Mises stress in the vacuum vessel and PSP.

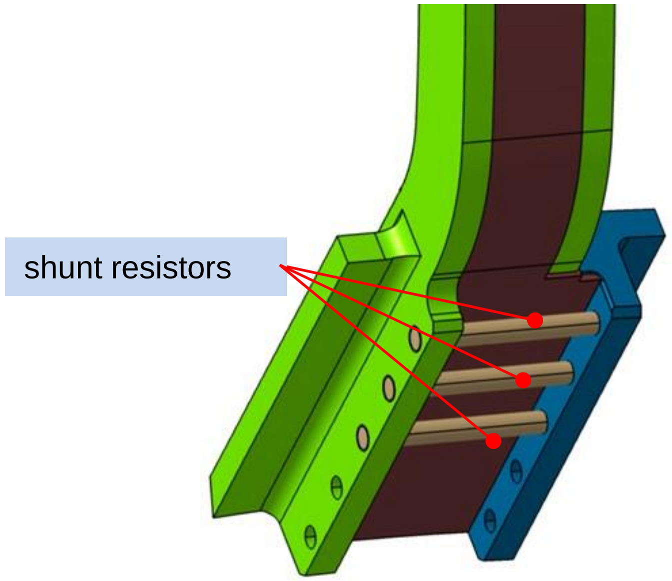

Vacuum vessel heating pipe routing.

Vacuum vessel
passive stabilising plates

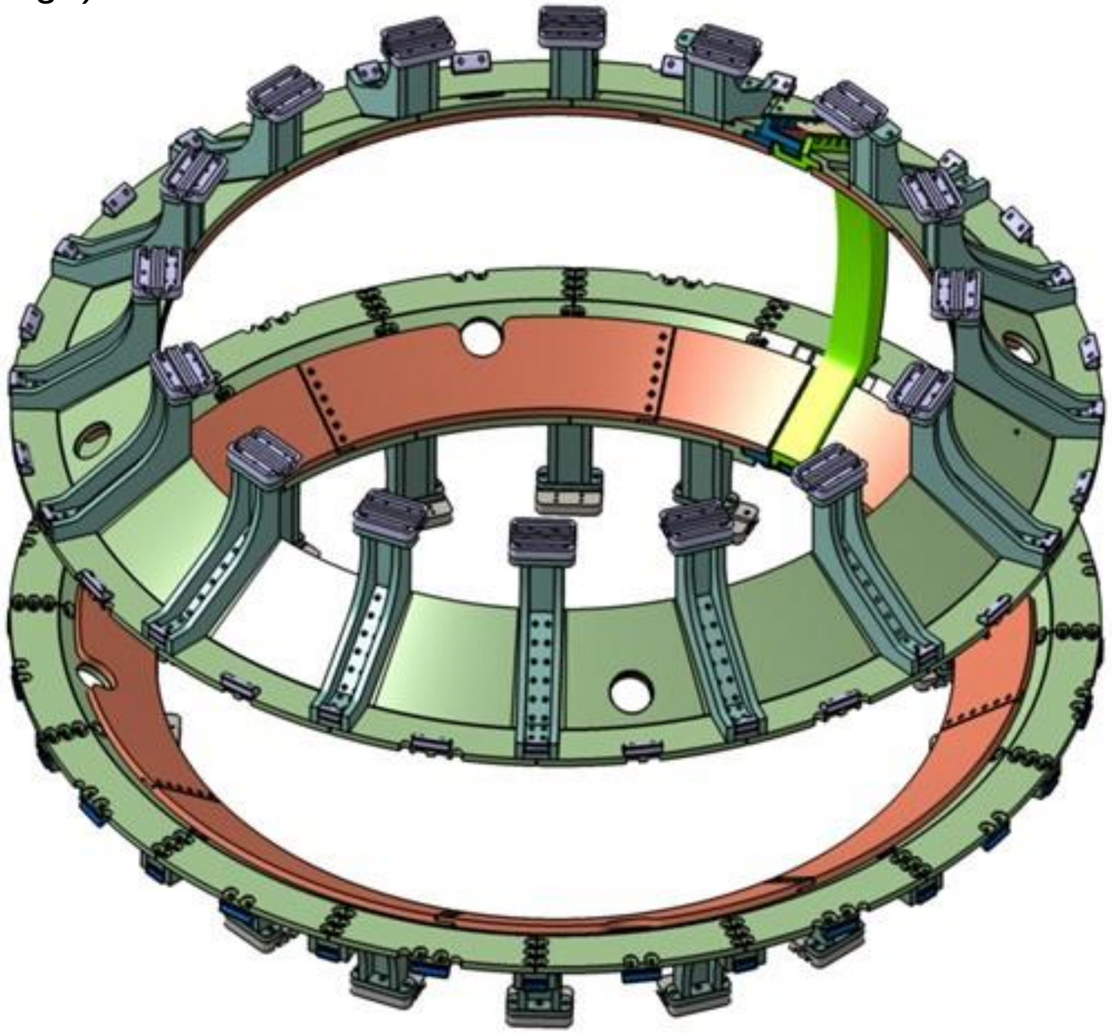
- 2 counterwound PSP loops with **coaxial bridge** (inspired by ASDEX Upgrade design)
  - Nominal loop time constant: τ = 40 ms
  - Total loop resistance: 180 $\mu\Omega$
  - Shunt resistors baseline: 150 $\mu\Omega$
- **20 mm Glidcop Al-60** plate + **20 mm Inconel 625** support
- 16 Inconel 625 support legs bolted to pads welded to the VV
- At least **8 bolted toroidal segments** (~30 kg parts)



Bolted connection to pads welded to the vessel



PSP bridge

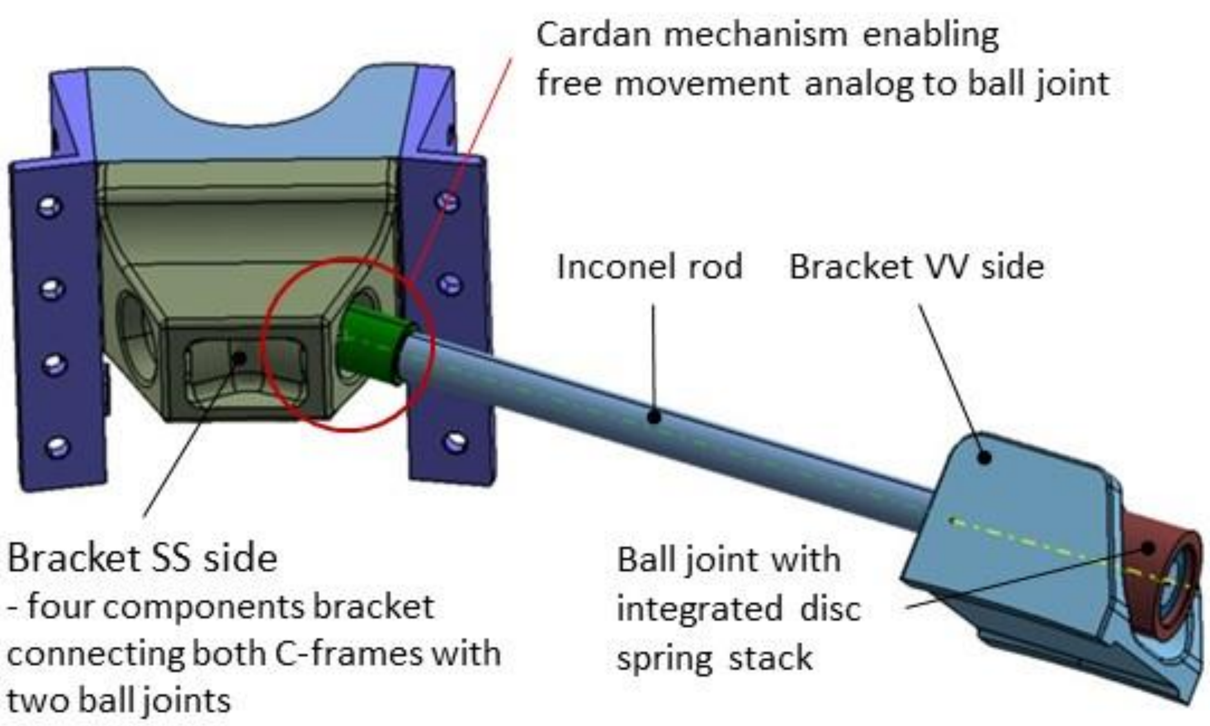


Passive stabilising plates

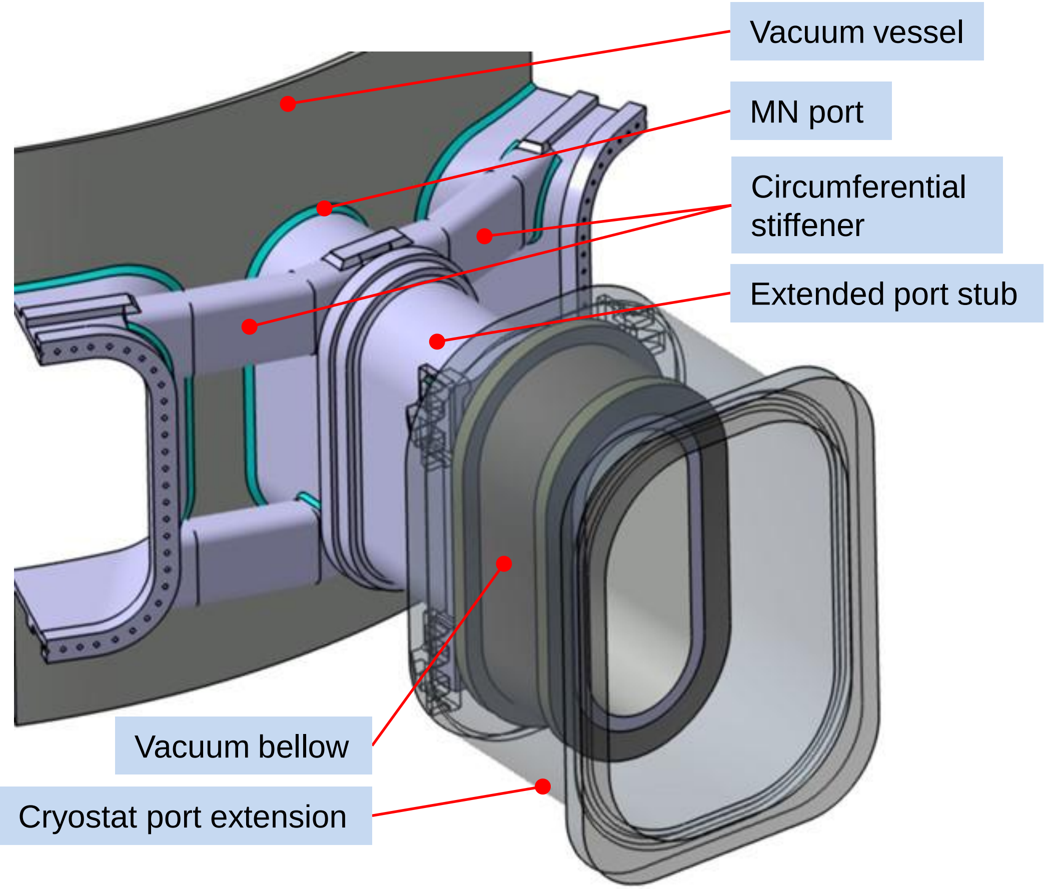
Vacuum vessel
toroidal support

Two main design concepts for stabilization of toroidal and latera movement of VV during disruptions

- Rod stabilizers connecting VV and support structure
- Stabilization by narrow midplane ports (to cryostat)



Rod stabilizer concept



Stabilization by narrow midplane ports

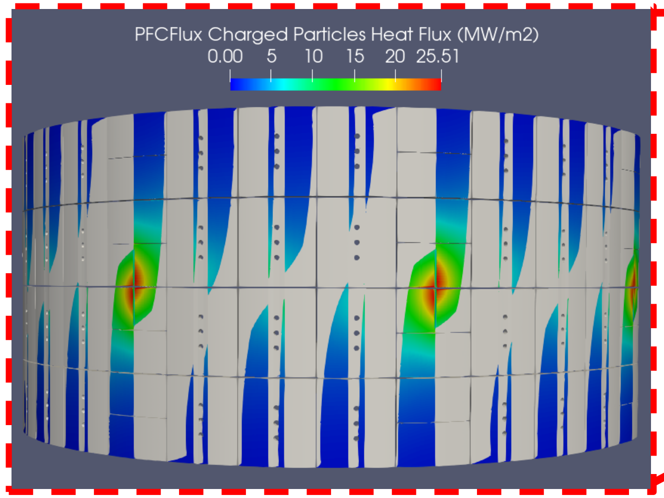
Plasma Facing Components

Inner wall limiters

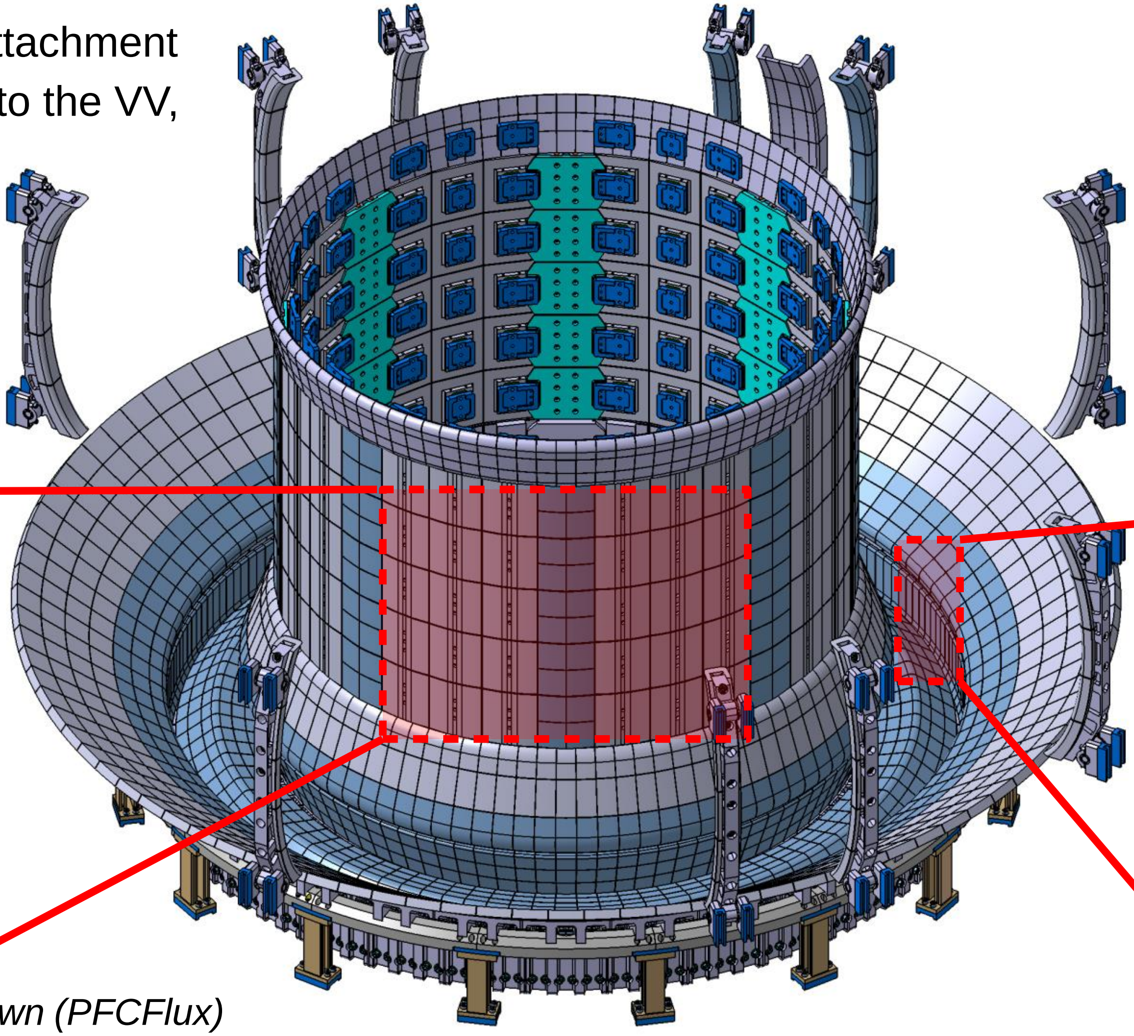
- Plasma start-up and termination (~0.4 s)
- Tungsten tiles forming **8 guard limiters**
- Inconel 718 tiles with frontside attachment
- Inconel 625 **U-brackets** welded to the VV, precisely machined surface

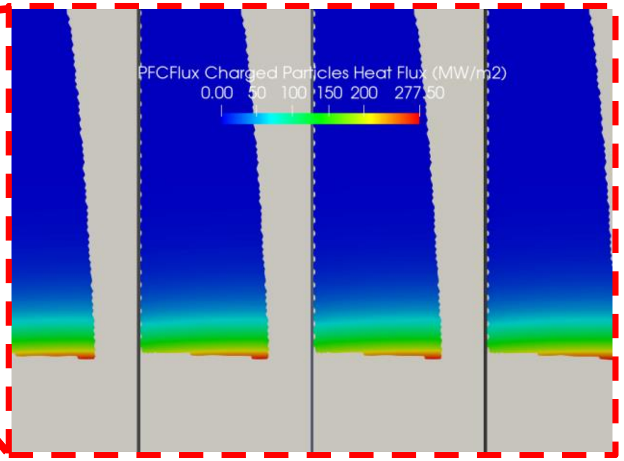
Divertor

- 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
- Tungsten tiles bolted from the cassette back side
- Toroidal bevel of 0.6°



Heat flux distribution during plasma ramp-down (PFCFlux)





Heat flux distribution in the divertor (PFCFlux)

Plasma Facing Components

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- Tungsten tiles with backside attachment forming **8 guard limiters**
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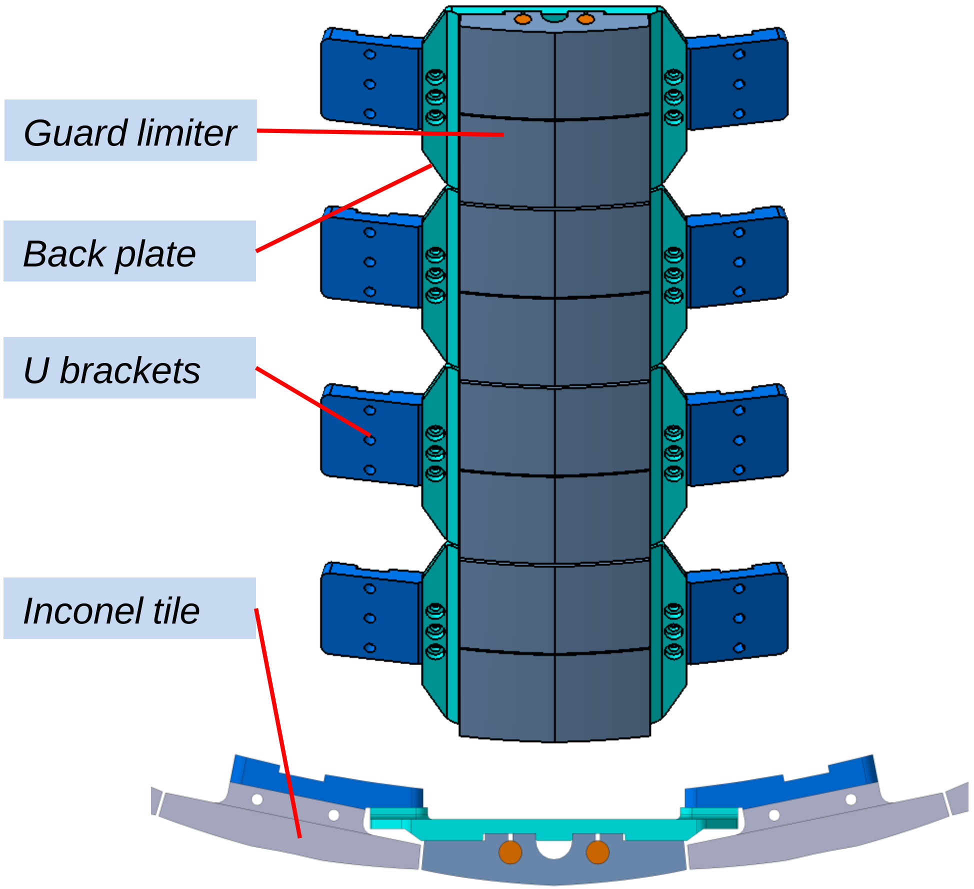
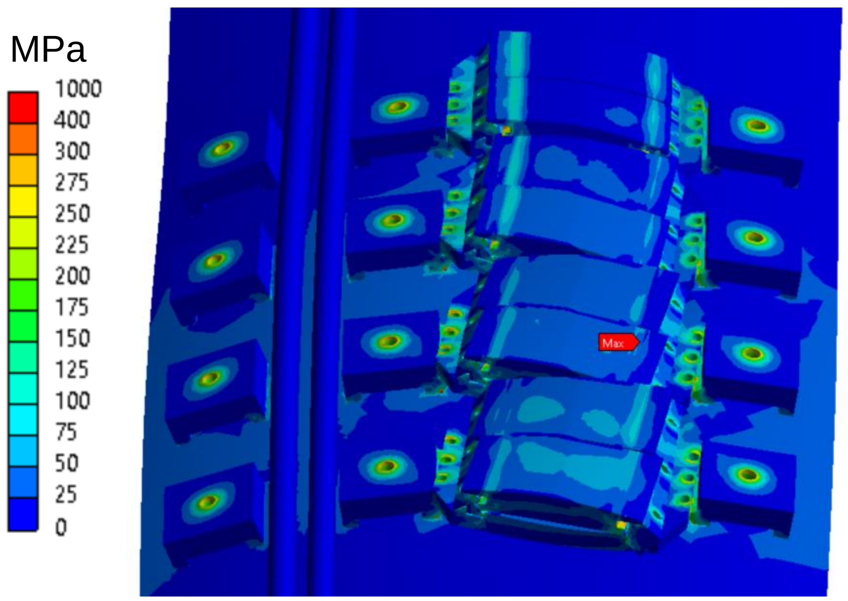
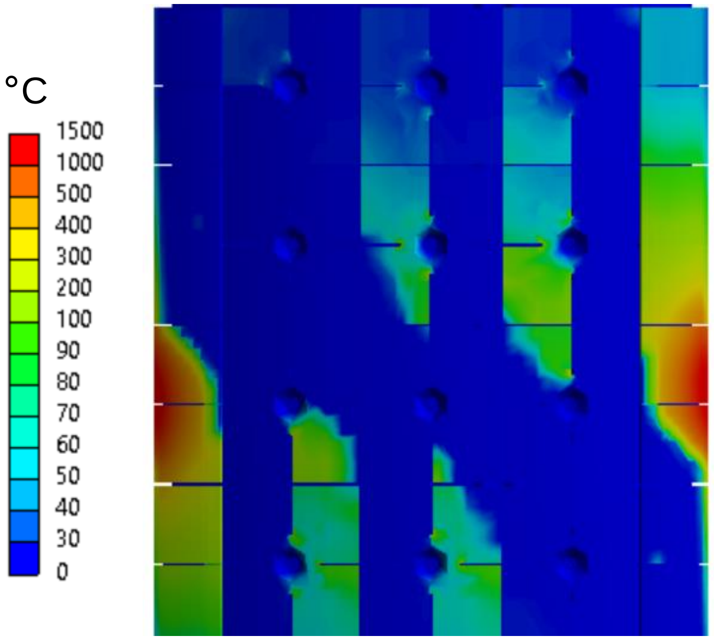




Von Mises stress in the inner wall under EM load.

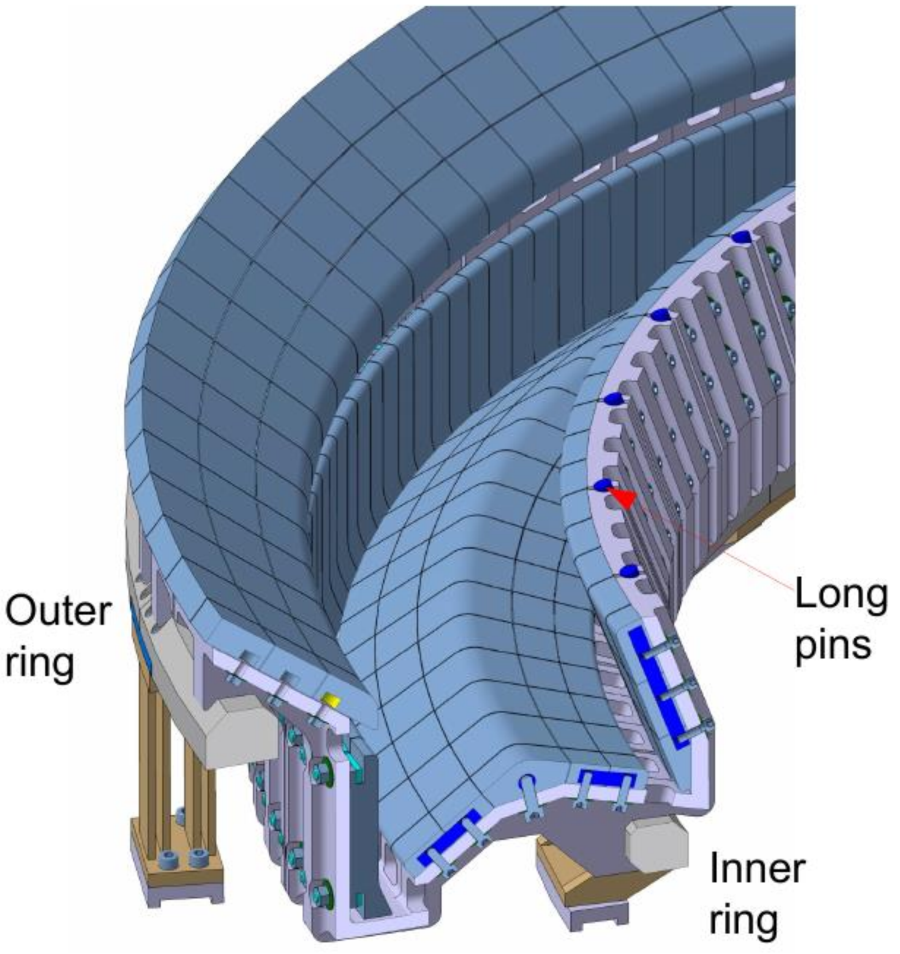


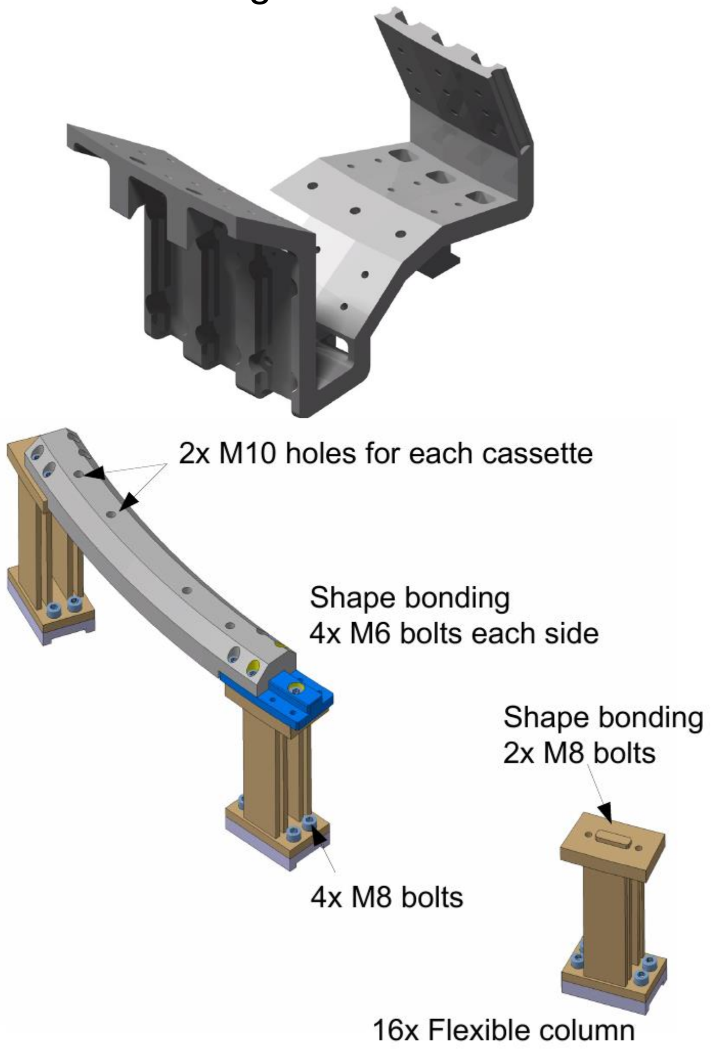
Temperature distribution after a plasma discharge.

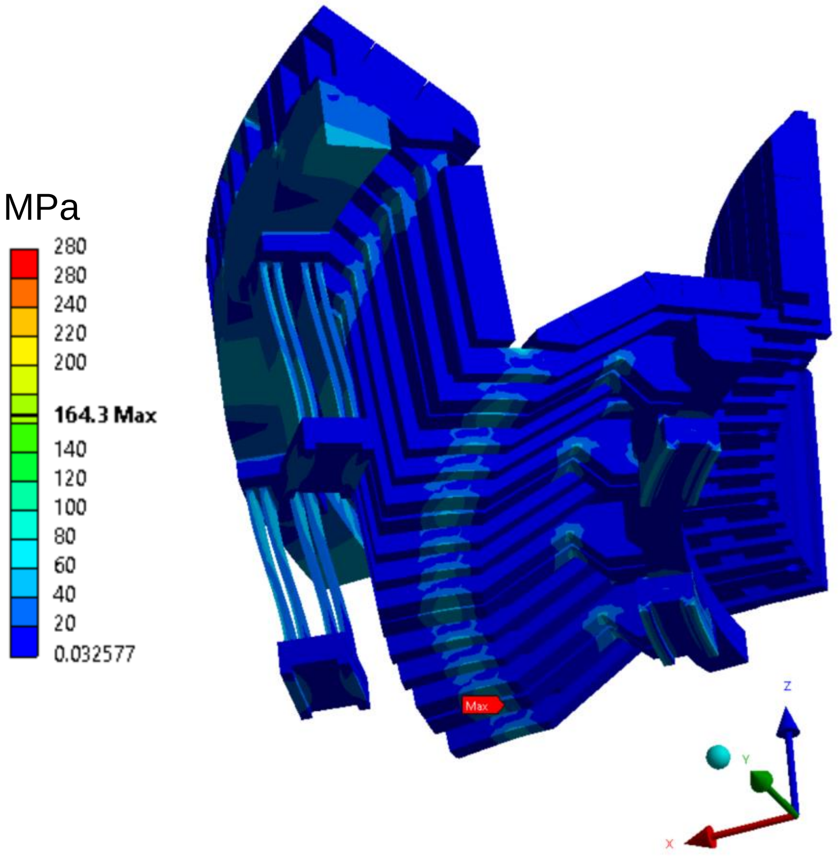
Plasma Facing Components

Divertor

- **Cassette divertor concept**
- 32 cassettes: Inconel 625 support, tungsten tiles
- Outer and inner continuous Inconel 625 rings for cassette alignment



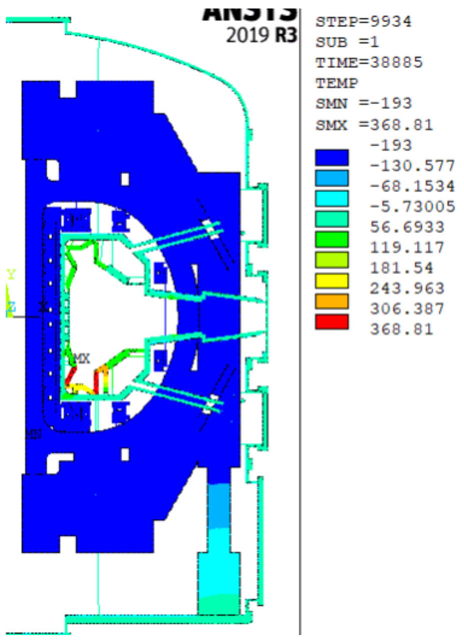




Von Mises stress in the Cassette under halo current EM loading.

Cryogenics

- **Cooldown after a top performance discharge within 30 min**
  - TF coils ~250 MJ, PF+CS coils ~50 MJ
  - => required cooling power ~200 kW @ 80 K
- **Multiple closed gaseous helium loops**
  - **CS** - high pressure p_{base} 60 bar, Δp 5 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**
  - ~50 m^3 of LN2 per day at full parameters
  - Optional: cycle cooler (Brayton, J-T, G-M, ...) for subcooling under 80 K



Global thermal model

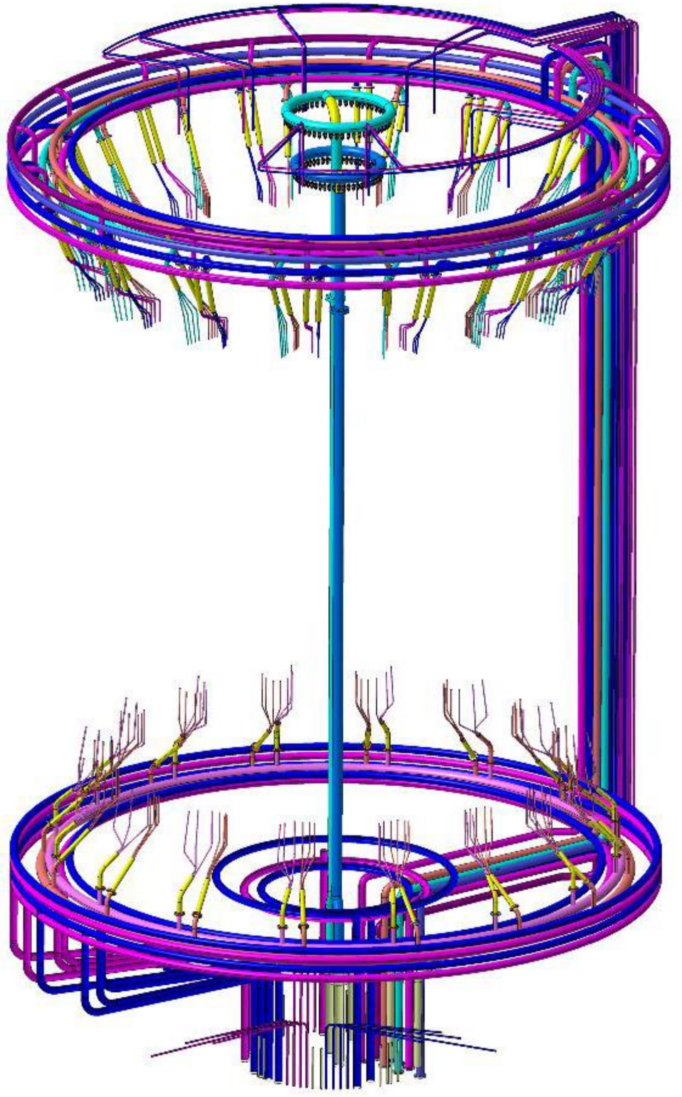
Vacuum vessel thermal insulation – 2 options considered

1) High temperature MLI
   - 10-20 mm space available, **30-40 (?) layers attached to VV**
   - **Glass fiber spacer** + **metalic reflector** (SS, Au, Cu, Al, Ti)
   - Insulation cuts needed because of **eddy currents** (mainly during disruptions)
   - **In-house MLI** experiments + FEM simulations of induced currents and forces

2) Microporous

Cryostat thermal insulation

- Standard MLI


Cooling collectors

Power supply system

Power Supply System

- Existing flywheel generators (50 MVA, 50 MJ each)
- Two new flywheel generators (108 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, 58 MJ
- In total: **268 MW, 490 MJ**

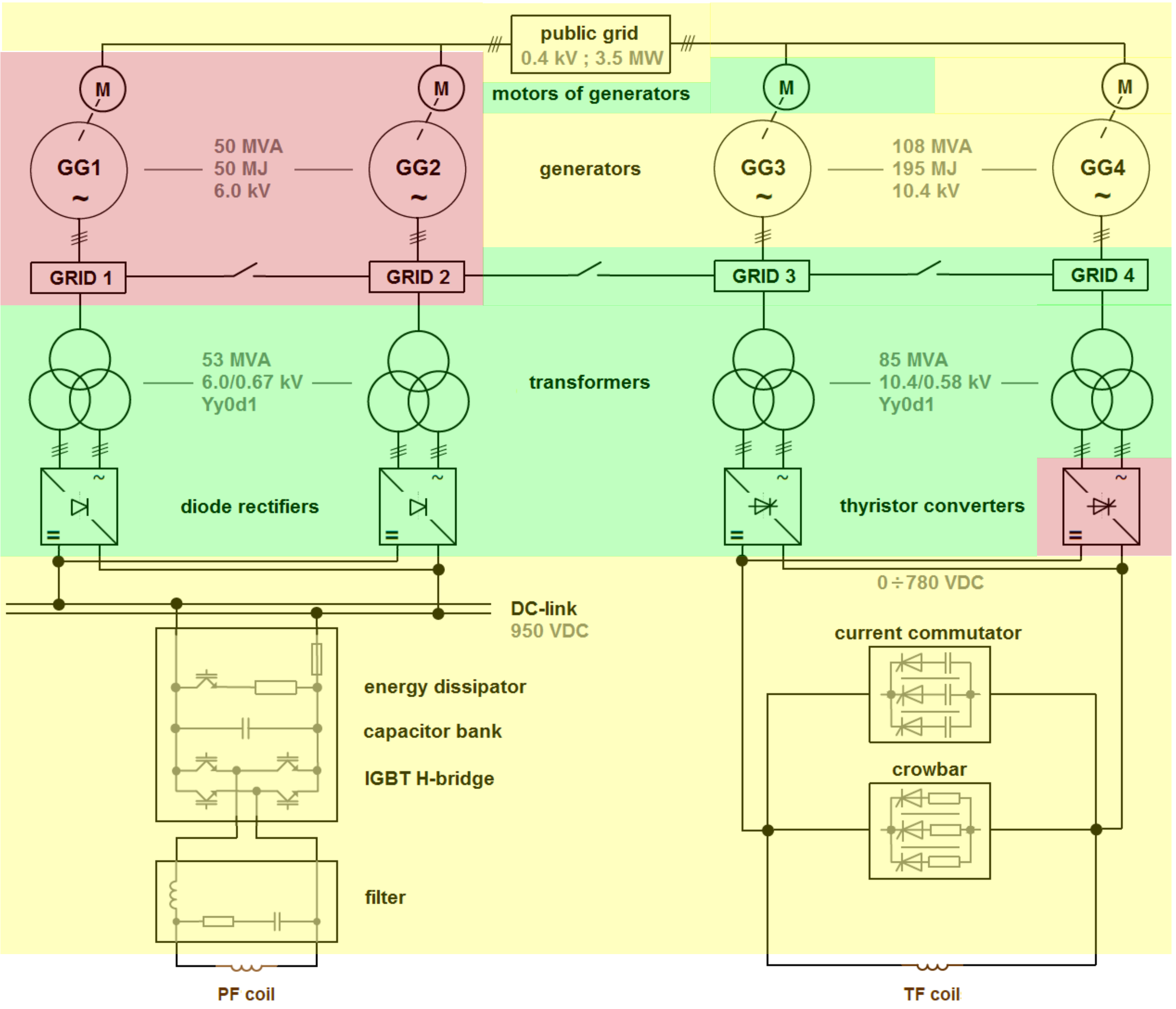
Status

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

Already manufactured

Existing equipment (reused from COMPASS)

In development / manufacturing process



Schematic overview of the power supply system.

Vacuum and gas-puff

Main vessel pumping

- 2x TMP ATH 2303 M – S_{main}=1100 l/s (H2), 2300 l/s (N_2)
- 2x „old“ COMPASS TMP TMU 521P – S_{div}=450 l/s (H2), 510 l/s (N_2)

Divertor cryo-pump

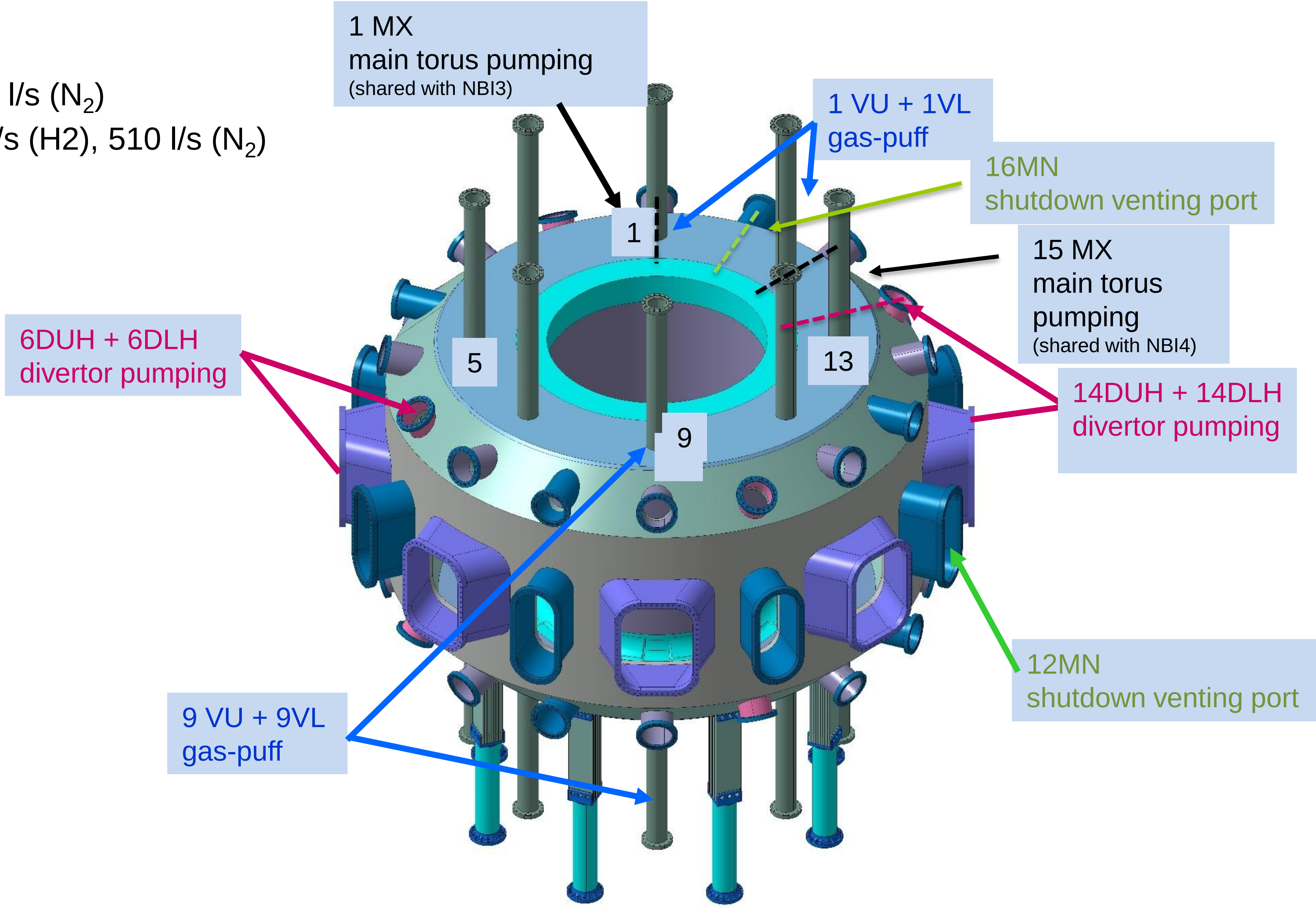
- planed S_{cryo} ~ 10 000 l/s

Cryostat pumping

- 4x diffusion pumps S ~ 2 500 l/s

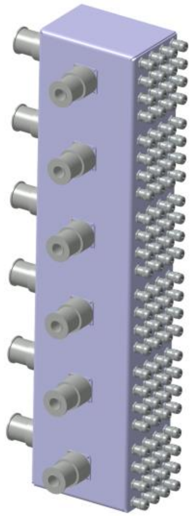
Gas puff system

- 2 lower and 2 upper vertical ports reserved
- 2x4 positions of gas-puff toroidally
- 3 position poloidally each

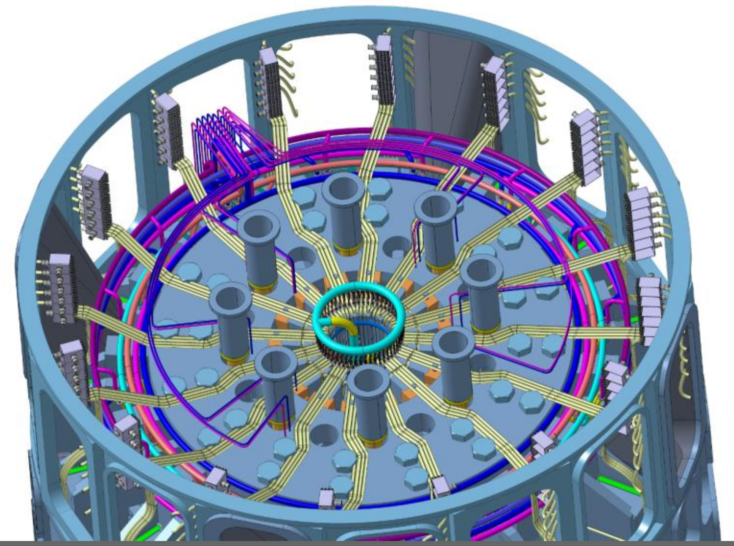


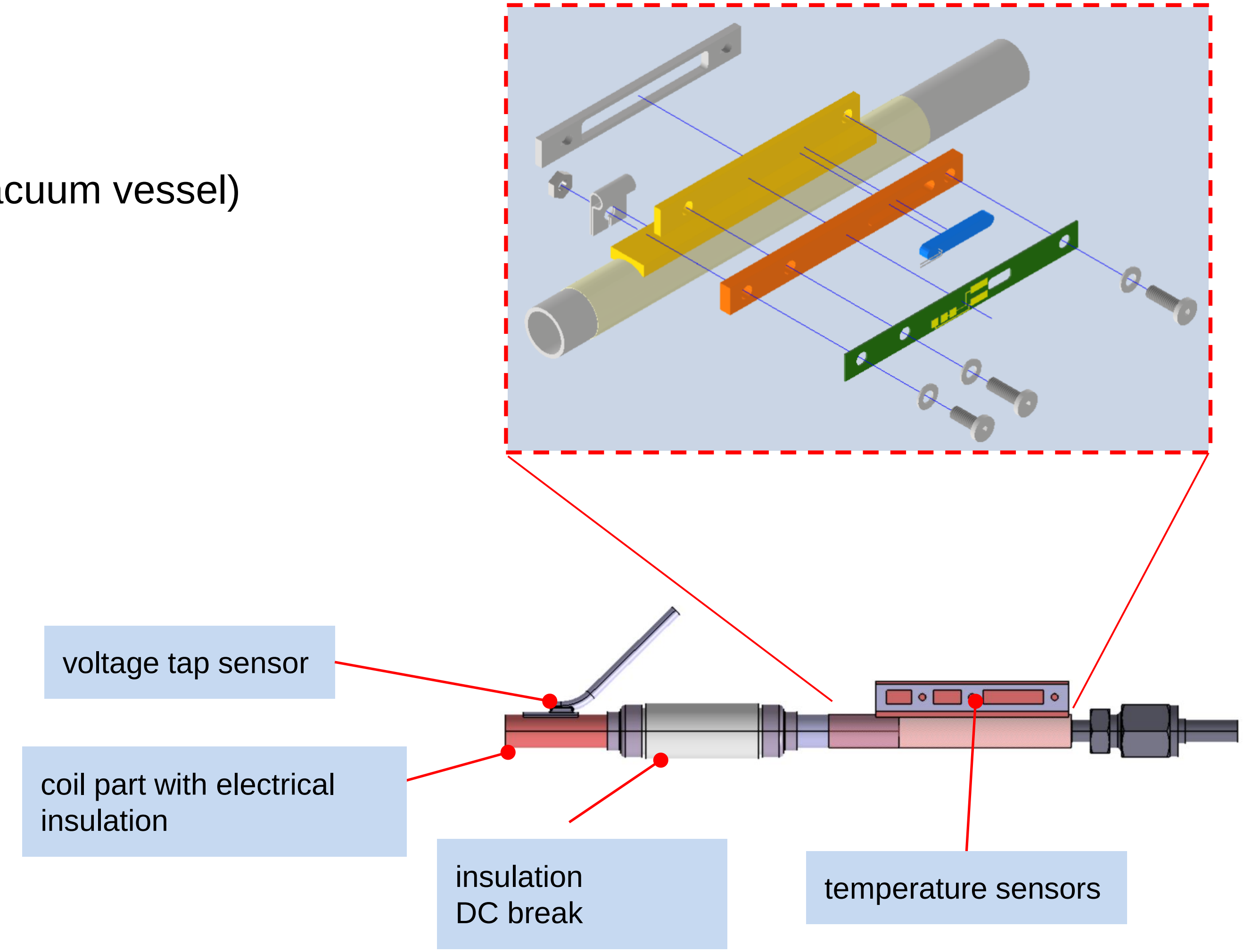
Machine monitoring

- Critical areas in main components and failure modes identified
- Planned machine instrumentation:
  - **Temperature**
    - ~ 400 resistance temperature sensors (coils,)
    - ~ 250 thermocouples (vacuum vessel, support structure)
    - Optical fibers + GaAs sensors (sliding joint monitoring)
  - **Strain**
    - ~ 350 linear and rosette strain sensors (support structure, vacuum vessel)
    - several Fiber Bragg gratins (monitoring of stresses in coils)
  - ~ 500 **voltage taps** (TF joints, coils)
  - **Displacement sensors** (vacuum vessel)



Patch panels

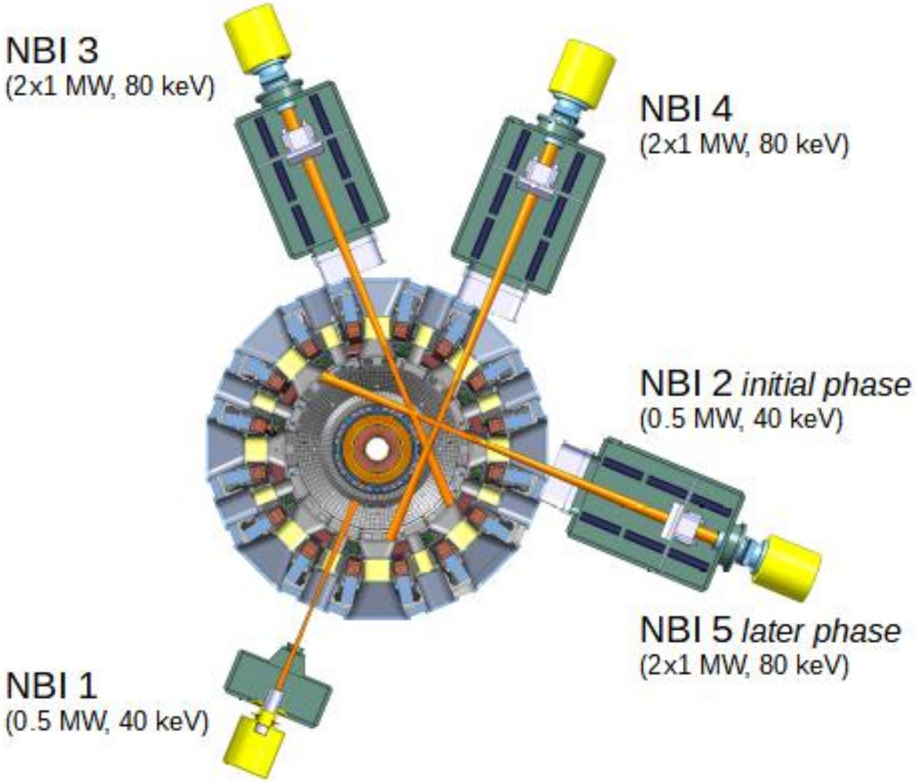




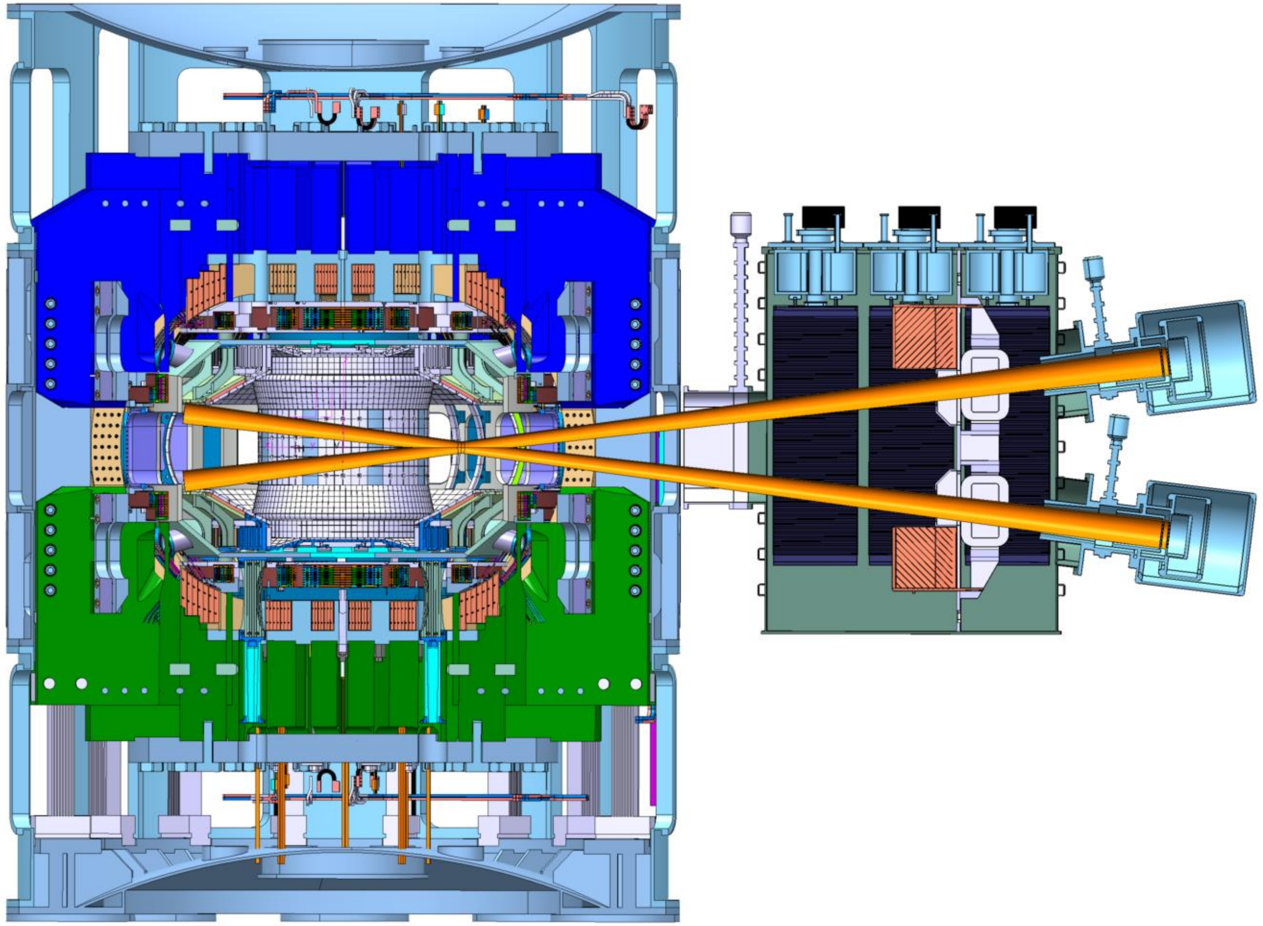
Plasma heating

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 1 MW unit was delivered by BINP Novosibirsk (will be tested on COMPASS)
- Aiming between magnetic axis and HFS wall - **tangency radius R<0.65 m**
- COMPASS 0.3 MW @ 40 keV NBI will be upgraded to 0.5 MW and used for diagnostic purposes
- NBI 4 (and NBI 5) on a stand **movable to counter-injection**



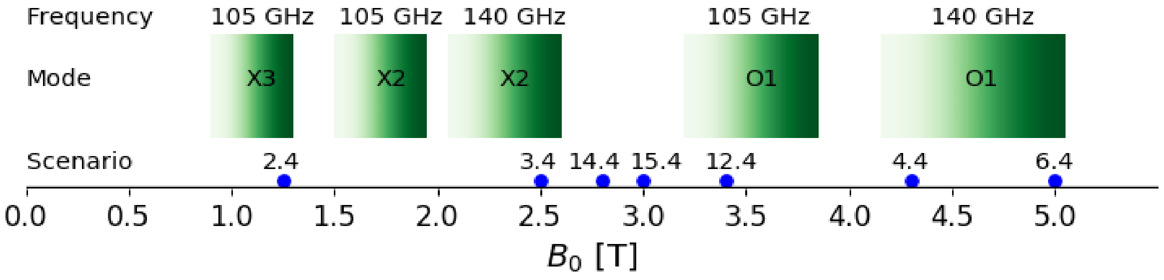
Top view of NBI distribution.



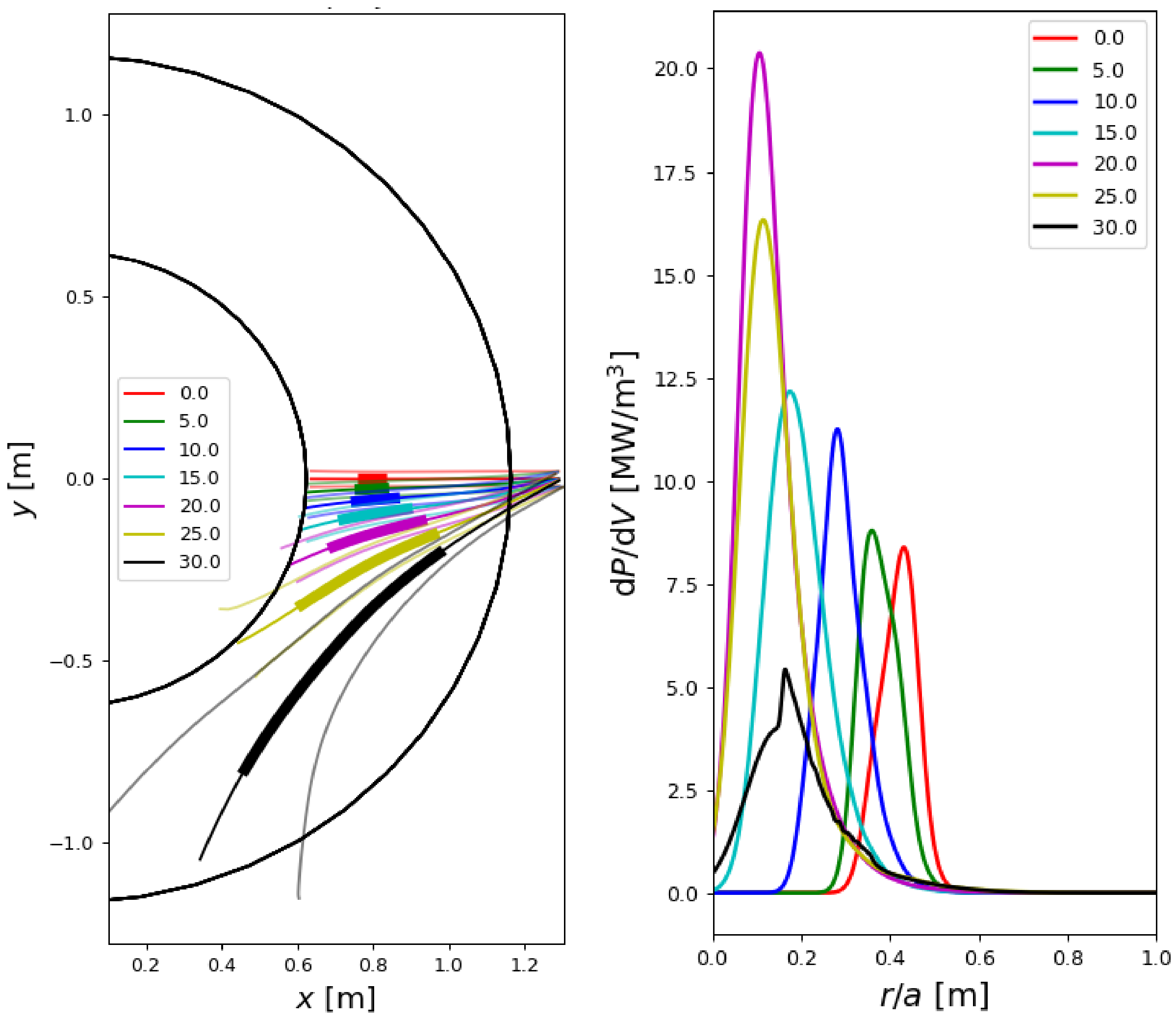
Plasma heating
ECRH

- 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
- Deposition on-axis is achieved for B_t 1-2.5 and 5 T
- Toroidal steering needed for B_t 3-4 T
- Density limit ~2.4×10^{20} m^{-3}

scenario	B [T]	n [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



- 170 GHz foreseen for later phase
  => density limit ~3.6×10^{20} m^{-3}



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

Plasma & physics diagnostics

- **Magnetic diagnostics**
  - **Basic set of magnetic diagnostics:** poloidal Flux Loops, Mineral Insulated Cable coils (equilibrium coils, Internal Partial Rogowski coils, coils for Bt, toroidal arrays at midplane), internal full Rogowski coils, diamagnetic loops, saddle loops, halo current sensors, PF coil poloidal flux loops, External Partial Rogowski coils, ex-vessel full Rogowski coils
  - **Extended set of magnetic diagnostics:** bare wire coils (poloidal and toroidal arrays of 2D coils), additional full Rogowski coils, *Thick Printed Cu coils**, Hall probes, *High frequency antenna for Ion Cyclotron Emission**
- **Electric probe diagnostics**
  - divertor probes, probes embedded in limiters, probe manipulators (horizontal, X-point, divertor)
- **Microwave diagnostics**
  - **interferometer**, reflectometer, *Electron Cyclotron Emission**, *extended set of reflectometers**, *multichord interferometer/polarimeter**
- **Optical diagnostics**
  - **impurity/working gas monitor (VIS/NIR/NUV spectroscopy)**, **Hard X-Ray flux monitors, overview & interlock cameras (VIS/NIR),** *extended set of Hard X-Ray flux monitors**, *Hard X-Ray (gamma) spectrometer**, core & edge Thomson Scattering, *divertor Thomson Scattering**, Zeff diagnostics, metallic bolometers, AXUV diodes ("fast bolometers"), Soft X-Ray detectors, high-speed cameras for VIS, IR cameras (for thermography), *divertor spectroscopy**, *Fast Ion D-Alpha detector**, *UV & USX spectrometers**

First plasma diagnostics *Proposed future diagnostics

Plasma & physics diagnostics

- **Particle diagnostics**
  - **neutron flux monitors**, *extended set of neutron flux monitors**, Neutral Particle Analyzer, *Fast Ion Loss Detector**, in-*vessel RE crystal detector**
- **Beam-based diagnostics**
  - Charge eXchange Recombination Spectroscopy, Beam Emission Spectroscopy (on Alkali beam), *Motional Stark Effect**, *He beam diagnostics**
- **Vacuum diagnostics**
  - *quadrupole Residual Gas Analyzer**, *fast pressure gauges (AUG type)**, *Penning gauges for partial pressures**
- **Diagnostics of Plasma Facing Components**
  - *Fiber Bragg Gratings*, surface thermocouples*, thermocouples**

First plasma diagnostics *Proposed future diagnostics

Diagnostic ports assignment

Neutron diags
HXR (gamma) spectrometers
UV&USX spectrometers
ECE
MGI
LFS probe cabling
<Zeff>

TF leads
PSP bridge
LFS probes

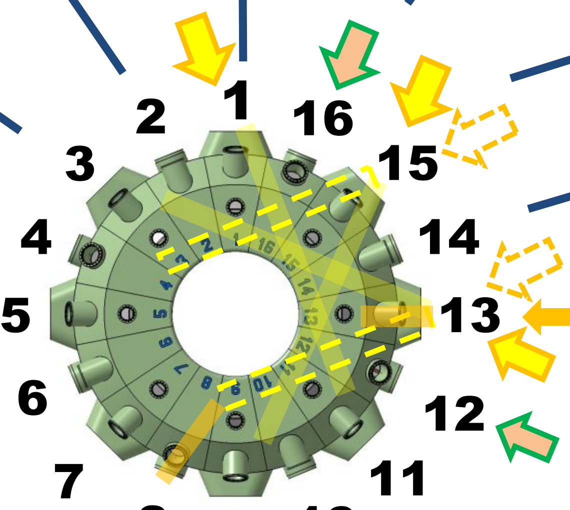
Gas puff
NBI (2 MW)
Pumping
Machine monitoring

ECRH (2+ MW)
Sniffer probe
VV cooling/heating
Shutdown venting

NBI (2 MW)
Pumping
Sniffer probes
MIC mag. diags cabling

Interferometer
MIC and GFIC mag. diags cabling

Divertor cryopump
HFS pellet injector
VIS/NIR camera
MIC mag. cabling



TS laser & dump
Core & Edge TS detection

Access to VV

NBI (0.5 or 2 MW)
Or alkali beam + BES
Div. probes and cabling

IR camera for DIVMAT
MIC mag. diags cabling
Divertor cryopump
Divertor spectroscopy

ECRH (4 MW)
GFIC and MIC mag. diags cabling
Shutdown venting

Access to VV

VIS/NIR cameras
IR camera
HFS probes & cabling
NPA
XRCP (with FILD)

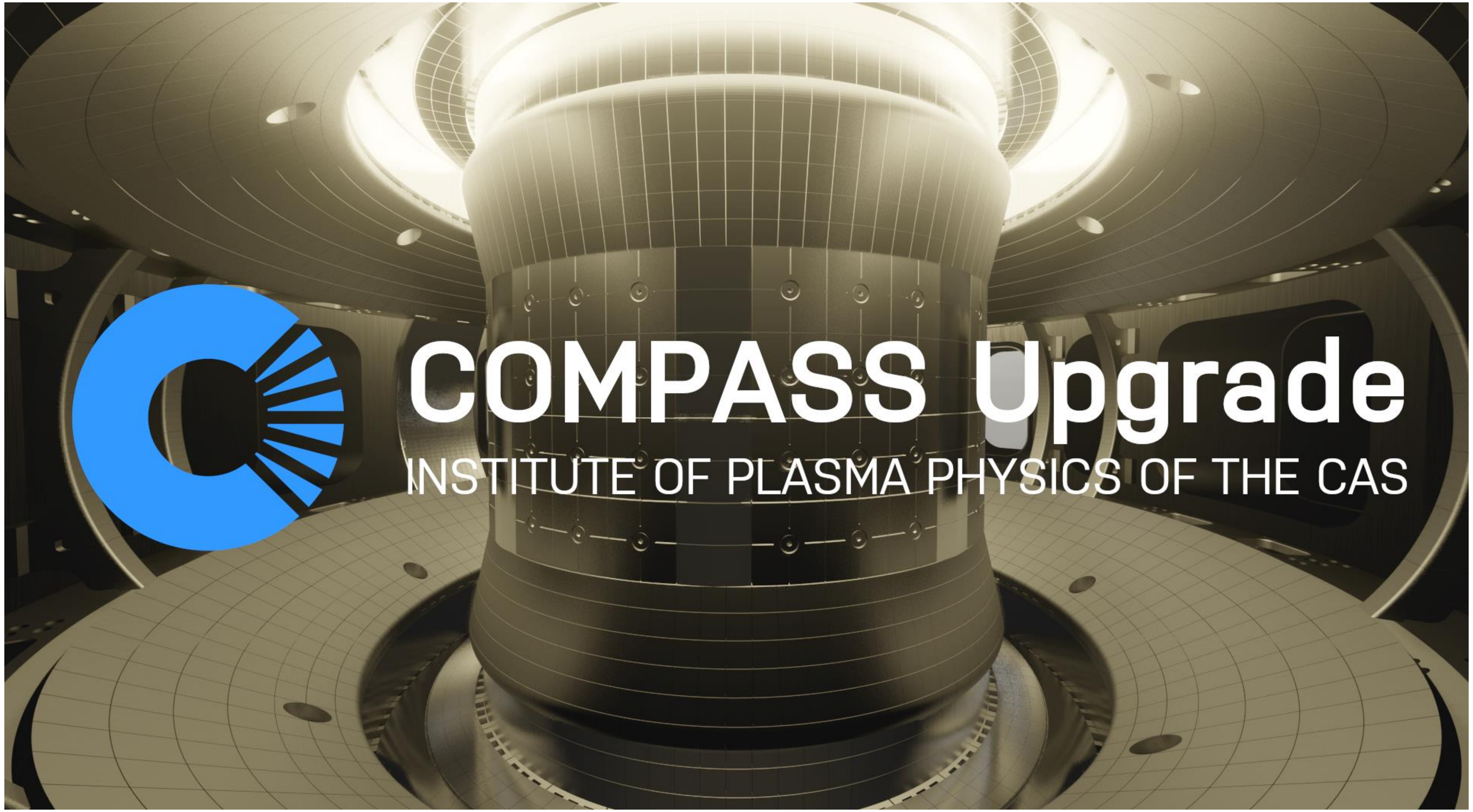
Diagnostic NBI
Reflectometer
MIC mag. diags cabling

CXRS
IR camera
Sniffer probe
Gas puff

Zeff – multi
VIS spectroscopy
HRCP (+FILD)
Divertor manipulator
GFIC mag. diags cabling

Met. bolom., AXUV
and SXR
VIS/NIR camera

Summary



Virtual tour around COMPASS Upgrade:

https://youtu.be/oGfg0A5EsSE