IPP INSTITUTE OF PLASMA PHYSICS OF THE CZECH ACADEMY OF SCIENCES

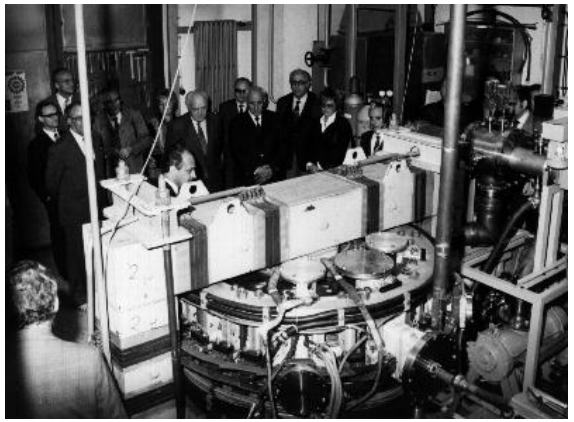
# COMPASS Upgrade overview

*12/2025*

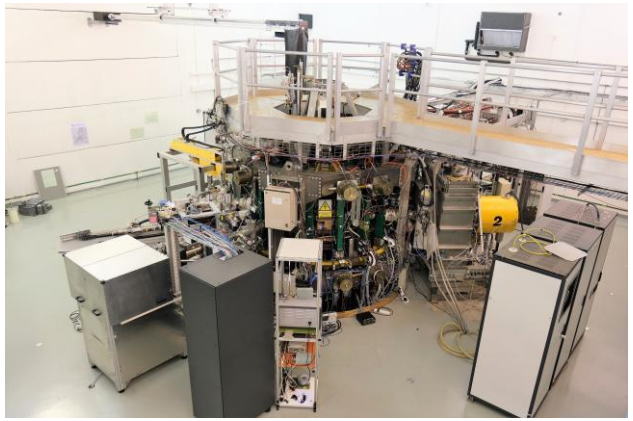
# INSTITUTE OF PLASMA PHYSICS OF THE CZECH ACADEMY OF SCIENCES

U Slovanky 2525/1a, 182 00 Prague 8

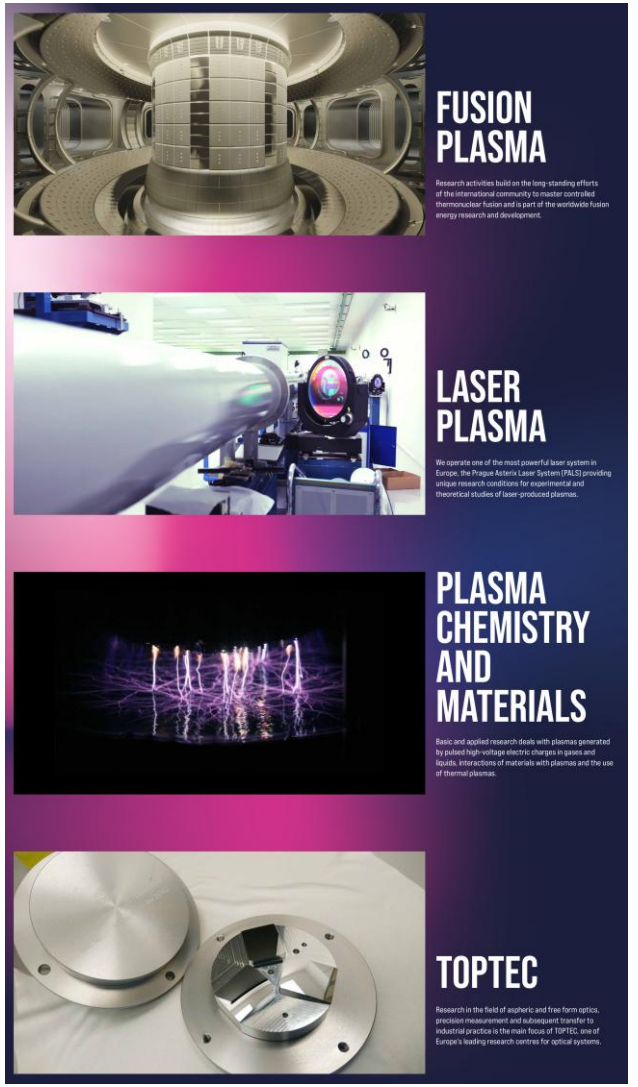
**tokamak CASTOR**
1977-2006



**tokamak COMPASS**
2008-2021

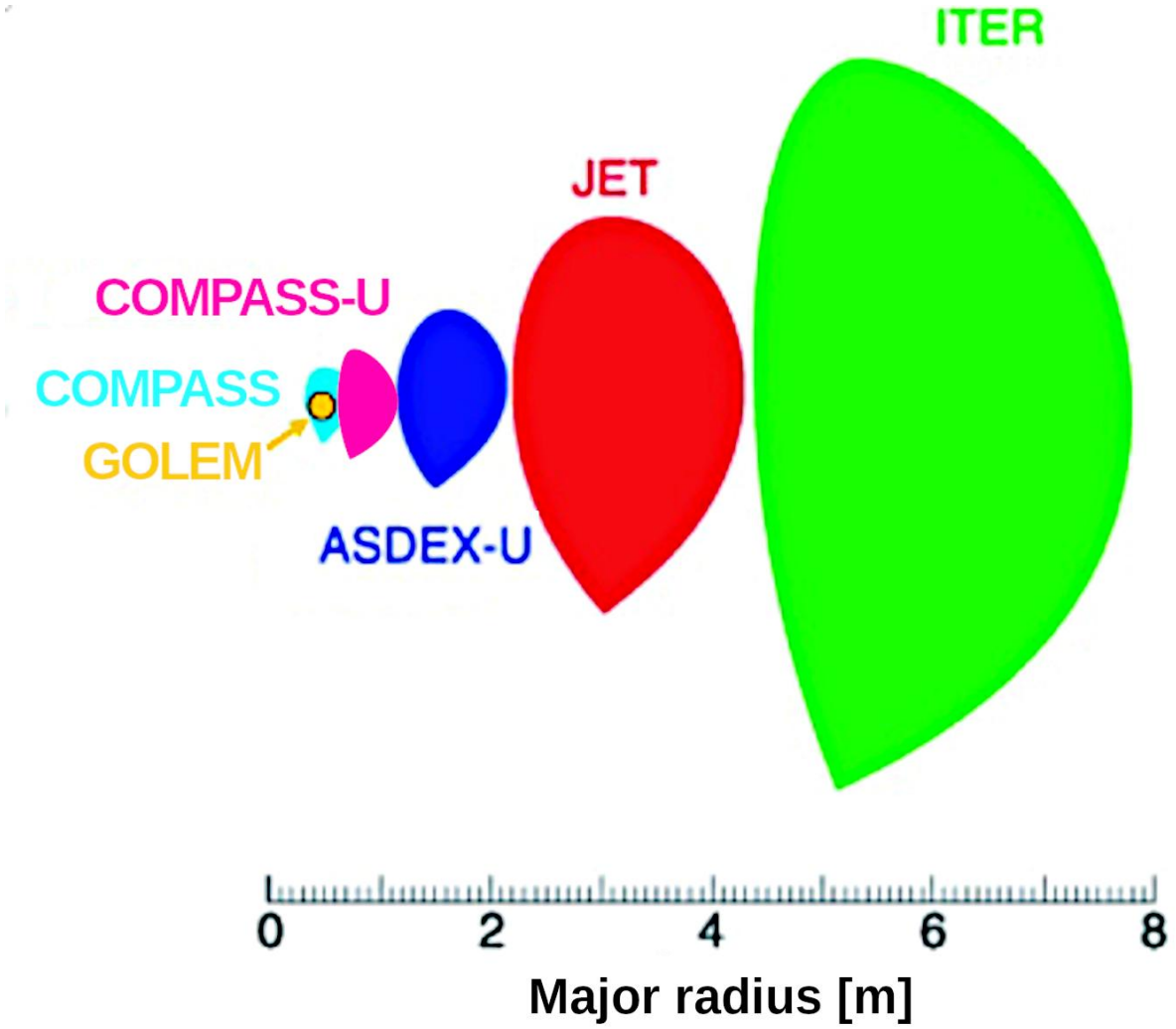


**tokamak COMPASS-U**
under construction



# COMPASS and COMPASS-U tokamaks

| | | COMPASS | COMPASS-U |
|---|---|---|---|
| **Toroidal magnetic field** | **T** | 1.5 (2.1) | 5 |
| **Plasma current** | **MA** | 0.4 | 2 |
| **Major radius** | **m** | 0.56 | 0.9 |
| **Minor radius** | **m** | 0.2 | 0.27 |
| **Triangularity** | | 0.4 | 0.6 |
| **Elongation** | | 1.8 | 1.8 |
| **Pulse length** | **s** | 0.4 | 2-10 |
| **First wall material** | | C | W |
| **Plasma shapes** | | fixed* | variable |
| **NBI heating power** | **MW** | 0.6 | 3-6 |
| **ECRH heating power** | **MW** | 0 | 1-8 |



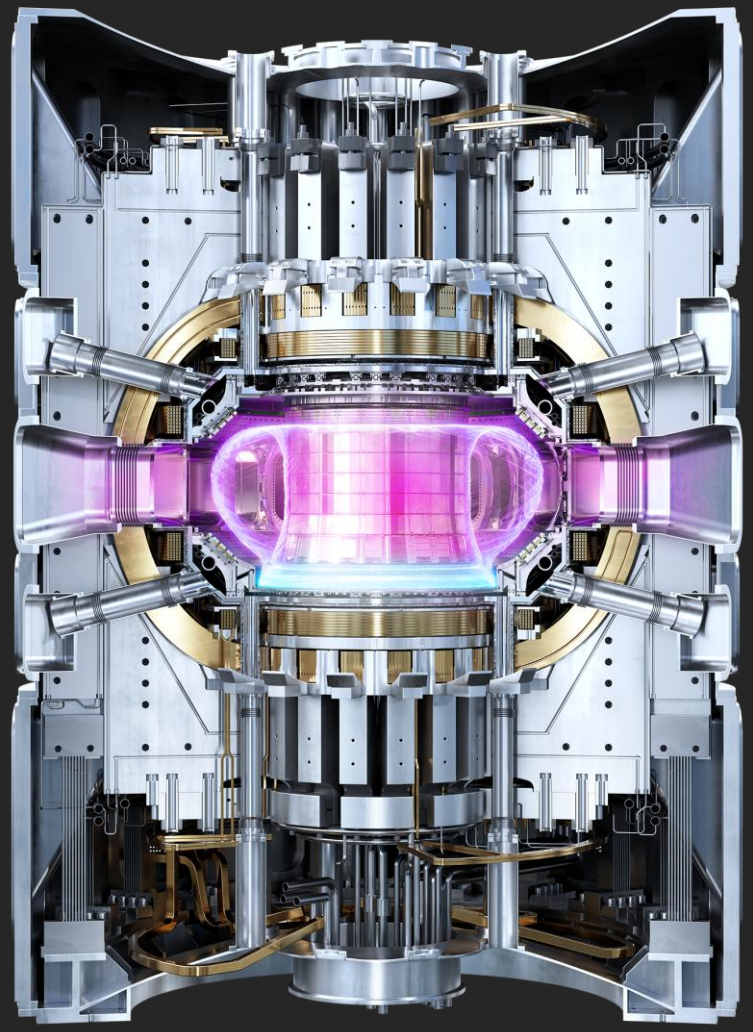
# COMPASS Upgrade

***Compact flexible device with set of unique parameters to support exploitation of ITER and development of DEMO***

**Focus on two of the EUROfusion Roadmap missions:**

- **Plasma regimes of operation**
- **Heat-exhaust systems**

- **High magnetic field (5 T)**, access to advanced confinement modes
- **High power fluxes (~ GW/m2)**, high plasma and neutral density in closed divertor
- **Hot first wall (500 °C)**, liquid metal technologies



# COMPASS-U parameters

## Main parameters

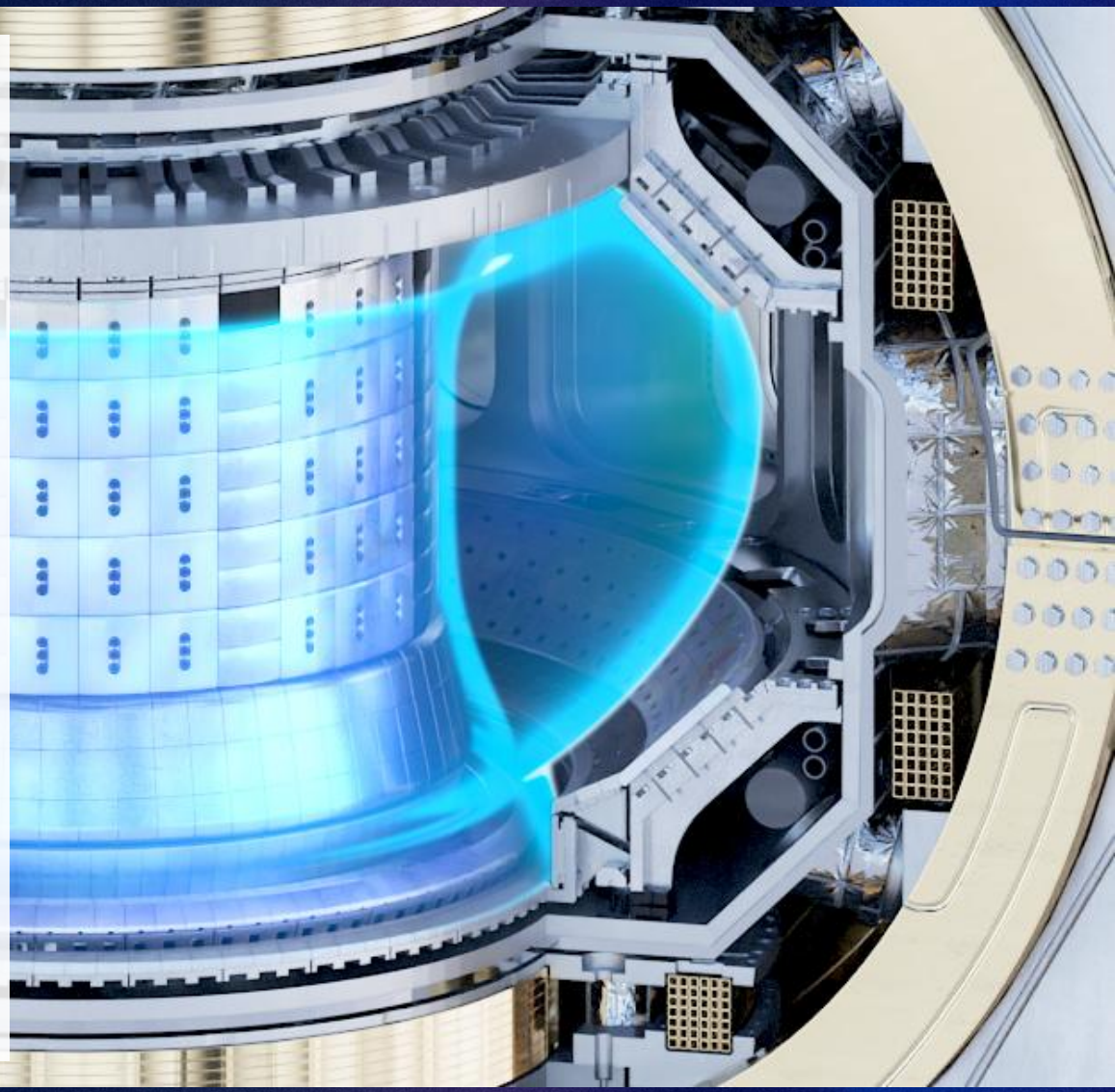
- **Toroidal magnetic field** $B_t$ **= 5 T**
- **Plasma current** $I_p$ **= 2 MA**
- **Major radius** $R_g$ **= 0.9 m**
- Minor radius $a$ = 0.27 m
- Aspect ratio $A$ = 3.3
- Triangularity $\delta$ = 0.3-0.6
- Elongation $\kappa$ = 1.8
- Enough space for different divertors
- Metallic first wall
- **Vacuum vessel operation temperature up to 500°C**

## Plasma shapes

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

## Plasma heating power

- Initial phase $P_{NBI}$ = 3 MW, $P_{ECRH}$ = 1 MW (P*B/R ~ 25)
- Later phase up to $P_{NBI}$ = 6 MW, $P_{ECRH}$ = 6 MW (P*B/R ~ 80)

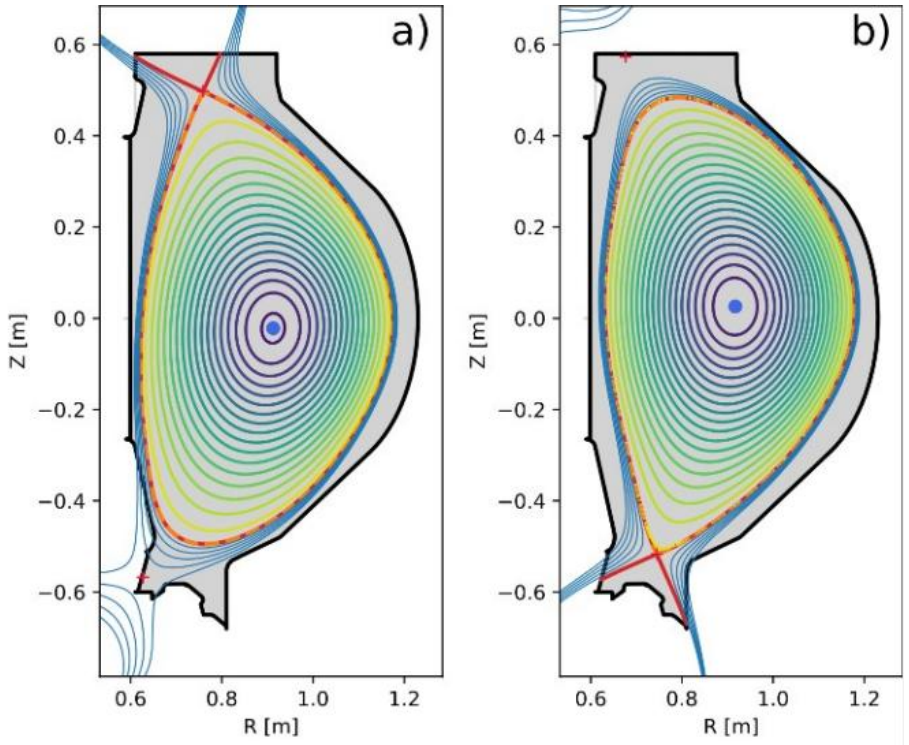


# Plasma scenarios - parameters

| Name | Scenario | $B_T$ [T] | $I_P$ [MA] | $P_{in}$ [MW] | $\overline{n_e}$ [$10^{19}$ m$^{-3}$] | $q_{95}$ | $\beta_n$ | $T_{e,ped}$ [eV] |
|---|---|---|---|---|---|---|---|---|
| Early L-mode | #3100 | 2.5 | 0.8 | 0+0 | 9.0 | 3.2 | 0.67 | – |
| Early H-mode | #3210 | 2.5 | 0.8 | 2+0 | 12 | 3.6 | 1.52 | 840 |
| ITER-like H-mode | #24300 | 4.3 | 1.3 | 3+1 | 19 | 3.8 | 1.19 | 820 |
| High perf. H-mode | #5400 | 5.0 | 1.6 | 4+2 | 20 | 3.4 | 1.15 | 1360 |

**Single null**

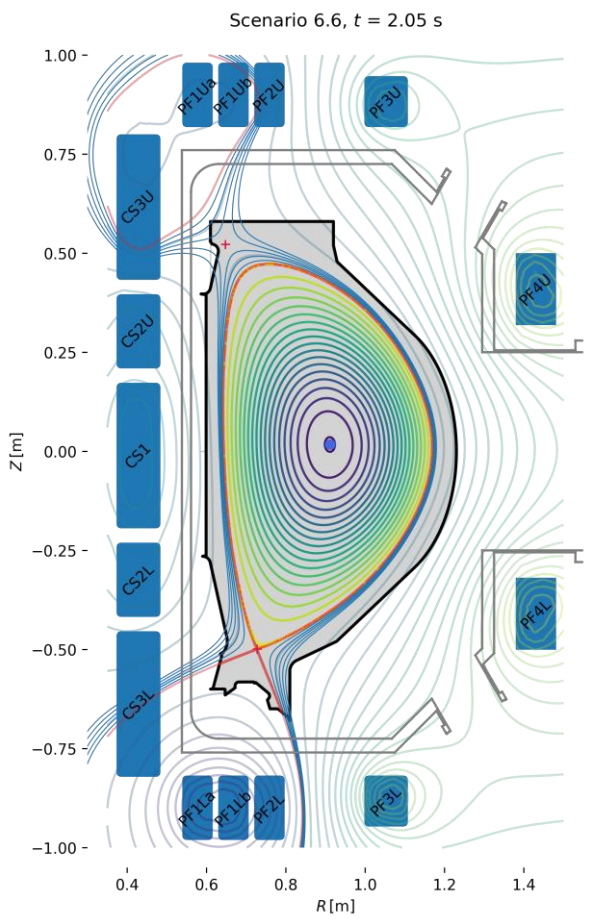
κ = 1.8, δ = 0.5



# Plasma scenarios - shapes

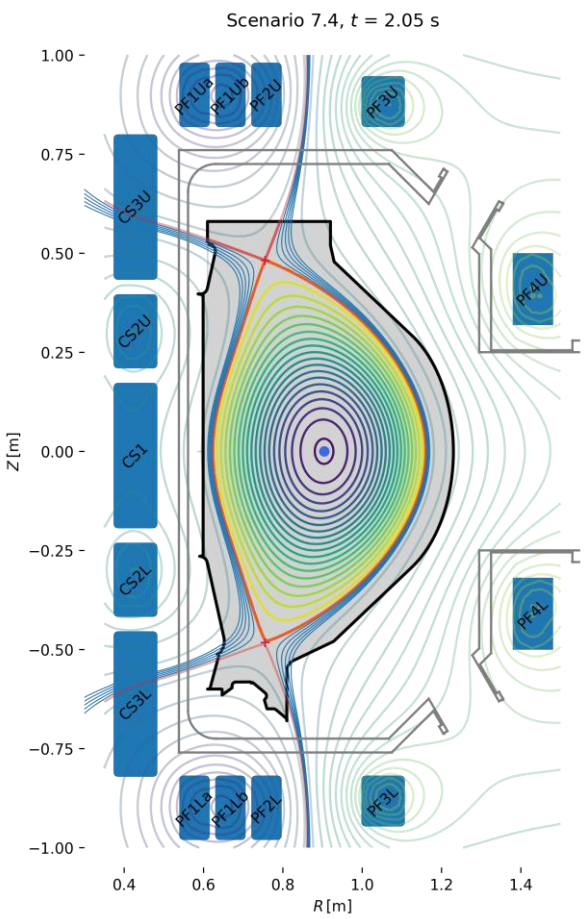
## Lower single null

κ = 1.8, δ = 0.6



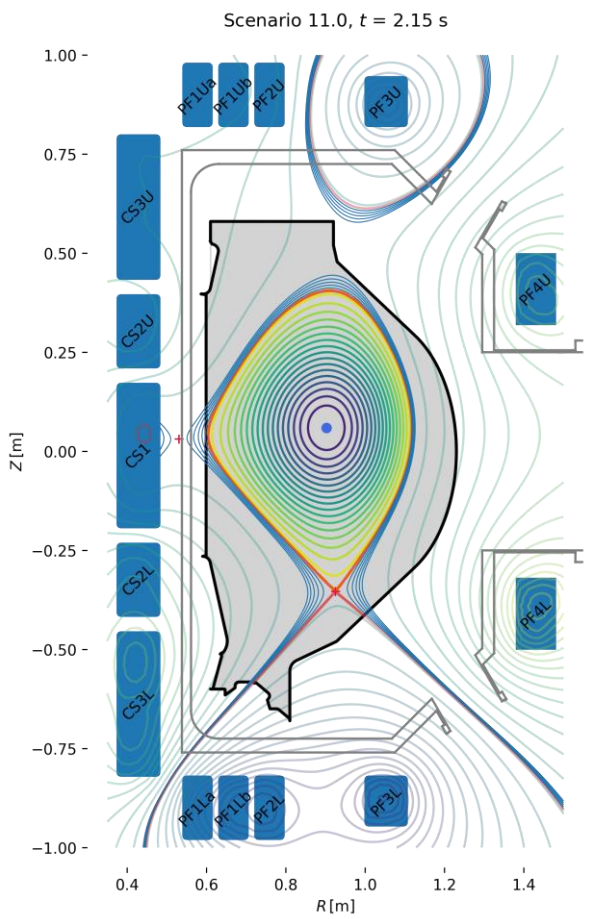

## Double null

κ = 1.8, δ = 0.5



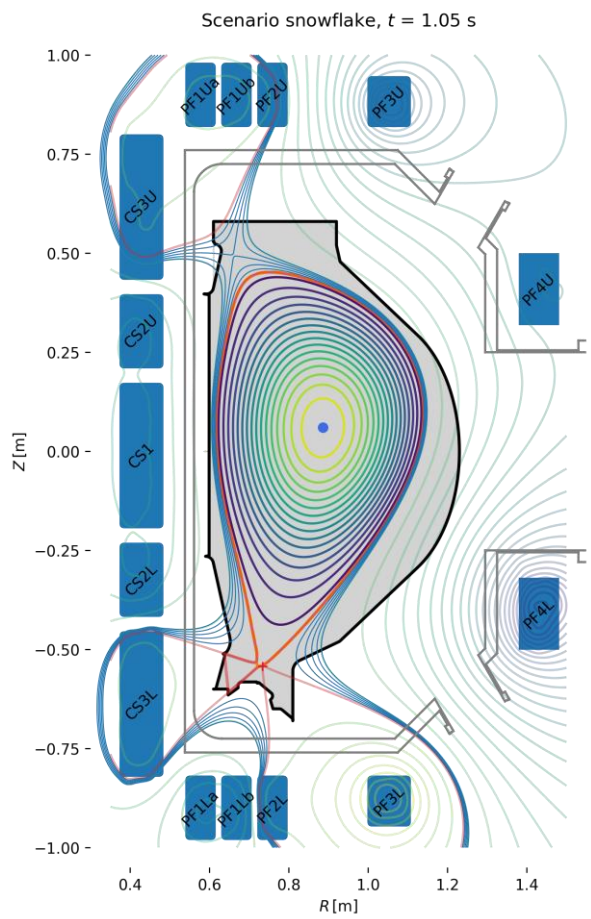

## Negative triangularity

κ = 1.4, δ = -0.2, $I$ = 1 MA




## Snowflake

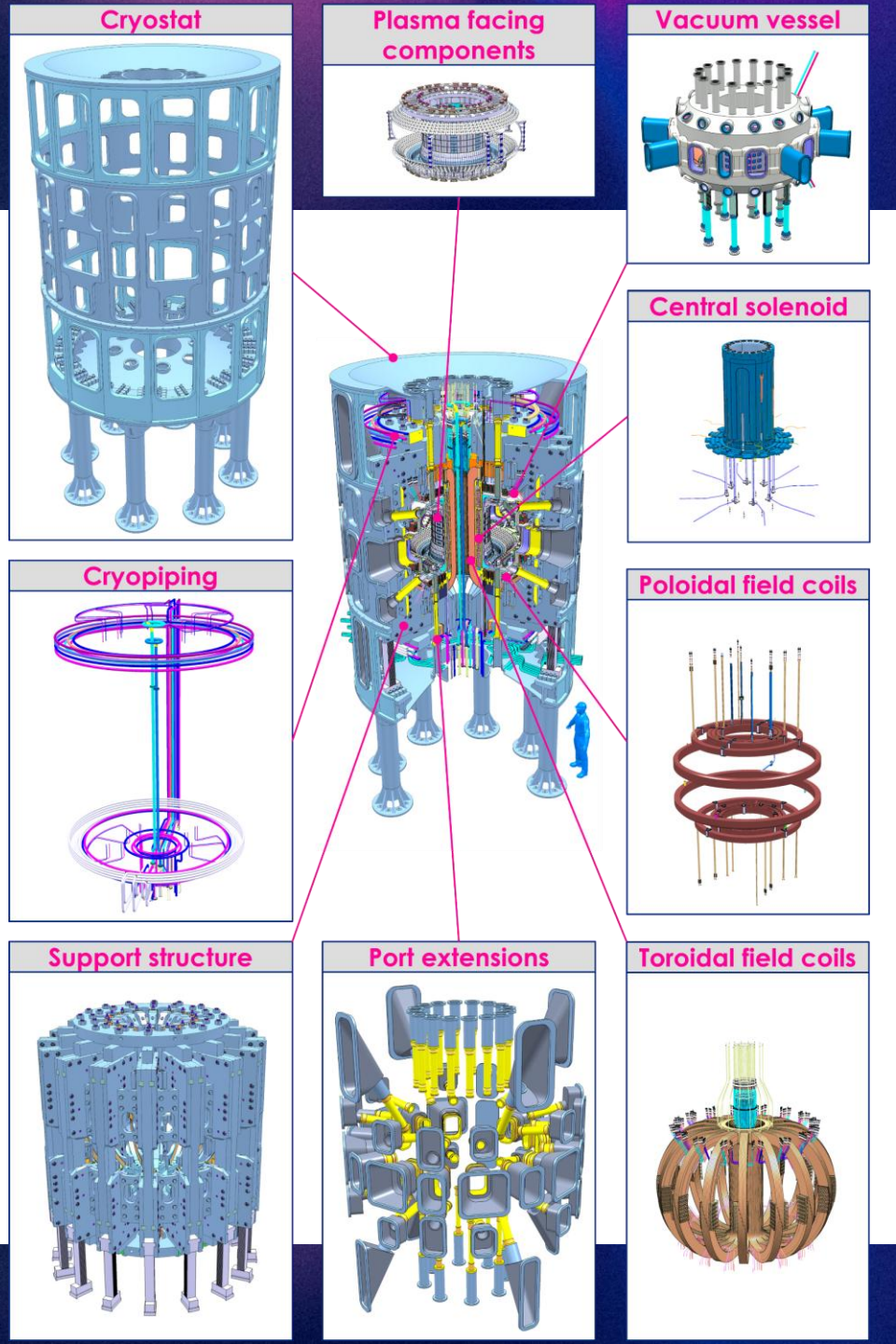
$I$ = 1.5 MA



# Main tokamak systems

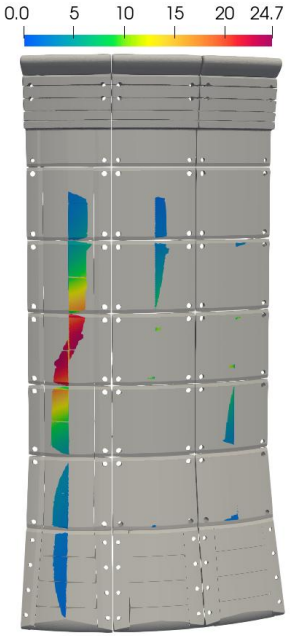
- **Plasma facing components:** Inconel, W-coated Inconel, W
- **Vacuum vessel:** up to 35 mm thick Inconel 625 (500°C)
- **Coils:** CuAg0.1 (OF) and CuCr1Zr cooled to 80K
- Central solenoid (5 segments) and PF coils (4+4) inside the TF
- Dismountable TF coils (sliding and bolted joints)
- **Support structure:** stainless steel AISI 316LN (DIN 1.4429)
- **Cryostat:** stainless steel AISI 304L
- **Cryogenic system:** LN2 heat exchanger, gaseous He, 80 K
- Vacuum vessel human access via large midplane ports

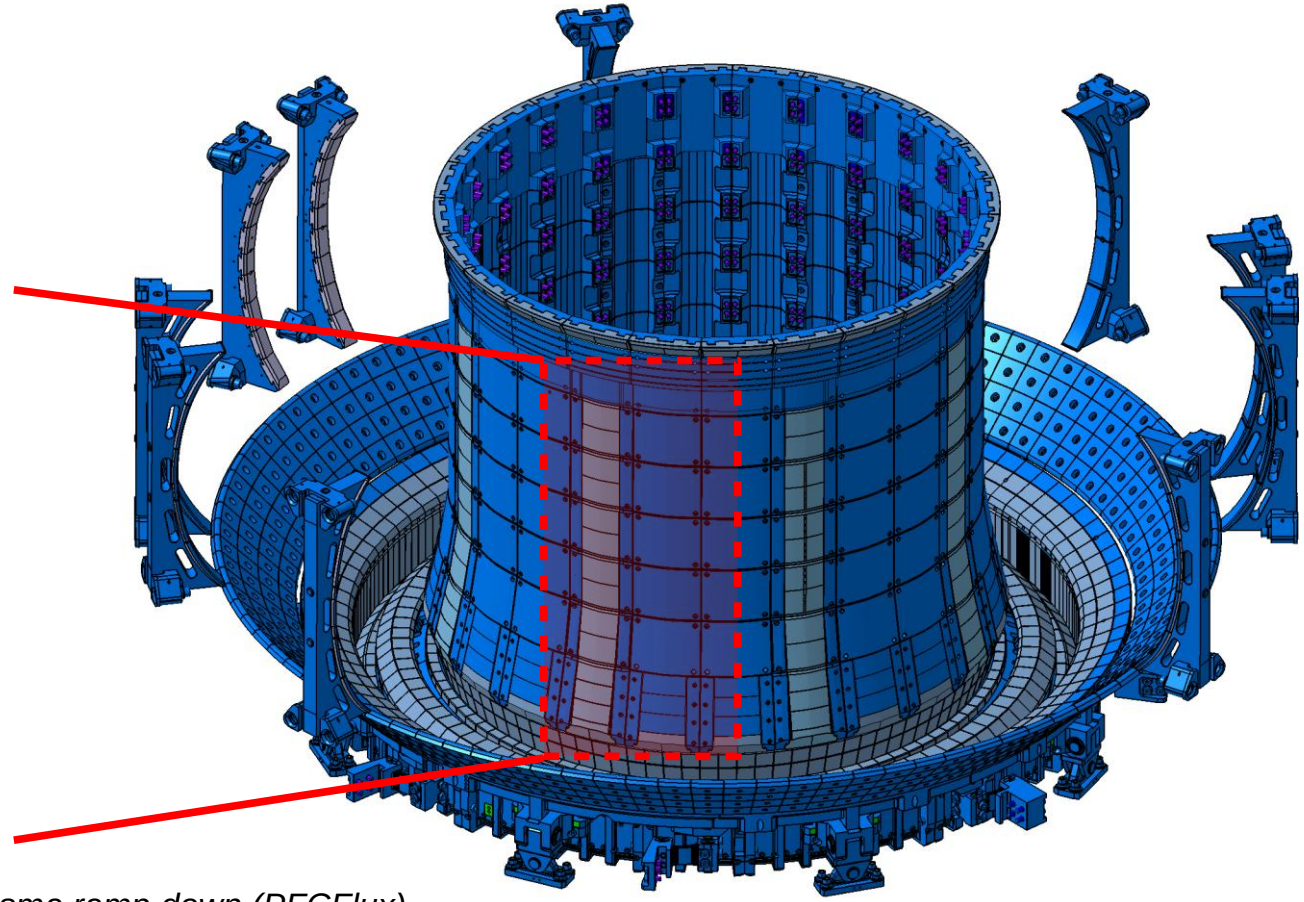
**Overall dimensions ~6.6x4.8 m, weight ~300 t**



## Inner wall limiters

- Plasma tiles for plasma start-up and termination (~0.4 s)
- **Tungsten** tiles forming **8 guard limiters**
- **Tungsten-coated Inconel$^{718}$** with frontside attachment

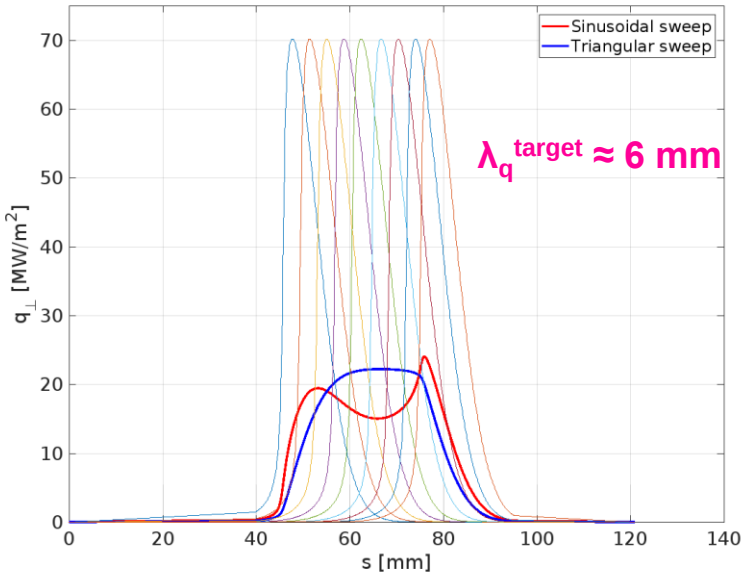


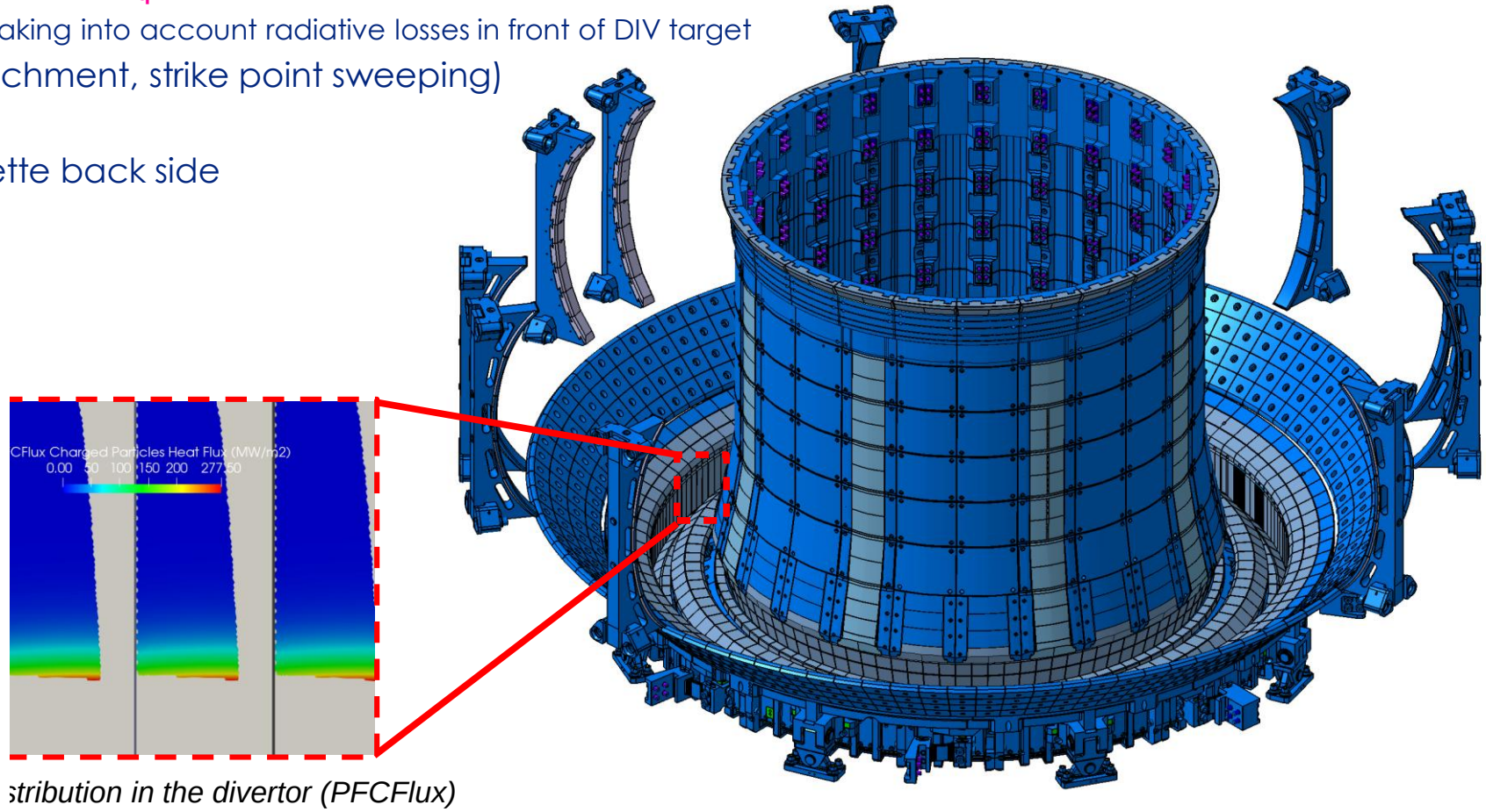



*Heat flux distribution during plasma ramp-down (PFCFlux)*

## Lower divertor

- Large $B_p$ => extremely peaked heat fluxes, $\lambda_q^{OMP} \leq 1$ mm
- Heat loads to divertor ~70 MW/m$^2$ (taking into account radiative losses in front of DIV target
  => heat dissipation required (detachment, strike point sweeping)
  => designed for **20 MW/m$^2$, 2-3 s**
- **Tungsten** tiles bolted from the cassette back side
- Toroidal bevel of 0.6°

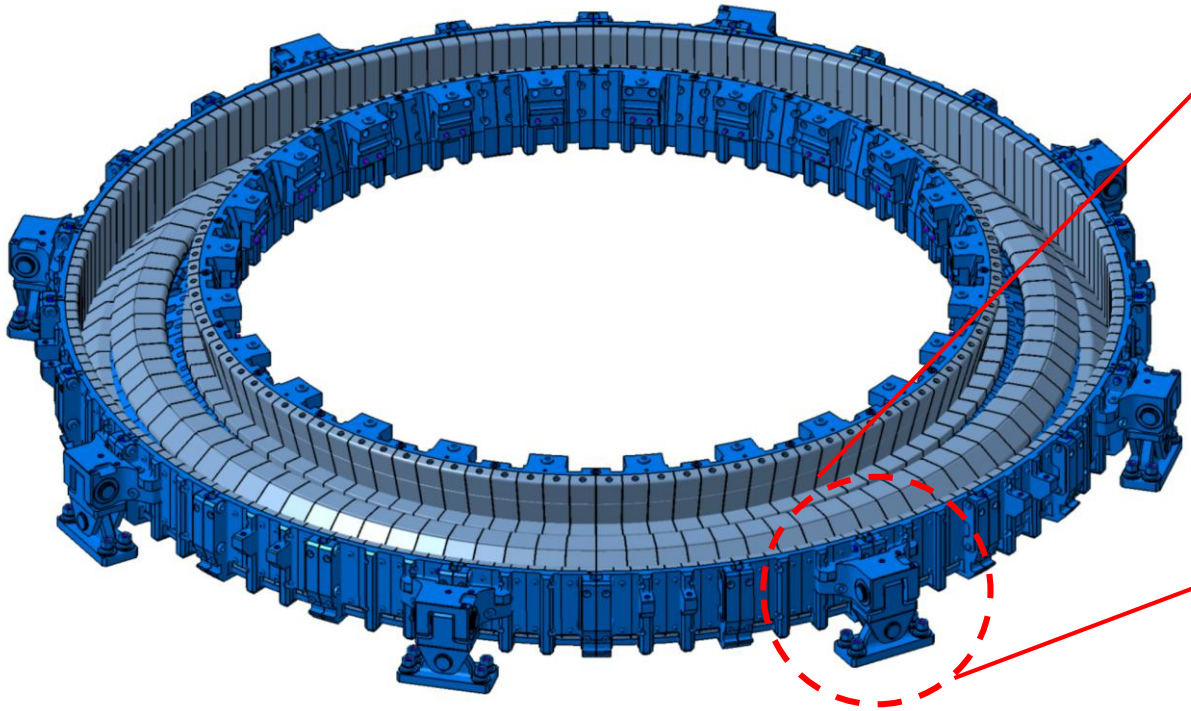


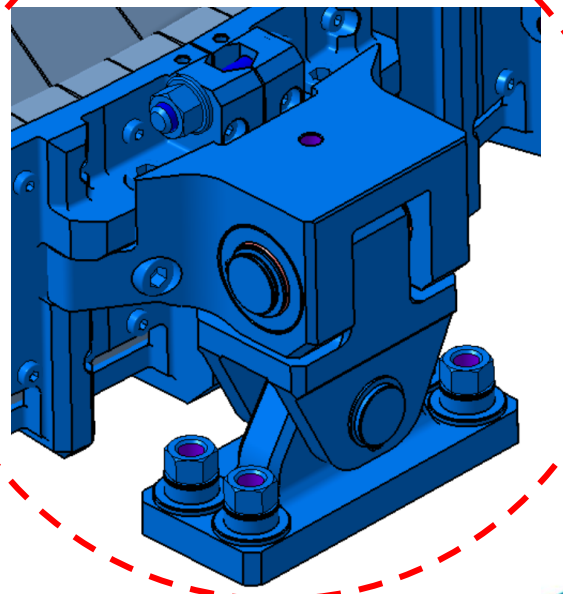




*stribution in the divertor (PFCFlux)*

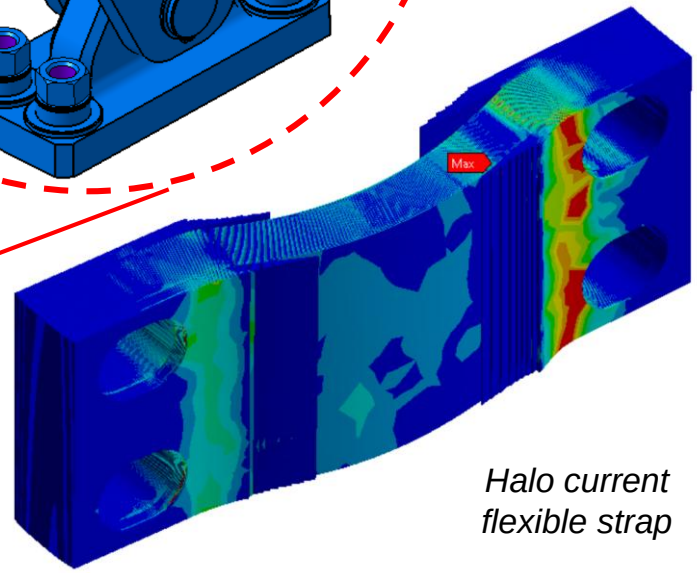
## Lower divertor

- Closed lower **cassette divertor** concept
- **24 cassettes**: Inconel 718 support, **bulk tungsten** tiles
- Supported by 8 **A-frames** with WS2 coated **spherical bearings** to allow thermal expansion





*A-frame with spherical bearings*




*Halo current flexible strap*

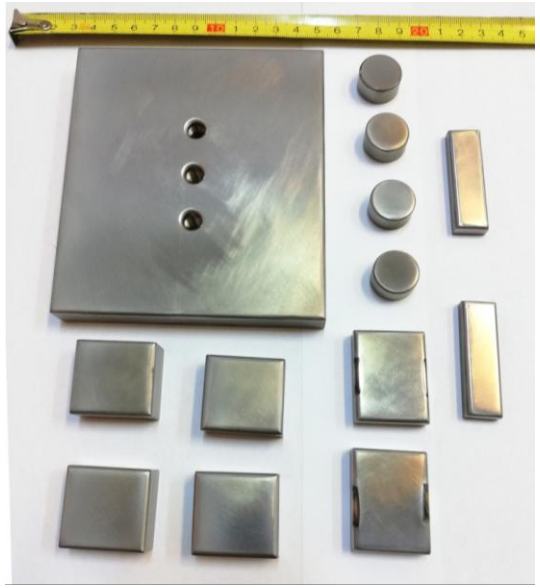
# Plasma Facing Components
## Material testing

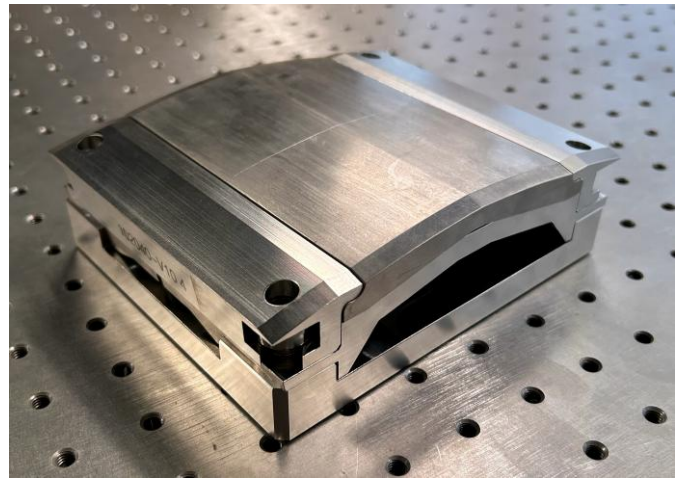
### W coating

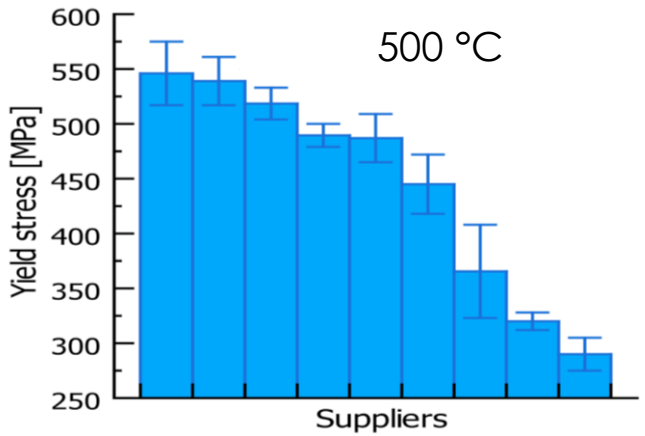
- **W coatings on Inconel$^{718}$ have been developed within an in-house R&D program** with 3 partners
- **7 – 20 µm** coatings based on **PVD magnetron sputtering**
- **No defect** (blister/crack/delamination) and **good adhesion** before/after annealing
- Post-mortem analyses confirm coatings conform to initial requirements + good homogeneity
- **W coatings validated by HHF tests** in GLADIS (50x 10 MW/m2 & 100x 30 MW/m2 )

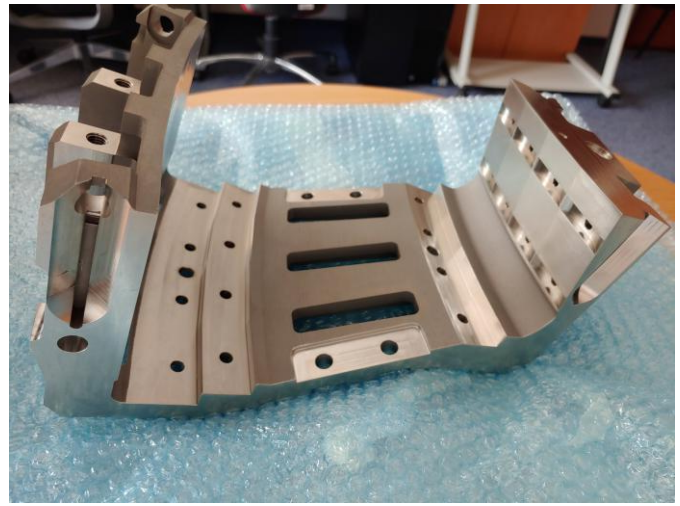
### W material testing

- **Testing of W from 9 suppliers** worldwide
- **Testing of real size COMPASS-U bulk W sample tiles**



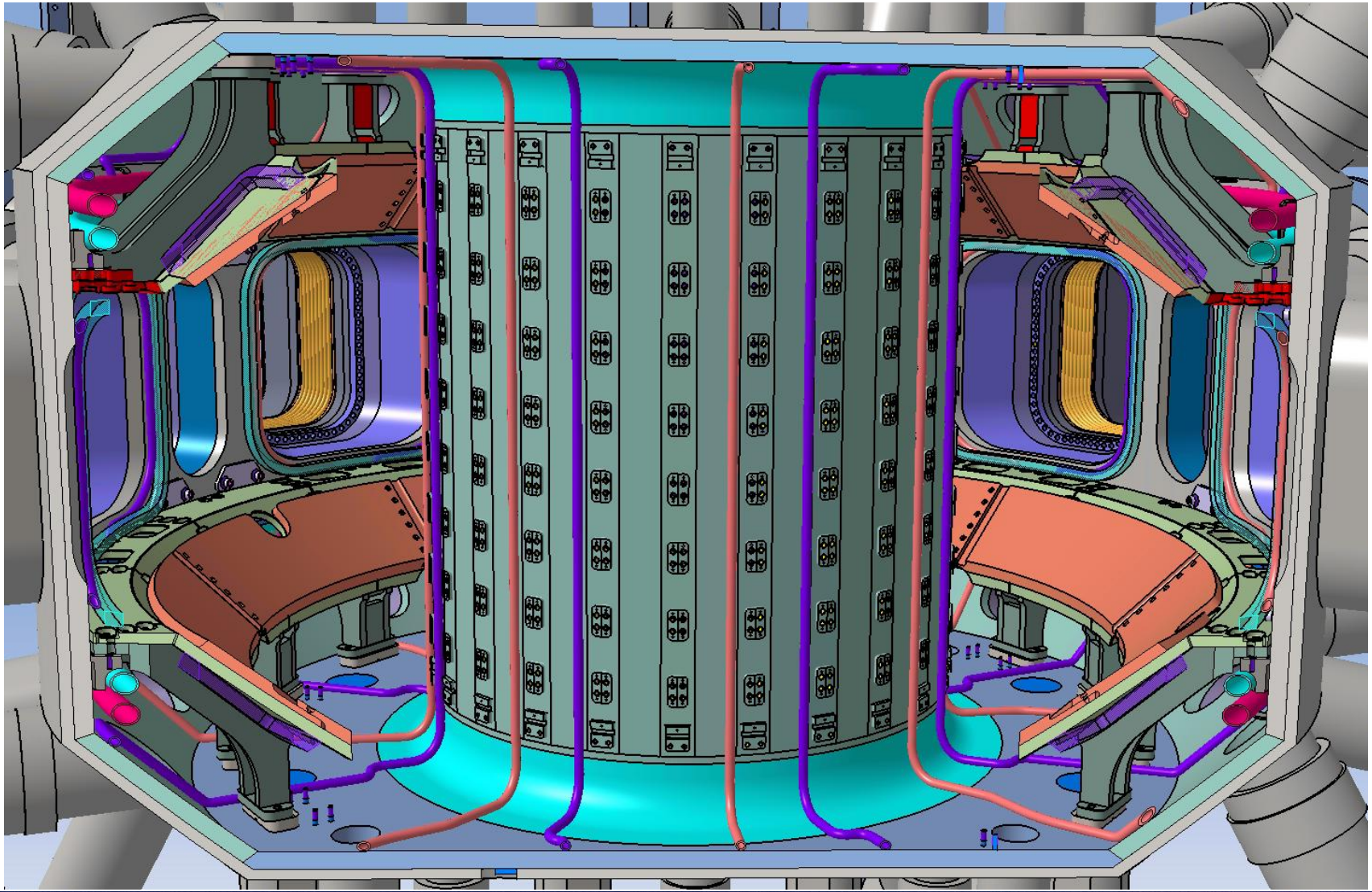




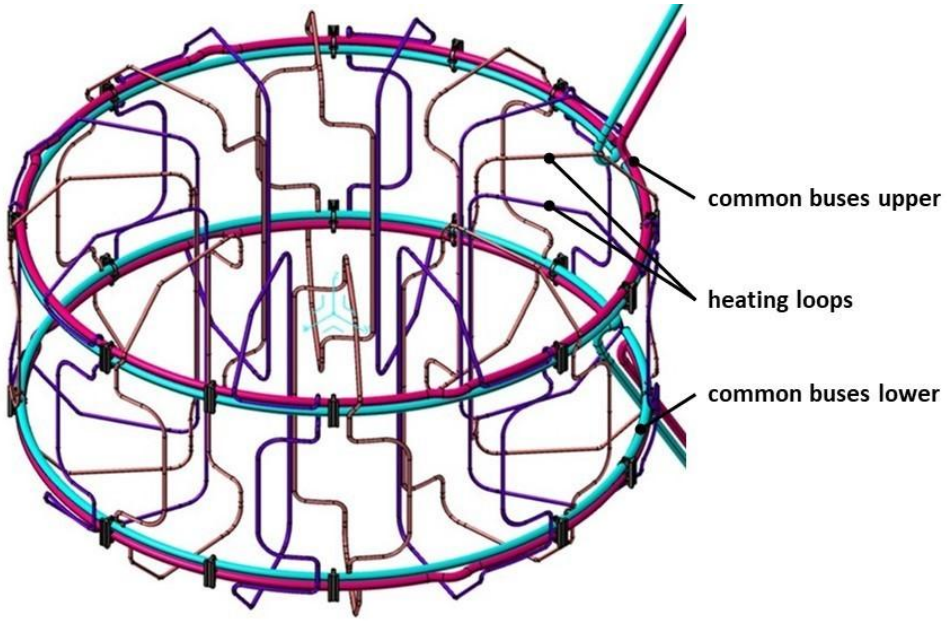
# Vacuum vessel

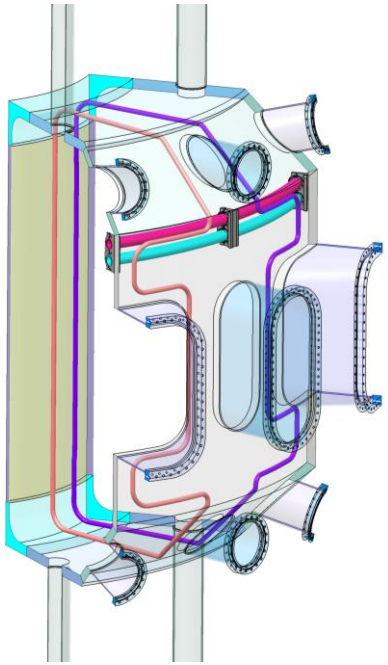
## PFC interfaces

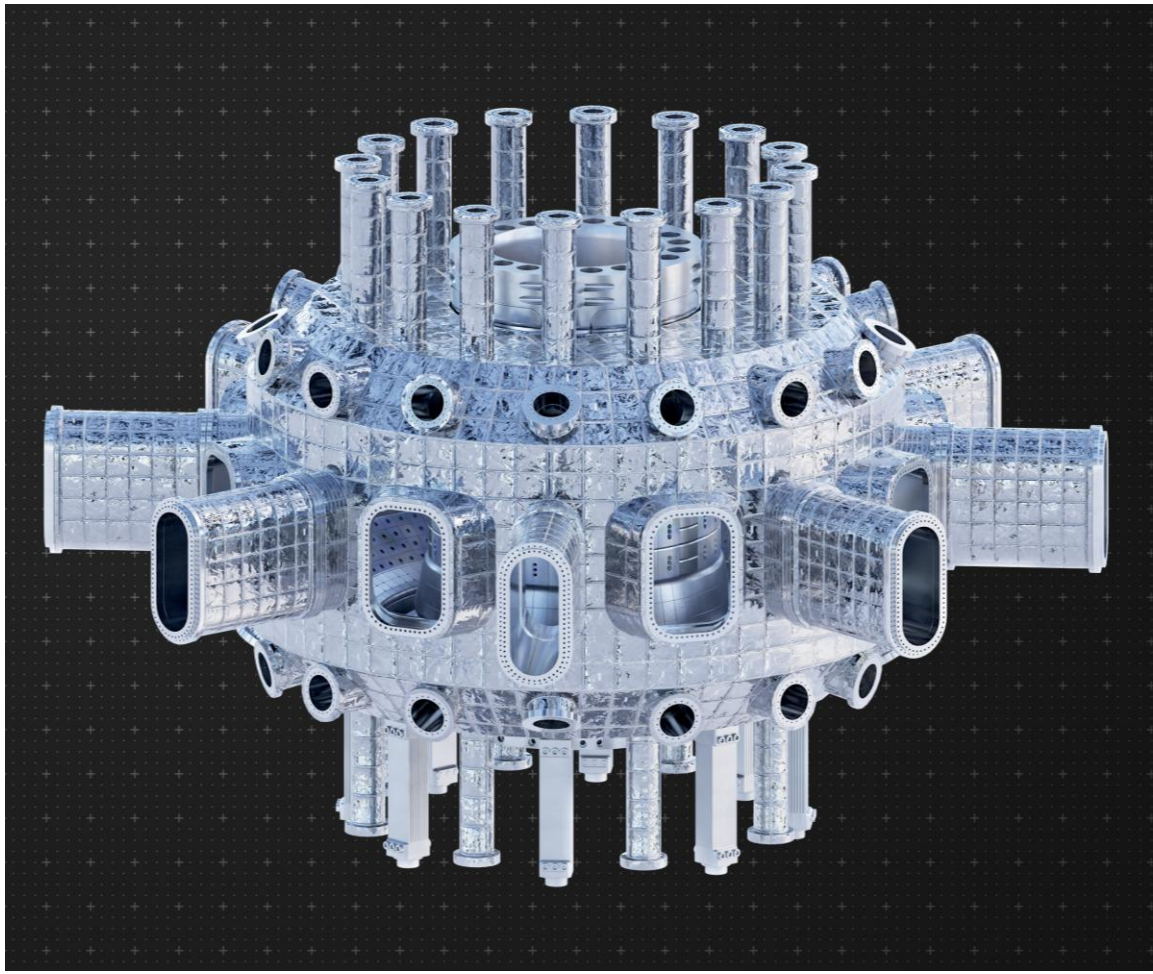


# Vacuum vessel

- **Material Inconel 625**, 23-35 mm thick walls
- Total **weight ~10 t, outer diameter ~3 m** (without ports)
- **Heating of VV up to 500 °C**, Inconel 625 pipes welded on inside of VV. Gaseous He or $CO_2$.
- **PFC heated mainly by radiation**
- 8 flexible Inconel 625 supports



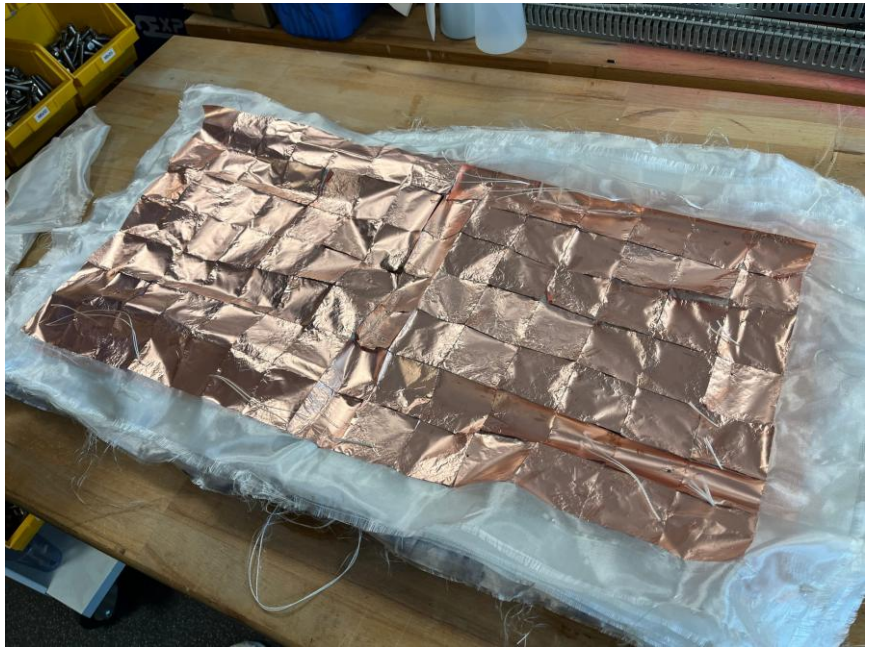


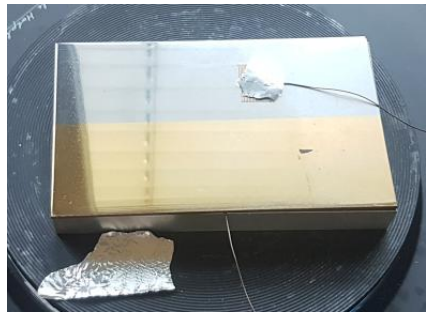
*Von Mises stress in the vacuum vessel and PSP.*

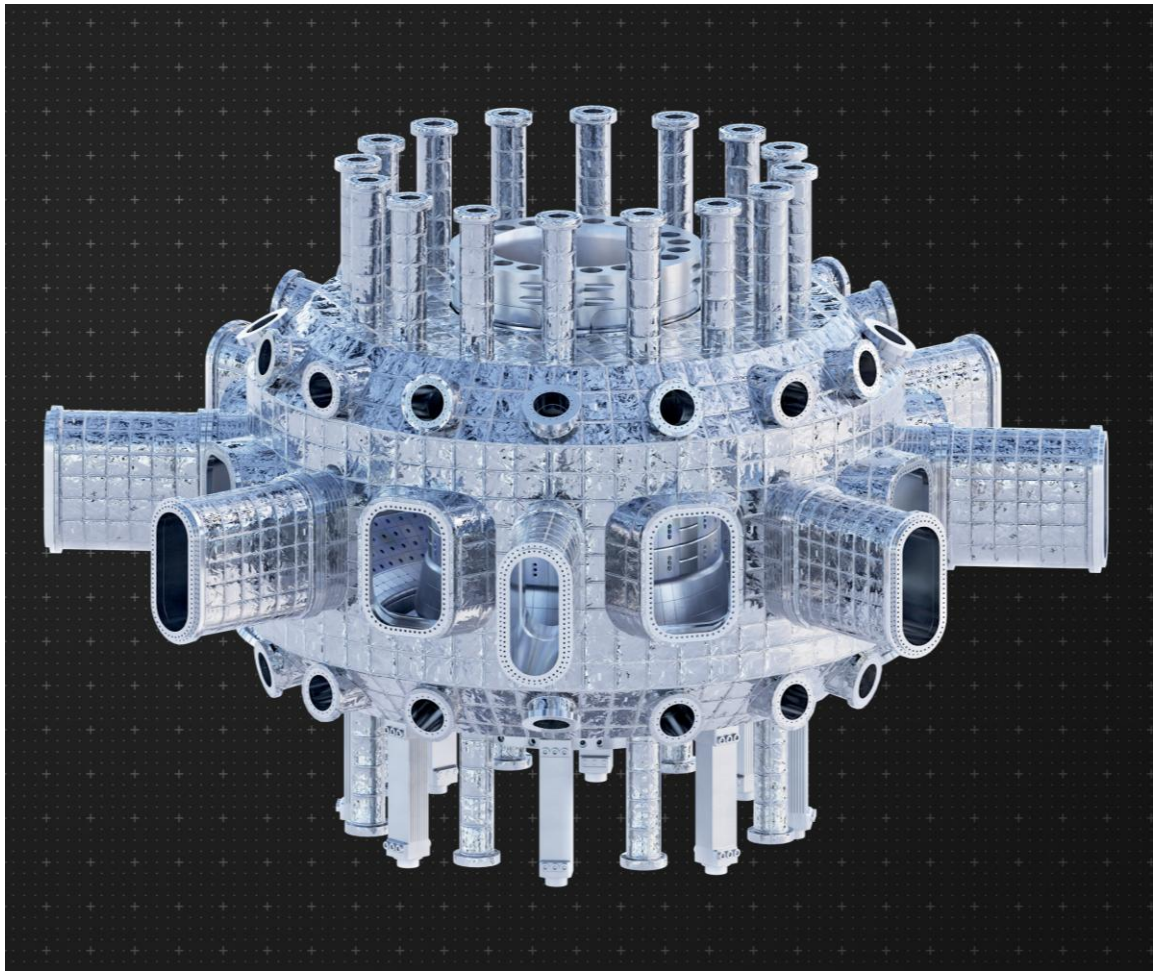
# Vacuum vessel

- Thermal insulation by 20 mm Multi Layer Insulation (MLI)

- **In-house high temperature disruption-proof MLI development**
- **Testing of Ag and Au coating => decision to polish only**



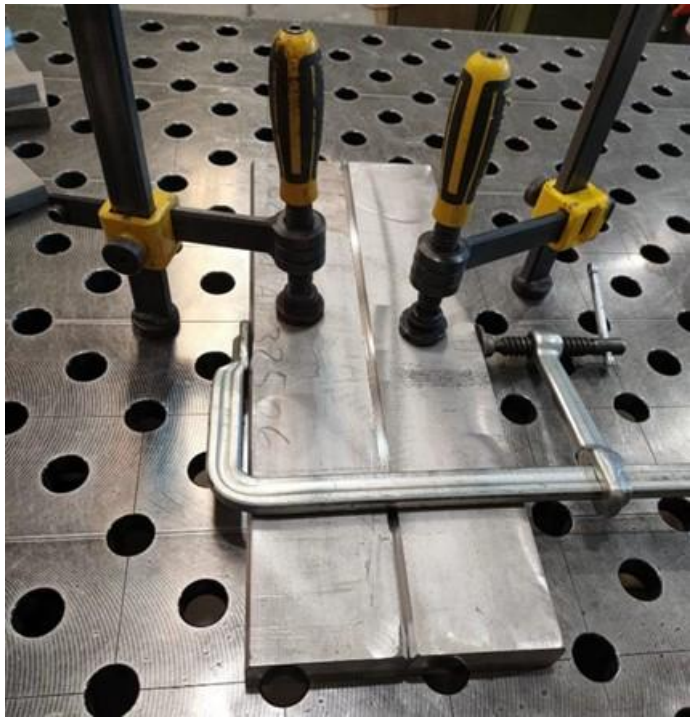




*Von Mises stress in the vacuum vessel and PSP.*

# Vacuum Vessel
## Manufacturing status

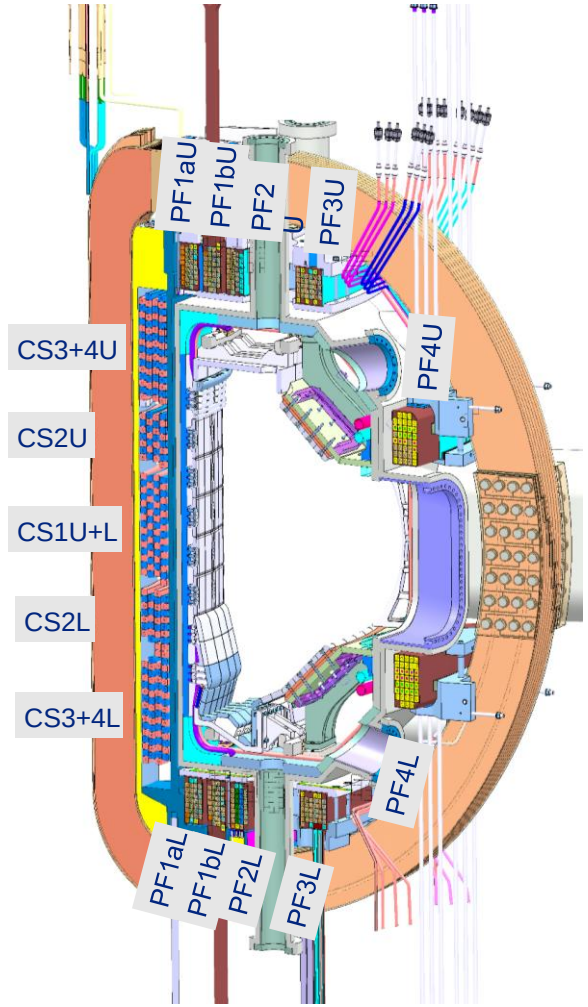
- Manufacturer: **Dal Ben S.p.A., Italy**
- Contract signed in **November 2024**
- Preliminary manufacturing documentation approved in **August 2025**
- Material procurement ongoing, welding samples are being prepared
- **Manufacturing to be finished in December 2026**



# Poloidal field coils

- **5 Central solenoid coils**
- **5+5 Poloidal field coils**
- **Material CuAg0.1 (OF)**, half or full hard hollow conductor
- Insulation: E glass tape + Kapton, epoxy, VPI
- **Cooled down to 80 K** by gaseous He
- Up to **50 kA current**

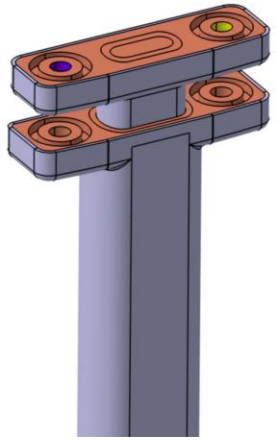
| name, qty. | Current range [kA] | Conductor w x h [mm] | D [m] | turns | winding length [m] | cooling segments |
|---|---|---|---|---|---|---|
| **2 x CS s** | **± 50** | 24 x 21 | **0.8** | 29 | 78 | 1 |
| **3 x CS d** | **± 50** | 24 x 21 | **0.8** | 61 | 164 | 2 |
| **2x PF1a** | **± 25** | 15 x 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 |

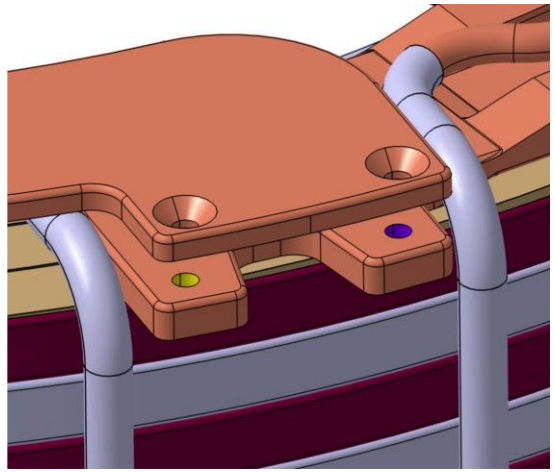



**Contract signed in 11/2025 with Revol TT Consulting (Slovakia)**

## Central solenoid design status

- **3 co-wound double segments + 2 single segments**
- **Coaxial feeders**
- **CS compression system** (~ 4 MN)
  - superbolts + **2x80 lamellae made of EN AW 2195 aluminum alloy**
  - low loss of preload during cool-down
  - Testing of aluminum lamellae in progress





# Central solenoid

## Central solenoid design status

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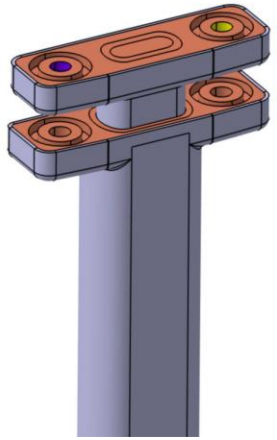
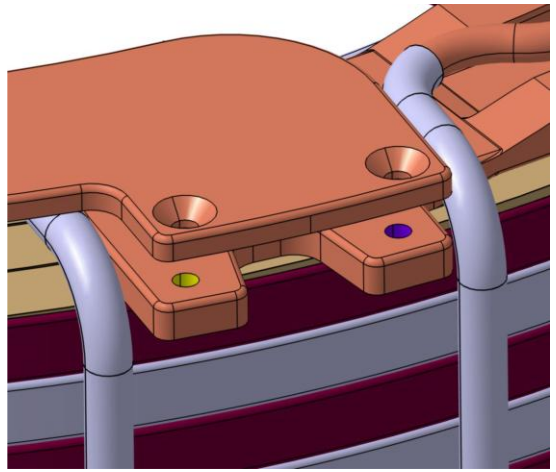
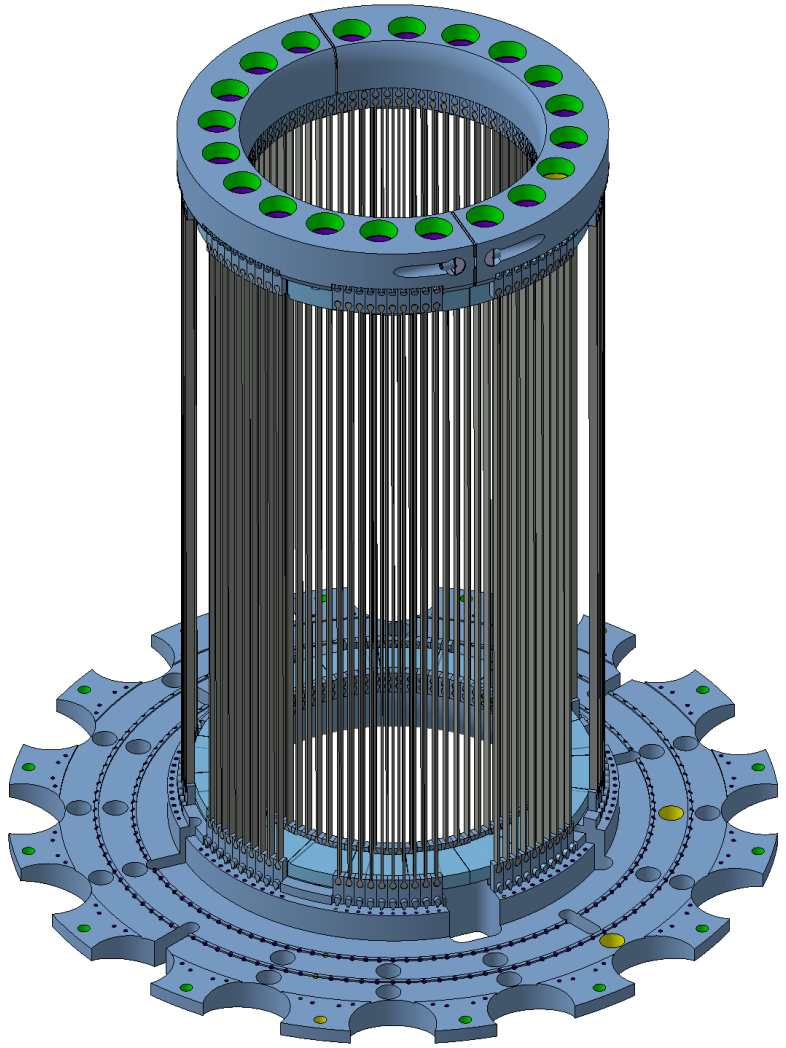
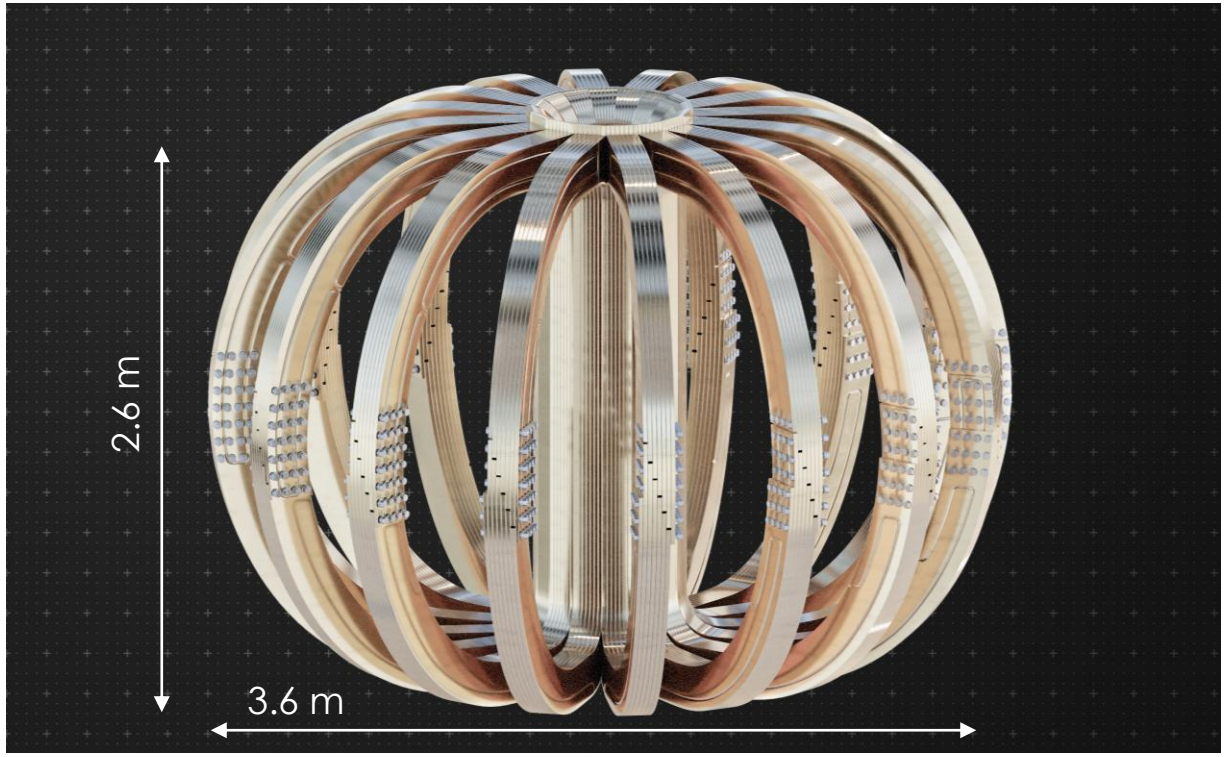


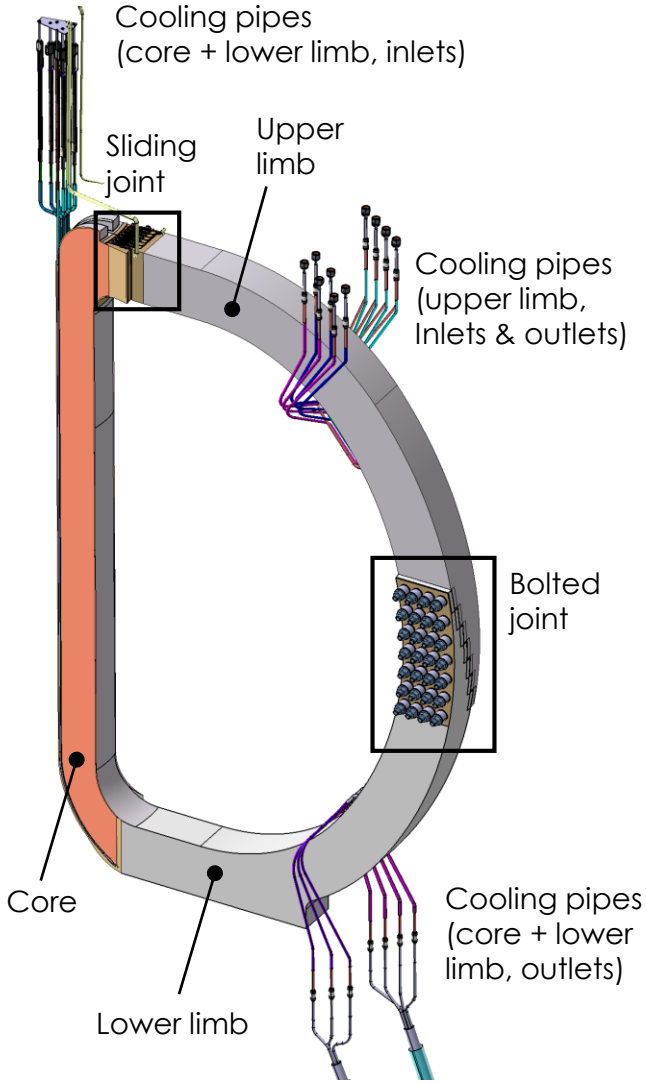




# Toroidal field coils

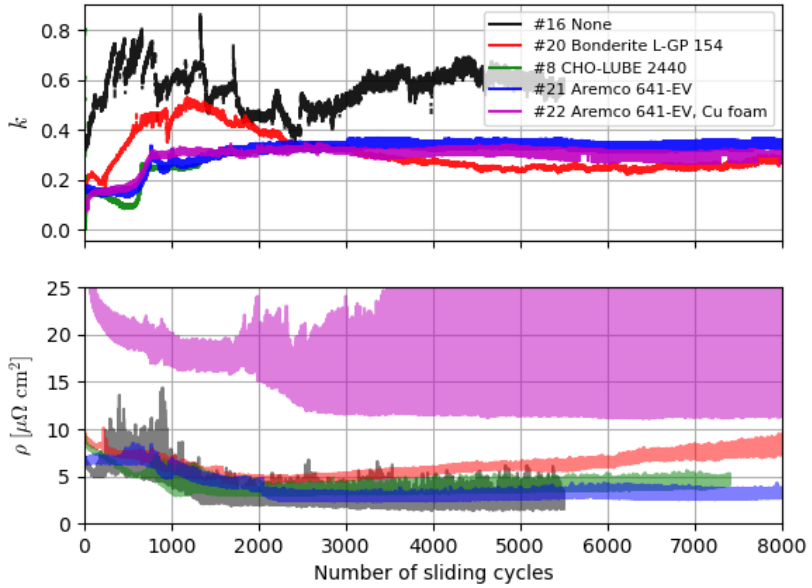
- TF core + 16 upper limbs connected via **bolted and sliding joints, 200 kA current**
- **Material full hard CuAg0.1 (OF) or CuCrZr**, 16 bundles, 7 turns each
- Insulation: E glass + epoxy resin, Vacuum Pressure Impregnation
- **Cooled down to 80 K**, gaseous He, Cu cooling pipes soldered to machined grooves
- **Radial pre-load** to provide additional TF core compression and prevent shearing

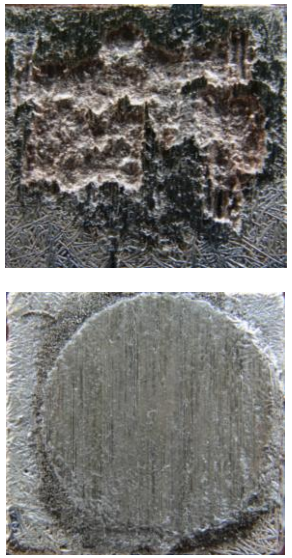


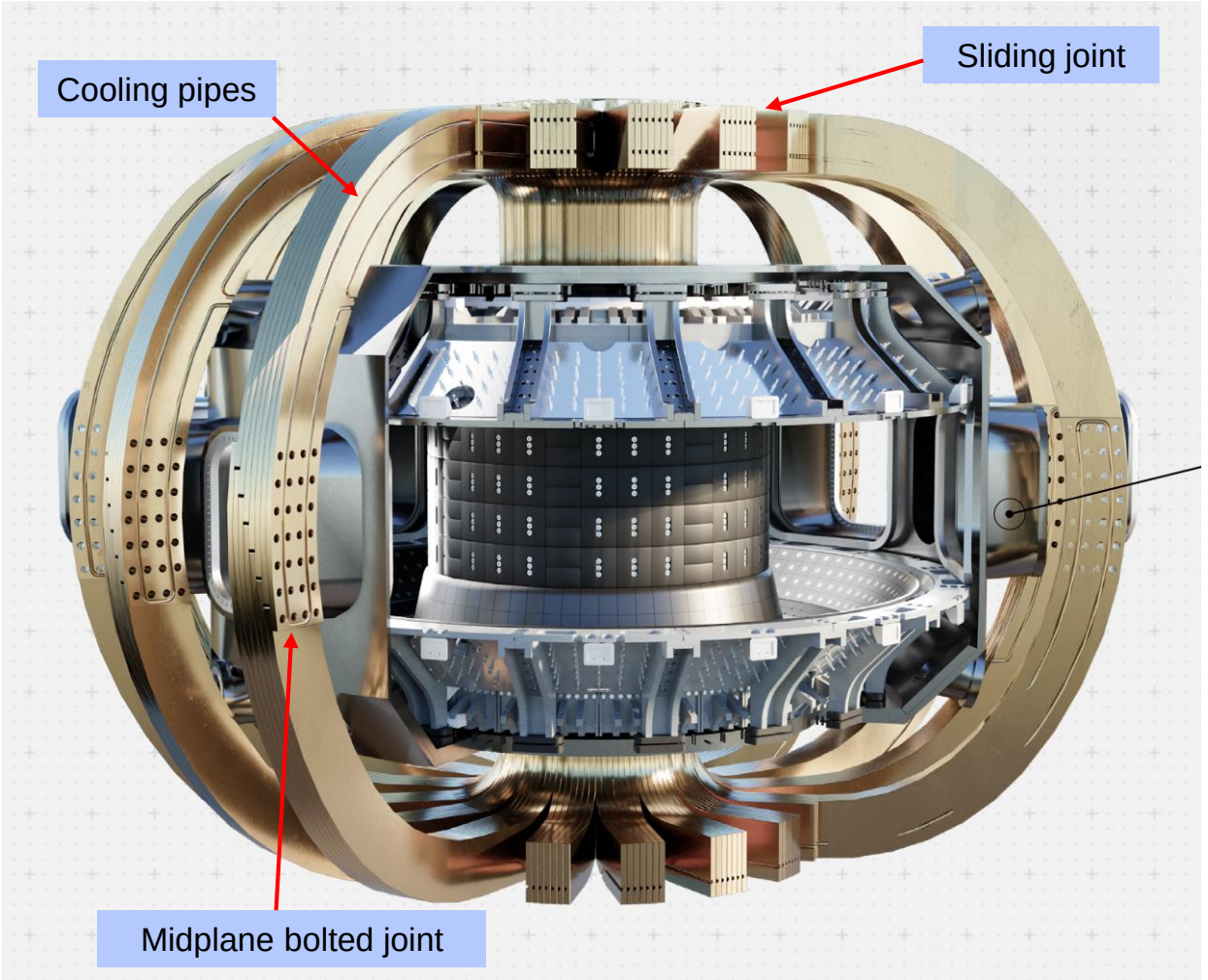
## Toroidal field coils sliding joints

- **Sliding joint** based on Alcator C-mod and MAST experience
- **Cu felt** used for good electrical contact
- Vacuum and cryo compatible el. conductive grease needed to prevent cold-welding
- Testing under vacuum, cryogenic temperatures and high current: **7 kA/cm2 tested**



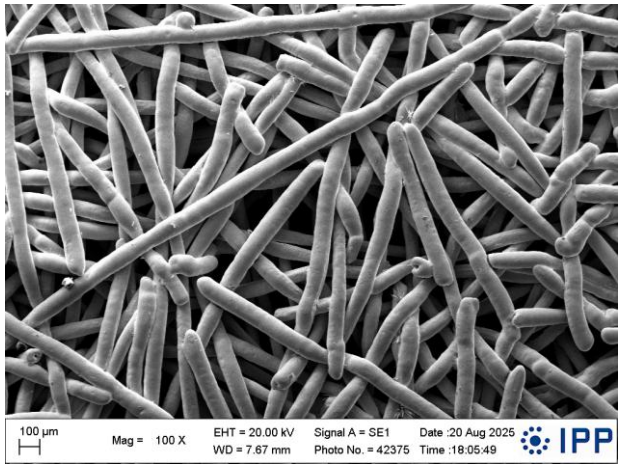



*Testing samples of sliding contact*

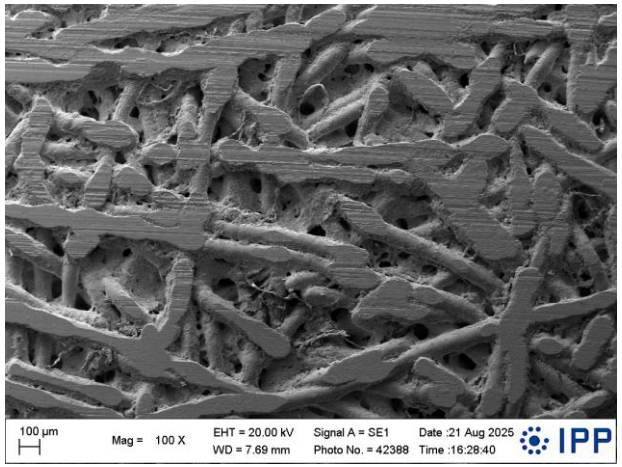


## Toroidal field coils sliding joints

- **Sliding joint** based on Alcator C-mod and MAST experience
- **Cu felt** used for good electrical contact
- Vacuum and cryo compatible el. conductive grease needed to prevent cold-welding
- Testing under vacuum, cryogenic temperatures and high current: **7 kA/cm2 tested**

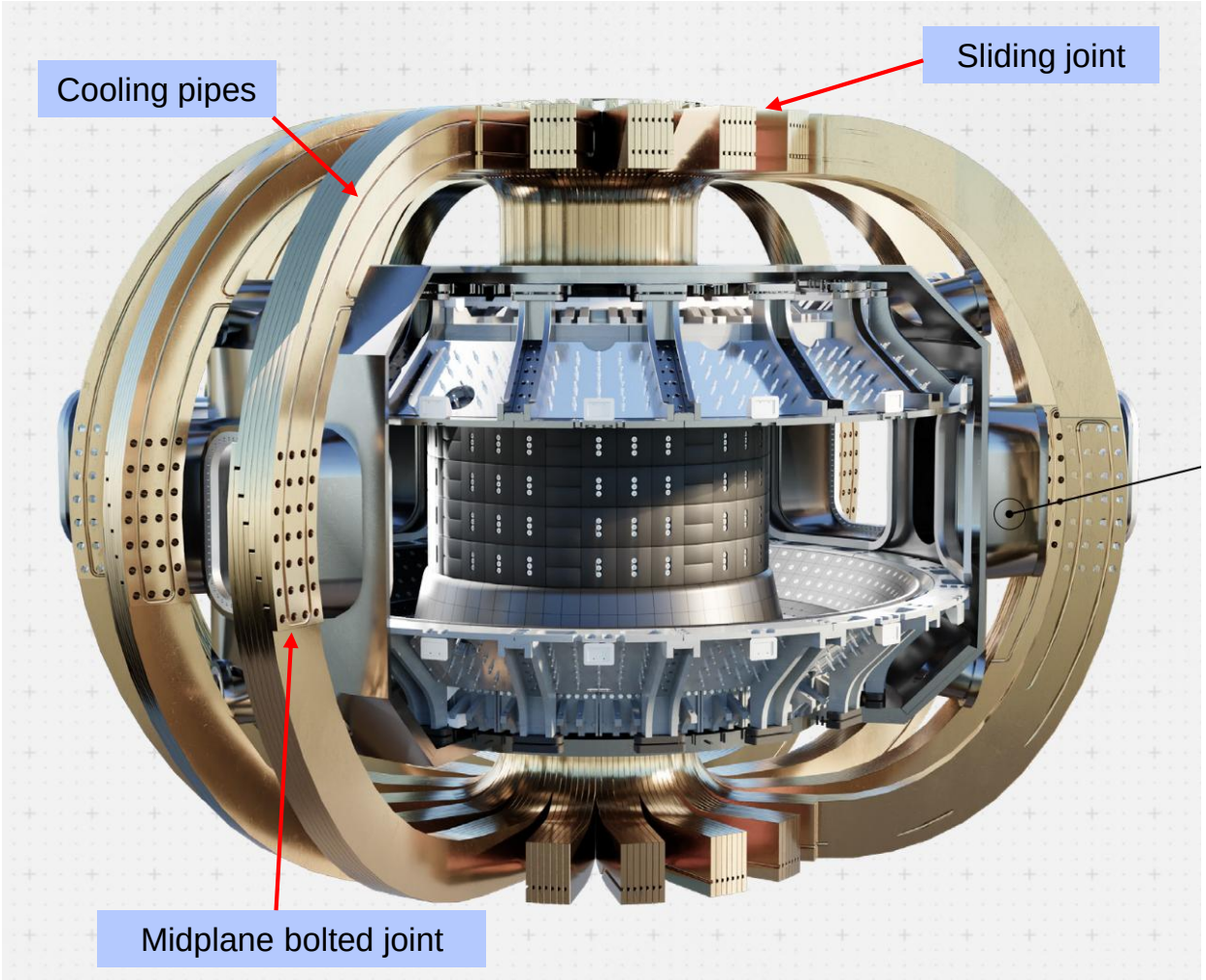



*Original*



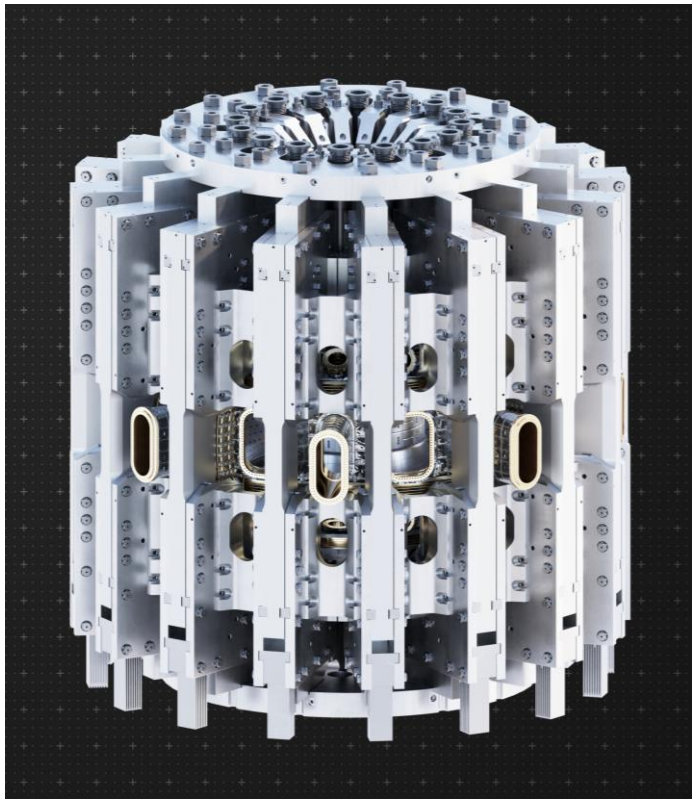

*After 12 000 cycles*

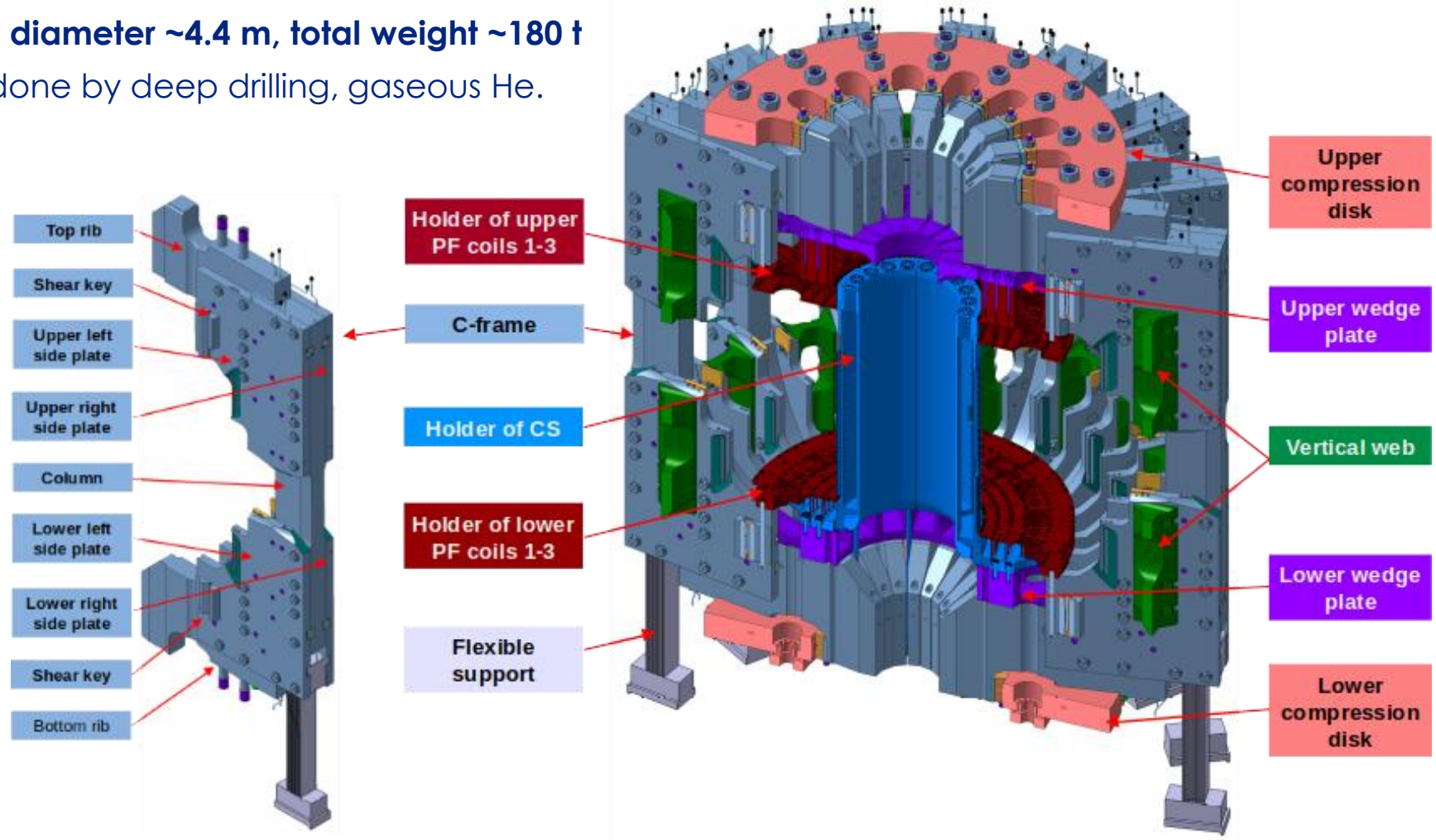
***Silverplated Cu felt***



# Support structure

- **Austenitic stainless steel 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





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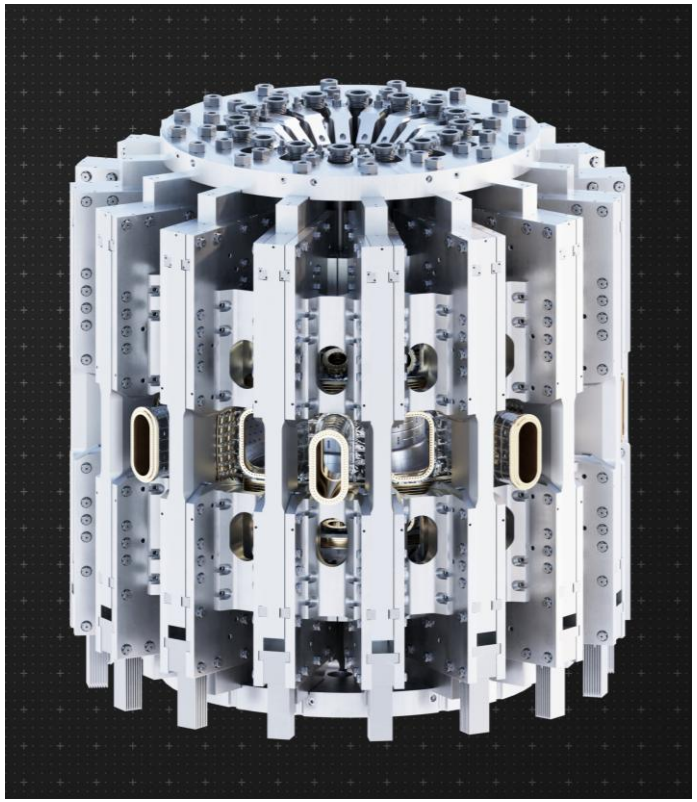
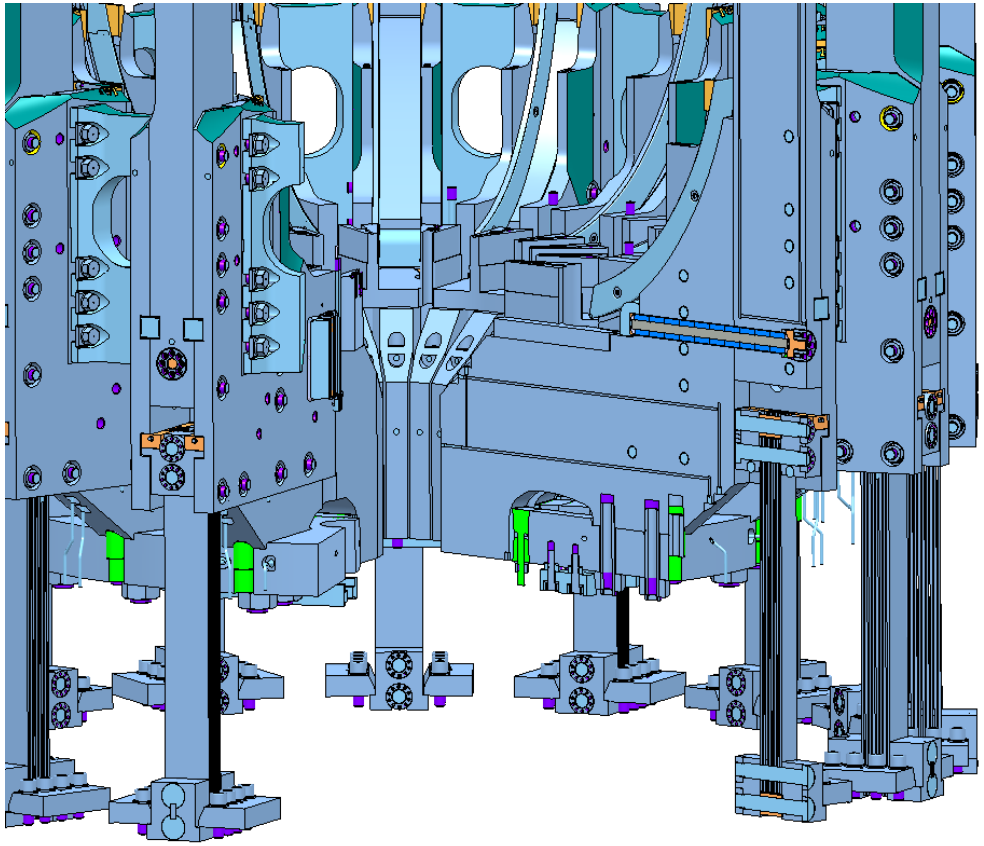
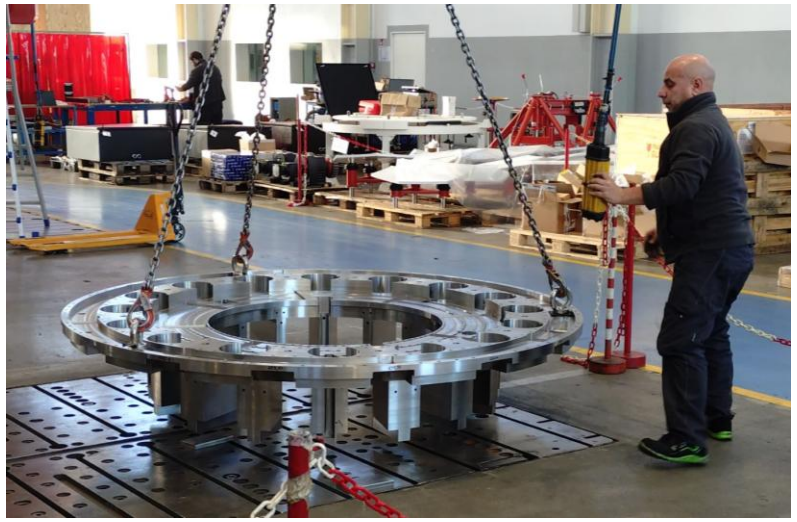
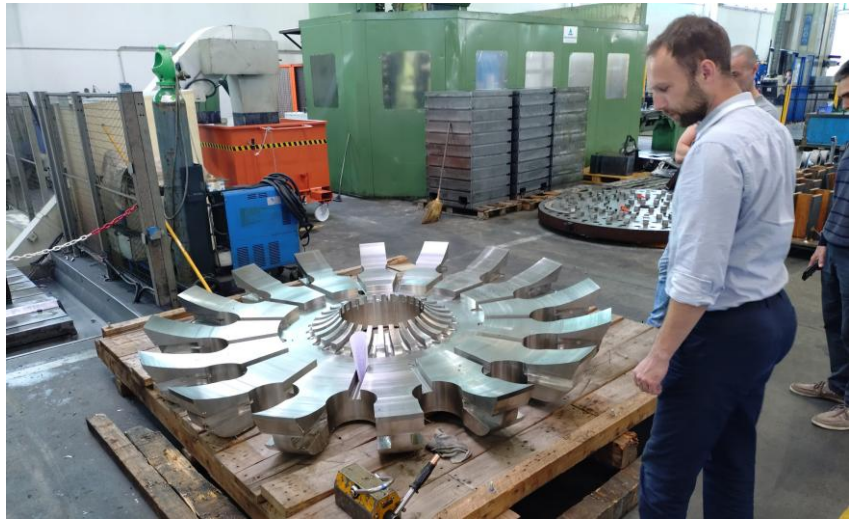




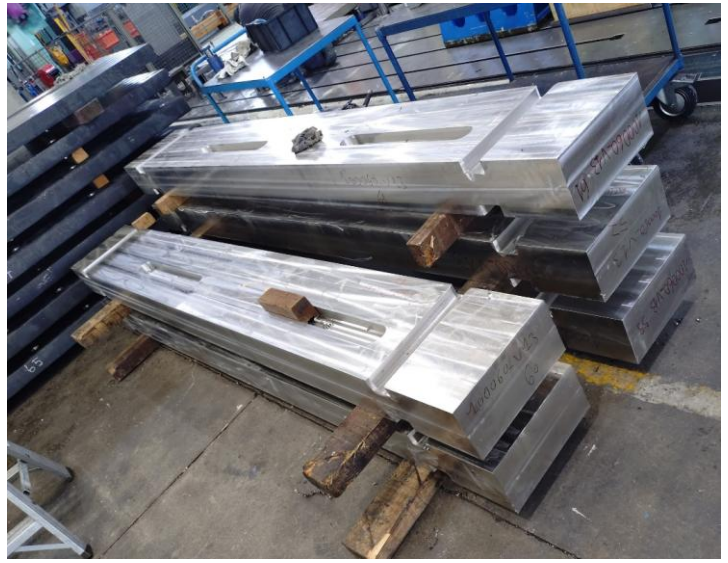
## Support structure manufacturing

- Manufacturer: **Dal Ben S.p.A. Italy**
- Contract signed 12/2023, **manufacturing started 01/2024**
- All forgings finished, machining and final tests of components ongoing
- **Manufacturing to be finished beginning of 2026**
- **Test assembly** in Italy in **Q2 2026**
- **Flexible supports tendered in 2025**





# Support structure
## Manufacturing status



# Cryogenics

**Cooldown after a top performance discharge within 30 min**

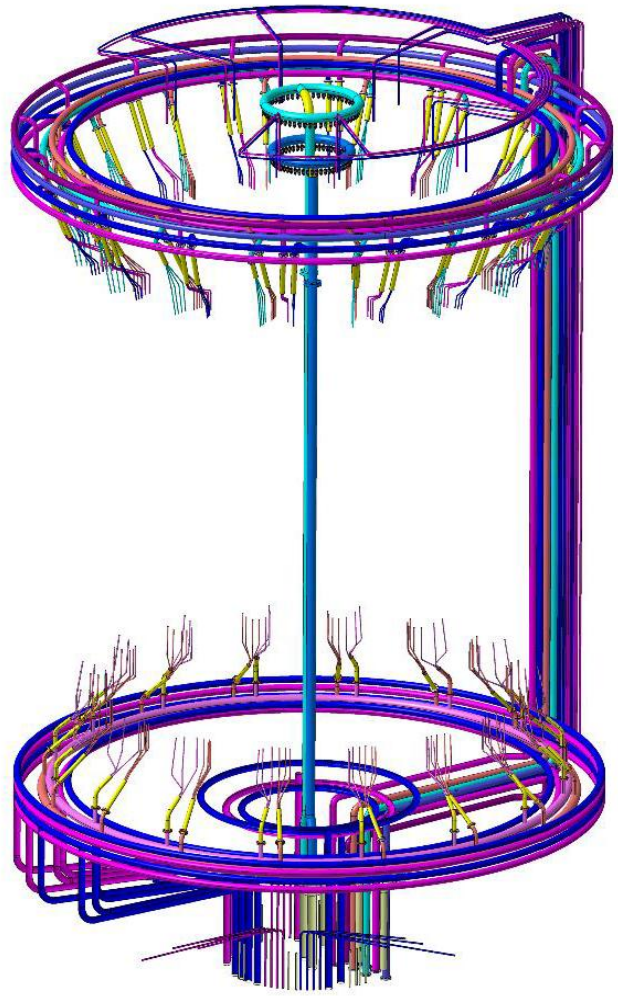
- TF coils ~250 MJ, PF+CS coils ~50 MJ
- => **required cooling power ~200 kW @ 80 K**

**Multiple closed gaseous helium loops *(6 km inside of cryostat)***

- **CS** $p_{base}$ 60 bar, Δp 5 bar, ṁ 80 g/s
- **PF** $p_{base}$ 20 bar, Δp 1 bar, ṁ 160 g/s
- **TF** $p_{base}$ 20 bar, Δp 0.1 bar, ṁ 800 g/s
- **Support structure** $p_{base}$ 20 bar, Δp 0.1 bar

Main „cold source“ – **liquid nitrogen heat exchanger**

- ~50 m3 of LN2 per day at full parameters

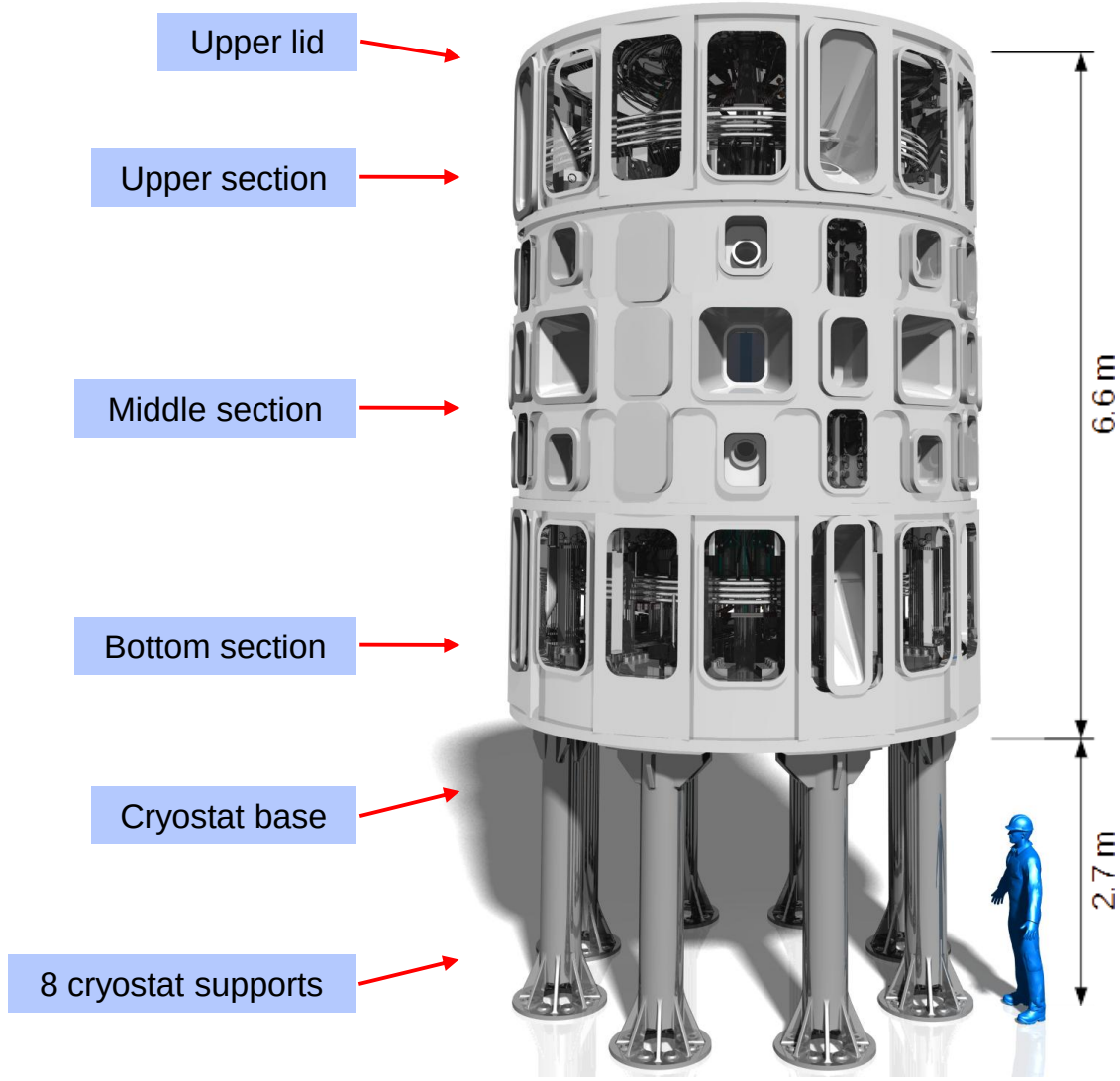


*Cooling collectors*

# Cryostat

- **Stainless steel cryostat** (AISI 304L)
- **Volume ~100 m3**, weight ~50 t
- Cylindrical shape with **large service ports** for maintenance
- 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

- **Manufacturer selected in 11/2025**



# Power supply system

## Flywheel generators
- 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

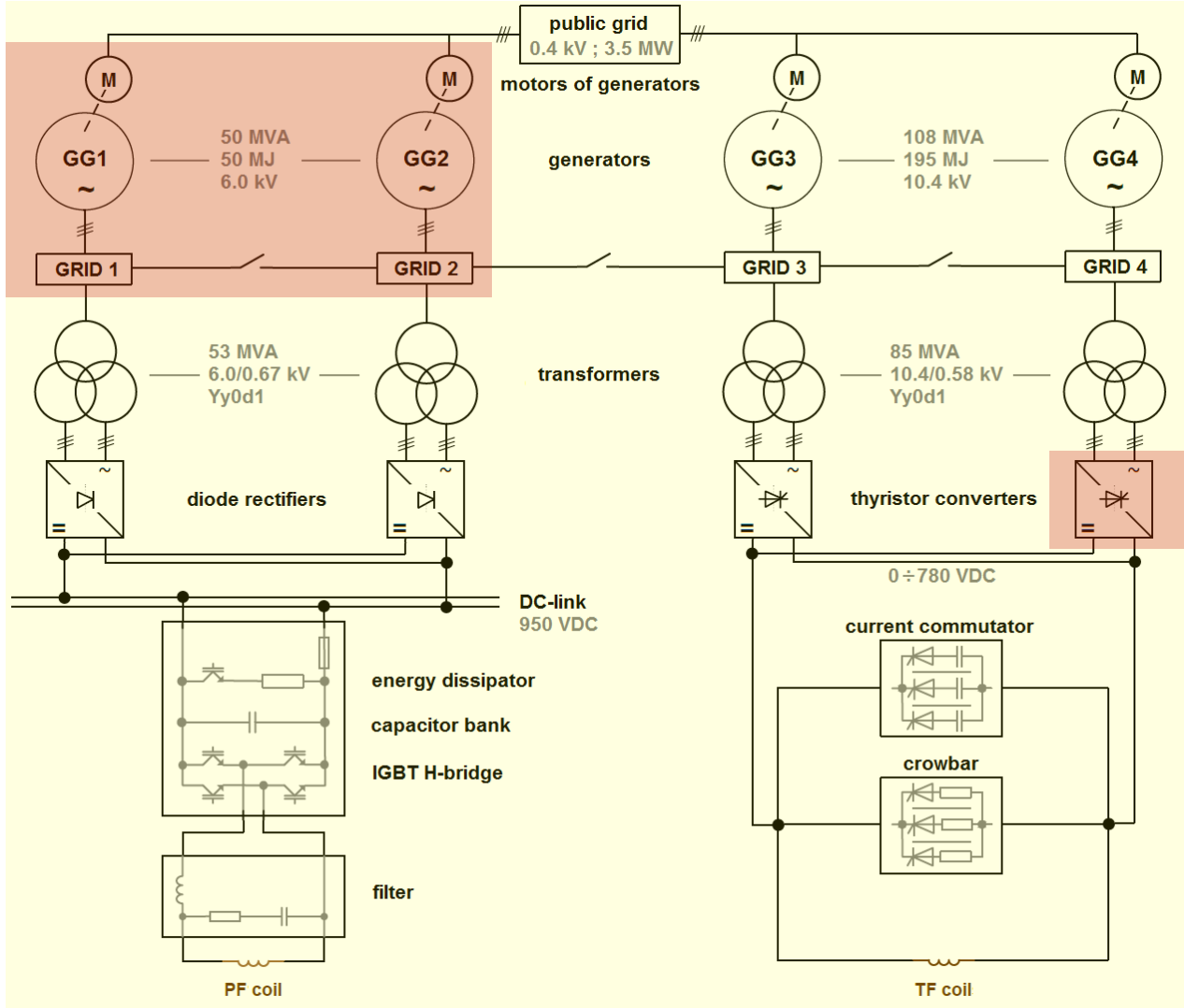
## Auxiliary heating + reserve
- 38 MW, 58 MJ

**In total: 268 MW, 490 MJ**

Equipment reused from COMPASS

New equipment

Manufacturer: **ELEKTROTECHNIKA, a. s., Czech Republic**
All components manufactured
Installation ongoing




*Schematic overview of the power supply system.*

# Power supply system
## Flywheel generator

Main manufacturer: **TES VSETIN a.s., Czech Republic**

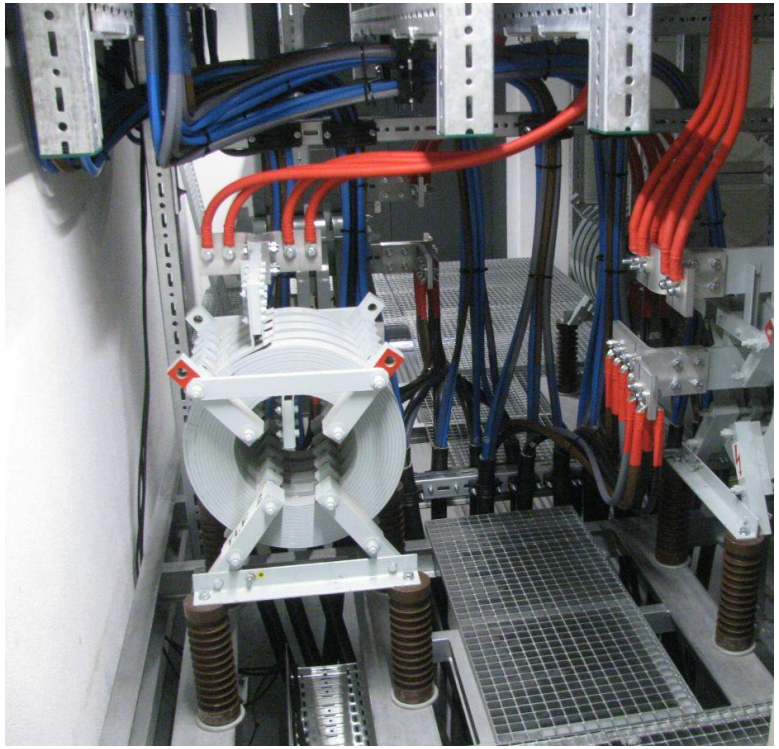
Manufacturer of stator winding: **Partzsch elektromotoren GMBH, Germany**

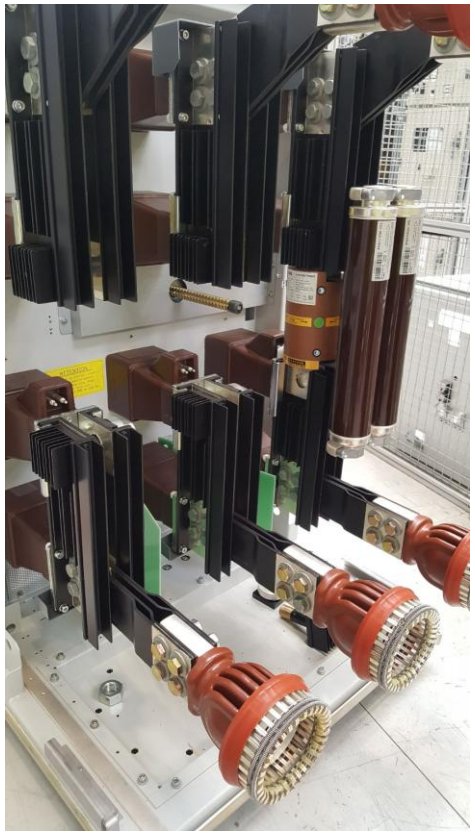
Manufacturer of flywheel: **ISMEC s.r.l., Italy**

| | Old GG1,2 | New GG3,4 |
|---|---|---|
| Electric energy | 50 MJ | **195 MJ** |
| Nominal power | 50 MVA | **108 MVA** |
| voltage | 6 000 V | **10 400 V** |
| current | 4800 A | **6000 A** |
| Max. speed | 1700 rpm | **1700 rpm** |
| Weight | 60 tons | **130 tons** |

## Power Supply System installation

- started in 10/2023 in Halls A and E
- will continue in Halls B and D by the end of 2025
- new flywheel generators installed in 09/2024 and 10/2025





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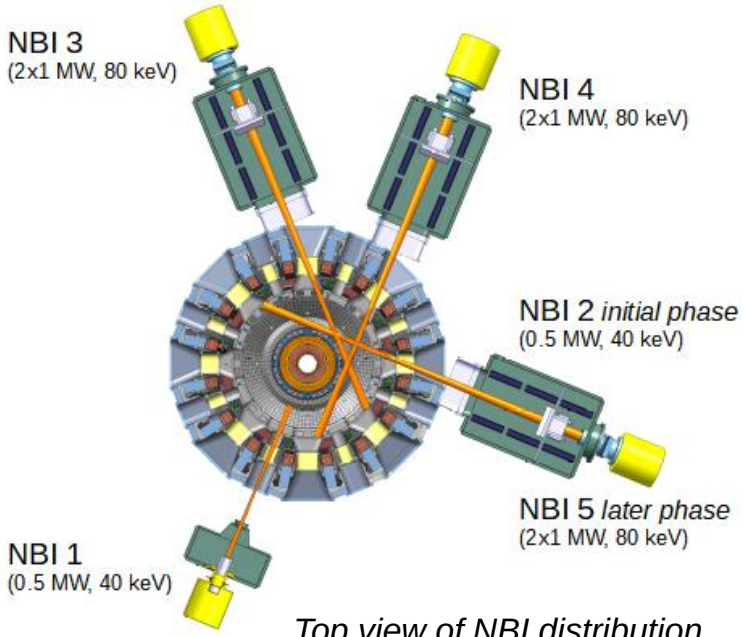
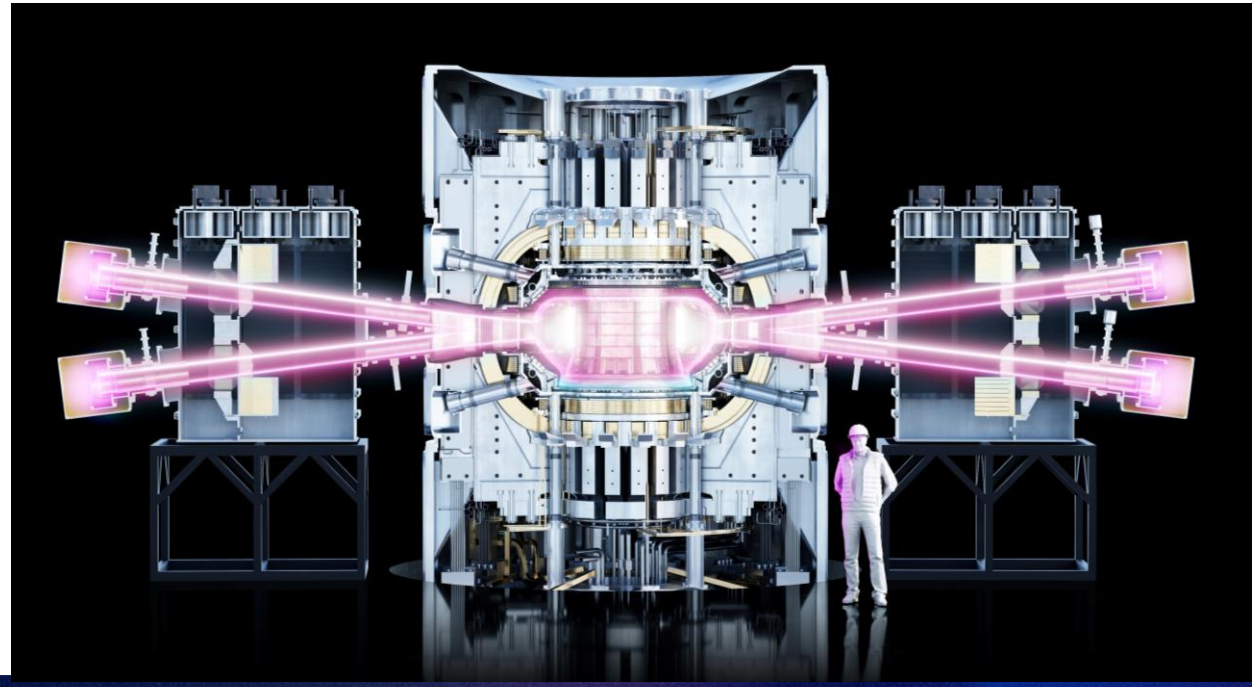
# Plasma heating
## NBI

- **NBI @ 80 keV**, 2 MW units (consisting of 2 ion sources)
- 2 ion RF sources above each other **inclined by ~7° from horizontal plane**
- 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
- NBI 4 (and NBI 5) on a stand **movable to counter-injection**
- **1 MW unit was delivered in 2021** by BINP Novosibirsk and tested on COMPASS
- Additional **2 MW under construction** (frozen because of EU-RF mutual sanctions) **=> internal development started**



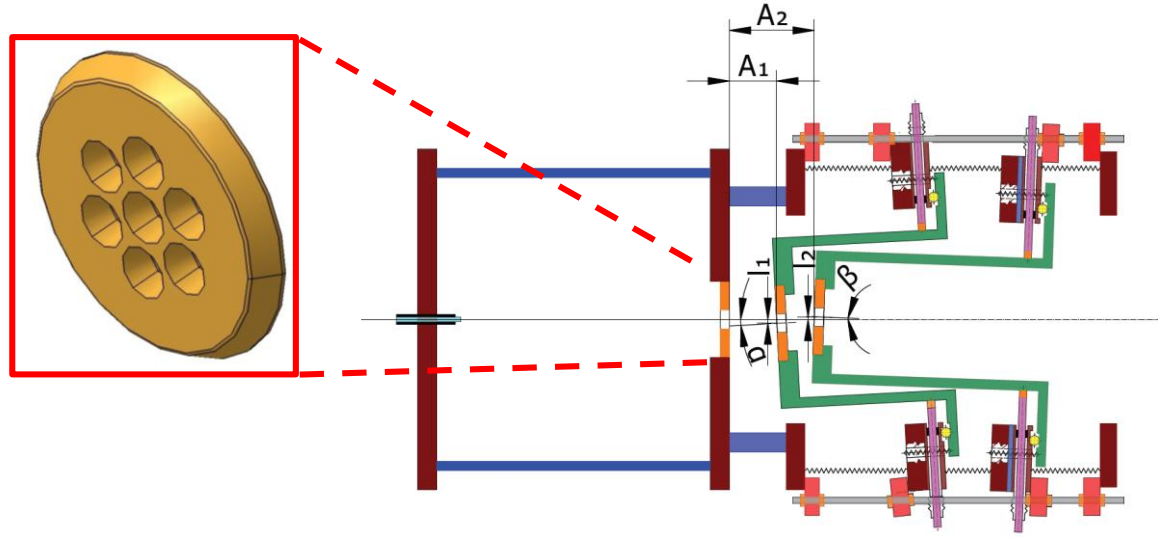

*Top view of NBI distribution.*



## Benchtop Neutral Beam Experiment – NIBBLER

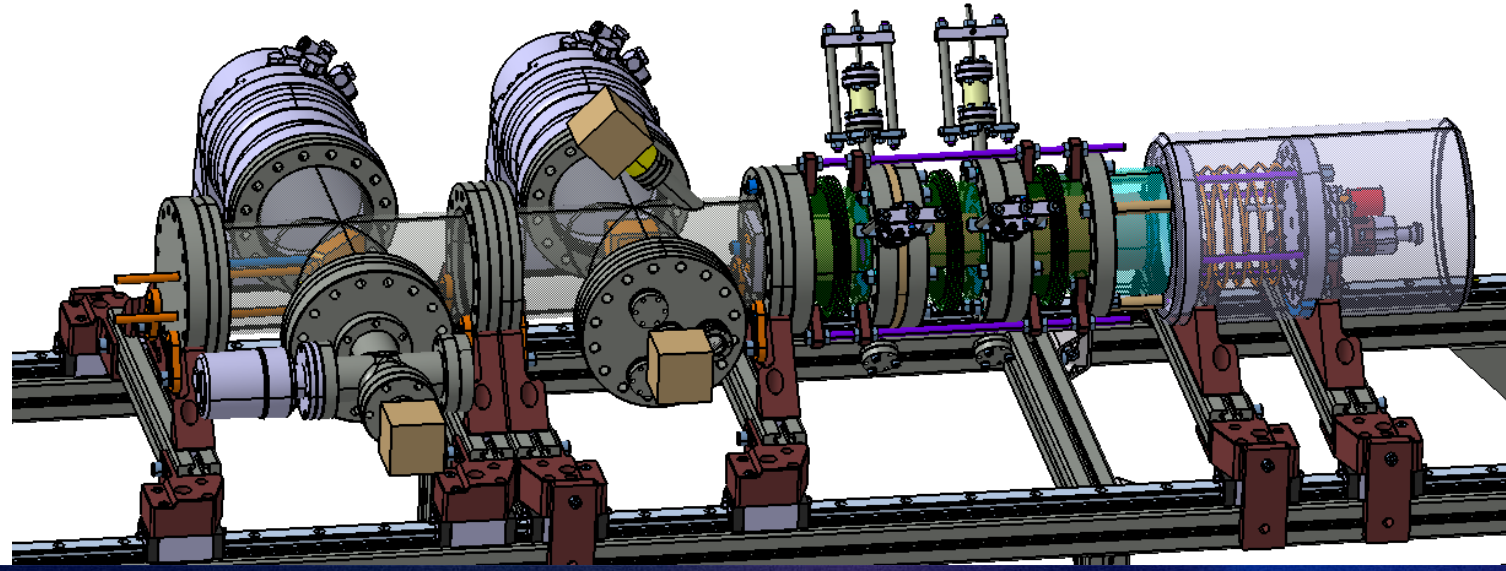
### Goals

- Optimization of the **ion optics**, including geometry, surface finish, and manufacturing tolerances.
- Gaining experience with **RF systems** and their integration into the NBI.
- Development of the **control system**




### Parameters

- **Easily exchangeable grid inserts**:
  - diam up to 35 mm
  - Up to 7 beamlets
- up to **100 keV**
- **6 degrees of freedom for grids positioning**
- Solid state 500 W RF source



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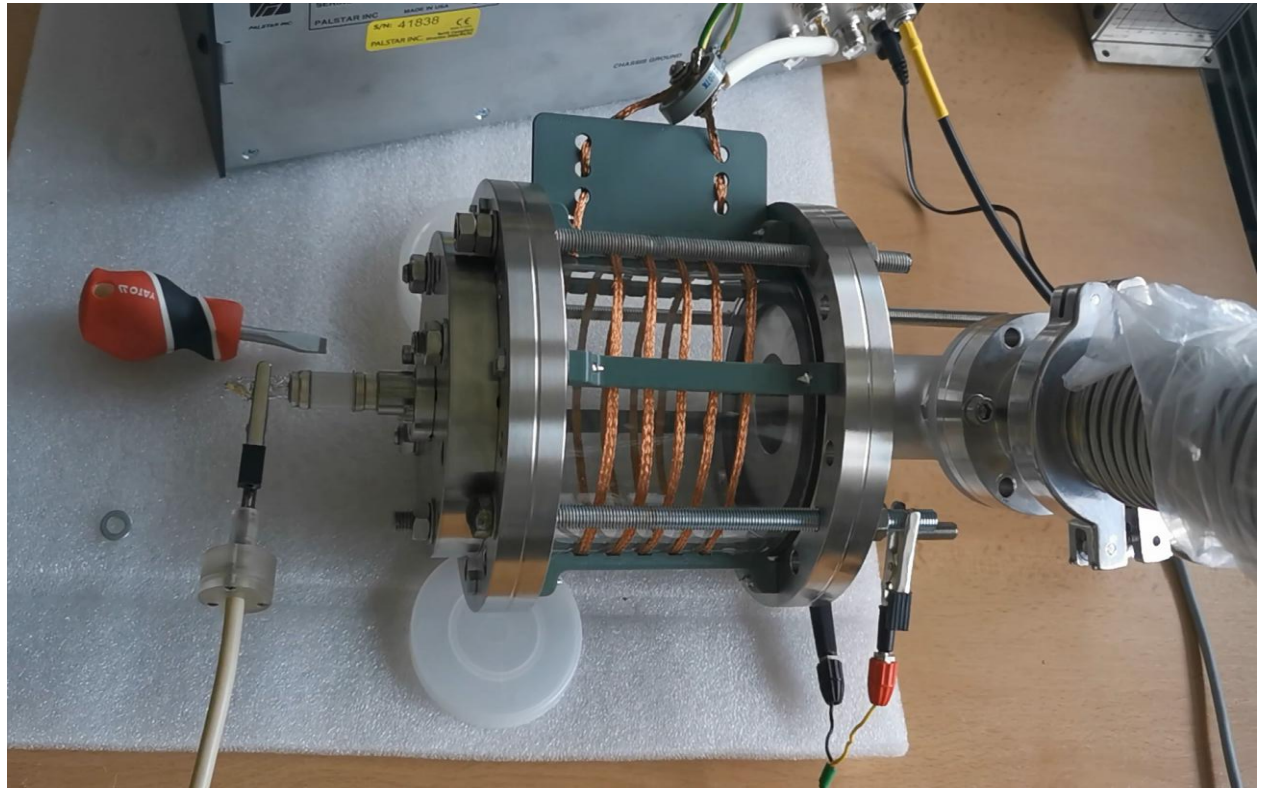
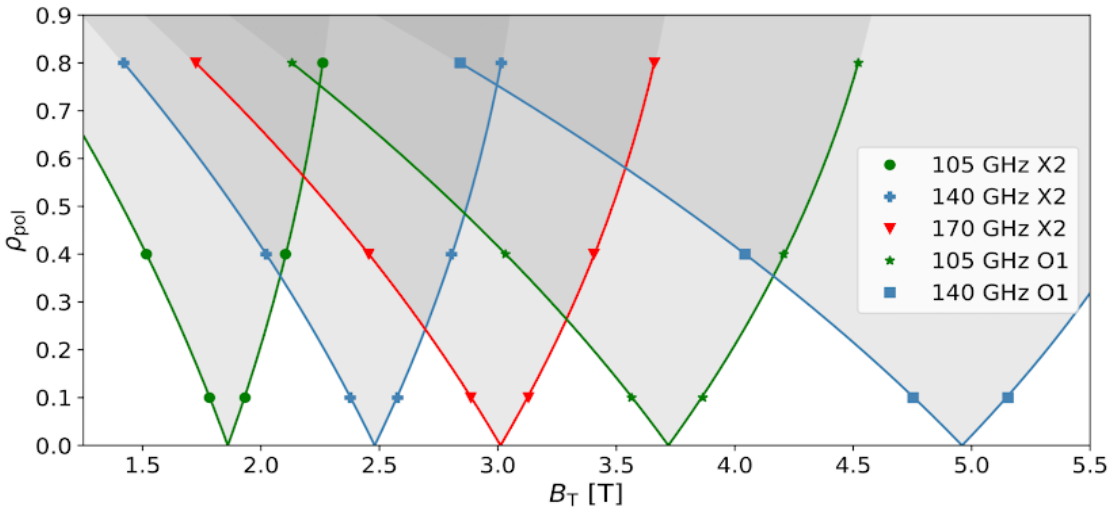
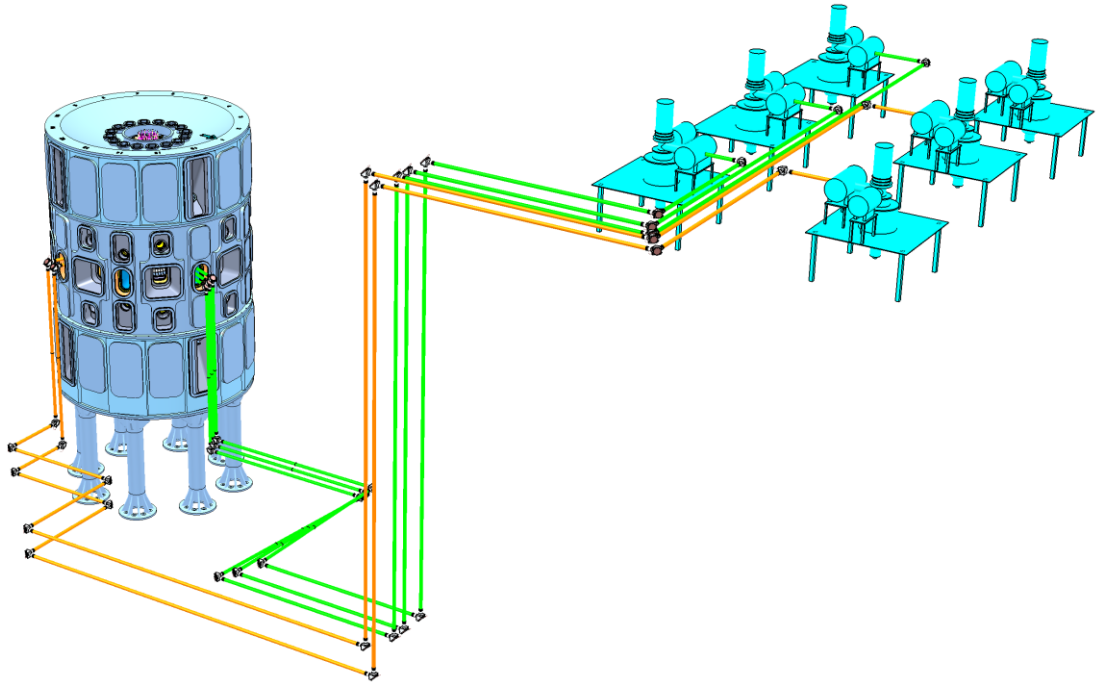


# Plasma heating
## ECRH

- **Multifrequency gyrotron: ~105, 140, 170 GHz**
- **1MW** @140 GHz
- **15 s** pulse length, up to 1 kHz power modulation
- **Transmission line**: evacuated 63.5 mm corrugated waveguide, total length ~30 m, 6-9 miter bends (water cooling)
- **Launchers:** at large equatorial port, steering mirrors (fixed mirror for initial operation)
- **Density limit:** 140 GHz ~2.4x$10^{20}$ $m^{-3}$, 170 GHz ~3.6x$10^{20}$ $m^{-3}$



| B [T] | n [$m^{-3}$] | Operation mode | f [GHz] |
|---|---|---|---|
| 2.5 | 1.1x$10^{20}$ | X2 | 140 |
| 3.0 | 1.7x$10^{20}$ | X2 | 170 |
| 3.8 | 1.3x$10^{20}$ | O1 | 105 |
| 4.3 | 2.0x$10^{20}$ | O1, toroidal steering | 140 |
| 5 | 2.3x$10^{20}$ | O1 | 140 |

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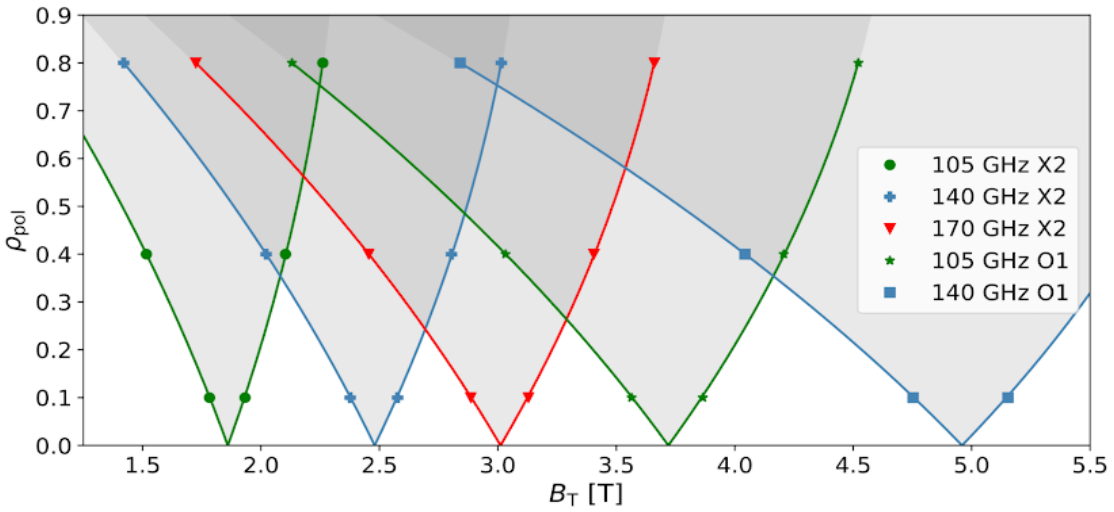


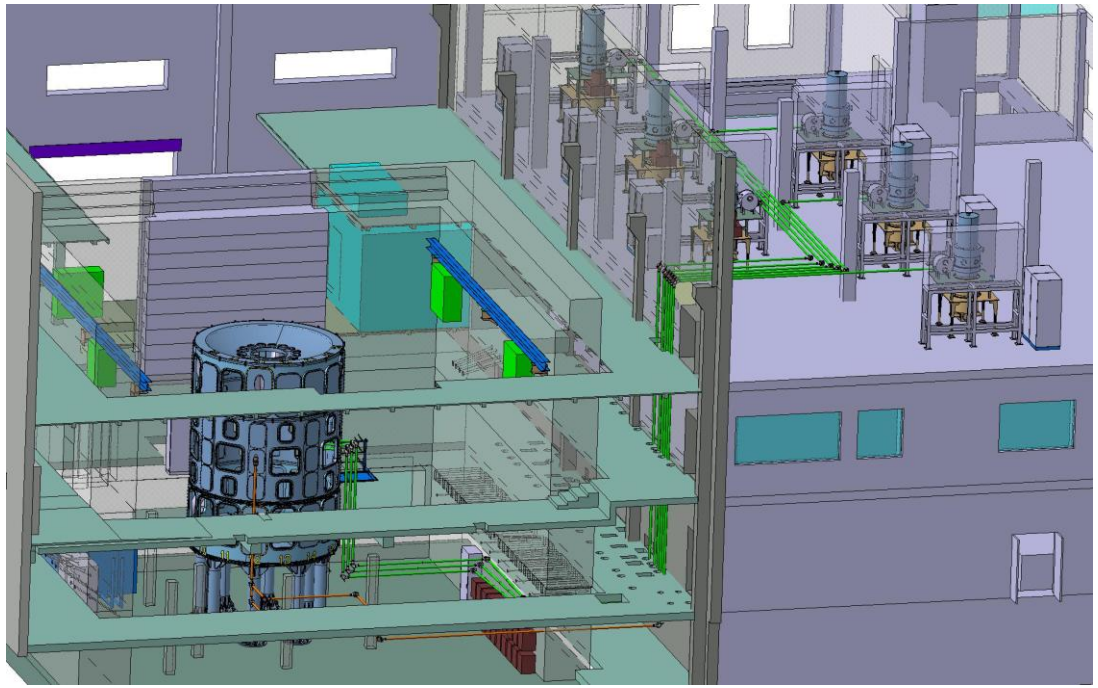

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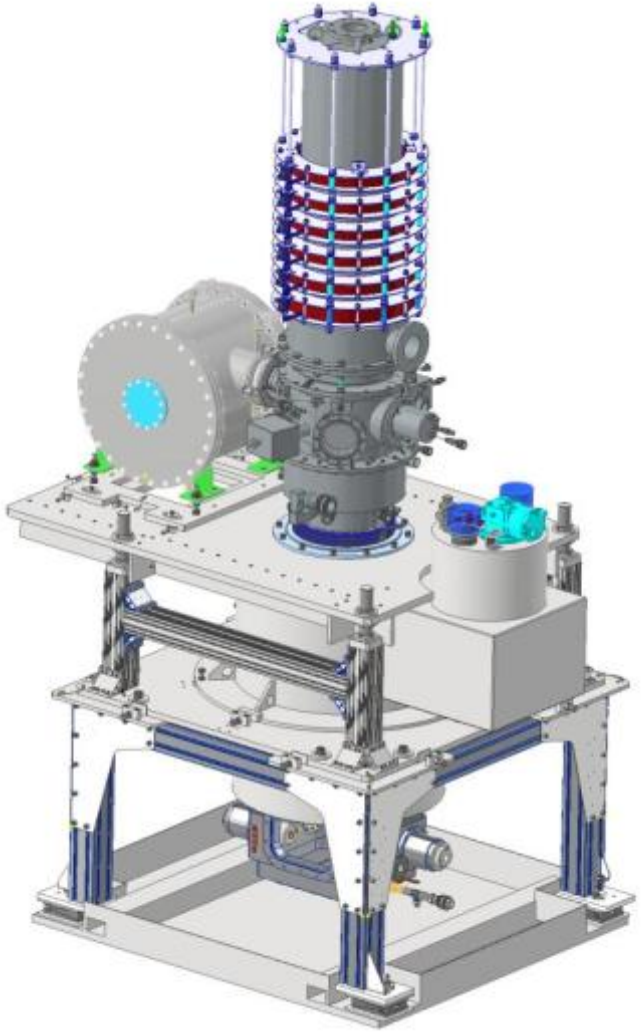
# Plasma heating
## ECRH

**1st gyrotron for COMPASS Upgrade** is manufactured by **KyotoFusioneerong** (Japan), design based on the ITER gyrotron

| Frequency | Power | Pulse length |
|---|---|---|
| 104 GHz | 0.8 MW | 5 s |
| 137 GHz | 0.9 MW | 15 s |
| 170 GHz | 0.8 MW | 5 s |



- Central EC deposition is effective at preventing impurity accumulation when power is large enough
- 1.4 MW NBI + 0.9 MW ECRH sufficient to enter H-mode (METIS, ASTRA)
- ECRH can reduce the critical field for breakdown to prevent early RE generation or save loop voltage

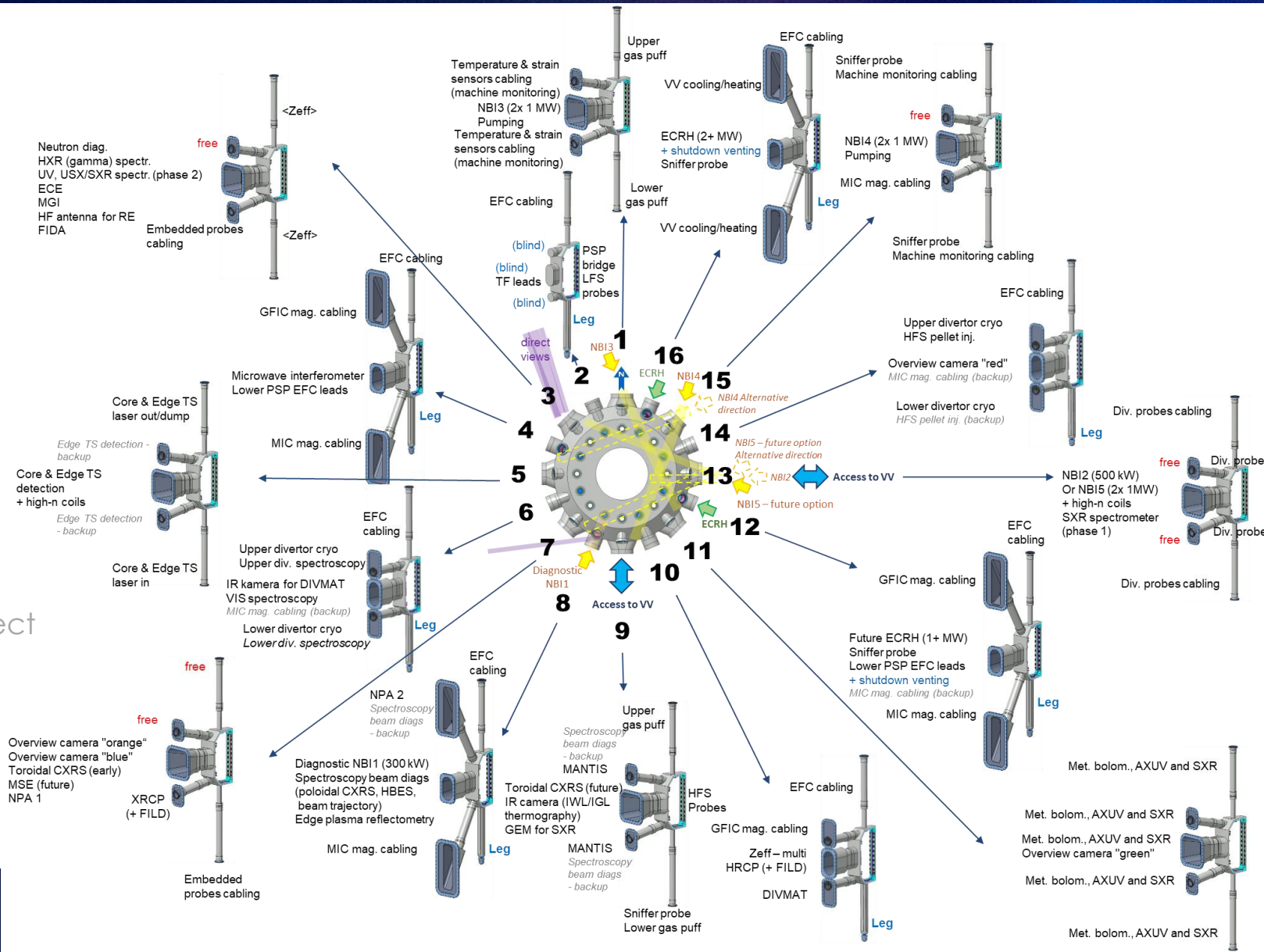
**Schedule of 1st gyrotron:**

- FAT and delivery **before end of 2026**
- Assembly and commissioning in 2027

# Plasma diagnostics

## Core diagnostics

- Full set of magnetics (1 mm EFIT precision)
- Thomson scattering (core*+edge)
- Sub-mm Interferometer*
- ECE
- HXR+neutronsSoft X-ray spectrometer SXR diodes*/ GEM
- Zeff
- AXUV+Bolometry *
- Neutral particle analyzer FILD
- Fast electron detectors
- X-ray microcalorimeter
- UV spectrometry
- Charge Exchange + BES + Motion Stark effect




*** REQUESTED FOR THE FIRST PLASMA**

# Plasma diagnostics

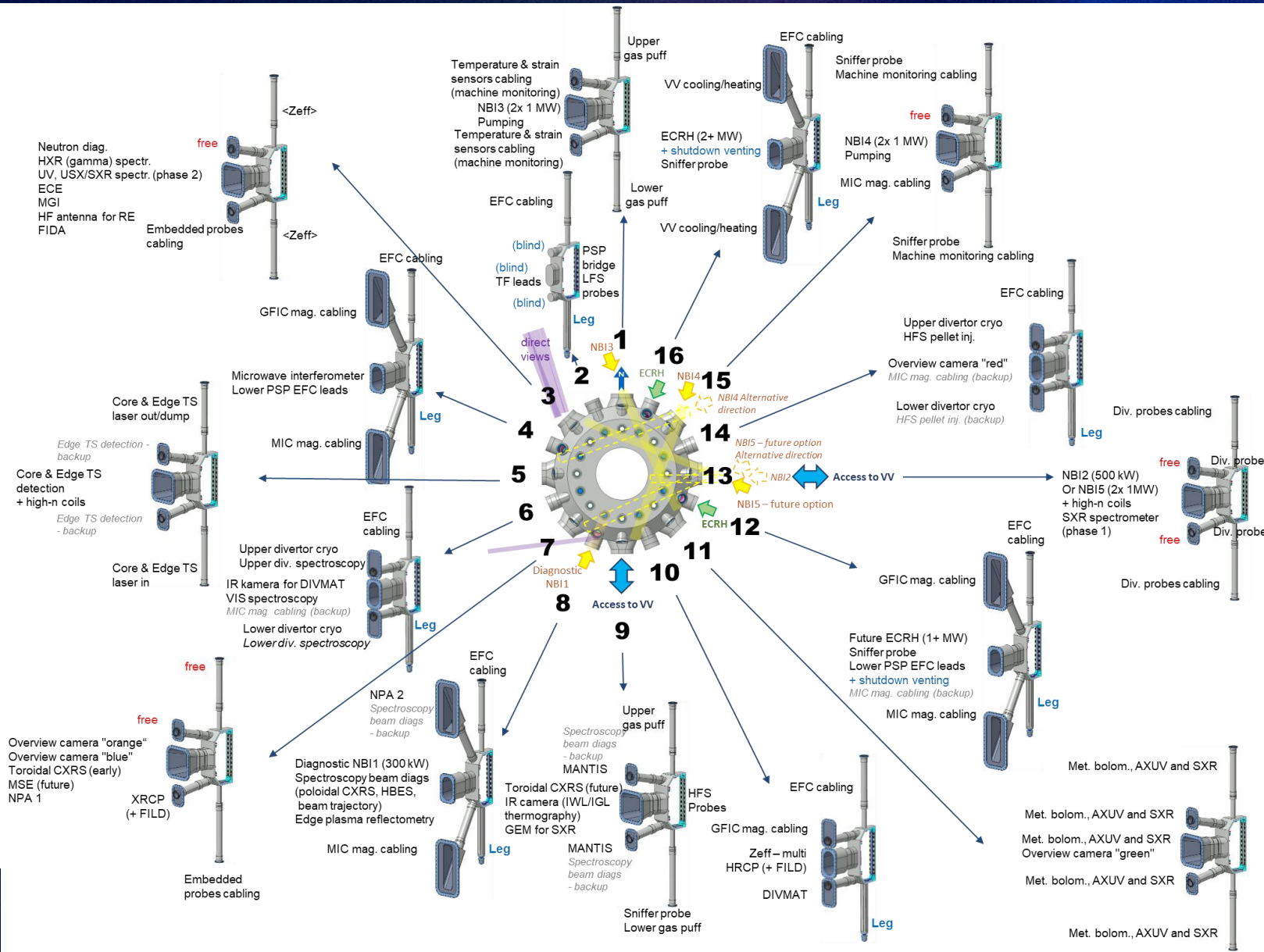
## Edge diagnostics

- Reflectrometer
- Midplane reciprocating manipulator
- X-point reciprocating manipulator
- Flush Langmuir probes in limiters*
- Visible & IR overview cameras*
- Limiter shunts
- Time of flight LENA

## Divertor diagnostics

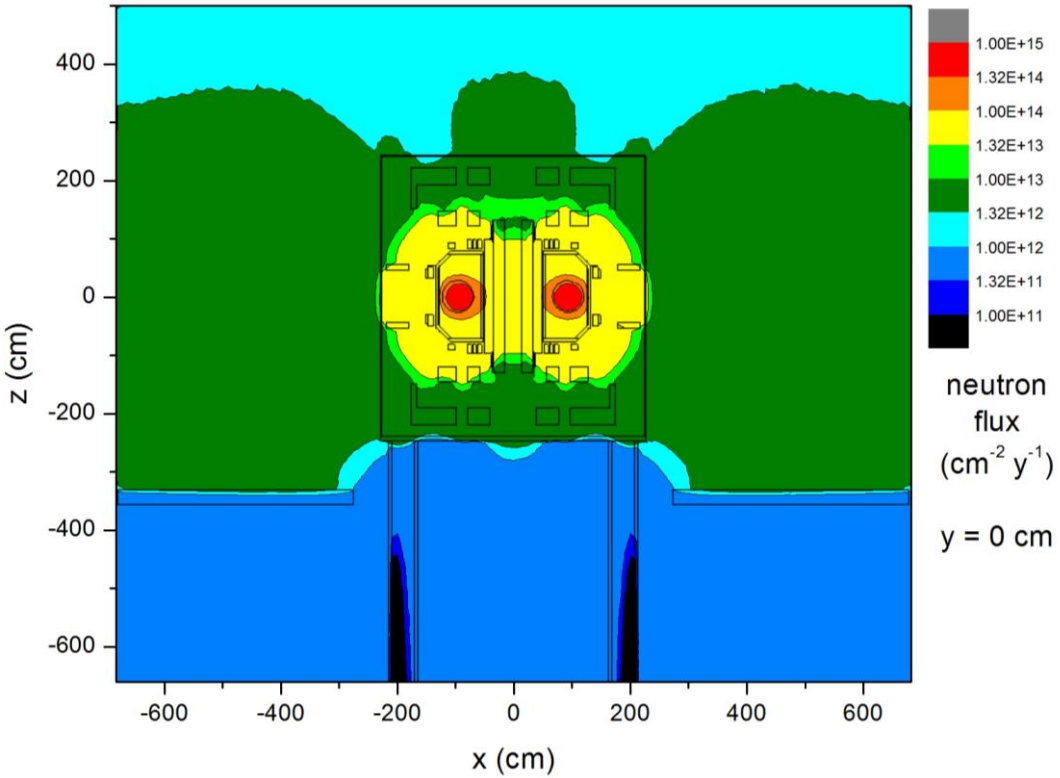
- IR cameras
- Rail Langmuir probes
- Divertor shunts
- Visible spectroscopy*
- Divertor reciprocating manipulator
- Fibre Bragg grating
- MANTIS
- Divertor Thomson scattering

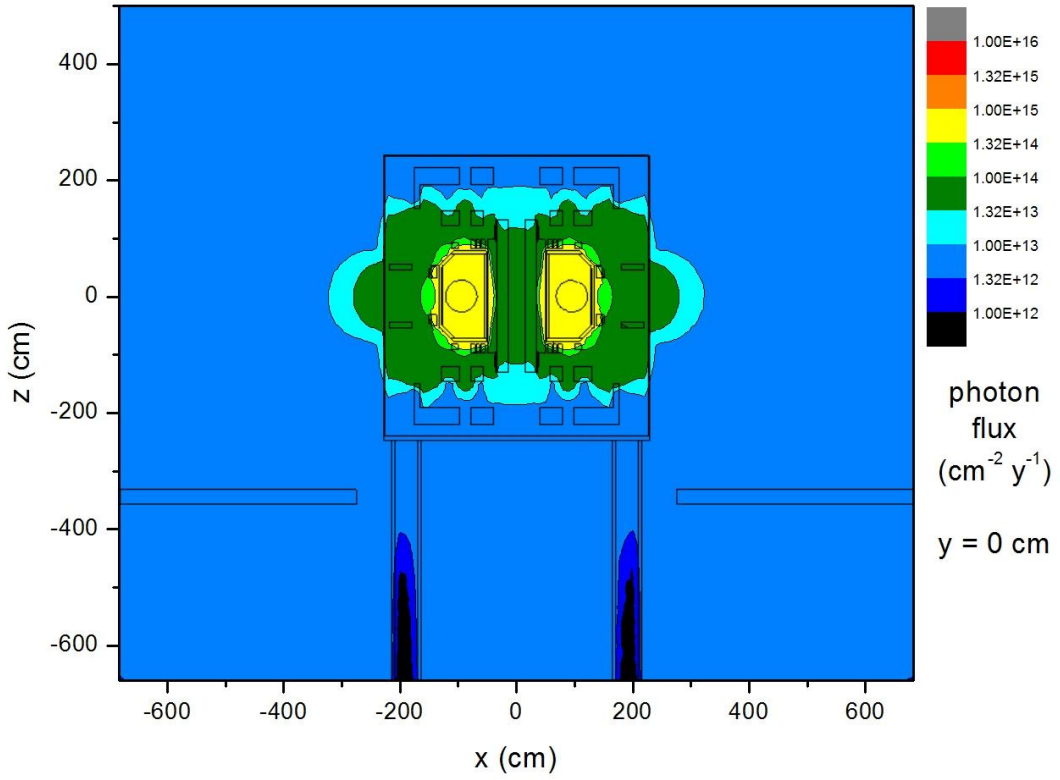
*** REQUESTED FOR THE FIRST PLASMA**



# Site preparation
## Neutronics

- The majority of ionizing radiation will come from **beam-target produced neutrons** during NBI operation.
- The expected neutron rate **$1\times10^{14}$ to $1.8\times10^{15}$ neutrons/s** (4 MW NBI)
  => yearly production of $3\times10^{18}$ 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)



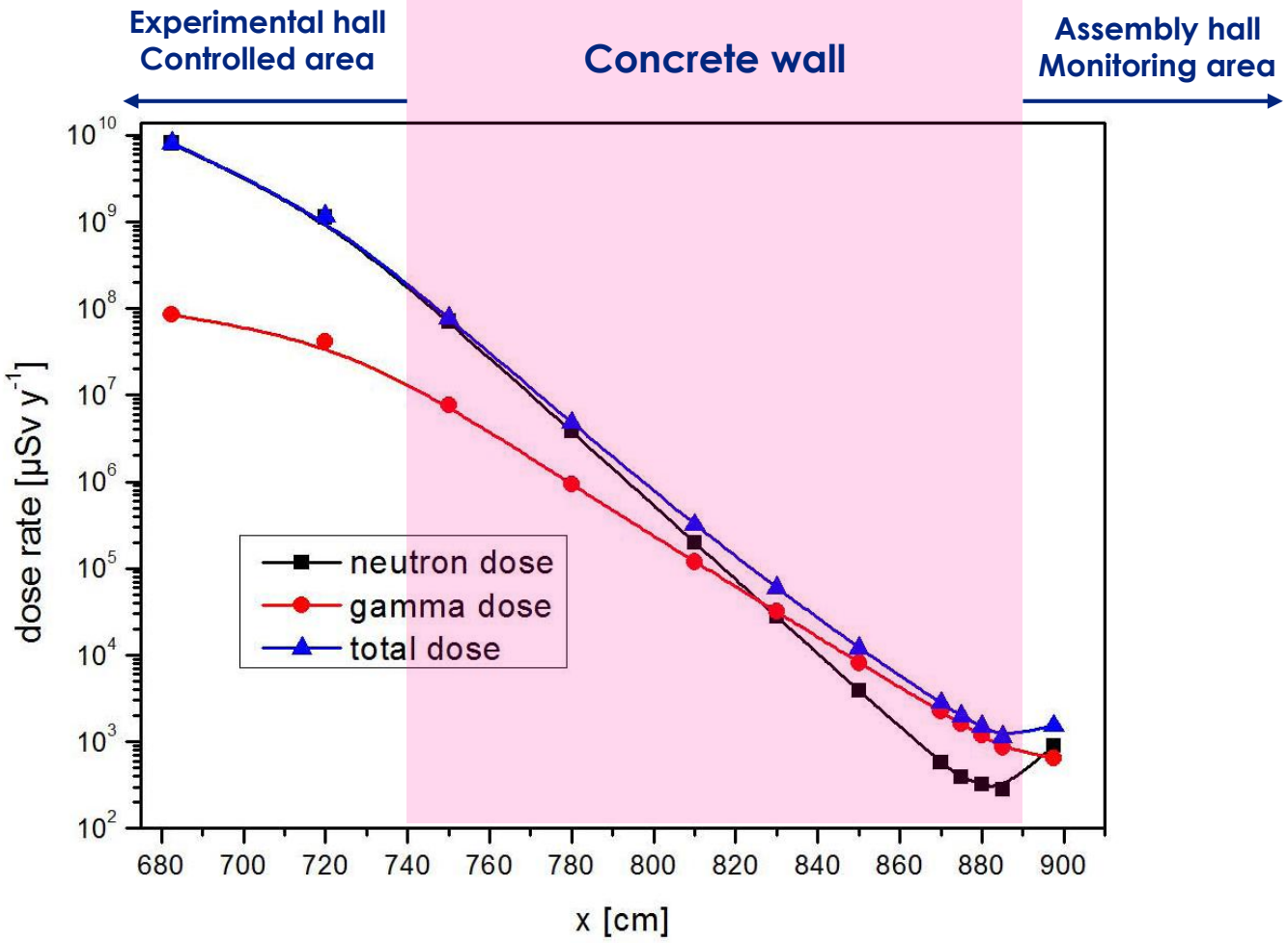
## Experimental hall radiation shielding

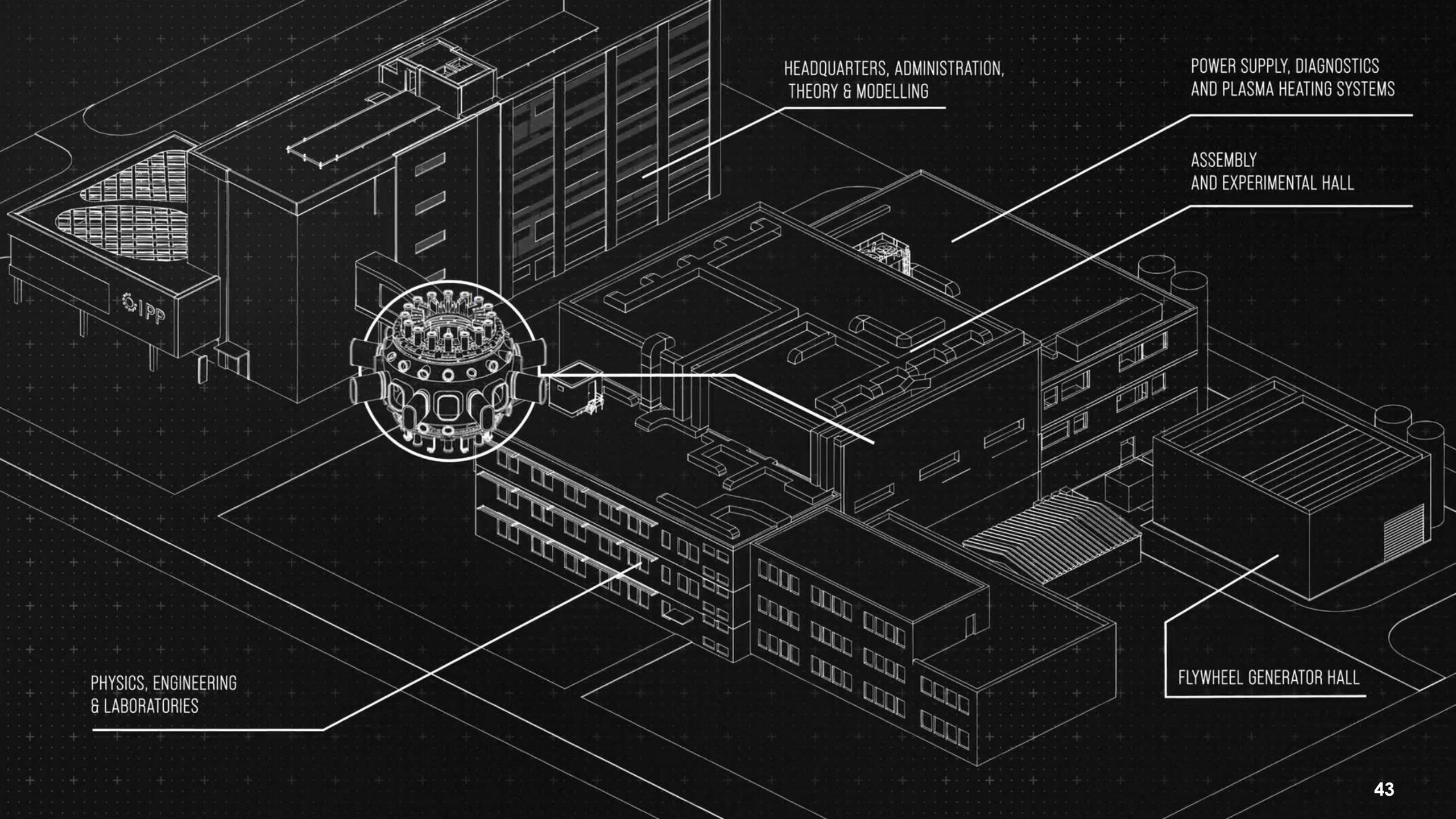
Custom concrete mixture for the shielding walls :

- **Hydrogen content >1%wt**
- **Boron content > 0,03%**

This was achieved by

- **Particular source of aggregate** – higher hydrate mineral content
- **Increased cement fraction** – binds more water in the resulting concrete
- Added **boron compound** – $B_4C$ used




HEADQUARTERS, ADMINISTRATION,
THEORY & MODELLING
POWER SUPPLY, DIAGNOSTICS
AND PLASMA HEATING SYSTEMS
ASSEMBLY
AND EXPERIMENTAL HALL
IPP
PHYSICS, ENGINEERING
& LABORATORIES
FLYWHEEL GENERATOR HALL

# Site preparation

## Construction works

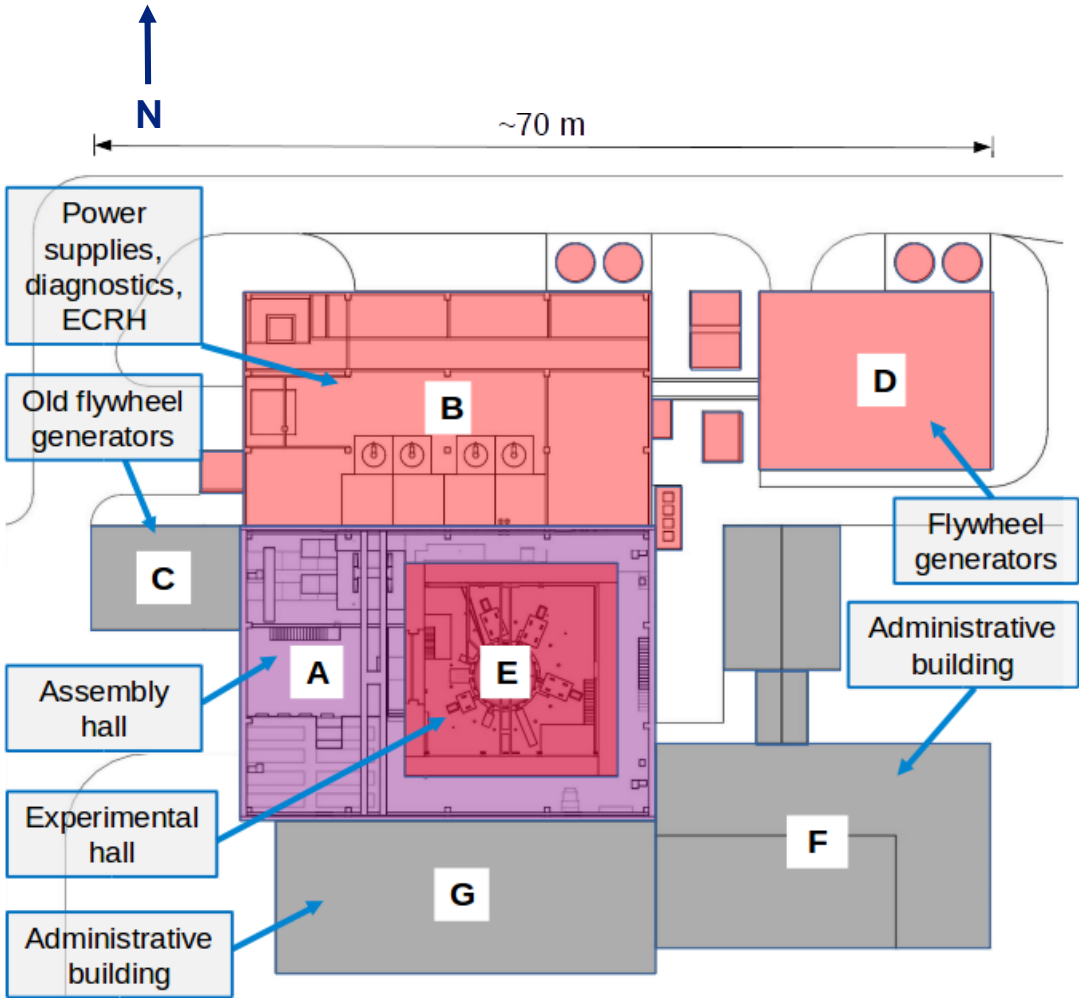
**Phase 1**: 12/2021-06/2023 ✔

- Modifications of the assembly (**A**) and experimental (**E**) halls
- Additional 90 cm of concrete (1.5 m in total) with enhanced fraction of cement and boron carbide addition for better shielding performance
- 2 sliding doors (27 tons and 11 tons)
- New 0.8 m thick base concrete slab, new concrete floor, new concrete ceiling
- Additional steel floor in the assembly hall

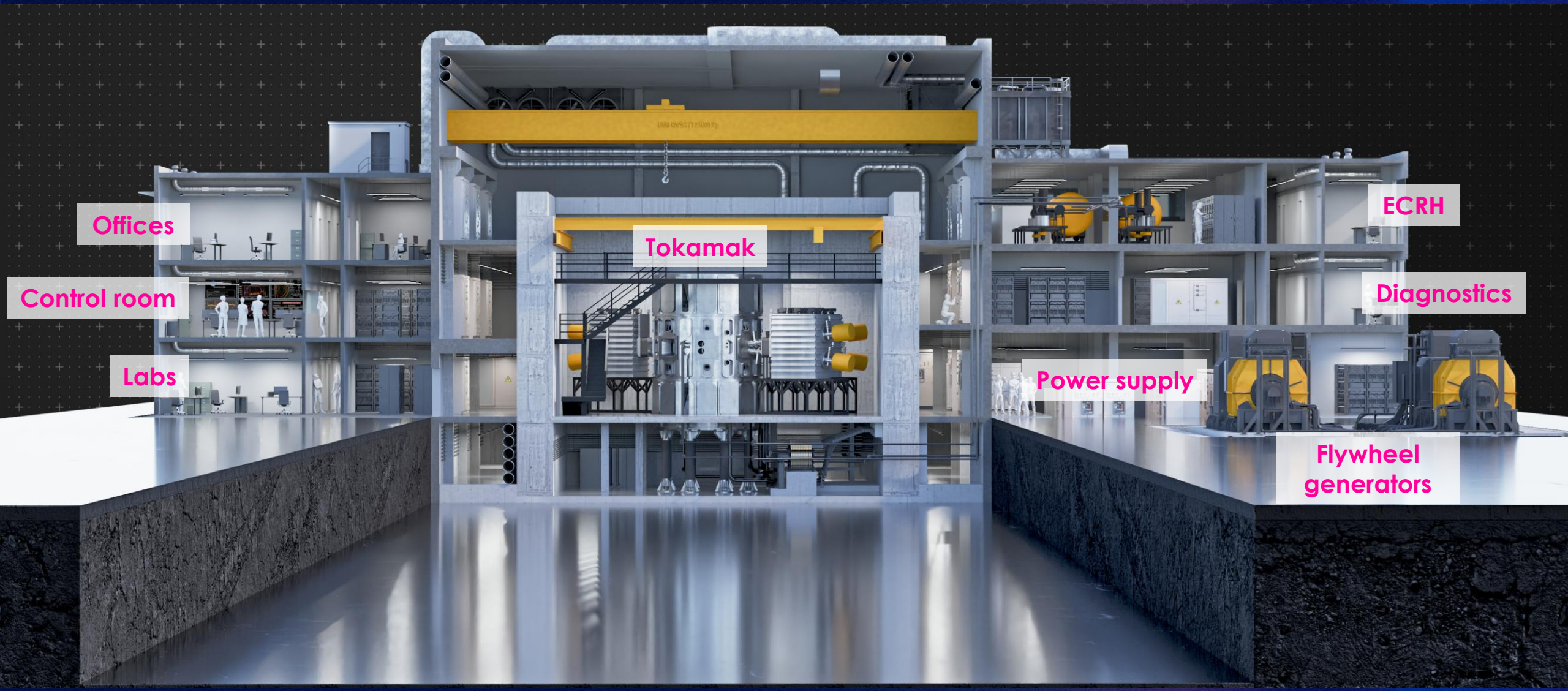
**Phase 2**: 06/2023-10/2024

- New hall for power supplies, diagnostics and ECRH (**B**)
- New hall for flywheel generators (**D**)
- New liquid nitrogen reservoirs, cooling stations, transformers etc.

**New 22 kV power line** 2024 ✔

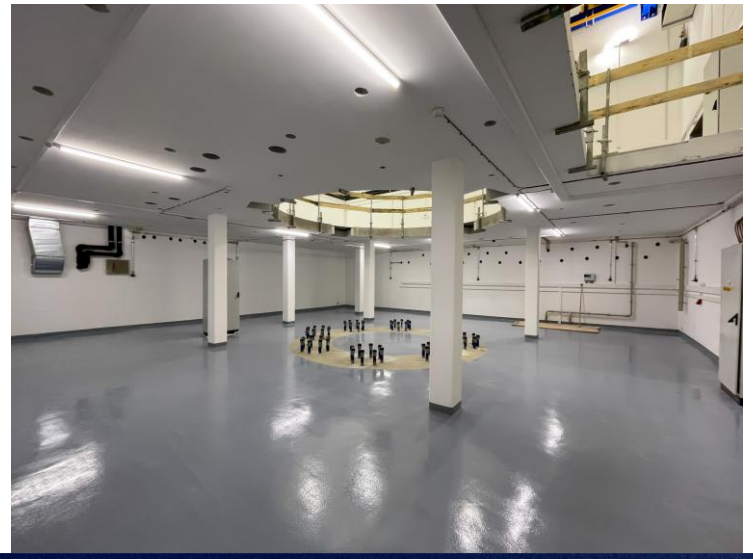


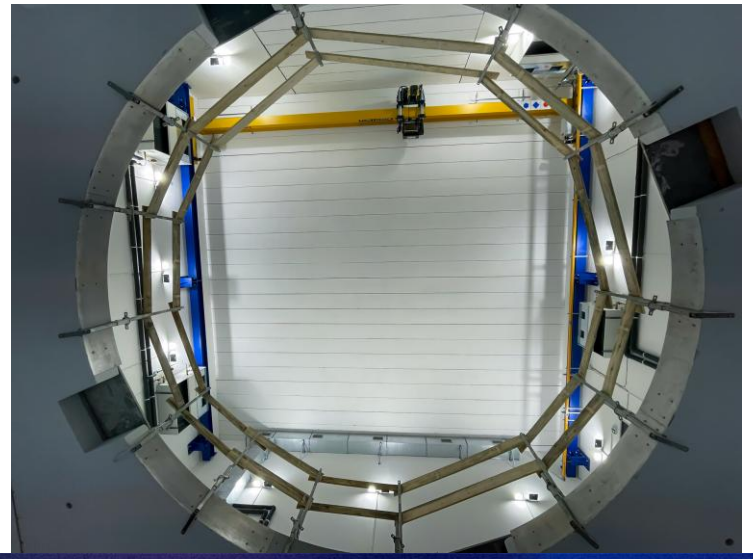
# Site overview



# Assembly and experimental halls







# Site preparation
## Ongoing civil works

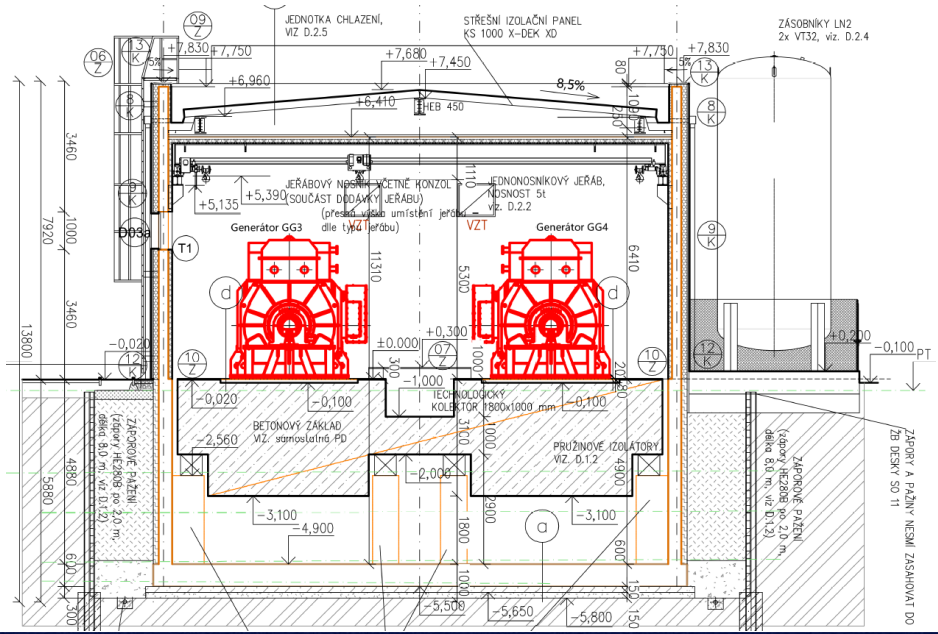
### Power Supply System, diagnostics, ECRH

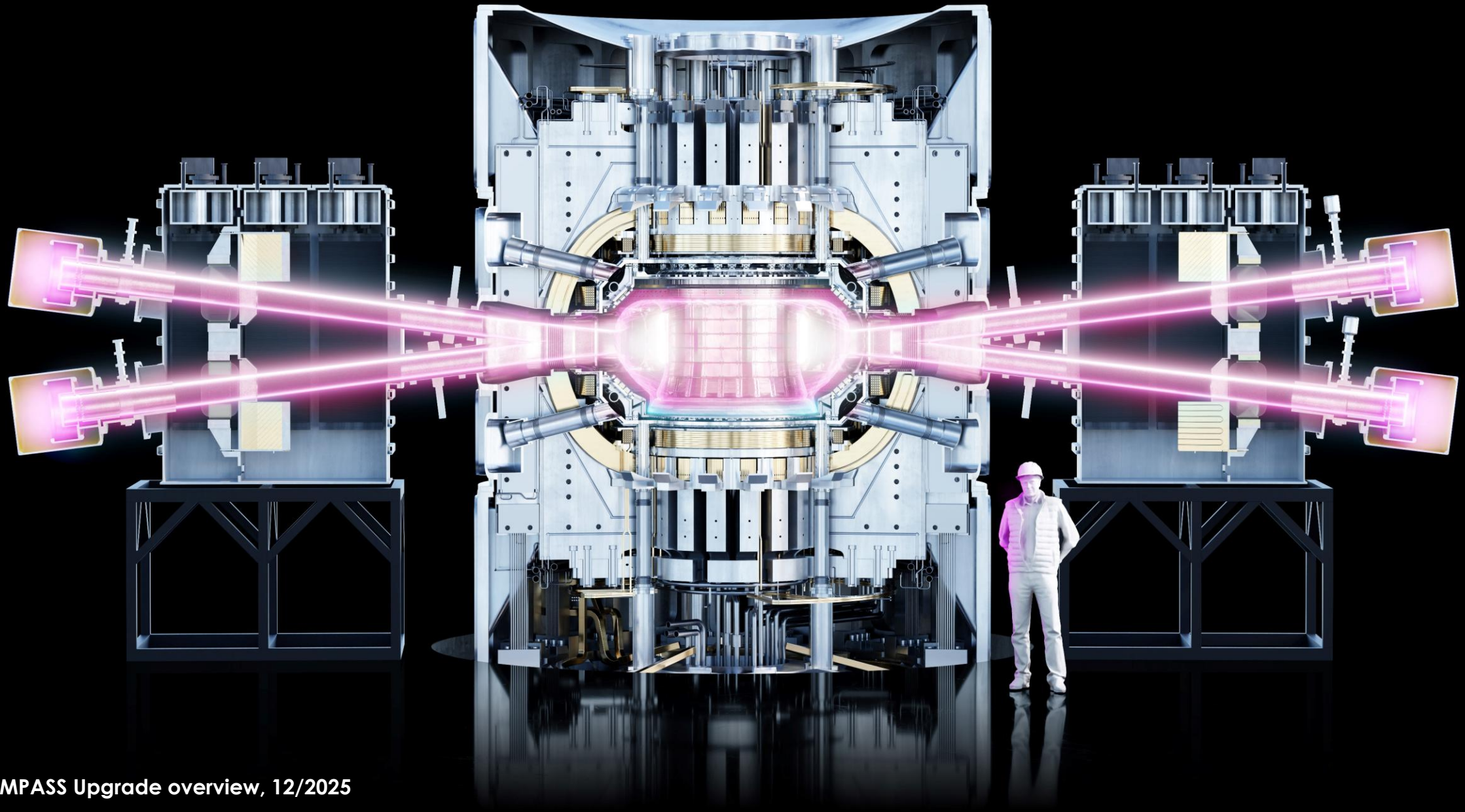
### Flywheel generators

# Site preparation
## Ongoing civil works

**Block under the new flywheel generators**

- size 13 x 14 x 3 m, **total weight ~ 1100 tons** (includng 60 tons of steel rebars)
- Floating on **24 spring boxes**
- Each flywheel connected to block with **92 rods M64** through the block (lenght of 3.5 m)

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