Design of the COMPASS Upgrade Tokamak

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Outline

- Introduction
- Basic features of COMPASS-U
- Priorities of the scientific programme
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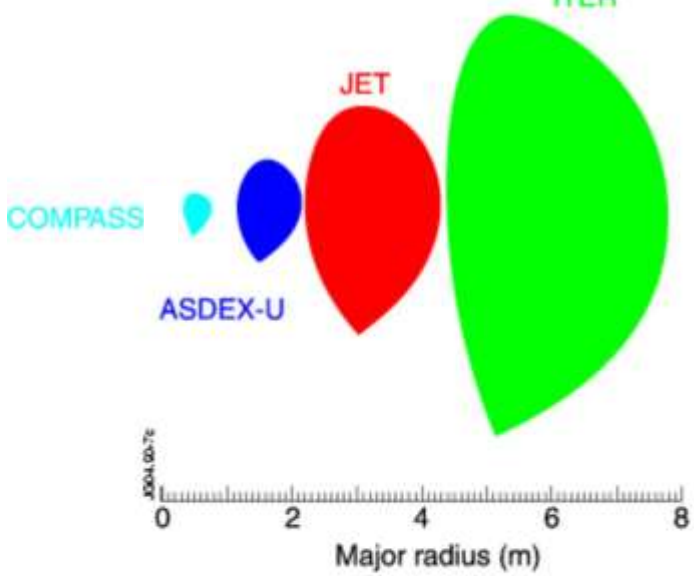
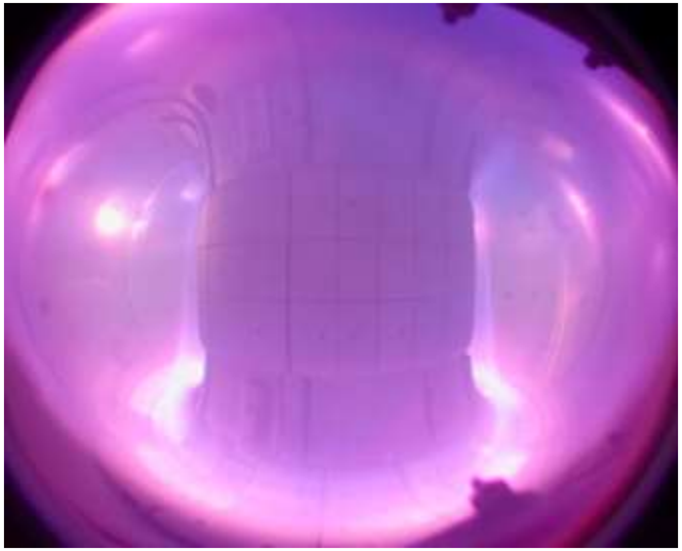
Present situation – the COMPASS tokamak

- Installation in Prague in 2006-2011 (buildings, all auxiliary systems)
- ITER-like geometry with a single-null-divertor (H, He, D) – 1:10
- Two NBIs enabling either co- or balanced injection (2x0.4 MW)
- Ohmic and NBI-assisted H-modes
- New comprehensive set of diagnostics focused on the edge, SOL and divertor plasma

Major radius [m]	0.56
Minor radius [m]	0.2
Plasma current [MA]	< 0.4
Magnetic field [T]	< 2.1
Triangularity	~ 0.4
Elongation	< 1.8
Pulse length [s]	< 1.0

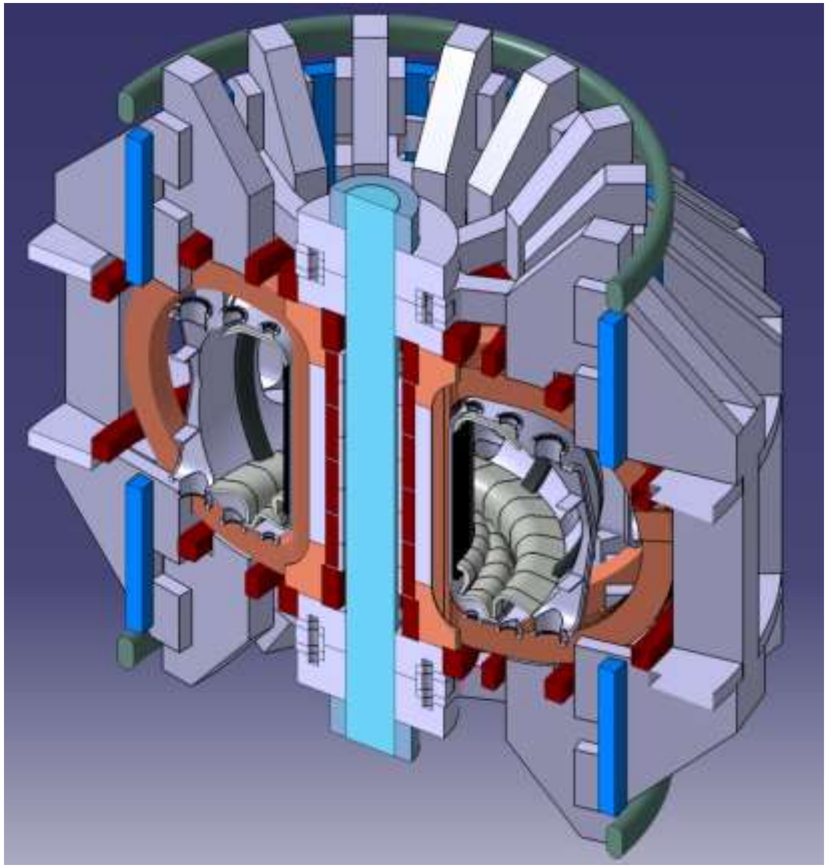




Plasma in COMPASS

Why to go for a major upgrade?

- Enlarge the operational space, improve performance, address some of the key gaps in the Plasma Exhaust Physics (PEX)
- Still keep the advantage of mid-size device with its flexibility for scalings towards ITER and DEMO
- High magnetic field device with relevant plasma geometries is missing in the European fusion programme (and world-wide after shut down of Alcator C-MOD)
- Project proposal submitted to the national call for project of new research infrastructure in the Czech Republic



COMPASS Upgrade

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Main features of COMPASS-U

- ITER and DEMO relevant geometry
- High magnetic field (5 T), high density operation (~ 10^{20} m^{-3})
- Advanced plasma configurations (double null, snow-flake)
- Closed and well diagnosed high density divertor
- Hot-wall operation (~ 300°C)
- High PB/R ratio (PB/qAR ratio)
- High power fluxes in the divertor (λ_q ~ 1 mm)
- Possibility to study physics of advanced modes (QH-mode, I-mode, EDA-mode, etc.)
- Possible future installation of Li vapour box divertor systems

High capability to address the key Plasma Exhaust Physics challenges

Basic parameters of COMPASS-U

Basic dimensions and parameters:

R = 0,84 m

a = 0,28 m

B_T = 5 T

I_p = 2 MA

P_{NBI} = 4-5 MW

P_{ECRH} = 4 MW (170 GHZ)

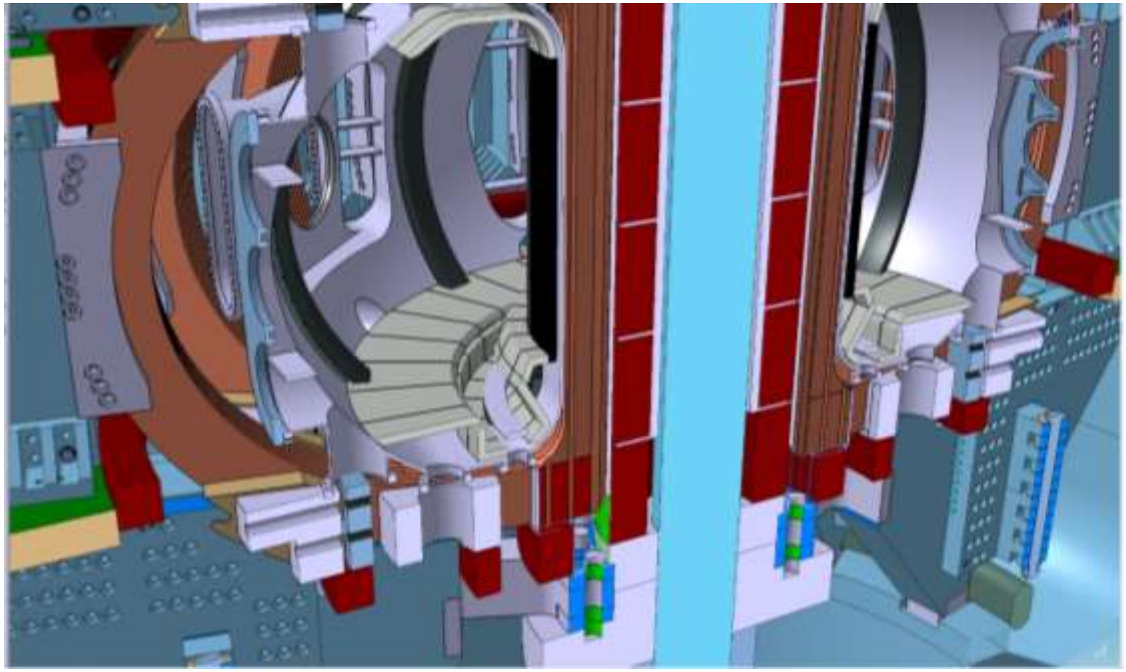
Triangularity up to 0,6

Plasma volume ~ 2 m^3

Discharge length 1-5 s

<Te> ~ <Ti> ~ 2,5 keV at high density

$n_G \sim 8 \times 10^{20}\ m^{-3}$



View inside COMPASS-U

- Metallic first wall device
- High-temperature operation (~ 300°C)

ITER relevant heat fluxes

ITER relevant parallel heat flux:

$q_{||} \sim P_{SOL}\ B_T/R$

ITER relevant power decay length:

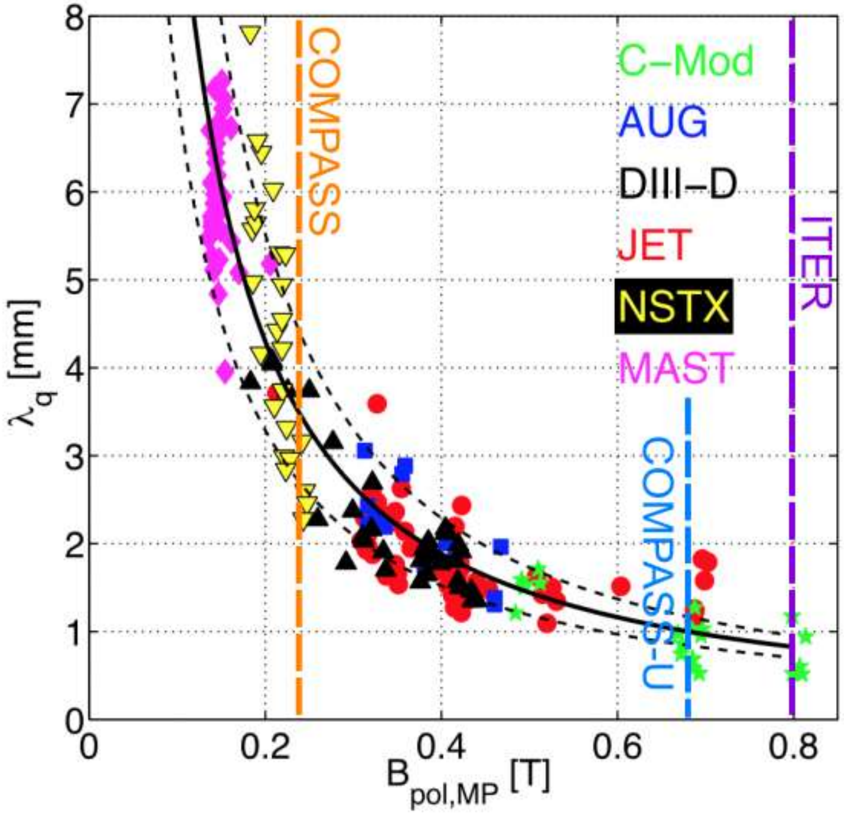
COMPASS-U (I_p= 2 MA):

B_{pol} = 0.7 T => $\lambda_q \sim 1$ mm

$P_{strike\text{-}points} \sim 15 – 20$ MW/m^2

$P_{SOL}\ B_T/R \sim 44$

$P_{SEP}\ B_T/qAR \sim 5$ (70% of ITER)



Eich scaling

Heat fluxes high and long enough to melt thin layer of the tungsten divertor tiles => study of related issues

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Priorities of the Scientific Programme

1. Conventional divertors

- **Experimental demonstration of detached operation (impurity seeding) at ITER/DEMO relevant power fluxes**
  - detached conditions on the divertor power decay length + in/out asymmetry
  - Ratio **PB/(qAR)^{COMPASS} = 5** *(=70% ITER)* **+ hot walls** (300^{o}C) **= reactor conditions**
    - influence of T^{wall}/recycling on SOL profiles (and related physics), operation and core performance
  - controlled melting exp. & comparison w/ codes (MEMOS), optimization of PWI
- **slow/fast transients, 3D perturbations**

2. Snow-flake divertor

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

- identification & demonstration of advantages (peak heat flux reduction, detachment threshold, cross-field transport etc..):
- acceptable response to slow/fast transients (reduced impact), 3D perturbation:
- Impact of snowflake configuration on core scenarios (pedestal, etc.)

3. Alternative materials

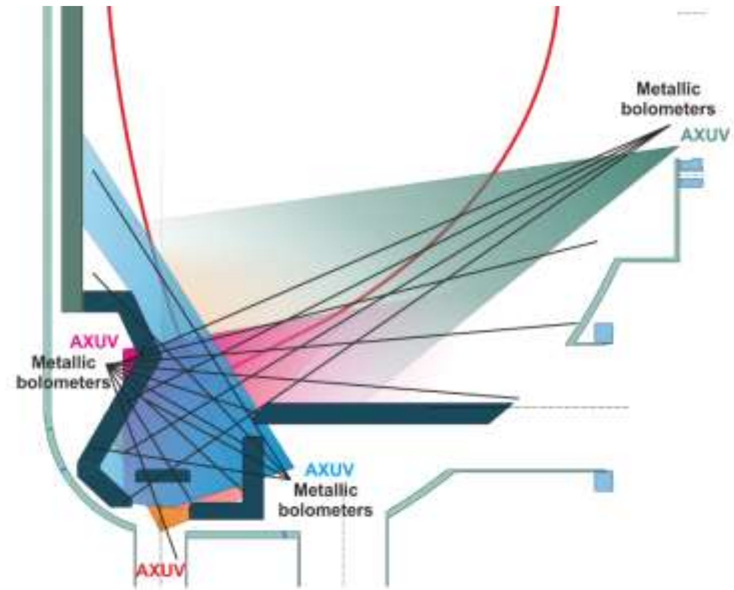
Qualification of suitable liquid metal (CPS), compatibility with main/divertor plasmas in steady-state & transients

Dedicated sample holder in the divertor at one toroidal location (→ possibility of full toroidal ring in a later stage).

- Effect of liquid metal on the divertor, comparison of heat fluxes on solid/liquid metals.
- Response to high heat flux & transient (RMPs).

Test of new concepts for plasma exhaust based on volumetric dissipation (Lithium vapor box) can be performed in a later stage.

Operation with high divertor neutral pressure and low chamber pressure



Tomography of radiated power in divertor

4. Edge plasma physics and confinement related activities

Edge plasma physics and confinement:

Edge turbulence, L-H transition, pedestal dynamics (understanding & scaling), link between upstream and downstream physics, low torque operation, enhanced confinement modes (QH-, I- and EDA-modes) + disruptions/toroidal asymmetry.

Validation of theoretical models:

The unique parameter space of COMPASS-U (ITER/DEMO relevant parameters) provides significant possibilities for validating theoretical/numerical models (from 1st principles physics to empirical scaling laws).

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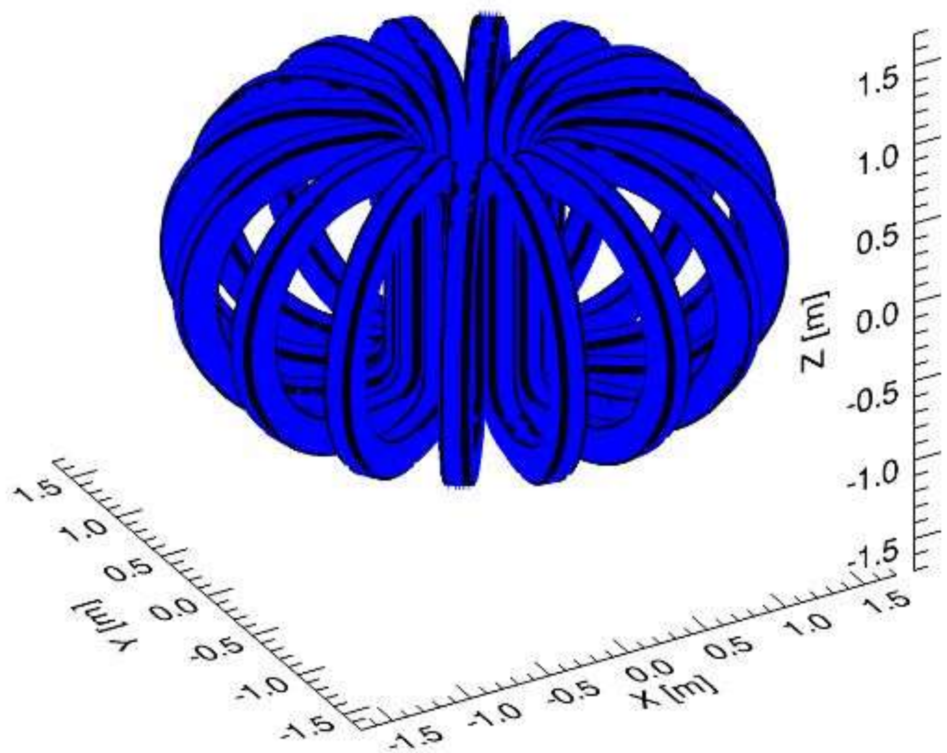
Toroidal Field coils

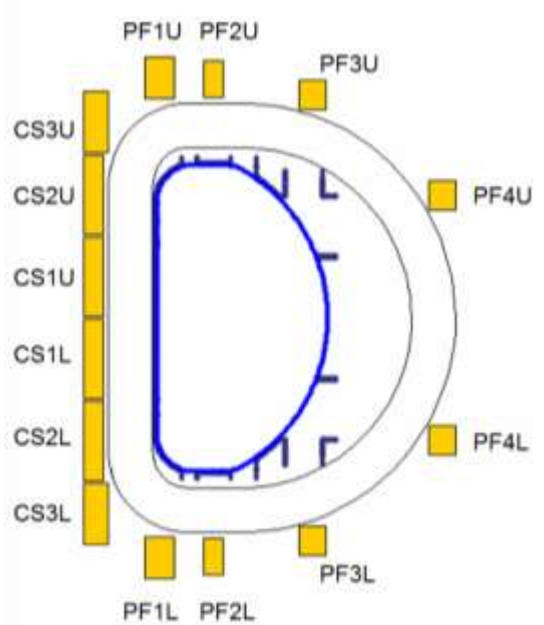
- 16 TF coils with 7 turns each and current 187.5 kA.
- 9 T on the High Field Side
- toroidal ripple similar to ITER ($\delta < 0.5\%$).
- Energy consumption ~ 130 MJ
- TF coils power inlets will be separated for even and odd TF coils => variable ripple.
- total force acting on one TF coil is 6.5 MN, i.e. 650 tonnes.
- TF coils resistance 0.65 mΩ at LN2 temperature and self-inductance 4.65 mH.



COMPASS-U tokamak TF coils reference design

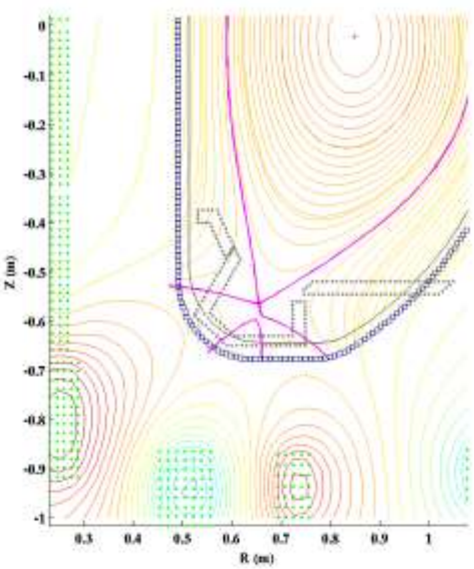
Poloidal Field Coils System

- possibility to create plasma with ITER-like shape (and higher triangularities)
- flexibility to create different plasma shapes, including double-null and snowflake
- additional pair of PF coils at R = 0.725
- Passive stabilization coils are expected to be needed. These will be in-vessel.



PF coil system

Conventinal single-null divertor

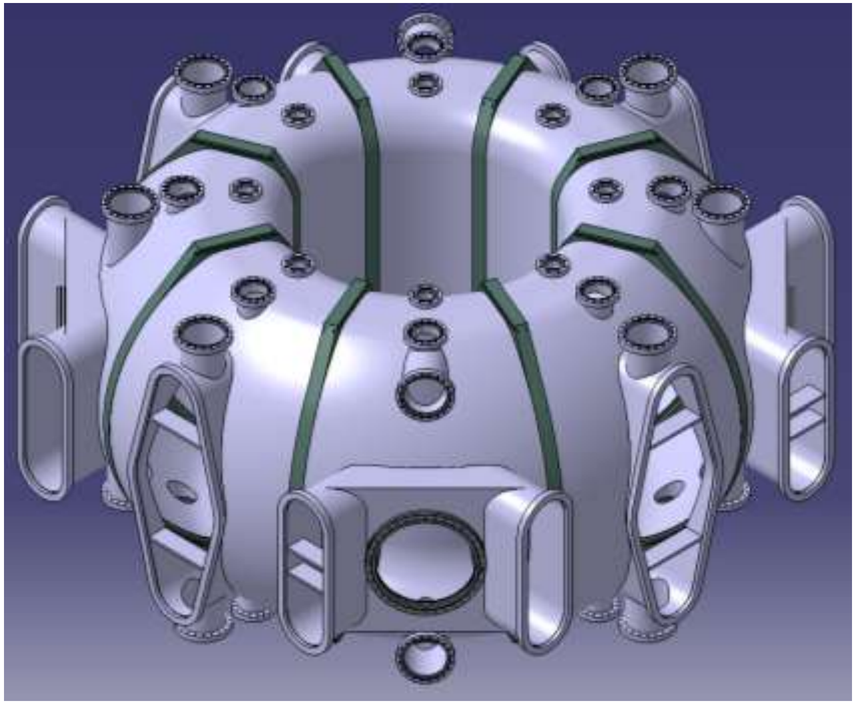


Snow-flake divertor

The same diveror design can be used to compare conventional and snow-flake configurations(at least up to Ip ~ 1 MA)

Vacuum vessel

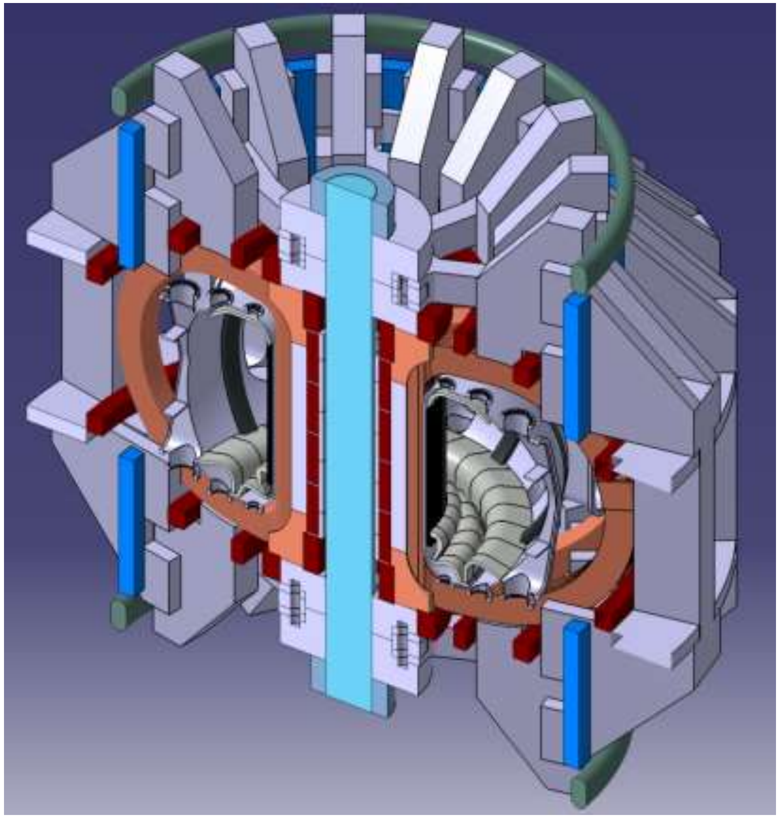
- Material - 10 mm AISI 316 L (or inconel)
- Large ports for
  - NBI access
  - human access
  - diagnostic access
  - Divertor part exchange
- High EM forces
- Operation at least at 300°C
- First wall, limiter and divertor material – combination of W-coated stainless steel/molybdenum and bulk tungsten



General view on the vacuum vessel. Three types of octants are connected by vessel holding rings (dark green).

Support structure (1/2)
Requirements

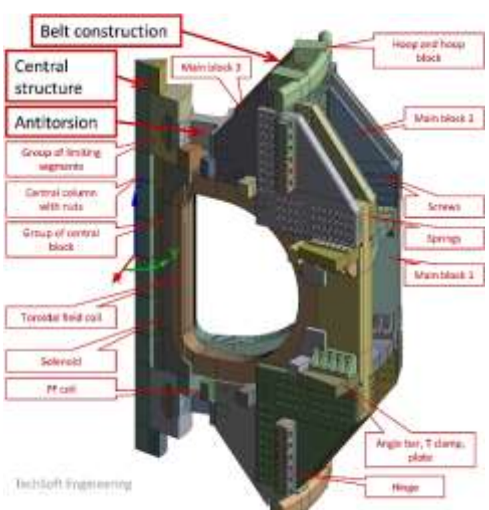
- Support Structure was designed taking into account the PF coils positions
- Needs to resist tremendous forces (650 tonnes from each TF coil)
- Industrially standard parts to keep the project cost as low as possible – e.g., steel sheets with widths up to 200 mm
- Designed to accommodate tangential NBI access, other auxiliary heating systems and for the required diagnostics.



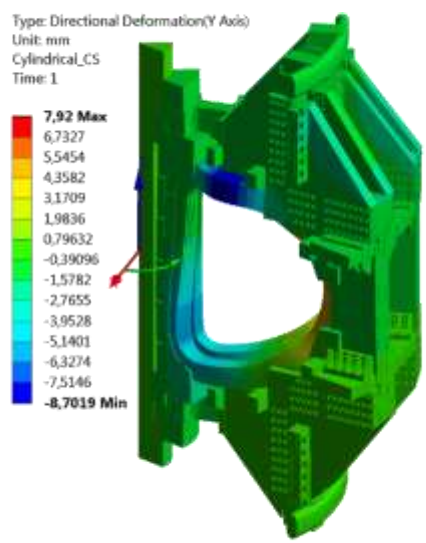
COMPASS-U support structure

Support structure (2/2)
Numerical Analysis

- CATIA preliminary Support structure model imported into ANSYS
- EMG analysis to obtain forces for 4 scenarios
- 1/8 of tokamak modelled, toroidal symmetry
- 1 081 000 elements, 2 098 000 nodes
- Design satisfactory, further improvements under way

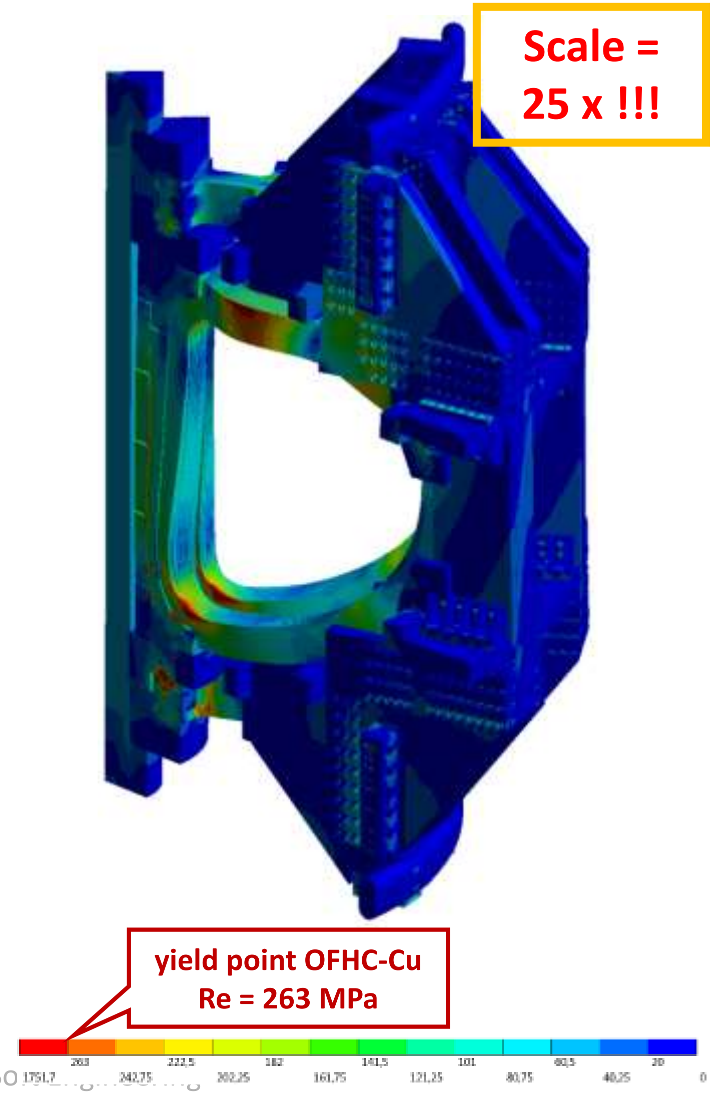


Main parts of the support structure



Tangential displacement

Mechanical stress [MPa]:



Power supply system Upgrades

Requirements for COMPASS-U:

- TF coils: 70 MW, 130 MJ
- PF coils: <90 MW, <110 MJ
- Additional heating and reserves: 70 MW, 150 MJ (for later increase of additional heating)
- In total: 180-230 MW, 300-400 MJ

Energy storage:

- Optimize operation of existing flywheel generators (rotation speed) => higher energy.
- two new flywheel generators (80 MW, 100 MJ each).

Toroidal Feld coil system:

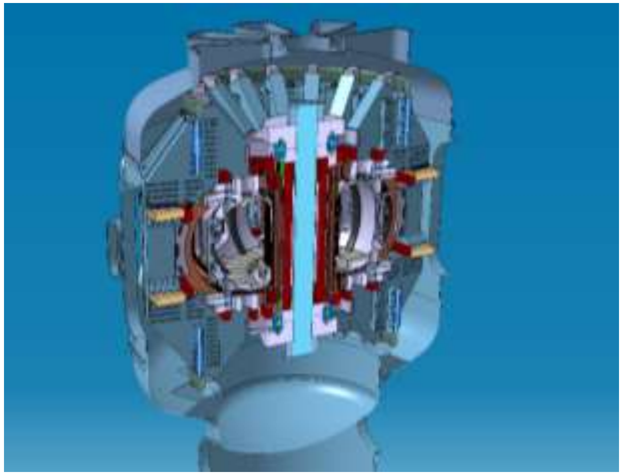
- Use of parallel operation of existing flywheel generators
- All existing thyristor converters + 6 new blocks
- 4 new transformers for the Power supplies of the TF winding.

Poloidal field coil system (and additional heating)

- Two new generators (80 MW, 100 MJ each) + 2 new transformers (100 MVA)
- new converters based on the IGBT transistors supplied from two common DC links.

Cryostat and cryogenics

- high operational temperature of the plasma facing components and simultaneously achieved cryogenic temperatures of the rest of the tokamak.
- a large amount of energy (~120 MJ) will be deposited into the tokamak PF and TF coils during the discharge.
- A vacuum cryostat necessary
- The closed He loop will allow us to cool PF coils below liquid nitrogen temperature if required.
- The target cooling power is approximately 30 kW.
- The cryogenerator will be designed as a modular device



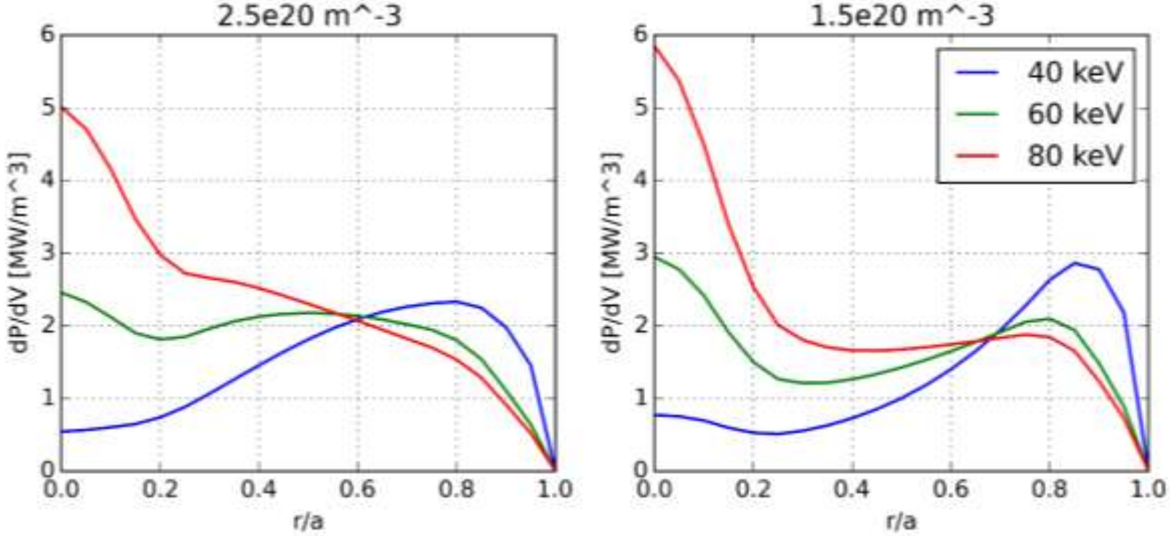
Conceptual design of the cryostat

Stirling SPC-4 Helium Refrigeration System

NBI additional heating

New NBI units:

- Neutral Beam Injectors
- high voltage power supplies,
- control and safety systems
- closed loop helium cryocoolers



Parameters:

- 2 x 2MW units
- 60-80 keV energy
- Hydrogen, helium, deuterium
- Co- or balanced injection

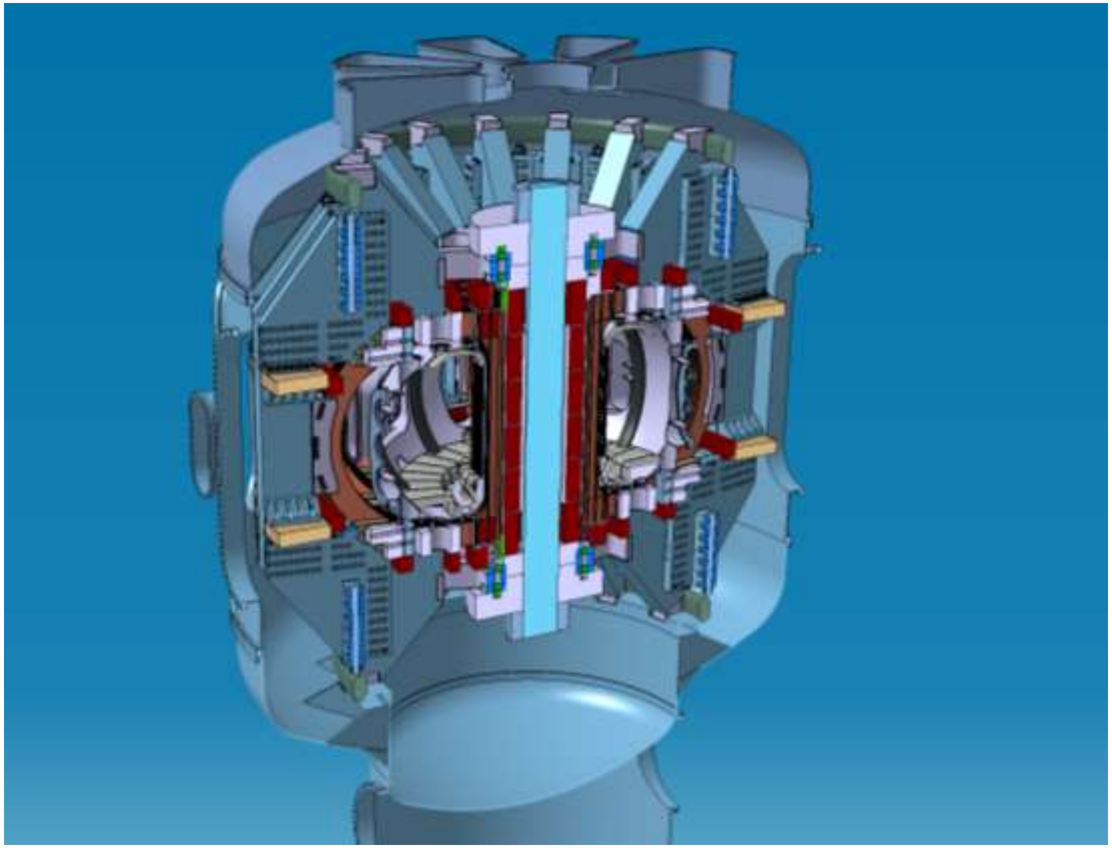
Deposited power density of a neutral beam with different energies in 2 MA plasmas with line averaged densities 2.5×10^{20} m^{-3} (left) and 1.5×10^{20} m^{-3} (right).

- Horizontal Tangential ports (200 mm width, 600 mm height)

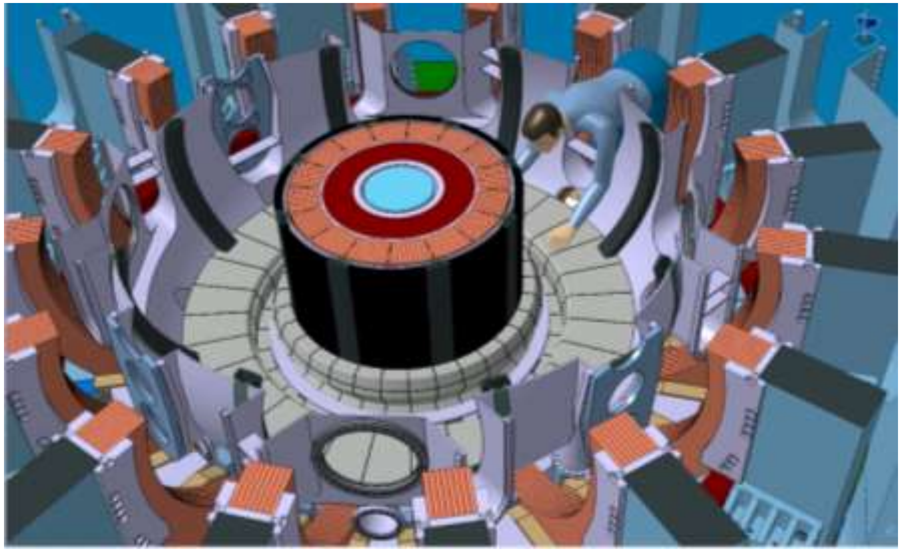
ECRH system

- ECRH is currently the most reliable and flexible heating and current drive option for tokamaks.
- COMPASS-U will operate at 5 T and thus the same ECRH frequency as ITER—170 GHz—is required.
- 2 – 4 secs pulses
- plasma heating and on/off axis current drive for core performance control.
- The cut-off density for the 170 GHz O-mode is 3.6×10^{20} m^{-3}, which is $0.44 n_{GW}$ at 2 MA and $0.88 n_{GW}$ at 1 MA current. => compatible with significant Greenwald fractions even at the highest plasma current.

Cryostat and human access



Cryostat and the support structure assembly

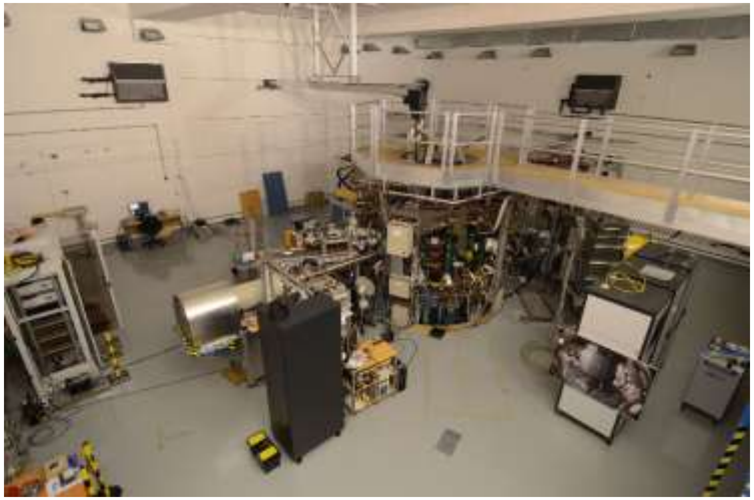


Human access into the vacuum vessel

COMPASS infrastructure

Tokamak building

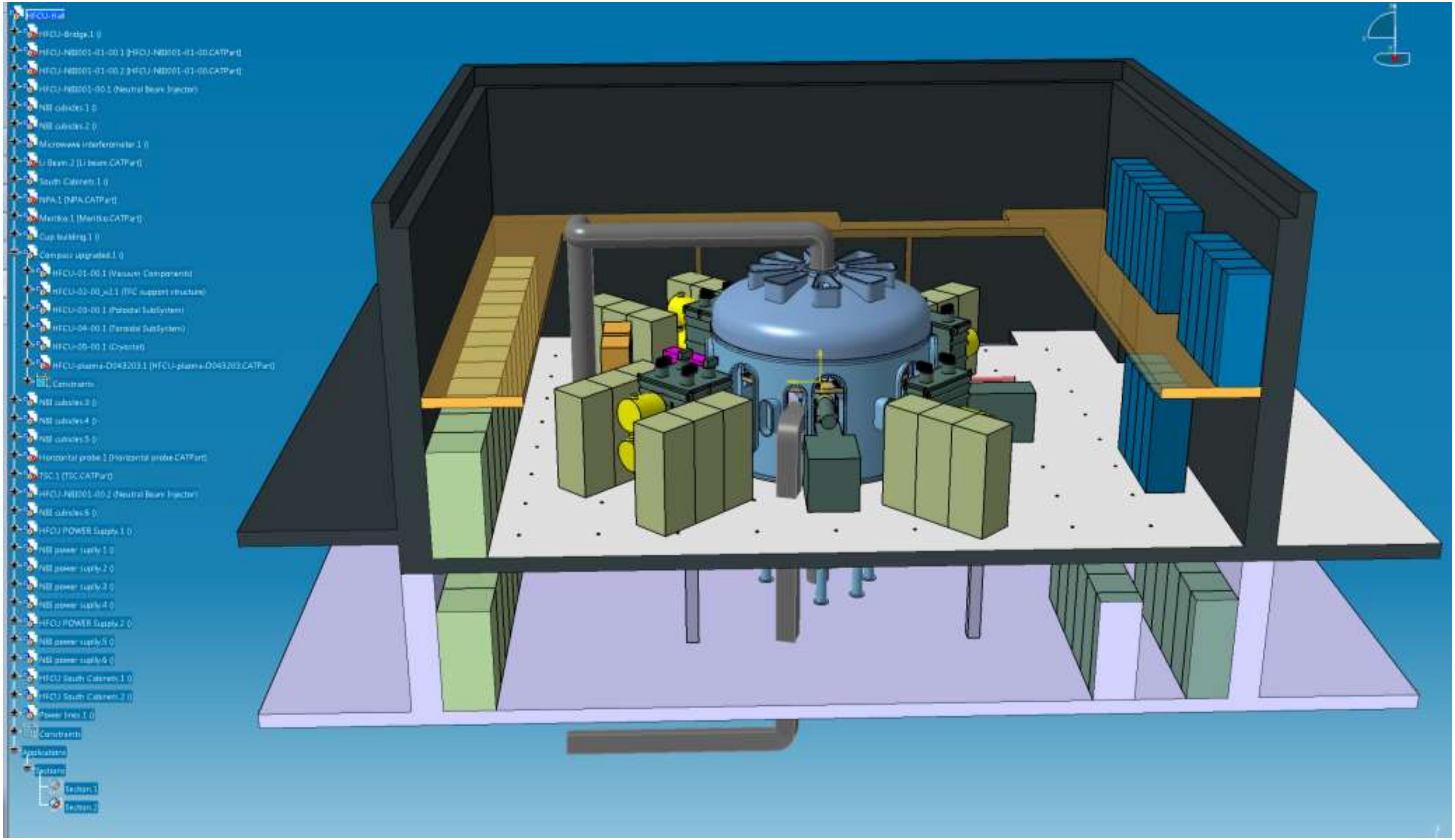
Tokamak building



View inside the COMPASS torus hall

View inside the COMPASS torus hall

Location of tokamak



Diagnostics on COMPASS-U

- benefit from diagnostics built recently for COMPASS – necessary upgrades (minimum cost & maximum gain)
- diagnostics focused mainly on edge, SOL and divertor regions
- fast data acquisition system available (over 1000 channels already available, 2/5/12 MSa/s)
- modern / state-of-art (installed in 2009 - 2014)
- strong international collaboration on diagnostics development, operation and exploitation

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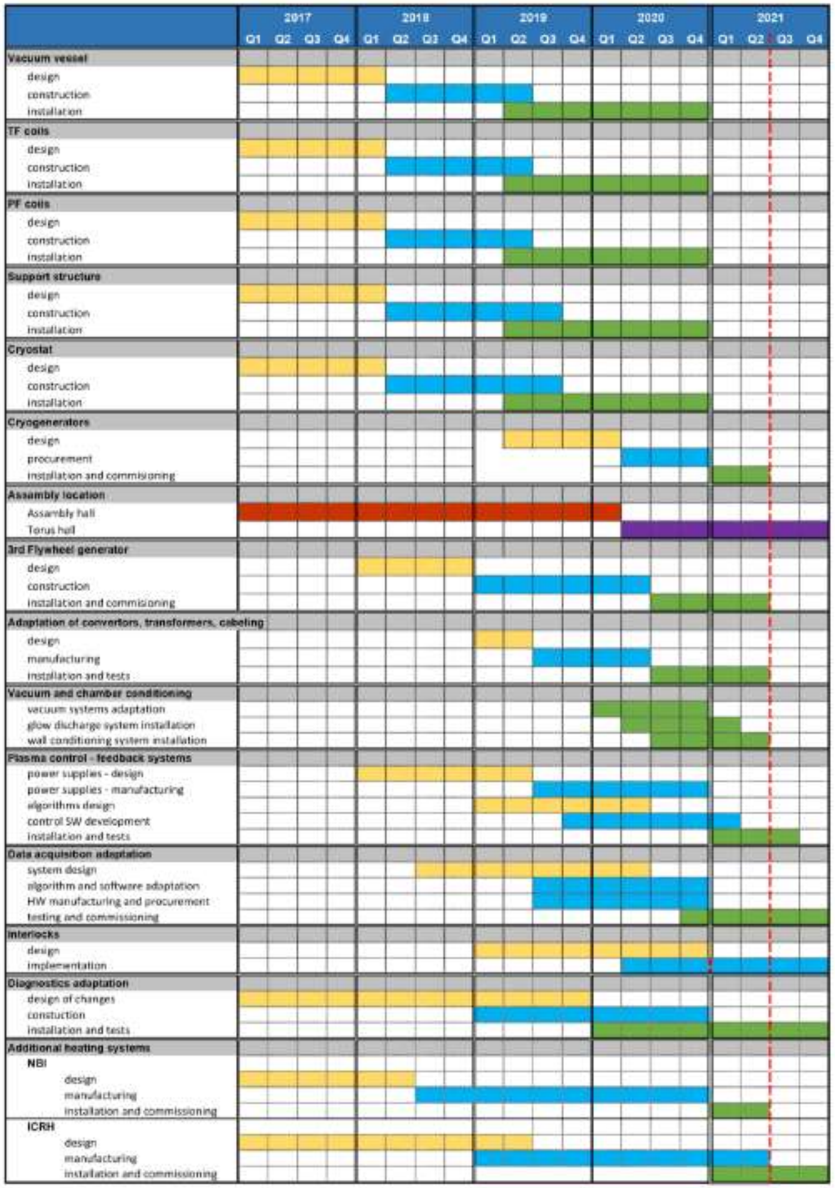
Indicative timetable



Key milestones:

Conceptual design	2016
Design of the components	2016 - 2017
Vessel, support structure manuf.	2018 - 2019
PF and TF Coil manufacturing	2018 - 2019
NBIs manufacturing	2017 - 2020
Assembly and installation	2019 - 2020
First plasma	2021/2022

Timetable depends on availability of the national funding.

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Conclusion

- The COMPASS-U design offers a wide (in many ways unique) parameter range and a high flexibility of operation to enabling to address some of the key issues in the field of plasma exhaust as well as to contribute significantly to other priorities of the EU fusion programme in a cost-effective way.
- Start of operation at the end of 2021
- Broad participation of the European and international partners in exploitation is expected and will be very welcome