Università degli Studi di Padova – Dipartimento di Ingegneria Industriale

Corso di Laurea in Ingegneria dell'Energia

Mechanical and electrical integration of the DTT divertor in the vacuum vessel

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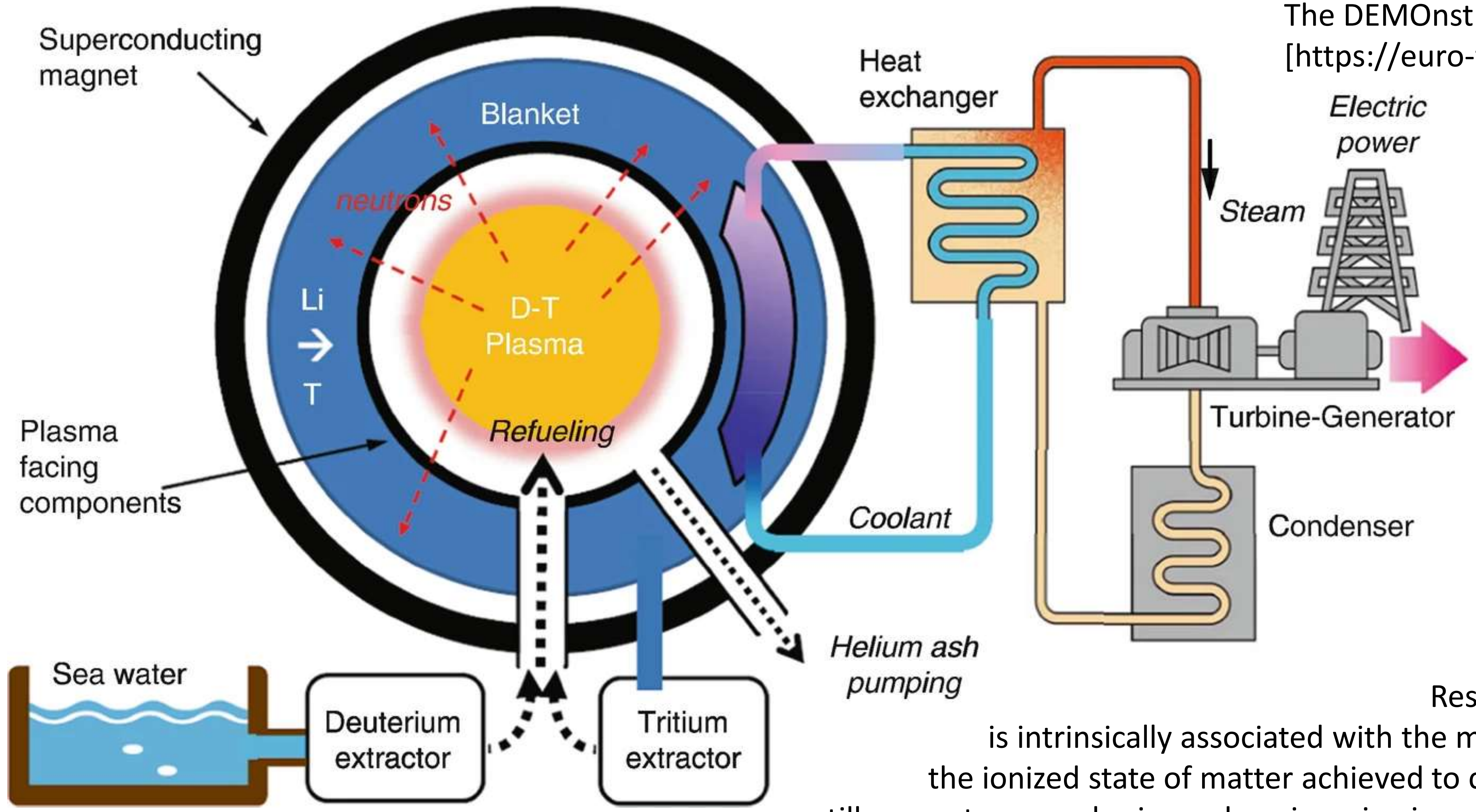
NUCLEAR FUSION POWER PLANT

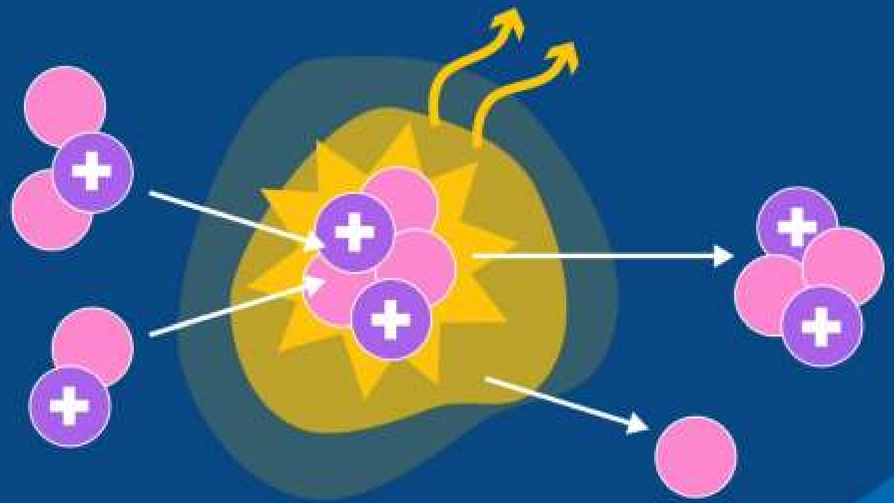
The DEMOnstration reactor is under design [https://euro-fusion.org/programme/demo/]

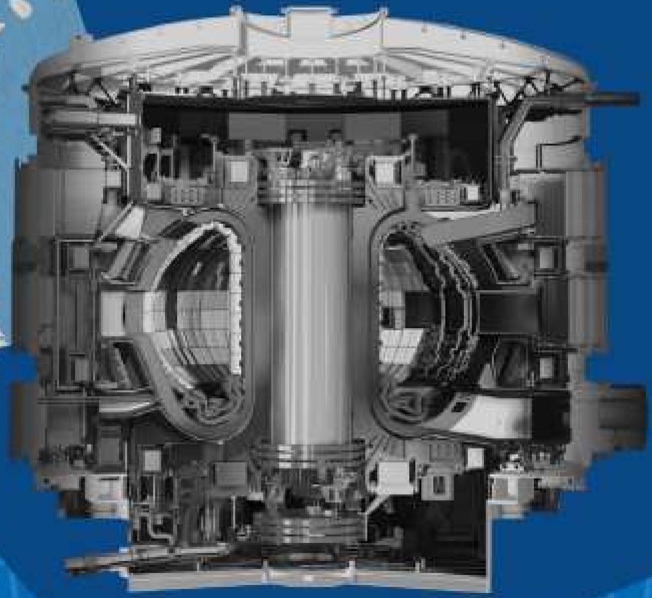


[H. Yamada, Handbook of Climate Change Mitigation and Adaptation. Nuclear Fusion. 2021, https://doi.org/10.1007/978-1-4614-6431-0_31-3]

Research on fusion energy for civil uses is intrinsically associated with the magnetic confinement of the plasma, the ionized state of matter achieved to carry out fusion reactions and which still presents open physics and engineering issues. In a magnetic fusion power plant, as well as in current experimental machines, thermal powers of the order of several hundred MW and power densities of the order of tens MW/m^2 will be deposited from the plasma edge to the plasma facing components, the divertor and the first wall or blanket.

The Main Fusion International Challenge: ITER Machine in Cadarache (France)





1. Achieve a deuterium-tritium plasma in which the fusion conditions are sustained mostly by internal fusion heating
2. Generate 500 MW of fusion power in its plasma for long pulses
3. Contribute to the demonstration of the integrated operation of technologies for a fusion power plant
4. Test tritium breeding
5. Demonstrate the safety characteristics of a fusion device

[https://www.iter.org/sci/Goals]

Objectives

The main objectives of the study are:

1. Development of a global method for verification of the mechanical designs and alignment of as built components to verify the plasma-wall clearance by limiting assembly asymmetries in magnetic fusion machines
2. Introduction of compensation members in the dimensional chains and verification of tolerances of manufacturing processes in magnetic fusion machines
3. Application of the developed method to the DTT facility

   The global method is applied for the first time during the design phase

THE DIVERTOR TOKAMAK TEST (DTT) FACILITY

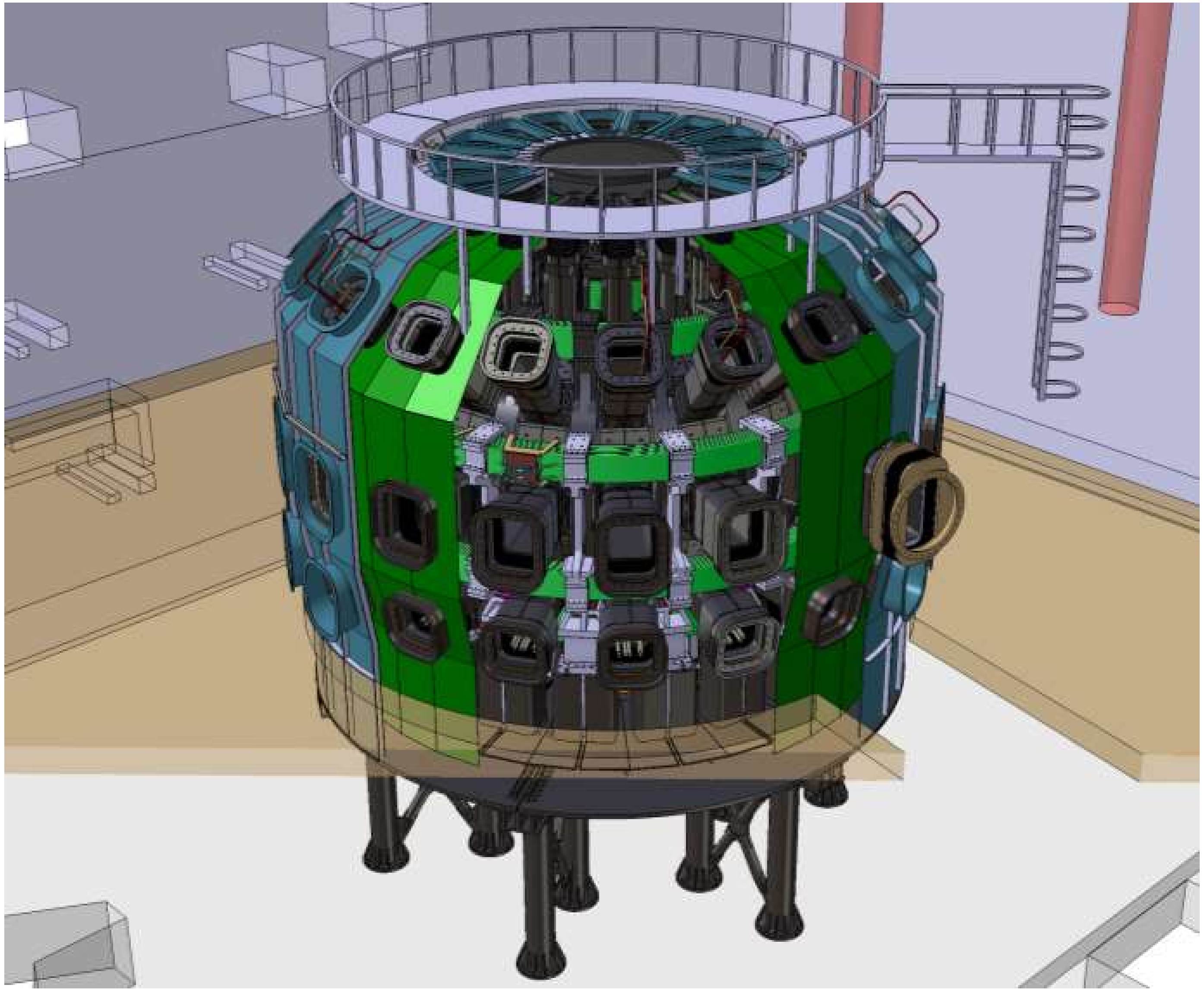
The Divertor Tokamak Test (DTT) facility is a new fusion device under construction in Frascati, Italy with:

- 6 T on-axis maximum toroidal magnetic field
- plasma current up to 5.5 MA
- pulses with total duration up to 100 s.

The D-shaped vacuum chamber is able to host a plasma with major radius R=2.19 m, minor radius a=0.70 m and average triangularity 0.3.

DTT is a divertor facility designed to accommodate a variety of divertor configurations, both in single and double null scenarios, in regimes where core and edge are in conditions of reactor-relevant power flow. In this context, DTT is designed to investigate high performance tokamak physics and to address core confinement to offer an integrated solution to this crucial aspect.

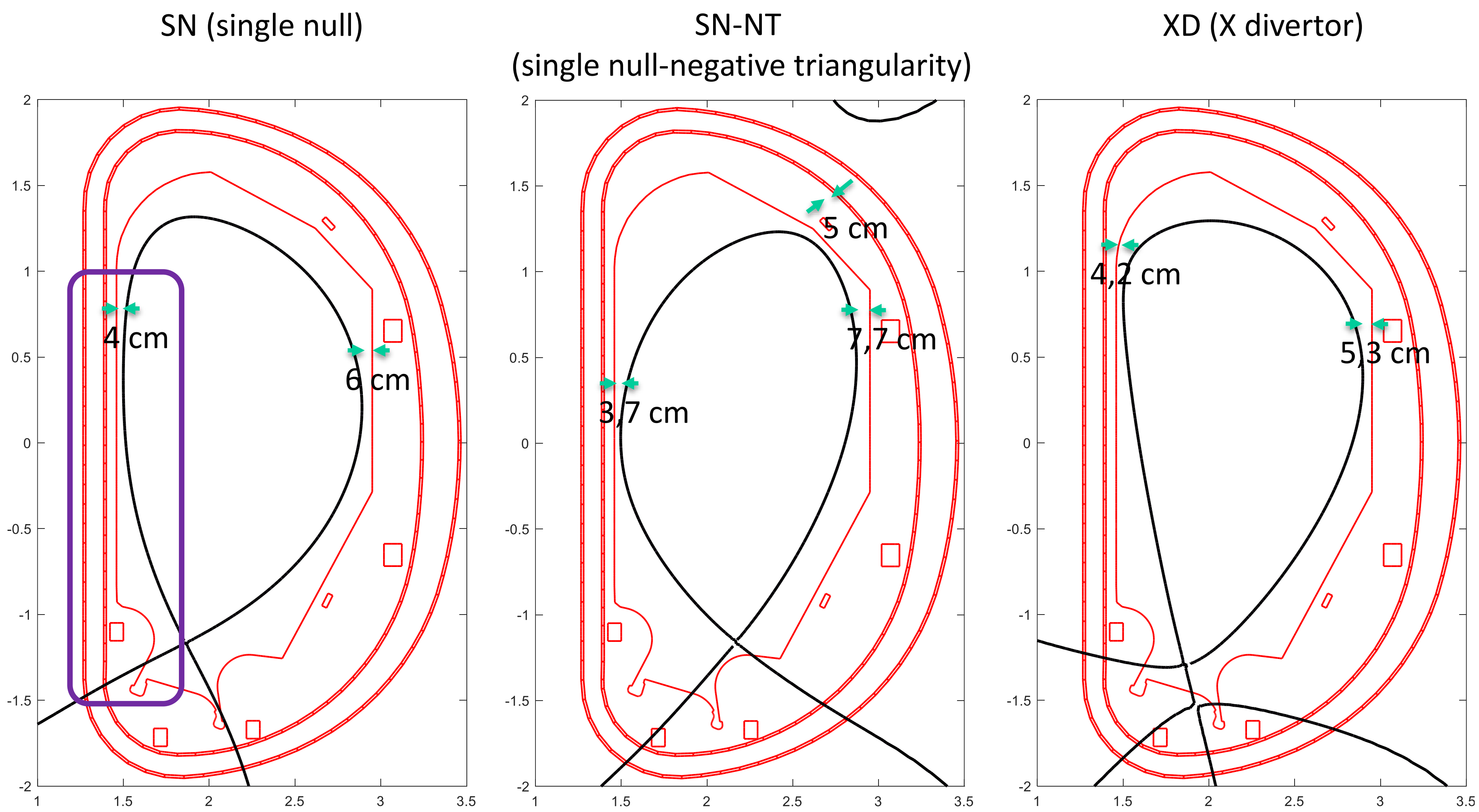
[https://www.dtt-project.it/index.php/about/what.html]



CAD view of the Divertor Tokamak Test (DTT) facility

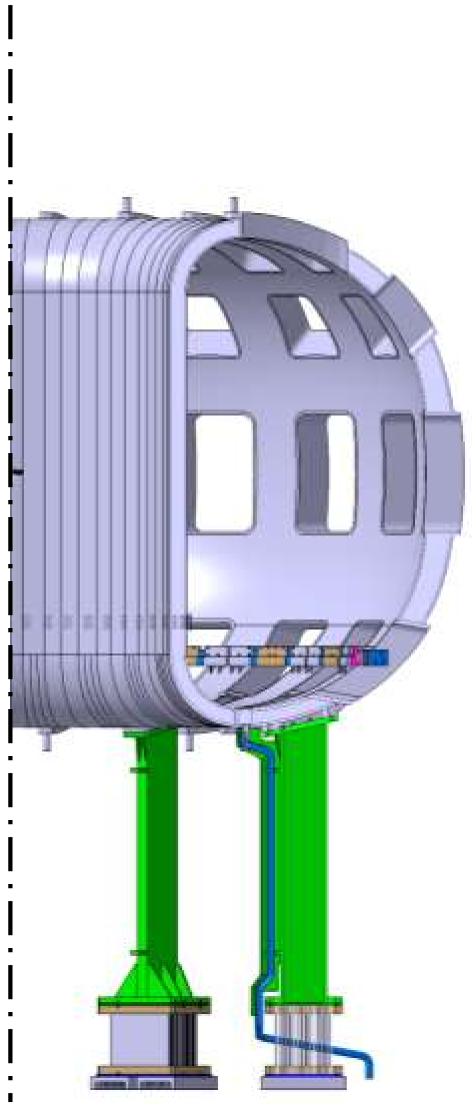
PLASMA CONFINEMENT IN DTT

Inboard - High Field Side (HFS) interfaces for plasma facing components: First Wall (FW) and divertor (DIV)



Plasma-wall clearances for steady state conditions in the different plasma confinements foreseen in DTT.
Reduced clearances are acceptable during plasma transient events.

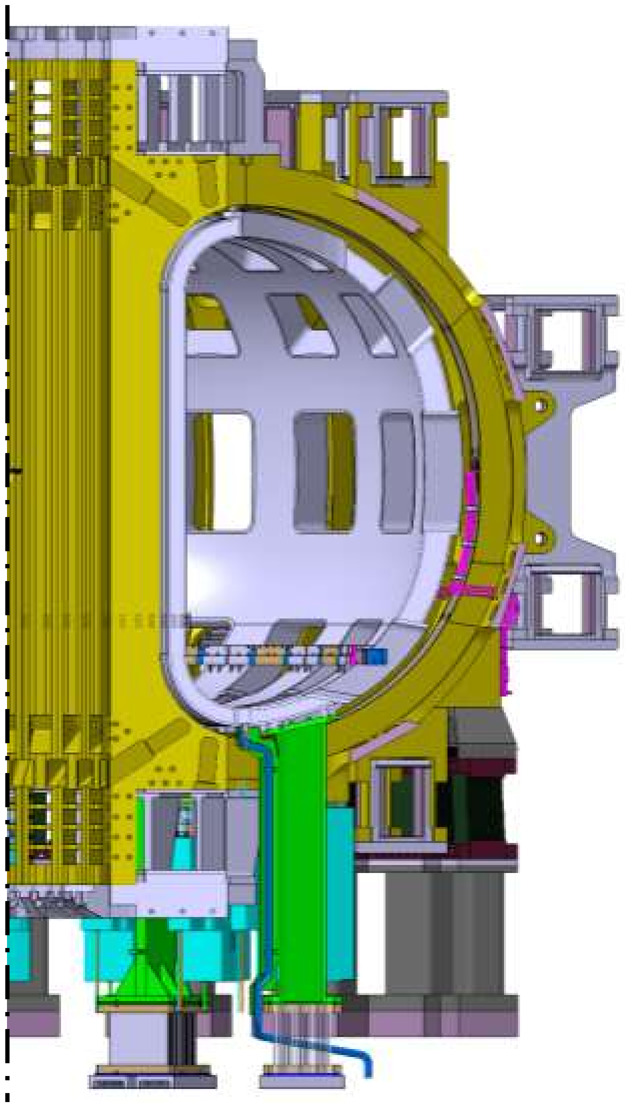
DTT ASSEMBLY



Assembly sequence main steps:

1. Integration of the vacuum vessel Multi-Sectors - 2 x 170° + 1 x 20° as built data with virtual assembly method to minimise machine deviations → first definition of the machine axis (machine global coordinate system)

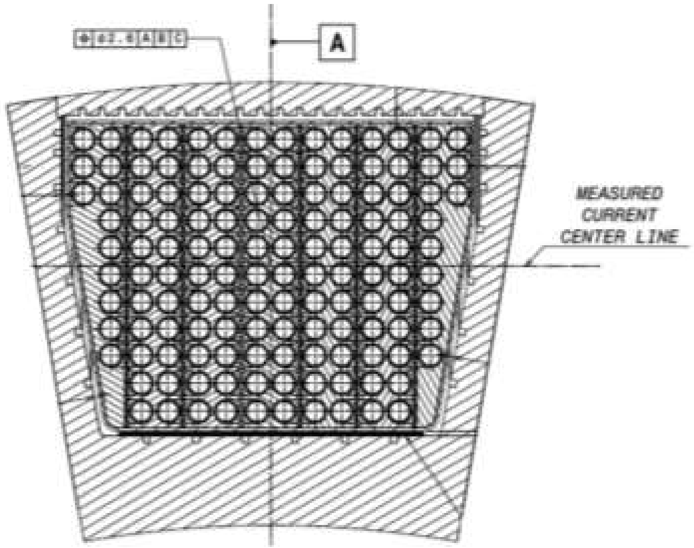
DTT ASSEMBLY



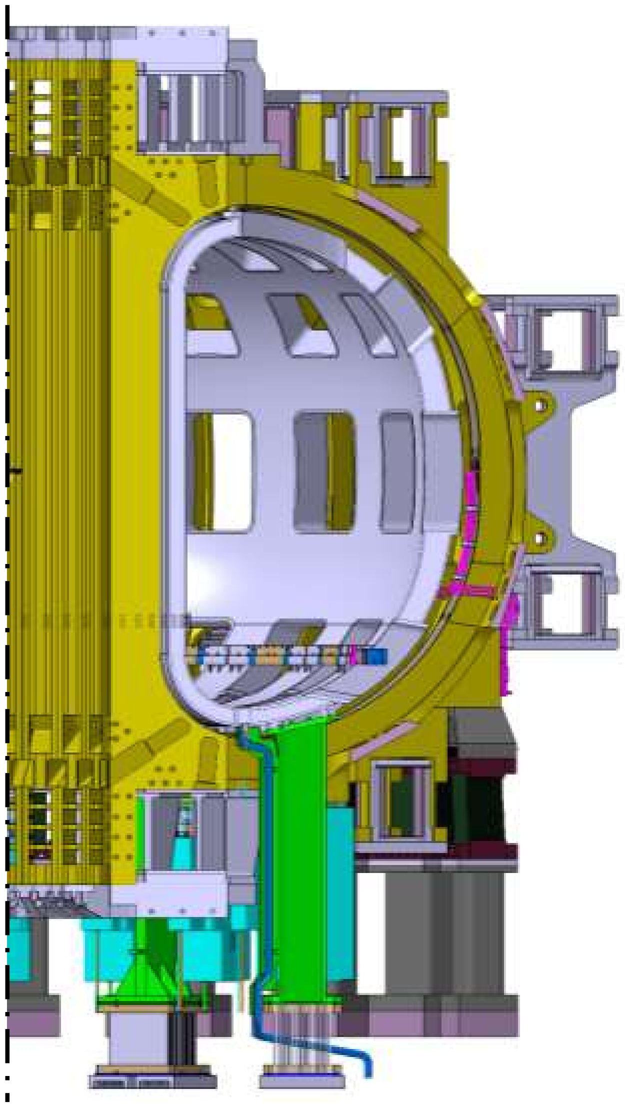
Assembly sequence main steps:

1. Integration of the vacuum vessel Multi-Sectors - 2 x 170° + 1 x 20°
   as built data with virtual assembly method to minimise machine deviations → first definition of the machine axis (machine global coordinate system)
2. Assembly of the Toroidal Field Coils (TFC) - 18 x 20°
   as built data with virtual assembly method to minimise magnetic deviations → definition of the magnetic axis (magnetic global coordinate system)
3. Alignment of the machine axis to the magnetic axis considering:
   - TFC Current CenterLine (CCL) misalignments
   - Cool down of TFC from room temperature to 4.5K
   - Deformed shape of energised TFC

[M. Jimenez, Current Center Line Integration in the Manufacturing Process of the ITER Toroidal Field Coils, IEEE TRANSACTIONS ON APPLIED SUPERCONDUCTIVITY, VOL. 30, NO. 4, JUNE 2020, 4202004]



DTT ASSEMBLY



Assembly sequence main steps:

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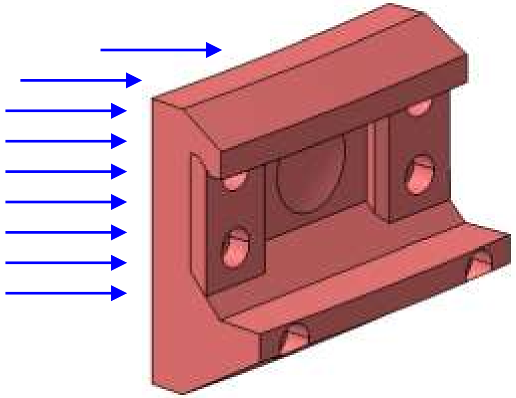
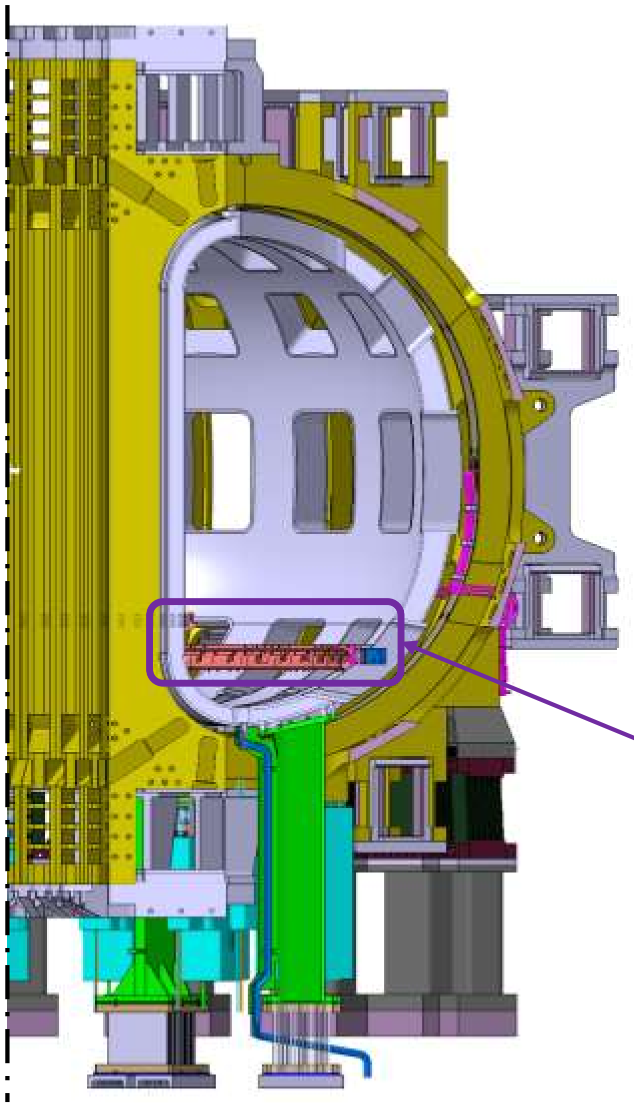
2. Assembly of the Toroidal Field Coils (TFC) - 18 x 20° as built data with virtual assembly method to minimise magnetic deviations → definition of the magnetic axis (magnetic global coordinate system)
3. Alignment of the machine axis to the magnetic axis considering:
   - TFC Current CenterLine (CCL) misalignments
   - Cool down of TFC from room temperature to 4.5K
   - Deformed shape of energised TFC
4. Measurement of as built data at in-vessel supports after welding the Multi-Sectors and virtual assembly of toroidal rails in the vacuum vessel
5. Adjustment of the 54 toroidal rails applying the reverse engineering method

Surface with over-material to be removed by machining in order to adjust the rail position (24-34 mm nominal thickness)



DTT ASSEMBLY



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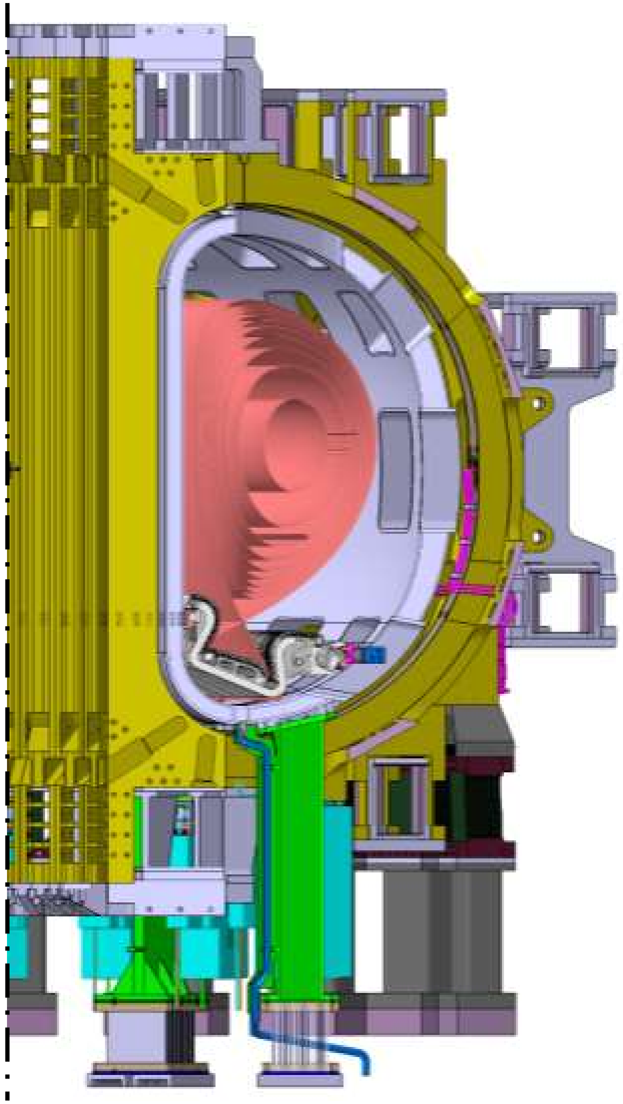
   - Deformed shape of energised TFC
4. Measurement of as built data at in-vessel supports after welding the Multi-Sectors and virtual assembly of toroidal rails in the vacuum vessel
5. Adjustment of the 54 toroidal rails applying the reverse engineering method
6. **Installation of the 54 toroidal rails (inboard + outboard)**

DTT ASSEMBLY



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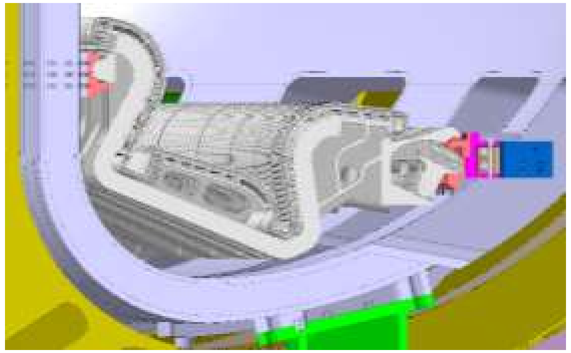
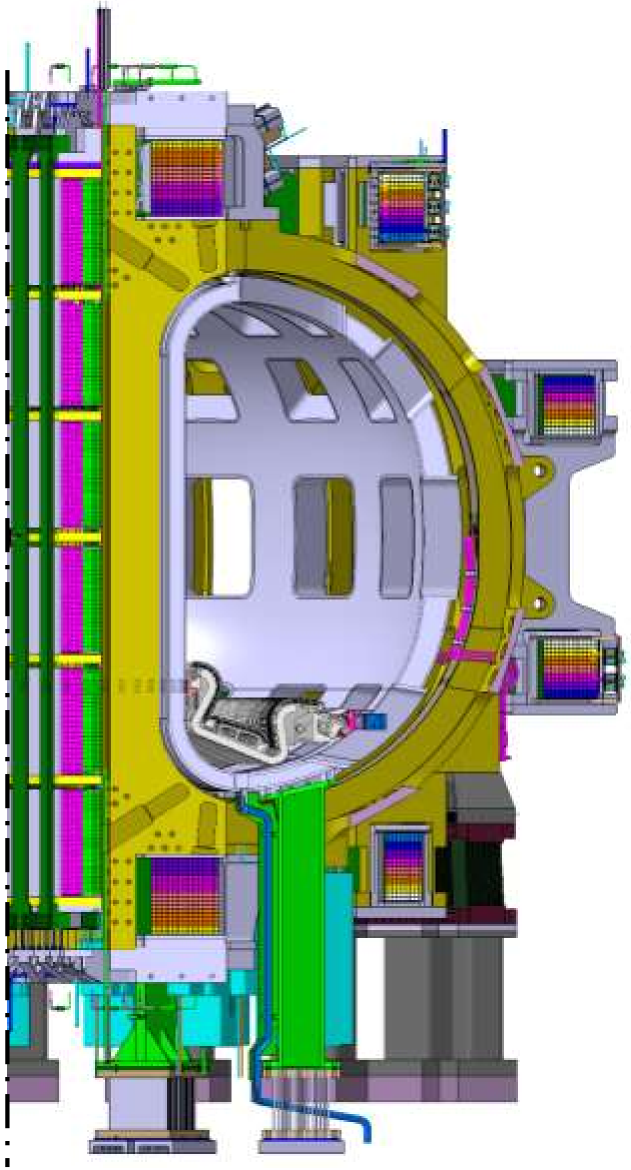
   - Deformed shape of energised TFC
4. Measurement of as built data at in-vessel supports after welding the Multi-Sectors and virtual assembly of toroidal rails in the vacuum vessel
5. Adjustment of the 54 toroidal rails applying the reverse engineering method
6. Installation of the 54 toroidal rails (inboard + outboard)
7. Installation of the 54 divertor cassettes



DTT ASSEMBLY



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4. Measurement of as built data at in-vessel supports after welding the Multi-Sectors and virtual assembly of toroidal rails in the vacuum vessel
5. Adjustment of the 54 toroidal rails applying the reverse engineering method
6. Installation of the 54 toroidal rails (inboard + outboard)
7. Installation of the 54 divertor cassettes
8. *Completion of the assembly sequence (poloidal field coils, central solenoid,…) with components to be installed also in the between of previous steps*

Assembly Asymmetries

Distortions or ripples of the toroidal magnetic field or perturbations of the field lines, relative to the ideal field lines with a circular shape, are caused by:

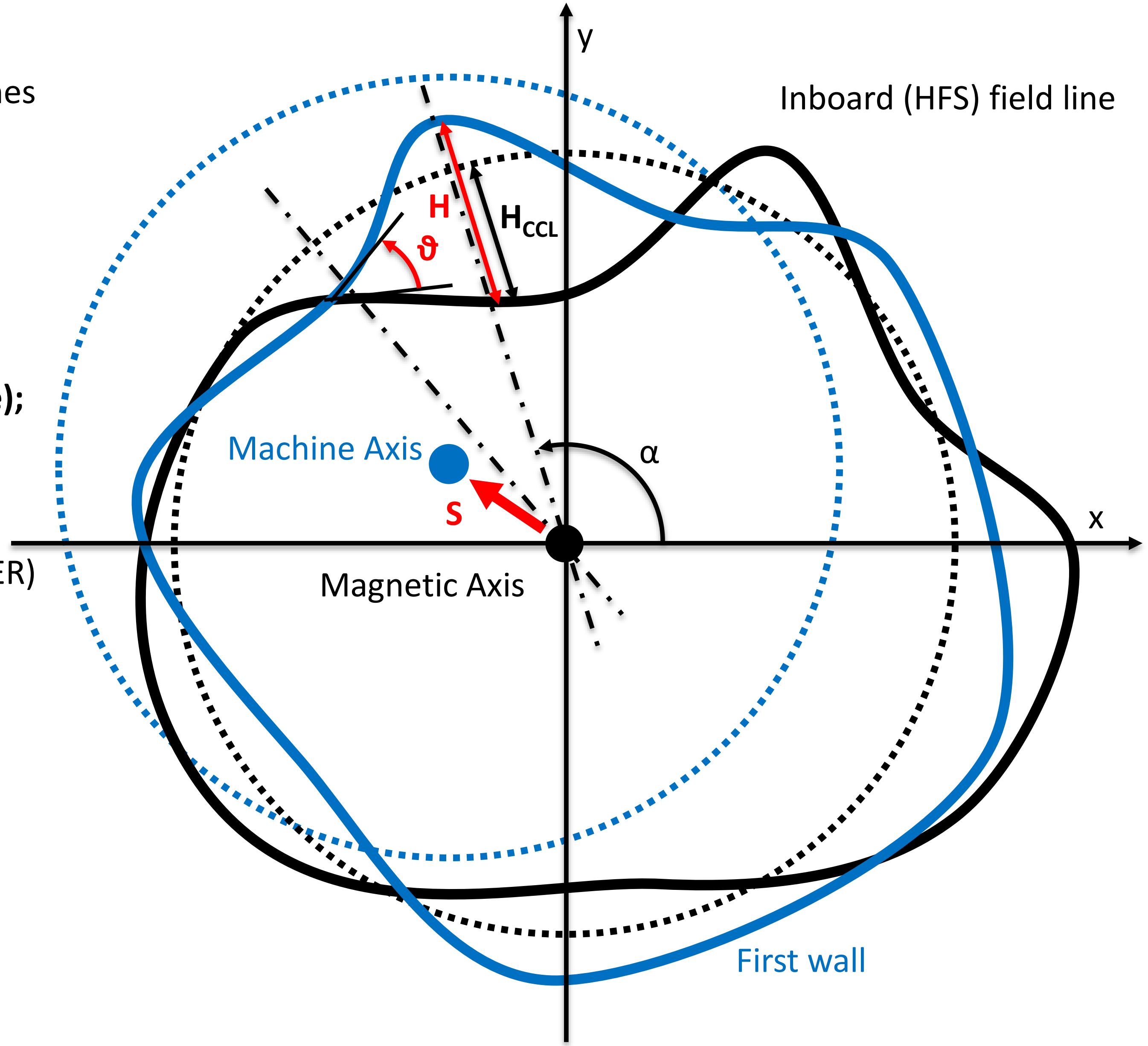
- the finite number of Toroidal Field Coils (TFCs) in their nominal positions which produce a TF ripple with the toroidal mode number n=18;
- **shifts of TFCs with respect to their nominal positions (next slide);**
- **TFC Current Centerline (CCL) misalignments (next slide);**
- ferromagnetic components of the machine (austenitic stainless steels as reference structural material).

The CCL real misalignments (3 scenarios are assumed in ITER) cause deviations of the plasma boundary quantified by:

- Displacement: $H_{CCL} \approx 4mm$
- Angle: $\vartheta_{CCL} \approx 0.1°$
- Shift of the torus reference system: $S \approx 0.7mm$

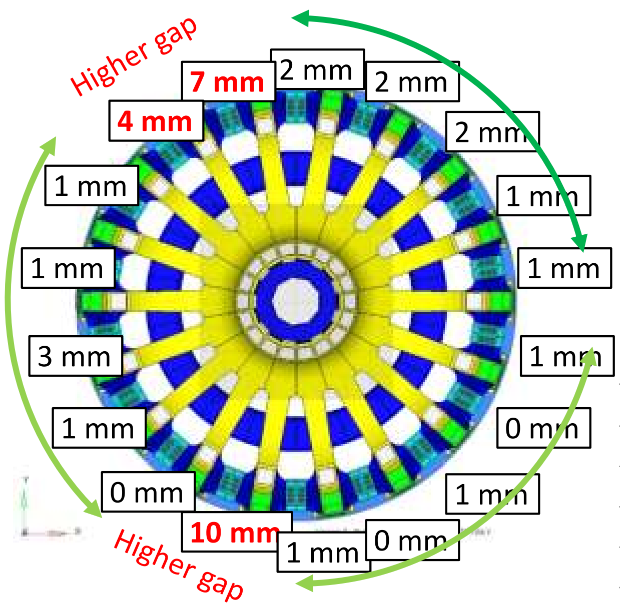
Total deviations (CCL + first wall)

- Displacement: $H = H_{FW} + H_{CCL} - H_{CC} = H_{FW} + 4 - 3$
- Angle: $\vartheta = \vartheta_{FW} + \vartheta_{CCL} + \vartheta_{CC}$
- Shift of the torus reference system: S



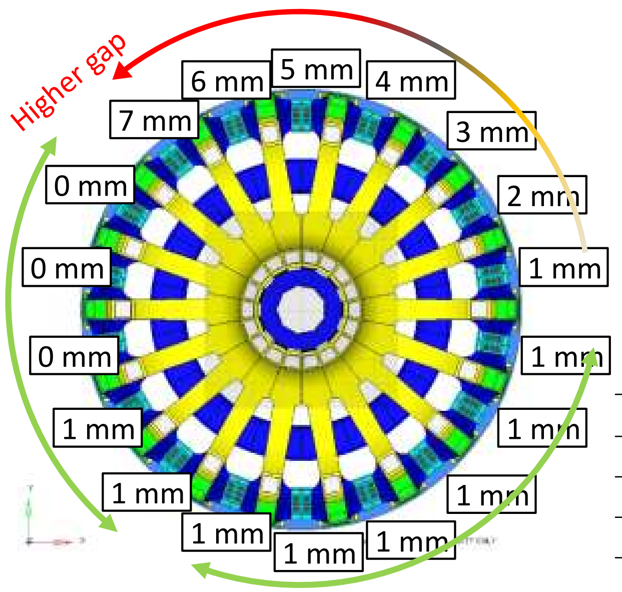
ITER STUDY ON TF ASSEMBLY ANALYSES

Version 1



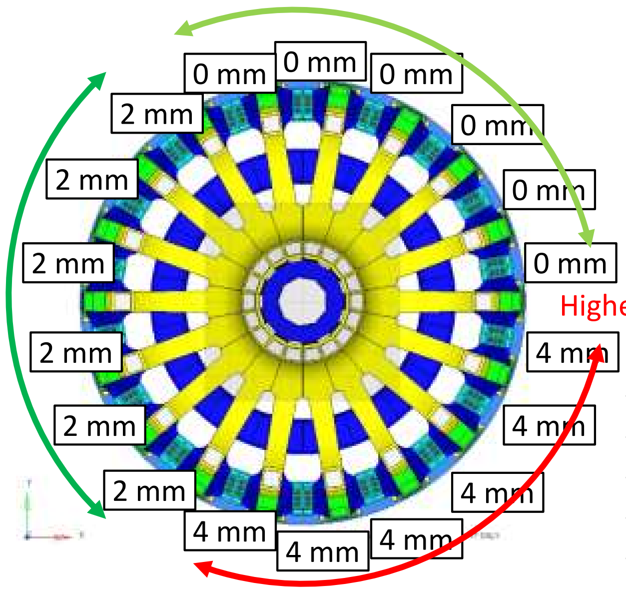
C WEDGE	v1 [mm]
1	1.0
2	1.0
3	2.0
4	1.0
5	1.0
6	7.0
7	4.0
8	1.0
9	1.0
10	3.0
11	1.0
12	0.0
13	10.0
14	1.0
15	0.0
16	1.0
17	0.0
18	1.0

Version 2



C WEDGE	v1 [mm]
1	1.0
2	2.0
3	3.0
4	4.0
5	5.0
6	6.0
7	7.0
8	0.0
9	0.0
10	0.0
11	1.0
12	1.0
13	1.0
14	1.0
15	1.0
16	1.0
17	1.0
18	1.0

Version 3



C WEDGE	v4 [mm]
1	0.0
2	0.0
3	0.0
4	0.0
5	0.0
6	0.0
7	2.0
8	2.0
9	2.0
10	2.0
11	2.0
12	2.0
13	4.0
14	4.0
15	4.0
16	4.0
17	4.0
18	4.0

[G. D’Amico, TF Magnet Assembly Analysis: FE Analysis simulating non constant gap between inner legs, 2015, F4E D 3LJTEG v2.0]

DIMENSIONAL CHAIN AND IDENTIFICATION OF THE COMPENSATION MEMBER (RAIL)

Tolerance analysis method: algebraic sum of the vectors (pessimistic scenario, root sum squared could be applied for future accurate analyses)

CI=MI-PI-DI-VI
(CO=VO-(MO+PO+DO))

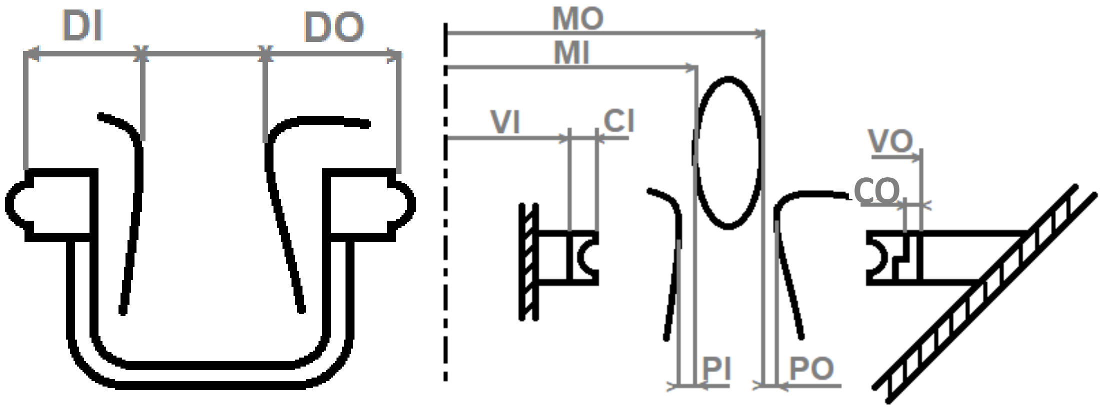
ΔCI = ΔMI+ΔDI+ΔVI = ± (1.0 + 0.5 + 6.2) mm = ± 7.7 mm → 10 mm to be compared with the thickness of the toroidal rail (24-34 mm @ inboard)
7.7 mm for manufacturing and assembly errors + 2.3 mm for nonconformities

(ΔCO=ΔVO+ΔMO+ΔDO)

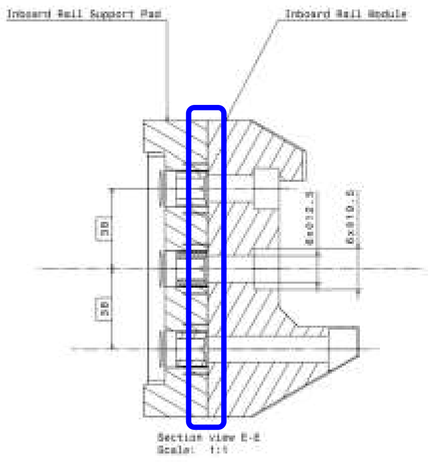
ΔPI=±5mm plasma-wall displacement requirement
Δ(ΔPI)=ΔCI+ΔDI plasma-wall angle requirement
ΔDI=±0.5mm manufacturing requirement with complete interchangeability (please see next slide)
(ΔD0=±0.5mm)
ΔVI=±(0.2+1+1+4)=±6.2mm
(ΔVO=±(0.2+2+1+4)=±7.2mm)
ΔMI=±1mm

ΔMI=TFCI+CCL+Energization+Positioning-CC
(ΔMO=ΔMI+TFCO)

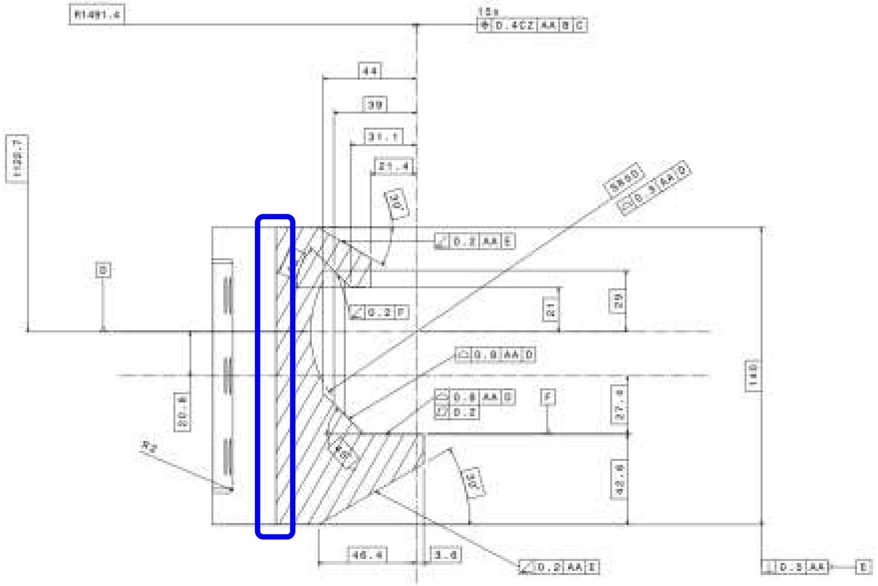
Support pad tolerance [±mm]	Vessel inner shell inboard	Vessel inner shell outboard	Vessel outer shell
Measurement system	0,2	0,2	0,2
Support pad welding	1	2	2
Multi-sector positioning	1	1	1
Vacuum vessel welding distortion	**4**	**4**	**4**
RSSS	4,25	4,59	4,59
SUM	6,2	7,2	7,2

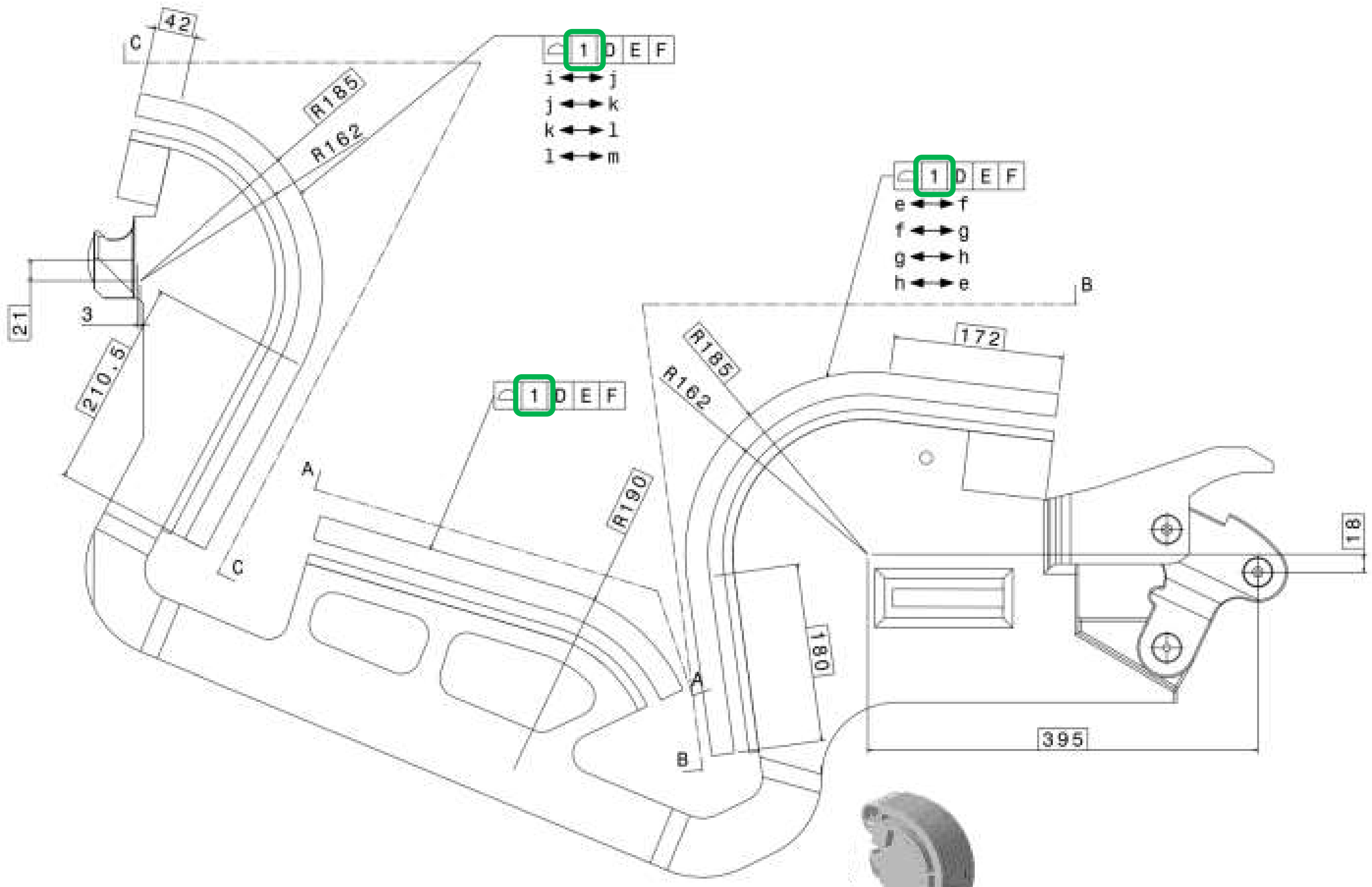


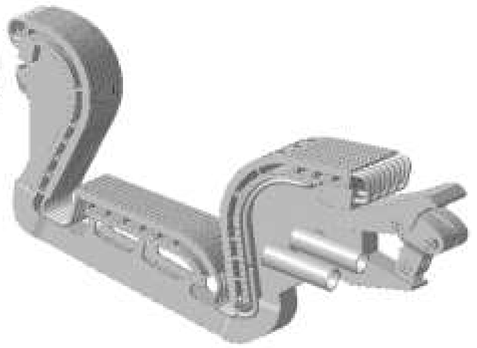
EXAMPLES OF FW-DIV MANUFACTURING ERRORS



Compensation member: toroidal rail (inboard)







Tolerances for complete interchangeability of the divertor cassette

Conclusions and Next Steps

Conclusions:

- A global method for verification of the mechanical designs and alignment of as built components to limit assembly asymmetries in magnetic fusion machines has been developed and applied to the DTT facility
- Custom installation needs have been matched during the whole assembly through a sound mechanical design which foresee suitable compensation loops/expansion joints, tolerances of manufacturing processes, and compensation members in the dimensional chains
- The compensation requirements are compatible with the detailed design of the DTT divertor inboard rail without electrical isolation

Verification of the main assumptions:

- Consistency of the TFC Current Centerline (CCL) misalignments with manufacturing drawings of DTT TFC casing
- Distortions during welding of Multi-Sectors to form the DTT vacuum vessel
- Finite element simulation of the toroidal rail residual thickness (minimum 14-24 mm)
- Verification of the DTT residual relative magnetic permeability with measurements performed on raw materials and in the welded regions in particular at the end of the fabrication process including the weld seams and the heat affected zones (a grid of measurements points with typical resolution 300 mm x 300 mm is required on products during manufacturing)
- Verification of the effect of the error field correction coils in DTT

Next steps:

- Relaxation of the component manufacturing tolerances, if possible (welding distortions)
- Extension of the evaluation of plasma boundary deviations: from displacement ($H = H_{FW} + H_{CCL} - H_{CC}$) to angle: ($\vartheta = \vartheta_{FW} + \vartheta_{CCL} + \vartheta_{CC}$)
- Extension of the method to the first wall inboard
- Definition of the coordinate system for installation and maintenance of in-vessel components referred to the machine global coordinate system