Integration and Design for Assembly

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Aula 318 in DEI/G, Via Gradenigo

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Outline

Integration and design for assembly:

A. Physical integration and design for assembly → DTT in-vessel components (divertor & in-vessel coils) interfaces

B. Physical and functional integration → DTT thermal shield integration

C. Global integration → DTT seismic isolators

A. Physical integration and design for assembly →

DTT in-vessel components (divertor & in-vessel coils) interfaces

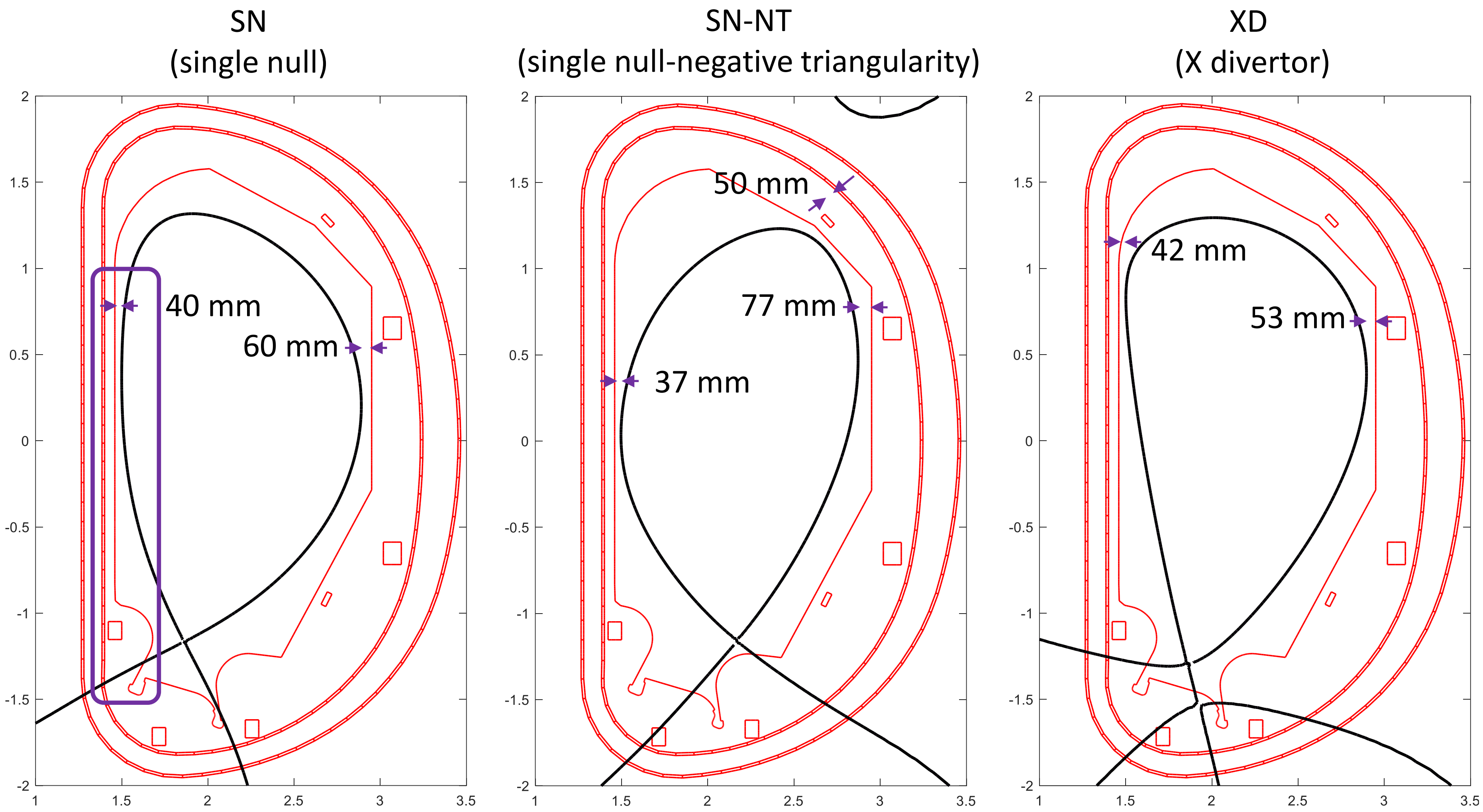
The main objectives of the activity are:

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

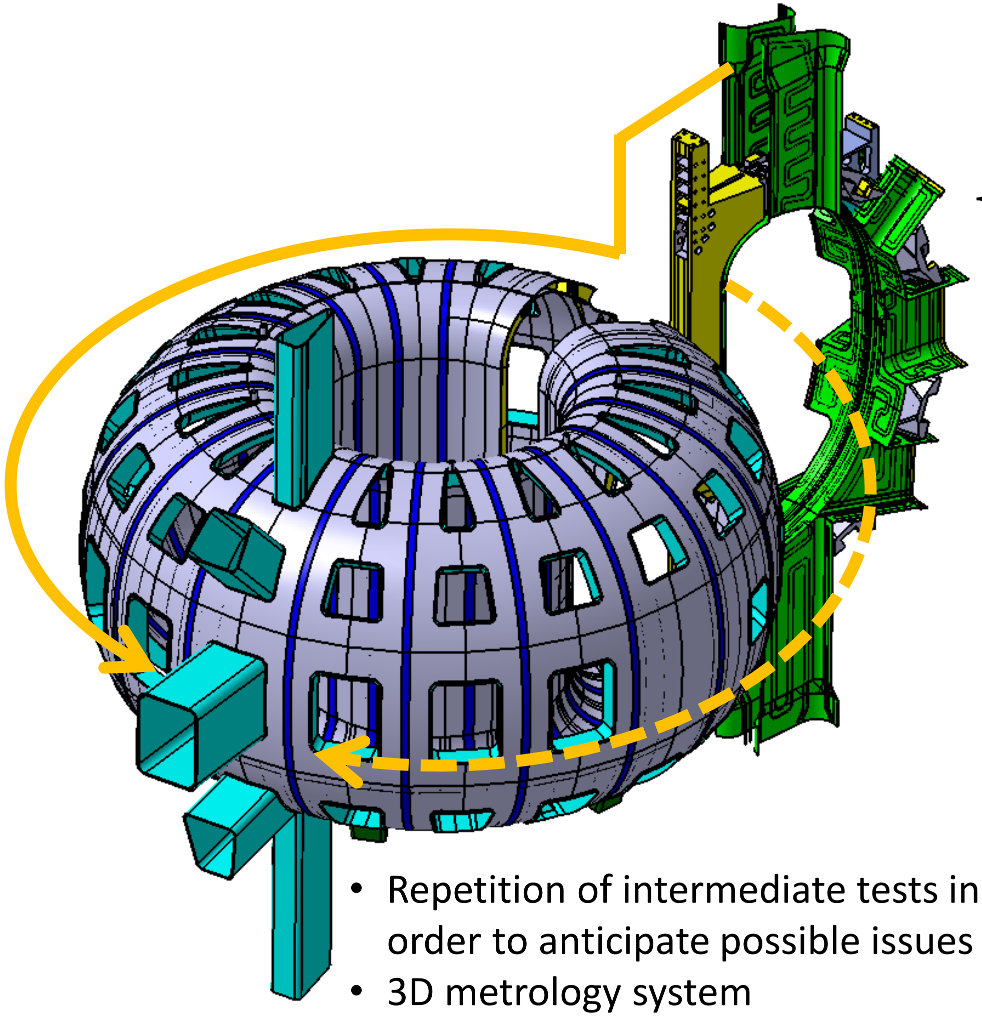
Plasma Confinement in DTT

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

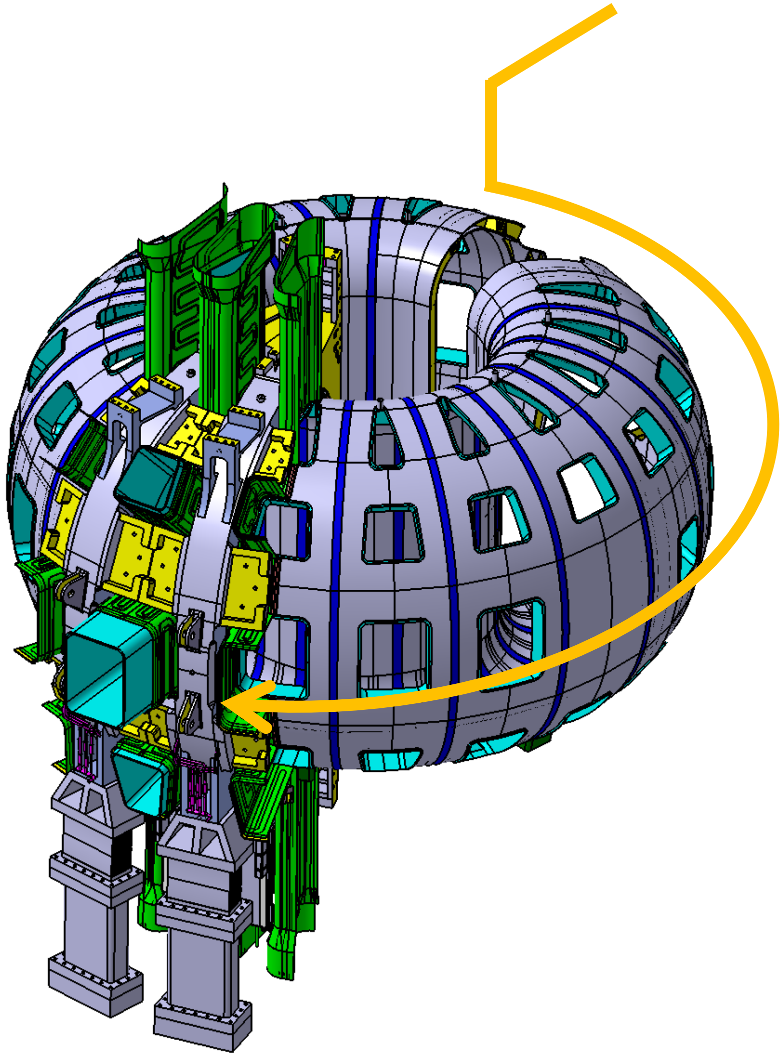


Plasma-wall clearances for steady state conditions in the different plasma confinements foreseen in DTT
Reduced clearances are acceptable during plasma transient events

DTT assembly sequence

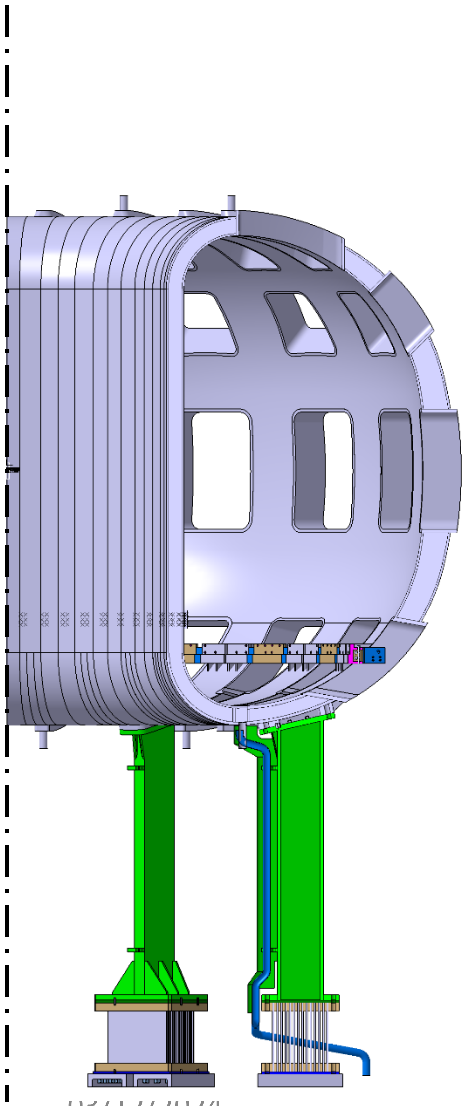


1. Vessel sectors #1 & #2 are welded & tested to form 340° of the vessel
2. Vessel thermal shield is mounted on the vacuum vessel
3. TFCs are inserted using vessel temporary gravity supports
4. TFC gravity supports are mounted
5. Vessel permanent gravity supports are mounted
6. Poloidal Field Coils are positioned and the Inter-coil Structures are mounted
7. Vessel sector #3 (20°) is integrated and the full vessel is tested
8. Port ducts, preassembled with bellows and port thermal shield, are positioned and welded on port stubs



- Repetition of intermediate tests in order to anticipate possible issues
- 3D metrology system
- Estimation, test, and measurement of weld distortions

DTT assembly sequence



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)

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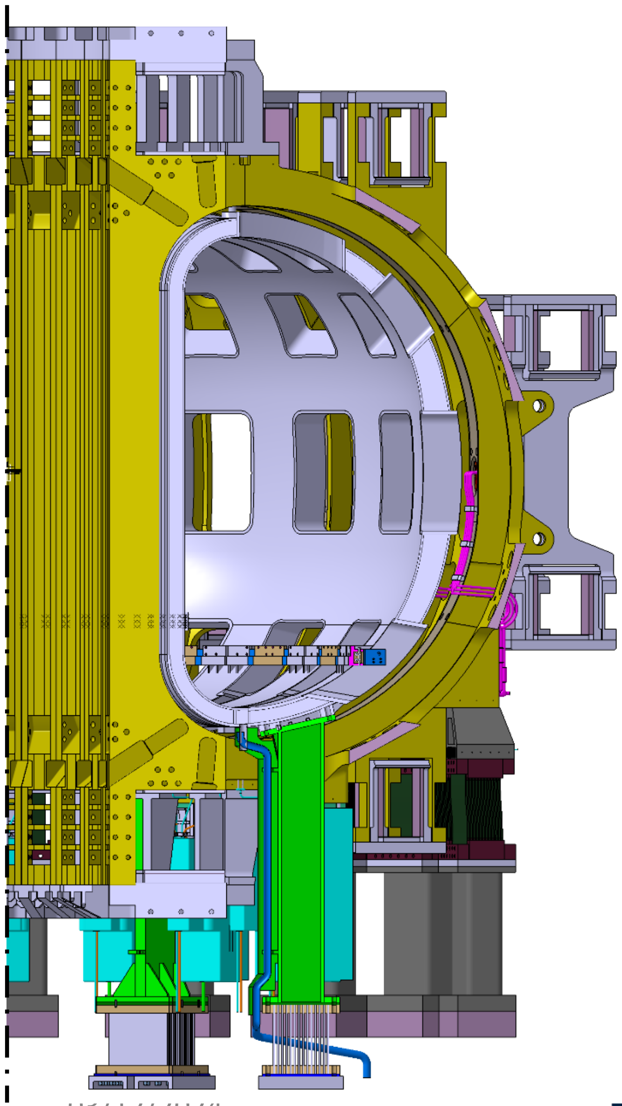
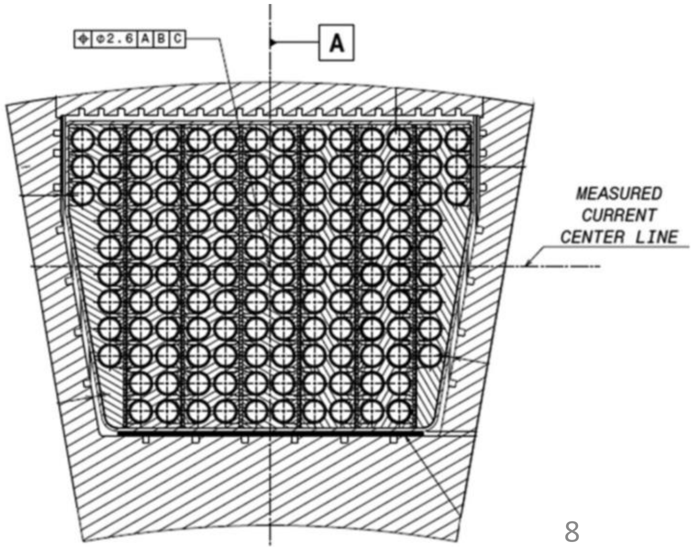
DTT assembly sequence



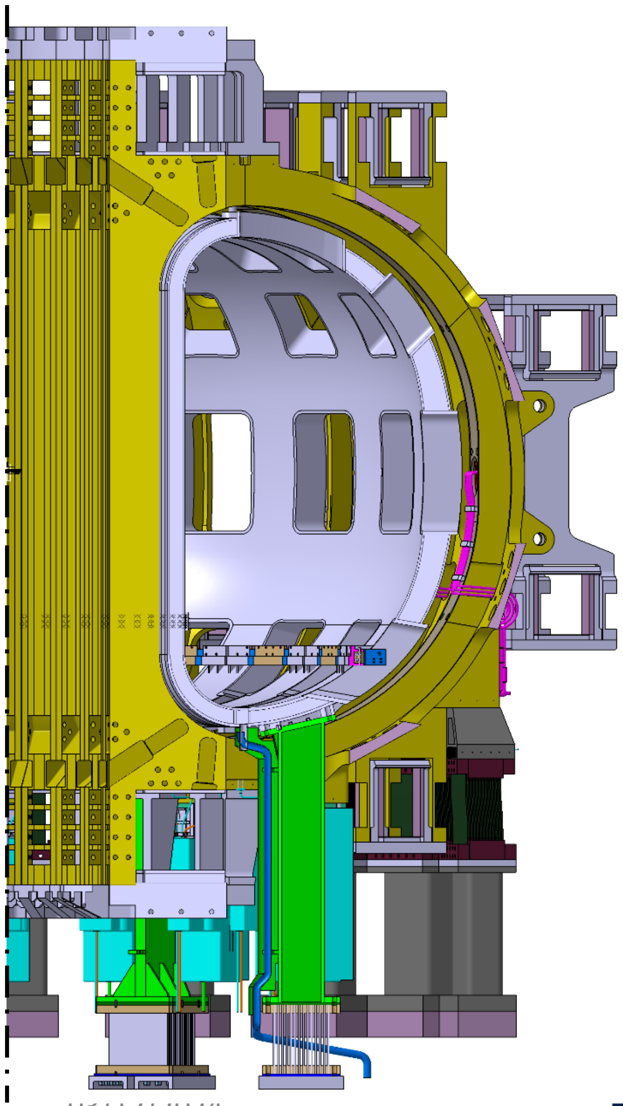
Assembly sequence main steps:

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 sequence



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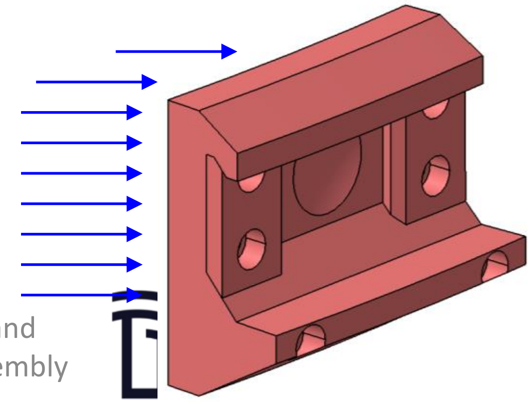
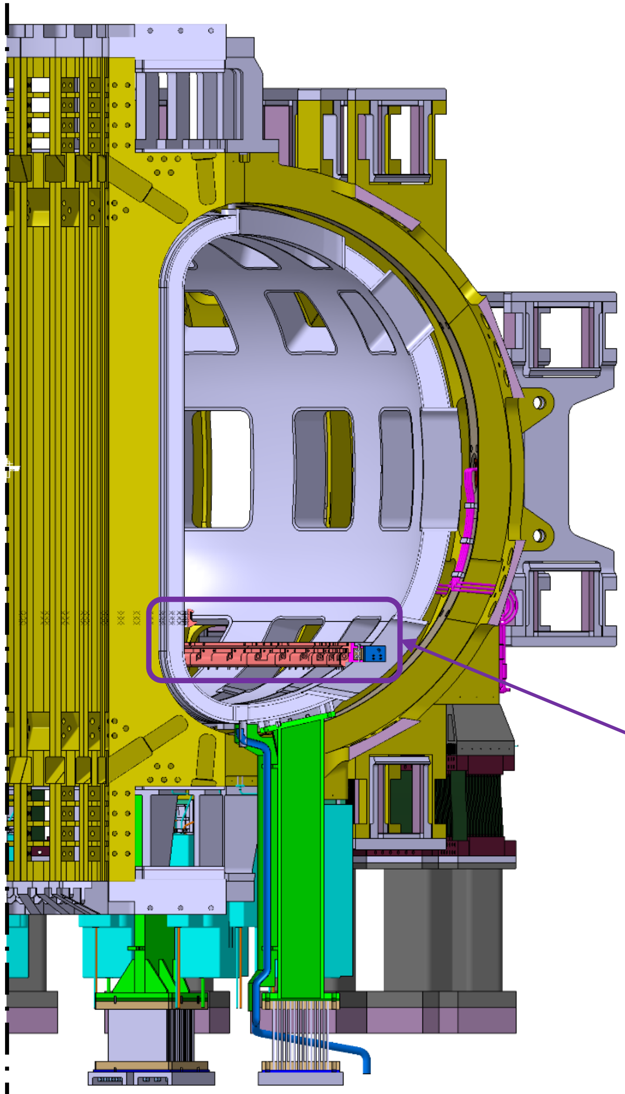
   - TFC Current CenterLine (CCL) misalignments
   - Cool down of TFC from room temperature to 4.5K
   - Deformed shape of energised TFC
4. Measurement of as built data at in-vessel supports after welding the Multi-Sectors and virtual assembly of toroidal rails in the vacuum vessel
5. Adjustment of the 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 sequence



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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)**

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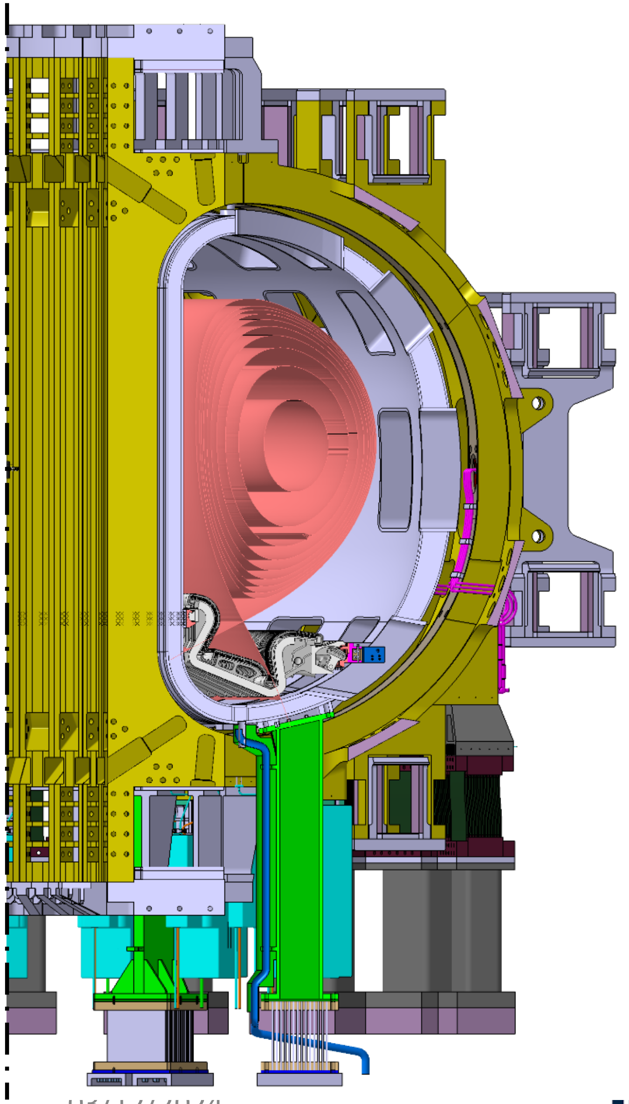
DTT assembly sequence



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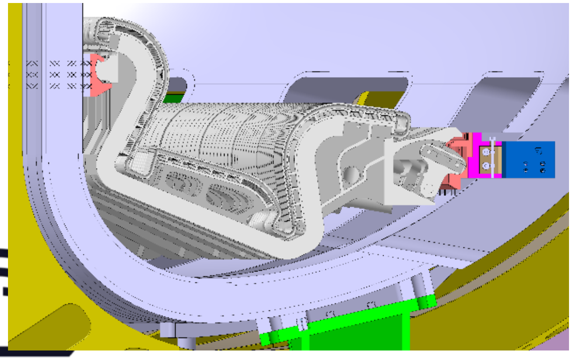
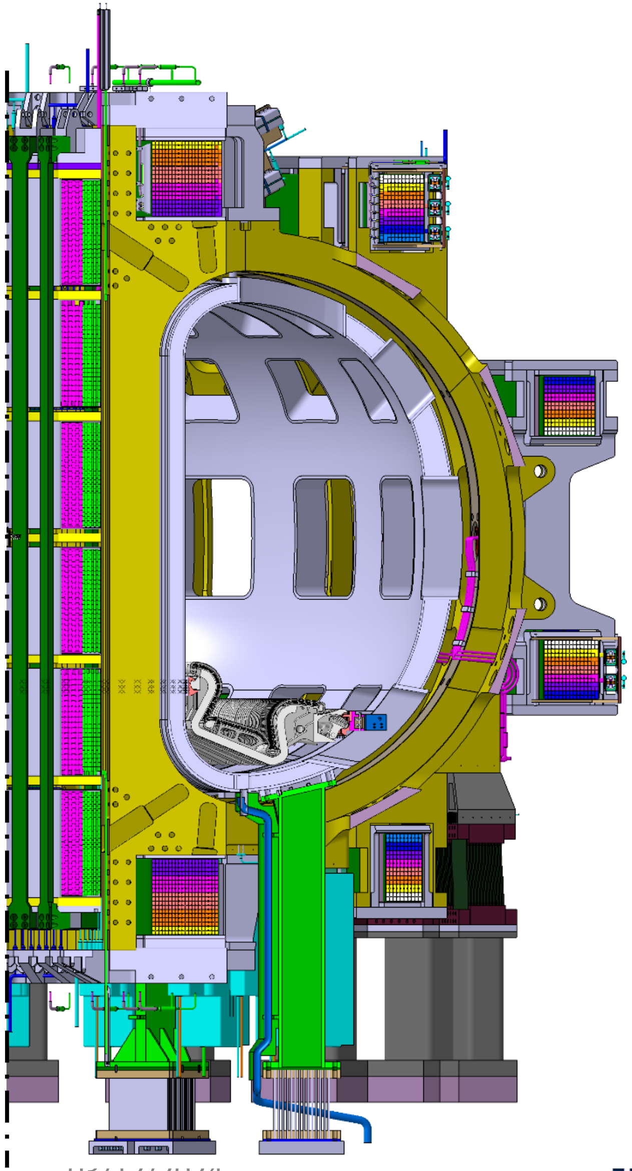
5. Adjustment of the 54 toroidal rails applying the reverse engineering method
6. Installation of the 54 toroidal rails (inboard + outboard)
7. Installation of the 54 divertor cassettes



DTT assembly sequence



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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:

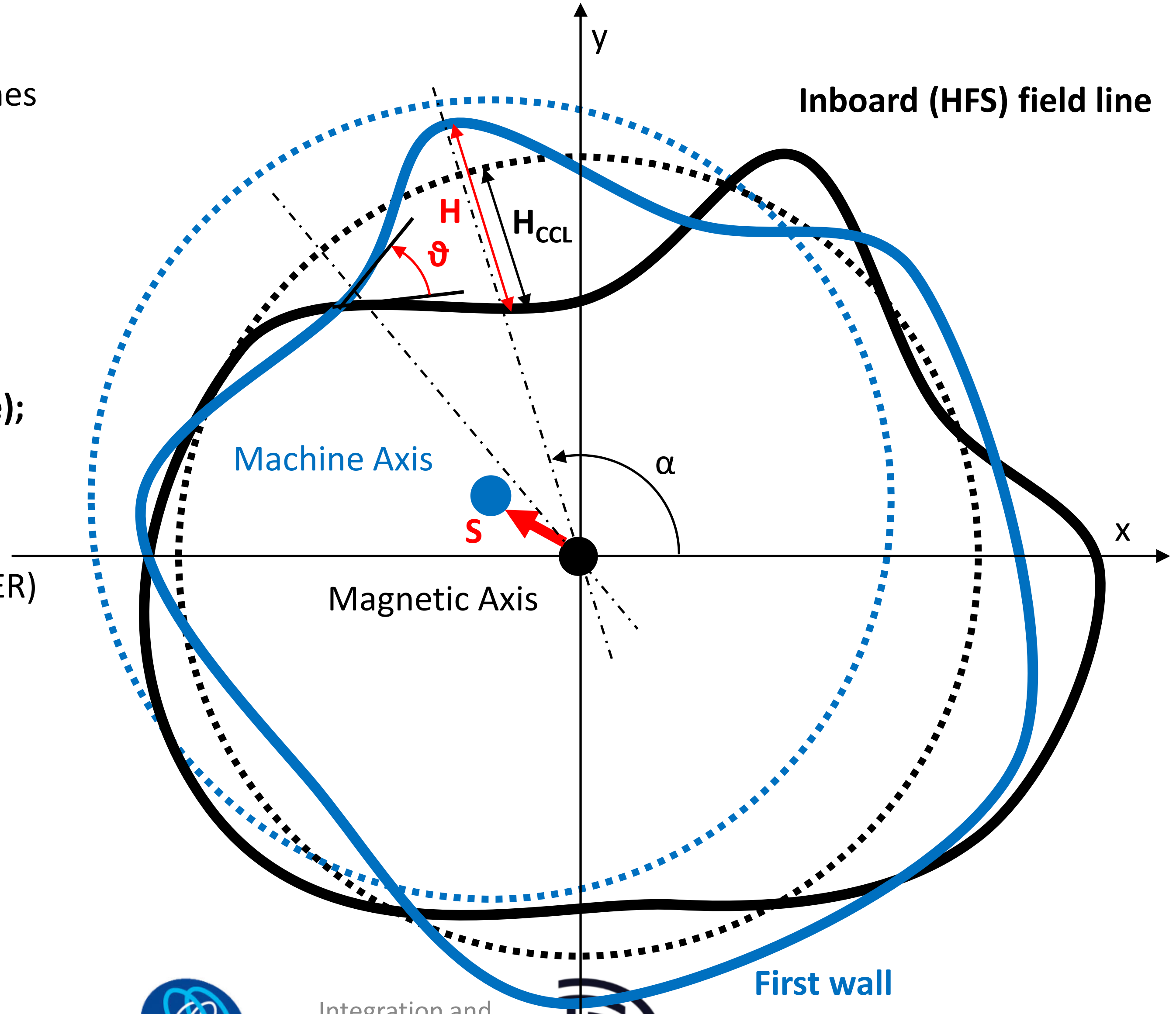
- the finite number of Toroidal Field Coils (TFCs) in their nominal positions which produce a TF ripple with the toroidal mode number n=18;
- **shifts of TFCs with respect to their nominal positions (next slide);**
- **TFC Current Centerline (CCL) misalignments (next slide);**
- ferromagnetic components 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: $H_{CCL} \approx 4$mm
- Angle: $\vartheta_{CCL} \approx 0.1°$
- Shift of the torus reference system: S ≈ 0.7mm

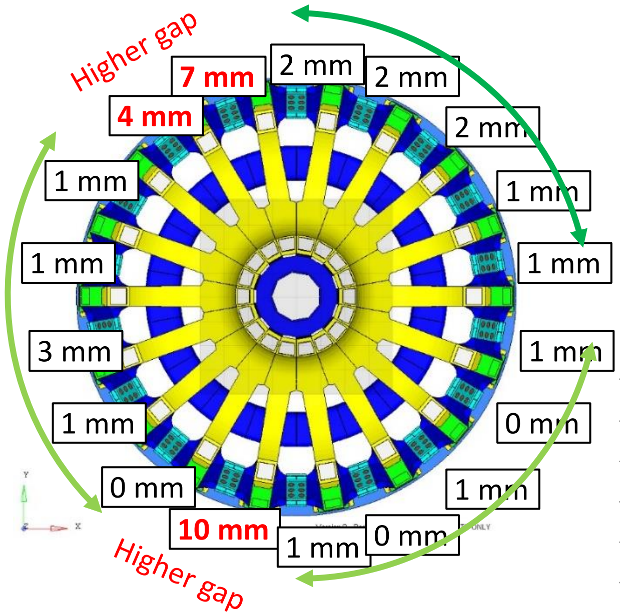
Total deviations with effect of correction coils (CC)

- 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



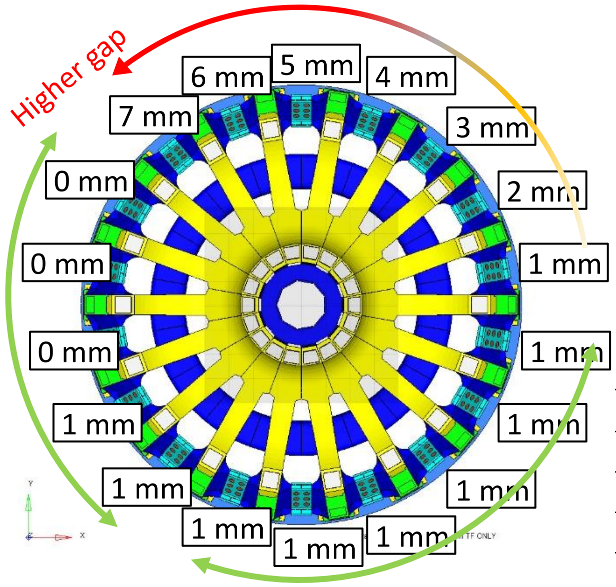
ITER study on TF Assembly Analyses

Version 1



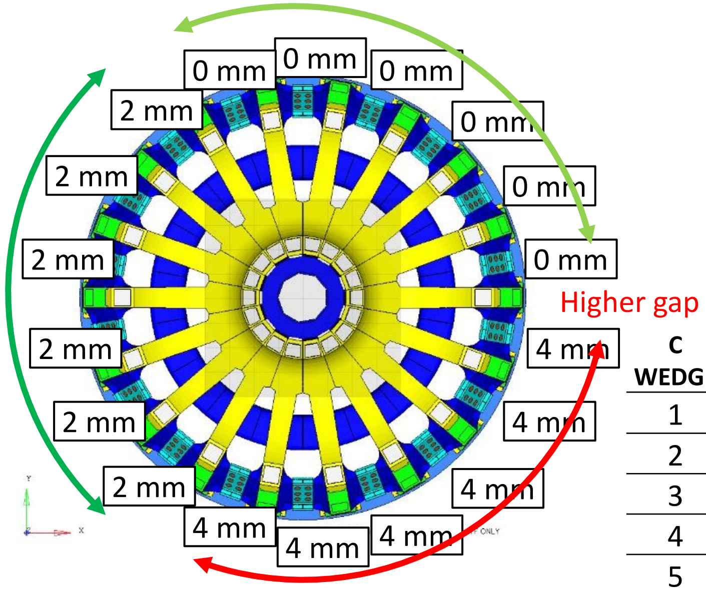
C WEDGE	v1 [mm]
1	1.0
2	1.0
3	2.0
4	1.0
5	1.0
6	**7.0**
7	4.0
8	1.0
9	1.0
10	3.0
11	1.0
12	0.0
13	**10.0**
14	1.0
15	0.0
16	1.0
17	0.0
18	1.0

Version 3



C WEDGE	v3 [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 4



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-square could be applied for accurate analyses)

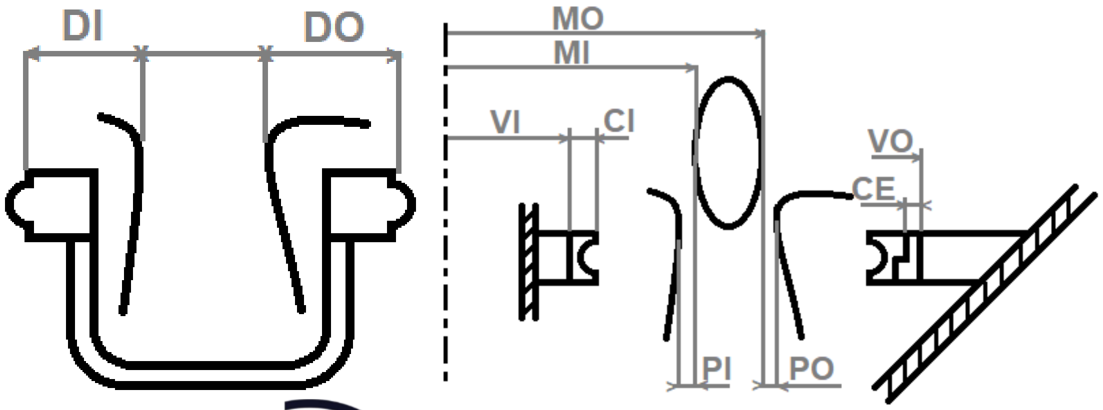
CI=MI-PI-DI-VI
(CO=VO-(MO+PO+DO))

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)

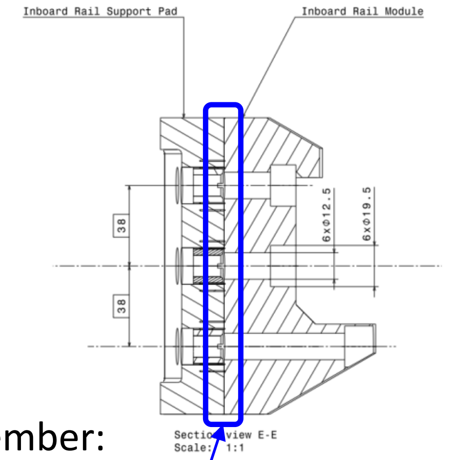
ΔPI=±5mm plasma-wall displacement requirement
Δ(ΔPI)=ΔCI+ΔDI **plasma-wall angle requirement**
ΔDI=±0.5mm manufacturing requirement with complete interchangeability (please see next slide)
(ΔD0=±0.5mm)
ΔVI=±(0.2+1+1+4)=±6.2mm
(ΔVO=±(0.2+2+1+4)=±7.2mm)
ΔMI=±1mm

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

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

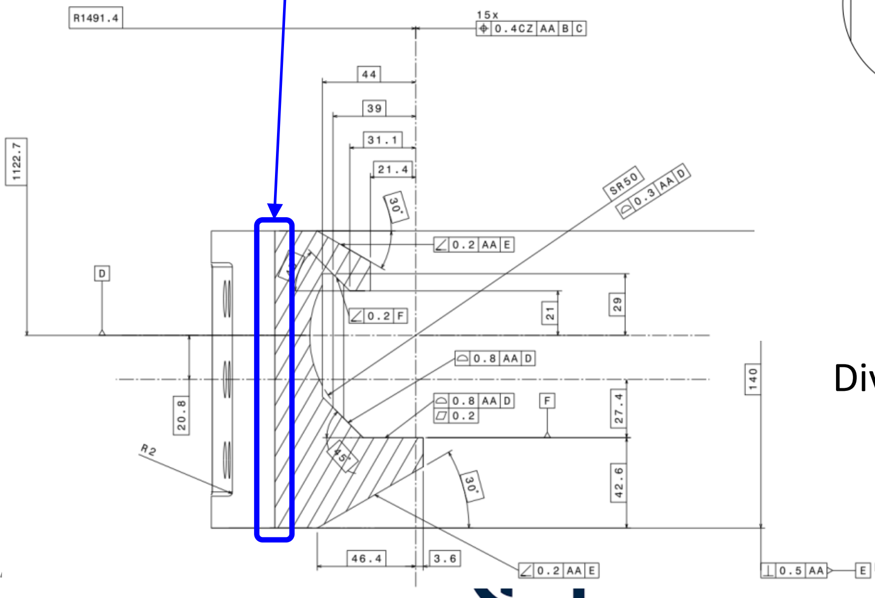


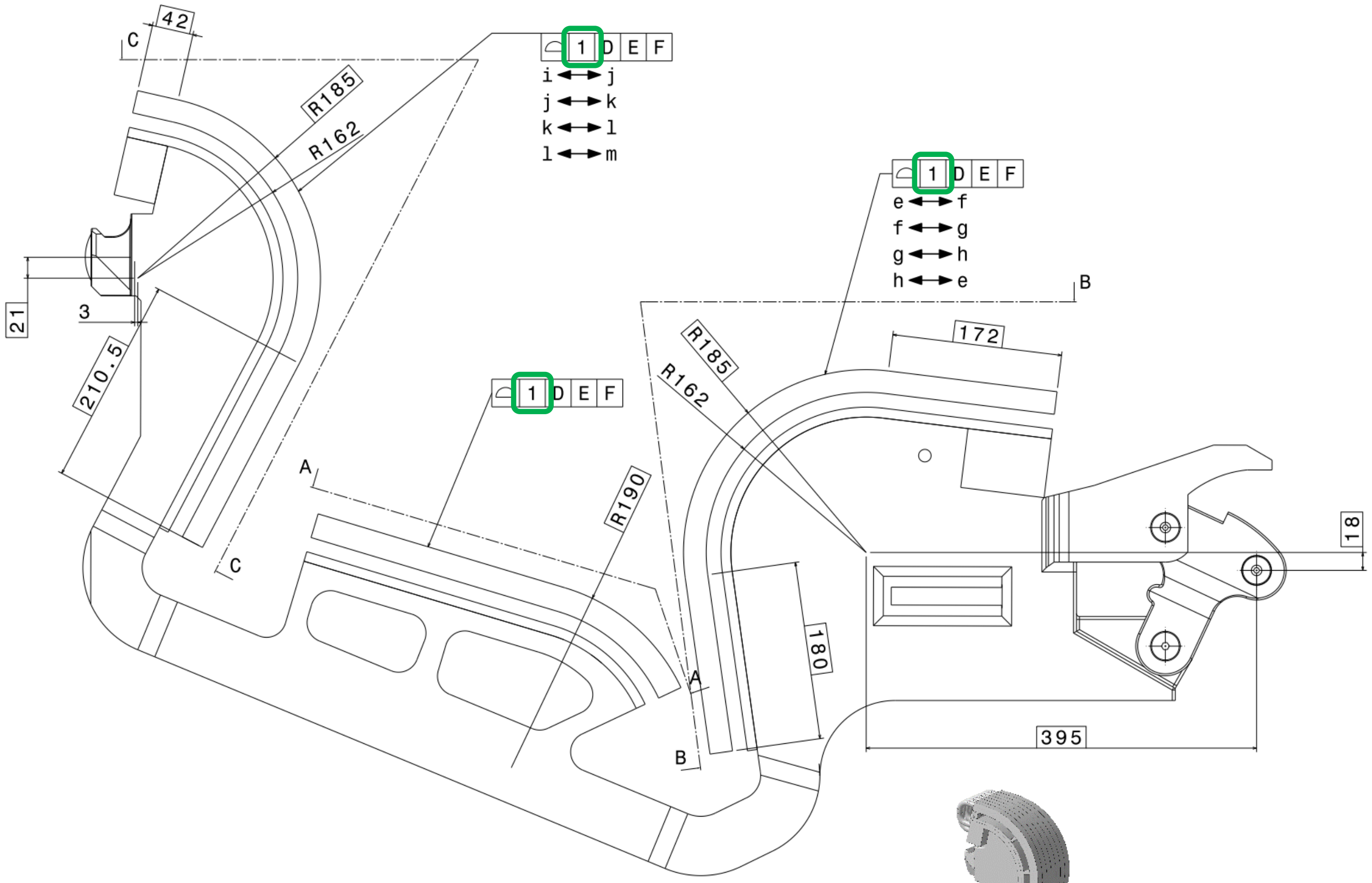
Examples of FW-DIV Manufacturing Errors



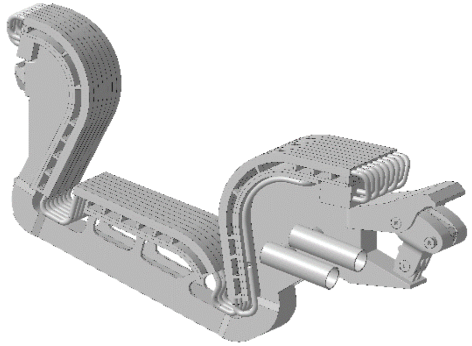
Compensation member: toroidal rail (inboard)

Adjusting interface





Divertor cassette with complete interchangeability



Status and next steps for divertor integration

Activity status:
- 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

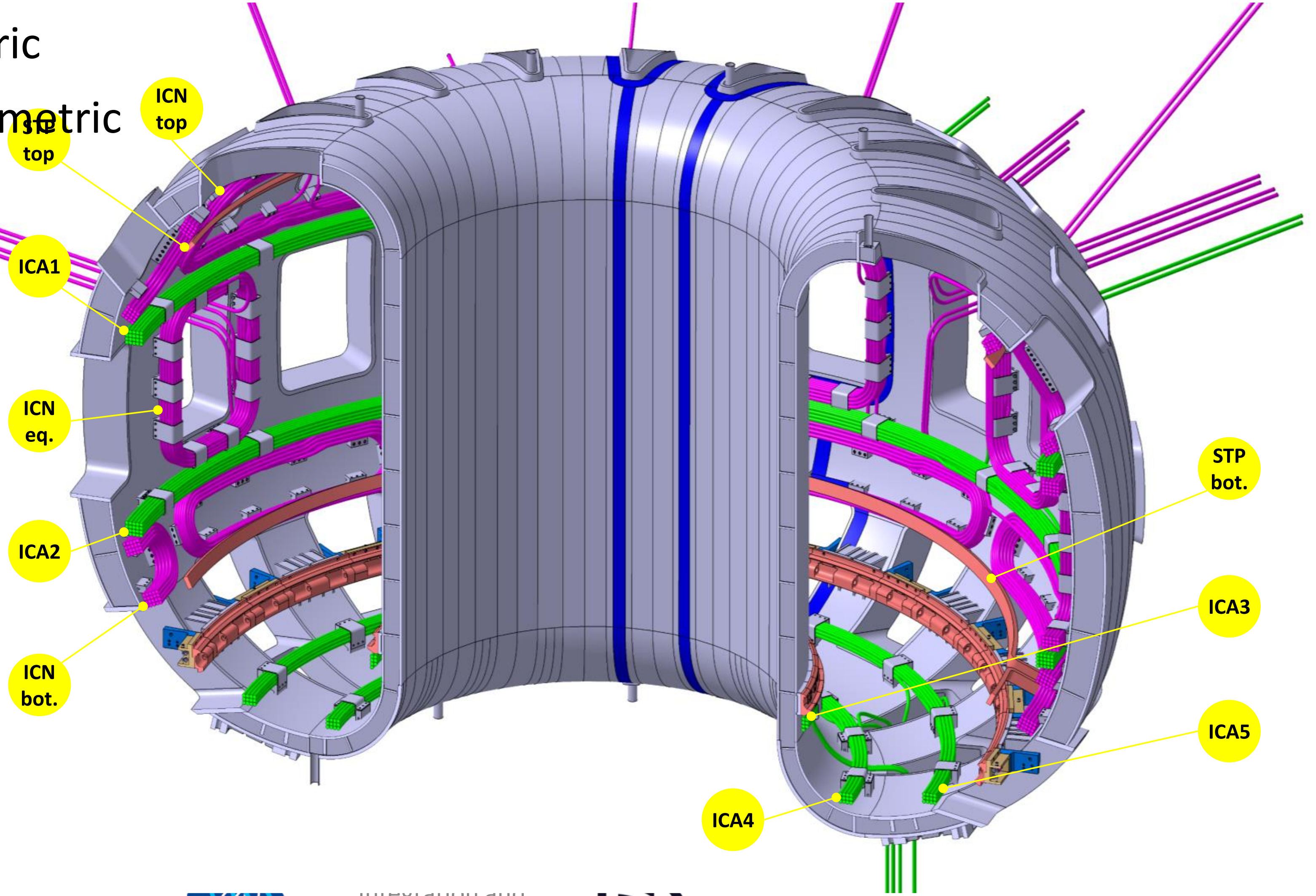
Next steps:
- Relaxation of the component manufacturing tolerances, if possible (welding distortions)
- Extension of the evaluation of plasma boundary deviations:
  from displacement ($H = H_{FW} + H_{CCL} - H_{CC}$) to angle: ($\vartheta = \vartheta_{FW} + \vartheta_{CCL} + \vartheta_{CC}$)
- Extension 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

In-vessel coils - project structure

Components included within the in-vessel coil system (INV) are:

- ICA: In vessel Coils Axial symmetric
- ICN: In vessel Coils Not axial symmetric
- STP: Stabilization Plates

Both the in-vessel coil systems (ICA and ICN) will be realised with the same conductor



SS ϕ24 mm
ins ϕ21 mm
Cu ϕ16 mm
w ϕ9 mm

ASDEX-U like conductor

Main tasks of the project

- R&Ds, tests, and qualifications: at the beginning of the procurement contracts
  Welds between coils (ICA and ICN) and their feeders:
  backup solution (repairs or when feeders cannot integrated with coils) investigated during design
- In-vessel coil cable used for ICA and ICN:
  design, interface verification, tech. spec. (including extralength for forming tests/qualifications)
- Supporting brackets for ICA, ICN, and STP:
  design, analysis, structural integrity verification, in-vessel integration
- Components:
  - STP, ICN: design, interface verification, in-vessel integration
  - ICA: design, interface verification, in-vessel integration, forming analysis
- Forming tools and machines: agreement with ASDEX-U Team
- Feedthroughs at the cryostat flange: design, interface verification, integration
- Assembly sequence of ICN and STP: development and analysis

Materials in the coil cable

- cooling channel: deionised water with maximum electrical conductivity of 0.2 µS/cm at @ 25 °C

- conductor: copper Cu-OF designation:
  - CW008A in accordance with European Standard EN 13601
  - C10200 in accordance with Unified Numbering System for Metals and Alloys (UNS)

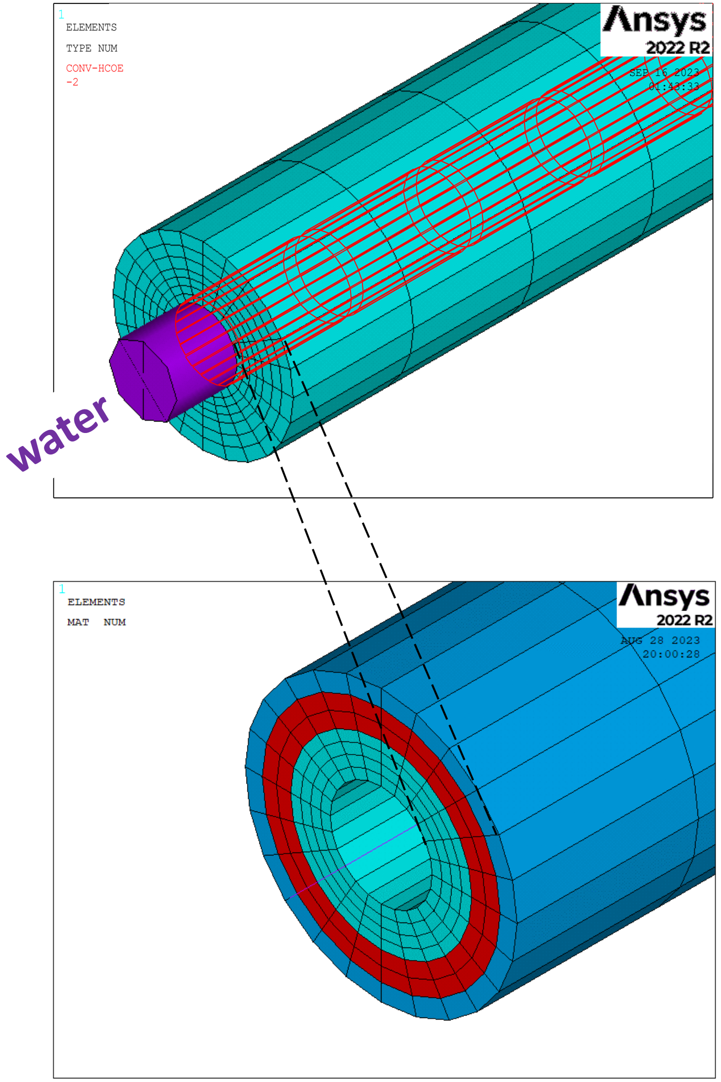
- insulation: perfluoroalkoxy (PFA)

- armour: stainless steel EN 1.4404

In-vessel Coils - thermo-hydraulic analyses

FE non-linear parametric model:

- The coil cable is modelled with solid thermal/electrical elements for: copper conductor, PFA insulator, SS armour
- The water bulk is modelled with coupled thermal-fluid pipe elements (temperature and pressure are degrees of freedom) and convection information are passed to thermal surface elements
- Thermal surface elements have extra-node used as bulk temperature. The convective heat transfer coefficient is depending on local conditions
- The material properties are function of temperature (non-linear analysis)
- The model can be improved modelling constraints of supporting brackets and introducing displacements as DOF for thermal expansion and structural analyses



Post-processing of the results:

- Verification of material temperature vs maximum allowables
- Verification of pressure drops
- Verification of the cooling capability to restore to initial cable temperature (e.g. 25°C)

Upper bound currents consistent with PSS (conservative assumptions)

VS coil current (ICA1 & ICA2):

- constant current for radial control: 6 kA applied 3 times for 3 s (tot. 9 s during a 100 s pulse)
- triangular waveform for vertical stabilization: PSS specification (tot. 91 s during a 100 s pulse) the possibility to extend the 6 kA subpart with triangular waveform is under investigation (effective current from 1.7 kA **to 2.3 kA?**)

Triangular waveform	Peak value	Period	Frequency	Repeated consecutive cycles	
				Figure 4 top	Figure 4 bottom
1	6 kA	18 ms	55.6 Hz	2 → **8?**	1 → **4?**
2	3 kA	8 ms	125 Hz	12	6
3	1 kA	2.5 ms	400 Hz	40	20
4	0.5 kA	1.2 ms	833 Hz	40	20

DIV coil current (ICA3, ICA4, ICA5):

- constant current: 5 kA applied for 40 s

ICN coil current:

- functions: correction field + ELM control
- upper bound of constant current:
  2.5 kA applied for 100 s

Disruption:

- huge electromagnetic loads are expected with about 100 ms duration, but thermal effects will be ignored as negligible

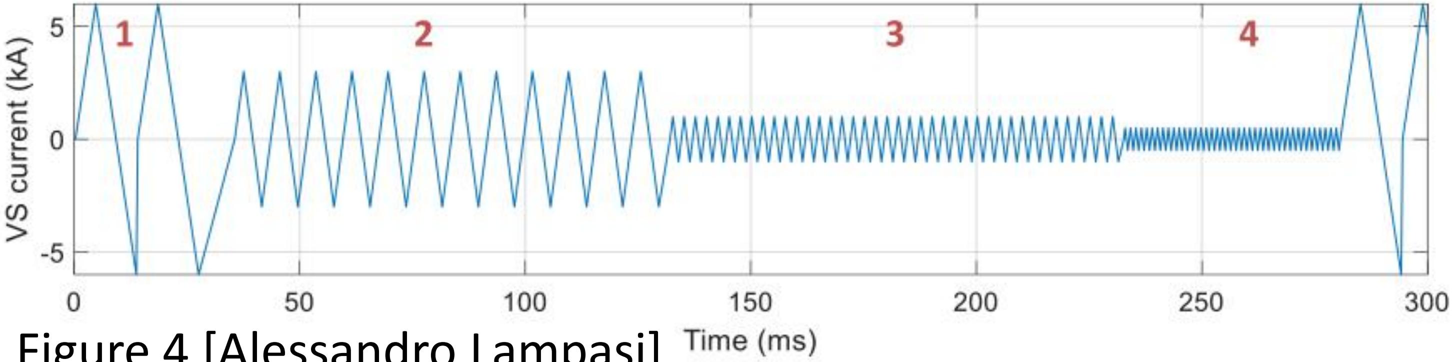
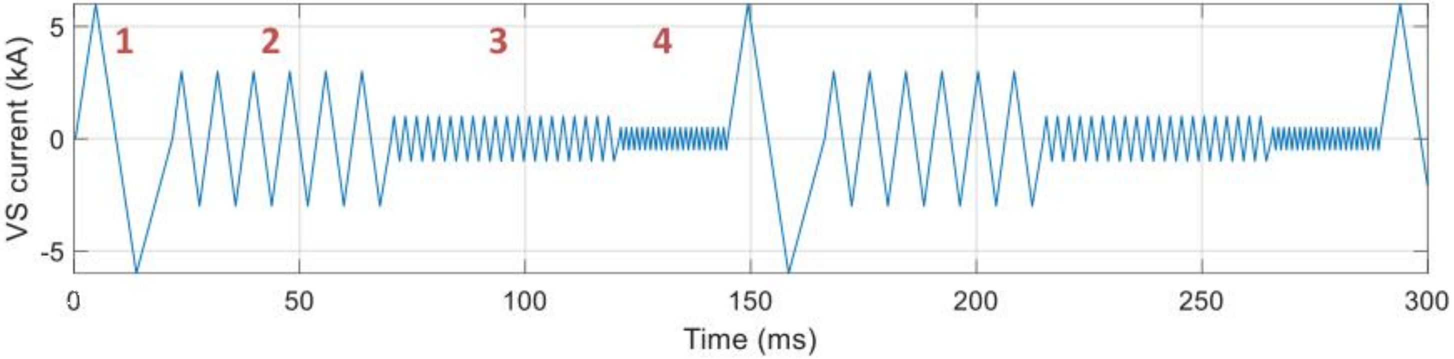


Figure 4 [Alessandro Lampasi]

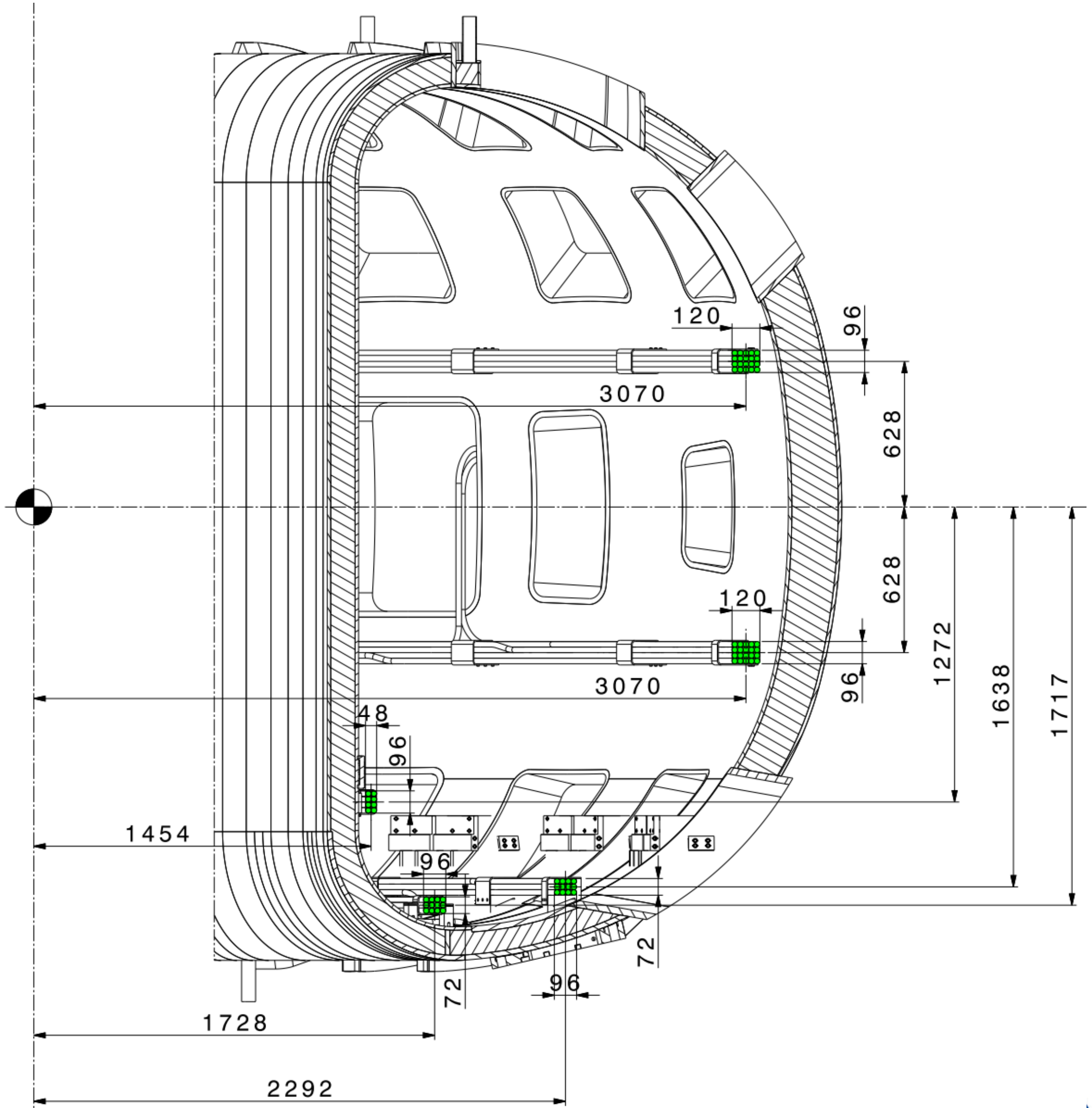


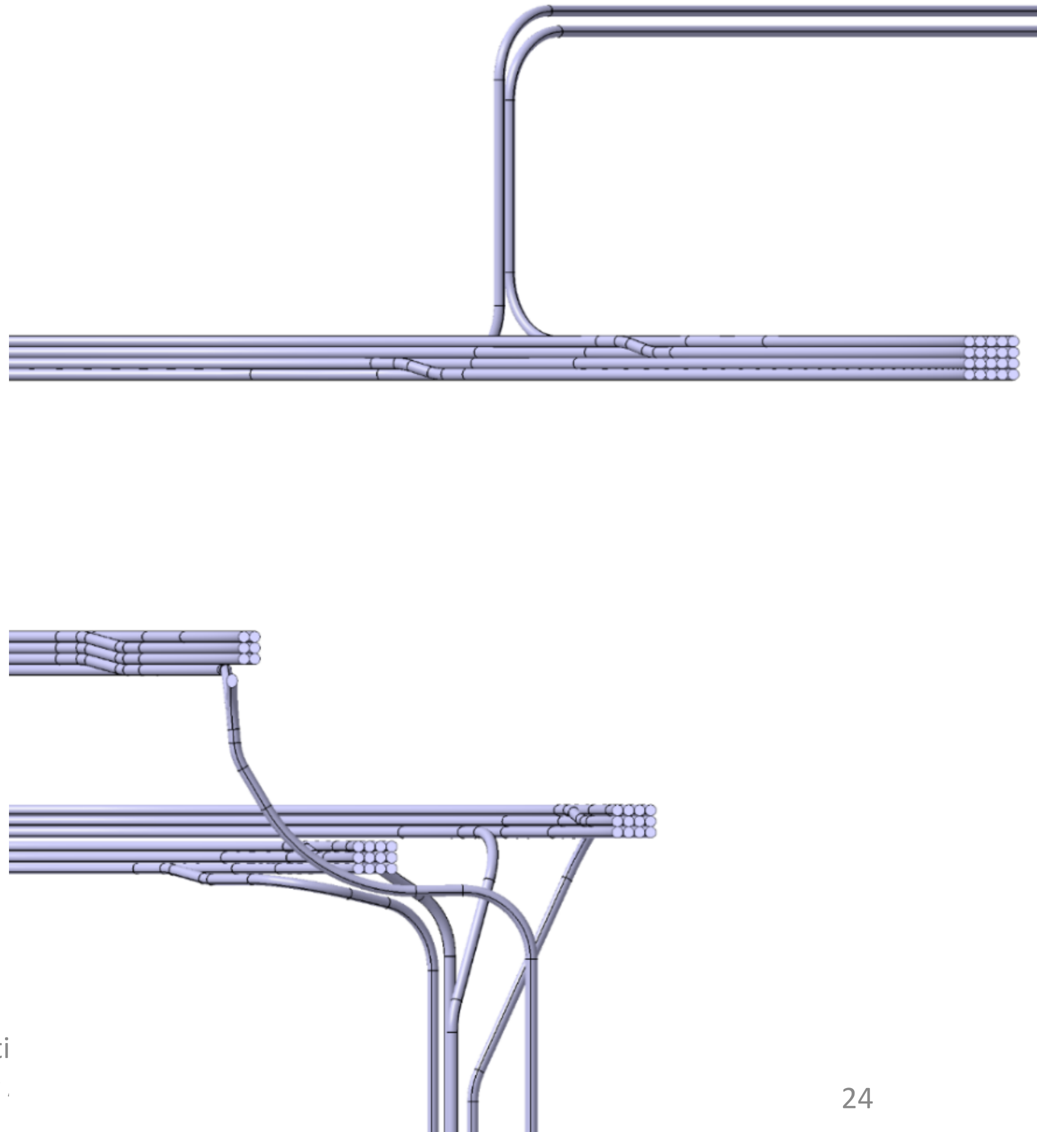
Design integration and interfaces

Analysis of the system interfaces:

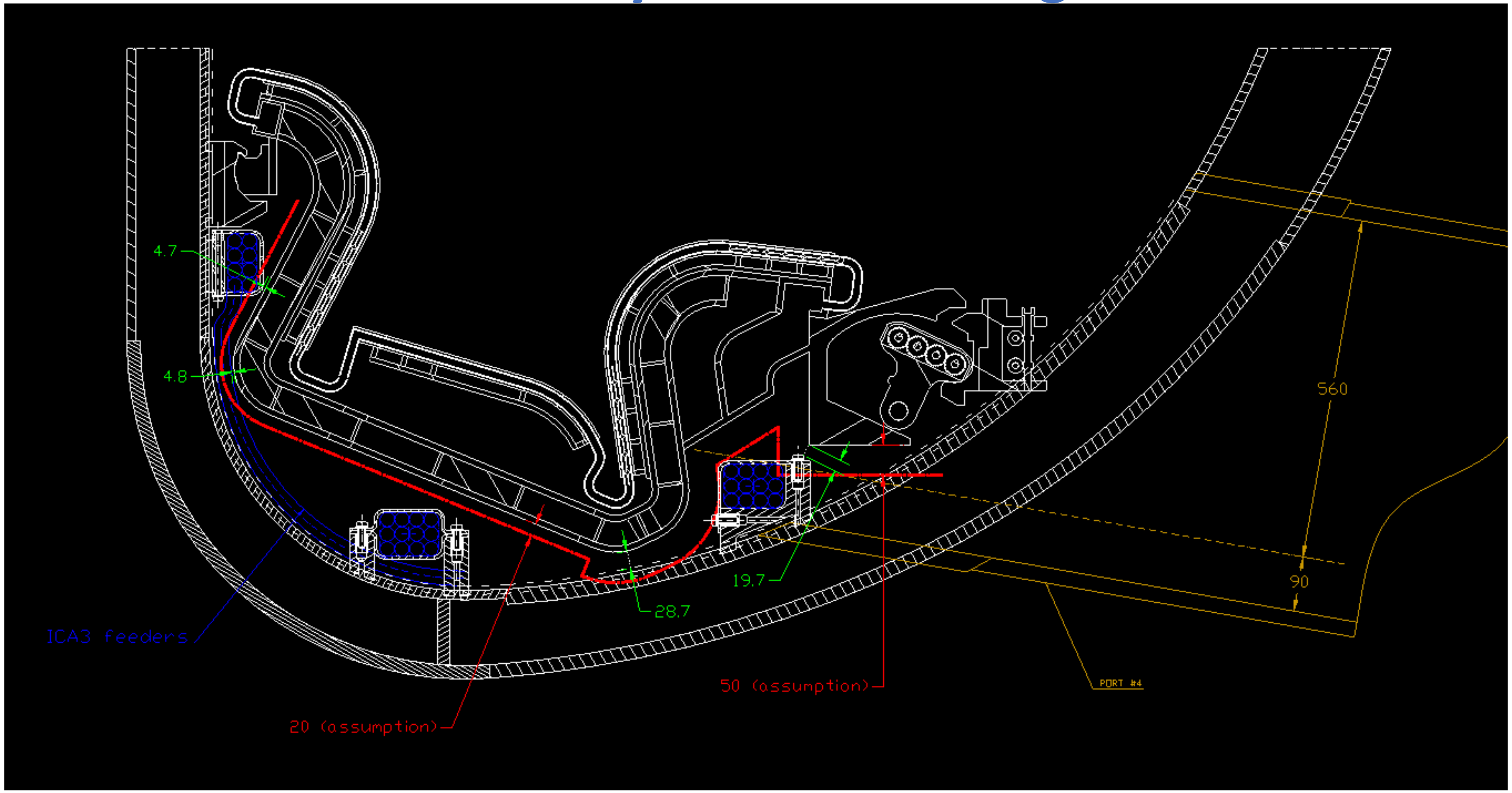
- vacuum vessel and installation with support pads
- in-port Diagnostics and Vessel Auxiliary systems including cryopanels
- assembly with draft sequences
- cryostat port flanges with feedthroughs
- first wall (support pads, clearances, heat load protection including neutral beam injection)
- divertor supports (rails and lower stop)
- heating and current drive systems (ECRH, ICRH, NBI)
- power supply (busbars physical interface and electric parameters)
- primary heat transfer system (WCS) cooling lines
- instrumentation (sensors and conduits, signal conditioning and acquisition up to CODAS)

In-vessel Coils Axisymmetric - coil cross sections and positions





In-vessel Coils Axisymmetric - integration of divertor coils

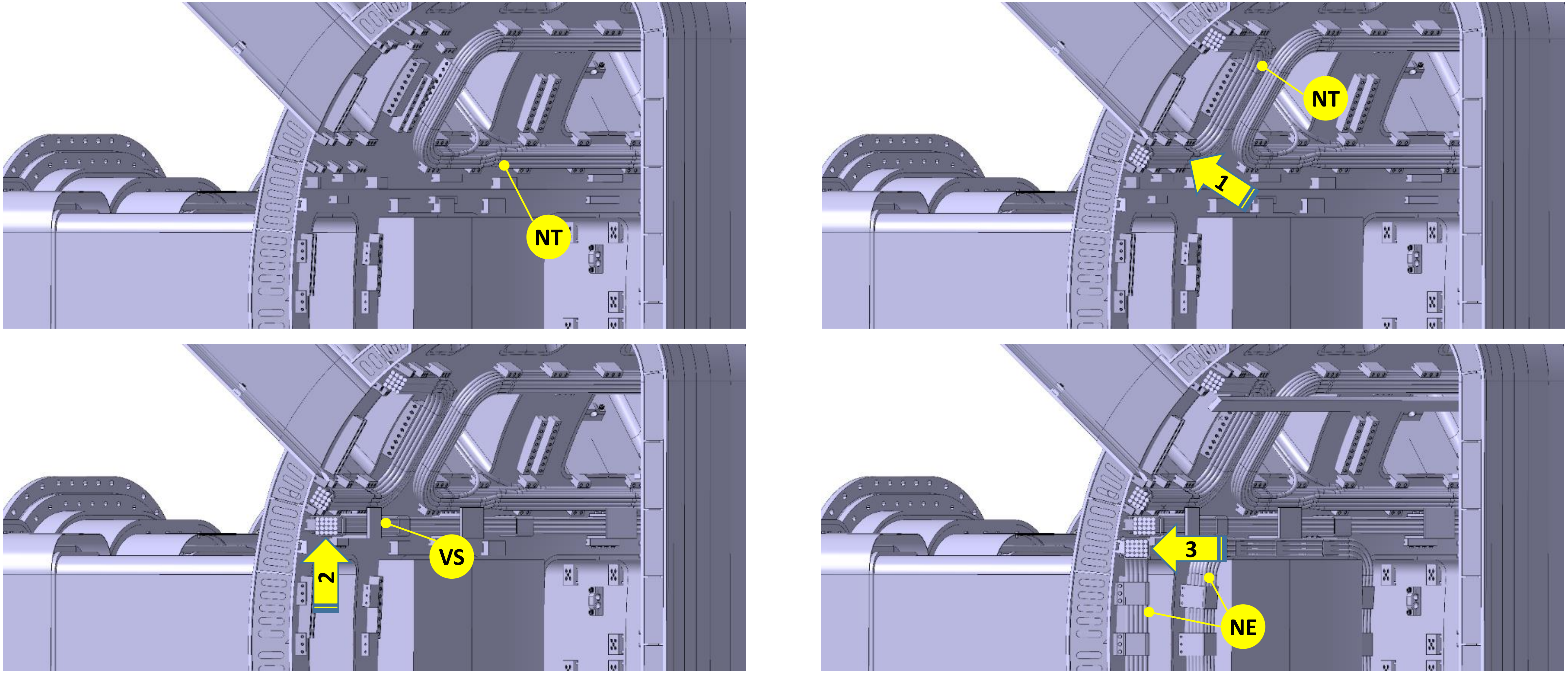


Minimum gaps are considered as a combination of construction tolerances and draft assembly errors

Confirmed changes considering integration with other in-vessel components:

a) new locations of the cross section of coils ICA 3, ICA 4, ICA 5
b) reduction from 8 to 7 of the number of turns for ICA 3 due to room constraints with divertor cassette and inboard rail (number of turns of ICA 4 and ICA 5 remains 12)

In-vessel Coils - integration in DTT and draft assembly sequence



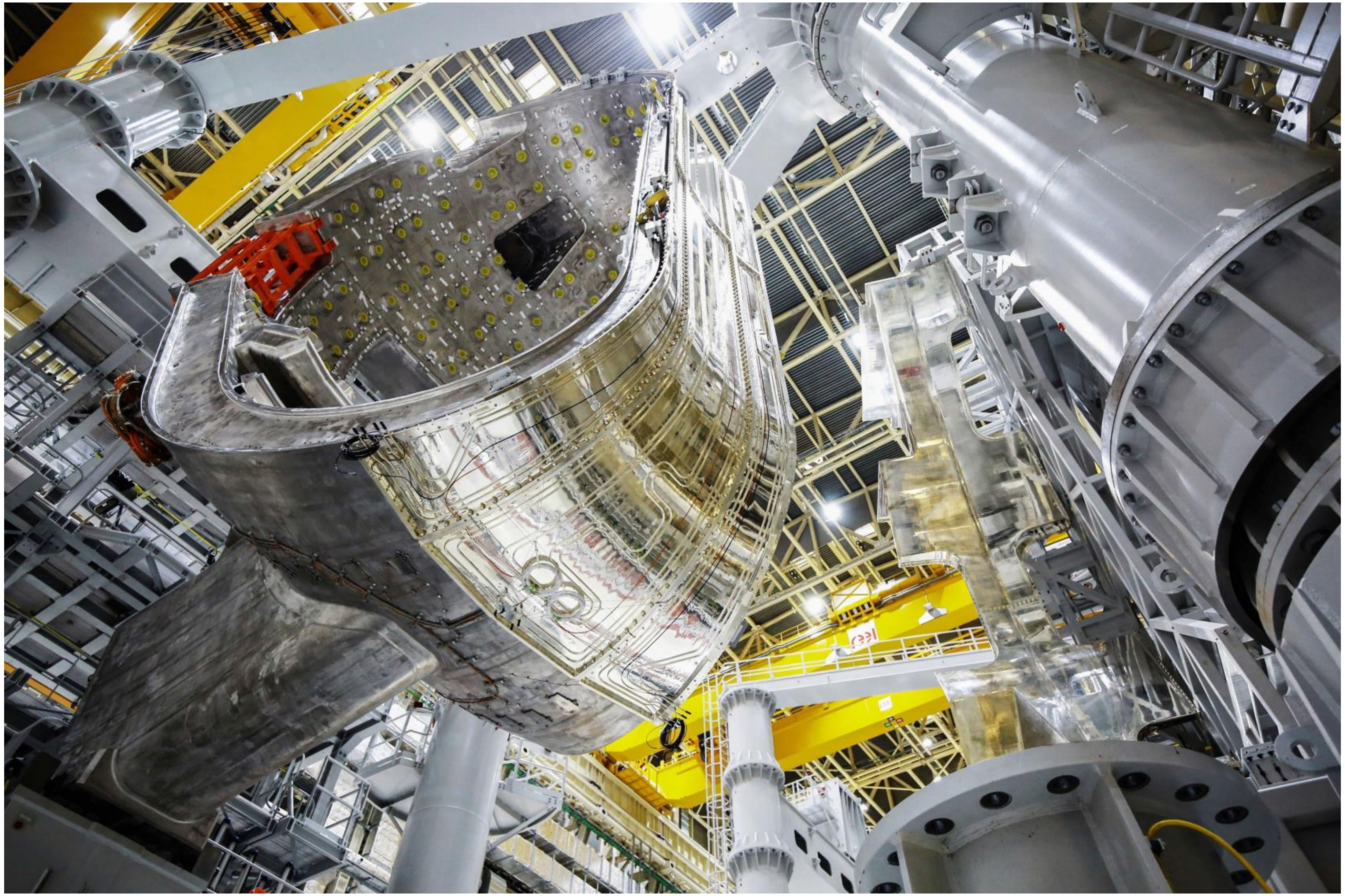
The design of the coil supporting brackets is ongoing considering:

- Integration and gap with other in-vessel components (FW+DIV)
- Draft assembly sequence
- Thermal expansion of turns considering cable temperature during transients wrt vessel temperature

B. Physical and functional integration →

DTT thermal shield integration

Functional integration and design for assembly → DTT thermal shield integration



ITER thermal shield [https://www.iter.org/node/20687/all-shine-and-precision]

Introduction

Definitions:

The main function of the thermal shield (THS) is to reduce the radiation heat transfer to the superconducting magnets at cryogenic temperature from the surrounding components (vacuum vessel at 20-110 °C, cryostat at ~20 °C, and primary heat transfer system tubes and manifolds). The surfaces of the THS panels realise low hemispherical emissivity.

Emissivity is the measure of an object's ability to emit infrared energy. Emitted energy indicates the temperature of the object. Emissivity can have a value from 0 (shiny mirror) to 1.0 (blackbody)

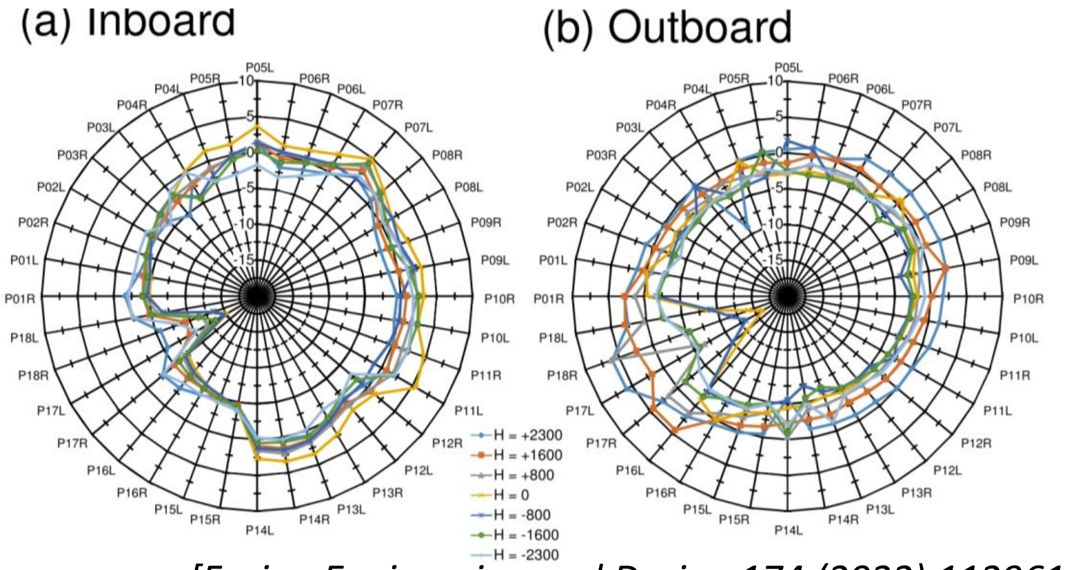
Requirements:

The thermal shield shall minimize the radiation to the superconducting magnets, by operating at a coolant temperature from 80 K to 100 K, and shall provide surfaces with low emissivity

The low-emissivity of the thermal shield surfaces shall not degrade to a level which precludes continuously the DTT facility operation over the life of the THS system, including all postulated events (Cat. I-III, except Cat. IV) that are specified in the Load Specification document

Vacuum vessels assembly errors

Vacuum Vessel assembly errors in JT-60SA



[Fusion Engineering and Design 174 (2022) 112961]

Inboard:
Specification tolerance = ± 10 mm
Actual error ± 5 mm
(apart final sector integration → special activity on DTT site to prevent unexpected distortions/contractions)

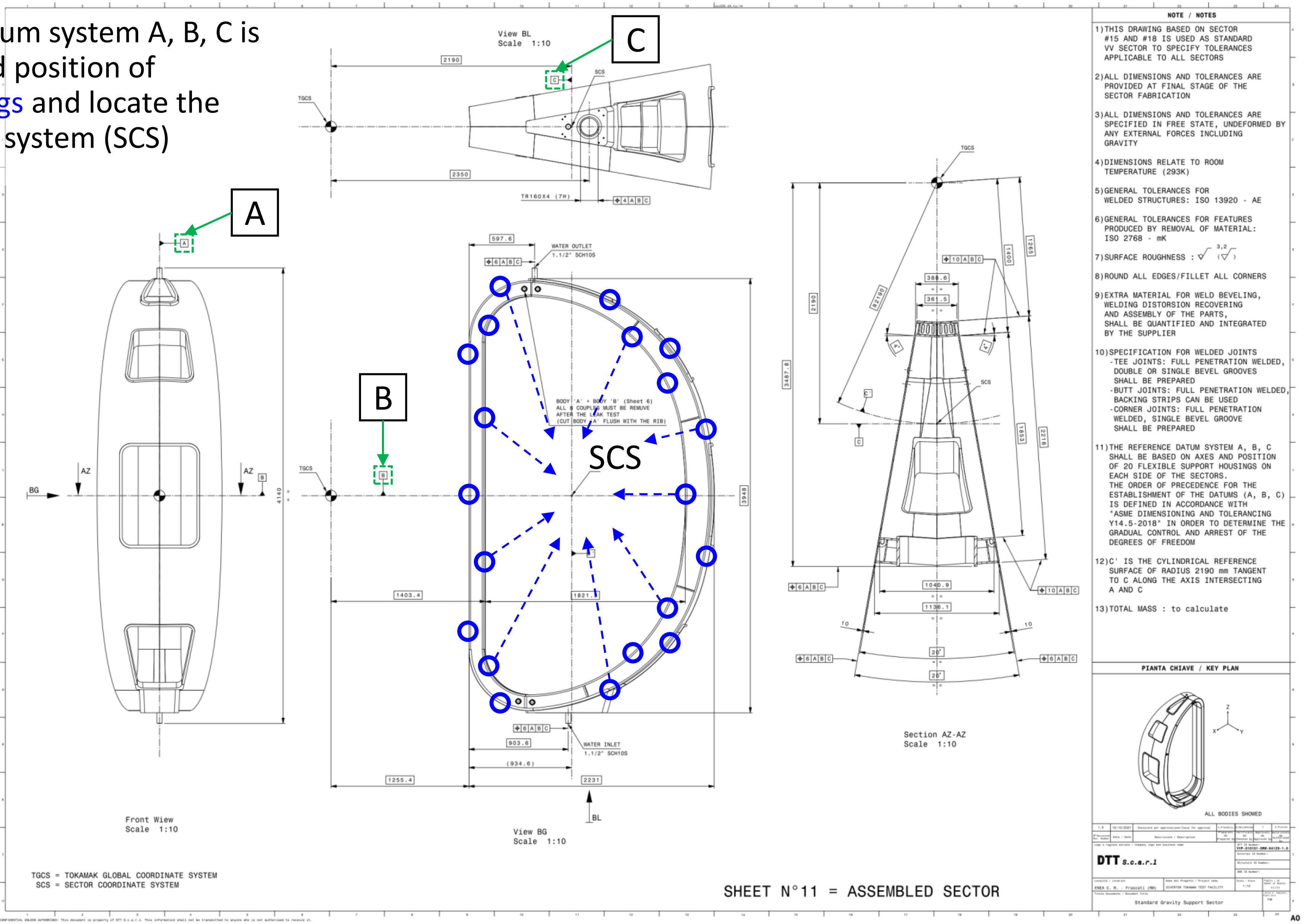
Outboard:
Specification tolerance = ± 20 mm
Actual error < ± 5 mm (apart final sector integration)

Vacuum Vessel assembly, mail shell position errors in DTT:

- Measurement procedure error (using photogrammetry/ laser tracker) for large dimension components (more than 4.0 m):
  ± 0.2 mm
- Multi-Sector construction (please see next slide) (sector inner / outer shell surface):
  ± 3 mm / ± 5 mm
- On-site position compensation through splice plate adjustment:
  ± 1 mm
- On-site movement after distortions for integration/welding of vessel sectors:
  ± 4 mm
- Total vessel inner / outer shell error:
  SRSS combination ≈ ± 5.1 / ± 6.5 mm (probability combination)
  sum of errors ≈ ± 8.2 / ± 10.2 mm (conservative)

Main shell construction error at each Multi-Sector

The reference datum system A, B, C is based on axes and position of 20 flexible housings and locate the sector coordinate system (SCS)



Assembly errors for thermal shield physical integration

DTT toroidal field coils (TFC) manufacturing + assembly:

- Measurement procedure error (using photogrammetry/ laser tracker) for large dimension components (more than 4.0 m):
  ± 0.2 mm
- Construction (TFC inner surface):
  ± 5 mm
- On-site position compensation through eccentric bushes and mechanical integration through outer/inner inter-coil structures:
  ± 1 mm
- Total TFC error :
  SRSS combination ≈ ± 5.1 mm (probability combination)

  sum of errors ≈ ± 6.2 mm (conservative)

Vacuum Vessel assembly, mail shell position errors in DTT:

- Measurement procedure error (using photogrammetry/ laser tracker) for large dimension components (more than 4.0 m):
  ± 0.2 mm
- Multi-Sector construction (please see next slide) (sector inner / outer shell surface):
  ± 3 mm / ± 5 mm
- On-site position compensation through splice plate adjustment:
  ± 1 mm
- On-site movement after distortions for integration/welding of vessel sectors:
  ± 4 mm
- Total vessel inner / outer shell error:
  SRSS combination ≈ ± 5.1 / ± 6.5 mm (probability combination)
  sum of errors ≈ ± 8.2 / ± 10.2 mm (conservative)

Gap deviation ≈ ± 16 mm

Gap analysis assumptions for thermal shield physical integration

Analysis of relative displacements between vacuum vessel and toroidal field coils (TFC) during operating states:

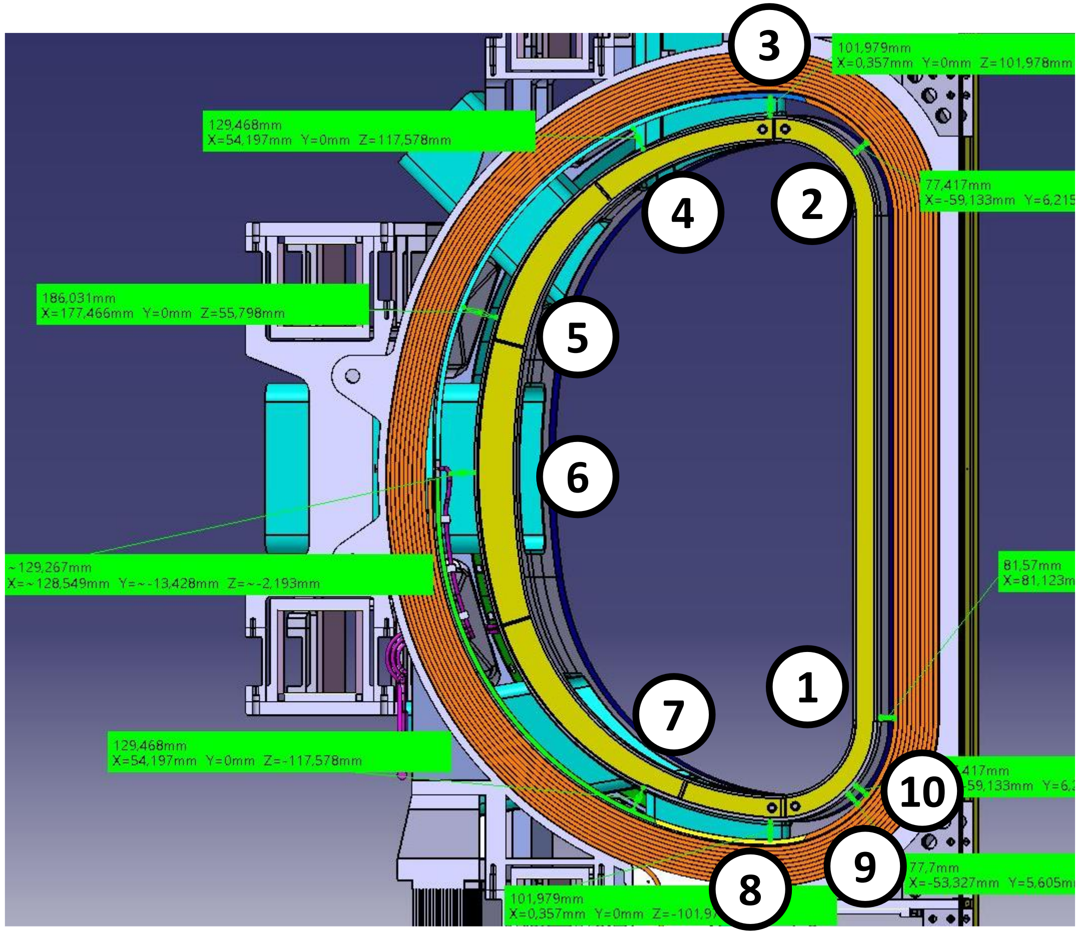
- plasma operation: vessel @ 60 °C, coils @ 4.5 K
- cold vessel: vessel @ 20 °C, coils @ 4.5 K
- baking hot coils: vessel @ 240 °C, coils @ 20 °C
- baking cold coils: vessel @ 240 °C, coils @ 4.5 K
- assembly: vessel @ 20 °C, coils @ 20 °C

Displacements/tolerances reducing the gaps:

- Thermal expansion/contraction
- Manufacturing + assembly: ± 16 mm (previous slide)
- Vessel deformation due to inter-shell water pressure: < 0.2 mm
- Ex-vessel flux loops magnetic probes: 10 mm thickness

Main assumptions:

- zero vertical thermal displacements wrt position 8
- no displacements produced by EM-mechanical & seismic loads
- points are fixed on components for gap estimation
- both cold/hot TFC are considered during baking to explore the worst scenario



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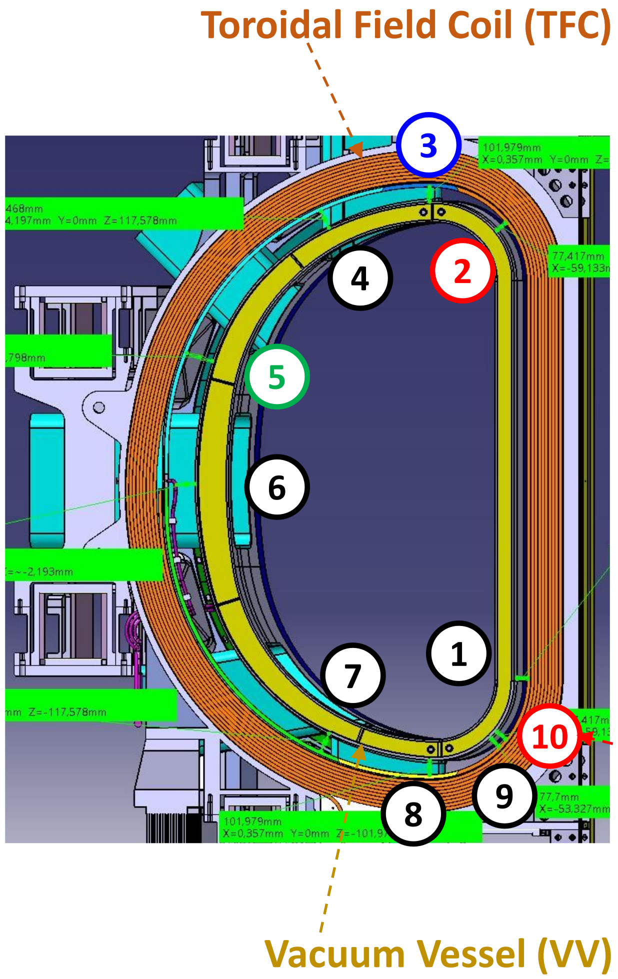
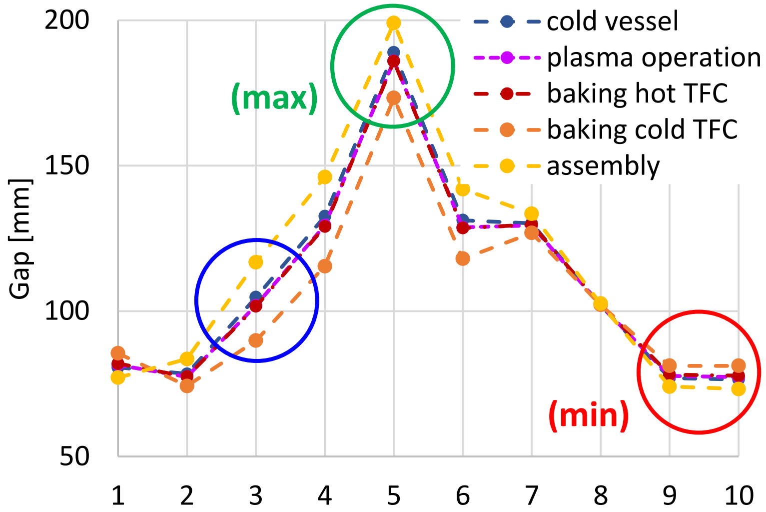
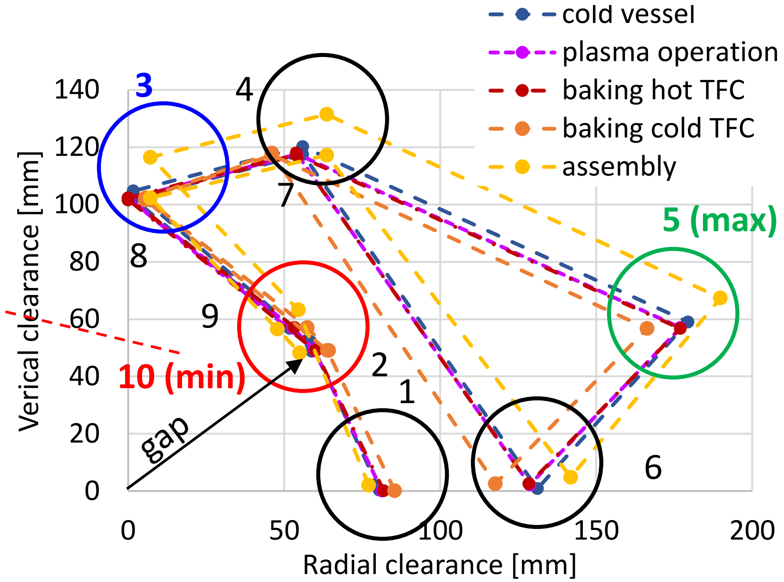
Gap analysis for the thermal shield







Thermal gaps [mm]

gap position	cold vessel	plasma operation	baking hot TFC	baking cold TFC	assembly
1	81	**81**	82	85	77
2	78	77	77	74	84
3	105	102	102	90	117
4	133	129	129	115	146
5	189	186	186	173	201
6	131	129	129	118	142
7	130	129	130	127	133
8	102	102	102	102	103
9	77	78	78	81	74
10	76	77	78	81	73

Manufacturing + assembly: ± 16 mm

Magnetic probes thickness: 10 mm

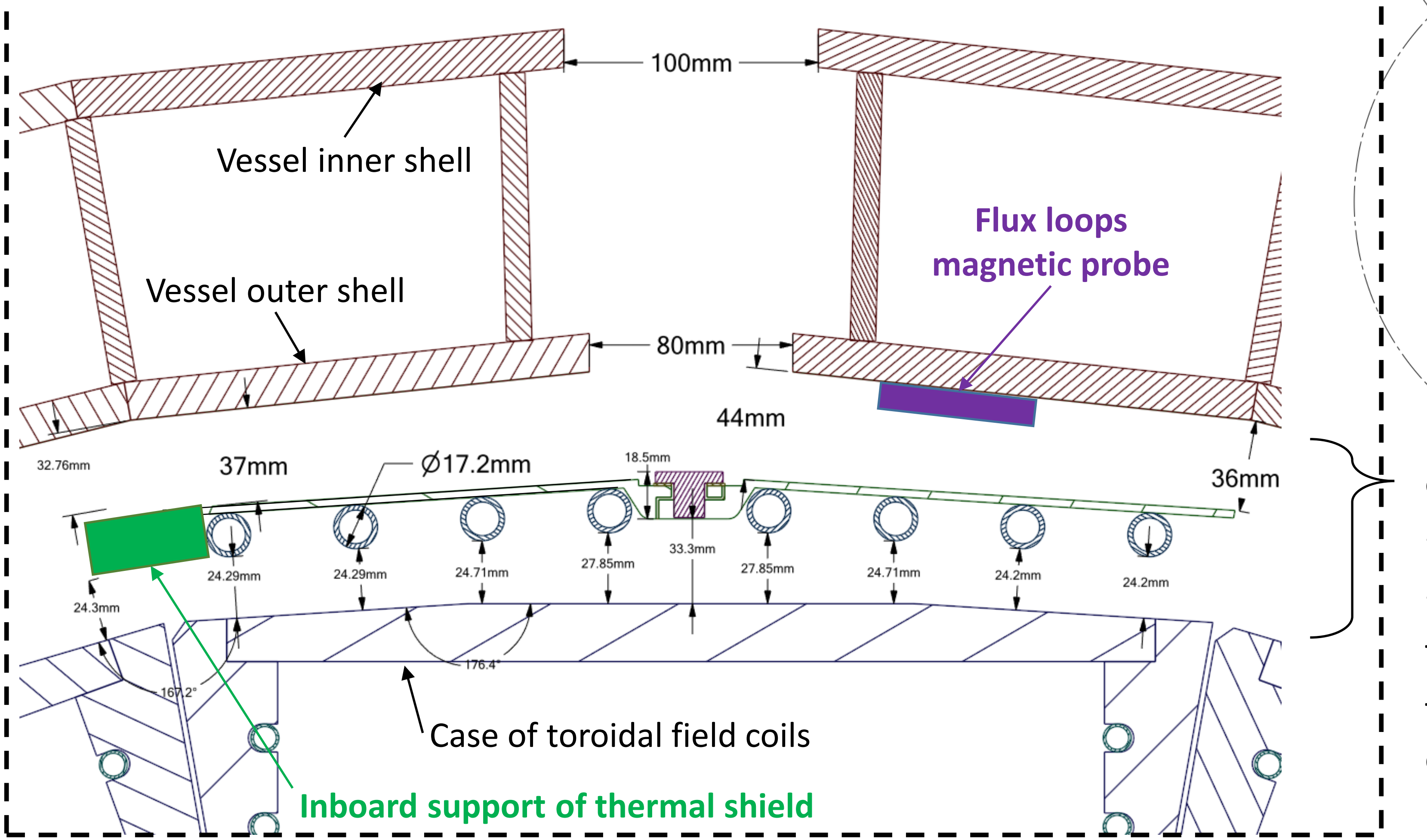
Thermal shield thickness: 20 mm

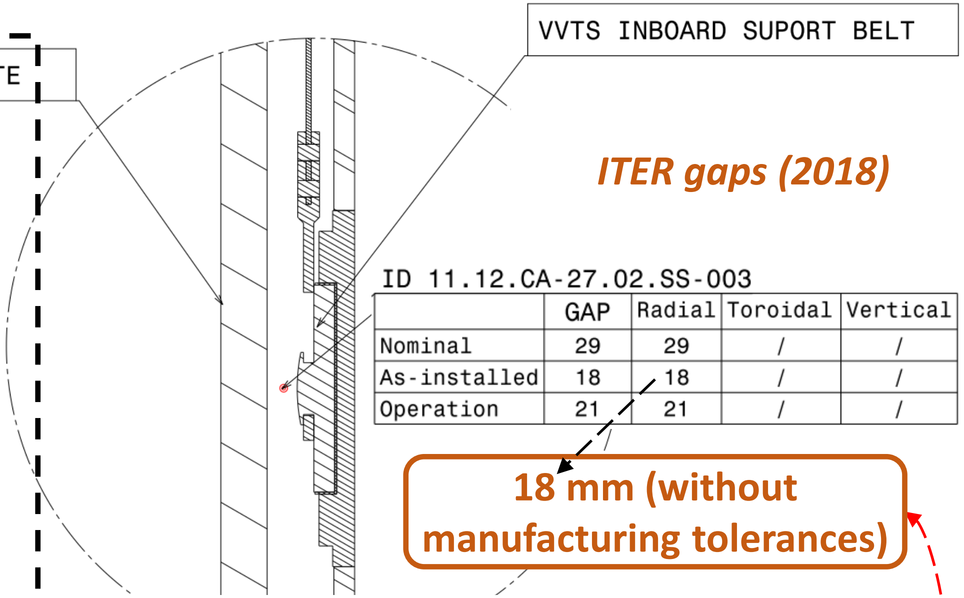
Net gaps [mm]

gap position	cold vessel	plasma operation	baking hot TFC	baking cold TFC	assembly
1	34	**35**	36	39	31
2*	42	41	41	38	47
3	59	56	55	44	71
4	86	83	83	69	100
5	143	140	140	127	155
6	85	83	82	72	96
7	84	83	83	81	87
8	56	56	56	56	56
9*	41	41	42	45	38
10*	40	41	42	45	37

Inboard gap for the thermal shield

Nominal DTT gaps during plasma operation:





	GAP	Radial	Toroidal	Vertical
Nominal	29	29	/	/
As-installed	18	18	/	/
Operation	21	21	/	/

Inboard gap (pos. 1) of 61 mm during plasma operation reduces to **35 mm** considering:

- 16 mm manufacturing + assembly
- 10 mm magnetic probe thickness

The gap reduces to **31 mm during assembly**

This single side gap of **15.5 + 15.5 mm** allows to compensate for <u>non conformities</u>

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Thermal shield functional integration: solutions implemented in other fusion machines

- KSTAR [G.H. Kim, et al. (NFRC), 2007 IAEA]:
  - Vacuum Vessel THS and Port THS:
    - single wall AISI 316L panels 4 mm thick are silver plated with 10 µm silver thickness
    - helium active cooling at 60 K and 20 bar
  - Cryostat THS (covering the lid, body, base): 1 mm thick stainless steel sheet with multi-layer insulation of 30 layers
- JT-60SA:
  - Vacuum Vessel THS and Port THS (Toshiba Plant Systems & Services Corporation) [https://www.qst.go.jp/site/jt60-english/6599.html]:
    - double wall shell stainless steel panels polished with Ra < 0.6 µm (ASTM A480 No.4)
    - helium active cooling at 80 K and 15 bar
  - Cryostat THS: actively cooled, but covered with multi-layer insulation
  - Vacuum Vessel: hot-rolled annealed and pickled-descaled (Ra≈5 µm) or single-sided Ra < 0.6 µm (ASTM A480 No.4)
- ITER:
  - Original design of Vacuum Vessel THS, Port THS, and Cryostat THS:
    - single wall AISI 304L panels 10-20 mm thick are silver plated with minimum 5 µm silver thickness (same procedure used for the silver coating of the KSTAR THS)
    - helium active cooling at 80 K and 18 bar
  - Repair (INOX India) [https://www.iter.org/newsline/-/3914]:
    - single wall panels 10-20 mm thick non-plated with Ra ≤ 0.1 µm, tubes made of AISI 316L

Emissivity measurements for silver coated and non-coated coupons

- Emissivity meter used on coupons: TSS-5X (reflective infrared energy measurement system)

- Normal and hemispherical thermal emittance calculated in accordance with ASTM E1585-93

[K. Nam, et al. Fusion Engineering and Design 146 (2019) 1171-1175]

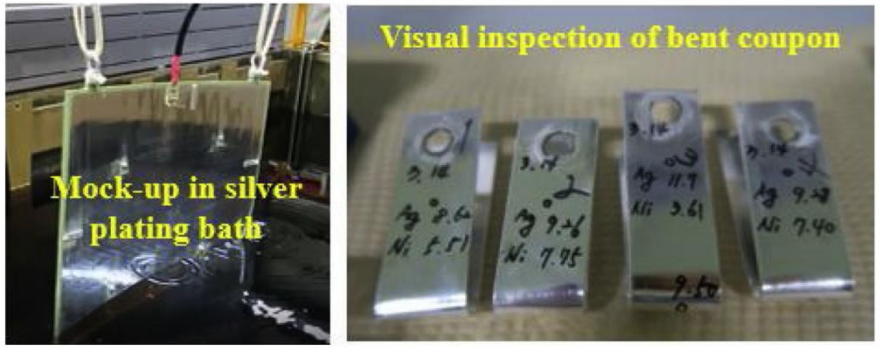


Fig. 9. Silver coated mock-up and coupon adhesion inspection.

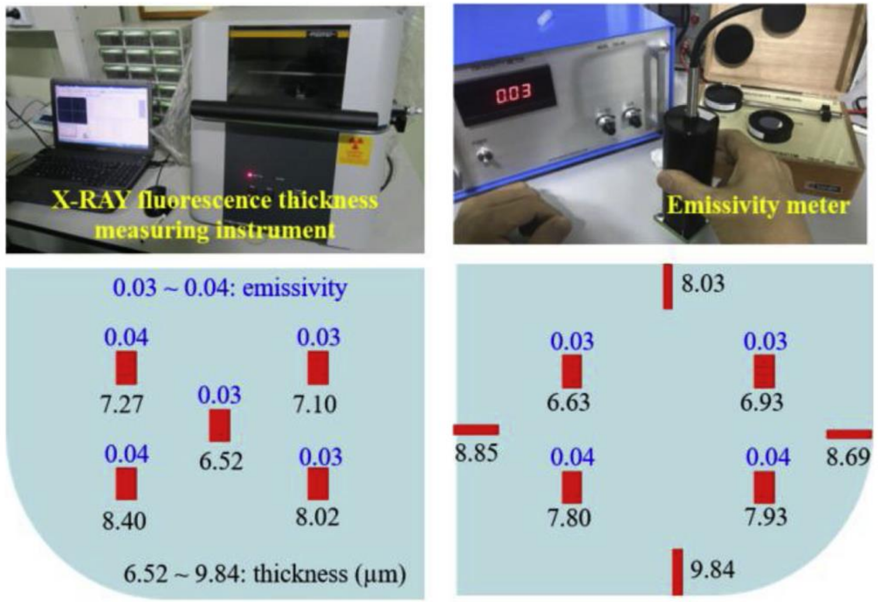
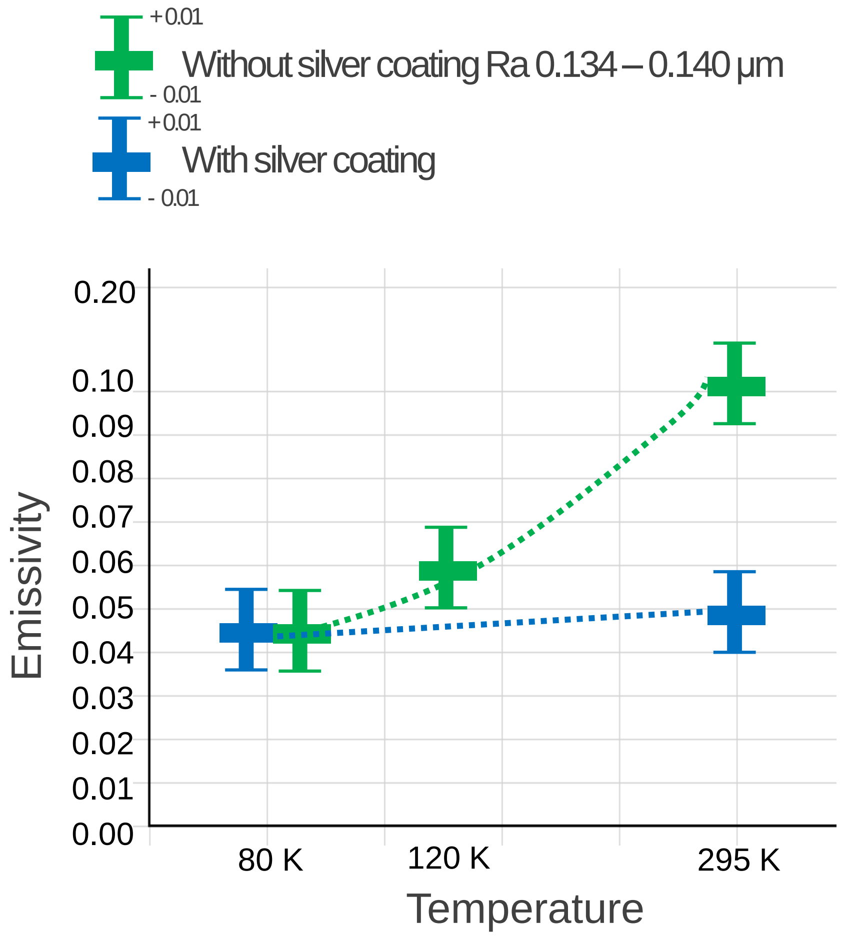


Fig. 10. Thickness and emissivity of coupons.



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ITER THS issue

Description of the issue on the ITER THS [https://www.iter.org/newsline/-/3818]:

- leaks on the helium circuit have been discovered after assembly tests with trapped material at leak positions
- the trapped material was confirmed to contain significant chlorine levels
- all leak positions showed some oxide indications on the surface of the inside of the pipe and significant amounts of Chlorine
- the cause of the leaks was stress corrosion cracking (SCC) as a result of trapped chlorides, humidity, and residual stress from the stitch welding

Two manufacturing methods were applied:

- Regular manufacturing process:
    - pipe (2D) → pre-bending (3D) → tack welding → stitch welding → buffing → silver coating → cleaning → packing
- Irregular manufacturing process:
    - pipe (2D) → tack welding → in-situation bending (3D) → stitch welding → buffing → silver coating → cleaning → packing

Description of the cause of the ITER THS issue:

- the chlorides used in activation of surfaces to ensure proper galvanic attachment were basically impossible to clean from the interstices of the cooling pipe stitch welds through buffing
- neither the buffing process nor the cleaning processes had been qualified
- choice of AISI 304L for the cooling pipes, against the more corrosion resistant of AISI 316L used on KSTAR's THS

Comment:

- Regarding stress corrosion cracking (SCC) of austenitic stainless steel, importance to prevent presence of halides (and in particularly chlorides) in the manufacturing processes must be underlined
- AISI 304/304L is the strongest susceptible grade to localized corrosion and SCC. AISI 316/316L is less susceptible, but remains susceptible when significant chloride contamination is present

DTT design

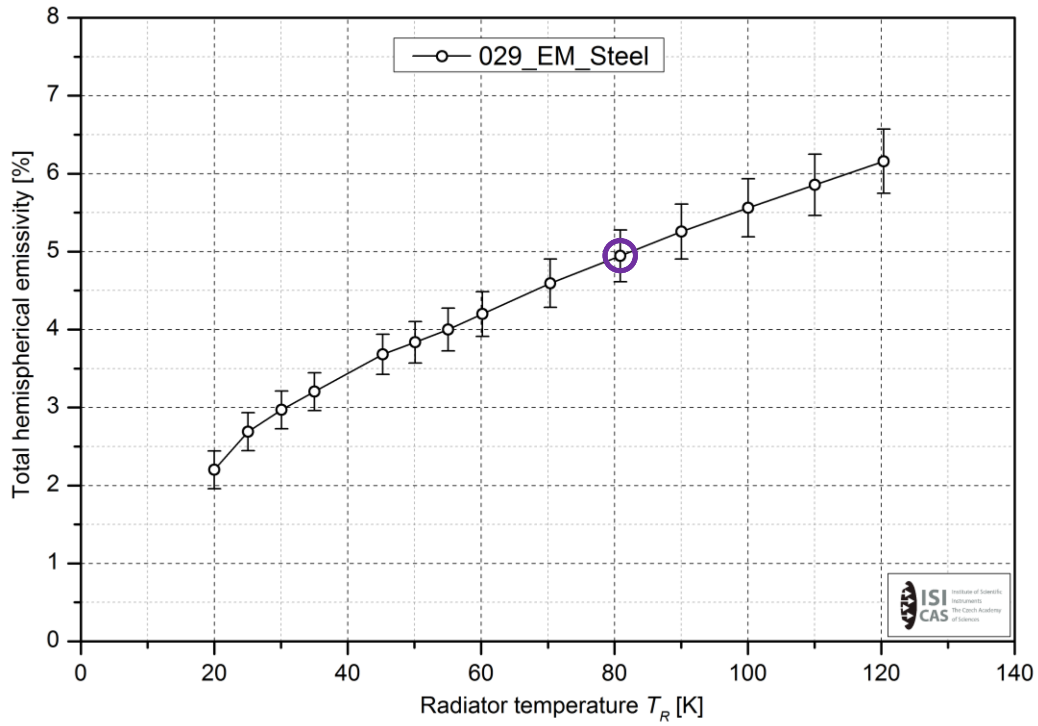
- THS:
  - Vacuum Vessel THS and Port THS:
    - double wall shell stainless steel panels (chemical composition is defined in the next slides) polished with Ra ≤ 0.4 μm (ISO N5 or better)
    - helium active cooling at 80 K and ~18 bar (depending on cryoplant interface and pressure drops) through seamless AISI 316L tubes (chemical composition is defined in the next slides)
  - Cryostat THS: actively cooled panels which could be covered with multi-layer insulation

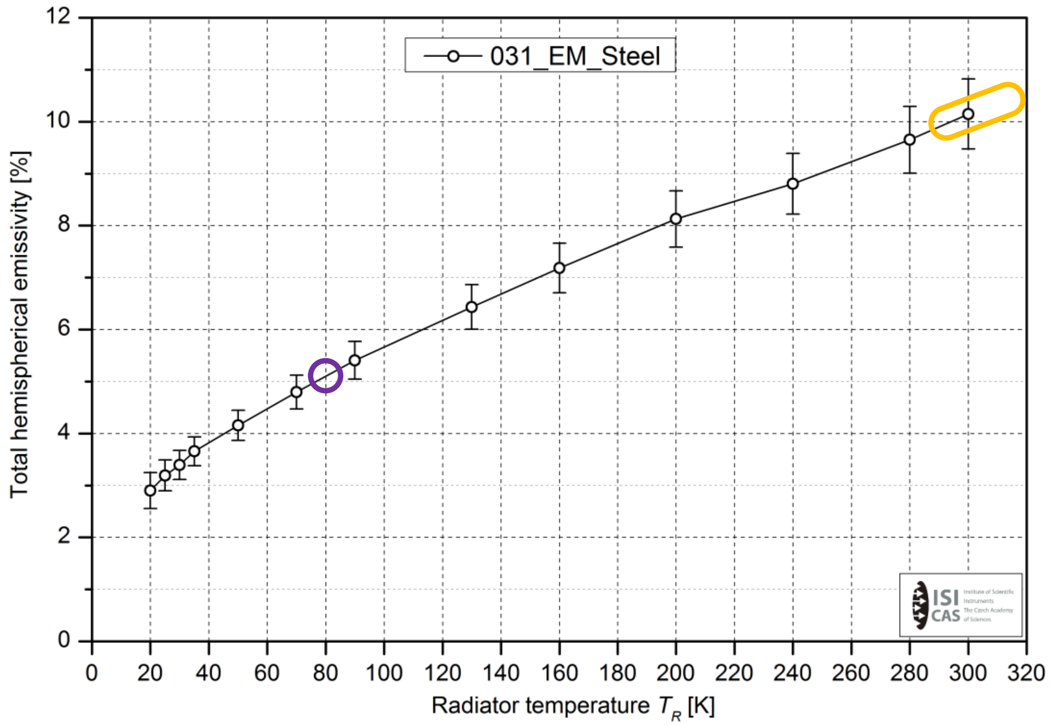
- Vacuum Vessel outer shell and ports:
  - hot-rolled annealed and pickled-descaled, then machining with Ra ≤ 3.2 μm for cleaning
  - (further investigations are presented in the next slides)

- Other provisions:
  - passive panels will be installed on other components like parts of the DTT vacuum vessel (bellows passive shields, water tubes of the primary heat transfer system,…)
  - protection of polished and cleaned surfaces will be required in order to prevent damages and contamination/dust deposition and to preserve the surface emissivity

Emissivity data 1/2

Stainless steel AISI 304 finely turned on a lathe (identical material and surface finishing of Ra < 0.15 μm) [Musilova et al., 2005]:





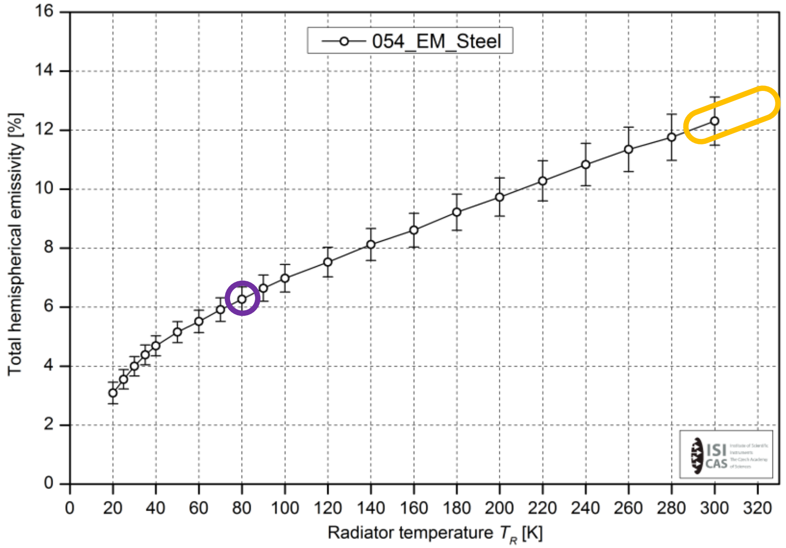
measurement repetition: 9 years after the first measurement

The effect of time on surface emissivity can be considered negligible:

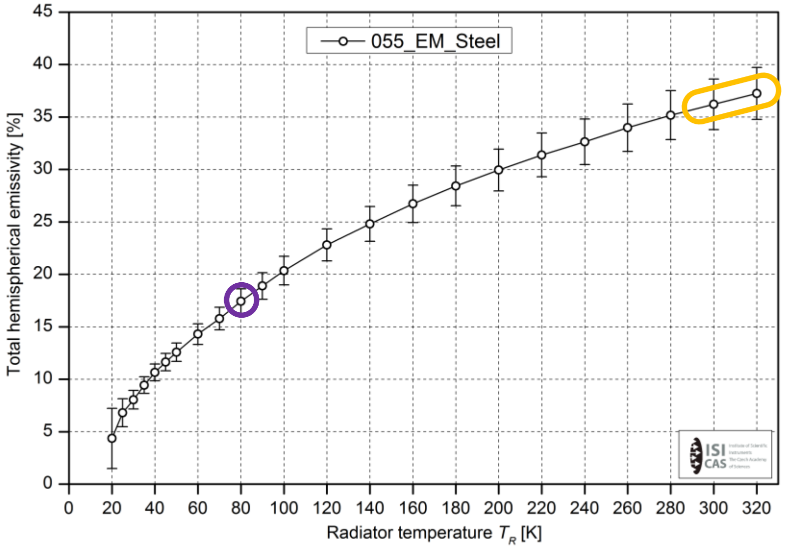
- at 80 K: from ε = 0.049 to ε = 0.051 after 9 years (without contamination/dust deposition)

Emissivity data 2/2

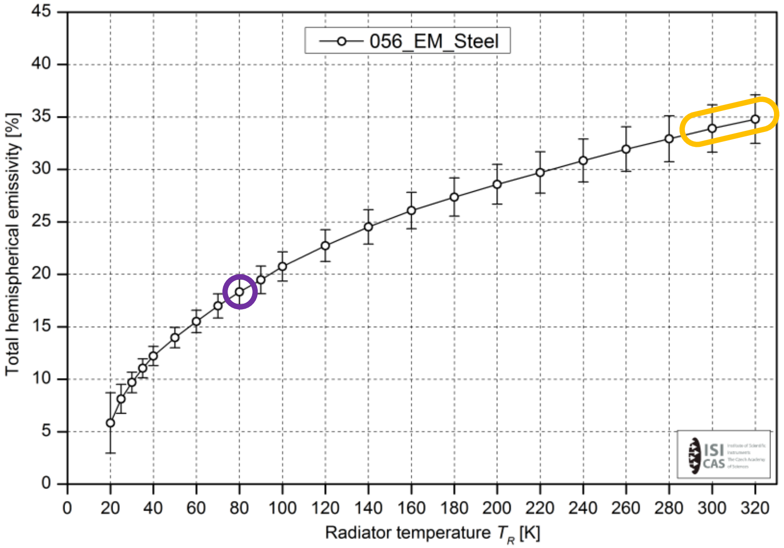
Stainless steel AISI 304 [Frolec, 2018, DOI: 10.17632/z8t423rwwd.2]:



Ra = 0.15 µm; Rz = 0.99 µm
- at 80 K: ε = 0.062
- at 290 K: ε = 0.122



Ra = 1.14 µm; Rz = 7.22 µm
- at 80 K: ε = 0.175
- at 290 K: ε = 0.365



Ra = 3.06 µm; Rz = 17.56 µm
- at 80 K: ε = 0.180
- at 290 K: ε = 0.330

- Roughness above ISO N6 (Ra ≥ 0.80 µm) does not produce significant advantages on AISI 304 emissivity
- Roughness below ISO N4 (Ra ≤ 0.20 µm) reduces the emissivity of about 3 times with respect to ISO N6 or worse
- Roughness specification for the THS is ISO N5 or better (Ra ≤ 0.40 µm) to be realised trough polishing in order to achieve ε ≤ 0.07 at 80K
- Roughness specification for the vacuum vessel is N8 or better (Ra ≤ 3.2 µm) and further investigations are ongoing

Influence of damages and dust on the emissivity

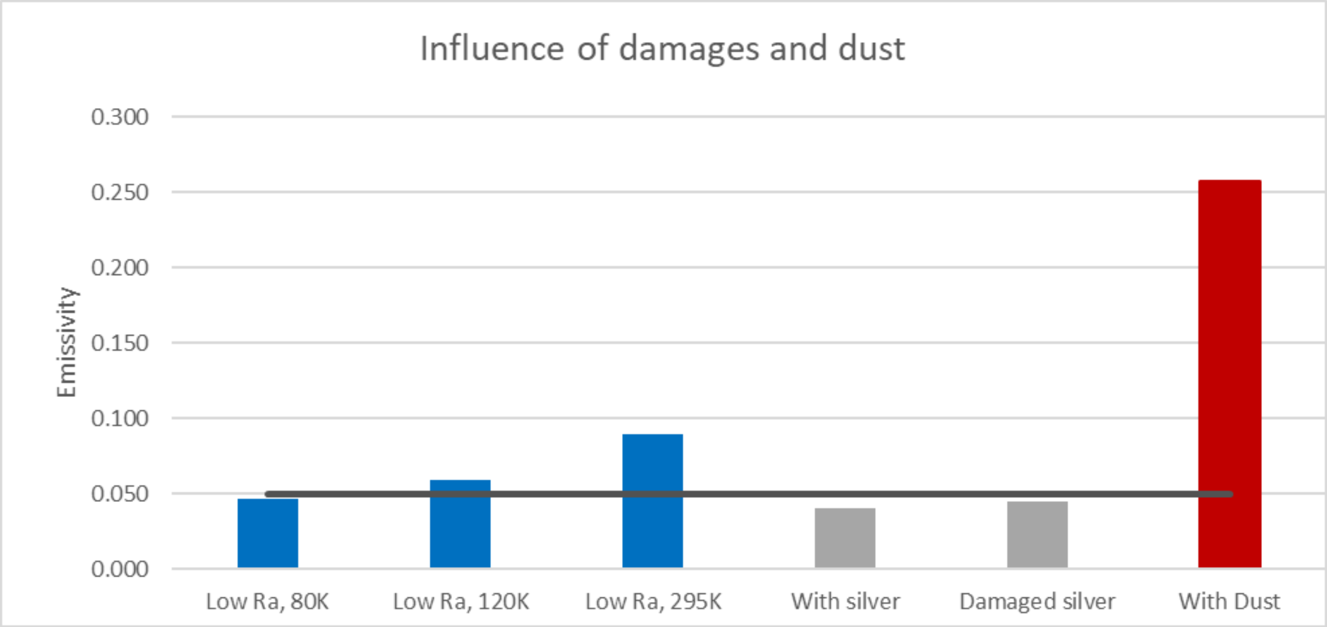
Additional data to those presented:

- Low impact on emissivity measured for:
  - deep scratches produced by sandpaper as damages to the silver coating
- Very high impact on emissivity measured for:
  - sprayed dust over samples

Additional requirement:

- Surface protection as strict preservation requirement during the assembly

[https://www.iter.org/construction/TokamakAssembly]



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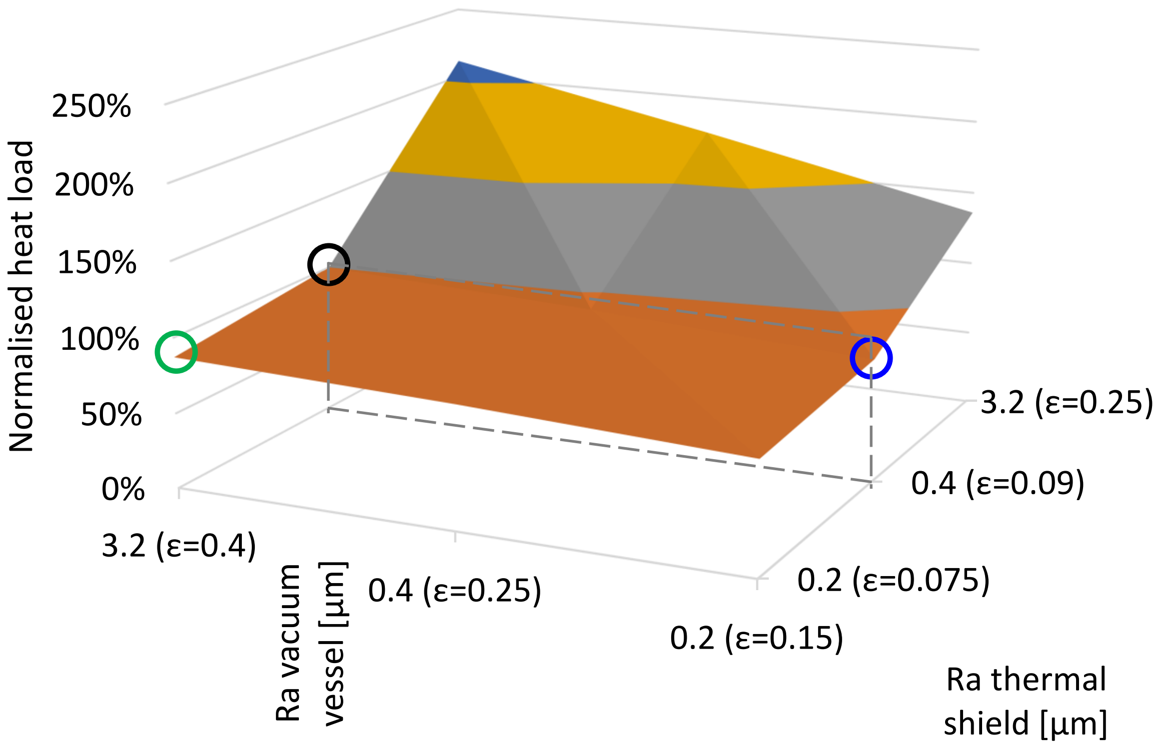
Influence of emissivity on heat load (thermal shield @ 120 K)



Ra thermal shield [µm]	Ra vacuum vessel [µm] 0.2 (ε=0.15)	0.4 (ε=0.25)	3.2 (ε=0.4)
0.2 (ε=0.075)	74%	82%	**87%**
0.4 (ε=0.09)	**82%**	93%	**100%**
3.2 (ε=0.25)	136%	175%	212%

- Average thermal shield temperature: 120 K
- Reference scenario (100% normalised heat load):
  - Ra vacuum vessel = 3.2 µm (ε = 0.4 @ 293 K)
  - Ra thermal shield = 0.4 µm (ε = 0.09 @ 120 K)
- Further data:
  - Ra cryostat = 3.2 µm (ε = 0.4 @ 293 K)
- The heat load can be significantly reduced by polishing the component working at lower temperature (thermal shield) @ Ra thermal shield ≤ 0.4 µm
- Polishing of the vacuum vessel (reducing Ra_{VVP} from 3.2 µm to 0.2 µm) produces effects (82%) similar to those of further polishing of the thermal shield (87% reducing Ra_{THS} from 0.4 µm to 0.2 µm) → need to verify He parameters interfacing with the cryoplant
- Normalised heat loads are calculated using the Carnot factor $(T_0\text{-}T)/T$

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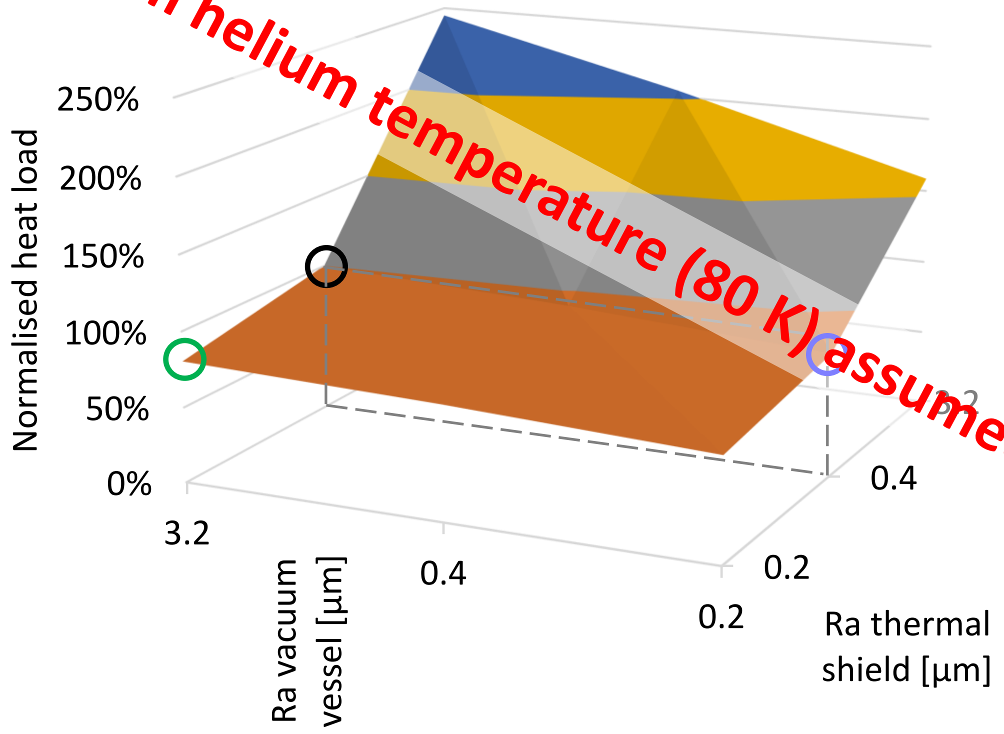
Influence of emissivity on heat load (thermal shield @ 80 K)

Minimum helium temperature (80 K) assumed uniformly applied on the thermal shield panels!



Ra thermal shield [µm]	Ra vacuum vessel [µm]: 0.2 (ε=0.15)	0.4 (ε=0.25)	3.2 (ε=0.4)
0.2 (ε=0.055)	69%	76%	80%
0.4 (ε=0.07)	**82%**	93%	**100%**
3.2 (ε=0.2)	158%	204%	245%

- Thermal shield temperature: 80 K!
- Reference scenario (100% normalised heat load):
  - Ra vacuum vessel = 3.2 µm (ε = 0.4 @ 293 K)
  - Ra thermal shield = 0.4 µm (ε = 0.07 @ 80 K)
- Further data:
  - Ra cryostat = 3.2 µm (ε = 0.4 @ 293 K)
- The heat load can be significantly reduced by polishing the component at lower temperature (thermal shield) @ Ra thermal shield ≤ 0.4 µm
- Polishing of the vacuum vessel (reducing Ra_{VVP} from 3.2 µm to 0.2 µm) produces effects (82%) similar to those of further polishing of the thermal shield (80% reducing Ra_{THS} from 0.4 µm to 0.2 µm)
- Normalised heat loads are calculated using the Carnot factor $(T_0-T)/T$

Delivery conditions for thermal shield raw materials

Seamless tubes made of EN 1.4404:

- Seamless tubes shall be procured in the technical delivery condition with reference to the process route CFA, test category 2, options 6, 11, 14, 15, 22, and 25 according to EN 10216-5 “Stainless steel tubes for pressure purposes - Technical delivery conditions - Part 5: Stainless steel tubes”. Equivalent delivery conditions of products can be specified according to ASME and ASTM standards.

Panel sheets made of 1.4306 or EN 1.4404:

- Flat products shall be procured in the technical delivery condition by reference to the process route 1D or 2D according to EN 10028-7 “Flat products made of steels for pressure purposes - Part 7: Stainless steels”, and EN 10088-4 “Stainless steels - Part 7: Technical delivery conditions for sheet/plate and strip of corrosion resisting steels for construction purposes”. Equivalent delivery conditions of products can be specified according to ASME and ASTM standards.

Filler metal for stitch welding of tubes to sheets could be ER317L (to be verified)

Special finishes on flat products are not required and they are shown together with the typical correspondence between Grit and Ra

Stainless Steel
Surface Finishes & Polishing

aalco®

BS EN 10088-2 / 10028-7 Finishes

BS EN Finish	Old BS Finish	Description
		Hot Rolled
1C	0	Hot rolled, heat treated, not descaled
1E	1	Hot rolled, heat treated, mechanically descaled
1D	1	Hot rolled, heat treated, pickled
1U	-	Hot rolled, not heat treated, not descaled
		Cold Rolled
2C	-	Cold rolled, heat treated, not descaled
2E	-	Cold rolled, heat treated, mechanically descaled
2D	2D	Cold rolled, heat treated, pickled
2B	2B	Cold rolled, heat treated, pickled, skin passed
2R	2A / (BA)	Cold rolled, bright annealed
2Q	-	Cold rolled, hardened and tempered, scale-free

Special Finishes*

BS EN Finish	Old BS Finish	Description	Typical Grit	Typical R_a
1G or 2G	-	Ground Grit	120	2.5 to 2.0 µ
1J or 2J	[redacted]	Brushed - Unidirectional	180	1.2 to 1.0 µ
1J or 2J	[redacted]	Dull Polished – Unidirectional	240	0.6 µ
1K or 2K	[redacted]	Satin polished – Unidirectional	320	0.5 Max
1P or 2P	[redacted]	Bright polished – Non-Directional with a high degree of image clarity	600	0.1 µ
1P or 2P	[redacted]	Mirror Finish – Non-Directional with a very high degree of image clarity	800	0.05 µ
1M or 2M	-	Patterned		
2L	-	Coloured		
2W	-	Corrugated		
1S or 2S	-	Surface Coated (Metallic coatings such as tin, lead or aluminium)		

***Note:** Special finishes indicate hot rolled (1) and cold rolled (2) sheets, e.g.: Ground polished hot rolled sheets = 1G / Ground polished cold rolled sheets = 2G

Main manufacturing requirements of the DTT thermal shield panels

- JT-60SA like configuration: double wall structure
- Tube outside diameter 13.5 mm, wall thickness 2 mm
  (in accordance with ISO 4200 and EN 10220)
- External surfaces of plates shall be polished: Ra ≤ 0.4 µm
- Cleaning requirements apply for vacuum compatibility
- Helium leak testing of the cooling circuit will be specified
- Use of emissivity meter (TSS-5X)
- Normal and hemispherical thermal emittance calculated from ASTM E1585-93

Table I.2 — Comparison of arithmetical mean deviation *Ra* and roughness grade numbers — (Table C.1 of ISO 1302:1992)

Roughness value *Ra*		Roughness grade numbers (given in the previous edition of ISO 1302)
µm	µin	
50	2 000	N 12
25	1 000	N 11
12,5	500	N 10
6,3	250	N 9
3,2	125	N 8
1,6	63	N 7
0,8	32	N 6
0,4	16	N 5
0,2	8	N 4
0,1	4	N 3
0,05	2	N 2
0,025	1	N 1

JT-60SA like panels [https://doi.org/10.1016/j.fusengdes.2019.03.194]:

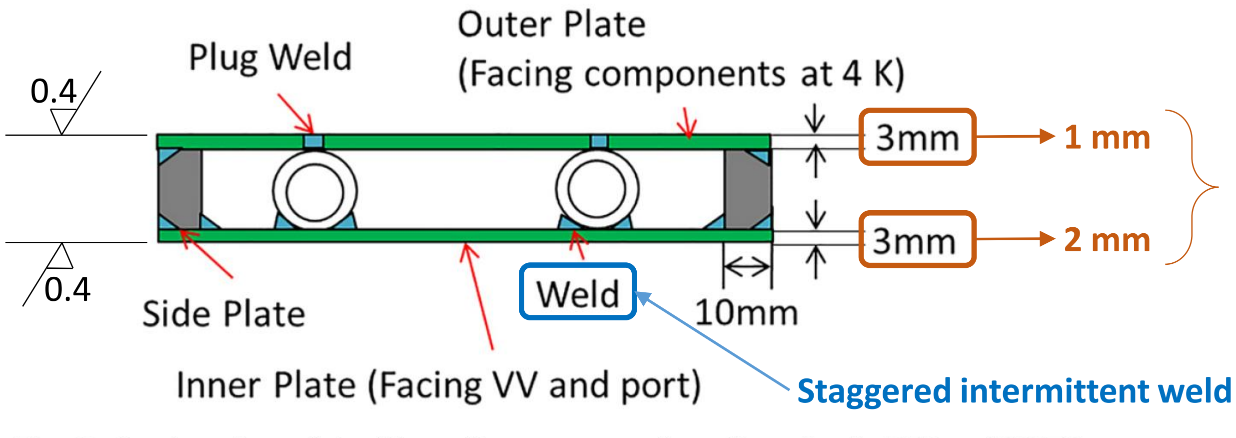
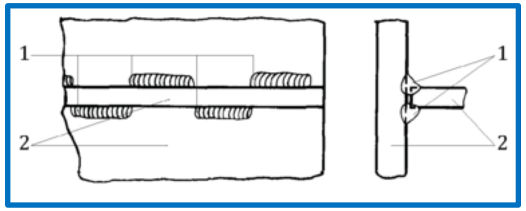


Fig. 3. Section view of double wall structure and cooling pipe in PTS and VVTS.

About 1000 m² overall surface extension for each side
Thickness will be reduced consistently with structural verification



C. Global integration →

DTT seismic isolators

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Main assumptions

- The isolators are **designed** with the RSL **SLC** (no-collapse local seismic response)
- No external horizontal loads (no wind, the machine is approximately axisymmetric, no loads from disruption events are transferred below the cryostat base)
- Single degree of freedom **analytical model** is suitable for preliminary design of the isolators. The equivalent stiffness of the modelled springs accounts for both the isolator stiffness (K_{iso}) and the stiffness of the superstructure (K_{ss}), which are in series with respect to the seismic action. Given that $K_{iso} \ll K_{ss}$, one can assume $K_{eq} = K_{iso}$
- The eccentricity is negligible for applied loads and for the geometry without NBI connection
- Mass participation of the rotational mode is negligible
- The suggested maximum damping is 15%. With higher damping, the isolation system may not work for RSL lower than SLC, e.g. SLO (**verification** is needed for serviceability limit state). Moreover, lower dissipation allows re-centring
- Among all isolators, the identified types are:
    - <u>rubber/elastomeric</u> bumpers which can be used in combination with planar support (free translation)
    - lead-rubber bumpers with one or more lead plugs inserted to increase the damping by hysteretic shear deformations (equivalent viscous damping up to 30%)
    - <u>pendulum isolators/curved surface</u> sliders with energy dissipation provided by friction: bilinear behaviour
    - steel hysteretic bumpers
- The isolators are weak against traction loads. The vertical stiffness is assumed to be 800 times higher than the horizontal one for preliminary evaluations

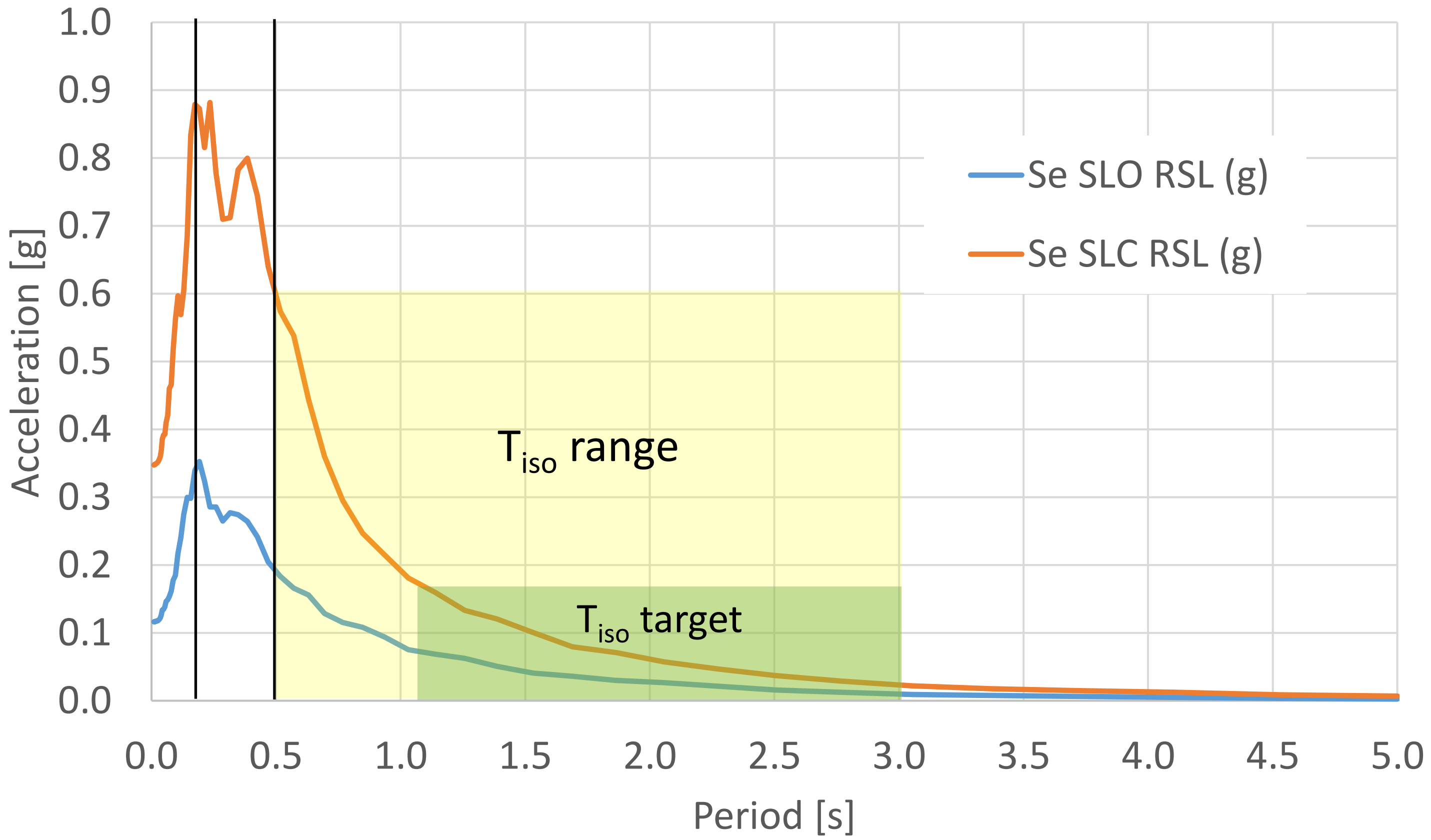
Preliminary design of the isolator system - Selection of the isolation period

- The natural period (T_{nat}) of the machine, without the isolation system, is T_{nat} = 0.17 s
- The isolation period must be included in the range $3 \cdot T_{nat}$ – 3.0 s in order to use the linear static analysis method [NTC 7.10.5.3.1]
- The target range for the isolation period is T_{iso} = 1.1 – 3.0 s, corresponding to:
  a ≈ 0.17 g for SLC RSL @ 5% damping, *a* ≈ 0.12 g for SLC RSL @ 15% damping

$$\omega_n = \sqrt{\frac{k}{m}} = \frac{2\pi}{T} \rightarrow k(T_{iso})$$

$$m\ddot{x} + kx = 0 \rightarrow x$$

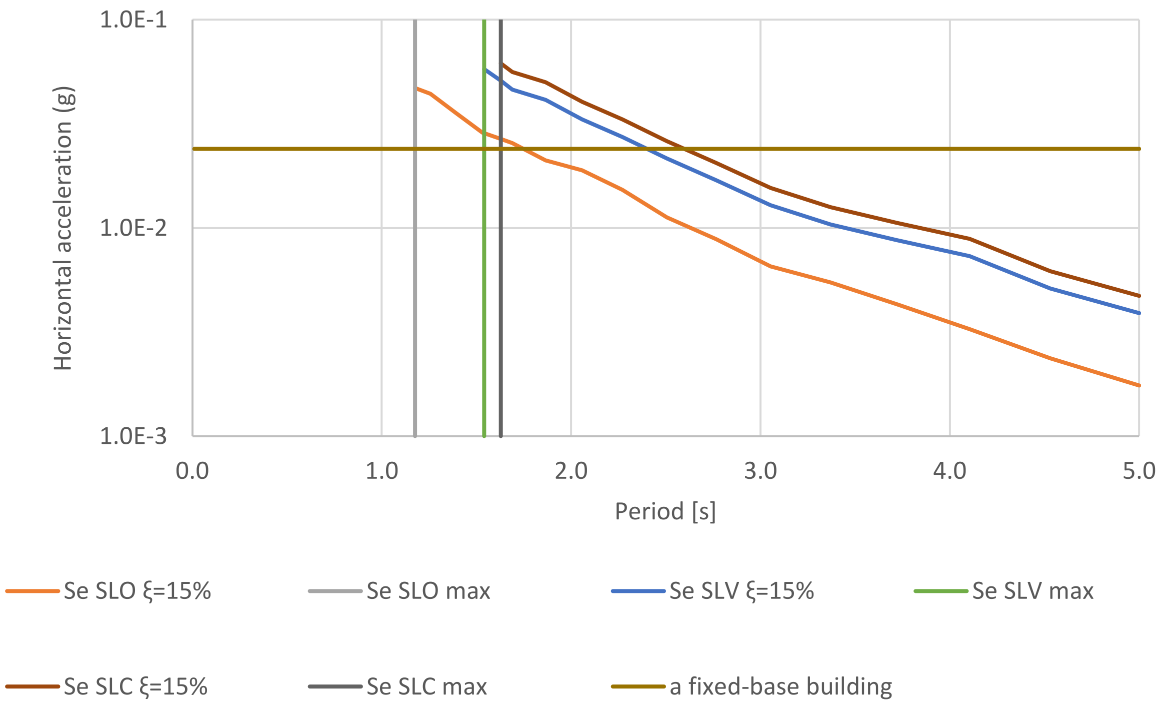
T_{nat} = 0.17 s → T_{iso} = 1.1 – 3.0 s

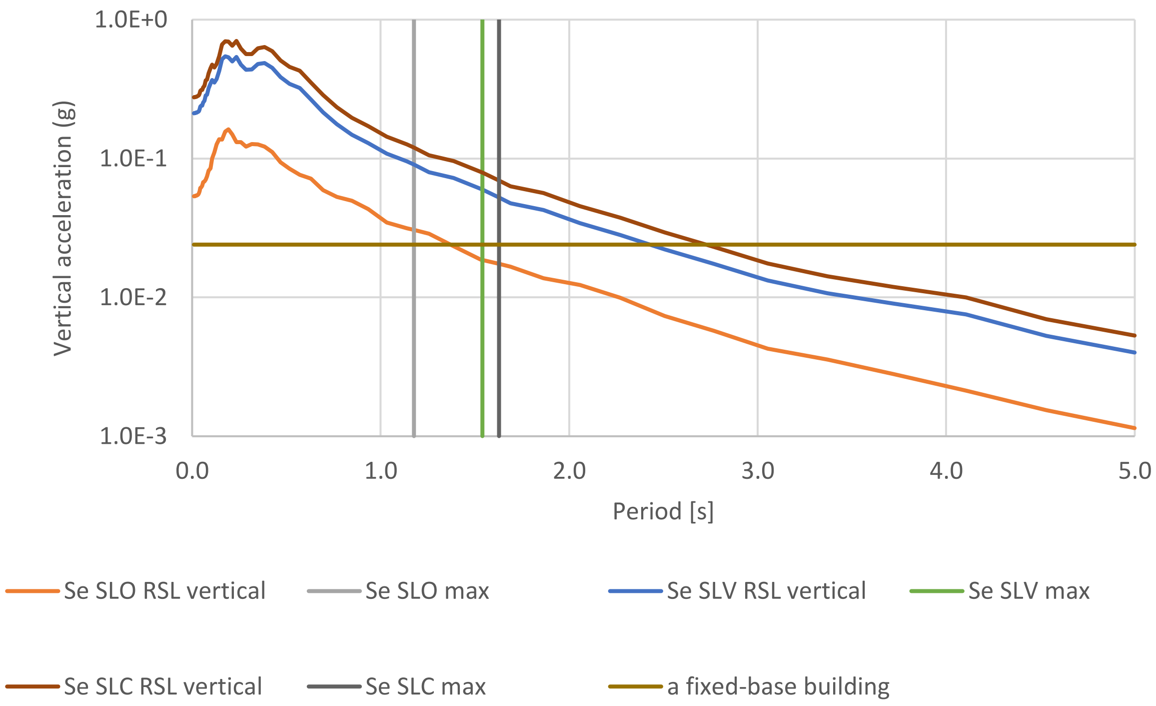


DTT site-specific seismic spectra for the superstructure (torus complex)

Site-specific seismic spectra are taken into account for buildings of importance class IV, as DTT is, in accordance with Eurocode 8-part 1 and with NTC 2018

param.	Damage limit states		Ultimate limit states		description
	SLO	SLD	SLV	SLC	Serviceability, damage, life safety, no-collapse
Fv/Fh=	0.46	0.53	0.73	0.80	calculated on output data





Model parameters of pendulum isolators/curved surface sliders [FIPMEC]

MODELLING

The mathematical model that best resembles the functioning of the curved surface sliders (both **FIP** and **FIP-D** series) consists of a bilinear force-displacement curve as shown in the figure, where:

$F_0 = \mu \cdot N_{Sd}$ ➡ friction force developed by the isolator

$F_{max} = F_0 + K_r \cdot d = \mu \cdot N_{Sd} + \frac{N_{Sd}}{R} \cdot d$ ➡ maximum horizontal force

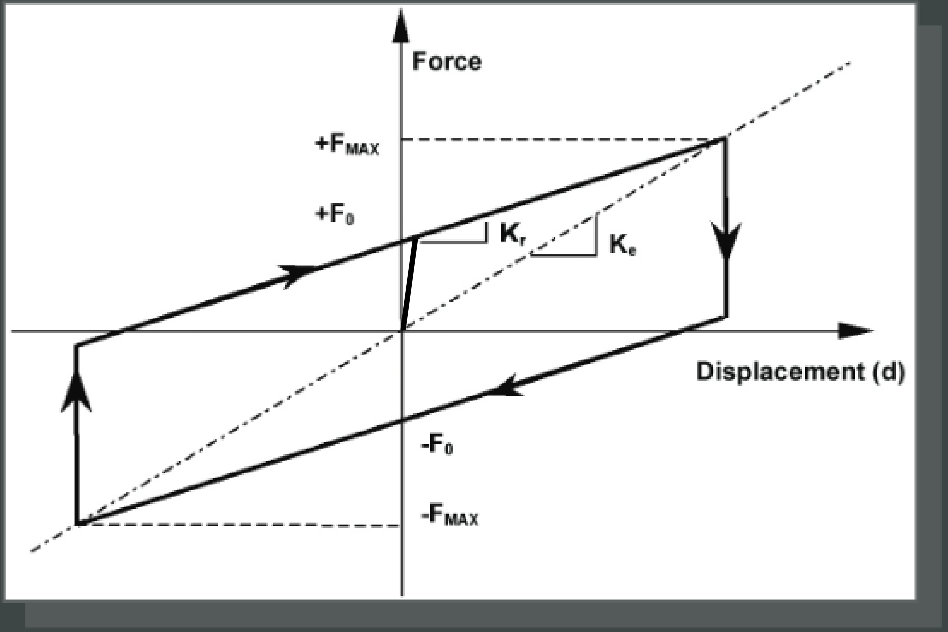
$K_r = \frac{N_{Sd}}{R}$ ➡ restoring stiffness

μ ➡ friction coefficient

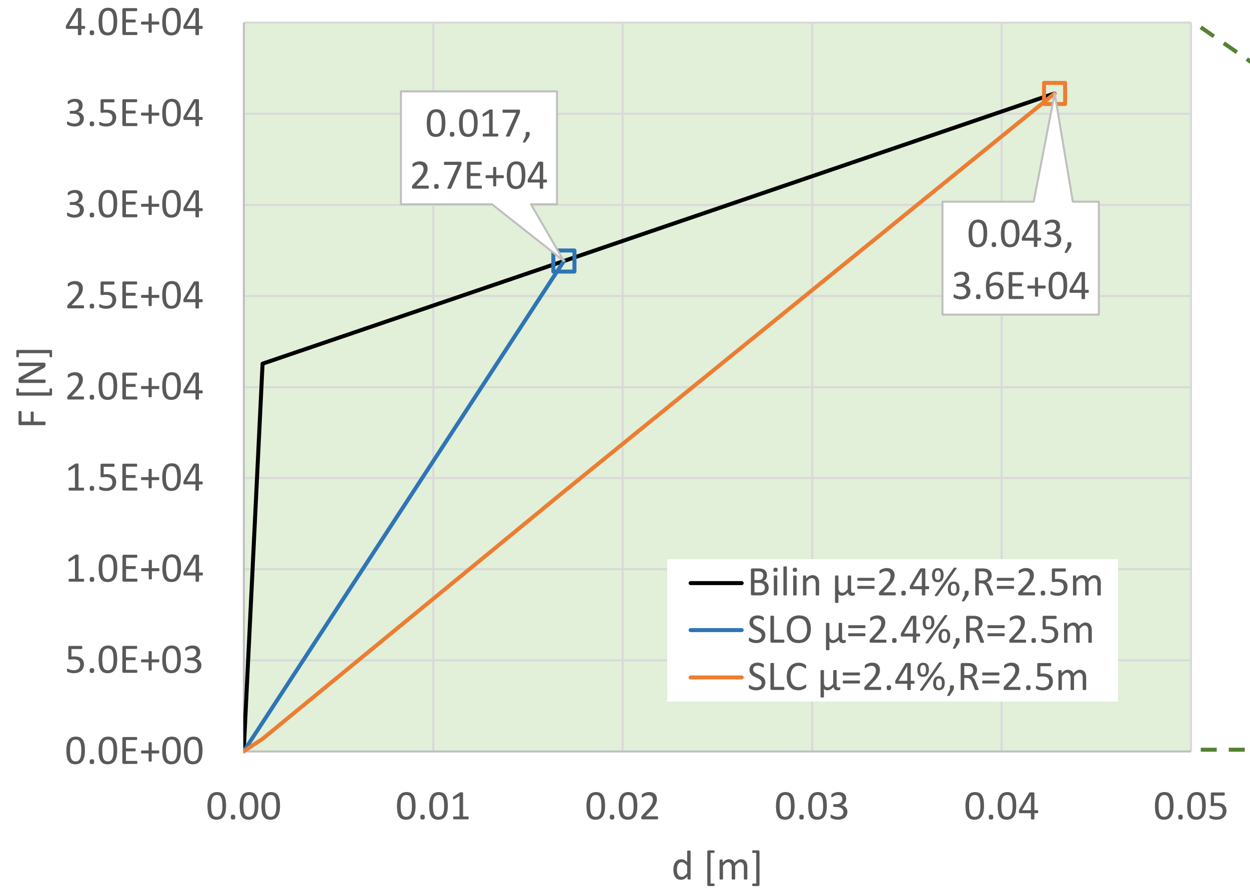
N_{Sd} ➡ vertical load acting on the isolator

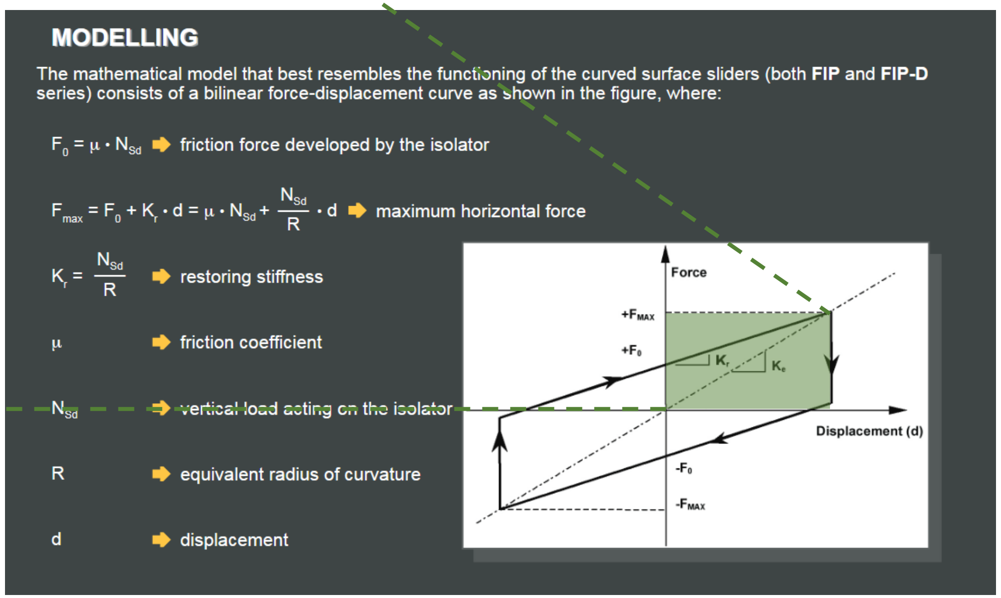
R ➡ equivalent radius of curvature

d ➡ displacement



Result summary of finite element analyses





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Seismic combination 100% x, 30% y, 30% vertical

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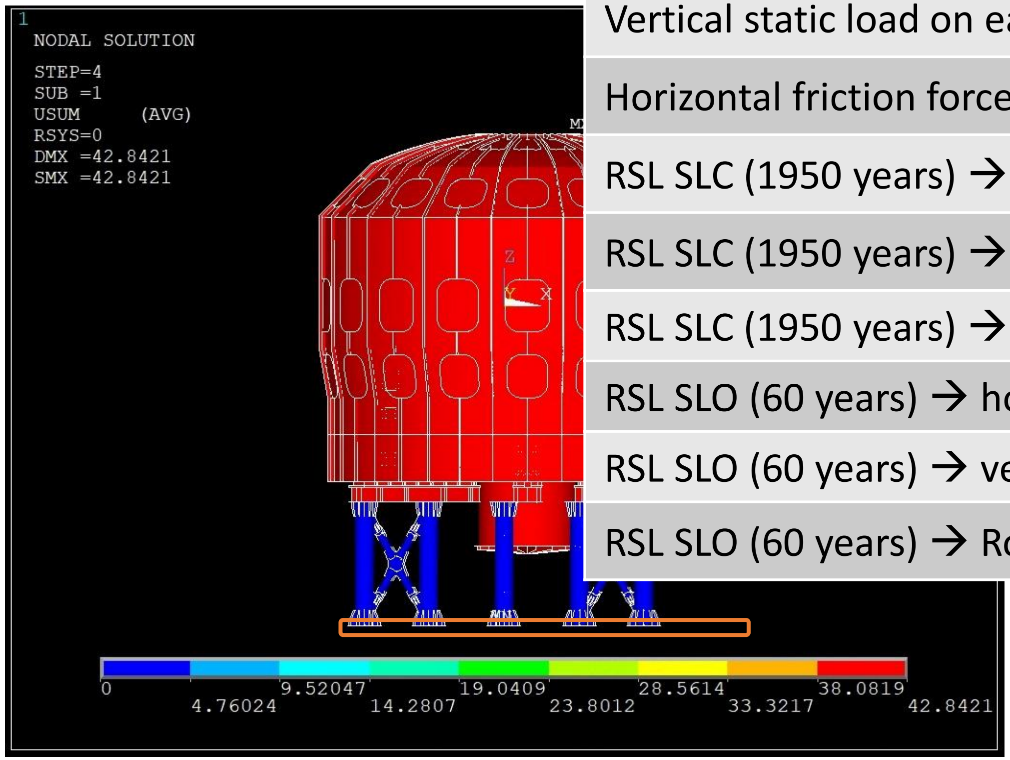
Preliminary loads between base and foundation



Parameter	Value (average)	Min.	Max.
Number of isolators at the top of columns of the CRS base	12		
Vertical static load on each column/isolator [kN]	887	-	-
Horizontal friction force on each column/isolator [kN]	21	21	21
RSL SLC (1950 years) → horizontal force on each column base* [kN]	37	21	54
RSL SLC (1950 years) → vertical load (on each external columns)* [kN]	887	629**	1145
RSL SLC (1950 years) → Rotation of the torus complex* [°]	0	-0.015	+0.015
RSL SLO (60 years) → horizontal force on each column/isolator* [kN]	28	15	40
RSL SLO (60 years) → vertical load on each column/isolator* [kN]	887	699**	1075
RSL SLO (60 years) → Rotation of the torus complex* [°]	0	-0.010	0.010

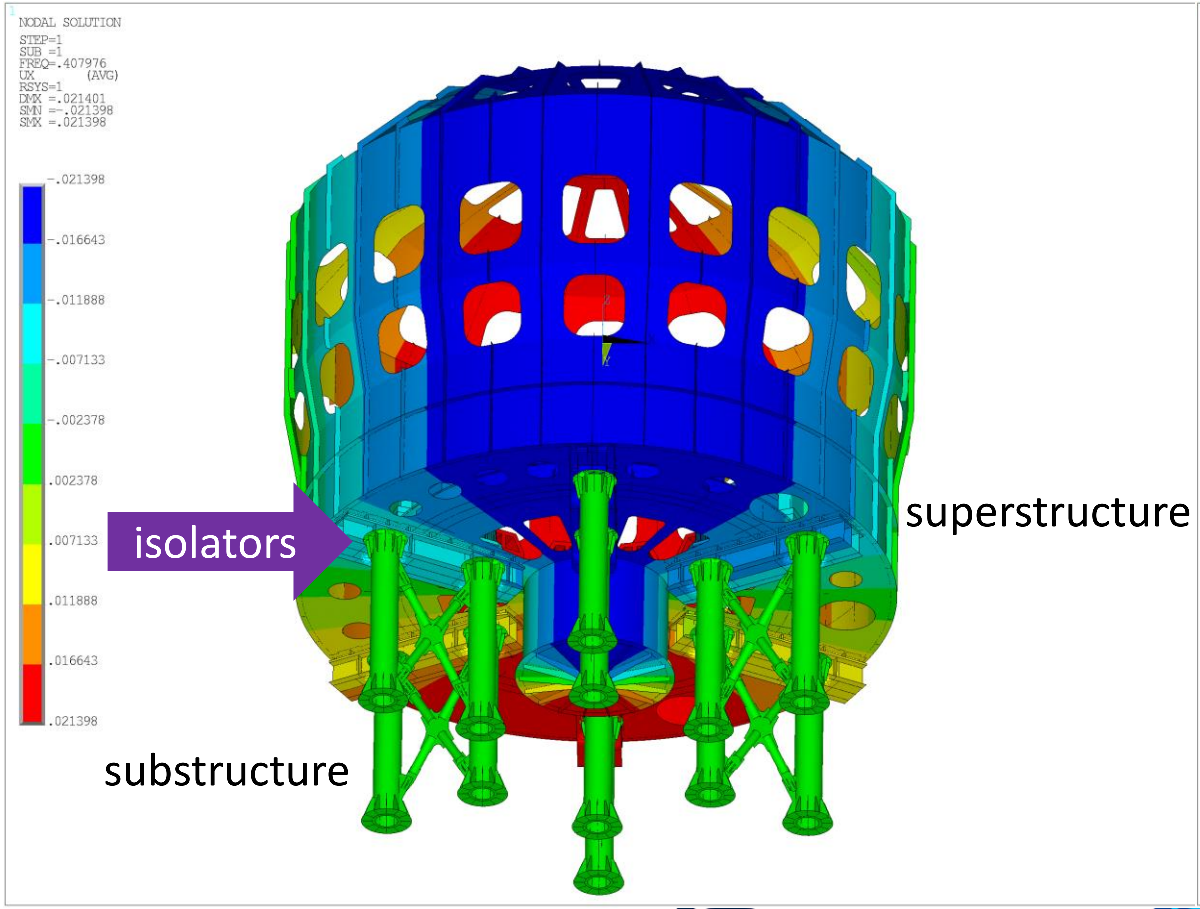
* Values at the ground interface calculated with seismic combination 100% x, 30% y, 30% vertical

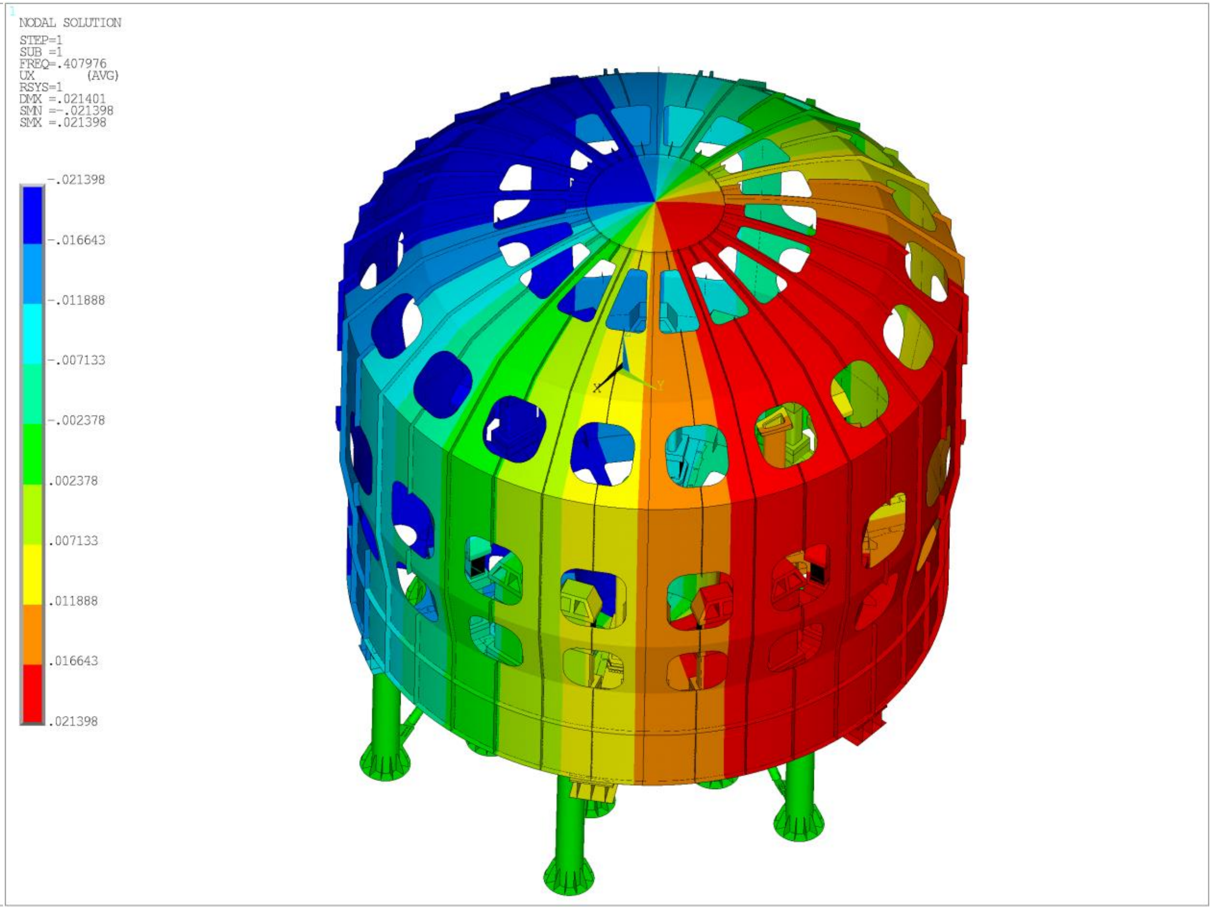
** Compressive conditions

FE analysis with seismically isolated torus complex

- Selected isolators: ***SI-S 350/50***, with k = **0.77 kN/mm**, x_{max} = ±100 mm

Isolators between the columns and the base plate: mode 2 along x direction
*(Period = **2.45 s**, Effective mass/Total mass = **0.735**)*





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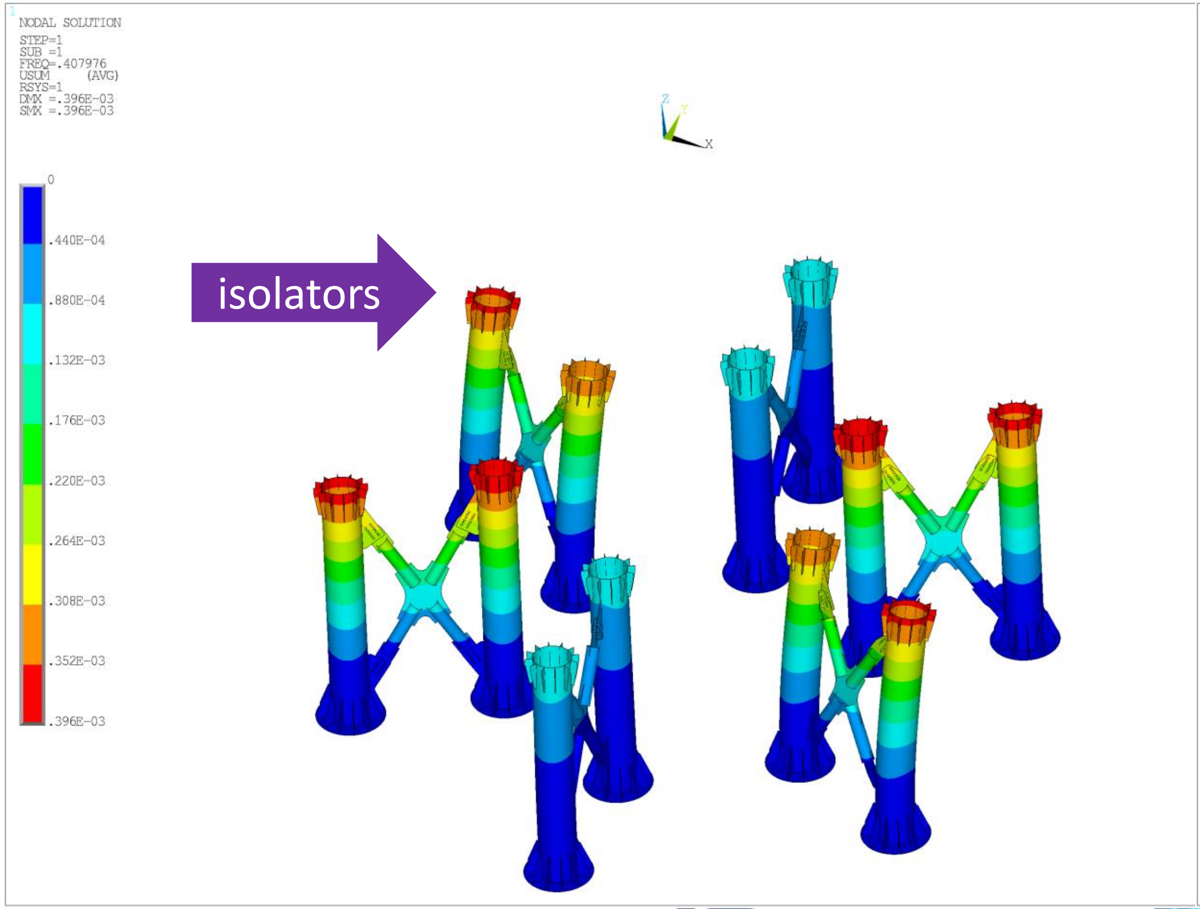
FE analysis - reactions at the basement

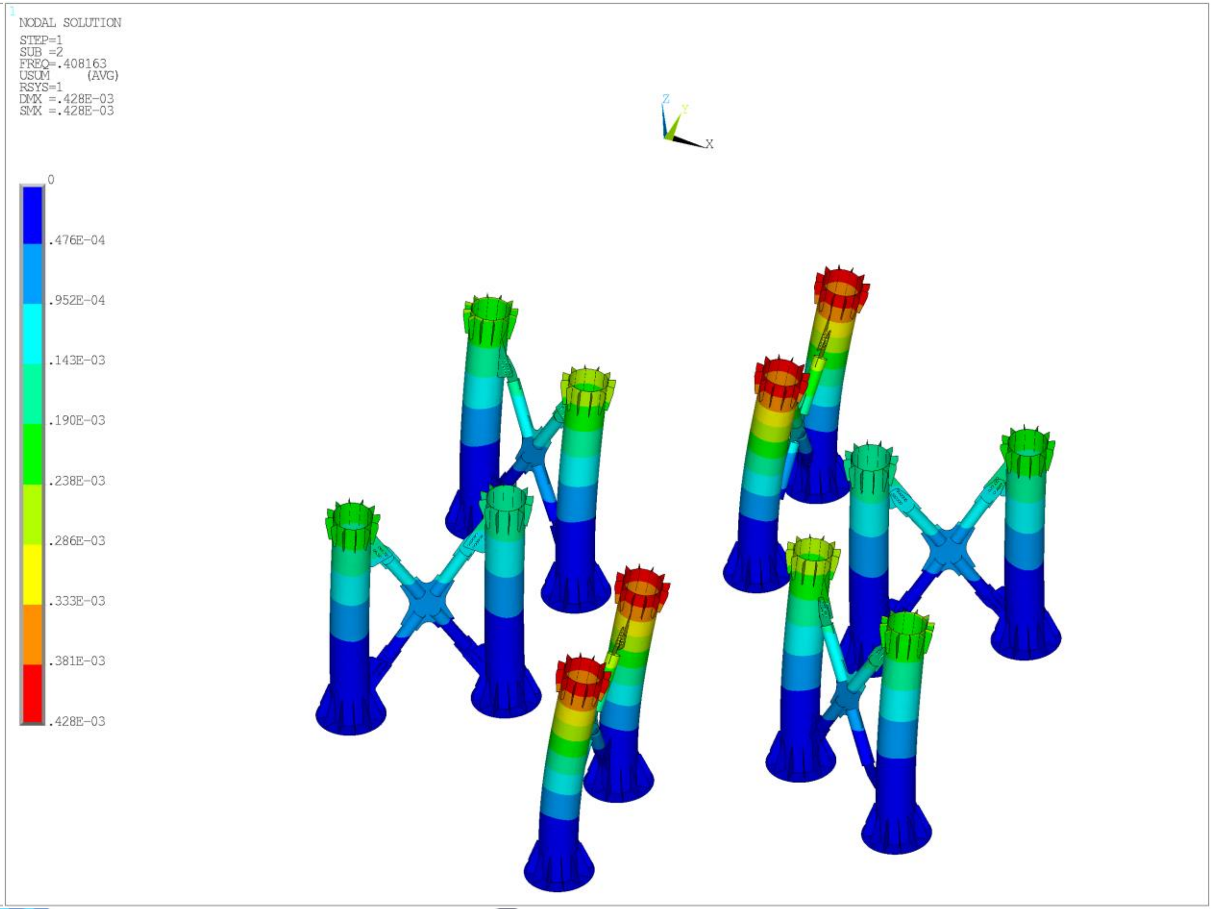
- Selected isolators: ***SI-S 350/50***, with k = **0.77 kN/mm**, x_{max} = ±100 mm

Isolators between the columns and the base plate

*Mode 1: Effective mass/Total mass = **0.735** (along y direction)*

*Mode 2: Effective mass/Total mass = **0.735** (along x direction)*





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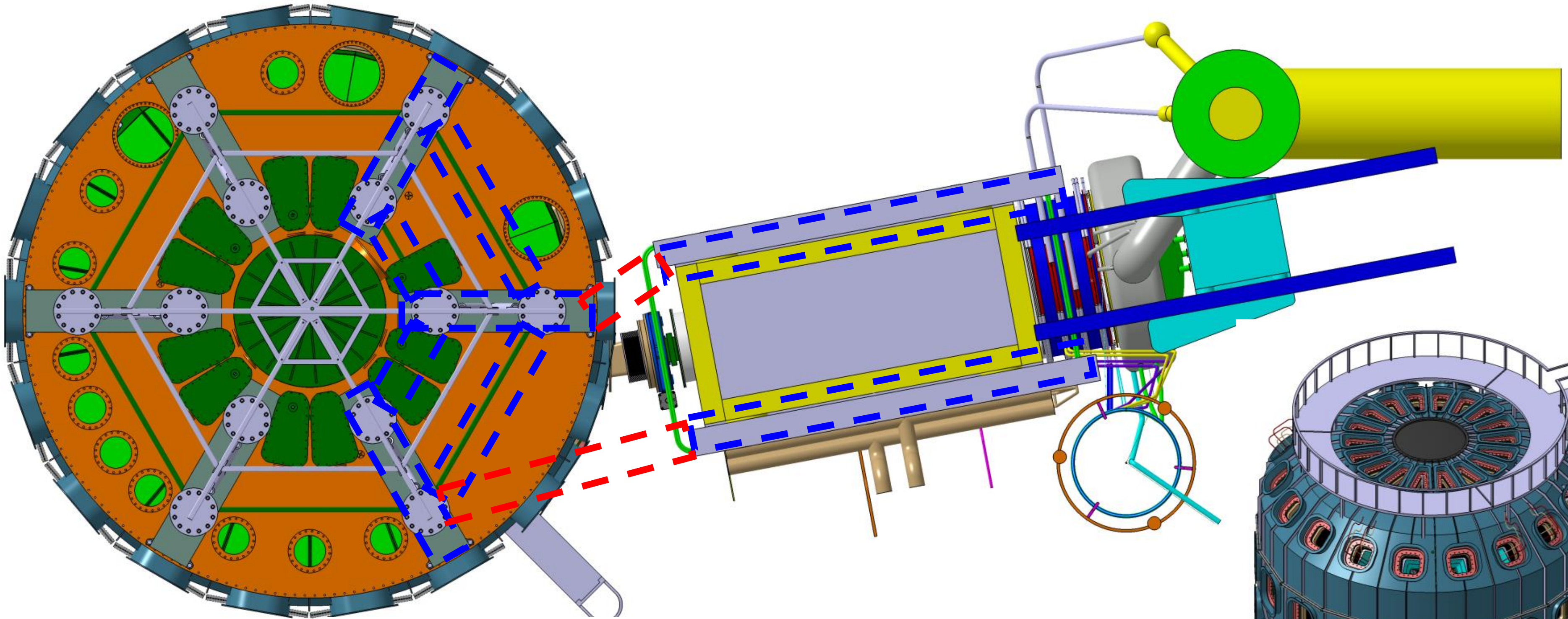
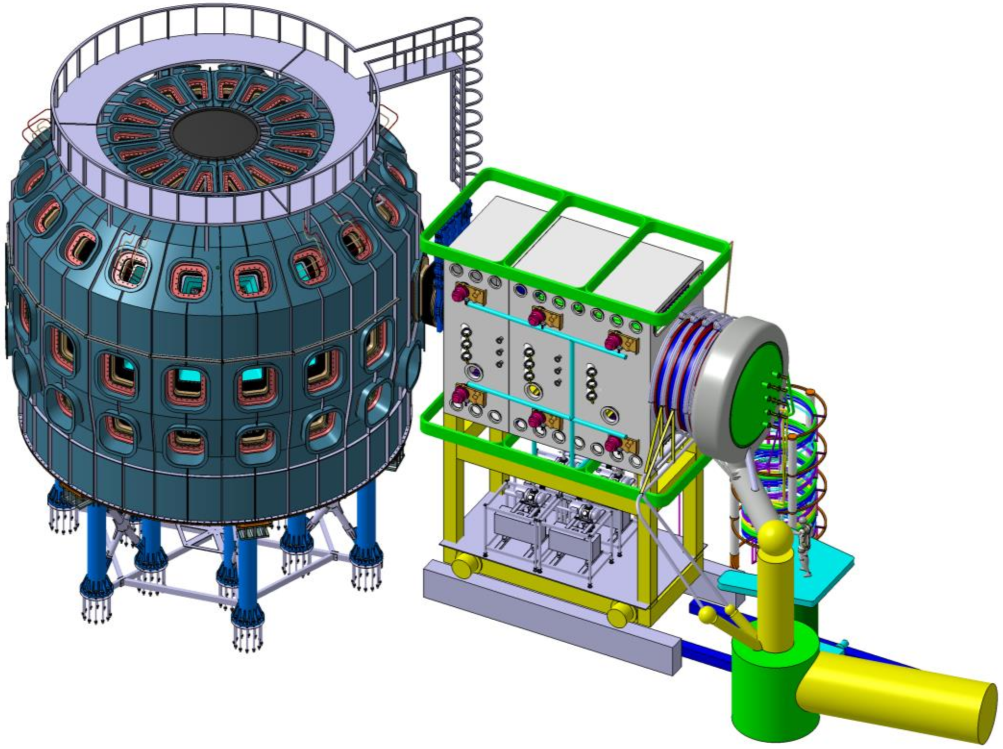
Integration of systems close to the torus complex



(bottom view)



Need of two isolation structures?

Need of connection btw isolation structures of torus complex and NBI?

The two isolated systems could oscillate at different frequencies → relative displacements to be evaluated

Observed General design provisions in accordance with Eurocode EN 1998-1 - 1/2

10.5.1 General provisions concerning the devices

O (1)P Sufficient space between the superstructure and substructure shall be provided, together with other necessary arrangements, to allow inspection, maintenance and replacement of the devices during the lifetime of the structure.

N (2) If necessary, the devices should be protected from potential hazardous effects, such as fire, and chemical or biological attack.

O (3) Materials used in the design and construction of the devices should conform to the relevant existing norms.

10.5.2 Control of undesirable movements

N (1) To minimise torsional effects, the effective stiffness centre and the centre of damping of the isolation system should be as close as possible to the projection of the centre of mass on the isolation interface.

N (2) To minimise different behaviour of isolating devices, the compressive stress induced in them by the permanent actions should be as uniform as possible.

N (3)P Devices shall be fixed to the superstructure and the substructure.

N (4)P The isolation system shall be designed so that shocks and potential torsional movements are controlled by appropriate measures.

N (5) Requirement (4)P concerning shocks is deemed to be satisfied if potential shock effects are avoided through appropriate devices (e.g. dampers, shock-absorbers, etc.).

O: ongoing activity

N: next activity

Observed General design provisions in accordance with Eurocode EN 1998-1 - 2/2

10.5.3 Control of differential seismic ground motions

- **O** (1) The structural elements located above and below the isolation interface should be sufficiently rigid in both horizontal and vertical directions, so that the <u>effects of differential seismic ground displacements are minimised</u>. This does not apply to bridges or elevated structures, where the piles and piers located under the isolation interface may be deformable.
- **O** (2) In buildings, (1) is considered satisfied if all the conditions stated below are satisfied:
  - a) a rigid diaphragm is provided above and under the isolation system, consisting of a reinforced concrete slab or a grid of tie-beams, designed taking into account all relevant local and global modes of buckling. This rigid diaphragm is not necessary if the structures consist of rigid boxed structures;
  - b) the devices constituting the isolation system are fixed at both ends to the rigid diaphragms defined above, either directly or, if not practicable, by means of vertical elements, the relative horizontal displacement of which in the seismic design situation should be lower than 1/20 of the relative displacement of the isolation system.

10.5.4 Control of displacements relative to surrounding ground and constructions

- **O** (1)P Sufficient space shall be provided between the isolated superstructure and the surrounding ground or constructions, to allow its displacement in all directions in the seismic design situation.

O: ongoing activity
N: next activity

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Thank you for your kind attention!

Integration and Design for Assembly

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3 Dec 2024