Outcomes of the DTT Vacuum Vessel Design Review

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DTT Vacuum Vessel and Ports Team

DTT S.c.a r.l.

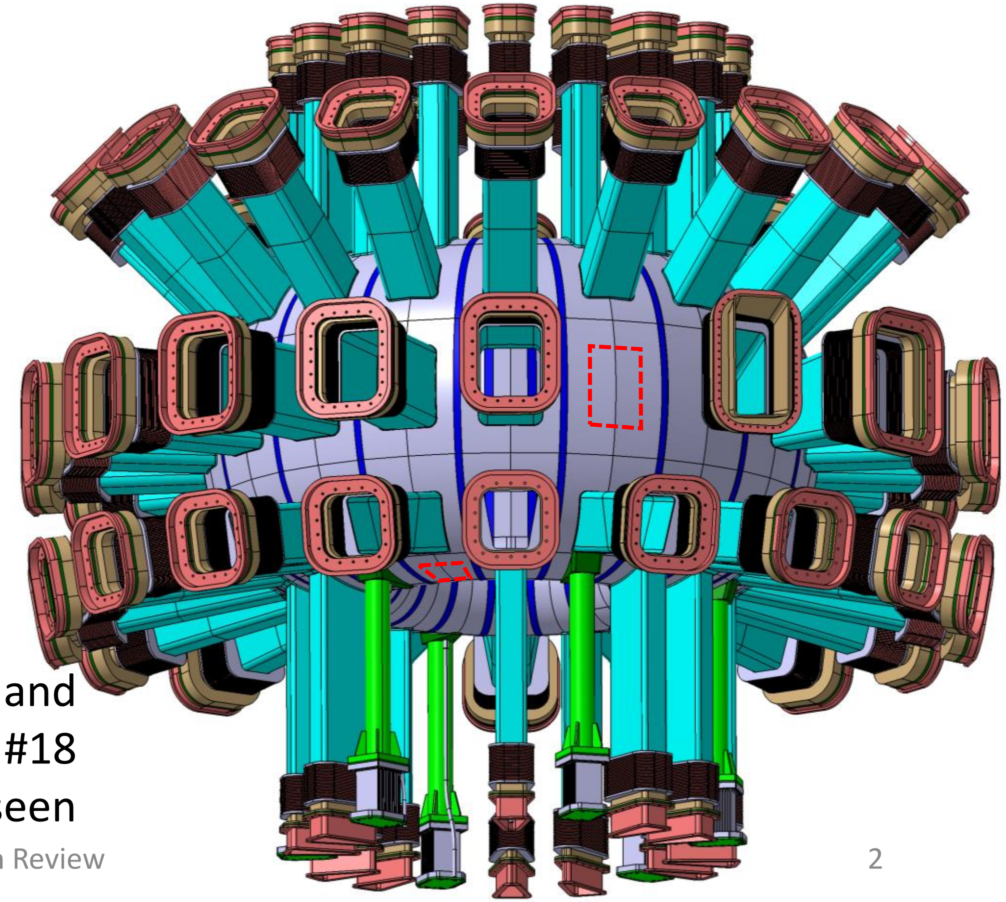
CTS-DTT meeting in Frascati

July 11-12, 2022

DTT vacuum vessel and ports: description - 1/2

DTT Vacuum Vessel (VV) functions and characteristics:

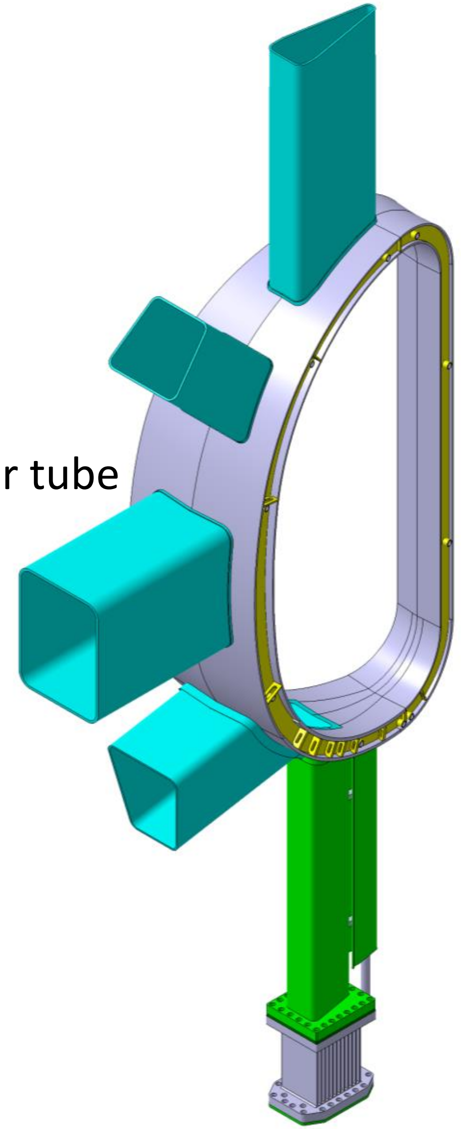
- first vacuum boundary for the plasma
- toroidal configuration with double wall D-shaped poloidal cross section
- inter-shell filled with water during plasma operation and with nitrogen during baking
- division in 17 sectors
- inclusion of 82 ports located:
  - every 20° in the toroidal direction
  - in 5 poloidal positions enumerated from the top, port #1, to the bottom, port #5
- inclusion of 6 gravity supports with spring plates
- smooth inner shell: field welding (on site) of supports of the in-vessel components

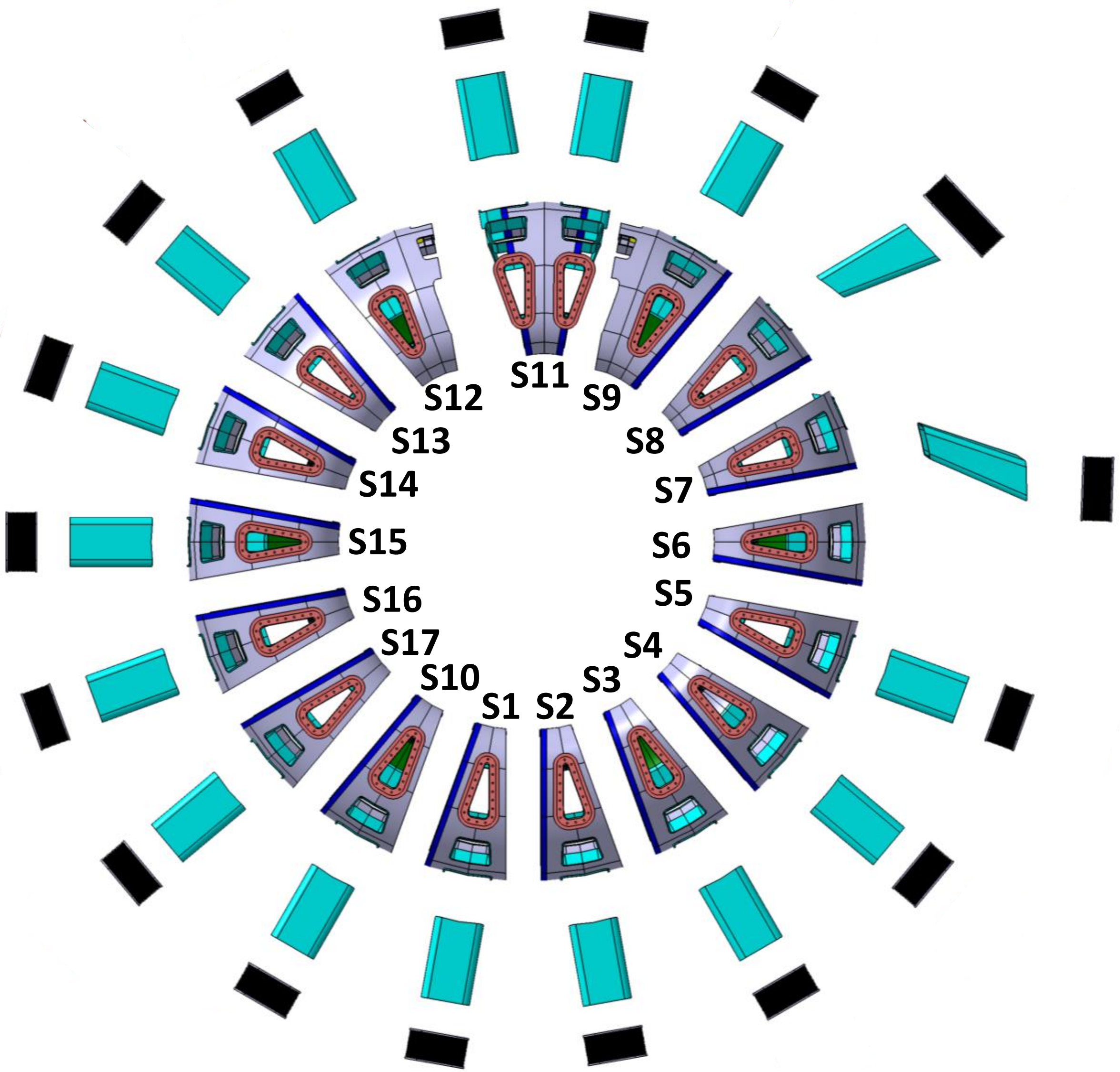


port #3 of toroidal position #6 and
ports #5 of toroidal positions #3, #4, #6, #9, #12, #15, #18
are not foreseen

DTT vacuum vessel and ports: description - 2/2

Vessel sector with:
- double-wall
- ports
  - duct
  - bellows
- gravity support
  - spring plates
  - primary heat transfer tube





DTT vacuum vessel and ports: parameters

Parameter	Unit	Value
Shell thickness (inboard)	[mm]	15
Shell thickness (outboard)	[mm]	15
Distance between shells (inboard)	[mm]	90
Distance between shells (outboard)	[mm]	200
Ports thickness	[mm]	10-20
Material	--	316LN - Co<0.05 wt%
Thickness of inter-shell ribs	[mm]	10-20
Torus outboard diameter	[mm]	6960
Torus inboard diameter	[mm]	2530
Weight	[ton]	40 (main vessel body)
Torus height	[mm]	3910
Inter-shell volume	[m^3]	13.5
Volume of the VV - plasma side	[m^3]	75
External surface of the vacuum vessel (holes subtracted)	[m^2]	112

List of documents for vacuum vessel design review

Topic	Document title	DTT ID Number
Design description	DTT Vacuum Vessel and Ports: Design Description Document	OVC-TEC-67521
	DTT VV planning 20210923 DTT2021 05690	A1 of OVC-TEC-67521
	Spring rates and draft design of expansion joints for DTT by Kompaflex	A2 of OVC-TEC-67521
	Standard Sector with Gravity Support Drawing	A3 of OVC-TEC-67521
System and interface requirements	System and Interface Requirements of Vacuum Vessel and Ports	OVC-TEC-67509
	Diagnostic-port interfaces	Attach. of OVC-TEC-67509
	DIA allocation ducts & Torus Hall 2021 rev28	DTT UID 02721
	Final Report on pellet injection	DTT UID 01426
Electromagnetic analyses	Completion of structural analyses under EM loads	OVC-TEC-67518
Load cases and load combinations for mechanical analyses and verifications	Vacuum Vessel & Port and Cryostat of DTT: load specification for analyses	OVC-TEC-67508
	Loads definition due to disruptions	DTT UID 01358
	Notes on DTT disruptions modelling	DTT UID 02878
Thermal and thermo-hydraulic analyses	Thermal-hydraulic analysis of the Vacuum Vessel of Divertor Tokamak Test Facility	OVC-TEC-67517
	Thermo-hydraulic analysis of vacuum vessel special sector	OVC-TEC-67510
	Preliminary assessment of baking operating state for vacuum vessel & ports	OVC-TEC-67512
Structural analyses and verifications	Structural analyses and verifications of the vacuum vessel and ports	OVC-TEC-67514
	Cryostat Base Preliminary Structural Analyses	OVC-TEC-67515
	Independent verifications with electromagnetic and mechanical global model	OVC-TEC-67522
Corrosion issues	Corrosion test and analysis, definition of water chemistry	OVC-TEC-67519
Integration of in-vessel components and remote handling operations	Integration of the DTT divertor with vacuum vessel and remote handling	OVC-TEC-67511
	Divertor Handling Operative Procedures	RHS-PRO-76008
	DTT divertor fixation solution	DTT UID 02877
Integration of machine sensors	DTT Vacuum Vessel & Ports: guidelines for diagnostic and machine instrumentation	OVC-TEC-67516
PED overpressure protection	PED hazard classification and overpressure protection for the DTT vacuum vessel	OVC-TEC-67513
Risk register	DTT Vacuum Vessel & Ports: Risk register	OVC-TEC-67520
Assembly	DTT assembly sequence report	DTT UID 05600
PID	DTT Plant Integration Document version 3	DTT UID 04719

Documentation - Risk Register

The prepared risk register considers outcomes of the ongoing procurement of ITER vacuum vessel.

Moreover, return on experience about other fabricated machines (JT-60SA, KSTAR) has also been considered.

Main identified risks are:

- dimensional and shape errors on shells and ports due to weld distortion produced during the welding sequence
- unavailability of qualified and certified personnel (levels 2 and 3 in accordance with EN ISO 9712) required to the supplier for qualification of Non Destructive Testing, in particular helium LT, UT of welded joints, 3D measurement systems (photogrammetry or laser tracker to be used for frequent intermediate dimensional tests)
- unavailability od skilled DTT resources during the procurement follow-up in particular to manage non-conformities
- in-port reduced access to integrate on site supports for services (cooling tubes, coils feeders, embedded sensors, supports of cryopumps)
- plasma performance reduction due to manufacturing non-conformities and first wall exceeding the required envelop
- excessive magnetic permeability at the completion of the fabrication processes

The Panel has not identified any risk that could cause a showstopper.

The Panel recommended the DTT Team:

- *To take advantage of the experience of other teams in the fabrication and assembly of VV (JT-60SA and W7-X);*
- …
- *To analyse urgently the consequence of possible plasma performance reduction due to manufacturing non-conformities and possible associated constraints on the inboard first wall and limiter surface locations* → actions are ongoing with manufacturing strategy
- *To strengthen the DTT VV Team to respond promptly to non-conformities and to guarantee presence at the manufacturer* → recruitment

Planning

Main assumptions with 40.3 months of procurement contract:

- one prototype sector will be produced first to qualify manufacturing and testing procedures;
- the prototype sector will be delivered 12 months after kick off meeting;
- standard 316LN (without limitation of Co content) will be procured for manufacturing the prototype sector;
- manufacturing drawings of production sectors will be updated and issued after completion of tests on the prototype sector;
- manufacturing of 1st sector requires 6 months (6.5 months with 2 weeks contingency margin) to implement production processes;
- 40 days are considered between deliveries of sectors (from 2nd to 17th with 2 weeks contingency margin).

Planning

Welding areas: 110 working days per sector (150 calendar days) -> 4 welding areas, full time, 1 working shift (clamping with specific templates will require more welding areas)

Three main welding areas working in parallel are identified for the fabrication of the inboard and outboard segments:

- rib welding on the inner shell
- welding of stubs
- outer shell welding

The number of welding areas for the fabrication of the segments and their integration is 4-7.

Assuming 3 persons working in each area during 28 months (m12 -> m40), the amount of required PPY is up to 49 (excluding preliminary activities [mock-up/prototype], engineering and management).

Plate cutting area: 15 working days per sector (20 calendar days) -> 1 cutting area, half time, 1 work shift

Plate shaping area: 15 working days per sector (20 calendar days) -> 1 shaping area, half time, 1 work shift

Machining centre (4 axes): 30 working days per sector (40 calendar days) -> 1 machining centre, full time, 1 work shift

Planning

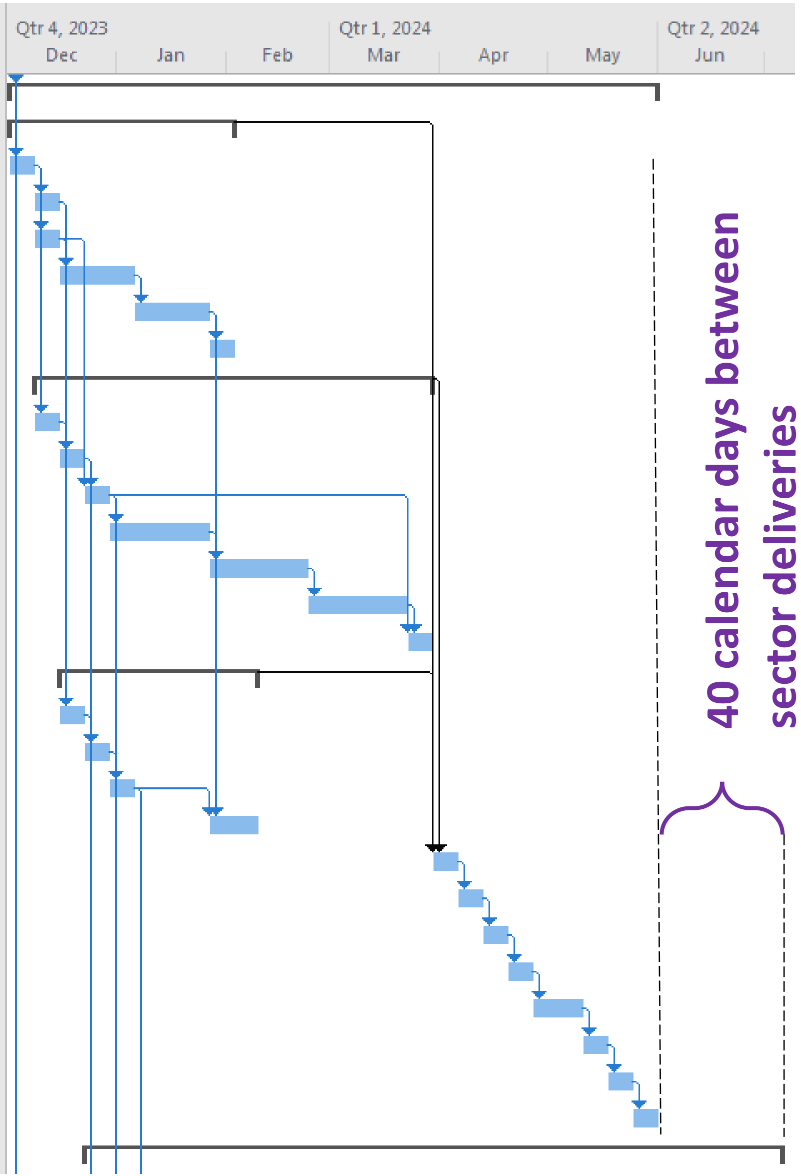
#	Activity	month -4	month -3	month -2	month -1	month 0	month 1	month 2	month 3	month 4	month 5	month 6	month 7	month 8	month 9	month 10	month 11	month 12	month 13	month 14	month 15	month 16	month 17	month 18	month 19	month 20	month 21	…	month 39	month 40	month 41
1	Independent EM analyses and structural verifications																														
2	Design Review with External Panel																														
3	Technical Specification Activity																														
4	Call for Tender + Evaluation of the tender submissions																														
5	Selection of vendor & Award of contract																														
6	KoM + Manufacturing Readiness Review																														
7	Manufacturing Drawings																														
8	Procurement of raw materials																														
9	Tools & equipment																														
10	Internal jig + Transportation & rotation tool																														
11	Qualification of processes (manufacturing, welding, testing)																														
12	Sector prototype manufacturing & testing																														
13	Drawing updated with outcomes of prototyping																														
14	Bellows + Splice plates + Sensors																														
15	VV sector 01 (fabrication + FAT + delivery + SAT)																														
16	VV sector 02 (fabrication + FAT + delivery + SAT)																														
17	VV sector 17 (fabrication + FAT + delivery + SAT)																														

Planning

Sector 01 manufacturing & testing: 6 months duration (6.5 months with 2 weeks contingency margin)

GANTT CHART

	Task Name	Duration	Start	Finish	Predeces
39	**Sector 01 manufacturing & testing**	**130 days**	**Fri 01/12/23**	**Fri 31/05/24**	**38**
40	**inboard segment fabrication**	**45 days**	**Fri 01/12/23**	**Fri 02/02/24**	
41	cutting of plates	1 wk	Fri 01/12/23	Fri 08/12/23	38
42	shaping of inner shell plates	1 wk	Fri 08/12/23	Fri 15/12/23	41
43	machining of outer shell and ribs (3 axes centre)	1 wk	Fri 08/12/23	Fri 15/12/23	41
44	welding of ribs on the inner shell (W1)	3 wks	Fri 15/12/23	Fri 05/01/24	42;43
45	welding of outer shell (W1)	3 wks	Fri 05/01/24	Fri 26/01/24	44
46	machining of segment (3 axes centre)	1 wk	Fri 26/01/24	Fri 02/02/24	45
47	**outboard segment fabrication**	**80 days**	**Fri 08/12/23**	**Fri 29/03/24**	
48	cutting of plates	1 wk	Fri 08/12/23	Fri 15/12/23	41
49	shaping of single curvature inner shell-outer shell plates	1 wk	Fri 15/12/23	Fri 22/12/23	42;48
50	machining of shells, ribs, stubs (3+1 axes centre)	1 wk	Fri 22/12/23	Fri 29/12/23	43;49
51	welding of inner shell plates and stubs (W2)	4 wks	Fri 29/12/23	Fri 26/01/24	50
52	welding of ribs on the inner shell (W2)	4 wks	Fri 26/01/24	Fri 23/02/24	51
53	welding of outer shell and stubs (W2)	4 wks	Fri 23/02/24	Fri 22/03/24	52
54	machining of segment (3 axes centre)	1 wk	Fri 22/03/24	Fri 29/03/24	53;50
55	**fabrication of ports (and gravity support)**	**40 days**	**Fri 15/12/23**	**Fri 09/02/24**	
56	cutting of plates	1 wk	Fri 15/12/23	Fri 22/12/23	48
57	shaping of plates	1 wk	Fri 22/12/23	Fri 29/12/23	49;56
58	machining of ports (3 axes centre)	1 wk	Fri 29/12/23	Fri 05/01/24	50;57
59	welding of plates (W1)	2 wks	Fri 26/01/24	Fri 09/02/24	58;45
60	welding of inboard and outboard segments (W2)	1 wk	Fri 29/03/24	Fri 05/04/24	40;47;55
61	welding of ports and gravity support (W2)	1 wk	Fri 05/04/24	Fri 12/04/24	60
62	machining of sector edges for welding on site (3+1 axes centre)	1 wk	Fri 12/04/24	Fri 19/04/24	61
63	pressure and leak test	1 wk	Fri 19/04/24	Fri 26/04/24	62
64	dimensional test	2 wks	Fri 26/04/24	Fri 10/05/24	63
65	preparation for shipment	1 wk	Fri 10/05/24	Fri 17/05/24	64
66	delivery at site	1 wk	Fri 17/05/24	Fri 24/05/24	65
67	site acceptance test (SAT)	1 wk	Fri 24/05/24	Fri 31/05/24	66
68	**Sector 02 manufacturing & testing**	**140 days**	**Fri 22/12/23**	**Fri 05/07/24**	



Planning

The Panel noted that the production sequence appears very tight, with a great deal of parallel manufacturing stations …; in addition no timing contingency has been considered in the critical path.

The Panel believes that the probability of completing the fabrications of the VV, ports and gravity supports in 40,3 months is low.

The Panel recommended the DTT Team:

- *To consider a duration of the procurement contract of 45 months in agreement with the previous estimation of an independent panel;*
- *To carefully verify that the chosen company has relevant experience in this type of fabrication, the equipment necessary to perform all the manufacturing steps and can guarantee the presence of the required experts in the different areas during the work.*

Actions are ongoing in DTT in order to mitigate the planning criticalities:

- Evaluation of the VV manufacturing strategy and revision of the on-site integration sequence of VV sectors.

Specific issues - ECRH stray radiation

Chit description:

In W7-X during the construction phase it was estimated that more than 10% of the ECRH power will not be coupled with the plasma, but will circulate among the in-vessel components.

Considering that the metallic surfaces will reflect such stray radiation, it will be absorbed by the insulation materials increasing their temperature beyond acceptable values.

… Could this phenomenon be present in DTT causing damages in some in-vessel components?

Chit response:

The ECRH heating scheme in DTT is based on a more efficient absorption (due to higher magnetic field (5T) and frequency (170GHz) than in W7-X. In any case in DTT the foreseen total ECH power is a factor 3 larger, that could lead to an absolute number of total not-absorbed power similar to those considered in W7-X (1MW). After an appropriate evaluation a power density limit on the inner wall will be given, to be used as a prescription for the design of the diagnostics. Protection sensors will be designed and installed in order to use such a limit as a threshold to stop ECH in case the not-absorbed power will be higher.

… analyses will be performed during the design of in-vessel components and sensors (existing physics task for DTT).

Indeed, the vessel inner shell will be procured smooth and supports of interfaced components will be developed in the future (after the call for tender).

Panel report (part):

The Panel recommended assessing the impact of Electron Cyclotron Resonant Heating (ECRH) stray radiation on insulating and electrically conductive materials and systems such as diagnostics/instrumentation, cryopumps and bellows and to take the appropriate measures to avoid any damage to the affected components. This assessment must be performed as soon as possible to be sure that protection sensors are compatible with the available space.

Specific issues - magnetic permeability

Magnetic permeability has been identified by DTT Team as an important requirement to be specified for the procurement:

1. vacuum vessel and ports: 316LN (steel number 1.4406 and 1.4429, lower ferrite content)
   spring plates and gravity supports: possibility to accept 316L (1.4404, 1.4435)
   bellows: 316L (1.4404, 1.4435) or 316LN (1.4406, 1.4429);
2. internal jig and transportation & rotation tool: parts in contact with vessel sectors shall be made of 316L or 316LN.

The Supplier shall take actions to limit the magnetic permeability during fabrication of point 1 parts. Recommended value after welding and at the completion of the fabrication is 1.05. Local values in small areas shall be lower than 1.1.

Magnetic permeability measurements shall be performed on raw materials and in the regions of the weld beads and in the heat affected zones.

Filler metal for welding: ER316LMn (minimal ferrite content).

Records of magnetic permeability measured during the manufacturing of VV are required in a map.

Tools, rigs, equipment used in contact with the stainless steel parts shall be made of 316L or 316LN thus avoiding contamination by contact with carbon steel.

Specific issues - magnetic permeability

…any large number of similar non-conformances equally spaced around the torus will have no significant effect on the plasma, whereas a single region with high magnetic permeability, when close to the plasma as all of the VV structure is, will have a serious detrimental effect on the plasma operational limits in density and kinetic pressure.

Accordingly, the Panel recommended the DTT Team:

- *…*
- *To recognise that the measurement of magnetic permeability is strongly sensitive to the orientation of any longitudinal martensitic grains in the steel with respect to the orientation of the probing magnetic field of the measurement device, ensuring that the worst direction parallel to the surface is probed and recorded;*
- *To set up a formal system for recording the measured values of the magnetic permeability of all the steel components and major welds surrounding the plasma so that it will be possible to respond promptly to requests for non-conformity concessions ...;*
- *To consider if any remedial arrangement could reduce the magnetic permeability of regions of fabricated structures and where required to verify that error field correction coils and/or Edge Localized Modes (ELM) control coils can minimise the resulting error fields.*

Specific issues - weld inspection and repair

Non destructive testing (NDT) required on **repaired joints**:

A. Visual test (VT):
   i. after completion of the root pass (first TIG pass),
   ii. after completion of the repair;

B. Detection of surface discontinuities: Eddy Current (ET), weld cap dressing by removing the cap elements on the completed multi-pass weld

C. Volumetric test on the completed multi-pass weld:
   i. radiographic test (RT) will be performed,
   ii. where RT is impractical → ultrasonic test (UT) will be performed, weld cap dressing by removing the cap elements
   iii. where UT is impractical → the volumetric test is replaced by production proof samples (PPS):
      - visual inspection (VT),
      - penetrant testing (PT),
      - examination via sectioned macrographs and micrographs;

D. Leak test (LT) after completion of the root pass;

E. Pressure test (PT) after completion of the repair;

F. Leak test (LT) after completion of the repair.

Panel recommendations:

- *a prescription is created for re-passivation treatment where oxygen or water could be in contact with the welded joints.*
- *weld cap grinding for any reason is to be strongly discouraged on finished UHV surfaces. Impact peening should be considered for any cap welds in such surfaces where local flats suitable for reliable ultrasonic testing are required.*

Design and manufacturing - qualification of processes

One prototype sector used for **qualification of processes during the procurement for manufacturing production sectors**:

- sector lifting using the internal jig
- welding procedures (TIG on UHV side, MIG on non-UHV side)
- weld repairs (previous slide)
- sequence of welds to minimize weld distortions on shells and ports
- measurement of post welding distortions (same tolerances of production sectors)
- verification of accesses for weld execution and testing
- integration of port stubs and alignment of port ducts
- Non Destructive Testing, in particular helium leak testing and UT of welded joints.

Evaluations are required to the manufacturer (weld distortion management plan) before fabrication can commence

The prototype sector will be delivered for **qualification of processes on site**:

- integration of ports and bellows
- testing of automated welding processes
- frequency of intermediate dimensional tests for dimensional control
- integration of divertor and first wall supports.

Design and manufacturing - qualification of processes

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Panel recommendations:

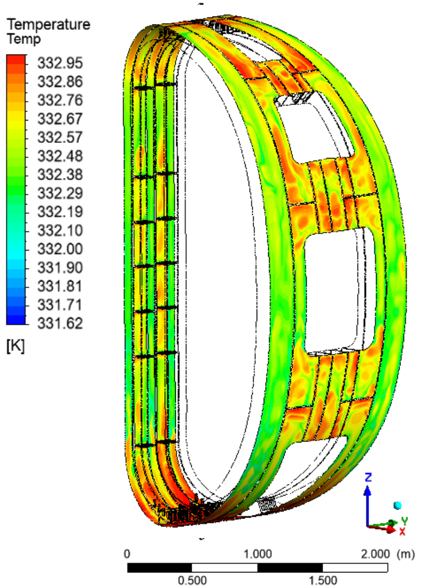
- *qualification plan for the control of deformations during the welding process;*
- *qualification of all the non-destructive tests;*
- *weld and welder qualification;*
- *procure 316LN for the fabrication of two prototype sectors.*

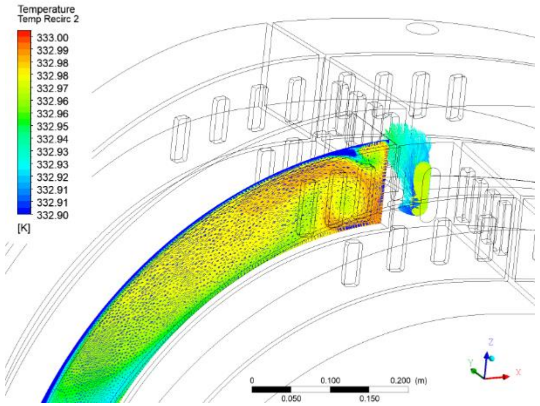
Analyses - thermal-hydraulic

10-12/05/2022, CFD steady-state analyses of the inter-shell circuit for special sectors

Requirements already fixed and to be further verified with the design of the special sectors:

- uniform distribution of fluid flow rate among sectors and among the different paths within the same sector
- limitation of recirculation/stagnation zones
- design compatibility with gravity draining
- uniform fluid temperature in the sector inter-shell
  - prevention of boric acid precipitation (Twater > 20 °C)
  - prevention of borated water corrosion (Twater < 80 °C)
- compatibility with helium leak test (hood method) of each sector
- circuit compatibility with PF6 terminations at position #4





Analyses - thermal-hydraulic

In case of over-pressure due to accidental events, the following protection devices are foreseen:

a) **Over-pressure of the volume enclosed by the inner-shell**
Proportional Relief Valve (PRV) and Rupture Disc (RD) in order to integrate safeguards devices which limit maximum pressure in the Vacuum Vessel by diverting excess fluid when pressures get too high in the volume delimited by the inner shell. The PRV shall be set below 1.2 bar absolute. The bursting pressure of the RD shall be within the range 1.4-1.5 bar absolute. A relief tube will be connected to one port #5 and relief gasses will be evacuated out of the torus all through a filter.

b) **Over-pressure of the volume in the inter-shell**
PRV limiting the maximum pressure in the primary cooling circuit of the vacuum vessel and diverting the excess fluid in the vapour suppression tank to protect the vacuum vessel against overpressure in case of a "loss of coolant accident" in the vacuum chamber.
The PRVs are mounted on suitable locations of the Primary Heat Transfer System (PHTS), please see next slide.

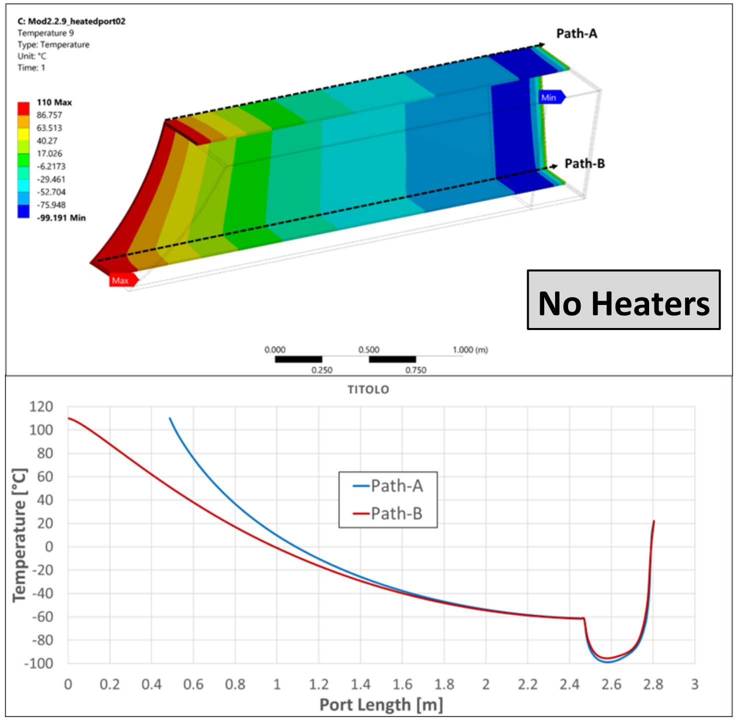
System dynamic analyses will verify the diverting capability including size and pressure at relief tubes, PRV, RD, filters.

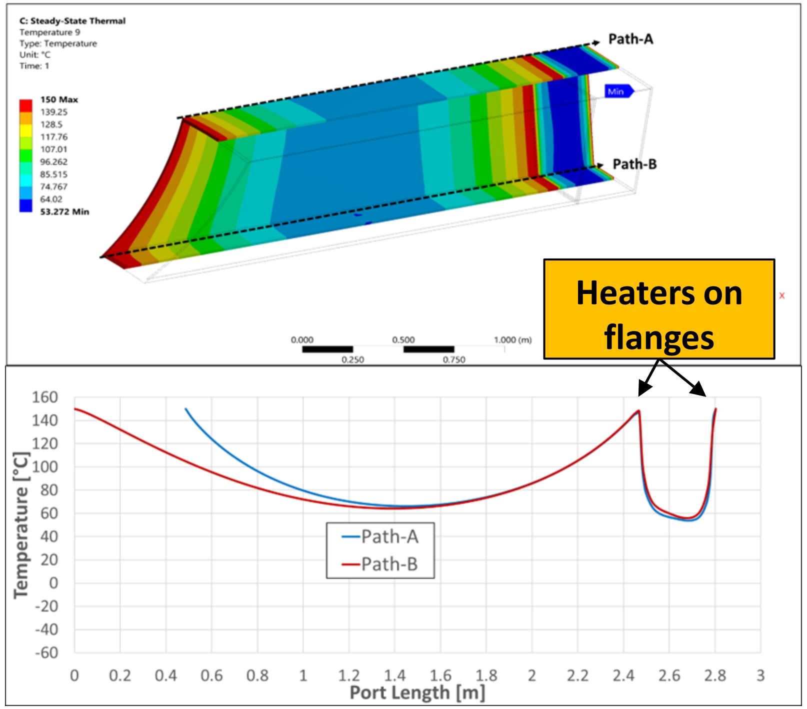
A rupture disc equipment is also foreseen for the cryostat volume, but it is not part of the VV system.

The Panel recommended the DTT Team to ensure that the described analyses are completed in the next few months in order to be able to introduce the necessary modifications (if needed) before the revision of manufacturing drawings.

Analyses - thermal & baking

- **Heaters on bellows flanges**:
  - Prevent extremely low temperatures/freezing issues in both POS and BAK state
  - Make less difficult the access in case of maintenance or replacement
  - Nevertheless, temperature profile is not uniform, and bellows remains the coldest zone (cold trap)
- **Solution under investigation**:
  - Distributed heating cables on duct inner surface. Not accessible for maintenance, redundancy recommended.
  - Bellows external sleeve and MLI



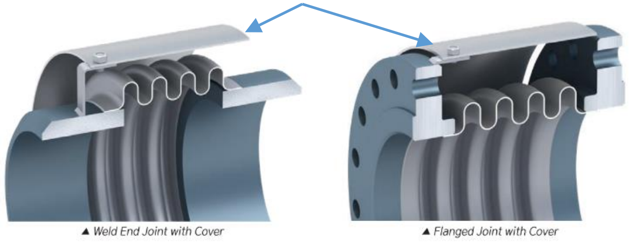


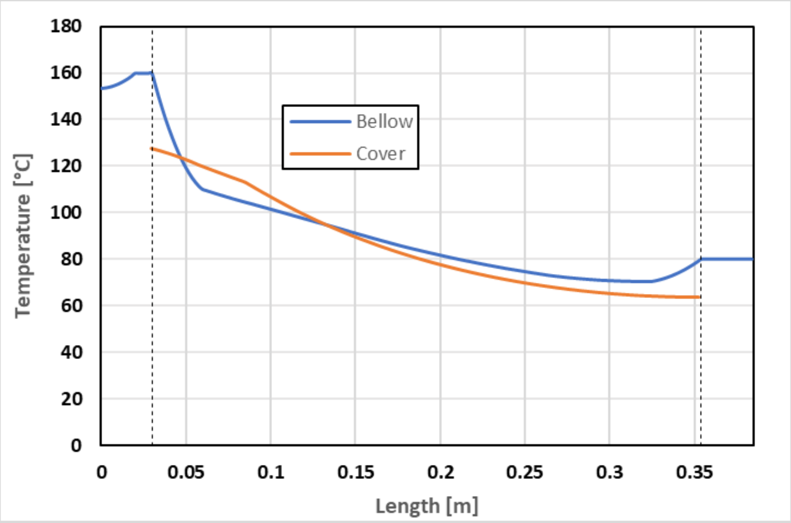
Analyses - thermal & baking

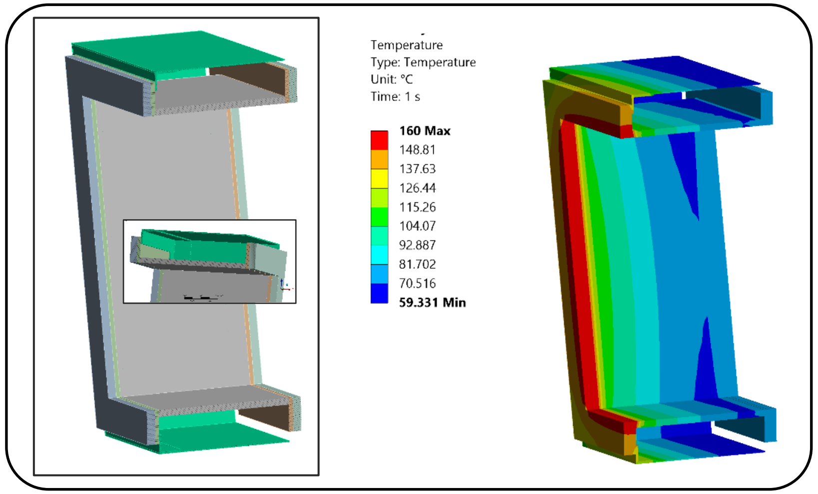
- **Distribute Heating cables**
  - The layout of heating cables will be determined on results of analyses simulating in-port systems and considering maintenance strategy of cables.
  - Heating conditions will depend on cooling/heating tubes of vacuum vessel and in-vessel components.
  - **Fixing techniques** with thermal contact conditions will be vacuum compatible for in-port and in-vessel heating cables (spot welded strips).

- **Bellows external sleeve**
  - Suitable design identified
  - In progress thermal analyses show positive results

Sleeve on bellows







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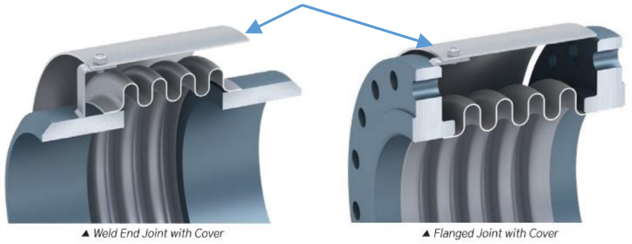
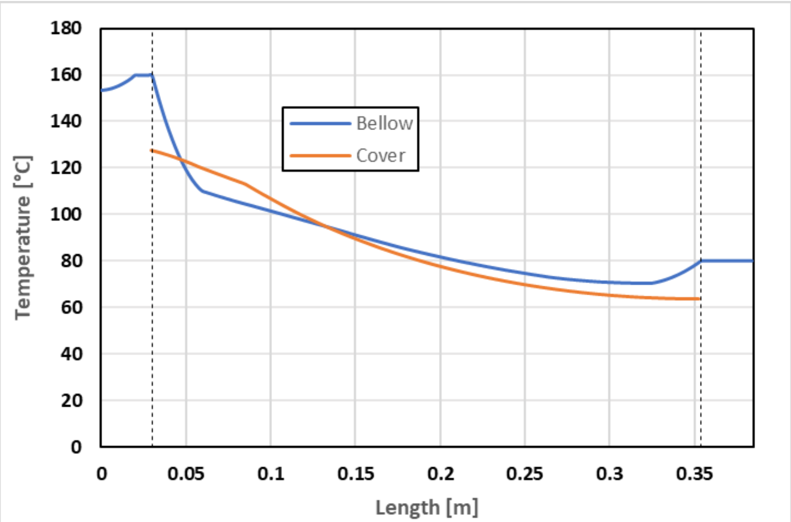
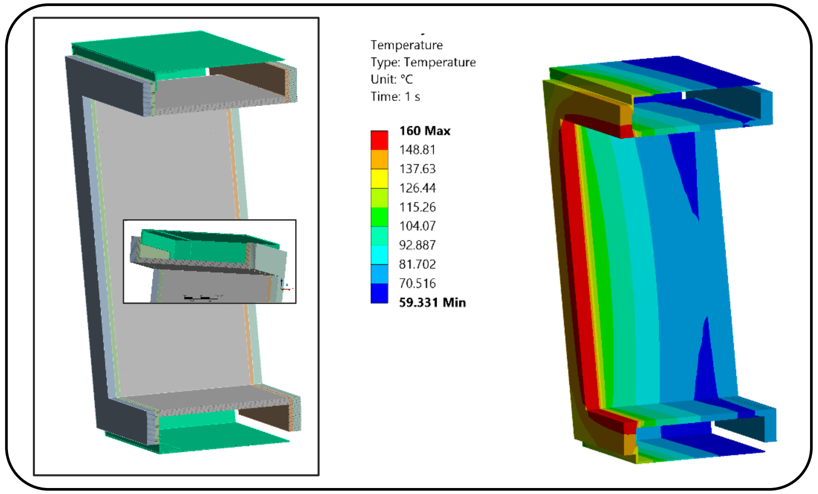






Panel recommendations:

- *heating cables to be placed in contact only with bellows flanges*
- *an external sleeve could be needed*

Analyses - electromagnetic

#	Load case identification	Load case description	Cycles	Service level	Priority
L5b	MD fast (MD III/MD IV in ITER)	Current quench duration: 4-6 ms (26/36 ms in ITER) Thermal quench duration: around 0.5 ms Halo factor (I_{halo}/I_{plasma}): around 0.1-0.2 Expected occurrence: a few times in the machine life	200 (1-2 in ITER)	C	1
L5f	MD slow (MD II in ITER)	Current quench duration: 40 ms (36 ms in ITER) Thermal quench duration: around 0.5 ms Halo factor (I_{halo}/I_{plasma}): around 0.1-0.2 Expected occurrence: likely event	1750 (400 in ITER)	A	2
L5c	VDE fast, downward (VDE III fast, downward in ITER)	Current quench duration: 4-6 ms (26 ms in ITER) Halo factor (I_{halo}/I_{plasma}): around 0.4-0.6 Expected occurrence: a few times in the machine life Sideways load and tilting moment due to asymmetric toroidal halo current: included	750 (4-8 in ITER)	C	1
L5d	VDE slow, downward (VDE III slow, downward in ITER)	Current quench duration: 40 ms (50-100 ms in ITER) Halo factor (I_{halo}/I_{plasma}): around 0.4-0.6 Expected occurrence: a few times in the machine life Sideways load and tilting moment due to asymmetric toroidal halo current: included			1
L5g	VDE fast, upward (VDE III fast, upward in ITER)	Current quench duration: 4-6 ms (26 ms in ITER) Halo factor (I_{halo}/I_{plasma}): around 0.4-0.6 Expected occurrence: a few times in the machine life Sideways load and tilting moment due to asymmetric toroidal halo current: included			2
L5h	VDE slow, upward (VDE III slow, upward in ITER)	Current quench duration: 40 ms (50-100 ms in ITER) Halo factor (I_{halo}/I_{plasma}): around 0.4-0.6 Expected occurrence: a few times in the machine Sideways load and tilting moment due to asymmetric toroidal halo current: included			2
L5e	TFD, all coils (MFD II in ITER)	Discharge on resistors: 5 s Expected occurrence: likely event	600 (50 in ITER)	A	1

Analyses - electromagnetic

#	Load case combination	Level of service	Priority	DTT	Ind.
LC5b	MD fast + Earthquake	C	1		
LC5c	VDE fast, downward + Earthquake	C	1		X
LC5d	VDE slow, downward + Earthquake	C	1	X	X
LC5e	TFD, all coils + Earthquake	C	1		
LC5i	MD fast + TFD, all coils + Earthquake	C	1		
LC5j	VDE fast, downward + TFD, all coils + Earthquake	C	1		
LC5k	VDE slow, downward + TFD, all coils + Earthquake	C	1		
LC6	Maintenance + Earthquake	C	1	X	X
LC7a	VV helium/water Ingress + Earthquake	C	1	X	X
LC7b	CRS helium/water Ingress + Earthquake	C	1	X	X
LC7c	VV helium/water Ingress + MD fast + Earthquake	C	1		
LC7d	VV helium/water Ingress + VDE fast, downward + Earthquake	C	1		
LC7e	VV helium/water Ingress + VDE slow, downward + Earthquake	C	1		X
LC7f	CRS helium/water Ingress + TFD, all coils + Earthquake	C	1		
LC4	Baking + Earthquake	C	1	X	X
LC1	Construction + Earthquake	C	2		
LC2	Pressure Test + Earthquake	C	2	X	
LC5a	Normal plasma operation + Earthquake	C	2		
LC5f	MD slow + Earthquake	C	2		
LC5g	VDE fast, upward + TFD, all coils + Earthquake	C	2		
LC5h	VDE slow, upward + TFD, all coils + Earthquake	C	2		
LC7g	VV helium/water Ingress + VDE fast, upward + Earthquake	C	2		
LC7h	VV helium/water Ingress + VDE slow, upward + Earthquake	C	2		

Defined priorities:

0. loads produced by XD configuration need to be analysed

1. higher priority requiring analyses to be carried out before the call for tender of the vacuum vessel

2. lower priority with analyses to be completed before the design review of manufacturing drawings prepared by the vacuum vessel supplier

Likely events are categorized as category II to be verified for service level A (higher safety factor) in accordance with ASME BPVC III, RCC-MRx.

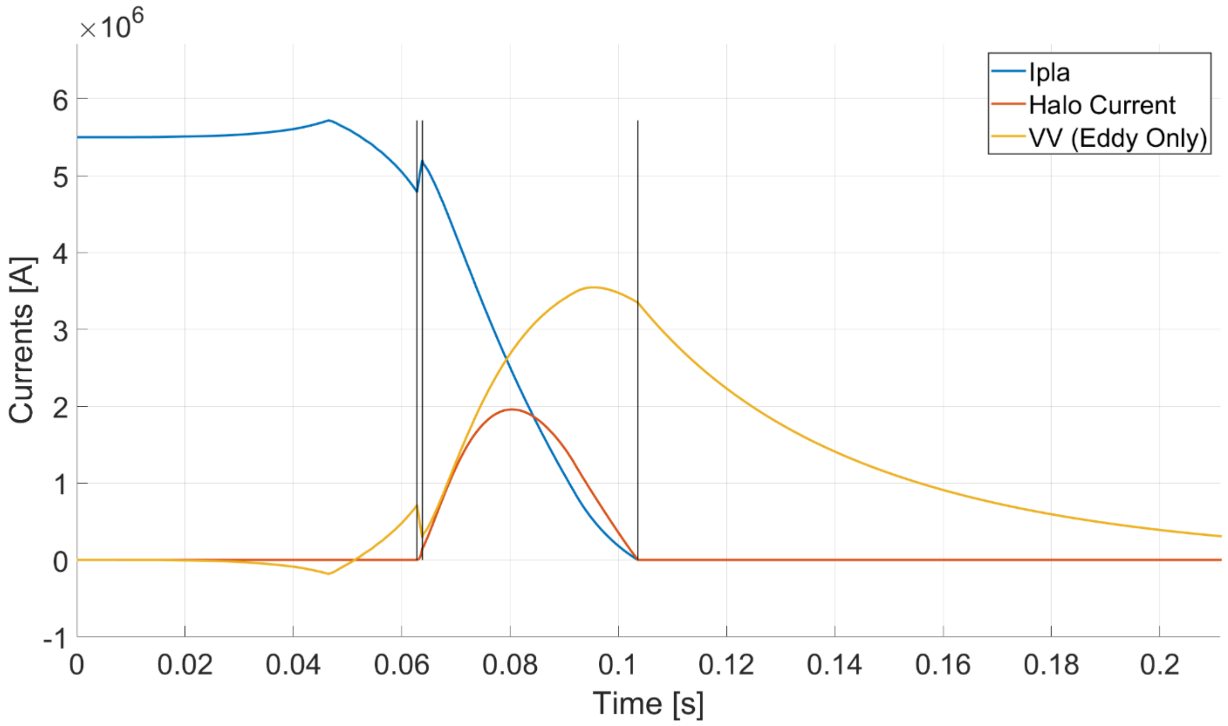
Events occurring a few times in the life of a machine correspond to unlikely events with very low probability of occurrence, corresponding to category III that must be verified for a service level C (lower safety factor).

Level of service C remains also when considering two off three events. In particular, the combination of MD slow (level A) and TFD of all coils (level A) is categorised as category III that must be verified for a service level C.

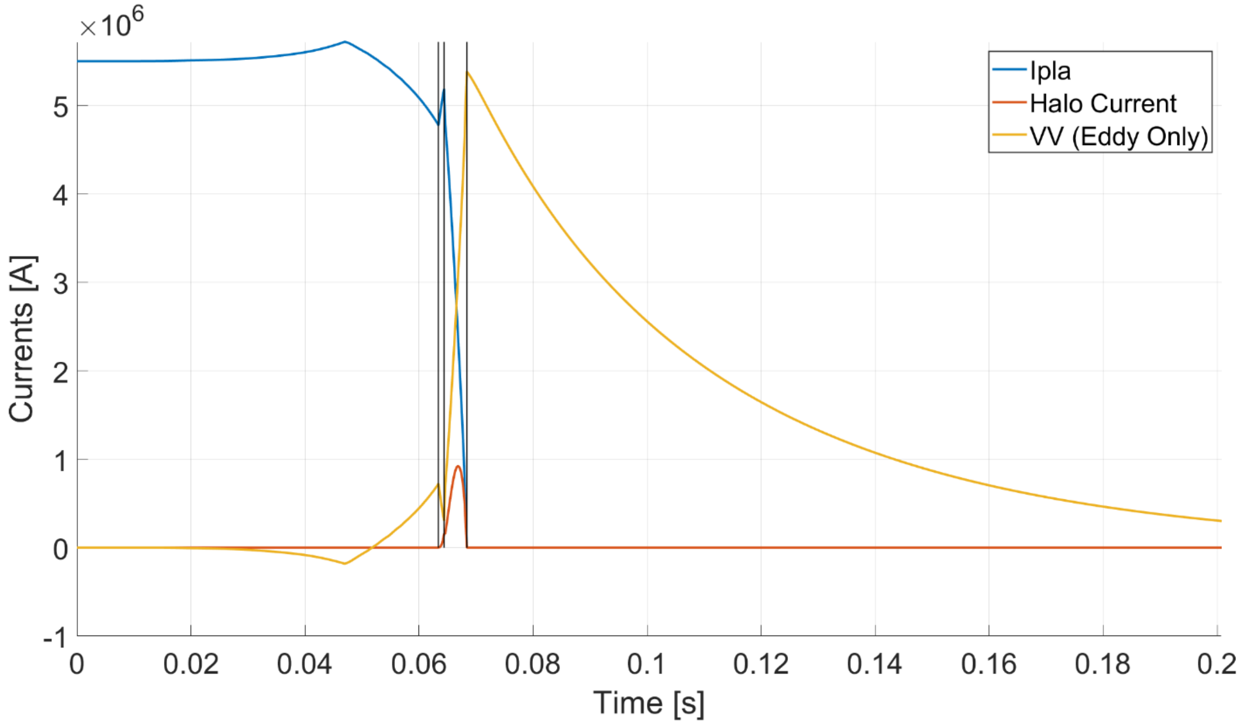
Analyses - electromagnetic - paths of halo currents - upward VDE 1/4

Graphs with time evolution of plasma current, halo current, and vessel current

- UVDE slow
- Maximum halo factor (I_{halo}/I_{plasma}) = 0.356



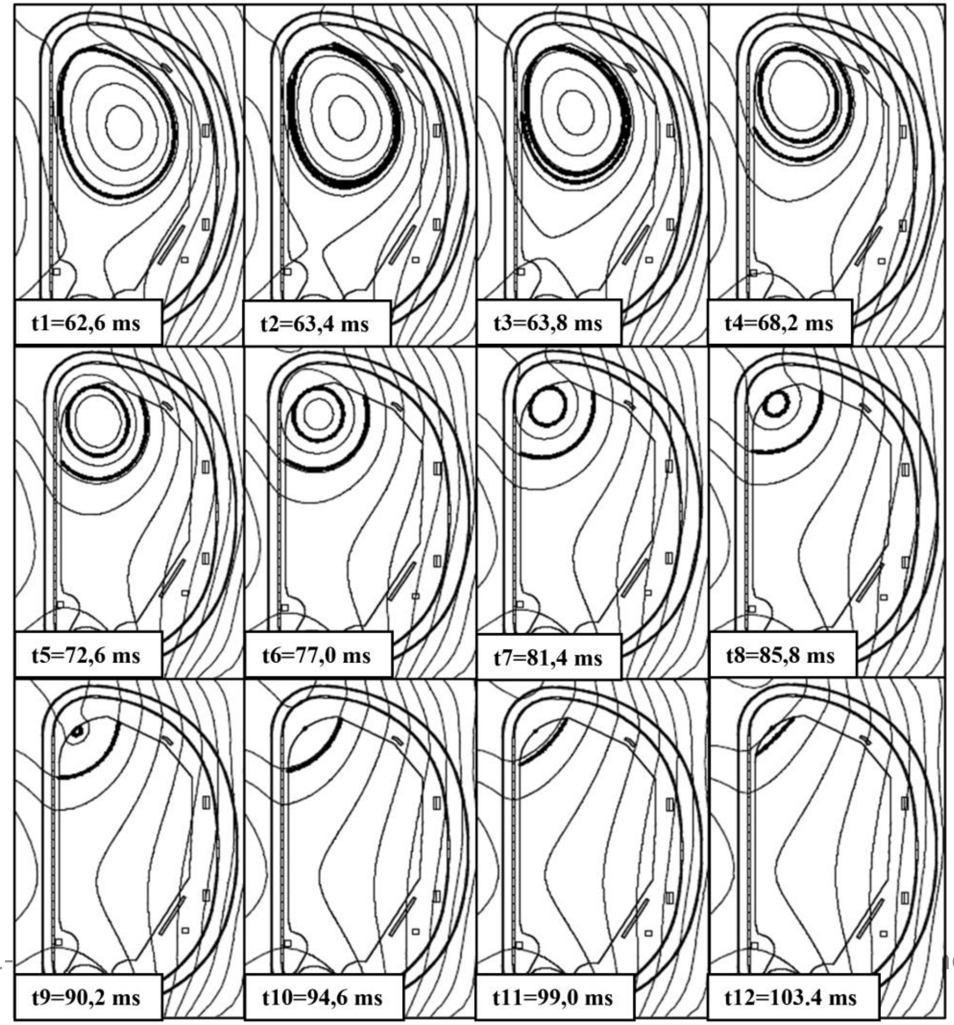
- UVDE fast
- Maximum halo factor (I_{halo}/I_{plasma}) = 0.168



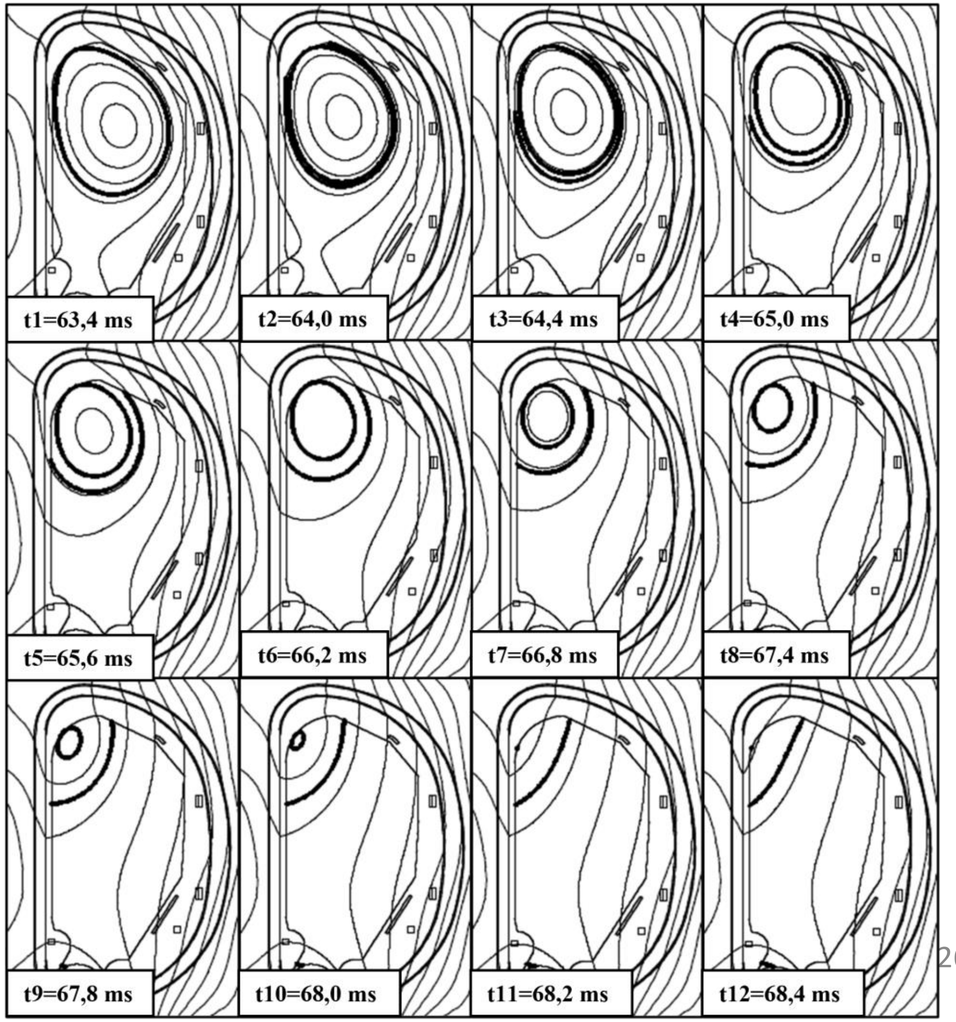
Analyses - electromagnetic - paths of halo currents - upward VDE 2/4

Images of shape evolution of the simulated plasma with positions of plasma boundary approaching the surfaces of in-vessel components is shown in the sequence with reference to the simulation time steps

- UVDE slow



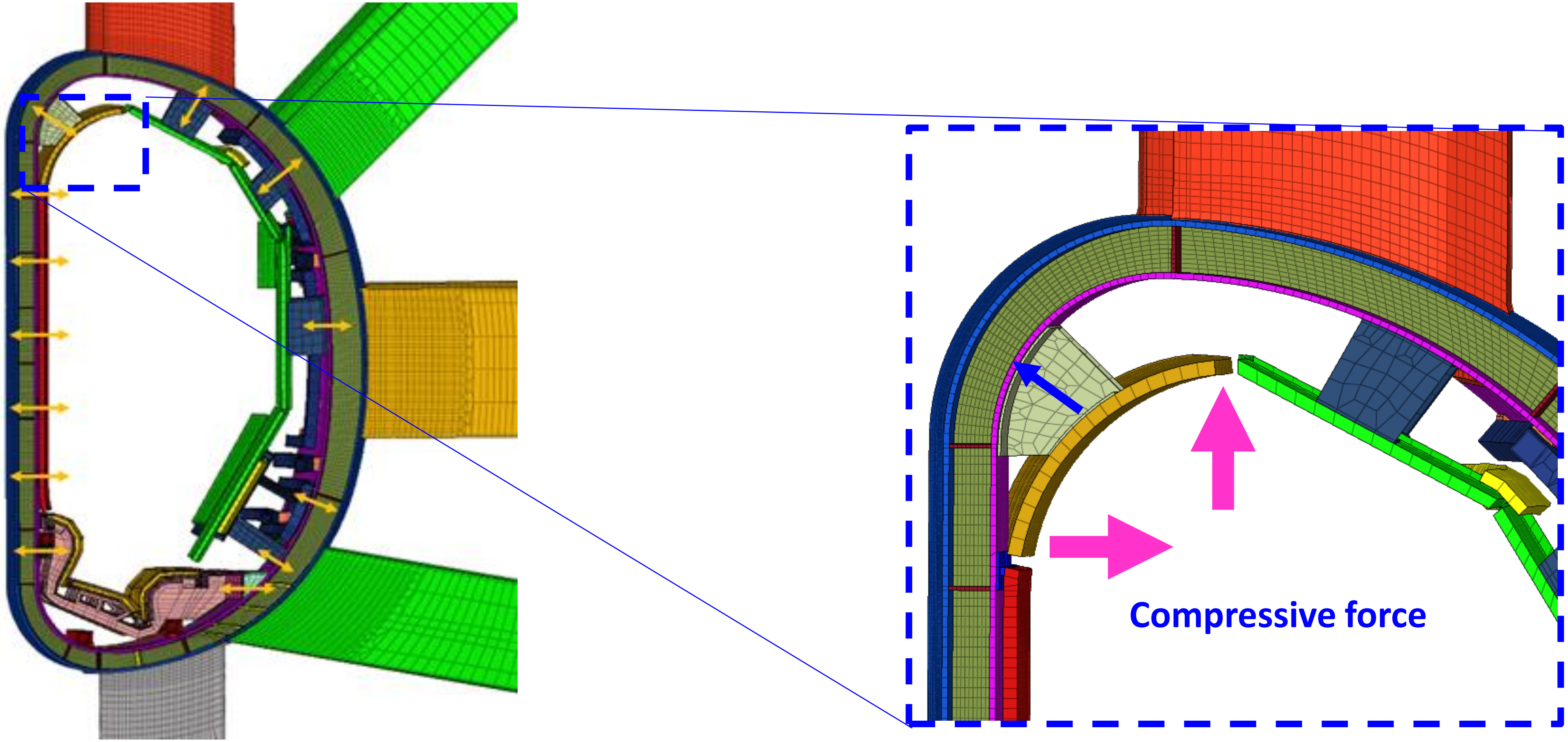
- UVDE fast



Analyses - electromagnetic - paths of halo currents - upward VDE 3/4

UVDE slow/fast, “scenario component”, priority 2:

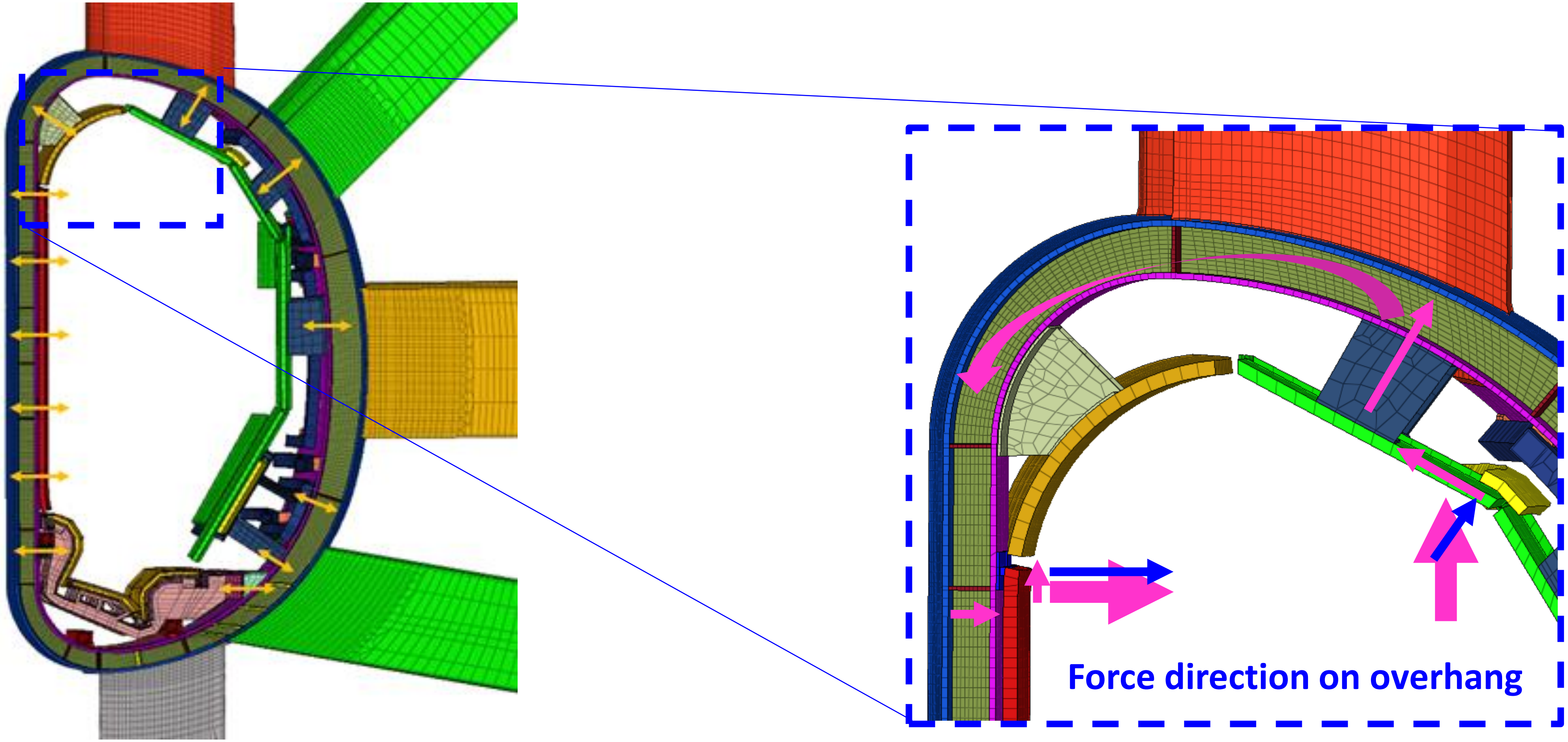
Almost all the halo current (HC) is expected to circulate in the FW top (for both slow and fast events)
→ conservative scenario for vessel verification with higher forces at the interface between vessel & FW top



Analyses - electromagnetic - paths of halo currents - upward VDE 4/4

<u>UVDE slow/fast, “scenario vessel a)”, priority 1</u>:

Halo Current (**HC**) circulating in the vacuum vessel with <u>longer path</u> (for both slow and fast events)
→ significant scenario with forces (**F**) for the verification of vacuum vessel and FW (inner and outer)



Analyses

Electromagnetic:

The Panel noted that the DTT Team has considered MD slow and TFD of all the TF coils as likely events that must be verified adopting a relatively high safety factor in the design rules in accordance with ASME BPVC III and RCC-MRx.

All the other plasma disruption events are considered with very low probability of occurrence and they will be verified adopting a lower safety factor in the design rules. This assumption must be verified considering the variety of plasma divertor configurations to be investigated by DTT during its life and the consequent probability of having larger numbers of plasma disruption events than those reported → severity and actual evolution of events will be also considered

The Panel recommended the DTT Team:

- *To consider in priority 1 the cases: Vertical Displacement Event (VDE) fast, upward + Toroidal field coils Fast Discharge (TFD), all Toroidal Field (TF) coils + Earthquake and VDE slow, upward + TFD, all TF coils + Earthquake with halo current path that maximises the loads in the VV;*
- *To investigate with priority 2 the Major Disruption (MD) and VDE upward plasma disruptions considering the halo current paths involving only the upper First wall (FW) panels in order to verify their support systems;*
- *To investigate with priority 1 the MD and VDE downward plasma disruptions considering the halo current circulating in one case mainly in the divertor and in another case mainly in the VV.*

Structural:

It is urgent to perform accurate analyses to fix stress values in the critical regions taking into account all the loads applied to the VV in the most critical scenarios.

On the basis of the received information, the Panel recommendations are:

- *To perform the stress analyses in priority 1 in particular taking into consideration the loads transferred by the divertor cassettes;*
- *To validate the adopted models for the EM and stress analyses by performing the same calculations for some critical cases by two independent groups.*

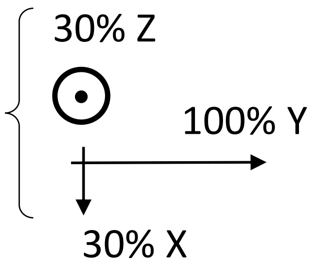
Analyses - buckling and fatigue

Instability verification of spring plates has been performed with the following conditions:

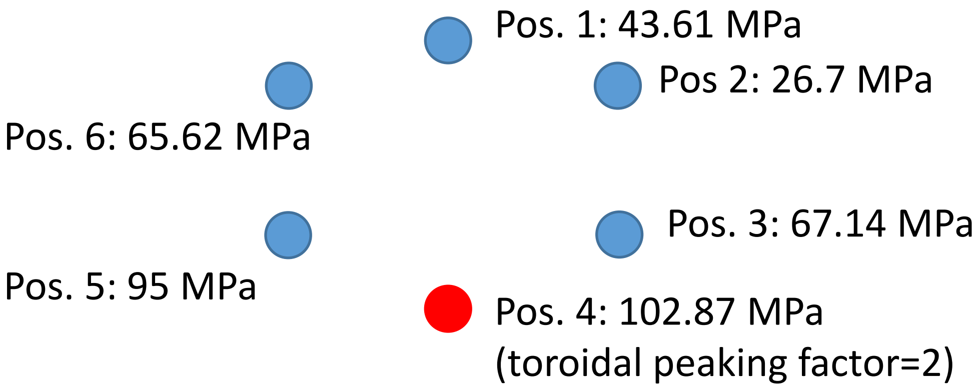
- Only spring plates are simulated as full loads are transferred on them.
- Four different load combinations: baking, baking + earthquake, DVDE slow, DVDE slow + earthquake

Steps:

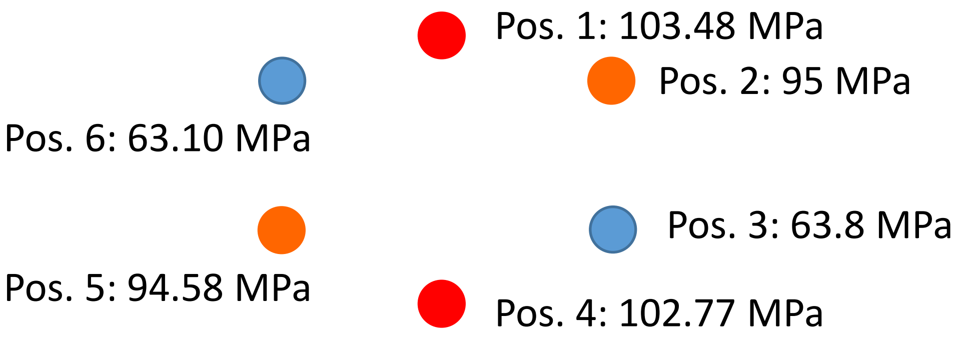
1. significant spring plate positions are identified: spring plates not aligned with combin. of seismic acceleration
2. then, vessel reactions on spring plates are applied for buckling analysis



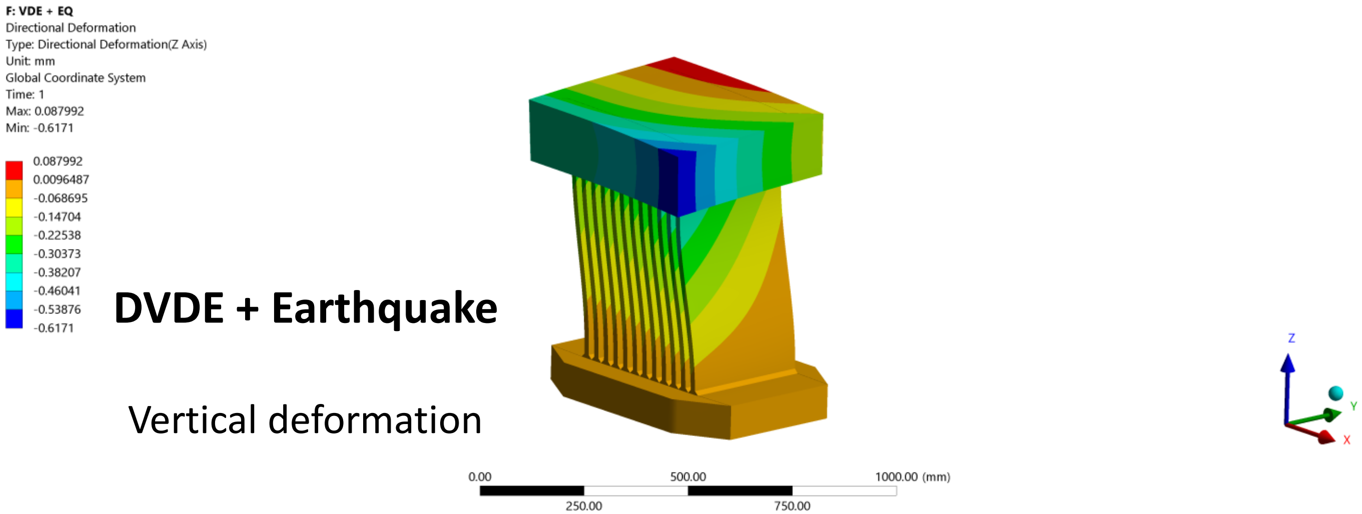
Effects (stresses) due to DVDE slow:



Effects (stresses) due to earthquake:



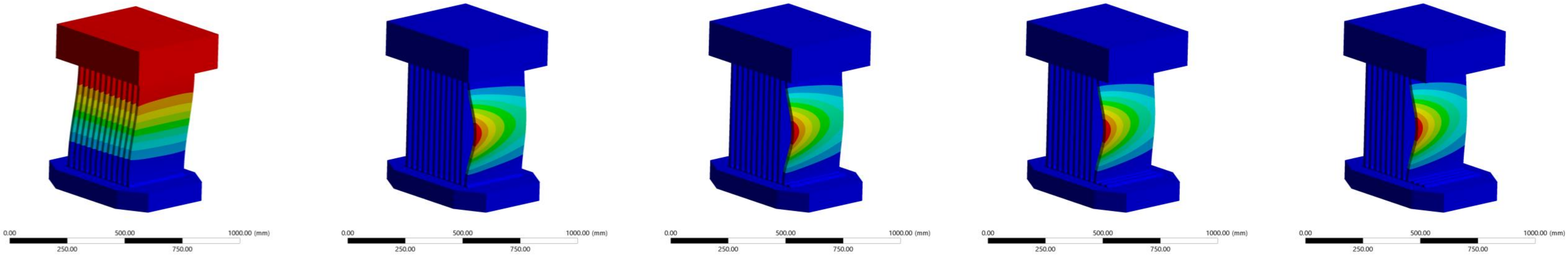
Analyses - buckling and fatigue



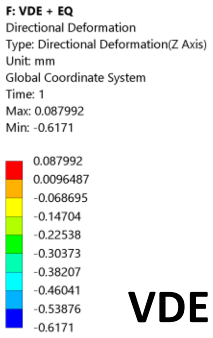
DVDE + Earthquake

Vertical deformation

2.67	5.77	6.55	7.28	8.02

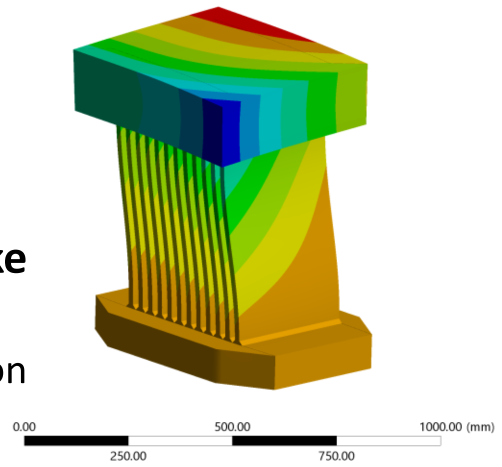


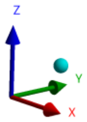
Analyses - buckling and fatigue



VDE + Earthquake

Vertical deformation

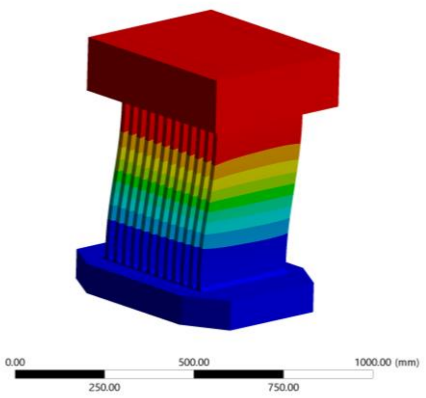


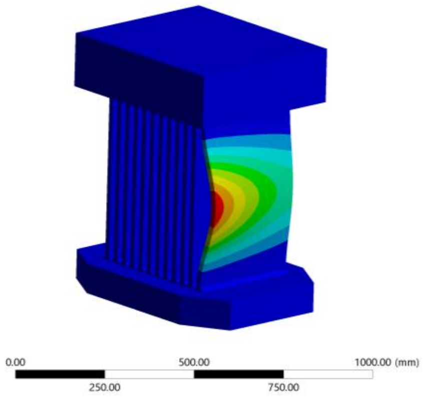


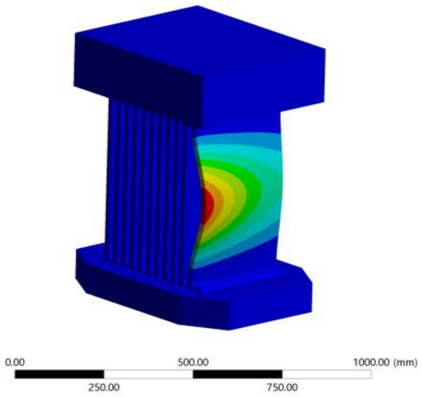
The Panel recommendations to the DTT Team are:

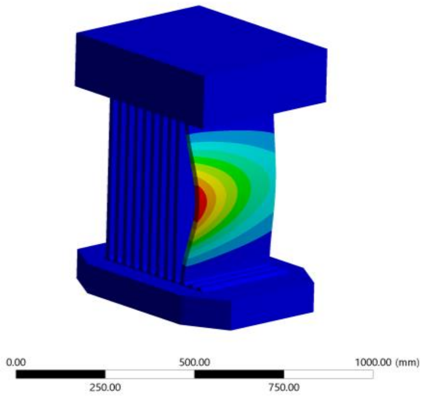
- *the design should be to improved so as to increase significantly the load multiplication factor;*
- *the fatigue verification should be completed before the revision of manufacturing drawings is prepared by the vessel supplier.*

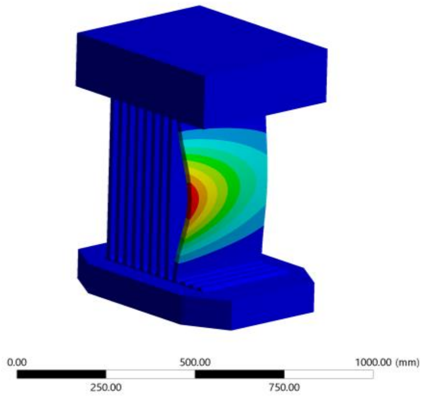
2.67	5.77	6.55	7.28	8.02











Analyses - corrosion test

Planned activities:

- metal release experiments will be carried out with the addition of LiOH to increase to at least 5.5 the pH of the borated water;
- transgranular stress corrosion cracking will be assessed for 316LN exposed to water and dissolved oxygen;
- water chemistry control will be required in order to monitor LiOH and assure low levels of contaminants such as chlorides and sulphates to minimise any risk of enhanced corrosion. (This activity will impact the borated water storage and chemistry control but not the VV structure.);
- the effects of radiolysis will be investigated to determine the water chemistry limits that will not impact the design of the VV.

Panel report (part):

The design solutions adopted for the VV appear to be satisfactory with respect to water corrosion issues.

The Panel recommended the DTT Team:

- *Planned activities should be completed*
- *The risk register should note an action to ensure that in all conceivable silent hours and fault condition circumstances, the machine protection system will ensure that the boric acid is not allowed to block the coolant flow by crystallising during any low temperature excursion.*

Interfaces - Divertor, Limiter, First Wall

The Panel recommended the DTT Team:

- *To accurately verify the drawings of all the supports of the in-vessel components in order to be sure of their suitability to function properly in every operating condition of the DTT machine. Such analysis is recommended to be performed before the design review of manufacturing drawings is prepared by the VV supplier;*
- *To pay particular attention to the design and verification of the divertor locking-alignment system;*
- *To check with the physics group that there will be sufficient gas conductance through the divertor structures for the required divertor exhaust pumping speed to be achieved;*
- *To verify in detail the FW / Limiter designs, their attachments and the loads acting upon them.*

Suitable actions are ongoing regarding all these topics.

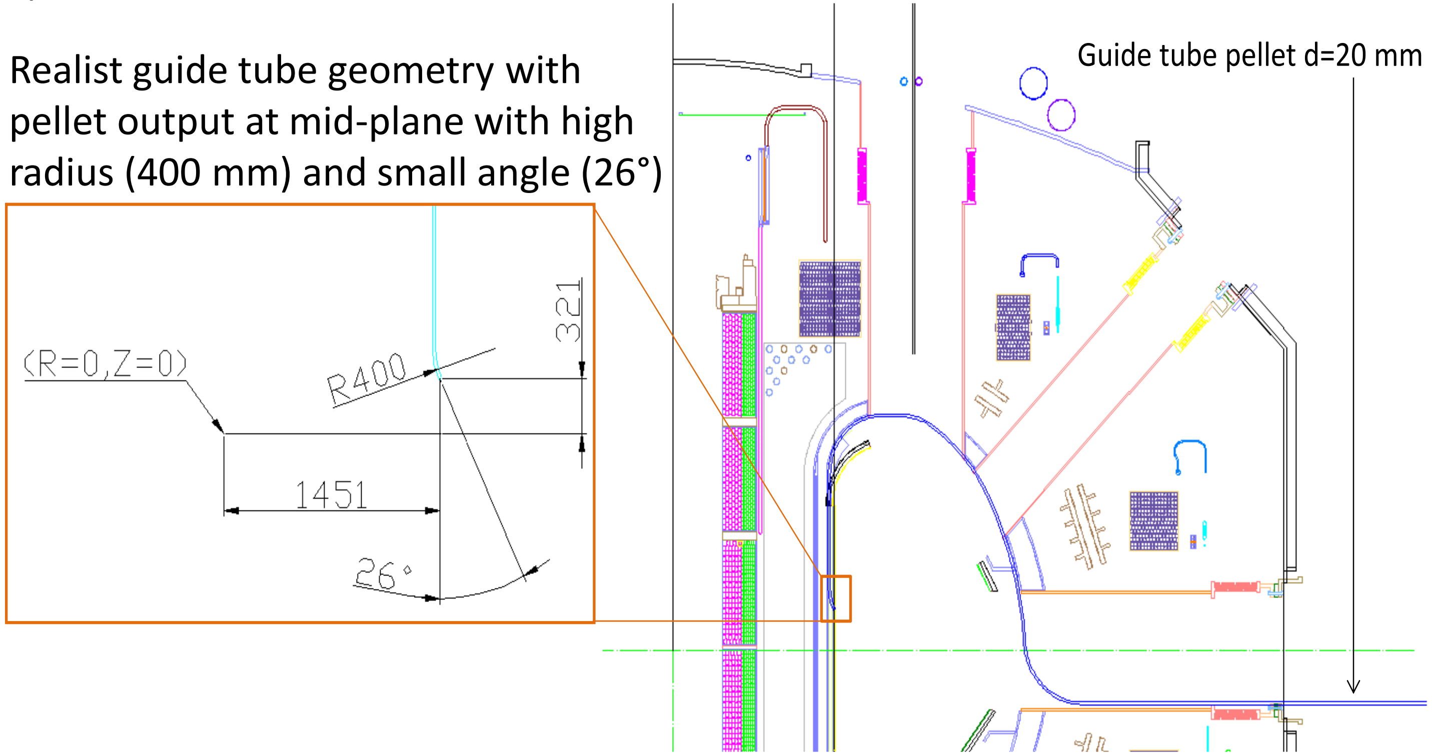
Interfaces - Gas Fuelling and Pellet Injection

The injection geometries located at the High Field Side (HFS) are the most promising configurations for pellet injection as demonstrated by detailed simulations [EUROfusion Deliverable-ID PMI-2.3-T011-D001].

These configurations satisfy physical requirements (deposition at a normalized radius ~ 0.8 and fuelling efficiency > 95%). They require velocities well in line with the performance of present day injectors. Curved guide tubes are mandatory and the maximum speed at which pellet can be launched without a too large erosion or braking is 200-300 m/s.

Estimation of the fuel cycle for pellets of diameter $\Phi pellet$ ~2.2 mm leads to a required injection frequency $finj$ ~25 Hz and fuel throughput of ~20 $Pa{\cdot}m3{\cdot}s^{-1}$.

Realist guide tube geometry with pellet output at mid-plane with high radius (400 mm) and small angle (26°)



The Panel recommended the DTT Team to ensure that provisions for at least one high field side pellet flight line are indeed built into the VV.

Manufacturing and integration tolerances - Limiter

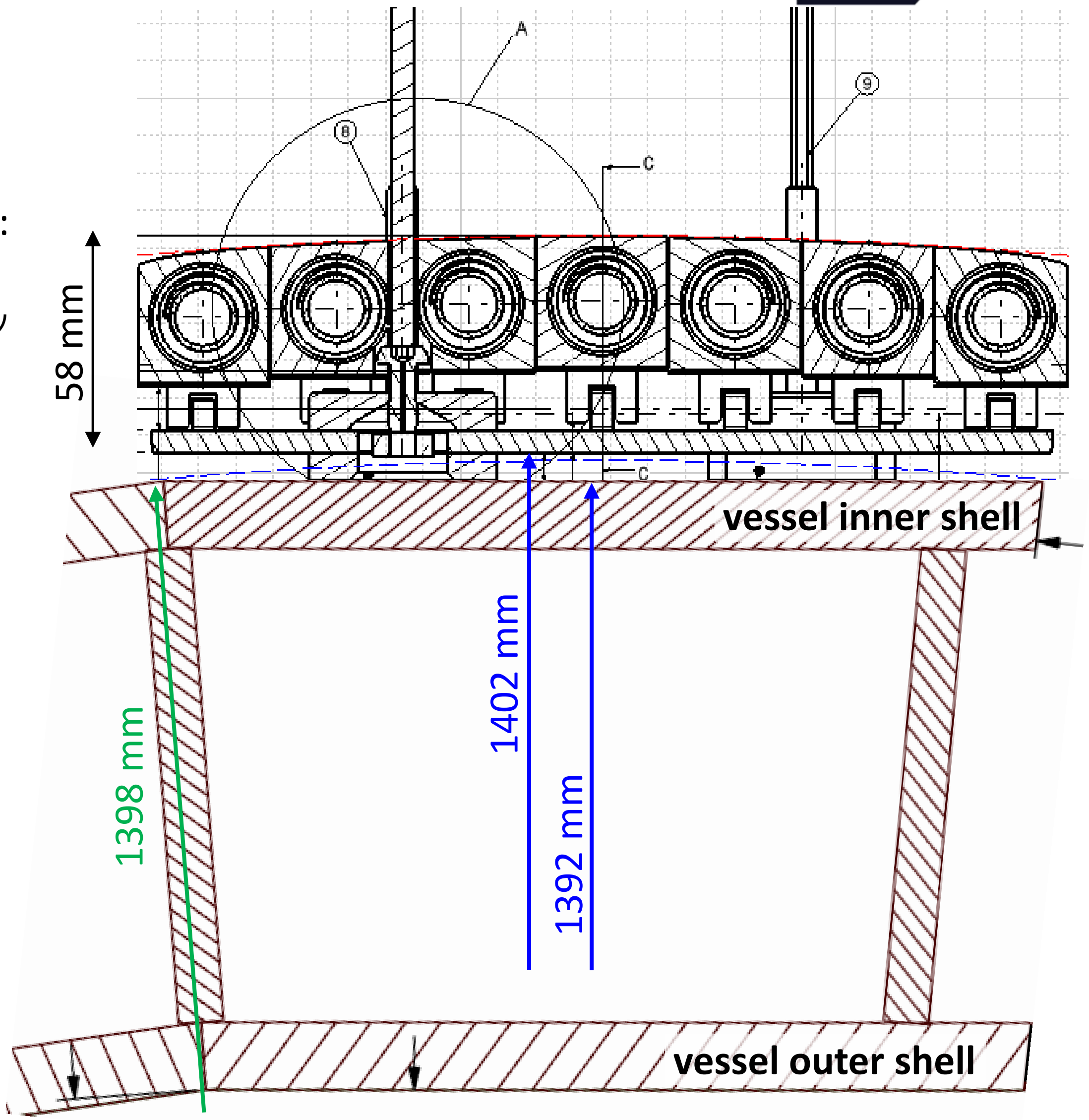
Main geometrical characteristics at the inboard:

- the plasma surface of the FW limiter (10° toroidal angle) is positioned at R = 1460 mm
- the thickness of the FW limiter is 58 mm
  → tolerance of FW limiter < ± 1 mm
- total vessel inner shell error: sum of errors ≈ ± 9.2 mm

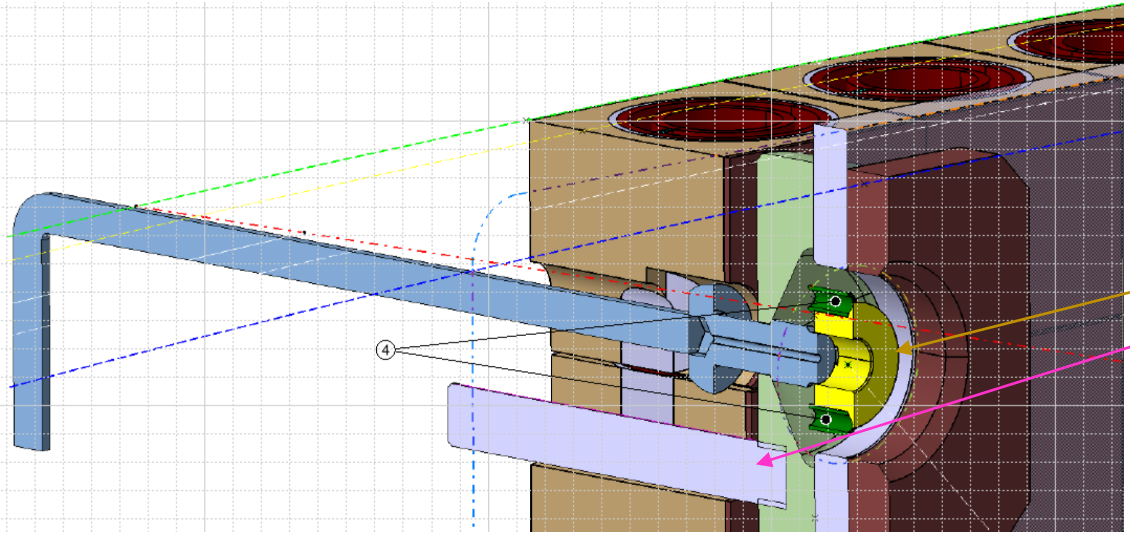
- required compensation: ± 10 mm
- the FW support plate needs to be mounted on 10 mm compensation gauge spacers (R = 1392 mm)

Main outcome:
the inboard position of the vessel inner shell is verified considering the compensation requirement of the FW limiter

Plasma side surface of FW limiter: R = 1460 mm
Inner surface of FW limiter (middle): R = 1402 mm
Vessel inner shell (middle): R = 1392 mm
Vessel inner shell (10° edge): R = 1398 mm ± 5 mm or
Vessel inner shell (10° edge): R = 1400 mm +3/-7 mm

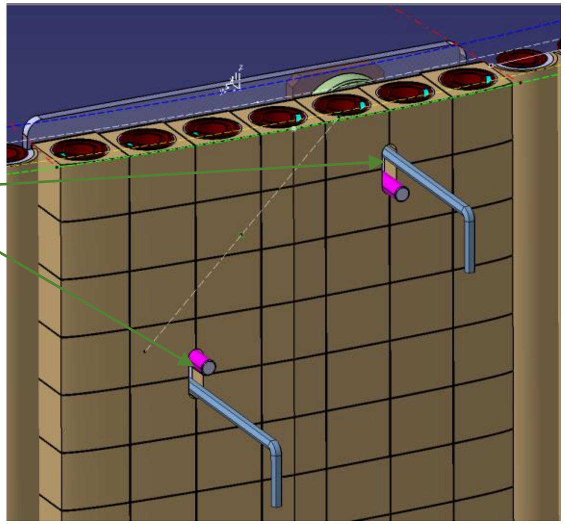


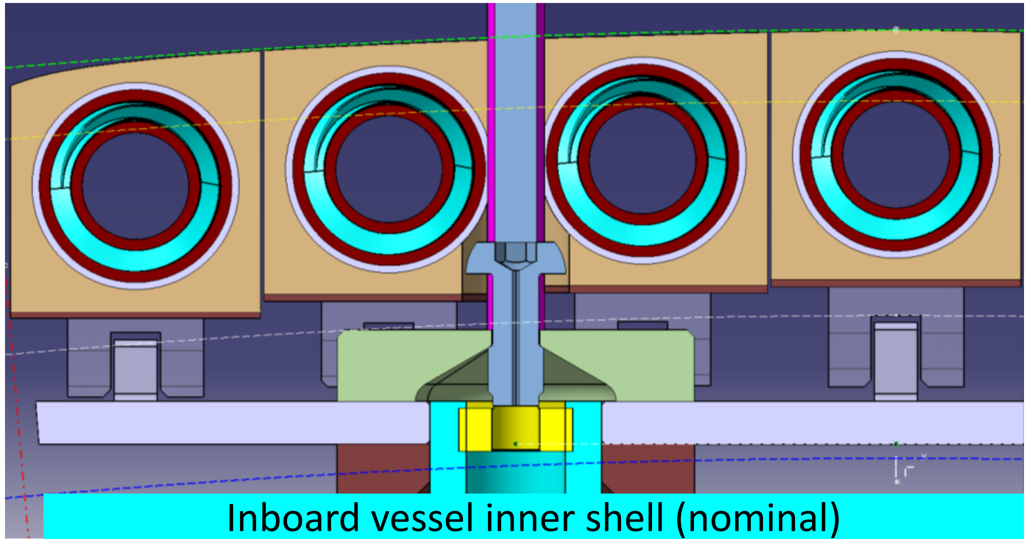
Manufacturing and integration tolerances - Limiter

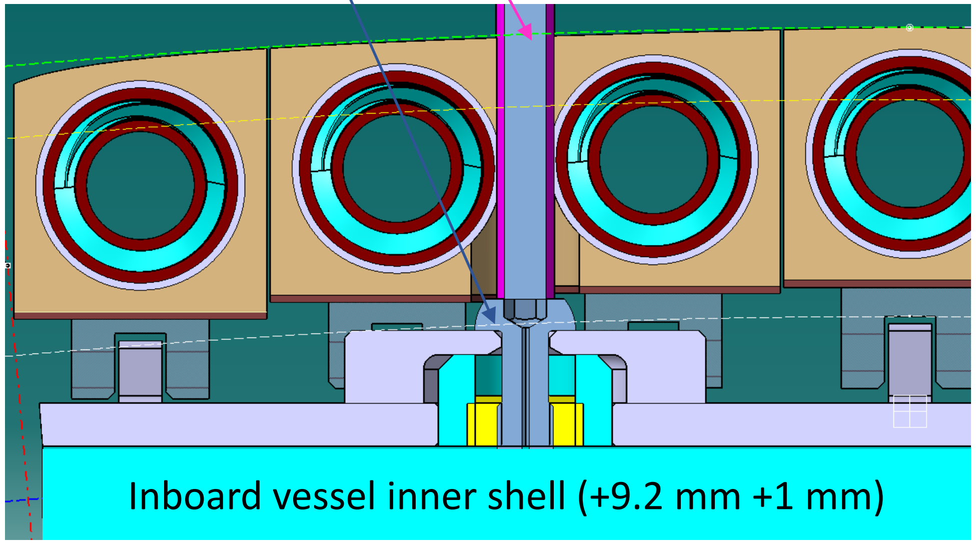


The FW limiter design integrates:

- apertures (plasma side concept)
- threaded inserts
- alignment threaded bars
- captivation screws







Manufacturing and integration tolerances

The Panel notes that a worst-case combination of non-conformities on the VV dimensions could bring the FW limiter to a radius R > 1460 mm resulting in a possible plasma performance reduction.

The Panel recommended the DTT Team to discuss with the physics group the possible impact on the plasma performance of operationally reducing the minor radius and/or increasing the major radius so that the inboard radius of the separatrix (Ro-a) increases by a few mm.

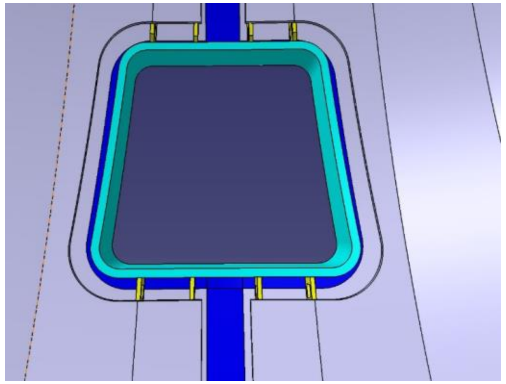
Another possibility is to mitigate this criticality by specifying asymmetric tolerances of the vacuum vessel on the inboard side in order to divide the available free space of 10 mm between VV and TFC so as to preserve the critical clearance lying between the VV and the plasma.

Suitable actions are ongoing considering also the VV manufacturing strategy and revision of the on-site integration sequence of VV sectors.

Assembly

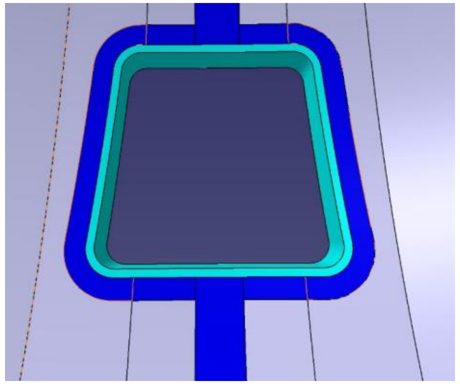
Assembly, welding, and non destructive testing (visual test, eddy current, and ultrasonic tests) issues during integration of the final sector are fixed through:

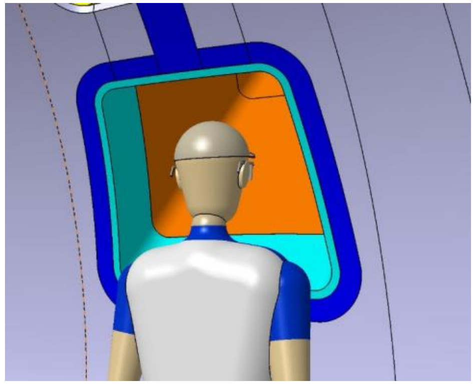
- manufacturing port stubs and port ducts made each in a single part
- welding splice frame and splice plate



Poloidal rib welding from the inner side

Welding of splice frame and plate from the inner side





Welding and inspection of the port duct

The Panel recommended the DTT Team:

- *To analyse in detail the assembly of the final sectors for the closure of the VV;*
- *To install in the final assembly phases port stubs and port ducts already prepared in one piece each; i.e. to avoid their installation on the VV in two pieces.*

Summary of the Panel’s assessment

- *The design input requirements relevant for construction and operation of the VV and gravity supports have been fully addressed;*
- *The status of the design in terms of completeness and quality of the project design output (drawings, models, documents and specifications) can be considered to be in an advanced state, but still some important analyses must be completed;*
- *With respect to the identification of critical points, the Panel has not identified any risk that could cause a showstopper;*
- *The probability of completing the fabrications of the VV, ports and gravity support in 40.3 months is low.*

Vessel manufacturing strategy and integration sequence of sectors

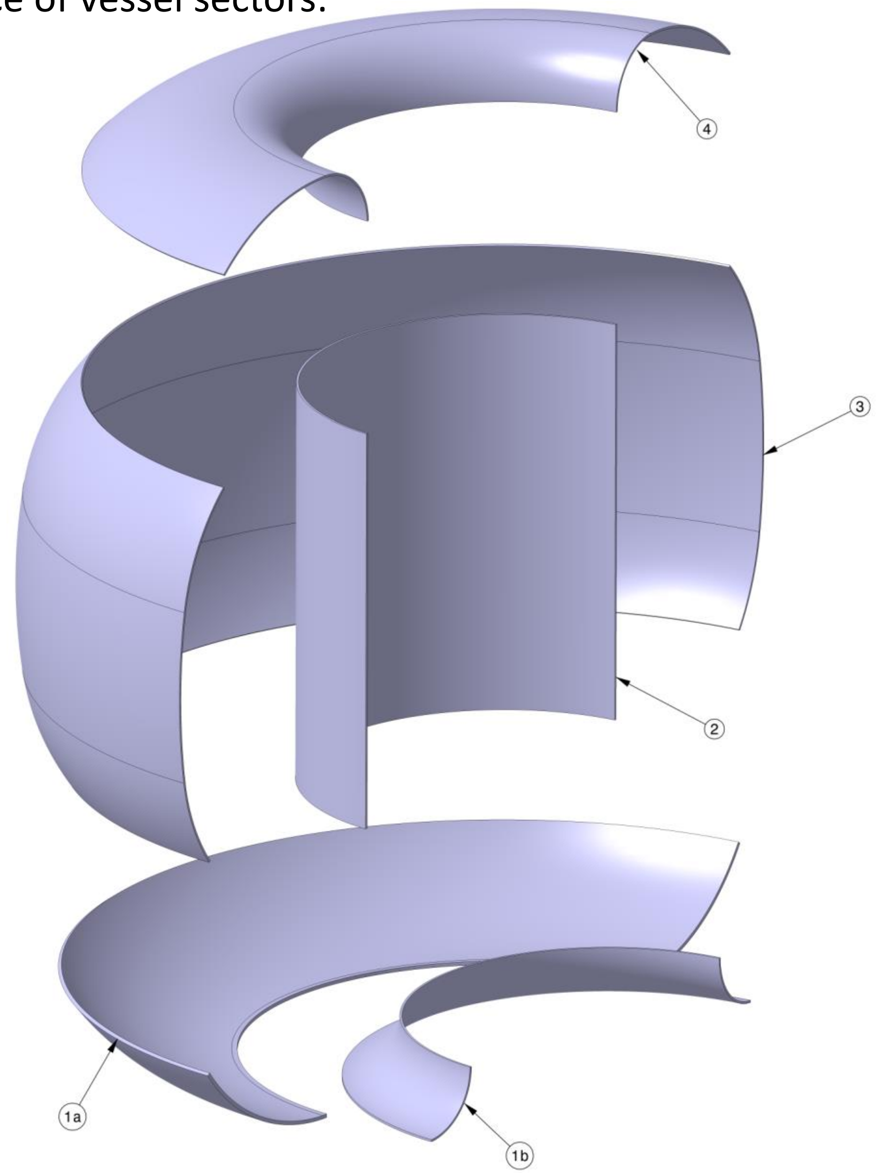
New vessel manufacturing strategy and revision of the on-site integration sequence of vessel sectors:

- 2 x 170° sectors + 1 x 20° final sector

Main evaluations:

- Analyses of the vacuum vessel: no showstopper
- Manufacturing and testing:
    - initial qualification and engineering: about 18 months
    - production of sectors: about 18 months
    - delivery of port ducts: a further additional period
- Revision of the CAD model for the technical specification
- Procurement deliverables
- Assembly: integration of other components needs to be revised, but it will not produce showstoppers (please see presentation prepared by M. Utili)

Position	Description	Thickness [mm]	Plate forming [mm x mm]
1a	Bottom outboard head	25	6344 x 6344
1b	Bottom inboard head	15	3568 x 3568
2	Inboard shell	15	4154 x 2790
3	Outboard shell	15	9696 x 2780
4	Top head	15	5906 x 5906



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