Design of Vacuum Vessel

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Outlook

A. Legislative framework on European level for the Vacuum Vessel

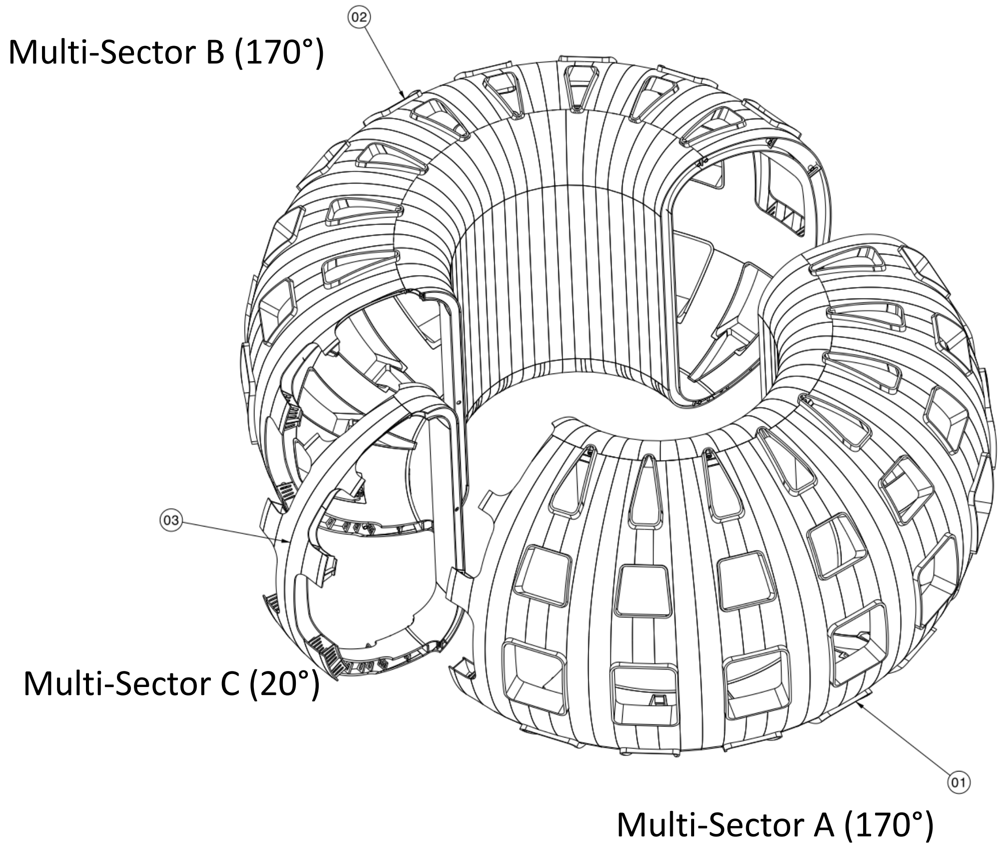
B. Vacuum Vessel interdisciplinary design

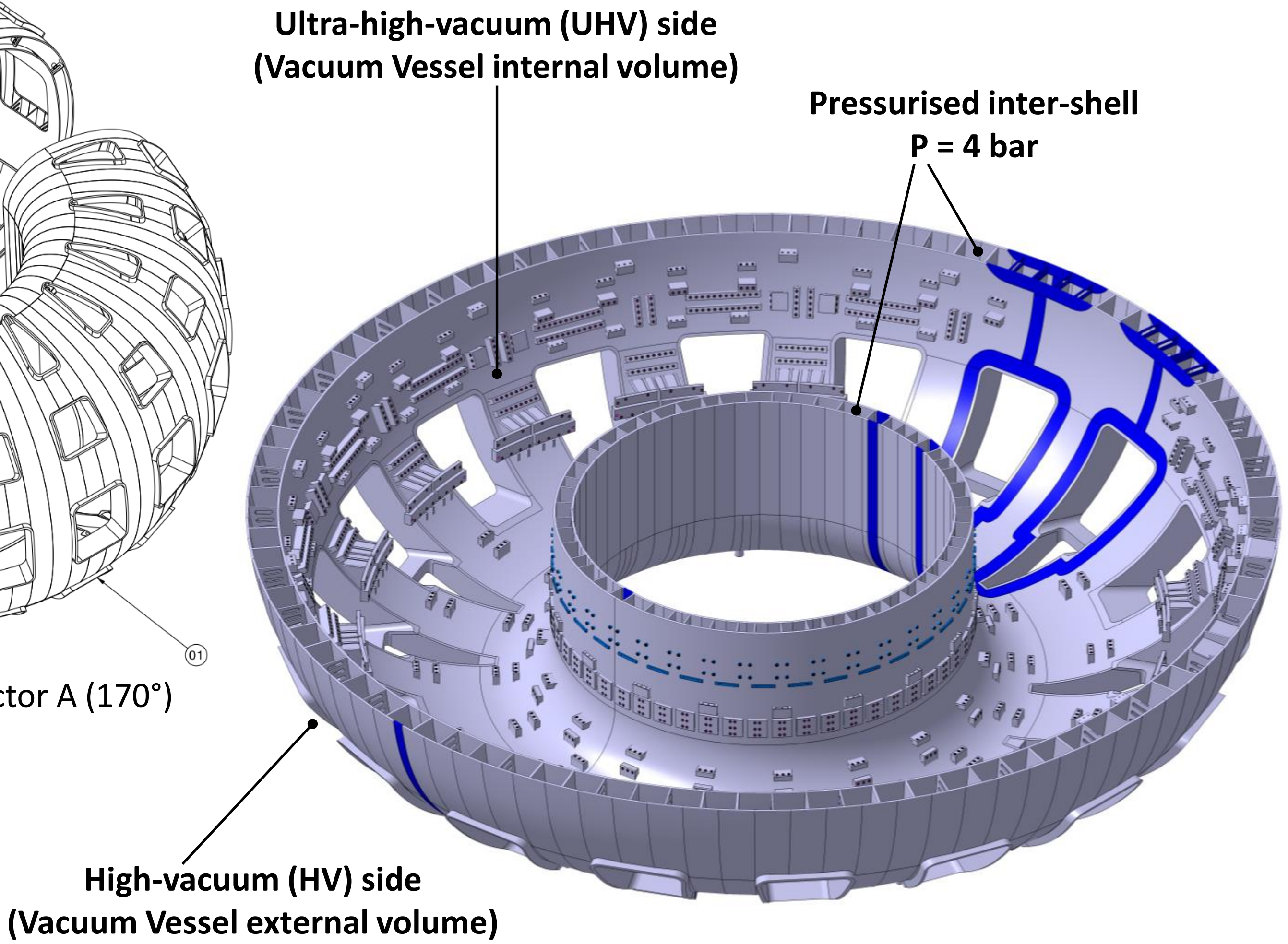
C. Structural integrity verifications

D. Design for manufacturing

A. Legislative framework on European level for the Vacuum Vessel

Vacuum Vessel (DTT machine)





Vacuum Vessel with inter-shell

- The vacuum vessel includes basically a box structure, named inter-shell, circulated by a pressurised fluid and it realises internally a ultra-high vacuum tight chamber to perform plasma pulses

- The main operating state, named normal plasma operation, requires the most enhanced levels of vacuum and cleanliness which can be achieved with specific cleaning procedures applied on the hermetic sealed chamber to secure against water vapor, manufacturing residues (such as oils, greases, packing), and foreign bodies in order to create and maintain the plasma discharge avoiding any contamination which may degrade plasma performance

Risk analysis

The overall hazards and risks relevant to a vacuum vessel (VV) are assessed to be taken into account from the design to the decommissioning. The risks identified, analysed, and treated for the vacuum vessel are recorded in the risk register and they are related, but not limited to:

- design (e.g. tight tolerances, need of forged parts, provision of compensation members for system integration, thermal behaviour and gap control, corrosion-erosion)
- interface identification, definition, and control for system integration
- design analysis and structural integrity verification considering operational loading (normal condition) and unlikely/extremely unlikely loading (emergency/faulted condition) such as disruptions
- radiological protection (shutdown and maintenance, decommissioning and waste management, corrosion-erosion and activated corrosion products)
- manufacturing (e.g. raw material procurement, welding defects, welding distortions, qualified personnel for welding and NDE, manufacturing experience of UHV tight chambers, inspectability, subcontracting, scheduling)
- management, review, and decision approval of procurement contract documentation
- assembly sequence, first installation, maintenance
- tests for commissioning and putting into service
- plasma operation (e.g. baking, plasma measurement and control, disruption mitigation system, heat balance)

Risk analysis → machine classifications

Possible classification, depending on the National Regulations, for machines with pressurised inter-shell to be used for plasma confinement and power exhaust experiments:

- Notification and Authorization for the Use of Radiation Sources: Radiological Protection Technical Report →
    - Specific requirements concerning radiological protection are analysed for the machine (shutdown and maintenance, decommissioning and waste management, corrosion-erosion and activated corrosion products)
    - The facility as well as the vacuum vessel is not an item specifically designed for nuclear use, failure of which may cause an emission of radioactivity, but is classified as a source of ionising radiations in accordance with the National legislative rules
- Analysis of the plant accidents and incidents through Functional Failure Mode and Effect Analysis (FFMEA) → The essential safety requirements of the Pressure Equipment Directive (PED) apply to the vacuum vessel
    - Accident: an unintended event that happens suddenly and leads to injury without one's foresight or expectation. It often causes damage to property or injury to people, but it doesn't have to be serious to be considered an accident
    - Incident: any unplanned event, from a near-miss to a major health and safety breach, that causes property damage, but doesn't harm any person. An incident is an event that could have resulted in an accident but didn't

Identification, analysis, and treatment of the vacuum vessel risks: radiological protection

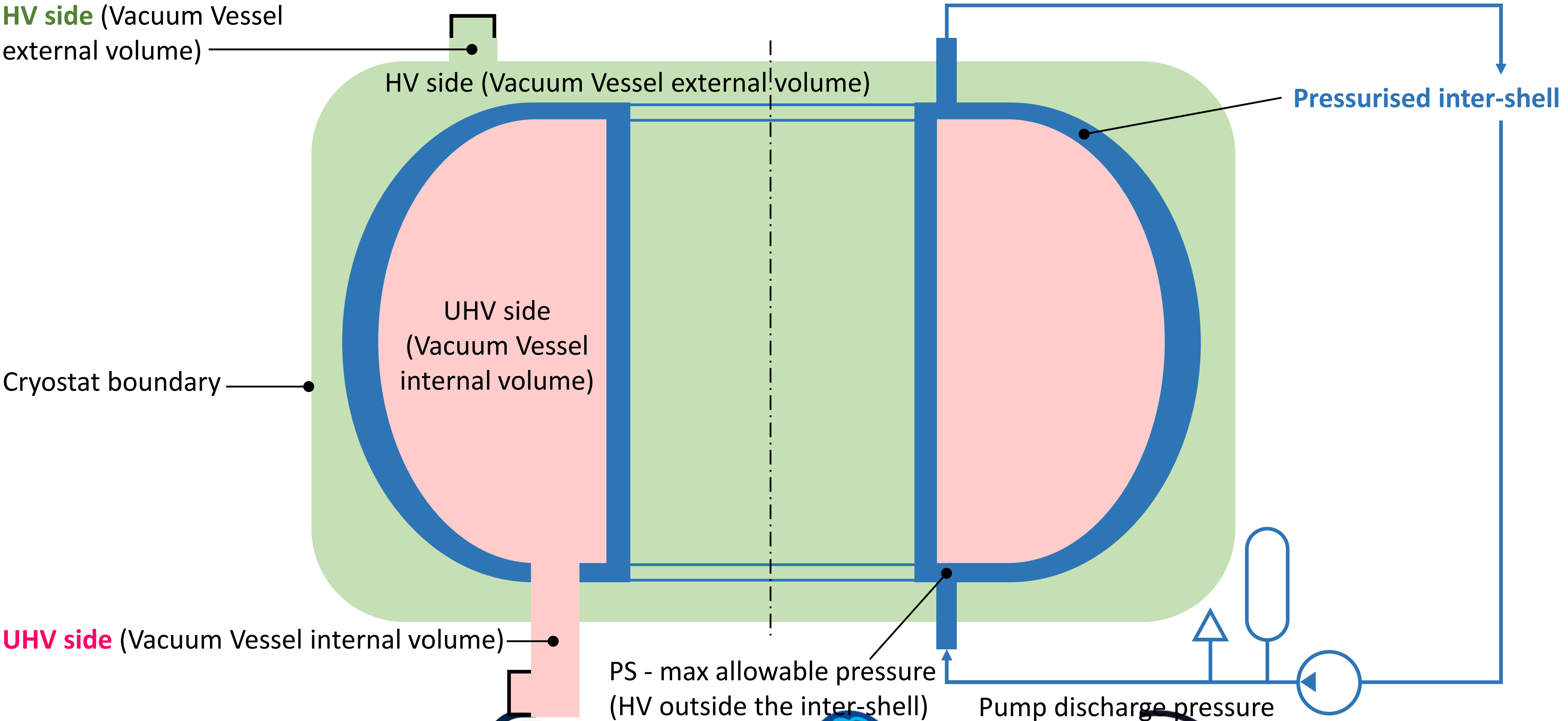
The inter-shell corrosion-erosion phenomena during high performance plasma operations can produce corrosion products

Corrosion products could be activated and their dilution and transport in the PHTS produce water contamination [FFMEA]

The Vacuum Vessel Draining System (VVDS) and the Vacuum Vessel Pressure Suppression System (VVPSS) include a set of massive water storage containers and they will be located inside a contained environment working as Drain Tank Room in order to ensure that, in case of a water leak, contaminated water would remain contained within. Indeed, the Drain Tank Room acts as:

1. confinement barrier of the activated corrosion products thus forming one of the key safety systems
2. if needed, segregation of the PHTS of VV and in-vessel components from other loops by placing the VVDS and the VVPSS in a separate fire zone to limit the absorbed heat flux from a fire

Identification, analysis, and treatment of the vacuum vessel risks: pressure hazard

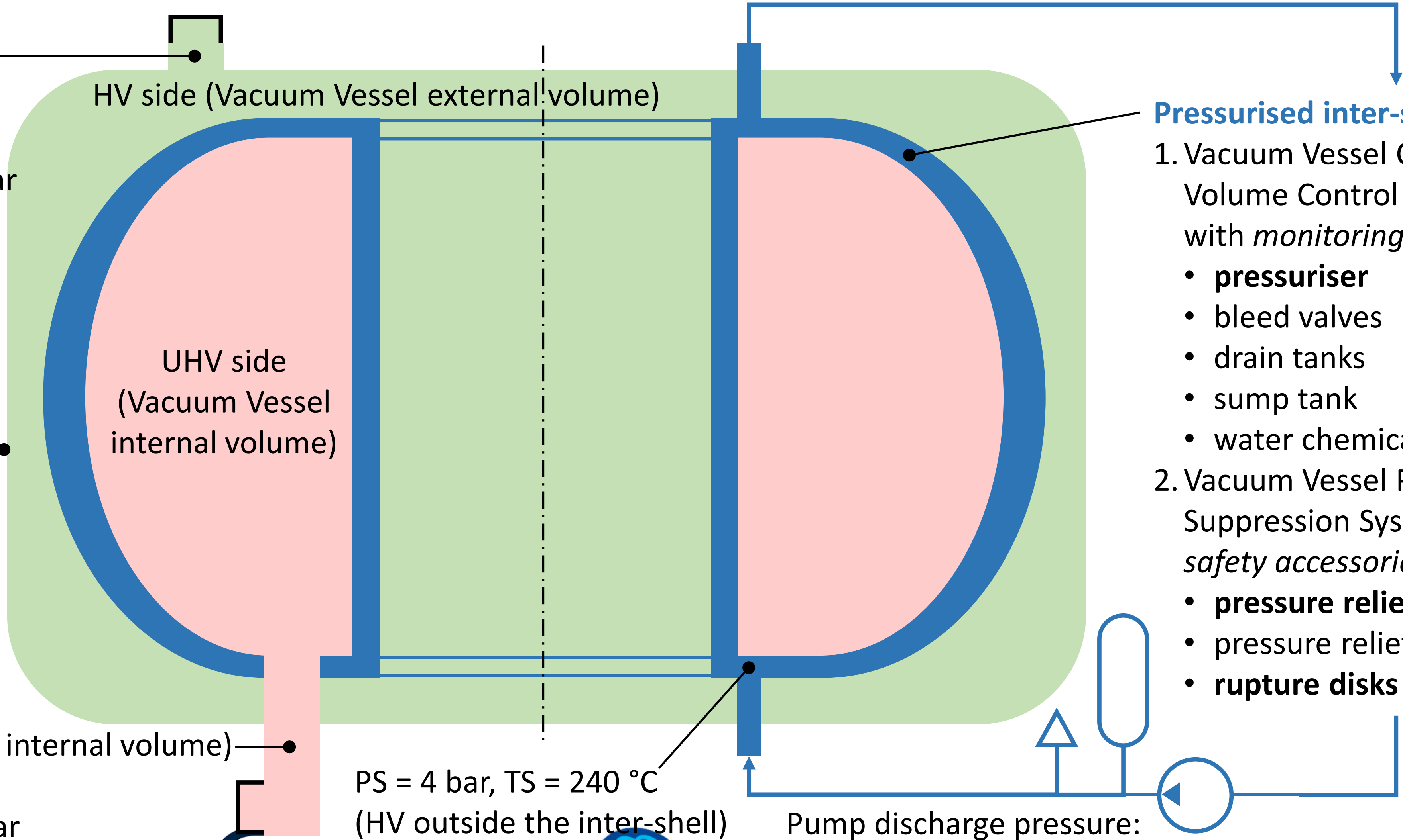


Integration of devices for protection against exceeding the allowable limits of pressure

HV side (Vacuum Vessel external volume)

- **Cryostat (CRS) rupture disc**
  $P_{CRS\ RD}$ = 0.2 bar < 0.5 bar

Cryostat boundary



Pressurised inter-shell

1. Vacuum Vessel Chemical and Volume Control System (CVCS) with *monitoring devices:*
   - **pressuriser**
   - bleed valves
   - drain tanks
   - sump tank
   - water chemical control system
2. Vacuum Vessel Pressure Suppression System (PSS) with *safety accessories:*
   - **pressure relief valves**
   - pressure relief tank
   - **rupture disks**

UHV side (Vacuum Vessel internal volume)

- **rupture disc**
  $P_{VVP\ RD}$ = 0.2 bar < 0.5 bar

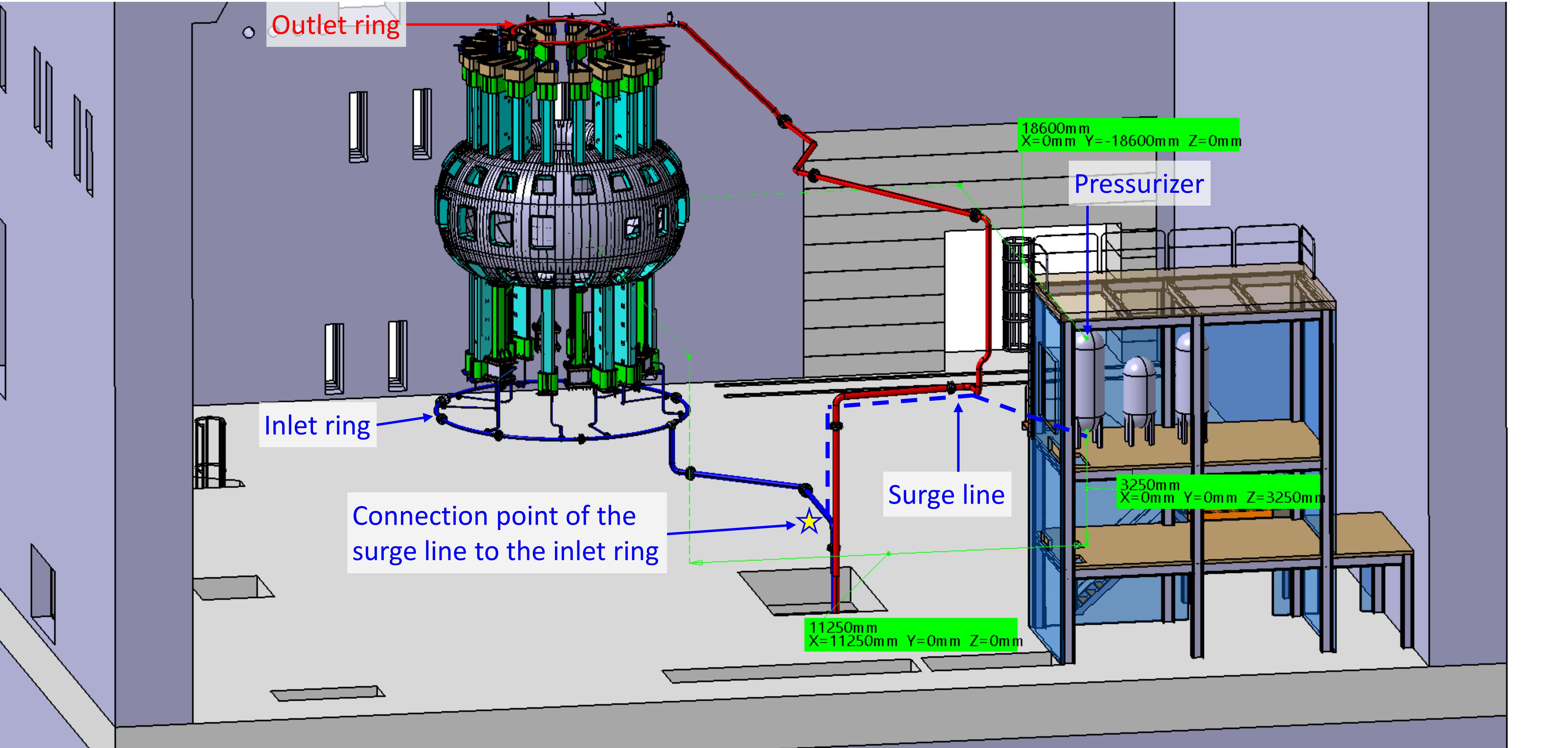
PS = 4 bar, TS = 240 °C
(HV outside the inter-shell)

Pump discharge pressure:
P = 3 bar (ambient pressure outside)

Control and monitoring devices (DTT machine)

- Control and monitoring devices shall have an adequate response time on safety grounds, consistent with the measurement function [Annex I of PED]
- The inter-shell pressure in the primary loop of the vacuum vessel is controlled by a pressurizer connected to the inlet ring of the PHTS through the surge line
- The thermal energy of the VV inter-shell will decrease during machine operations and the fluid temperature and pressure (due to pressure drops and the hydraulic head) will diminish passing from the inlet ring to the outlet ring; conversely, heat is generated in a nuclear reactor and possible overpressures with two-phase fluid could be expected at the outlet ring as hot leg
- Then, the surge line for the VV will be connected to the inlet ring
- Moreover, vapour suppression tanks are not required in the PHTS connected to the vacuum vessel

Surge line connection and hydraulic heads of the pressurizer in the torus hall for the vacuum vessel



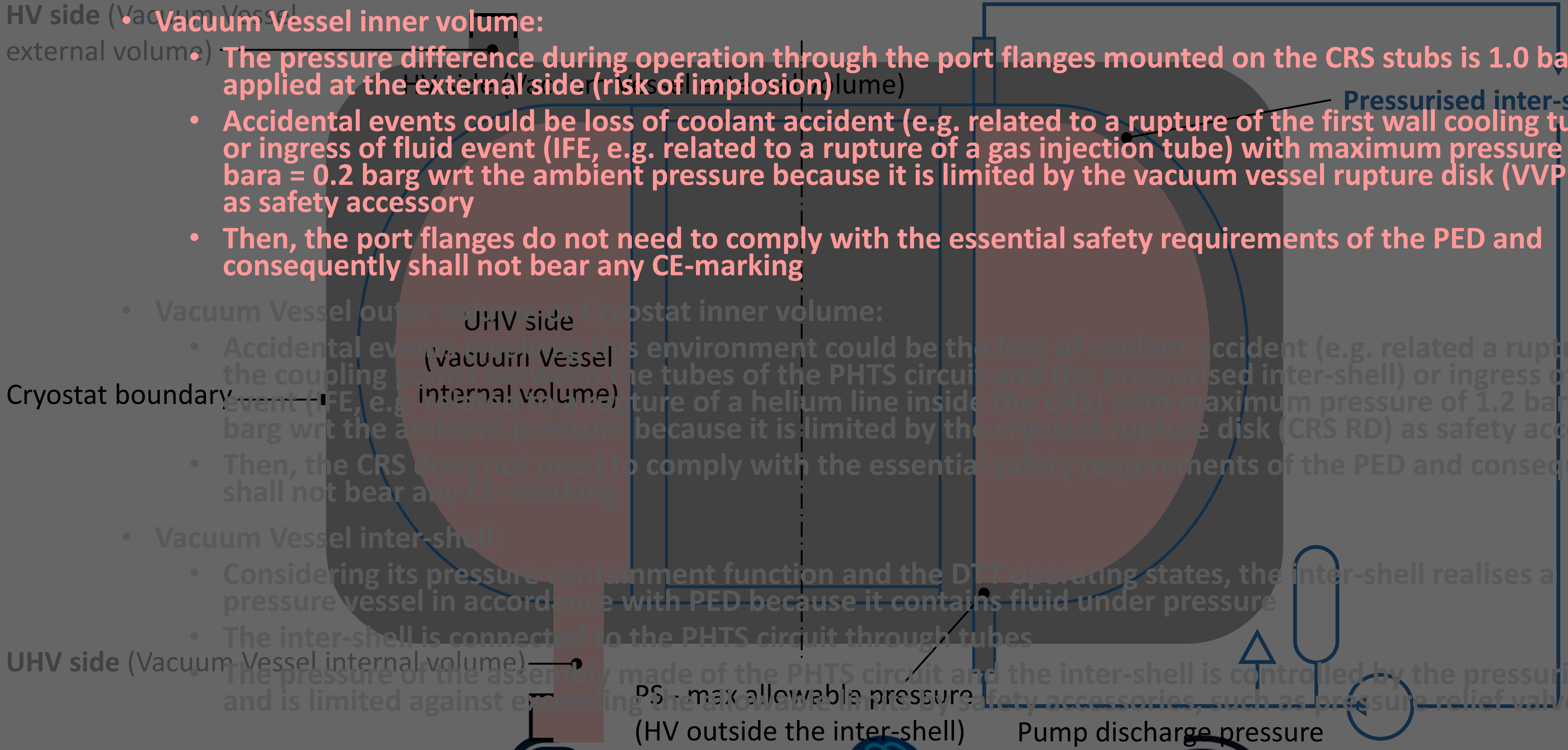
Safety accessories (DTT machine)

- Regarding safety accessories, the pressure limiting devices shall be designed that the pressure will not permanently exceed the maximum allowable pressure
- Momentary pressure surges shall be kept to 10 % of the maximum allowable pressure [Annex I of PED]
- The relief requirements of pressure relief valves and rupture disks are determined analysing the different scenarios that could generate overpressure in the VV and considering the form of energy input to the VV:
    1. heat input with pressure increase through vaporization or thermal expansion of the blocked-in fluid e.g. during baking
    2. direct pressure input from higher-pressure sources e.g. close outlets, transient pressure surges
    3. fire exposure considered as an extreme case of overpressure due to heat input
- The risk analysis for protection and safety of the DTT systems considers loss of coolant accident (LOCA), ingress of fluid (helium or water) event (IFE), and loss of vacuum accident (LOVA)

Parameters in boundaries and environments of the vacuum vessel 1/3

Parameters for the vacuum vessel operating states:

- Vacuum Vessel inner volume:
  - The pressure difference during operation through the port flanges mounted on the CRS stubs is 1.0 bar applied at the external side (risk of implosion)
  - Accidental events could be loss of coolant accident (e.g. related to a rupture of the first wall cooling tubes) or ingress of fluid event (IFE, e.g. related to a rupture of a gas injection tube) with maximum pressure of 1.2 bara = 0.2 barg wrt the ambient pressure because it is limited by the vacuum vessel rupture disk (VVP RD) as safety accessory
  - Then, the port flanges do not need to comply with the essential safety requirements of the PED and consequently shall not bear any CE-marking
- Vacuum Vessel outer volume = Cryostat inner volume:
  - Accidental events involving this environment could be the loss of coolant accident (e.g. related a rupture of the coupling points between the tubes of the PHTS circuit and the pressurised inter-shell) or ingress of fluid event (IFE, e.g. related to a rupture of a helium line inside the CRS) with maximum pressure of 1.2 bara = 0.2 barg wrt the ambient pressure because it is limited by the cryostat rupture disk (CRS RD) as safety accessory
  - Then, the CRS does not need to comply with the essential safety requirements of the PED and consequently shall not bear any CE-marking
- Vacuum Vessel inter-shell:
  - Considering its pressure containment function and the DTT operating states, the inter-shell realises a pressure vessel in accordance with PED because it contains fluid under pressure
  - The inter-shell is connected to the PHTS circuit through tubes
  - The pressure of the assembly made of the PHTS circuit and the inter-shell is controlled by the pressurizer and is limited against exceeding the allowable limits by safety accessories, such as pressure relief valves



Parameters in boundaries and environments of the vacuum vessel 2/3

Parameters for the vacuum vessel operating states:

- Vacuum Vessel inner volume:
  - The pressure difference during operation through the port flanges mounted on the CRS stubs is 1.0 bar applied at the ...
  - Accidental events could be loss of coolant accident (e.g. related to a rupture of the first wall cooling tubes) or ingress of fluid event (IFE, e.g. related to a rupture of a gas injection tube) with maximum pressure of 1.2 bara = 0.2 barg wrt the ambient pressure because it is limited by the vacuum vessel rupture disk (VVP RD) as safety accessory
  - Then, the port flanges do not need to comply with the essential safety requirements of the PED and consequently shall not bear any CE-marking
- **Vacuum Vessel outer volume or Cryostat inner volume:**
  - **Accidental events involving this environment could be the loss of coolant accident (e.g. related a rupture of the coupling points between the tubes of the PHTS circuit and the pressurised inter-shell) or ingress of fluid event (IFE, e.g. related to a rupture of a helium line inside the CRS) with maximum pressure of 1.2 bara = 0.2 barg wrt the ambient pressure because it is limited by the cryostat rupture disk (CRS RD) as safety accessory**
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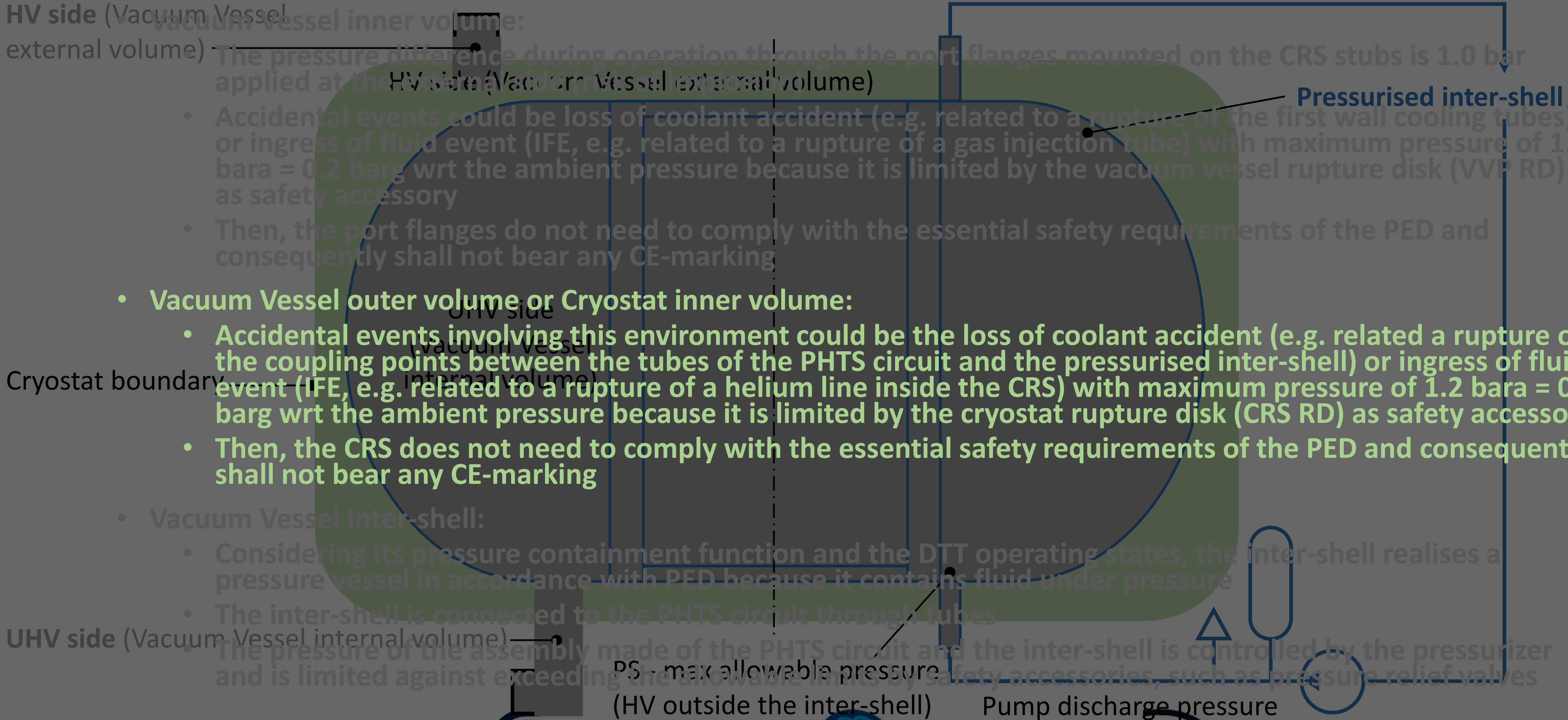

Parameters in boundaries and environments of the vacuum vessel 3/3

Parameters for the vacuum vessel operating states:

- Vacuum Vessel inner volume:
  - The pressure difference during operation through the port flanges mounted on the CRS stubs is 1.0 bar applied at the external side (risk of implosion)
  - Accidental events could be loss of coolant accident (e.g. related to a rupture of the first wall cooling tubes) or ingress of fluid event (IFE, e.g. related to a rupture of a gas injection tube) with maximum pressure of 1.2 bara = 0.2 barg wrt the ambient pressure because it is limited by the vacuum vessel rupture disk (VVP RD) as safety accessory
  - Then, the port flanges do not need to comply with the essential safety requirements of the PED and consequently shall not bear any CE-marking
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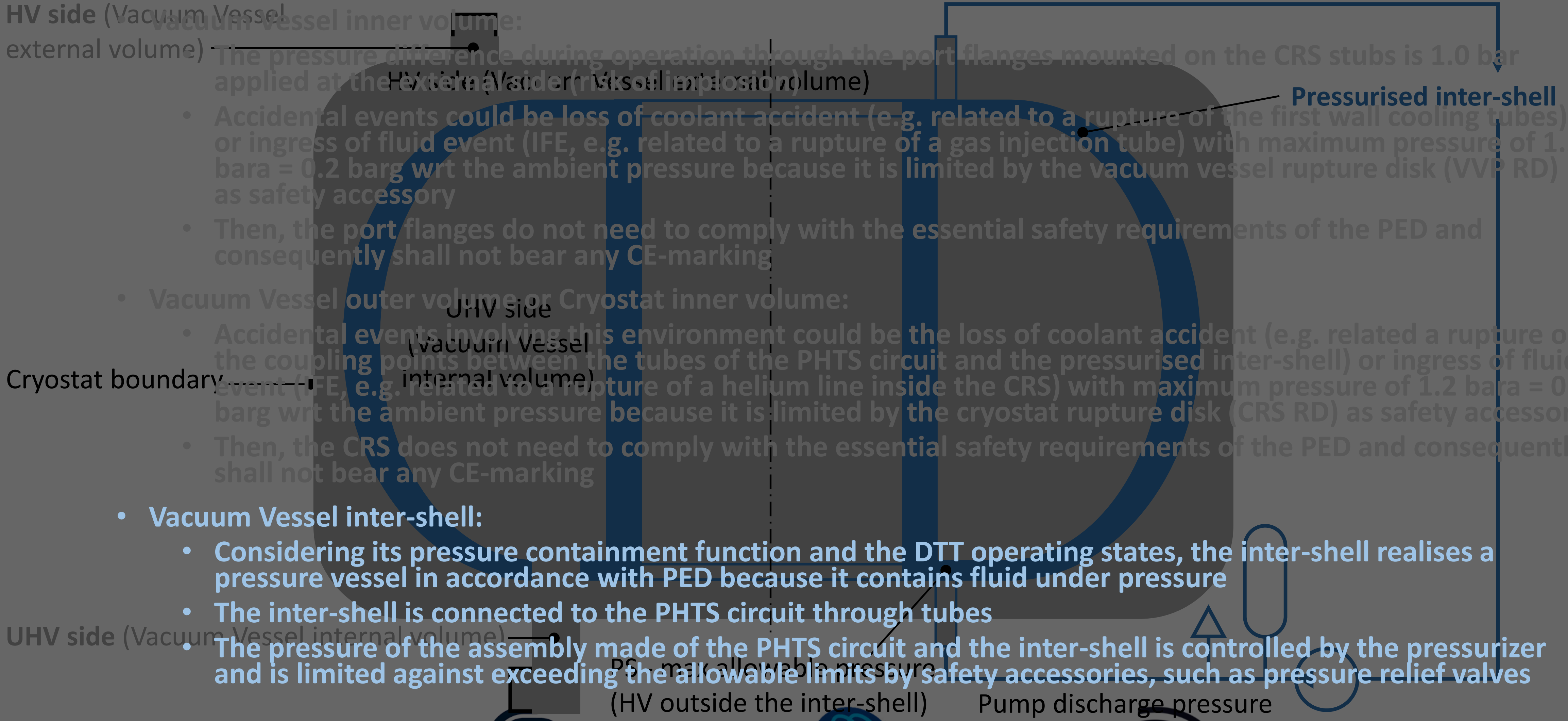


Operating states of the torus identified for the thermal and mechanical analyses of Vacuum Vessel 1/3

Tokamak state	Level	State description
Pulse-on, pulsed operation sequence (POS) with plasma	Level A (Normal and upset category conditions, operational/ likely loading)	The tokamak is operated in the pulse-on mode (POS) with plasma discharges. State description of OVC systems: VV is thermally conditioned by the water flowing through the inner and outer shells (POS values of flow rate, temperature, and pressure of water). The Thermal Shield (THS) is actively cooled with helium at its POS values of flow rate, temperature, and pressure of helium. CRS inner volume is vacuumed (POS pressure). State description of other interfaced systems: IVC are actively cooled with their POS values of flow rate, temperature, and pressure of water. MAG systems (TFC, PFC, and CS) are actively cooled with their POS values of flow rate, temperature, and pressure of helium.
Pulse-off, pulsed operation sequence (POF) without plasma	Level A (Normal and upset category conditions, operational/ likely loading)	The tokamak is operated in the pulse-off mode (POF) without plasma discharges. State description of OVC systems: VV is thermally conditioned with its POF=POS values of flow rate, temperature, and pressure of water. THS is actively cooled with its POF=POS values of flow rate, temperature, and pressure of helium. CRS inner volume is vacuumed (POF=POS pressure). State description of other interfaced systems: IVC are thermally conditioned with their POF=POS values of flow rate, temperature, and pressure of water. MAG systems (TFC, PFC, and CS) are actively cooled with their POF=POS values of flow rate, temperature, and pressure of helium.

Operating states of the torus identified for the thermal and mechanical analyses of Vacuum Vessel 2/3

Tokamak state	Level	State description
Pulse-off/on extended vessel temperature, pulsed operation (POX) with or without plasma and with inter-shell circulation within a temperature range	Level A (Normal and upset category conditions, operational/ likely loading)	The tokamak is operated in the pulse-off mode (POX=POF) with or without plasma discharges. State description of OVC systems: VV is thermally conditioned by the fluid flowing through the inner and outer shells (POF values of flow rate and pressure of water; extended fluid temperature within the POX range considering boric acid limits (20-80 °C) or 110 °C temperature limit given by the Pressure Equipment Directive). THS is actively cooled with its POX=POF values of flow rate, temperature, and pressure of helium. CRS inner volume is vacuumed (POX=POF pressure). State description of other interfaced systems: IVC are actively cooled with their POX=POF values of flow rate, temperature, and pressure of water. MAG systems (TFC, PFC, and CS) are actively cooled with their POX=POF values of flow rate, temperature, and pressure of helium.
Baking strong (SBAK) and baking light (LBAK)	Level A (Normal and upset category conditions, operational/ likely loading)	The tokamak is operated in the baking mode (SBAK/LBAK). State description of OVC systems: VV is circulated with fluid (SBAK/LBAK temperature) at the same pressure of water during pulse-on operation (SBAK/LBAK=POS pressure). Port ducts are internally heated with electrical heaters up to their SBAK/LBAK temperature. THS is actively cooled with its SBAK/LBAK=POF values of flow rate, temp., and pressure of helium. CRS inner volume is vacuumed (SBAK/LBAK=POS pressure). State description of other interfaced systems: IVC are thermally conditioned with their SBAK/LBAK values of flow rate, temp., and pressure of water. MAG systems (TFC, PFC, and CS) are actively cooled with their SBAK/LBAK=POF values of flow rate, temperature, and pressure of helium.

Operating states of the torus identified for the thermal and mechanical analyses of Vacuum Vessel 3/3

Tokamak state	Level	State description
POS with Toroidal Field Coil Fast Discharge (TFD), all coils*	Level A (Normal and upset category conditions, operational/ likely loading)	The TFD of all coils is assumed to occur with a discharge time on resistors of 5 s.
POS with Major Disruption (MD), slow*	Level A (Normal and upset category conditions, operational/ likely loading)	The considered MD, slow event is associated to the Single Null plasma scenario and is described by: • current quench duration: 40 ms; • thermal quench duration: around 0.5 ms; • halo factor (I_{halo}/I_{plasma}): around 0.1-0.2.
POS with seismic event "stato limite di operatività" (SLO)*	Level A (Normal and upset category conditions, operational/ likely loading)	The SLO earthquake is a seismic event with return period t_R=60 years producing acceleration spectra to be considered for the design analyses and for the structural integrity verification.
Manufacturing & integration	Testing	The PHTS circuits of the components are pneumatic pressure tested with pressure cycles of nitrogen before carrying out helium leak testing during manufacturing and integration (the pneumatic pressure testing is applied as a propaedeutic measure for detecting major early crack propagation before helium leak testing).

Combination of load cases for operational loadings

* Load cases of the operating states can be combined with POS producing the load combinations with level of service A:
  - POS + TFD, all coils + SLO (load case combination LC5e in DTT)
  - POS + MD slow + SLO (load case combination LC5f in DTT)
  - POS + TFD, all coils + MD slow (load case combination LC5l in DTT)
  - POS + TFD, all coils + MD slow + SLO (load case combination LC5m in DTT)

The **operational loadings** (level of service A) during the normal plasma condition

deriving from gravity, seismic, temperature, and electromagnetic (EM) events related to the plasma pulses

produce effects comparable with those of pressure in the VV inter-shell. Therefore, the VV cannot be excluded from the application of the PED

In view of this, the VV inter-shell can be recognised as a **pressure vessel** and the obligations of the PED apply

The maximum allowable pressure PS of the fluid is greater than 0.5 barg relative to atmospheric pressure (i.e. gauge pressure) so the PED is applied to the design before and during manufacture of the VV, as well as during assembly (on site welding of VV main shells) and integration (test for commissioning and putting into service)

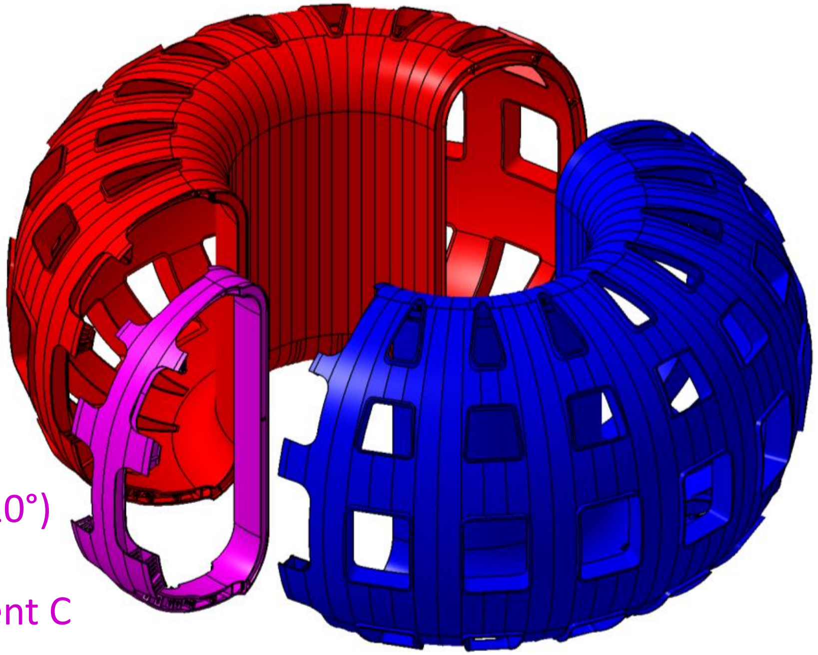
Pressure loading is therefore considered as a reference loading factor for the compliance of essential safety requirements

Conversely, this PED compliance does not apply to hazards and risks not due to pressure like during the emergency or faulted conditions in which the design verifications are evaluated for investment protection. These conditions will occur with unlikely and extremely unlikely loadings and are produced by severe EM events (plasma disruptions): other load case combinations with level of service C and D are expected by combining these load cases

Design parameters and pneumatic pressure test

Pressure equipment presenting a risk due to pressure

Multi-Sector B (170°)
↓
Pressure equipment B



Multi-Sector C (20°)
↓
Pressure equipment C

Multi-Sector A (170°)
↓
Pressure equipment A

Pressurised inter-shell (*operating parameters*)

liquid water:

P = 4 bar, T_{max} = 110 °C

gaseous nitrogen:

P = 2 bar, T_{max} = 200 °C

PED definitions (*design parameters*):

maximum allowable pressure PS = 4 bar

maximum allowable temperature TS = 240 °C

AISI 316LN: $R_{p0.2}$(20 °C) / $R_{p0.2}$(TS)

$$P_{test} = 1.15 \cdot \frac{Sm(T_{test})}{Sm(TS)} \cdot PS = 1.15 \cdot 1.33 \cdot 4.00 = 6.11 < 6.5\ bar$$

A pneumatic test will be used in lieu of the hydrostatic test because of the following two conditions applied to the components under consideration [PED]:

- the component cannot be safely filled with water
- traces of testing liquid cannot be tolerated in the component

The pneumatic test pressure shall be not less than the specified test pressure P_{test} as defined in Part 8.3 of ASME BPVC Sec. VIII Div. 2

A pneumatic pressure test of the integrated Vacuum Vessel will be carried out on DTT site with monitoring of the joints between Multi-Sectors

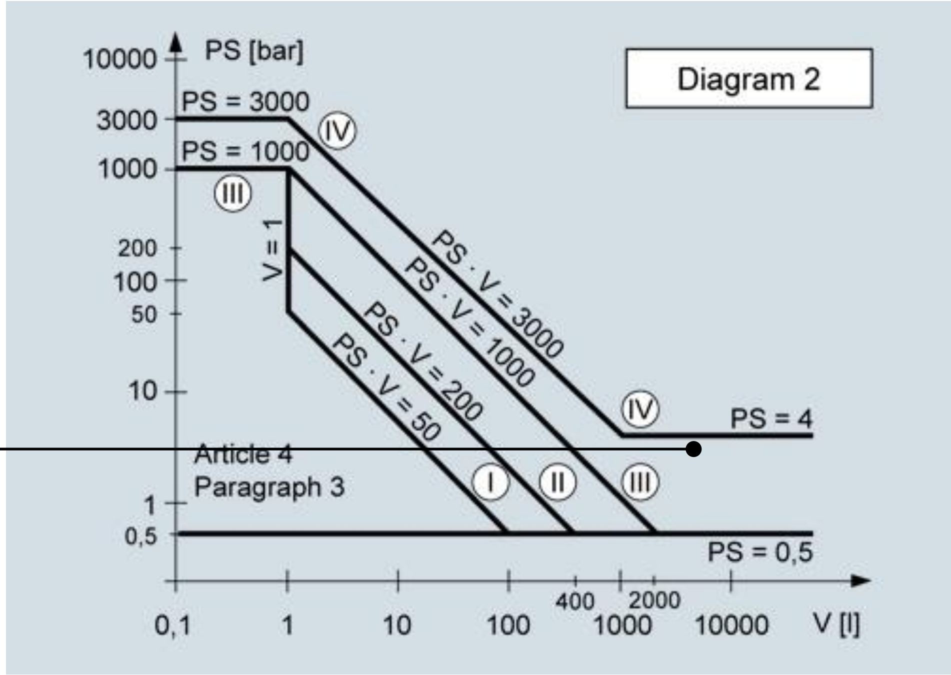
PED classification of the vacuum vessel (DTT machine)

Applicable regulation for inter-shell pressurisation (P > 0.5 bar): PED

PED classification for the inter-shell of a Multi-Sector:

- Gaseous fluid in Group 2 (not hazardous)
- PS = 4 bar
- Multi-Sector volume V = 6500 l

PED category III



(conformity assessment for piping is not detailed in this slide because maximum category for piping is III)

Application of the PED obligations

The resulting global classification is category III and then, applying as an example the Modules B (design type) + F, the manufacturer shall lodge an application, with a single notified body, which shall include:

- the technical documentation with:
    - hazard/risks analysis
    - a general description of the pressure equipment
    - conceptual design and manufacturing drawings and diagrams
    - results of design calculations made, examinations carried out, etc.
- information regarding the qualifications or approvals required for permanent joining and non-destructive tests
- the supporting evidence for the adequacy of the technical design solution

The Contractor committed in the procurement of the VV, in order to be in the position to assume the design as manufacturer of the VV, will receive from the Design Team the technical documentation. Moreover, the manufacturer shall operate with the surveillance of a notified body which control the compliance with the Essential Safety Requirement of the Directive. The notified body:

- checks the risk analysis (hazard analysis)
- checks the design (calculation note, plans…)
- performs stage inspection during manufacture
- monitors final inspection and test
- approves welding procedures and welder qualifications
- approves NDE personnel
- approves materials

All these activities have been addressed in the risk register of the vacuum vessel

PED as a legislative framework on European level for the VV

- In order to assure the product's quality in particular during the manufacturing process and its monitoring, non-destructive examinations (NDE) have been specified for the raw material procurement and during fabrication including welding in order to anticipate any issue, analyse root causes of evidences, and prevent nonconformities. Then, NDE ensures that the final quality matches the specifications of design and regulation requirements and that the product is fit for the service environments it will operate in
- Then, the PED provides for an already defined and an adequate legislative framework on European level for the VV that is subjected to a pressure hazard **without the need to develop a new set of rules based on specific justifications**
- The ASME Boiler & Pressure Vessel Code, VIII Rules for construction of pressure vessels, Division 2 Alternative rules has been used as the basis and reference for technical regulations, in particular for NDE

Gradual application of the PED obligations to the Vacuum Vessel

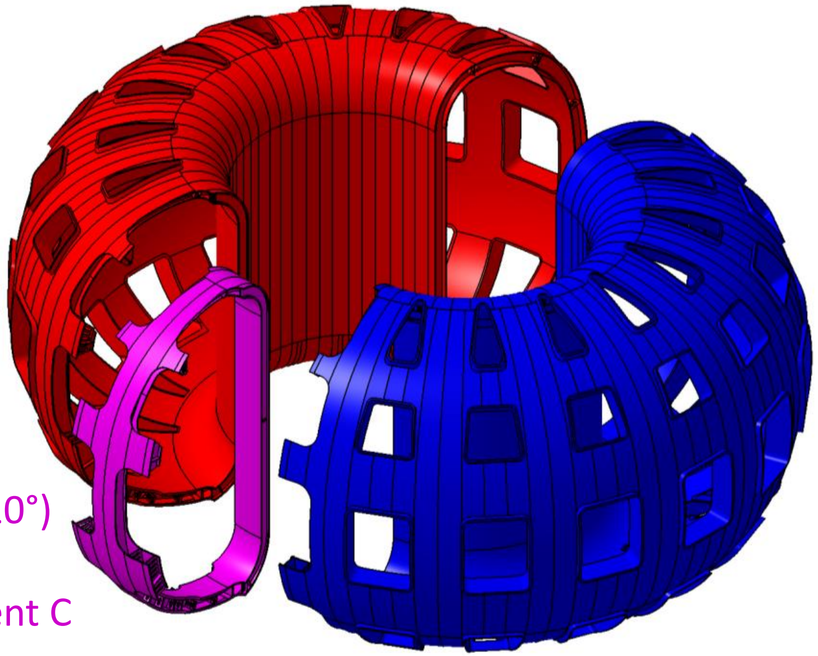
Certification steps are identified with the National institute for accidents at work:

1 Manufacturer of the vacuum vessel: NDE + pressure test + CE marking of each multi-sector

2 Integrator of the vacuum vessel: NDE + pressure test + CE marking of the vacuum vessel

3 National Institute for Insurance against Accidents at Work: putting into service of the vacuum vessel including protective devices with the cooling system

Multi-Sector B (170°)
↓
Pressure equipment B



Multi-Sector C (20°)
↓
Pressure equipment C

Multi-Sector A (170°)
↓
Pressure equipment A

The step sequence regarding the fulfilment of the PED obligations during manufacturing, assembly, and integration has been developed considering only the accessibility requirements for the examination, e.g. the inspectability, of the welded joints at the VV main shells and those at the coupling points between the tubes of the PHTS circuit and the pressurised inter-shell

Indeed, the maintenability of the VV main shells is not required and any maintenance operation of the inter-shell will not be performed over the VV life

Certification steps of the Vacuum Vessel - step 1/3

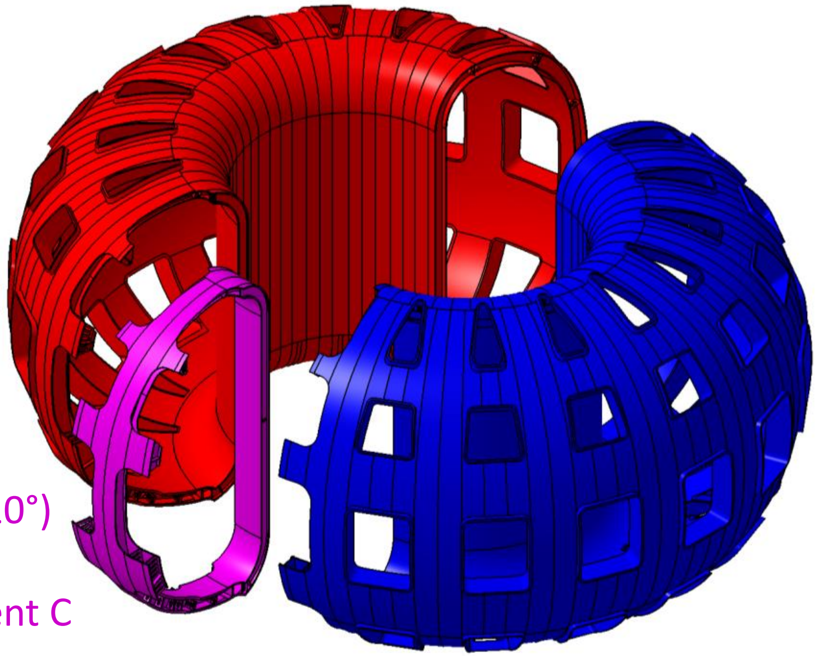
Certification steps are identified with the National institute for accidents at work:

1 Manufacturer of the vacuum vessel: NDE + pressure test + CE marking of each multi-sector

2 Integrator of the vacuum vessel: NDE + pressure test + CE marking of the vacuum vessel

3 National Institute for Insurance against Accidents at Work: putting into service of the vacuum vessel including protective devices with the cooling system

Multi-Sector B (170°)
↓
Pressure equipment B



Multi-Sector C (20°)
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Pressure equipment C

Multi-Sector A (170°)
↓
Pressure equipment A

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Indeed, the maintenability of the VV main shells is not required and any maintenance operation of the inter-shell will not be performed over the VV life

1. Activities that are required at the Contractor premises

Activities to be performed by the Contractor which is identified as the manufacturer of the individual Multi-Sectors as defined by the PED. The Contractor is responsible for carrying out the PED conformity assessment procedure to each individual Multi-Sector. These activities include:

a. non-destructive examination of the raw material needed for manufacturing the VV, in particular of the plates and sheets forming the main shells as required in sections 3.2 “Welding Requirements” and 3.10 “Delivery Conditions for Raw Materials” of the Technical Specification for the procurement of the DTT Vacuum Vessel

b. manufacturing of the VV Multi-Sectors including:
    i. welding of the plates and sheets to form the main shells and welding of the reinforcing ribs to form the inter-shell box structure
    ii. manufacturing of the VV nozzles as coupling points connecting the tubes of the PHTS circuit to the inter-shell volume

c. non-destructive examination of the welded joints on the main shells of each Multi-Sector during manufacturing as specified in the required Welding Map and Matrix of Weld Details because access to some welds will not be possible at advanced manufacturing stages

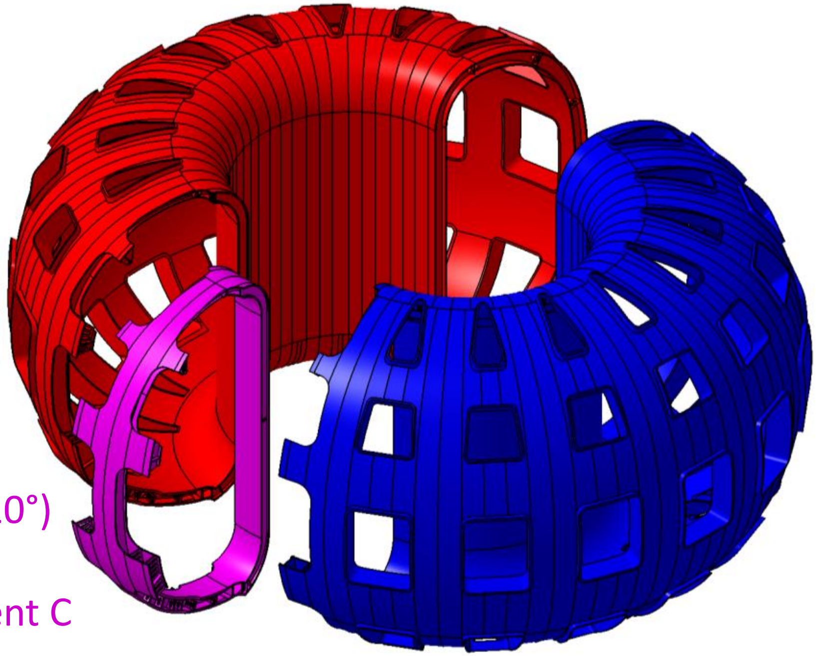
d. pressure test of the inter-shell of each Multi-Sector with accessible welded joints at the main shells for inspection

e. application of the PED obligations to each individual Multi-Sector (EU declaration of conformity and CE marking)

Certification steps of the Vacuum Vessel - step 2/3

Certification steps are identified with the National institute for accidents at work:

1. Manufacturer of the vacuum vessel: NDE + pressure test + CE marking of each multi-sector
2. Integrator of the vacuum vessel: NDE + pressure test + CE marking of the vacuum vessel
3. National Institute for Insurance against Accidents at Work: putting into service of the vacuum vessel including protective devices with the cooling system



Multi-Sector B (170°)
↓
Pressure equipment B

Multi-Sector C (20°)
↓
Pressure equipment C

Multi-Sector A (170°)
↓
Pressure equipment A

The step sequence regarding the fulfilment of the PED obligations during manufacturing, assembly, and integration has been developed considering only the accessibility requirements for the examination, e.g. the inspectability, of the welded joints at the VV main shells and those at the coupling points between the tubes of the PHTS circuit and the pressurised inter-shell

Indeed, the maintenability of the VV main shells is not required and any maintenance operation of the inter-shell will not be performed over the VV life

2. Activities foreseen during assembly of Multi-Sectors at site

Activities to be performed by the Assembler that is identified as the VV manufacturer (as defined by the PED) during assembling at the site. The Assembler is responsible for carrying out the PED conformity assessment procedure to the assembled VV, in particular regarding:

a. positioning of the Multi-Sectors A and B using 3D metrology
b. welding of the main shells between Multi-Sector A and Multi-Sector B to form an assembly
c. non-destructive examination of the welds made to join the main shells of Multi-Sector A with Multi-Sector B
d. pressure test of the inter-shell with accessible welded joints at the main shells between Multi-Sector A and Multi-Sector B for examination
e. mounting of the VV thermal shield onto the assembly made of Multi-Sectors A and B. The access for inspection of the outer shell of Multi-Sectors A and B will not be possible at the completion of this mounting operation
f. mounting of the toroidal field coils (TFCs) onto the assembly made of Multi-Sectors A and B
g. preparation of the assembly made of the Multi-Sector C, the VV thermal shield, and the corresponding TFC
h. positioning of the assembly prepared as for point f. above between Multi-Sectors A and B using 3D metrology. The back side of the main shells of the Multi-Sector C will be inaccessible after this mounting operation, then single-side inspection will be performed
i. welding of the main shells to assembly the Multi-Sector C with the assembly made of Multi-Sectors A and B
j. non-destructive examination of the welds made to join the main shells between Multi-Sector C and the assembly made of Multi-Sectors A and B (single-side inspection)
k. pressure test of the inter-shell with accessible welded joints at the inner shell between Multi-Sector C and the assembly made of Multi-Sectors A and B for examination
l. application of the PED obligations to the assembly made of Multi-Sectors A, B, and C (EU declaration of conformity and CE marking

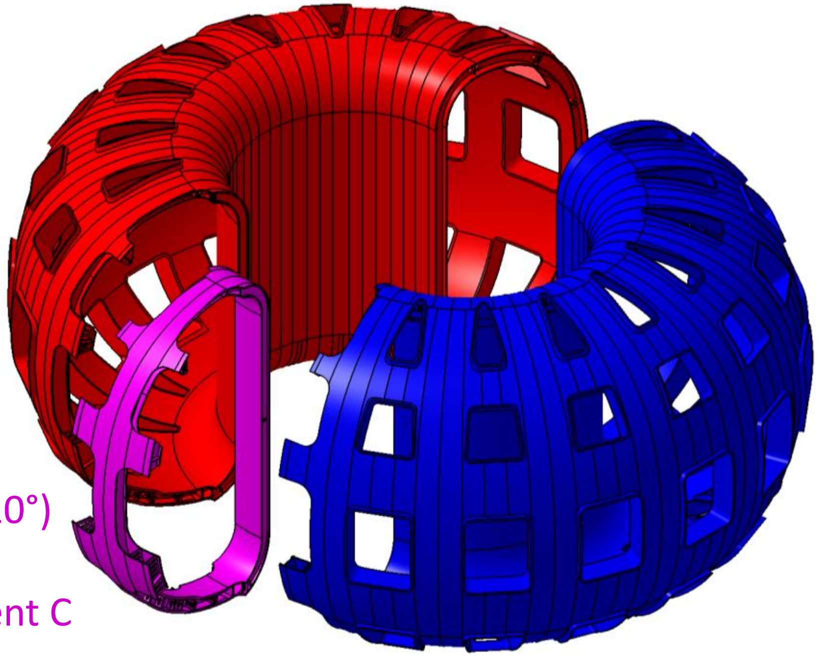
Certification steps of the Vacuum Vessel - step 3/3

Certification steps are identified with the National institute for accidents at work:

1 Manufacturer of the vacuum vessel: NDE + pressure test + CE marking of each multi-sector

2 Integrator of the vacuum vessel: NDE + pressure test + CE marking of the vacuum vessel

3 National Institute for Insurance against Accidents at Work: putting into service of the vacuum vessel including protective devices with the cooling system



The step sequence regarding the fulfilment of the PED obligations during manufacturing, assembly, and integration has been developed considering only the accessibility requirements for the examination, e.g. the inspectability, of the welded joints at the VV main shells and those at the coupling points between the tubes of the PHTS circuit and the pressurised inter-shell

Indeed, the maintenability of the VV main shells is not required and any maintenance operation of the inter-shell will not be performed over the VV life

3. Activities that are foreseen to perform the integration at site

Test for commissioning and putting into service of the VV once the assembly operations of the DTT components are completed. These activities will be performed under the supervision and the responsibility of the National Institute for Insurance against Accidents at Work as Integrator and they consist mainly of:

a. checking everything associated with the VV, including verification of the integration of the VV with the PHTS circuit into the pressure system after assembly of the DTT components

b. commissioning as testing process of the complete design of the pressure equipment: simulation of operating states for all items with testing of all possible events, accounting of all methods of failure. In particular, protective devices, such as pressure relief valves, will be tested against exceeding the allowable limits of pressure

c. putting into service the VV integrated with the PHTS circuit including the pressurisation system

B. Vacuum Vessel interdisciplinary design

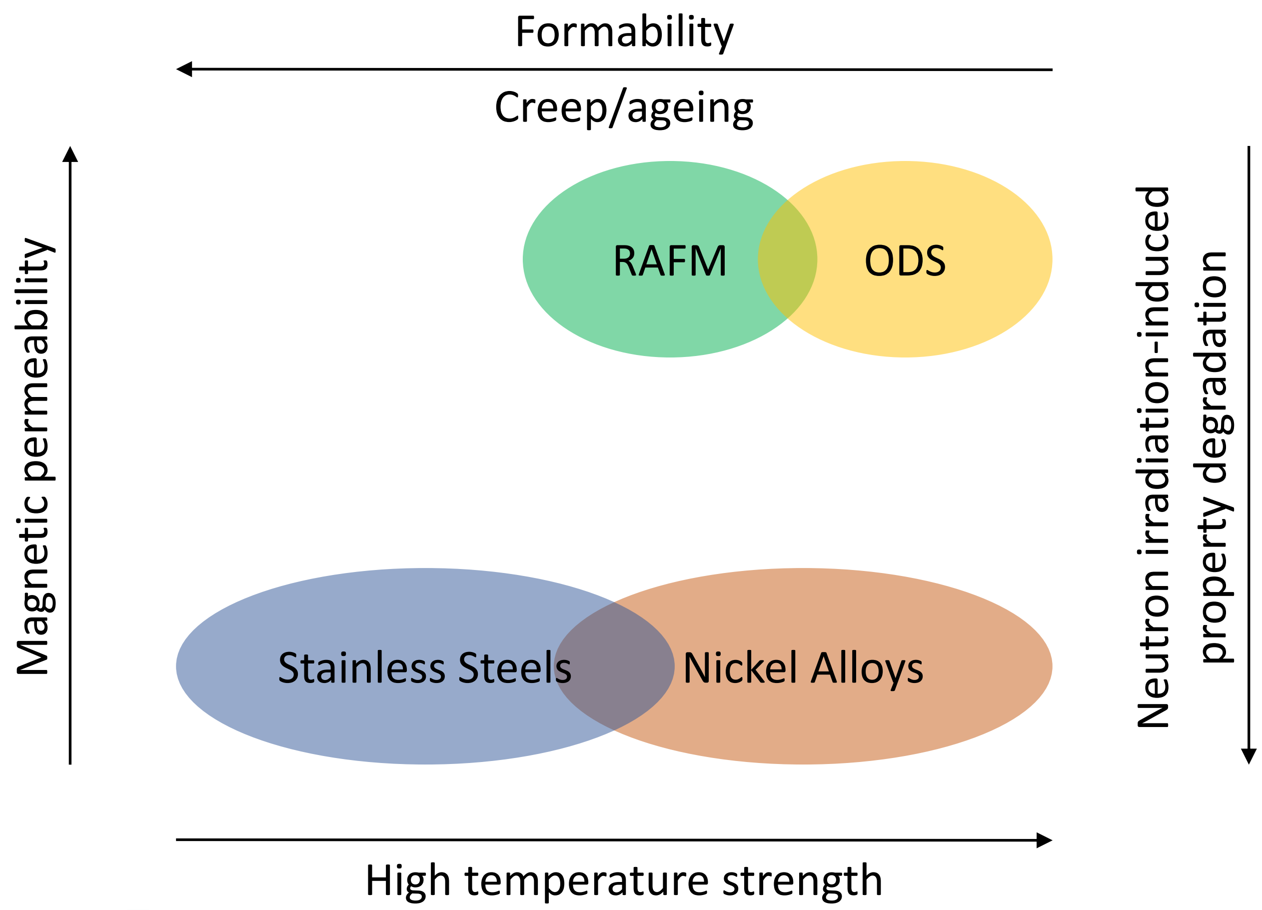
Peculiarities of tokamak mechanical structures

1. Performance and physics requirements coming from plasma magneto-hydrodynamics/particle transport
2. Interdisciplinary design:
   - material science and engineering
   - electromagnetic
   - thermo-hydraulic
   - structural
   - irradiation-inducted swelling (neutron irradiation-induced property degradation)
   - erosion-corrosion
   - sputtering
   - vacuum technology and compatibility with ultra-high vacuum (UHV)
   - plant integration and assembly
   - remote handling
   - engineering drawing
   - manufacturing technology
3. One of a kind and complex components: even if a iterative process is applied, specific lessons learned are acknowledged once the component has already been designed/made

Structural material selection

- RAFM: Reduced Activation Ferritic-Martensitic steels (e.g. F82H, EUROFER)
- ODS: Oxide Dispersion Strengthened RAFM

Need of further advanced steel R&D [S.J. Zinkle et al 2017 Nucl. Fusion 57 092005]



Design requirements - magnetic configurations 1/2

Among all possible plasma scenarios that will be tested in DTT, SN configuration is expected to be the most severe (5.5 MA) for the vacuum vessel (VV) structural integrity, even if a comparison between SN and XD shows a comparable global force on VV

Abbreviation	Configuration	Plasma current [MA]
SN	Single Null (reference)	5.5
XD	X-Divertor	4.5
NT	Negative Triangularity	4.0
DN	Double Null	5.0

Electromagnetic events analysed for the DTT facility:

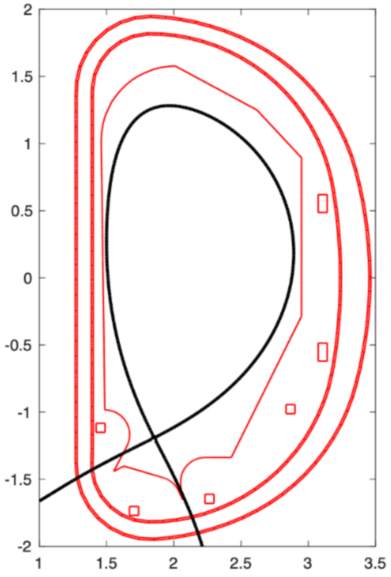
- Vertical Displacement Events (upward/downward, slow/fast)
- Major Disruptions
- Fast Discharge of all Toroidal field coils

Design requirements - magnetic configurations 2/2

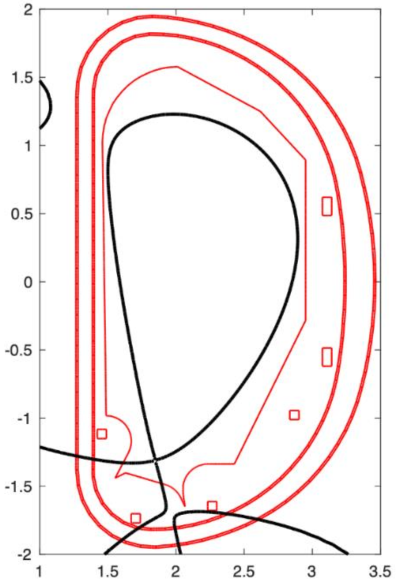
DTT magnetic configurations – First divertor

For the design of the first divertor only a subset of the alternative configurations has been considered: SN, XD and (at low priority) NT

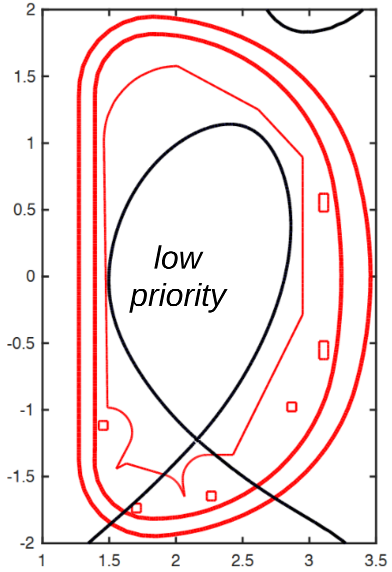
Reference Single Null I_{pl}=5.5 MA



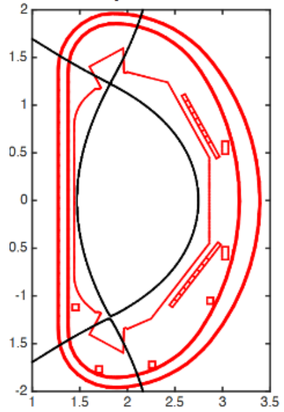
X-Divertor I_{pl}=4.5 MA



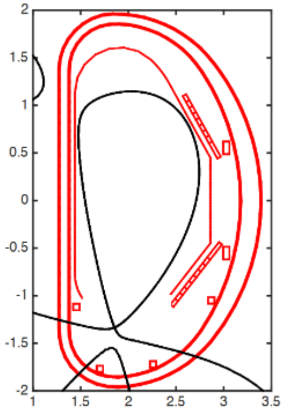
Neg. Triangularity I_{pl}=4 MA



Double Null I_{pl}=5 MA



Snowflake I_{pl}=4.5MA



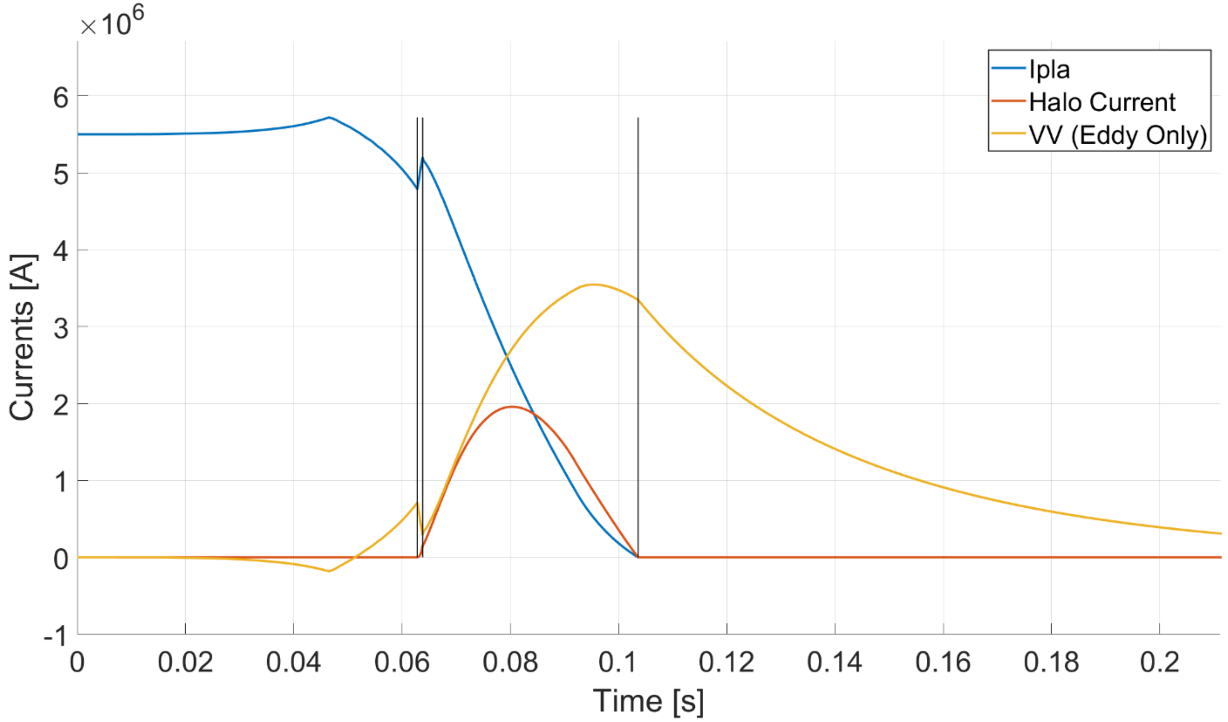
Possible future DTT configurations/divertors

Analyses - paths of halo currents (upward VDE) 1/2

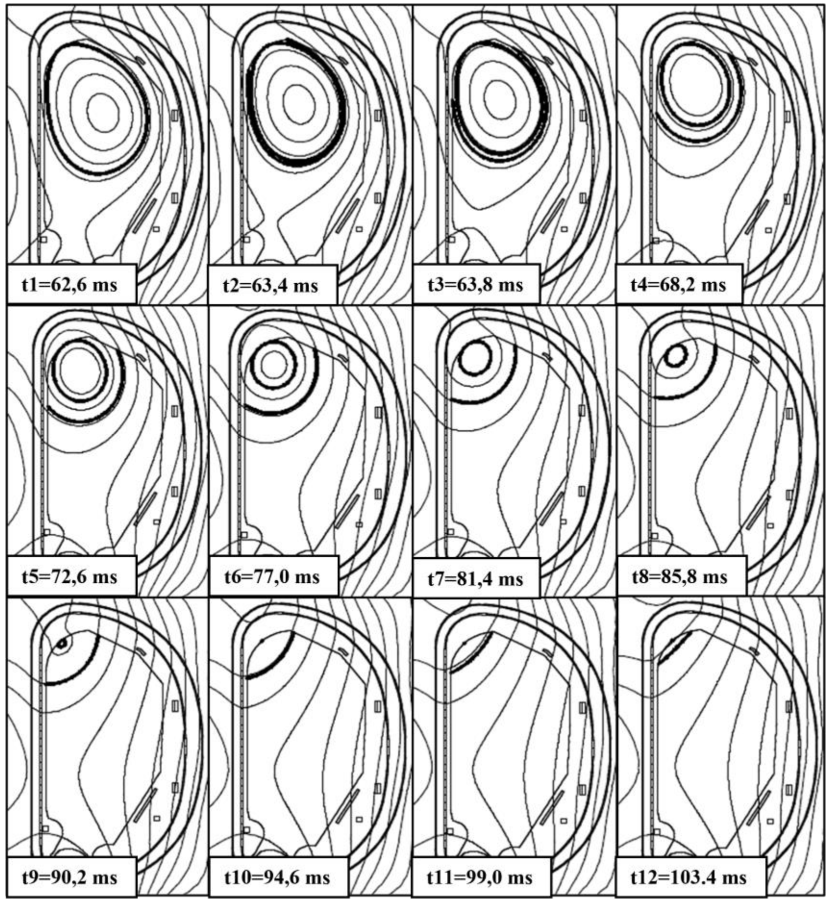
Simulations of plasma events using MAXFEA, CARMA0NL

Results are the time evolution of currents (plasma, halo, vessel eddy)

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



[F. Giorgetti, R. Lombroni, et al, 2022 Fus. Eng. Des. 184 113273]
[S.L. Chen, F. Villone, et al, 2019 Nucl. Fusion 59 106039]

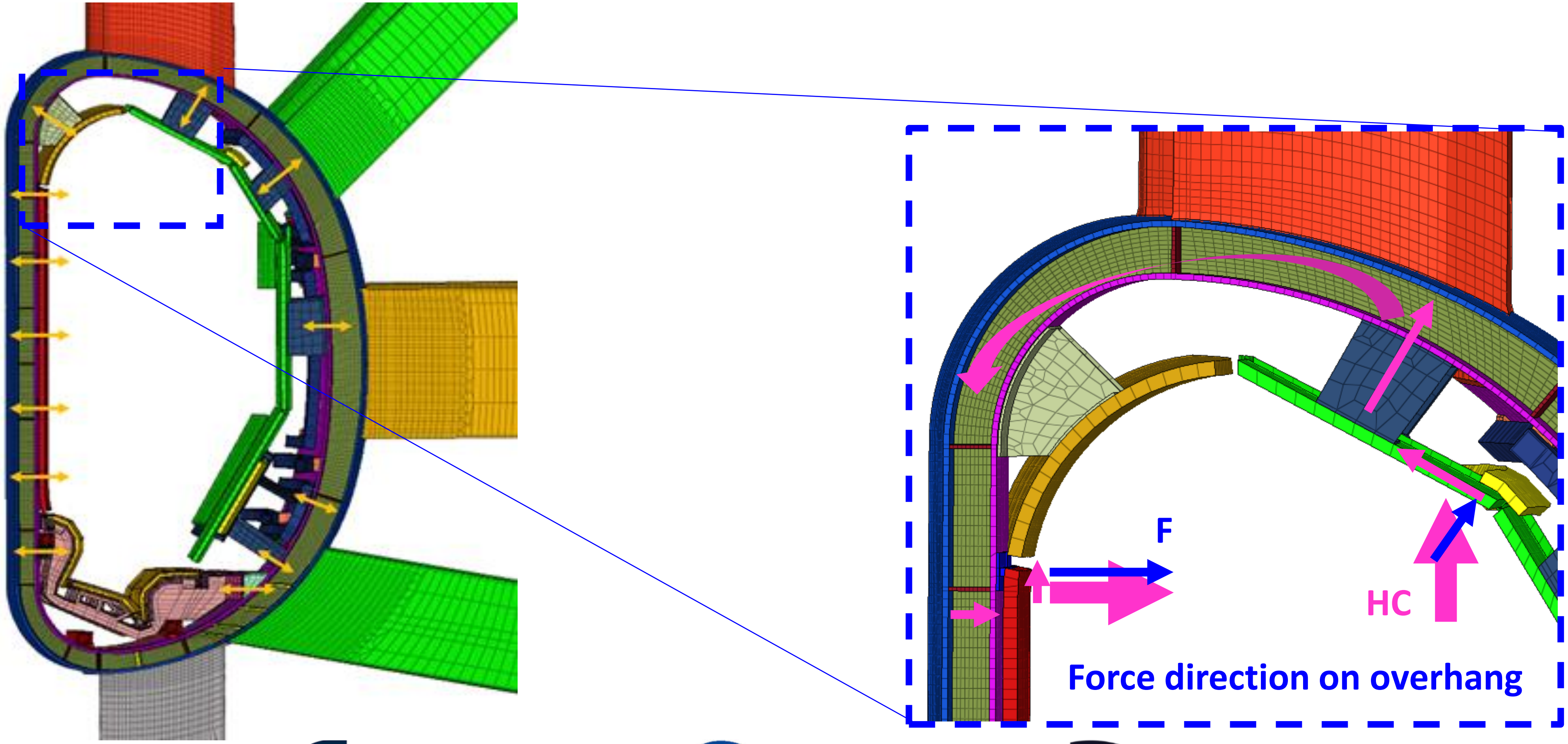


Shape evolution of the simulated event with positions of plasma boundary approaching the surfaces of in-vessel components

Analyses - paths of halo currents (upward VDE) 2/2

Priority 1, UVDE slow/fast:

Halo Current (HC) circulating in the vacuum vessel with longer path (for both slow and fast events)
→ significant scenario with forces (F) for the verification of vacuum vessel and inner-outer first wall (FW)



C. Structural integrity verifications

Analyses - load combinations

#	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		X
LC5i	MD fast + TFD, all coils + Earthquake	C	1		
LC5j	VDE fast, downward + TFD, all coils + Earthquake	C	1		X
LC5k	VDE slow, downward + TFD, all coils + Earthquake	C	1		X
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		X
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:

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.

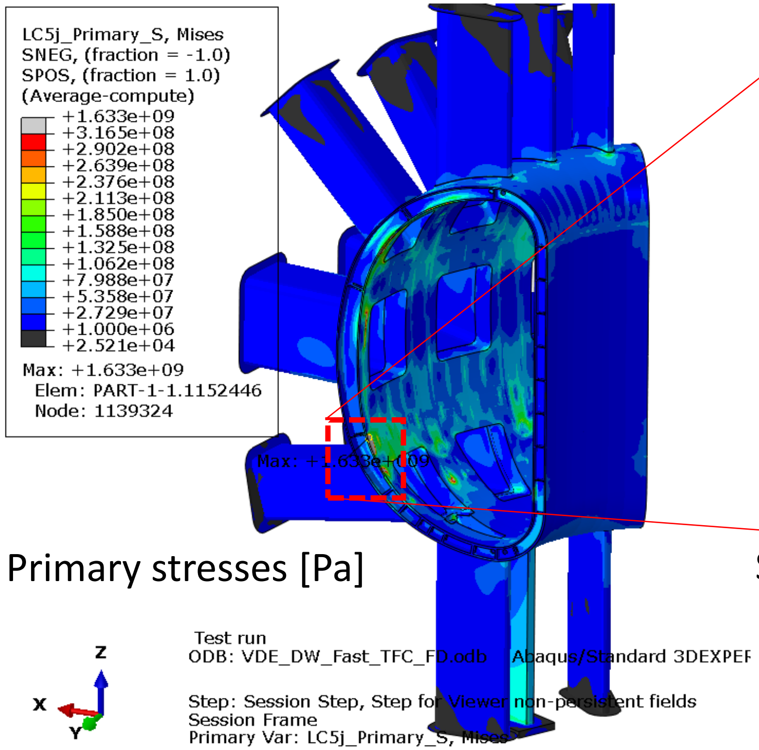
Events occurring a few times in the life of a machine correspond to unlikely events with very low probability of occurrence, corresponding to category III that must be verified for a service level C (lower safety factor).

Structural analysis & verification

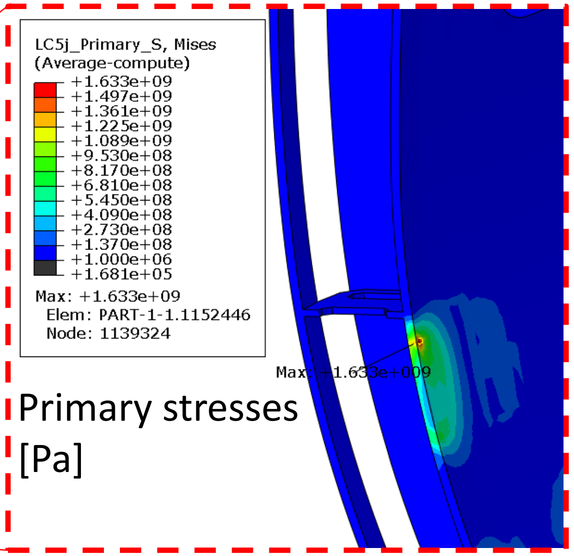
Post-processing of displacements for the design specification of port bellows (interface between vessel and cryostat):

- Baking displacements: results of baking operating state
- VDE & MD displacements: results of FE analyses
- Seismic displacements simulating both vessel and cryostat.

EM → structural integrity verification: service level C for load combination VDE fast, downward + TFD, all coils + Earthquake (LC5j), full scale set to 1.5Sm:

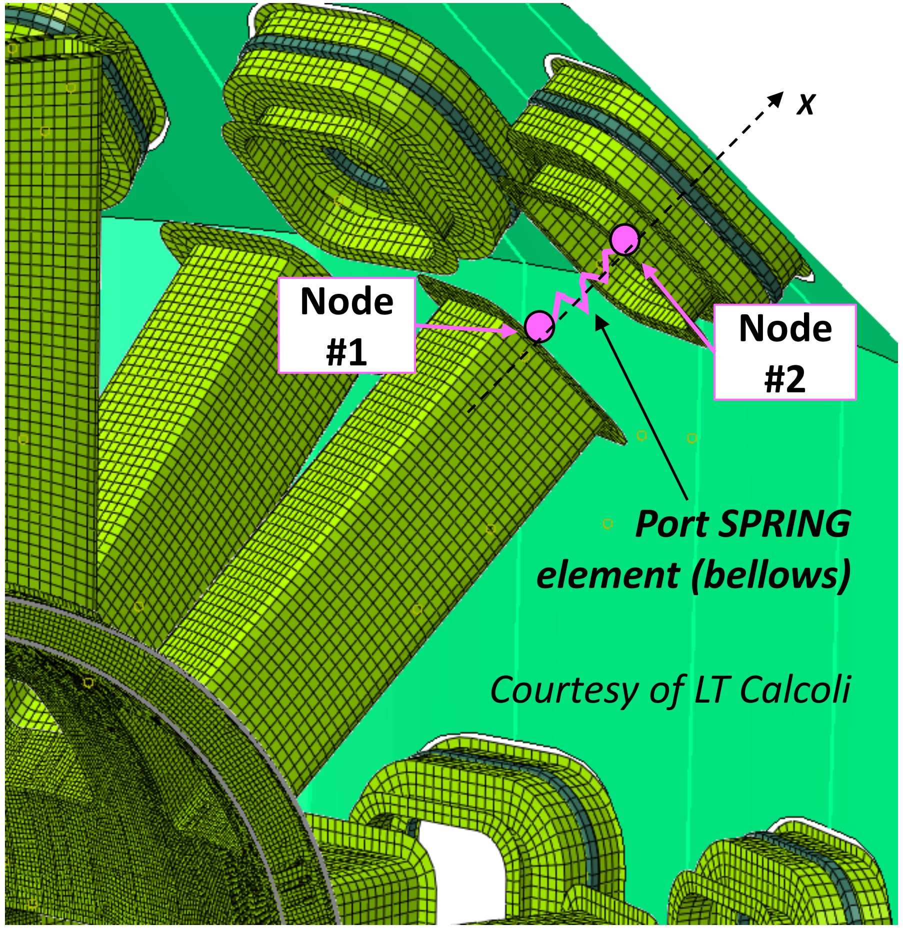


Primary stresses [Pa]



Primary stresses [Pa]

Structural verifications for LC5j passed, apart local stresses at FW supports requiring further investigations



Mechanical design and verification

- A specific code should be used for components subjected to interdisciplinary design of:
  - Vacuum vessel
  - In-vessel components
- Fusion related codes have been developed and they attained a high maturity level to be used for the design of ITER and other experiments. Main features included are:
  - Criteria levels consistent with ASME III and RCC-MRx to verify complex load combinations with occurrence on probabilistic base and loads produced also by the interaction with electromagnetic fields
  - Specific design Rules for:
    - Creep-fatigue combination
    - Irradiation-induced swelling
    - Welded/Brazed joints
    - Bolted joints
    - Multilayer Heterogeneous Structures
- Non-linear material behaviour (e.g. Ramberg-Osgood) for monotonic and cyclic verification can be used to exploit the material properties in local regions where severe loading conditions are applied

D. Design for manufacturing

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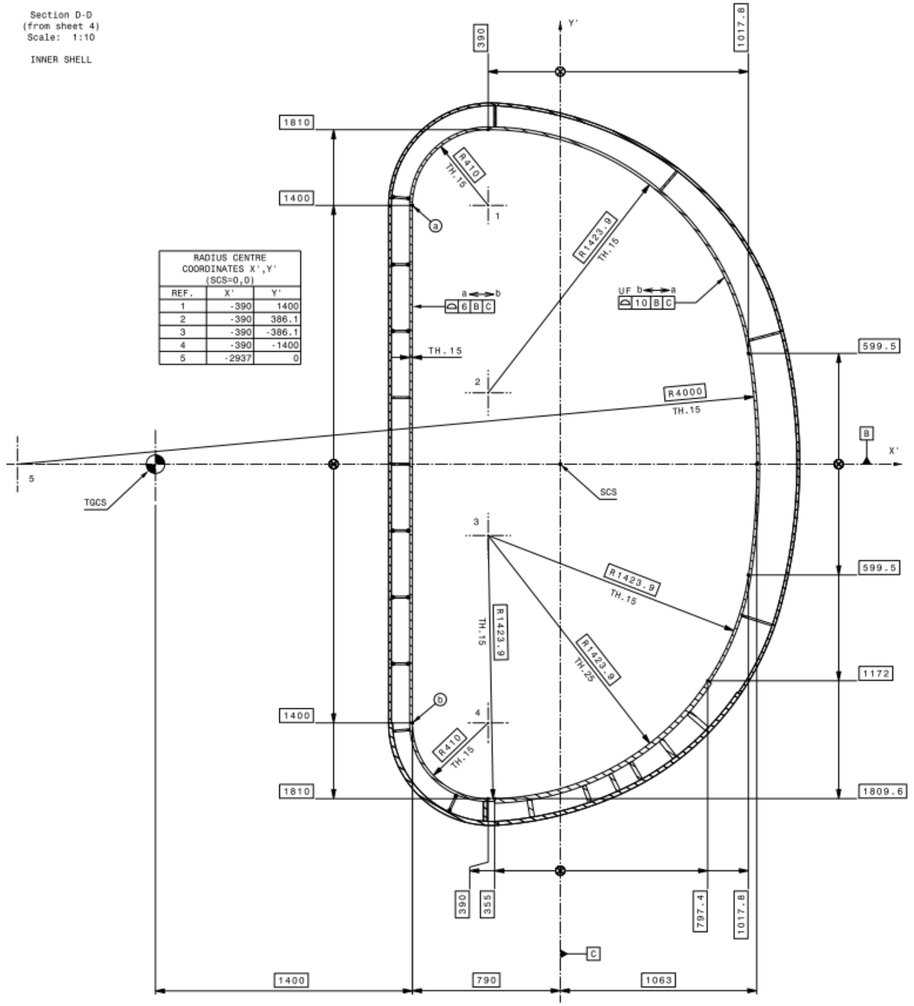
Tolerancing and Metrology

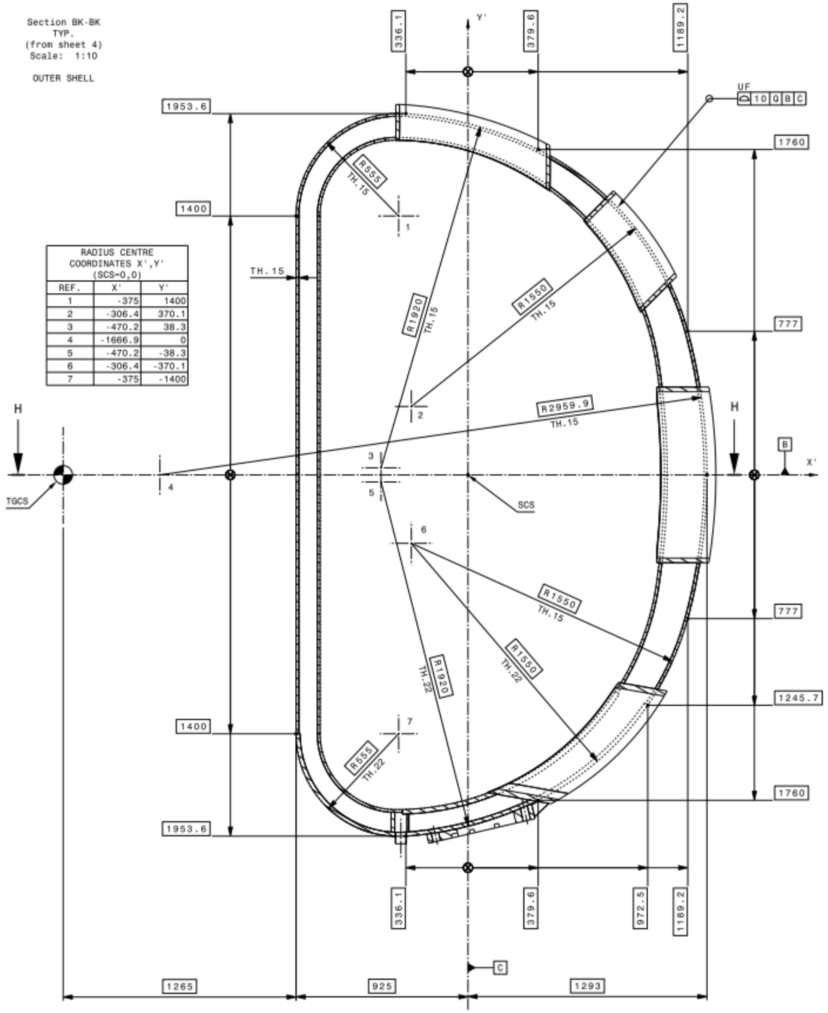
Design:

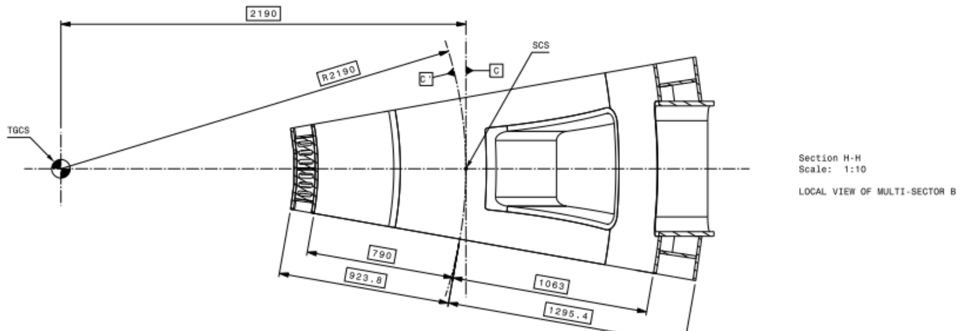
- Definition of feasible tolerances for machined parts and for welded structures (additive manufacturing?)
- Introduction of compensation members in the dimensional chain to fit functional tolerances with manufacturing errors and possible nonconformities
- DATUM definition:
  - dimensional inspections with 3D metrology extraction and recording of fiducial coordinates
  - verification of the DATUM repeatability
- Definition of specific Geometric Dimensioning & Tolerancing on features to be checked:
  - linear/angular dimensions, localization, shape (and other geometrical) with ref. to datums
- Virtual assembly simulation in order to:
  - define target coordinates of the fiducials
  - verify the compliance with the required dimensional and geometrical tolerances

Manufacturing:

- Dimensional inspections should be performed during the thorough manufacturing process with intermediate inspection and high frequency to anticipate any issue and to prevent nonconformities
- Application of the virtual assembly simulation before, during, and after welding with uniform distribution of fiducials







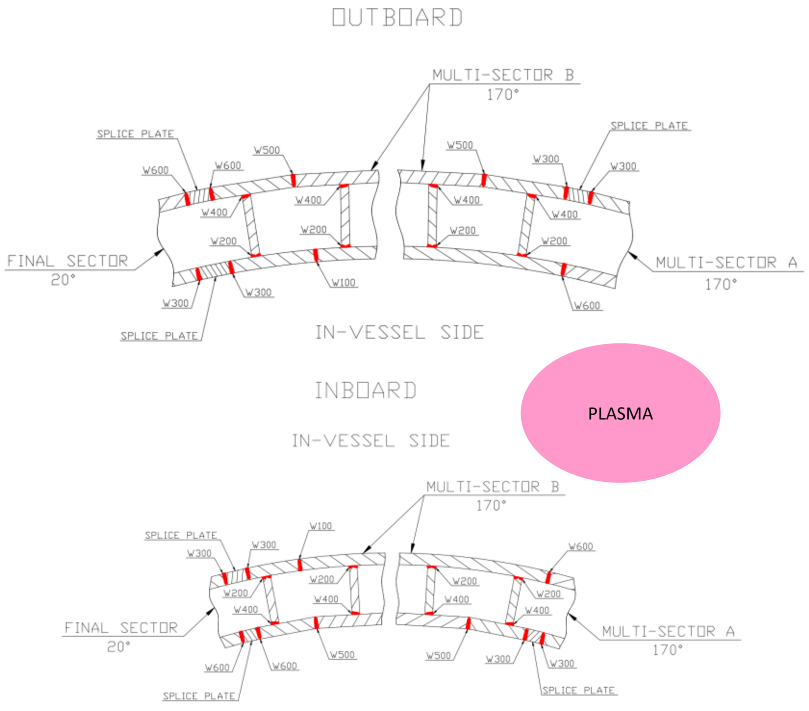
Manufacturing drawing of the DTT vacuum vessel

Welded joints at the inter-shell

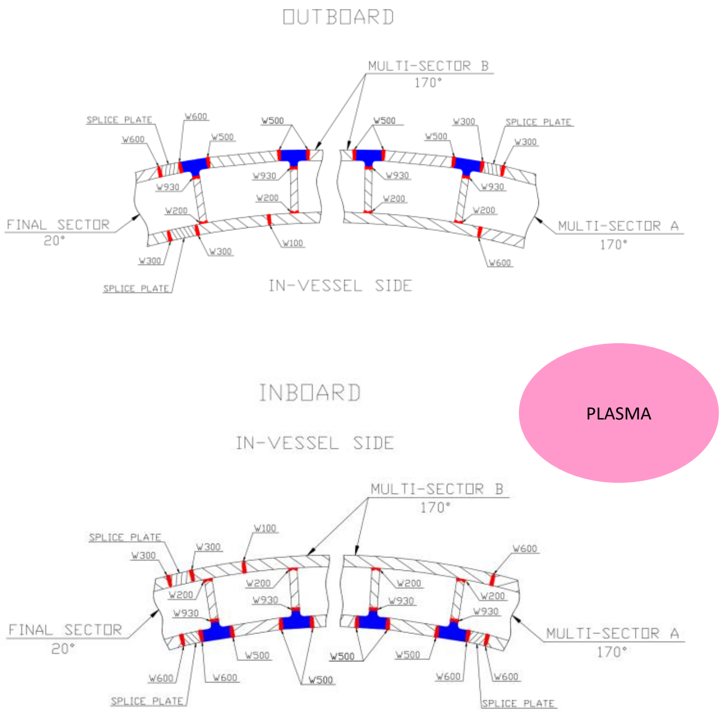
Types of welded joints to address a sound construction consistently with:

- the machine requirements and life duration
- the design and construction code (e.g. ASME)

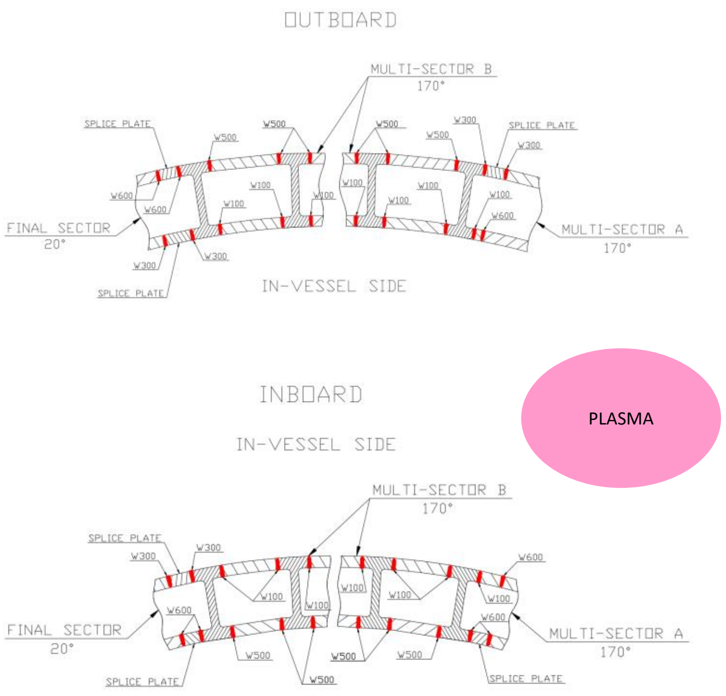
Proposal 1



Proposal 2



Proposal 3

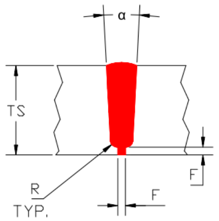


Welding map and non destructive examination

Example about the DTT vacuum vessel:

Application of the technical specification requirements to full penetration butt welds of longitudinal/circumferential joints at the inner shell

Weld Matrix proposed to the Contractor as reference, but not as applicable/mandatory document

Weld detail								Weld process				Weld testing			Note
Ref.	Weld joint sketch	T1 [mm]	T2 [mm]	Type of joint [RCC-MRx RC3800]	Base material	Edge preparation	Drawing	Weld mode	Process number [ISO 4063]	Filler metal	Weld cap removal	Type	Extent	Acceptance level	
W100		15-25	15-25	I.2 butt welding, full penetration, two sides accessible, gaseous back protection	EN 1.4406 or EN 1.4429	single-U groove	inner shell	001 manual	141 (TIG) root layer	Bare electrodes or rods of ER316LMn (AWS 5.9 Class ER316LMn, ASME SFA 5.9 Class ER316LMn, UNS S31682, EN 1.4455 A#9 F#6)	everywhere	VT	100%	level B [EN ISO 5817] [EN ISO 17637]	
												LT	qualification	B.2.1 [EN ISO 20485] [ASTM E1603]	
												PT (back side)	100%	level 1 [EN ISO 5817, ISO 23277]	leak detection
									(process compatible with volumetric inspection) overlay layers			VT	100%	level B [EN ISO 5817] [EN ISO 17637]	
												RT	100%	level 1 [EN ISO 10675-1] level B [EN ISO 5817, ISO 17636-1, ISO 17636-2]	consistent with E=1: joint efficiency in ASME VIII-2, Table 7.2; joint coefficient (n) in RCC-MRx
												PT (weld side)	100%	level 1 [EN ISO 5817, ISO 23277]	leak detection
												magnetic permeability	100%	$\mu_r \leq 1.05 - 1.10$	

Design and manufacturing code (DTT machine)

Technical requirements:

1. Design and manufacturing code: no nuclear safety req. → ASME Boiler and Pressure Code (BPVC), Section VIII, Division 2
2. Thermo-nuclear fusion requirements:
   i. Vacuum compatibility requirements (leak detection + cleanliness)
   ii. Electro-magnetic permeability requirements (possible impact on filler metal and welding processes)

Manufacturing and testing:

A. Types of welded joints (e.g. full penetration butt joints for longitudinal and circumferential welds within the main shell)
B. Types and extension of non-destructive examinations (NDE):
   i. RT or UT: extent = 100% → *E* = 1.0 or extent = 10% → *E* = 0.85 (*E* is the weld joint efficiency in accordance with ASME BPVC)
   ii. PT on the surface opposite to UHV for cracks, porosity, leaks
   iii. VT, LT, magnetic permeability

Figure 4.2.1
Weld Joint Locations Typical of categories A, B, C, D, and E

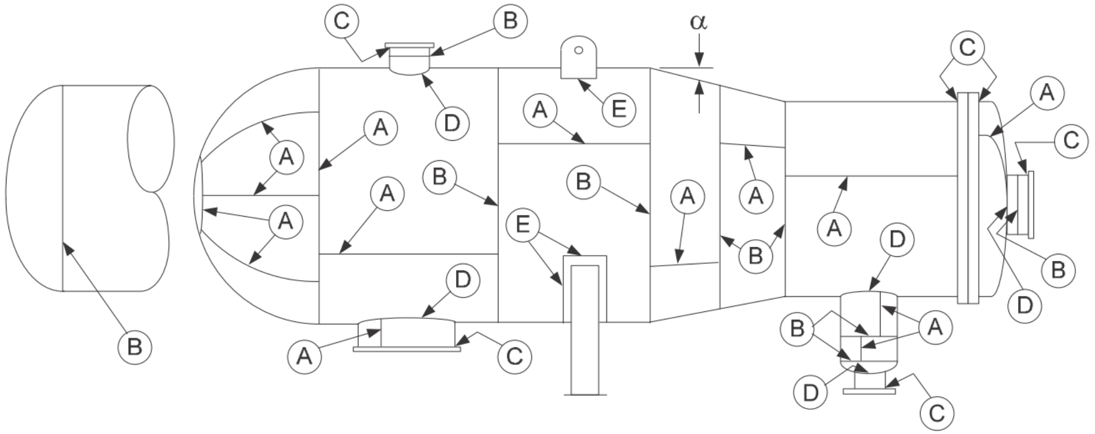


Table 7.2
Nondestructive Examination

Examination Group					1a	1b	2a	2b	3a	3b
Permitted Materials					All Materials in Annex 3-A [Note (18)]	P-No. 1 Gr 1 and 2 P-No. 8 Gr 1	P-No. 8 Gr 2 P-No. 9A Gr 1 P-No. 9B Gr 1 P-No. 11A Gr 1 P-No. 11A Gr 2 P-No. 10H Gr 1	P-No. 1 Gr 1 and 2 P-No. 8 Gr 1	P-No. 8 Gr 2 P-No. 9A Gr 1 P-No. 9B Gr 1 P-No. 10H Gr 1	P-No. 1 Gr 1 and 2 P-No. 8 Gr 1
Weld Joint Efficiency					1.0	1.0	1.0	1.0	0.85	0.85
Joint Category	Type of Weld [Note (1)]			Type of NDE [Note (2)]	Extent of NDE [Note (10)] [Note (11)] [Note (12)]					
A	Full penetration butt weld [Note (19)]	1	Longitudinal joints	RT or UT	100%	100%	100%	100%	25%	10%
				MT or PT	10%	10% [Note (4)]	10%	10% [Note (4)]	10%	10% [Note (4)]
B		1	Circumferential joints on a shell	RT or UT	100%	100%	100%	100%	10%	10% [Note (3)]
				MT or PT	10%	10% [Note (4)]	10%	10%[Note (4)]	10%	10% [Note (4)]

Manufacturing Readiness Review and Qualifications

- Distortion Management Plan (DMP) for welded and for additive manufacturing structures.
  It should be prepared by the Contractor for each sub-assembly and should include:
    - intermediate dimensional inspections during machining, welding, material deposition
    - execution order or operations
    - description of auxiliary jigs designed and used by the Contractor to limit distortions
    - evaluation of expected distortions to be consistent with specified tolerances
    - recovery procedures for deformations/distortions
    - consideration of the welding sequence/orientation and deposition path in the evaluation of the deformations
  - The DMP should be detailed consistently with technical risks during manufacturing and assembly, available information from previous experiences and from prototypes
- Qualification of processes, in particular for welded structures:
  - Preliminary activities (Welding Book): pWPS, Qualifications (WPQR), Welding Repair Procedures, Welding Inspection Plan, preliminary Welding Map, pre-Production Proof Samples
  - Production activities (Welding Book): WPS, Limits for imperfections, Production Proof Samples
  - NDE procedures and qualifications including UT phased-array in austenitic stainless steels (reflection at the fusion line or deflection in the weld metal of the shear beam because of velocity and grain structure differences, which may appear to be caused by incomplete fusion and can cause the unnecessary repair of good welds)

Prototype sector - Qualifications for risk mitigation

Prototype sector manufactured for **qualification of processes and product with the Contractor**:

- welding processes and procedures including weld repairs
- optimisation of weld sequence to minimize weld distortions on shells and ports
- measurement of post welding distortions (same tolerances of production sectors)

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

- verification of accesses for weld execution and testing, including helium LT
- integration of port stubs and verification of alignment tool for port ducts
- re-pickling, re-passivation, and cleaning treatments of the welded joints in the inter-shell
- measurement of the magnetic permeability at the completion of the fabrication processes

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

- integration of port ducts with bellows on port stubs
- tests of automated/manual welding processes
- forming of in-vessel coils
- verification of the frequency of intermediate dimensional tests for dimensional control
- integration of divertor rails and first wall supports

Manufacturing and testing - Factory and Site Acceptance Tests

Please see next slides

The pneumatic pressure testing is applied as a propaedeutic measure for detecting major early crack propagation before helium leak testing

Table 5-1 Summary of Factory Acceptance Tests and Site Acceptance Tests

Test description	Section	Required Tests	Factory Acceptance Test	Site Acceptance Test
Visual inspection	5.2	-	FAT.01	SAT.01
Weld inspection	5.3	-	FAT.02	-
Magnetic permeability	5.4	-	FAT.03	-
Surface roughness	5.5	-	FAT.04	-
Total hemispherical emissivity	5.6	TES.05	-	-
Dimensional inspection	5.7	-	FAT.06	SAT.06
Cyclic pressure test of inter-shell of the individual vessel Multi-Sectors	5.8	-	FAT.07	-
Helium leak test of the inter-shell boundary of the individual Multi-Sectors and Prototype Sector	5.9	-	FAT.08	SAT.08
Helium leak test of the torus vacuum boundary of the individual port assemblies	5.9	-	FAT.09	-
Tests of bellows	5.10	-	FAT.10	SAT.10
Assembly test of gravity supports (GS) on vacuum vessel (VV)	5.11	-	FAT.11	-
Electrical isolation tests	5.12	-	FAT.12	SAT.12
Functional tests of In-port Welding Equipment for field joining of port ducts to port stubs	5.13	-	FAT.13	-
Functional tests of sector equipment	5.14	-	FAT.14	-
Tests on vacuum vessel instrumentation	5.15	-	FAT.15	SAT.15
Flow test of the individual Multi-Sectors A and B	5.16	-	FAT.16	-

Thank you for your kind attention!

Design of Vacuum Vessel

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3 Dec 2024