AWP 2022

# Title: Coordination of Vacuum Vessel Design and Analysis work 2022

IMS task ID: DIV-IDTT.P.1-T023

# Title: Vacuum Vessel Design and Analysis work 2022

IMS task ID: DIV-IDTT.S.11-T002

DIV-IDTT.P.1-T023 Del. Owners: Mauro Dalla Palma, Antonio Cucchiaro, Pierluigi Fanelli

DIV-IDTT.S.11-T002 Del. Owners: Gianluca Barone, Roberto Bonifetto, Giuseppe Di Gironimo, Pierluigi Fanelli, Nicholas Terranova and the DTT Vacuum Vessel Team

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*DTT Consortium (DTT S.C.a r.l. Via E. Fermi 45 I-00044 Frascati (Roma) Italy)*

# Outline

**Assessment of effects of design review on vacuum vessel analysis and procurement *(first part of the presentation):***

- Coordination of Vacuum Vessel (VV) Design and Analysis work 2022: deliverables and allocated resources
- Vacuum Vessel Design and Analysis work 2022: deliverables and allocated resources
- Vacuum Vessel Design and Analysis work 2022: outcomes of the Design Review (DR) regarding:
    - design of components
    - VV analyses and verifications
    - VV interfaces and instrumentation
    - VV manufacturing
    - VV assembly
- Plan of next VV activities

**Electromagnetic and structural analyses of VV *(second part of the presentation):***

- Electromagnetic events and plasma scenarios for DTT
- Load case parameters of electromagnetic events of the DTT facility
- Load case combinations and limits for operating states of the DTT facility
- Paths of halo currents - assumptions
- Paths of halo currents - upward VDE (as an example among all the other plasma excitations)
- Downward vertical displacement event slow: SN-XD comparison
- Summary of plasma excitations with analysis priorities

# Coordination of Vacuum Vessel Design and Analysis work 2022

DIV-IDTT.P.1-T023 deliverables and allocated resources:

| ID | Title | Start Date | End Date | RU | Del. Owner | AWP2022 |
|---|---|---|---|---|---|---|
| | | | | | | PM 50% standard |
| DIV-IDTT.P.1-T023 - D001 | Coordination of the Design and Analysis of Vacuum Vessel 2022 – Lead Engineer | 01-Jan-22 | 31-Dec-22 | ENEA | Mauro Dalla Palma | 2.000 |
| DIV-IDTT.P.1-T023 - D002 | Coordination of the Design and Analysis of Vacuum Vessel 2022 – Deputy Engineer | 01-Jan-22 | 31-Dec-22 | ENEA | Antonio Cucchiaro | 2.000 |
| DIV-IDTT.P.1-T023 - D003 | Coordination of the Design and Analysis of Vacuum Vessel 2022 – Deputy Engineer | 01-Jan-22 | 31-Dec-22 | ENEA | Pierluigi Fanelli | 2.000 |
| | | | | | TOTAL: | 6.000 |

# Vacuum Vessel Design and Analysis 2022

DIV-IDTT.S.11-T002 deliverables and allocated resources:

| ID | Title | Start Date | End Date | RU | Del. Owner | AWP2022 |
|---|---|---|---|---|---|---|
| | | | | | | PM 50% standard |
| DIV-IDTT.S.11-T002 - D001 | Thermal-hydraulic static (CFD) analyses of VV sectors | 01-Jan-22 | 31-Dec-22 | ENEA | Roberto Bonifetto | 2.000 |
| DIV-IDTT.S.11-T002 - D002 | Dynamic (LOCA, LOFA, LOVA) analyses of VV | 01-Jan-22 | 31-Dec-22 | ENEA | Roberto Bonifetto | 2.000 |
| DIV-IDTT.S.11-T002 - D003 | Assessment of baking operating state for vacuum vessel & ports | 01-Jan-22 | 31-Dec-22 | ENEA | Gianluca Barone | 2.000 |
| DIV-IDTT.S.11-T002 - D004 | Simulations to assess activated corrosion products (ACP) | 01-Jan-22 | 31-Dec-22 | ENEA | Nicholas Terranova | 4.000 |
| DIV-IDTT.S.11-T002 - D005 | Vacuum vessel analyses for interface components with divertor system | 01-Jan-22 | 31-Dec-22 | ENEA | Giuseppe Di Gironimo | 6.000 |
| DIV-IDTT.S.11-T002 - D006 | Mechanical design and verification of the VV under machine operating states | 01-Jan-22 | 31-Dec-22 | ENEA | Pierluigi Fanelli | 10.000 |
| | | | | | TOTAL: | 26.000 |

# Vacuum Vessel Design and Analysis - outcomes of the design review

Design Review (DR) with external Panel of Experts: completed on May 2022

- DR outcomes about design of components:
    - ECRH stray radiation on insulating and electrically conductive materials: protection devices for diagnostics, cryopumps, and bellows should be developed consistently with the available space
    - Vacuum tribology: evaluation of using titanium alloys as high flexibility materials considering hydrogen absorption and release when heated
- DR outcomes about VV analyses and verifications:
    - Thermal-hydraulic (steady-state and dynamic analyses): modifications (if needed) introduced before the revision of VV manufacturing drawings (please see DIV-IDTT.S.11-T002-D001-2, R. Bonifetto)
    - Baking: heating of bellows region (please see DIV-IDTT.S.11-T002-D003, G. Barone)
    - Buckling & fatigue: increase of spring plate multiplication factor; fatigue verification completed before the revision of VV manufacturing drawings (please see DIV-IDTT.S.11-T002-D006, P. Fanelli)
    - Corrosion test and analysis: completion of foreseen activities; boric acid crystallising at low temperature (please see DIV-IDTT.S.11-T002-D004, N. Terranova)
    - Electromagnetic & structural: plan of analyses with prioritization (please see the second part of the presentation)
- DR outcomes about VV interfaced components and instrumentation:
    - Divertor, Limiter, and First Wall:
        - Verification of drawings of supports before the revision of VV manufacturing drawings (please see DIV-IDTT.S.11-T002-D005, G. Di Gironimo)
        - Design and verification of the divertor locking-alignment system (please see DIV-IDTT.S.01b-T002, D. Marzullo)
        - Check of gas conductance through the divertor structures for the required divertor exhaust pumping speed to be achieved (please see DIV-IDTT.S.03-T005, P. Innocente)
        - Verification of FW / Limiter designs, in particular considering the position of the inboard separatrix and the possible impact on the plasma performance reduction (please see DIV-IDTT.S.10-T003, G. Dose, M. Furno Palumbo)
    - Pellet flight line: ensure at least one high field side
    - Sensors: redundancy for plasma configuration control and machine protection against EM and thermo-mechanical loads

# Vacuum Vessel Design and Analysis - outcomes of the design review

Design Review (DR) with external Panel of Experts (ctd.)

- DR outcomes about VV manufacturing:
  - Magnetic permeability:
    - Orientation of the probing magnetic field of the measurement device with respect to longitudinal grains
    - Formal recording the measured values of the magnetic permeability of all the steel welded components surrounding the plasma for non-conformity concessions that may arise during the manufacture and for error field correction using coils
  - Weld treatment: re-passivation of inter-shell welds after weld cap removal for reliable ultrasonic testing
  - Prototype sector: qualification activities for weld distortions; qualification of NDT; procurement of enough raw material to build a second prototype sector if needed
  - Integration of port stubs manufactured in a single piece
  - Procurement plan: an increase of 5 months about the duration of the procurement contract should be considered (from 40 to 45 months)
    Actions are ongoing in order to mitigate the planning criticalities:
    - Evaluation of the VV manufacturing strategy and revision of the on-site integration sequence of VV sectors
    - No effects on analyses and verifications of the VV
- DR outcomes about VV assembly:
  - Qualification activities for weld distortions
  - Analysis of final sector integration for the closure of the VV
  - Integration of port ducts manufactured in a single piece

# Plan of VV activities from now to the end of the year

| # | *Activity* | Jun-22 | Jul-22 | Aug-22 | Sep-22 | Oct-22 | Nov-22 | Dec-22 |
|---|---|---|---|---|---|---|---|---|
| 1 | **Identification of last structural changes implemented on the CAD model** (thickness and shape of shells, ribs, port stub, splice plates, gravity support) | ■ | | | | | | |
| 2 | **System fluid-dynamic analyses:** | ↔ | ↔ | ↔ | ↔ | ↔ | ↔ | ↔ |
| | Identification of a first set of safety devices and machine primary boundary | ■ | | | | | | |
| | Analyses results with indication of response parameters of safety devices | ■ | ■ | ■ | ■ ◇ | ■ | ■ | ■ |
| 3 | **VV special sectors for CFD steady-state analyses:** | ↔ | ↔ | ↔ | ↔ | ↔ | ↔ | ↔ |
| | CAD implementation of structural input and inter-shell flow paths at VV special sectors | ■ | | | | | | |
| | CFD analyses with flow optimisation | ■ | ■ | ■ | ■ ◇ | ■ | ■ | ■ |
| 4 | **Electromagnetic (EM) analyses, thermal (TH), and structural (STR) verifications:** | ↔ | ↔ | ↔ | ↔ | ↔ | ↔ | ↔ |
| | Structural verification (under DVDE slow) of the VV sector with the modified gravity support | ■ | | | | | | |
| | Assessment of effects of CAD changes on the analysed electromagnetic (EM) configuration | ■ | | | | | | |
| | Update of the VV EM (if needed), TH, and STR models for verification of load combinations (CAD changes, double plate supports of outboard FW, bushed supports of inboard FW, divertor rails and supports) | | ■ | | | | | |
| | EM analyses and STR verifications under load combinations (priority 1 first, then priority 2) | | ■ | ■ | ■ ◇ | ■ | ■ | ■ |
| 5 | **Manufacturing and assembly:** | ↔ | ↔ | ↔ | ↔ | ↔ | ↔ | ↔ |
| | Prepration and approval of the change request about VV manufacturing strategy and integration sequence: | ↔ | | | | | | |
| | Evaluation of VV manufacturing processes (from forming of large plates to double wall manufacturing) | ■ | | | | | | |
| | Evaluation of the VV manufacturing strategy and revision of the on-site integration sequence of VV sectors | ■ | | | | | | |
| | Assessment of effects on VV manufacturing and integration tolerances | ■ | | | | | | |
| | Assessment of effects on VV analyses and verification | ■ | | | | | | |
| | Assessment of effects on VV interfaced systems, in particular first wall, divertor, and thermal shield | ■ | | | | | | |
| | Revision of the VV manufacturing schedule | ■ | | | | | | |
| | Assessment of effects on machine integration sequence | ■ | ■ | ■ | ■ ◇ | ■ | ■ | ■ |
| | Corrosion test and analysis | ■ | ■ | ■ | ■ ◇ | ■ | ■ | ■ |
| 6 | **Technical specification:** | ↔ | ↔ | ↔ | ↔ | | | |
| | Revision of the VV 3D CAD model in accordance with the manufacturing strategy | | ■ | | | | | |
| | Conceptual design of transportation tools | | ■ | ■ | | | | |
| | Design of jig and movement tool for on-site integration of the VV sectors, in particular the final sector | | ■ | ■ | | | | |
| | Revision of the VV technical specification (drawings and document) | | ■ | ■ | ■ | | | |
| | Revision of machine sensor layout | | ■ | ■ | | | | |
| 7 | **Preparation and launch of the call for tender in September 2022** | | | ■ | ■ | | | |

*The presentation about work coordination will continue after the coffee break*

*Thank you for your attention and enjoy next presentations*

# Electromagnetic events and plasma scenarios for DTT

Electromagnetic events analysed for the DTT facility:

- Vertical Displacement Events
- Major Disruptions
- Fast Discharge of all Toroidal field coils

Among all possible plasma scenarios that will be tested in DTT, SN configuration is expected to be the most conservative (5.5 MA), even if a preliminary comparison between SN and XD shows comparable global force on VV (see next slides)

| 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 |
| **SF** | SnowFlake | 4.5 |

# Load case parameters of electromagnetic events of the DTT facility

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

# Load case combinations and limits for operating states of the DTT facility

| # | Load case combination | Level of service | Priority |
|---|---|---|---|
| LC5b | MD fast + Earthquake | C | 1 |
| LC5c | VDE fast, downward + Earthquake | C | 1 |
| LC5d | VDE slow, downward + Earthquake | C | 1 |
| 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 |
| LC7a | VVP helium/water Ingress + Earthquake | C | 1 |
| LC7b | CRS helium/water Ingress + Earthquake | C | 1 |
| LC7c | VVP helium/water Ingress + MD fast + Earthquake | C | 1 |
| LC7d | VVP helium/water Ingress + VDE fast, downward + Earthquake | C | 1 |
| LC7e | VVP helium/water Ingress + VDE slow, downward + Earthquake | C | 1 |
| LC7f | CRS helium/water Ingress + TFD, all coils + Earthquake | C | 1 |
| LC4 | Baking + Earthquake | C | 1 |
| LC1 | Construction + Earthquake | C | 2 |
| LC2 | Pressure Test + Earthquake | C | 2 |
| 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 | VVP helium/water Ingress + VDE fast, upward + Earthquake | C | 2 |
| LC7h | VVP 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.

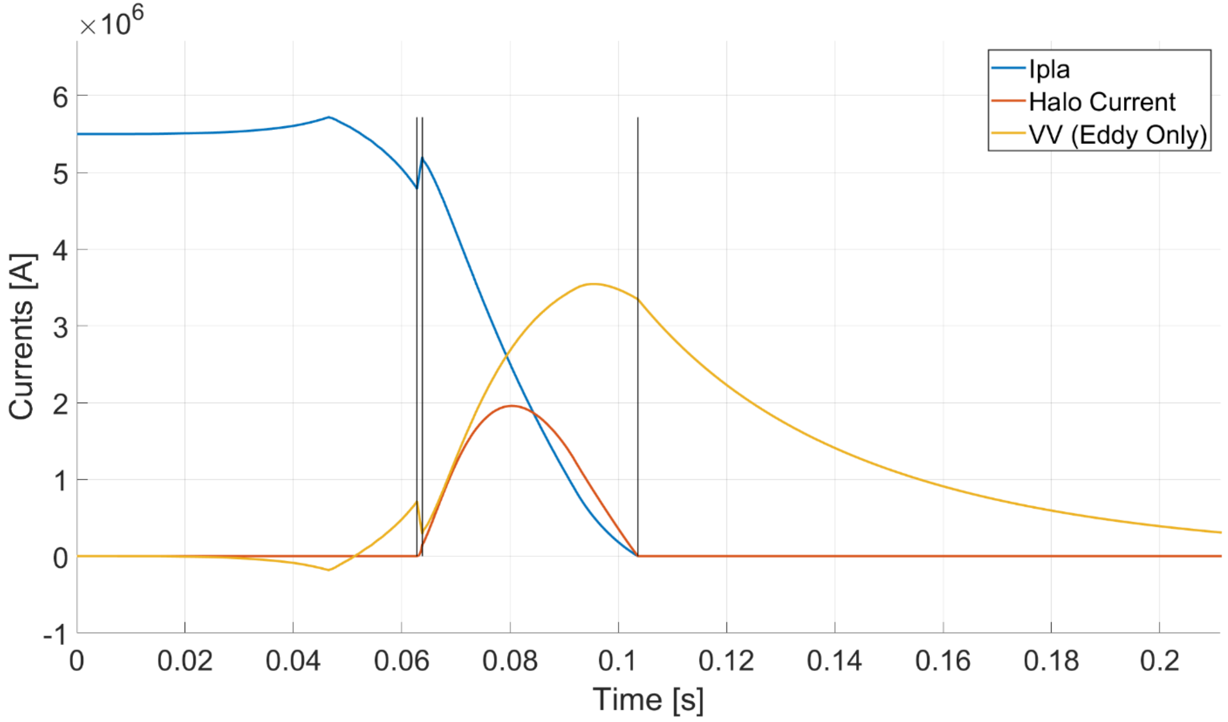
# Paths of halo currents - assumptions

- Loads due to the poloidal halo currents in the vessel are considered for MDs and VDEs
- Loads correspond to the point in time when the halo current reaches its peak
- Entrance and exit points of halo currents are assumed for alternative scenarios:
    1. almost all the halo current is expected to circulate in the in-vessel component involved in the discharge (e.g. divertor) with current entrance/exit positioned at the ends (longer path) of the component
       → conservative scenario for vessel verification with higher forces at interfaces btw vessel & component
    2. halo current circulating in the vacuum vessel (in particular 100%)
       → also significant for the verification of vacuum vessel and for the in-vessel components
- Combinations of scenarios 1 & 2 with distribution of current fractions can be considered in the next analysis stage
- Longer halo current paths are considered at the inboard or outboard wall resulting in a more severe and hence conservative pressure load
- Directional electrical properties of simulated components are implemented in the FE model, in particular at the supports on the vessel
- Electrical properties define all possible paths of halo and eddy currents
  → calculated paths of halo and eddy currents depend on actual resistances and inductances

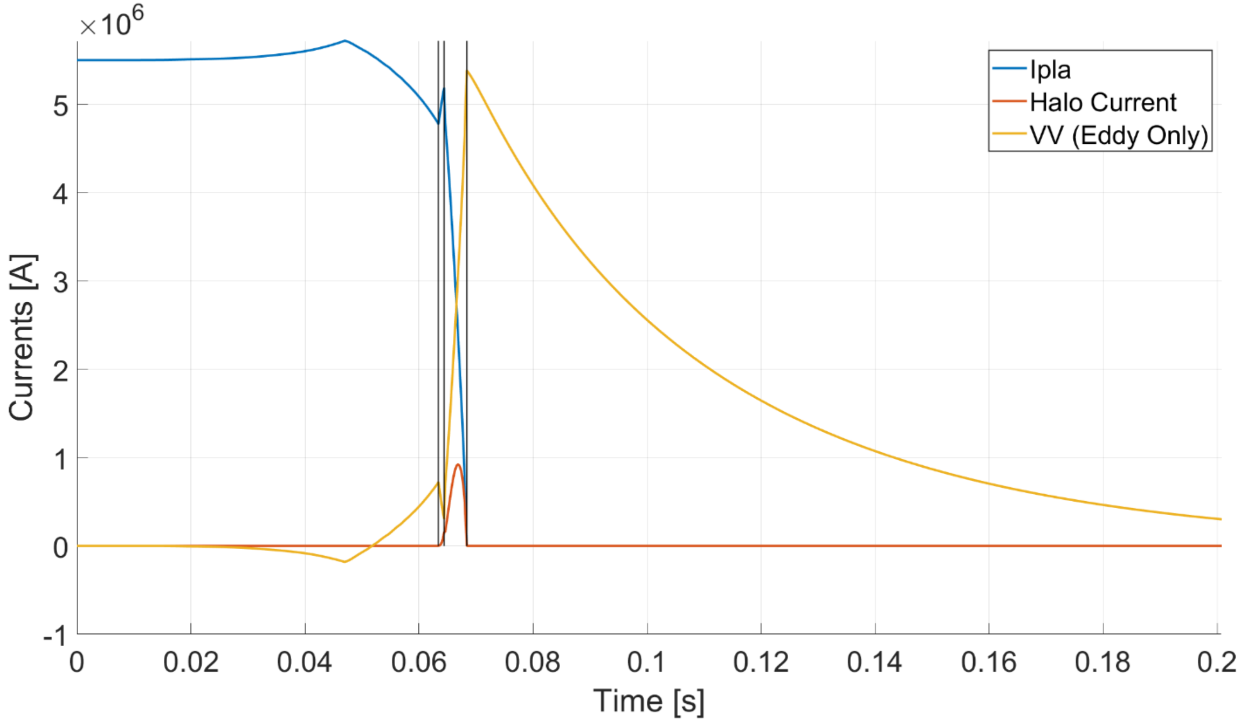
# Paths of halo currents - upward VDE 1/5

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

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



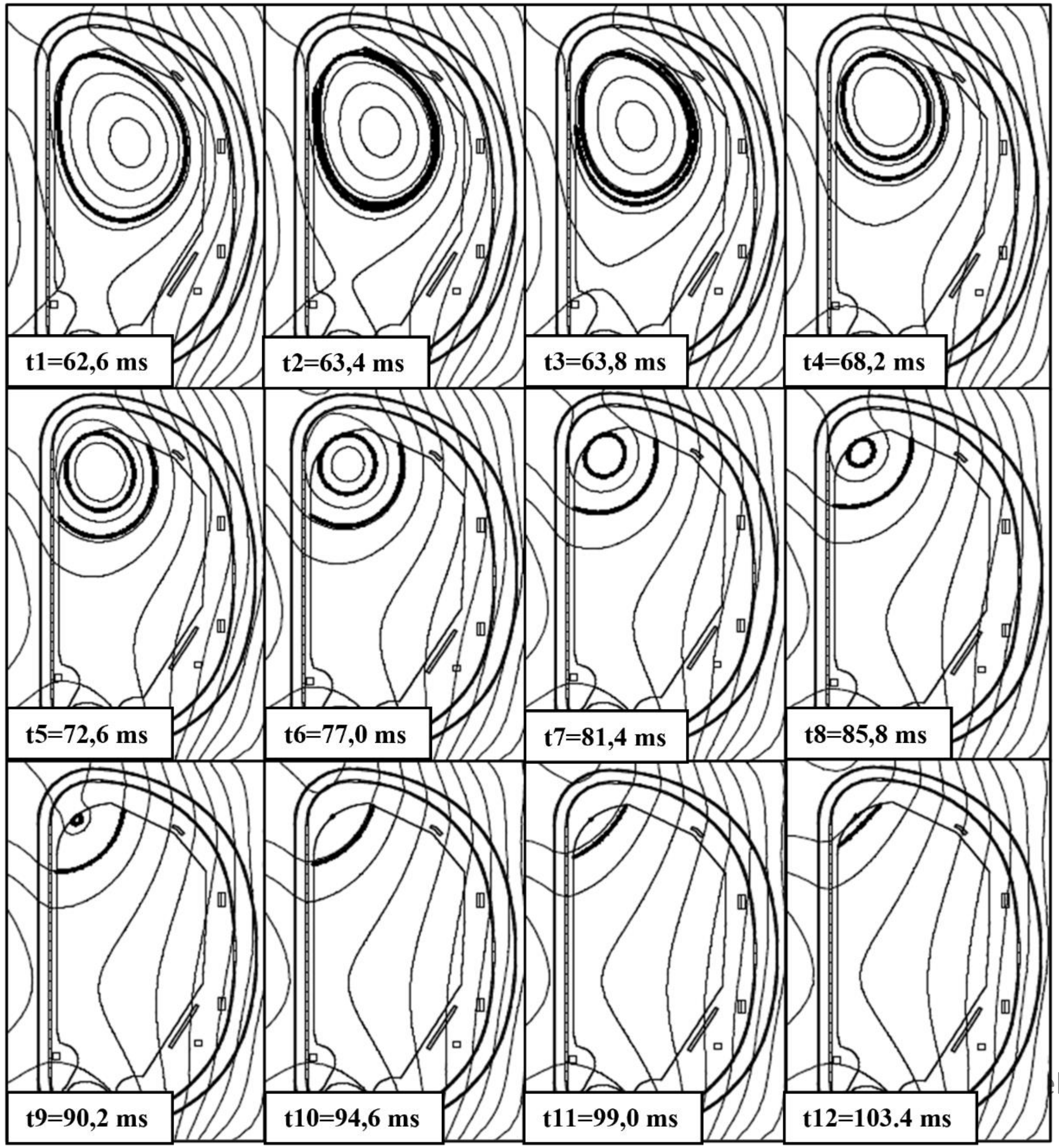

- UVDE fast
- Maximum halo factor ($I_{halo}/I_{plasma}$) = 0.168



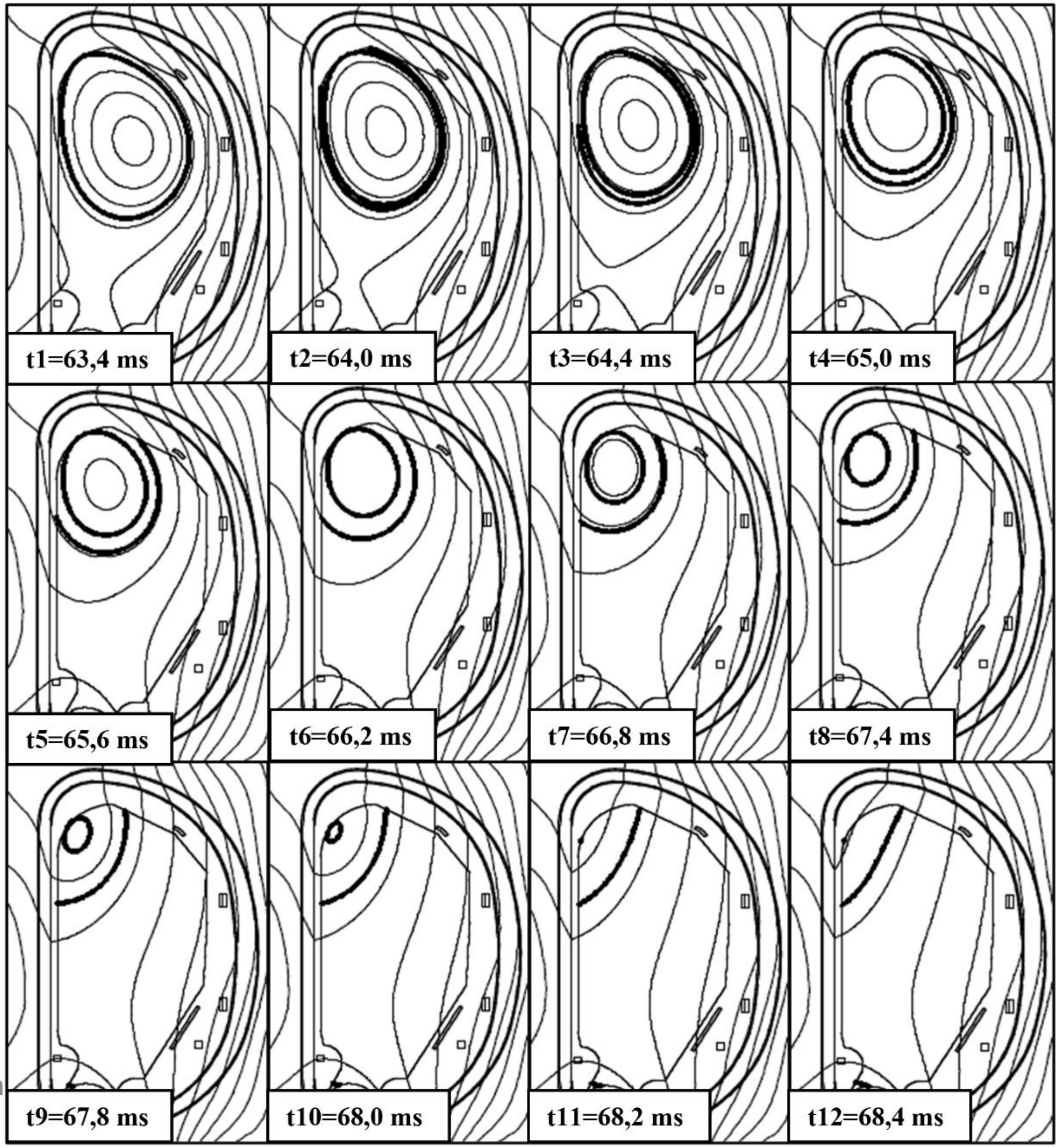
# Paths of halo currents - upward VDE 2/5

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



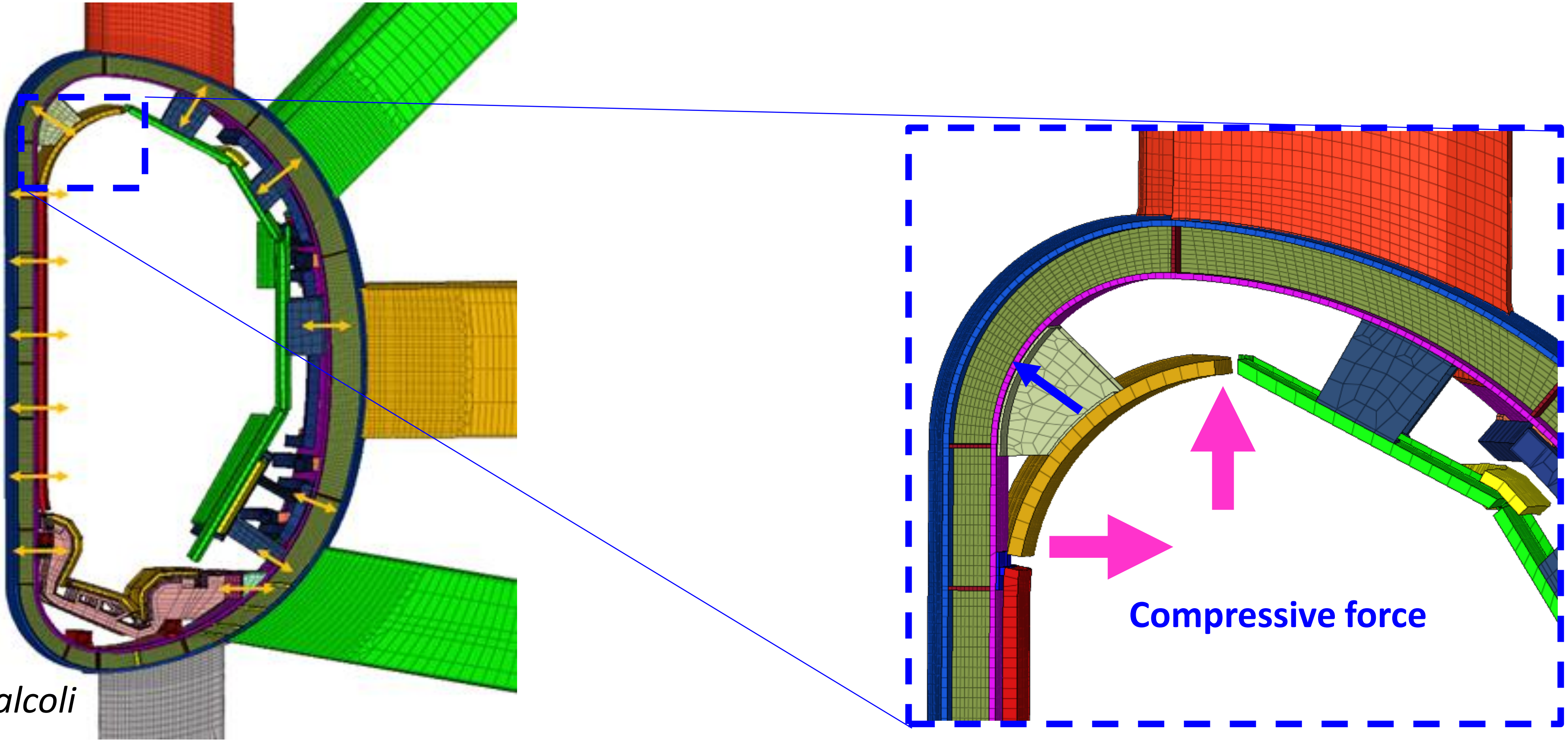

- UVDE fast



# Paths of halo currents - upward VDE 3/5

UVDE slow/fast, scenario 1, 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

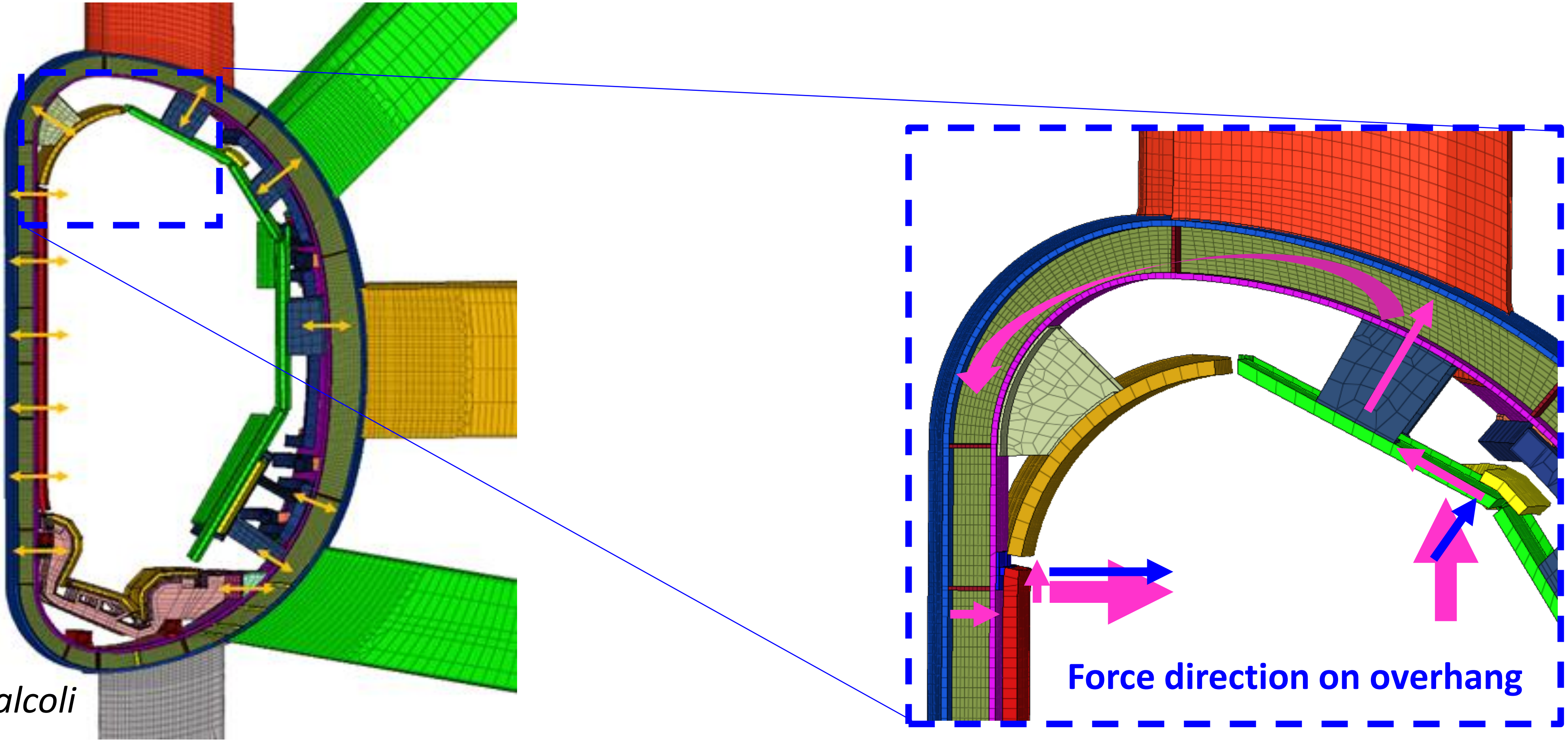



*Courtesy of LT Calcoli*

# Paths of halo currents - upward VDE 4/5

UVDE slow/fast, scenario 2a, priority 1:

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 FW (inner and outer)

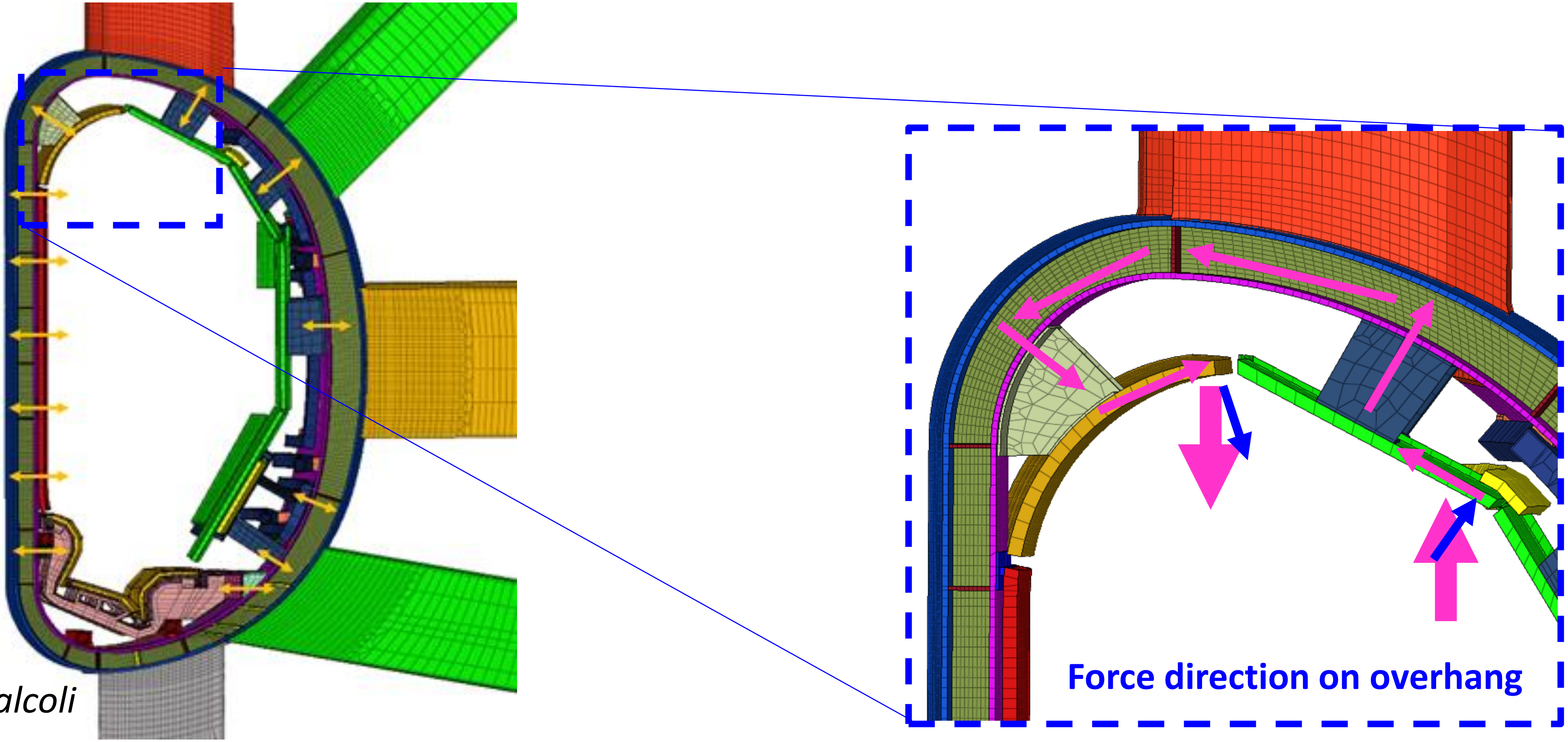



*Courtesy of LT Calcoli*

# Paths of halo currents - upward VDE 5/5

UVDE slow/fast, scenario 2b, priority 2:

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




*Courtesy of LT Calcoli*

# Summary of plasma excitations with analysis priorities

<table>
<tr><th>Plasma excitation</th><th>Almost all the halo current circulating in the in-vessel component (scenario 1)</th><th>Almost all the halo current circulating in the vacuum vessel (scenario 2a)</th><th>Almost all the halo current circulating in the vacuum vessel (scenario 2b)</th></tr>
<tr><td>DVDE slow</td><td>1</td><td colspan="2">1</td></tr>
<tr><td>DVDE fast</td><td>1</td><td colspan="2">1</td></tr>
<tr><td>UVDE slow</td><td>2</td><td>1</td><td>2</td></tr>
<tr><td>UVDE fast</td><td>2</td><td>1</td><td>2</td></tr>
<tr><td>UMD slow</td><td>2</td><td colspan="2">2</td></tr>
<tr><td>UMD fast</td><td>2</td><td colspan="2">2</td></tr>
<tr><td>DMD slow</td><td>2</td><td colspan="2">2</td></tr>
<tr><td>DMD fast</td><td>1</td><td colspan="2">1</td></tr>
<tr><td>DVDE slow (XD)</td><td>2</td><td colspan="2">2</td></tr>
</table>

The matrix analysis is consistent with outcomes of the VV design review. Further verifications are ongoing

*Thank you for your attention and enjoy next presentations*