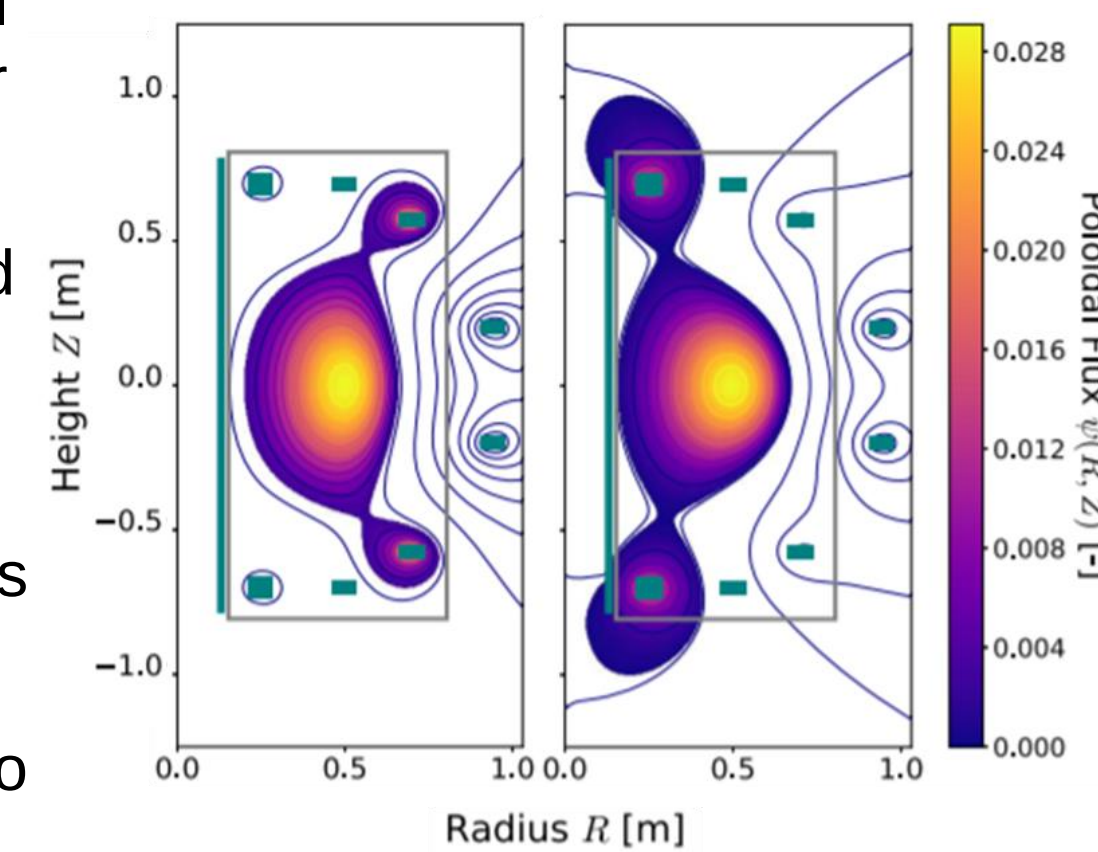


## Motivation

- The Small Aspect Ratio Tokamak (SMART) is a new spherical device<sup>[1]</sup> currently under assembling at the University of Sevilla enabling studies with positive and negative triangularity<sup>[2,3]</sup> plasmas.
- The Vacuum Vessel (VV) design is critical as it needs to withstand the EM loads for all the three phases<sup>[4,5]</sup>, considering both **normal** and **off-normal events** (i.e Vertical Displacement Event (UVDE/LVDE) and Major/Minor Disruption (MD/mD)).
- In the **Normal Events (NE)** the VV need to withstand  $J_{eddy} \times B_p$  loads.
- In the **Off normal Events (OE)**, the VV need to withstand:
  - the  $J_{eddy} \times B_p$  forces due to the plasma movement and its current quench (CQ)
  - the  $J_{halo} \times B_T$  forces due to the interaction of the halo current with the  $B_T$ .

|                  | Phase 1     | Phase 2     | Phase 3     |
|------------------|-------------|-------------|-------------|
| $I_p$ [kA]       | 100         | 200         | >500        |
| $B_T$ [T]        | 0.1         | 0.4         | 1           |
| $\tau_{FI}$ [ms] | 100         | 150         | 500         |
| $\kappa$         | $\leq 1.95$ | $\leq 2.00$ | $\leq 2.30$ |
| $\delta$         | $\pm 0.4$   | $\pm 0.5$   | $\pm 0.5$   |



## SMART Vacuum Vessel

- Stainless steel (AISI 316 L) Vacuum Vessel (VV) ( **$h=1.6$  m,  $\phi=1.6$  m,  $m_{total} \approx 2$  t**) with mixed thickness of 18 mm in the upper/lower lid, 8 mm in the outer wall and 3 mm in the central column (CC)<sup>[5]</sup>.
- CF 100 DN** ports for diagnostics and **CF 250 DN ports** for diagnostics, pumps and coils connections and rectangular ports for NBI connection and maintenance<sup>[5]</sup>.
- Design optimized** to reduce eddy current, minimize  $J \times B$  forces and assuring UHV conditions in all phases.
- Ultra High Vacuum (**UHV**) of  $10^{-6}$  Pa through 2 dry pumps of 80 m<sup>3</sup>/h, and 2 turbomolecular pumps of more than 2300 l/s<sup>[5]</sup>.
- VV** already **manufactured** and **now under electropolishing**

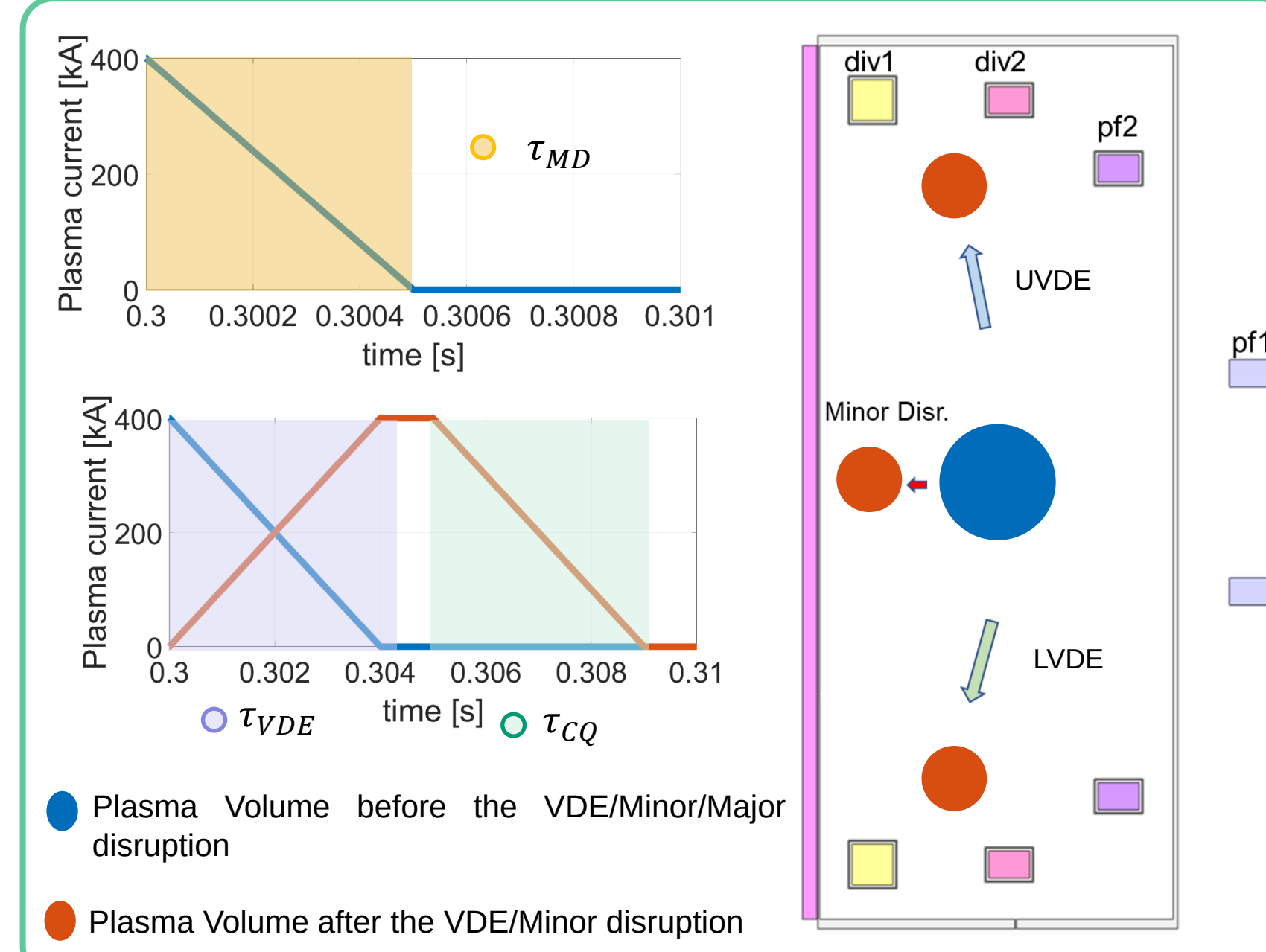


## Parameters for the EM analysis of off-normal events

- VDEs and disruption defined by the VDE growth rate  $\tau_{VDE}$  and current quench time  $\tau_{CQ}$ <sup>[4]</sup>
- $\tau_{VDE}$  estimated as  $L_{Vessel}/R_{Vessel} \approx 4$  ms
- $\tau_{CQ}$ <sup>[6]</sup> has been estimated by  $\tau_{CQ} = \frac{L}{2\pi R_p \eta_{par}} S \approx 4$  ms
- CQ for Major disruption<sup>[7]</sup> as  $\tau_{MD} \approx 1.8 \times S \approx 0.5$  ms

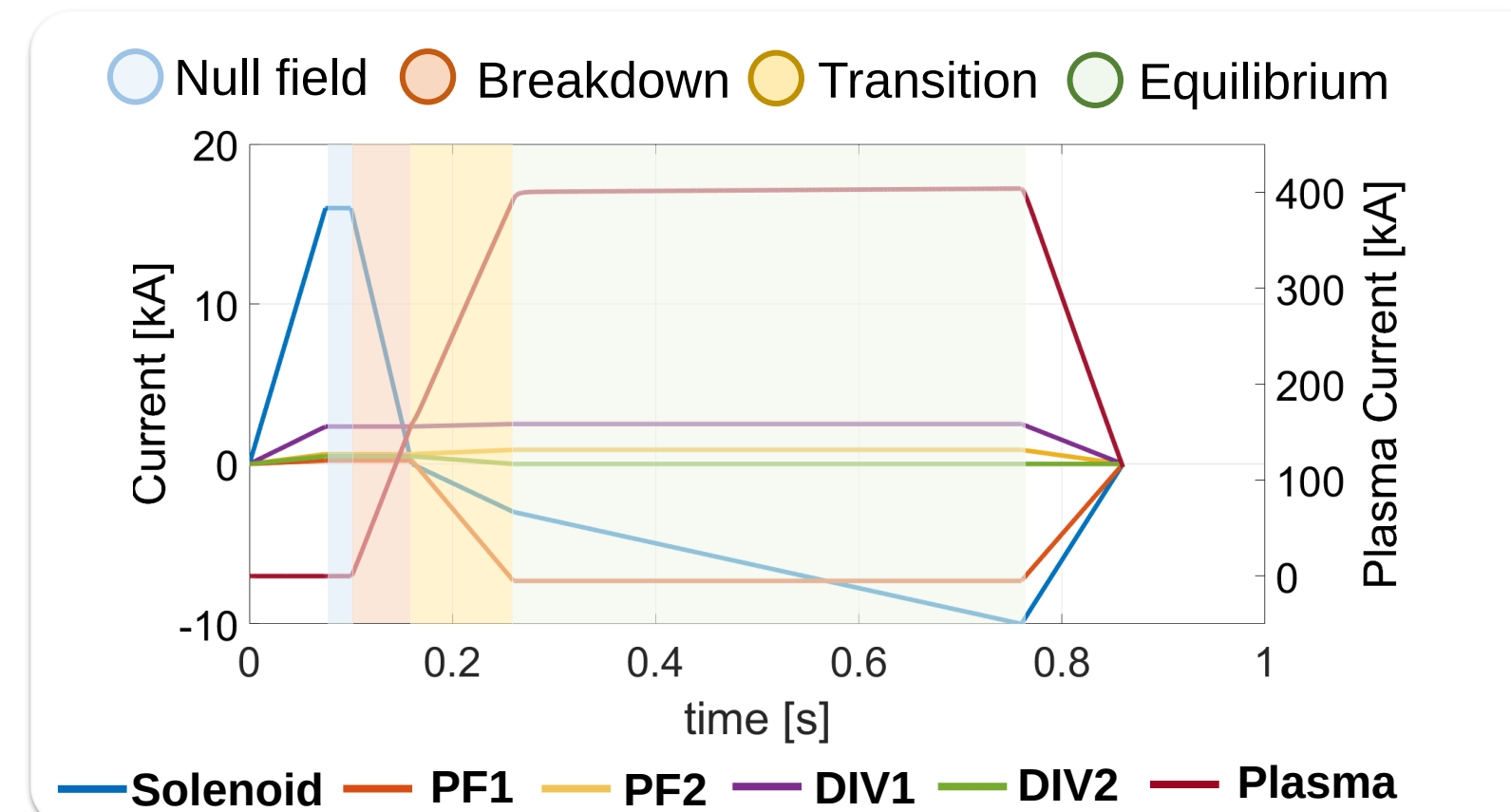
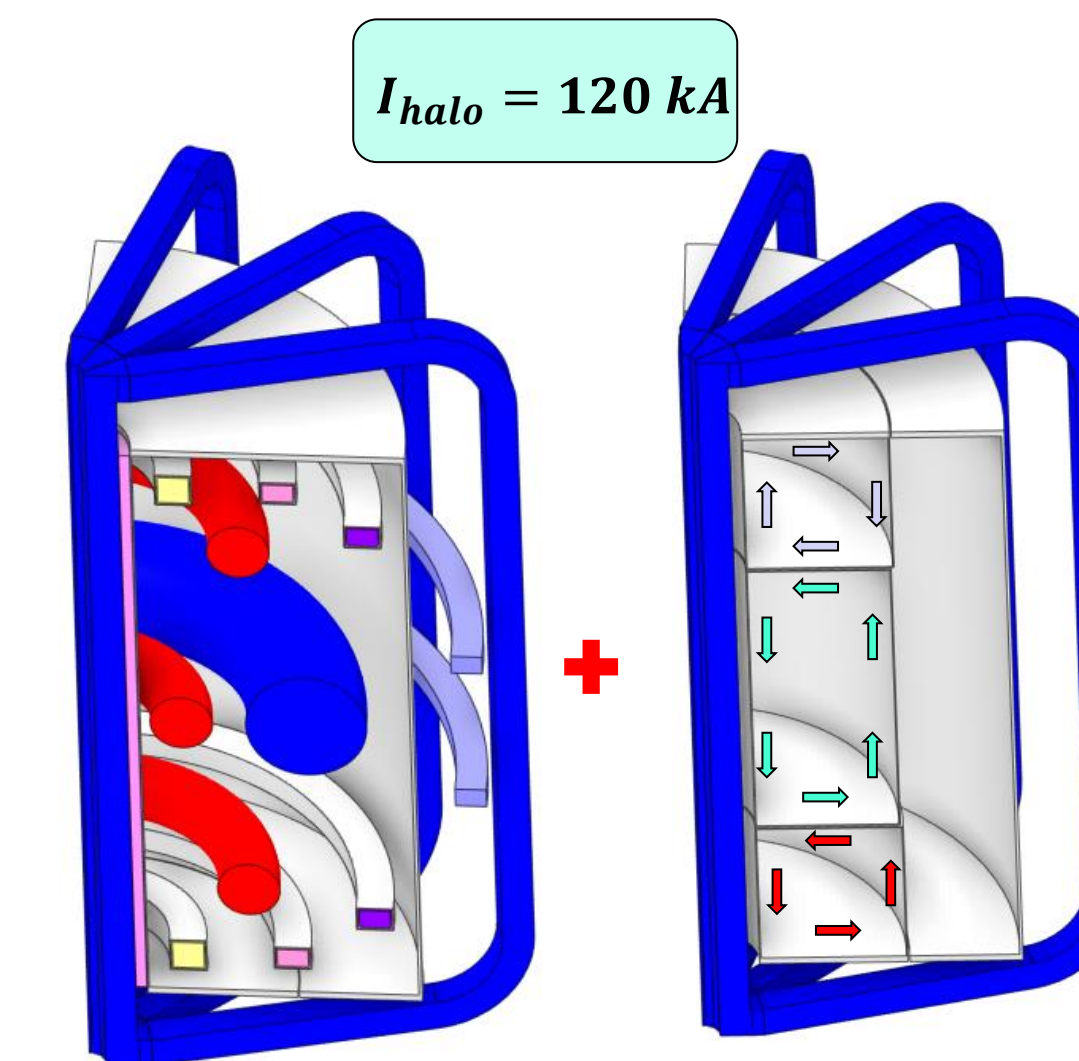
| Plasma parameter                       |                       |
|----------------------------------------|-----------------------|
| $I_p$ [kA]                             | 400                   |
| $R_p$ [m]                              | 0.42                  |
| $a$ [m]                                | 0.22                  |
| $\kappa$                               | 2.25                  |
| $S = \pi \kappa a^2$ [m <sup>2</sup> ] | 0.35                  |
| $L$ [H]                                | $6.5 \times 10^{-7}$  |
| $\eta_{par}$ [ $\Omega$ m]             | $2.05 \times 10^{-5}$ |

- Two plasma volume simulate the VDEs (**Volume 1** and **Volume 2**).
- Currents in **Volume 1** and **Volume 2** are switched **off/on** in  $\tau_{VDE}$  to simulate the movement of the plasma, and finally the current in **Volume 2** is switched **off** in  $\tau_{CQ}$  to simulate the CQ
- Switching **off** the current **Volume 1** in  $\tau_{MD}$  simulates the major disruption
- Fraction of halo current<sup>[8]</sup>  $\frac{I_{halo}}{I_p} = 0.3$
- No halo for major disruptions (rapid phenomena assumption)



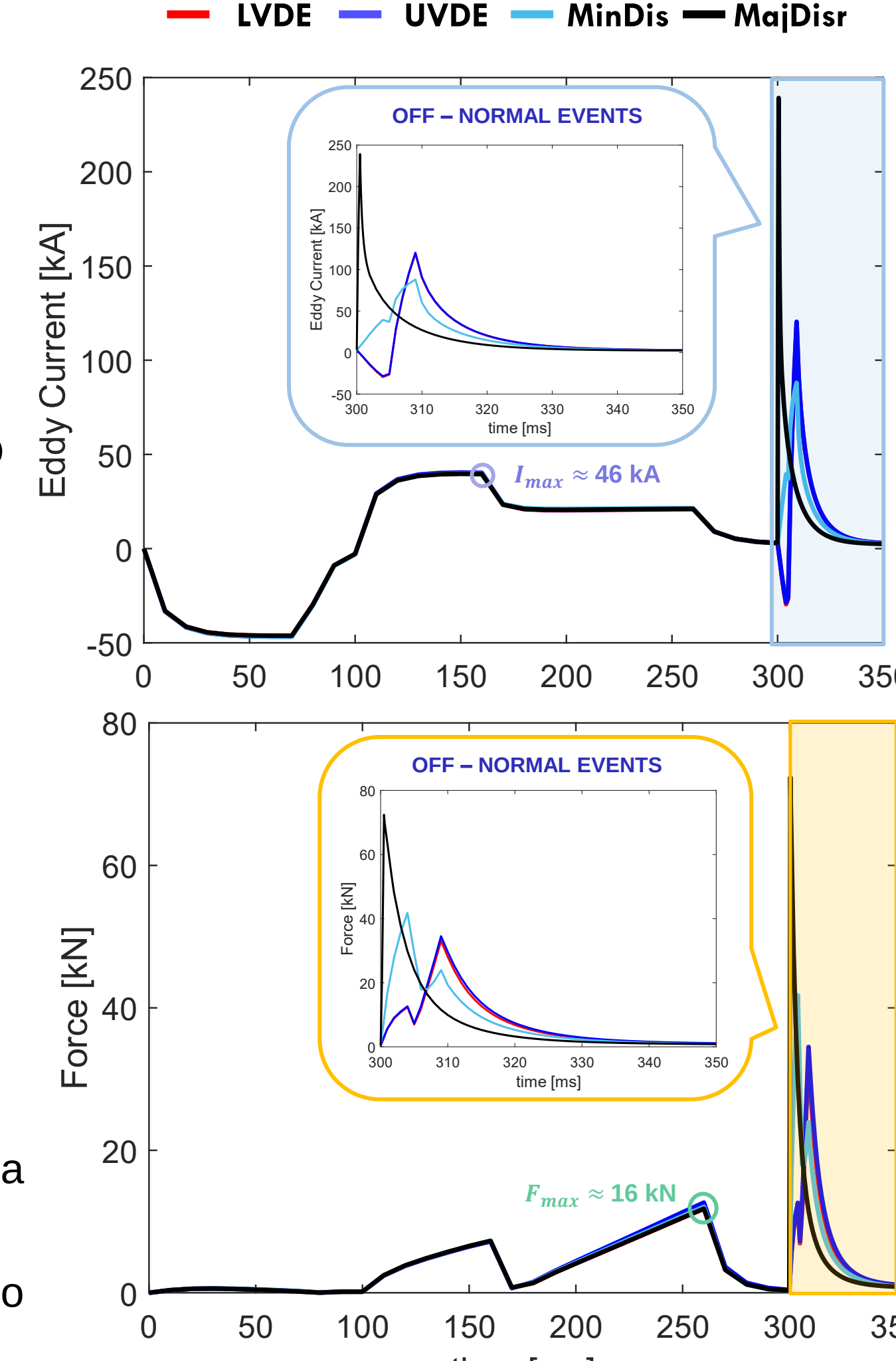
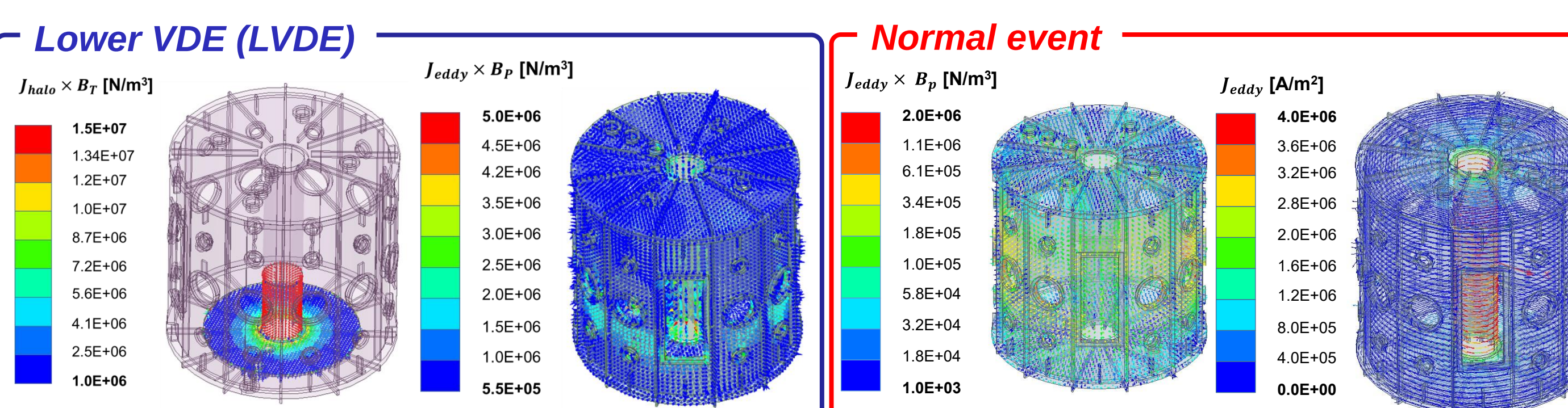
## Magnetic Finite Element Model

- 90° FEM transient model in ANSYS Maxwell including the magnetic system and 2 plasma volumes for the initial/final position of the plasma in a VDE/Disruption.
- Normal events** performed using only the blue volume (**no movement of the plasma**).
- Coils current input from FIESTA code<sup>[2,3]</sup> while TFC coils current constant during the pulse @ **166 kAturn**.
- VDEs/Disruption starts @300ms, during the equilibrium, and stopped @ 350 ms where  $I_{eddy} \approx 0$ .
- Halo current** simulated with a **separate model** for VDEs and minor disruptions.



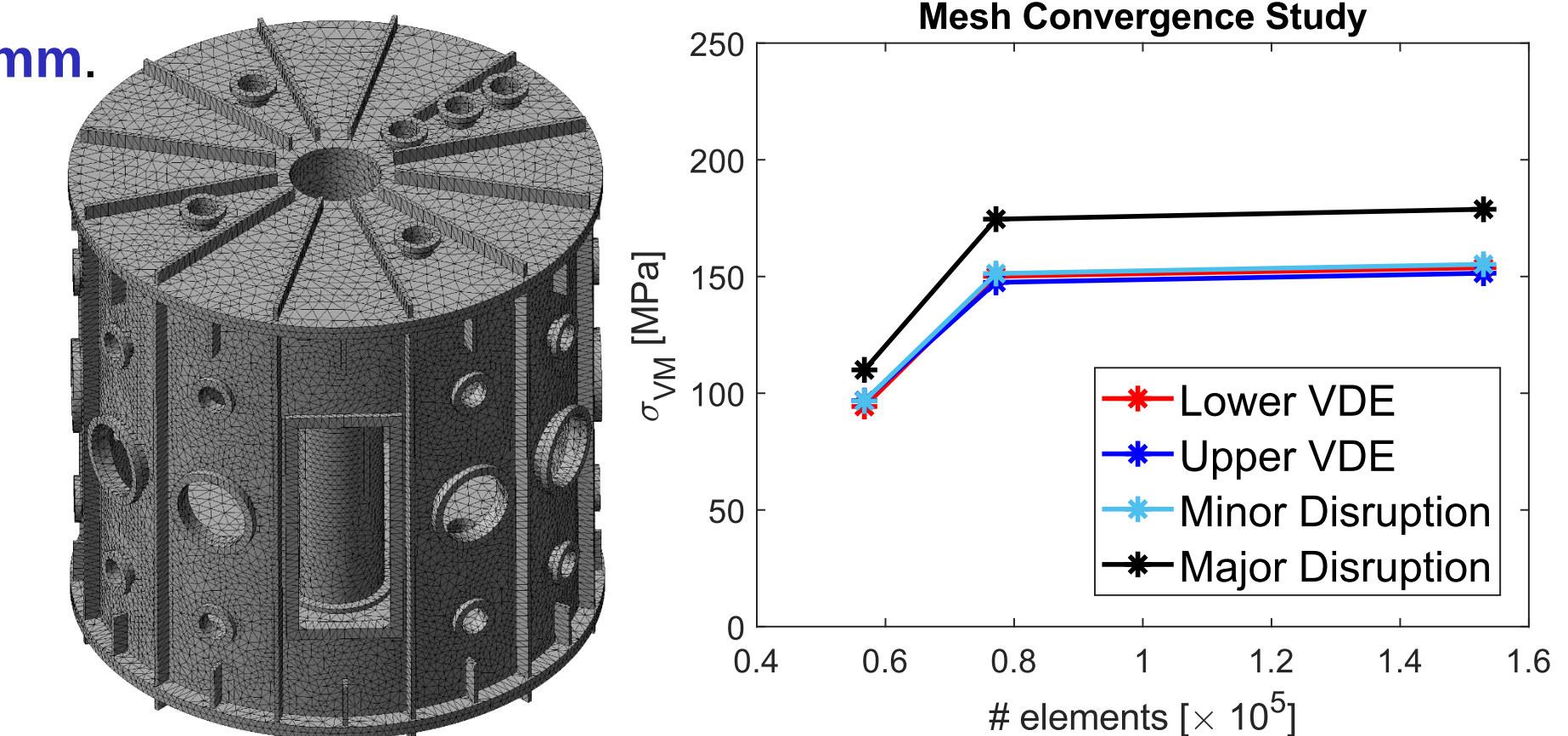
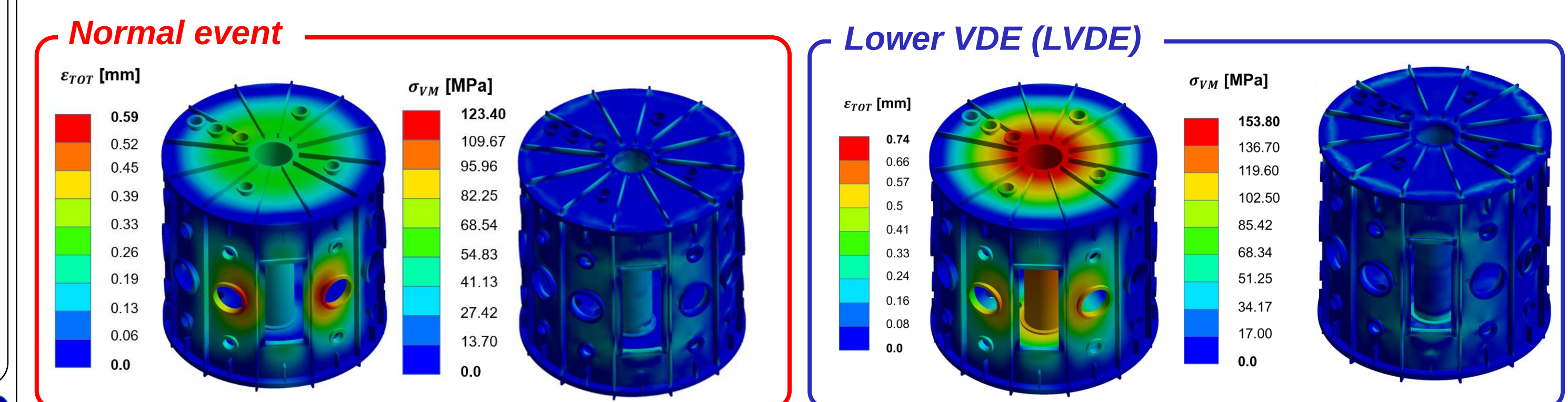
## ElectroMagnetic FEM model results

- Max eddy current induced during the pulse of  $I_{tot} \approx 46$  kA @ max  $dI_{sol}/dt$  (breakdown phase).
- Max operational force mostly radial and equal to  $F_{NE} = F_r \approx 16$  kN when  $B_p$  is maximum (transition phase).
- In the off-normal events, during the CQ maximum current are induced in the VV:
  - 240 kA** during a MD,
  - 120 kA** during a LVDE/UVDE,
  - 90 kA** during a mD.
- Max total forces ( $F_{eddy} = I_{eddy} \times B_p$ ) of:
  - 72 kN** in the MD ( $F_{eddy}/F_{NE}=5.5$ )
  - 41 kN** during a mD ( $F_{eddy}/F_{NE}=2.5$ )
  - 35 kN** during LVDE/UVDE ( $F_{eddy}/F_{NE}=2.2$ )
- Halo total Forces ( $F_{halo} = I_{halo} \times B_T$ ):
  - $F_r$  and  $F_z$  of **166 kN** and **66.7 kN** during a LVDE/UVDE
  - $F_r$  of **195 kN** in the CC in the mD (no halo forces considered for major disruption).

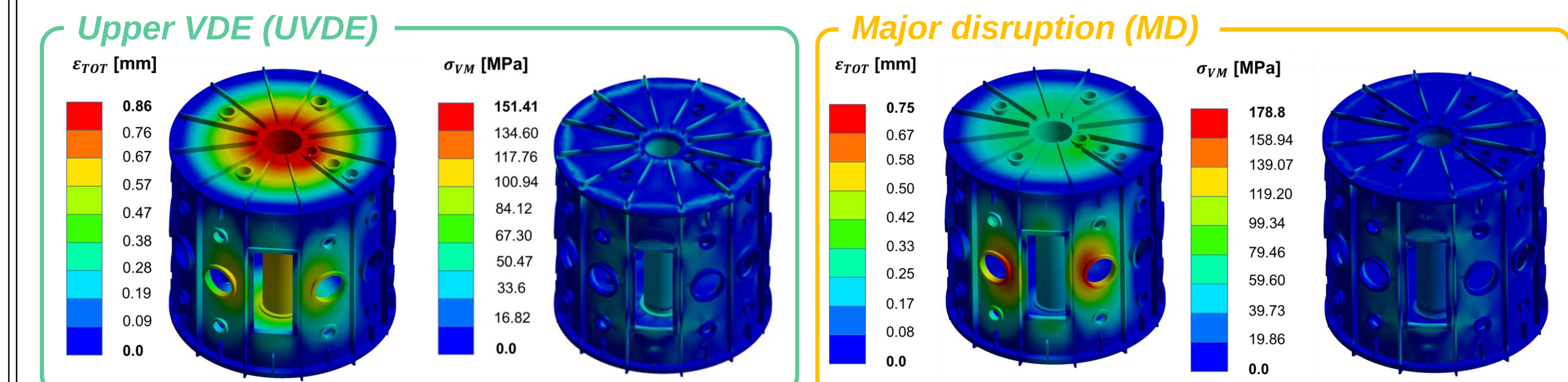


## Mechanical Assessment

- The Mechanical integrity of the vessel assessed considering the real 3D geometry in ANSYS Mechanical<sup>[4]</sup>.
- Mesh converges** with a size of **25 mm**.
- During normal pulse  $\sigma_{VM}$  of **125 MPa** and  $\epsilon_{tot}$  of **0.6 mm**.
- Highest deformation in the upper VDE with a max  $\epsilon_{tot}$  of **0.86 mm** in the CC (mainly vertical) and a max VonMises stresses  $\sigma_{VM}$  of **151 MPa** (below the yield limit of the Stainless Steel **205 MPa**).



- Max deformation during a axisymmetric major disruption of **0.75 mm** (radial) and a max  $\sigma_{VM}$  of **180 MPa** higher than in the minor disruption case ( $\epsilon_{tot}$  of **0.68 mm** and  $\sigma_{VM}$  of **155 MPa**).



- Submodelling analysis will be performed near the location of the maximum Von Mises stresses,  $\sigma_{VM,max}$

## Summary and Conclusions

- The robustness of the design of the vacuum vessel has been proven against normal and off-normal events in phase 3 (most challenging one).
- Forces during the normal operation of the machine are radial and give rises to stresses up to  $\sigma_{VM}$  of **125 MPa**, 2 times lower than the stainless steel yield limit.
- Max vertical VV deformation  $\epsilon_{tot}$  of **0.86 mm** and **0.74 mm** in the UVDE and LVDE with  $\sigma_{VM}$  lower than **155 MPa**, below the yield limit of the steel.
- Max radial VV deformation  $\epsilon_{tot}$  of **0.75 mm** during a major disruption with  $\sigma_{VM}$  of **180 MPa**, still considerably lower than limit for the steel.
- Submodelling studies will be performed at the location where  $\sigma_{VM,max}$  occur.
- The design open the window to increase the plasma current  $I_p > 400$  kA (Scenarios with 500 kA and more are under development).

## References

- [1] Y-K. M. Peng, et al, Nucl. Fusion, 1986
- [2] S.J. Doyle et al, PRE, 2021
- [3] S.J. Doyle et al, FED,2021
- [4] A. Mancini et al, IEEE, 2021 (accepted)
- [5] A. Mancini et al, FED, 2021
- [6] Chen Da-Long et al, Chin. Phys.,2015
- [7] H. Boozer, Physics of Plasma, 2012
- [8] T.C. Hender et al EPS,2007