Models for Asymmetric VDEs and assessment of AVDE loads for ITER

Status of the AVDE issue for the design of ITER systems

- Asymmetric VDEs are defined in the ITER Load Specification
- Independently on the number and severity of AVDEs that will actually occur in the ITER tokamak, all Safety Important Components must be designed to survive mechanical loads produced by those events
- In the past AVDE loads on the ITER VV have been assessed through EM analysis assuming the *source and sink* model developed at JET
- Structural assessment based on the *source and sink* showed extremely high acceleration spectra transmitted by VV in case of AVDE rotating close to the VV resonant frequencies
- Recent conclusion of the ITPA Working Group led by C. Myers on multi-machine analysis of rotating asymmetries show that they scale unfavorably for ITER and frequencies in the resonance range have to be expected (even though amplitude scaling has not yet been attempted)
- The finalization of the design of many ITER components needs input loads to assess AVDEs. At the moment we do not have "justified" loads or acceleration spectra for these events

Models for Asymmetric and rotating VDE loads in tokamaks

ITPA MHD TG has been requested to conduct review of models of AVDEs which is underway – initial report in October 2017 identifying additional experiments required, further detailed analysis during 2018

Several models have been proposed to explain the horizontal forces rising during AVDEs and to extrapolate those forces to ITER. In particular asymmetric loads have been explained:

- Through the interaction of the kinked plasma with the external field
- Assuming that part of the plasma current enters and leaves the structure at approximately opposite toroidal angles (*source & sink*) or
- Assuming that the plasma current asymmetry is caused by the halo current distribution associated with a kinked plasma
- Through the surface (or "Hiro") currents which are induced on the plasma surface to compensate the radial component of the field generated by the plasma kink
- Through asymmetric distribution of induced currents in the structures caused by partial short-circuiting of the gaps between plasma facing components (ATEC)

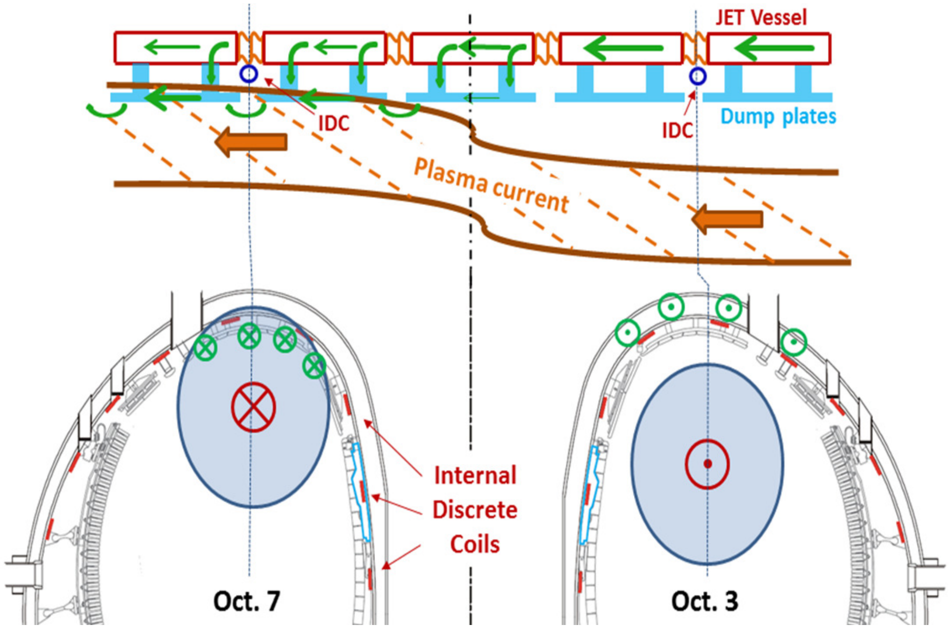
Present definition of AVDE loads in ITER

- At present, loads during AVDE have been calculated in ITER by fixing the plasma current asymmetry (ΔI_p) to 10% of the pre-disruption plasma current, which is consistent with the worst measurements at JET.
- ΔI_p has then been considered entering and leaving the VV structure along a narrow wetting ring through specified time and angular functions as produced by a current generator (Source and Sink model).
- The peak forces and moments obtained through the S&S approach were substantially independent from the frequency when applied to a rotating AVDE (i.e. the modulus of the sideways force does not decrease at increasing rotating frequencies) resulting in dangerous conditions when the AVDE rotates at the frequencies corresponding to the ITER VV first modes.

Model of Asymmetric Toroidal Eddy Currents

- An Asymmetric distribution of Toroidal Eddy Currents is a possible cause of the loads during AVDEs
- The ATEC model solves most of the inconsistencies of the older models.
- It is assumed that Plasma Facing Components (PFC) separated by small gaps in the toroidal direction could be short circuited by the plasma where this touches the wall. In this way is established a parallel circuit for the current induced in the vessel to compensate the quenching plasma.
- The PFCs are located in front of the plasma current measurement sensors and thus the electric current which runs through the PFCs is seen as part of the plasma in sectors where this is in contact with the wall.

- The poloidal current from vessel to dump plates and back to vessel interacts with the toroidal field producing sideways forces



Schematic view of asymmetric toroidal eddy current patterns in JET structures during AVDEs. Top: toroidal section at vessel top; bottom: vertical section of the machine at octants 3 and 7.

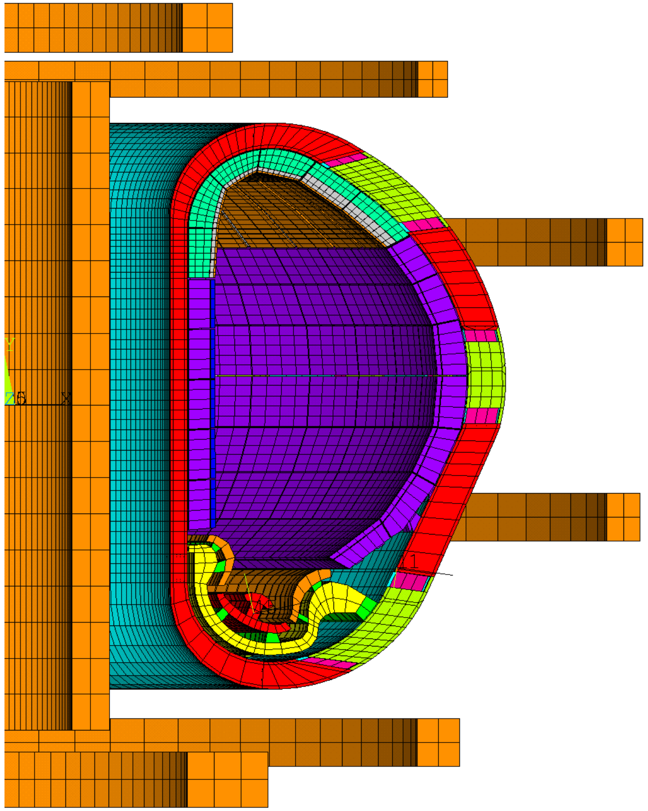
JET experimental data Vs simulation results

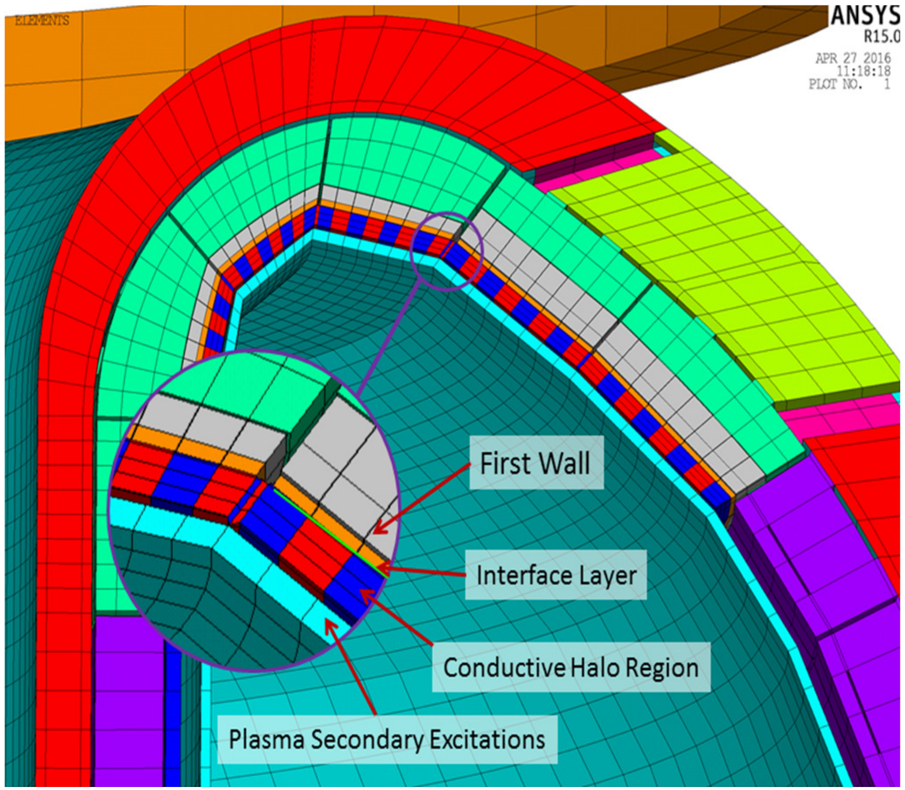
- When applied to the JET cases the ATEC model produces results which are consistent with many relevant measurements taken during asymmetric VDEs:
  - the measurement of plasma vertical position higher at the toroidal location where the plasma current is measured higher
  - The correspondence between the measured amplitude of the plasma current asymmetry and the inferred horizontal force acting on the vessel;
  - The phase relationship between the asymmetry of the plasma current and the asymmetry of the plasma current first vertical moment
  - The phase shift and the amplitude of the halo current (HC) asymmetry, demonstrating that plasma and HC asymmetries are two different measurements of the same current.
- The ATEC model is based on a simple assumption (net toroidal current flowing in the PFCs) (*Nucl. Fusion 56 (2016) 106010*)

ATEC model applied to ITER - Assumptions

- The plasma kink deformation has small effect on the on the loads (i.e. the simulated disruption is based on a DINA axisymmetric hot VDE with superimposed asymmetry of the first wall conduction)
- The halo and plasma current asymmetries are two symptoms of the same phenomenon so no HC asymmetry is included in the analysis
- Where the plasma wets the FW it does it for the full toroidal length of the panel (i.e. effect of shaping on the effective wetting is not taken into account)
- The conductivity of the plasma at the wall is evaluated with the Spitzer's formula and is the only variable parameter in the analyses

ATEC model applied to ITER - Model

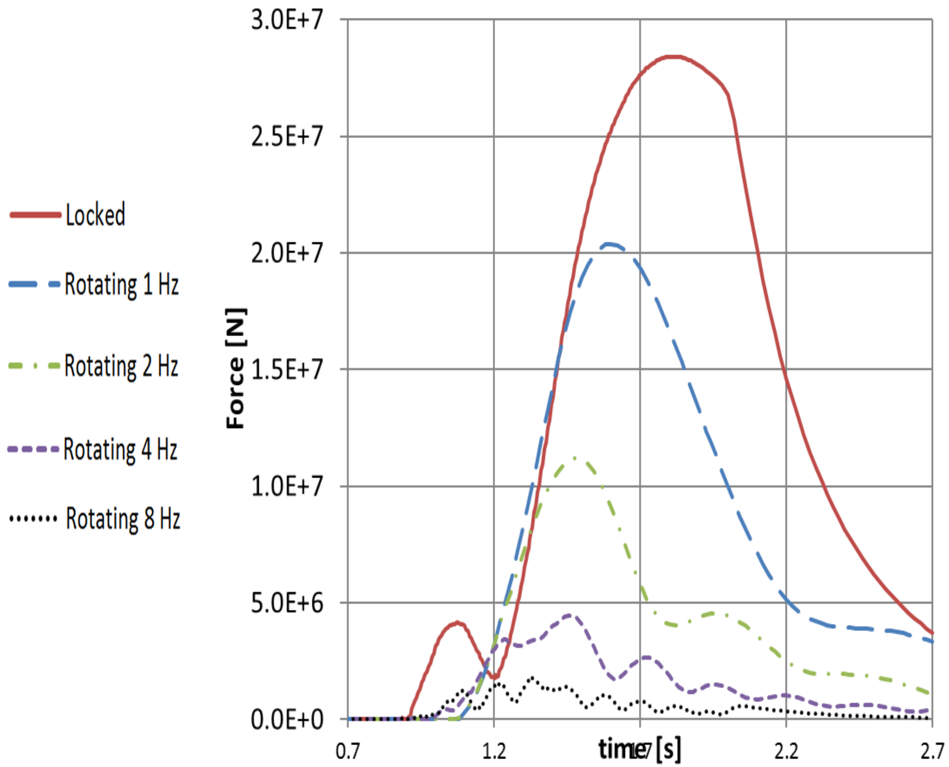


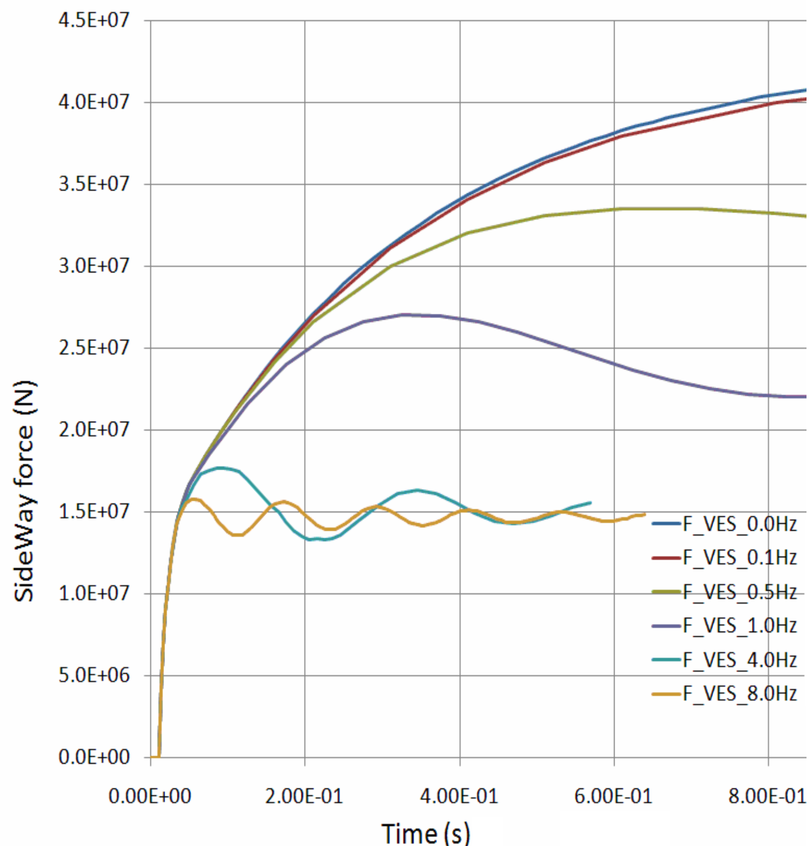


- Analyses are performed through FE EM simulations with a 360 degree model of ITER VV and in-vessel components
- The model is geometrically axisymmetric
- The asymmetry is imposed with an asymmetric distribution (in toroidal direction) of the contact between plasma halo region and structure

ATEC model applied to ITER – Forces on VV

Locked and rotating AVDEs have been simulated in ITER applying the ATEC model and results show important reduction of net forces and moments acting on the VV when compared to the results obtained with the older model (source&sink)

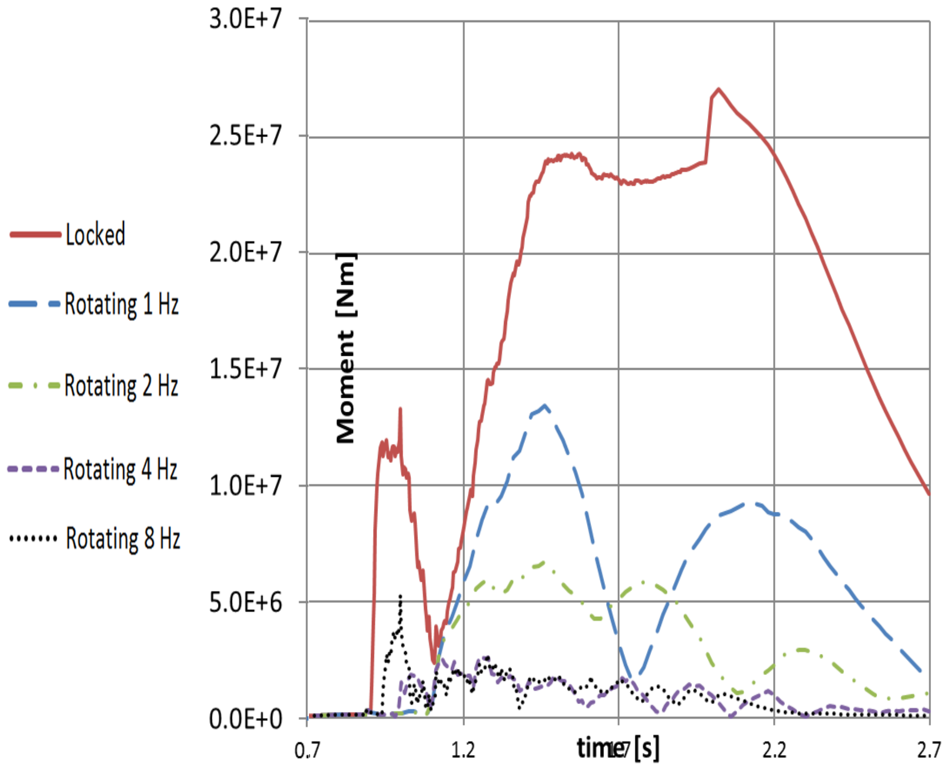




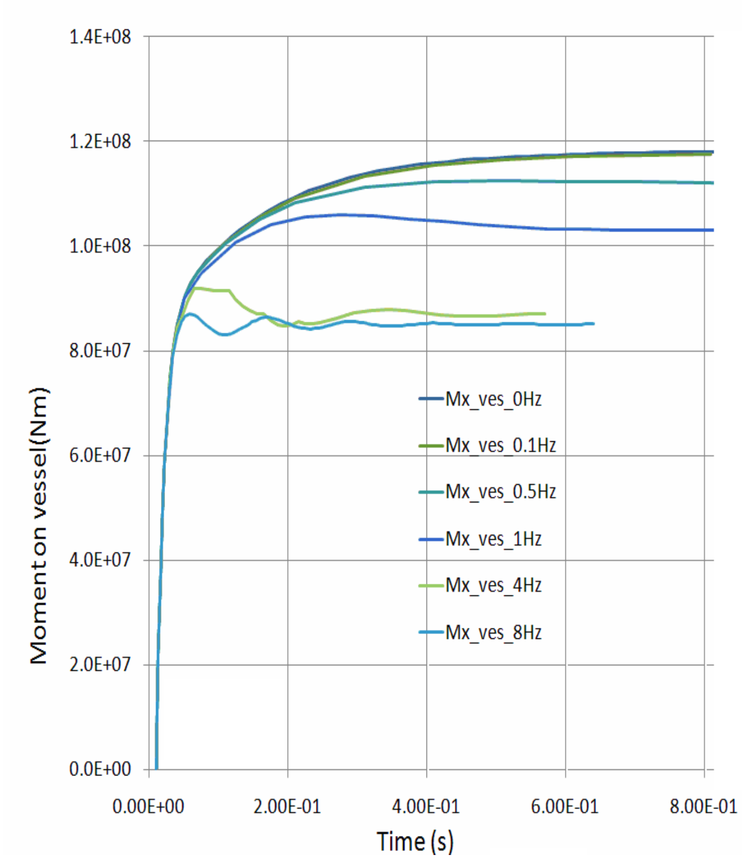
Horizontal Forces on the ITER VV by means of the ATEC model… *and by means of Source and Sink model*

ATEC model applied to ITER – Moments on VV

Maximum moments on the VV decrease about 5 times for locked AVDE up to 15 times for rotating AVDE at 8 Hz

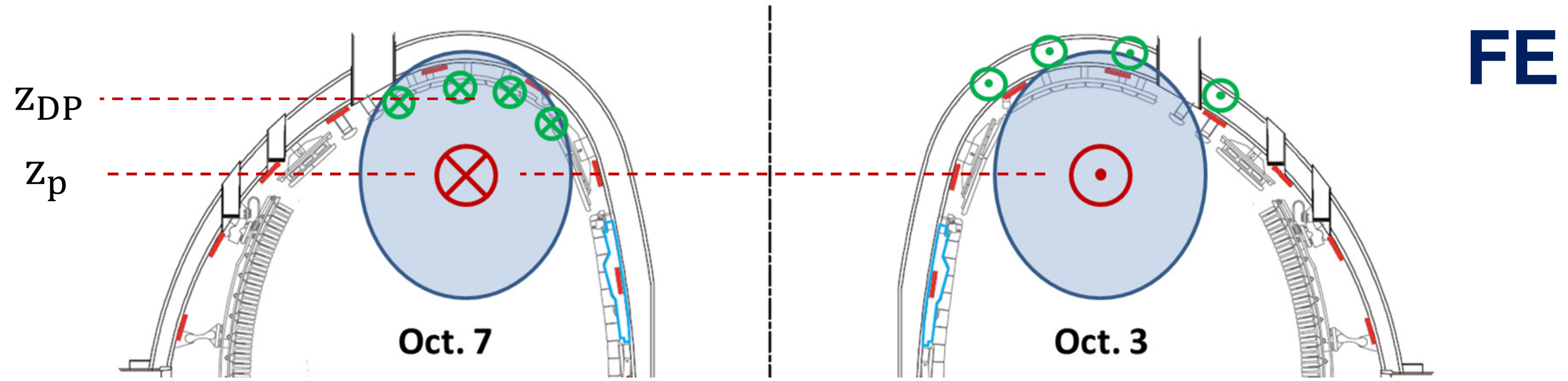


Horizontal Moment on the ITER VV by means of the ATEC model…

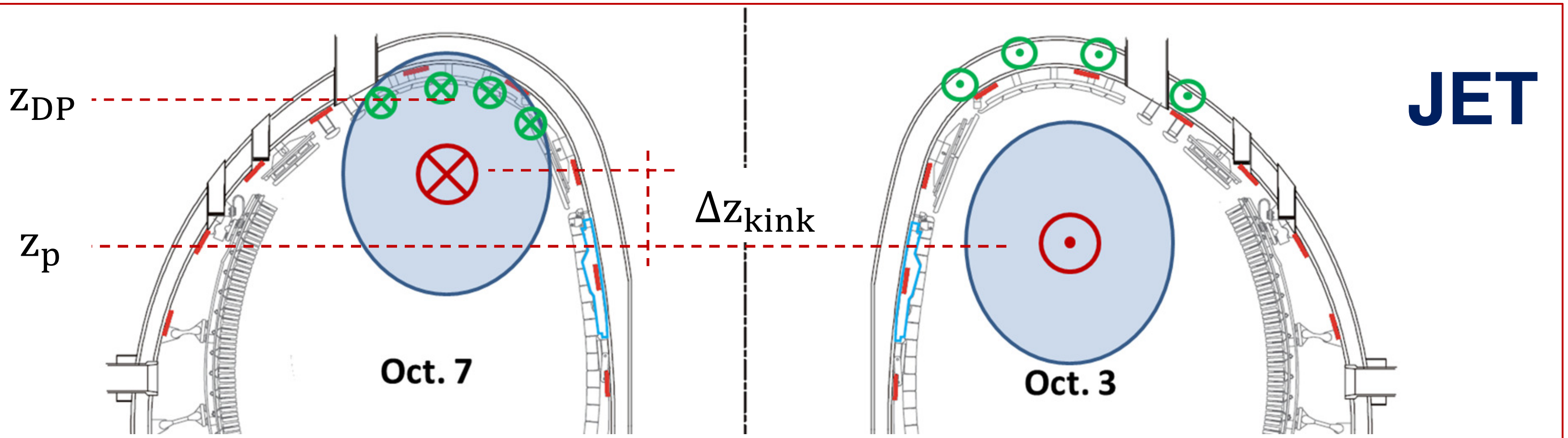


and by means of Source and Sink model

ΔIp vs ΔMIz in the in FE simulation and JET



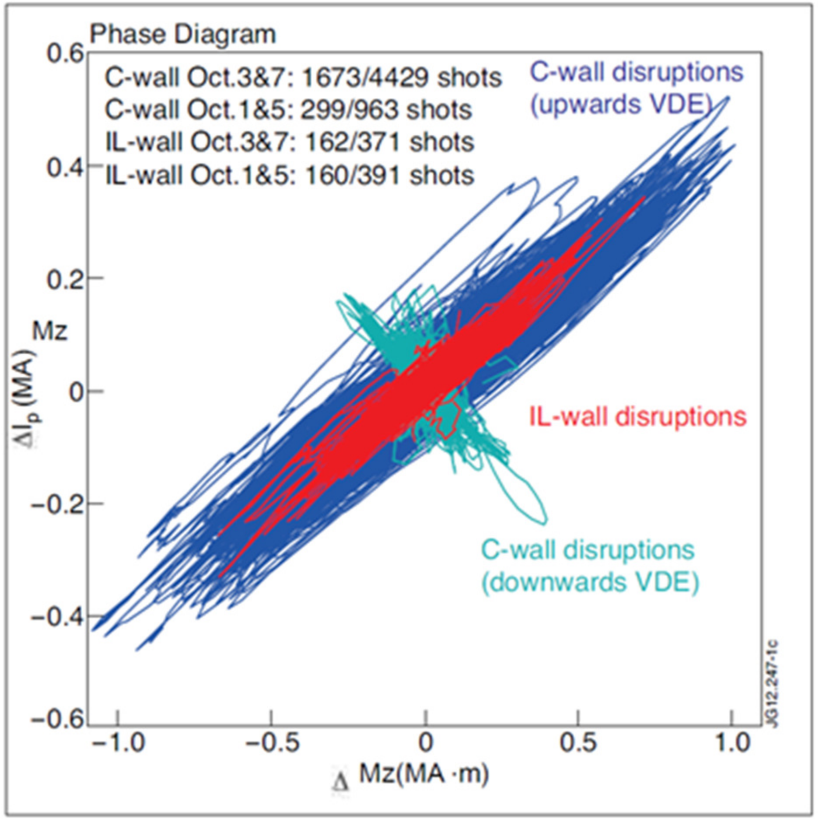
$$\Delta M_{Iz}^{FE} = M_{Iz}^{\pi} - M_{Iz}^{0} = I_p \cdot z_p + \Delta I_p \cdot z_{DP} - I_p \cdot z_p = \Delta I_p \cdot z_{DP} \rightarrow \frac{\Delta M_{Iz}^{FE}}{\Delta I_p} = z_{DP}$$



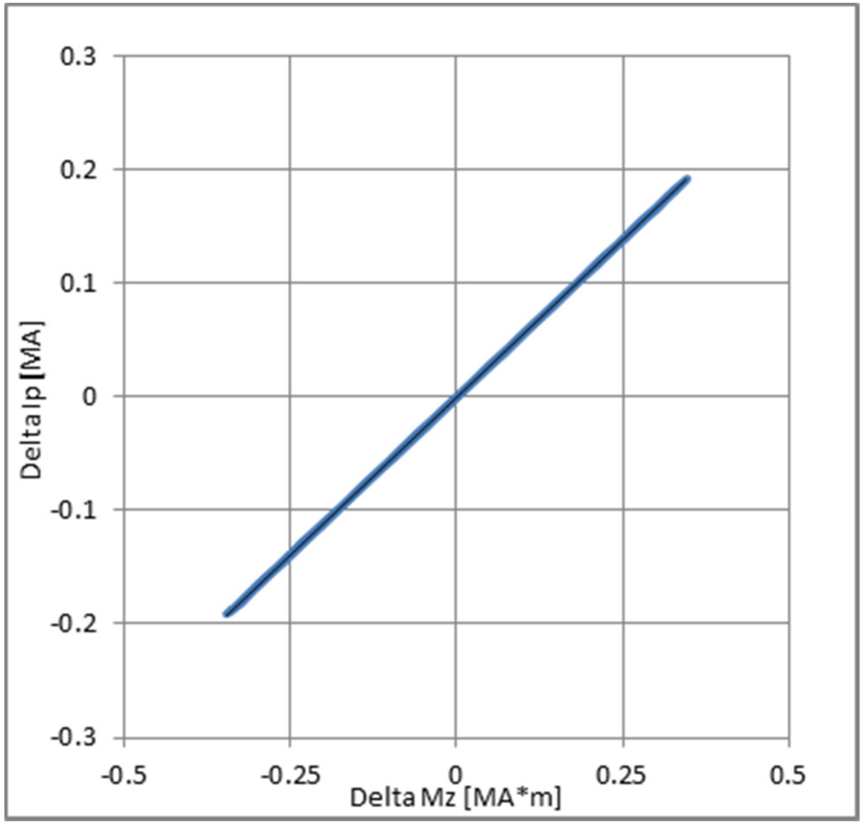
$$\Delta M_{Iz}^{JET} = I_p \cdot \left(z_p + \frac{\Delta z_{kink}}{2}\right) + \Delta I_p \cdot z_{DP} - I_p \cdot \left(z_p - \frac{\Delta z_{kink}}{2}\right) =$$

$$= I_p \cdot \Delta z_{kink} + \Delta I_p \cdot z_{DP} = \Delta M_{Iz}^{kink} + \Delta M_{Iz}^{FE}$$

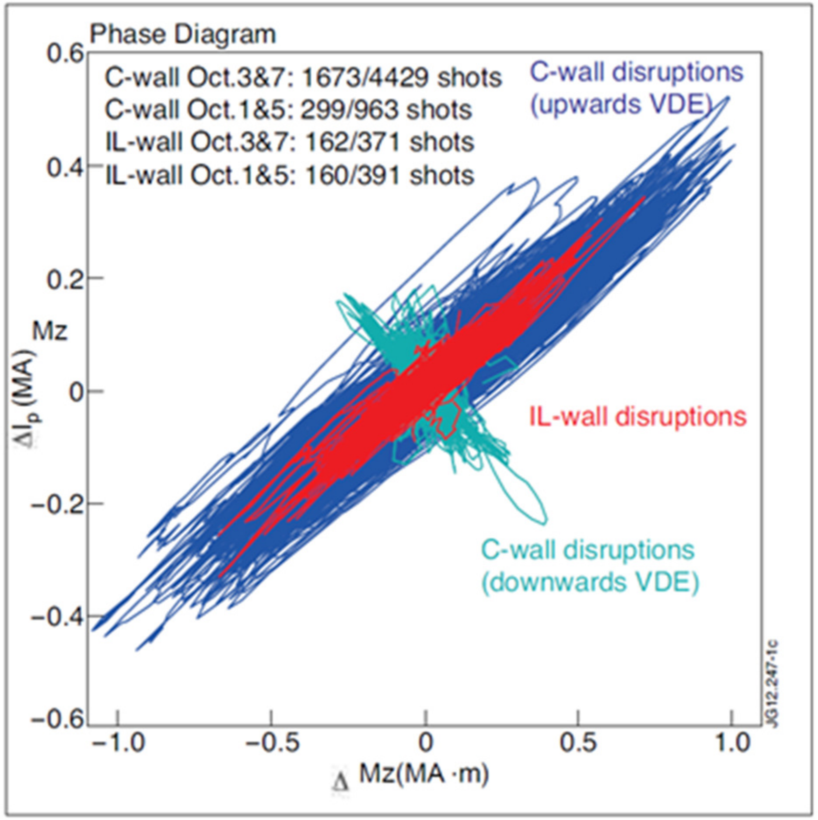
ΔIp vs ΔMIz in the in FE simulation and JET



S. N. Gerasimov, Nucl. Fusion 54 (2014) 073009



ΔI_p vs ΔM_{Iz} in the in FE simulation in ITER



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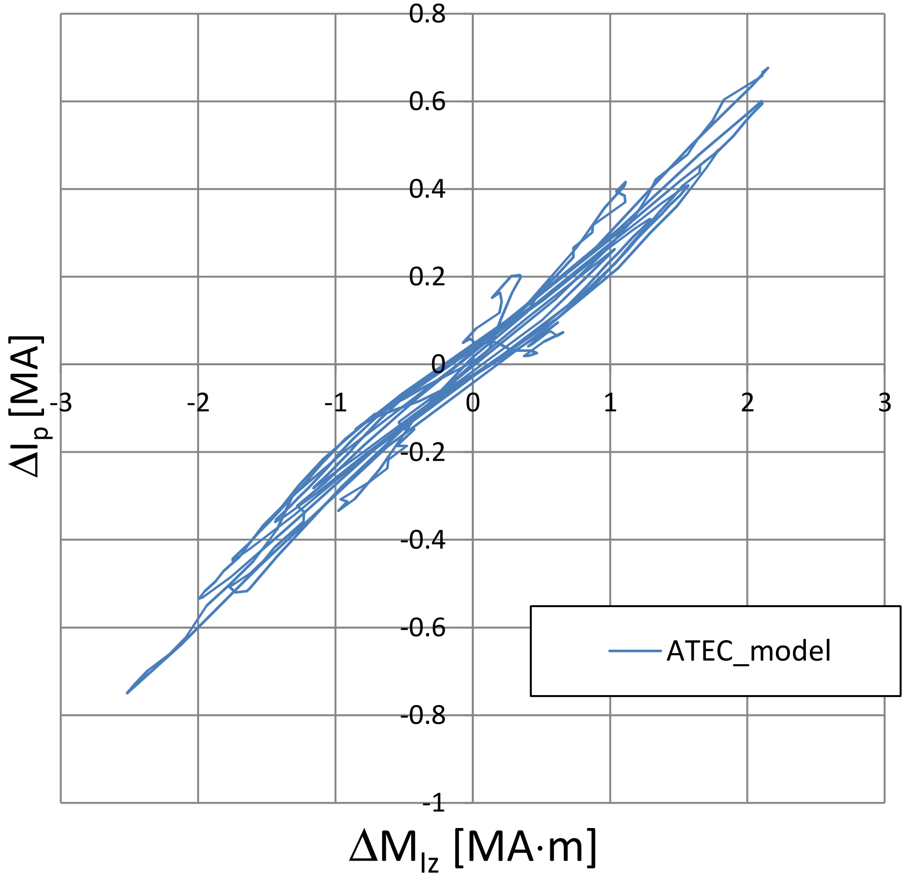
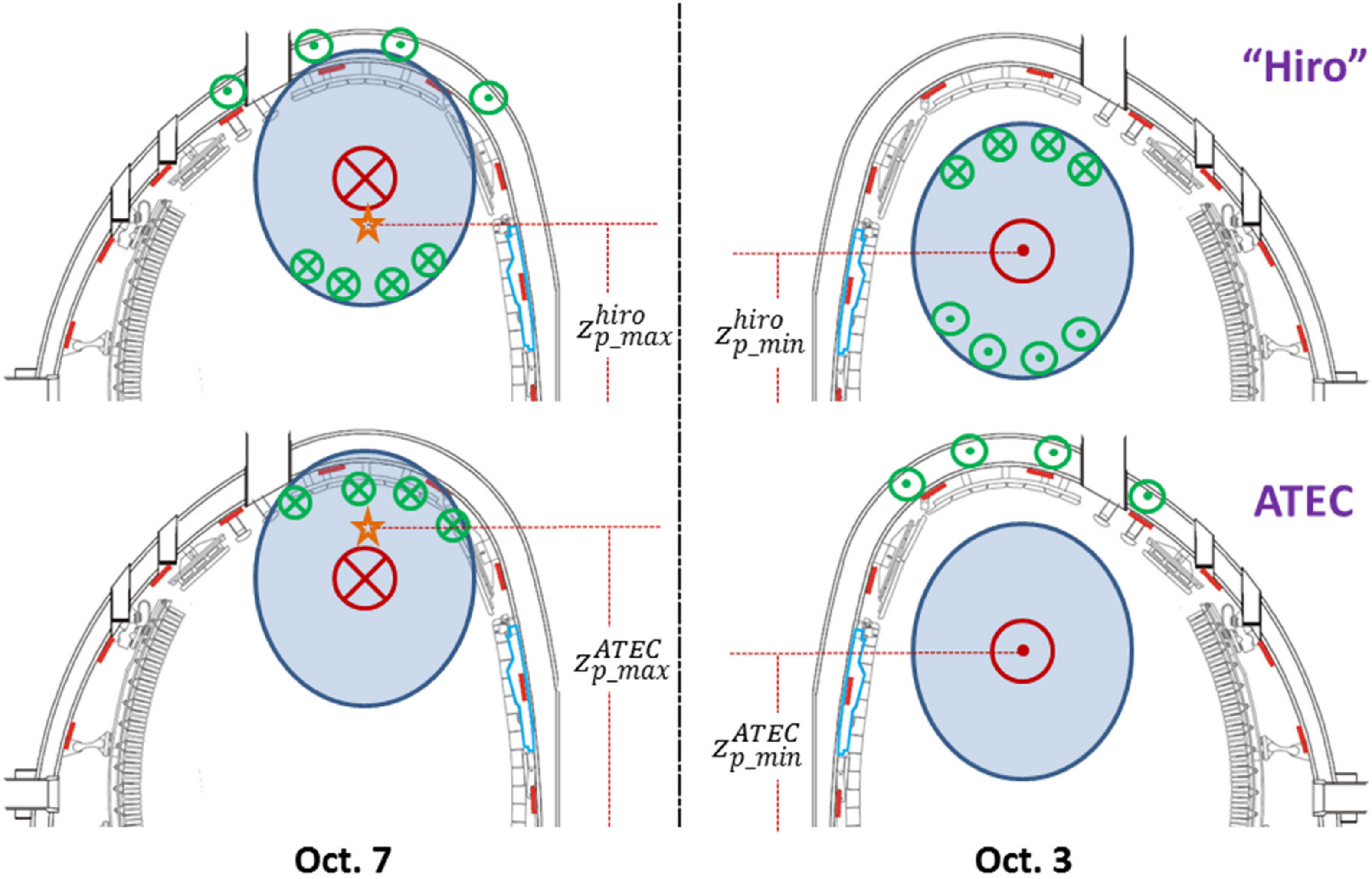
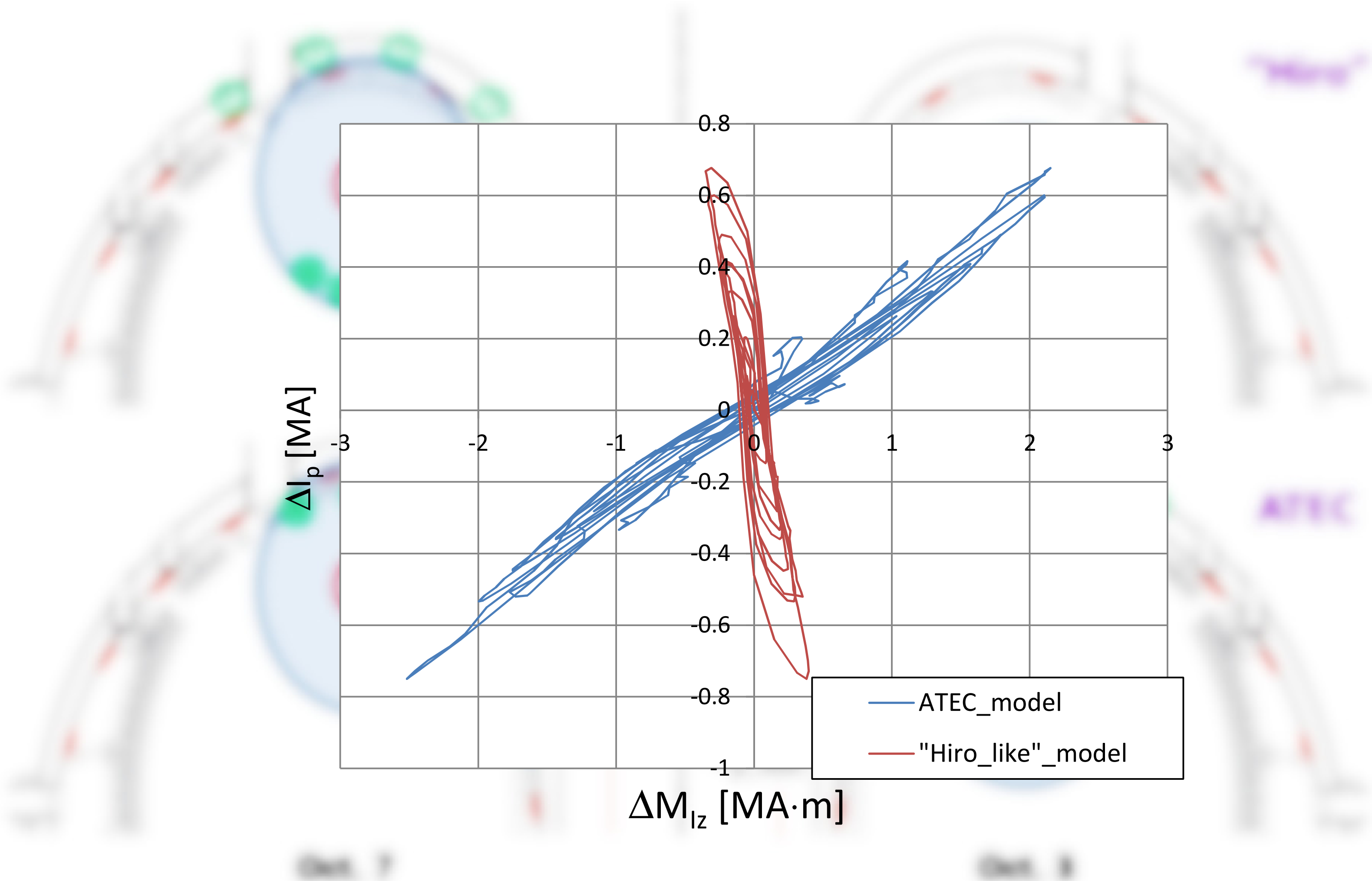


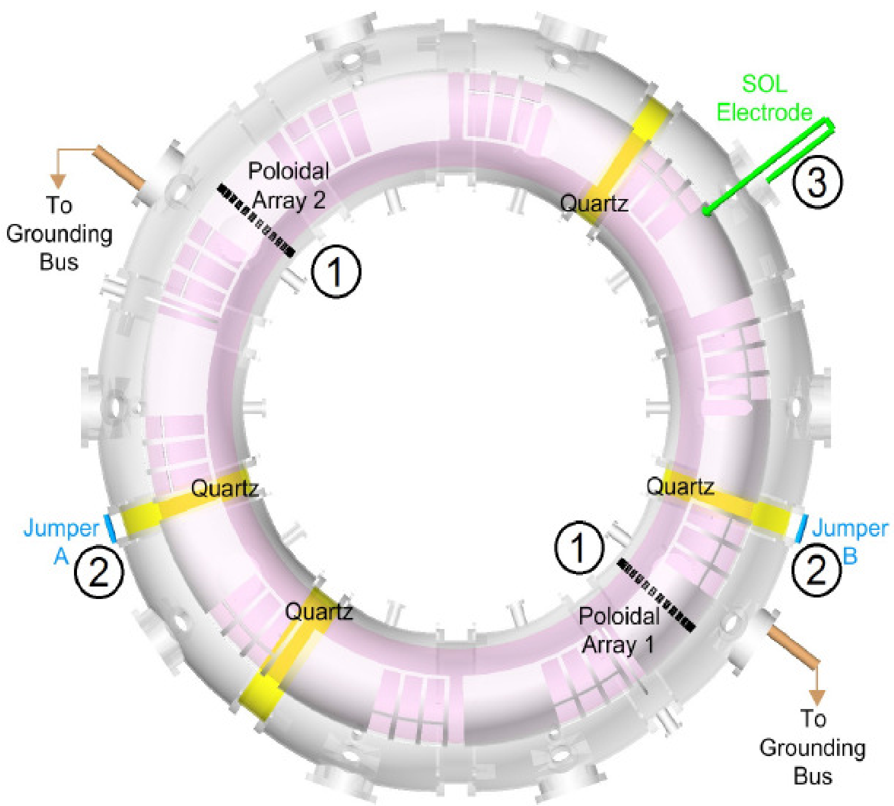
Surface currents and ATEC

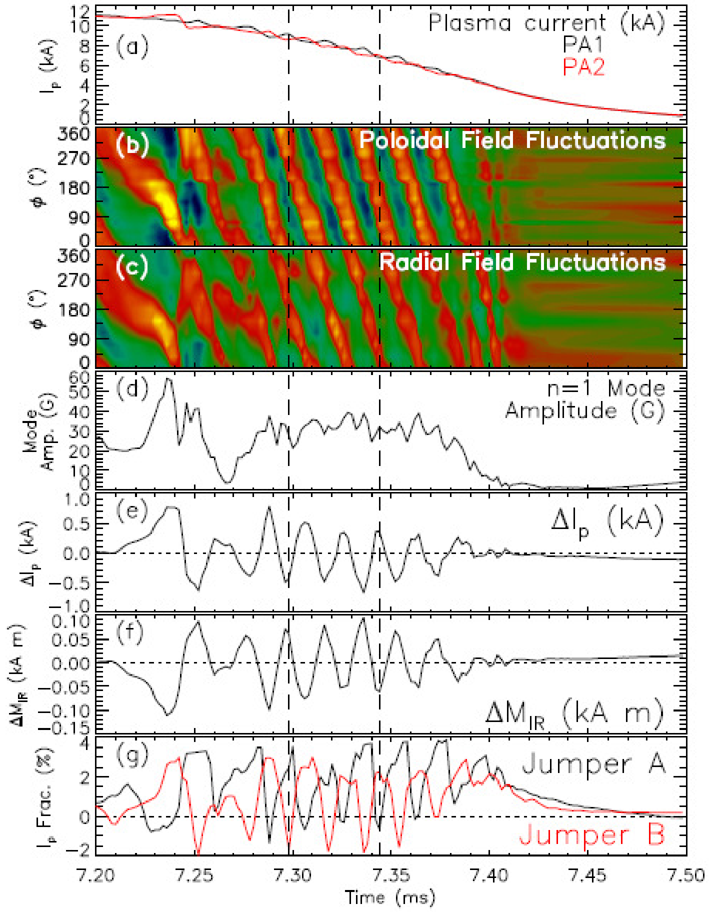


Surface currents and ATEC



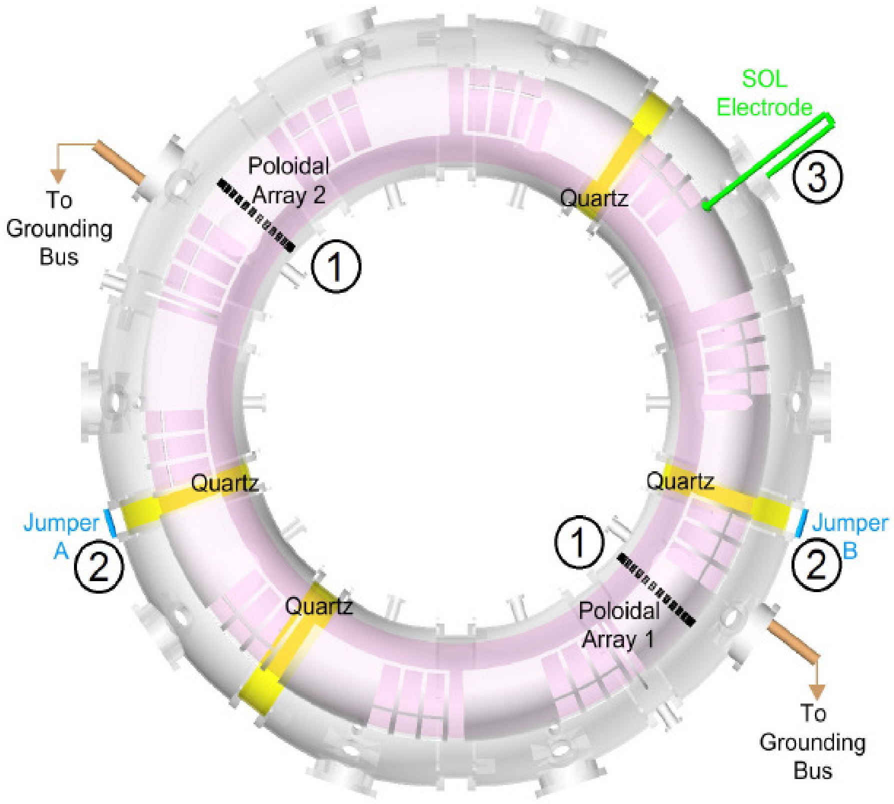
Experimental validation at HBT-EP

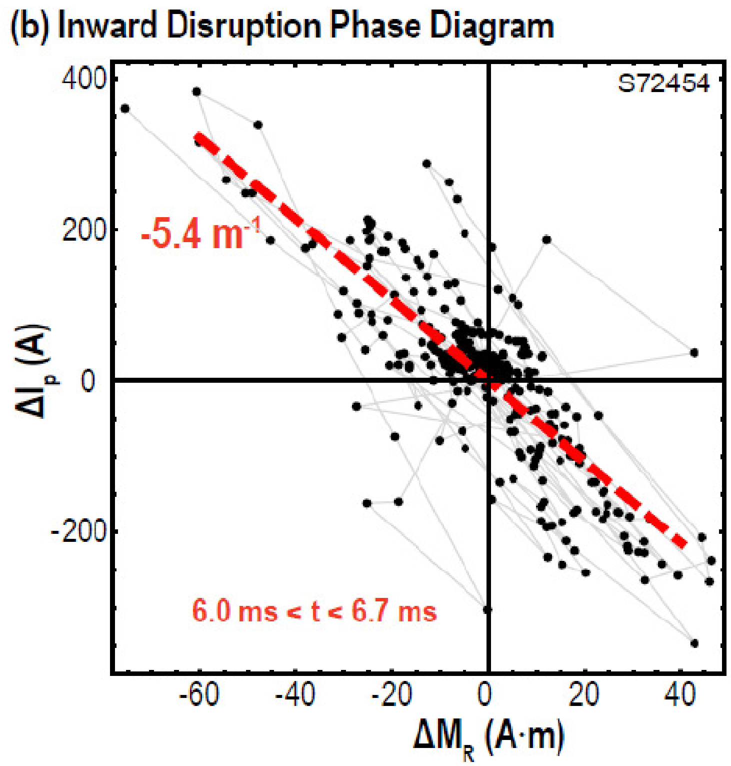




HBT-EP has the unique feature of insulating brakes at four locations around the vessel

Experimental validation at HBT-EP





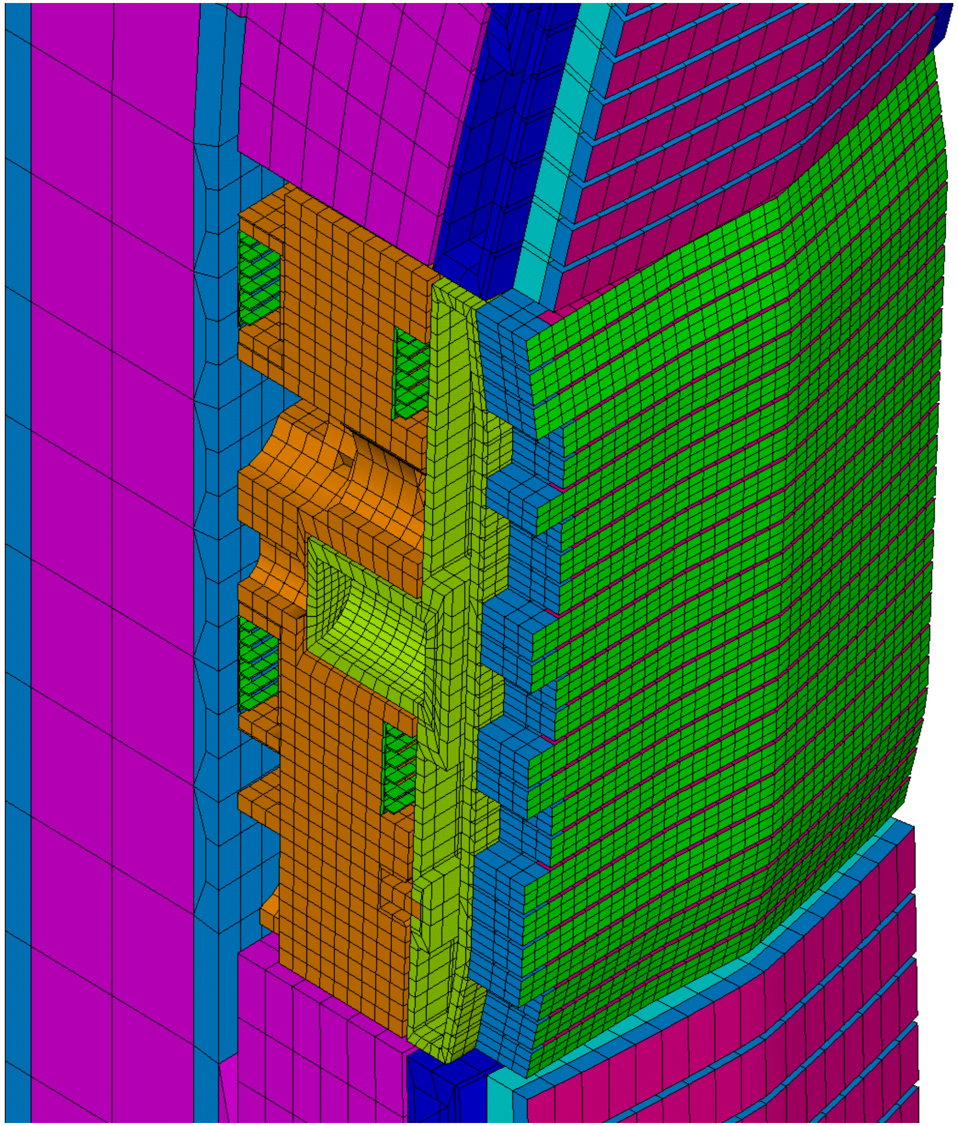
HBT-EP has the unique feature of insulating brakes at four locations around the vessel

Loads on internal components

- The net toroidal current flowing on FW panels will affect loads on BMs not only during asymmetric but also in case of symmetric events for two main reasons:
  - The interaction of the net toroidal current on the FW panels with the poloidal field resulting in a detaching radial force on the FW panels
  - The sudden field variation seen by the BMs at the end of the disruptions when the conduction between adjacent FW panels cannot be anymore sustained by the plasma current
- The loads on some BM rows (1, 18 in case of downward VDEs and 7 to 9 in case of upward VDEs) could increase significantly
- On the other hand all loads transferred by the VV movements (VDE generated acceleration spectra) to all the components attached to the VV but not affected by direct EM loads will be greatly reduced

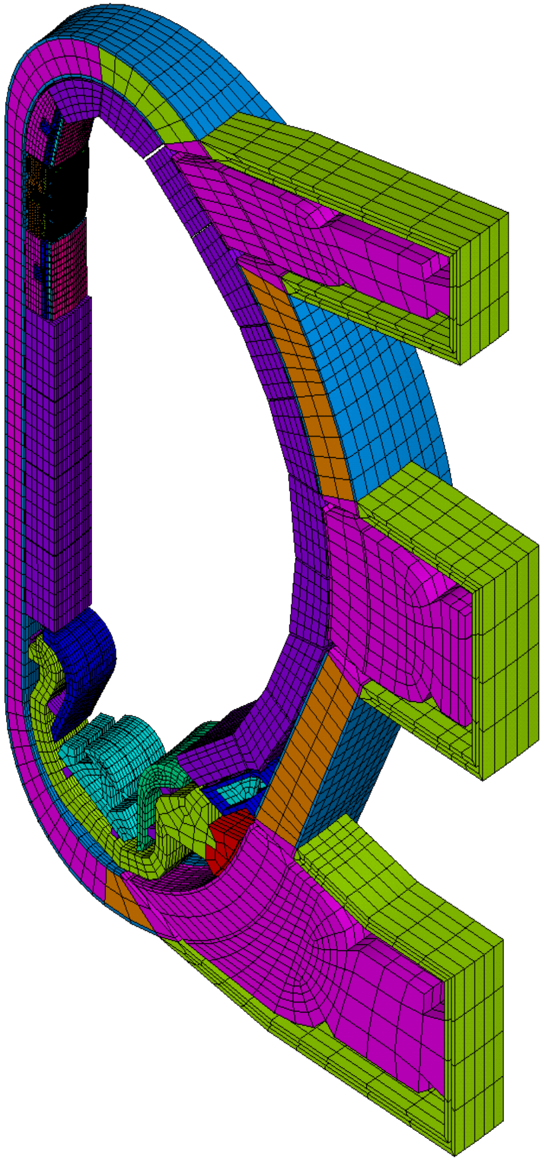
Effect of FW current on Blanket Modules – FE model of BM#6

This model is among the ones prepared to assess detailed EM loads on BMs during disruptions (minimum size of elements in finger gaps = 2 mm)



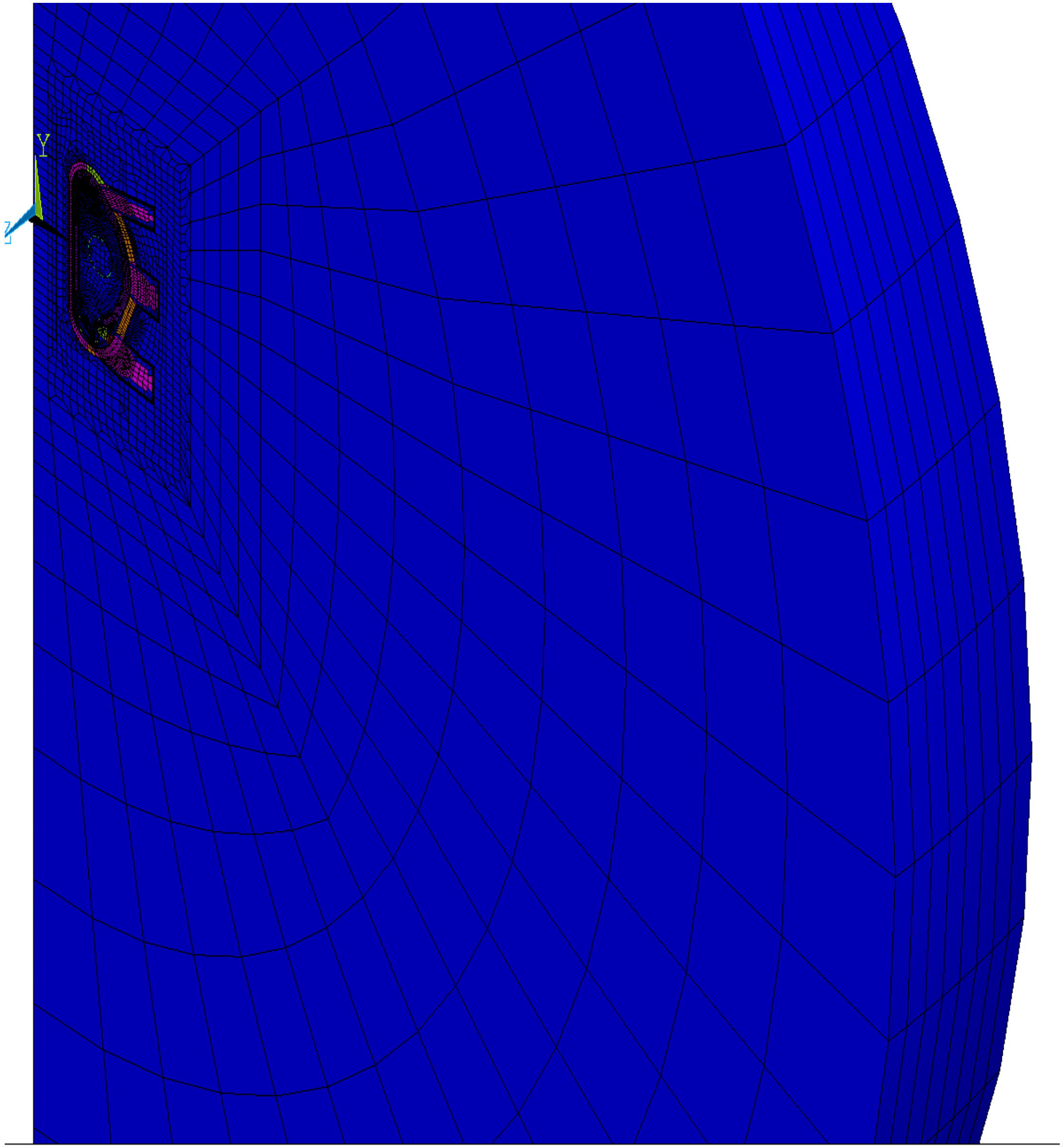
Effect of FW current on Blanket Modules – FE model of BM#6

The BM model is included in a 10 degree sector of the ITER VV with details of all main conductive structures (vertical dimension of the VV ~ 12 m)



Effect of FW current on Blanket Modules – FE model of BM#6

The structures are immersed in the vacuum which is modelled up to about 80 m from the machine axis



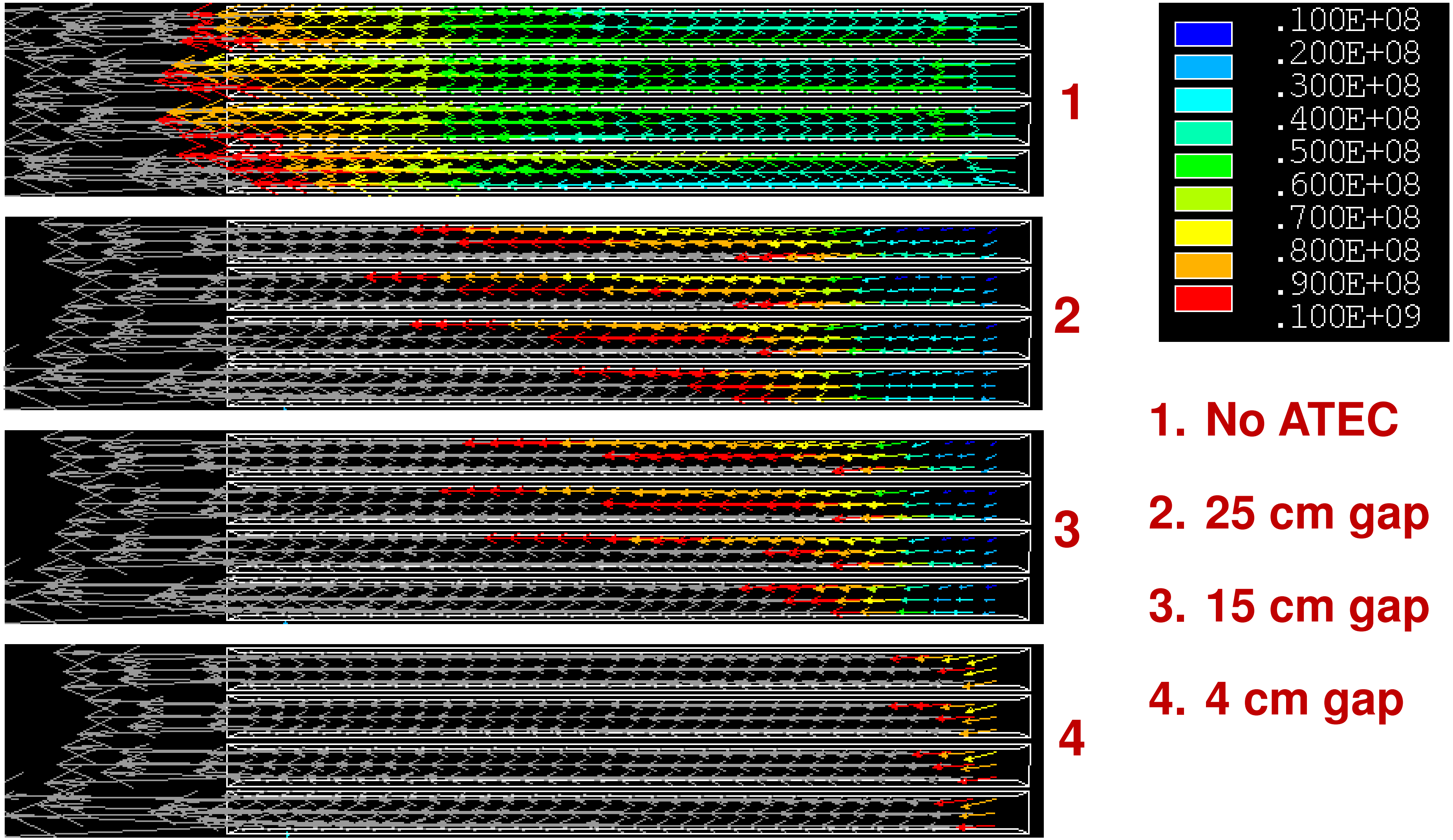
Effect of FW current on Blanket Modules – Analyses

Several parameters can affect the loads on the BM:

- The current quench duration
- The poloidal location (whether and for how long the BM would be affected by FW current)
- Toroidal location (in case of locked AVDE) as this affects the main induced current paths (mainly toroidal or radial/poloidal current)
- Plasma resistivity in the gaps
- Effective extension of the gaps because of the FW shaping

The following results refer to inboard poloidal locations (BM#6/7) in case of locked asymmetric (locking in front of the analyzed BM) during fast upward Asymmetric VDE.

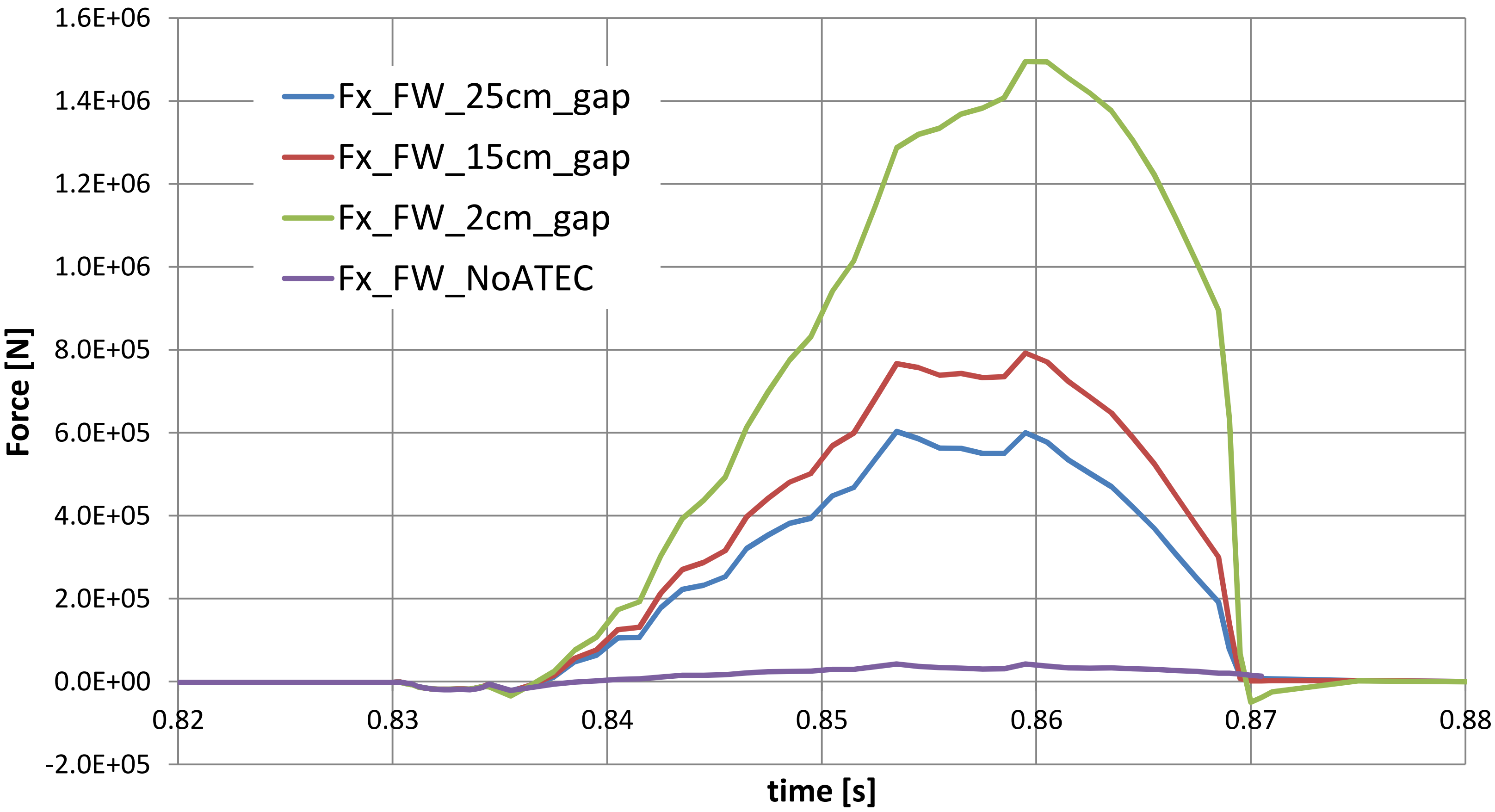
Effect of FW current on Blanket Modules – Results



1. No ATEC
2. 25 cm gap
3. 15 cm gap
4. 4 cm gap

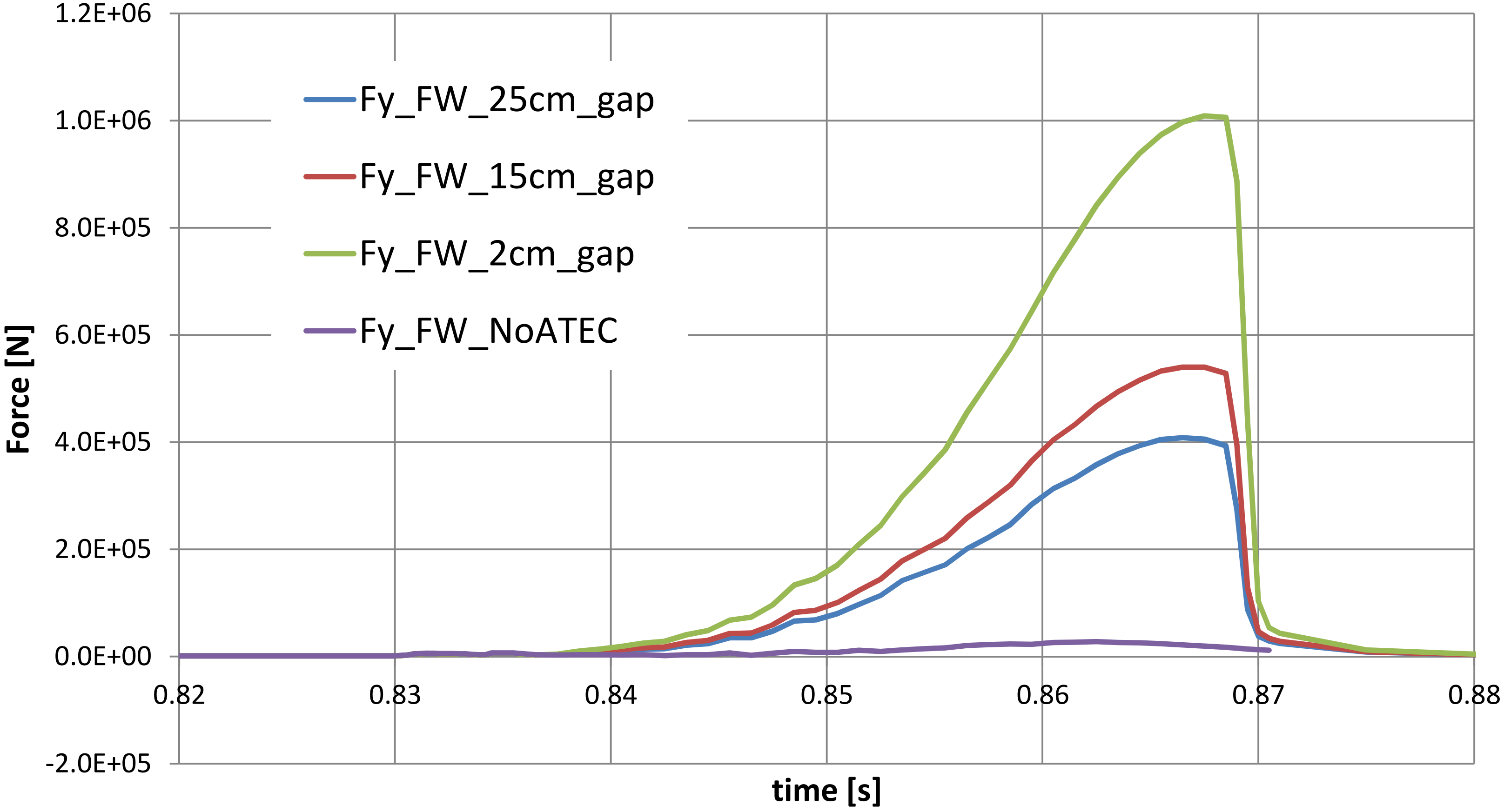
Induced current density (A/m^2) on FW central fingers for decreasing gaps

Effect of FW current on Blanket Modules – Results



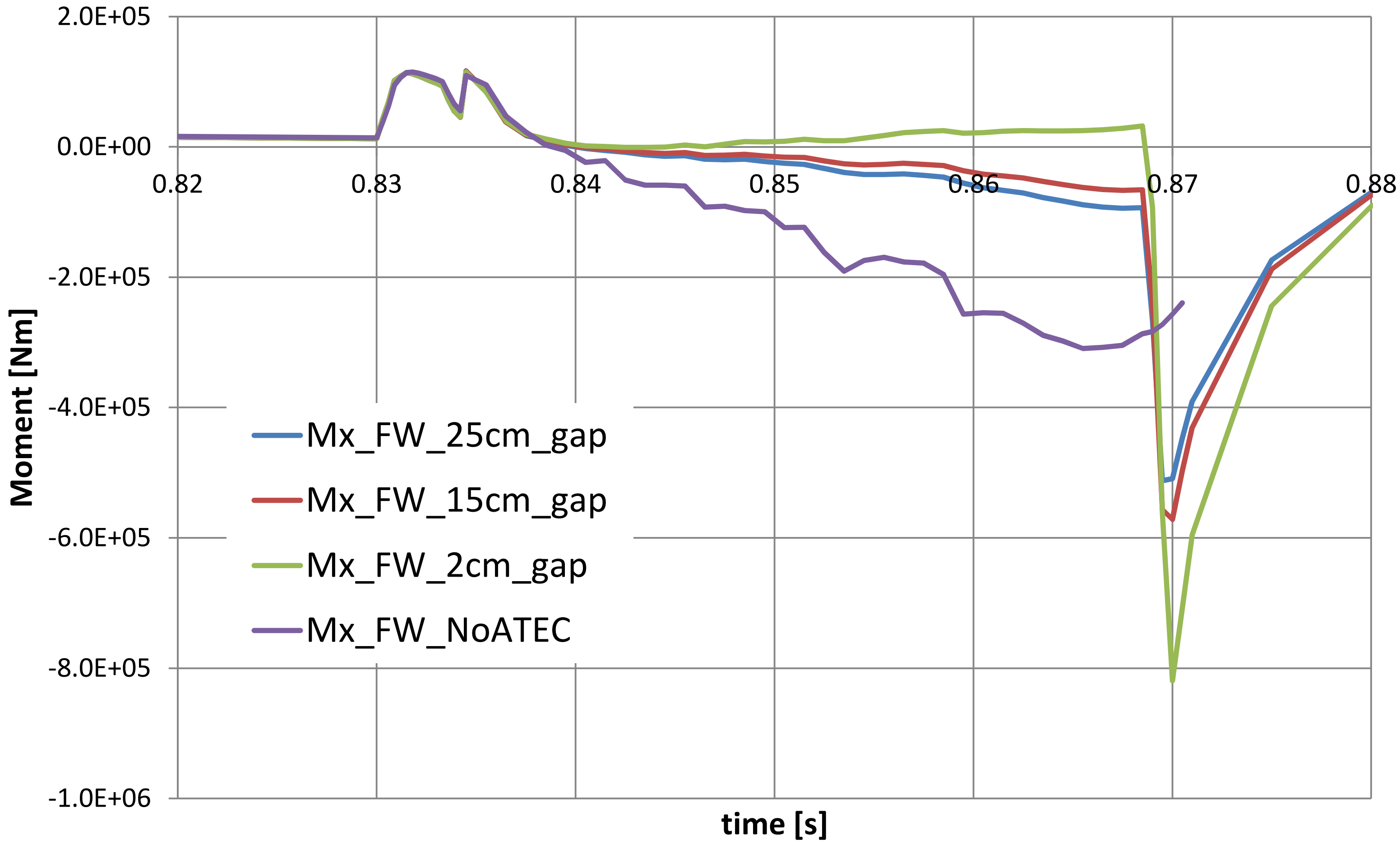
Radial force on the First Wall panel (detaching force)

Effect of FW current on Blanket Modules – Results



Poloidal force on the First Wall panel

Effect of FW current on Blanket Modules – Results



Radial force on the First Wall panel (detaching force)

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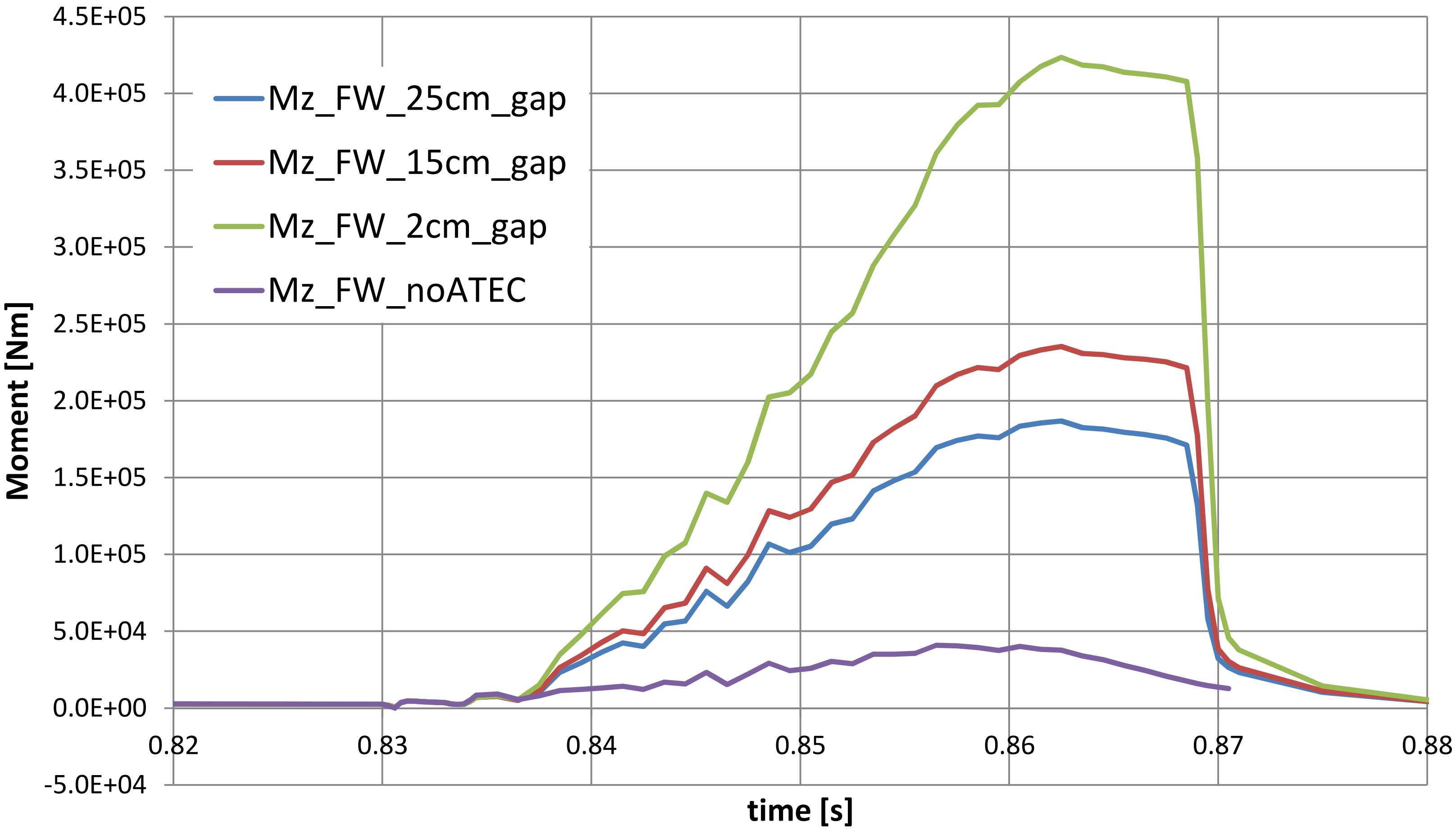

Effect of FW current on Blanket Modules – Results