Sideways force caused by Asymmetric Toroidal Eddy Current

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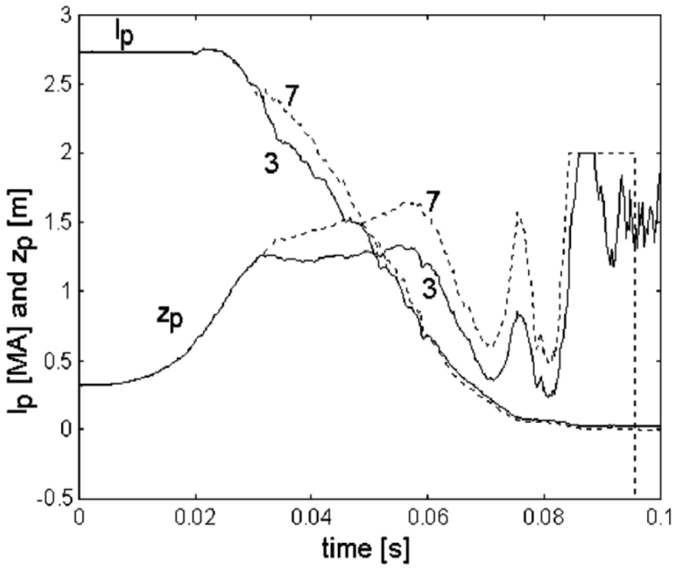
Sideways forces at JET

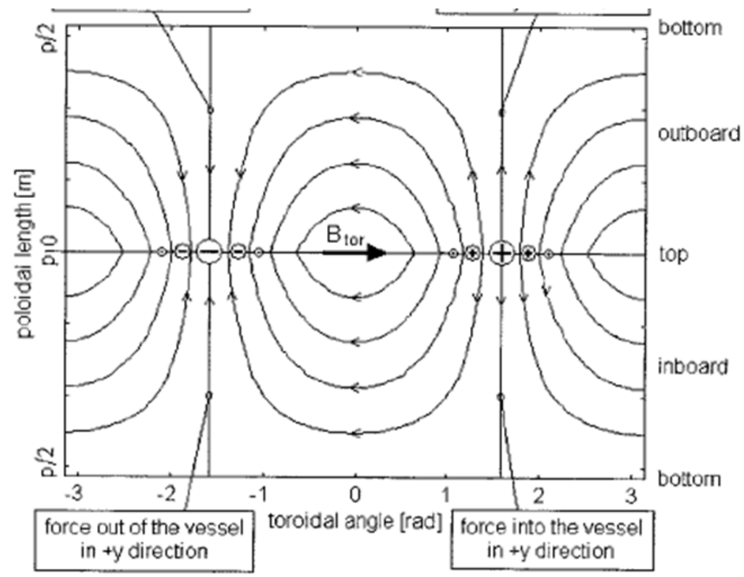
- Sideways forces are experienced at JET associated to Asymmetric VDEs (mostly upward VDEs after installation of divertor)
- During AVDEs plasma current and position are measured asymmetric in toroidal direction
- Sideways force peak 3~4 MN (horizontal) is inferred from mechanical measurements.



Locked AVDE of pulse 38070 with vertical position (z_p) and plasma current (I_p) measured at opposite octants (3 and 7)

Source and sink model

- Basic assumption is that the sideways force is caused by exchange of current between plasma and vessel.
- the plasma, while dispacing vertically during a VDE, touches the inner wall of the VV in a narrow region close to the top.
- The wetting ring is the area of the asymmetric current exchange with the vessel



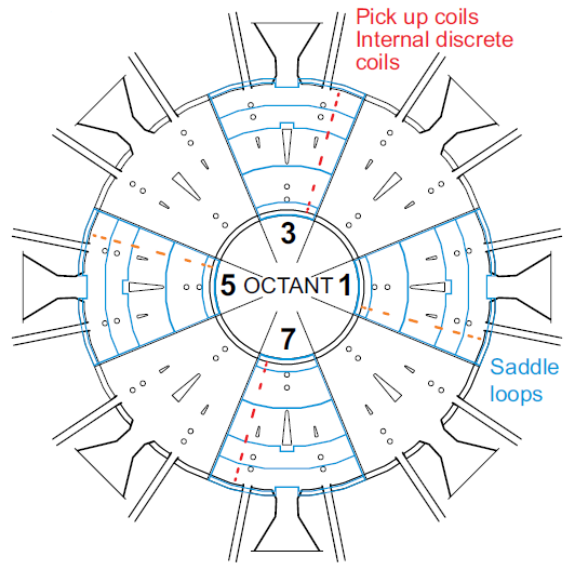
Source and sink asymmetric current pattern in the vessel asymmetric.

Main AVDE measurements at JET

- Asymmetry of toroidal plasma current through measurement of plasma current in two or four octants by means of 18 (red) internal discrete coils (IDC)[1]:

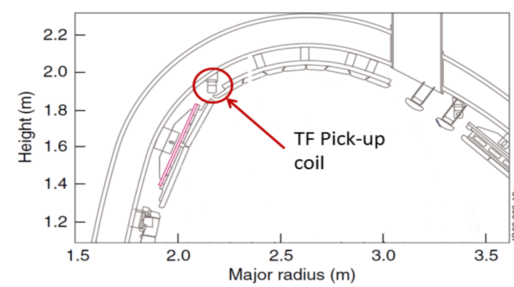
$$I_p = \frac{1}{\mu_0} \sum_{i=1}^{18} B_{\theta i}\, d_i ;$$

$$I_p^{asym} = \sqrt{(I_{p7} - I_{p3})^2 + (I_{p5} - I_{p1})^2}$$



- First plasma current vertical (and radial) moment which gives the position of the plasma centroid normalized over the total current:

$$M_{IR} = \int Z J_\varphi \, dR dZ ; M_{IR} = \int R J_\varphi \, dR dZ$$



- Halo current measured in two or four octants by means of a toroidal field pick-up coil

Outstanding issues

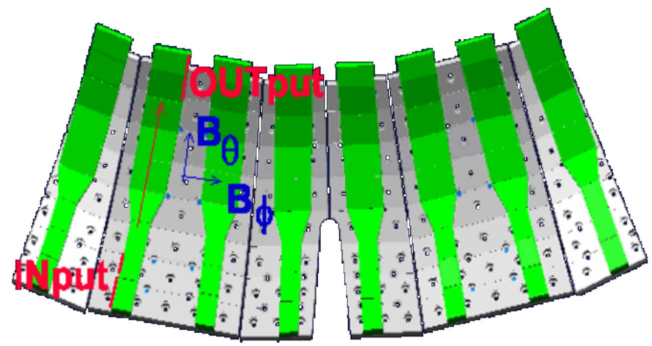
- The measurement of higher vertical position of plasma column where plasma current is higher is not well explained (explained qualitatively by surface currents)
- In asymmetries dominated by m=n=1 mode ΔM_{IZ} *and* ΔM_{IR} *should be comparable but is not the case* ($\Delta M_{IZ} >> \Delta M_{IR}$)
- Phase relationship between ΔM_{IZ} and ΔI_p cannot be explained
- The large spread correlation between plasma and halo asymmetry has no clear explanation

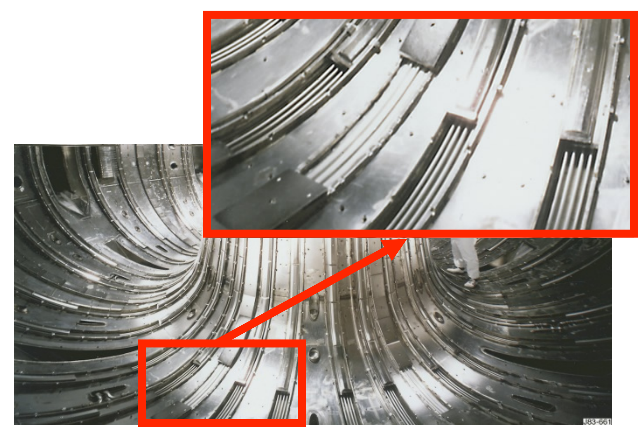
JET geometry

We focused on the specific JET geometry to find a possible mechanism behind the experienced sideways forces:

The upper in vessel structure is made by thick inconel dump plates protected by CFC tiles separated by small poloidal gaps

Vessel sectors are separated every ~12 degrees by high resistance bellows (increasing toroidal resistivity)



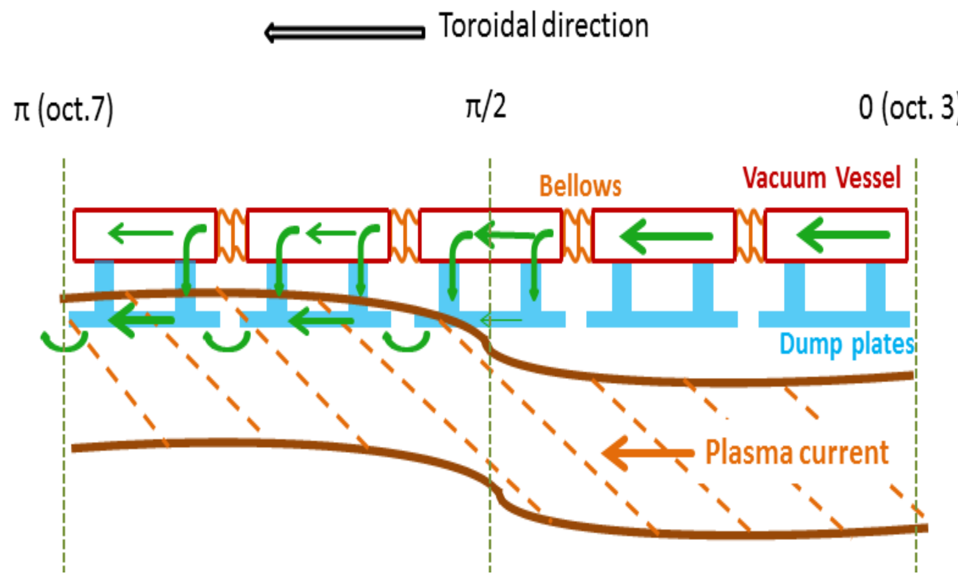


Asymmetric toroidal eddy currents

Plasma asymmetric instabilities (typically m=n=1 mode) imply toroidal asymmetry of the PFCs surface wetted by the plasma.

It is possible that in the wetted area due to plasma conductivity (depending on plasma temperature) the poloidal gaps between adjacent dump plates are short circuited by the plasma

Significant net toroidal current could flow in the dump plates placed in the upper region

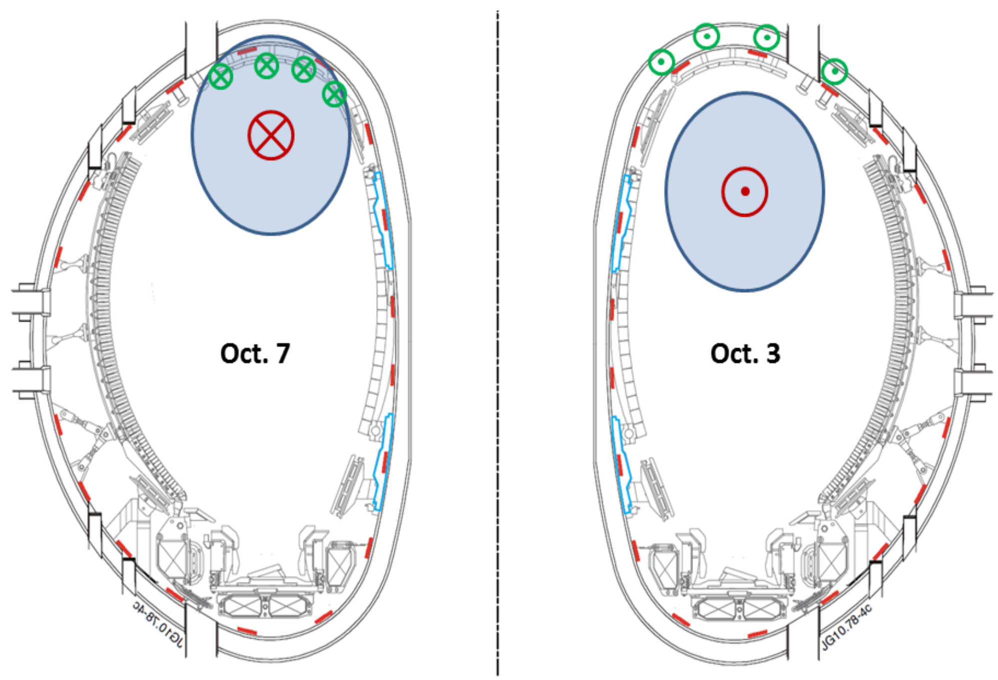


Measured plasma current asymmetry

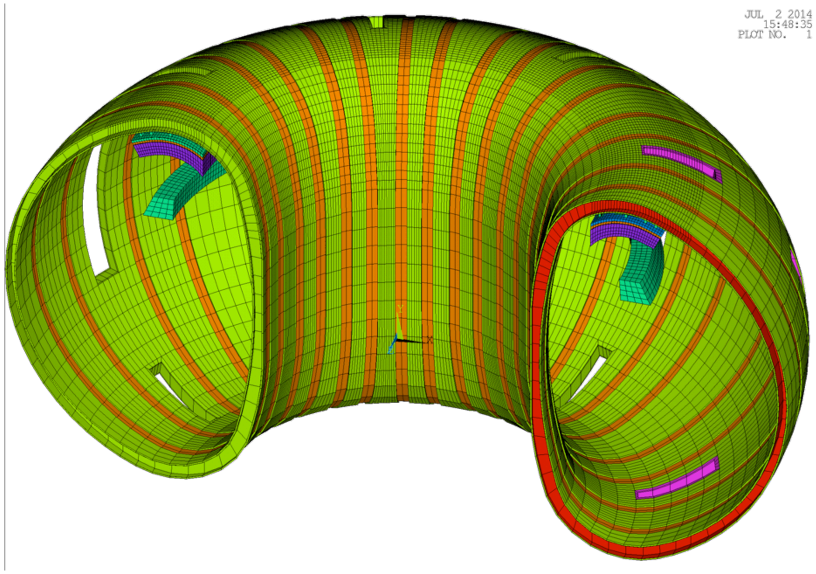
Reason of the plasma current measured asymmetry:

in octant 3 the whole induced toroidal current flows in the vessel and only the plasma current is measured;

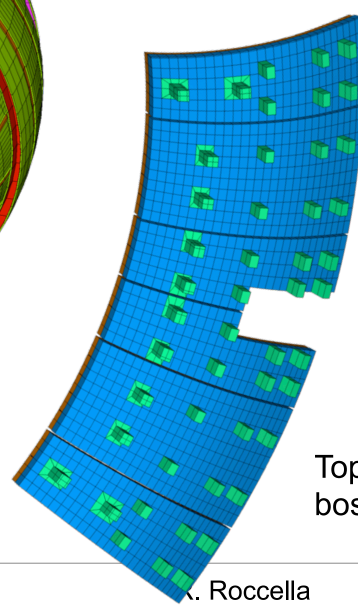
in octant 7 the part of induced current which flows toroidally in the dump plates falls inside the countour of in-vessel poloidal pick-up coils (in red) and thus measured as part of plasma current.



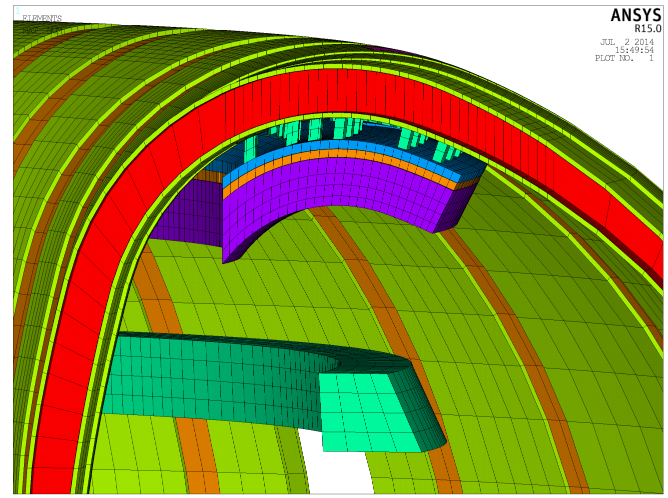
FE model (JET) for ATEC calculation



View of conductive structure as it is modeled in the FE



Top view dump plates (with bosses) in one octant



upper in-vessl structure and simplified plasma

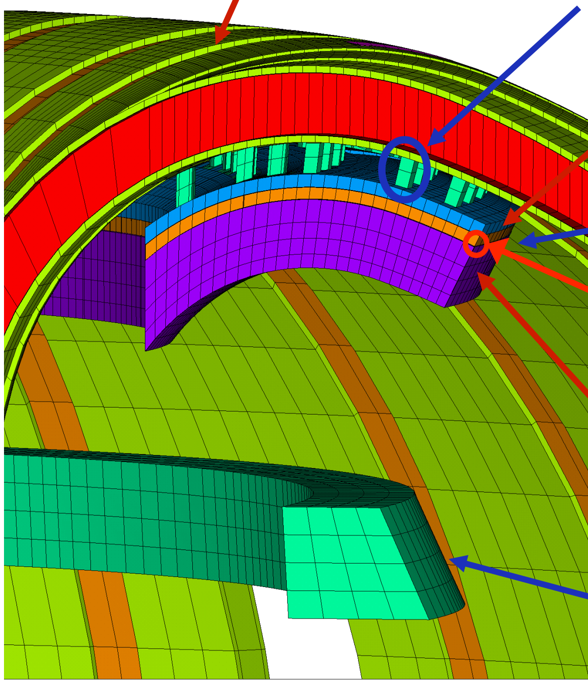
FE model details

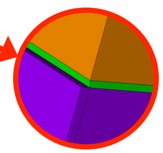
Double shell Vessel with ribs and bellows

Bosses (about 8 cm length)

Top dump plates (~80 cm in poloidal direction, 3 cm thick)

CFC tiles (3 cm thick)

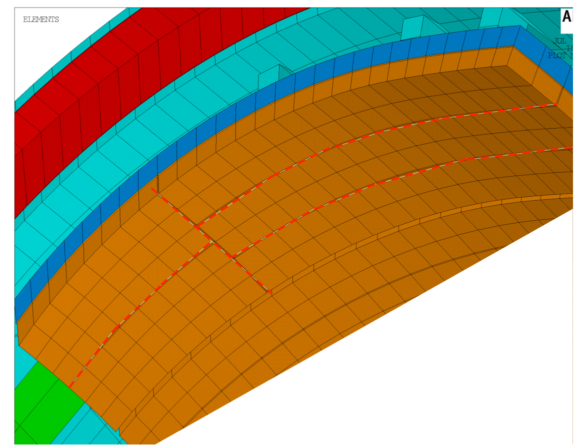




2 mm interface layer (green)

Halo region (15 cm thick)

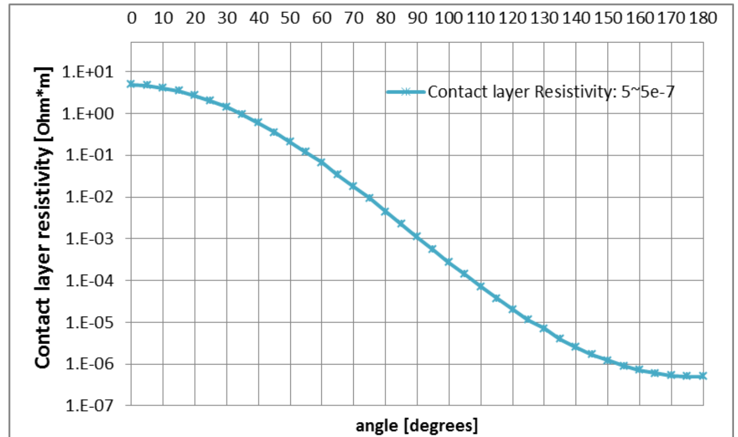
Axisymmetric plasma displaced vertically to the position it has when the asymmetry starts (1.25 m)

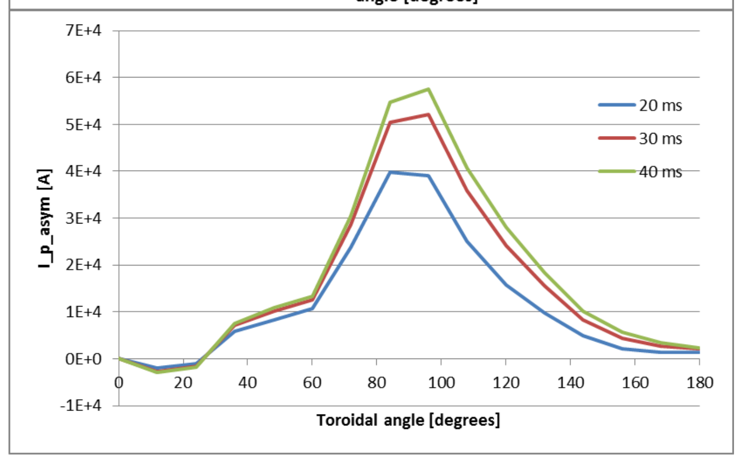


Details of the CFC tiles segmentation

Simulation of the plasma asymmetry

- In the FE model both plasma and halo region are axisymmetric.
- The asymmetry is introduced by changing in toroidal direction the resistivity of the thin (2mm) contact layer elements between CFC tiles and halo region.
- The law of resistivity change is the blue curve (top) and is the same for all simulations.
- This causes the peak of aymmetric current to be around 90 degrees like in the source and sink model (bottom picture).





FE analysis: material properties

Components resistivities:

- CFC tiles: 5*10-6 Ω·m
- Inconel structures: 1.3*10-6 Ω·m
- Vessel bellows (radial and poloidal direction): 1.4*10-6 Ω·m
- Vessel bellows (toroidal direction): 5*10-6 Ω·m

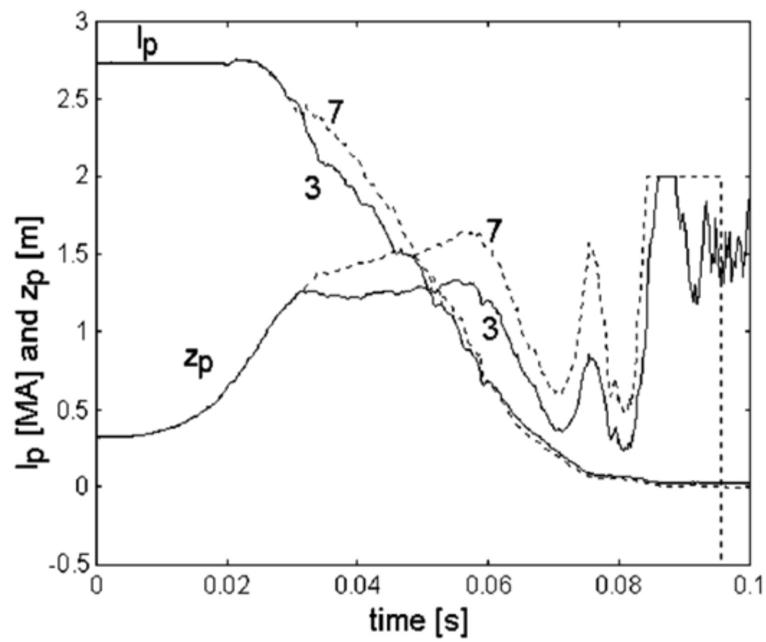
- The halo region resistivity is evaluated through the Spitzer's formulas:
  - $\eta_{\|} = 2.8 \cdot 10^{-8} / T_e^{3/2}$ resistivity in toroidal direction
  - $\eta_{\perp} = 1.96 \cdot \eta_{\|}$ resistivity in poloidal and radial direction

Several cases have been analysed with electron temperature in the range between 0.005 and 0.02 keV

Locked AVDEs Analysis

The simulations aim to reproduce JET pulse 38070 disruption:

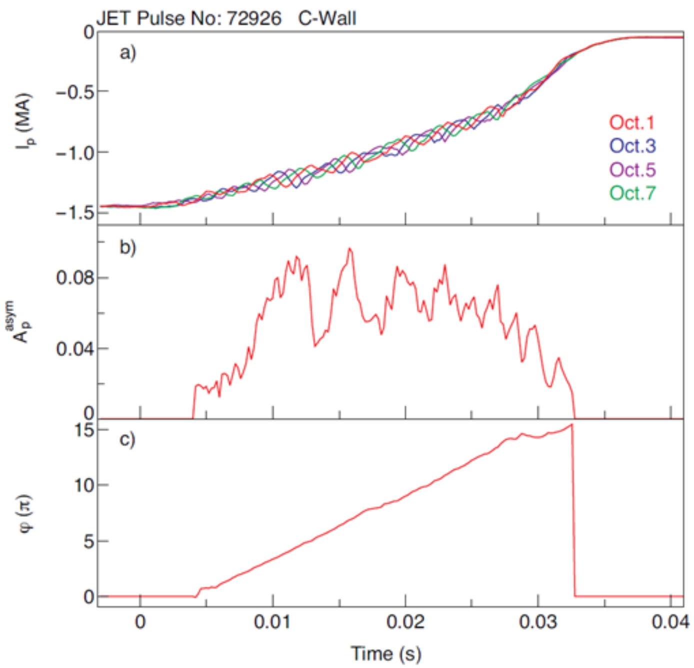
- 180 degrees FE ANSYS model
- Plasma current before disruption = 2.7 MA
- Current quench time = 40 ms
- 4 cases analysed:
  - 5, 10, 15, 20 eV



Rotating AVDE Analysis

The simulations aim to reproduce JET pulse 72926 disruption:

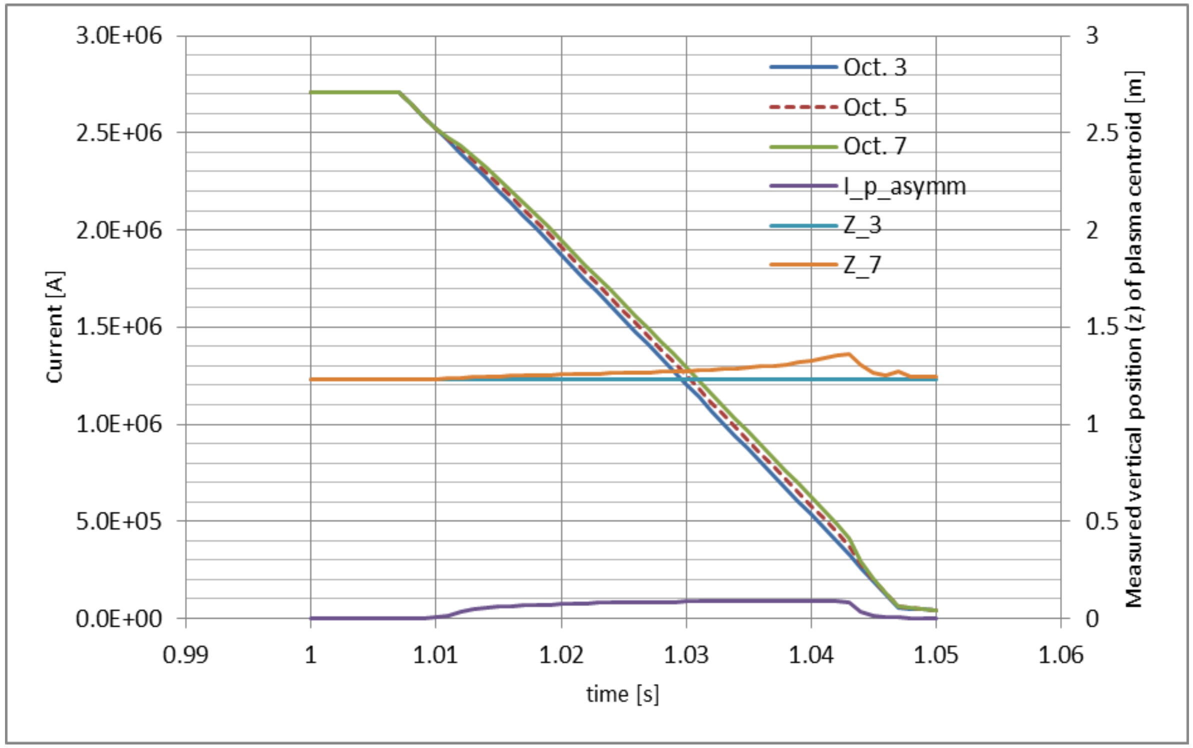
- 360 degrees FE ANSYS model
- Plasma current before disruption = 2.7 MA
- Current quench time = 40 ms
- Rotation is imposed after 10 ms of locked asymmetry and covers 5 revolutions in ~30 ms (rotation frequency = 170 Hz)



Locked AVDE results – 5eV

- *Simulation of pulse 38070 with plasma temperature of 5 eV*

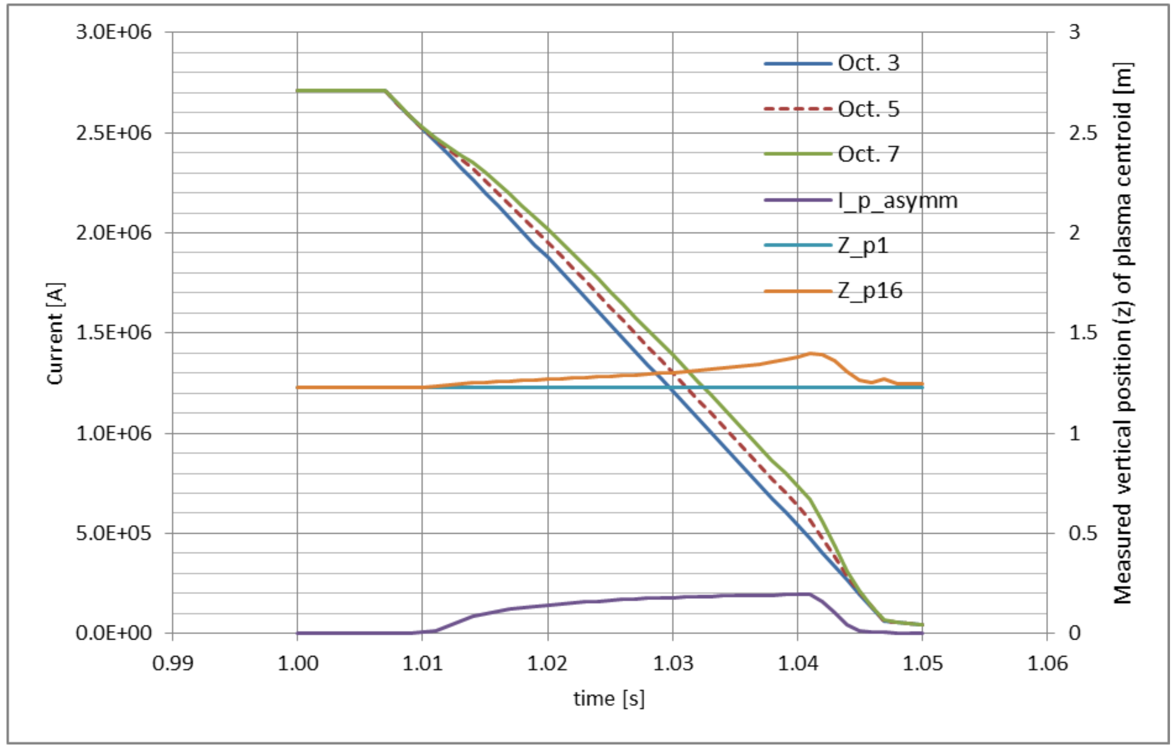
Halo region resistivity: $\eta_{||} = 7.92 \cdot e^{-5}$; $\eta_{\perp} = 1.58 \cdot e^{-4}$; $I_p^{asym} = 91$ kA; $A_p^{asym} = 0.033$;Δz_{max}



Locked AVDE results – 10 eV

- *Simulation of pulse 38070 with plasma temperature of 10 eV*

Halo region resistivity: $\eta_{||}=2.8\cdot e^{-5}$; $\eta_{\perp}=5.6\cdot e^{-5}$
$I_p^{asym}=193$ kA; $A_p^{asym}=0.072$;Δz_{max}

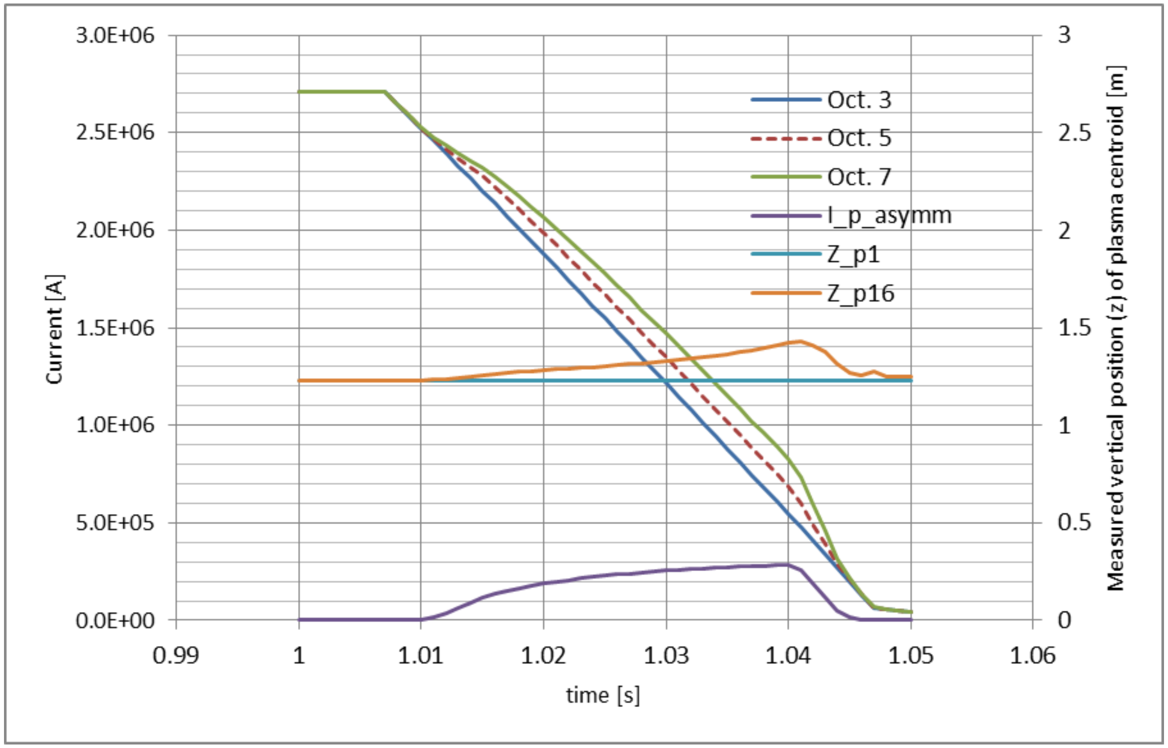


Locked AVDE results – 15 eV

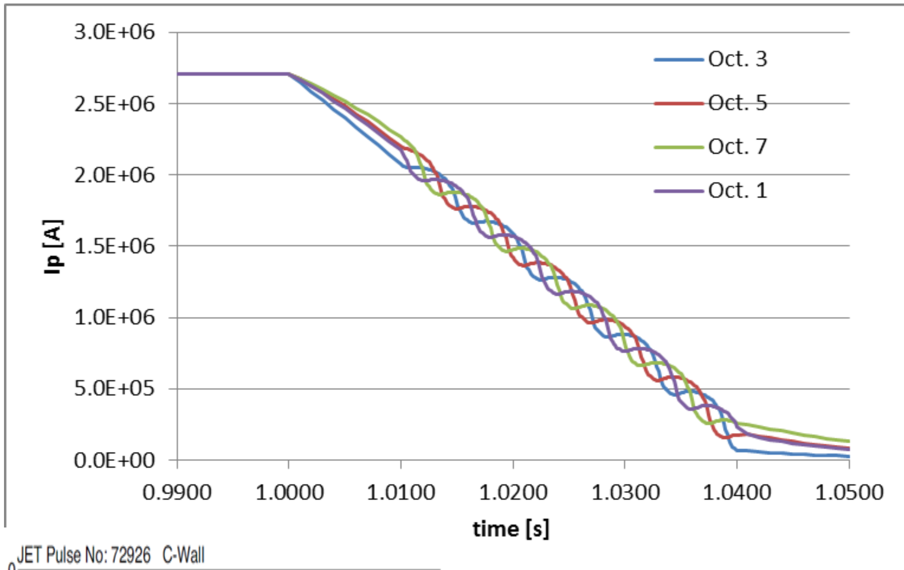
- *Simulation of pulse 38070 with plasma temperature of 15 eV*

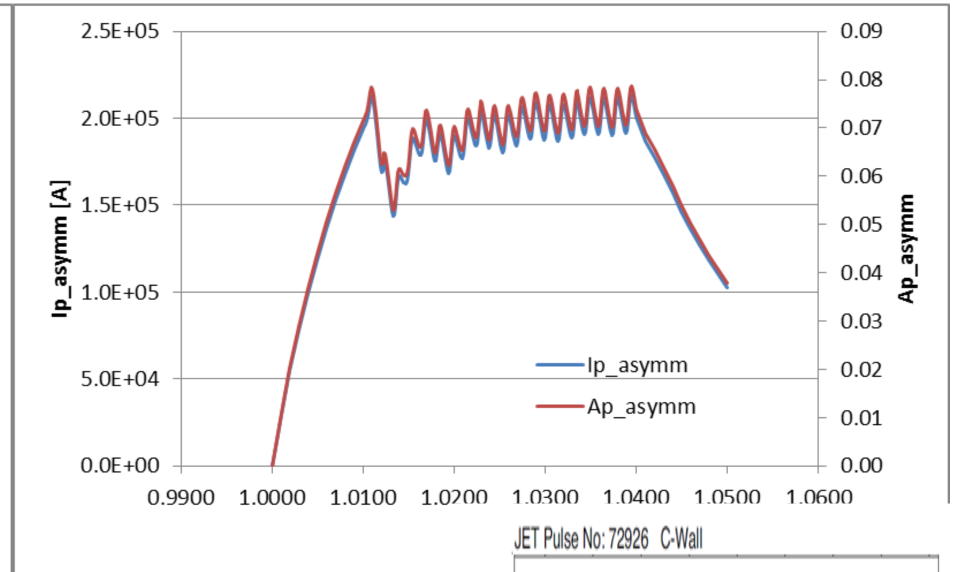
Halo region resistivity: $\eta_{||} = 1.5 \cdot e^{-5}$; $\eta_{\perp} = 3 \cdot e^{-5}$

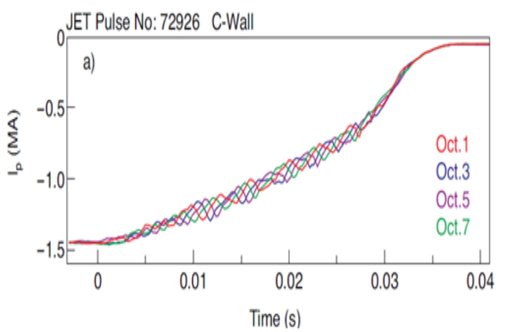
$I_p^{asym} = 285$ kA; $A_p^{asym} = 0.105$; Δz_{max}



Rotating AVDE results (~15 eV)

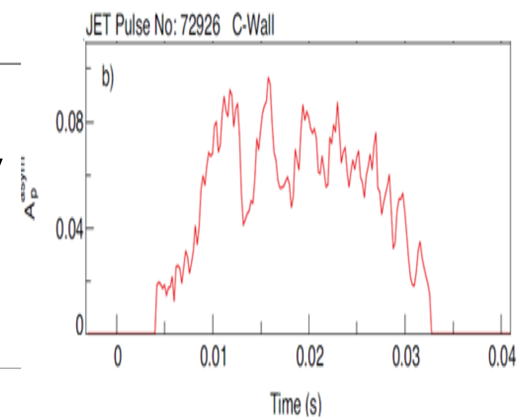




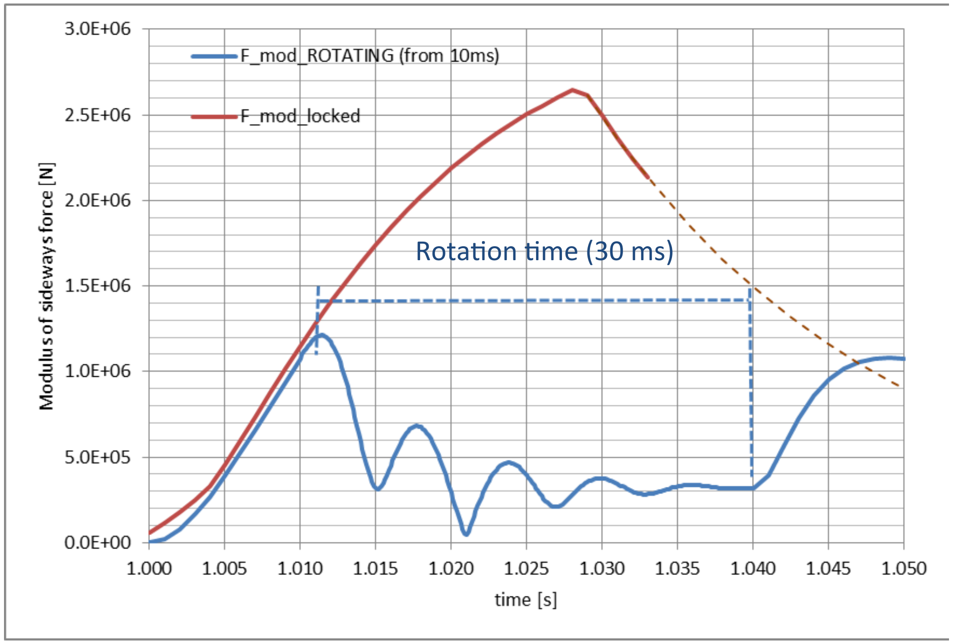


Plasma current calculated (top) and measured (left) in 4 octants

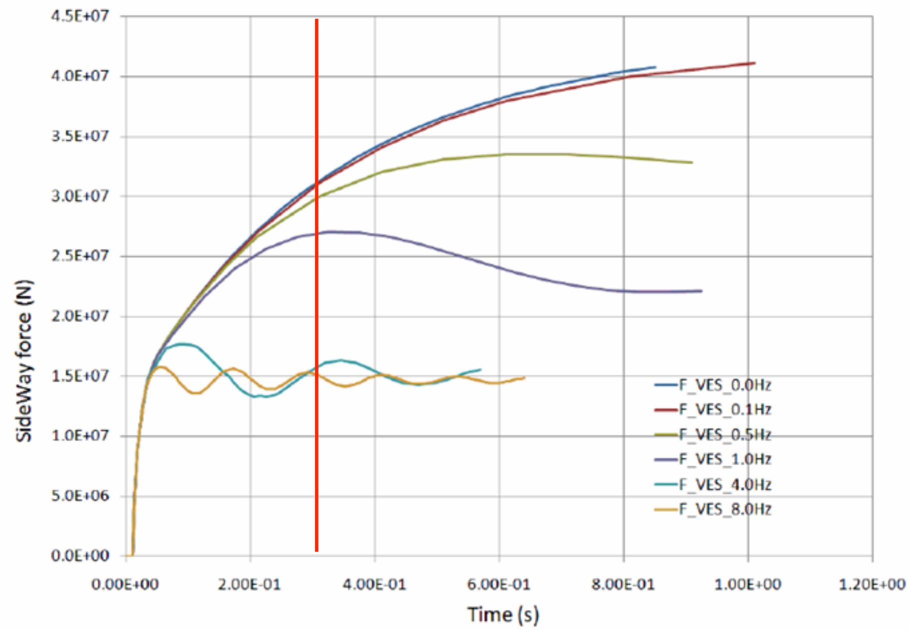
Plasma current asymmetry and normalized asymmetry calculated (top) and measured (right)



Rotating AVDE results – Sideways force



*Comparison of calculated modulus of sideways force for JET locke**d** and rotating AVDE (plasma current before disruption and current quench time are same for both cases).*

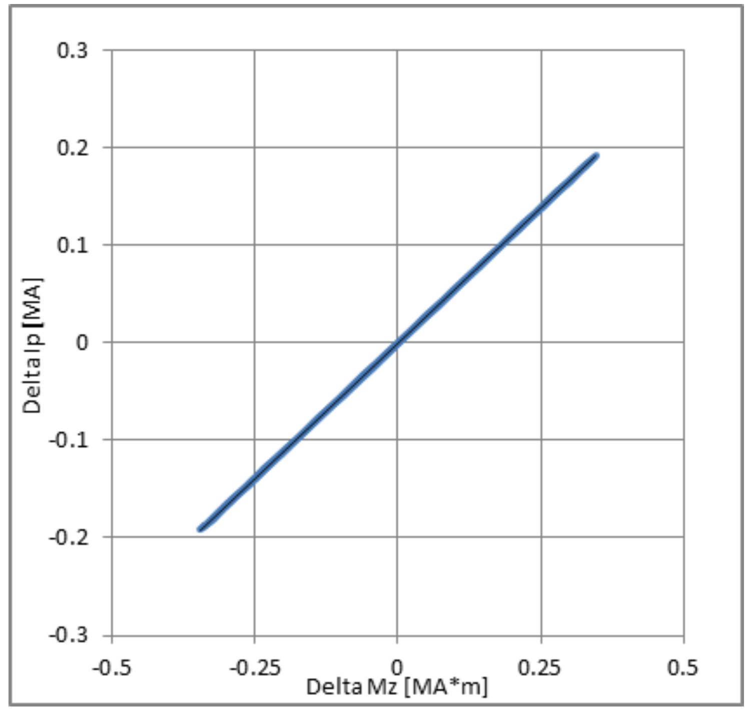


Modulus of the sideways force on ITER tokamak for different AVDE rotation frequencies using the source and sink *model (2010 analysis)*

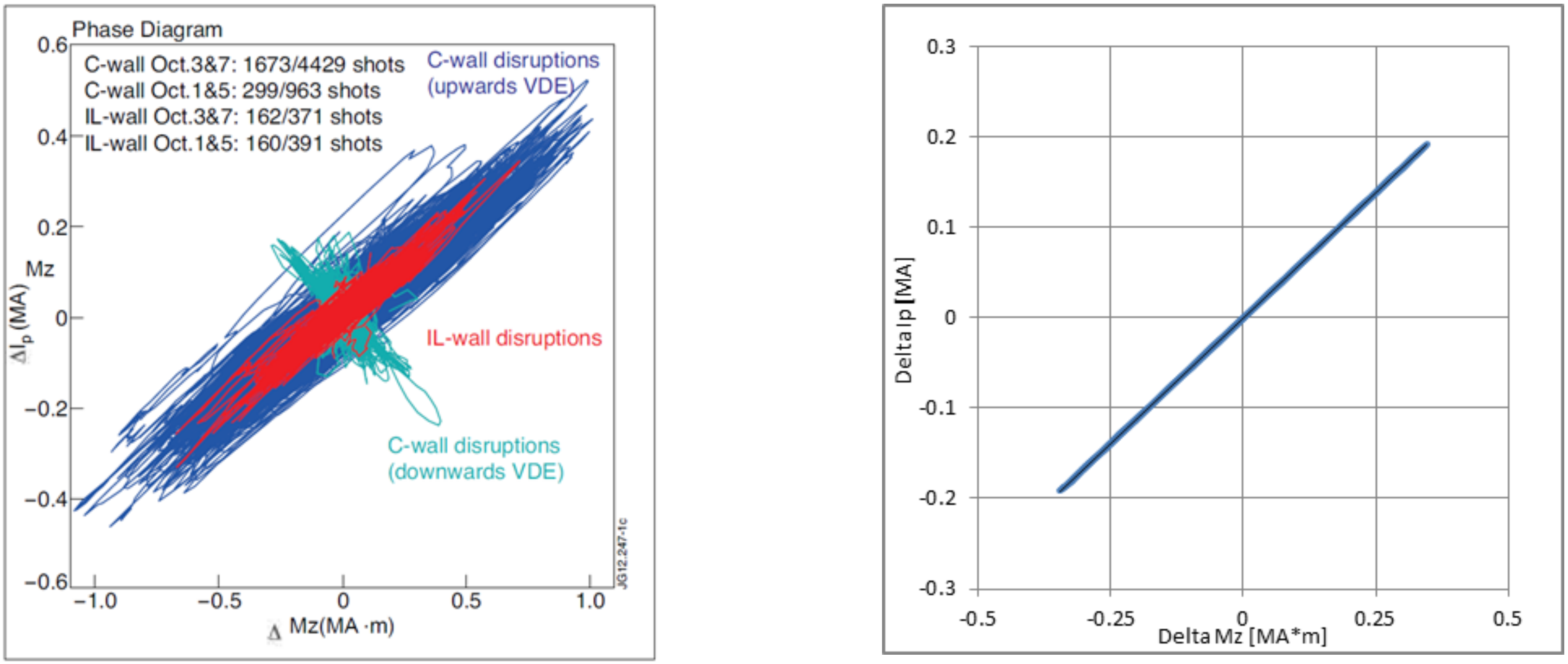
ΔI_p and ΔM_{IZ} phase relationship

Part of the measured difference of plasma vertical position in opposite octants is not caused by the real plasma deformation (m=n=1 mode) but by induced current flowing at fixed height (dump plates).

Clear phase relationship between plasma current asymmetry (ΔI_p) and first vertical current moment (ΔM_{IZ}) is expected as ΔM_{IZ} *is* the sum of the moment of the current ΔI_p flowing in the plates and of the moment of quenching plasma current which in the simulation does not change position.



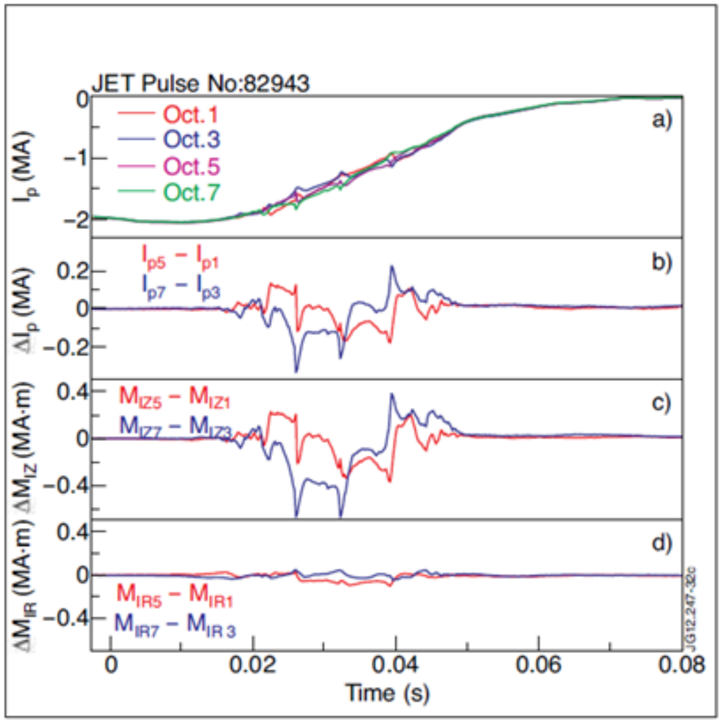
ΔI_p and ΔM_{IZ} phase relationship



Measured (at JET left) and calculated (right) phase relationship between plasma current (ΔI_p) and first plasma current vertical moment (ΔM_{IZ}) asymmetries.

ΔI_p and ΔM_{IZ} phase relationship

Taking away form the measured ΔM_{IZ} the apparent portion due to current flowing in the dump plates it becomes comparable with the measured ΔM_{IR} (c and d in the figure) as it should be in asymmetries dominated by m = n = 1 modes

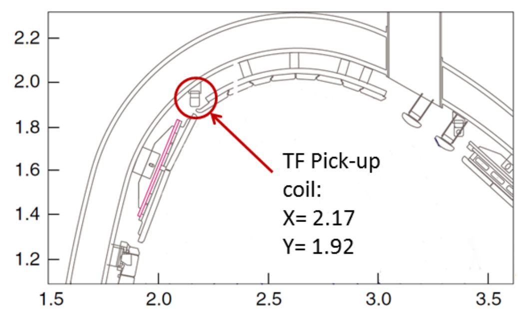


Variation of first radial (ΔMIR) and vertical (ΔMIZ) plasma current moment measured at JET.

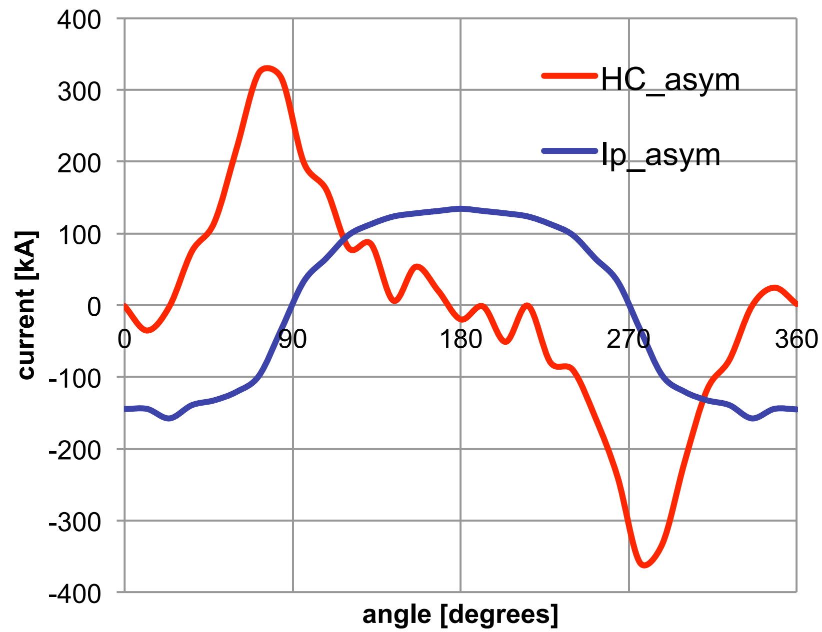
Relationship between ΔI_p and HC asymmetry

The TF pick-up coils used to measure HC in JET are affected by the toroidal field produced by poloidal current flowing from the vessel to the PFCs through the bosses. The red curve shows the HC “measured” in the FE analysis by a sensor located in the same position of the TF pick-up coil without any *real* HC included in the simulation.

The 90 degrees phase shift is evident.



Position of the toroidal field pick-up coil used for HC measurements in 4 octants



Evaluated phase relationship between plasma current and halo current asymmetries

Conclusions - 1

- All the main asymmetry related parameters measured at JET during locked and rotating AVDEs are well reproduced supposing the sideways force caused by ATEC distribution in the conductive structure
- At equal A_{p}^{asym} (0.1) a locked AVDE simulated with the ATEC model produce the same sideways force as the *source and sink* model
- ATEC and S&S give quite different results in case of rotating AVDEs
  - ATEC shows higher dependency on the rotation frequencies: much higher damping of sideways force with increasing freq.

Conclusions - 2

- Independently on the physics mechanism responsible for the asymmetrical short circuits of the PFCs through the plasma, the simulations and the measurements (in particular the phase relationship between ΔI_p and ΔM_{IZ}) show that an asymmetric current of the same sign of the plasma current flowing at a location near to the upper dump plates is very likely.