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Modelling ITER Asymmetric VDEs through Asymmetries of Toroidal Eddy Currents

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Abstract. In this paper the model of asymmetric toroidal eddy currents is presented, discussed and applied to JET and ITER asymmetric VDE analyses. It is assumed that in certain condition of temperature during the last phase of hot VDEs, the plasma could short-circuit the poloidal gaps between adjacent Plasma Facing Components allowing net toroidal current to be induced on the First Wall. In case of asymmetries, if the area wetted by the plasma is consistent with an n=1 deformation, the vessel structures become electrically asymmetric with sectors where the induced toroidal current can be shared between the vessel and the short-circuited PFCs. The resulting Asymmetric distribution of Toroidal Eddy Current (ATEC) interacting with the toroidal field produces, on the vessel, the typical loads (sideways forces) measured in JET during these events.

1. Introduction

During some JET vertical displacement events plasma current and position have been measured to be non-uniform in the toroidal direction. While the changing plasma position along the toroidal angle is reckoned to be the effect of kink instabilities, reconciling it with the concomitant plasma current asymmetry is rather complicated. Unlike the causes, the effects of these asymmetries are clearly seen especially at JET where the vessel has been observed to move horizontally during asymmetric VDEs (AVDEs) and thus strong horizontal forces are expected to be related to the plasma asymmetries. Scaled through the Noll/Riccardo's formula [1] these events are foreseen to produce on ITER up to about 20 times the sideways forces experienced at JET and, in case of rotation close to the vacuum vessel eigenfrequencies, could cause the worst electromagnetic loads on the ITER tokamak. A clear identification of the mechanism triggering the asymmetric loads is then fundamental to insure an efficient design of the ITER tokamak main structures.

Several models have been proposed so far to reproduce the loads seen at JET and to predict the effect of the asymmetries on ITER. Through the *source and sink* model originally developed at JET [1], it is possible to correlate the amplitude of plasma current asymmetry to the vessel horizontal force leaving, however, unexplained the non-intuitive combination of plasma current and vertical position asymmetry which is typical of JET AVDEs. An attempt to solve this issue has been included in a recent wider disruption theory [2] where the surface (or Hiro) current induced in the plasma to compensate kink instability is explained to be responsible for both sideways forces and plasma asymmetries. It will be shown that also this model is not consistent with JET measurements.

In the following sections 2 and 3 is resumed the work which led to the proposal of Asymmetric distribution of Toroidal Eddy Currents (ATEC) [3] as the main cause of measured asymmetries and how this model, applied to simulations of JET asymmetric VDEs, is capable of reproducing most of the magnetic and dynamic measurements observed during these events. The results obtained applying the ATEC model to simulations of AVDEs on the ITER tokamak will be presented in section 4, while in section 5, will be shown comparisons with results obtained in the past with different models.

2. The ATEC model

Since the first observations of JET asymmetric VDEs [4], it has been supposed that the difference in plasma current measured at different toroidal locations could be caused by part of the current flowing from the plasma column to the vessel and then, at the opposite octant, back to the plasma (*source and sink*). The toroidal plasma current is measured, at JET, approximately every 90 degrees, by poloidal loops of Internal Discrete Coils (IDC) attached to the inner wall of the vessel [5]. Following the initial interpretation, at the locations where the asymmetry current flows toroidally in the wall, it bypasses the IDC loops and is thus not accounted as part of the plasma. As a consequence, the measured plasma current will be different at different toroidal locations. In fact, in the case of an n=m=1 kink mode, it would be expected that where the plasma vertical position is farther from the wall, no current exchange would take place while where the plasma is closer to the wall, the shared current would be maximum and the plasma current measurement would show its minimum. In reality, this is never the case (the I_p and z_p measured during a typical AVDE are shown in the left part of figure 2) and the interpretation of plasma current shared with the wall systematically contradicts the most peculiar feature observed with all AVDEs in JET, which is that the larger plasma current is measured in the toroidal location where the plasma is closer to the wall. Nevertheless Riccardo's formula $F_{side} = \pi \cdot B_{tor} \cdot a \cdot \delta I_p$ (with B_{tor} the toroidal field at plasma center and a the plasma minor radius) derives from the *source and sink* model and predicts well the sideways forces on the JET vessel from the measured asymmetry in the plasma current. This apparent inconsistency can be solved assuming that the asymmetric loads are caused not by a direct exchange of current between the plasma and the structure (as in the case of halo currents), but due to asymmetric conductive paths that arise in the structures when the plasma column asymmetrically wets the wall.

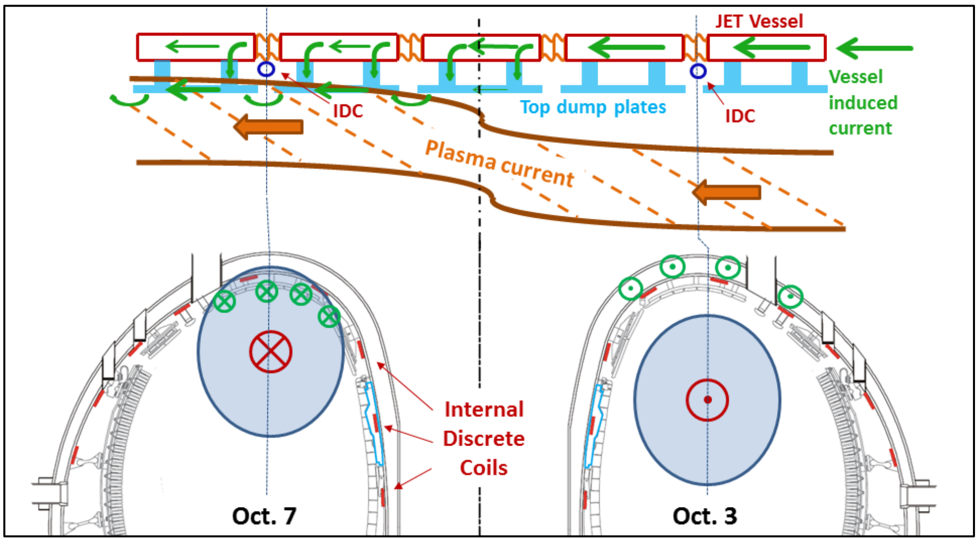

Figure 1 - Schematic view of asymmetric toroidal eddy current patterns in JET structures during AVDEs. Top: toroidal section at vessel top; bottom: vertical section of the machine at octants 3 and 7.

More in detail, adjacent Plasma Facing Components (PFC) separated by small gaps in the toroidal direction could be short-circuited by the plasma where this touches the wall and create a parallel circuit for the current induced in the vessel to compensate the quenching plasma. The PFCs are located internally to the loop of the magnetic diagnostic measuring the toroidal component of the plasma current and thus, the induced current flowing through the gaps contributes positively to the plasma current measurements. If the wetted area is consistent with a kinked n=m=1 plasma, the passive structures become electrically asymmetric (in the toroidal direction) with sectors where the compensating current can be shared between the vessel and the short-circuited PFCs. The resulting Asymmetric distribution of Toroidal Eddy Current (ATEC) interacting with the toroidal field produces, on the vessel, the sideways force typical of JET AVDEs. The upper part of Figure 1 shows a schematic view of ATEC patterns during an upward locked AVDE. The eddy current (green) is induced only in the vacuum vessel where the plasma vertical position is measured low (octant 3) but where the plasma wets the structure, part of it is transferred to the dump plates. The poloidal path of the eddy current from the VV to the DPs in octants 3 to 7 (and its anti-symmetric counterpart from the DPs to the VV on the opposite side of the machine) interacts with the toroidal field resulting in a net sideways force. The lower part of the figure shows a simplified plasma cross-section in two opposite octants. In octant 3, the entire induced toroidal current flows in the vessel and only the plasma current is measured by the IDC loop (in red); in octant 7, the part of induced current that flows toroidally through the dump plates falls inside the contour of the IDC and contributes to the measurement of the plasma current. It is important noticing that the asymmetries in JET start always after the thermal quench and thus the induced current in the vessel during asymmetries has the same sign as the plasma current. The two main unknowns in the formation of ATEC are then:

a) the conditions needed to establish the conduction through the PFCs gaps;
b) the plasma conductivity near the wall.

Discussion of the first point is out of the scope of this work as here the aim is to provide an indirect demonstration of the existence of conduction through the PFCs gaps. In fact the results of electromagnetic (EM) finite element (FE) analyses reported in the next section show that, at JET, allowing conduction through part of the poloidal gaps between adjacent top dump plates, all of the main asymmetry related measurements done during AVDEs can be reproduced. The same measurements, on the other hand, cannot be explained if the asymmetry current is plasma current flowing in the structure. The main variable in the simulations is then the resistivity of the plasma, which has been evaluated through the Spitzer formula for a range of plasma temperatures between 5 and 20 eV.

3. Comparison with JET experimental data

The validation of the ATEC model against JET experimental data has been extensively discussed in [3]. Through FE analysis simulation, an asymmetric contact between the JET top dump plates and the plasma has been implemented consistent with an n=m=1 kink mode, and, in the wetted area, electrical conduction between adjacent dump plates was allowed through a relatively hot plasma (temperature range between 5 and 20 eV). In these conditions, it has been found that for a plasma temperature of about 15 eV (and resistivity assumed through Spitzer's formula), all of the main asymmetry related measurements could be reproduced for both locked and rotating AVDEs. In particular simulating the disruption of pulse 38070 [1], the predicted asymmetry in the plasma current ($\Delta I_p = \sqrt{(\mathrm{I}_{\mathrm{p90}} - \mathrm{I}_{\mathrm{p270}})^2 + (\mathrm{I}_{\mathrm{p0}} - \mathrm{I}_{\mathrm{p180}})^2}$, where $\mathrm{I}_{\mathrm{p0,90,180,270}}$ are the plasma currents measured at the indicated toroidal angles) of about 10% gave 3 MN of sideways forces on the JET vessel with a maximum plasma current asymmetric vertical displacement ($\Delta \mathrm{z}_{\mathrm{p}}$) of 0.25

m, in perfect agreement with the measurement. The typical linear phase relationship (figure 7 right later in the text) between ΔM_{Iz} (asymmetry of the first plasma current vertical moment) and ΔI_p was also very well reproduced in the simulations and gave a strong indication that the ΔI_p is, most likely, a current with the same sign as the plasma current flowing at the top dump plate level. The asymmetry in the halo current and its 90 degree phase shift with respect to ΔI_p have also been reproduced. In fact the asymmetric distribution of toroidal eddy current has been shown to be responsible for a significant part of the measured halo current asymmetry as it affects the toroidal field at the location where the halo current measurements are taken. The extensive work done on JET simulations proved the soundness of the ATEC model assumptions, which can then be applied to the evaluation of loads on the ITER VV.

4. ATEC model applied to ITER

The loads due to AVDEs in case of non-uniform toroidal conductivity of the first wall (FW) panels have been assessed, on the ITER tokamak by means of FE analyses. A similar procedure has been applied as the one used for the JET analyses reported in the previous section and in [3]. A 360 degree finite element (FE) model (figure 2 left) of the ITER vessel (VV), in-vessel components, central solenoid (CS) and poloidal field coils (PFC) has been prepared to analyse upward AVDEs. To this extent, the top blanket modules (BM) rows 7 to 12 have been slightly more detailed with a separate FW and copper FW fingers (figure 2 right). In front of the FW, a thin layer (a few mm) with radial resistivity assigned as a function of the toroidal angle, controls the plasma-wall contact. The halo region (red and blue stripes in figure 2) is responsible for the toroidal current through the gaps and its resistivity depends on the imposed plasma temperature through Spitzer's formula ($\rho = 2.8 \cdot 10^{-8} / T_e^{3/2} [Ohm \cdot m]$ with T_e in keV). The disruption that has been analysed for both locked and rotating cases is a worst case slow upward VDE. This is an axisymmetric disruption simulated by means of the DINA code [7] and is one of the reference ITER disruption simulations. In figure 3 (left), are shown the plasma current and its vertical and radial position during the DINA simulation. The poloidal field and the poloidal field time derivative associated with the DINA current filament are reproduced in the FE model by currents imposed in a set of fixed toroidal conductors surrounding the plasma region by means of the Secondary Excitations interface procedure [8].

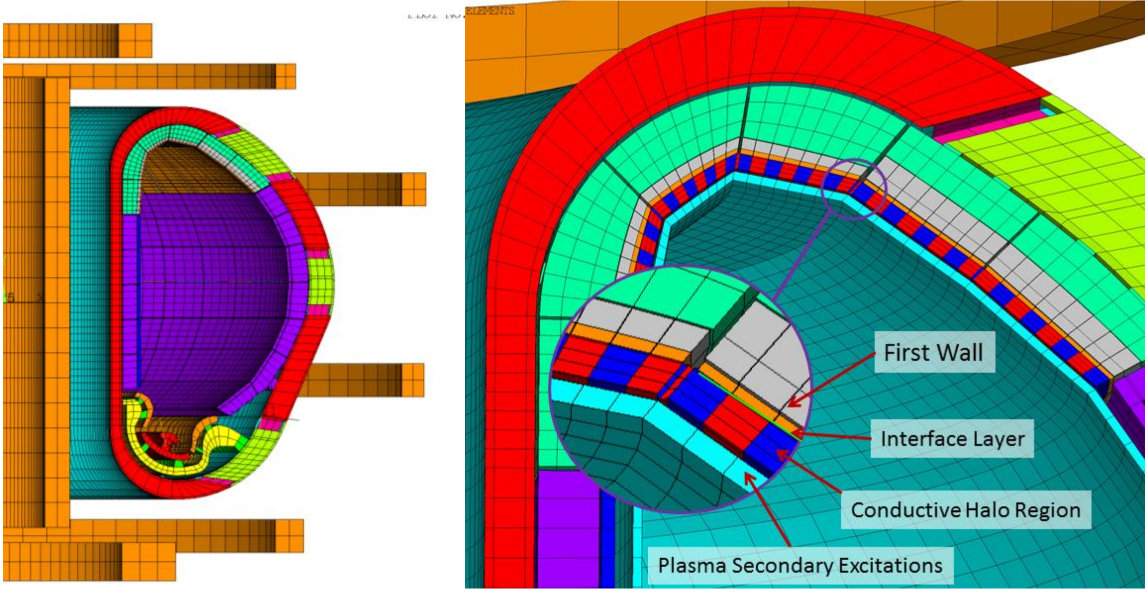

Figure 2 – Left: section of the conductive components included in the ITER tokamak 360 degrees Ansys FE model; right: details of the machine top

The asymmetry is triggered (a few tens of milliseconds after the thermal quench) by switching on the toroidally non-uniform radial conductivity of the interface layer. In the case of rotating AVDEs, the whole distribution of radial conductivity rotates at an assigned frequency. First analyses have been performed to evaluate the sensitivity of the loads on the VV to the resistivity of the plasma in the regions across the gaps. These results (figure 4 left) show significant differences with respect to the JET AVDE analyses presented in [3], where for a plasma temperature of about 15 eV, the corresponding ΔI_p reached about 10% of the pre disruption current.

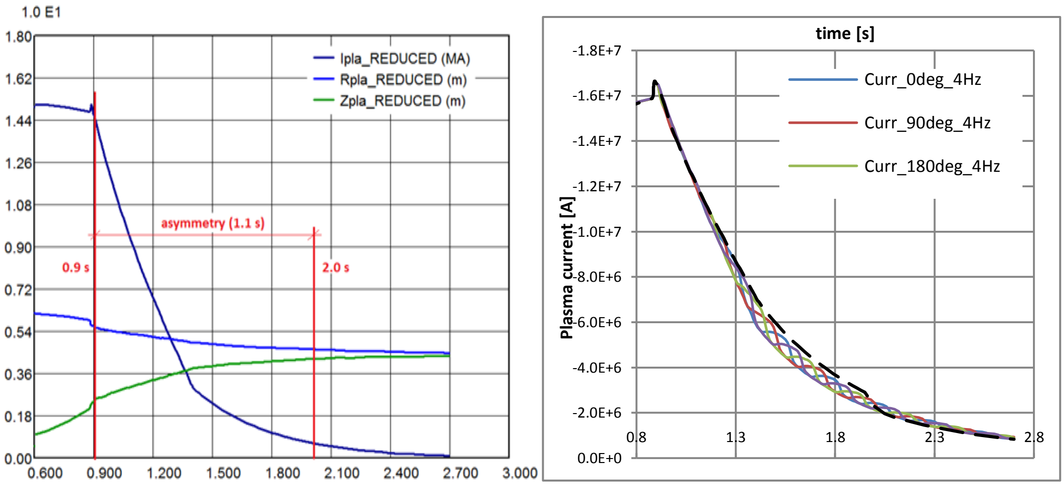

Figure 3 – Left: The main plasma parameters of the axisymmetric DINA disruption simulation of a worst case slow upward VDE used as basis for the simulations. Right: The plasma current asymmetry as a result of the FE analysis in the case of locked and rotating (at 4 Hz) AVDEs.

Due to its toroidal segmentation with 32 thin bellows, the JET vessel is, in this direction, very resistive and its resistance is almost constant at any poloidal location (because of the constant toroidal length of the bellows). As a consequence the time constant of the current induced in the ITER structure is much longer (on the order of hundreds of milliseconds compared to a few milliseconds).

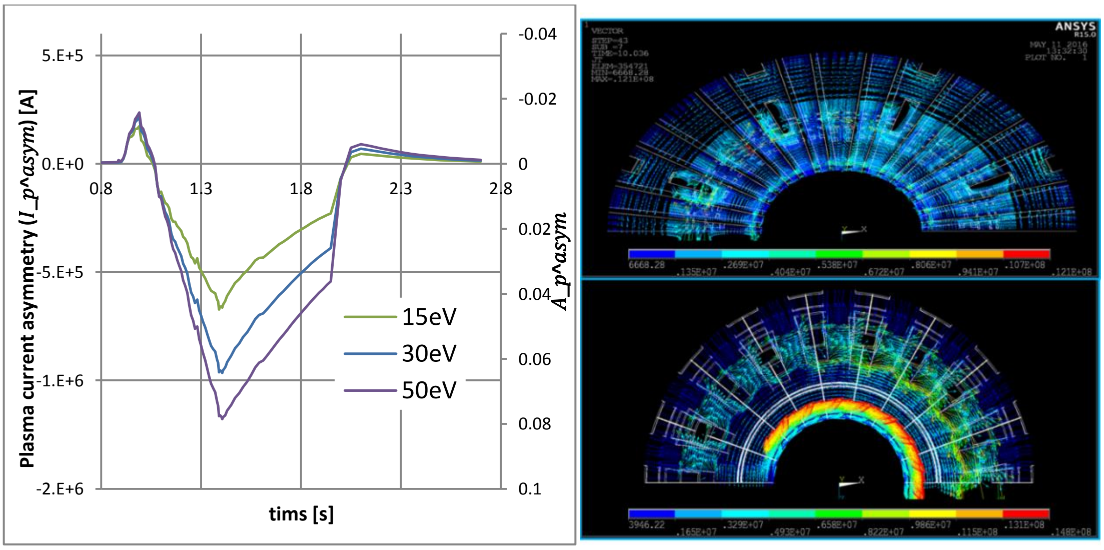

Figure 4 – Left: ΔIp and normalised plasma current asymmetry (A_p^asym) during locked upward slow AVDEs with a plasma temperature across the gaps of 15, 30 and 50 eV. For all simulations the thermal quench is at 885 ms. The asymmetry is triggered at 900 ms and lasts until 2000 ms when the plasma has lost about 90% of its original current. Right: The induced current distribution in JET (top) and ITER VV (bottom) during the current quench phase of an upward AVDE.

Furthermore, while in the JET vessel the current is homogenously distributed along the poloidal angle, in ITER (where the toroidal resistance is proportional to the inverse of the radius), it is for the most part of the disruption concentrated at the inboard region. This effect is shown in the right side of figure 4 where the current distributions in the JET (top) and ITER (bottom) structures during the current quench phase are compared. In the end, with respect to the JET case, it appears that, in ITER, the average resistance of the path along the inboard segment of the VV is low enough to ensure a lower normalised asymmetry of the plasma current, even at higher plasma temperature. In figure 5, the modulus of the sideways force (left) and of the horizontal moment with respect to the machine centre (right) for locked and rotating (at frequencies of 1, 2, 4, and 8 Hz) AVDEs, in the conservative assumption of 50 eV plasma temperature across the gaps (the peak loads are proportional to the ΔI_p so, the maxima in case of lower plasma resistivity can be deduced from figure 4 and 5) are shown. During the simulated locked slow AVDE, the horizontal forces and moments on the VV structures reach 28 MN and 27 MNm, respectively. These loads quickly decrease at increasing rotation frequency and at 8 Hz (which is close to the first vertical and rocking modes and thus the most dangerous for the VV) the horizontal forces and moments are not higher than 10% of the locked values. The phase relationship between ΔI_p and ΔM_{Iz} has been evaluated for the 8Hz rotating AVDE and reported in figure 7 (left, blue line). The first plasma current vertical moment has been evaluated as follows in the FE analysis: $\mathrm{M_{IZ}} = \sum_\mathrm{i} \mathrm{J_i^{tor}} \cdot \mathrm{A_i} \cdot \mathrm{Z_i}$ where $\mathrm{J_i^{tor}}$ is the toroidal component of the current density in the element i; $\mathrm{A_i}$ is the area of element i orthogonal to the toroidal direction, and $\mathrm{Z_i}$ is the vertical position of the element i. The sum is extended to all elements carrying toroidal current inside the VV. The combination of the self-consistent axisymmetric plasma disruption simulation (from DINA) with the asymmetry produced by the ATEC model results in a very realistic phase relationship when compared to the JET measurements (figure 7 right). The slope of the curves, which corresponds (as shown in [3]) to the vertical position of the current centroid asymmetry, is different in the two plots, but is consistent with the geometry of the two tokamaks.

5. Comparison with previous results and models

Asymmetric loads on the ITER VV have been evaluated in the past by means of the “source and sink” model [1] and used as the basis for the definition of peak loads during AVDEs in the load specification of the ITER vacuum vessel [6]. In those analyses, the maximum amplitude

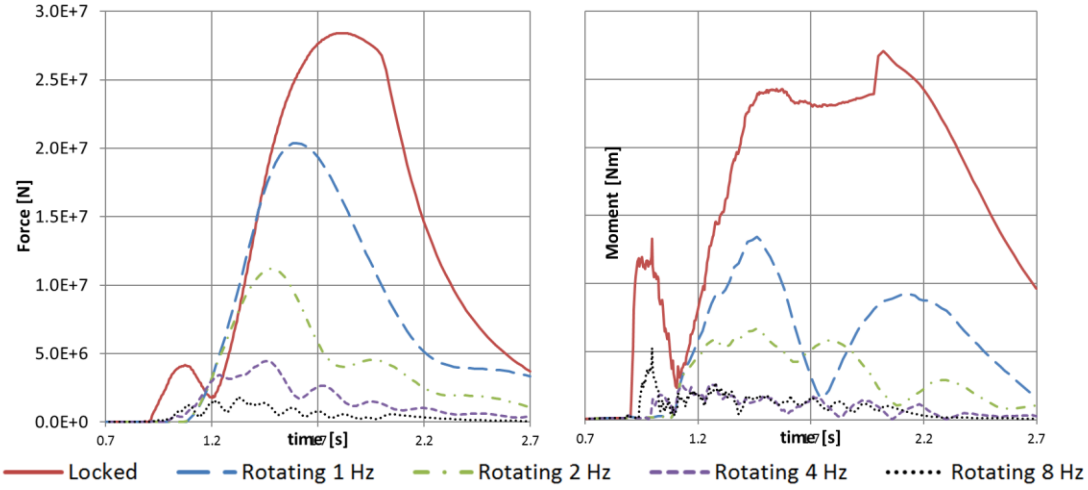

Figure 5– Forces (left) and moments (right) on ITER VV and in-vessel components during locked and rotating AVDEs (through ATEC model). Same scale applies to both plots.

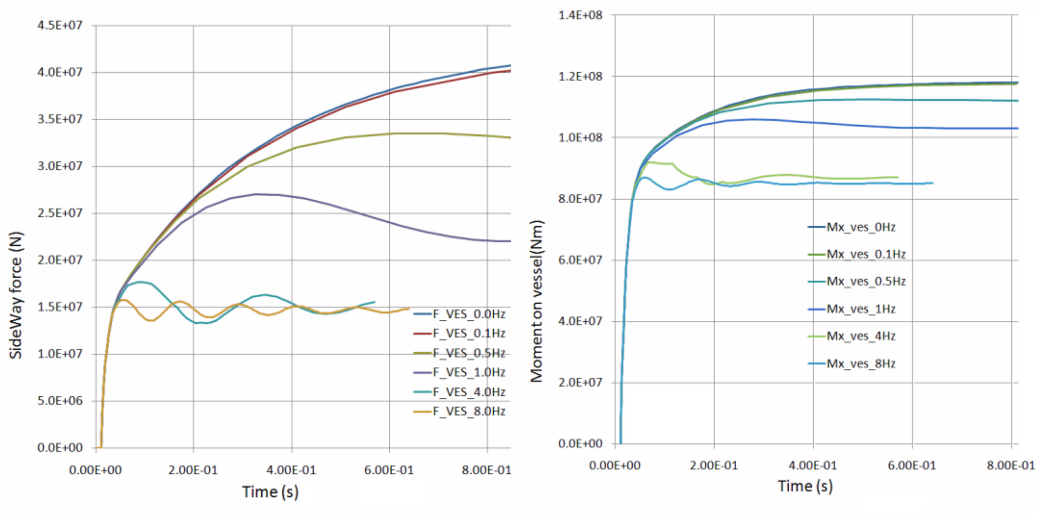

Figure 6 – Forces (left) and moments (right) on ITER VV and in-vessel components during locked and rotating AVDEs (through the source and sink model)

of the plasma current asymmetry (ΔI_p) has been fixed to 10% consistently with the worst JET measurements. The poloidal location of the current asymmetry exchanged between the plasma and the VV has been assumed to take place along a narrow wetting ring close to the machine top (on the FW of BM row 9). The asymmetric exchange of current has been assumed to be sinusoidal in the toroidal direction and rotating at assigned frequencies through the following functions: $j(t,\varphi) = \frac{I_0(t)}{2\pi R}\sin\left(\varphi + \frac{2\pi}{T}t\right); I_0(t) = 0.1 I_p\left(1 - e^{-t/\tau}\right)$ where $j(t,\varphi)$ is the linear current density, as a function of time t and toroidal angle ϕ, entering the vessel along the wetted area and $I_0(t)$ is the amplitude of toroidal asymmetric current flowing in the vessel. The current amplitude was assumed to increase with a characteristic time τ = 0.01 s up to its maximum value equal to 10 % of flat top plasma current I_p and then remain constant for about 1 s. Results of these analyses are resumed in the figure 6.

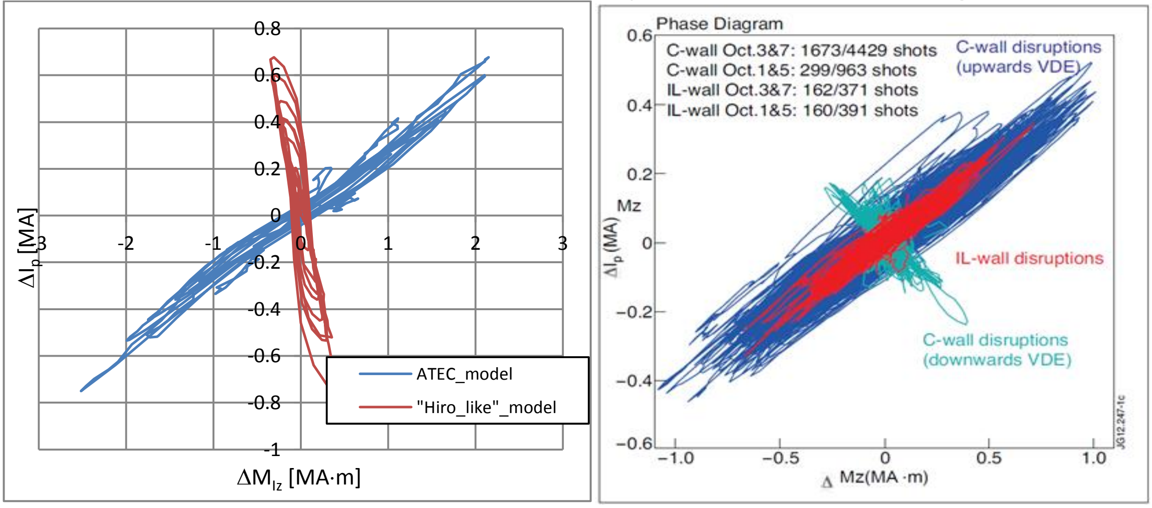

Figure 7 – Measured at JET (right) and calculated applying ATEC model to ITER (left) phase relationship between plasma current (ΔIp) and first plasma current vertical moment (ΔMIZ) asymmetries. "Hiro_like" shows how the plot would look in the case of a positive surface current mirrored with respect to the plasma centroid.

At rotation frequencies higher than 4-8 Hz there was no additional damping of horizontal force and moments with peak sideways force (at 8Hz) of about 15 MN against about 2 MN of the present analysis (figure 5 left). The horizontal moment showed even more worrying behaviour with values exceeding 80 MNm rotating at 8Hz. The main reason that there was little dependency of the peak loads on the rotation frequency in those simulations is that the current entering and leaving the structure was imposed in both the location and intensity, as shown in the relation above. On the other hand, through the ATEC model, the current is induced in the structure with a relatively long time constant. Starting from very low frequencies, in the time needed for the current to saturate (about half a second in the locked case), the average conductive path can cover more than a full revolution cancelling most of the effects of the asymmetry.

6. Conclusions

The work done on JET analyses showed that an asymmetric distribution of eddy currents caused by the partial short circuit of PFCs in the toroidal direction (ATEC model) explains most of the measurement taken at JET during AVDEs and solve the issues left open with the models proposed in the past. The main achievement of the ATEC model is the demonstration that most of the phenomena experienced during AVDEs can be explained only if the measured asymmetric part of the toroidal and halo current is not plasma current entering and leaving the structures in specific locations, but instead current induced in the vessel structures, which, for a relevant angle, flows toroidally through the PFCs, jumping over the gaps through the plasma. The analyses presented here to predict loads on the ITER structures during AVDEs are based on the ATEC assumptions. These simulations, compared to the previous analyses based on the source and sink model, showed that fixing the amplitude of the plasma current asymmetry during locked and rotating AVDEs to the same peak value as measured in JET ($\Delta I_p = 0.1 \cdot I_p$) would lead to excessively high conservativism. In fact, because of the opposite characteristics of the JET and ITER vessel structures (very high toroidal resistance and short time constant in JET and vice versa in ITER), also considering very high conductivity through the gaps (equivalent to plasma temperature of 50 eV during the current quench), the plasma current asymmetry has reached no more and 8% of the pre disruption plasma current. Furthermore, a rotation asymmetry, even at very low frequencies, considerably smooths all the evaluated loads and, at the first ITER VV rocking mode frequency (8Hz), the peak sideways force and horizontal moment are ten times lower than in case of a locked asymmetry.

7. References

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8. acknowledgment

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