The rotation of plasma current asymmetries during disruptions in JET

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** See the Appendix of F. Romanelli et al., Proceedings of the 23rd IAEA FEC 2010, Daejeon, Korea*

Introduction

Toroidal variations in the measured plasma currents (I_p) have been observed on JET during VDEs (Vertical Displacement Events) [1],[2],[3]. The theoretical explanation of the I_p asymmetries, based on the JET disruption database, is that a long lasting $m=n=1$ kink mode is accompanied by negative helical surface plasma currents (Hiro currents) which have a pathway inside the vacuum vessel (or "machine wall") [5],[6], see Fig. 1. The m=n=1 kink modes are responsible for the sideways forces, which occur during asymmetrical VDE disruptions. The disruptions have become a serious issue for future large-scale tokamaks. For example, the sideways forces on the vessel are expected to be tens of times greater on ITER in comparison with JET: $F_x \propto B_T I_p a$, $F_x^{ITER} \cong 2 \cdot 5 \cdot 2 F_x^{JET} \cong 20 F_x^{JET}$ [3], [6].

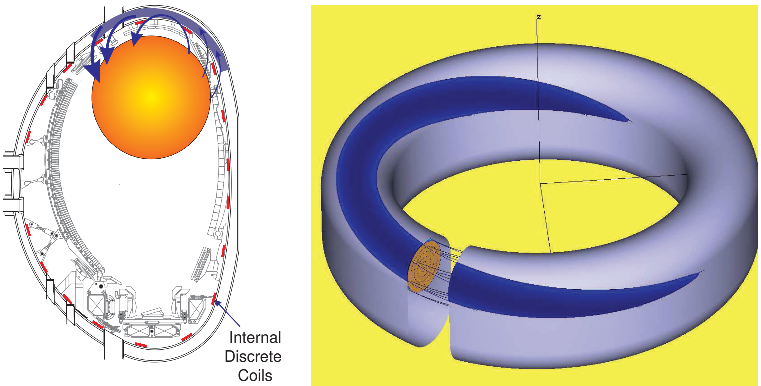

Fig. 1. Dark blue colour represents negative Hiro current shared between vacuum vessel and plasma in VDE due to $m=n=1$ kink mode Inter Discrete Coils are used for I_p measurements in four octants.

Apart from the forces itself, the force durations (or impulse) and force time behaviour are important for the vessel structure loads. Mode frequencies that are close to the structural natural frequencies of the machine components can cause major dynamic amplifications of the loads.

Plasma current asymmetries (Hiro current) disruption database

Replacement of carbon plasma-facing components (referred to here as JET "C-wall") by solid beryllium limiters and beryllium tiles in the main chamber, and a combination of bulk W and W-coated divertor tiles (referred to here as JET "IL-wall") was completed on JET in 2011 [7],[8]. The mode rotation analysis requires I_p measurements in 4 octants, each separated by 90^o [3]. Only disruptions with $\left| I_p^{dis} \right| \geq 1$ MA have been analysed, where I_p^{dis} is pre-disruptive plasma current, defined as the average I_p over 20-50 ms before the disruption time. The C-wall I_p asymmetries rotation database contains 951 shots. The C-wall database also contains 3483 pulses of two-octant disruption data, which has been used for non-rotational analysis. The first half year of IL-wall operation provided rotation data for 199 disruptions, and an additional 59 disruptions have only two-octant recorded data.

Plasma current quench time

It was known that wall material strongly effects the disruption due to impurity radiation during the current quench (CQ) [9]. There is a significant difference in the current decay for C-wall and IL-wall disruptions [7],[10]. The IL-wall CQ time distribution is broader and generally shifted to the range of longer decay time, Fig.2. Moreover, a large fraction of IL-wall disruptions last for hundreds of milliseconds.

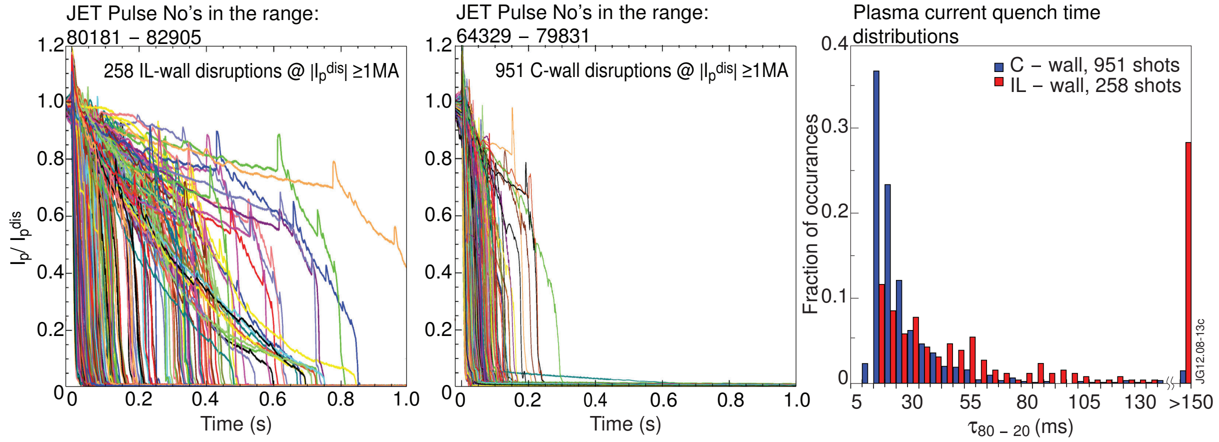

Fig.2. Normalised plasma current during IL-wall (left), C-wall (centre) disruptions and their CQ time distributions (right); where $\tau_{80\text{-}20}$ is the CQ time extrapolated from time to quench from 80 to 20% of I_p^{dis} .

Plasma current asymmetries (Hiro current) static data

To systematically quantify the severity of I_p asymmetries the $A(A_{4oct}\ or\ A_{2oct}) = \int A_p^{asym} dt$ integral has been used, where $A_p^{asym} = I_p^{asym} / \left|I_p^{dis}\right|$, $I_p^{asym} = \sqrt{(I_{p7} - I_{p3})^2 + (I_{p5} - I_{p1})^2}$ with I_{p1}= octant 1 plasma current etc [3]. To avoid noise contributing to the results, the A integral is only evaluated for times when the start and end time window satisfied conditions: $\left|I_p^{asym}\right|$>10kA, A_p^{asym}>0.5%, $|I_p|$>0.1$\left|I_p^{dis}\right|$ and $|I_p^{asym}|$>20kA for the first and last 1 ms window to disregard the short-lived spikes. Ignoring transients then $A \sim \int F_x dt / I_p B_t$ where F_x is the asymmetric (or sideways) force. So A is related to the magnitude of the sideways impulse force. Fig.3 shows the entire I_p asymmetry (Hiro current) data. In cases where just two orthogonal octant data values are available then a 2 octant asymmetry was defined assuming a pure sine wave in time $A = \pi A_{2oct} / 2$. The data boundary for the whole current quench duration are:

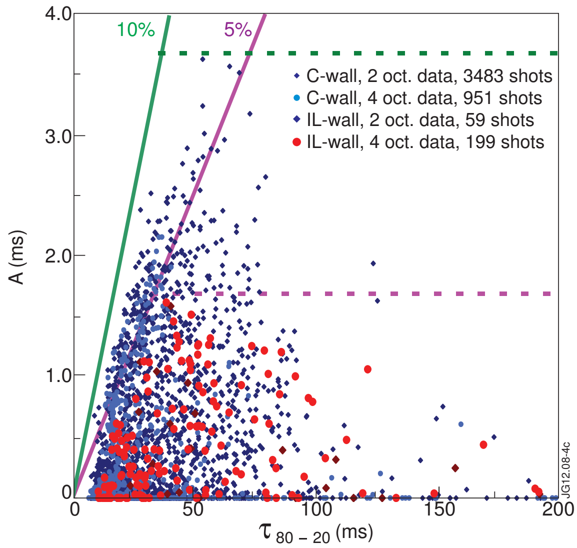

Fig.3. The severity of I_p asymmetries (Hiro currents) for C- and IL-walls.

- A=0.10$\tau_{80\text{-}20}$ with A_{max} = 3.7 ms on the C-wall data (green lines);
- A=0.05$\tau_{80\text{-}20}$ with A_{max} = 1.7 ms on the IL-wall data (magenta lines).

Rotation numbers

The $m=n=1$ kink mode, which is experimentally observed on JET as I_p toroidal asymmetries, usually rotates. The mode rotation shows significant scatter in magnitude, frequency and direction [3], [6]. The 4 octant JET magnetic diagnostics allows the extraction of reliable information about toroidal mode rotation during disruptions. Fig.4 shows distinctive asymmetrical disruptions and the traces of the tip of vector $\delta \vec{I}_p(t) = \delta I_{51}(t)\vec{e}_x + \delta I_{73}(t)\vec{e}_y$.

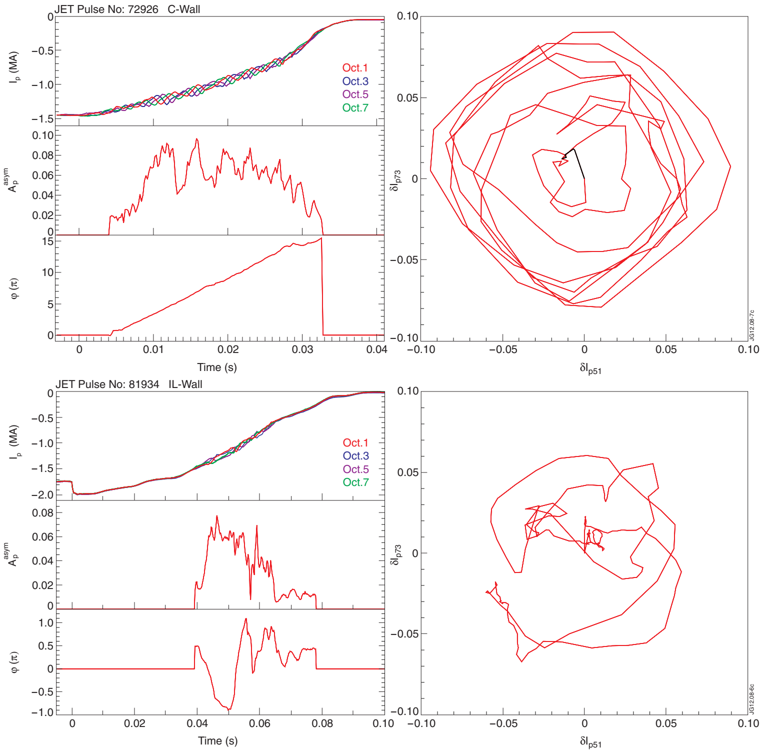

Fig.4. Waveforms of the the I_p, A_p^{asym}, mode toroidal angle (φ) and JET top view on trajectories of the tip of I_p asymmetry vector: multi-turn fast rotation (top), rotation with reversal (bottom).

Mode rotations have sporadic behaviour. This indicates that plasma wall interactions are specifically responsible for rotation rather than due to a plasma core related effect. There is no understanding of the rotational physics or appropriate scaling at the present point in time.

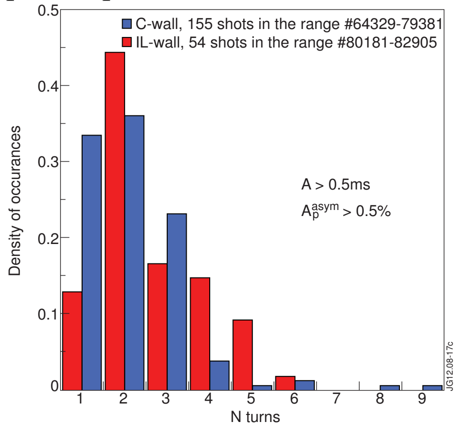

Fig.5. Distribution of the number of rotations.

Statistical analysis requires the use of criteria to extract a subset to avoid the noise contribution. Only shots satisfying $A = \int A_p^{asym} dt > 0.5ms$ (see Fig.3) condition have been used for the rotation statistical analysis. So the rotational statistic has been reduced from 951 to 155 shots for C-wall and from 199 to 54 shots for IL-wall. The number of rotations during disruption was defined as $N = (\varphi_{\max} - \varphi_{\min})/2\pi$. The N distributions are very similar for C- and IL- walls. However the mode rotation slightly increased for the IL-wall μ_{IL}^N = 2.1 (σ_{IL}^N = 1.2) in comparison with the C-wall μ_C^N = 1.6 (σ_C^N = 0.8), Fig.5.

Rotation frequencies

An additional condition has been applied for the frequency statistical analysis of the observed rotations. Analysis was only performed for pulses where the rotation exceeded one full turn during a disruption. As a result of this constraint, the total number of the asymmetry rotated shots was reduced to 103 shots for C-wall and to 47 shots for IL-wall.

The rotation frequency, presented in the current analysis, has been calculated as $f = 1/\tau$, where τ is the one turn period. The average $\langle A_p^{asym} \rangle$ plasma current asymmetry (Hiro current) amplitude has been calculated during τ.

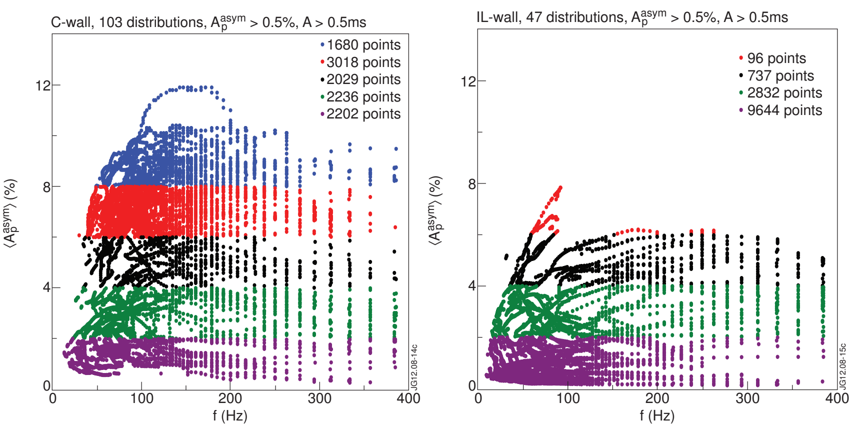

Fig.6. Normalised amplitude of plasma current asymmetry divided on the five $\langle A_p^{asym} \rangle$ regions vs "one turn" rotation frequency.

The above described algorithm has been applied to C- and IL- walls disruptions independently, see Fig.6. On the next step the data points have been divided into five $\langle A_p^{asym} \rangle$ regions: $\langle A_p^{asym} \rangle < 2\%$, $2\% \le \langle A_p^{asym} \rangle < 4\%$, $4\% \le \langle A_p^{asym} \rangle < 6\%$, $6\% \le \langle A_p^{asym} \rangle < 8\%$, $\langle A_p^{asym} \rangle \ge 8\%$. The means and the standard deviations of the distributions have been calculated and plotted in Fig.7, where it can be seen that, at least, the mode amplitude does not decrease with frequency.

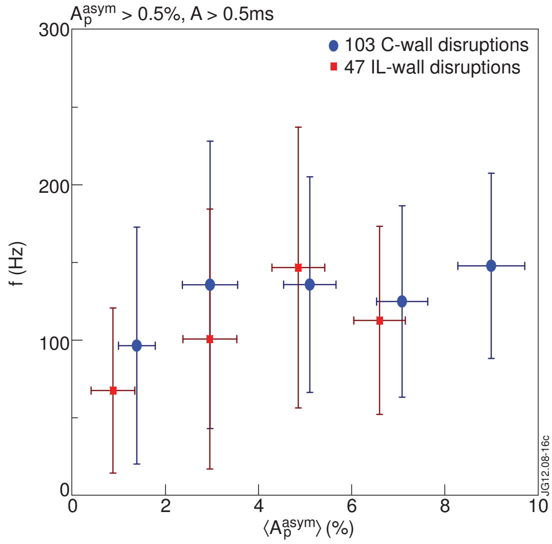

Fig.7. Variation of the “one turn” frequency vs average I_p asymmetry (Hiro current) amplitude.

Summary

1. Plasma current quench time is significantly increased for IL-wall compared with C-wall disruptions. In spite of this, the observed I_p toroidal asymmetry integral (~ sideways force impulse) did not increase for IL-wall disruptions. It remains inside the C-wall data domain.
2. The m=n=1 kink mode rotation during I_p quench has sporadic behaviour. Distributions of the number of rotations are very similar for both C- and IL-wall disruptions, although rotations slightly increased for the IL-wall. Multi-turn mode rotations were observed for C- and IL-wall disruptions.
3. The Hiro current (I_p toroidal asymmetry) amplitude seems to have no degradation with mode rotation frequency for both C- and IL-walls disruption data.

Dynamic amplification remains a serious issue since high amplitude multi-turn m=n=1 kink mode (which are responsible for the sideways forces) rotation can cause mechanical resonance of the machine components.

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