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1. Introduction

During VDEs toroidally asymmetric vessel currents can flow and these are related to toroidal variations in the measured toroidal plasma current [1]. These asymmetries in the currents during VDEs can lead to substantial sideways forces of over 4MN in JET [1,2], and are expected to be an order of magnitude larger in ITER [3]. There is thus an urgent need to develop and record understanding of plasma current asymmetries during VDEs; to facilitate this process a Working Group (WG 6) on sideways forces on the vacuum vessel and magnets was established under the auspices of the ITPA MHD Topical Group.

This report discusses the asymmetries of plasma and vessel currents measured in JET and as such is an update of previous reports [4,5]. It also discusses related measurements of halo current asymmetries in ASDEX Upgrade (AUG) and DIII-D.

For ITER the asymmetric forces are being modelled using the source and sink model described in Ref [1]. The plasma current asymmetries are assumed to have an n=1 toroidal variation and so the input needed is the amplitude of the plasma current asymmetry, its duration and its rotational frequency (if any). More specifically information is needed on the amplitude/duration of asymmetry for the worst 6% of asymmetric VDEs (termed Cat III/IV) and for the least bad 94% (termed Cat II). The asymmetry rotation is also an issue; in ITER the main vessel resonant frequencies are in the range 3-8Hz [6] and so if the current asymmetries were to rotate in this range of frequency there will be an enhancement of the vessel distortions. Also smaller in-vessel components have higher resonant frequencies of up to ~100Hz.

A previous assessment by the ITER of JET data [5] concluded that the Cat III/IV plasma current asymmetries can be covered by an envelope of 10% of the pre-disruptive I_p lasting for 37.5ms (in JET). This assessment was based however on just 7 pulses with incomplete data on the toroidal variation – hence the importance of revisiting this issue with a larger and more complete dataset.

2. JET asymmetry amplitude

On JET the toroidal asymmetries of the plasma current (I_p), and its moments, are measured using arrays of in-vessel poloidal field coils at 4 toroidal locations, each 90^o separated (see Fig. 1). In addition the halo currents can also be measured for upward going VDEs in the same octants, from local changes in the toroidal field. Data from the internal coils that measure the poloidal field (and hence the plasma current) is shown in Fig 2. This figure shows the poloidal field subtracted on 2 opposite sides of the torus (octant 7 – octant 3), during an upward going VDE. The change of sign of the poloidal field in Fig 2, with time, is due to rotation of the non-axisymmetric component of the plasma current. It can be seen that the region with a significant change in poloidal field is spread over most of the top of the vessel (for an upward going VDE). Two of the coils from the poloidal arrays, coils 8 and 11 (Fig 2, inset) are shielded behind the vessel retaining rings. It can be seen by inspection that the field at coil 8 is opposite in sign to that expected by simple interpolation between coils 7 and 9, and likewise for coil 11. It is thought this change in sign is caused by currents flowing in the vessel retaining ring, between the coil and plasma. To assess the impact of this on the deduced plasma current, the signal in coil 8 has been replaced by an average of the coils 7 and 9 signals, and the coil 11 signal replaced by an average of coil 10 and 12. This procedure indicates that the shielding effect produces a ~15% underestimate of the asymmetric current (see Fig 6 below, and associated text).

In the present JET disruption database there are 954 pulses with reliable 4 octant data and 4457 pulses with reliable data from octants 3 and 7 – it should be noted this database includes disruptions, with I_p^{dis} ≥1MA, from all causes, not just VDEs (where I_p^{dis} is the pre-disruptive plasma current).

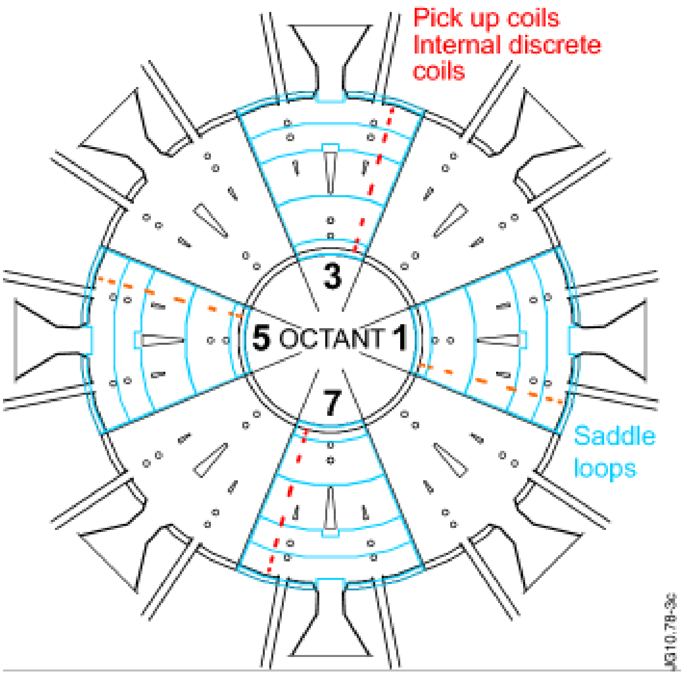

Fig 1. View from above of JET vessel, showing the toroidal locations of the internal discrete pick-up coils used to measure the local value of I_p.

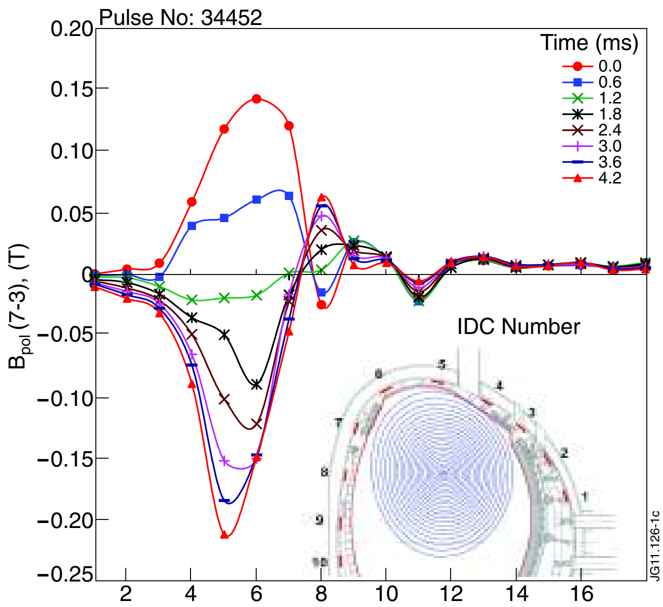

Fig 2. Poloidal field measurements from internal discreet coils (IDCs), with measurements from pairs of toroidally opposite coils subtracted. The inset shows the coil locations in the upper vessel (coils 10 to 18 are a mirror image in the lower vessel of coils 9 to 1).

Figure 3 shows the asymmetric halo and plasma currents for a pulse (74449) with a significant asymmetry.

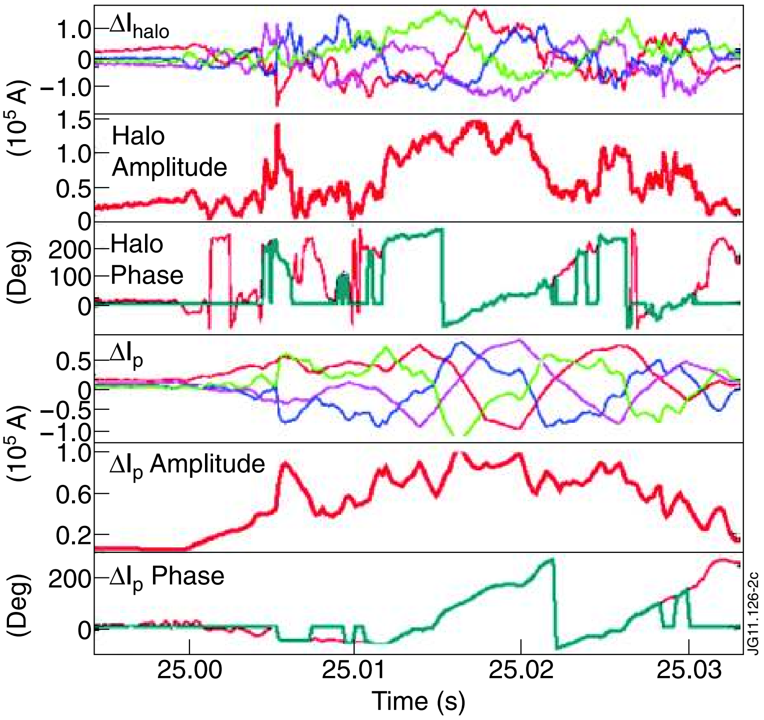

Fig 3 (a) Halo current asymmetry defined as difference of local signal and the toroidal average [red=octant 1, blue=octant 3, purple=octant 5, green=octant 7]; (b) amplitude of the halo asymmetry; (c) phase of halo asymmetry; (d) to (f) as (a) to (c) but for plasma current.

Both the halo current and plasma current asymmetries rotate and may be linked [7], though the exact physics underlying this relationship is not yet clear.

To systematically quantify the plasma current asymmetries the following quantity is used:-

$$A_{4oct} = \frac{1}{I_p^{dis}} \int I_p^{asym} dt$$

where I_p^{dis} =pre-disruptive plasma current and $I_p^{asym} = \sqrt{(I_7 - I_3)^2 + (I_1 - I_5)^2}$ with I_1= octant 1 plasma current etc. To avoid noise contributing to the results, the A_{4oct} integral is only evaluated for times when $|I_p^{asym}|$>10kA and $|I_p^{asym}|$>0.5% $|I_p^{dis}|$ and $|I_p|$>10% $|I_p^{dis}|$. In the results presented the time of disruption is defined as the point when $|dI_p/dt|$>25MA/s for at least 2ms for VDEs, or the peak of the negative loop voltage spike for disruptions that occur before vertical instability onset. I_p^{dis} is then defined as the average I_p over 20-50ms before the disruption time.

It is important to note that A_{4oct} is a measure of the peak-to-peak variation, and not the amplitude of plasma current asymmetry. $A_{4oct} \sim \frac{\int F_{asym} dt}{a I_p B_t}$ where F_{asym} is the asymmetric force and a the minor radius. So $A_{4\,oct}$ is related to the magnitude of the asymmetric impulse force.

In cases where just octant 3 and 7 data are available then a two octant asymmetry $A_{2\,oct}$ can be defined. If the asymmetric currents (I_7-I_3 and I_5-I_1) are assumed as a pure sine wave in time then

$$A_{4\,oct} = \pi/2\, A_{2\,oct}$$

Figure 4 shows the variation of $A_{4\ oct}$ for the whole 954 shot four octant database and the variation of $A_{2\ oct}$ for the whole two octant database. Also shown is the $\pi/2\ A_{2\ oct}$ together with $A_{4\ oct}$ for shots where four octant data are available – it can be seen on average that $\pi/2\ A_{2\ oct}$ gives a good description of the four octant data.

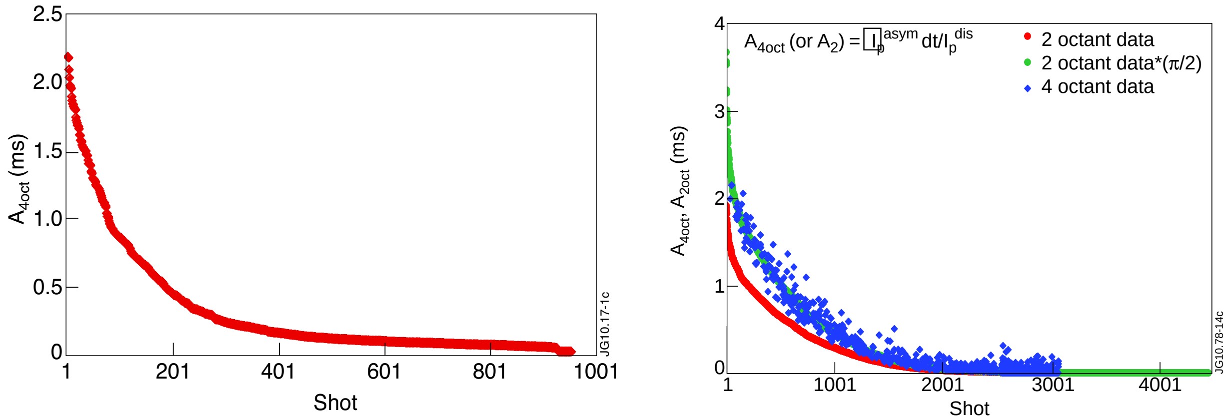

Fig 4 Left-hand plot shows A_{4oct} for the whole 4 octant database. The right-hand plot shows the entire 2 octant database (red), data for 4 octant shots (dark blue) where it exists, and $\pi/2\ A_{2\ oct}$ (green). In the right-hand plot the data are sorted by descending size of $A_{2\ oct}$

The extrapolated 2 octant data ($\pi/2\ A_{2\ oct}$) has a maximum value (3.68ms) just below the ITER envelope value of 3.75ms (10% of I_p for 37.5ms) assumed in Ref [5].

There is also a significant difference in the asymmetry between upward and downward going VDEs in JET. Figure 5 shows the integral asymmetry, with upward and downward going VDEs discriminated. The upward going VDEs have a peak $\pi/2\ A_{2\ oct}$= 3.68ms whereas the downward going VDEs have a peak of 1.34ms; the reason for this difference is not clear but presumably depends on the machine magnetic and physical geometry. It should also be noted that some of poloidal field pick-up coils (used to deduce I_p) are shielded by the divertor structure and this may impact the accuracy for downward goings VDEs.

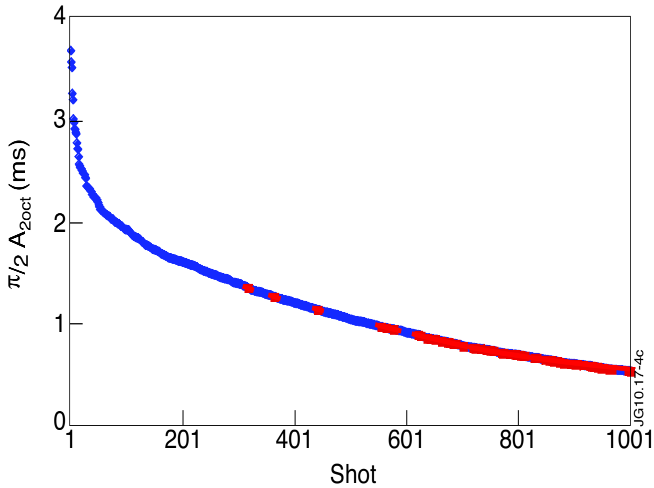

Fig 5 $\pi/2\ A_{2\ oct}$ with upward going disruptions in blue and downward going in red – showing the first 2000 shots from the two octant database.

As noted in the introductory paragraph to this section, the vessel retaining rings that shield 2 of the internal sensor coils used to evaluate I_p, are likely introducing a systematic error. To quantify this effect the signals of the shielded coils (8 and 11) have been replaced by averages of their neighbours – the resulting values of $\pi/2\ A_{2\ oct}$ are shown in Fig 6. It can be seen that the shielded coils introduce a systematic underestimate of $\pi/2\ A_{2\ oct}$ by 15%. For the remainder of this report values of I_p using the raw coil 8 and 11 data will be used – this must be regarded as a systematic error on the results presented.

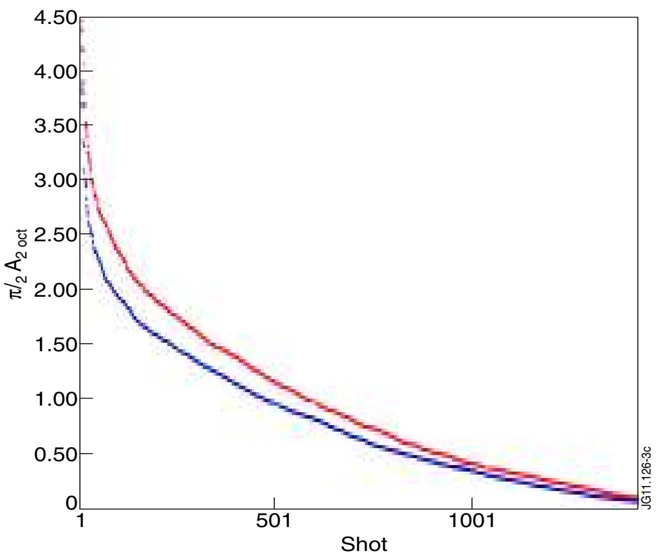

Fig 6 $\pi/2\ A_{2\ oct}$ with I_p evaluated with (red) and without (blue) sensor coils 8 and 11 replaced by averages of their neighbours. In both cases the data are sorted into descending order.

Figure 7 shows the cumulative percentage of pulses with an asymmetry up to a given value for the 2 octant database.

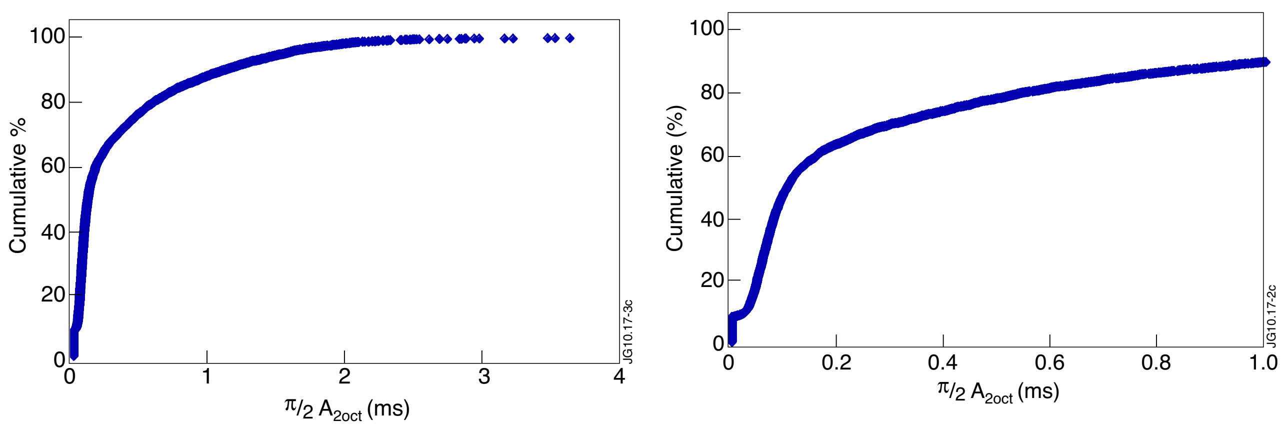

Fig 7 Cumulative % of shots with $\pi/2\ A_{2\ oct}$ less than a given value. The right figure is a zoom of the left figure for the range $\pi/2A_{2oct}$= 0 to 1ms.

The behaviour at low asymmetry (seen in Fig 7, right) is caused by the criteria (discussed above) used to determine the times over which the asymmetry integral is evaluated.

The traces of I_p^{asym}/I_p^{dis} for the cases with largest values of $A_{4\ oct}$ and $A_{2\ oct}$ are shown in Figs 8 and 9, respectively. In these plots t=0 is defined such that $\int_{t<0} I_p^{asym}dt = \int_{t>0} I_p^{asym}dt$. Under the previously developed ITER specification [5] a +/-2ms rectangular smoothing of the JET data was applied, on the basis that such short timescale behaviour (when extrapolated to ITER) will have no mechanical effects. Given the ~3 to 8Hz ITER vessel frequency the choice of +/-2ms smoothing time (though somewhat arbitrary) is conservative (how to extrapolate timescales to ITER is discussed below). It can be seen from Fig 8 (right) that with the 2ms smoothing the previously developed ITER envelope (I_p^{asym}/I_p^{dis} =10% for 37.5ms) is reasonable for the 4 octant data.

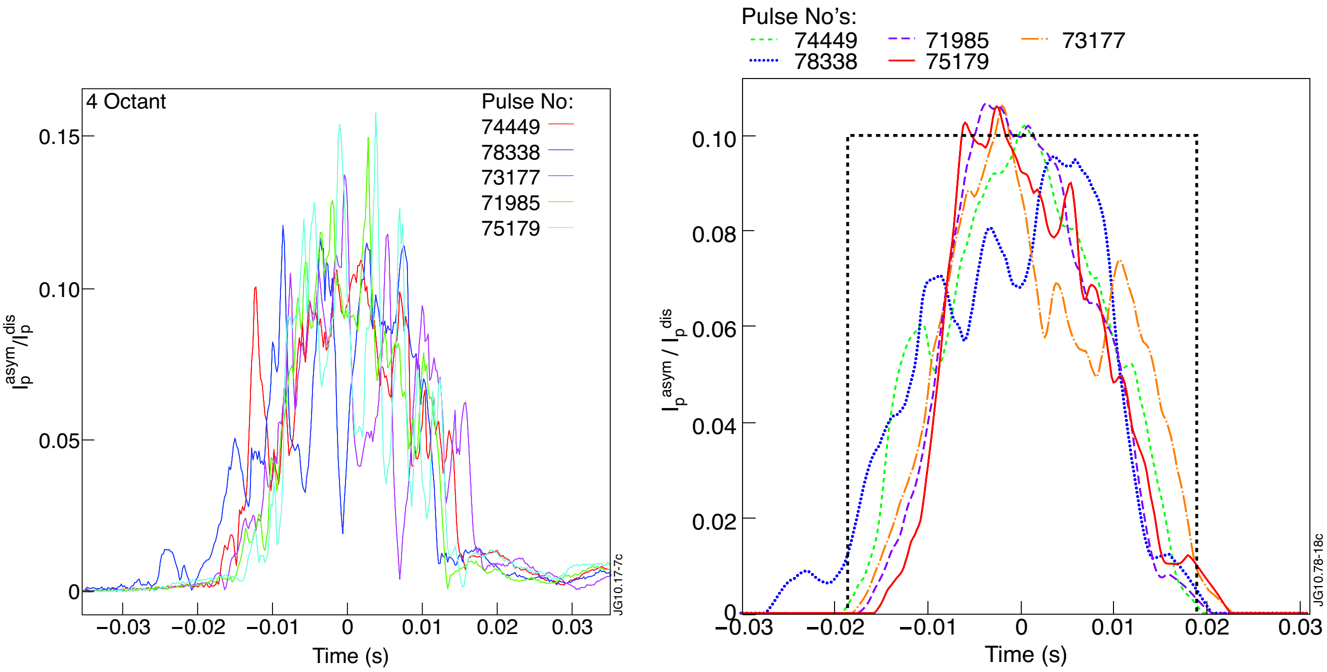

Fig 8 I_p^{asym}/I_p^{dis} *for pulses with the maximum* A_{4oct} *values. In the right-hand figure the data are smoothed with a +/-2ms rectangular window and an envelope of 37.5ms is indicated.*

For the 2 octant data, in terms of impulse, $(\pi/2)A_{2\ oct}$ is closely bounded by 3.75ms. However the data in Fig 9 show the 37.5ms window does not envelope the data. A conservative choice would be a 10% envelope for 55ms.

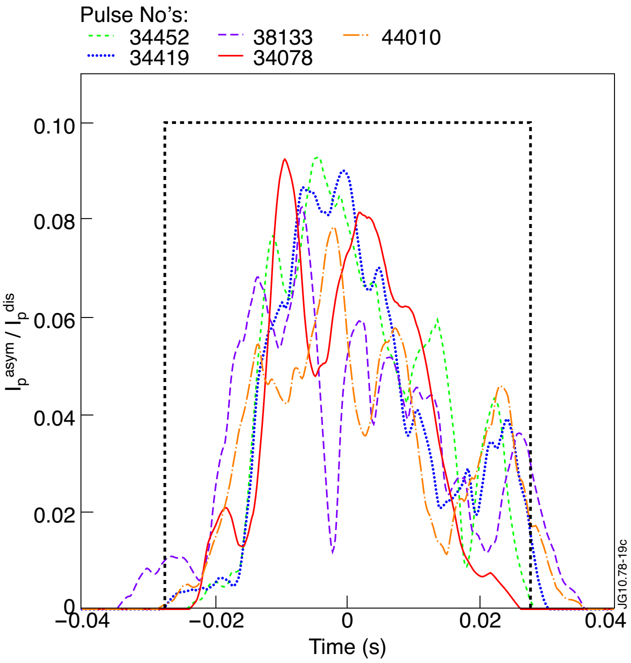

Fig 9 I_p^{asym}/I_p^{dis} *for pulses with highest* A_{2oct} *values; the data are smoothed with a +/-2sms rectangular window. With an envelope of 55ms indicated.*

This lengthening of envelope between the 4 and 2 octant data, corresponds to some pulses with longer current quenches at high values of $A_{2\ oct}$ occurring (Fig 10). Since the duration of the I_p asymmetry is always within the current quench duration, the quench data is consistent with the lengthening of the I_p

asymmetry between the 4 and 2 octant data. The line in Fig 10 corresponds to I_p^{asym}/I_p^{dis} =10% for the whole current quench duration - this line provides a good bound on the data. Also since the I_p quench duration is known to scale linearly with plasma area [8], this possibly justifies scaling the asymmetry duration with plasma area – implying the asymmetries will persist a factor of ~5 times longer in ITER than JET. Though it should be noted that the reason the peak asymmetry occurs at τ_{80-20}=50-60ms is not clear, and so it is not certain this time will scale as the plasma area.

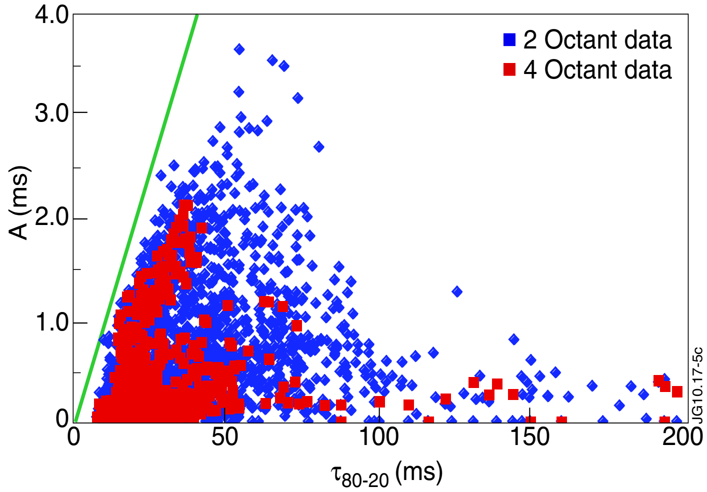

Fig 10 A_{4oct} (red) and $\pi/2$ A_{2oct} (blue) vs the current quench time extrapolated from time to quench from 80 to 20% of I_p^{dis} (ie. the time from 80 to 20% multiplied by 5/3). The green line is the integral asymmetry if the I_p asymmetry is 10% for the whole τ_{80-20} time.

The maximum magnitude of the asymmetry I_p^{asym}/I_p^{dis} from just the 2 octant (3 and 7) data is shown in Fig 11. It can be seen that at the highest asymmetries (determined by $A_{2\ oct}$) that the 10% maximum is a good envelope (when the +/-2ms smoothing is applied).

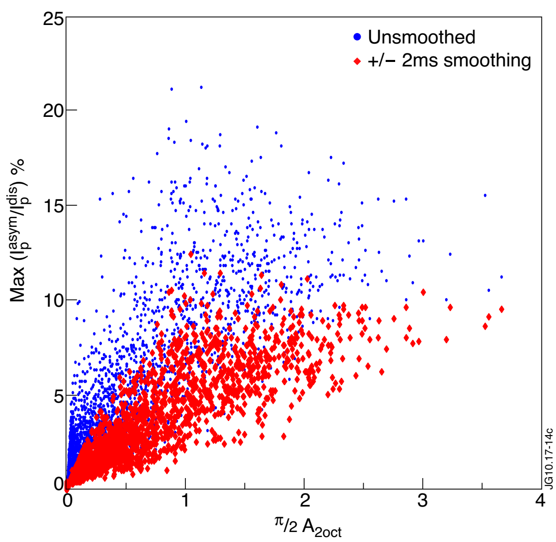

Fig 11 Maximum value of I_p^{asym}/I_p^{dis} versus $\pi/2A_{2\ oct}$. Results are shown with and without a +/-2ms rectangular smoothing window.

For the 4 octant data using $A_{4\ oct}$ as the asymmetry measure to define the CAT III to CAT II boundary, this occurs at 1.19ms; giving a ratio of the peak CAT III/IV to CAT II I_p asymmetries of 2.15/1.18=1.82. The equivalent ratio for the 2 octant dataset is rather bigger at 3.68/1.45=2.55. A simple envelope description of the peak CAT II pulses is not so easy; it can be inferred from Fig 10 that there will be some pulses where a 10% envelope for the duration of the I_p quench gives a good description of the data, but others where the asymmetry is less than 10%, but for longer durations in slower current quenches. However it can also be seen from Fig 11 that there are a few CAT II pulses where an envelope of I_p^{asym}/I_p^{dis} >10% is needed (even for the smoothed data). The 2 octant CAT II data might thus be described by a I_p^{asym}/I_p^{dis} envelope of 10% for 15ms. However to account for the reduced amplitude but longer pulses in CAT II it might be prudent to also examine the forces arising from an envelope I_p^{asym}/I_p^{dis} =5% for 30ms and I_p^{asym}/I_p^{dis} =15% for 10ms.

3 JET asymmetry rotation

In the majority of pulses the halo and I_p asymmetry rotates counter to I_p, at ~100Hz, though there is significant scatter and a few pulses even rotate in the I_p-direction [9,10]. For the ITER vessel the most problematic rotation frequency is ~3-8Hz, the fundamental mechanical vessel frequencies for VDE loading conditions [6]. Rotating modes resonating with the vessel frequency will lead to dynamic amplification of the structural forces. Figure 12 shows the number of revolutions calculated for four different time windows specified by the condition $I_p^{asym}/I_p^{dis} (\equiv A_p^{asym})$ >0.5%, 1%, 2% and 5% for first and last window time points (subject to the additional criteria on noise level that$|I_p^{asym}|$>10kA and $|I_p^{asym}|$>0.5% $|I_p^{dis}|$ and $|I_p|$>10% $|I_p^{dis}|$ and also $|I_p^{asym}|$>10kA for the first and last 1ms window to ignore the shortlived spikes). The degree of rotation is in the range from -2 turns to +8 turns for the entire 4 octant database, where a positive number of turns corresponds to rotation counter to I_p. The physical processes leading to these rotation variations are not presently understood, however at the ITER vessel frequency (up to ~8Hz) around 2 turns maximum will occur through the duration of the peak CAT III/IV events (where the duration is extrapolated from JET on the plasma area weighting basis), limiting dynamic amplification.

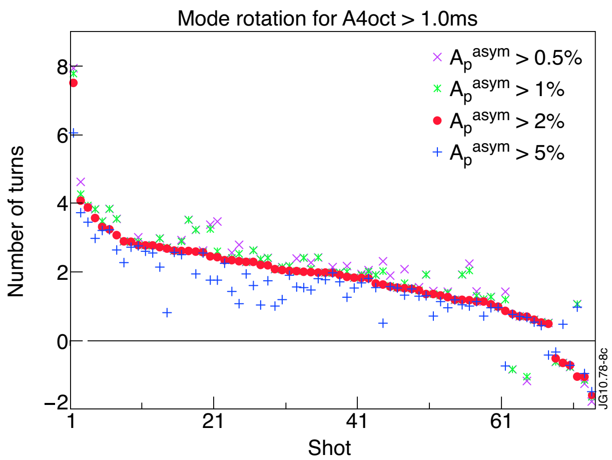

Fig.12. The number of turns calculated for the four octant databases. Only pulses with a measurable rotation of >0.5turns are included.

The cumulative probability of reaching a given number of turns is shown in Fig 13, for various amplitudes of the plasma current asymmetry.

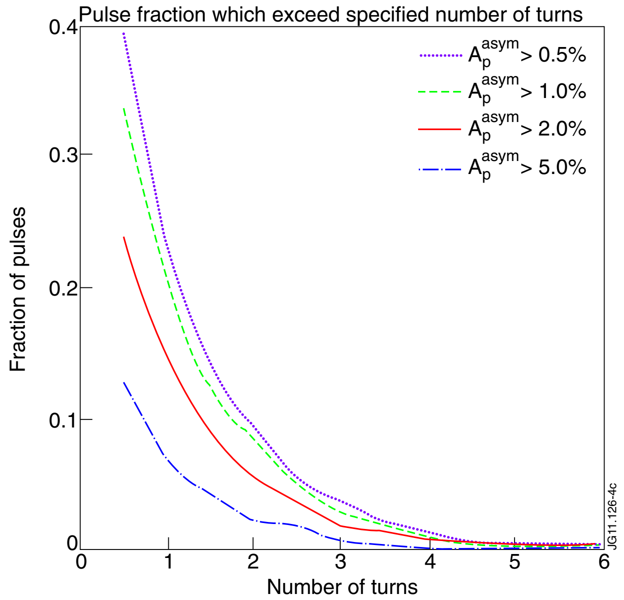

Fig 13 Fraction of shots (from 954 shot 4 octant database) that exceed a specified number of turns, with the different curves showing the fraction for different asymmetry amplitudes.

5. ASDEX Upgrade and DIII-D results

Unfortunately no data is available from tokamaks other than JET on the toroidal variation of the plasma current during disruptions events. However many tokamaks have halo current data. Empirically in JET there is a clear relationship of the toroidal current asymmetry and the measured poloidal halo current, as shown in Fig 14.

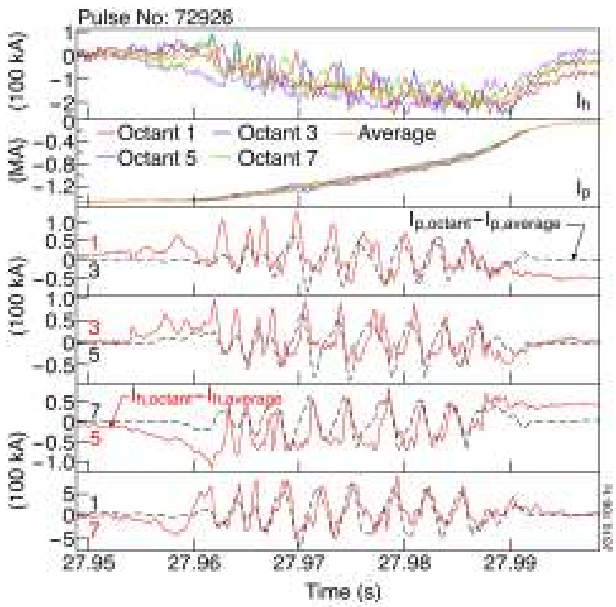

Fig 14 The poloidal halo current and the plasma current measured in four octants are in the top two boxes. The plasma current flows clockwise in JET, hence the negative sign. Negative halo current in the top of the vessel means current entering outboard and exiting inboard. The bottom four boxes have the asymmetric component of the poloidal halo current and the asymmetric component of the toroidal plasma current in each octant, with the comparison octant shifted toroidally by π/2 between the halo and plasma current data. From [9].

It can be seen that the plasma current and halo current asymmetries are 90^o out of phase and of approximately equal magnitude (as also reported in [7]). While this is not fully understood there are related results from the M3D code that confirm the phase relationship, but for the case studied show the fluctuating halo currents are ~2 times the toroidal current variation [11].

Although the relationship of the toroidal variation of the halo current and that of toroidal plasma current is not fully quantitatively understood, results are presented from AUG and DIII-D on the halo current variations since they are clearly related to the plasma current variation, and may be of future relevance.

From the definition of the toroidal peaking factor as

$$TPF = \frac{I_{halo}(\max)}{I_{halo}(average)}$$

it can be seen that the amplitude of the halo current asymmetry normalised to the pre-disruptive plasma current is

$$A(t) = (TPF - 1)\frac{I_{halo}(t)}{I_P^{dis}} \qquad (1)$$

and that ∫A(t)dt is related to $A_{4,oct}$ (though it should be noted that the peak-to-peak variation of the toroidal plasma current is used in the $A_{4,oct}$ definition). The data for A(t) in AUG are published in Ref [12]. Figure 15 shows the ∫A(t)dt over the corresponding AUG shot database and also the equivalent results from DIII-D.

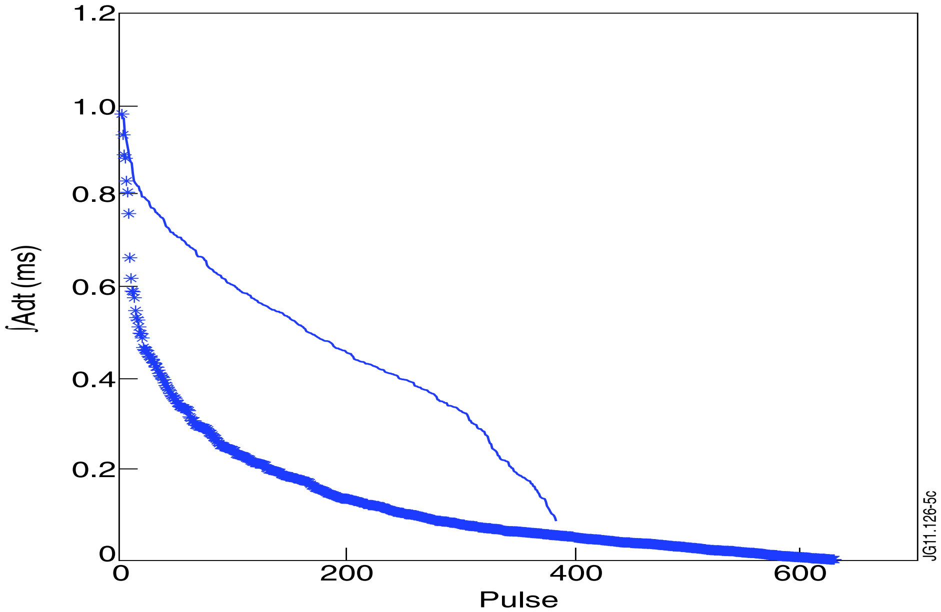

Fig 15 ∫A(t)dt values arranged in monotonically decreasing order for AUG (solid line) and DIII-D ('' symbols); the AUG data are from Ref [12].*

It can be seen that AUG and DIII-D have similar peak levels of asymmetry (∫A(t)dt) but that higher halo current asymmetry is more common in AUG over the considered databases (i.e. the fall-off of ∫A(t)dt with shot number is much more rapid in DIII-D). Taking account of the fact that the peak-to-peak (and not amplitude) is used to define $A_{4,oct}$ and assuming an area weighted scaling then one would expect from the JET I_p asymmetry results a peak value of ∫A(t)dt ~ 0.5ms in AUG or DIII-D (not the observed 1ms).

However as noted one should be very cautious in directly comparing the halo and toroidal current asymmetry amplitudes.

There is limited data on rotation of the halo current in AUG and DIII-D. It should be noted that current quench rates are faster in AUG and DIII-D than in JET (since they scale as plasma area), and so rotations of less than O(100)Hz are more difficult to observe in the smaller tokamaks due to very few periods of rotation occurring. In AUG the rotation is most commonly in the counter-I_p direction but sometimes occurs in the co-I_p direction. Generally there is very limited rotation, but this has not yet been systematically quantified. In DIII-D a database of 315 pulses has been analysed (Fig 16) and in general shows very little rotation.

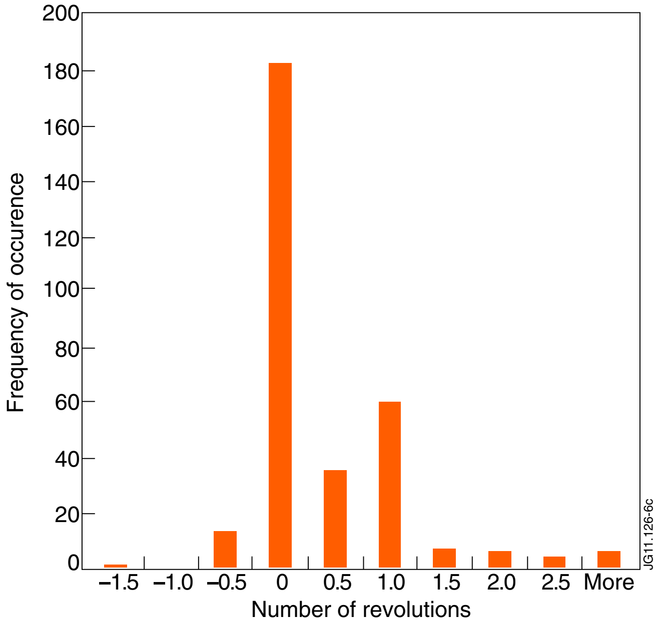

Fig 16 Data from DIII-D on the number of revolutions of the halo current asymmetry, from right to left the histogram bins for the data are - 3.0≥data >2.5, 2.5≥data >2.0, etc to -1.5≥data >-2.0. A negative number of revolutions indicates rotation counter to I_p.

6. Comparison of JET halo and Ip asymmetry results

Although halo and I_p asymmetries are clearly linked an approach to evaluating disruption loads is to treat them separately as cumulative loads. An issue then is whether you can simultaneously get a maximum of the halo and I_p asymmetries. Figure 17 shows the temporal maximum of the I_p asymmetry (normalised by pre-disruption I_p) versus the normalised halo current asymmetry (see Eq(1) in section 5).

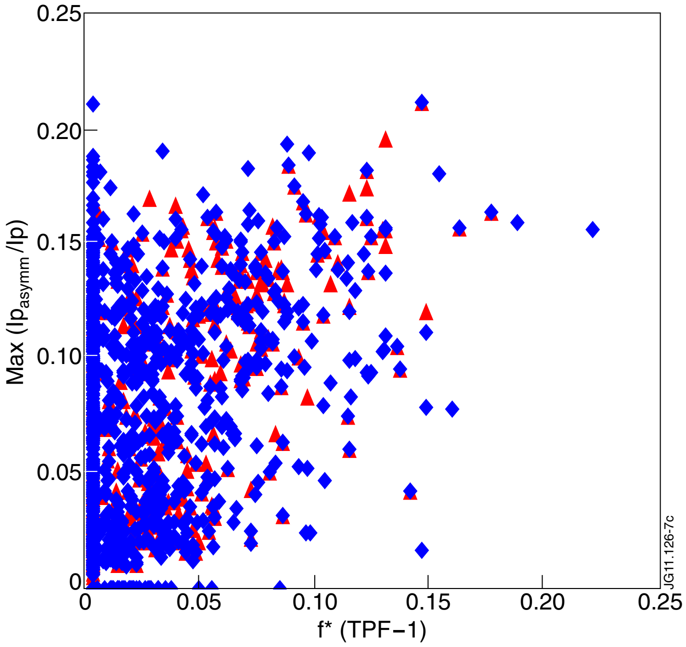

Fig 17 Maximum I_p asymmetry versus the maximum halo current asymmetry. The blue diamonds are 2 octant data with I_p asymmetry derived from the difference between octants 1 and 5. The red triangles are 4 octant data with I_p asymmetry defined as the maximum of the difference between octants 1 and 5 I_p, and octants 3 and 8 I_p.

From Fig 17 it can be seen that there is a correlation between the I_p asymmetry and halo asymmetry, though with a large spread. It thus might be conjectured that the largest sideways force and halo current can occur simultaneously. However, it has to be remembered that the I_p asymmetry maximum can be very transient (this is indicated by Fig 11, where the averaging substantially reduces the maximum). Using instead the time integrated measure of the I_p asymmetry (A_{4oct}), shows the maximum sideways impulse force is not coincident with either maximum spatially averaged halo fraction (*f*) or with the maximum local halo fraction (*f*TPF*) – this is shown in Fig 18.

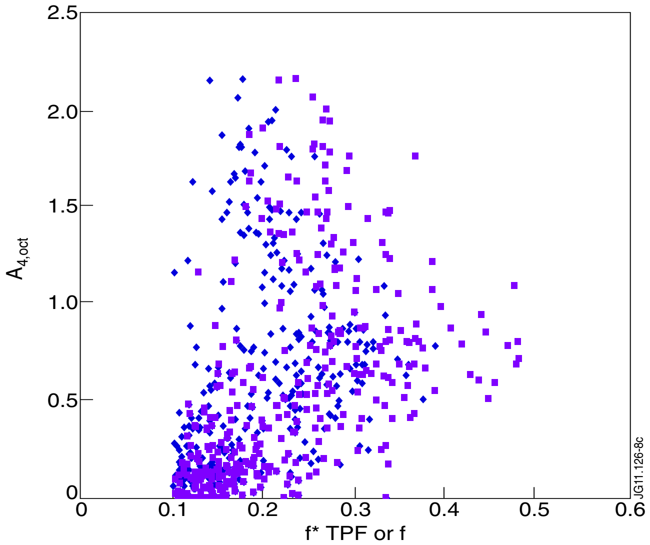

*Fig 18 A_{4oct} versus halo fraction (f, blue diamonds) and maximum local halo fraction (f*TPF, purple squares)*

7. Summary and future work

The JET data show toroidal asymmetries in I_p, that can translate into substantial sideways forces on the vacuum vessel [1]. For fairly recent shots I_p data are available in 4 toroidally opposite octants, allowing phase and amplitude to be deduced. Previously only 2 toroidally opposite octants of data were recorded.

A measure of the I_p-asymmetry has been defined as $A_{2or4oct} = \frac{1}{I_p^{dis}} \int I_p^{asym} dt$. It is found on average that $A_{4oct}=\pi/2\ A_{2oct}$, as would be expected for a rotating n=1 structure.

The data are sorted into 2 categories: CAT III/IV which are largest 6% of pulses, and CAT II which are the remaining 94%. The peak values of A_{2oct} or A_{4oct} for these categories are :-

Category	A_{4oct}	$\pi/2A_{2oct}$	$A_{4oct}(up)$	$\pi/2A_{2oct}(up)$
III/IV	2.15ms	3.67ms	2.15ms	3.67ms
II	1.18ms	1.44ms	1.47ms (514 pulses)	1.21ms (2333 pulses)

Table 1 Peak values of A_{2oct} or A_{4oct} for the indicated categories. Also the statistics for upward going VDEs alone are discriminated. An upward VDE is defined as ΔZ>0.2m when I_p/I_p^{dis}=0.5

Since it is observed that the peak I_p^{asym}/I_p^{dis} ~10% (when smoothed by +/-2ms, see Fig 11), the values in Table 1 can be used to provide waveforms for the peak CAT III/IV and CAT II events, i.e I_p^{asym}/I_p^{dis}=10% for 37ms (for CAT III/IV events). For CAT II events there is a wider spread of amplitudes and it is recommended that windows with I_p^{asym}/I_p^{dis}=5, 10 and 15% are also considered. The likely systematic underestimate of the I_p asymmetry (see Fig 6) should be noted and it is strongly recommended that a substantial margin is allowed in applying these results to ITER vacuum vessel loading calculations. The large, and as yet unexplained, difference in asymmetry (A_{4oct}) between upward and downward going VDEs in JET also reinforces the need for allowing a large margin.

The observation that the asymmetry is within the I_p quench phase duration and the known scaling of this with plasma area [8], suggest that the durations of CAT III/IV and CAT II waveforms be scaled as plasma area (NB. S_{ITER}/S_{JET}~4.7*)*. This issue should be revisited when halo data from other machines can be incorporated to give a size scaling.

Rotation of the asymmetry is important since it can lead to dynamic amplification of the applied force if resonance with the vessel or an in-vessel component occurs. The main vessel frequency is up to ~8Hz and so the upper bound of the JET CATIII/IV envelope which is 258ms in duration when extrapolated to ITER, allows up to just over 2 periods of rotation – thus limiting the scope for dynamic amplification. However it should be noted that smaller amplitude asymmetries I_p^{asym} / I_p^{dis} can last longer and also in-vessel components have higher resonant frequencies allowing greater dynamic amplification.

A key weakness is that the data on I_p asymmetries is solely from JET. Data on halo current asymmetries is however available on other tokamaks including AUG and DIII-D, and some is presented here. There are empirical observations on JET on the link between the poloidal halo current asymmetry and the plasma current asymmetry. Also M3D calculations are starting to shed light on this link. Thus if a physics understanding can be developed this would be very valuable in providing experimental confirmation of the size scaling of the I_p (or poloidal halo current) asymmetry duration; this is the key near-term development to be pursued.

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