EUROfusion

JET and COMPASS Asymmetrical Disruptions

Sergei Gerasimov

Theory and Simulation of Disruptions, PPPL 13-15 July 2015

JET COMPASS INSTITUTE OF PLASMA PHYSICS ASCR CCFE CULHAM CENTRE FOR FUSION ENERGY

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Acknowledgements

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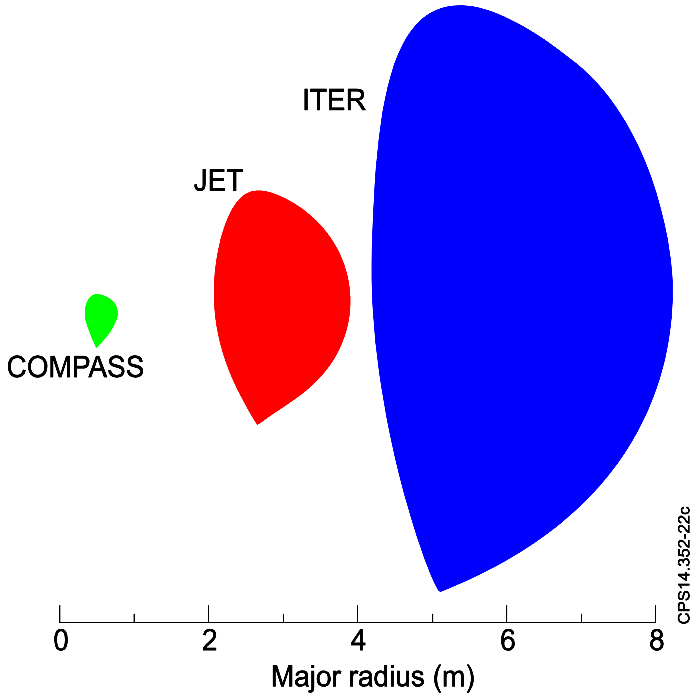
JET and COMPASS Asymmetrical Disruptions

- For many years JET was the only machine which provided *Ip* toroidal asymmetry data.

- Would COMPASS data be in line with the large JET disruption database?



Outline

- JET and COMPASS
  - Diagnostics
  - Database and signal processing
  - Ip asymmetry data
  - Rotational data
  - The edge safety factor at a disruption
- JET
  - Sideways force impulses and vessel displacements
  - Asymmetry in the toroidal magnetic flux and its possible physical interpretation
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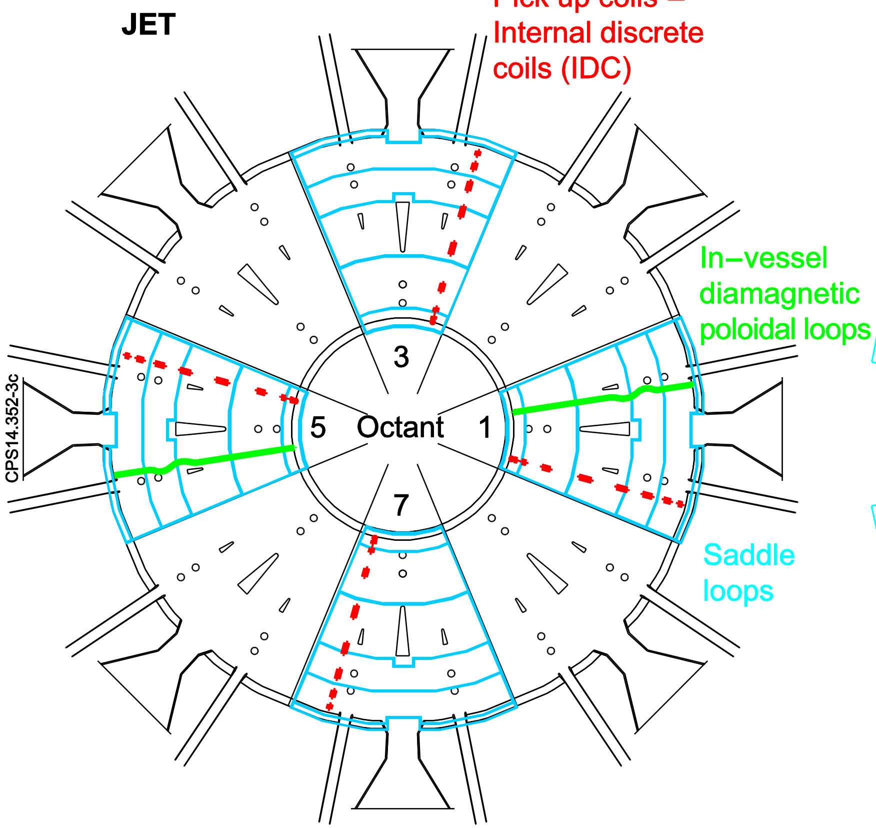
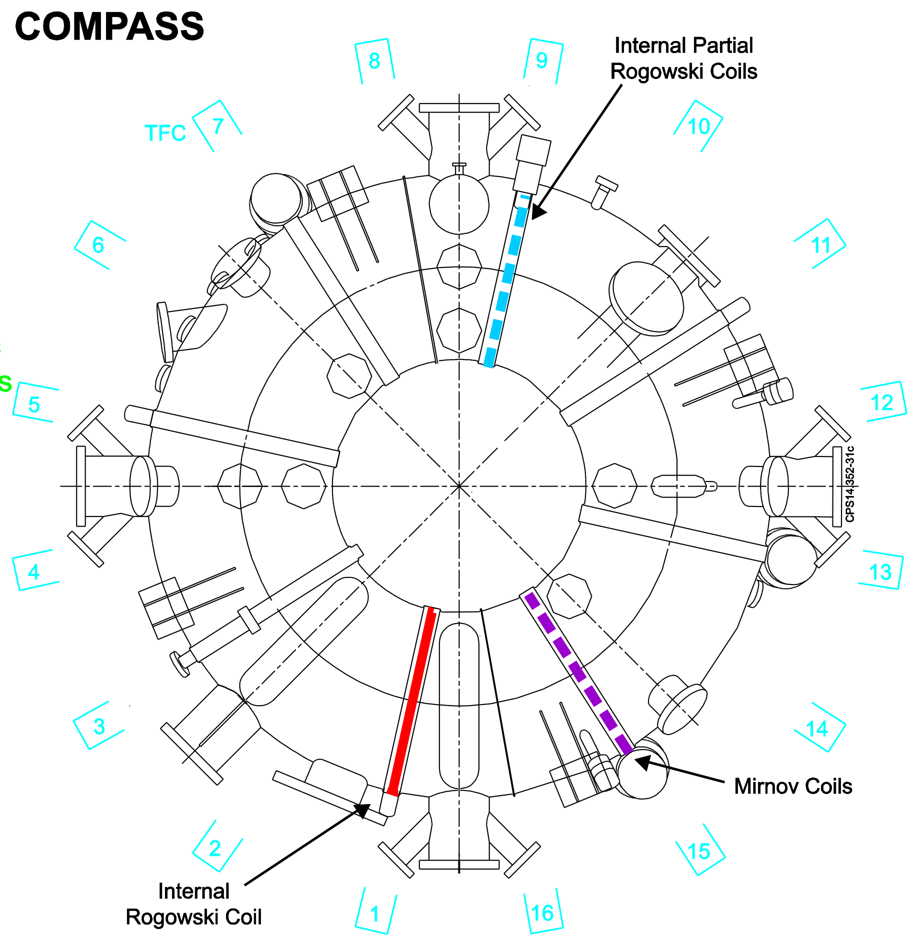
JET and COMPASS Magnetic Diagnostics (1)





JET and COMPASS plan view

JET: 18 pick up coils and 14 normal saddles at 4 toroidally orthogonal locations

COMPASS: various pick up coils at 3 toroidal locations

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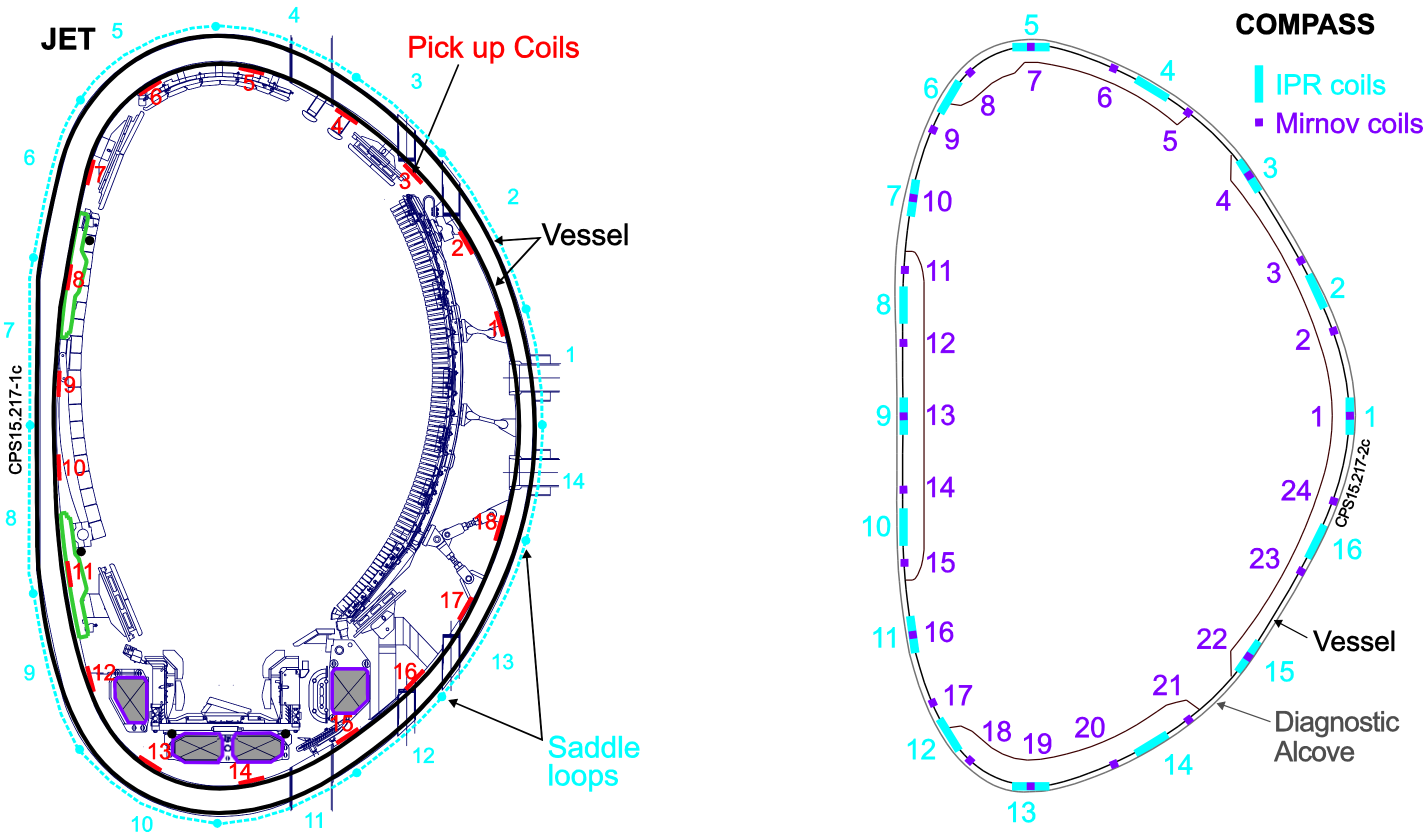
JET and COMPASS Magnetic Diagnostics (2)

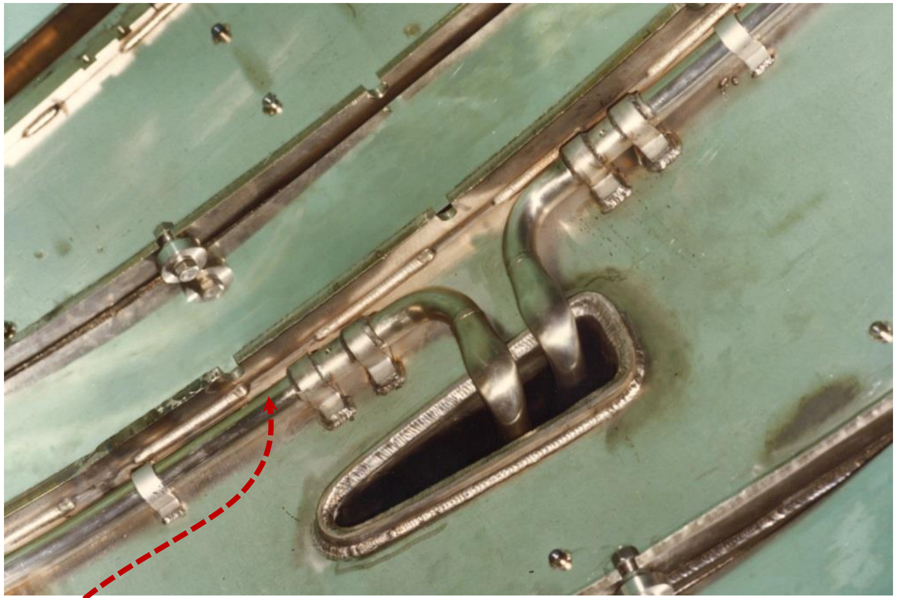


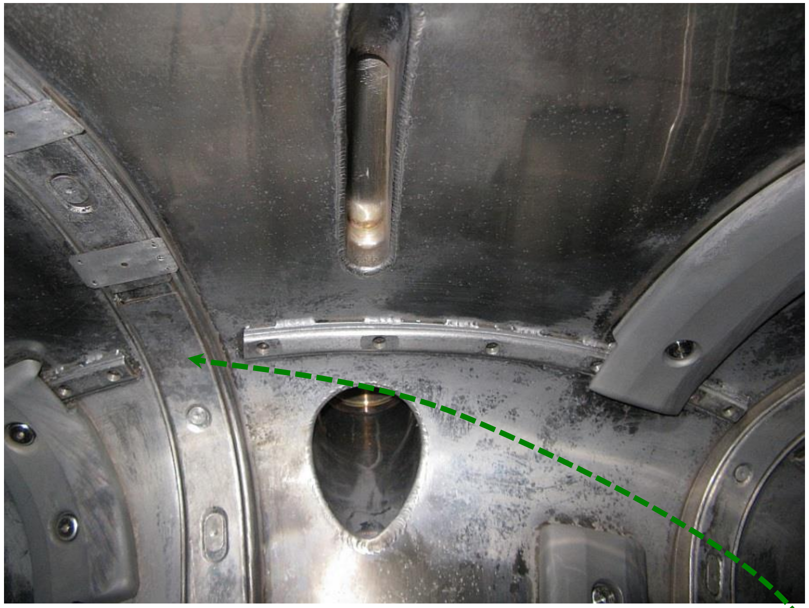
JET and COMPASS cross-sections

JET: Each vessel octant was identically equipped with pick up coils and saddles

COMPASS: 3 types of pick up coils at various toroidal locations – IPR, Mirnov and Rogowski coils

JET and COMPASS Magnetic Diagnostics (3)



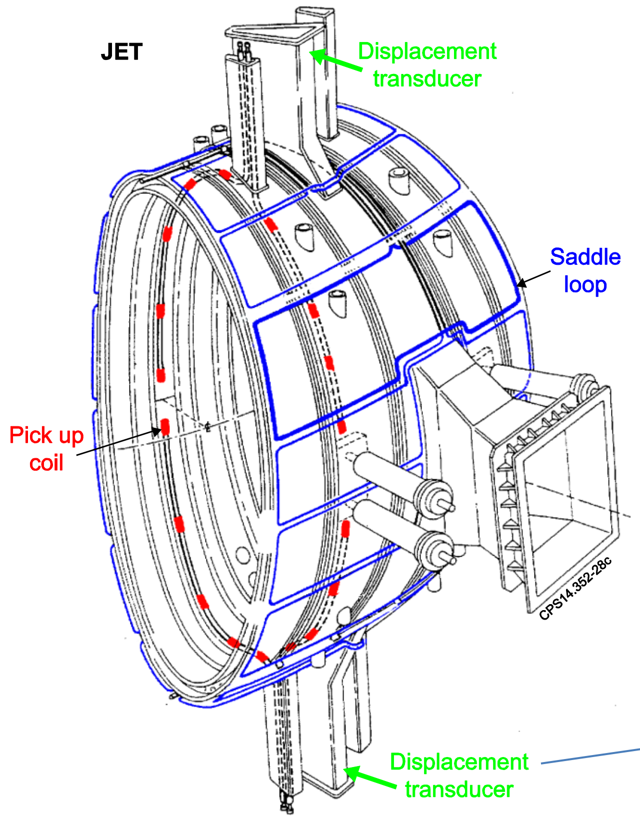


JET and COMPASS top of the vessel (inside)

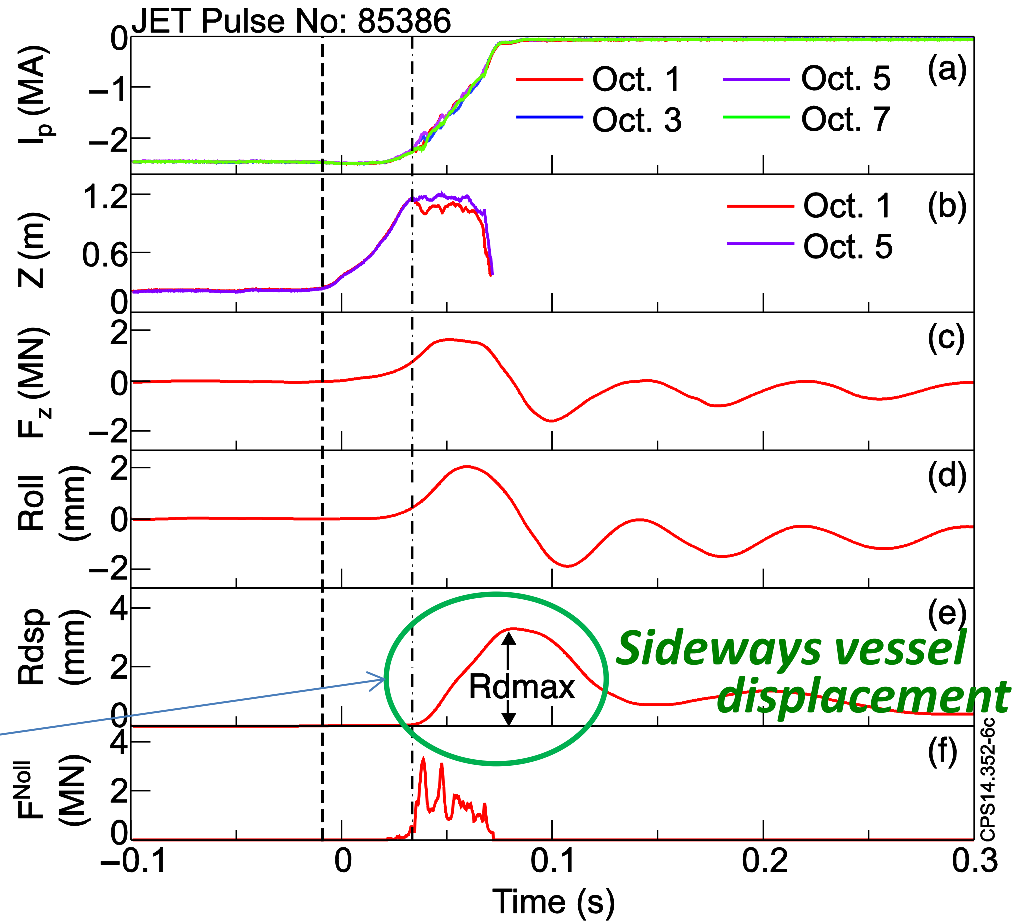
JET: pick up coils are located inside the tube

COMPASS: pick up coils are located inside the vessel alcove

JET Vessel Displacement Diagnostic



Transducers measure radial movement at vertical port of each vessel octant with respect to mechanical structure



The JET vessel undergoes a complex, damped oscillation

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JET and COMPASS Database

- **JET 4 octant data with pre-disruptive Ip ≥ 1 MA**
- **1990 = 950 (C-wall) + 1040 (IL-wall) disruptions**

  from 3/11/2005 (#64326) up to 9/10/2014 (#87944)
- **5 kHz sampling rate → Current Quench (CQ) ≥ 10ms**

- **COMPASS 3 "octant" data**
- **78 C-wall *asymmetrical* disruptions**

  from 12/11/2013 (#6033) up to 27/11/2014 (#8788)
- **2 MHz sampling rate → Current Quench ≥ 2ms**

JET and COMPASS Data Processing (1)

The toroidal variation of the measured plasma current is approximated by a finite Fourier sum of degree n:

$$I_p^n(\varphi) = X_o + \sum_{k=1}^{n}[X_k \cos(k\varphi) + Y_k \sin(k\varphi)]$$

where f is the toroidal angle, X_o is the toroidally averaged plasma current (to be found), *k* is toroidal harmonic number, X_k and Y_k are Fourier coefficients (to be found).

4 JET and 3 COMPASS toroidal measurements have been approximated by *n = 1* toroidal harmonic:

$$I_p(\varphi) = X_o + X_1 \cos(\varphi) + Y_1 \sin(\varphi)$$

4 JET measurements	3 COMPASS measurements
$X_o = (I_{p1} + I_{p3} + I_{p5} + I_{p7})/4$	$X_o = (I_{p1} + I_{p9})/2$
$X_1 = (I_{p1} - I_{p5})/2$	$X_1 = (I_{p1} - I_{p9})/2$
$Y_1 = (I_{p3} - I_{p7})/2$	$Y_1 = \sqrt{2} I_{p15} - \frac{\sqrt{2}+1}{2} I_{p1} - \frac{\sqrt{2}-1}{2} I_{p9}$

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JET and COMPASS Data Processing (2)

Absolute and normalised quantities are used to characterise the magnitude of the 3-D effect:

- **Ip asymmetry:** $I_p^{asym} = 2\sqrt{X_1^2 + Y_1^2}$ → **JET** $\equiv \sqrt{(I_{p7} - I_{p3})^2 + (I_{p5} - I_{p1})^2}$
- **Normalised Ip asymmetry:** $A_p^{asym} = I_p^{asym} / \left| I_p^{dis} \right|$
- **Impulse of Ip asymmetries :** $A = \int A_p^{asym} dt$
- **Sideways force directional impulse:** $Imp_r = \sqrt{Imp_x^2 + Imp_y^2}$

$$Imp_x = \int F_x^{Noll} dt = \tfrac{\pi}{2} B_T \int \Delta M_{IZy} dt$$

- **Sideways force impulse modulus:** $Imp = \int F^{Noll} dt$

$$F^{Noll} = \tfrac{\pi}{2} B_T M_{IZ}^{asym} \qquad M_{IZ}^{asym} = \sqrt{\Delta M_{IZx}^2 + \Delta M_{IZy}^2}$$

JET and COMPASS Data Processing (3)

The data processing for COMPASS is similar to that of JET:

- **Signal smoothing to eliminate the noise contribution (COMPASS - done on initial stage; JET- done on final stage only to get peak quantities)**
- **Trimming waveforms from left and right hand side where** $|I_p| > 0.1|I_p^{dis}|$ **and**

$$A_p^{asym} > 0.5\% \quad (JET)$$

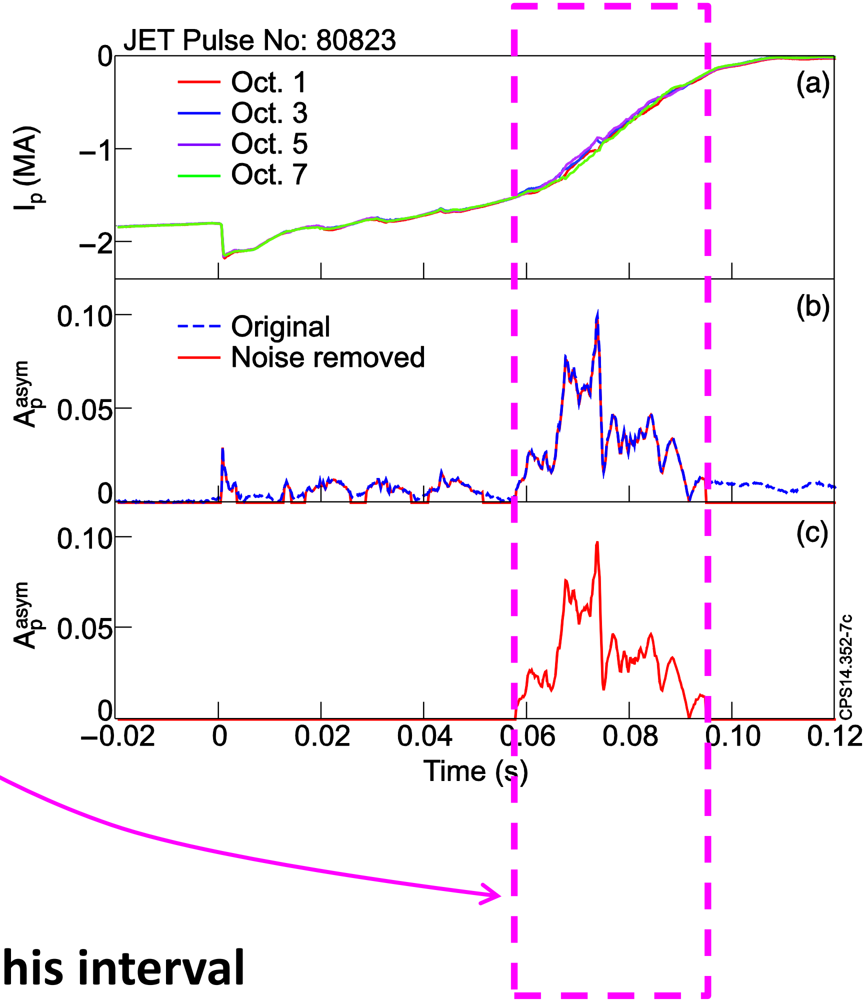
$$A_p^{asym} > 2.0\% \quad (COMPASS)$$

- **"Main asymmetry time window" was used, namely if**

$$I_p^{asym} < 10kA \quad for \quad 2ms \quad (JET)$$

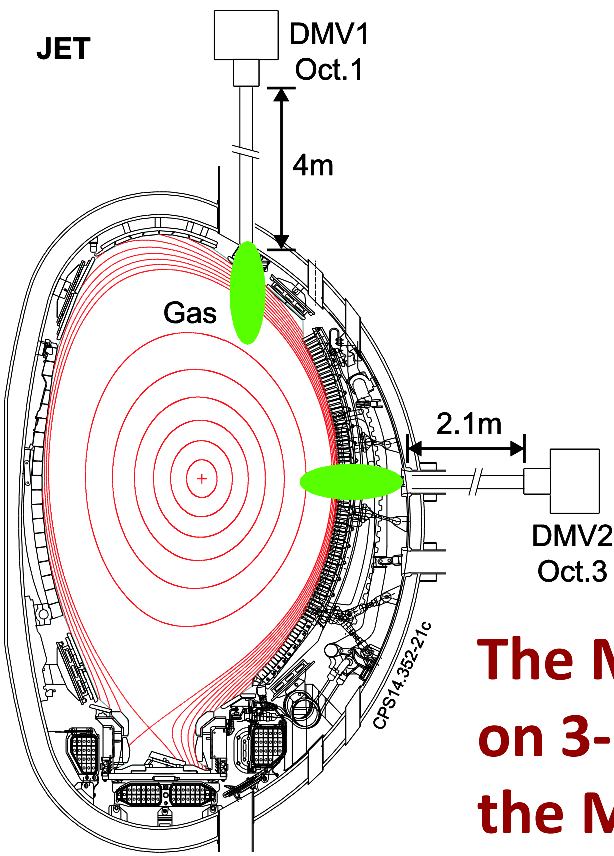
$$A_p^{asym} < 2.0\% \quad for \quad 0.1ms \quad (COMPASS)$$

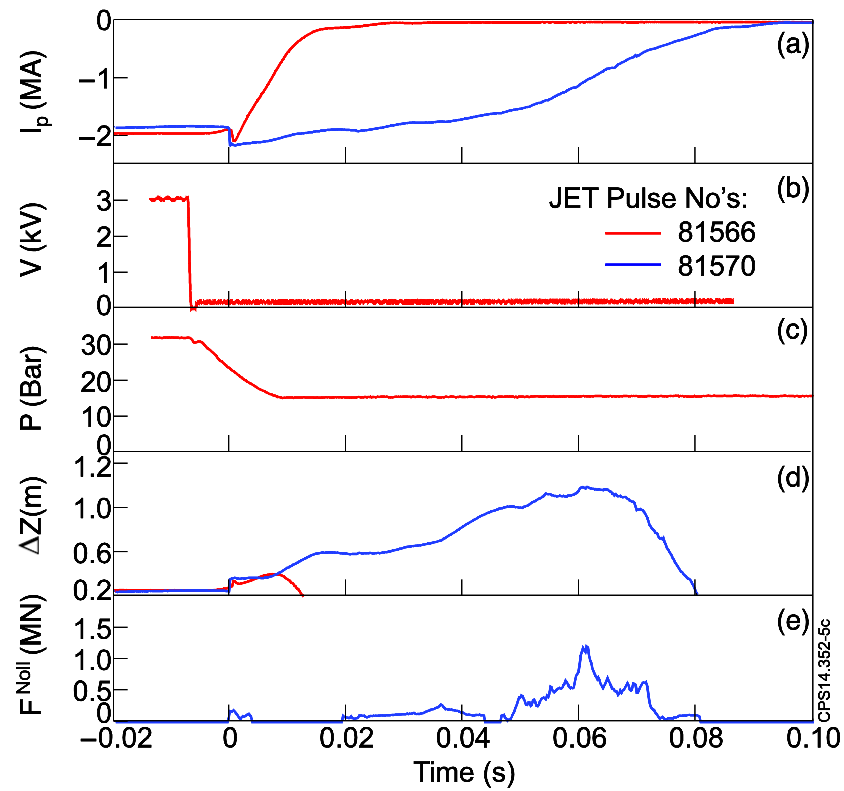
then waveforms are forced to zero during this interval



JET Database and MGI

Massive Gas Injection (MGI) is routinely used to mitigate disruptions in JET





The MGI (90% D_2 + 10% Ar) has a profound effect on 3-D phenomena during the plasma CQ, hence the MGI shots are specifically labelled on the figures presented

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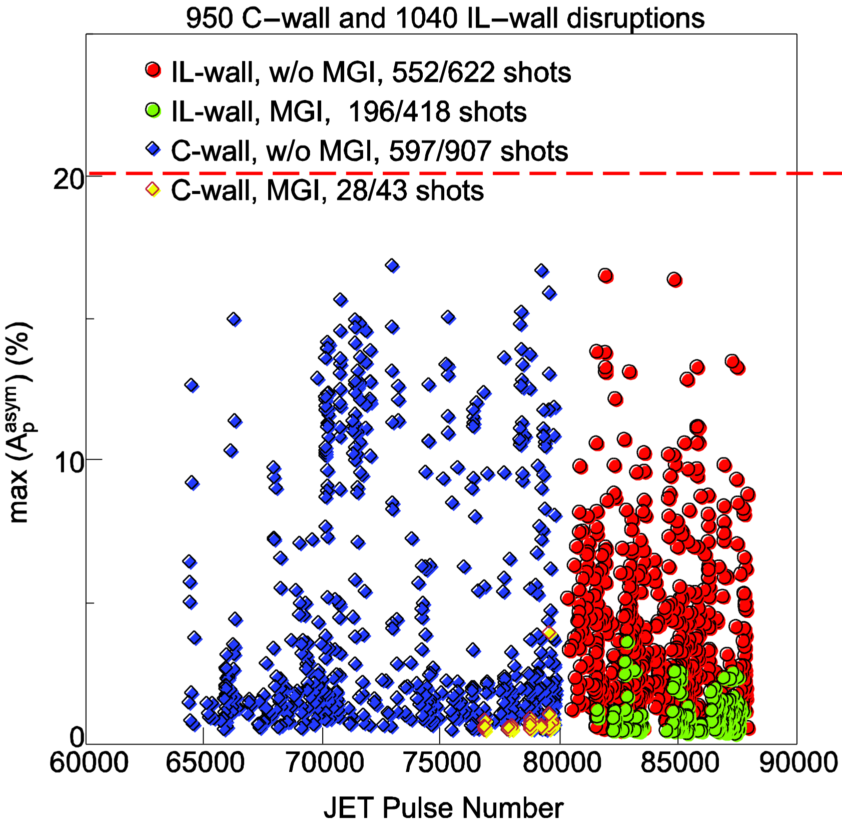
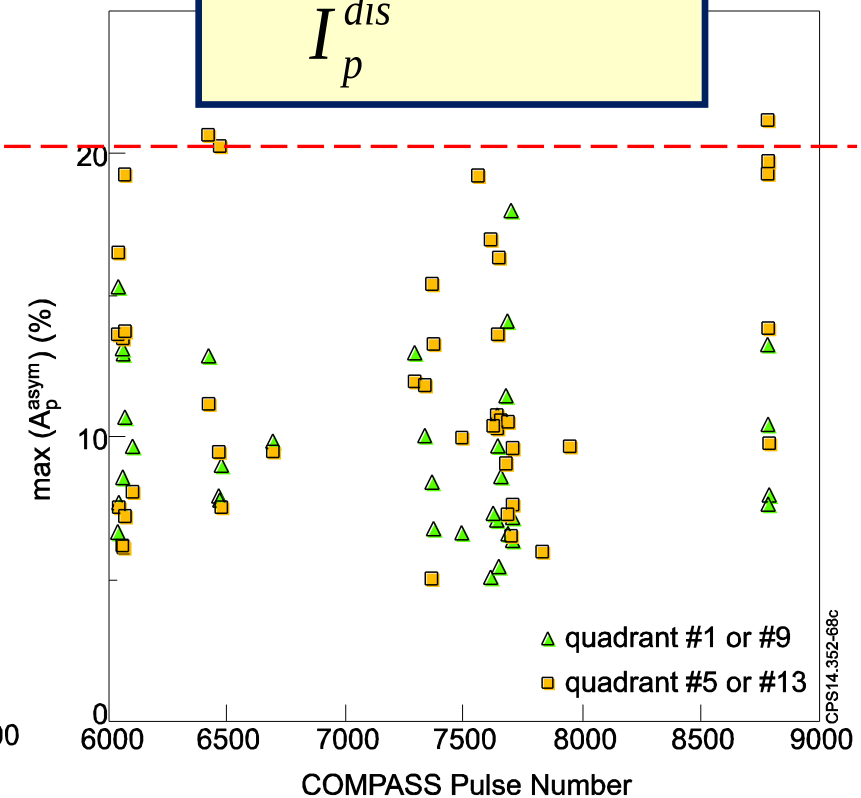
JET and COMPASS Ip Asymmetry Data (1)



$$\frac{\max\left|I_p^{asym}\right|}{I_p^{dis}} \leq 20\%$$



JET and COMPASS data is consistent in terms of Ip asymmetry magnitude

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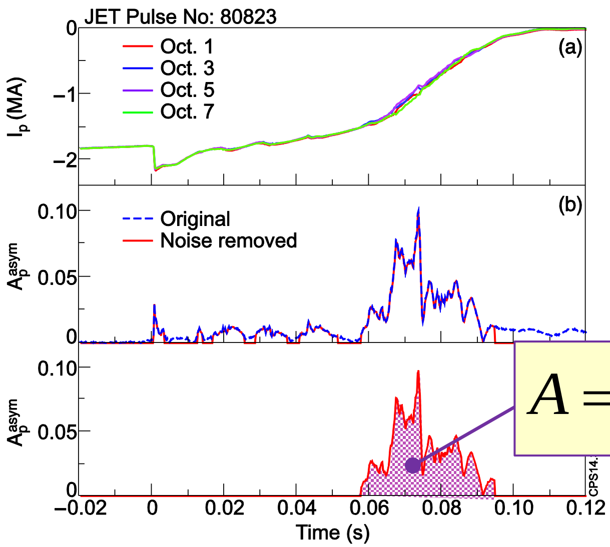
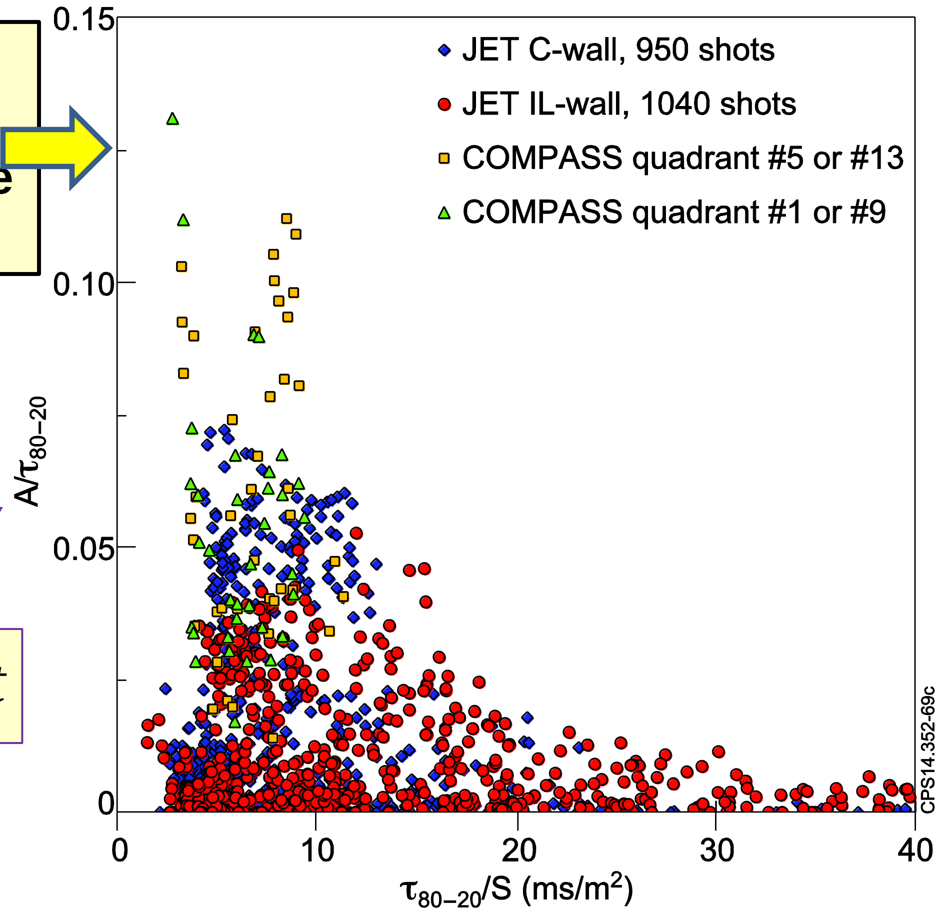
JET and COMPASS Ip Asymmetry Data (2)

JET and COMPASS data showing the Ip asymmetry integral normalised by the 80-20% current quench time vs the area normalised CQ time



$$A = \int A_p^{asym} dt$$



- ***COMPASS** data is in line with the large scale **JET** database, however …*
- ***COMPASS** outermost points are approximately factor 2 greater than **JET** C-wall maximum values*

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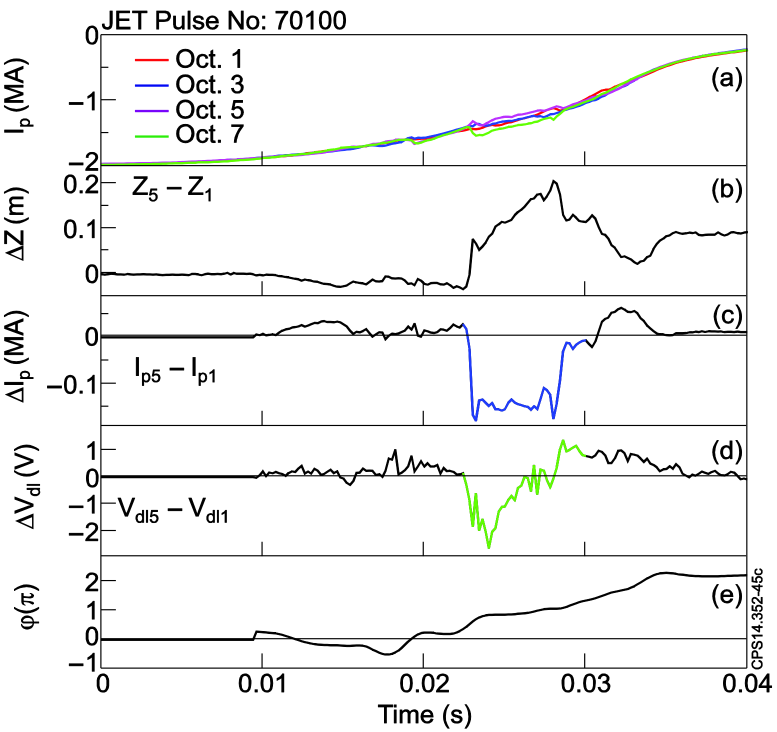
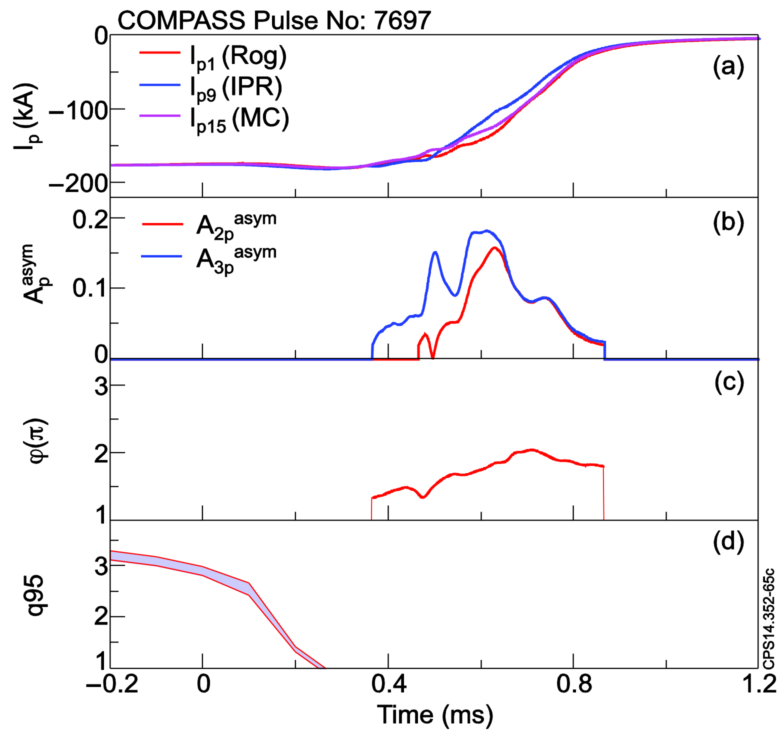
JET and COMPASS Rotational Data (1)

Examples of locked asymmetries – no rotation

JET



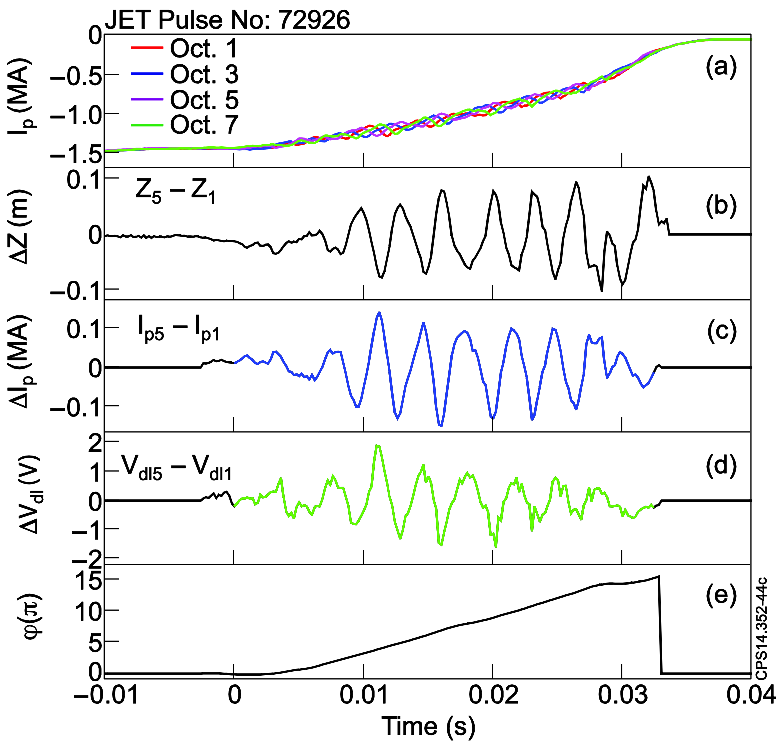
COMPASS



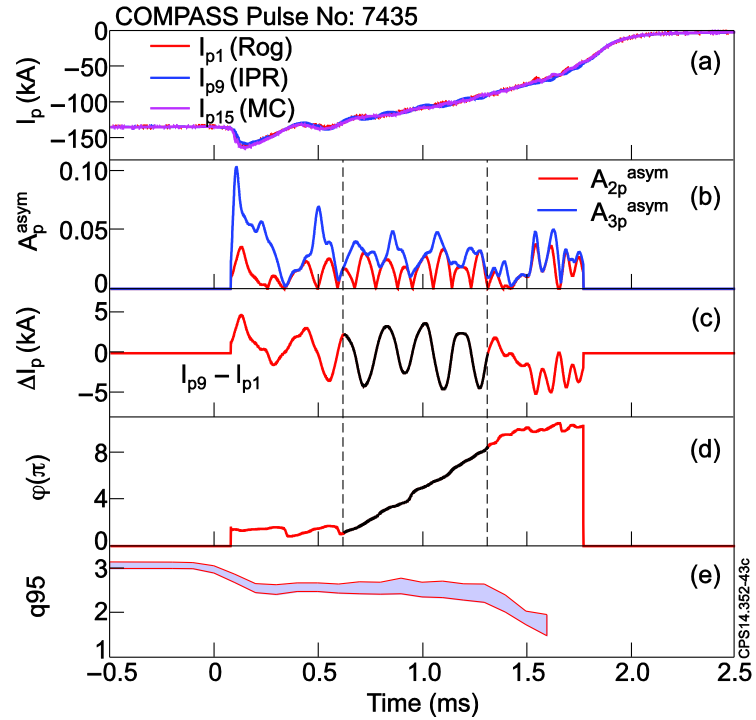
JET and COMPASS Rotational Data (2)

Examples of multi turn Ip asymmetry rotational disruptions

JET



COMPASS



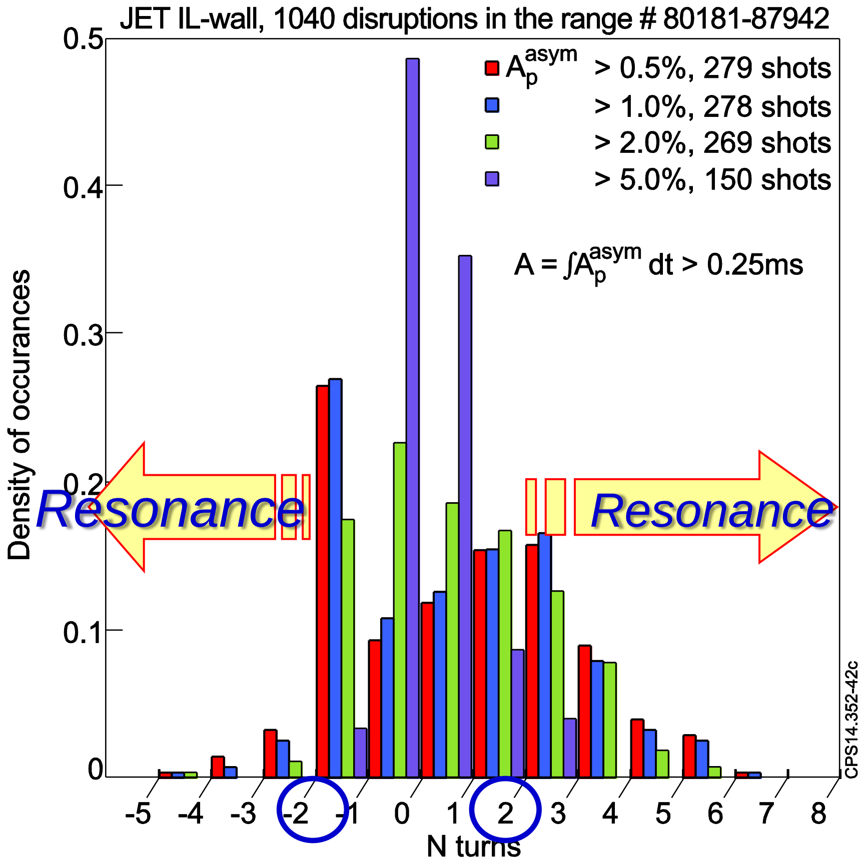
JET and COMPASS data is consistent in terms of toroidal rotation behaviour

JET Rotational Data

Force dynamic amplification:

1. **Rotation occurs near a resonance frequency**

2. **More then 2 periods take place, see JET data**



- For JET the duration of the rotation is short compared to resonance period of the vessel (~1/(14–17 Hz)), and so dynamic amplification is not an issue.
- For ITER the situation can be reversed (the duration of rotation is greater than the mechanical resonance period) making this an issue.

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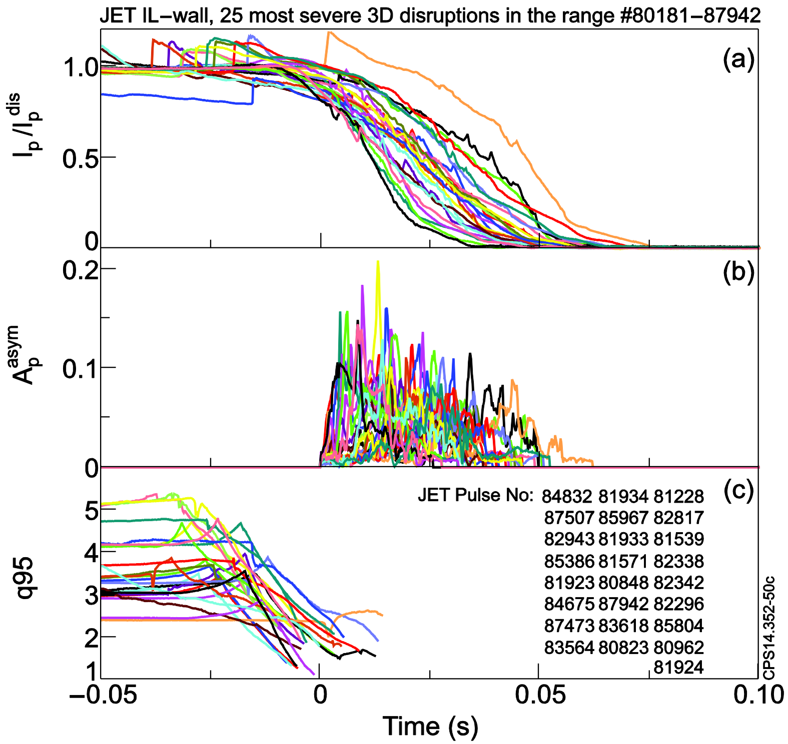
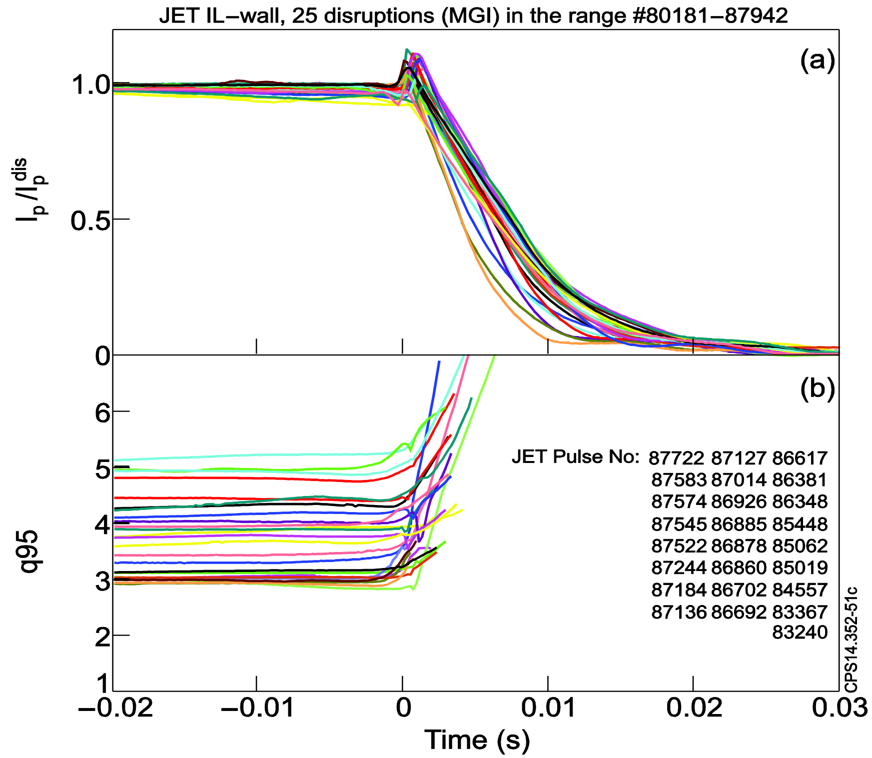
JET Edge Safety Factor at a Disruption



Development of the toroidal asymmetry (large sideways forces) precedes the drop to unity of q95.



In MGI mitigated disruptions q95 rises and any 3-D features are below magnetic diagnostic noise level.

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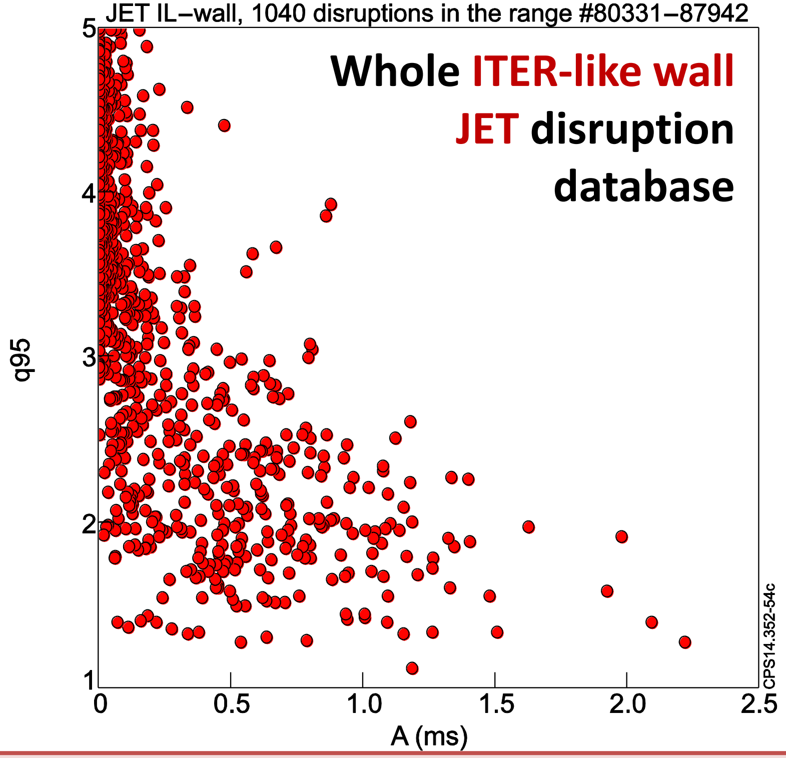
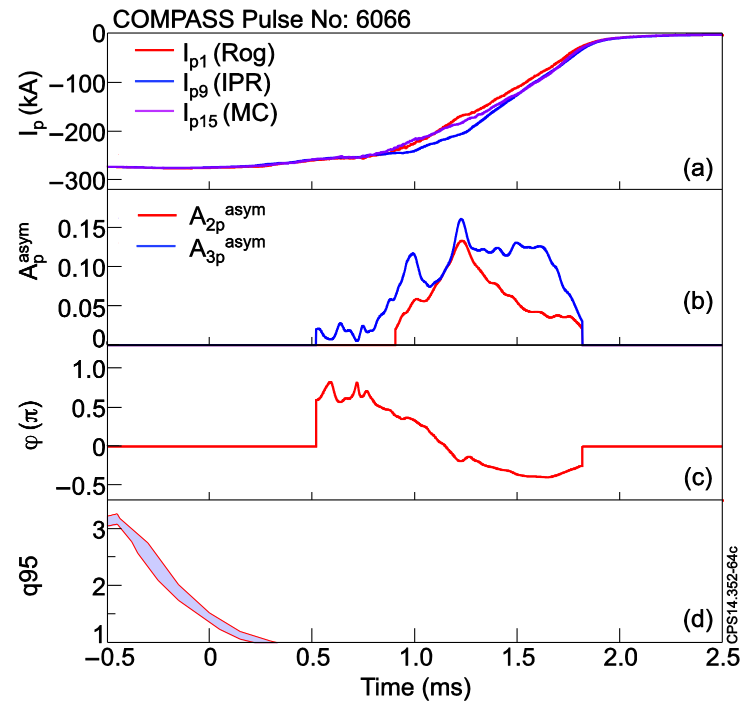
JET and COMPASS Edge Safety Factor at a Disruption



COMPASS



JET-ILW *(whole database)* ***and COMPASS*** *(limited examined disruptions),* ***confirm that the development of the toroidal asymmetry precedes the drop of q95 – sometimes down to unity***

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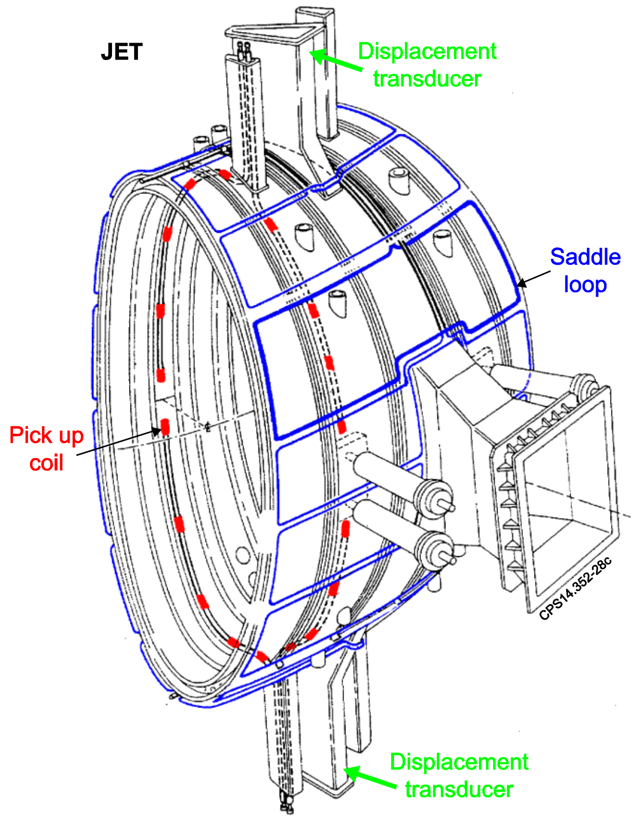
Sideways Force Impulses and Vessel Displacements in JET (1)



Transducers **measure radial movement of each vessel octant with respect to mechanical structure**

Sideways force directional impulse calculated from magnetics data:

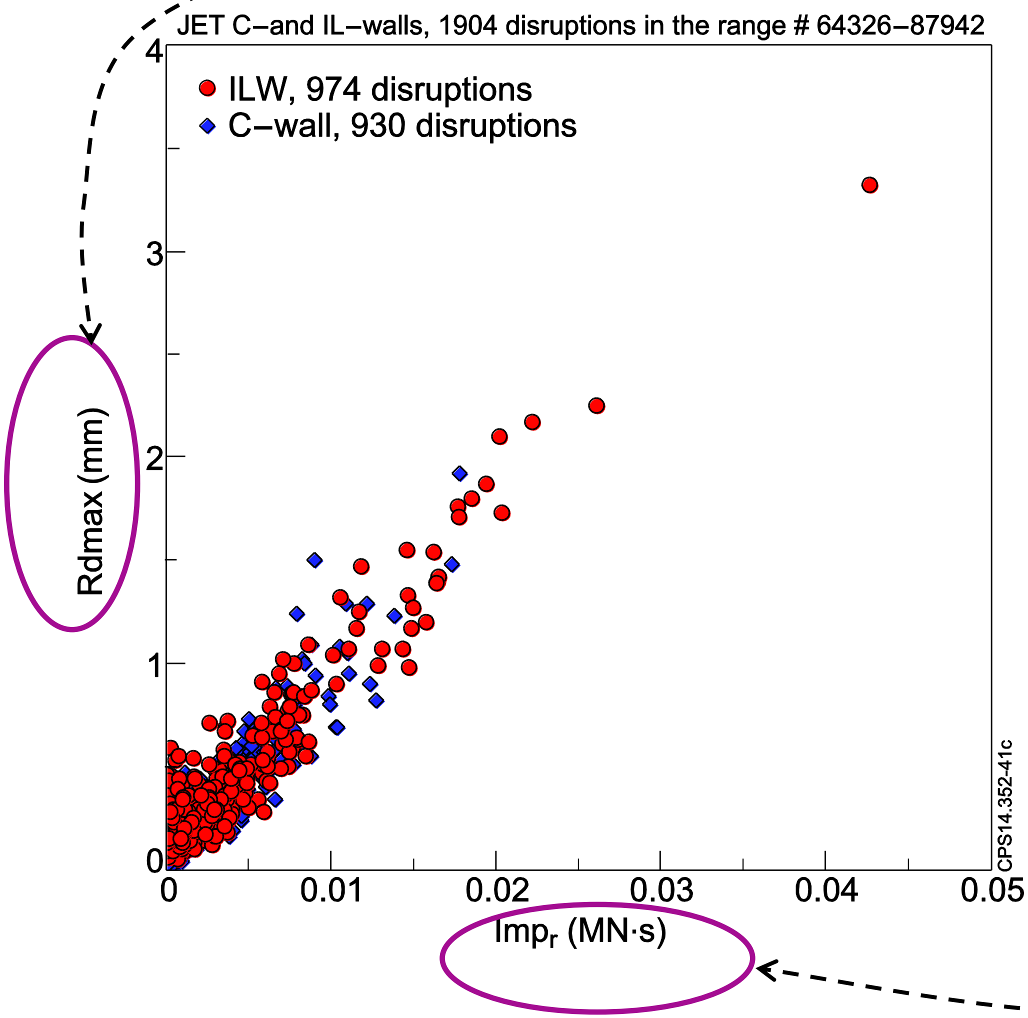
$$Imp_x = \int F_x^{Noll} dt \ (= \tfrac{\pi}{2} B_T \int \Delta M_{IZy} dt)$$

$$Imp_y = \int F_y^{Noll} dt \ (= \tfrac{\pi}{2} B_T \int \Delta M_{IZx} dt)$$

$$Imp_r = \sqrt{Imp_x^2 + Imp_y^2}$$

Sideways Force Impulses and Vessel Displacements in JET (2)

Relationship between mechanical and magnetic measurements



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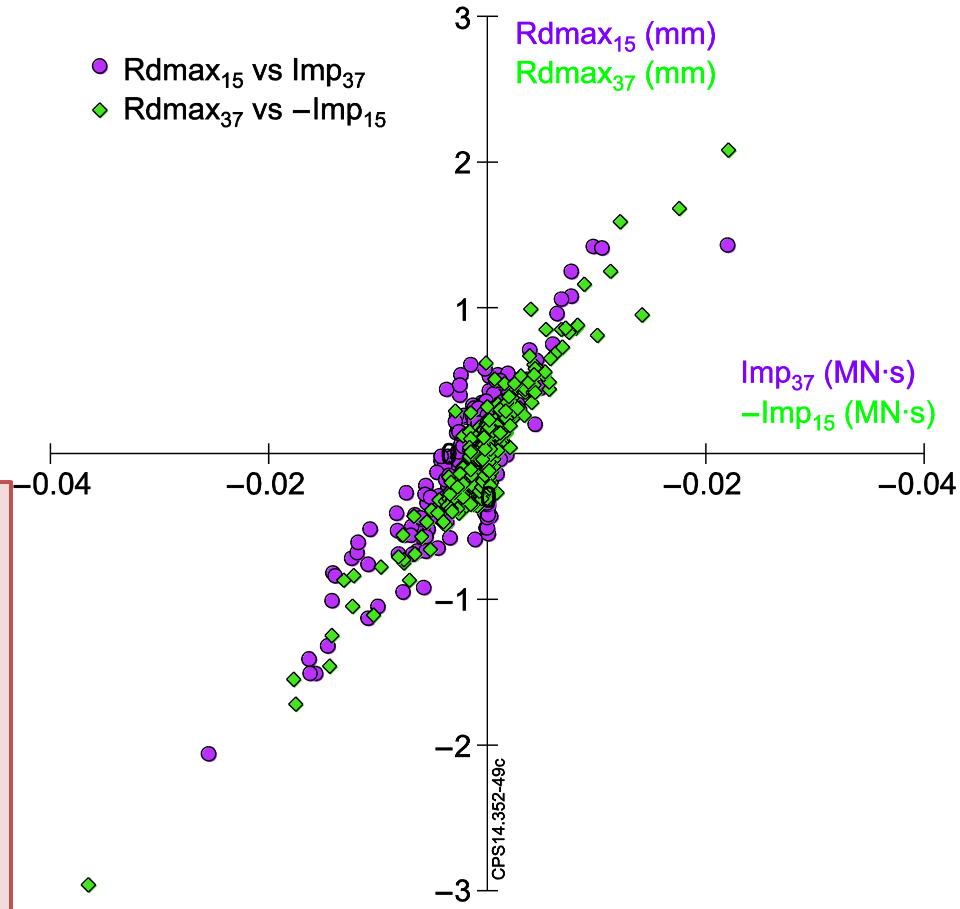
Sideways Force Impulses and Vessel Displacements in JET (3)

Vessel radial displacement orthogonal components in direction #5 to #1 octants and #7 to #3 octants against the corresponding sideways force impulses

JET radial vessel displacement correlates with sideways force directional impulse, which is estimated only from magnetic diagnostic data

JET IL–wall, 974 disruptions in the range #80181 – 87942



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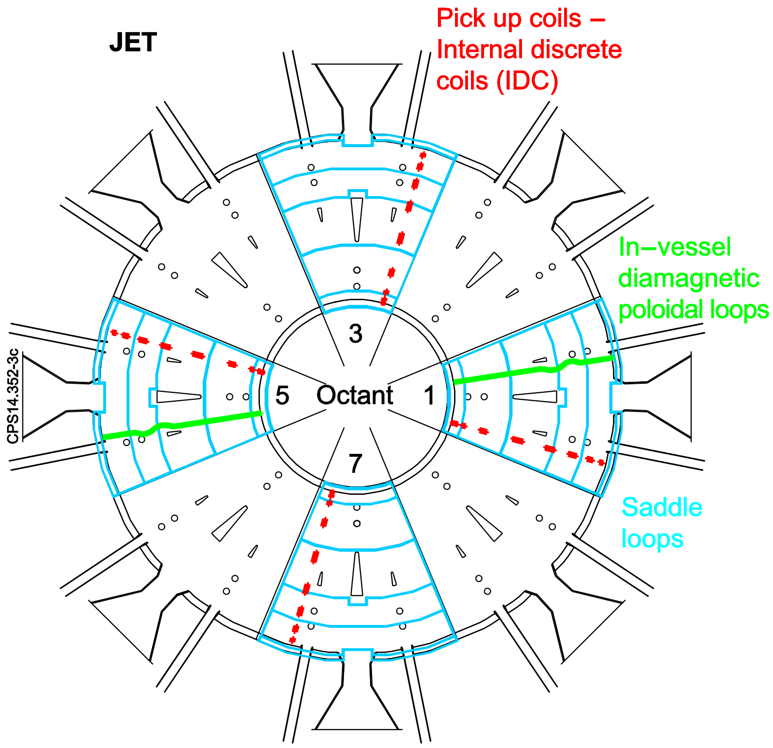
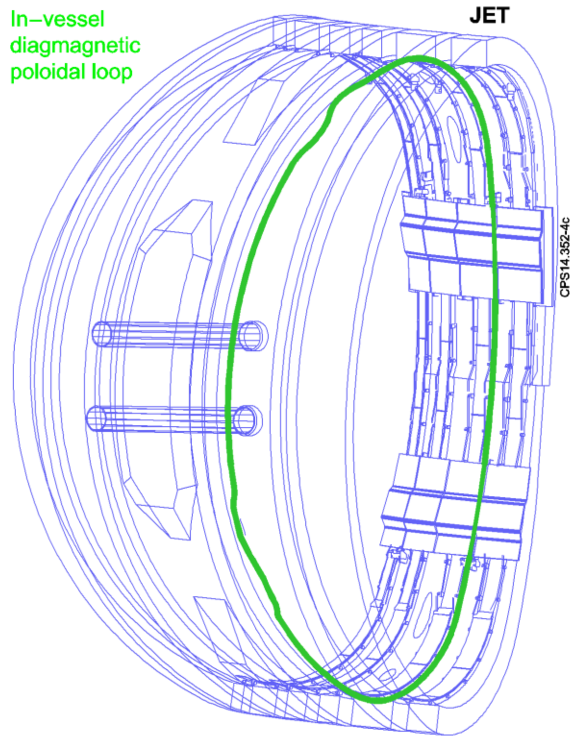
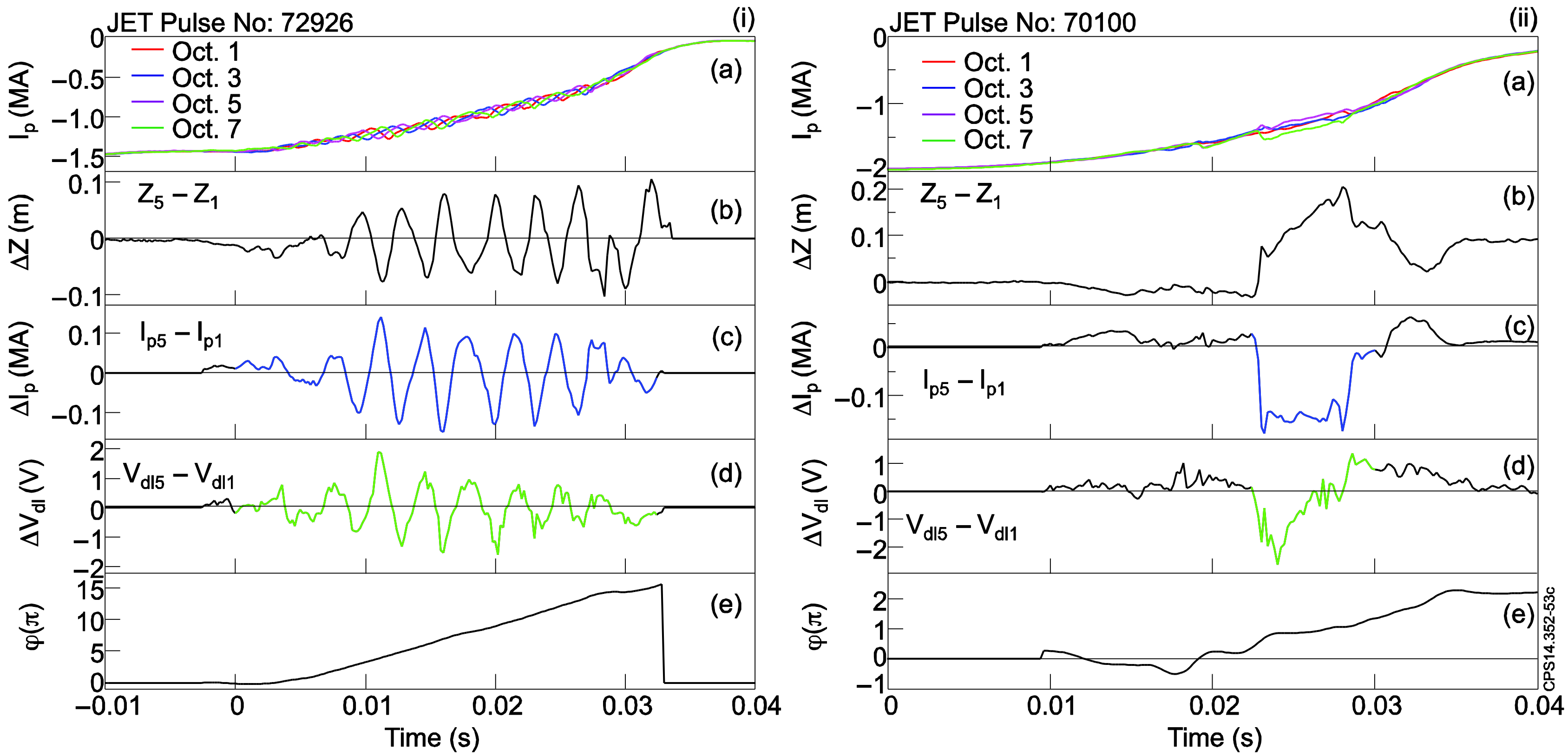
Toroidal Magnetic Flux In-Vessel Diagnostic





Two **JET** opposite octants equipped with **in-vessel diamagnetic poloidal loops**

Asymmetry in the Toroidal Magnetic Flux



JET Ip asymmetrical disruptions:

(i) rotational mode disruption and

(ii) 'locked' mode disruption

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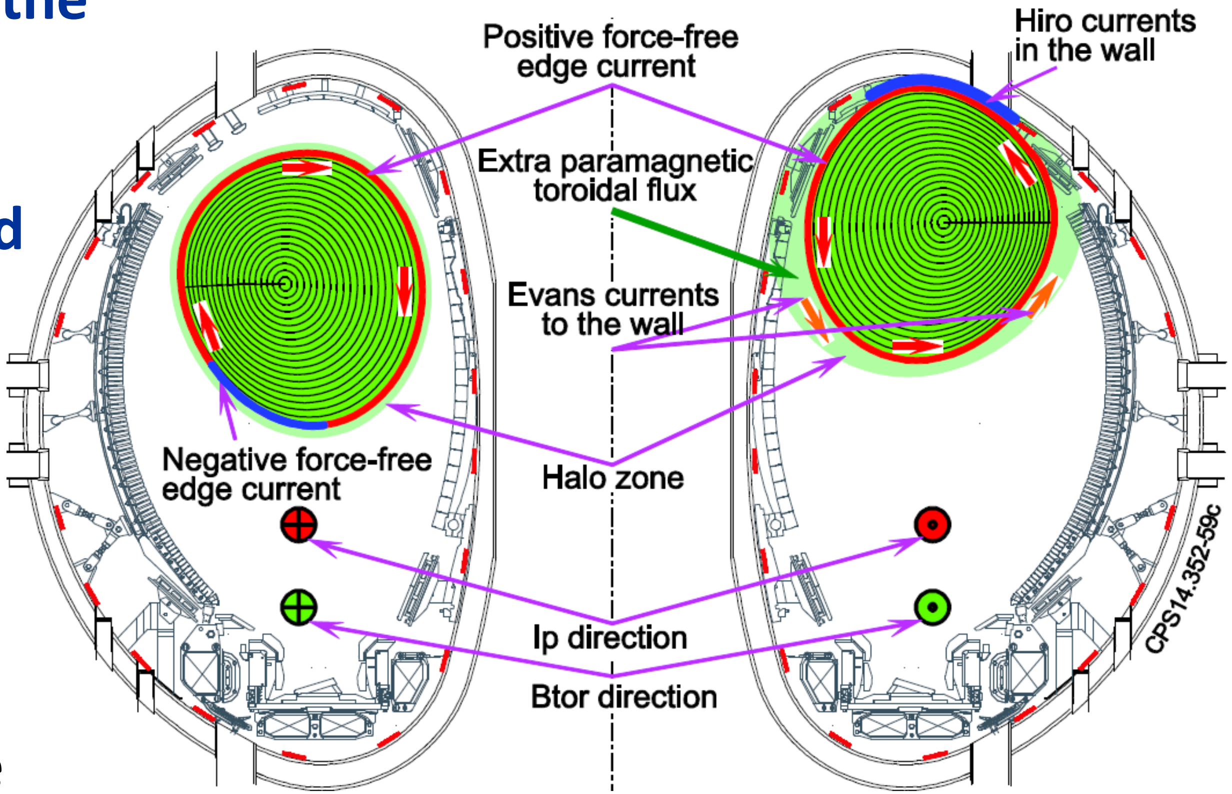
Asymmetry in the Toroidal Magnetic Flux and its Possible Physical Interpretation by Zakharov

The understanding of the asymmetry in the diamagnetic signal requires a step beyond the MHD model.



The particles released from the plasma core, determine the "source limited" (Evans) currents in the halo zone:

$$I^{Ev} \le e\frac{dN_e}{dt}$$

Illustration of asymmetrical disruption with a wide halo zone in vicinity of the plasma-wall contact with the Hiro and Evans currents

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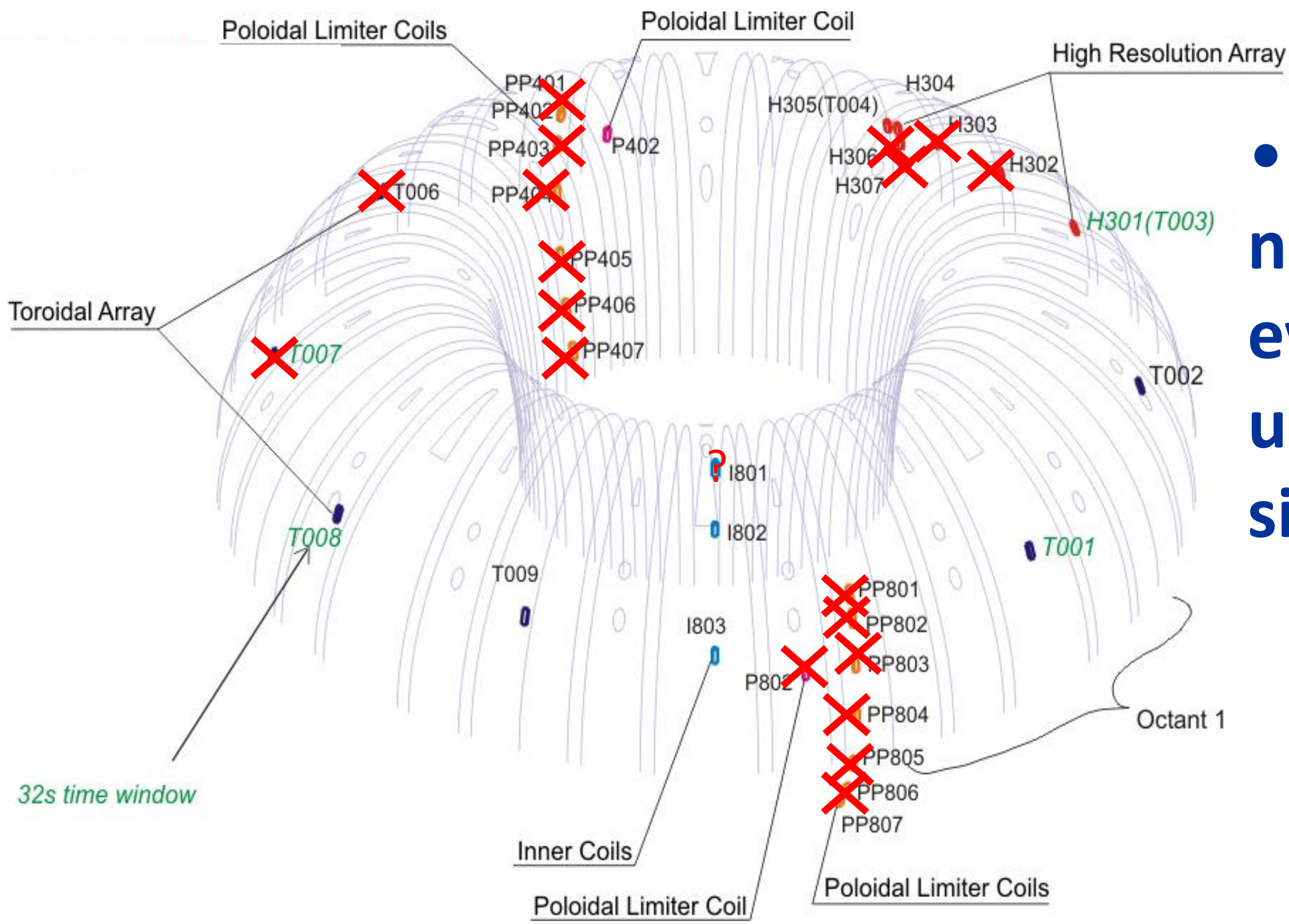
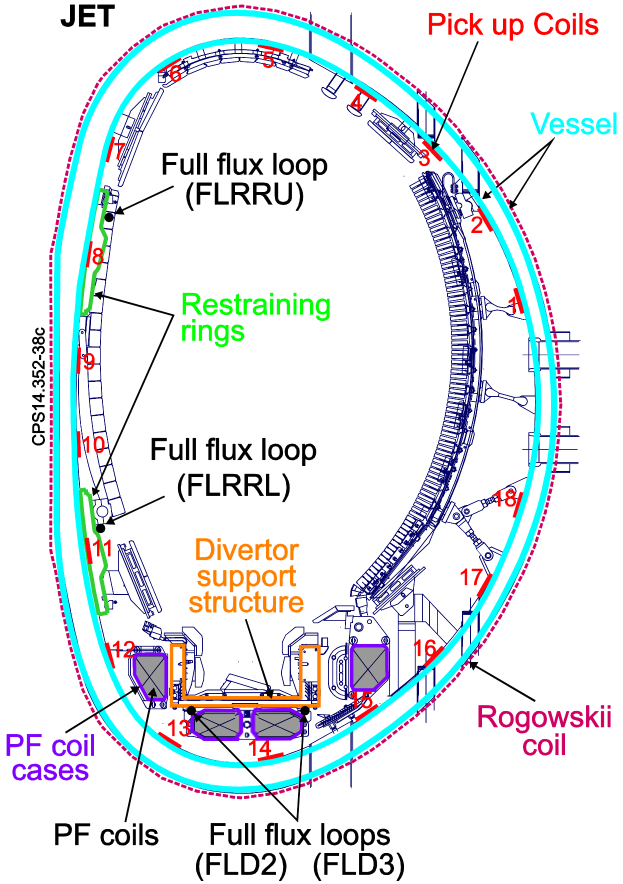
High Resolution Coils – Status at end of 2014

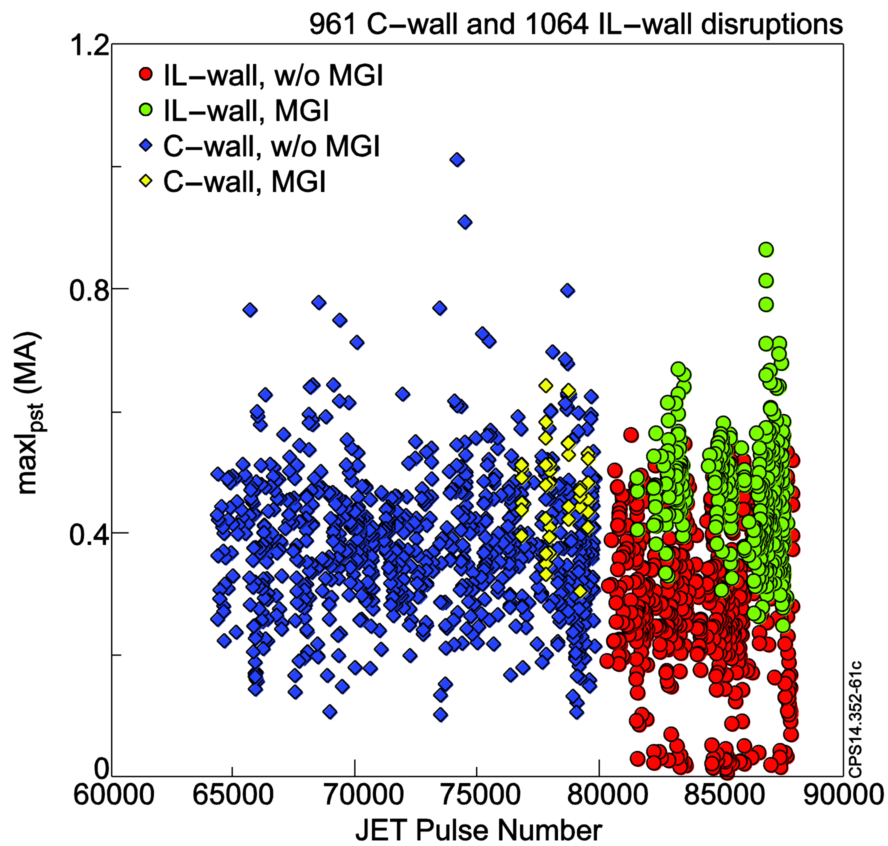


- **Poloidal m number can be evaluated by using only two HF side coils**

- **Toroidal n number calculation possible only for low n numbers (n~3/4)**

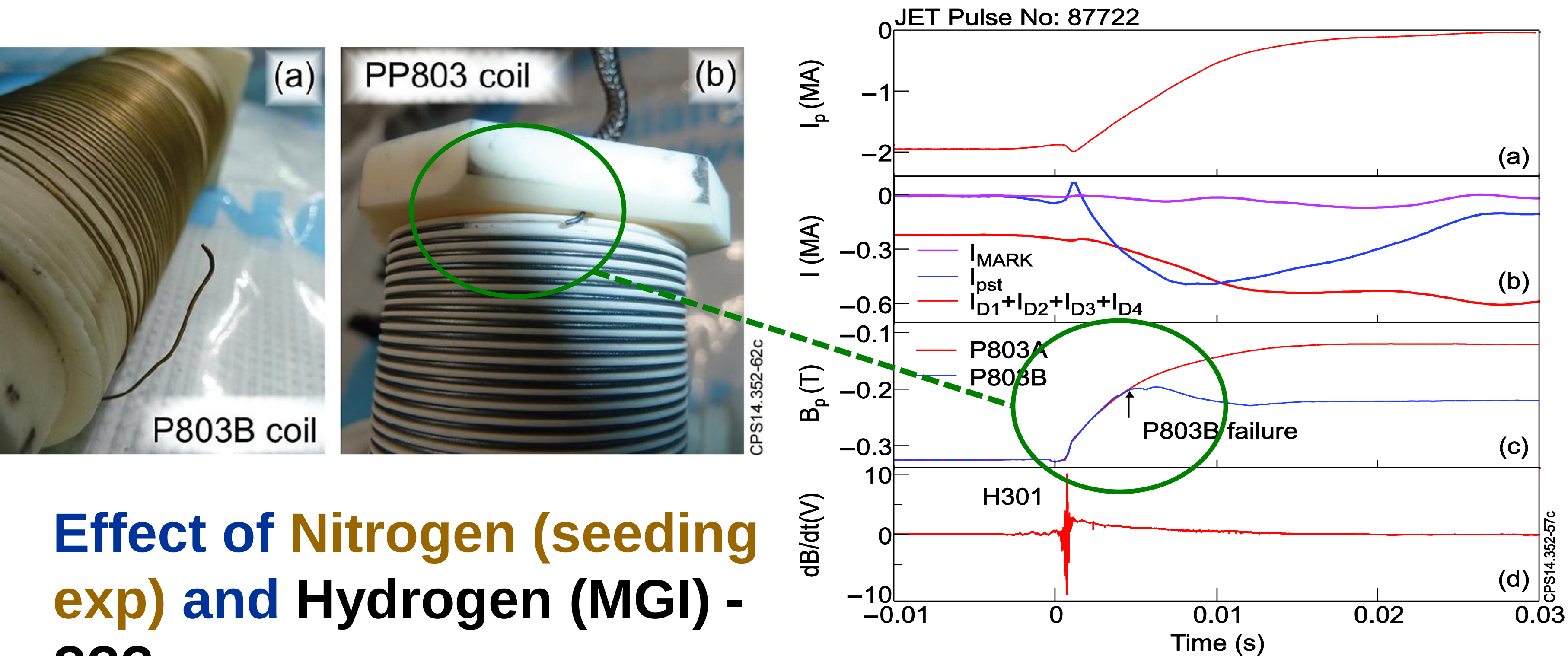
Unfavourable Effect of the MGI Disruption Mitigation (1)





MGI produces fast plasma current quench and high induced currents, which expose the machine to additional stresses

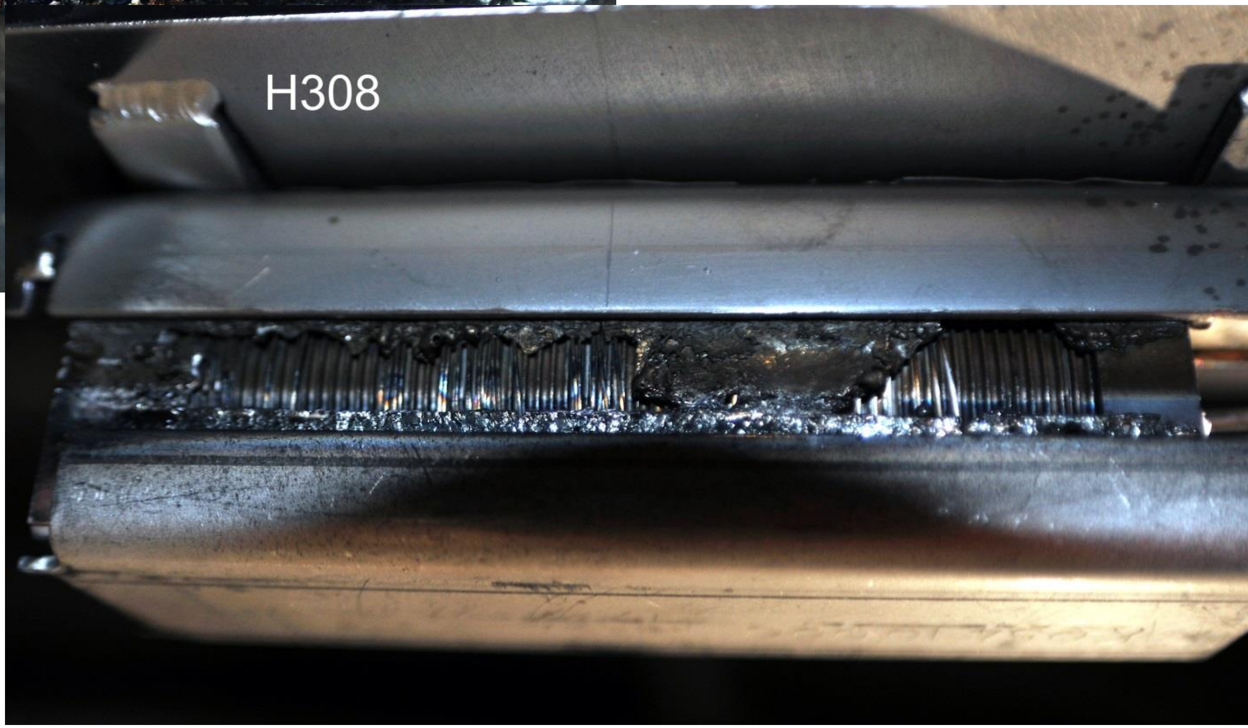
Unfavourable Effect of the MGI Disruption Mitigation (2)



Effect of Nitrogen (seeding exp) and Hydrogen (MGI) - ???

- ✓ **Many Fast coils were killed during MGI disruptions**

Unfavourable Effect of the MGI Disruption Mitigation (3)



✓ **The effect of the large <u>hydrogen</u> quantity used by MGI is of particular concern**

Summary (1)

- The presented data covers the period of JET operations from 2005 until late 2014, and recent COMPASS data. The COMPASS data has been found to be in line with the large JET disruption database in terms of amplitude of the plasma current asymmetries and toroidal rotation behaviour;
- Multi-turn Ip asymmetry rotation has been observed on JET and COMPASS, which covers the domain of the possible dynamic amplification of the sideways forces in ITER;
- The JET radial vessel displacement correlates with sideways force directional impulse, which is estimated only from magnetic diagnostics;

Summary (2)

- **All of the ITER-like wall JET disruption database and the some COMPASS disruptions confirmed that the development of the toroidal asymmetry precedes the drop of *q95* – sometimes down to unity;**

- **The JET and COMPASS unique experimental data on asymmetries in poloidal plasma current and toroidal magnetic flux would help to improve the understanding of disruptions and provide an opportunity to develop and calibrate robust 3-D models, which could be used to predict the loads at future machines, such as ITER;**

Summary (3)

- **MGI significantly reduces the I_p asymmetries during the plasma current quench on JET;**

- **However, MGI produces fast CQ and respectively high vessel eddy currents, which expose the machine to additional stresses. The large quantity of hydrogen used during MGI may create additional problems for in-vessel components.**