Overview of JET Asymmetrical Disruptions

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Acknowledgements to: -
Tim Hender, Leonid Zakharov, James Morris, Valeria Riccardo, Maximus Tsalas, Matteo Baruzzo, Fabio Villone, Raffaele Albanese, Guglielmo Rubinacci, Francesco Maviglia ….

Theory and Simulation of Disruptions Workshop
Princeton Plasma Physics Laboratory
July 9- 11, 2014

Outline

- ✓ **Diagnostics**
- ✓ **Signal processing**
- ✓ **Database**
- ✓ **Sideways force, impulse and vessel displacement**
- ✓ **Rotation**
- ✓ **Outstanding issues**
- ✓ **Summary and discussion**

See also S. N. Gerasimov et al "Plasma current asymmetries during disruptions in JET" Nucl. Fusion 54 (2014) 073009 – data till #83794 (27/07/2012)

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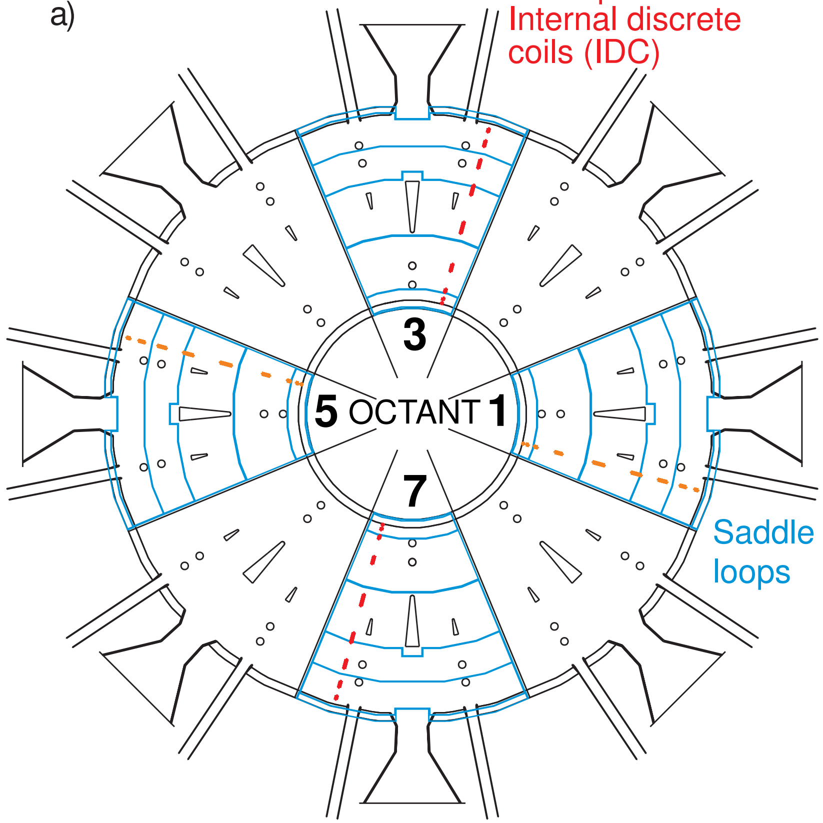
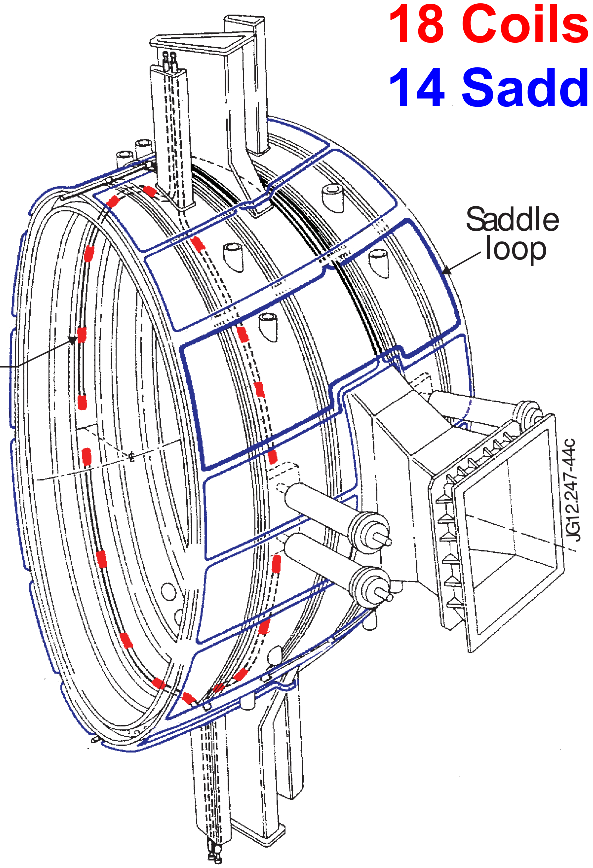
Magnetic Diagnostic (1)

a)



Plan view of JET vessel, showing the toroidal locations of **pick up coils** and **saddle loops**

b)

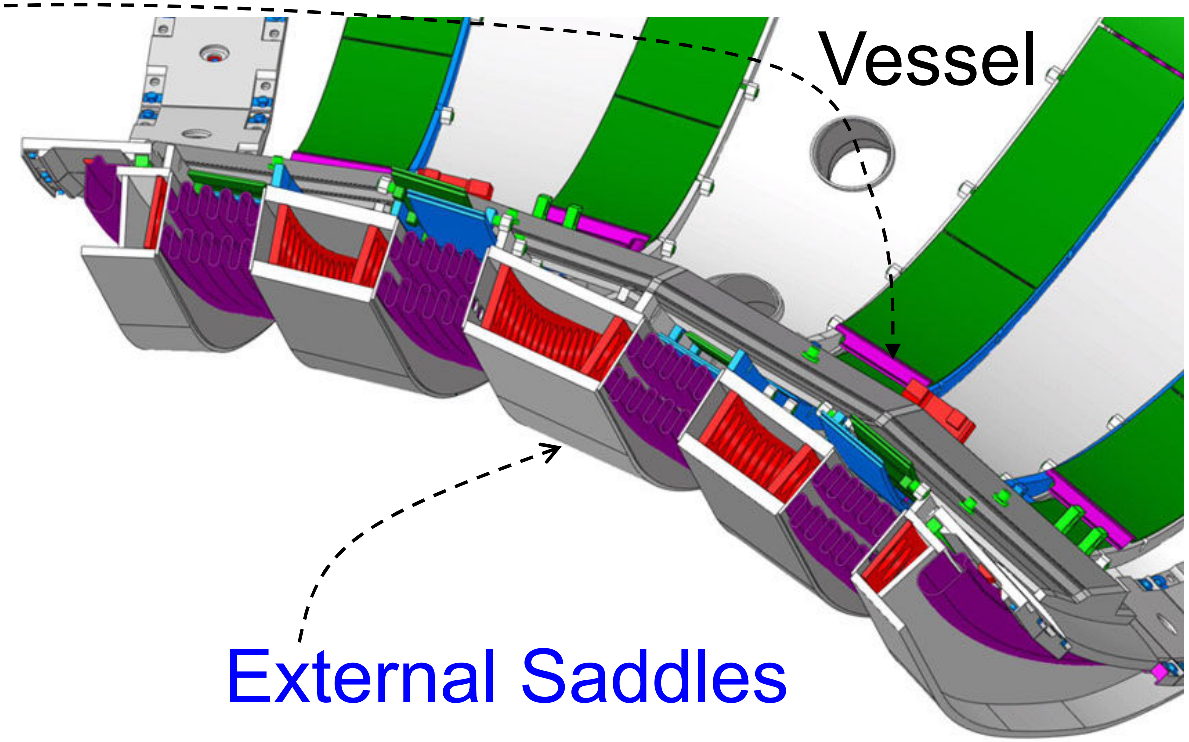


18 Coils
14 Saddles

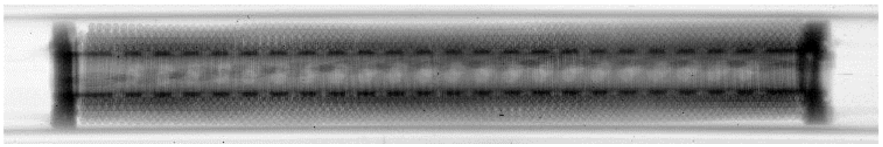
Each vessel octant was equipped with **pick up coils (IDC)** and **saddle loops**

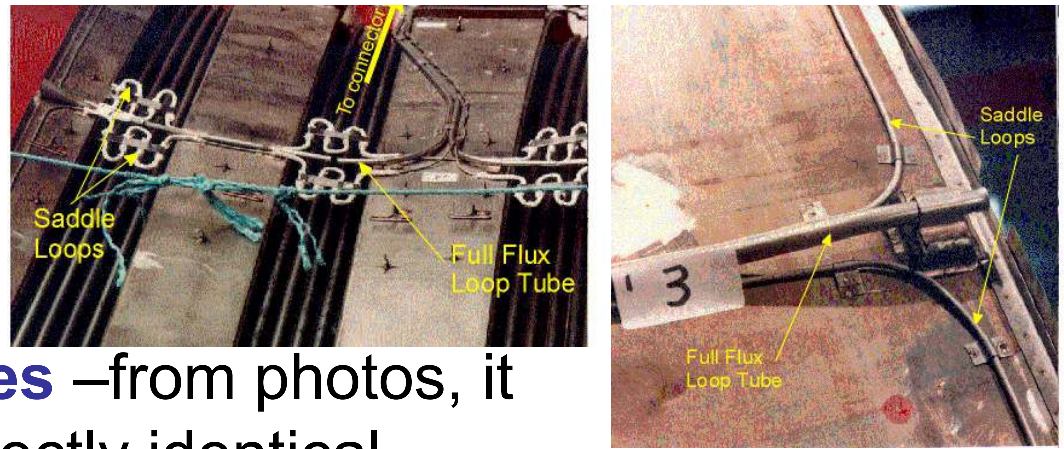
The integrated signals are recorded regularly with 16-bit ADC at 5 kHz from 3/11/2005 onwards. *(The plasma current quench durations > 10ms)*

Magnetic Diagnostic (2)



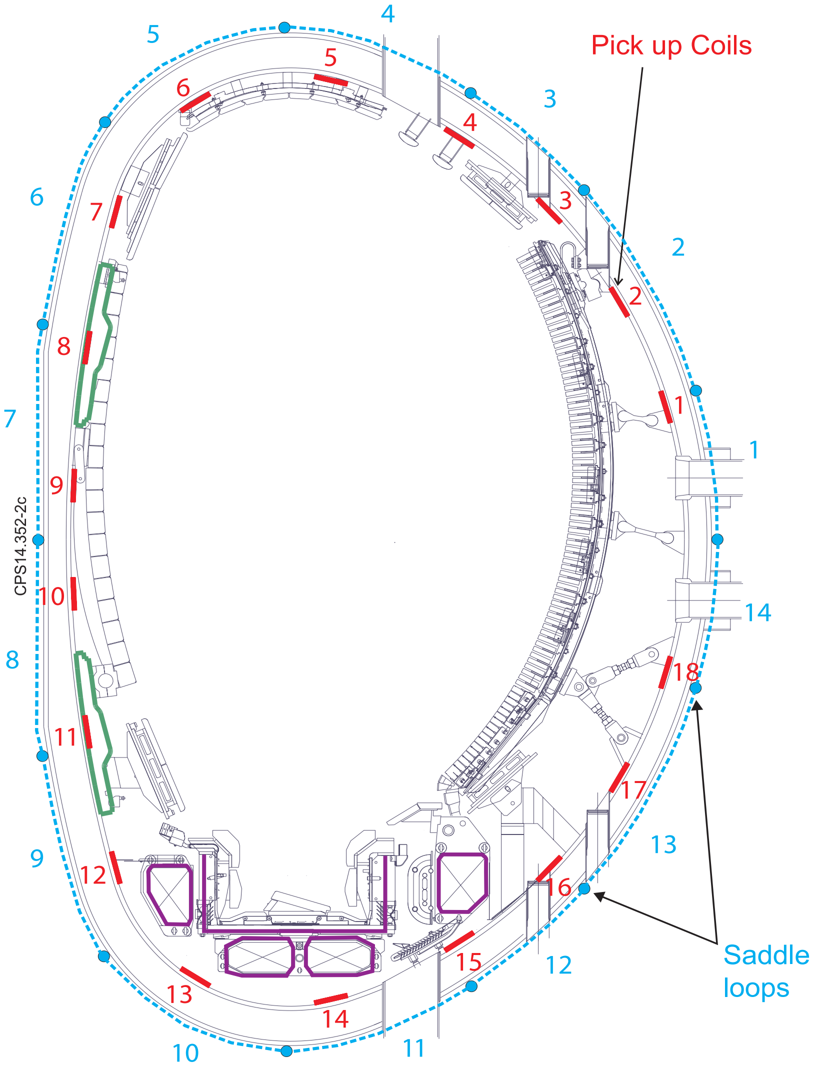
Internal Discrete Coils





Eight octants were equipped with
"identical" set of **coils** and **saddles** –from photos, it
can be seen that they are NOT perfectly identical.

Magnetic Diagnostic → Current Moments



Plasma Current Calculation ⇒

$$\mu_0 I = \oint \vec{B}\vec{dl}$$

⇓

$$I_p = \frac{1}{\mu_0}\sum_{i=1}^{18} B_{\vartheta i} d_i - \sum_{i=1}^{4} n_{Di} I_{Di} - (I_{RRU} + I_{RRL})$$

First Plasma Current Moment Calculations ⇒

$$M_{IR} \equiv \int (R-R_o) J_\phi dRdZ$$

$$M_{IZ} \equiv \int Z J_\phi dRdZ$$

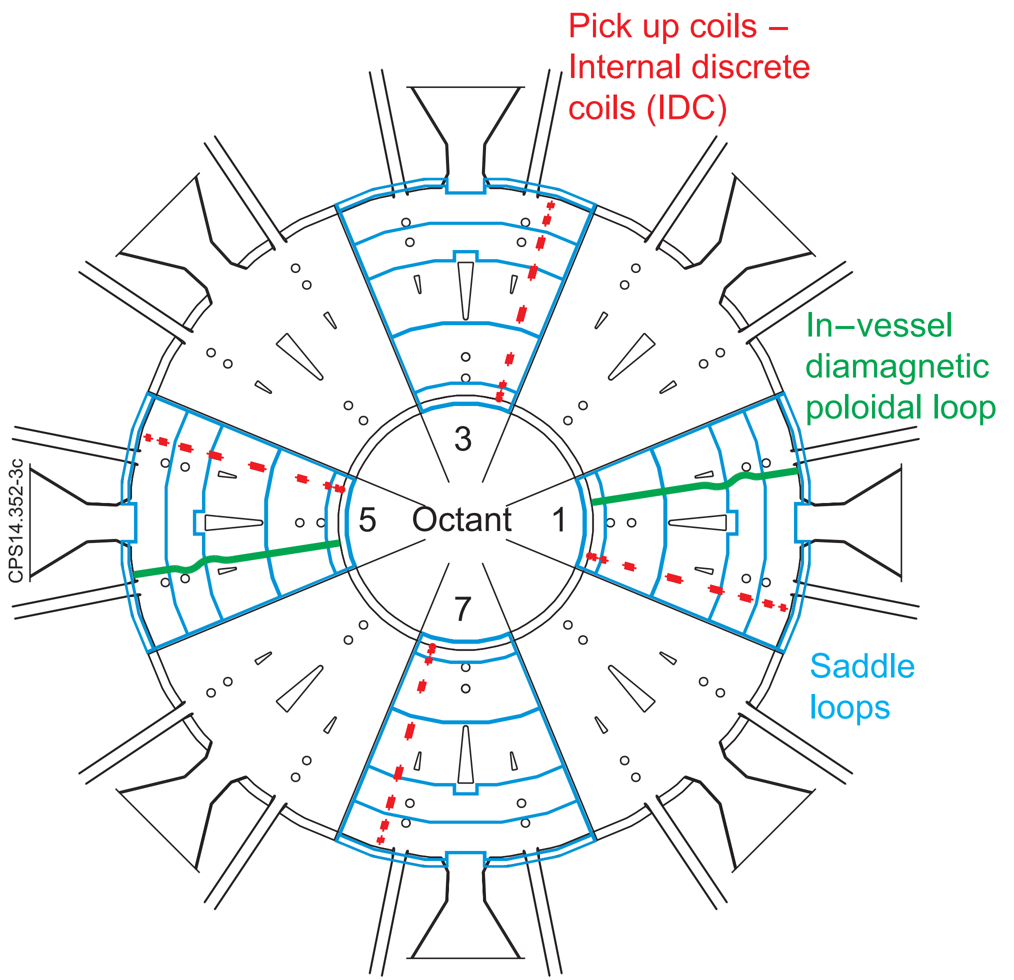
⇓

$$M_{IZ} = \frac{1}{\mu_0}\left(\sum_{i=1}^{18} B_{\vartheta i} z_i d_i + \frac{1}{2\pi}\sum_{i=1}^{14} \Psi_i \ln\left(\frac{R_o}{r_i}\right)\right)$$

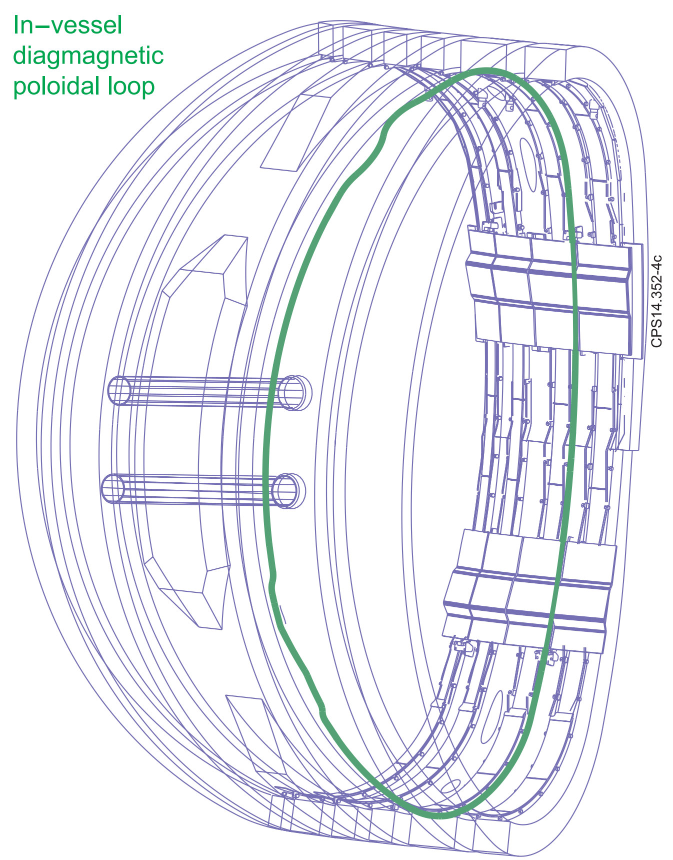
$$-\sum_{i=1}^{4} z_{Di} n_{Di} I_{Di} - (z_{RRU} I_{RRU} + z_{RRL} I_{RRL})$$

Divertor support structure and divertor PF coil cases are not included in calculations (~5% of Ip at disruption), because there are no reliable measurements. It does not affect the asymmetry calculation.

Magnetic Diagnostic – Diamagnetic Poloidal Loops

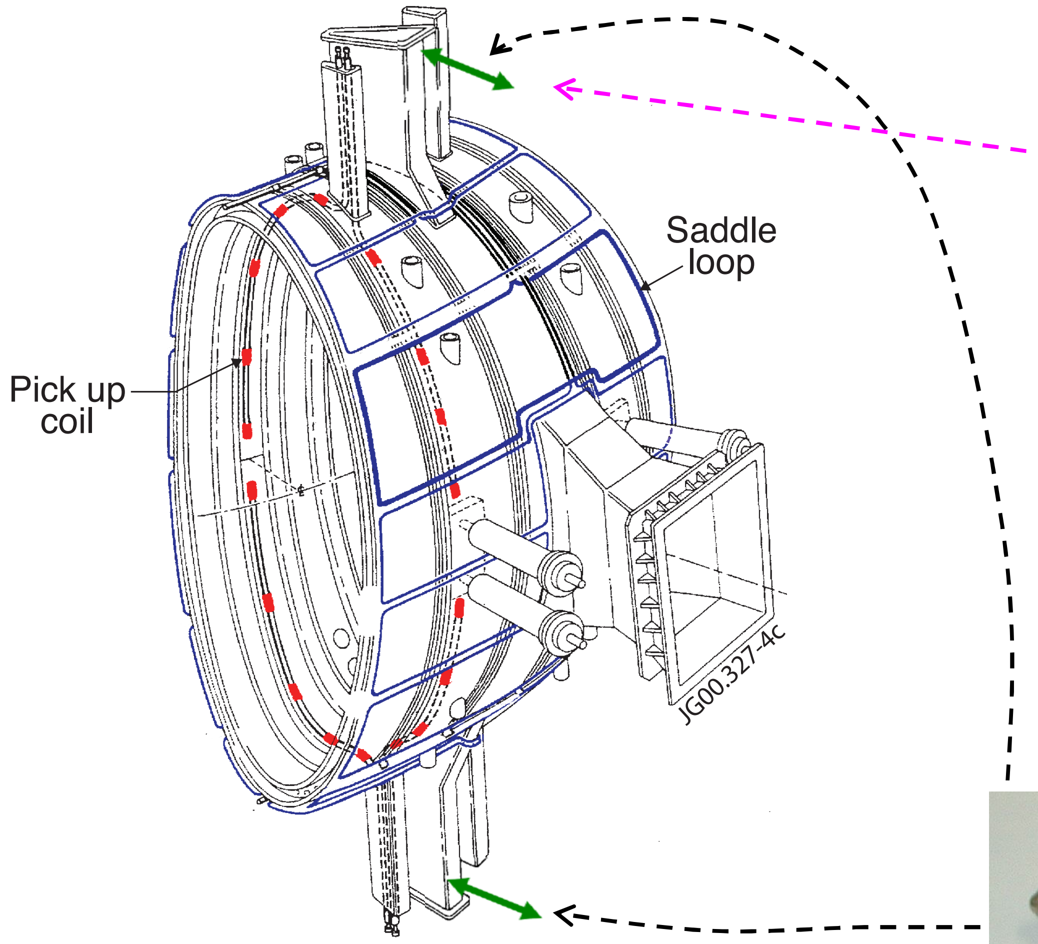


Plan view of JET vessel, showing the toroidal locations of **in-vessel diamagnetic poloidal loops**



#1 and #5 octants equipped with **in-vessel diamagnetic poloidal loops**

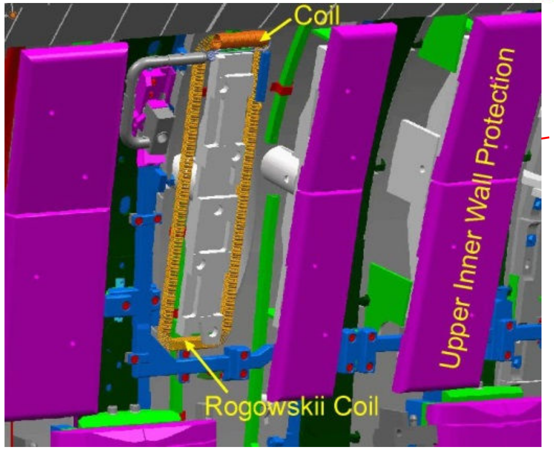
Radial Vessel Displacement Diagnostic

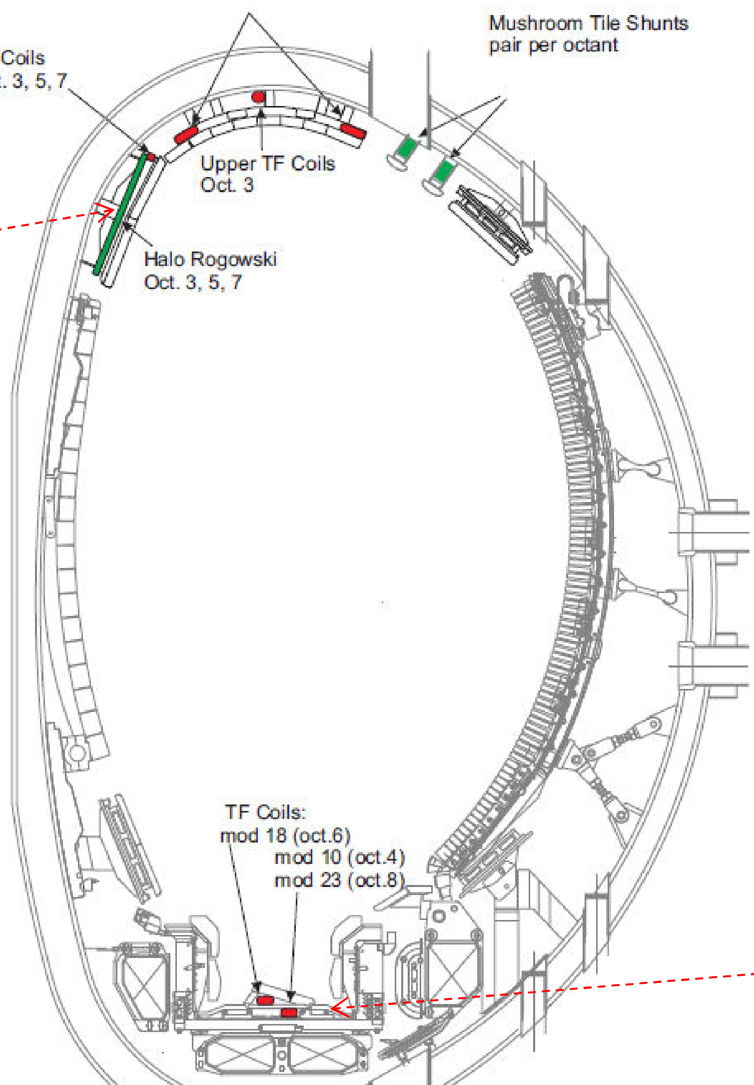


Displacement transducer

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

"Halo" Diagnostic

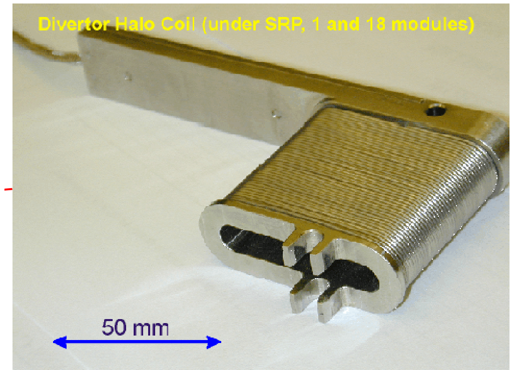




Shunts and Rogowskii coils

TF pick-up coils

(Not all of them are reliable)



JET "Halo" diagnostic will not be discussed in current presentation

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Data Processing – Dealing with Noise

- To avoid **noise** contributing to the results, only the trimmed waveforms were used for analysis

$$A_p^{asym} \geq 0.5\%, |I_p| \geq 0.1 |I_p^{dis}|$$

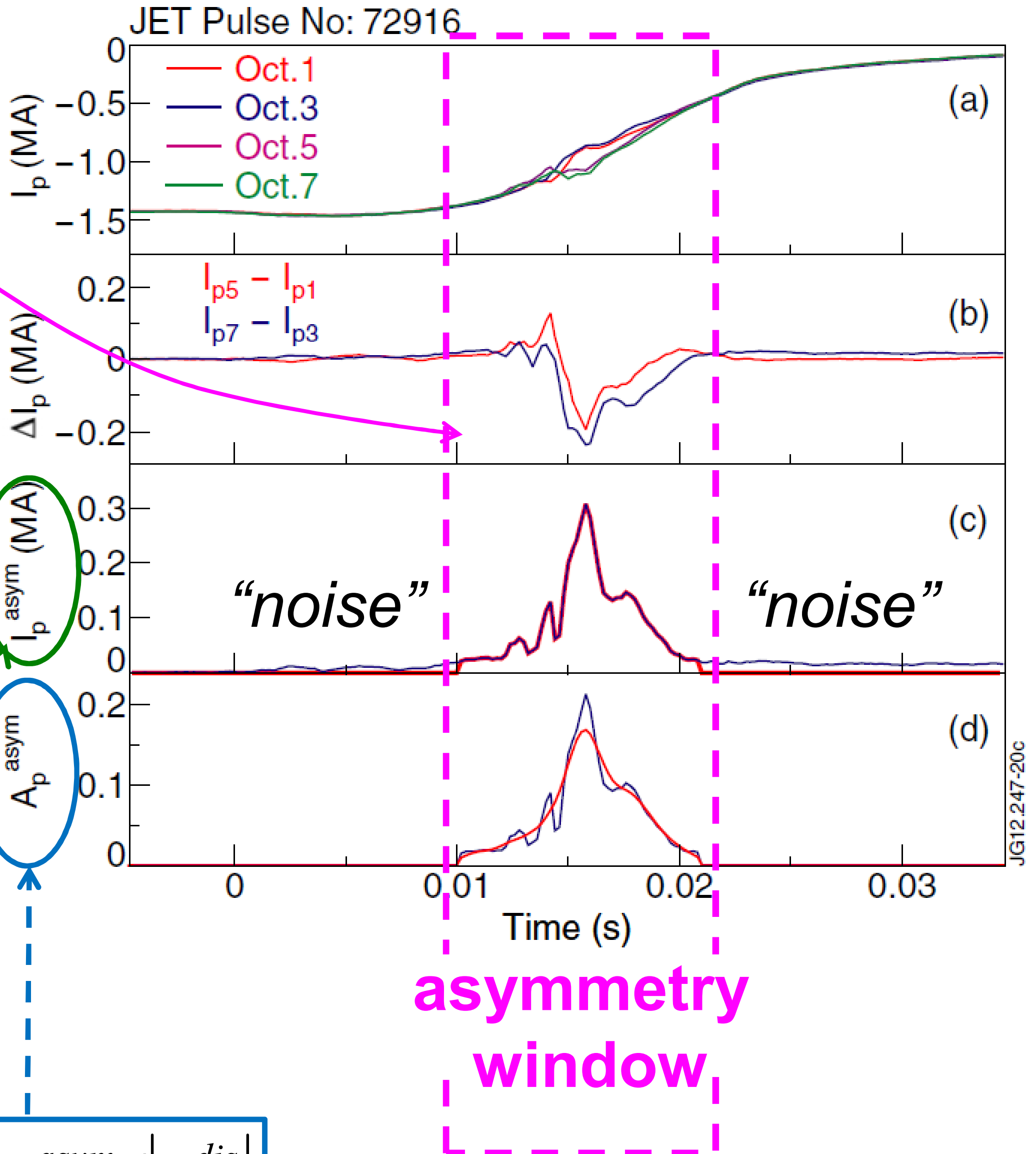
$$|I_p^{asym}| \geq 10kA^*$$

for the first and last 1 ms window in order to disregard short-lived spikes;

*The conditions were modified compared with our latest paper Nucl. Fusion 54 (2014), where $|I_p^{asym}| > 20kA$

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

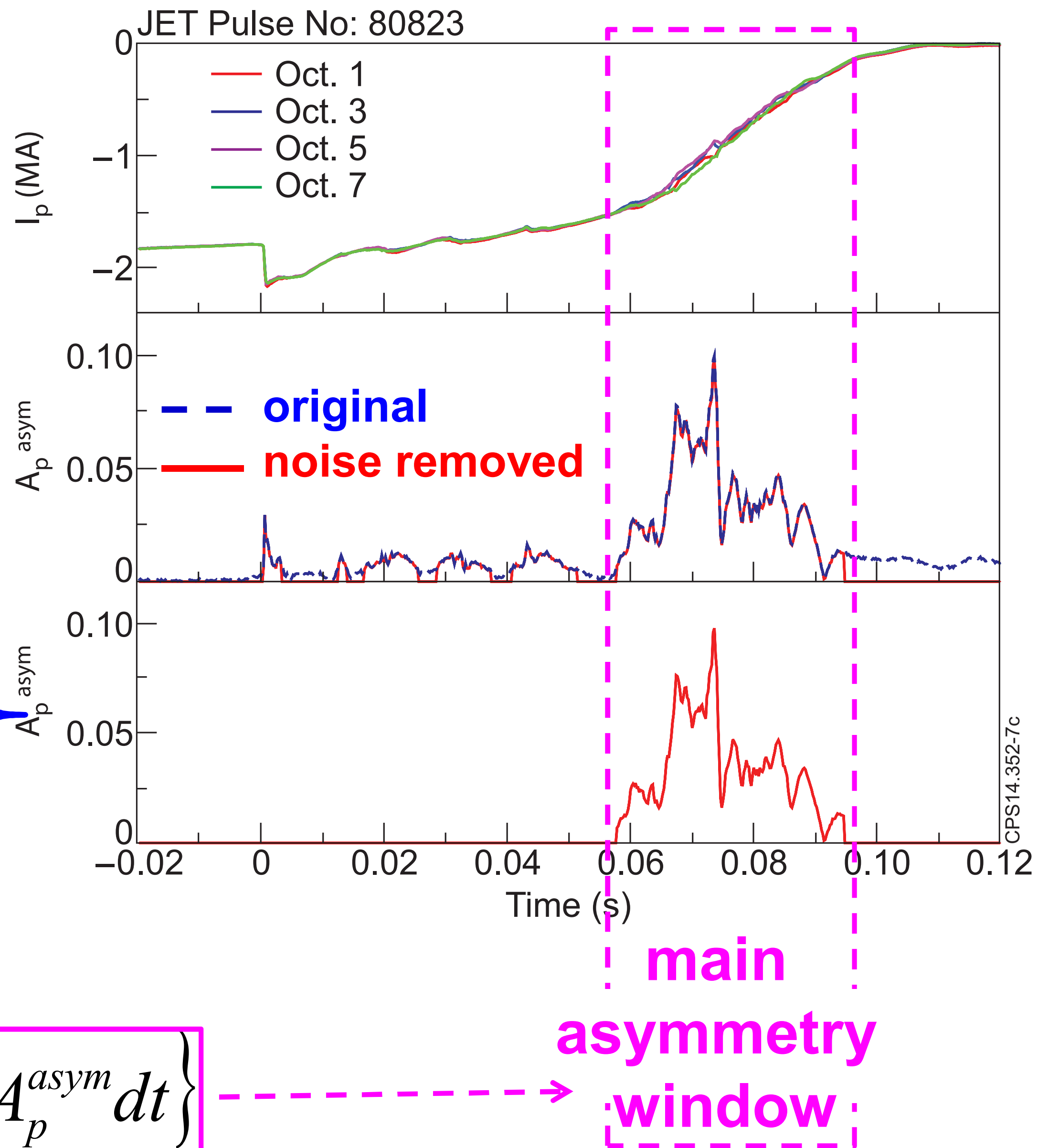
$$A_p^{asym} = I_p^{asym} / |I_p^{dis}|$$



Data Processing – Dealing with Multiple Bursts

Several Ip asymmetry bursts observed during ILW disruptions. Only the main burst is used to calculate time-dependent parameters such as impulse, number of rotations etc.

New constraint was introduced in 2014:
if $|I_p^{asym}|$ <10kA for 2ms inside the ***"asymmetry window"*** then trimmed waveforms are forced to zero during this interval, *as result the **"main asymmetry time window"** was invented.*



$$\max\left\{\int A_p^{asym}dt\right\}$$

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I_p Asymmetry Disruption Database

- **I_p just before disruption > 1.0MA**
- **Only shots with 4 octant magnetics data used for analysis**
- **1634 JET disruptions from November 2005 up to January 2014:**

✓ ***C-wall:*** **951** = 907 (No MGI*) + 44 (MGI) disruptions in the range #64329 - #79853 (03/11/2005 - 23/10/2009)

✓ ***IL-wall:*** **683** = 491 (No MGI) + 192 (MGI) disruptions in the range #80181 - #85978 (09/09/2011 - 10/01/2014)

**MGI - Massive Gas Injection*

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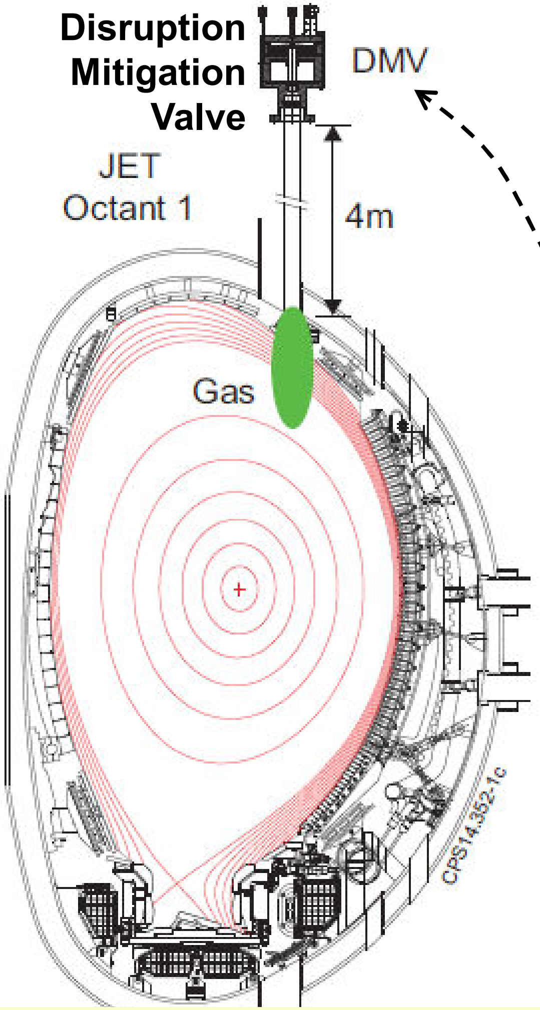
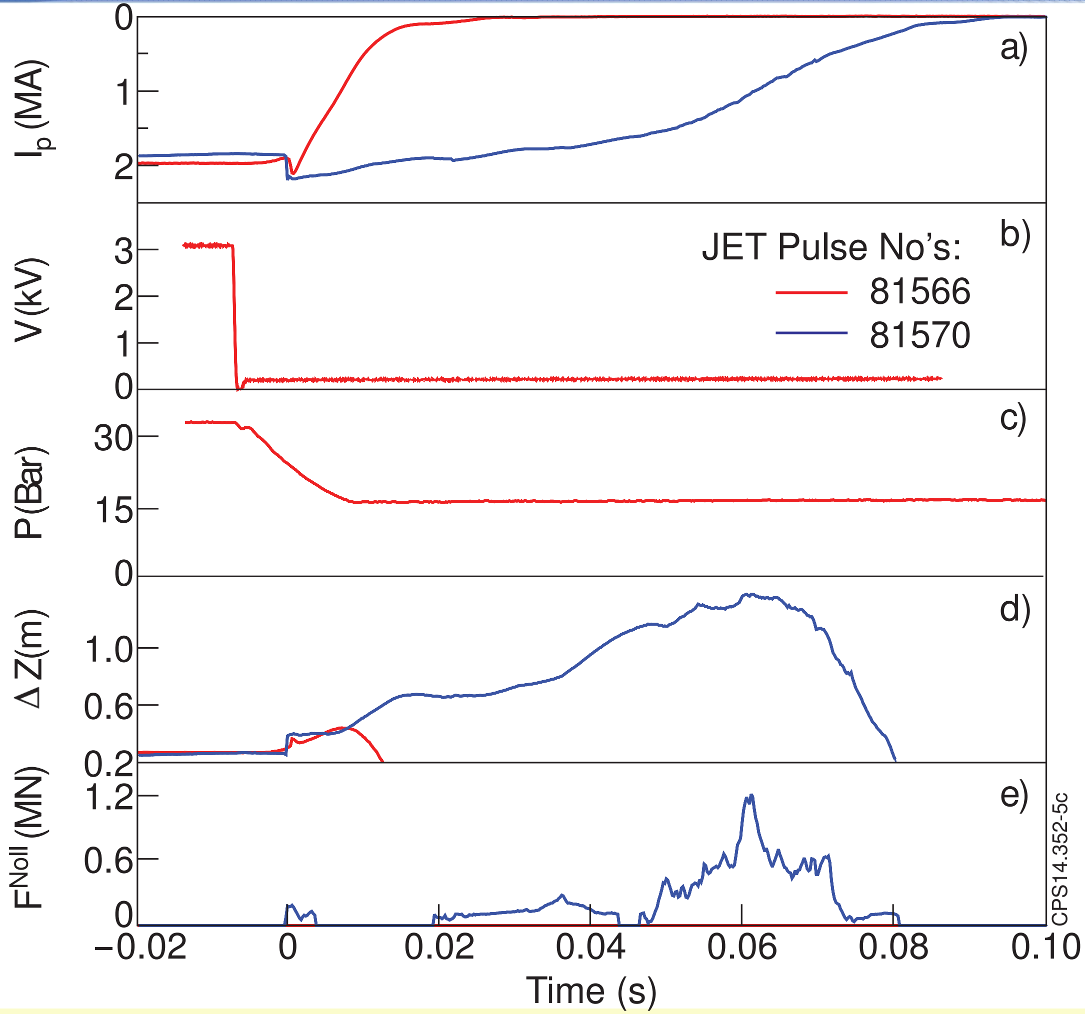
Disruption Mitigation and Sideways Forces



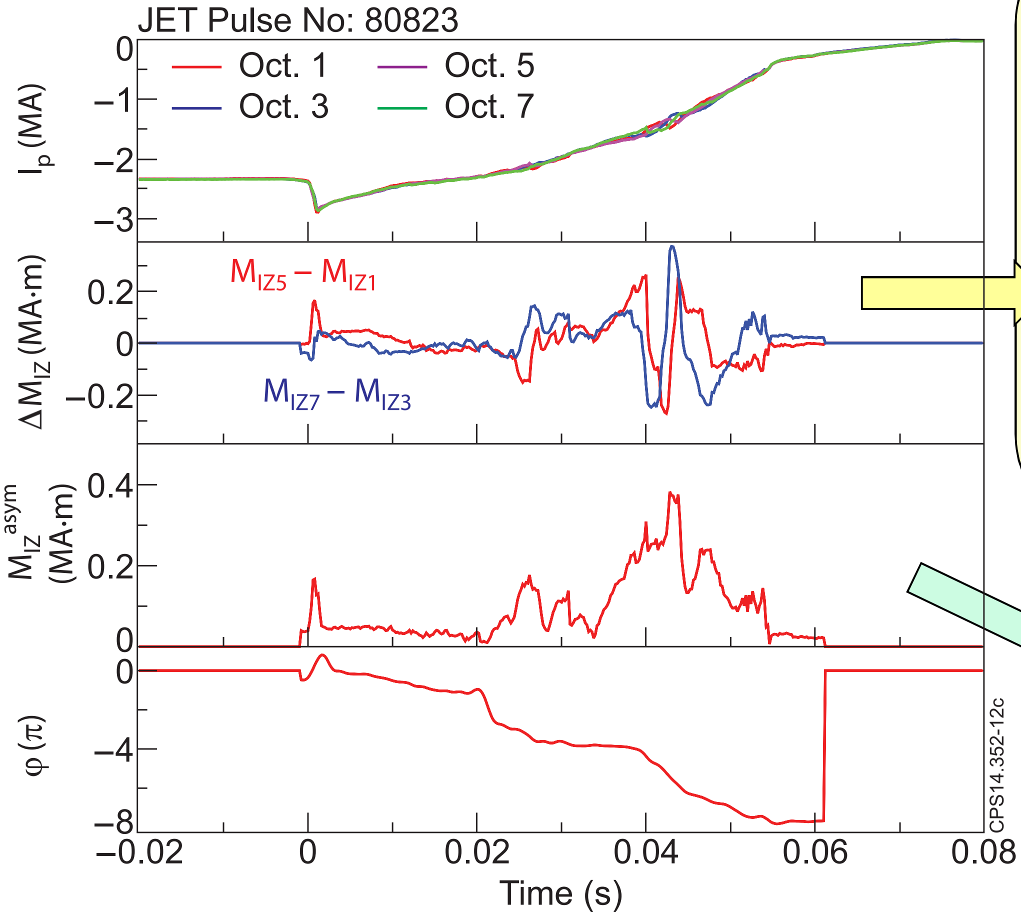


DMV set up for disruption suppression:

P = 30 bar *($\Delta P \approx 15$ bar),* ***90% D_2 + 10% Ar***

To be successful DMV must satisfy the following conditions: $\Delta P > 5$bar, $|I_p(t_{DMV})| > 0.7|I_p^{dis}|$, $\Delta Z(t_{DMV}) < 0.6$m

Sideways Force Impulse Definitions



Sideways Force Directional Impulse:

- $$Imp_x = \int F_x^{Noll} dt \ (= \tfrac{\pi}{2} B_T \int \Delta M_{IZy} dt)$$
- $$Imp_y = \int F_y^{Noll} dt \ \ (= \tfrac{\pi}{2} B_T \int \Delta M_{IZx} dt)$$
- $$Imp_r = \sqrt{Imp_x^2 + Imp_y^2}$$

Sideways Force Impulse Modulus:

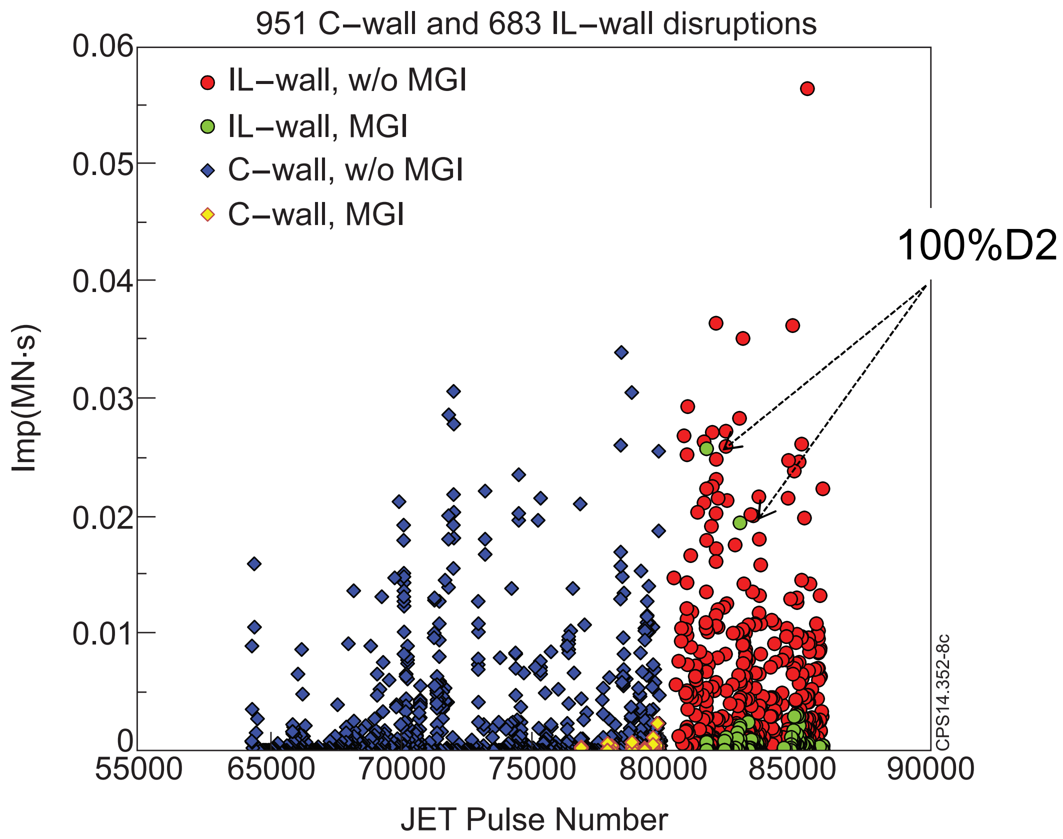
- $$M_{IZ}^{asym} = \sqrt{\Delta M_{IZx}^2 + \Delta M_{IZy}^2}$$
- $$F^{Noll} = \tfrac{\pi}{2} B_T \Delta M_{IZ}$$
- $$Imp = \int F^{Noll} dt$$

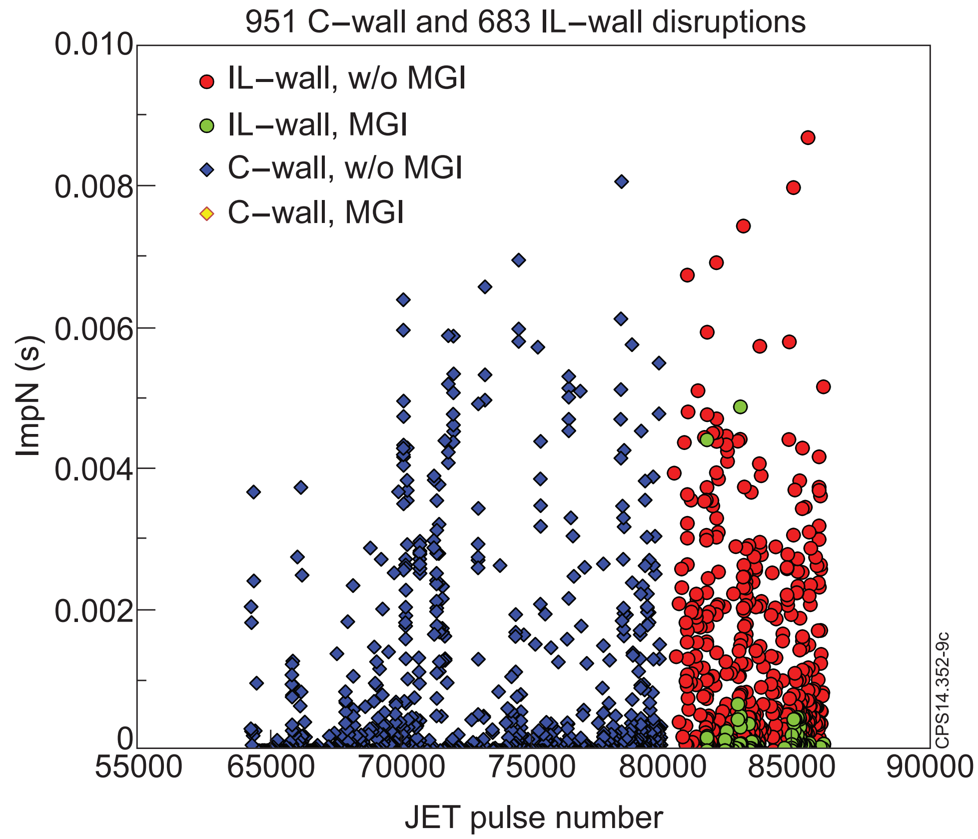
Sideways Force Impulses

- ✓ **Impulse Modulus** is a critical parameter in case of ***multi-turn rotational mode*** due to possible mechanical resonance of the machine components with the rotating asymmetry. It is a potentially serious issue for ITER, but not for JET.

- ✓ **Directional Impulse** is an essential parameter in case of ***trapped (or locked) mode*** in which the toroidal rotation can slow down and remain stationary during a significant part of the CQ on an ITER-size machine. Directional Impulse is always "responsible" for sideways vessel displacement on JET for any rotational behaviour.

Sideways Force Impulse Modulus





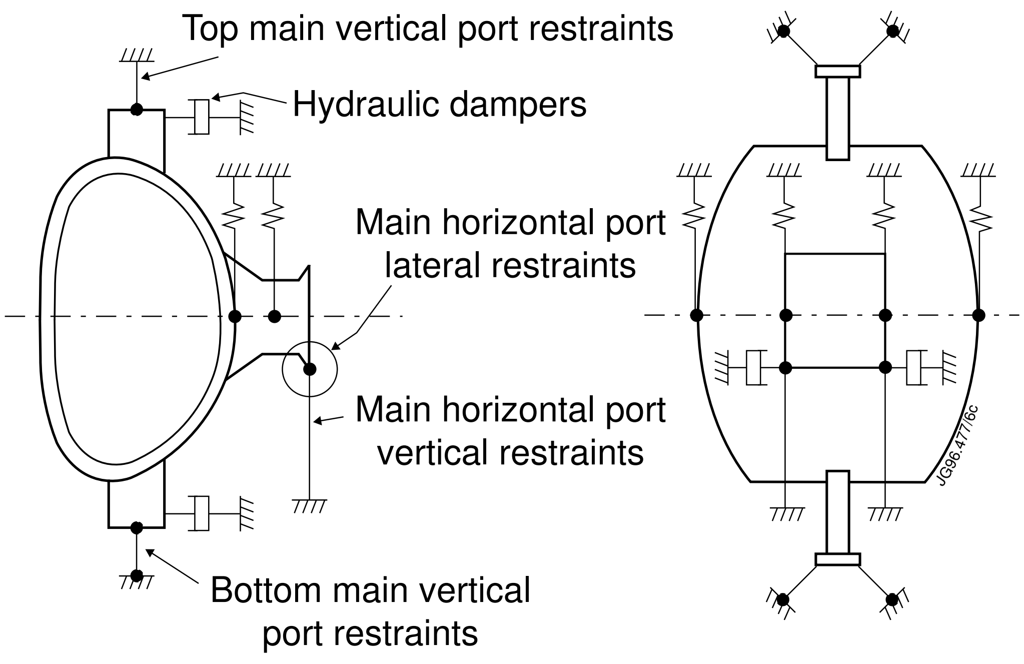
Impulse was calculated for main *Ip* asymmetry time window:

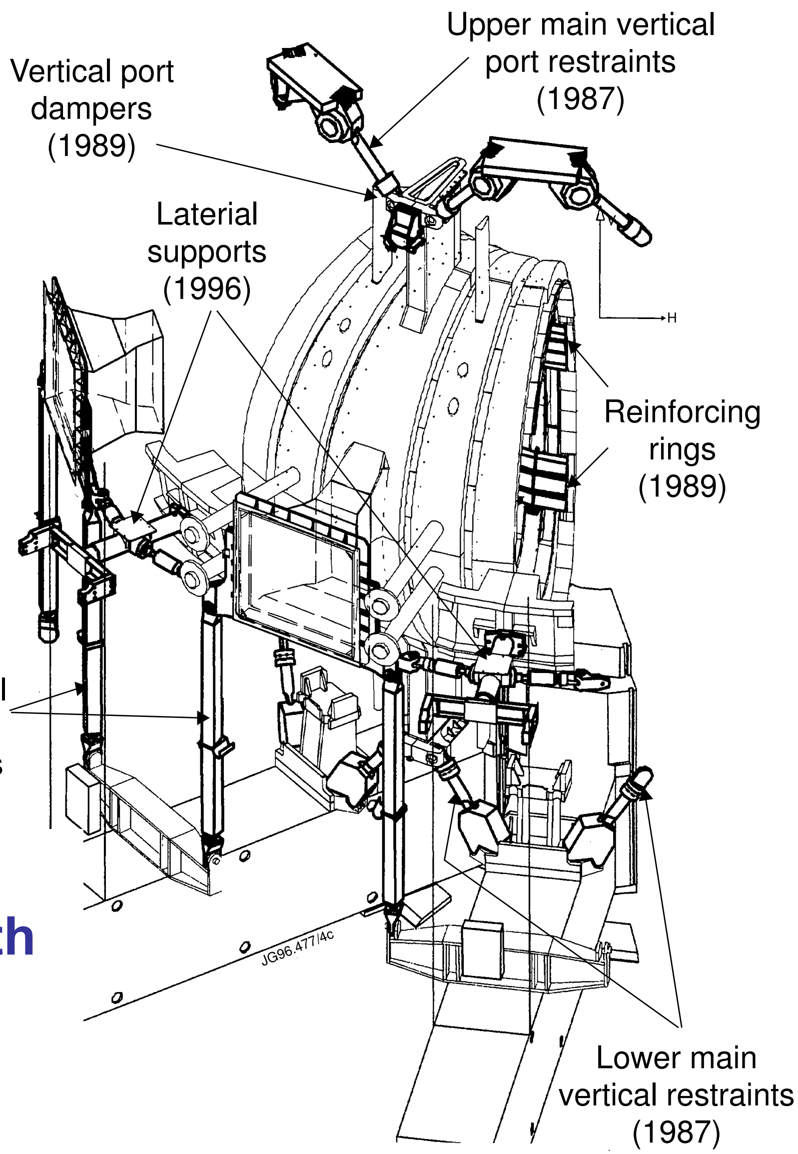
$$Imp = \int F^{Noll} dt$$

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

$$ImpN = \frac{Imp}{B_T I_p a}, (a = 1m)$$

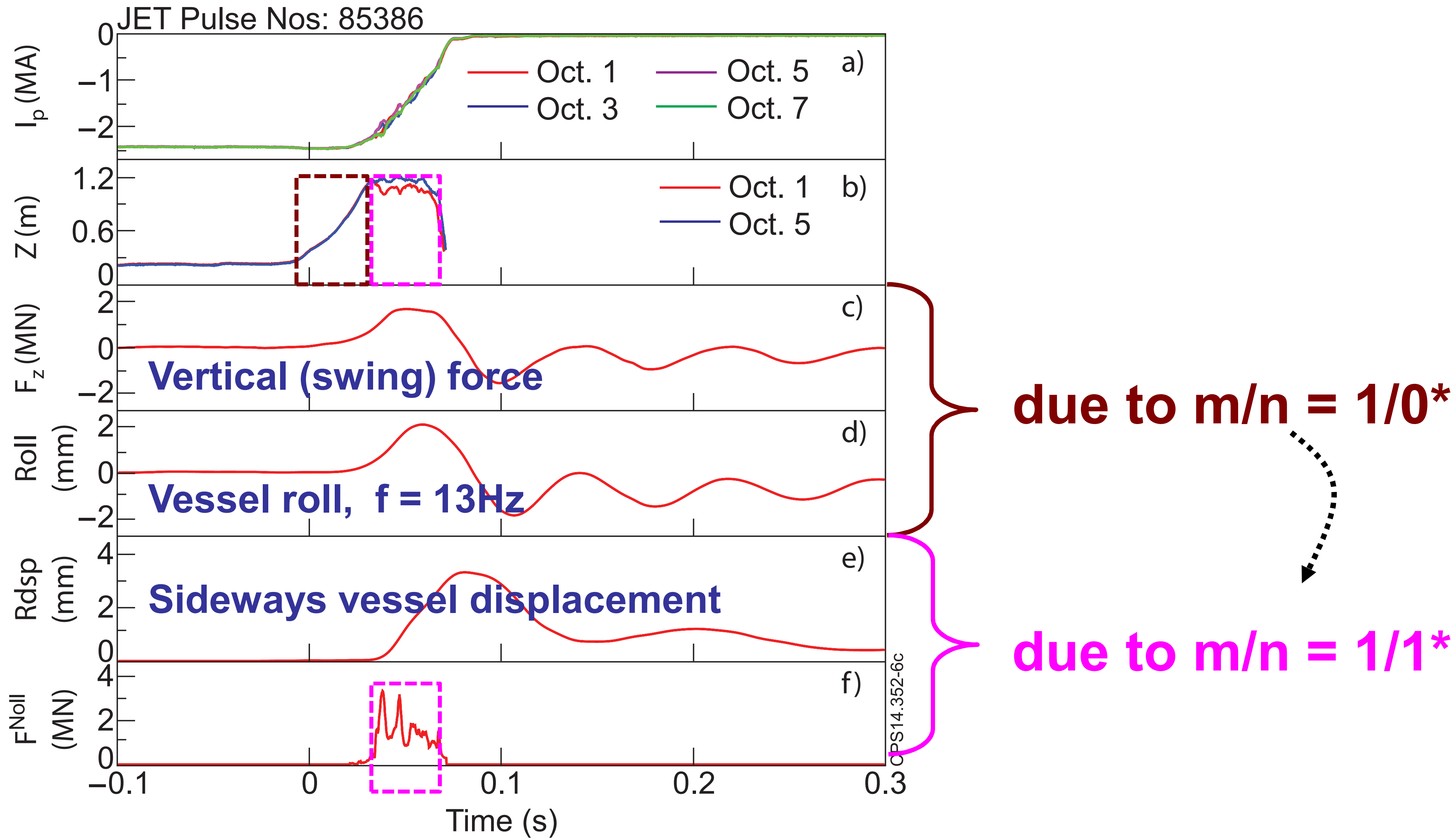
JET Vessel Reinforcements





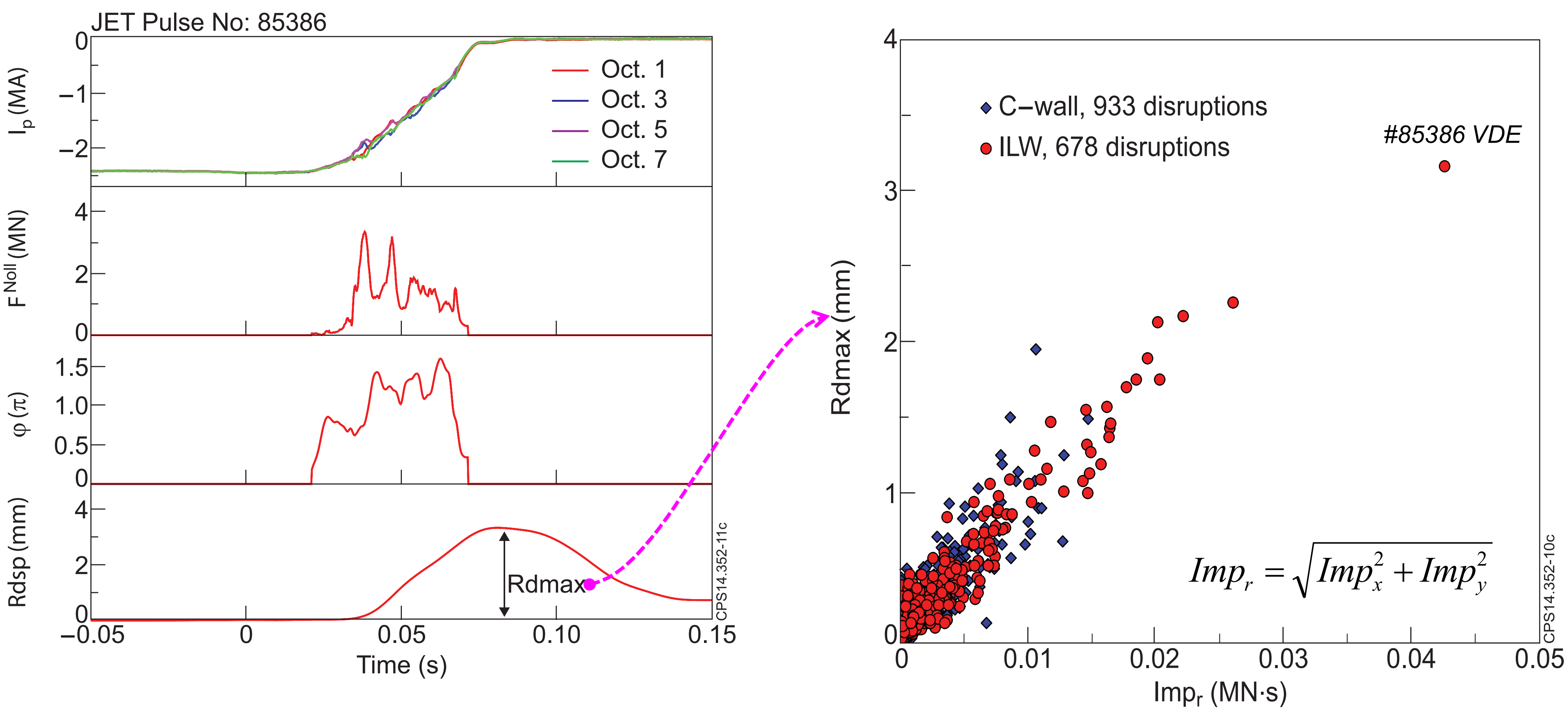
As a result of disruptions, <u>the vacuum vessel can undergo a complex, damped oscillation</u> with a peak displacement in the order of a few mm.
The vessel can experience violent mechanical forces in excess of few MN.

Forces and Vessel Displacement



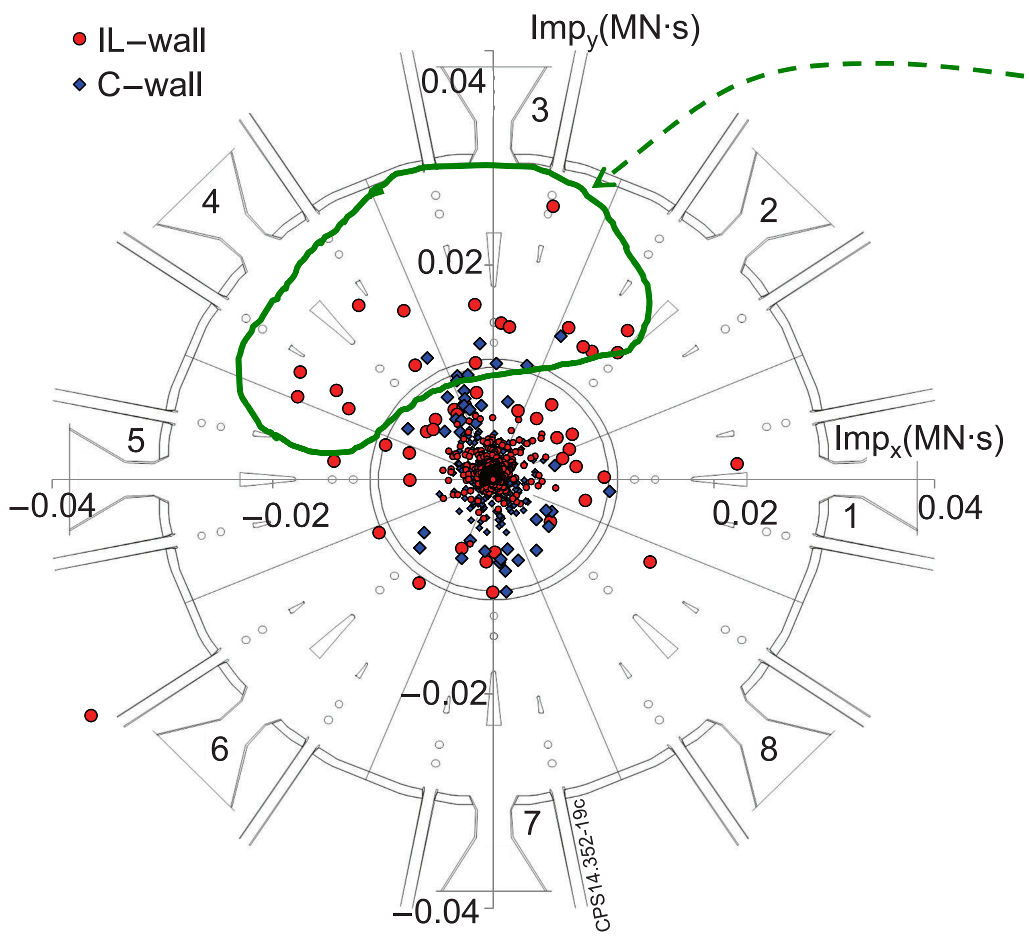
*Other poloidal and toroidal harmonics are superimposed to *m/n* = 1/0 and 1/1 during the VDE.

Radial Vessel Displacement vs Sideways Force Directional Impulses



✓ JET sideways vessel displacement is correlated (proportional?) to the directional impulse estimated from magnetics

Sideways Force Directional Impulses



There is preferred toroidal phase of the sideways force impulse namely in #3 - #4 octants

JET vessel top view

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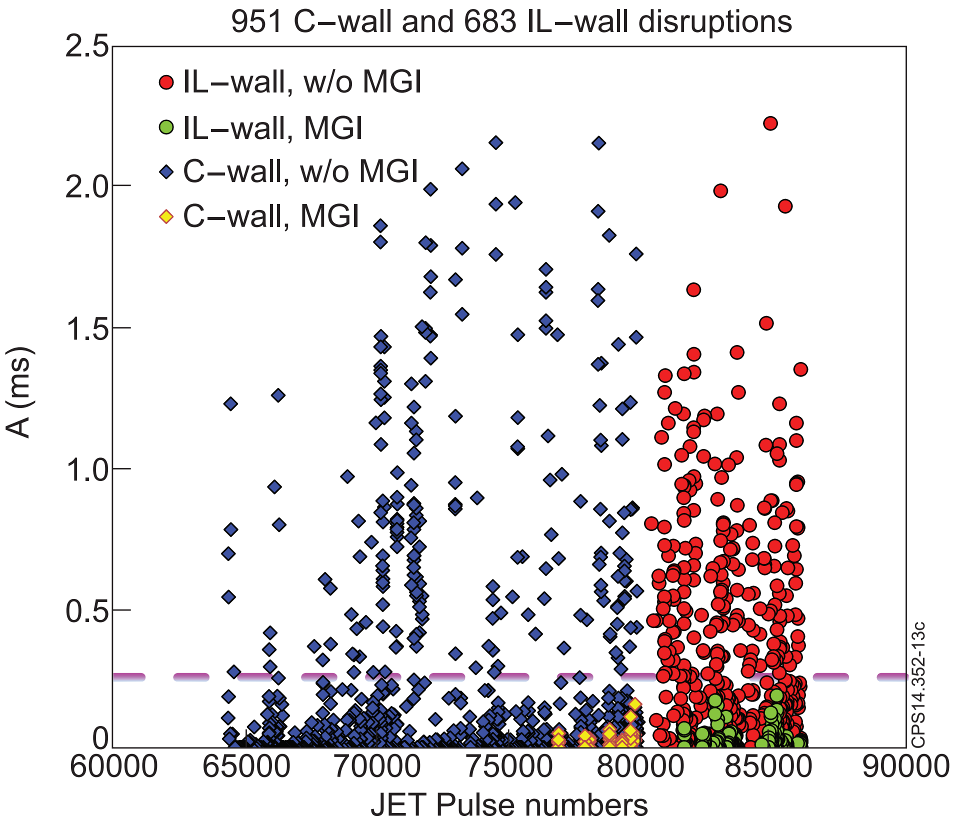
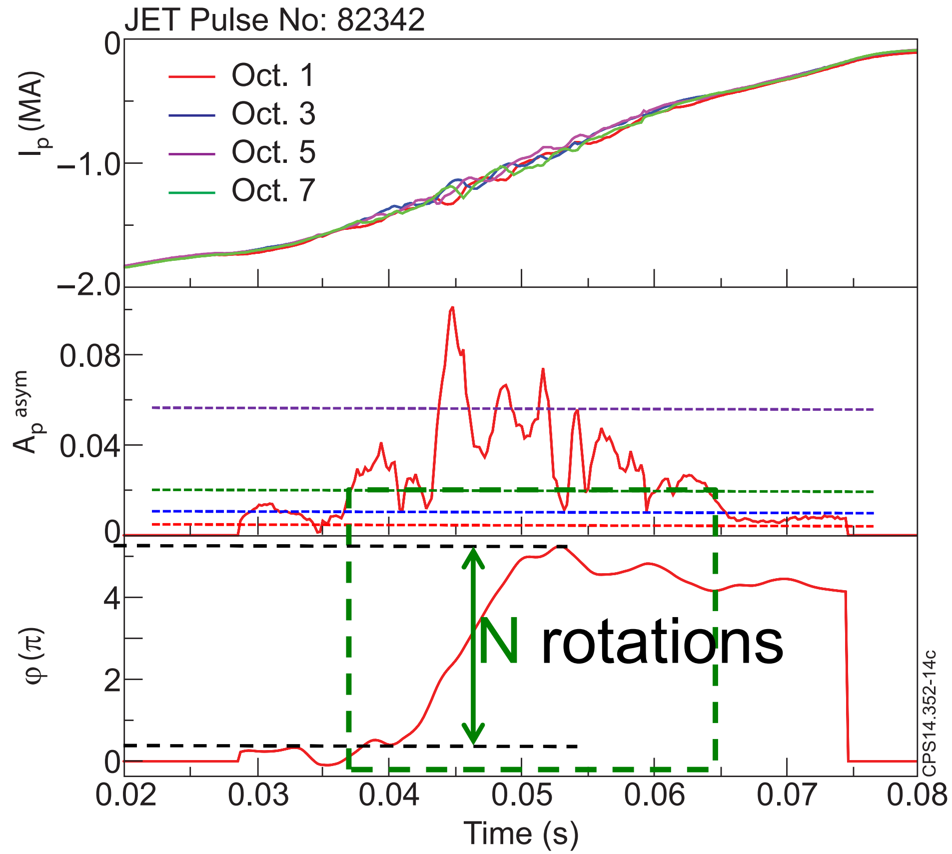
How the Number of Rotations was Calculated





$$A = \int A_p^{asym} dt > 0.25ms$$

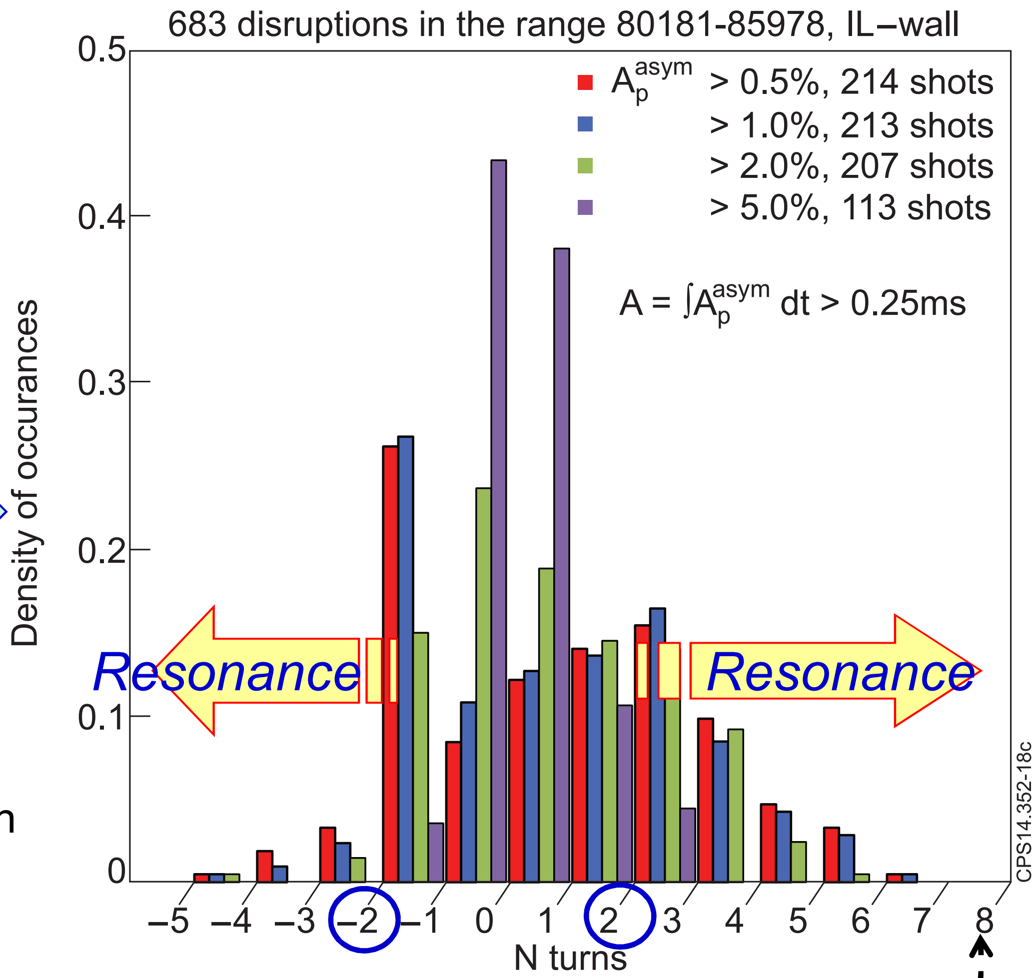
$$A_p^{asym} = \sqrt{(I_{p7} - I_{p3})^2 + (I_{p5} - I_{p1})^2} / \left| I_p^{dis} \right|$$

- A_p^{asym} > 0.5%
- > 1%,
- > 2%,
- > 5%,

Number of Rotations

Force dynamic amplification:

1. **Rotation occurs at near a resonance frequency**
2. **More then 2 periods take place, see JET data**



On JET, rotation is most commonly seen in the electron drift direction

- 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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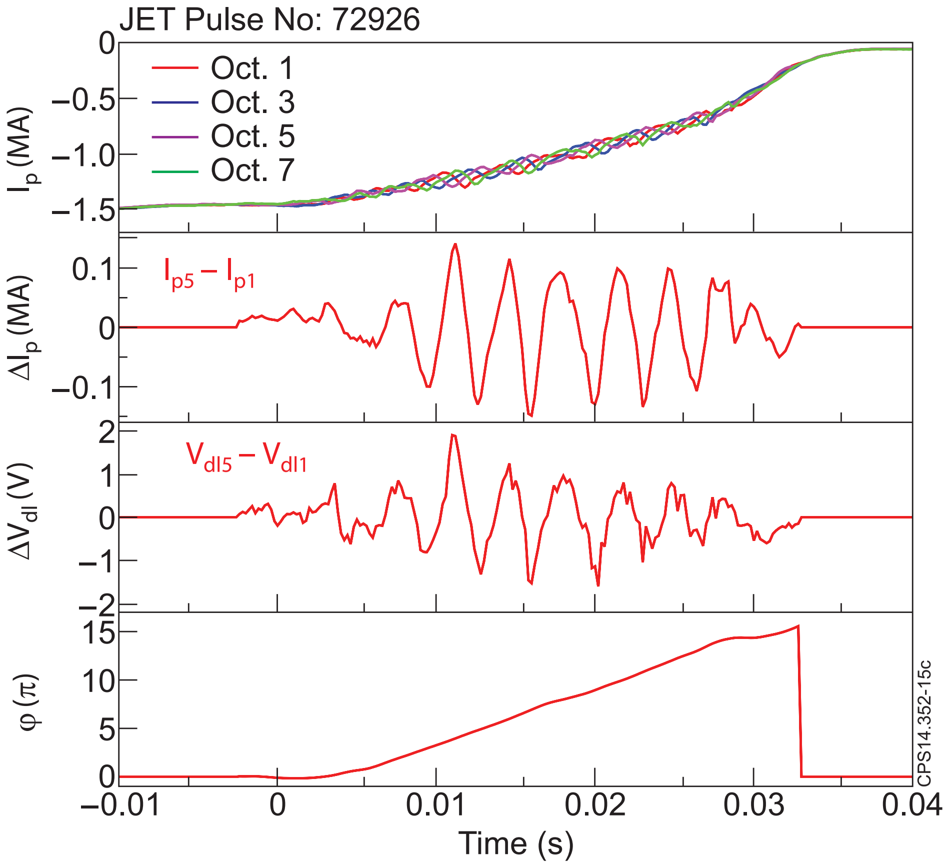
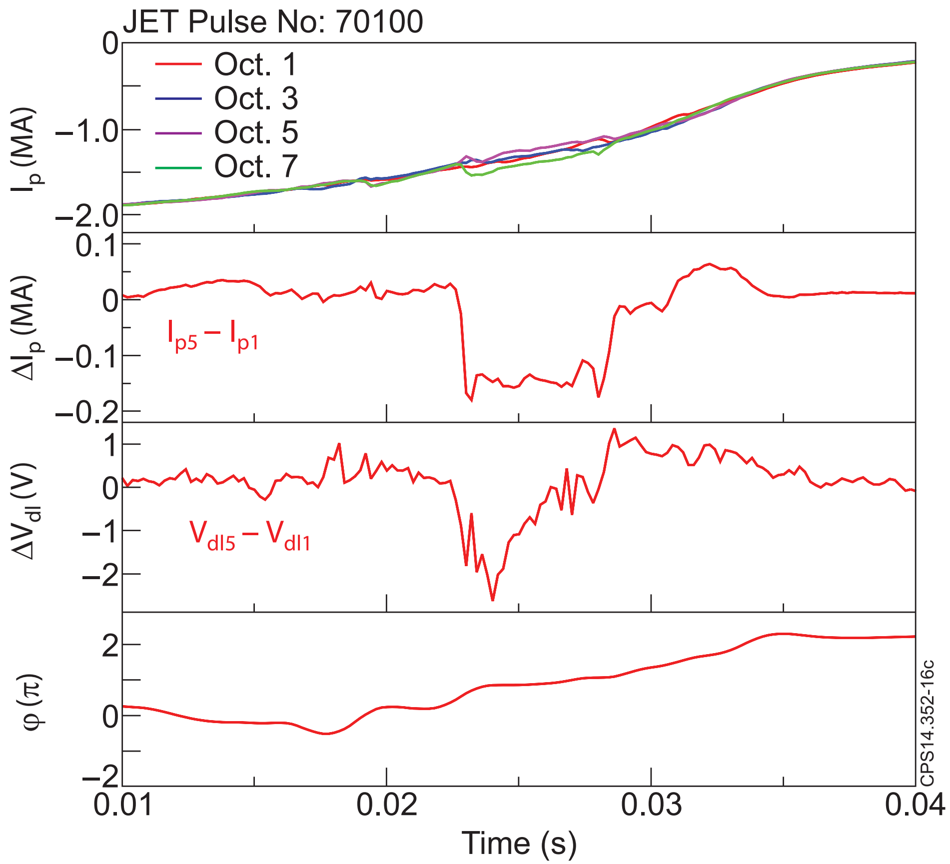
Asymmetry of Poloidal Loop Voltages

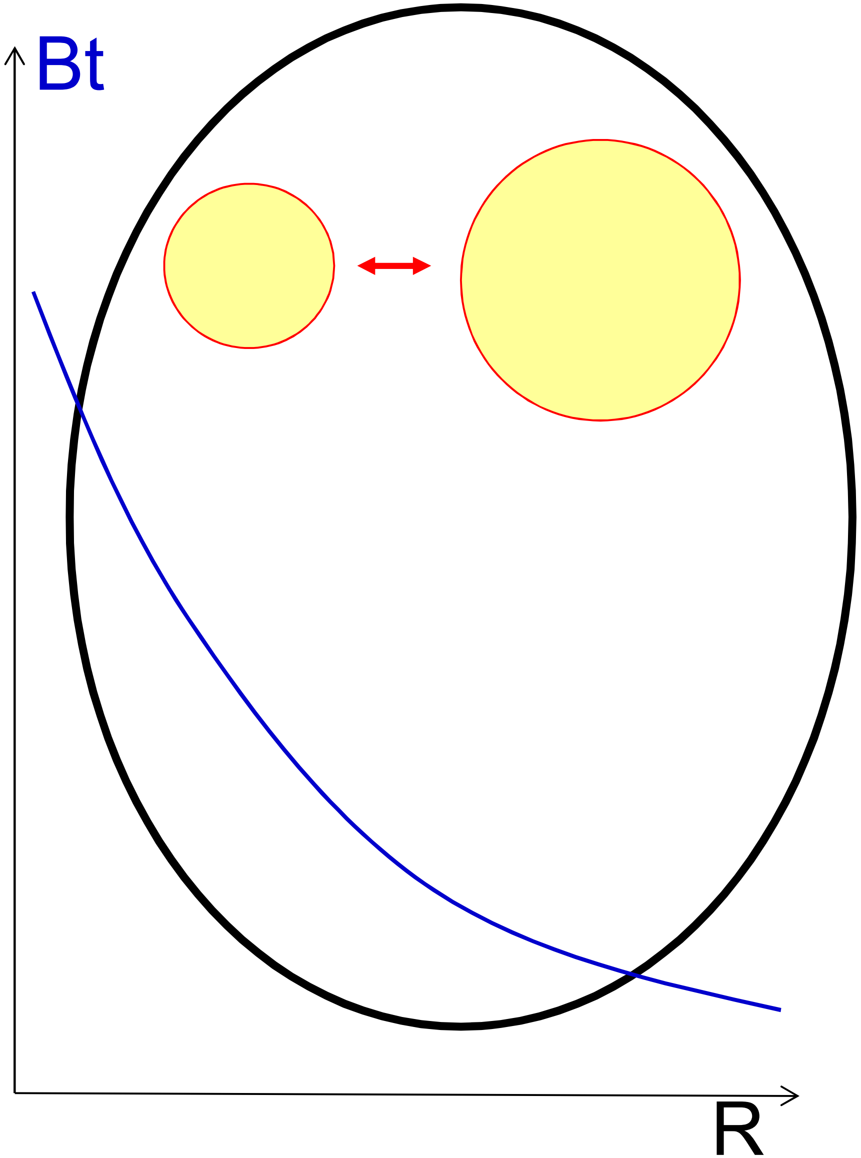




Uniform rotation – poloidal voltage asymmetry followed by toroidal current asymmetry

Tripped (locked) mode – rise and decay of poloidal voltage asymmetry (~ poloidal current ?)

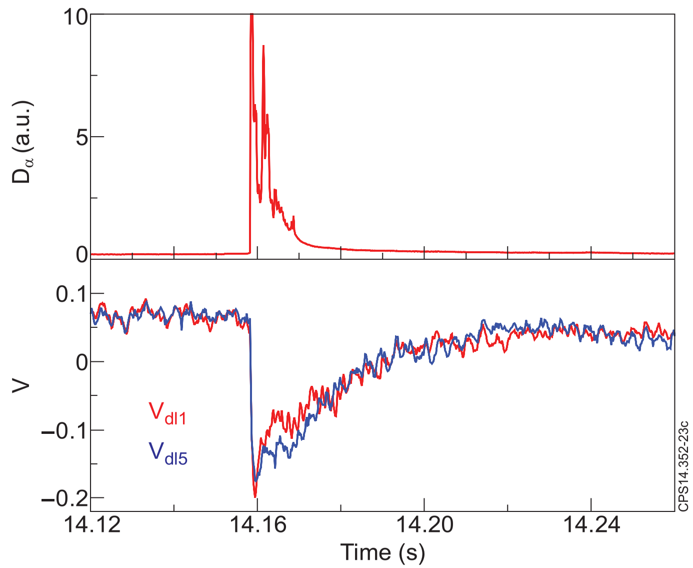
What is the Reason for Poloidal Loop Voltage Asymmetry?

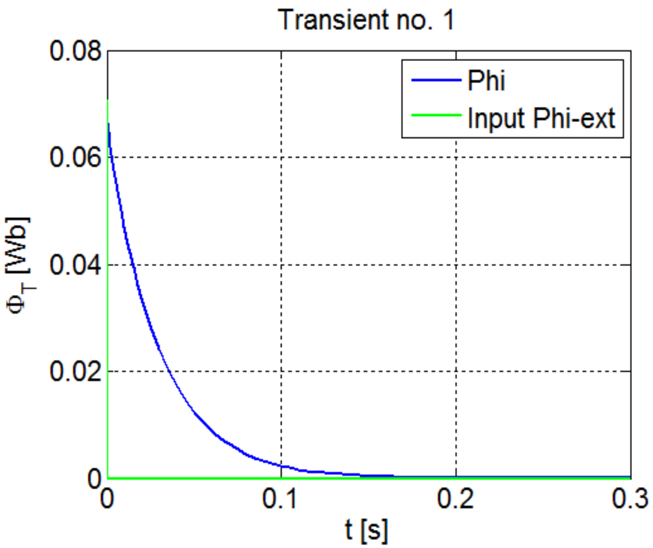


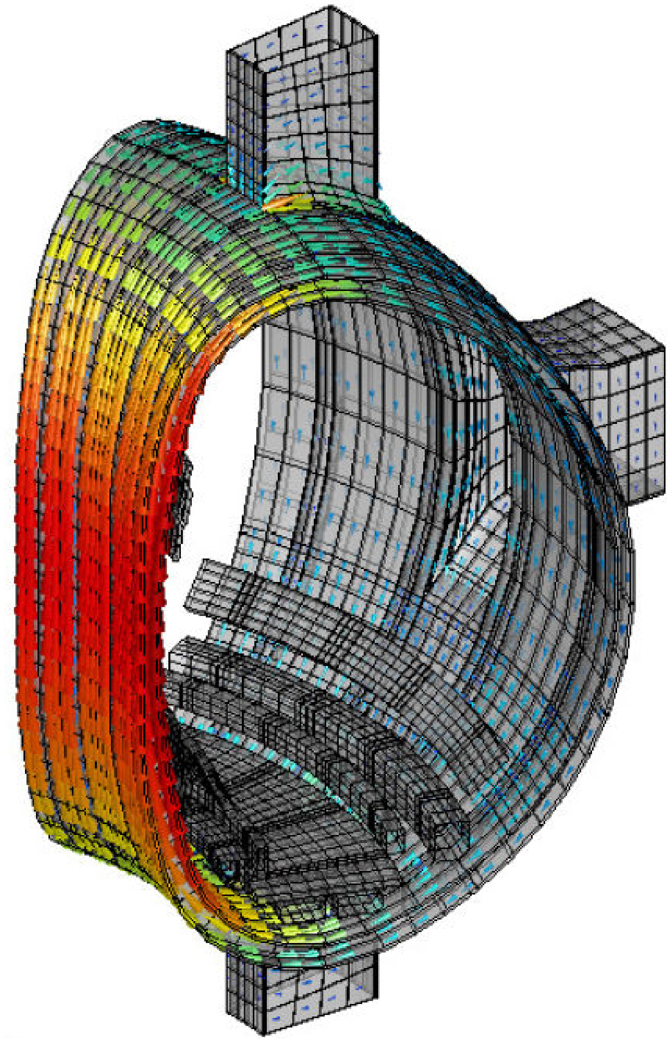
1. Plasma radially shifted because of the m/n=1/1(3D effect);
2. Leads to plasma contraction and expansion (toroidal flux conservation);
3. Plasma contraction /expansion leads to variation of toroidal flux inside the vessel;
4. Variation of toroidal flux creates the poloidal voltage which generates the poloidal vessel current.

Similar model can be applied to poloidal loop voltage behaviour during ELMs (2D effect) – where (1.) *event is beta drop and recovery*

Vessel Poloidal Current Induced by ELM - CarMa0NL Code Simulation*







Verifying the CarMa0NL 3D JET vessel model

- The decay time of poloidal currents in the vessel model is slightly less (30 ms) than in JET estimation from TF variation (38-39 ms);
- Next step – simulate toroidal flux variation during the ELM;
- Next step – quasi 3D asymmetry simulation during disruption.

** Fabio Villone, Francesco Maviglia, Raffaele Albanese, Guglielmo Rubinacci …*

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Summary and Discussion

- Plasma current asymmetries during current quench and hence sideways forces can be successfully mitigated by MGI – 100% (232 shots) success so far;

- Multi-turn Ip asymmetry rotation in both toroidal directions has been observed on JET that can lead to resonance condition on ITER;

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