



# 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

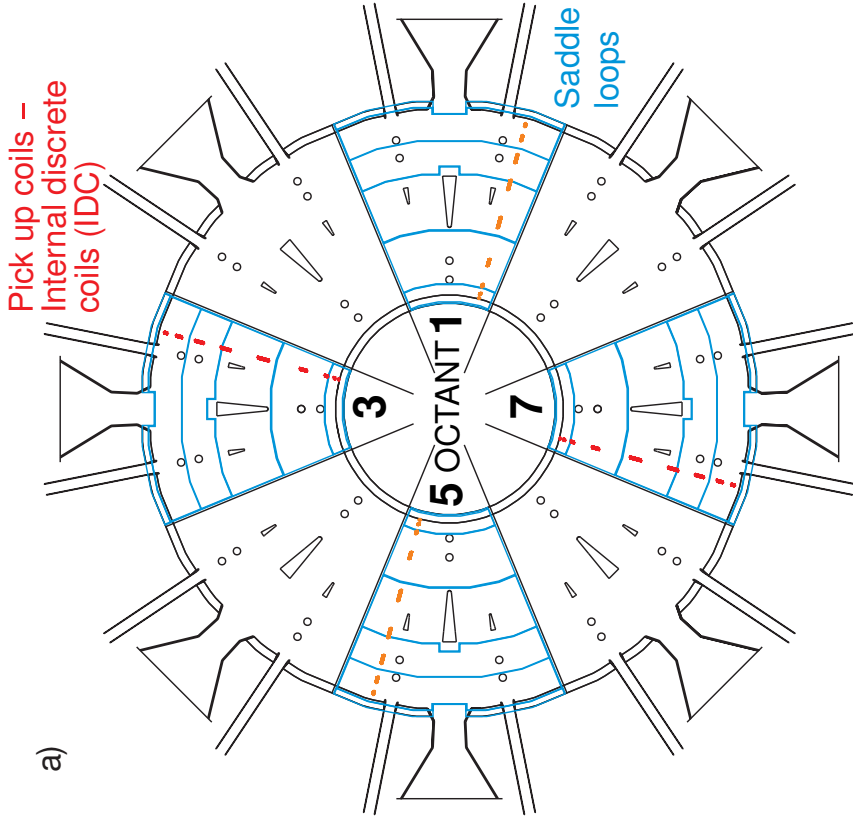
Theory and Simulation of Disruptions Workshop  
Princeton Plasma Physics Laboratory

July 9- 11, 2014

- ✓ **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)

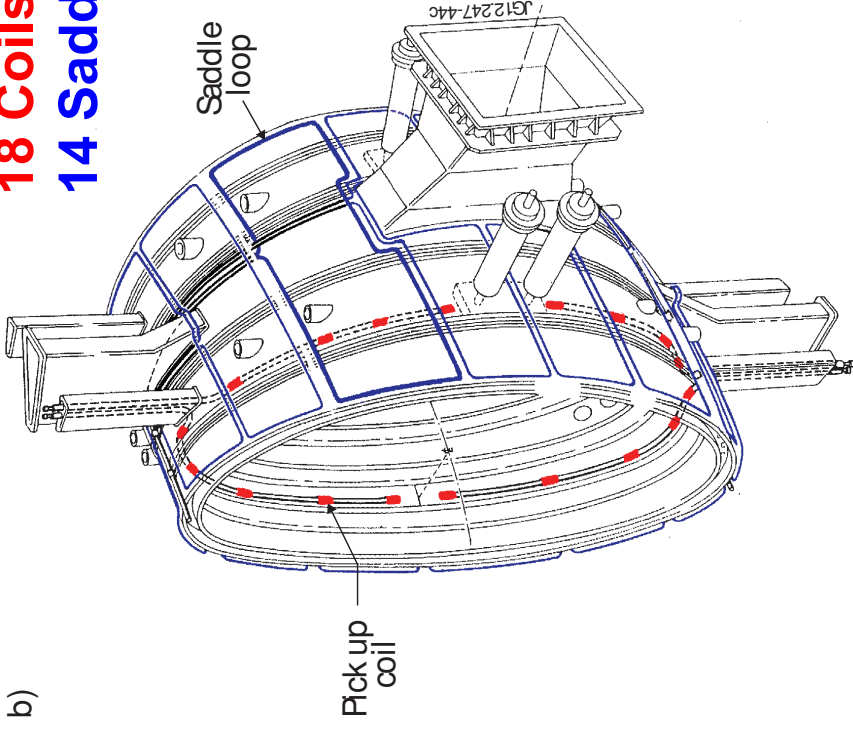
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Pick up coils -  
Internal discrete  
coils (IDC)

a)

**18 Coils**  
**14 Saddles**

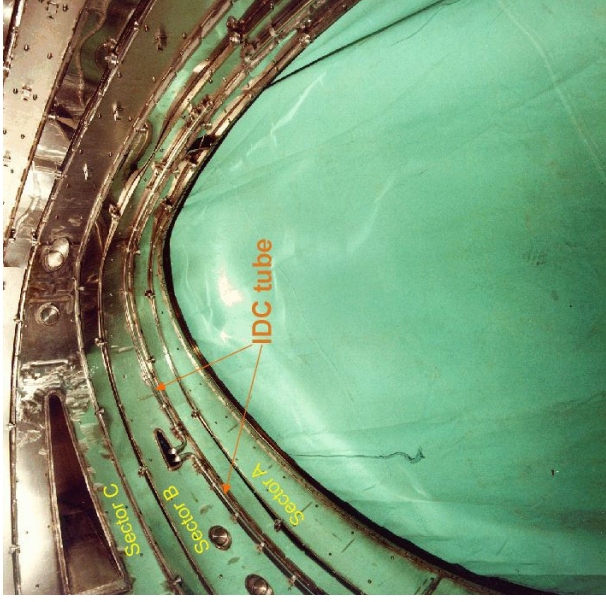


b)

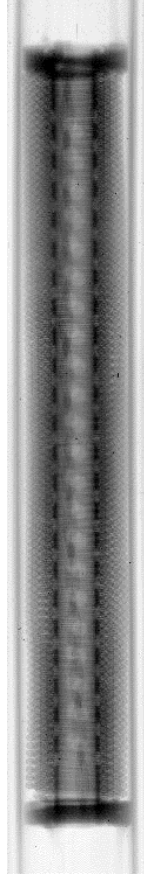
Plan view of JET vessel, showing the toroidal locations of **pick up coils** and **saddle loops**

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)

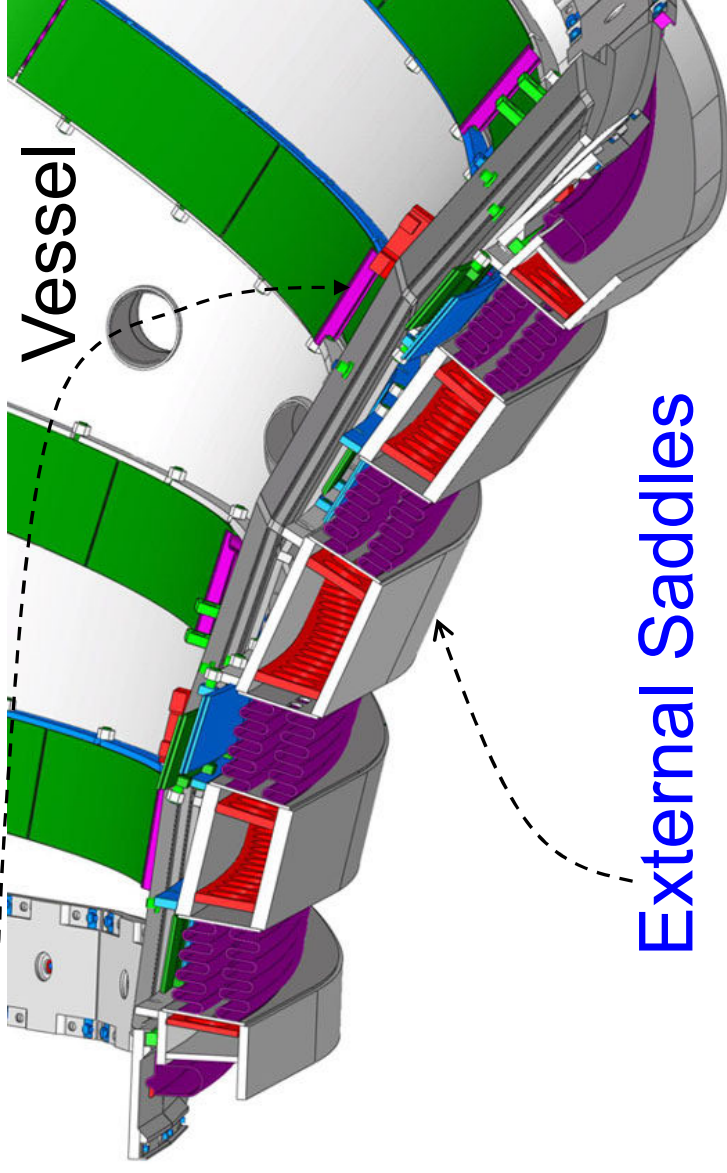


## Internal Discrete Coils

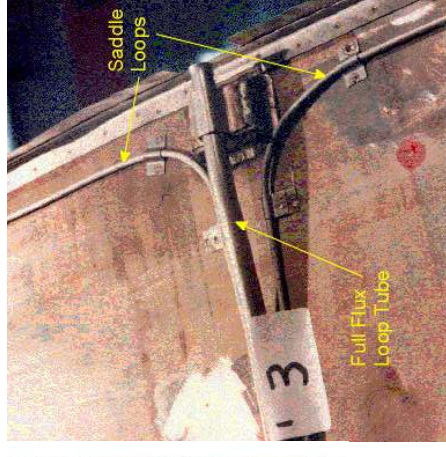
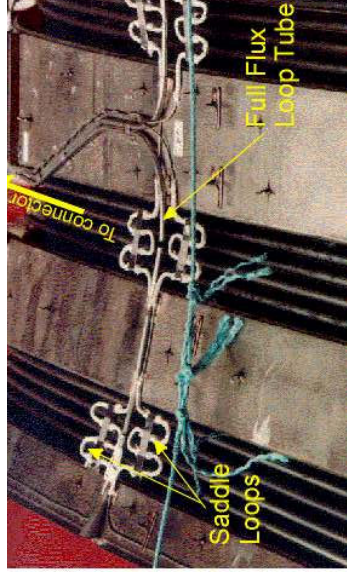


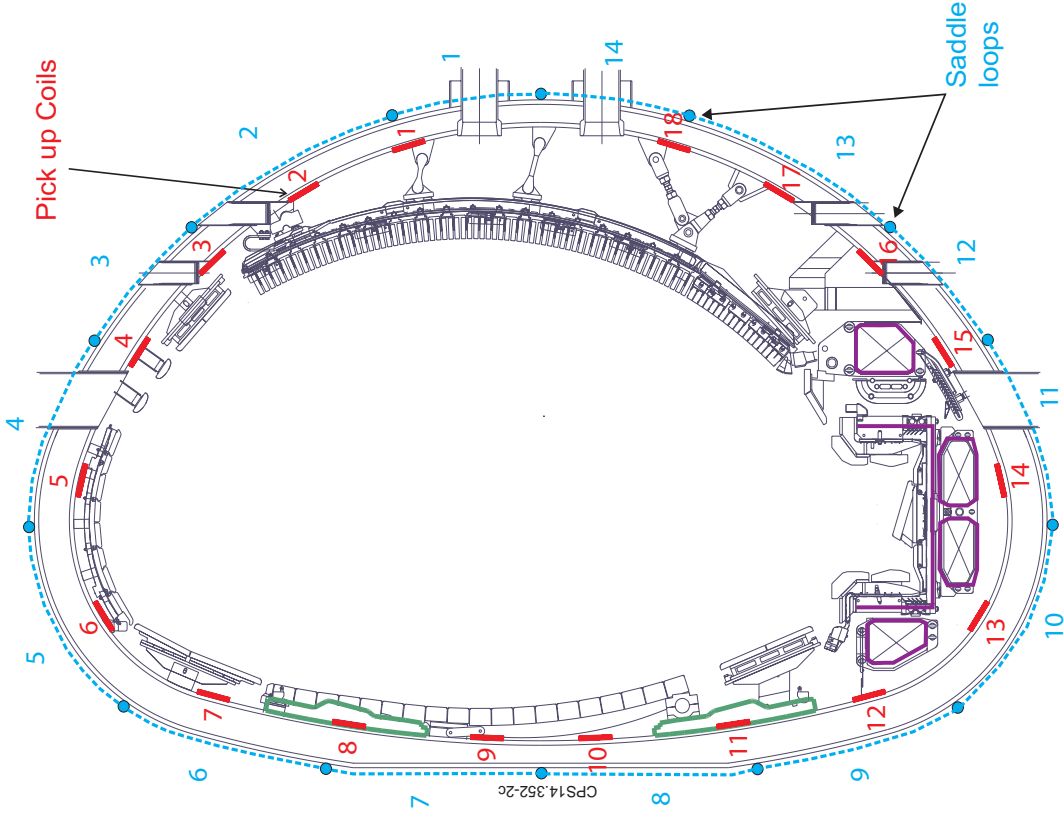
Eight octants were equipped with

“**identical**” set of **coils** and **saddles** –from photos, it can be seen that they are **NOT** perfectly identical.



## External Saddles





## Plasma Current Calculation

$$\mu_0 I = \oint \vec{B} d\vec{l}$$

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

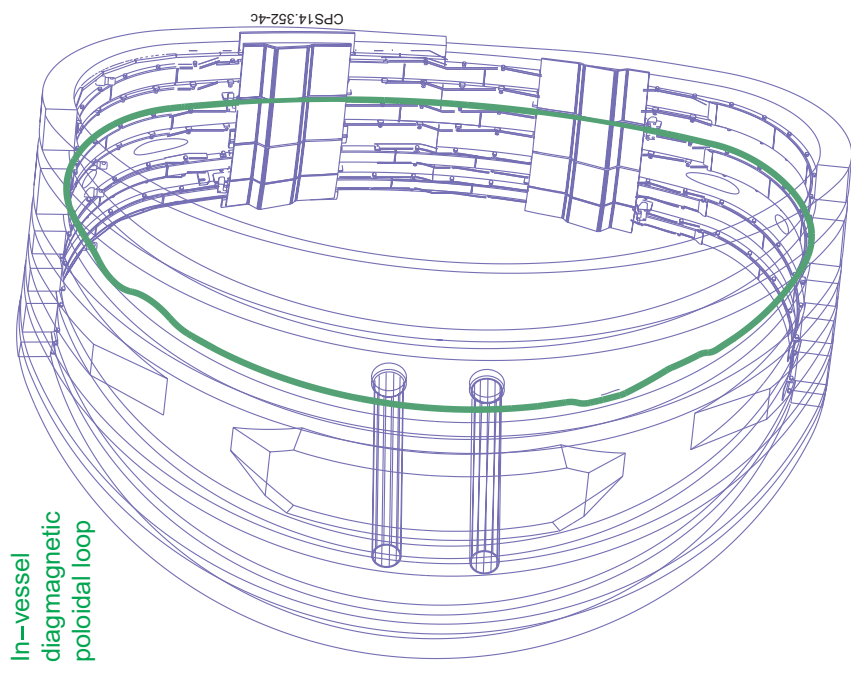
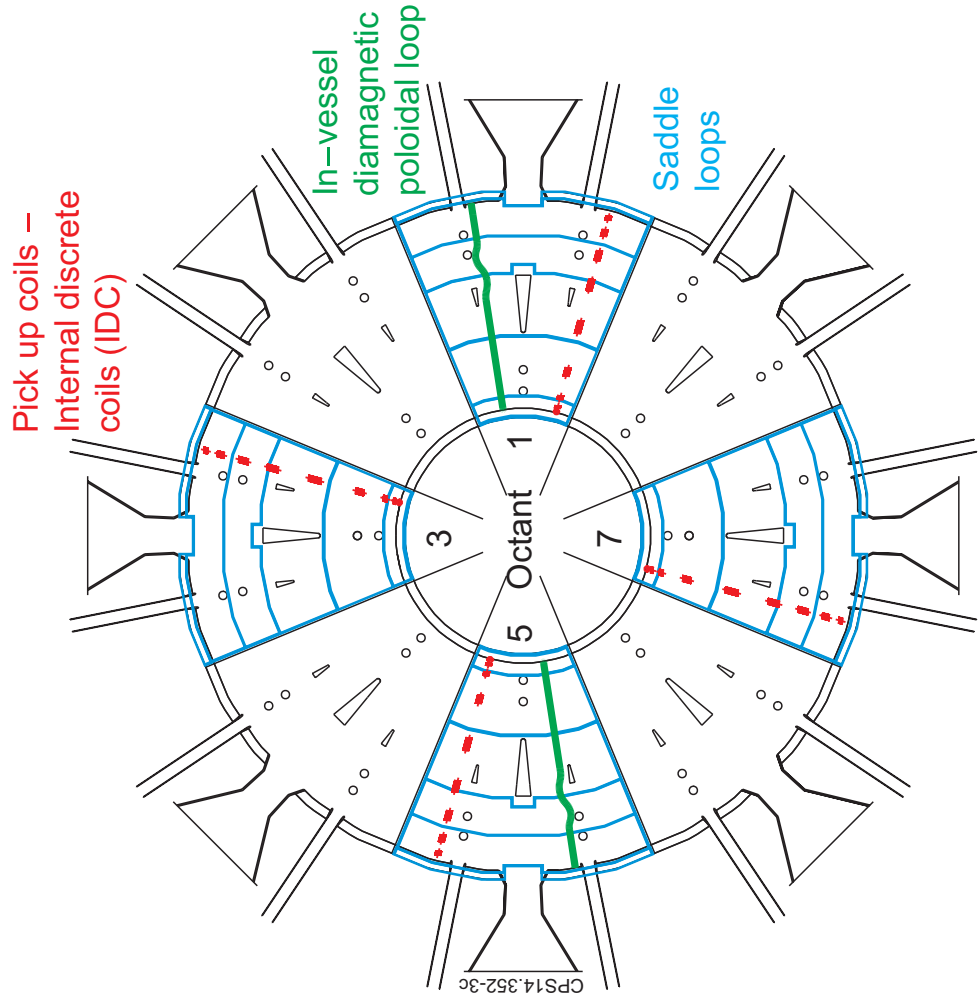
## First Plasma Current Moment Calculations

$$M_{IR} \equiv \int (R - R_0) J_{\phi} dR dZ$$

$$M_{IZ} \equiv \int Z J_{\phi} dR dZ$$

$$M_{IZ} = \frac{1}{\mu_0} \left( \sum_{i=1}^{18} B_{\theta i} z_i d_i + \frac{1}{2\pi} \sum_{i=1}^{14} \Psi_i \ln \left( \frac{R_o}{r_i} \right) \right) - \sum_{i=1}^4 z_{Di} n_{Di} I_{Di} - (z_{RRU} I_{RRU} + z_{RRL} I_{RRL})$$

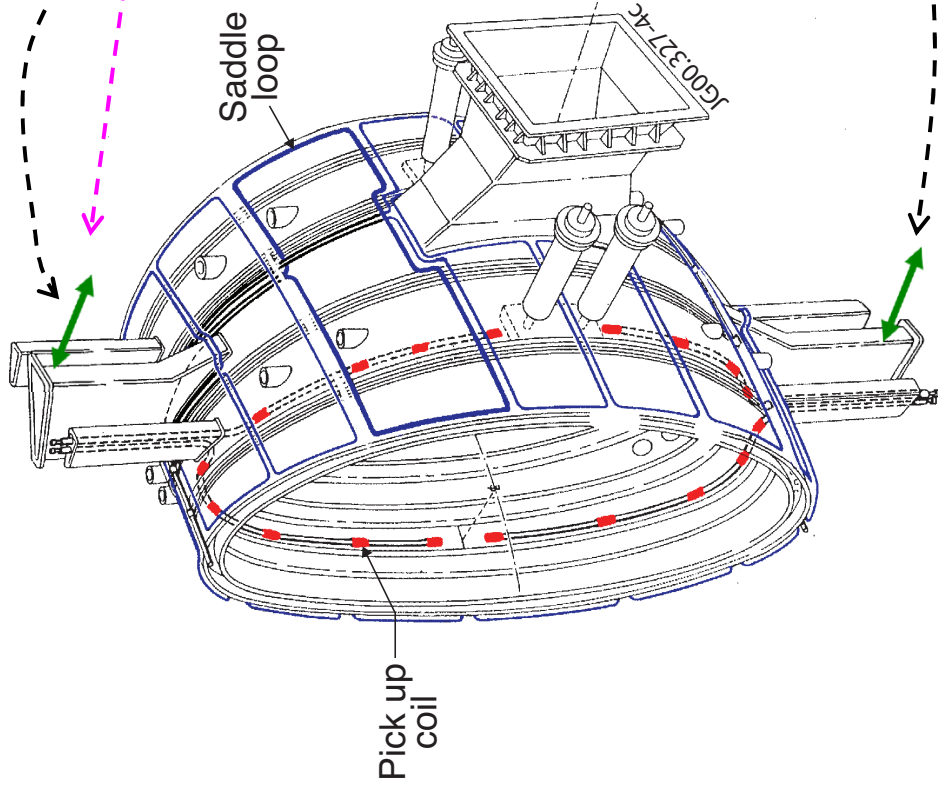
*Divertor support structure and divertor PF coil cases are not included in calculations (~5% of  $I_p$  at disruption), because there are no reliable measurements. It does not affect the asymmetry calculation.*



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**

Displacement transducers

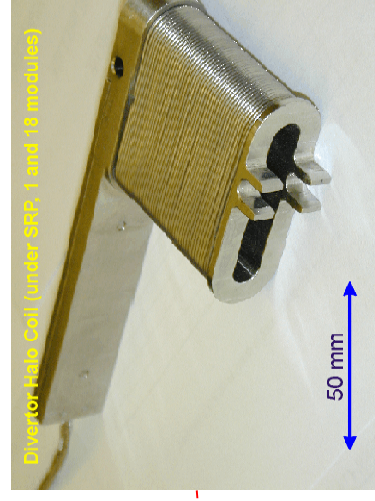
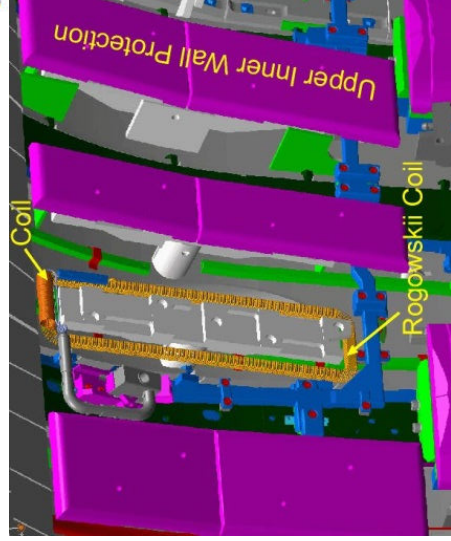
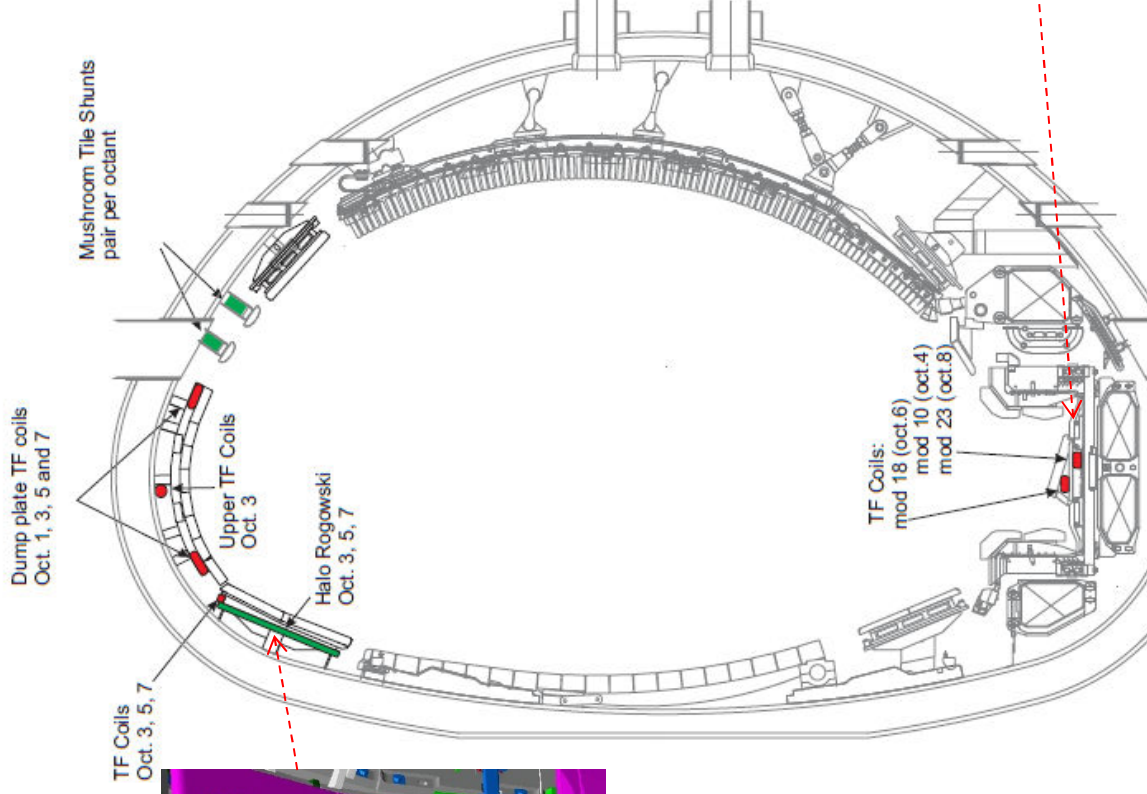


**Transducers** measure radial movement at vertical port of the each vessel octant with respect to mechanical structure

Displacement transducer



**Shunts and Rogowski coils**  
**TF pick-up coils**  
 (Not all of them are reliable)



JET “Halo” diagnostic will not be discussed in current presentation

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

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

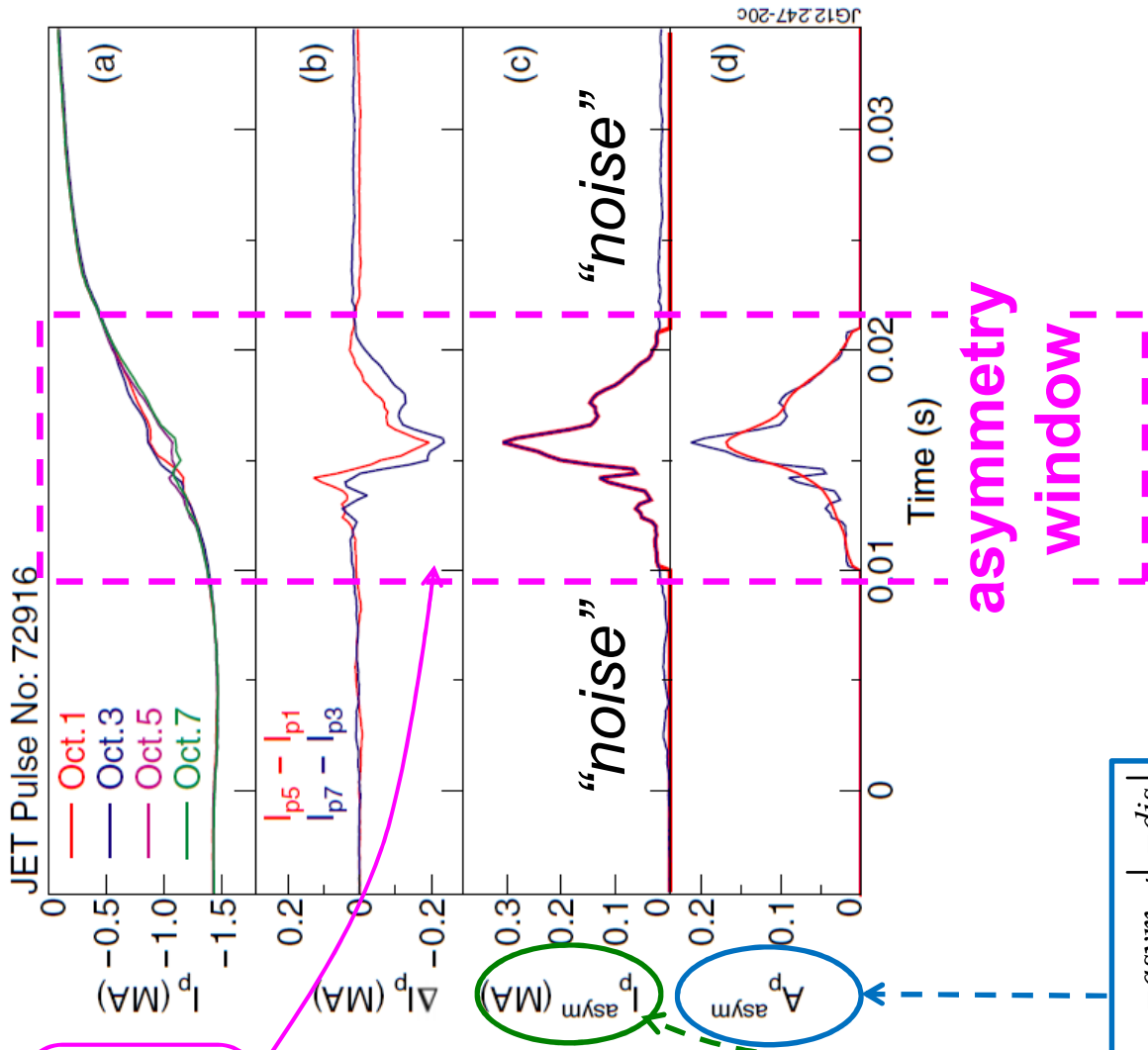
for the first and last 1 ms window in order to disregard short-lived spikes;

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

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

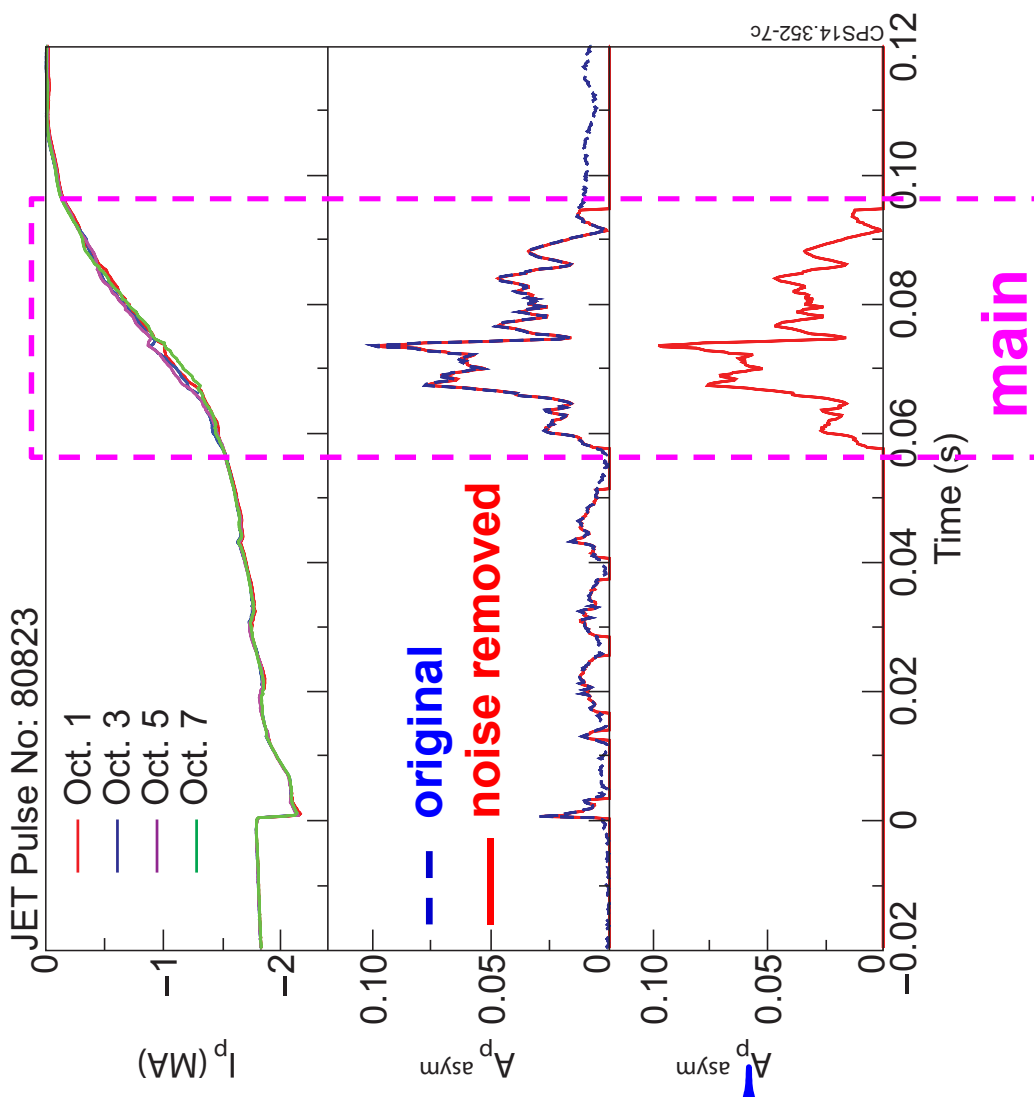
$$I_p^{asym} = \sqrt{(I_{p7} - I_{p3})^2 + (I_{p5} - I_{p1})^2}$$

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



asymmetry window

Several  $I_p$  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  $|I_p^{asym}| < 10\text{kA}$  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.

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

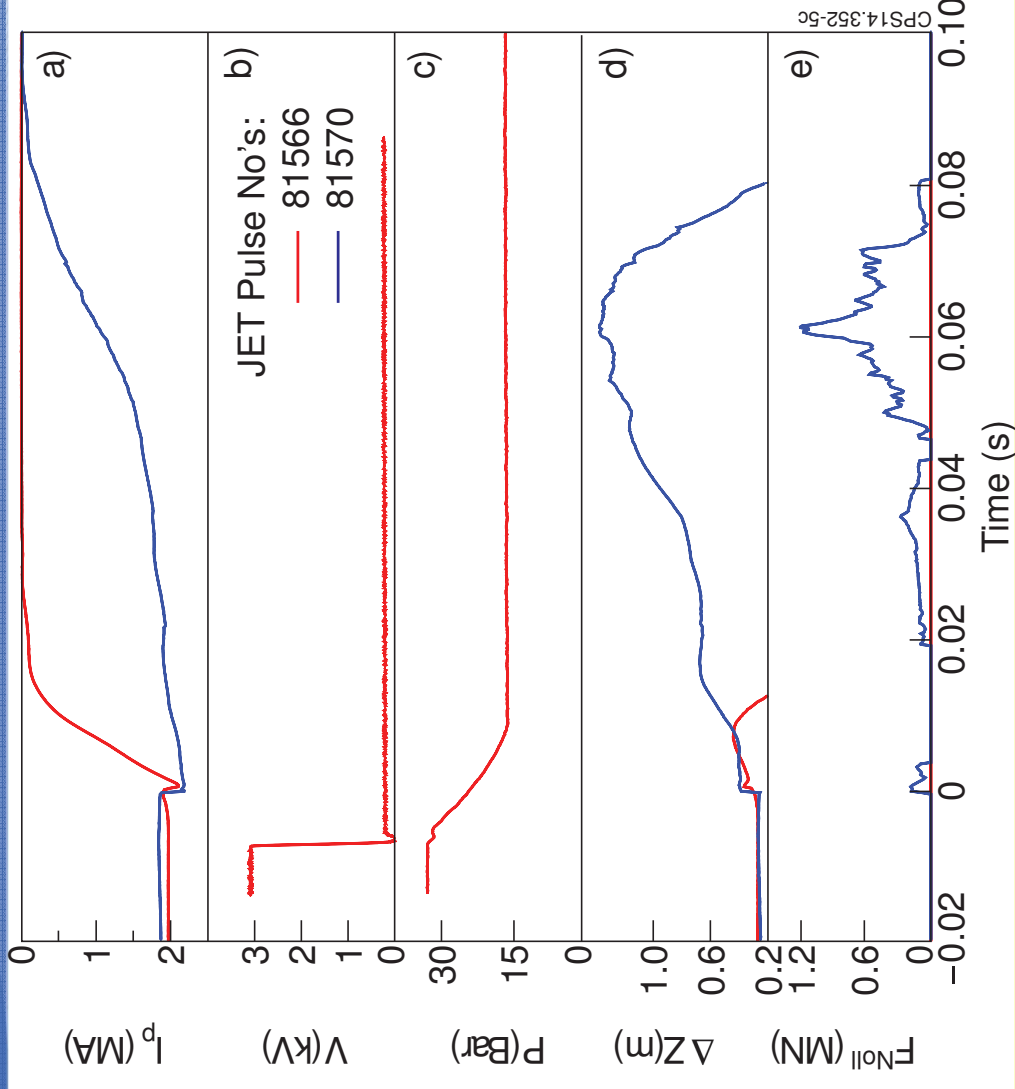
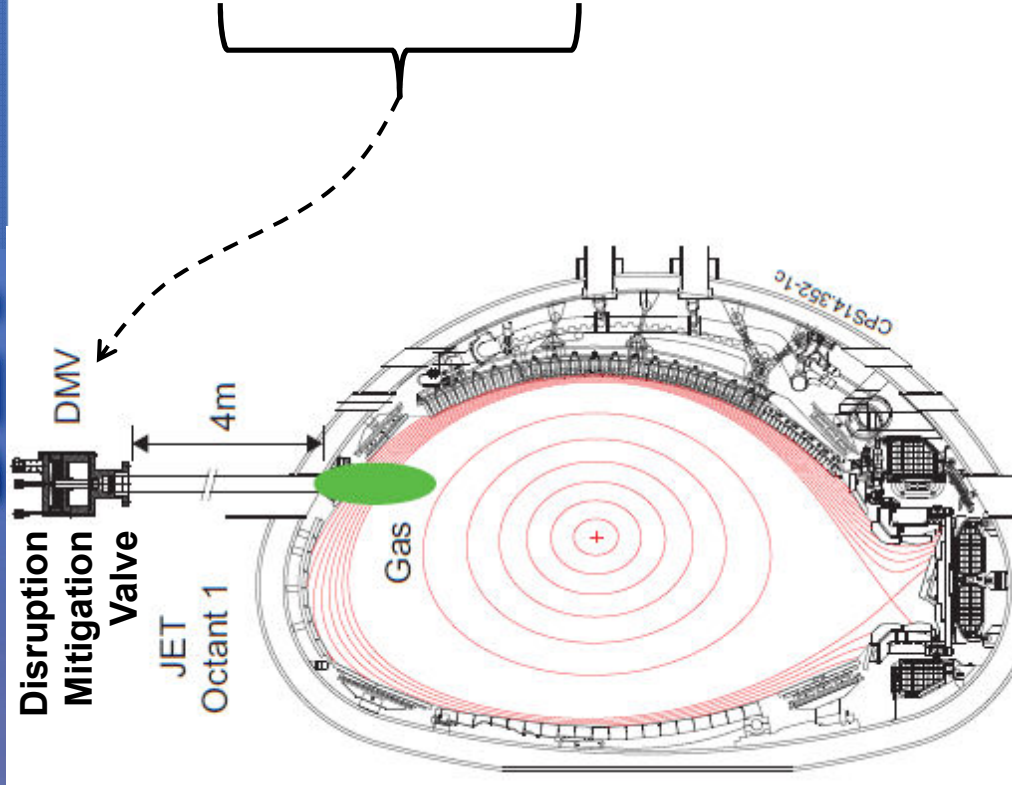
asymmetry window

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- $I_p$  just before disruption  $> 1.0\text{MA}$
- 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)

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\*MGI - Massive Gas Injection

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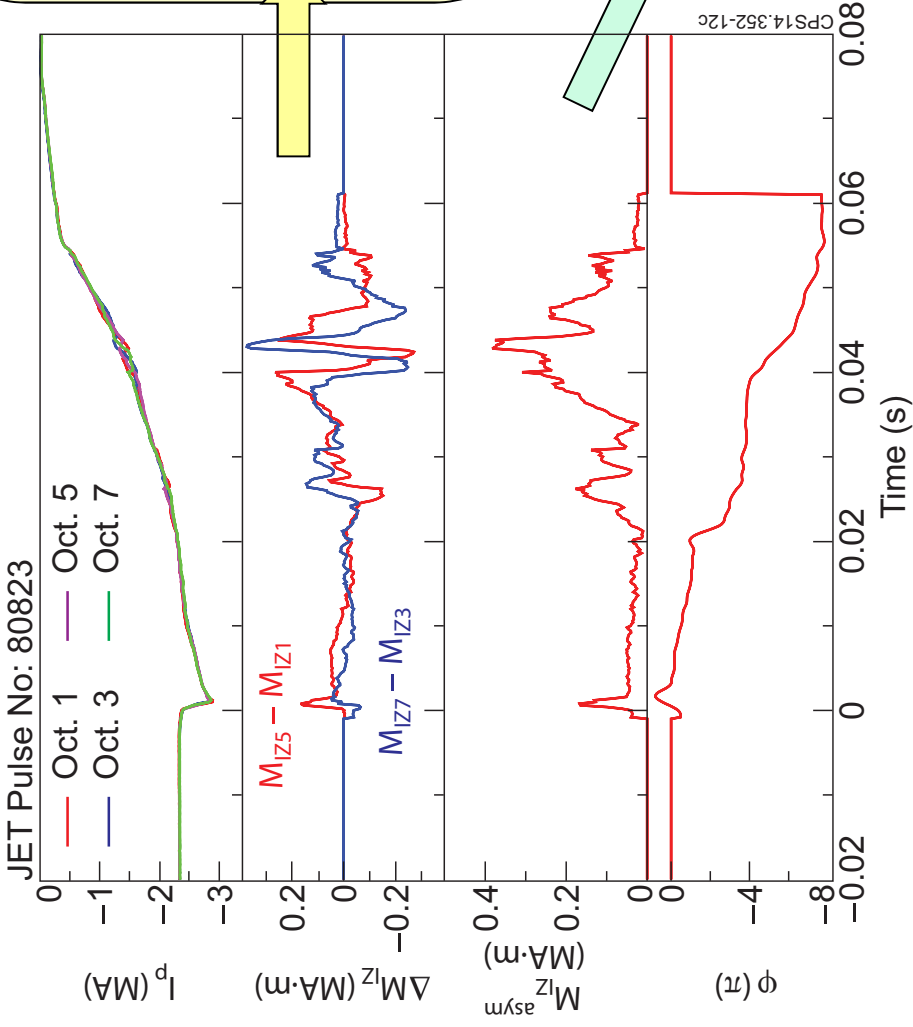


**DMV set up for disruption suppression:**

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

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





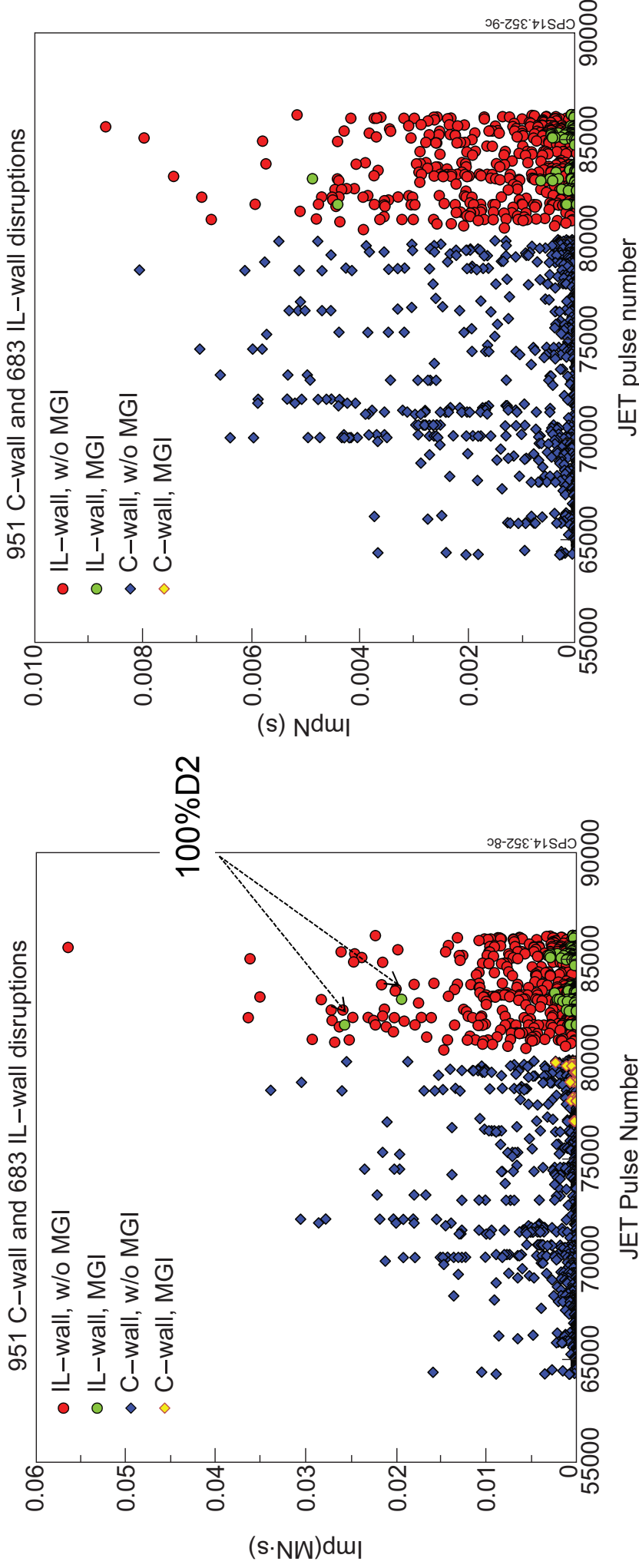
## Sideways Force Directional Impulse:

- $Imp_x = \int F_x^{Noll} dt \quad (= \frac{\pi}{2} B_T \int \Delta M_{Iz_y} dt)$
- $Imp_y = \int F_y^{Noll} dt \quad (= \frac{\pi}{2} B_T \int \Delta M_{Iz_x} dt)$
- $Imp_r = \sqrt{Imp_x^2 + Imp_y^2}$

## Sideways Force Impulse Modulus:

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

- ✓ 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.

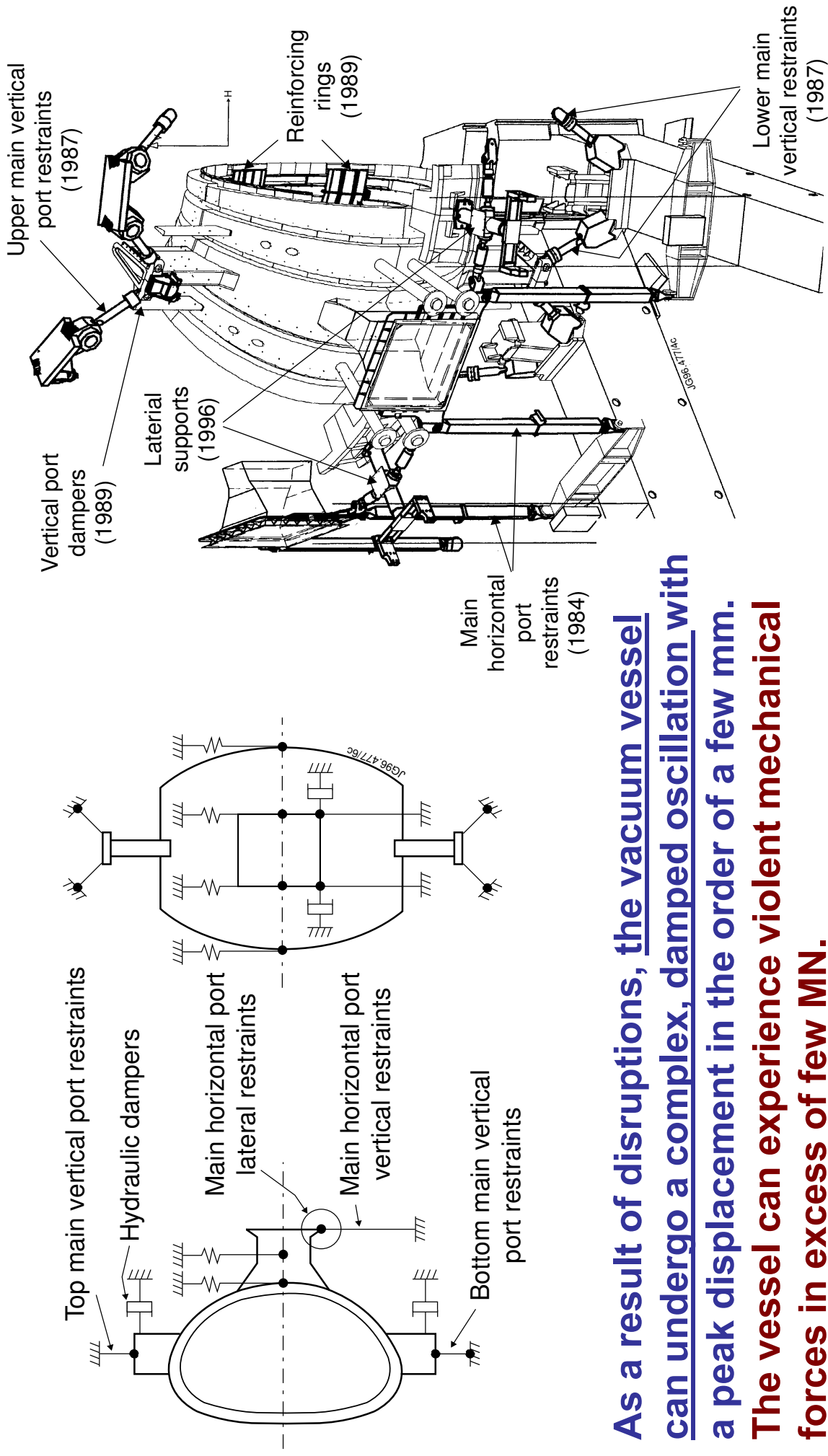


Impulse was calculated for main  $I_p$  asymmetry time window:

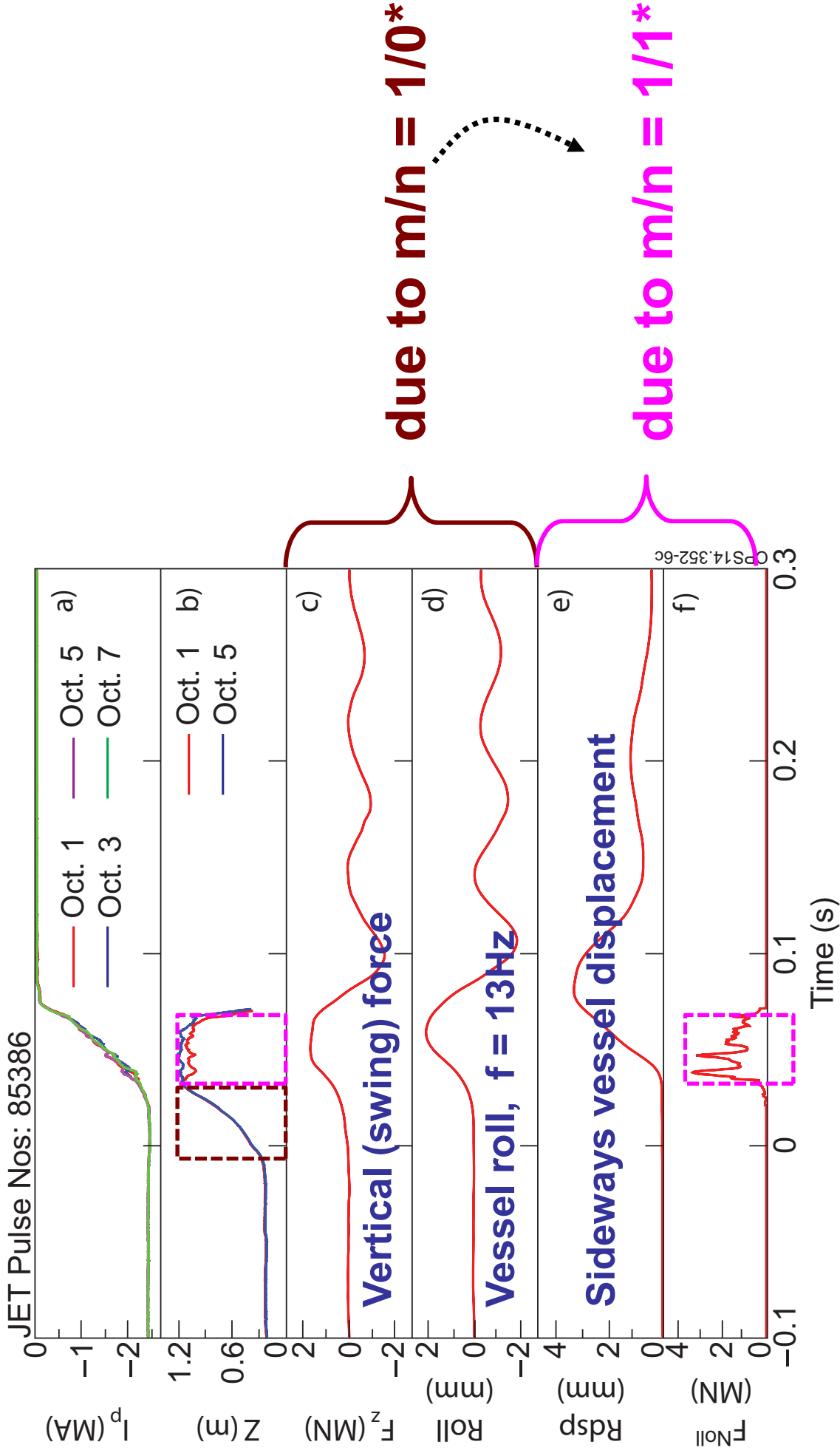
$$Imp = \int F^{Noll} dt$$

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

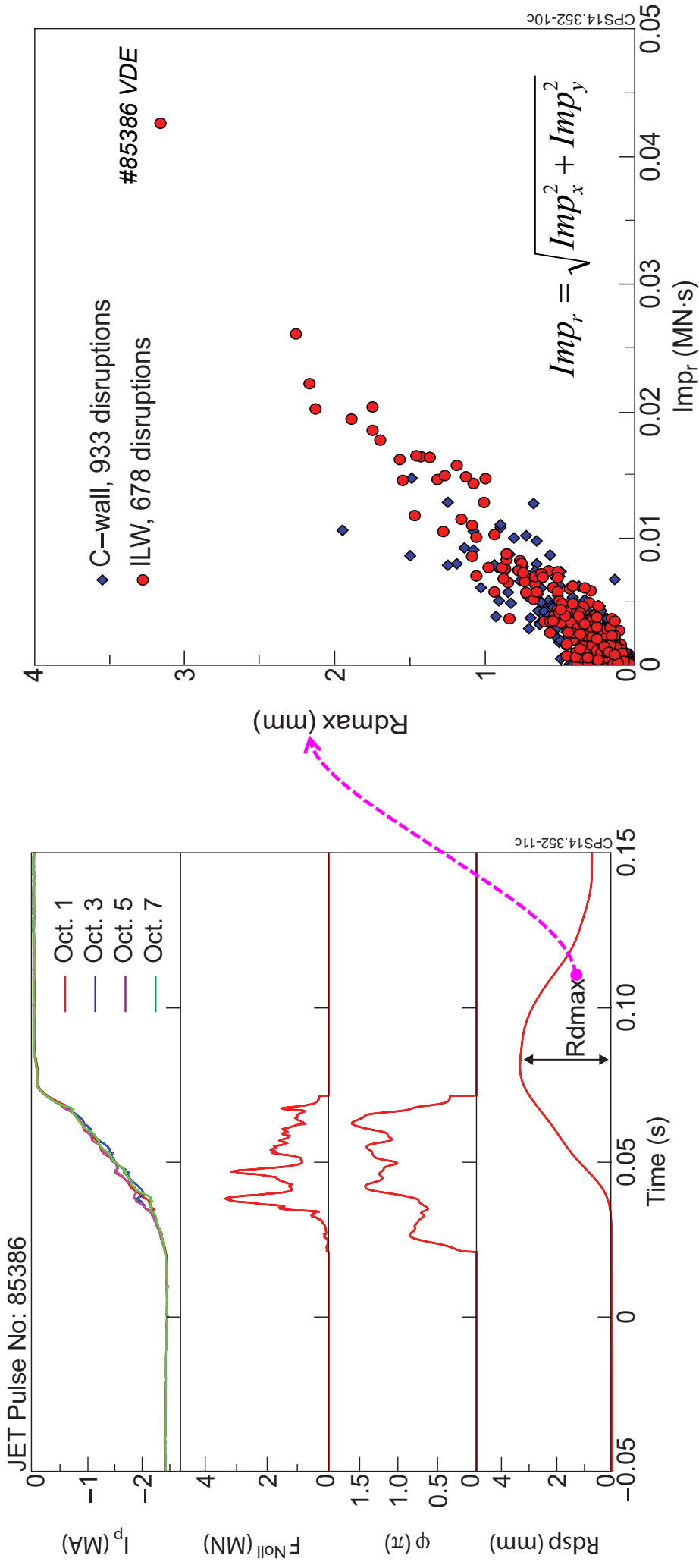
$$ImpN = \frac{Imp}{B_T I_p a}, (a = 1m)$$



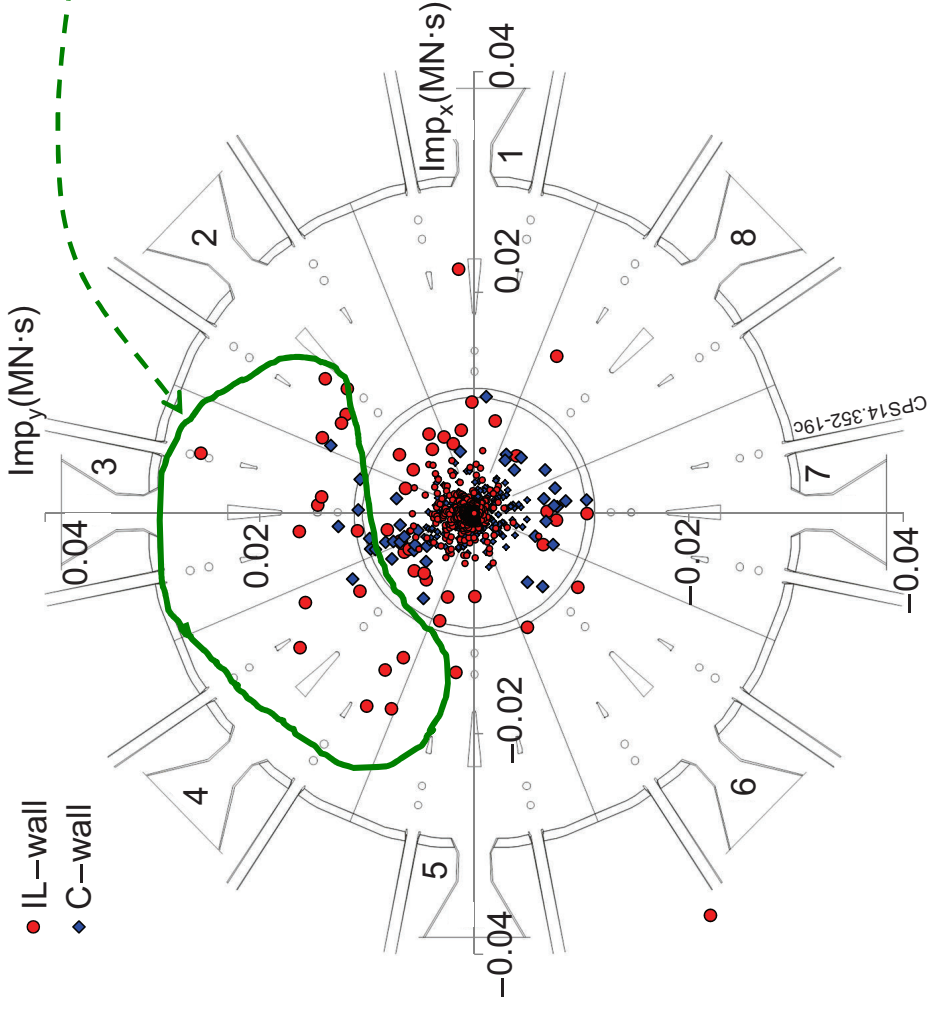
**As a result of disruptions, the vacuum vessel can undergo a complex, damped oscillation with a peak displacement in the order of a few mm. The vessel can experience violent mechanical forces in excess of few MN.**



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



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

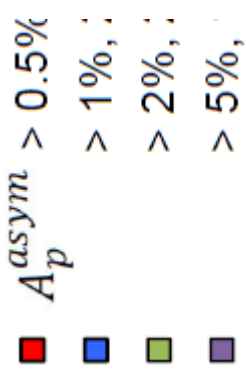
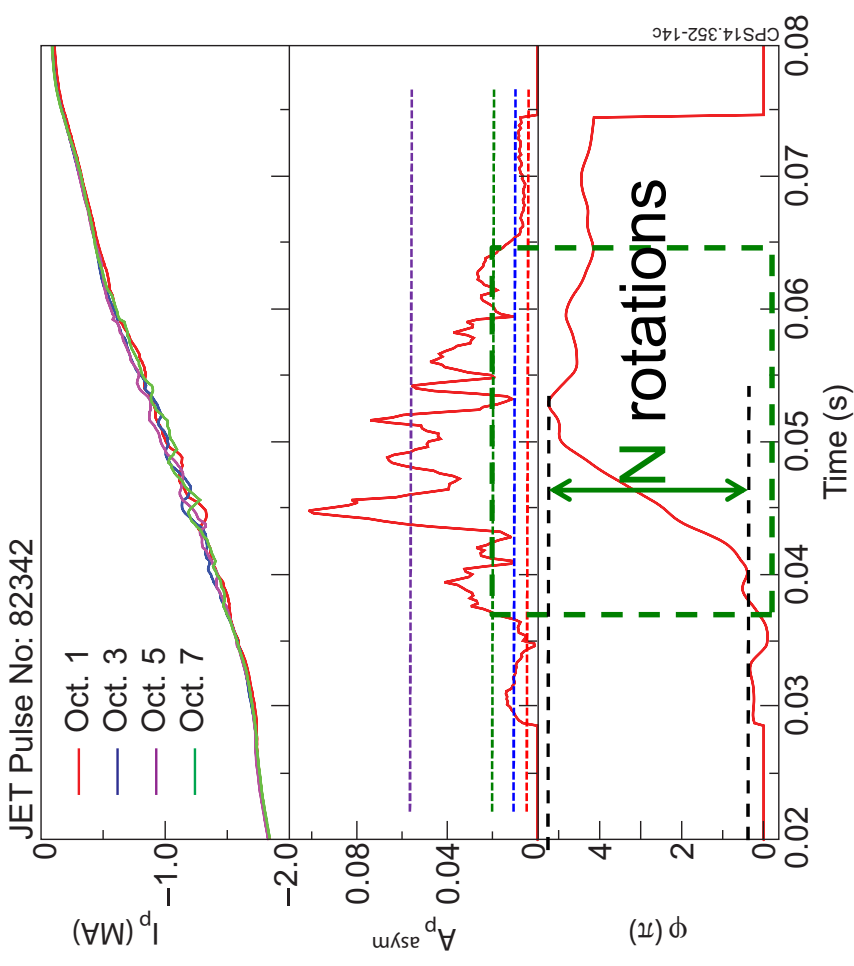
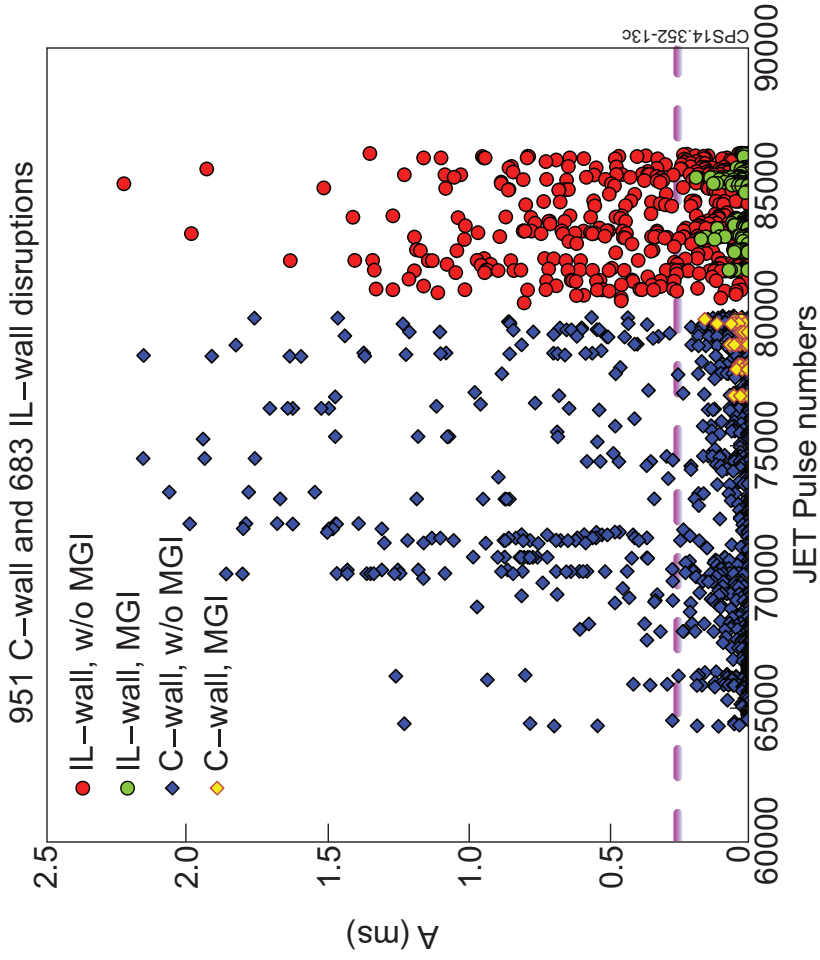


***There is preferred toroidal phase of the sideways force impulse namely in #3 - #4 octants***

## JET vessel top view

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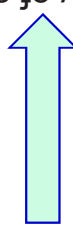




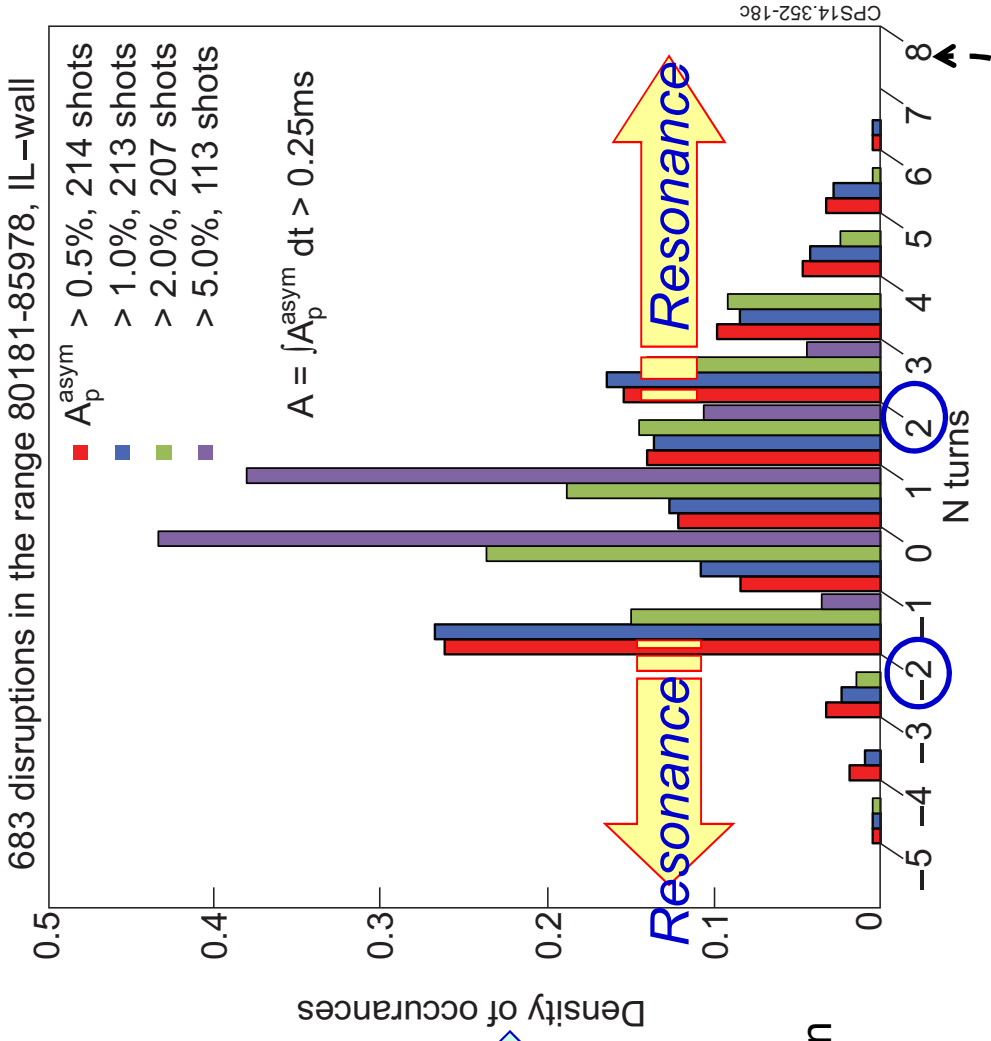
$$A = \int A_p^{asym} dt > 0.25ms$$

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

## Force dynamic amplification:

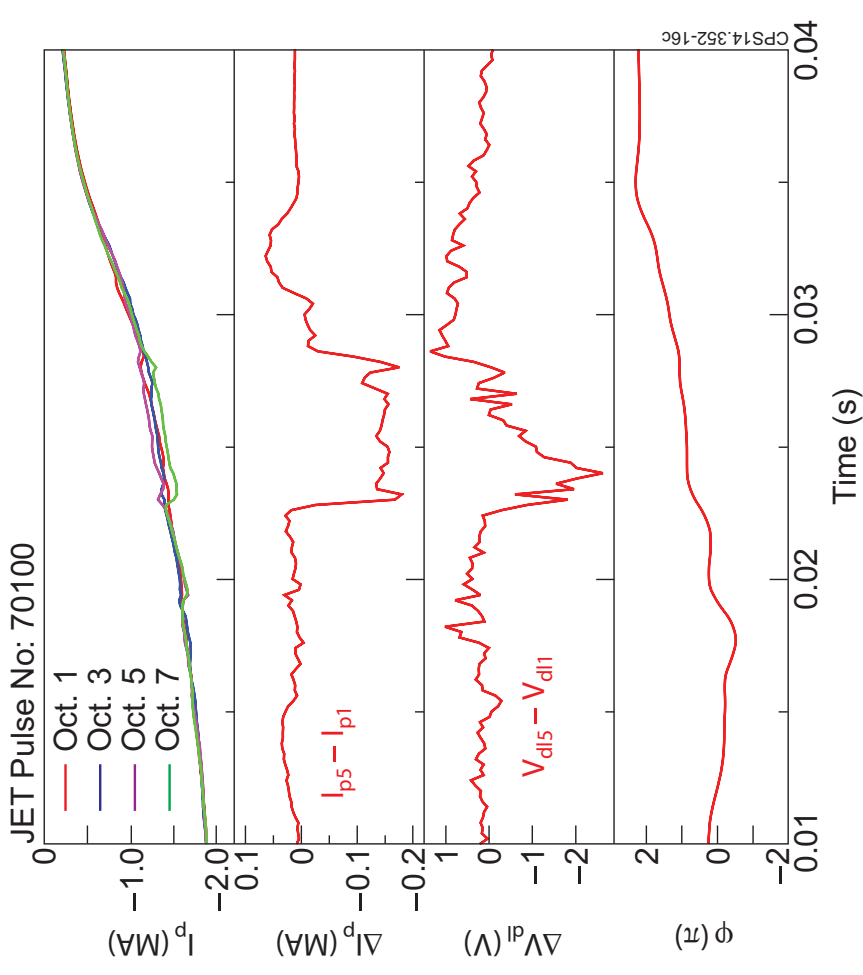
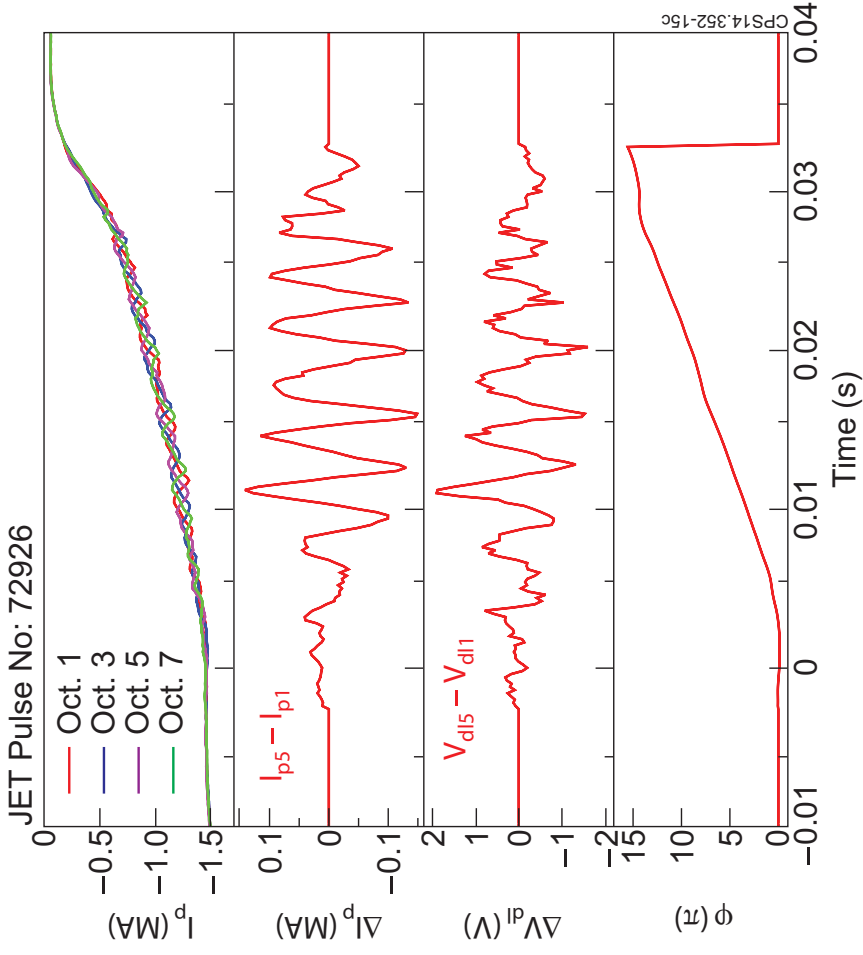
1. Rotation occurs at near a resonance frequency
2. More than 2 periods take place, see JET data 

- For JET the duration of the rotation is short compared to resonance period of the vessel ( $\sim 1/(14-17 \text{ Hz})$ ), 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.



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

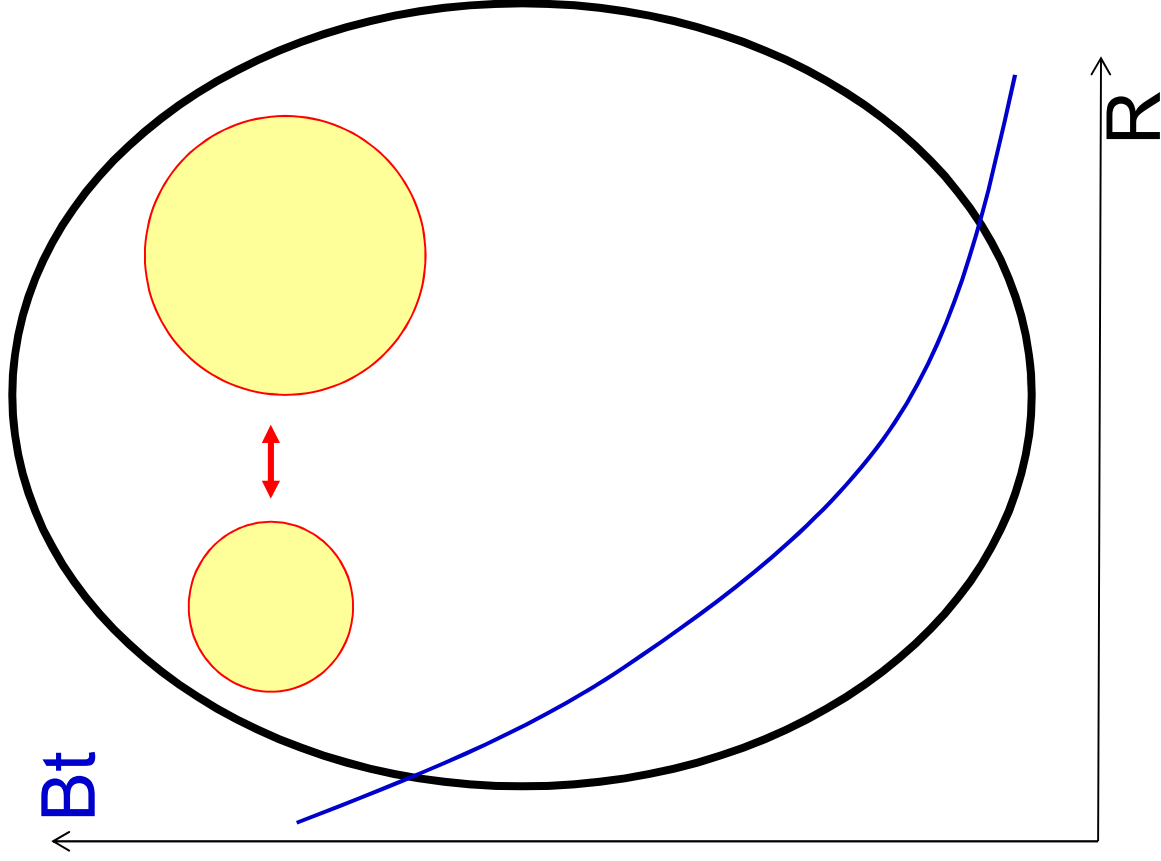
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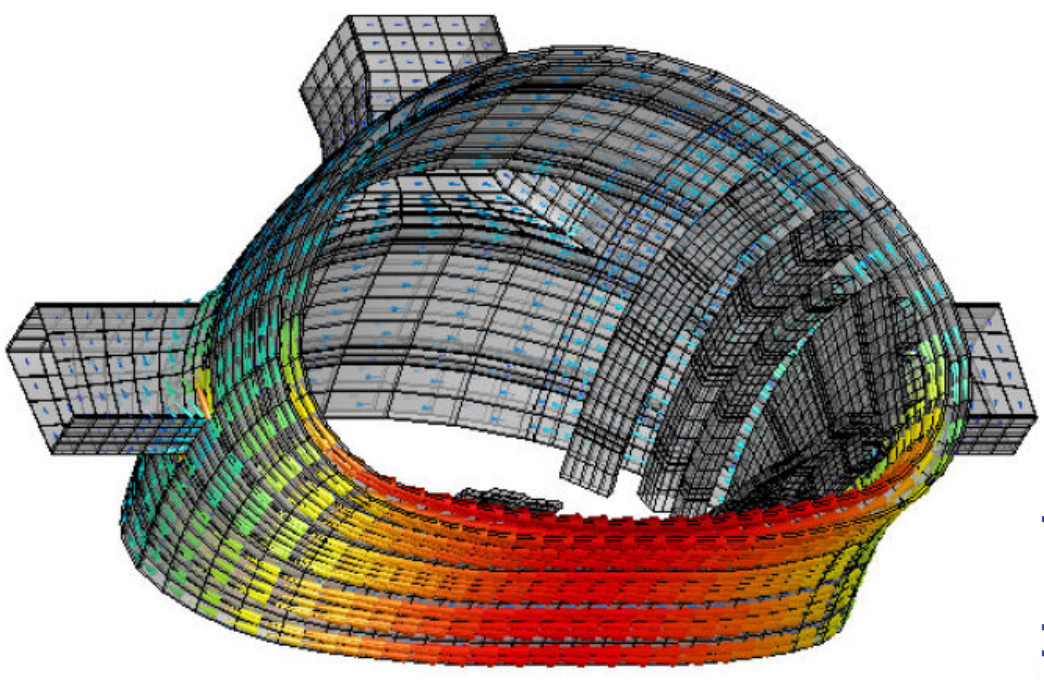
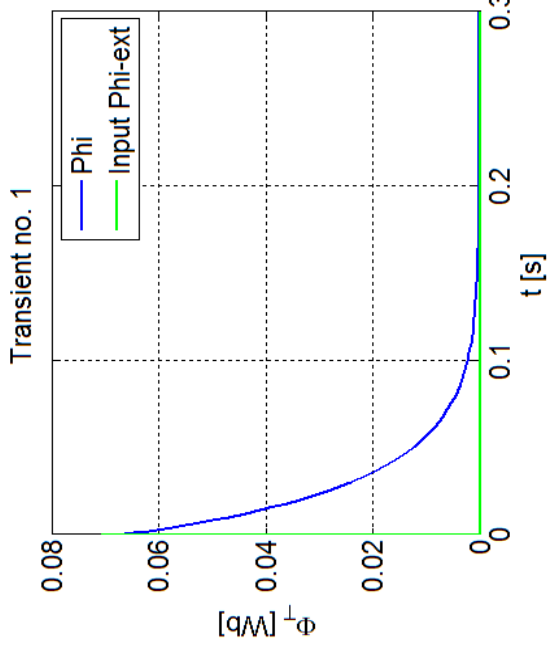
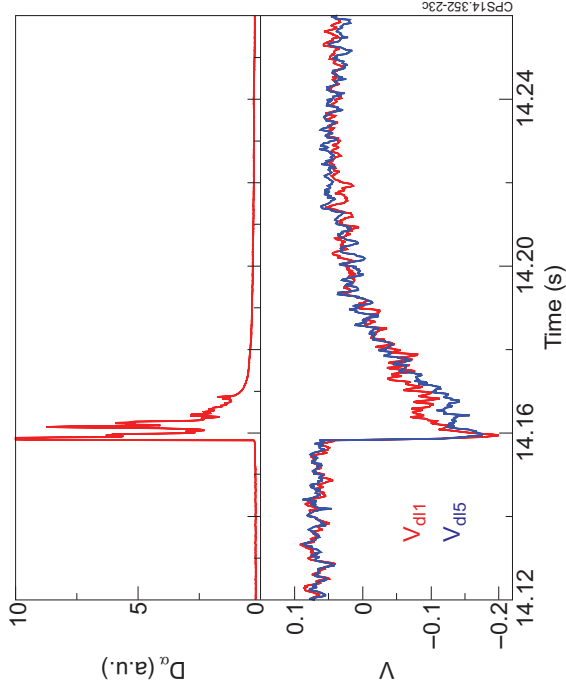
Uniform rotation – poloidal voltage asymmetry followed by toroidal current asymmetry

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

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*



## 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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- **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.**