Sideways forces during asymmetrical plasma disruptions

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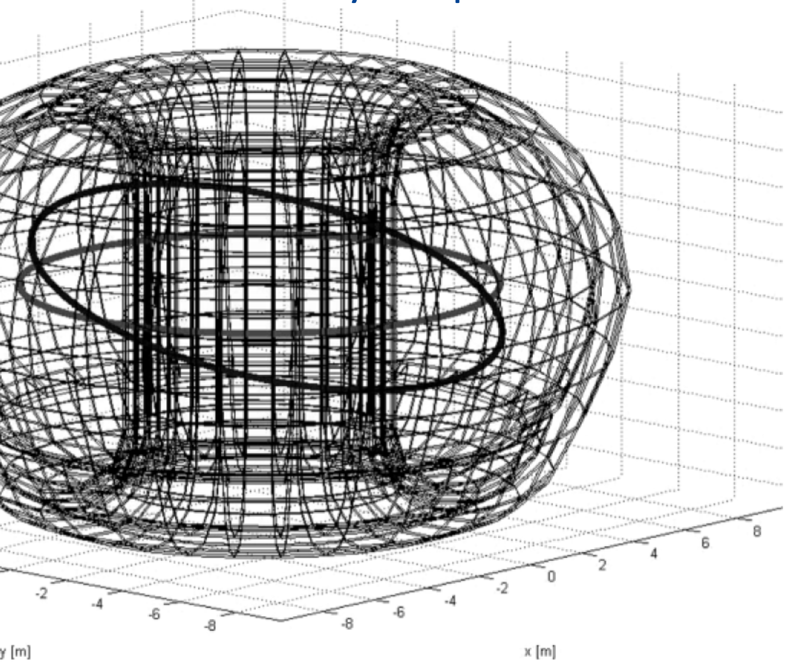
March 2020 WPSA Planning Meeting

This work has been carried out within the framework of the EUROfusion Consortium and has received funding from the Euratom research and training programme 2014-2018 and 2019-2020 under grant agreement No 633053. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

Sideways force during AVDEs and the Noll's formula

Sideways displacement of VV was for the first time observed on JET after an AVDE.



Noll's formula for sideways force on vacuum vessel (VV)*:

$$F_x^{Noll} = \pi B_0 I_p \Delta z \qquad F_{x,ITER}^{Noll} = 80\,\mathrm{MN}$$

- It was derived for a solid conductor (representing plasma) tilted in toroidal magnetic field.
- In general, there is a non-zero force on this conductor.
- But the force on plasma must be zero…

*P. Noll, et al., Present understanding of electromagnetic behaviour during disruptions at JET, Proceedings of the Nineteenth Symposium on Fusion Technology, Lisbon, Portugal, 1996, vol 1, p. 751.

Sideways force: recent analytical predictions

For wall-touching m/n=1/1 kink mode (and non-zero force on plasma)

- L. E. Zakharov, S. A. Galkin, S. N. Gerasimov, and JET EFDA Contributors, Phys. Plasmas 19, 055703 (2012).

$$F_X^{LZ} = \left(1 - \frac{\lambda}{q_a}\right) F_x^{Noll}$$

For coupled m/n=1/1 and m/n=1/-1 kink modes (zero force on plasma, plasma separated from the wall by a vacuum gap)

- D. V. Mironov and V. D. Pustovitov, Phys. Plasmas 24, 092508 (2017).

$$\frac{F_{\max}}{F_X^{LZ}} = -0.04$$

Motivation for ITPA MDC-25 JEX on Sideways Forces

Motivation 1:

- Present predictions for sideways force for ITER vary by almost two orders of magnitude from 1.2 to 80 MN [1-3].

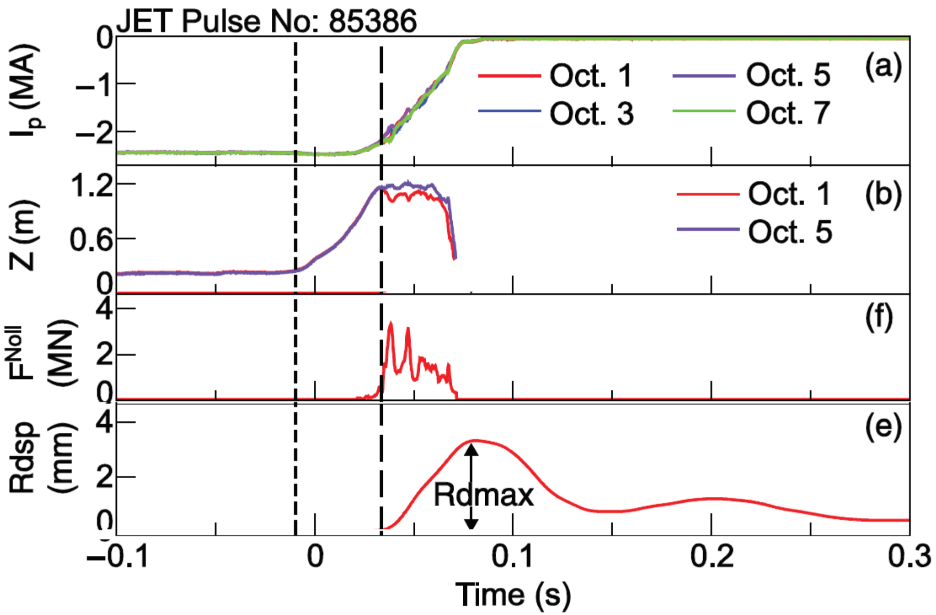
Motivation 2:

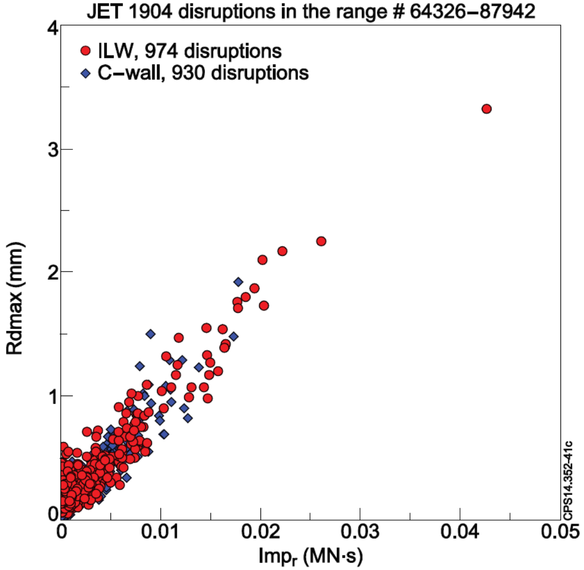
- The upper estimate (80 MN) in combination with mode rotation at the resonance frequency may be potentially damaging for ITER vacuum vessel [4].

[1] S. C. Jardin et al, "VDE simulations with M3D-C1", 34th MDC ITPA meeting, Garching, 15.10.19
[2] D. V. Mironov and V. D. Pustovitov, Phys. Plasmas 24, 092508 (2017).
[3] L. E. Zakharov, S. A. Galkin, S. N. Gerasimov, and JET EFDA Contributors, Phys. Plasmas 19, 055703 (2012).
[4] C.E. Myers et al 2018 Nucl. Fusion 58 016050

Sideways displacement of JET vacuum vessel

- JET data doesn't contradict to the Noll's model*: $F_x^{Noll} = \pi B_0 I_p \Delta z$
- Proportional relationship between magnetic and mechanical measurements.
- Modelling of vessel displacement in response to sideways impulse (in progress).



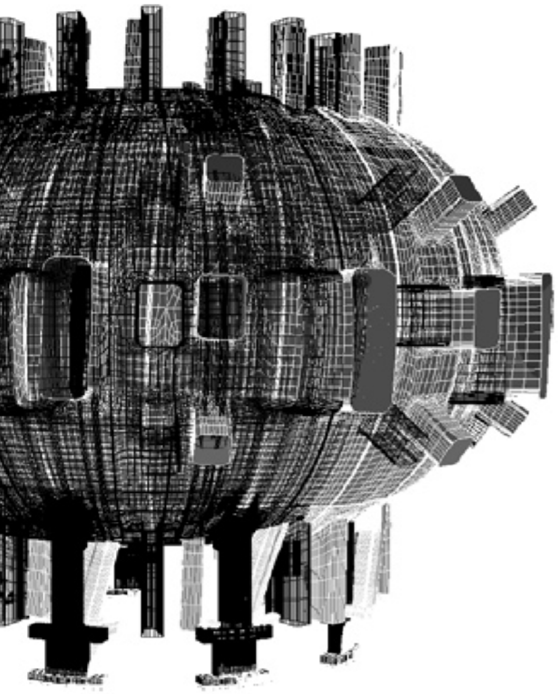


*Gerasimov, S. N., et al. "JET and COMPASS asymmetrical disruptions." Nuclear Fusion 55.11 (2015): 113006.

Open questions

- What is the maximum sideways force JT-60SA vacuum vessel is designed to withstand?
- What is the range for sideways force amplitude, rotational frequency and duration that one can expect for JT-60SA?
- What is the most optimal instrumentation for the monitoring/studying of sideways forces and related vessel displacement on JT-60SA?
- (At the moment only instrumentation for monitoring of TF coils and vertical force on the vessel is available)

Sideways loads on JT-60SA VV during asymmetrical VDEs



Noll's formula as an upper estimate:

$$F_x^{Noll} = \pi B_0 I_p \Delta z$$

For JT – 60SA

$$sideways\ force:\ F_x^{Noll} = 3\,\mathrm{MN}$$

sideways displacement:

$$maximum\ \ allowed:\ x = 9\,\mathrm{mm}^*(for\ seismic\ analysis)$$

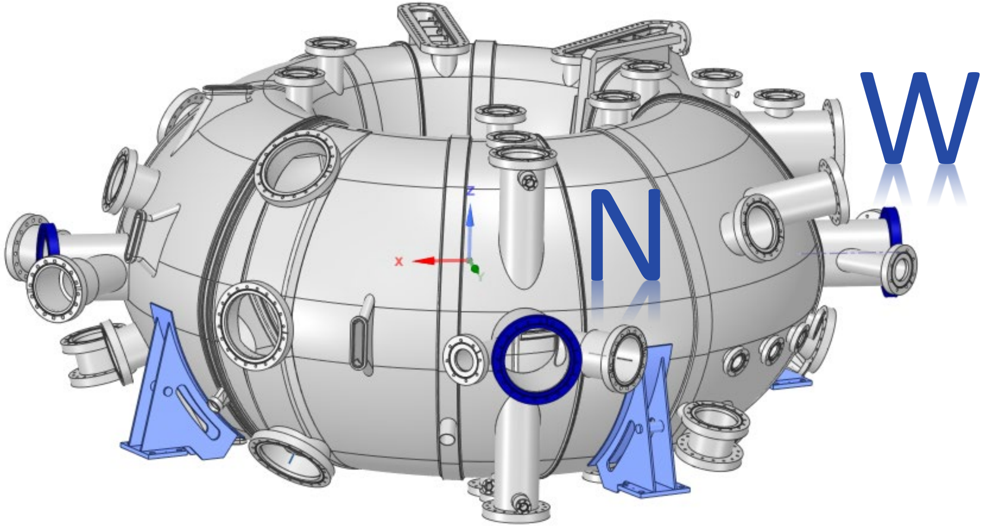
$$maximum\ \ analytical\ estimate:\ x = 4\,\mathrm{mm}^{**}$$

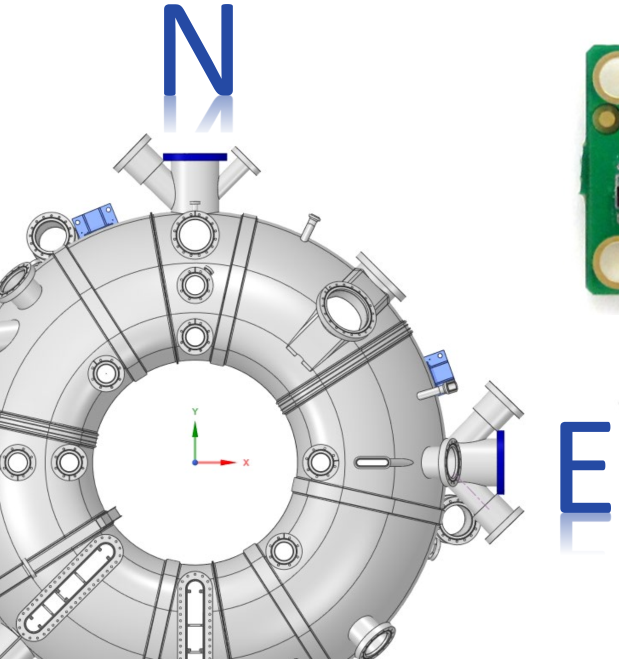
$$CARIDDI + ANSYS\ \ modelling\ \ x = ?^{***}$$

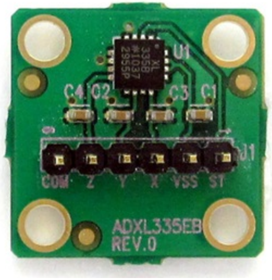
*Y. K. Shibama et al. "Design status of JT-60SA vacuum vessel." *J. Plasma Fusion Res. SERIES* 9 (2010): 180-185.
**V. V. Yanovskiy et al, "Modelling of vessel sideways displacement during AVDEs on JET, AUG, COMPASS, COMPASS-U and ITER", 34th MDC ITPA meeting, Garching, 15.10.19
***Final report of expert contract F4E-2015-EXP-227 (2016).

New instrumentation on COMPASS

- 4 MEMS accelerometers at 4 orthogonal positions (N, E, S, W) have been installed on equatorial ports of COMPASS vacuum vessel

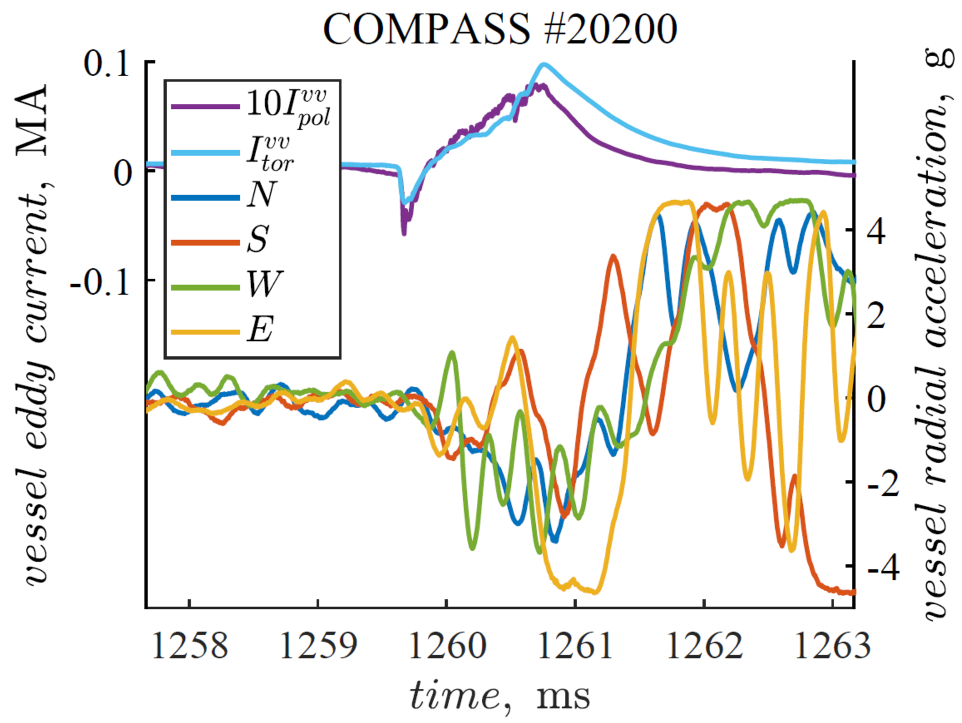






- Together with two displacement sensors on two opposite ports (West-East)

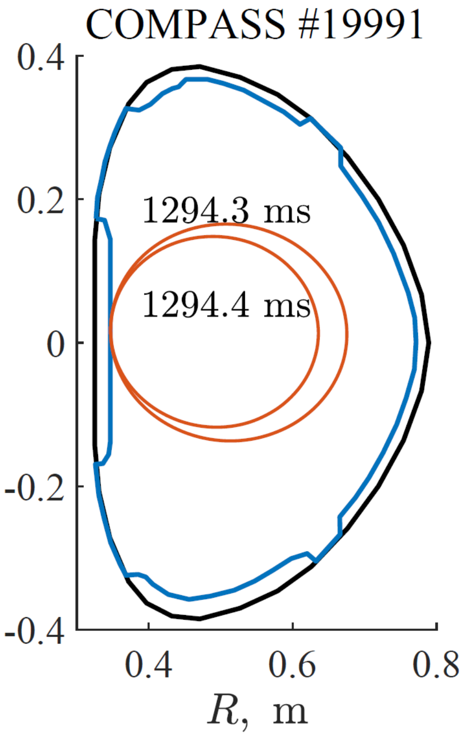
Results obtained with MEMS accelerometers - 1

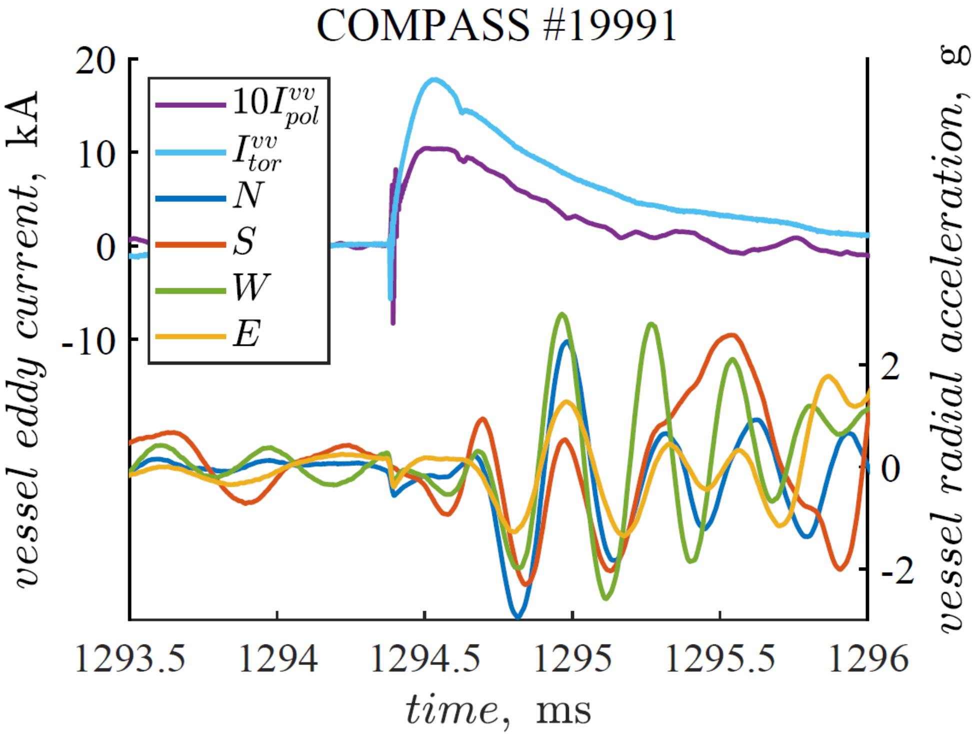


- MEMS accelerometers are found to be almost insensitive to electromagnetic transients.
- Tested model: ADXL335 (10 EUR/pc)
- Survived a run-away electron campaign
- In general, the vessel mechanical response to plasma disruptions is quite complicated, because multiple harmonics overlap.
- To interpret data, dynamic mechanical modelling for the vessel is necessary (work in progress).
- Present g-range (+/-4.5) is not enough.

Results obtained with MEMS accelerometers - 2

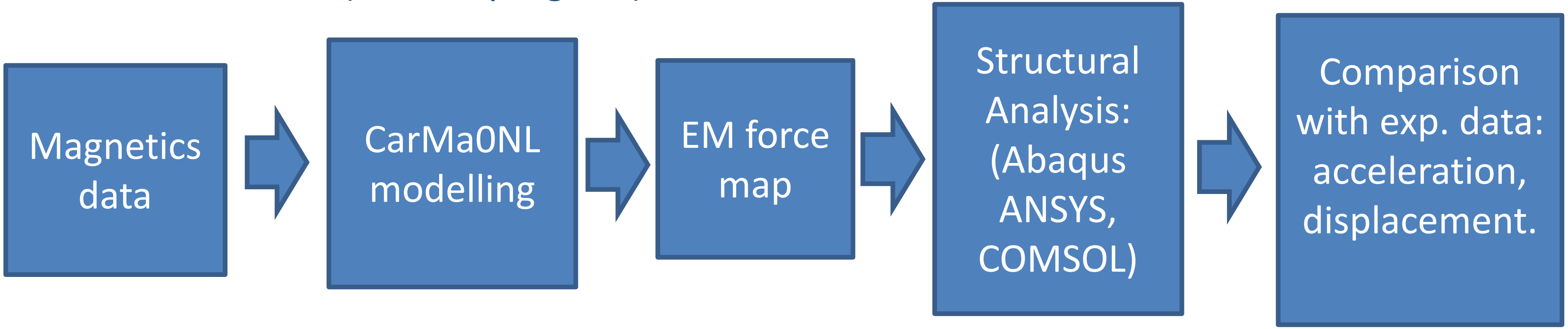
- For minor disruptions of circular plasmas the main harmonic of radial vessel oscillations can be distinguished.





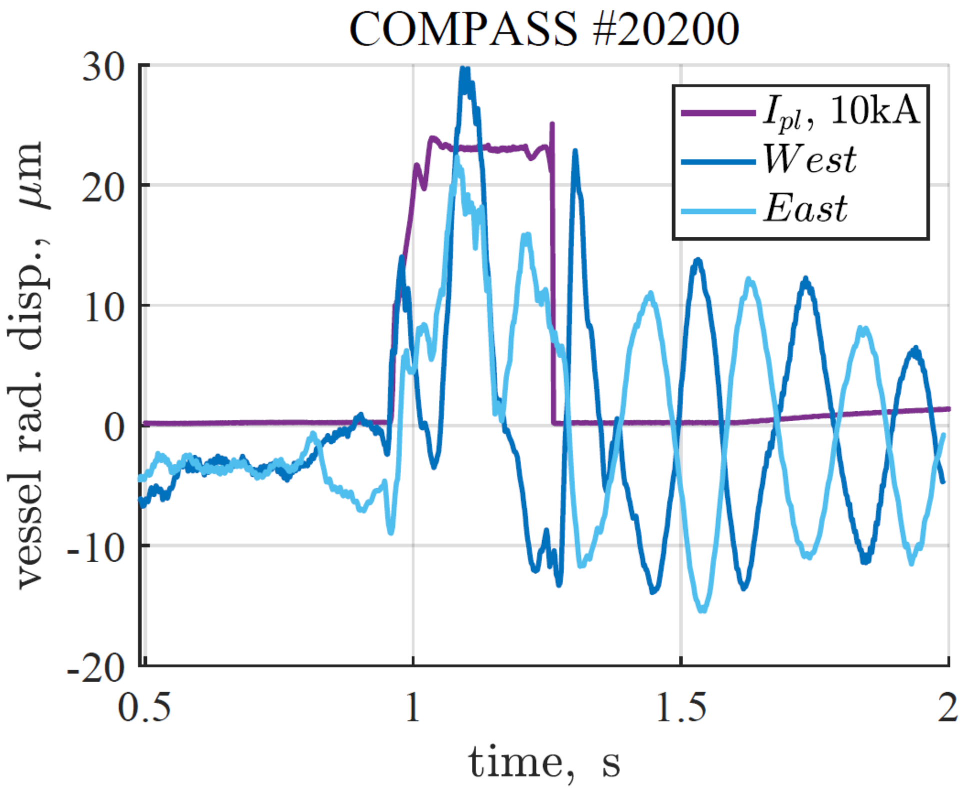
Radial force on vacuum vessel

- In contrast to the sideways force case, the theory for radial force on vessel during TQ/CQ is firmly established*.
- Therefore, the radial force and related vessel motion can serve for benchmarking of the modelling and measurements (to prepare us for sideways force hunting).
- Procedure (work in progress):



*Pustovitov, V. D. "Disruption forces on the tokamak wall with and without poloidal currents." Plasma Physics and Controlled Fusion 59.5 (2017): 055008.
**Isernia, N., Pustovitov, V. D., Villone, F., & Yanovskiy, V. (2019). Cross-validation of analytical models for computation of disruption forces in tokamaks. Plasma Physics and Controlled Fusion, 61(11), 115003.

Results obtained with displacement sensors - COMPASS



- 2 displacement sensors (MicroMeasurements HS-A10/25, lent from JET) have been installed in opposite locations (East-West) to complement measurements with MEMS accelerometers.
- Currently we are trying to estimate the mass involved in the sideways movement: only VV or VV + support structure?

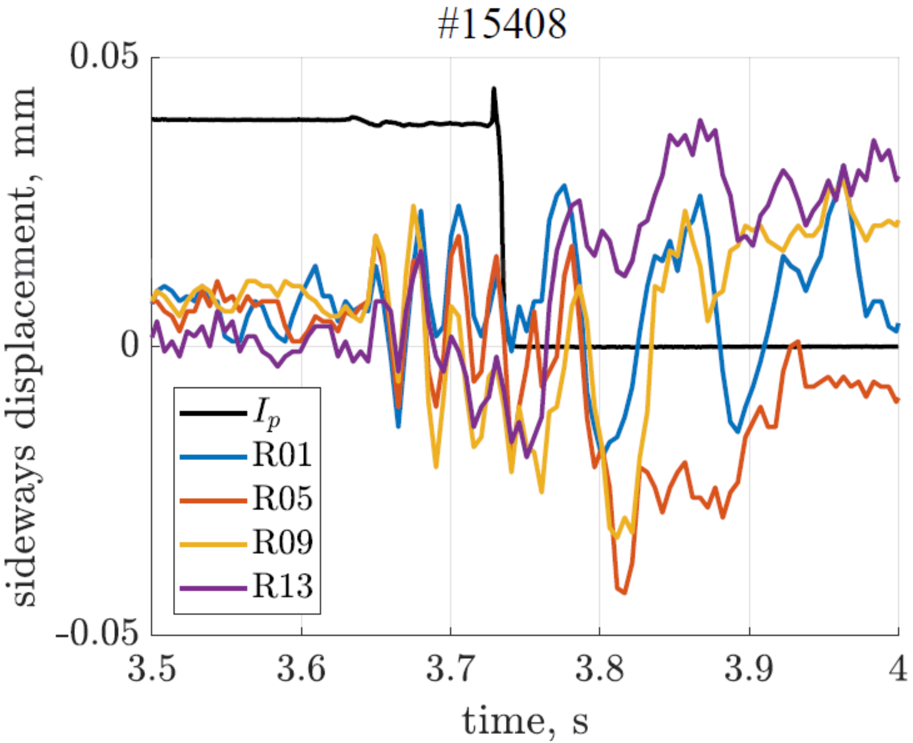
Results obtained with displacement sensors - AUG

AUG: Present instrumentation

- 4 displacement sensors at 4 orthogonal positions
- Plasma asymmetries (1.8%) are much smaller than on JET (10%)*

AUG: shot #15408

- Radial oscillations caused by TQ overlap with sideways vessel motion after CQ.
- Electromechanical modelling can help to interpret results.



* Pautasso, G., et al. "The halo current in ASDEX Upgrade." Nuclear Fusion 51.4 (2011): 043010.

Summary

- JT-60SA may provide key data for understanding of sideways forces.
- Electromechanical modelling is necessary to find the optimal solution for instrumentation (accelerometers, displacement sensors, etc.)
- More measurements and modelling of radial/sideways forces on AUG, COMPASS, DIII-D, JET and TCV can provide some insight for the best choice of instrumentation for JT-60SA.
- Experimental and modelling results can be cross-validated for radial forces (which are understood much better than sideways forces).