EFDA–JET–CP(10)07/20

C. Bachmann, M. Sugihara, R. Roccella, G. Sannazzaro, Y. Gribov, V. Riccardo,
T.C. Hender, S.N. Gerasimov, G. Pautasso, A. Belov, E. Lamzin, M. Roccella
and JET EFDA contributors

Specification of Asymmetric VDE Loads of the ITER Tokamak

Specification of Asymmetric VDE Loads of the ITER Tokamak

C. Bachmann[1], M. Sugihara[1], R. Roccella[1], G. Sannazzaro[1], Y. Gribov[1], V. Riccardo[2],
T.C. Hender[2], S.N. Gerasimov[2], G. Pautasso[3], A. Belov[4], E. Lamzin[4], M. Roccella[5]
and JET EFDA contributors*

JET-EFDA, Culham Science Centre, OX14 3DB, Abingdon, UK

1ITER Organization CS90 046, 13067 St. Paul lez Durance, Cedex, France
[2]EURATOM-CCFE Fusion Association, Culham Science Centre, OX14 3DB, Abingdon, OXON, UK
[3]Max Planck Institute for Plasma Physics, D-85748 Garching, Germany
[4]D.V. Efremov Institute, Scientific Technical Centre 'Sintez'
[5]L. T. Calcoli, 23087 Merate (Lecco), Italy
** See annex of F. Romanelli et al, "Overview of JET Results",*
(Proc. 22nd IAEA Fusion Energy Conference, Geneva, Switzerland (2008)).

Preprint of Paper to be submitted for publication in Proceedings of the
26th Symposium on Fusion Technology (SOFT), Porto, Portugal
27th September 2010 - 1st October 2010

ABSTRACT.

During Asymmetric Vertical Displacement Events (AVDEs) associated with the kink mode of the plasma two asymmetry phenomena were observed in existing tokamaks, in particular in JET [1]. The related halo currents flowing in the passive structure were identified as the cause of asymmetric EM loads on tokamak components. The first phenomenon is a toroidal peak of the poloidal halo current that flows in the passive structure. The second phenomenon is that the toroidal plasma current is not uniform toroidally, so a toroidally non-uniform current flows in the vessel [2]. The specification of the expected characteristics of both phenomena as well as of the consequent asymmetric loads in ITER are summarized here. The related loads are specified for likely, unlikely and extremely unlikely AVDEs.

1. INTRODUCTION

Plasma vertical displacement events (VDEs) and especially slow asymmetric VDEs cause the largest deformations of the tokamak components associated with severe stress states as well as the highest reaction forces on most tokamak supporting structures. These loads are therefore design drivers for most tokamak components. The aim of this article is to present how the specification of the net loads due to slow AVDEs was derived.

In a three-step approach first in section II an overview over the experimental data on plasma asymmetries from existing machines is given and the extrapolation to ITER is made. Second in section III the consequent ElectroMagnetic (EM) loads are calculated based on the sink and source model proposed in [2]. And third in section IV the asymmetric loads are specified aiming at a simple and conservative load specification.

2. OBSERVED PLASMA ASYMMETRIES

2. KINK MODE

Data from all existing tokamaks show toroidal asymmetry of poloidal halo current, see Figure 4. It is considered that this asymmetry is generated by the plasma deformation associated with the kink mode. Depending on the machines and discharge conditions different mode numbers of the kink were observed. In some cases the dominant mode number of the kink was m = 1, n = 1, which correlates with the largest asymmetric loads. A second observation related to kinked plasmas is the toroidal asymmetry of the plasma current Ip, which was observed in some machines, notably JET. The difference between maximum and minimum plasma current is defined as dIp. It is speculated that this asymmetry must be associated with an exchange of toroidal current between the vessel and the plasma when the plasma touches the wall. In fact an empirical model with such an exchange has been developed, which fits the JET experiments consistently (sink and source model [2]). Recently a clear correlation between dI_p and the asymmetry of the poloidal halo current has been found [3], [4], which suggests a common mechanism behind the two phenomena. It is recognized that for a more accurate and machine-specific load prediction an appropriate wall model linked to the kink mode evolution is needed [5].

2.2. POLOIDAL HALO CURRENT

It is a well known phenomenon that part of the plasma poloidal halo current flows in the passive structure when the halo region touches the first wall during a VDE [6]. The halo current in the passive structure (here: I_{halo}) causes an equal and opposite vertical load on the vessel and the Poloidal magnetic Field (PF) coils due to the coupling with the Toroidal magnetic Field (TF). At the same time the plasma - although vertically displaced - is in a force-free state.

I_{halo} was observed in all existing tokamaks during VDEs causing Vertical loads on the Vessel (VV) and the TF coils, often with a toroidally non-uniform magnitude and hence additionally causing a tilting moment. This non-uniformity is described through the Toroidal Peaking Factor (TPF), see Figure 4 and Figure 5.

2.3. TOROIDAL CURRENT ASYMMETRY

2.3.1. Description

One possible physics mechanism of the occurrence of the asymmetric plasma current is the exchange of part of the toroidal plasma current between the plasma and the vessel in the toroidal direction. It is assumed that the current exchange varies sinusoidally in the toroidal direction from a source on one side of the vessel to a sink on the opposite side. In this case it is expected that associated with this loss and gain of plasma current, a net vertical and radial current path would be generated inside the plasma column, which could provide the force balance to the kinked plasma. The current exchange must take place in the halo wetted regions of the first wall, the local current pattern of the exchange currents is however not well understood. Large sideways forces and tilting moments occur as dIp spreads in the vessel and develops a poloidal component crossing the toroidal field. Since the spread takes place with the toroidal and poloidal time constant of the vessel, asymmetric loads due to dI_p have an exponential time variation.

2.3.2. Observation

The amplitude of the asymmetry current dI_p was derived from the measured plasma toroidal current $I_p(\varphi)$, which varies at different toroidal locations φ, [1,2,3,4,5]. From that observation the sink and source model is derived in [1].

In JET experimental data on dI_p was recorded for a large number of AVDEs including recent data obtained at four toroidal locations, [5]. Since also the most distinct plasma asymmetries have been observed in JET the specification of dI_p for ITER is based on JET data.

2.3.3. Scaling of JET Data to ITER

The asymmetry current dI_p (normalized by I_p before disruption) fluctuates significantly in time. However, the details of the fluctuations are not important for the EM load analysis and instead the time integration of dI_p/I_p is calculated for all JET data, see paragraph IV.B. The most severe dI_p data observed at JET can be approximately enveloped by $dI_p/I_p = 0.1$ as shown in Figure 1. Given the empirical link between poloidal halo current and dI_p in JET, the dI_p envelope in ASDEX Upgrade can be inferred from poloidal halo data – initial results seem consistent with JET. Since the current quench time is machine dependent tdIp, the duration of dI_p, needs to be scaled to ITER. Given similar plasma shape, plasma profiles, mode structure and mode-wall interaction in JET and ITER this is done based on the plasma cross sectional area (as a rough measure of the plasma L/R time, [1]) whose ratio between ITER and JET is 4.73. Conservatively an uncertainty factor of 1.2 was applied, hence a scaling factor of 5.64 was used to scale tdIp.

3. EM ANALYSIS OF ASYMMETRY CURRENT LOADS

3.1. ANALYSIS APPROACH

The Finite Element (FE) method was used to perform the EM analyses. Several steady-state EM analyses using a simple FE model including no other tokamak components but the vessel were performed at the Efremov Institute. The results of these analyses were used to identify the poloidal location of the current exchange PS+S which leads to the most severe asymmetric loads. The Efremov calculations [8] also served as an independent verification of the results obtained by the final assessment performed by LT Calcoli, which was performed on a FE model including all main tokamak components (each PF and Central Solenoid (CS) coil, the TF coil system, the VV, and the shielding components, i.e. blanket and divertor). It included two transient EM analyses, simulating an upward and a downward AVDE. The plasma was modeled in a simplified form as a single toroidal filament adjacent to P_{S+S} carrying only the asymmetric part of the plasma current dI_p.

dI_p was imposed to be exchanged between vessel and plasma with a sinusoidal distribution, the toroidal current variation in the plasma having opposite sign compared to that in the vessel. As a consequence the sum of all toroidal currents in the FE model was zero at any location φ. The transient analysis was performed over a duration of 2000ms. dI_p was in principle applied as a step function with an almost instant increase and decrease (within 10ms). Note: The duration of the dIp step function in the EM analyses is much larger compared to the specification, see Table 1. Validity and use of the EM analysis results are however not affected by this inconsistency.

On VV and shielding components sideways forces and tilting moments occur due to the TF in the horizontal direction (Fy, Mx), and due to the PF in the perpendicular horizontal direction (Fx, My), see Figure 3. Consequently opposite asymmetric loads occur on the TF coils and on the PF/CS coils respectively. Although the real plasma must be force-free, due to the simplified modeling of the plasma relatively small loads are found in the EM analysis to act on the plasma. The consequent imbalance of the loads on VV and shielding components compared to those on the magnet system is <10% (due to the TF) and < 30% (due to the PF), which is considered an acceptable error of the EM analysis. Note: The error in the load calculation due to the PF was assessed only in the steady-state case.

3.2. RESULTS

Time functions of sideways forces Fx and Fy and tilting moments My and Mx were calculated for each tokamak component. For simplification the time functions of the loads due to the PF were calculated only for the coils, whereas the corresponding loads on the passive structure are assumed to be equal opposite, see Figure 2. As an example the figure below shows the sideways forces in the case of an upward AVDE.

4. SPECIFICATION OF ASYMMETRIC VDE NET LOADS

4.1. DEFINITIONS

The positive directions of the specified sideways forces and tilting moments due to the TF are defined as shown in Figure 3, which also shows the poloidal path of dIp in the vessel, the consequent pressure loads, and the subsequent forces and moments on the VV:

4.2. VDE SEVERITY

In ITER slow VDEs are classified into three categories II, III, and IV of load severity according to their predicted frequency of occurrence: likely, unlikely, and extremely unlikely. The load severity of slow VDEs is defined as the product of the symmetric and the asymmetric halo currents, hence a VDE that causes relatively large asymmetric halo currents causes relatively small symmetric halo currents I_{halo}. Consequently the severity of I_{halo} is specified as the product of its symmetric part, which causes vertical load and its asymmetry factor, the TPF. The worst ever recorded severity on existing machines is specified as the severity of category III and IV VDEs:

$$\mathrm{TPF} \cdot I_{halo}/I_p = 0.75 \tag{1}$$

Additionally, the maximum worst case value of I_{halo}/I_p is specified 8% larger than the largest ever recorded value. As a consequence the largest magnitude of Ihalo specified for ITER is 8.1MA (category III).

The structural integrity of the tokamak components is affected mainly by the magnitude and the duration of dI_p. Hence the severity of dI_p is specified as the integral of dI_p over time normalized to the plasma current I_p:

$$\frac{1}{I_p}\int dI_p\,(t)\,dt \cdot dI_p\,(t) \text{ is specified as a step function.}$$

4.3. LOADS DUE TO THE TPF OF THE POLOIDAL HALO CURRENT

The TPF of the poloidal halo current causes a non uniform vertical force, which causes effectively a (symmetric) vertical force, $F_{vert,halo}$, and an (asymmetric) tilting moment, $M_{tilt,TPF}$. No sideways force is specified to occur due to the TPF. The tilting moment $M_{tilt,TPF}$ is specified to act entirely on the vessel and the TF coil system, not on other tokamak components.

For the calculation of $M_{tilt,TPF}$ the function of the vertical force along the toroidal coordinate φ, $F_{vert}(\varphi)$, and its average radial coordinate RF_vert are required. Whereas $F_{vert}(\varphi)$ is assumed to have a sinusoidal distribution for $1.39 \leq \mathrm{TPF} \leq 2$, for $\mathrm{TPF} = 2.78$ ($= 2 \cdot 1.39$) the distribution was chosen somewhat arbitrarily, see Figure 5. No other values for TPF are considered in ITER. As value of

RF_vert the approximate radial position of the plasma centre during the VDE as predicted by the DINA plasma simulation was chosen: 5.4 m (downward VDE), 5.1 m (upward VDE). $M_{tilt,TPF}$ is calculated as:

$$M_{tilt,\,TPF} = \begin{cases} \dfrac{F_{vert,\,halo}(t)}{2} \cdot R_{F\_vert} \cdot (TPF(t)-1), & 1.39 \le TPF \le 2 \\ F_{vert,\,halo} \cdot R_{F\_vert} \cdot 0.1604, & TPF = 2.78 \end{cases} \tag{2}$$

The time function $F_{vert,halo}(t)$ is the total vertical force due to halo current as calculated by the DINA plasma simulation code. The time function TPF(t) peaks at the specified TPF value and has the same shape as $F_{vert,halo}(t)$.

4.4. LOADS DUE TO DIP ASYMMETRY

Sideways force and a tilting moment are specified for each tokamak component. The sideways forces on the TF coil system, the blanket system and the VV are specified to act at the vertical locations −2.2m/3.5m (downward / upward VDE) in the ITER tokamak coordinate system. The sideways forces on the PF and CS coils are specified to act at their respective elevation. For each tokamak component the time functions of the sideways force Fside(t) and the tilting moment Mtilt(t) are specified as in eq. (3) and (4) but with individual magnitudes Fside,steadyState and Mtilt,steadyState:

$$F_{side}(t) = \begin{cases} 1.2 \cdot F_{side,\,steady\,State} \cdot \left(1 - 0.5 \cdot e^{-\frac{t}{110ms}}\right), & for\, t \le t_{dIp} \\ F_{side}(t_{dIp}) \cdot e^{-\frac{t-t_{dIp}}{400ms}} & for\, t > t_{dIp} \end{cases} \tag{3}$$

$$M_{tilt}(t) = \begin{cases} 1.2 \cdot M_{tilt,\,steady\,State} \cdot \left(1 - 0.7 \cdot e^{-\frac{t}{110ms}}\right), & for\, t \le t_{dIp} \\ M_{tilt}(t_{dIp}) \cdot e^{-\frac{t-t_{dIp}}{400ms}} & for\, t > t_{dIp} \end{cases} \tag{4}$$

where t_{dIp} is the duration of dI_p.

The individual magnitudes were chosen for each component based on the steady-state magnitudes as well as the shape of the individual time function calculated in the EM analyses and with the aim to preserve the force balance within the tokamak:

$$F_{VDE,\,y,\,VV\,+\,shielding} = -F_{VDE,\,y,\,TFCoils}$$

$$F_{VDE,\,y,\,VV\,+\,shielding} = -(F_{VDE,\,y,\,TFCoils} + F_{VDE,\,x,\,CSCoils})$$

where $F_{VDE,x}$ represents $F_{side,x}$ or $M_{tilt,y}$ and $F_{VDE,y}$ represents $F_{side,y}$ or $M_{tilt,x}$.

Note: Although the specification of the magnitudes $F_{side,steadyState}$ and $M_{tilt,steadyState}$ meets the force balance above, a small tilting moment un-balance occurs due to the different time constants of $F_{side}(t)$ and $M_{tilt}(t)$, see eq. (3) and (4). This un-balance is considered negligible in the structural and dynamic assessment of the tokamak.

4.5. COMBINATION OF ASYMMETRIC LOADS DUE TO TPF AND DIP

Since the asymmetric net loads discussed in this article are presumed to be due to halo currents, their time functions are synchronized with $F_{vert,halo}(t)$, which is predicted by the DINA plasma simulation code. AVDEs with distinct plasma asymmetries are specified to cause the maximum dIp (10% I_p) as well as a large TPF of 2.78, whereas the associated symmetric halo current Ihalo is smaller compared to a symmetric VDE, see also eq. (1).

The investigation of AVDEs is still evolving, and thus the views and specifications expressed herein may be subject to further revision. The views and opinions expressed herein do not necessarily reflect those of the ITER Organization.

ACKNOWLEDGEMENT

The work that is summarized in this article was partly performed in collaboration with EFDA.

REFERENCES

[1]. P. Noll, et al, in Proceedings of the 19th Symposium on Fusion Technology, Lisbon, 1996 , Vol. 1, p. 751
[2]. V. Riccardo, P. Noll, S.P. Walker: Forces between plasma, vessel and TF coils during AVDEs at JET, IAEA, 2000
[3]. V. Riccardo et al., Nuclear Fusion **49** (2009) 055012.
[4]. V. Riccardo et al, 'JET disruption studies in support of ITER', sub to Plasma Physics and Controlled Fusion (2010)
[5]. S. N. Gerasimaov et al: Scaling JET Disruption Sideways Forces to ITER (EPS 37th Conference on Plasma Physics 2010)
[6]. T. Hender et al., Nuclear Fusion **47** (2007) S128.
[7]. ITER Physics Basis 1999 Nuclear Fusion **39** 2137
[8]. Efremov Institute, "Final Report on Asymmetric Forces during Upward VDE with rot. freq. 0 Hz", ITER document: ITER_D_2FP9F5

Category	TPF·I_{halo}/I_p	I_{halo}	TPF	Severity of dI_p	dI_p / I_p	Duration of dI_p: t_{dIp}
II	0.42	4.5 MA	1.39	4 ms	5%	80 ms
		3.2 MA	2.0	5.8 ms	7.2%	80 ms
		2.3 MA	2.78	8 ms	5%	160 ms
		2.3 MA	2.78	8 ms	7.2%	114 ms
		2.3 MA	2.78	8 ms	10%	80 ms
III	0.75	8.1 MA	1.39	10 ms	5%	200 ms
		5.6 MA	2.0	13 ms	7.2%	175 ms
		4.1 MA	2.78	21 ms	10%	210 ms
		4.1 MA	2.78	21 ms	6.1%	338 ms
IV	0.75	8.1 MA	1.39	15 ms	5%	300 ms
		5.6 MA	2.0	22 ms	7.2%	300 ms
		4.1 MA	2.78	30 ms	10%	300 ms

Table 1: Specified combination of poloidal halo current and toroidal current asymmetry in the different load categories.

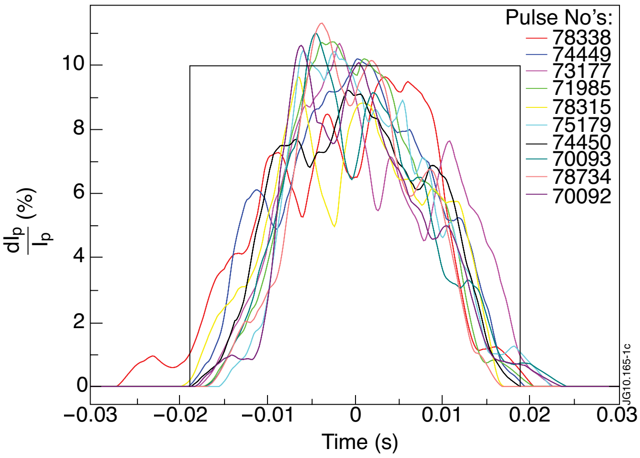

Figure 1: Magnitude of dI_p with respect to initial plasma current (smoothed over ±2ms) during the disruptions of the 10 JET shots with the maximum $\int dI_p$ dt out of all JET shots with measurements in 4 octants (best quality data) and envelop step function, on the right: JET pulse numbers.

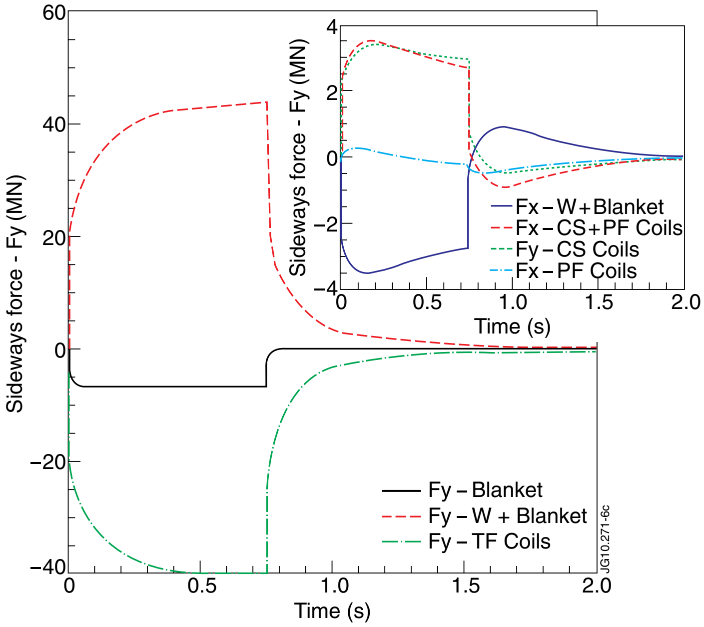

Figure 2: Sideways forces on the tokamak components calculated in the FE analysis of the upward AVDE, note: "Fx - VV+Blanket" is predicted as -"Fx - CS+PF coils".

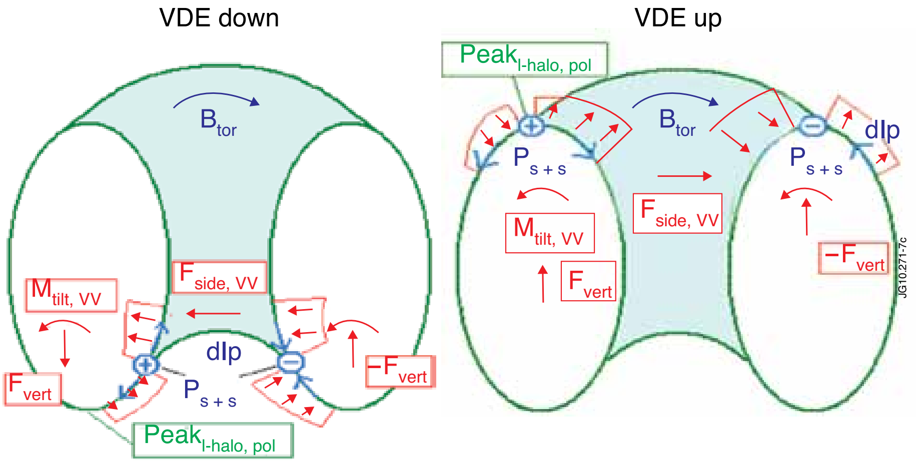

Figure 3: Defined positive directions of $F_{side,dIp}$ and $M_{tilt,dIp}$ due to the toroidal field, real occurring directions (on vessel) and corresponding location of the peak of the poloidal halo current.

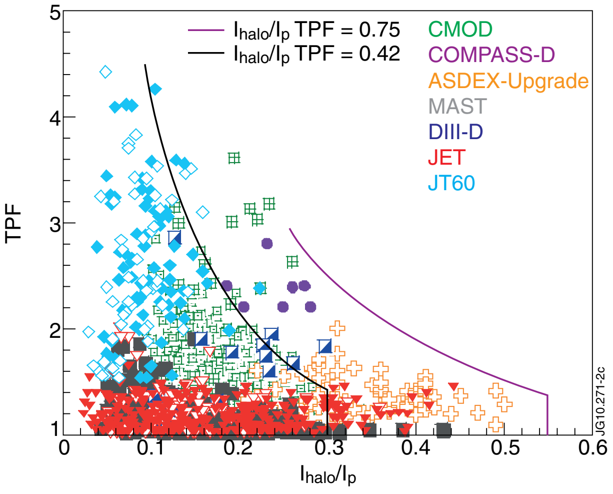

Figure 4: Experimental data from different tokamak machines on the relationship of I_{halo}/I_p with the TPF, [6].

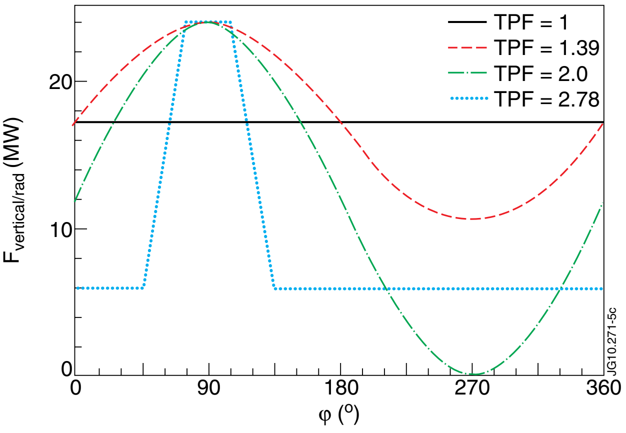

Figure 5: $F_{vert}(\varphi)$ depending on TPF, here $F_{vert,halo}$ = 108 MN for TPF = 1.