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Initial definition of structural load conditions in DEMO

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An essential goal of the EU fusion roadmap is the development of design and technology of a Demonstration Fusion Power Reactor (DEMO) to follow ITER. A pragmatic approach is advocated considering a pulsed tokamak based on mature technologies and reliable regimes of operation, extrapolated as far as possible from the ITER experience. The EUROfusion Power Plant Physics and Technology Department (PPPT) started the conceptual design of DEMO in 2014.

This article describes the most important load combinations that have to be considered in the design of the DEMO systems including their categorization into four classes based on the expected frequency of occurrence. Furthermore, with exception of heat loads from plasma particles and radiation to the plasma facing components, the most important load cases are described and quantified. These include (i) electromagnetic (EM) loads due to toroidal field coil fast discharge, (ii) EM loads in fast and slow plasma disruptions due to eddy and halo currents, (iii) seismic loads, and (vi) pressure loads in the dominant incident/accident events.

Keywords: DEMO, tokamak, load, electromagnetic, disruptions

1. Introduction

1.1 DEMO parameters

The main parameters of the DEMO tokamak machine are listed in Table 1. Their definition is described in [1].

Major radius, R	9.07 m
Minor radius, a	2.93 m
Plasma current, I_p	19.6 MA
Plasma cross section, A_p	44.8 m²
Vacuum toroidal field at R, B_0	5.667 T
Number of TF coils	18
Total current in single TF coil	14.28 MA

Table 1 Parameters of the DEMO tokamak

1.2 Load cases abbreviations

MFD: Magnet fast discharge
MD: Major (or central) disruption
VDE: Vertical displacement event
In-vessel LOCA: In-vessel loss of coolant event
Cr ICE: Cryostat ingress of coolant event
Ex-vessel LOCA: Loss of coolant event outside the vacuum vessel
LOCA NB: Loss of coolant event in NB cell
VV LOVA: Loss of vacuum event in plasma chamber
Cr LOVA: Loss of vacuum event in cryostat
LOOP: Loss of offsite power
LOSP: Loss of site power (incl. emergency generators)

2. Load Categories and Damage Limits

2.1 Load Categories

Based on the definitions in ASME III, Div. 1, subsection NB-3113 four categories of load conditions are defined in DEMO. The indicated frequencies of occurrence associated to categories II and III are based on the IAEA definitions [2]:

Cat I includes *operational* loading conditions, i.e. conditions intentionally triggered by the plant operator.

Cat II includes *expected* loading conditions, i.e. conditions that are expected to occur in the life of the plant up to about 100 times.

Cat III includes *possible* loading conditions, i.e. conditions that are expected to occur less than about once during the plant life.

Cat IV are *unlikely* loading conditions, i.e. conditions with an expected frequency of occurrence of less than once every 10,000 years.

2.2 Damage Limits

A structural design code must be selected for the design of each DEMO component. Design codes define different *criteria levels* each aiming at preventing specific structural damages of a component. Based on ASME Sec. III NCA-2142.4 the following damage limits are defined:

- Level A and B: No damage requiring repair occurs. The plant shall be able to resume operation without special maintenance or test.
- Level C: Large (plastic and hence permanent) deformations permitted in areas of structural discontinuity. Shutdown for component inspection and repair may be required before proceeding operation.
- Level D: Gross general (plastic and hence permanent) deformations permitted including some loss of dimensional stability, e.g. local buckling. Component repair or replacement may be required.

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The general approach applied in DEMO regarding the association of loading conditions to damage criteria is as follows:

- Cat I loading condition → damage criteria level A
- Cat II loading condition → damage criteria level A
- Cat III loading condition → damage criteria level C
- Cat IV loading condition → damage criteria level D

Based on specific requirements of a component regarding safety or investment protection a modified approach can be adopted.

3. Single load events

3.1 Magnet fast discharge

A magnet abnormal condition or fault will induce a quench that will actuate a fast discharge of the huge coils' magnetic energy into resistors. The fast discharge of the PF and CS coils (MFD I) is not considered in this article since the effect on the DEMO structures of the fast discharge of all coils (MFD II) is typically more severe.

3.2 Plasma disruptions

Main parameters: Plasma disruptions can cause a variety of electrical currents flowing in the tokamak components during the disruption. Electromagnetic (EM) forces are generated as these currents cross the magnetic field. Three phenomena occur during disruptions: (i) During a rapid *thermal quench* the plasma current profile flattens causing an increase of the plasma toroidal current (by ~5-10%) and also affecting the poloidal plasma current. The change of plasma current induces (eddy) currents in the surrounding passive structures. (ii) During the *current quench* the plasma current decays inducing currents in the passive structures. In this phase the plasma may move vertically. A disruption is referred to as MD if the thermal quench occurs before plasma vertical control is lost. During an MD the plasma vertical movement is moderate and generates significant eddy currents only locally. If instead initially the plasma vertical control is lost and the thermal quench occurs during plasma vertical movement the event is considered a VDE. The plasma vertical movement in a VDE is significant, see Figure 2. (iii) In the later phase of a disruption the plasma will usually be in contact with the wall. In this phase currents flowing in the outer (halo) region of the plasma partly exit and re-enter the plasma running through the passive structure. These currents are referred to as halo currents, I_{halo}. In particular in slow VDEs, i.e. VDEs with a low plasma current decay rate, halo currents can be significant.

In DEMO eddy currents are typically design drivers of the in-vessel components (IVCs) and port plug components. Halo currents are typically design drivers of the IVCs, the vacuum vessel (VV), and the magnet system.

Parameter scaling: The initial specification of these parameters, see Table 1 is based on the ITER specification, [3]. The thermal quench time was scaled as suggested in [4] with the plasma minor radius (2.93m/2m). The minimum current quench time was scaled as suggested in [4] with the plasma cross-sectional area (44.8m²/22m²). Given the early phase of the DEMO development for simplification no exponential but only linear current quench profiles need to be considered in the design development. Halo currents were often observed with a toroidally non-uniform magnitude. Toroidal peaking of I_{halo} affects in particular the design of the toroidally discrete IVCs. The toroidal non-uniformity is described through the toroidal peaking factor (TPF) that is considered in the definition of the halo current severity: $TPF \cdot I_{halo}/I_p$.

For a large number of disruption cases observed in existing tokamaks the halo current severity has been collected, Figure 1. In ITER, based on the definition of 300 expected VDEs, probabilistic assessments have led to the definition of the halo current severity of Cat II VDEs to be $TPF \cdot I_{halo}/I_p = 0.42$. In DEMO, initially, the same halo current severity of Cat II VDEs is defined. In addition the following halo current scaling is applied in DEMO based on ITER: In fast VDEs the halo current limit is reduced to 60% of that in slow VDEs. For upward VDEs the halo current limit is reduced to 80% of that in downward VDEs. An overview over the main parameters of different types of disruptions is provided in Table 2.

Disruption mitigation: To reduce the number of disruptions to be considered in the design a disruption mitigation system is considered in DEMO. At this point this is assumed to mitigate *most* disruptions and in addition to limit the severity of the structural loads of *all* slow VDEs to the severity defined for Cat II events. The latter is a working assumption that will require validation before the conclusion of the DEMO licensing process. The time scale to detect such slow VDEs is an order of magnitude longer in slow VDEs compared to fast disruptions (in DEMO >100ms based on [5]); hence a reliable detection is considered technically feasible, e.g. by installing independent and hence redundant detection systems. High reliability of the mitigation system itself might also be achieved installing different types of mitigation systems, e.g. a massive gas injection system (MGI). MGI is reported to inject within 10 ms reducing halo current magnitude by at least 50% and the TPF to unity [6].

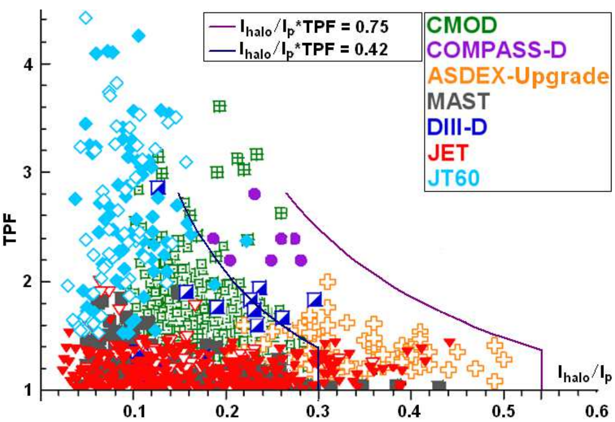

Figure 1 Experimental data from different tokamak machines on the relationship of I_{halo}/I_p with the TPF, [6]. Event data

points below the blue line are considered for the definition of the category II load severity

Hence in DEMO no Cat III slow VDEs are specified. The *unlikely* event of an unsuccessful disruption mitigation of a slow VDE is considered through the definition of Cat IV VDEs with a severity of $TPF \cdot I_{halo}/I_p = 0.75$. This is consistent with the ITER specification [3] and envelops the most severe VDEs in the ITER physics basis database, [6].

	t_{TQ}	t_{CQ}	I_{halo} (360°)	peak I_{halo} (ψ =6.7°)	$TPF \cdot \frac{I_{halo}}{I_p}$
Unit	[ms]	[ms]	[MA]	[kA]	
MDI	4.4	97	2.12	54	0.15
MDII	1.5	70	2.12	54	0.15
MDIII	0.7	70	2.12	54	0.15
MDIV	0.7	51	2.12	54	0.15
VDEII fast up	1.5	70	2.74	73	0.202
VDEII fast down	1.5	70	3.43	91	0.252
VDEII slow up	1.5	70	4.57	122	0.336
VDEII slow down	1.5	70	5.71	152	0.42
VDEIII fast up	0.7	70	5.08	131	0.36
VDEIII fast down	0.7	70	6.35	163	0.45
VDEIII slow up	n/a				
VDEIII slow down	n/a				
VDEIV fast up	0.7	51	5.08	131	0.36
VDEIV fast down	0.7	51	6.35	163	0.45
VDEIV slow up	0.7	51	8.46	218	0.60
VDEIV slow down	0.7	51	10.58	272	0.75

Table 2 Specified minima of thermal and current quench time (t_{TQ} and t_{CQ}) and specified halo current maxima

Halo currents in IVCs: The magnitude of the halo current in an individual IVC is an important design parameter for the IVC structure, its supports and its electrical connection to the VV. Based on DEMO plasma disruption simulations for a moderately slow current quench time of 200 ms carried out with an evolutionary equilibrium code [7], see Figure 2, the fraction of the halo current defined in Table 2 as "peak I_{halo}" entering IVCs is given in Table 3. It is worth noting that unlike in ITER the main halo current source and sink are on different poloidal locations of the outboard blanket, hence in these particular events the major part of the halo current will flow within the outboard blanket and not enter into the VV. This peculiarity is probably due to the specific pre-disruption magnetic flux map and to the excitation used to trigger the VDE (voltage kick in one of the PF coils). In order to consider reasonable deviations from the plasma trajectories found in these simulations some fraction of the halo current is specified to enter also the inboard IVCs.

Component	Toroidal extent, ψ	VDE up	VDE down	VDEII slow down
Vacuum vessel	360°	30%	20%	1.2 MA
Inboard blanket	10°	30%	20%	46 kA
Outboard blanket	6.7°	100%	100%	152 kA
Div. outer target	6.7°	0%	30%	46 kA
Div. inner target	6.7°	0%	10%	15 kA

Table 3 Fraction of total halo current defined in Table 2 entering/exiting the component and absolute magnitudes during VDEII slow down

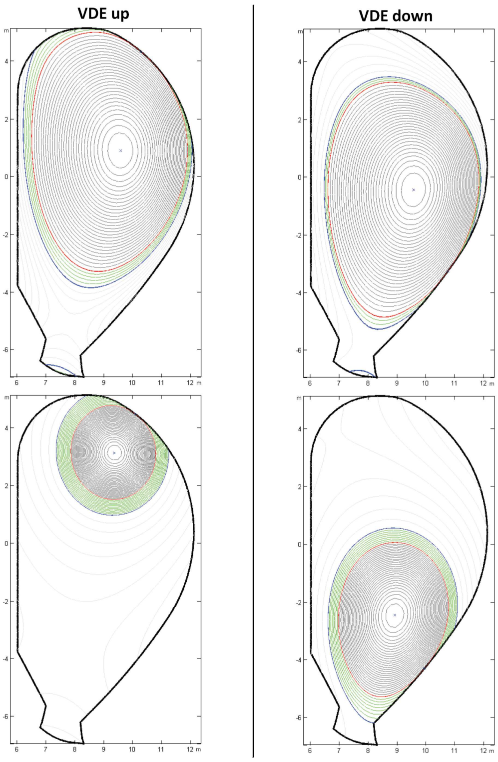

Figure 2 Plasma boundary at specific instants during upward and downward VDEs with t_{CQ} = 200ms, (halo region indicated in green)

3.3 Seismic loads

The DEMO site not being identified, initially the ITER seismic loads [3], [8] are defined for DEMO. Three levels of ground motion are considered for housing safety critical equipment (SL-2, SMHV, and SL-1). A SL-2 is a category IV event and corresponds to the seismic level required by French nuclear practice [8]. The DEMO SL-2 soil response spectra are shown in Figure 3 and are based on those defined for the ITER buildings on the Cadarache site (rock soil) [9]. A SMHV (Maximum Historically Probable Earthquake) is a Cat III event and is the most penalizing earthquake liable to occur over a period of about 1000 years. The accelerations of a SMHV are roughly half of the SL-2 values for frequencies up to 0.4Hz and ~70% of the SL-2 values for frequencies above 2Hz. A SL-1 is a category II event with a probability of occurrence in the order of 10^{-2} per year and represents an investment protection earthquake level. The accelerations in the SL-1 spectra are ¼ of those in the SL-2, however smaller damping need to be considered. To avoid performing specific analyses for SL-1 and SMHV the results obtained in the SL-2 analysis can be multiplied by 0.34 and 0.73, respectively [10].
The floor response spectra at the *basemats* of nuclear buildings shall be defined assuming the buildings to sit on ITER-like seismic isolation pads. Seismic loads on other buildings are defined in Eurocode 8 [11].

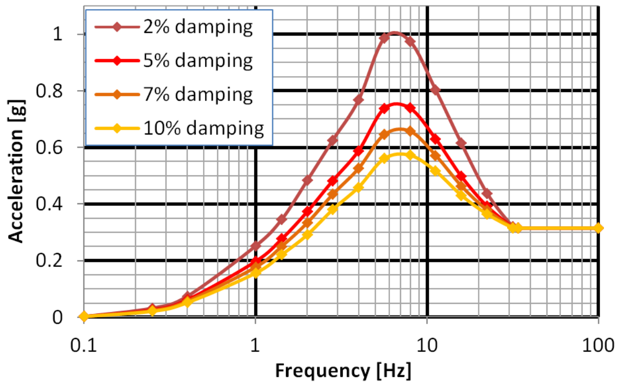

Figure 3 DEMO horizontal ground design response spectrum for SL-2 for different damping values; vertical design soil spectra are equal to 2/3 of the horizontal ones.

3.4 Pressures loads and leak incidents/accidents

During plasma operation all zones of the tokamak building outside the cryostat are at atmospheric pressure (~95 kPa). All zones inside the cryostat, the plasma chamber, and the vacuum vessel pressure suppression system (VVPSS) are at vacuum pressure (0 kPa). The transient conditions during incidents/accidents events involving leaks are assessed and defined through accident analyses that have so far not been concluded. The extreme pressures listed in Table 4 are preliminary recommendations to guide the design progress and based on the ITER specifications [3] and the following assumptions:

In-vessel LOCA: Initiating events of an in-vessel LOCA are breaks of plasma-facing components cooling channels or – with lower frequency - breaks of IVC cooling pipes. The coolant discharging into the plasma chamber causes the plasma to disrupt very quickly, hence the triggering of a disruption is considered. VV LOVA events are considered enveloped by in-vessel LOCA events assuming similar transients as in ITER, [10].

Cr ICE: The cryostat vacuum may be lost due to air ingress (Cr LOVA), a helium-, or cooling water leak. In case of Helium ingress the Helium remains in gaseous state causing conduction heat transfer between the cryostat (20°C) and the magnets (4K), hence the triggering of a magnet fast discharge is considered when the leak is significant. Cr LOVA events are considered enveloped by Cr ICE event assuming similar transients as in ITER, [10].

Event	Abs. pres.	Zone
In-vessel LOCA	~1 bar	Plasma chamber
In-vessel LOCA	> 1 bar, tbd	Plasma chamber + VVPSS
In-vessel LOCA	> 1 bar, tbd	Plasma chamber + VVPSS
Cr ICE II	~30 kPa	Cryostat
Cr ICE III	~ 1 bar	Cryostat
Cr ICE IV	tbd	Cryostat
LOCA NB III	~1.6 bar, [10]	NB cell
Ex-vessel LOCA III	tbd	Parts of tokamak building including port cells

Table 4 Overview over leak incidents/accidents and recommendations for associated design pressure values

2. Load combinations and classification

The load combinations to be considered in the design of the tokamak components and the equipment inside the nuclear buildings during plasma operation are listed in Table 5. All of these load combinations include the operational loads that are present at the time the event combination occurs, e.g. dead weight, coolant or vacuum pressure, thermal loads, etc.

Cat.	Initiating event	Potentially triggered events
I	MDI	
II	SL-1	MDI or MFD II
II	Cr ICE II	MFD II
II	In-vessel LOCA II	MDII or VDEII
II	MDII	In-vessel LOCA II
II	VDEII	In-vessel LOCA II
II	MFD II	MDI
III	SMHV	Cr ICE II and/or MFD II or LOOP
III	SL-1	(MDII or VDEII) and/or MFD II
III	SL-1	MFD II + MDII
III	MDIII	In-vessel LOCA III
III	VDEIII	In-vessel LOCA III
III	MFD II	MDII or VDEII
III	In-vessel LOCA III	MDIII
III	Cr ICE III	MFD II
III	Ex-vessel LOCA III	
III	LOCA NB III	
IV	SL-2	Cr ICE III or MDI or Ex-vessel LOCA III or LOOP
IV	SL-1	MDIII
IV	MDIV	In-vessel LOCA IV
IV	VDEIV	In-vessel LOCA IV
IV	Ex-vessel LOCA III	In-vessel LOCA II
IV	Airplane crash	

Table 5 Postulated events combination and classification in plasma operation state

Acknowledgments

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