

2.12 Mechanical Loads and Machine Supports Configuration

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2.12.1 Overview of Mechanical Loads

Part of the technical difficulties associated with the design of the ITER tokamak are due to the substantial mechanical loads which can develop in multiple components. This section will briefly describe the main static and transient loading conditions that concern the ITER system design.

The mechanical loads acting on ITER can be divided into four independent categories.

1. *Inertial loads*: these are due to accelerations due to gravity and seismic events.
2. *Kinetic pressure loads*: significant on the ITER vessels, include coolant pressure (e.g., vacuum vessel cooling water), and externally applied atmospheric pressure to vacuum (e.g., cryostat vessel).
3. *Electromagnetic loads*: these are normally a strong design driver and not only affect, in their static form, the magnet system (e.g., TF magnet) but also act upon nearly all conductive structures during fast transients (e.g., plasma disruptions and resulting induced currents on the in-vessel components).
4. *Thermal loads*: these often induce mechanical loads, and are typically circumscribed within a single component and thus do not give rise to significant global effects.

To better explain the mechanical loads from a system point of view it is worth briefly describing the general layout of the main component supports (as shown in Figure 2.12.1-1).

The support schemes for the tokamak magnet and vacuum vessel systems have a number of constraints. The supports must allow for radial shrinkage of the magnets, and radial growth of the vacuum vessel, due to thermal differentials, while providing adequate resistance to seismic and disruption forces. Moreover, the general arrangement of supports has been developed to minimise the reaction of each support to loads internal to the component, with the following consequences.

- The tokamak gravity support from the basemat acts exclusively through the TF magnet assembly and consists of support pedestals made up of flexible compression plates resting on a support ring. The gravity support pedestals are rigid in the toroidal and vertical directions to resist inertial loads, but they are flexible in the radial direction to allow TF coil case thermal movements. These pedestals are supported on a steel support ring beam that is a part of the cryostat vessel. This ring is in turn supported, vertically, by a set of columns, and horizontally by a radial shell also part of the cryostat floor which, mainly by shear, carries the load onto the lower part of the bioshield.
- The vacuum vessel is supported by the TF magnet assembly also by means of a set of flexible plates located between the two components in the outer region of the machine. These supports have been located in this region to be efficient in the reaction of seismic

loads as well as to minimise the cyclic toroidal motion which the VV undergoes as a consequence of the out-of-plane loads and deflections of the magnet system.

- Each PF coil is connected directly to the TF magnet assembly by means of radially unconstrained supports.
- The in-vessel systems (blanket modules, divertor) are directly supported by the vessel.
- Cryostat and building are supported from the basemat.

The support hierarchy can therefore be schematically drawn as in Figure 2.12.1-2.

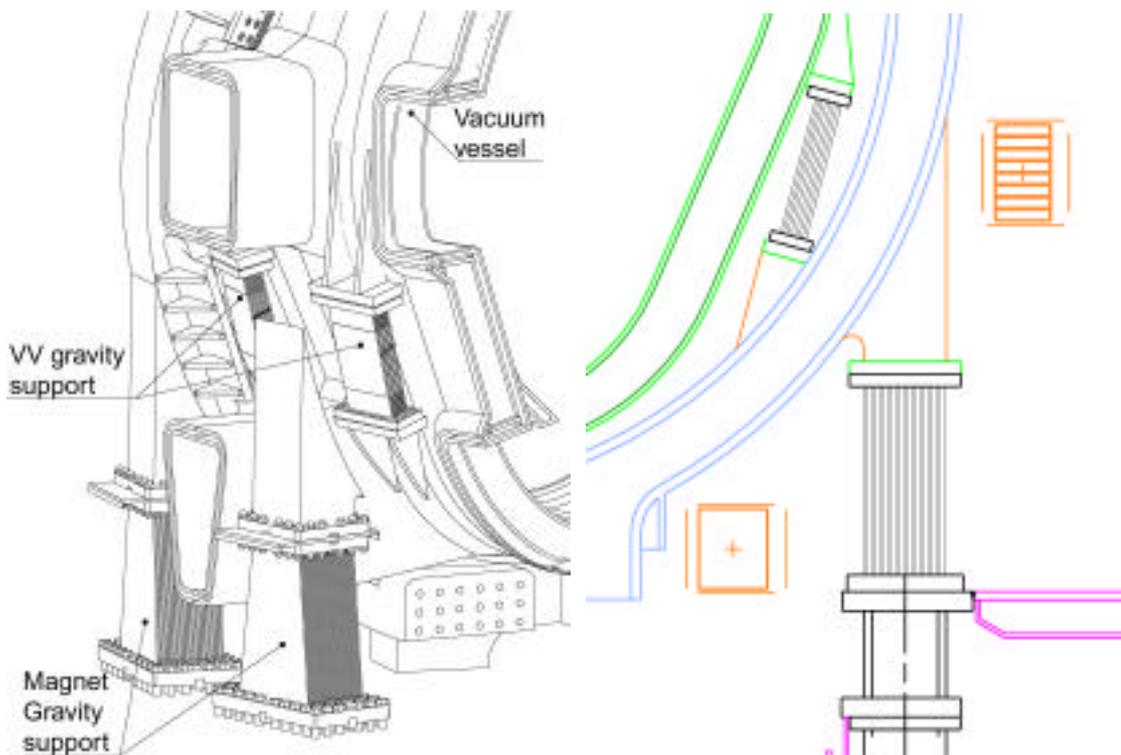


Figure 2.12.1-1 Vacuum Vessel to Magnet supports and Magnet Gravity supports

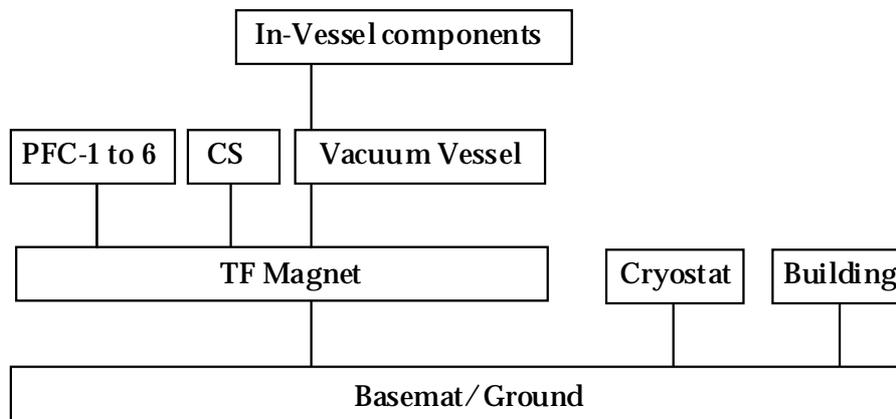


Figure 2.12.1-2 Schematic of Supports Hierarchy

The general philosophy utilised in the design of the support scheme has been to interconnect components and choose the load paths so to increase as much as possible the stiffness associated with the load path itself. This is quite evident with the choice of the supporting scheme of the vacuum vessel which has been directly connected to the magnet. In so doing, the relative deflection between the two components, and therefore the allocated radial build space, has been minimised while also avoiding any load through the main machine gravity supports during a plasma electromagnetic fast transient such as a **vertical displacement event (VDE)** or a disruption.

The ITER design uses a classification of plant conditions which divides them into categories in accordance with the anticipated likelihood of occurrence. This categorization is chosen to accommodate design criteria for safety importance components as well as in order to obtain a well balanced design also for non-safety importance components. The categories are:

Category I:	Operational events	(Normal)
Category II:	Likely event sequences	(Incidents)
Category III:	Unlikely event sequences	(Accidents)
Category IV:	Extremely unlikely event sequences	(Accidents)

Some type of loads, for example seismic or plasma events, have different events with different intensity defined in different categories.

2.12.2 Seismic Loads

Earthquakes produce random ground motions which are characterised by simultaneous but statistically independent horizontal and vertical components. Their severity is typically associated with the peak ground acceleration. The ground acceleration can be both in the horizontal and in the vertical direction and typically has a spectral content which leads to some level of support reaction load amplification.

The effect of seismic events on ITER are described in the specially devoted section 2.15.

2.12.3 Electromagnetic Loads, Slow Transients

Energies in excess of 40 GJ are normally stored in the ITER superconducting magnet system in the electromagnetic fields that provide stability to, equilibrium in, and drive current in the plasma. Associated with the provision of such strong fields, considerable magnetic loads have to be reacted by the magnet assembly.

2.12.3.1 TF Magnet Loads

During normal operating conditions, the TF magnet system has to withstand the EM loads arising from the interaction of its conductor current with both the toroidal and poloidal fields.

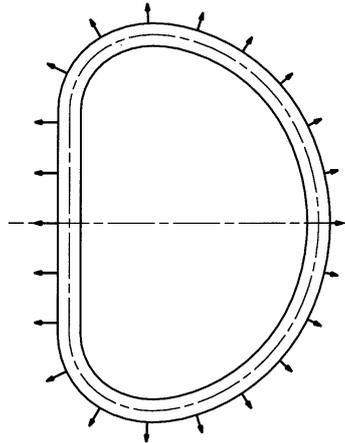


Figure 2.12.3-1 In-Plane Loads on a TF Coil

The interaction with the toroidal field gives rise to a force distribution (see Figure 2.12.3-1) acting in the plane of the each coil, and which can be pictured as a pressure acting from the vacuum vessel side outward with an intensity which reduces as the distance from the machine centreline increases. These loads are referred to as “in-plane“ loads in section 2.1.

As a consequence of this load distribution, each coil experiences a strong internal tension along its length as well as a radially directed force towards the machine centreline which is reacted in hoop compression by the straight legs of the TF magnet which behave as a vault. Even if this load is basically internal to the TF magnet assembly in that no *net* loads are transmitted onto other components, it is certainly one of the most important loading conditions for the whole machine with significant structural consequences. The shear tension in each TF coil is about 100MN thus requiring a significant amount of structural steel over the TF cross section. The radial force in each coil is about 400MN giving rise, as a consequence of the "wedged" type of structural support, to a toroidal wedging load of about 1150MN, requiring a thick enough vault in the innermost region of the TF cross section.

The interaction of the TF magnet current with the poloidal field, present only during plasma operation or when the CS or the PF coils are energized, gives rise to a load which is normal to the plane of each TF coil. This load is referred to as “out-of-plane” load in section 2.1. This load does not produce a net moment around the vertical axis of the machine but tries to twist the whole TF magnet with opposing sign toroidally directed forces. While being a load of somewhat smaller intensity, when compared with the in-plane load, it is of a pulsed nature and hence is rather challenging to react as a consequence of the cyclic nature of the arising stresses. The reaction of this load is accomplished by the TF coils casings and the intercoil structures, which increase both stiffness and strength of the magnet assembly. Also in this case no net load is reacted by the gravity supports and, by careful choice of the support location, cyclic loadings **on them** are minimised.

An extensive amount of finite element analyses have been performed to investigate the mechanical behaviour for several design options of the TF-coil system. For these investigations, several non-linear, two and three dimensional finite element models have been used, most often representing a 20 degree symmetry section of the TF coil. The present ITER design takes into account the results of these studies.

A discussion of the main analysis of the TF magnet loads is given in 2.1.

2.12.3.2 PF Magnet and Plasma Loads

The PF magnet system includes the CS and the PF coils and produces the poloidal magnetic field necessary for plasma equilibrium and shaping, as well as the toroidal electric field needed to build and sustain the plasma current. The forces acting on the PF coils are radially and vertically directed and are essentially axisymmetric in their distribution (except for the small ripple effect due to the discrete TF coils).

During the development of slow transients (e.g., plasma initiation, shutdown, etc...), the net force on the whole PF magnet system is nearly zero due to the essential absence of induced currents in the passive structures (VV, Blanket, etc.).

Net vertical loads acting on each PF coil and the central solenoid (CS) are reacted through the TF magnet structure but without affecting its supports to ground (Figure 2.12.3-2). In this scheme the TF magnet is acting as the main load path. Radial loads, acting on the CS and the PF coils, are instead reacted within each coil by the development of toroidal hoop stress in the conductor jacket. Radial expansion due to this hoop stress is accommodated by supports which are radially flexible.

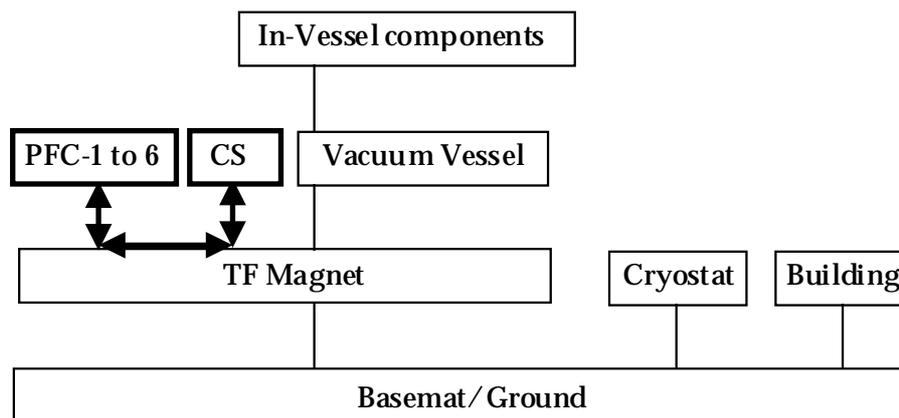


Figure 2.12.3-2 Load Paths between PF Coils

The load on each PF coil (and within the CS coil) varies greatly as a function of other PF coil currents, plasma current, plasma profiles, etc. Therefore, in order to size these coils and their supporting structures, the envelope of all conditions must be considered. In particular it has been necessary to verify the capability to withstand each design reference plasma with its different ranges of plasma internal inductance and beta poloidal as well as induced currents and loads arising during plasma electromagnetic fast transients such as VDE's and disruptions.

2.12.4 **Electromagnetic Loads, Fast Transients**

Electromagnetic fast transients typically will occur-as a consequence of problems encountered in sustaining currents (e.g., fast magnet discharge, and plasma disruption) or loss of vertical position control of the plasma (VDE).

Due to the experimental nature of ITER where different plasma operation modes will be explored, these loads, such as plasma disruptions and VDE's, are considered part of the (normal) operational (Category I) loading events¹. For this reason, the systems in ITER are designed to withstand a large number of them.

Typically, fast electromagnetic transients produce significant forces and stresses in all in-vessel components and are a determining factor in their structural design.

2.12.4.1 Disruptions

The tokamak disruption is a severe instability in which the plasma confinement is suddenly destroyed, both thermal and magnetic plasma energies are rapidly dissipated, and the discharge is terminated.

If the plasma current quench takes place in a time short compared with the vertical resistive plasma motion (e.g., < 100 ms) no significant total net vertical forces are generated in the whole passive structure. Nonetheless, given the up-down asymmetric coupling of the ITER plasma with the passive conducting structure, significant plasma fast vertical displacements may take place. A significant poloidal current may also be induced in the passive structure as a consequence of the variation of toroidal flux (during thermal and current quench). This current leads to loads internal to the vessel without significant transfer of forces to the magnet.

The most important structural consequence of a plasma disruption is the induction of local loads on the blanket modules, vacuum vessel, and plasma facing components. The severity of this event depends on the assumed total current quench duration.

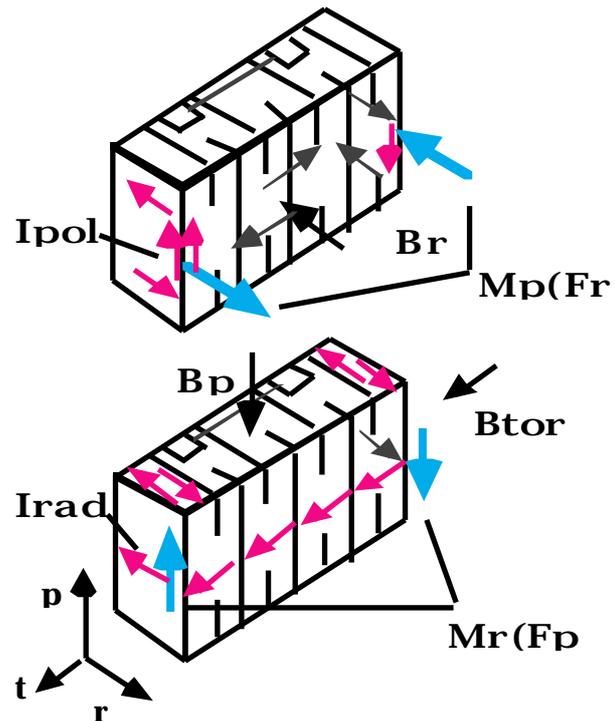
A more severe condition takes place during the current quench phase where toroidal currents are induced in the vacuum vessel, applying a pressure toward the plasma in the order of 1MPa. This is nevertheless a rather unchallenging loading condition for the vacuum vessel itself, which is sized to withstand larger magnetic pressures during a TF coil fast discharge and/or VDEs.

The current quench phase is a significantly demanding condition for the design of the blanket modules where significant saddle current loops are induced.

The interaction of these current loops with the toroidal field, generates significant radial and poloidal moments which determine in large part the type and sizing of the blanket module support scheme (Figure 2.12.4-1). For this type of loads the current quench duration is the single most important design parameter. In the worst case this could be ~ 25 ms, and the disruption analysis has shown that the arising maximum moment in a single module is about 0.6 MNm in the poloidal direction and 0.7 MNm in the radial direction (see 2.3).

¹ Other loading categories are II (likely), III (unlikely), and IV (extremely unlikely).

Figure 2.12.4-1 Current Loops in the Blanket Module During a Plasma Current Quench



The electromagnetic (EM) and structural modelling of an EM transient, such as a disruption, is usually performed in three steps.

- Several cases of axisymmetric MHD plasma equilibria transients are analysed to obtain a proper modelling of the plasma motion during the thermal and current quench phases. This is essential to make sure that the plasma is in equilibrium and hence no artificial loads are introduced in the analysis, where also the PF coils response is self-consistently taken into account.
- The results of the initial analysis are then used to introduce current changes (plasma and/or magnet) into three-dimensional EM models which include all significant parts of the passive structure. Several different finite element meshes may be used to model with a sufficient level of detail, all the regions of interest.
- The mechanical loads are passed into a suitably meshed structural model used for the evaluation of mechanical stresses. Also in this case, several meshes are used to describe, for example, the global overall behaviour of the vacuum vessel, the local structural response of the blanket module supports on the vacuum vessel, the blanket modules themselves, the divertor cassette, etc..

Figures 2.12.4-2, 2.12.4-3 and 2.12.4-4 below show some of the models employed in the process outlined. Detailed analytical results are reported in 2.2-2.4.

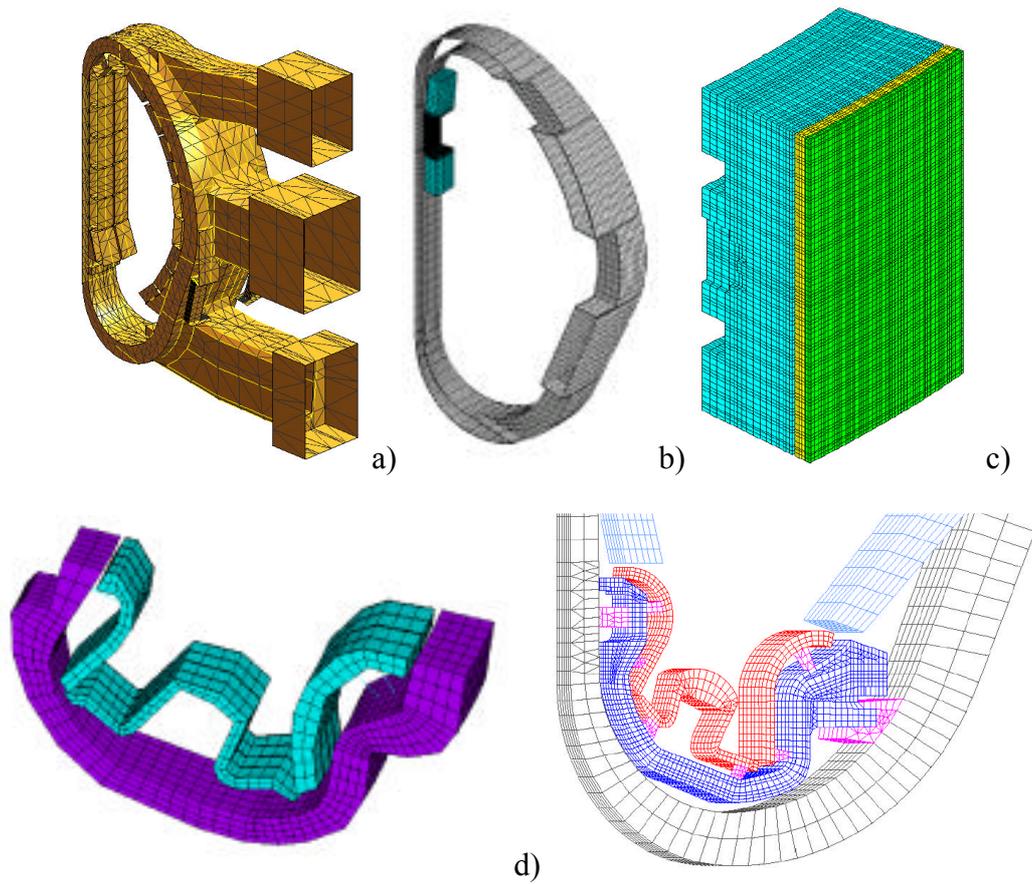


Figure 2.12.4-3 The Second Step - Several Types of EM Analysis 3D models Using the Results of Step 1 as Input. The vessel (a,b), a detail showing the module (c), and the divertor (d,e)

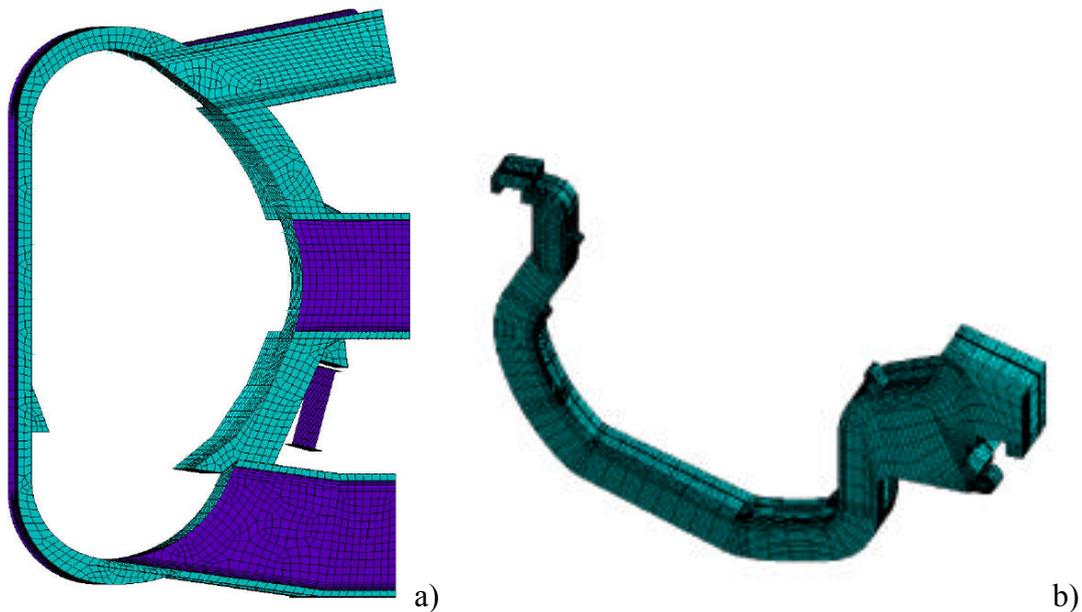


Figure 2.12.4-4 The Third Step - The Use of Structural Codes Applied to a Suitably Meshed Model Taking Loads from the Outputs Obtained in Step2. The example models shown are the vessel (a) and the divertor cassette (b).

2.12.4.2 VDE's

In a VDE the vertical position control of the plasma is lost as a consequence of a failure of the feedback control system. The plasma motion, in this case, may take place initially without significant plasma current reduction (current quench) and would progress relatively slowly (on the time scale determined by the resistance of the passive structure). This type of instability takes place in elongated plasmas that require for their stability an external feedback system. The loss of vertical position can be caused by external malfunctioning of the control system or by too fast and large variations in the plasma profiles (e.g. major disruptions) to be stabilised by a system with finite voltage limitation.

The VDE is composed of an initial slow vertical drift phase, when the plasma vertical position follows an exponential growth, an onset of plasma-wall contact followed by the onset of a disruption and/or rapid loss of remaining plasma thermal energy. Halo currents may appear as soon as the plasma comes in contact with the first wall. The thermal quench is assumed to start in either of the two cases: one is at the same time as the plasma contact with the first wall; the other is when the plasma edge safety factor q_{edge} reaches a critical value which has been conservatively assumed to be 1.5.

During a VDE, the forces acting on the plasma during its motion are mainly (but not only):

- destabilising force due to the external applied quadrupolar poloidal field;
- stabilising force deriving from the plasma motion in a conducting shell.
- destabilising force due to up-down asymmetric toroidal current induced in the passive structure by the decay of the plasma current.

Since VDE's terminate with a plasma current quench, their severity depends on the delay between the onset of the VDE and the onset of the current quench as well as the duration of the latter. If the onset of the current quench is delayed, the plasma moves further into the destabilising quadrupolar field giving rise to higher net loads on the passive structure.

In other words, the plasma current quench causes a transfer of current from the plasma to the passive structure which, while still continuing to interact with the destabilising poloidal field, forces it to stop drifting vertically. For this reason the worst (higher vertical force) VDEs are typically the ones where the plasma current does not decay before the plasma has undergone a large displacement from its initial position. This is because the destabilising force is roughly proportional to the plasma displacement multiplied by the plasma current itself. The exchange of forces between plasma and passive structure is sustained by the presence of eddy currents as well as poloidal currents which flow through both plasma and passive structure. These are known as halo currents.

The VDE typically gives rise to significant net forces between the PF magnet and the passive structure. The typical load path of these forces can be visualised in Figure 2.12.4-5.

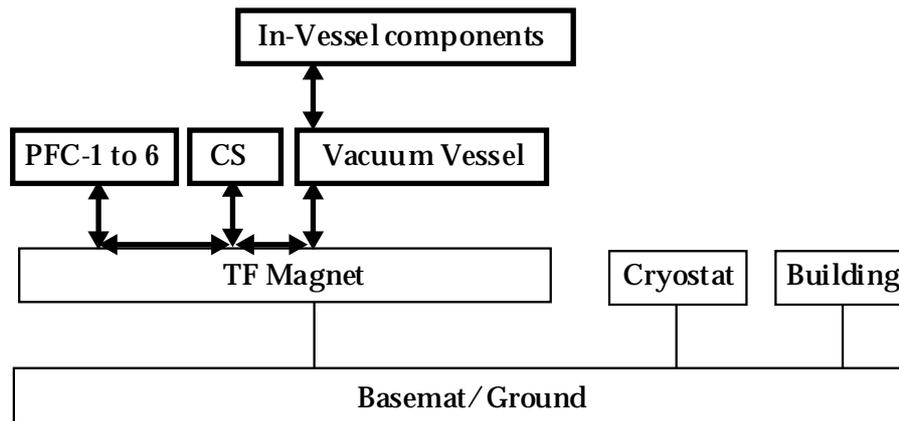


Figure 2.12.4-5 Mechanical Load Paths During a VDE

VDE's can be divided into two classes with slightly different EM load consequences: one is a VDE followed by a fast current quench, that results in more demanding eddy currents on modules, divertor, and vacuum vessel; the other is a VDE followed by a slow current quench that results in higher halo currents and vertical loads on the structure. The estimated current quench time depends mainly on the assumption on halo and plasma temperatures. A lower halo temperature leads to higher resistance in the plasma region and results in the fast VDE and lower halo current, and the higher one results in the slow VDE and higher halo current. For the modelling of both fast and slow current quench types of VDE's the initial scenario is the same. The vertical control system is deactivated and the plasma is given, from its initial unstable equilibrium point, a small initial upward or downward kick. The plasma then drifts in the direction of the displacement and rapidly becomes limited by the first wall. The plasma remains limited and shrinks in cross-section while maintaining its current as it continues to drift. During the drift phase, which typically lasts a few hundreds of milliseconds, no power is supplied to the plasma and the plasma energy slowly decays at a rate determined by the thermal transport in the equilibrium state.

It has also been observed, in present experiments, that VDE's sometimes give rise to net horizontal loads between magnet and passive structure as a consequence of plasma instabilities of a non-axisymmetric nature. The understanding of these phenomena is not clear and their modelling is still somewhat primitive. Nonetheless, some design guidelines have been established for ITER.

The effects of VDE's on in-vessel components can be very severe. It is therefore essential to be able to predict, with some degree of confidence, what will be the loading conditions caused by these events.

Some initial numbers can be estimated by simple force balance considerations.

- The destabilising force on the plasma will have to be transferred to the passive structure by electromagnetic force exchange (between the plasma and the passive structure).
- The external quadrupolar (destabilising) field is well-known and therefore the destabilising force can be easily found once a maximum plasma displacement for the VDE is established.

- The latter is strongly linked with the value of the safety factor at the plasma edge. In fact, during the VDE, the plasma soon becomes limited, and the more the plasma displaces the smaller it becomes and hence (since plasma current \sim constant) the more q_{edge} decreases.
- Once the destabilising force is known, the total value of halo currents can be simply estimated by ascribing the totality of the stabilising force (on the plasma) to the latter.
- It is therefore essential to establish a reference value of q_{edge} at which the plasma will start its current quench. Various considerations lead to setting the lower bound to 1.5. This should be a sufficiently conservative value especially because in ITER the plasma motion during the VDE is very slow (growth time $>0.5\text{s}$).

Given the above, and with simple additional geometrical considerations, the upper bound of the vertical destabilising force can be calculated to occur for a downward VDE and to be about ~ 70 MN, and that the needed halo current will have to be in the order of 6 MA.

In ITER, several numerical studies have been carried out to verify the upper bound of vertical forces. Generally, numerical modelling of VDE's is carried out with free-boundary plasma axisymmetric equilibrium codes solving the Grad-Shafranov equation with the inclusion of eddy currents and halo current terms. The main conclusions which can be drawn from these analyses are the following.

1. The ITER control system is capable of maintaining plasma vertical position control for all nominal plasma disturbances, including minor disruptions. A VDE, in ITER, is therefore expected to occur only as a consequence of a major disruption or a failure of the control system.
2. Should the VDE be caused by a major disruption followed by the plasma current quench, the plasma is expected to undergo an upward VDE. This is a consequence of the asymmetric vertical inductive coupling between plasma and passive structure. Furthermore, upward VDE's give rise to vertical forces on the passive structure substantially smaller than downward VDE's as a consequence of the smaller quadrupolar field present in the upper section of the vacuum chamber.
3. Smaller vertical forces are generated when the plasma current quench takes place early in the vertical drift. This aspect has generated the idea of using a plasma terminating impurity gas puff, to trigger a plasma disruption, should the vertical position of a 'healthy' plasma be lost.
4. When the vertical position of a 'healthy' plasma is lost for no reason other than a functional failure of the controller, there are equal chances for the VDE to be downward or upward. Should, in this event, a plasma terminating impurity gas puff be used to trigger a plasma current decay early enough, (the displacement would be less than $\sim 30\text{cm}$), and the plasma would go upward.
5. The worst case peak vertical load has been observed for downward VDEs. The main results of this loading condition are shown in Table 2.12.4-1. Figure 2.12.4-6 shows the magnetic flux in a particular point during this simulation.

Several additional scenarios of VDE's, as well as fast central disruptions analyses, have been performed. These analyses have then been utilised in a self-consistent way to perform more detailed stress analyses of all affected components.

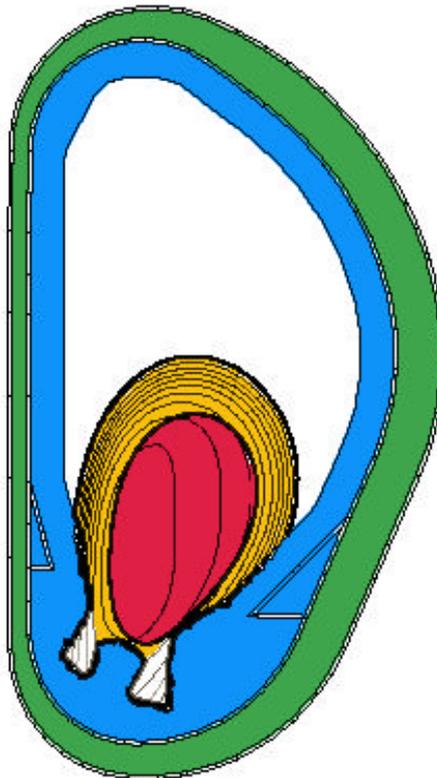


Figure 2.12.4-6 Worst Case Downward VDE

Table 2.12.4-1 Main Results of a Worst Case Slow Downward Category III VDE

Input Data	
Initial Plasma State	EOB
Current Quench initiator	q=1.5
Additional assumptions	
Peak ($I_{\text{halo}} * P_f / I_{\text{plasma}}$)	0.58
Peak total net horizontal load	-25 MN
Main results of simulation: Downward VDEIII	
Peak Z force on passive structure (eddy+halo)	-72 MN
Peak Total Halo current	~7 MA
Peak Z force due to halo currents	-68 MN
Peak Z force due to toroidal eddy currents	-66 MN

2.12.4.3 Magnet System Fast Discharge

A magnet fast discharge is an event where the current flowing in the magnet (TF, PF, or both) is rapidly brought to zero by means of discharge resistors which dissipate the large stored magnetic energy. Such an event is usually triggered by the magnet quench detection system which intentionally does so to protect the conductor from overheating or, in other words, to limit the hot spot temperature of the magnet superconductor.

In particular in the case of the TF magnet, where a significant energy is involved during the fast discharge of the coil circuit, the passive structures surrounding the TF coil conductors, i.e. the radial plates, the coil cases and the vacuum vessel, will absorb part of the stored magnetic energy of the TF coils. This implies that significant currents (Figure 2.12.4-7), in the order of 4MA, will be induced in the VV, producing electromagnetic forces to be also combined with loads which may arise simultaneously such as halo currents arising during a VDE.

The forces acting on the VV act like an internal pressure but with a local value proportional to the local toroidal field. The force distribution is similar to the in-plane load on the TF coils and results (similarly to the TF coils) in a toroidal compressive load at the inboard region of the VV. This inboard compressive load is a structural design driver for the VV.

The mechanical loads arising as a consequence of a TF coil fast discharge are a rather strong function of the discharge time constant that hence is an important machine design parameter (11 s in ITER) subject to trade and system studies. A longer discharge time constant allows a reduction of the EM pressure acting on the VV, but this choice implies that a larger energy is deposited in the quenched conductor, thus requiring a smaller cable space current density and hence a larger TF winding pack dimensions. This type of trade study has been performed so as to find a near optimal configuration which depends on many other design inputs and choices such as magnet conductor design criteria, material choice for the VV, assumptions on VDE's and halo currents, etc...

As far as the load path through the supporting structure is concerned, due to symmetry, all loads can be considered internal and no significant net loads are exchanged between components other than between the VV and the divertor cassette.

Also with regard to the PF magnet system fast discharge, as a consequence of the decay of the poloidal field a toroidal electric field is generated and subsequent eddy currents are induced in the passive structure. These are, in this case, typically smaller than the ones generated by the quench of the plasma current (disruption) which involves similar field variations but in much shorter times. However, from the support structure standpoint, during the transient, some net loads may be exchanged between the passive structure and the PF magnet.

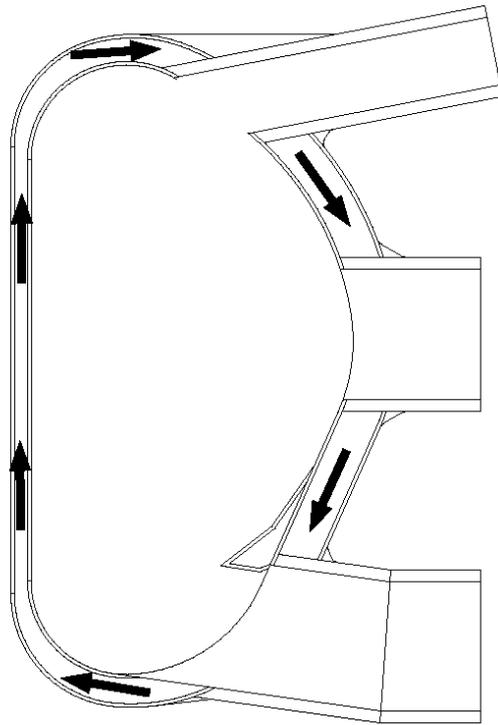


Figure 2.12.4-7 Circulation of Induced Poloidal Currents in VV During TF Magnet Fast Discharge