Eddy Current and Gap Voltage at Electrical Contacts of ITER Diagnostic First Walls and Shield Modules during Plasma Disruptions

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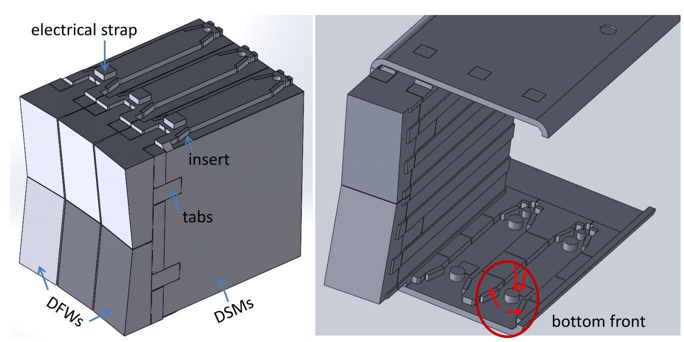
***Abstract*—ITER diagnostic port plugs perform many functions including structural support of diagnostic systems under high electromagnetic loads while allowing for diagnostic access to the plasma. During plasma disruptions, a large amount of induced current flows locally at electrical contacts between diagnostic first walls (DFWs) and the diagnostic shield modules (DSMs). Even a small gap voltage (10-30V) between DFWs, DSMs and supporting rails may trigger local arcing and cause arc damage to the conducting structure. This is particularly true when we consider the ionized gas environment and halo current effect. We perform global electromagnetic analysis with contact details for DFWs and DSMs to quantify the gap voltage and local current transfer effect during plasma disruptions. Electrical contacts between the DFWs and DSMs may also have significant impact on disruption load and thus affect design of the DFW attachment scheme. Large current transfer (>100 kA) between DFWs and DSMs through the attachment keys and tabs during disruption implies local heating and potential welding. This paper reviews the contact current and electrical potential difference between the DFWs, DSMs and the port plug structure. We also assess the impact on the system design itself due to electrical contact among various components.**

Keywords*—Eddy current analysis; transient voltage difference; plasma disruption; diagnostic first wall; diagnostic shield module

I. Introduction

ITER diagnostic port plugs perform many functions including structural support of diagnostic systems under high electromagnetic loads while allowing for diagnostic access to the plasma. The design of diagnostic first wall (DFW), diagnostic shield module (DSM) and their support on the port plug structure are largely driven by the electromagnetic loads during fast plasma disruptions and vertical displacement events (VDEs) [1,3]. When major plasma instabilities occur, rapid decay of the 15MA plasma current induces large amounts of eddy current and transient voltage on the conductive structures facing or near the plasma. The induced voltage may be sufficiently high to cause arcing across section gaps between adjacent DFWs or DSMs.

As a result of early design review studies, the DFWs and DSMs are sectored with small gaps to significantly reduce disruption loads. The vertical slits between DFWs and DSMs are designed to reduce mutual inductance between the plasma and the first wall conducting structure. The slits break large eddy current loops during disruption and reduce the disruption loads on the full port plug (PP) structure by a factor of 2-3. A potential concern is, however, possible arcing across small sector gaps due to transient voltage induced during a plasma disruption. Previous studies show that even a small gap voltage (10-30 V) may trigger local arcing and cause arc damage to the global integrity of the PP structure [4-5]. Fig. 1 shows the generic equatorial DFWs, DSMs and their support on the PP structure. Each DFW is attached to the DSM through three rectangular tabs and the DSM is supported on the PP structure via the top and bottom rails. Similar design of DFWs, DSMs and the electrical contacts is used for the upper PPs. We perform global electromagnetic analysis with contact details for DFWs and DSMs to quantify the local current transfer and extract induced voltage on the PP conductive components during plasma disruptions. Electrical contacts between the DFWs and DSMs may also impact the disruption loads and thus affect the design of the DFW attachment scheme. Large current transfer (>100 kA) between DFWs and DSMs through the attachment keys and tabs during disruption implies local pulse heating and potential welding. This paper reviews local current transfer and transient voltage difference between DFWs and DSMs through the attachment tabs, inserts and electrical straps and the PP structure. We also discuss the impact on the system design itself due to electrical contacts among various components.



Electrical contacts:

1. Rectangular inserts
2. Square electric strap
3. Cylinder vertical support

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Fig. 1. Generic equatorial diagnostic first walls, shield modules, port plug structure and local electrical contacts (design is similar for the upper port).

II. ELECTROMAGNETIC ANALYSIS

A. Global Models

A 20 degree sector of the ITER vacuum vessel (VV), DFWs, DSMs, the equatorial and upper diagnostic PP structure are modeled separately with COBHAM Opera 3d and ANSYS Maxwell electromagnetic analysis tools. Transient analysis was performed for both equatorial and upper port plug structures. Fig. 2 presents the cutaway view of coils and plasma filaments modeled as secondary excitations.

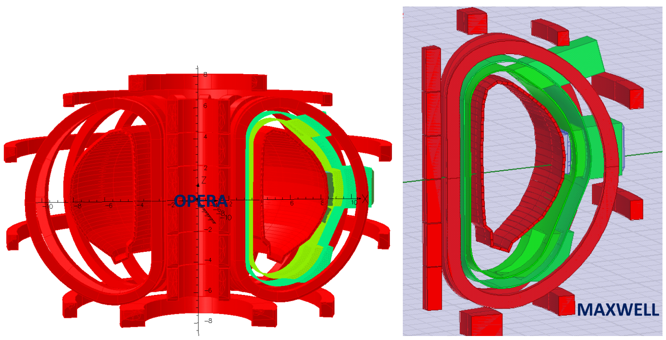


Fig. 2. OPERA and MAXWELL models - Cutaway view of the ITER coils and plasma filaments with 20 degree model of VV and diagnostic PPs.

The material electrical conductivity of the diagnostic PP structural components are listed in Table I. Aluminum bronze inserts are used between the rails and the DSMs to avoid welding risk in case of local arcing. Electrical straps are simply modeled as square blocks between DSMs and the PP structure. The straps are used to facilitate current transfer between DSMs and the PP structure so to reduce potential arcing at the small gap between the inserts and the DSMs during plasma disruptions.

TABLE I. ELECTRICAL CONDUCTIVITY

Electrical conductivity	***S/m***
DFWS/DSMs	1.35×10^6 (SS)
Bolts and Tabs	1.35×10^6 (SS)
Rails and PP structures	1.35×10^6 (SS)
Inserts	4.065×10^6 (Al. Bronze)
Electrical straps	50×10^6 (Cu)
VVs	1.35×10^6 (SS)

B. Disruption Scenarios

Four major disruption scenarios have been identified from previous CDR and PDR studies and considered here to be the worst case for the PP structure design [1, 3]. More specifically, MDUPLIN36, a major upward disruption with linear decay of plasma current in 36 ms, is the worst case for the equatorial PP structure. MDUPLIN36 generates a maximum radial moment of 4~5 MNm on the full PP structure. The VDEUPLIN36, a plasma vertical upward displacement event followed by a linear decay of the plasma current in 36 ms, is the worst case for the upper PP structure. VDEUPLIN36 generates poloidal and radial moments of ~1 MNm for the full PP structure respectively. The dominant moments tend not to change polarity but all minority loads will switch polarity during plasma disruptions.

III. EDDY CURRENT

The rapid decay of magnetic flux associated with plasma instability induces eddy currents and transient voltages in the conducting structure of diagnostic PPs facing or close to plasma. The dominant poloidal field change in the DSM of equatorial PP is about 10 T/s and it peaks at over 20 T/s in the plasma facing DFWs. The poloidal field change induces eddy current flowing in the horizontal plane for the equatorial PP. Fig. 3 presents the eddy current induced in the VV and the EPP structure during MDUPLIN36. The model global behavior shows that eddy current appears on the inner vessel wall first before penetrating into the outer wall, implying that diffusion of the induced current and magnetic field into the conducting structure is much slower than the 36 ms plasma current disruption.

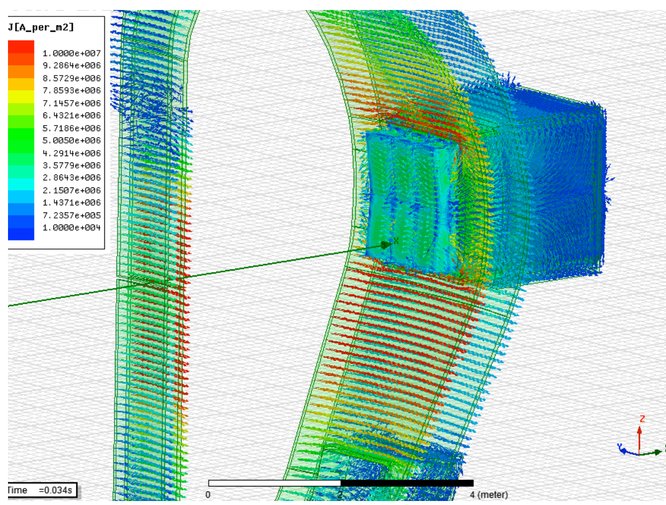


Fig. 3. Eddy current induced on VV and the DFWs of equatorial Port plug during MDUPLIN36. Color represents current density and arrow indicates eddy current flow direction.

A. Equatorial Diagnostic Port Plug

Fig. 4 presents the eddy current density distribution on the DFWs and the DSMs from both MAXWELL and OPERA simulations. Fig. 4 clearly shows eddy current concentration at the copper electrical straps which indicates a large current transfer between DSM and the PP structure via the copper straps. The straps help to prevent potential arcing at local contact between DSM and the supporting rails during transient disruptions. Most eddy current flows in the front of DFWs and DSMs.

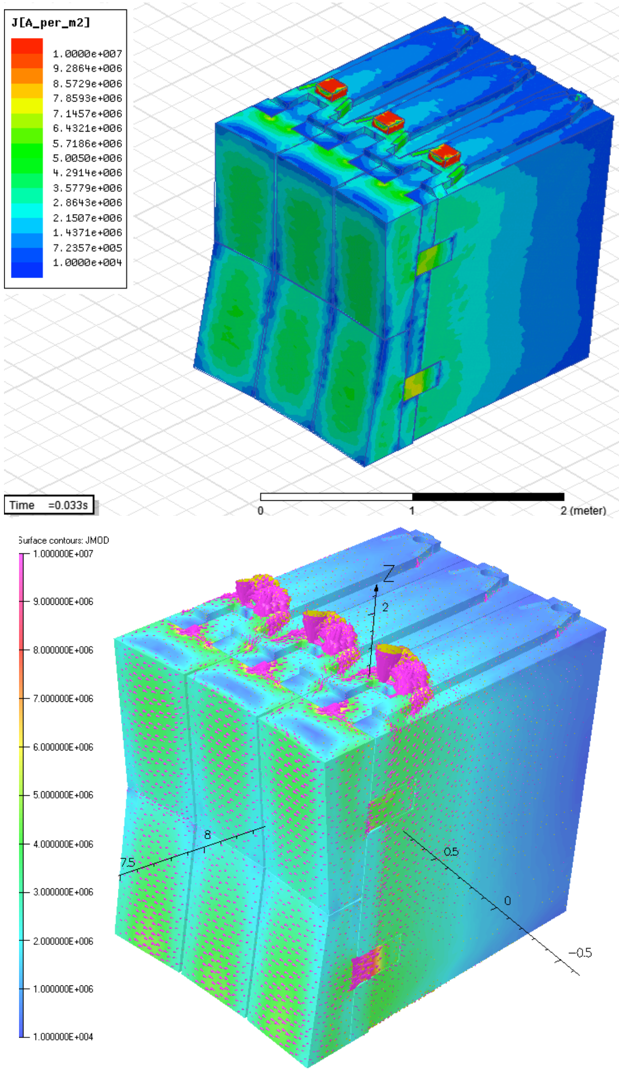


Fig. 4. Eddy current density from MAXWELL (top) and OPERA (bottom with direction vector) on generic equatorial DFWs and DSMs.

Fig. 5 presents the time-varying change of poloidal field at mass center of six EPP DFWs (lower/upper left/middle/right) during MDUPLIN36. The maximum poloidal field change is over 20 T/s during a major disruption. This indicates that large eddy current flowing in the DFWs. The vertical slits and gaps between the DFWs and DSMs significantly reduced magnetic coupling between the plasma and the PP structure by breaking large eddy current loops into 6 smaller local loops for each DFW. This reduces overall disruption loads on the DFWs and the full PP structure by a factor of 2-3 [3].

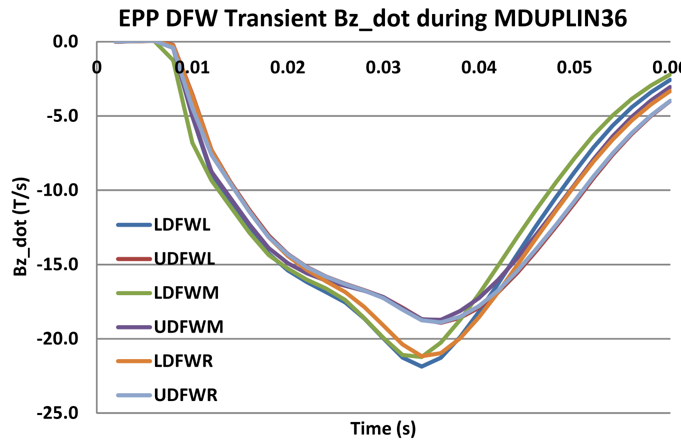
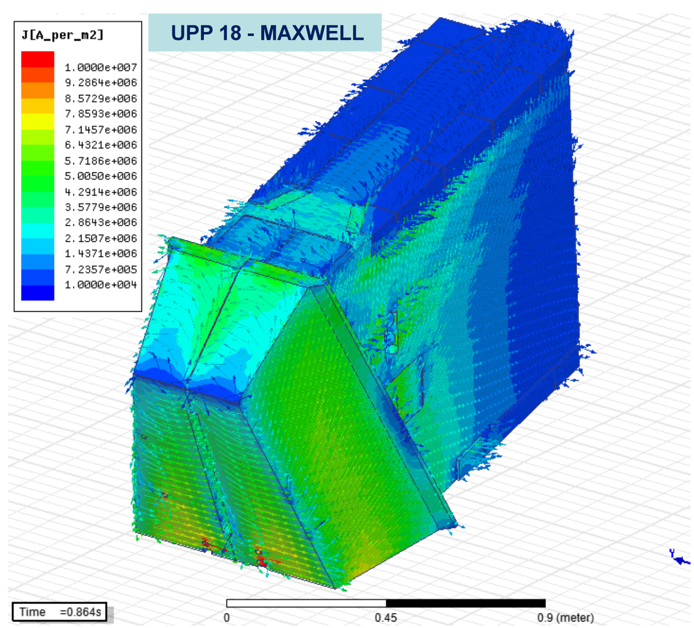


Fig. 5. Transient vertical field change of GEPP at the mass center of Lower/Upper Left/Middle/Right DFWs during MDUPLIN36 disruption.

B. Upper Diagnostic Port Plug

Instead of major disruptions, plasma vertical displacement VDEUPLIN36 generates the worst disruption loads on the upper PP [6]. Fig. 6 presents eddy current distribution on the UPP 18 DFWs, DSMs and the local electrical contacts from both MAXWELL and OPERA simulations. Similar to the EPP, eddy current flows in the two DFWs in separate loops due to the vertical slits. Voltage or potential difference at the gap between the two DFWs is a concern for possible arcing. A smaller gap (< 1mm) between the DSM rails and Aluminum inserts may create local hot spot for melting during disruptions.



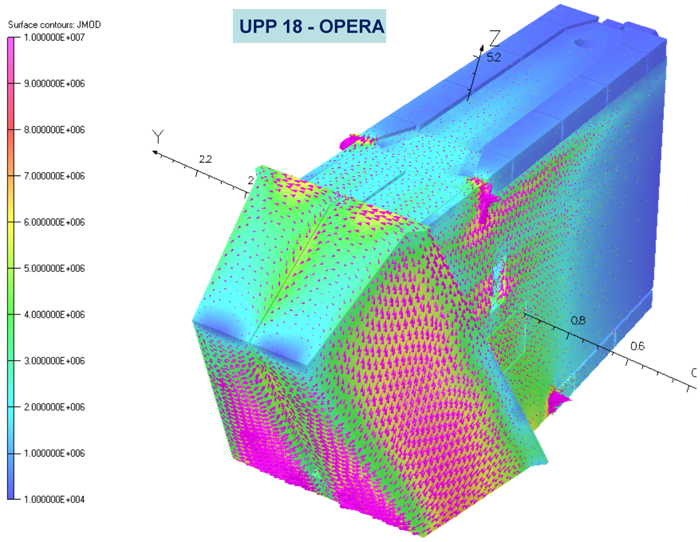


Fig. 6. Eddy current flowing on UPP18 diagnostic first walls, shield modules and local electrical contacts from MAXWELL (top) and OPERA (bottom). Color contour shows eddy current density and arrow indicates eddy current flow direction.

C. *Local current transfer*

Large current transfer during plasma disruptions at the DFW attachment tabs, between the DSM inserts and the supporting rails is a concern for potential pulse heating and local welding. Previous studies indicate that most minority disruption loads tend to change polarity during a plasma current quench [3]. This will create undesirable on and off electrical contact situations due to the small gap (<1 mm) at the contact surface between the DSM supporting rails and the Aluminum Bronze inserts. Electrical straps are used to mitigate gap voltage and thus reduce arcing possibility.

The 5 mm vertical gap between DFWs and DSMs forces the induced eddy current on the DFWs to flow in a smaller loop and thus reduces the net disruption loads on the full PP structure. Despite this design feature >100 kA local current transfer between DFW and DSM via the attachment tabs is expected during disruptions for the equatorial and upper ports. In addition, ~135 kA net current transfer is expected via the electrical straps for the equatorial port during major disruptions. It is important to have a design of electrical contact that promotes more uniform local current transfer. Table II lists the estimated peak local current transfer during plasma disruptions or VDEs for the equatorial and upper ports.

TABLE II. LOCAL CURRENT TRANSFER ON PP STRUCTURES

Current (kA)	**Peak local current transfer**			
	DFW Tabs	***Inserts***	***Straps***	***Rails***
GEPP	100-150	10-30	135	10-30
UPP 18	100	20	n/a	7

IV. TRANSIENT VOLTAGE

Transient voltage induced on the DFWs and DSMs during plasma disruptions is another potential issue associated with electric arcing and arc damage. Once an arc develops, it continues to conduct current until the current is driven to zero or until the available voltages drop below the point where electrons are emitted [4]. Although there is considerable uncertainty concerning the allowable level for arc damage, the basic condition for arc initiation is that the driving potential difference at the DFW surface must exceed 10-30 V arc voltage. This threshold has been observed experimentally in a similar environment [4-6]. Several calculation methods can be used to extract transient voltage induced on the conductive components and derive the gap voltage. In this section, we first review transient voltage calculations and then discuss potential arcing and arc damage.

A. *Induced voltages*

For the transient fields during plasma disruptions, voltage induced between two points along a path l_{12} is path-dependent and generally given as

$$V_{12} = \int_{l_{12}} E \cdot dl = (\Phi_1 - \Phi_2) - \frac{\partial}{\partial t} \int_{l_{12}} A \cdot dl \qquad (1)$$

where Φ_1 and Φ_2 are the electrical scalar potential at points 1 and 2, and A is the magnetic vector potential. The A-Φ potential formulation is used in Opera Elektra transient solver while the electrical vector potential and reduced magnetic scalar potential T-Omega formulation is used in ANSYS Maxwell transient solver.

a) Voltage between surfaces: Calculation is performed via the line integral of component Ex*Tx+Ey*Ty+Ez*Tz in OPERA where the system variables Tx, Ty and Tz are the components of tangential vector to the line.

b) Voltage around a closed loop: Calculation of voltage induced around a closed loop is performed by applying surface integral of the normal magnetic field component and ploting Bx*nx+By*ny+Bz*nz to obtain

$$V = emf = -\frac{\partial}{\partial t} \int_{s} B \cdot dS \qquad (2)$$

c) MAXWELL EMF: Bn on surfaces of the conductive components can also be calculated in MAXWELL, so we can compare results of the surface integrals from two different solutions to be more confident with the estimate on EMF.

Fig. 7 presents the electrical potential distribution of EPP DFWs from OPERA at the maximum disruption load during MDUPLIN36. This implies a maximum gap voltage of ~15 V between DFWs. Fig. 8 presents the electrical potential distribution of UPP DFWs from OPERA at maximum disruption load during VDEUPLIN36. This indicates a peak gap voltage of 15-20 V. Calculation of electrical field line integration for a closed eddy current loop on each DFW showing the same voltage level.

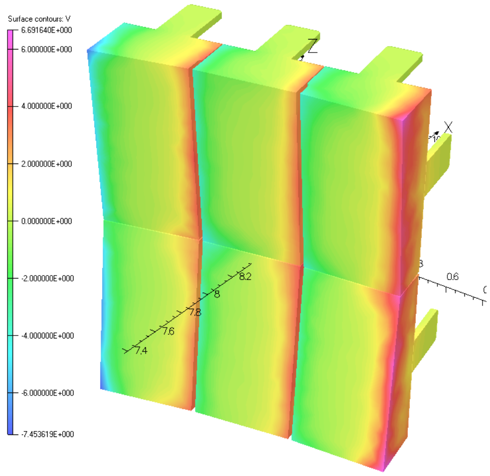


Fig. 7. Electrical potential distribution of EPP DFWs from OPERA showing an estimate of ~15 V gap voltage between adjacent DFWs.

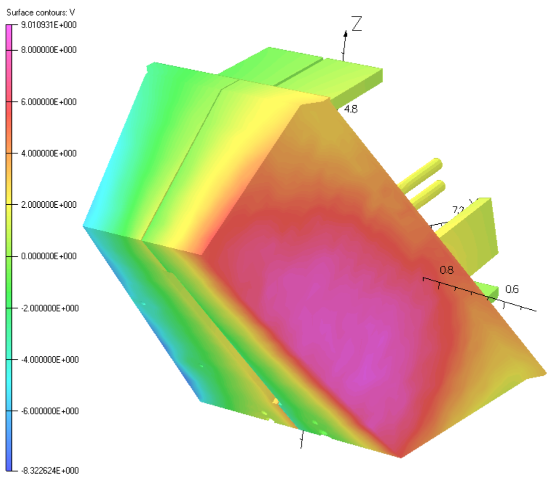


Fig. 8. Electrical potential distribution of UPP DFWs from OPERA showing an estimate of 15~20 V gap voltage between the two DFWs.

Table III presents the maximum voltage induced on the conductive structure components during plasma disruptions or VDEs for the equatorial and upper PPs. The maximum gap voltage between the PP structure components is expected to be at the same level. The table shows that as the plasma facing component, the maximum induced voltage on the DFWs can be higher than the 10-30 V threshold limit for arcing.

TABLE III. Induced Voltage on PP Structures

Voltage (V)	Maximum voltage during plasma disruptions			
	DFWs	***DSMs***	***Inserts***	***PP structure***
GEPP	10-15	8-10	1-3	~5
UPP 18	15-20	3-5	1-3	3-5

B. *Potential arcing*

The total energy loss due to eddy current flowing on the conductive structure is limited to ~300 kJ during plasma disruption for the full EPP structure and ~200 kJ for the full UPP structure. Although this is a negligible amount of heating associated with <0.1 degree C temperature rise if dissipated uniformly, transient voltages induced on the conductive structure components may trigger electric arcing and thus significantly increase local heating and may cause undesirable local welding.

On the other hand, if the above disruption-induced pulse heating is dissipated locally at electrical contacts, it will create a local hot spot and a simple hand calculation can show that the energy is sufficient to cause a few cm^3 melting of conductive material or welding. Therefore, it is recommended that the design of electrical contacts should prevent the development of local hot spot by sufficient contact area and ensuring a more uniform local current transfer during disruptions.

Table IV presents the total energy dissipated on the conductive components due to plasma disruptions. The design of the DFW tabs attached to the DSM has a flat and uniform contact area for current transfer, the local contact between the DSM rails and the Aluminum inserts can be problematic due to the fact that a much smaller contact area may cause arcing.

C. *Discussions*

Previous studies show that electric arcs could be developed across hot stainless steel electrodes subjected to an ionized gas environment within about 25 V [4-6]. Once an arc develops, it continues to conduct current until the current is driven to zero or until the available voltages drop below the point where electrons are emitted. An approximate value for stainless steel is estimated to be 10 to 20 V in the absence of an external magnetic field. The major factor in determining material erosion due to arcing is whether the arc currents remain diffused or the arc develops into constrictive arcs. Diffused arcs have little damage to the conductive material while constrictive arcs can result in erosion of materials [4]. The main criterion will be to design the conductivity of the passive circuits so that the voltage across all gaps would be less than the minimum arc sustaining voltage before a constricting arc with anode spots develops. If developed, these arcs can result in structure currents and forces being different than those calculated without arcs. The forces and torques being developed in structures may exceed the design values and produce structural damage.

TABLE IV. Total Energy Loss during Disruptions

Loss (kJ)	Total energy loss due to plasma disruption			
	DFWs	***DSMs*** [a]	***Others*** [b]	***PP structure*** [c]
GEPP	70	180	3-5	50
UPP18	100	50	1-2	30

[a] DSM and NAS diagnostics for UPP 18.

[b] Electrical straps, inserts and bolts.

[c] PP structure and DSM supporting rails.

V. Conclusions

Transient voltage induced on the DFWs and DSMs during plasma disruptions pose potential issue of electric arcing and arc erosion to the first wall materials. The basic condition for arc initiation is that the driving potential difference at the DFW surface must exceed the 10-30 V arc voltage threshold observed [3-5]. Our study shows that gap voltage between adjacent DFWs may exceed 15 V and thus there is potential arcing on the DFWs and DSMs during plasma disruptions. It is thus important to provide a design that would not support arcs long enough to cause excessive damage. The current would be allowed to flow as a diffused arc but would extinguish before becoming a constrictive arc channel and dissipating a large percentage of the plasma external magnetic field energy.

The large current transfer between DFW and DSM via the attachment tabs generates a total energy loss of ~100 kJ on the DFW during a major disruption. The disruption induced energy dissipation is small if distributed uniformly and has little impact on heating of the tabs. On the other hand, a local hot spot can be developed during disruptions and potential welding is a concern at the contact points between DSM rails and the Aluminum Bronze inserts.

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