National Spherical Torus eXperiment Upgrade

NSTX-U Disruption Analysis Requirements

NSTX-U-RQMT-RD-003-02

11/20/18

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Rev. 2

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Revisions

Rev	Date	Description
0	12/13/17	Initial Revision
1	7/23/18	Added Refs. [3] and [4]
		Modified 5b and added 5c. Added a table to represent the previous content of 5a. Modified the relative distribution of disruptions between the P1 through P6 cases in 5a.
		New Fig. 2.1 and Table 2.1, based on guidance in DIS-180529-SPG-02
		Removed Scenario #2 disruption thermal loading.
		Added new 2d, allowing intermediate locations in the VDE drift simulations. Renumbered subsequent statements in Section 2.
		Changed the PE signature to I. Zatz
		Changed P. Titus signature authority to be Technical Authority, in keeping with documents and records plan.
		Add VV&IH and PFC REs as reviewers, in keeping with documents and records plan.
		Changed that the plasma bridging between the outer vessel and the upper -1c reentrant flange has a temperature of 0.1 eV. This is in Table 4.4, row 1.
2	11/20/18	Fixed a typo in Table 2-2 (the drift time for centered plasmas was 0.002 seconds, now set to N/A). Also fixed the caption in Table 2.2, which was a copy/paste error in Rev. 1 of this document. Finally, added parameters for new shapes Aux. 1 and Aux. 3.
		Augmented Table 2.1 with the new scenarios Aux. 1 through Aux. 3
		Added 4j, along with Table 4.5.
		Adjusted Figure 2.1 to show the new shapes Aux. 1 through Aux. 3.
		Added Appendix 2 and Appendix 3.
		Added note in Table 4.2 and 4.3 that the bellows and CHI bus rises should have the halo current fraction computed, and the TPF may be computed.

		Changed Project Engineer to Y. Zhai; consolidated the PFC and VV&IH REs to a single person as per Engineering Department change

References:

[1] NSTX-U-RQMT-GRD-001, *NSTX-U General Requirements Document*

[2] DIS-170511-SPG-02, *Design Guidance for halo currents in NSTX-Upgrade*

[3] DIS-180529-SPG-02, *Local Field Variations at the Passive Plates*

[4] DIS-180529-SPG-01, *Spectrum of Quench Rates and Fast Disruptions*

1. Scope

a. Components on NSTX-U shall be designed to withstand forces and loads due to plasma disruption [1].

b. These loads can include thermal loads, eddy current loads, and halo current loads, as described in Table 1.1.

Table 1.1: *Different load types from plasma disruptions.*

Load	Description
Thermal	The disruption process can result in significant impulsive heat loads to in-vessel surfaces, either from radiation from the plasma or direct and rapid conduction of plasma heat.
Eddy Current	Rapid changes to the plasma equilibrium (loss of vertical position control, loss of I_P) results in flux-swings through conducting structures. This in turn creates currents in those structures, that interact with the local field to create JxB forces on the components.
Halo Current	Current injected from the plasma into the PFCs or in-vessel structures when position control is lost and the plasma comes in contact with those structures. The current returns to the plasma in another location, after passing through vessel structures and components. JxB forces are applied to the structures in the current path.

c. Table 1.2 describes some typical components and the types of disruption loads to which they may be exposed. Other structures and components not mentioned in the table may additionally be subject to loads.

Table 1.2: *Types of disruption loads typically experienced by various components. Note that the table is not exhaustive with regard to components that can experience disruption loads, and a specific assessment should be made for each component under considerations*

	Thermal Loads	Eddy Current Loads	Halo Current Loads
Plasma Facing Components	X	X	X
Passive Plates		X	X
CS Casing		X	X
Vessel	X	X	X
Window Shutter	X	X	

d. Eddy current flow in these structures shall be calculated based on the disruption cases described in Section 2. Halo current flow shall be computed based on assumptions presented in Section 3.

e. Forces shall be calculated based on the induced current flow calculated from the disruption scenario, plus the halo current, crossed with the worst case field at each location which causes the magnitude of the force to be maximized at that location. See Section 3 for definition of worst case field.

2. Eddy Current Loads

a. Two disruption modes shall be assessed in the context of eddy currents:

Mode 1: induction due to current quench where the plasma position is fixed and no halo currents are included.
Mode 2: Induction due to both plasma motion (e.g. Vertical Displacement Event (VDE) or inward translation of the plasma) and the current quench, with halo current included.

Note that current flow in conducting structures, crossing with the background toroidal and poloidal fields, generally produces a force towards the plasma during the current quench, and forces either towards or away from the plasma due to plasma motion depending on the location of the component and the direction of plasma motion,

b. The disruption requirements for Mode 1 and Mode 2 are phrased in terms of seven plasma cross-sections, indicated in Fig 2.1 and described in Table 2.1, with the cross-sections denoted P0-P6. The P0 cross-section is a full plasma cross-section, as specified by the 95% surface parameters of the GRD in section 4.1.2. The P1 cross section is a slightly elongated circle centered at the midplane. The cross-sections P2-P6 and Aux. 1 through Aux. 3 represent different shifted plasma configurations.[1]

***Table 2.1**: Locations of plasma for various disruption cases.*

Location		Shaped	Centered	Offset, Midplane	Offset, Inboard	Offset, Central	Offset, Outboard	Crown	Crown	Crown	IBDH Halo
Designation		P0	P1	P2	P3	P4	P5	P6	Aux. 1	Aux. 2	Aux. 3
R, Center	m	0.950	0.934	0.720	0.740	0.850	1.000	0.630	0.725	0.680	0.776
Z, Center	m	0.000	0.000	0.000	-0.950	-0.790	-0.650	-0.830	-0.910	-0.810	-0.940
Minor radius	m	0.570	0.570	0.400	0.344	0.395	0.395	0.293	0.370	0.350	0.320
κ	---	2.500	1.130	1.310	1.700	1.700	1.500	1.700	1.500	1.500	2.000
δ	---	0.600	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.400

[1] Note that Rev. 0 of this RD utilized circular plasmas at the final locations. These are indicated in Appendix 1. Calculations utilizing those shapes shall be considered valid, and no recalculation with the elliptical shapes is required if components satisfy the loading associated with the Rev. 0 shapes.

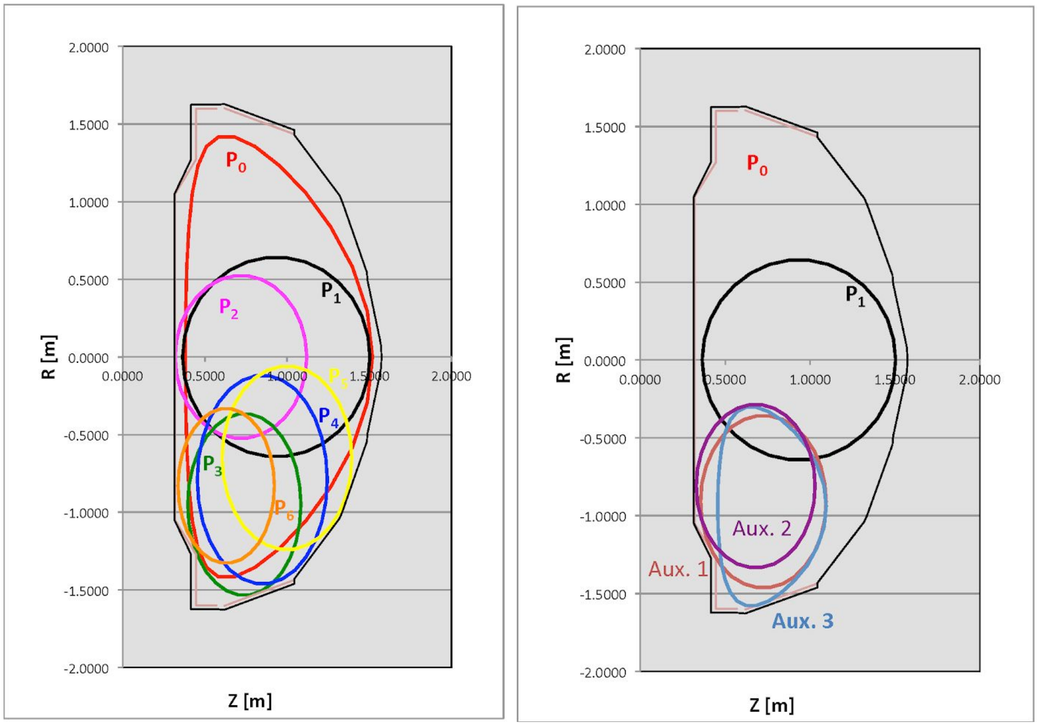


Fig. 2.1*: Various plasma shapes used in the disruption simulations. Shapes P0-P6 shall be used for most analysis. The shapes Aux. 1 through Aux. 3 <u>may</u> be used for specific CS-Casing related requirements.*

c. The eddy current dynamics shall be derived from the data in Table 2.2. In most cases, the plasma starts in an initial position. For a basic calculation, the current at that location is ramped down, while the current at a second position is ramped up; this simulates the effect of plasma motion, and is indicated in Fig. 2.2.

d. If desired to provide higher fidelity, the process or ramping one current down and another up may be repeated at an intermediate number of locations between the stated initial and final positions, simulating the plasma drift. The total time across all transitions should be identical to that implied by c).

e. These particular cases are described as follows:

- **Scenario 0** (2 cases): Centered major disruptions in the shaped plasma cross-section (P0). No halo current considered.
- **Scenario 1** (2 cases): Centered major disruptions in the circular shaped plasma cross-section (P1). No halo current considered.
- **Scenario 2** (3 cases): Inward shift (P2) to the elliptical shaped plasma cross-section. Consider halo current.
- **Scenario 3** (4 cases): Down and inboard (P3) shift to the elliptical shaped plasma cross-section. Consider halo current.

- **Scenario 4** (4 cases): Down and centered (P4) shift to the elliptical shaped plasma cross-section. Consider halo current.
- **Scenario 5** (4 cases): Down and outboard (P5) shift to the elliptical shaped plasma cross-section. Consider halo current.
- **Scenario 6** (4 cases): Down and angle-section (P6) shift to the elliptical shaped plasma cross-section. Consider halo current.
- **Scenario A1** (4 cases): Down and angle-section (Aux. 1) shift to the elliptical shaped plasma cross-section. Consider halo current. This case has a slightly lower center than P6.
- **Scenario A2** (4 cases): Down and angle-section (Aux. 1) shift to the elliptical shaped plasma cross-section. Consider halo current. This case is a slight variation on P6.
- **Scenario A3** (4 cases): Down and inboard (Aux. 1) shift to the elliptical shaped plasma cross-section. Consider halo current. This case has a slightly different shape that P3, allowing halo currents to enter the inner horizontal target tiles (see Section 4)..

f. The column "Consider Halo Current" in Table 2.2 indicates whether the halo current loading described in Section 3 should be included in the load inventory. If the column indicates "No", then halo currents need not be applied. If "Yes", then halo currents should be applied if they increase the load from eddy currents, but should not be applied if they decrease the load.

g. For small components, maps of dB/dt from previously run computations of these scenarios can be used to assess eddy currents

Table 2.2*: Parameters describing the VDE and current quench dynamics.*

Scenario category	Mode	Disruption scenario description	Initial Ip [MA]	Initial position index	Final position index	Drift time [s]	Quench time [s]	Ip quench rate [GA/s]	Consider Halo Current
0.1	1	Centered disruption, shaped plasma, fast quench	2	P0	P0	N/A	0.001	2	No
0.2	1	Centered disruption, shaped plasma, medium quench	2	P0	P0	N/A	0.004	0.5	No
1.1	1	Centered disruption, circular plasma, fast quench	2	P1	P1	N/A	0.001	2	No
1.2	1	Centered disruption, circular plasma, medium quench	2	P1	P1	N/A	0.004	0.5	No
2.1	2	Inward drift to CS, fast quench, halo	2	P1	P2	0.01	0.001	2	Yes
2.2	2	Inward drift to CS, medium quench, halo	2	P1	P2	0.01	0.004	0.5	Yes
2.3	2	Inward drift to CS, slow quench, halo	2	P1	P2	0.01	0.01	0.2	Yes
3.1	2	Vertical drift to inboard, fast quench, halo	2	P1	P3	0.01	0.001	2	Yes
3.2	2	Vertical drift to inboard, medium quench, halo	2	P1	P3	0.01	0.004	0.5	Yes
3.3	2	Vertical drift to inboard, slow quench, halo	2	P1	P3	0.01	0.01	0.2	Yes
3.4	2	Vertical drift to inboard, very slow quench, halo	2	P1	P3	0.01	0.1	0.02	Yes
4.1	2	Vertical drift to middle, fast quench, halo	2	P1	P4	0.01	0.001	2	Yes
4.2	2	Vertical drift to middle, medium quench, halo	2	P1	P4	0.01	0.004	0.5	Yes
4.3	2	Vertical drift to middle, slow quench, halo	2	P1	P4	0.01	0.01	0.2	Yes
4.4	2	Vertical drift to middle, very slow quench, halo	2	P1	P4	0.01	0.1	0.02	Yes
5.1	2	Vertical drift to outboard, fast quench, halo	2	P1	P5	0.01	0.001	2	Yes
5.2	2	Vertical drift to outboard, medium quench, halo	2	P1	P5	0.01	0.004	0.5	Yes
5.3	2	Vertical drift to outboard, slow quench, halo	2	P1	P5	0.01	0.01	0.2	Yes
5.4	2	Vertical drift to outboard, very slow quench, halo	2	P1	P5	0.01	0.1	0.02	Yes
6.1	2	Vertical drift to angle, fast quench, halo	2	P1	P6	0.01	0.001	2	Yes
6.2	2	Vertical drift to angle, medium quench, halo	2	P1	P6	0.01	0.004	0.5	Yes
6.3	2	Vertical drift to angle, slow quench, halo	2	P1	P6	0.01	0.01	0.2	Yes
6.4	2	Vertical drift to angle, very slow quench, halo	2	P1	P6	0.01	0.1	0.02	Yes
A1.1	2	Vertical drift to angle, fast quench, halo	2	P1	Aux. 1	0.01	0.001	2	Yes
A1.2	2	Vertical drift to angle, medium quench, halo	2	P1	Aux. 1	0.01	0.004	0.5	Yes
A1.3	2	Vertical drift to angle, slow quench, halo	2	P1	Aux. 1	0.01	0.01	0.2	Yes
A1.4	2	Vertical drift to angle, very slow quench, halo	2	P1	Aux. 1	0.01	0.1	0.02	Yes
A2.1	2	Vertical drift to angle, fast quench, halo	2	P1	Aux. 2	0.01	0.001	2	Yes
A2.2	2	Vertical drift to angle, medium quench, halo	2	P1	Aux. 2	0.01	0.004	0.5	Yes
A2.3	2	Vertical drift to angle, slow quench, halo	2	P1	Aux. 2	0.01	0.01	0.2	Yes
A2.4	2	Vertical drift to angle, very slow quench, halo	2	P1	Aux. 2	0.01	0.1	0.02	Yes
A3.1	2	Vertical drift to IBDH, fast quench, halo	2	P1	Aux. 3	0.01	0.001	2	Yes
A3.2	2	Vertical drift to IBDH, medium quench, halo	2	P1	Aux. 3	0.01	0.004	0.5	Yes
A3.3	2	Vertical drift to IBDH, slow quench, halo	2	P1	Aux. 3	0.01	0.01	0.2	Yes
A3.4	2	Vertical drift to IBDH, very slow quench, halo	2	P1	Aux. 3	0.01	0.1	0.02	Yes

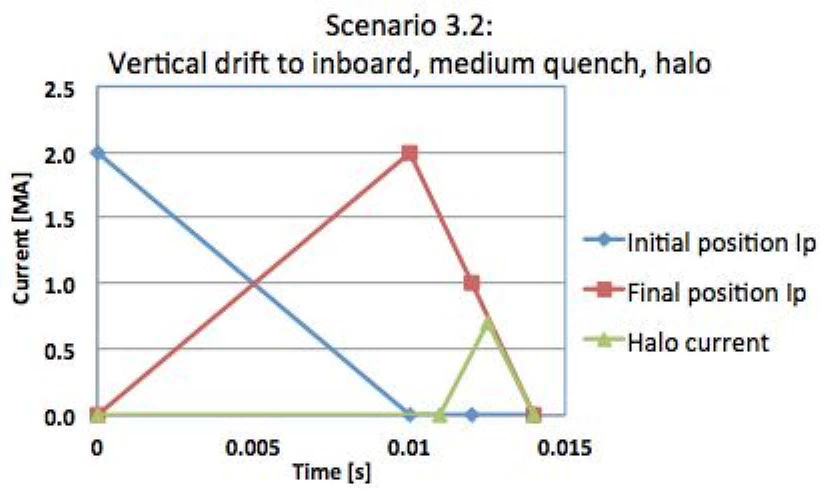


***Fig. 2.2**: Time evolution of the currents in the simulations*

3: Worst Case Fields

a. Worst case poloidal fields shall be computed at the location of interest as the *sum* of the "disruption field" and the "equilibrium field":

b. The "disruption field" is defined as the worst case field created by either of:

- The worst case of the rapidly translated plasmas in Table 2.1. This shall include the field from the translating plasma and from the eddy currents induced by that translation.
- The field from a stationary plasma located at any of the positions P1-P6.

c. The equilibrium field is defined as worst case vacuum field of the 96 equilibria from the Design Point Spreadsheet at the location of interest, scaled by a factor of 1.1.

d. These worst case fields may be corrected by experimental projections if those projections show larger fields than in a).

e. Pre-computed maps of the local field maxima may be used for small components whose presence does not appreciably modify the background fields, i.e., tiles.

4: Halo Current Loads

Halo current loads must be added to the eddy current loads for most cases in table. Halo current loads are determined from Ref. [2], and are summarized here. ***Please see that reference for elaboration.***

a. The design requirements in Table 4.1 through Table 4.5 apply to various components.

b. The toroidal distribution of halo current at a fixed poloidal location is described as a simple sinusoidal distribution, i.e., a distribution $1 + f_{\phi} cos(\phi)$, with f_{ϕ} adjusted so that the maximum halo current normalized to the toroidal average is equal to the given toroidal peaking factor (TPF). For instance, f_{ϕ} =1 yields a TPF of 2.

c. The halo current fraction f_h represents the fraction of the equilibrium plasma current that enters the PFCs surface, i.e. $f_h = I_h / I_P$.

d. The halo current time evolution shall be taken as a triangle, with peak amplitude given by 4b)-4c). The base of the triangle shall be 3 msec wide, with the halo current pulse ending when the plasma current goes to zero. See Fig. 2.2 for an example of this evolution.

e. There are two types of halo currents considered here: the *normal halo currents*, where the halo currents flow into and out of the plasma-facing surface of the PFCs, and the *structure currents*, which connect the input and output points via the vessel, tiles, and in-vessel components.

- The local maximum *normal halo current* density entering or exiting a tile surface can be computed as $J_{norm,max} = \left(1 + f_{\phi}\right) I_{P,max} f_h / 2\pi R w_{halo}$. This current is largely determined by plasma physics considerations.

- The “structure halo current” is intended to be that halo current that flows in both the PFCs and structures between the entrance and exit points at the tile surfaces. The nature of these currents is influenced by the design of the components through which current flows. The direction of the structure halo current can be such that, were it flowing poloidally in tiles, it would either pull the tiles away from the wall or compress them against the wall. Note that the component of the $J_{structure} \times B_T$ normal to the PFC surface will typically push the component away from the plasma, provided that the current is taking a direct path from between the halo current entrance and exit points. This current will only pull the component away from the plasma if there are “reversals” of the current. See Ref. 2 for more discussion on this point, including numerous example figures. The details of tile fastener design can also contribute to local forces and moments on tiles if those fasteners lead to local current concentrations. These details of the structure current paths and resulting load must be assessed on a case-by-case basis during design.

f. A ~20 cm poloidal width (w_{halo}) of the halo current footprint on the target should be assumed. This requirement shall apply to all wetted surfaces at the entrance of exit points.

g. A worst-case toroidal phase between the peaks at the entrance and exit locations should be assumed. This implies that there will be toroidal structure currents in the underlying structures, in addition to the poloidal structure currents that connect the entrance and exit locations.

Table 4.1: *Halo Current Requirements for Outboard Divertor*

	Component	f_h	TPF	Note
1	Tile Normal Current	±0.35	2	
2	Poloidal Structure Current Pushing Toward Vessel	0.35	2	Resistive Sharing Between Tiles and Backing Structure
3	Poloidal Structure Current Pulling from Vessel (Rows 2 & 3)	0.075	2	
4	Poloidal Structure Current Pulling from Vessel (Rows 1)	0.35	2	
5	Clevis Current	0.35	1.5	

h. Note that the clevis current can be shared among the various clevises with the TPF as per the table.

Table 4.2: *Halo Current Requirements for CS*

	Component	f_h	TPF	Note
1	IBDH Tile Normal Current	±0.35	2	---
2	IBDV Tile Normal Current	±0.10	2	---
3	Crown Normal Current	±0.10	2	---
4	CSFW Normal Current	±0.10	2	---
5	IBDV, Crown, and CSFW Poloidal Structure Current Pushing Toward the Vessel	0.1	1.5	CSFW limited disruptions, resistive sharing should be assumed
6	IBDVL, IBDHL, Crown, and CSFW Poloidal Structure Current Pulling from Vessel due to **upward VDE**	0.08	1.1	Based on evidence presented in Ref. [2], current can be assumed to flow in the casing only
7	Bellows	Computed Sharing	1.5, or Computed	See below

Note: Bellows current and TPF may be computed as per Table 4.4

Table 4.3: *Halo current requirements for other components.*

	Component	f_h	TPF	Note
1	PPP/SPP Tile Normal Current	0.35	2	---
2	CHI Bus Risers	Computed Sharing	1.5, or computed	See below
3	Structure Current in Outer Vessel	0.1	1.1	---

Note: CHI bus riser current and TPF may be computed as per Table 4.4

i. As elaborated in Ref. 2, when the halo strike lines bridge the inner-outer vessel boundary, there are up to three possible current paths, corresponding to i) arcing across the tiles (between the IBDH and OBDR1 tiles), ii) flowing through the bellows and other structural elements to close the circuit, iii) and flowing through any elements shunting the bellows (the bakeout bus work, for instance, or the upper "shims"). The $I_H=f_hI_P=0.35I_P$ current shall be resistively/inductively distributed amongst these paths, with an assumption of 1 eV deuterium plasma filling the IBDH/OBDR1 tile gap. Further details are provided in Table 4.4

Table 4.4: *Halo current calculations in bellows to supplement 4.i).*

1	Upper	For the upper case, a 0.1eV deuterium plasma of height 1 cm can be assumed to be filling the PF-1cU-vessel gap, resulting in a resistance in series with the bellows and any metal parts. This plasma forms a parallel path to the 1 eV plasma conducting across the IBDH/OBDR1 gap. Shims may be included as additional parallel paths if they have reliable electrical characteristics.
2	Lower	All three parallel paths in i. shall be included in the assessment of the inductive/resistive current sharing

j. Where halo current entrance and exit points need to be specified in support of structural calculations, the locations used in Table 4.5 shall be used.

Table 4.5*: Halo current entrance and exit locations for each scenario*

	Offset - P2		IBD/OBD - P3		OBD/SPP - P4		SPP/PPP - P5		Crown - P6		
$R_{entrance,1}$ [m]	0.315	0.350	0.642	-1.600	0.780	-1.530	1.150	-1.290	0.315	-0.500	$Z_{entrance,1}$ [m]
$R_{entrance,2}$ [m]	0.315	0.150	0.830	-1.530	0.970	-1.460	1.260	-1.120	0.315	-0.700	$Z_{entrance,2}$ [m]
$R_{exit,1}$ [m]	0.315	-0.150	0.830	-1.530	1.080	-1.380	1.370	-0.890	0.445	-1.280	$Z_{exit,1}$ [m]
$R_{exit,2}$ [m]	0.315	-0.350	1.014	-1.451	1.195	-1.215	1.425	-0.700	0.445	-1.480	$Z_{exit,2}$ [m]

	Aux. 1		Aux. 2		Aux 3		
$R_{entrance,1}$ [m]	0.315	-0.680	0.315	-0.550	0.445	-1.600	$Z_{entrance,1}$ [m]
$R_{entrance,2}$ [m]	0.315	-0.880	0.315	-0.750	0.645	-1.600	$Z_{entrance,2}$ [m]
$R_{exit,1}$ [m]	0.445	-1.280	0.445	-1.290	0.750	-1.560	$Z_{exit,1}$ [m]
$R_{exit,2}$ [m]	0.445	-1.480	0.350	-1.110	0.929	-1.470	$Z_{exit,2}$ [m]

5: Shot Spectrum

a: If fatigue analysis is required, then it should be assumed that all shots disrupt with the distribution as per Table 5.1. The quench rate that gives the maximum load for a particular component shall be assumed.

Table 5.1*: Occurrence of various disruption scenarios*

Scenario Category	Final Position Indicator	Upper/Lower/Centered	Percentage
0	P0	Centered	10
2	P2	Centered	10
3	P3 or Aux. 3 (N1)	Upper	20
3	P3 or Aux. 3 (N1)	Lower	20
4	P4	Upper	10
4	P4	Lower	10
5	P5	Upper	5
5	P5	Lower	5
6	P6, Aux. 1 or Aux. 2 (N2)	Upper	5
6	P6, Aux. 1 or Aux. 2 (N2)	Lower	5

N1: either the P3 or Aux. 3 halo current path should be selected, based on whichever more severely loads the component under consideration.

N2: either the P6, Aux. 1, or Aux. 2 scenario should be selected, based on whichever most severely loads the component under consideration.

b: If components cannot be qualified based on the assumption of a) one of the approaches in Table 5.2 may be taken:

Table 5.2: *Means of developing fatigue analysis*

1	The loads can be scaled by I_P and B_T as per the shot spectrum provided in the GRD, with the same assumed spatial distribution of disruptions.
2	If needed, the quench rate distribution from Ref. [4] may be used for fatigue analysis.
3	Experimental data from NSTX and NSTX-U may be used to define occurrences of specific disruption cases, or loading on specific components.

c. Fatigue assumptions for specific components, based Tables 5.1 and 5.2, shall be documented in a design report, calculation, or memo.

6: Thermal Loads

a. Each of the two disruption heat load scenarios should be considered independently. These should be added to the heat load on any component from a full power, full duration discharge.

b. **Scenario 1** - Applicable to PFCs or any surface facing the plasma:
Disruption thermal quench loading based on thermal and magnetic energy converted to radiated power flux. Assume a radiative heat flux of 100 MW/m^2 is applied for 1 ms applied normal to the tile or component surface. This is based on an assumption of 1.5 MJ of energy in 1 ms, with 100% of the energy distributed into 15 square meters (~½ of the area).

c. **Scenario 2** - Applicable to divertor PFC loading
This Scenario has been removed in Rev. 1.

Appendices

Appendix 1: Legacy Plasma Shapes at the End of the VDE.

Table A1.1 and Figure A1.1 were used in Rev. 0 of this document, as Table 2.1 and Figure 2.1 in that revision. Analysis done using these shapes shall be considered acceptable for the qualification of components, and no reanalysis is required.

***Table A1.1**: Locations of plasma for various disruption cases.*

Location		Shaped	Centered	Offset, Midplane	Offset, Inboard	Offset, Central	Offset, Outboard	Offset, Angle
Designation		**P0**	**P1**	**P2**	**P3**	**P4**	**P5**	**P6**
R, Center	m	95% shape in section 4.1.2 of GRD	0.9344	0.5996	0.7280	0.8174	1.0406	0.6300
Z, Center	m		0.0000	0.0000	-1.1376	-1.1758	-0.8768	-0.8000
Minor radius	m		0.5696	0.2848	0.2848	0.2848	0.2848	0.2848

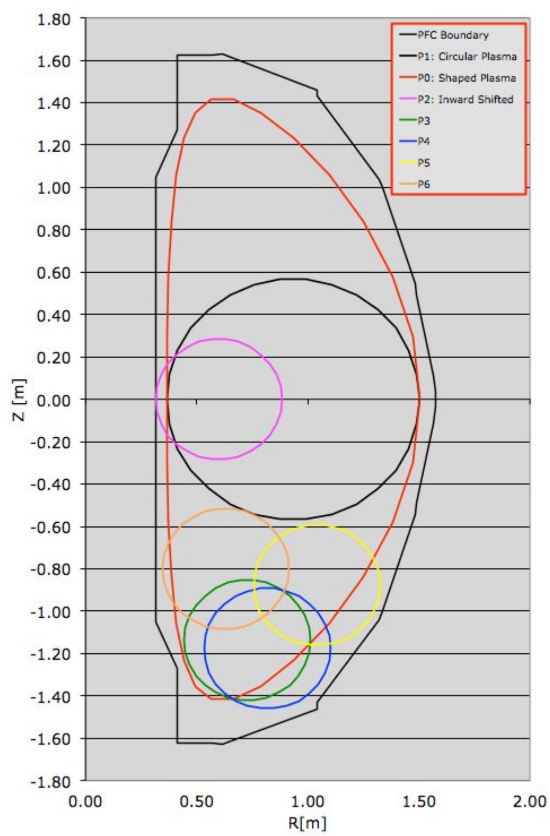


***Fig. A1.1**: Various plasma shapes used in the disruption simulations.*

Appendix 2: Halo Current Entrance and Exit Point

The scenarios noted in Table 4.5 have halo current entrance and exit points as indicated in Figs. A2.1 through A2.8.

***Figure A2.1**: Halo entrance and exit points for the P2 case*

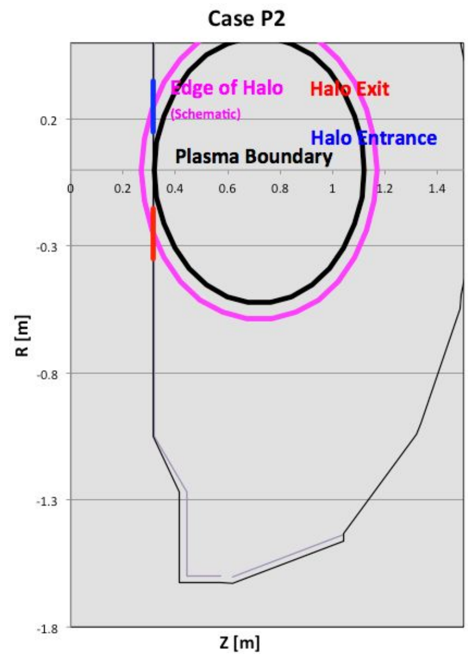


***Figure A2.2**: Halo entrance and exit points for the P3 case*

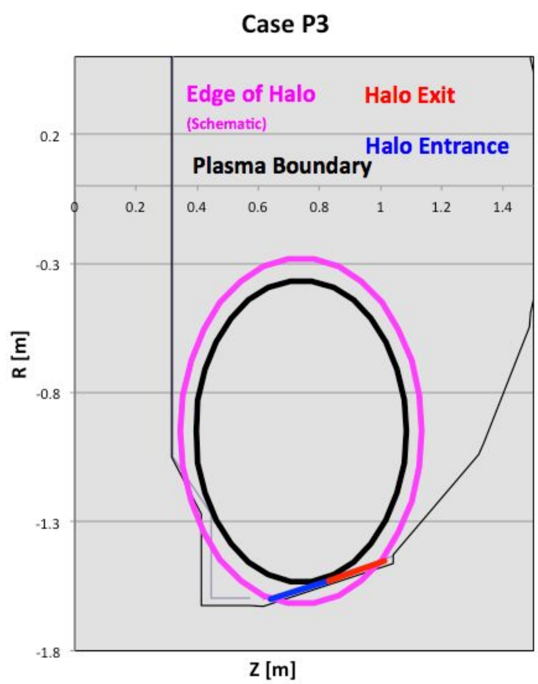


***Figure A2.3**: Halo entrance and exit points for the P4 case*

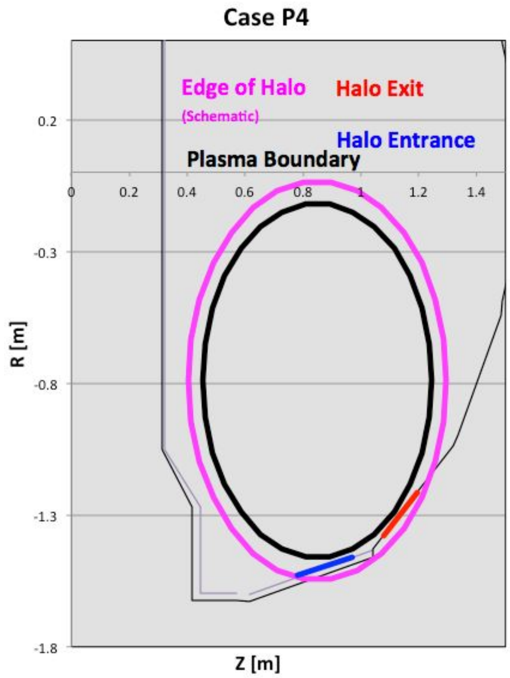


***Figure A2.4**: Halo entrance and exit points for the P5 case*

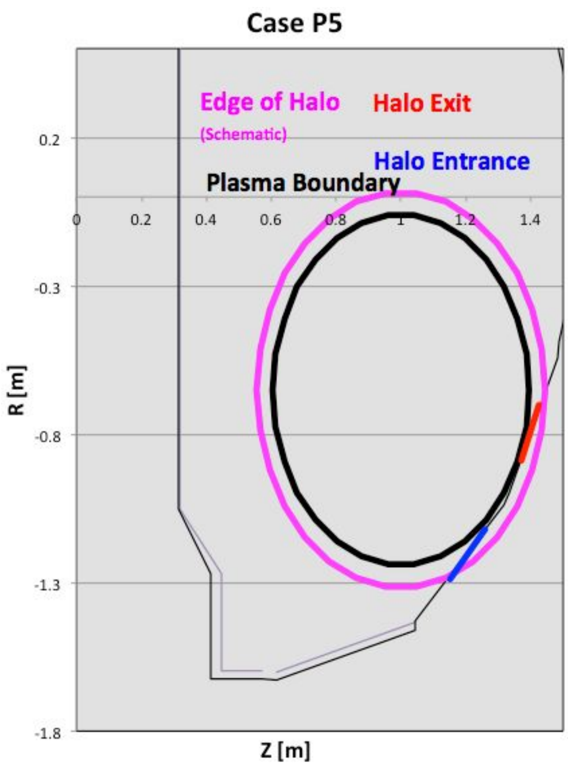


Figure A2.5*: Halo entrance and exit points for the P6 case*

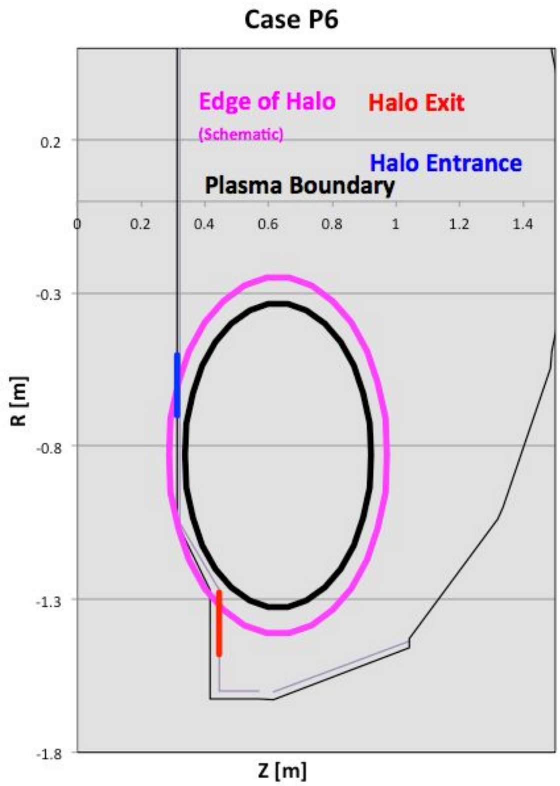


Figure A2.6*: Halo entrance and exit points for the Aux. 1 case*

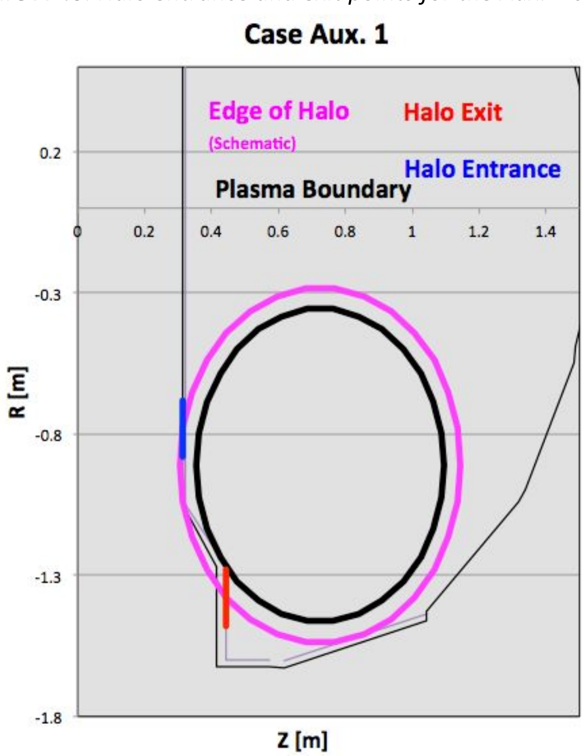


Figure A2.7: Halo entrance and exit points for the Aux. 2 case

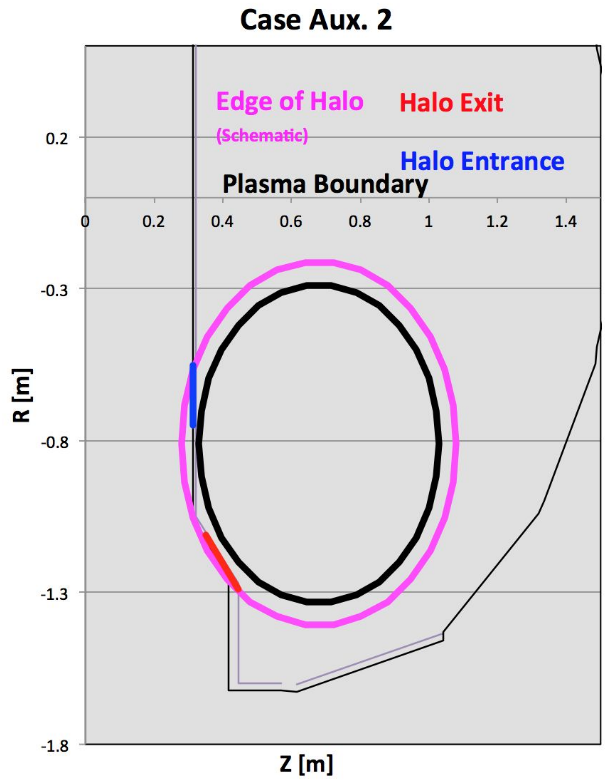
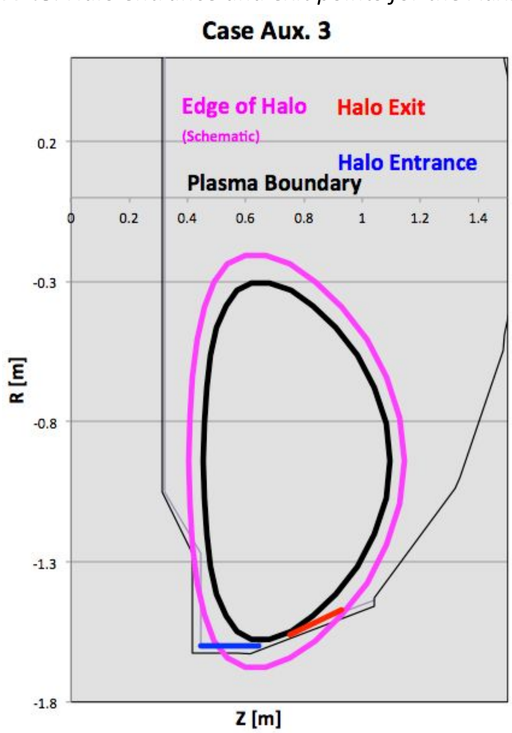


Figure A2.8: Halo entrance and exit points for the Aux. 3 case



Appendix 3: Bellows Loading

The distribution of shots for each disruption scenario is shown in Table 5.1. The distribution of load cases in Table A3.1 cases is then derived. Note that 10% of disruptions are centered at P0 and have no halo current in any structure.

Table A3.1: *Load cases on the bellows for different disruption scenarios*

Position	% of the discharges	Lower Bellows Halo Current	Upper Bellows Halo Current	CS Midplane Halo Current	CS Upper Halo Current	CS Lower Halo Current
P2	10	No	No	Yes	No	No
Aux. 3 - Upper[2]	20	Yes - modest, see footnote	Yes	Yes - modest, see footnote	Yes - modest, see footnote	Yes - modest, see footnote
P4 - Upper	10	No	No	No	No	No
P5 - Upper	5	No	No	No	No	No
Angle - Upper	5	No	No	No	Yes	No
Aux. 3 - Lower	20	Yes	No	No	No	No
P4 - Lower	10	No	No	No	No	No
P5 - Lower	5	No	No	No	No	No
Angle - Lower	5	No	No	No	No	Yes

Note: The phrase “Angle” here is a reference to the chosen P6, Aux 1, or Aux. 2 scenario used in the analysis.

The meaning of the columns are described in Table A3.2.

[2] Some upward VDEs (such as the upper Aux. 3 case) have a component of current that flows the “long way” around the vessel. The toroidal peaking factor and halo current fraction in the currents flowing around the vessel are low, resulting in minimal CS side load. See row 6 of Table 4.2, as well as Ref. [2], for additional data.

***Table A3.2**: Explanation of the load cases.*

#	Heading in A3.1	Explanation	Explanatory Figure [3]
1	**Lower Bellows Halo Current**	Current flows through the lower bellows, resulting in direct EM loads on the bellows	For the lower Aux. 3 case, in Fig. A2.8 and A3.1, current is shared between bellows, shunts, and tile-gap plasma. See Row 2 of Table 4.4 For the upper Aux. 3 case in Figs. A3.2 and A3.3, a small amount of largely axisymmetric current flows in the lower bellows. See Row 6 of Table 4.2.
2	**Upper Bellows Halo Current**	Current flows through the upper bellows, resulting in direct EM load on the bellows.	For the upper Aux. 3 case, current can be shared between the tile-gap plasma and an arc from the -1c can to the outer nozzle, as indicated in Aux. 3-2. If the upper halo current shims form a reliable electrical path, they they may also be considered in the evaluation as a third parallel path. See row 1 of Table 4.4.
3	**CS Midplane Halo Current**	Current flows through the casing near the midplane, resulting in sideways force on the CS. This force is then transferred to the bellows	For the P2 disruption as per Fig. A2.1, the current enters and exits the CS.
4	**CS Lower Halo Current**	Current flows through the casing at the bottom, resulting in sideways force on the CS. This force is then transferred to the bellows. No current flows directly in the bellows.	For the lower P6, Aux. 1 or Aux. 2 case as per Fig. A3.4, current enters and exits the casing toward the bottom. No current flows through the bellows. For the upper Aux. 3 case, a small amount of nearly axisymmetric current traverses the lower CS as per Fig. A3.3.
5	**CS Upper Halo Current**	Current flows through the casing at the top, resulting in sideways force on the CS. This force is then transferred to the bellows. No current flows directly in the bellows.	For the upper P6, Aux. 1, or Aux. 2 case, this is the mirror image of Fig. A3.4. For the upper Aux. 3 case, a small amount of nearly axisymmetric current traverses the upper CS as per Fig. A3.3.

It is noteworthy that no scenario has currents in the CS resulting in strong side loads while also having current flowing directly through the upper or lower bellows.

When the GRD shot spectrum (Table 4.1.6-1 of Ref. 1) is used in convert with the content of Table A3-1, it is possible to determine the number of shots that load the bellows in each case.

A few examples:

- For disruptions that force current through the upper bellows (Aux. 3), there are 0.2*4000 = 800 shots at $\{I_P,B_T\}$={2 MA,1T}, 0.2*6000 = 1200 shots at $\{I_P,B_T\}$={1.8 MA,0.9T}, and so on.

- For CS midplane limited disruptions (P2), there are 0.1*4000 = 400 shots at $\{I_P,B_T\}$={2 MA,1T}, 0.1*6000 = 600 shots at $\{I_P,B_T\}$={1.8 MA,0.9T}, and so on.

Fig A3.1*: Halo current flow for a case typical of a lower Aux. 3 disruption. Current is shared between plasma in the IBDH/OBDR1 gap, current flowing through the lower bellows, and current in the CHI bus work. See Row 2 of Table 4.4, and Table 4.5 for the specific entrance and exit points.*

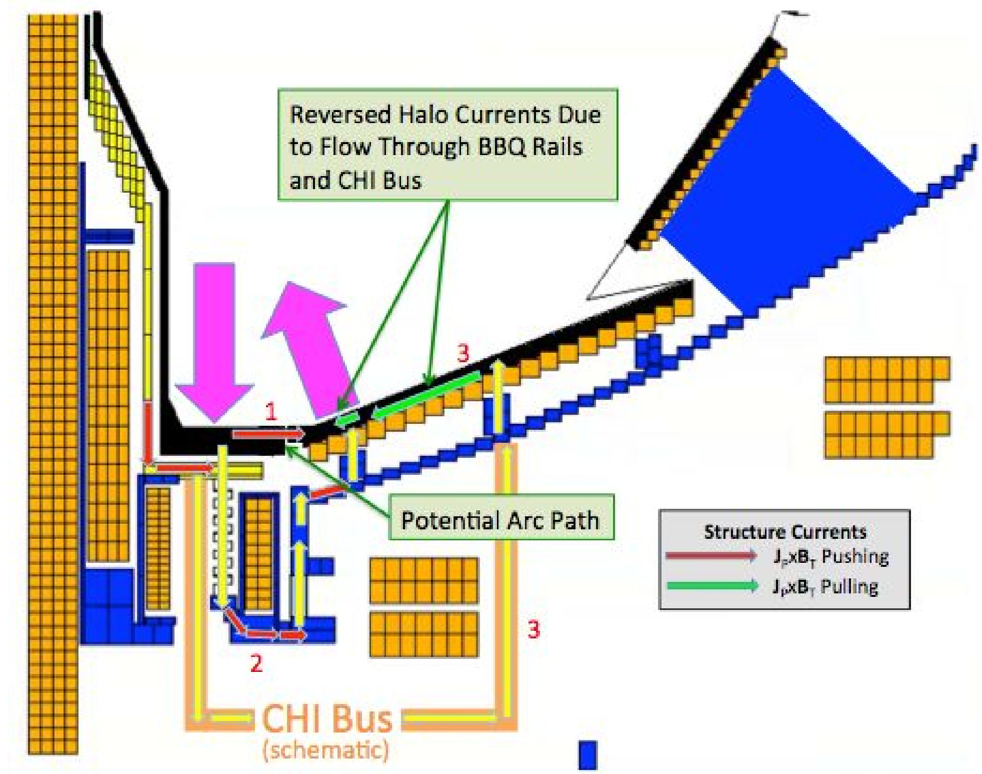


Fig A3.2: *Halo current flow for a case typical of a upper Aux. 3 disruption. Current flows between the IBDH and OBDR1 tiles via plasma bridging the gap, through the upper bellows via another plasma path, and also around the full vessel as indicated in Fig. A3.3. As per Row 1 of Table 4.4, if the upper shims provide a reliable electrical path, then they may be considered as an additional parallel path. See Row 1 of Table 4.4 for computation of the current sharing amongst the parallel paths, and Table 4.5 for the specific entrance and exit points.*

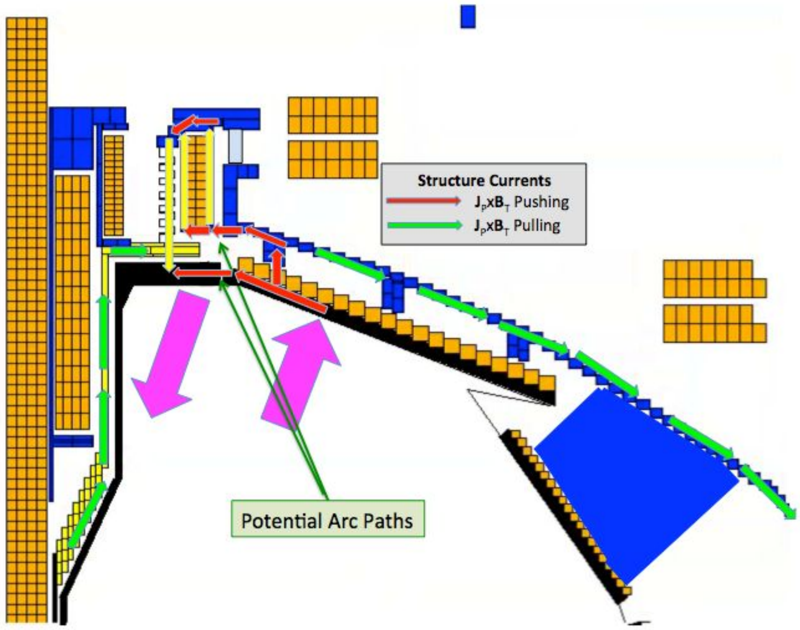


Fig A3.3: *Halo current flowing around the full vessel for an upper P3 disruption [3]. As per row 6 of Table 4.2, the peaking factor and halo current magnitude for the component flowing around are small, resulting in modest side loads. Note that this case also has current flowing directly in the upper bellows.*

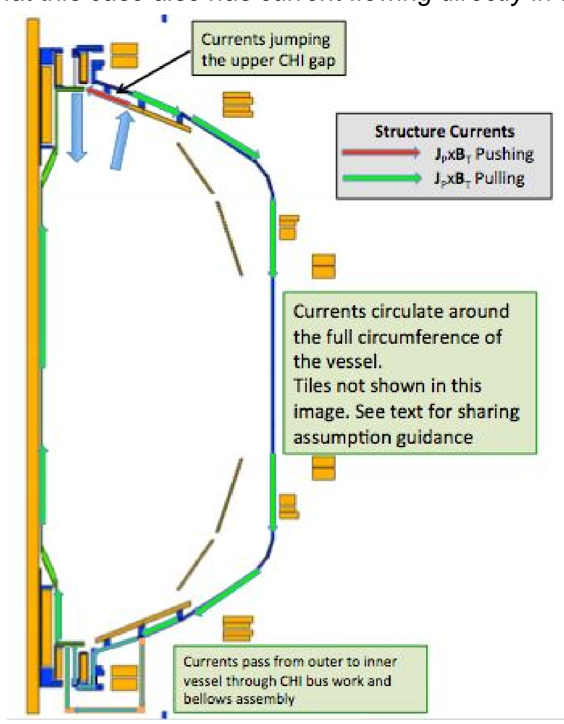


Fig A3.4*: Halo current flow for a case typical of an Aux. 1, Aux. 2, or P6 disruption. For the Aux. 2 disruption, the exit point is actually on the angled section, not the vertical target.*