Calculation No: NSTXU-CALC-011-08-00 **Revision No: 0**

Title: **PFCs Fields and dBdts**

Purpose of Calculation: (Define why the calculation is being performed.)

Calculate the worst case magnetic fields and dB/dts at the PFCs during the 96 operating scenarios and 7 plasma disruption scenarios

Codes and versions: (List all codes, if any, used)

Spark v2.0

References (List any source of design information including computer program titles and revision levels.)

See attached report section "References"

Assumptions (Identify all assumptions made as part of this calculation.)

See attached report section "Assumptions"

Calculation (Calculation is either documented here or attached)

See attached report sections "Method of Analysis" and "Results"

Conclusion (Specify whether or not the purpose of the calculation was accomplished.)

The B and dB/dt values at the PFC tiles are tabulated in the results section of the attached report. The data is intended to be used in further analysis of the PFCs. See section "Using Results - Halo Currents and Forces"

Cognizant Individual (or designee) printed name, signature, and date

Michael Jaworski Digitally signed by Michael Jaworski Date: 2018.10.11 11:11:01 -04'00' M. Jaworski

Preparer's printed name, signature and date

Art Brooks Digitally signed by Art Brooks Date: 2018.09.13 07:45:14 -04'00' A.Brooks

I have reviewed this calculation and, to my professional satisfaction, it is properly performed and correct.

Checker's printed name, signature, and date

Peter H. Titus Digitally signed by Peter H. Titus Date: 2018.09.12 17:07:55 -04'00' P. Titus

Checks for Calculation No: NSTXU-CALC-011-08-0 #
Revision No: #

Title PFCs Fields and dBdts

Component was checked against latest design
Yes

All required load cases are included and current

Yes – Envelope of all GRD specified disruptions and all 96 EQ

Discuss method used in the calculation

The calculation uses the SPARK Code to run multiple disruptions and envelope them. The solution includes the effects of passive structures. The background fields are calculated using a fortran code that readily allows all 96 EQ to be checked. These checkers calculations may be found in the DRAFT calculation NSTXU-CALC-13-07-00. dBdt's were also compared with measured and extrapolated values based on the NSTXU 2016 run magnetics data to ensure conservative dBdt's were being specified for the tiles – See Appendix I.

Discuss how the calculation was checked (*)

The calculation was checked using a code that uses elliptic integrals to calculate fields from the coil set for all 96 EQ and tallies maxima and minima. This is similar to the Fortran code used in the main calculation. The disruption dBdt's were checked by calculating the static field around the final plasma shape and location prior to quench, then dividing that field by the quench time. This approach is best for components not shielded by or affected by passive structures the vessel and tile support hardware. It produces larger dBdt's because the passive structure shielding effects mitigate the field transients.

List issue identified and how they were resolved

There is a possibility that drift times larger than those in the GRD may alter the passive structure shielding effect. This is considered outside the scope of this calculation because drift times were as specified in the GRD and RD and the dB/dt values should be driven by the quench times which were also those specified in the GRD

Checker's name: Peter H. Titus Peter H. Titus Digitally signed by Peter H. Titus Date: 2018.09.12 17:08:45 -04'00'

Technical Authority: Andrei Khodak Digitally signed by Andrei Khodak Date: 2018.09.27 10:21:26 -04'00' (sign and date)
Andrei Khodak (TA Alternate)

(*) See Appendix II at the end of the calculation

National Spherical Torus eXperiment - Upgrade

NSTX-U

PFCs Fields and dBdts

NSTXU-CALC-11-08-00

October 13, 2017

Prepared By:
Art Brooks Digitally signed by Art Brooks Date: 2018.10.01 08:55:31 -04'00'
Art Brooks, Engineering Analyst
Reviewed By:
Peter H. Titus Digitally signed by Peter H. Titus Date: 2018.10.01 10:02:50 -04'00'
Peter Titus, Group Head, Engineering Analysis Group

NSTX-U CALCULATION

Record of Changes

Rev.	Date	Description of Changes	Revised by
0	01/17/18	Initial Release	

Executive Summary

This report is intended to provide input to designers of the PFCs that can be used to calculate Lorentz forces on tiles from plasma disruption. That input is in the form of fields and dBdts at each of the PFCs.

The results calculated herein are compared in Appendix I to the scaled experimental measured results provided in Ref 1. The measured results do not provide data at each of the points in this calculation but where they do agreement is reasonable except for the radial field at the IBDV. *This discrepancy at present is unresolved*. It is prudent to assume the higher measured value in further analysis.

Introduction

The analysis of the PFCs and other structures inside the VV must include their response to the Lorentz forces induced by plasma disruptions. Disruptions will induce eddy currents in surrounding conducting structures as a result of magnetic coupling with the plasma motion and decaying currents. Plasma contact with the structures can also drive large halo currents that enter the structures at one poloidal and toroidal location, flow thru the structures and return to the plasma at a different poloidal and toroidal location.

The disruption requirements are specified in NSTX-U-RQMT-RD-003-00_Disruptions which prescribes a number of scenarios of plasma shapes, movement and current decay. To use these requirements requires a global analysis of the NSTX-U Vacuum Vessel and enclosed conduction structures. From this analysis the flux swing (dBdt) at the PFC tiles and the field (B) from the plasma and induced eddy currents in the surrounding structures can be evaluated and used for detailed modeling of current flows and Lorentz forces in individual tiles.

The halo currents are also specified in NSTX-U-RQMT-RD-003-00_Disruptions as a surface current density into and out of the PFCs. The flow of current within each tile must be determined by modeling of the individual tiles, its support structure and electrical interface conductance between components, and is not part of the scope of this analysis. The fields to be used to calculate the Halo Lorentz forces are the same as for the eddy currents since they occur at roughly the same time.

This report documents the results of scanning through all the disruptions specified to determine the maximum and minimum values of dBdt at each of the PFC tile locations. The maximum and minimum values of the field at each location are also given. These dynamic fields are then added to the static background field produced by the PF and TF coils.

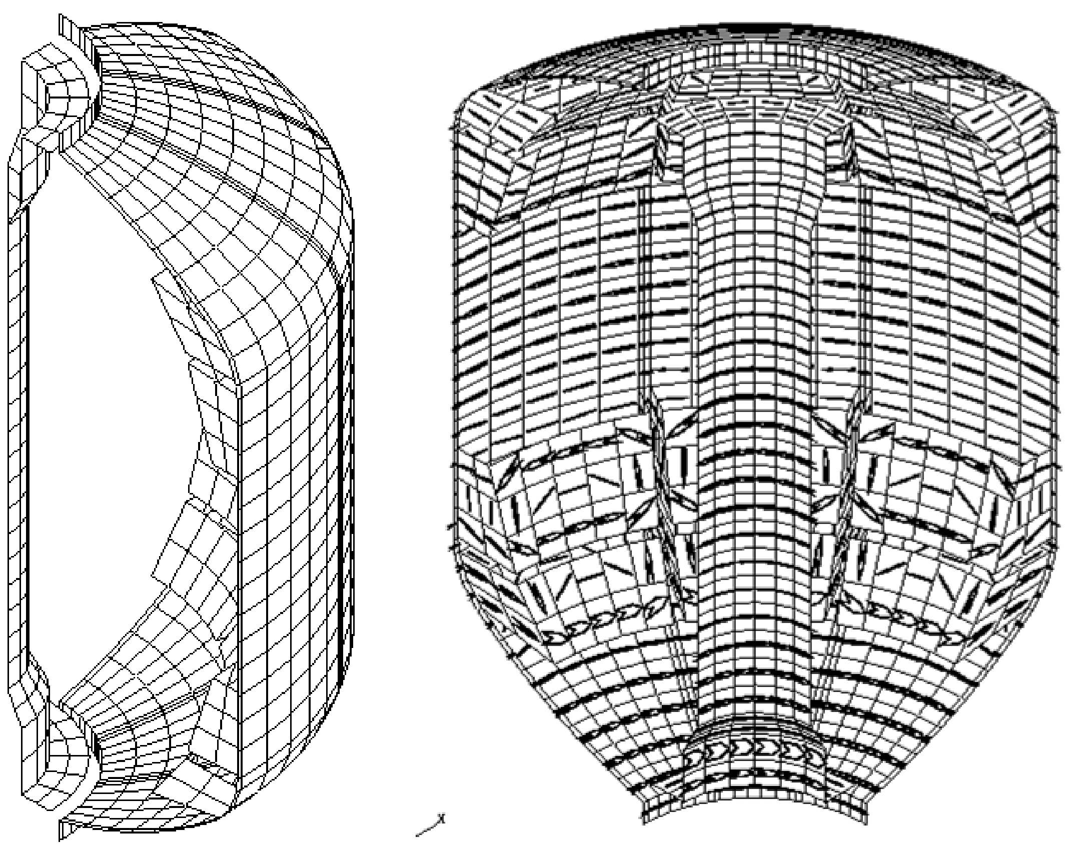
Assumptions

The determination of worst case Lorentz forces can be daunting. There are many variables that can affect the results such as plasma disruption scenario (7 cases each with many time points), pre-disruption state (assumed to be one of 96 equilibria) and the location of halo current strike and return path (infinite), not to mention the actual design and current paths thru each tile. Ideally, self-consistent calculations should be done for each combination, looking at worst case forces vs time. To simplify the process to something manageable with finite resources calculations of peak background fields for each of the 96 scenarios was done independent of the disruptions. The 7 disruption scenarios were likewise calculated independently and the peak dBdt's over time presented are not self-consistent or concurrent with the peak fields over time. This should provide a worse case.

Method of Analysis

The transient plasma disruption analysis was done using the PPL code SPARK (PPPL-2494, "Spark v1.1 User Manual, by D.W.Weissenburger, 1988. SPARK is a code based on mesh current analysis where 3D structures built of plates are modeled as a mesh of quadrilateral and/or triangular elements, each formed of resistors and inductors.

The modeled is shown. It is a 90 degree sector of the VV, CS and PP which are the primary toroidally continuous structures. (The PP is continuous thru their mounts to the VV whereas the OBD and inner PFCs are not)



90 deg model of NSTX-U VV, CS and PP

The Model is driven by a plasma which is assumed to drift and disrupt as given in the disruption requirements excerpted below.

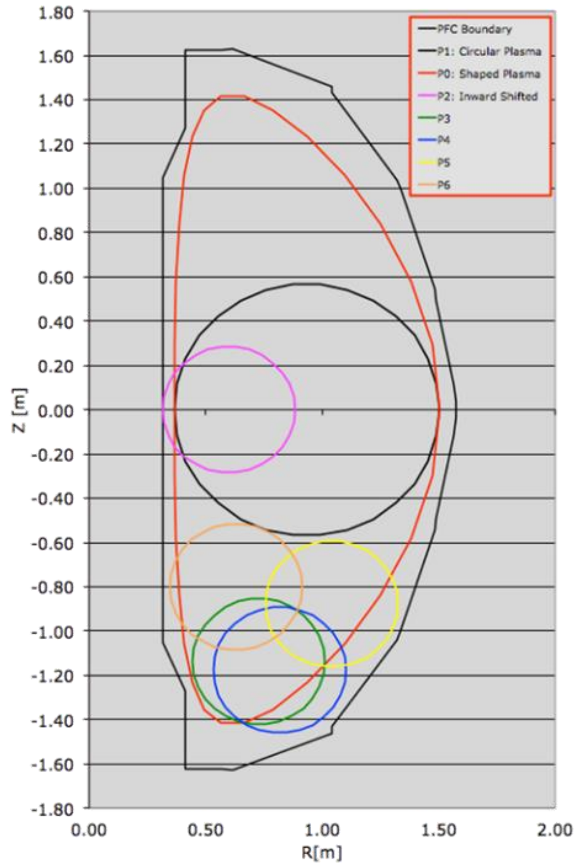
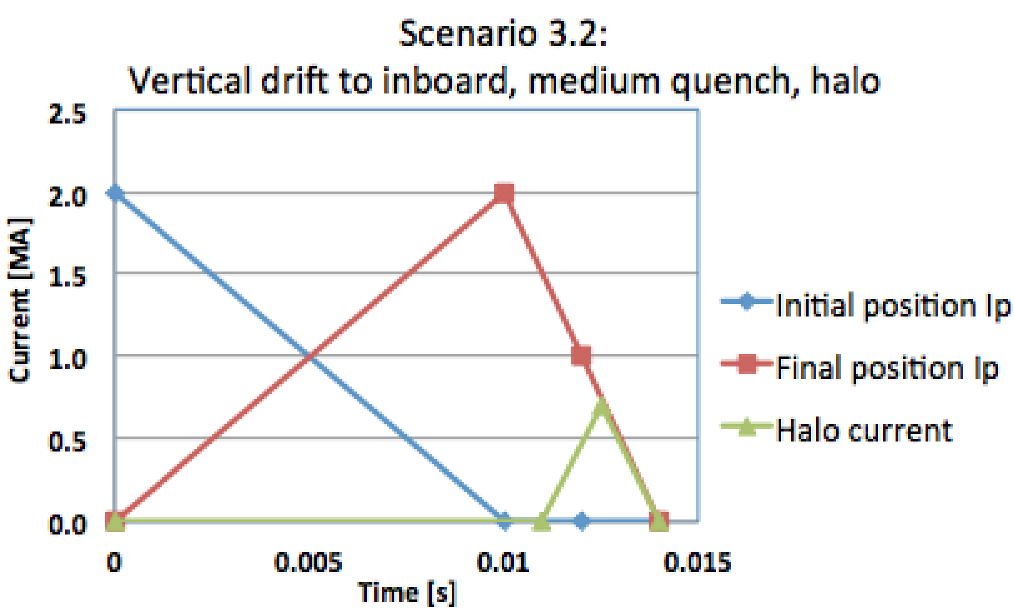


Fig. 2.1: Various plasma shapes used in the disruption simulations.



PFCs Fields and dBdts

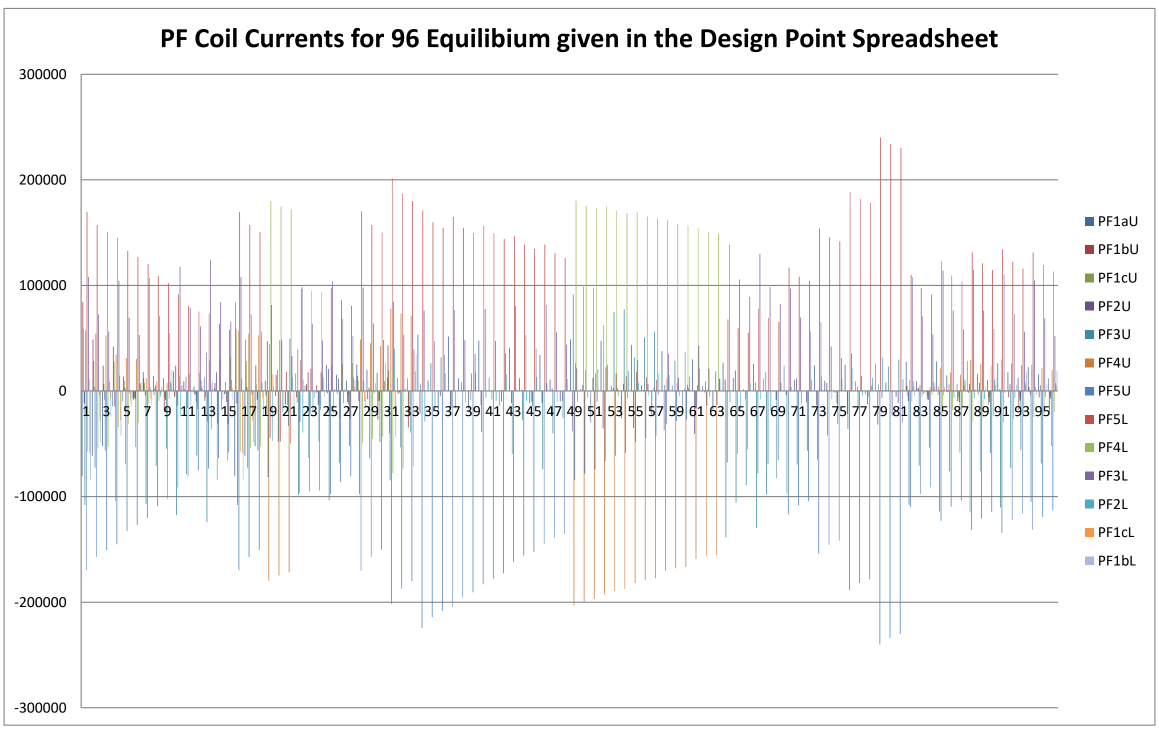
Table 2.1: Locations of plasma for various disruption cases.

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	0.002	0.001	2	No
0.2	1	Centered disruption, shaped plasma, medium quench	2	P0	P0	0.002	0.004	0.5	No
1.1	1	Centered disruption, circular plasma, fast quench	2	P1	P1	0.002	0.001	2	No
1.1	1	Centered disruption, circular plasma, medium quench	2	P1	P1	0.002	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

PFCs Fields and dBdts

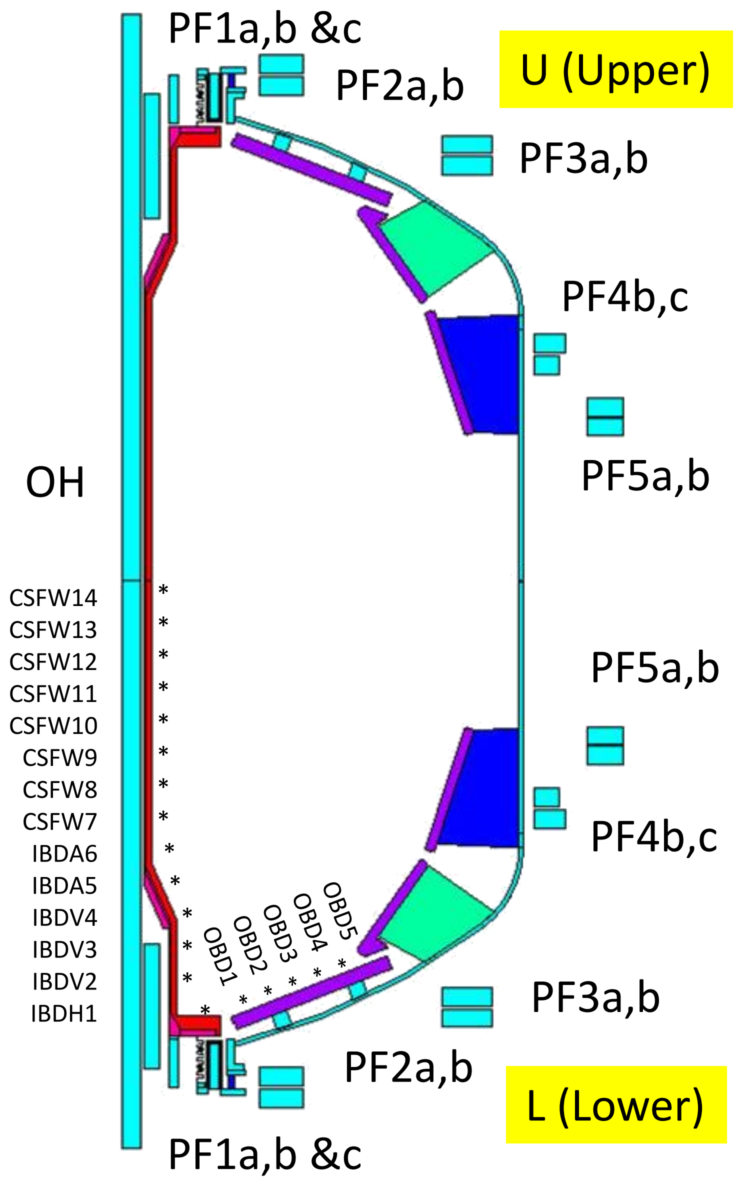
The background PF fields are calculated using the PPPL Magnetics Library of FORTRAN codes. The NSTX-U Design Point Spreadsheet defines 96 equilibrium scenarios and the PF coil geometry.

Coil	rc, m	zc, m	dR, m	dZ, m	Turns	Cur, kA
OHU	0.2421	1.0604	0.0693	2.1208	884	24
PF1a	0.3244	1.5906	0.0625	0.4633	64	19
PF1b	0.4004	1.8042	0.0336	0.1812	32	13
PF1c	0.5505	1.8136	0.0373	0.1664	20	16
PF2a	0.8000	1.9335	0.1627	0.0680	14	15
PF2b	0.8000	1.8526	0.1627	0.0680	14	15
PF3a	1.4945	1.6335	0.1864	0.0680	15	16
PF3b	1.4945	1.5526	0.1864	0.0680	15	16
PF4b	1.7946	0.8072	0.0915	0.0680	8	16
PF4c	1.8065	0.8881	0.1153	0.0680	9	16
PF5a	2.0128	0.6521	0.1353	0.0686	12	34
PF5b	2.0128	0.5780	0.1353	0.0686	12	34



PFCs Fields and dBdts

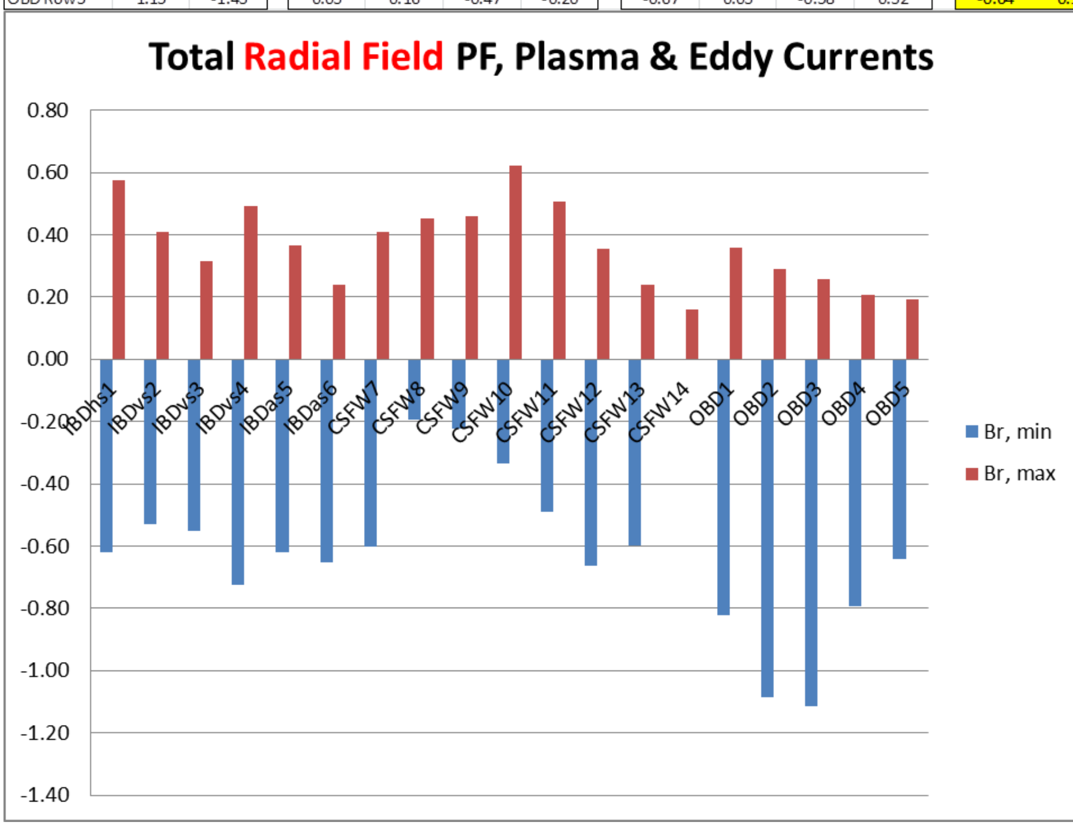
Fields and dBdts are given at the points on the PFCs identified below:



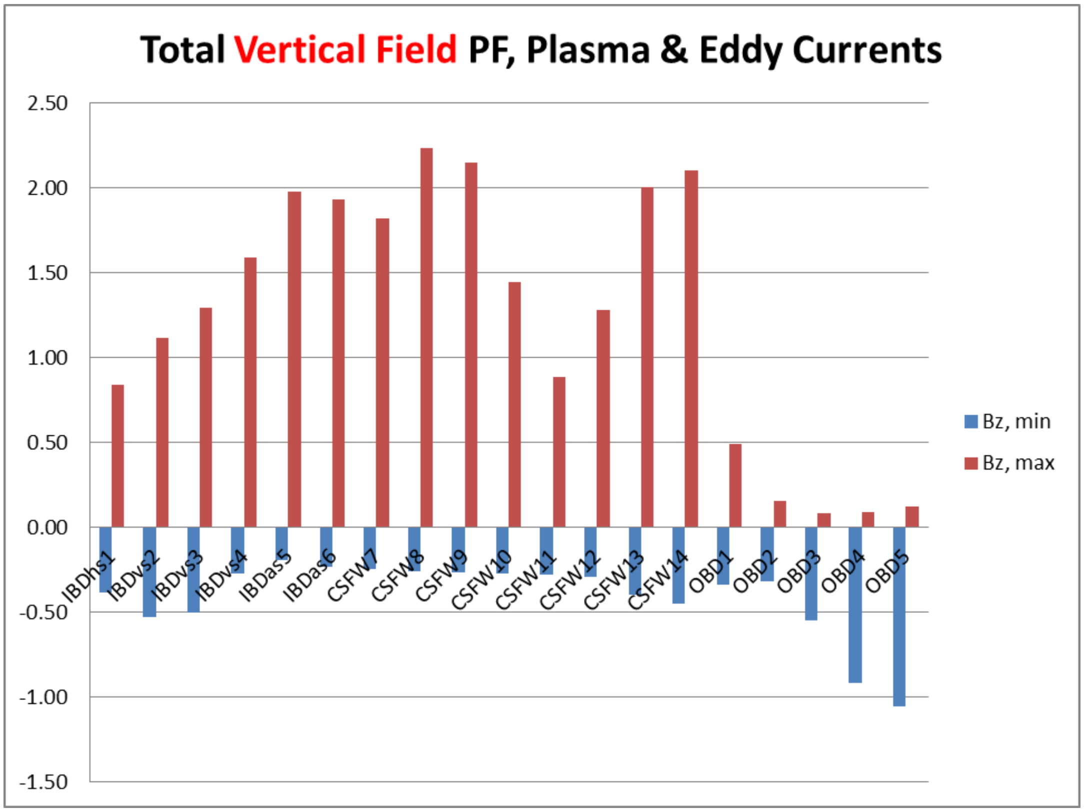
Results

The Max Field Ranges at PFCs from 96 Equilibria and 7 Disruptions Scenarios

			Max Field from 96 Scenarios (without Plasma)				Max Disruption Fields from 7 Scenarios (plasma + eddy)				Combined			
re: /p/eaddata/abrooks/nstxu/pfcalc/pfcalc3.x							(Plasma + Eddy Currents)							
Tile	r	z	brmin	brmax	bzmin	bzmax	Br, min	Br, max	Bz, min	Bz, max	Br, min	Br, max	Bz, min	Bz, max
IBDhs Row1	0.50	-1.62	0.00	0.54	-0.43	0.03	-0.62	0.04	0.04	0.81	-0.62	0.58	-0.39	0.84
IBDvs Row2	0.40	-1.56	0.01	0.39	-0.57	0.26	-0.54	0.02	0.04	0.86	-0.53	0.41	-0.53	1.11
IBDvs Row3	0.40	-1.45	0.10	0.29	-0.55	0.10	-0.65	0.03	0.05	1.19	-0.55	0.32	-0.50	1.30
IBDvs Row4	0.40	-1.33	-0.05	0.41	-0.32	-0.12	-0.68	0.08	0.05	1.71	-0.72	0.49	-0.27	1.59
IBDas Row5	0.38	-1.22	-0.03	0.27	-0.24	-0.13	-0.59	0.09	0.05	2.10	-0.62	0.37	-0.19	1.98
IBDas Row6	0.33	-1.11	-0.01	0.17	-0.29	-0.13	-0.64	0.07	0.05	2.06	-0.65	0.24	-0.23	1.93
CSFW Row7	0.31	-0.98	0.00	0.10	-0.30	-0.19	-0.61	0.31	0.05	2.01	-0.60	0.41	-0.25	1.82
CSFW Row8	0.31	-0.84	0.01	0.06	-0.31	-0.24	-0.20	0.39	0.05	2.48	-0.20	0.45	-0.26	2.23
CSFW Row9	0.31	-0.70	0.01	0.04	-0.32	-0.28	-0.23	0.42	0.06	2.43	-0.22	0.46	-0.27	2.15
CSFW Row10	0.31	-0.56	0.01	0.03	-0.33	-0.31	-0.34	0.60	0.06	1.75	-0.33	0.62	-0.27	1.45
CSFW Row11	0.31	-0.42	0.01	0.02	-0.34	-0.32	-0.50	0.49	0.06	1.21	-0.49	0.51	-0.28	0.89
CSFW Row12	0.31	-0.28	0.00	0.01	-0.35	-0.33	-0.67	0.34	0.06	1.61	-0.66	0.35	-0.29	1.28
CSFW Row13	0.31	-0.14	0.00	0.01	-0.36	-0.33	-0.60	0.23	-0.04	2.33	-0.60	0.24	-0.40	2.00
CSFW Row14	0.31	0.00	0.00	0.00	-0.36	-0.33	0.00	0.16	-0.09	2.43	0.00	0.16	-0.45	2.10
OBD Row1	0.67	-1.60	0.06	0.29	-0.38	-0.15	-0.89	0.06	0.04	0.64	-0.82	0.36	-0.34	0.49
OBD Row2	0.80	-1.56	0.06	0.21	-0.36	-0.20	-1.15	0.08	0.04	0.36	-1.09	0.29	-0.32	0.16
OBD Row3	0.91	-1.52	0.07	0.18	-0.40	-0.20	-1.18	0.07	-0.14	0.28	-1.11	0.26	-0.55	0.08
OBD Row4	1.03	-1.48	0.05	0.16	-0.45	-0.20	-0.85	0.05	-0.47	0.29	-0.79	0.21	-0.91	0.09
OBD Row5	1.15	-1.43	0.03	0.16	-0.47	-0.20	-0.67	0.03	-0.58	0.32	-0.64	0.19	-1.05	0.12



PFCs Fields and dBdts

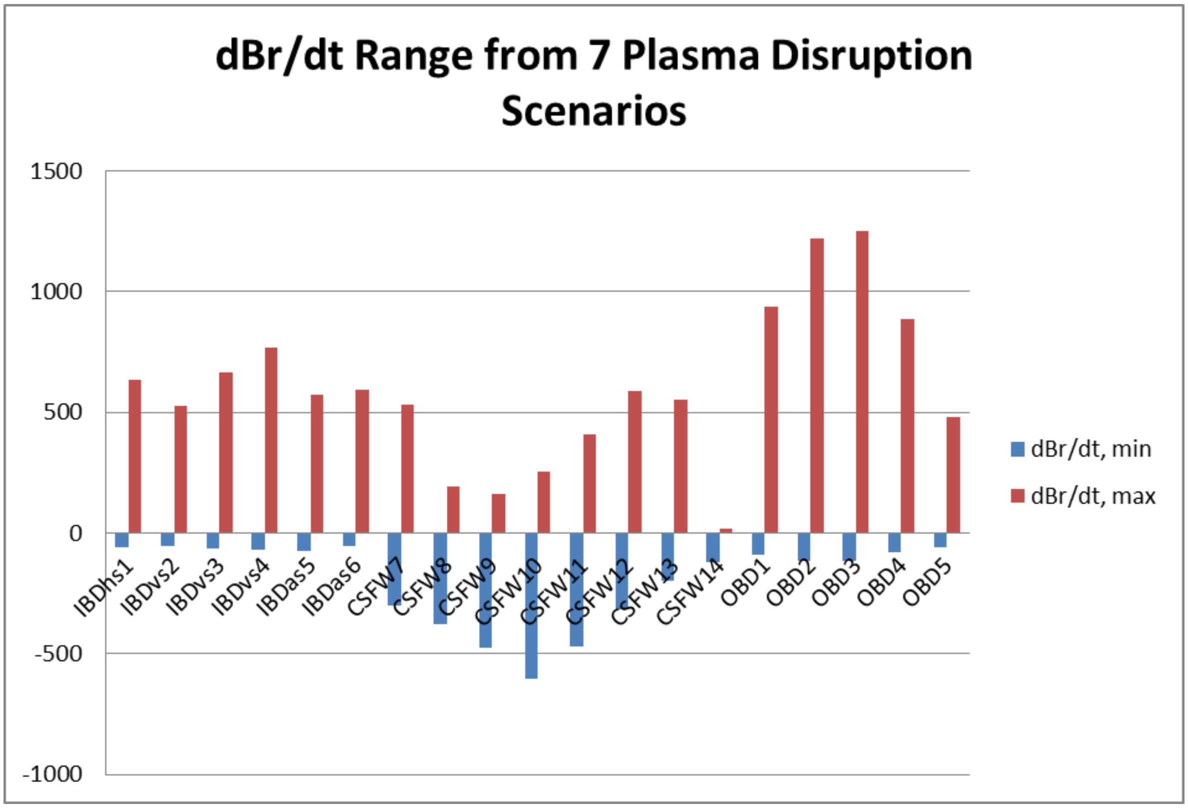


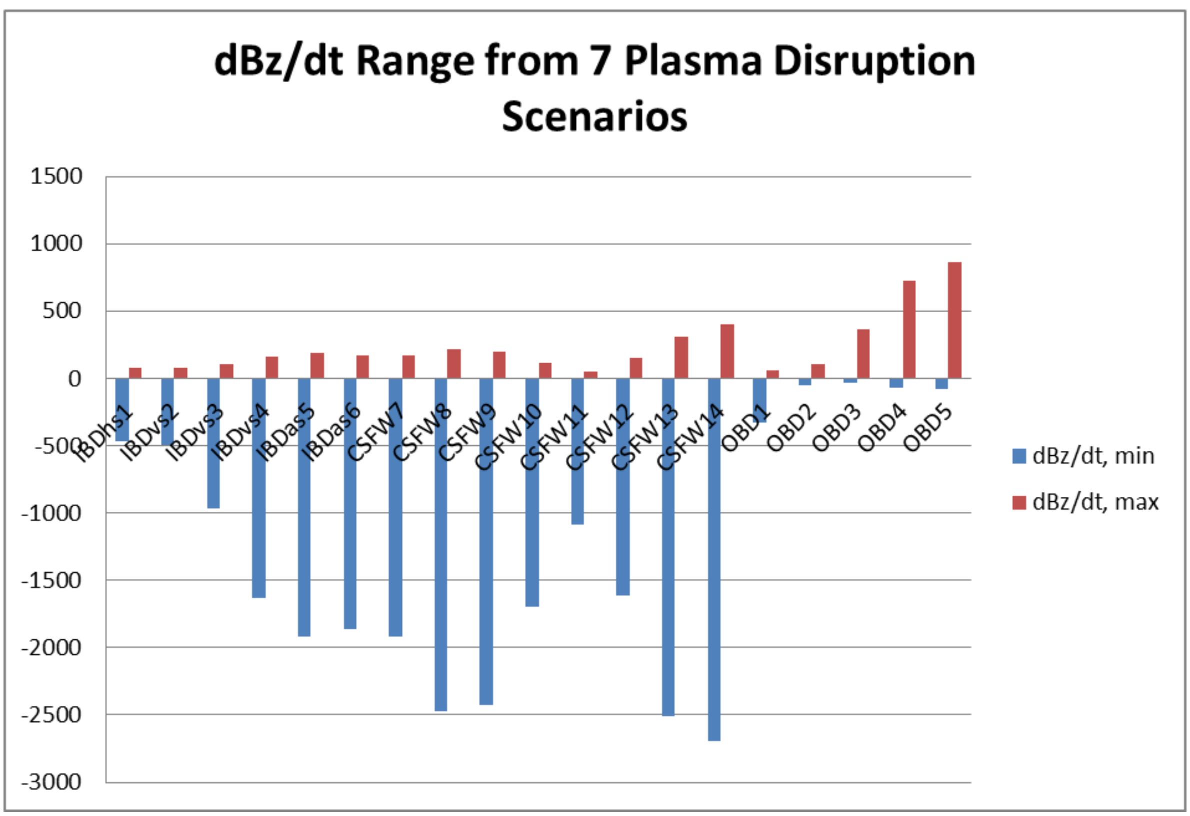
PFCs Fields and dBdts

Max dB/dt Ranges at PFCs from 7 Disruptions Scenarios

	dBrmin	dBrmax	dBzmin	dBzmax
IBDhs1	-60	636	-466	78
IBDvs2	-52	524	-496	82
IBDvs3	-63	663	-966	110
IBDvs4	-71	769	-1633	167
IBDas5	-77	574	-1920	188
IBDas6	-56	592	-1863	176
CSFW7	-303	533	-1915	170
CSFW8	-378	194	-2469	214
CSFW9	-477	160	-2430	196
CSFW10	-604	256	-1697	117
CSFW11	-472	406	-1082	52
CSFW12	-314	587	-1613	158
CSFW13	-198	552	-2508	315
CSFW14	-123	17	-2698	399
OBD1	-88	938	-327	62
OBD2	-115	1220	-47	106
OBD3	-118	1252	-35	364
OBD4	-81	883	-70	732
OBD5	-59	478	-81	865

PFCs Fields and dBdts





Using Results - Halo Currents and Forces

As described in the disruption requirements document imposed halo currents are assumed to strike in a toroidal band of specified poloidal width (poloidal footprint) on the PFCs. Current is assumed to resistively distribute within all connected structures (VV, CS, PFCs, etc) and return to plasma from a similar toroidal band at a different poloidal location.

The magnitude of the current density in the toroidal band is assumed to have a cosine variation toroidally but uniform poloidally. The strike point and return point may be phase shifted toroidally as well as striking at different poloidal locations.

At the strike points the tiles see a large thru thickness current that is independent of material resistivity. Away from strike points, tiles see predominately poloidal and toroidal currents which are shared with the underlying structure so are dependent of material resistivity, relative thickness, tile segmentation and interface conductance. Graphite tiles have a relatively high electrical resistivity ~1000 mW-cm vs SS ~74 mW-cm so currents favor underlying structure. Grafoil or gaps between the tile and support structure by design or induced by thermal distrortions further reduce the tendency for poloidal flowing currents to leak into the tiles.

Tile Halo loads need to be calculated for a given design by first calculating the resistive current distribution within the tile at a strike point using the imposed surface halo currents and tile grounding to support structures. Note since the halo current can flow in a poloidal Forces are then calculated using the above current distribution with the peak fields given herein. Peak fields can be applied in ANSYS classic by imposing constraints on the vector potential. Scripts (macros) are available to aid in this process.

Eddy loads need to be calculated for a given design by first calculating the resistive current distribution with the tile using the specified dB/dt's. Note this is only a reasonable approach for small highly resistive components that reach a resistive limit within the timescale of a disruption. Graphite tiles and Inconel structures meet this criteria. Within Ansys Classic dBdt's can be specified as a change in the magnetic field over a specified time step. The initial field is chosen such that the final field is the field of interest (given herein) for calculating forces.

Summary

The results presented herein provide the peak fields and dBdt's for the 7 disruption scenarios given in the disruptions requirements is intended to provide input to designers of the PFCs that can be used to calculate Lorentz forces on tiles from plasma disruption.

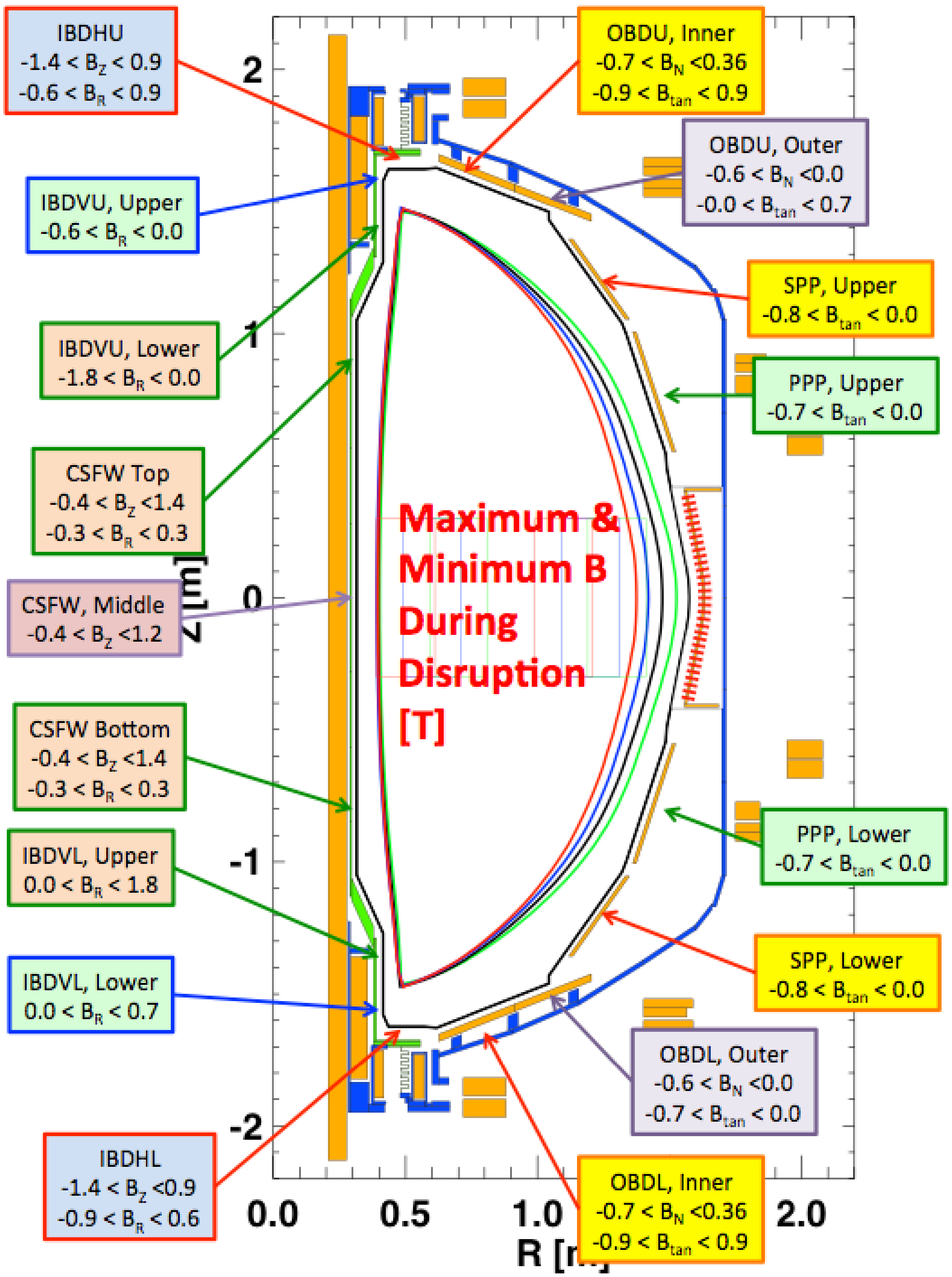
References

1) "Magnetic field strengths and time derivatives along PFCs during disruptions", memo NT-170602-SPG-01 from Stefan Gerhardt, dated 6/02/17

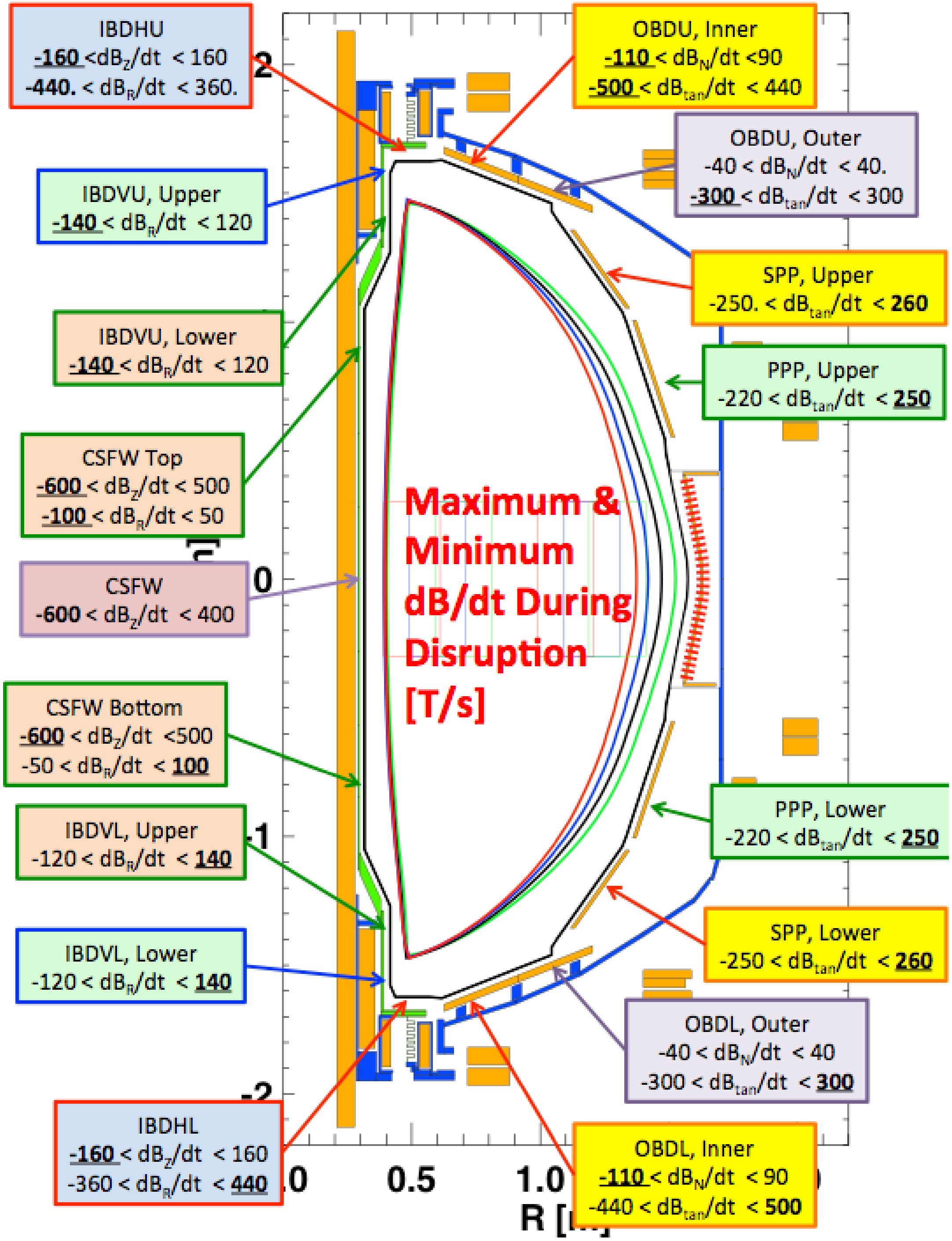
Appendix I

Calculated vs Measure/Scaled data

Reference 1 provides a scaling of the magnetic field strength and time derivatives obtained from NSTX experimental data. The summary figures are reproduced below.

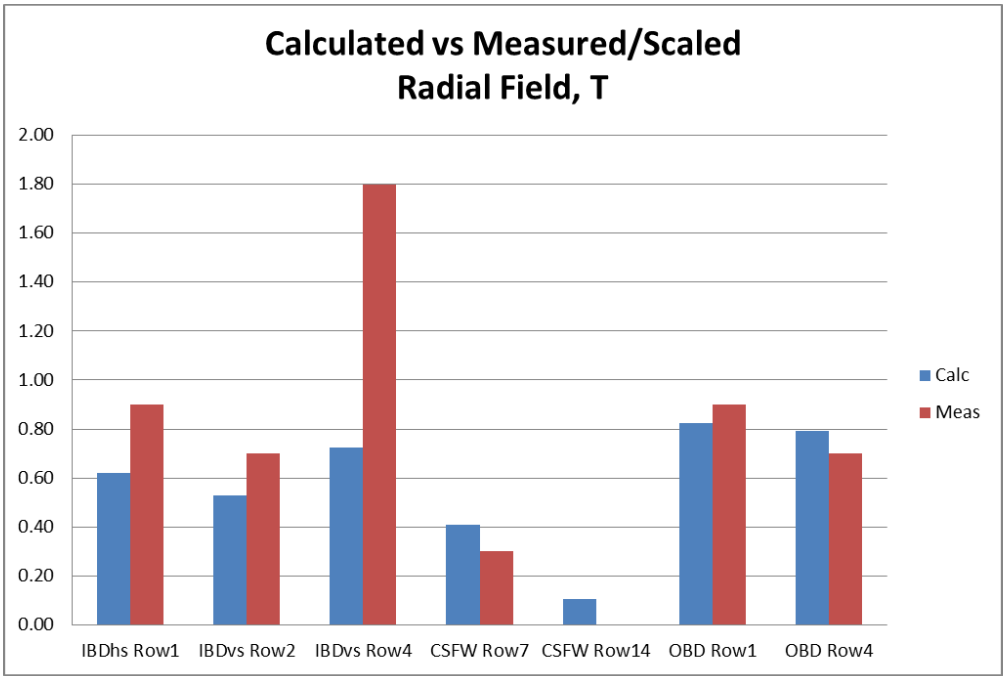


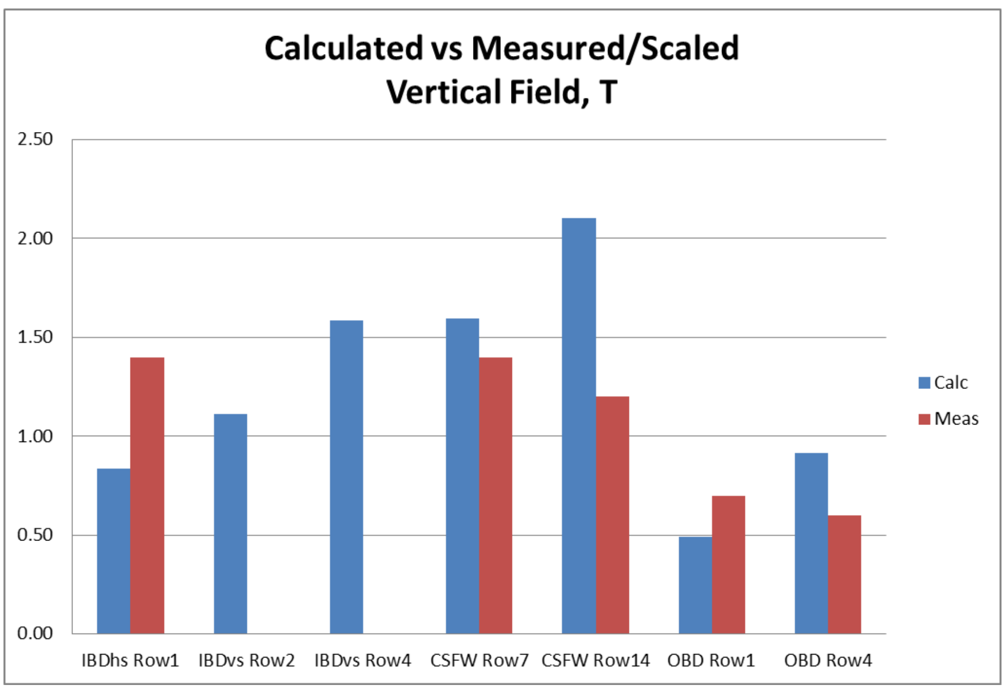
PFCs Fields and dBdts



PFCs Fields and dBdts

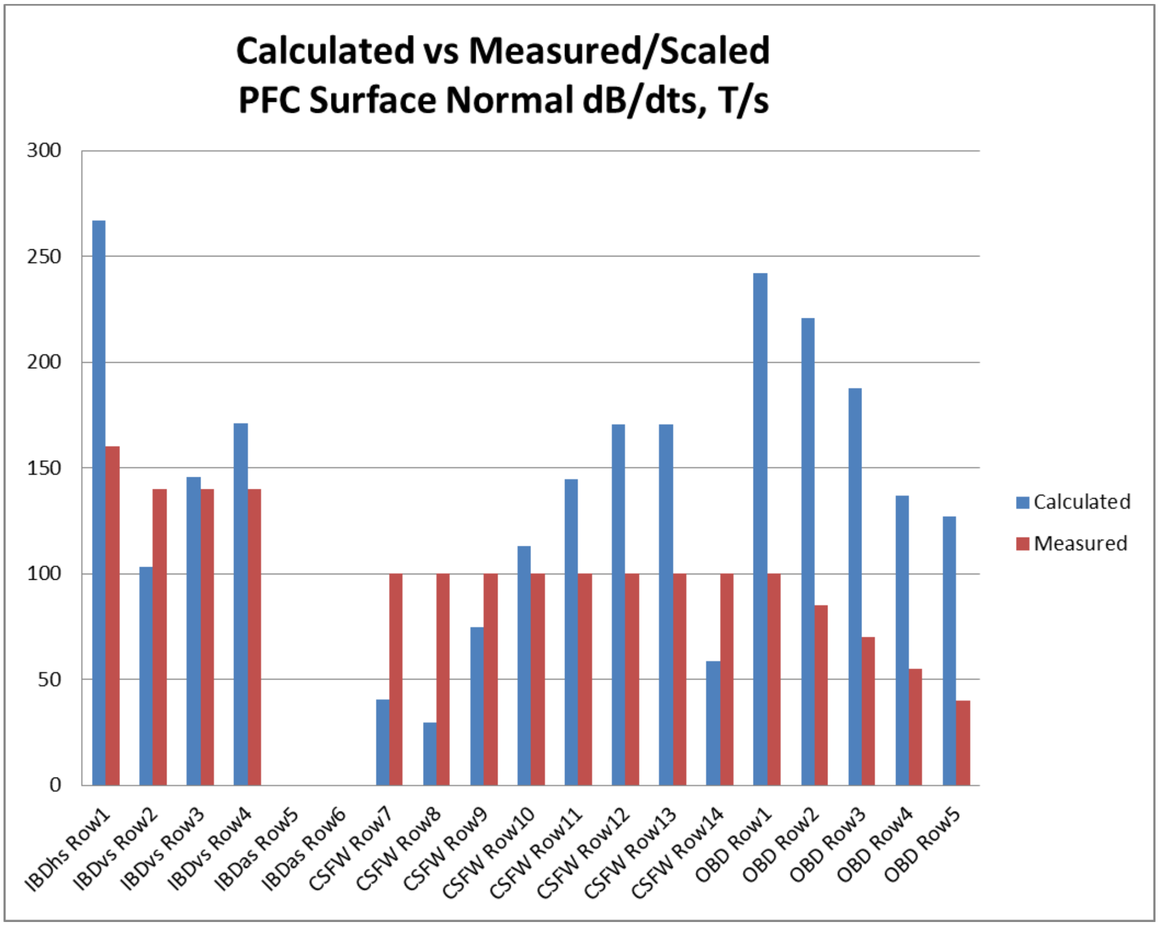
Below is a comparison of the calculated vs measured/scaled field data. Results compare reasonably well in most locations where data is available with the exception of the radial field data at the IBDV. *This discrepancy at present is unresolved*. It is prudent to assume the higher value in further analysis. This can be revisited if it proves onerous although it is not expected that the radial field at the IBDV will interact with the largest current flow which is a halo driven radial current. (The TF field, which is higher and orthogonal, is expected to drive the analysis)





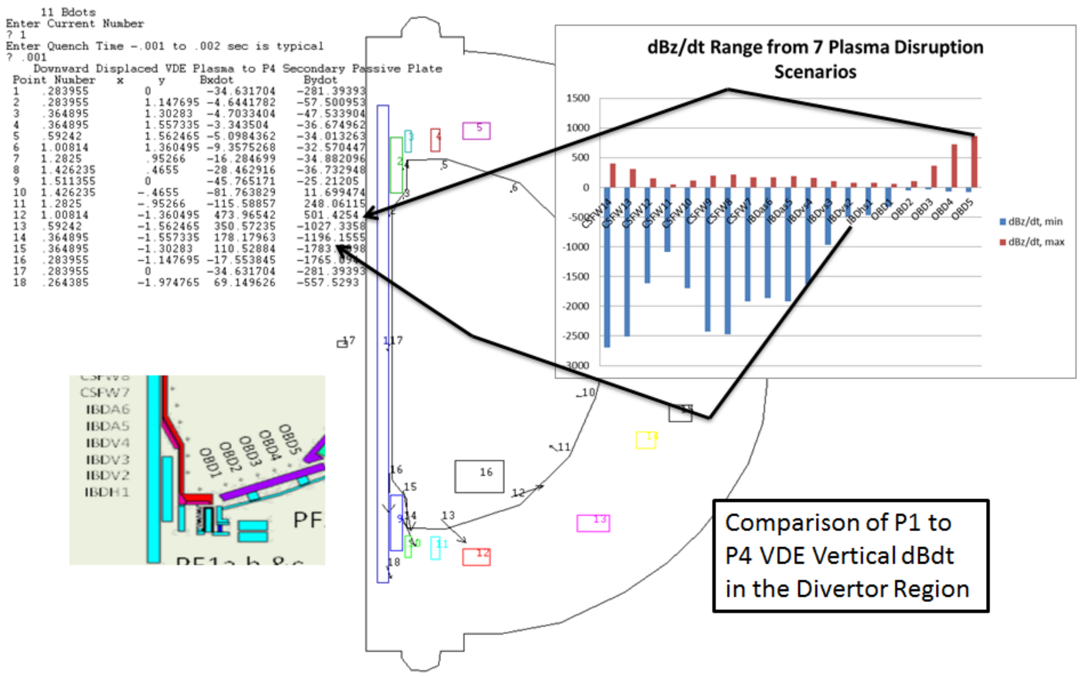
PFCs Fields and dBdts

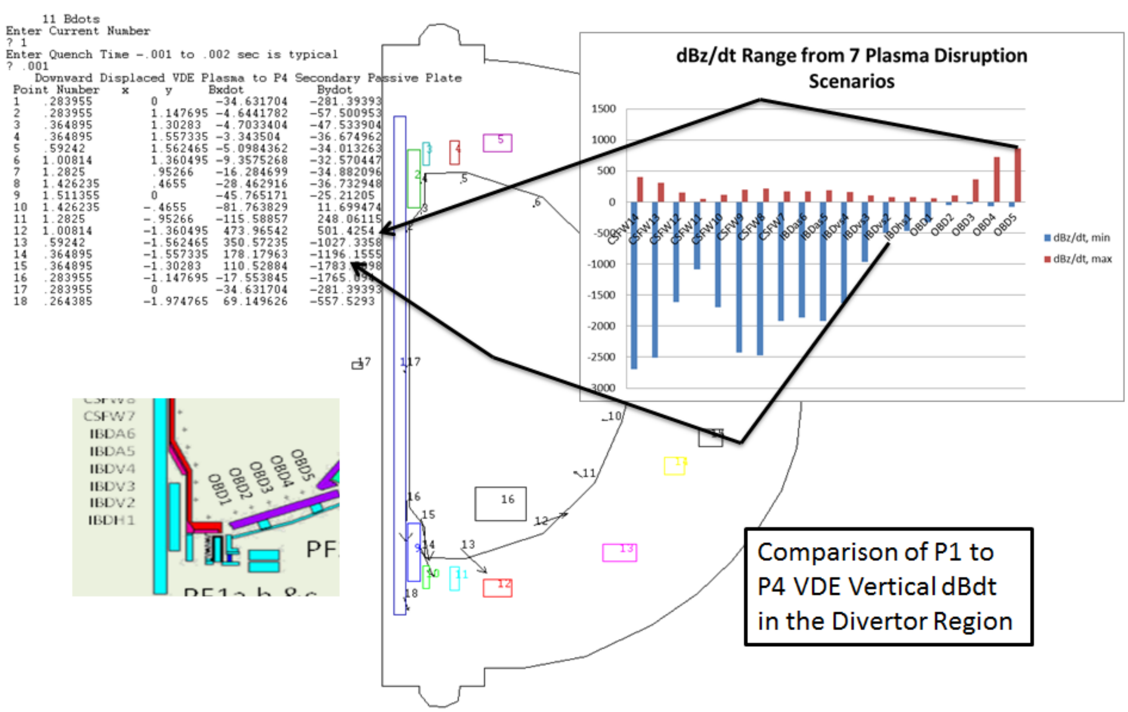
While eddy currents can be driven by dBdt in any direction the in plane current loops tend to dominate due to the exposed area. The plots below compared the calculated vs measured/scaled data dB/dts normal to the surface of the PFCs. In general the calculated results are more severe.



PFCs Fields and dBdts

Appendix II
Checkers Calculations





PFCs Fields and dBdts