Requirements, database analysis, and simulations of disruption loading for NSTX-U Recovery

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PRINCETON PLASMA PHYSICS LABORATORY

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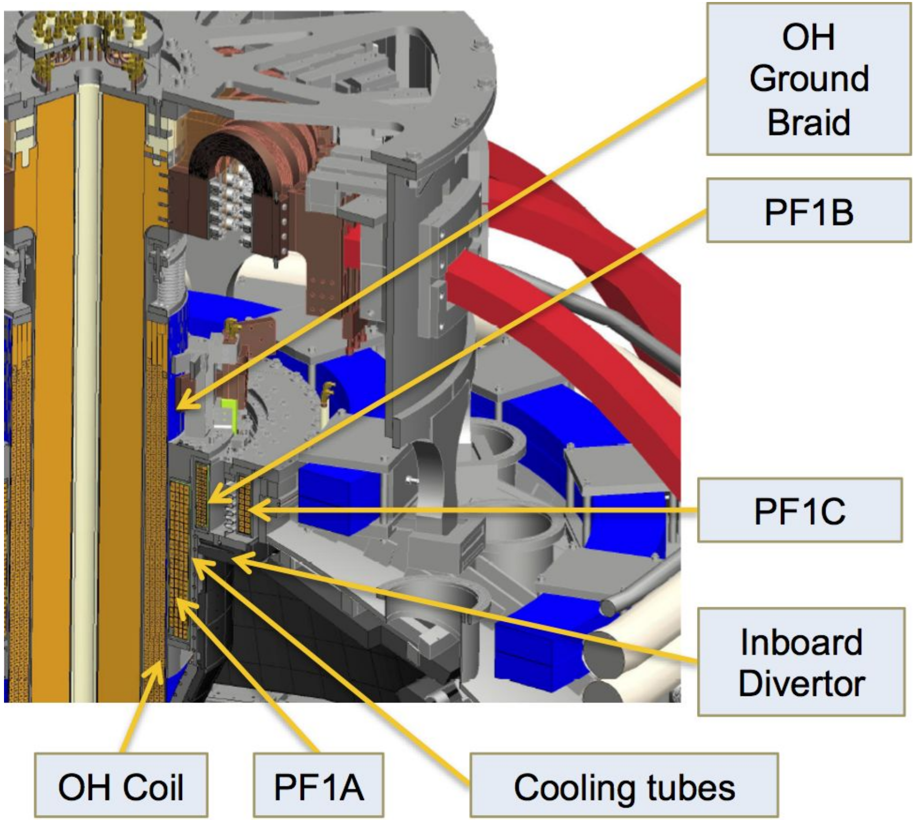
NSTX-U Recovery Project

- **FY2016:** NSTX-U had a scientifically productive first run, cut short by failure of PF1AU divertor coil
- **FY2017:** Motivated by a series of technical issues, DOE requested PPPL to review **"Extent of Condition"** and submit **Corrective Action Plan (CAP)** as a laboratory Notable Outcome
  - 17 reviews (including 47 external reviewers) in FY2017 to develop Corrective Action Plan (CAP)
- **Recovery = Implementation of CAP**



6 Major Scope Areas Define Recovery

Improved reliability **Safety and compliance**

1. Rebuild **all six inner-PF coils** with a mandrel-free design
2. Replace **plasma facing components** that cannot be qualified for the full range of mechanical and projected thermal loads →
3. Improve the "**polar regions**" (machine top and bottom) →
4. Implement **mechanical instrumentation** to assess quality of mechanical models, trend machine behavior
5. Eliminate the safety issues identified with the **medium temperature water system** used during bakeout, improve **He distribution system**
6. Improve the **neutron shielding** of the test cell

These two areas significantly influenced by disruption loads

Disruption requirements

- NSTX-U disruption load analysis requirements

VDEs and current quench

- Requirements
- PF coil mounting structures

Halo currents

- Requirements
- Plasma facing components

Disruption requirements

- **NSTX-U disruption load analysis requirements**

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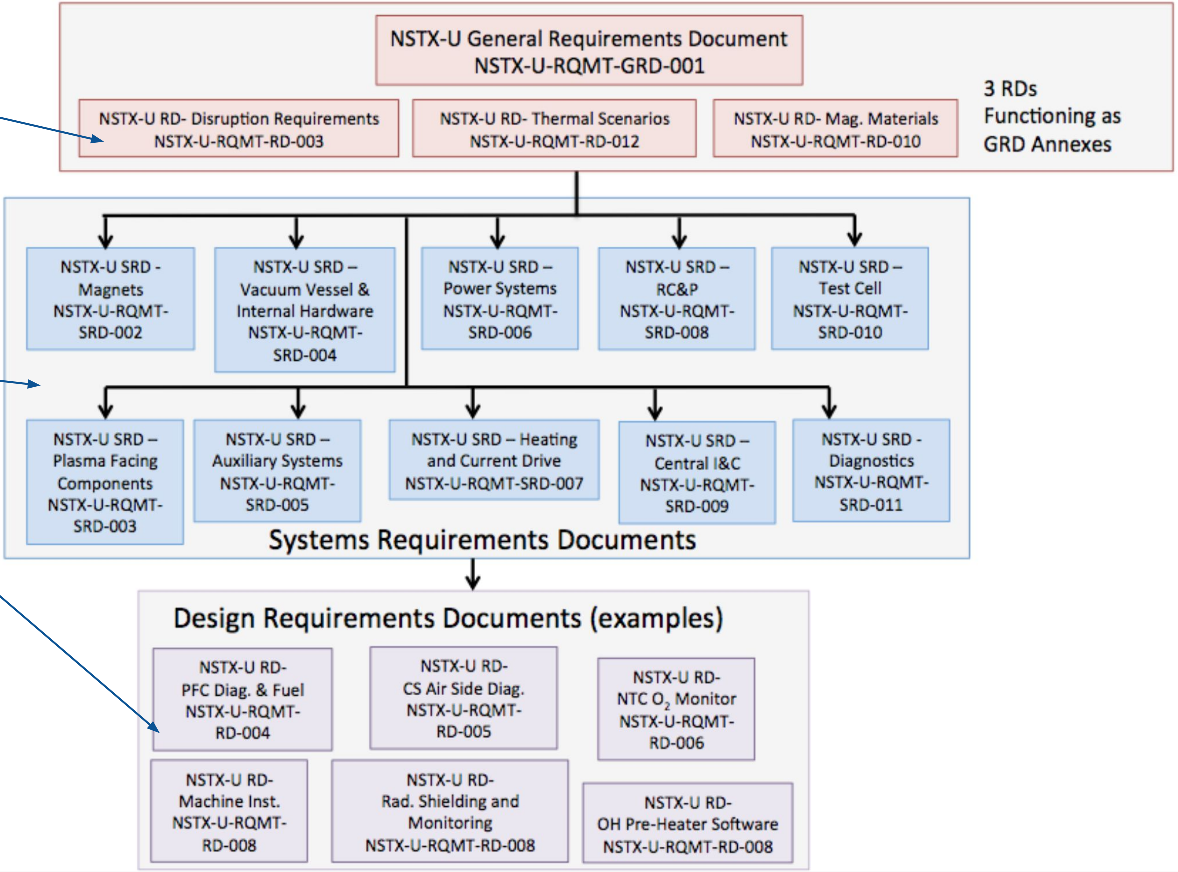
Disruption analysis requirements defined at the general requirements level to ensure all components consistently and adequately account for disruption loads

- Defined at the **General Requirements Document** level
- System/component specific disruption analysis requirements detailed in **Systems Requirements Document (SRD)** and **Design Requirements Documents (RD)**
- Supporting documentation and elaboration provided in a **series of memos**



NSTX-U General Requirements Document
NSTX-U-RQMT-GRD-001

NSTX-U RD- Disruption Requirements
NSTX-U-RQMT-RD-003

NSTX-U RD- Thermal Scenarios
NSTX-U-RQMT-RD-012

NSTX-U RD- Mag. Materials
NSTX-U-RQMT-RD-010

3 RDs Functioning as GRD Annexes

NSTX-U SRD - Magnets
NSTX-U-RQMT-SRD-002

NSTX-U SRD – Vacuum Vessel & Internal Hardware
NSTX-U-RQMT-SRD-004

NSTX-U SRD – Power Systems
NSTX-U-RQMT-SRD-006

NSTX-U SRD – RC&P
NSTX-U-RQMT-SRD-008

NSTX-U SRD – Test Cell
NSTX-U-RQMT-SRD-010

NSTX-U SRD – Plasma Facing Components
NSTX-U-RQMT-SRD-003

NSTX-U SRD – Auxiliary Systems
NSTX-U-RQMT-SRD-005

NSTX-U SRD – Heating and Current Drive
NSTX-U-RQMT-SRD-007

NSTX-U SRD – Central I&C
NSTX-U-RQMT-SRD-009

NSTX-U SRD - Diagnostics
NSTX-U-RQMT-SRD-011

Systems Requirements Documents

Design Requirements Documents (examples)

NSTX-U RD- PFC Diag. & Fuel
NSTX-U-RQMT-RD-004

NSTX-U RD- CS Air Side Diag.
NSTX-U-RQMT-RD-005

NSTX-U RD- NTC O_2 Monitor
NSTX-U-RQMT-RD-006

NSTX-U RD- Machine Inst.
NSTX-U-RQMT-RD-008

NSTX-U RD- Rad. Shielding and Monitoring
NSTX-U-RQMT-RD-008

NSTX-U RD- OH Pre-Heater Software
NSTX-U-RQMT-RD-008

Disruption loading analysis requirements for NSTX-U

- **Requirements document** defines treatment of each disruption load
  - **Thermal loads:** Transient heat loads due to radiation, conduction
  - **Eddy current loads:** Currents induced by plasma motion, loss of Ip, etc.
  - **Halo current loads:** Current injected from contact with plasma into PFCs/in-vessel structures.
  - No significant disruption runaway electron problem anticipated for NSTX-U
- Components required to be analyzed with **‘worst case’** combinations of
  - **Equilibrium field** (based on 96 scenarios)
  - **Thermal load** from full power, full duration shot
  - **Disruption field**
    - Eddy currents calculated for a range of disruption cases
    - Halo currents calculated according to an empirically driven model
  - Calculations of loads performed in ANSYS and benchmarked with experimental data from NSTX/NSTX-U

VDEs and quench: **Requirements**

Disruption requirements

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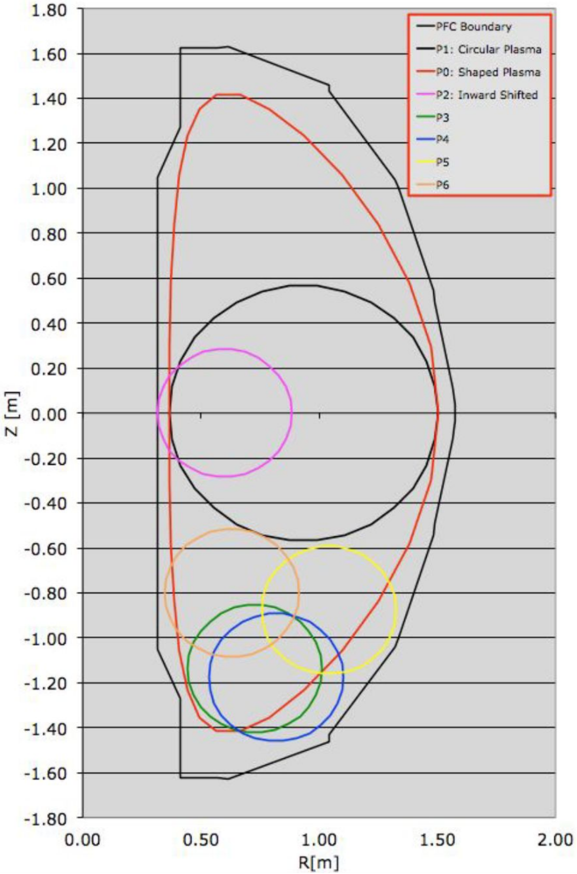
- **Requirements**
- PF coil mounting structures

Halo currents

- Requirements
- Plasma facing components

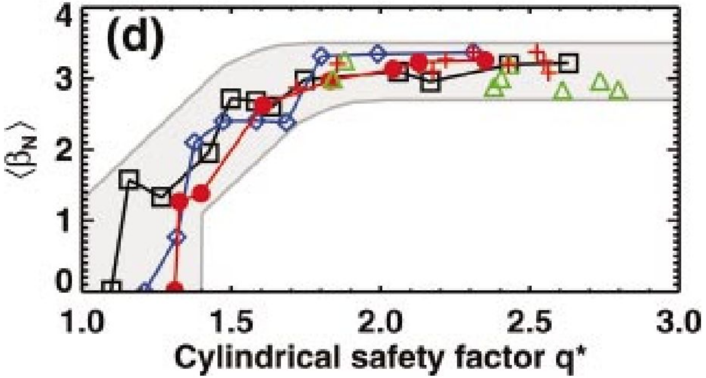
An envelope of possible eddy current loads are determined based on several disruption scenarios

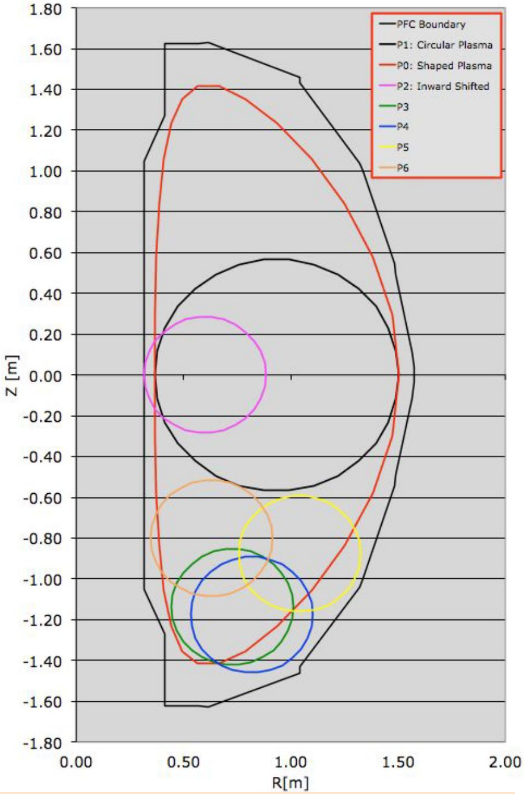
- Two disruption modes considered
  - **Quench** ➔ Current quench at fixed position, no halo currents
  - **Drift** ➔ Induction due to plasma motion and current quench, halo currents included
- Requirements phrased in terms of 7 representative cross-sections



Original terminal plasma shape scenarios were conservative

- The small, off-midplane shapes result in **very high forces** - challenge for slings, plates
  - **Likely unphysical**, overly conservative
- At 2MA, 1T, terminal shapes would result in **very low cylindrical safety factor**
  - $q^*=5a^2(1+\kappa^2)B_T/(2RI_p[\text{MA}])$





q*

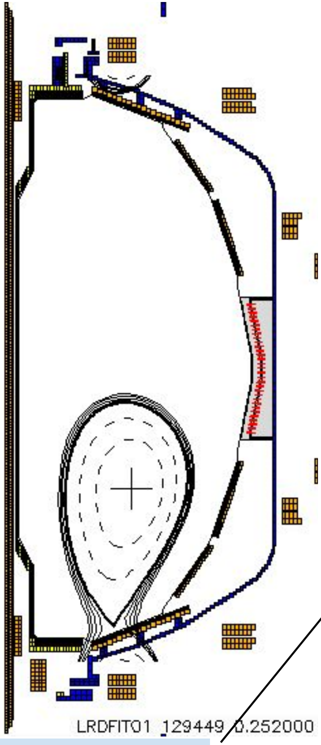
0.88
0.54
0.36
0.29
0.18
0.49
3.10

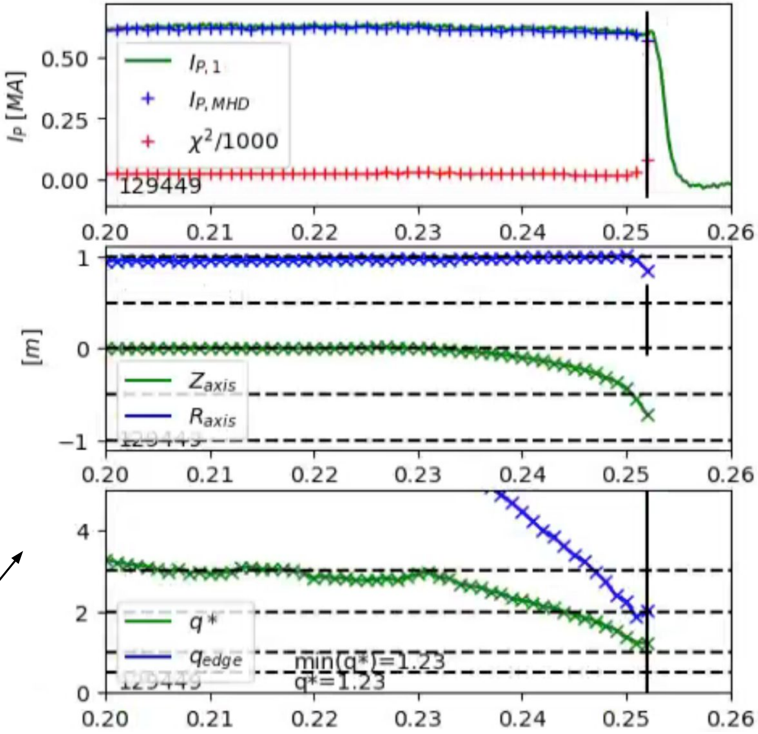
Menard et al., Phys. Plasmas 11, 639 (2004)

Minimum q* at quench identified for database of NSTX disruptions

- **q* <1 not experimentally supported** for VDEs terminating near **CS, IBD, OBD**

- **q* as low as 0.6 observed** for VDEs terminating **near SPP/PPP**
  - Plates may provide stabilization





Time traces from 129449, which limits on **lower divertor plates**

S. Gerhardt

Revised terminal plasma shape scenarios relax overly conservative analysis

- **q* <1 not experimentally supported** for VDEs terminating near **CS, IBD, OBD**

- **q* as low as 0.6 observed** for VDEs terminating **near SPP/PPP**
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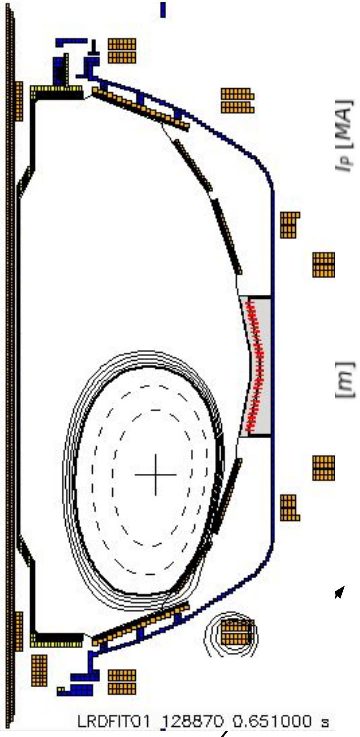

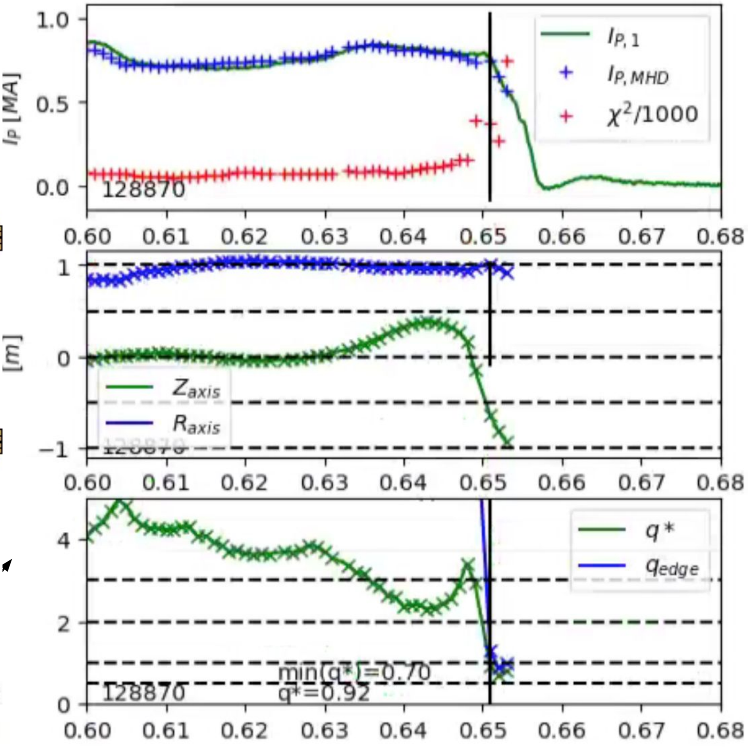

Time traces from 128870, which limits on the **passive plates**

S. Gerhardt

Revised terminal plasma shape scenarios relax overly conservative analysis

- **q* <1 not experimentally supported** for VDEs terminating near **CS, IBD, OBD**

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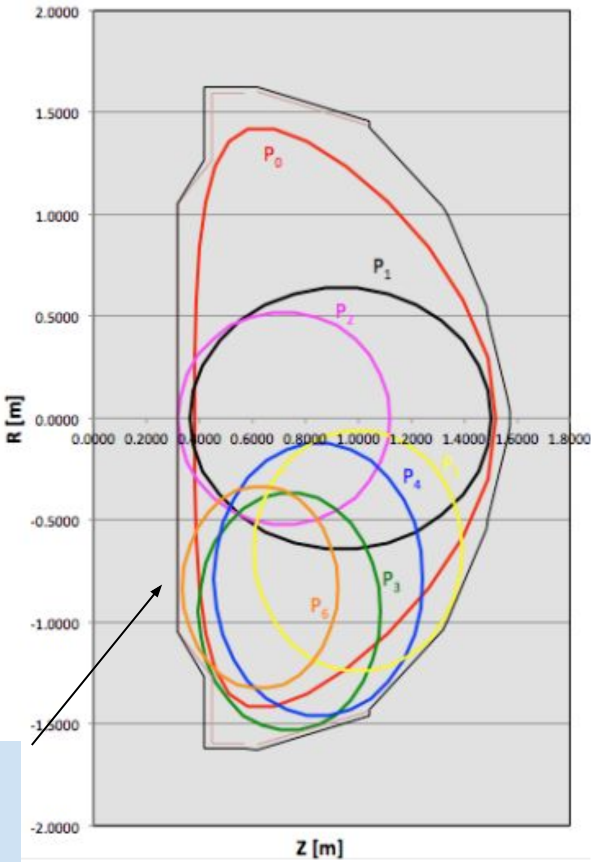

q*

1.00
1.00
1.00
1.00
0.60
1.00
3.10

Revised shapes with experimentally supported q* values

S. Gerhardt

VDEs and quench: Requirements

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VDEs and current quench

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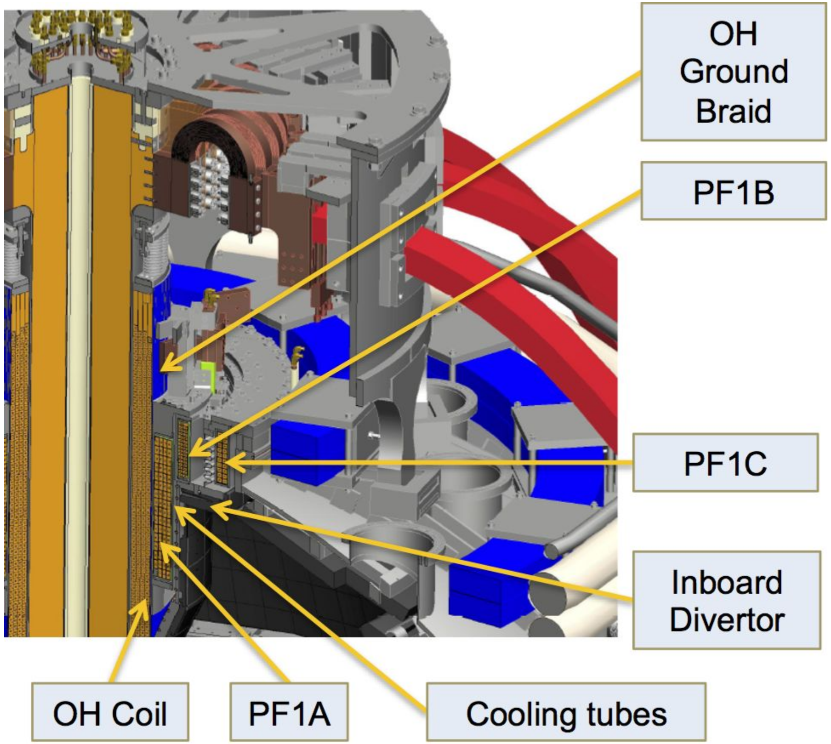
- **PF coil mounting structures**

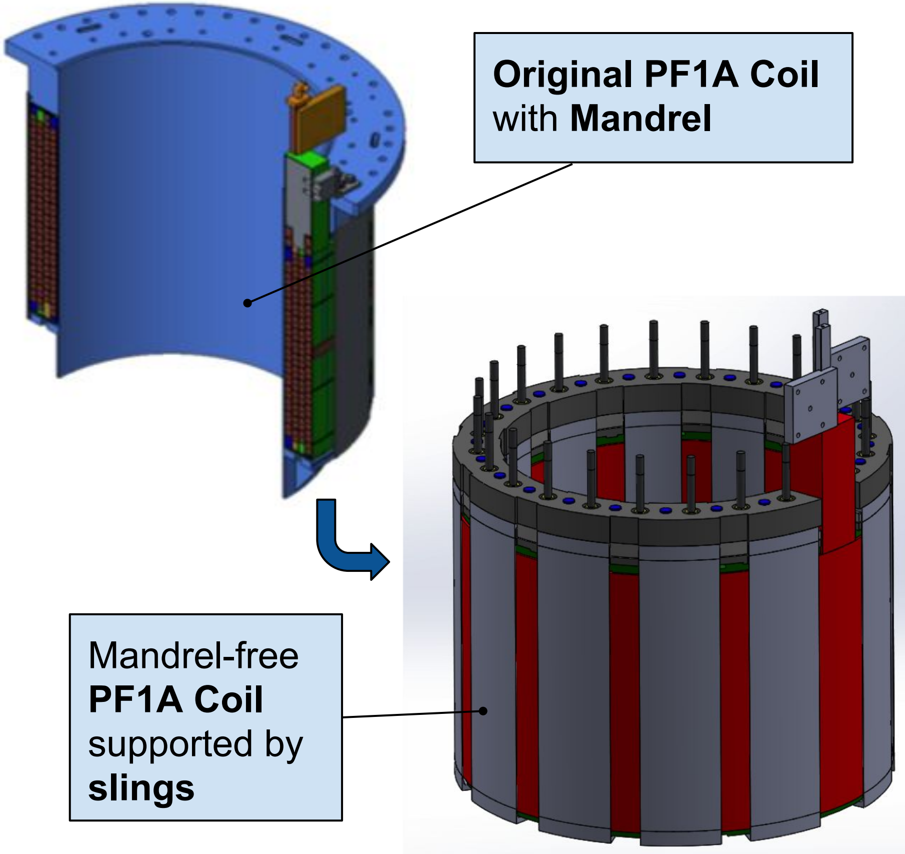
Halo currents

- Requirements
- Plasma facing components



Divertor coil mounting scheme and loads from VDEs

- Previous coils fabricated on permanent mandrels
  - Advantages: Precision winding surface, VPI model, intrinsic structural support
  - Disadvantages: mandrel is passive conductor
    - Impacts turn-to-turn acceptance tests
    - Deemed unacceptable during extent of condition review
- New coils: removable mandrels
  - Requires new mounting scheme: slings/straps
  - Slings apply preload to coil

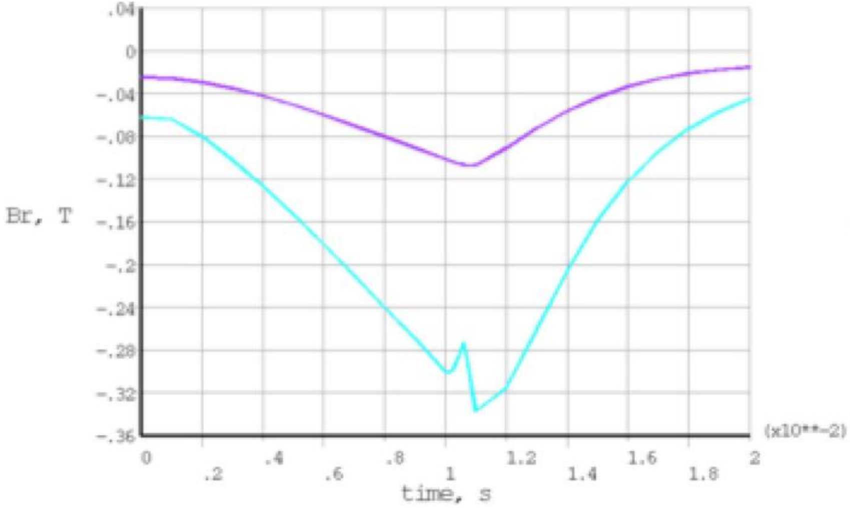


Original PF1A Coil with **Mandrel**

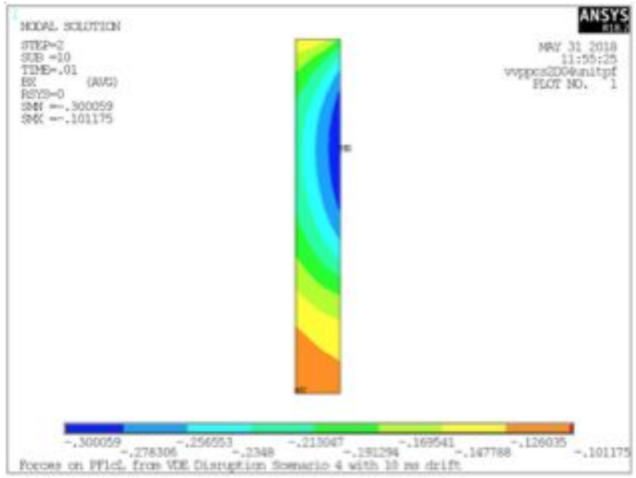
Mandrel-free **PF1A Coil** supported by **slings**

Radial field on PF1A coil from 2D ANSYS

Radial field at PF1AL



Spatial distribution of radial field on coil at time of peak



- Peak radial magnetic field magnitude **0.34T** for circular terminal shape OBD/SPP VDE
  - Peak field of **0.45T** for IBDV VDE
  - Results in large forces>stresses, design likely incompatible with fatigue requirements
- Field peak not centered in coil

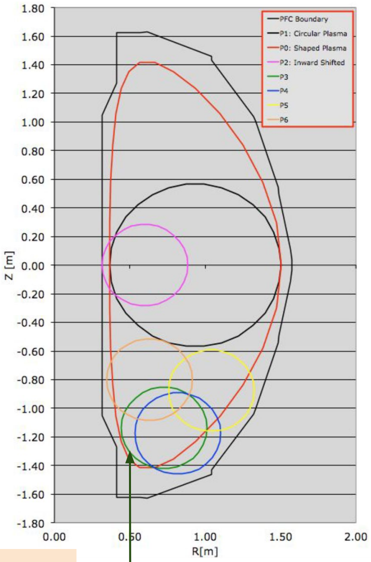
A. Brooks

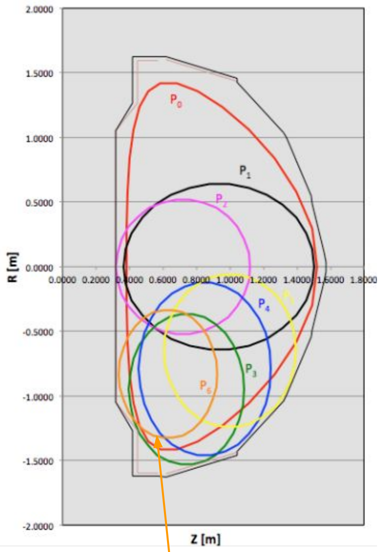
Modified analysis approach lowers worst case fields to manageable values

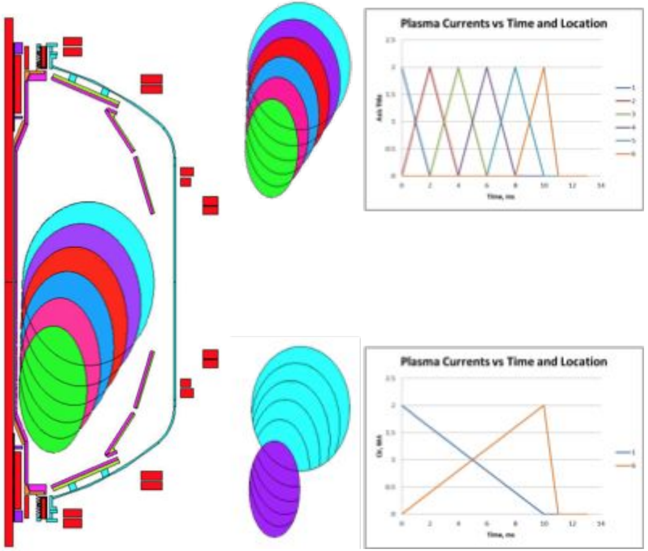
Original terminal shapes

Elliptical terminal shapes

Refined motion model







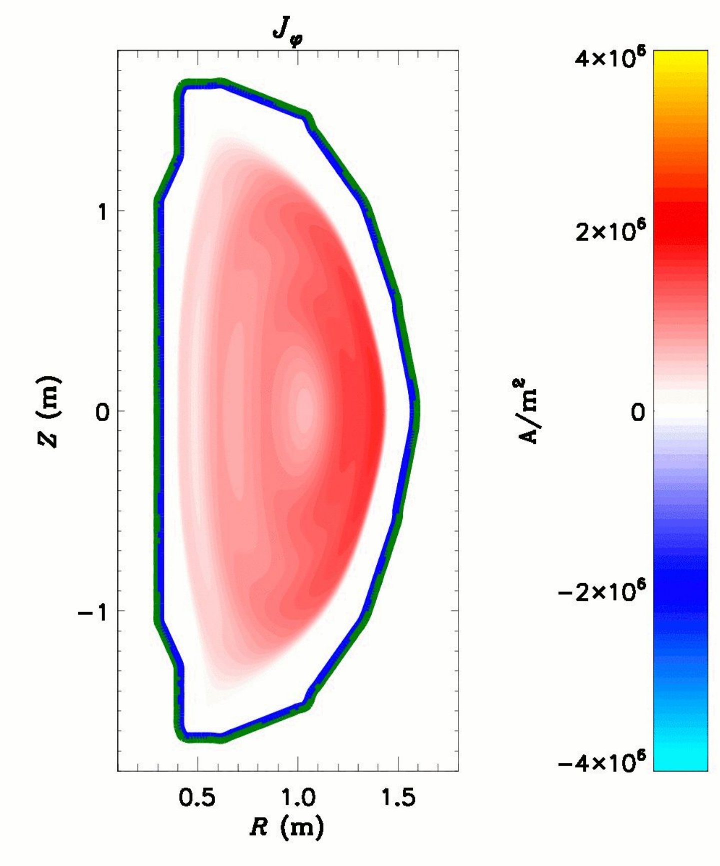
A. Brooks

Worst case: 0.45T

Worst case: 0.34T

Worst case: 0.28T

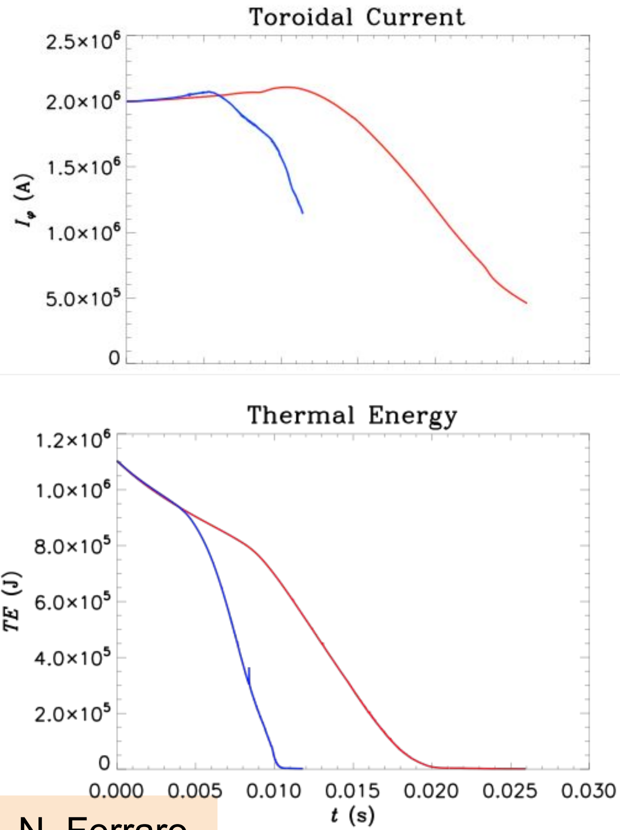
M3D-C1 simulation of 2MA VDE in NSTX-U provides confidence in reduced engineering analysis model

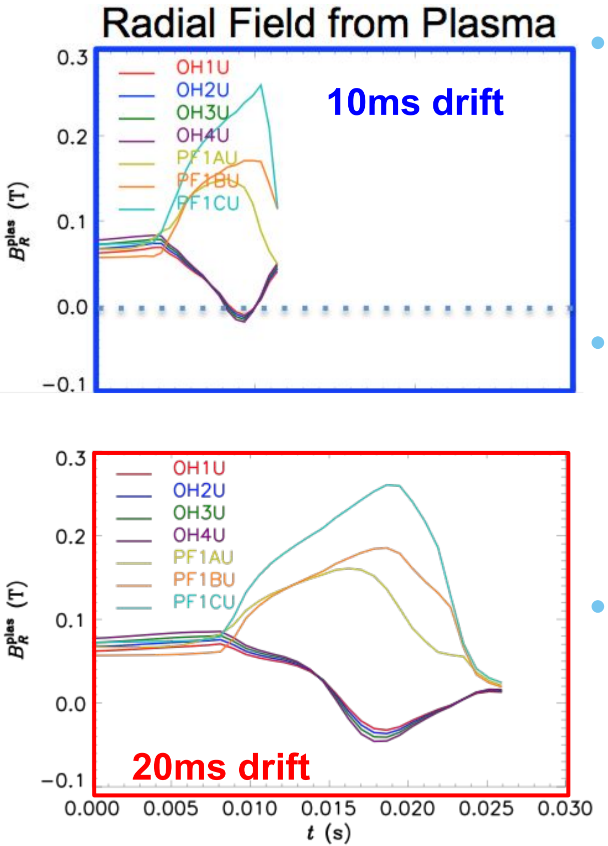


- Axisymmetric simulation
- Coil currents held fixed
- No mitigation, plasma remains hot as it hits the wall
  - Long current quench, large current when plasma is maximally displaced
- Slow drift time (~20ms)
  - Set by vessel resistivity
- For comparison, a faster case is considered (~10ms)

N. Ferraro

M3D-C1 simulation of 2MA VDE in NSTX-U provides confidence in reduced engineering analysis model





- Similar to reduced model, though PF1A fields are smaller
  - **No current drive** here, reduced current leads to reduced forces
  - Not ‘worst case’ **position of VDE**
- **Experimental database** shows smaller fields like these are most common, worst case **fields of 0.25T infrequent**
- **Analysis of fatigue life underway** based on revised (realistic q*, refined motion) engineering model

N. Ferraro

Halo currents: **Requirements**

Disruption requirements

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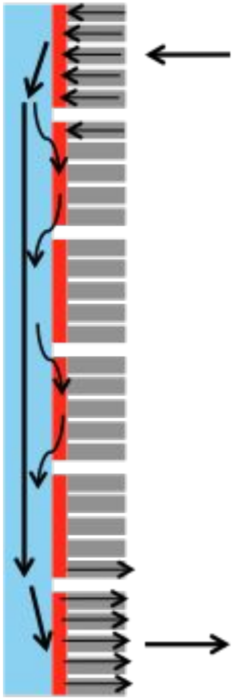
Halo currents

- **Requirements**
- Plasma facing components

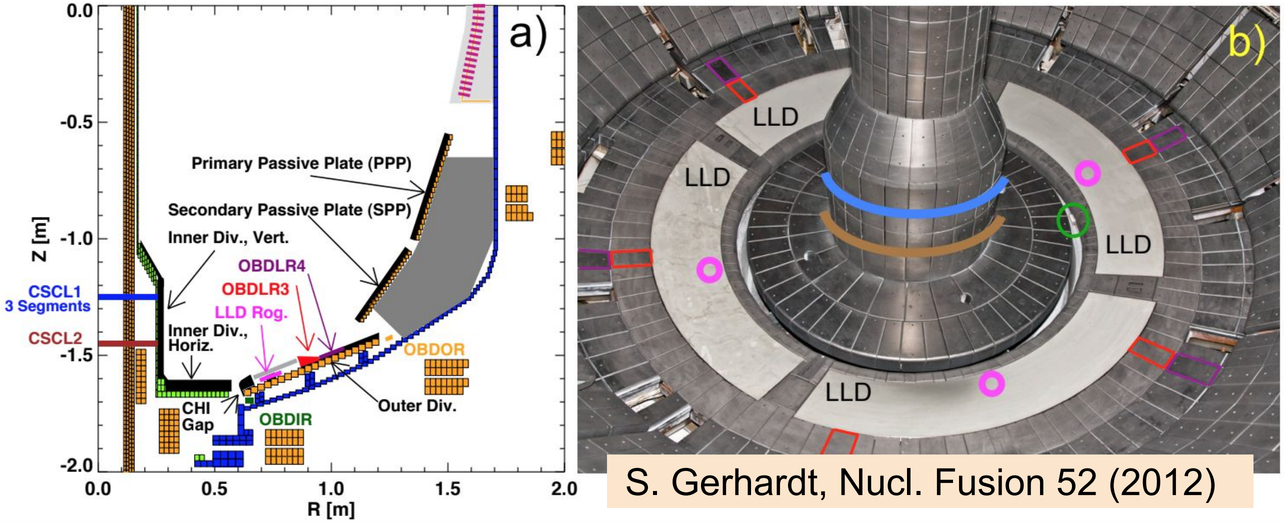
Halo current distribution assumptions

- **Poloidal footprint:** Imposed halo currents assumed to enter/exit tiles in two **toroidal bands of specified poloidal width** on the PFCs
- **Toroidal peaking:** Magnitude of current density in toroidal bands assumed to have a **cosine variation toroidally but uniform poloidally**. *Entrance and exit point may be phase shifted.*
  - $J_{nor,max}=I_p*HCF*TPF/(2*p*R*w_{halo})$
    where $\mathbf{I_p}$ = 2 MA, **HCF** is the halo current fraction, **TPF** is the Toroidal Peaking Factor and $\mathbf{w_{halo}}$ is the Poloidal width = ~20cm
- **Structure current distribution:** current assumed to **resistively distribute within all connected structures (VV, CS, PFCs, etc)** and **return to plasma at different poloidal location** in a toroidal band
- **At strike points**, tiles see a large thru thickness current independent of material resistivity (**plasma acts as current source**)
- **Away from strike points,** tiles see predominately **poloidal and toroidal currents, shared with underlying structure**
  - Graphite tiles have a relatively high electrical resistivity ~1000 mW-cm vs SS ~74 mW-cm. **Currents favor underlying structure**

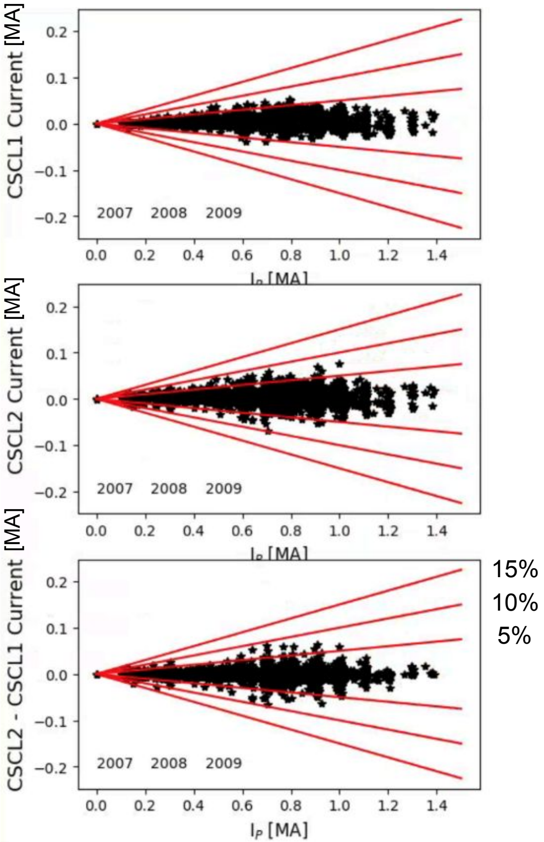


Halo current requirements were based on measurement database from NSTX and NSTX-U

NSTX halo current diagnostics



S. Gerhardt, Nucl. Fusion 52 (2012)



- Poloidal variation of **halo current fraction** and **toroidal peaking factor**
    - Generally requirements take **TPF=2**, **halo current fraction=0.35**
- **CSCL1** and **CSCL2** Rogowskis provide only **poloidally resolved halo current measurements on an ST centerstack**
    - Difference indicates **halo current source on inner divertor (vertical)**
    - Limited to ~10% halo current fraction➔**reduced centerstack HCF in requirements to ease component design**

Halo currents: Requirements

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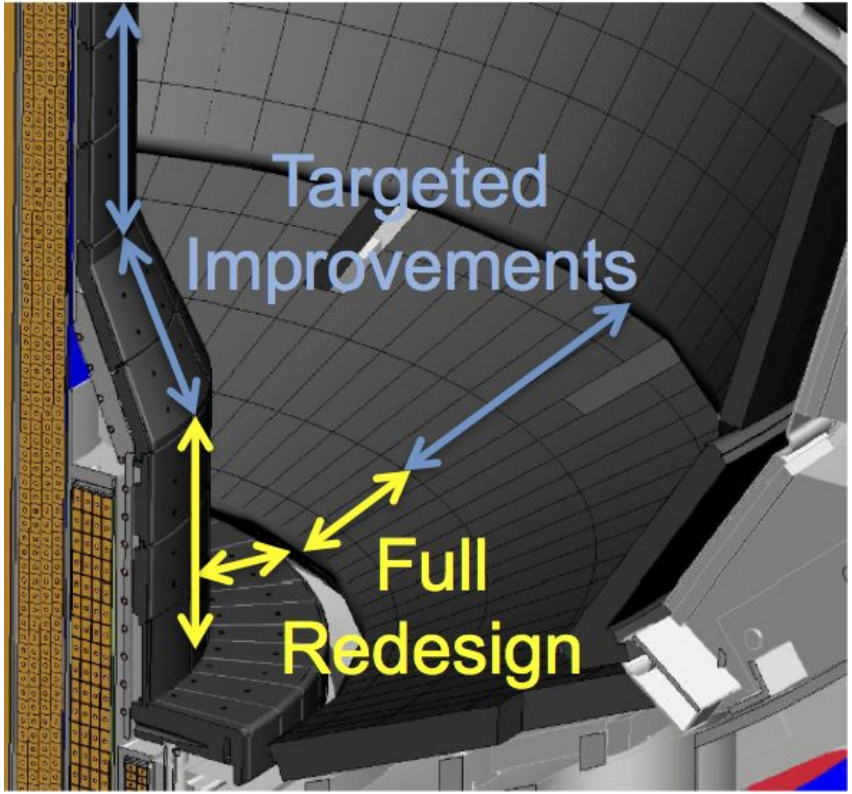
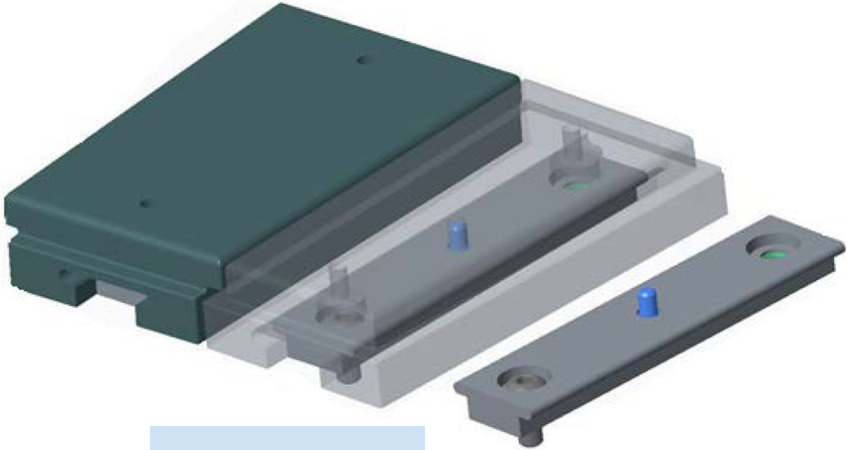
- Requirements
- **Plasma facing components**

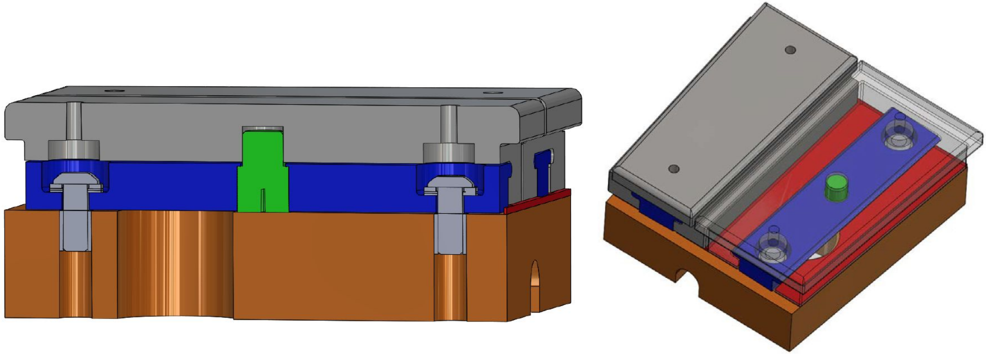


New tile attachment schemes and tile designs handle halo current loads, meet highest performance heat flux requirements

- Existing T-bar design inadequately constrained tile motion from halo currents loads, compressed tile, front mounting access holes incompatible with highest heat flux areas
- For low heat-flux region, targeted improvements made to existing design
  - Larger shear pin to constrain motion
  - Elongated T-bar to reduce preload stress on tiles
  - Stronger grade graphite to meet stress requirements



Existing T-bar

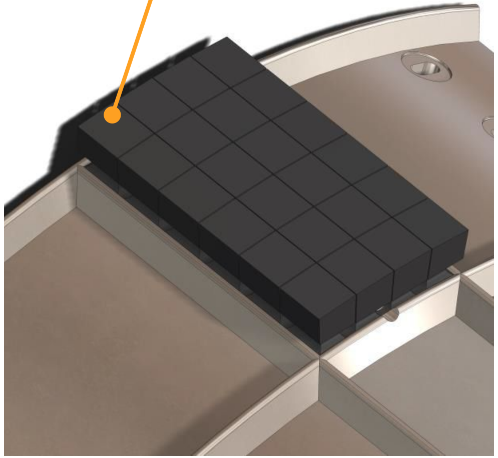


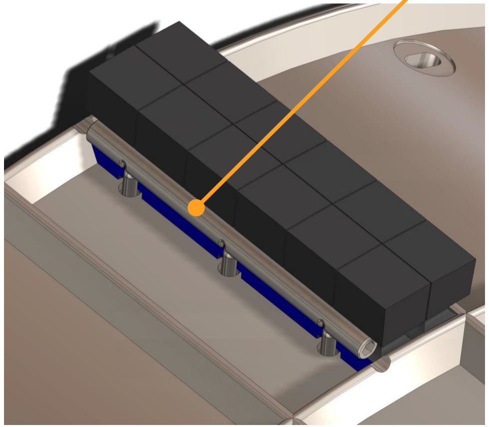
Improved T-bar

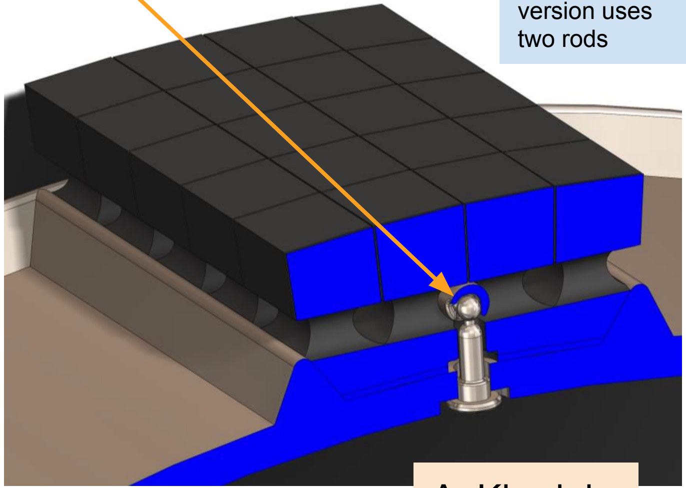
New tile attachment schemes and tile designs handle halo current loads, meet highest performance heat flux requirements

- For **high heat-flux region**, new tiles have been designed
  - Halo current loads reacted by tray
  - **Castellations** allow surface stress relief and break up eddy currents
  - No front mounting access holes - internal **rod mounting scheme**

Castellated surface







Conceptual design, revised version uses two rods

A. Khodak

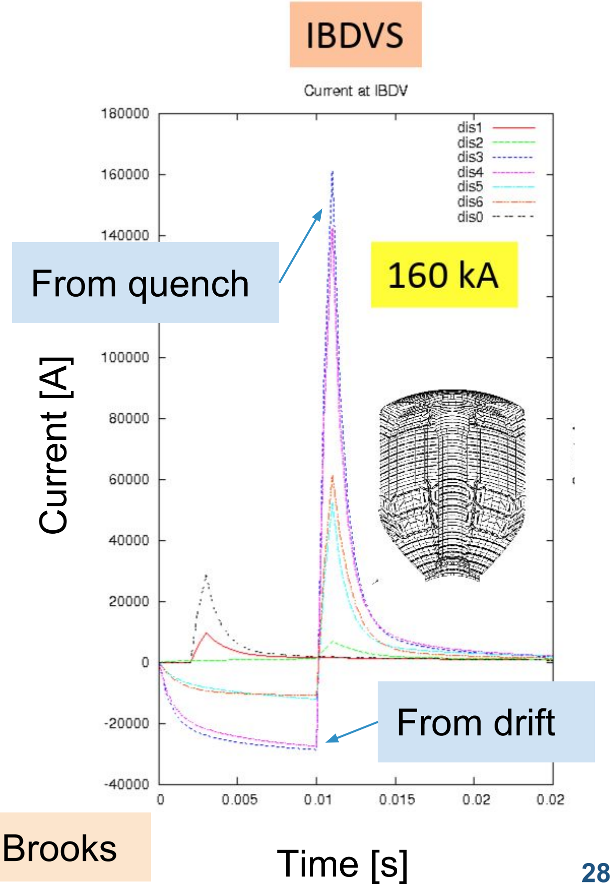
Summary and conclusions

- NSTX-U Recovery project engineering is analyzing components/system in light of **revised designs and refined disruption load definitions**
- Several **key areas** are very **sensitive to disruption loads**
  - VDE+quench loads on **PF1A coil mounts**
    - Simulations and data used to refine loading assumptions
    - New sling design being analyzed and refined based on load models
  - Halo current forces on **tiles**
    - Paths, distribution refined based on experimental database
    - New mounting scheme for high heat flux tiles
- **Reduced disruption loading models** are critical for engineering design
  - ***Theory/simulation*** *contributes to developing reduced models, benchmarking, and identifying overlooked scenarios in design requirements*

Thank you

Original plasma current quench rates also very conservative

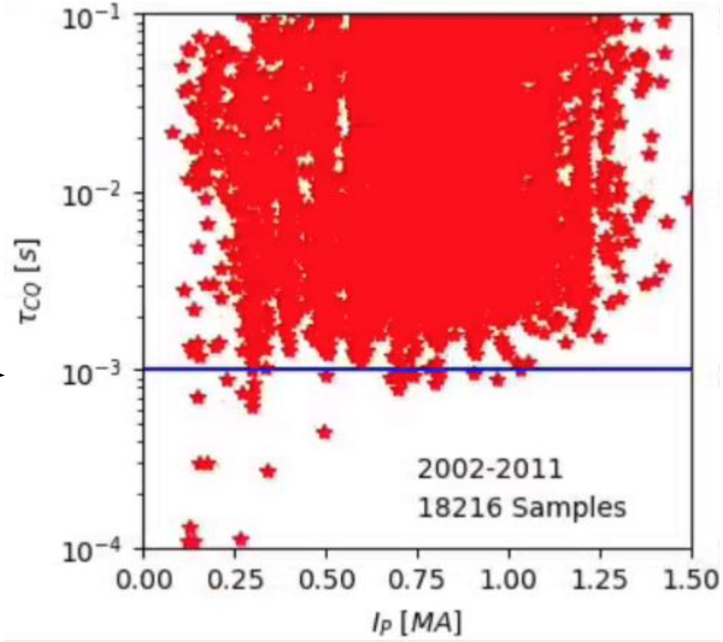
- Quench rates determine **magnitude of induced currents** in structural components
  - Assuming the **'worst case'** (fastest quench) for all cycles is conservative but makes **fatigue requirements challenging** to meet
  - **Variations in quench rates** from shot to shot lead to **variation in loading**, impacting fatigue studies
- **A database of quench rates on NSTX** has been developed
  - analyzed to generate a **spectrum of quench rates** for use in fatigue analysis



A. Brooks

Quench rate experimental database shows that worst case quenches are rare

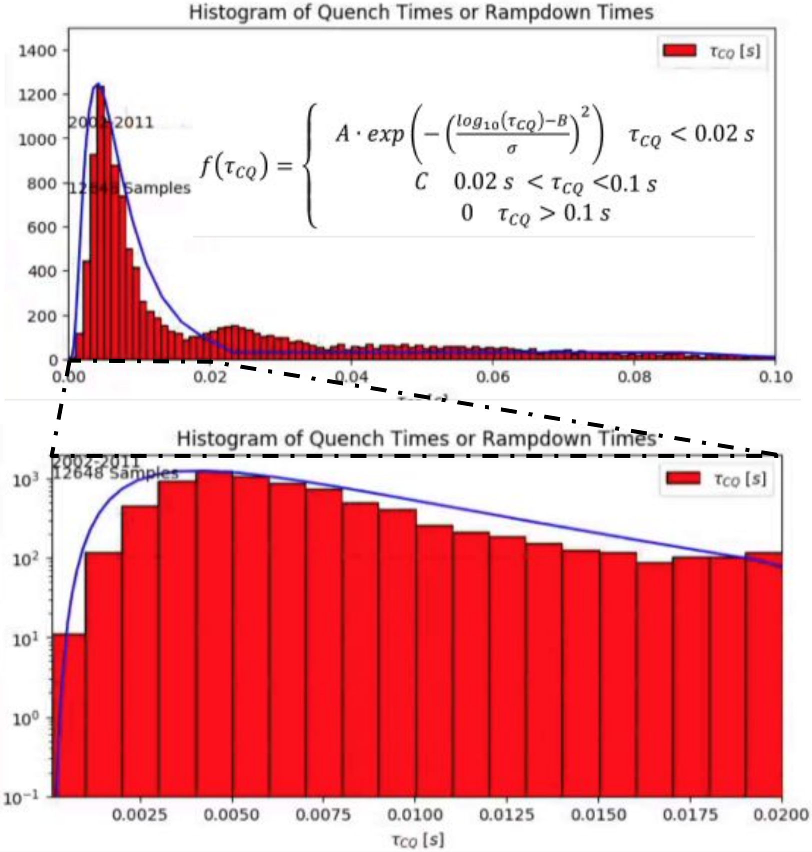
- Used NSTX data only
  - NSTX-U I_p measurements were contaminated by PF1A ripple and had filters applied - fast disruption time-scale not fully resolved
- Nearly all quenches >1ms



S. Gerhardt

Quench rate experimental database shows that worst case quenches are rare

- Used NSTX data only
  - NSTX-U I_p measurements were contaminated by PF1A ripple and had filters applied - fast disruption time-scale not fully resolved
- Nearly all quenches >1ms
- The worst case 1-2ms quench is only <5% of shots
  - More than half of shots have quench times between 2-10ms



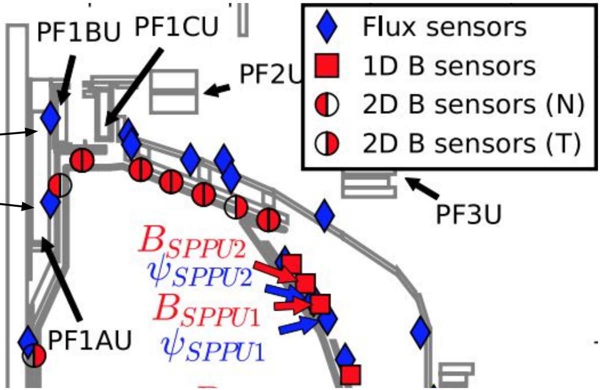
$$f(\tau_{CQ}) = \begin{cases} A \cdot exp\left(-\left(\frac{log_{10}(\tau_{CQ})-B}{\sigma}\right)^2\right) & \tau_{CQ} < 0.02\,s \\ C & 0.02\,s < \tau_{CQ} < 0.1\,s \\ 0 & \tau_{CQ} > 0.1\,s \end{cases}$$

S. Gerhardt

Experimental database of coil loads give confidence in modeling assumptions and a sense of event spectrum

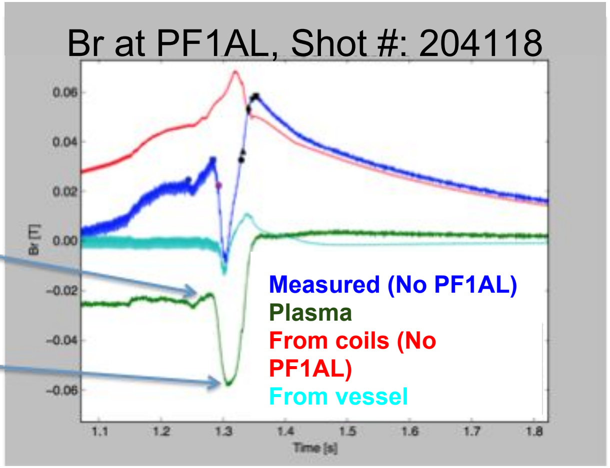
- Database of **radial field on PF1A coils** during VDEs developed
  - Measured flux during VDEs separated into **contribution from coils, vessel currents induced by vessel, and flux from plasma** (or currents induced by plasma)
    - Single coil vacuum shots used to identify contributions to measured fluxes from coils, currents induced by coils.
  - Identified **largest change in field from plasma** between onset of VDE and quench
  - **Scaled to 2MA** based on flattop current

Two flux loops on PF1AU/L used to calculate radial field



undershoot

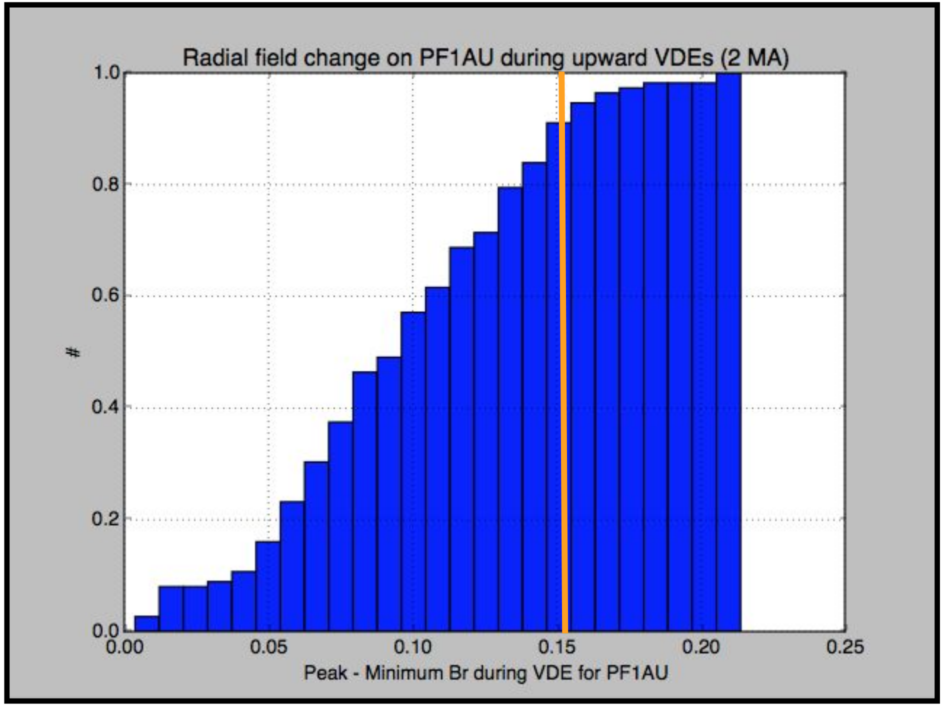
peak



Highest experimental fields consistent with models, but these events were rare

- May be overly conservative to consider worst case for every shot in fatigue analysis
- Upper and lower forces are asymmetric (higher forces on the coil the plasma moves toward)
- Approximate event spectrum based on database:

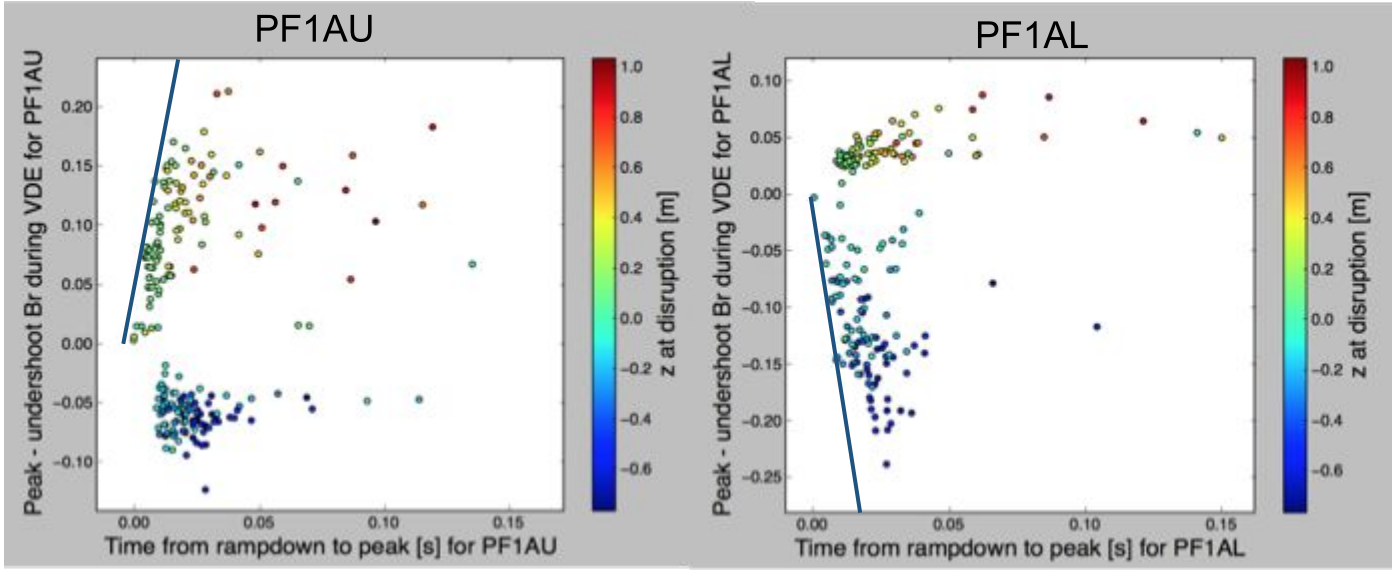
	Typical Field Change [T] (70% of shots)		Worst Case Field Change [T] (30% of shots)	
Coil	**Upward (50%)**	**Downward (50%)**	**Upward (50%)**	**Downward (50%)**
PF1AU	0.15	-0.07	0.25	-0.12
PF1AL	0.07	-0.15	0.12	-0.25



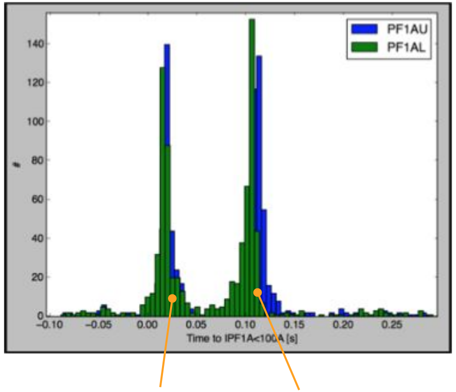
Cumulative histogram of radial field change during NSTX-U VDEs, scaled to 2MA

PCS response time provides possibility of actively limiting fatigue impact of VDEs

- Database indicates a **minimum time between VDE detection and reaching the highest fields**
  - 0.3T cases should have **~20ms between detection/peak**
  - Divertor coils typically ramped down once VDE is detected
- **Coil current response** shows two peaks: fast current control and slow power supply bypass
  - If coils are kept in current control until end of shot, should be able to **limit force on coil** and **limit fatigue damage**



Time from VDE detection to IPF1A<100A

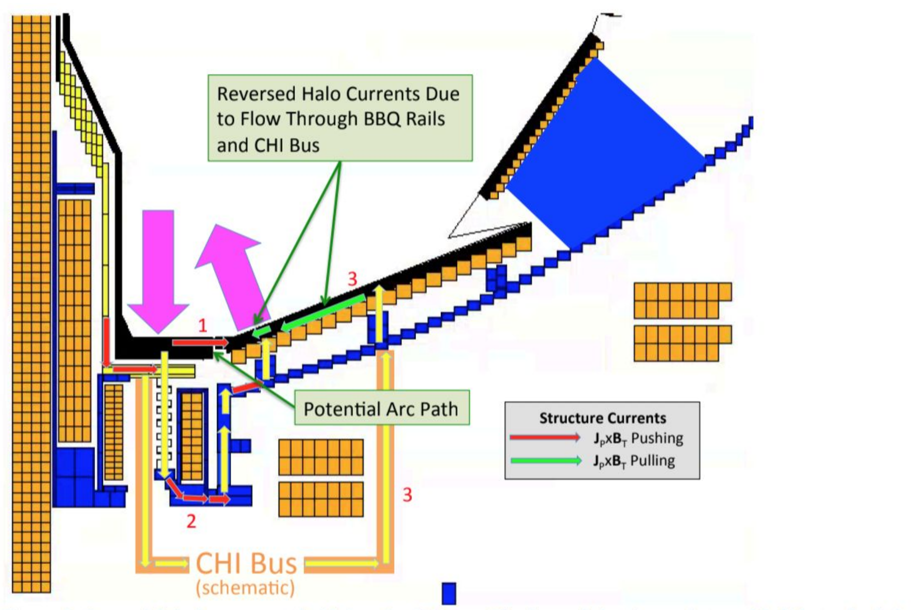


Current control ➔~20ms

Power supply bypass ~110ms

Analysis considers 6 potential halo current paths

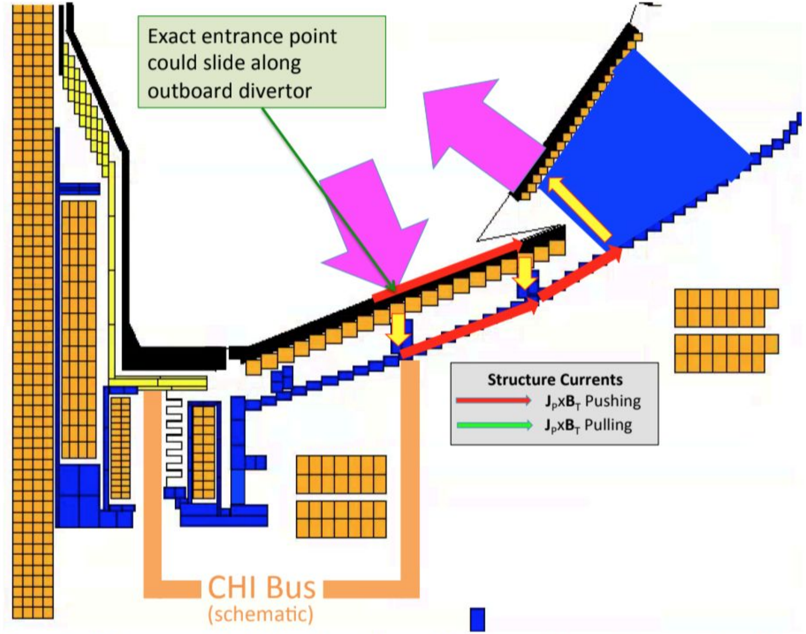
- Guidance provided for sharing of currents in structures and toroidal peaking factors for each structure involved in each case
- 2 examples shown here:



Reversed Halo Currents Due to Flow Through BBQ Rails and CHI Bus

Potential Arc Path

Figure 3: Case with halo currents bridging the CHI gap. The inner injection point could slide to the left, wetting the IBDV tiles as well.

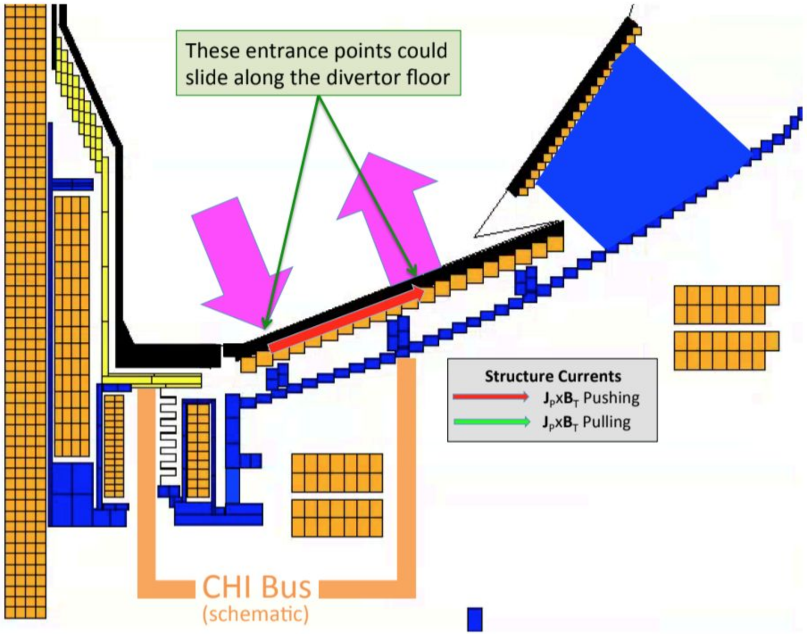


Exact entrance point could slide along outboard divertor

Figure 2: Halo currents bridging the outboard divertor and secondary passive plates

Halo current poloidal locations

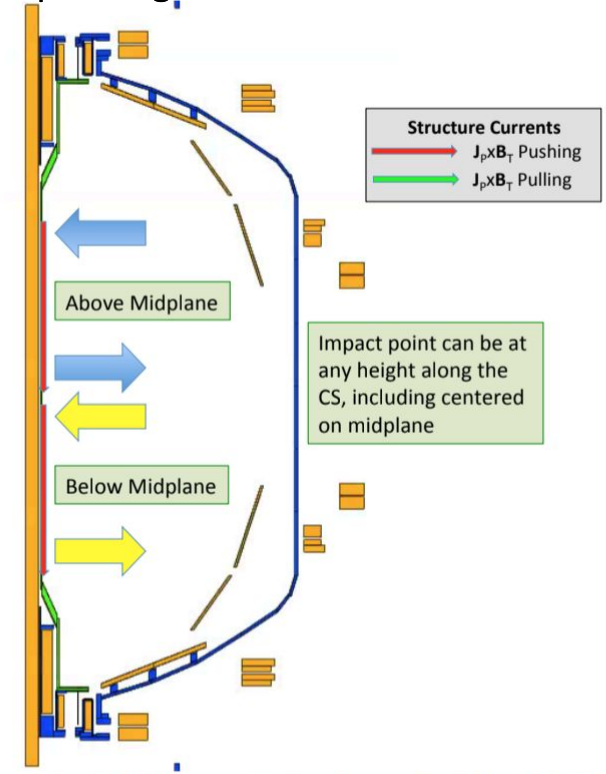
- Guidance provided for sharing of currents in structures and toroidal peaking factors for each structure involved in each case



These entrance points could slide along the divertor floor

Structure Currents
$J_p x B_T$ Pushing
$J_p x B_T$ Pulling

Figure 4: Halo currents local to the outboard divertor



Structure Currents
$J_p x B_T$ Pushing
$J_p x B_T$ Pulling

Impact point can be at any height along the CS, including centered on midplane

Figure 5: Halo currents for plasmas limited on the CS

Halo current poloidal locations

- Guidance provided for sharing of currents in structures and toroidal peaking factors for each structure involved in each case

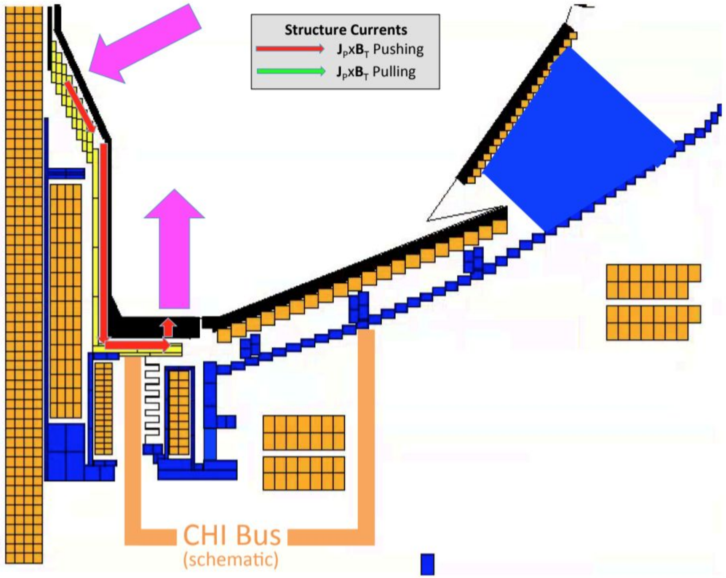
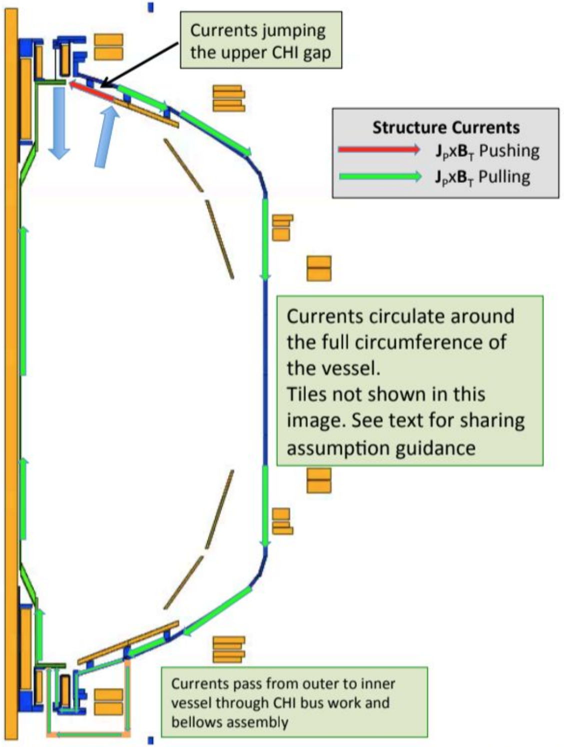


Figure 6: Halo currents bridging the horizontal and vertical inner targets. The entrance and exit points can slide along the PFC surface.



Currents jumping the upper CHI gap

Currents circulate around the full circumference of the vessel.
Tiles not shown in this image. See text for sharing assumption guidance

Currents pass from outer to inner vessel through CHI bus work and bellows assembly

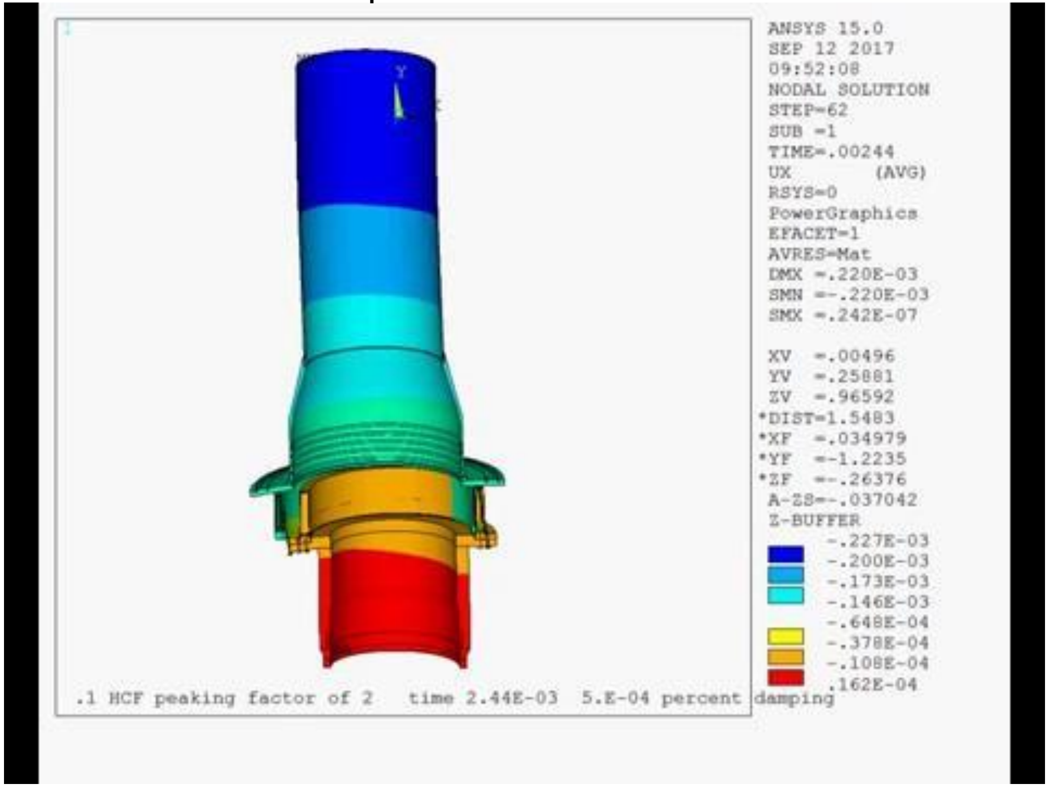
Figure 7: Current path circulating around the full vessel during an upward VDE.

Effect of halo current loads on centerstack

- Vertical poloidal currents from halo currents lead to radial forces on centerstack
- Toroidal peaking of halo currents results in an imbalance that pushed centerstack to one side
  - CS is supported from the bottom
  - Blocks required to react these loads at the top of device
- Previous blocks transferred load to vacuum seal

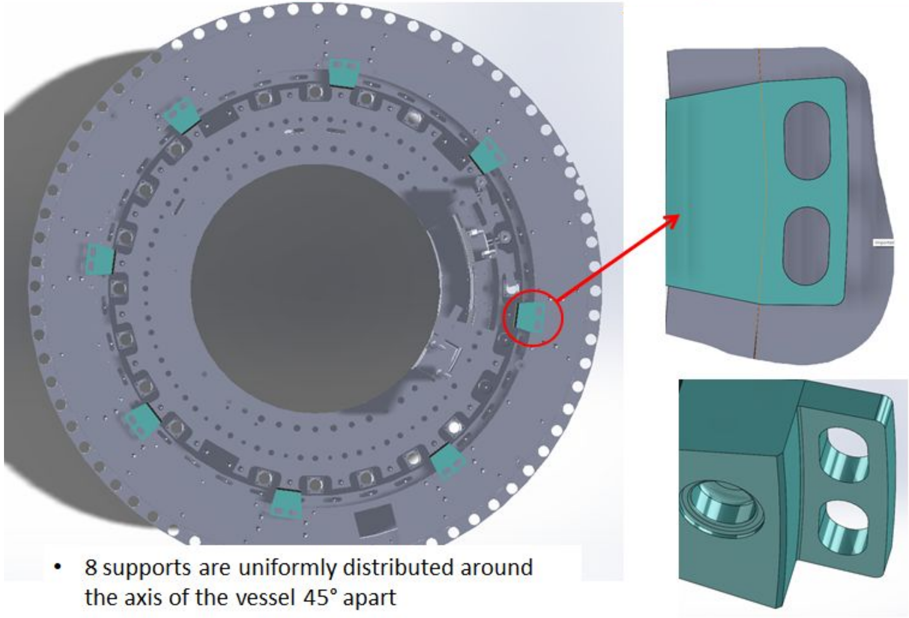
P. Titus

Midplane of centerstack

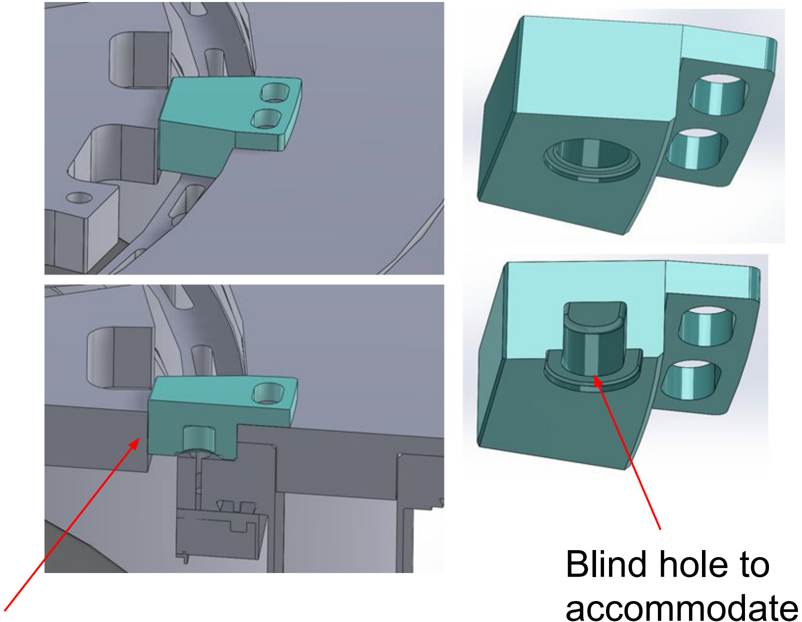


Bottom of centerstack

Planned modifications to centerstack support structures



- 8 supports are uniformly distributed around the axis of the vessel 45° apart



Sliding contact to allow thermal expansion of centerstack

Blind hole to accommodate other hardware

- Blocks to be instrumented with strain gauges and accelerometer enabling measurement of transient loads, distribution, rotation, etc.