DCPS & Running with Aquapour/CTD-425 Composite between the OH and TF

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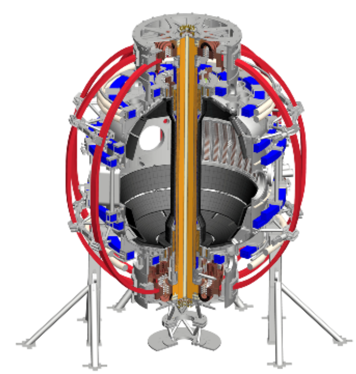
2015 Physics Operator Training



Disclaimer

This is not a complete or uniform overview of DCPS.

I'll skip many details about the hardware, software design, test procedures,…

It is weighted towards things the PiC needs to know.

Outline

- Overview of DCPS
- Algorithms
- Aquapour Consequences and Protection
- dI/dt Protection
- PiC as a Protection System
- Demonstration of DCPS Fault Determination

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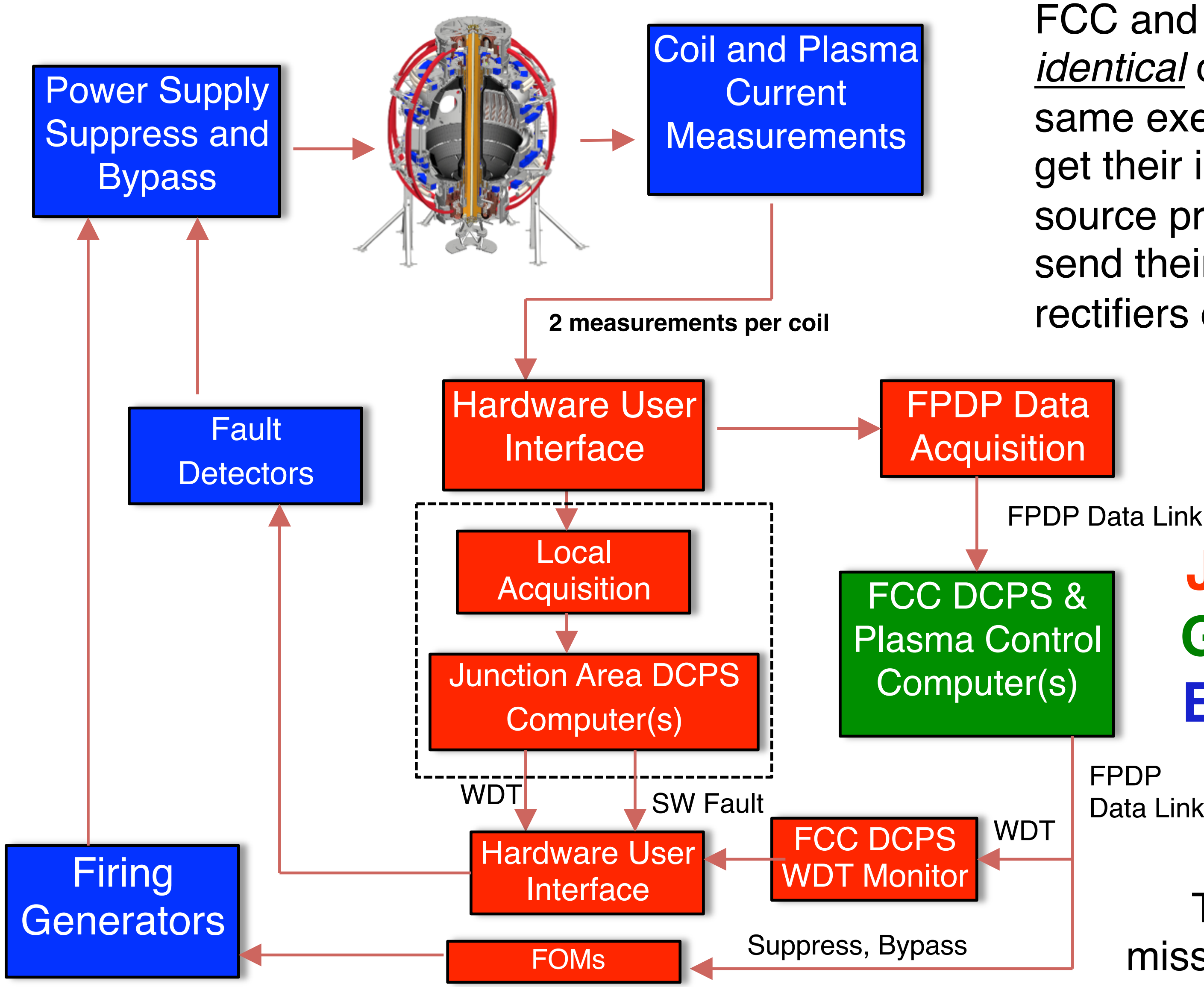
What is DCPS?

- DCPS is the “Digitial Coil Protection System”
- It is a suite of computers, data acquisitions systems, custom software, custom hardware, automated testing systems, procedures, and parameter data.
- The DCPS is primarily designed to protect the NSTX-U coils and their mounting hardware against excessive thermal & mechanical loads.
- It is NOT a global machine protection system.
- It is NOT a rectifier protection system.
- It does NOT know about the RWM coils, and cannot protect them.

Two DCPSs, and for Each, Two Ways of Stopping the Shot

- There are two instances of DCPS:
  - One at D-Site, in the “Junction Area”
  - One a C-site, in the FCC
  - Same executable runs on both system
- Each can terminate the shot by a pair of actions:
  - Can declare a “software fault”, because of an algorithm trip.
    - This becomes a L1 fault via hardware for the JA DCPS.
  - Can stop the “Watch Dog Timer” because of a software or input problem.
    - WDT is a [JA,FCC]=[5 kHz, 2.5 kHz] pulse train generated by the program.
    - Obviously, if the software is not running, the timer will not toggle.
    - Hardware detects this loss of toggling and declares a L1 fault.
- The shutdown is a suppress and bypass applied to all rectifiers.
  - Suppress = Stop the rectifier from rectifying
  - Bypass = Short out the coil through a diode

Simplest Block Diagram



FCC and JA DCPS have *identical* code, and are the same executable file, but i) get their input from different source providers, and ii) send their output to the rectifiers different ways

Red for Junction Area
Green for FCC
Blue for FCPC

This block diagram is missing A LOT of details!

Input Data to DCPS

- Parameter data controls all of the DCPS functions
  - Stored in MDS+ trees
  - One tree for FCC DCPS, and one for JA DCPS
  - Pairs of trees are controlled so that the FCC has more restrictive parameters (by a few %)
    - FCC should always trip first!
- Realtime data is limited to some digital status and timing information, and 2 measures of the coil current for each coil system.
  - No line-switch positions, no coil voltages, no water temperatures, no strain gauges, no displacement monitors

Sign Convention
Same sign convention is used in PCS, DCPS

- Right handed with {R,ϕ,Z} cyclic order.
  - R (major radius) increases moving out of the vessel.
  - Φ (toroidal angle) increases in the CCW direction as viewed from above.
  - Z (vertical direction) increases moving towards the NTC ceiling.
- This leads to the following “rules”
  - I_P is a positive number in standard co-injected operation.
  - I_{TF} is a negative number in normal operation with the lower X-point in the favorable drift direction.
    - TF is CW from above, the rod current is down.
  - PF-5 is negative for positive I_P.
  - OH coil pre-charges positive, and swings negative.
- These enforced by careful sign-corrections on current measurements, magnetic measurements.

Who's who in DCPS

- Cognizant Engineer: Tim Stevenson
  - He acquired this role when Ron Hatcher passed away.
- DCPS software: Keith Erickson (who wrote it) and Roman Rozenblat
- DCPS hardware: Hans Schneider (and Ed Lawson, and Paul Sichta)
- DCPS MDS+: Greg Tchilinguirian
- DCPS morning startup: Ed Lawson
  - Done using DCPS-779
- Moral support: Stefan Gerhardt

Procedural Response to a Fault

- We gotta figure out why.
  - You can use the GUI to assess if it was plasma control dynamics.
- Need authorization from correct people before faults can be reset.
  - Governed by D-NSTX-OP-G-176

Coil Protection Systems

Protection Device	Set-Up	Authority to Reset
DCPS - FCC. (FCPC Suppress/Bypass)	OP-DCPS-779	Chief Operating Engineer (+) Physics Operator (or) PC-EIC (or) DCPS Protection Eng.
DCPS - Junction Area (FCPC Level 1 Fault)	OP-DCPS-779	Chief Operating Engineer (+) DCPS Protection Engineer
Pulse Duration Period (PDP) Timer	OP-NSTX-17	Chief Operating Engineer (+) FCPC Engineer
FCPC Fault Detector Section Overcurrent	PTP-ECS-39	Chief Operating Engineer (+) DCPS Protection Engineer (+) FCPC Engineer
FCPC Fault Detector Module Overcurrent	PTP-ECS-39	Chief Operating Engineer (+) FCPC Operations Supervisor (or) FCPC Engineer

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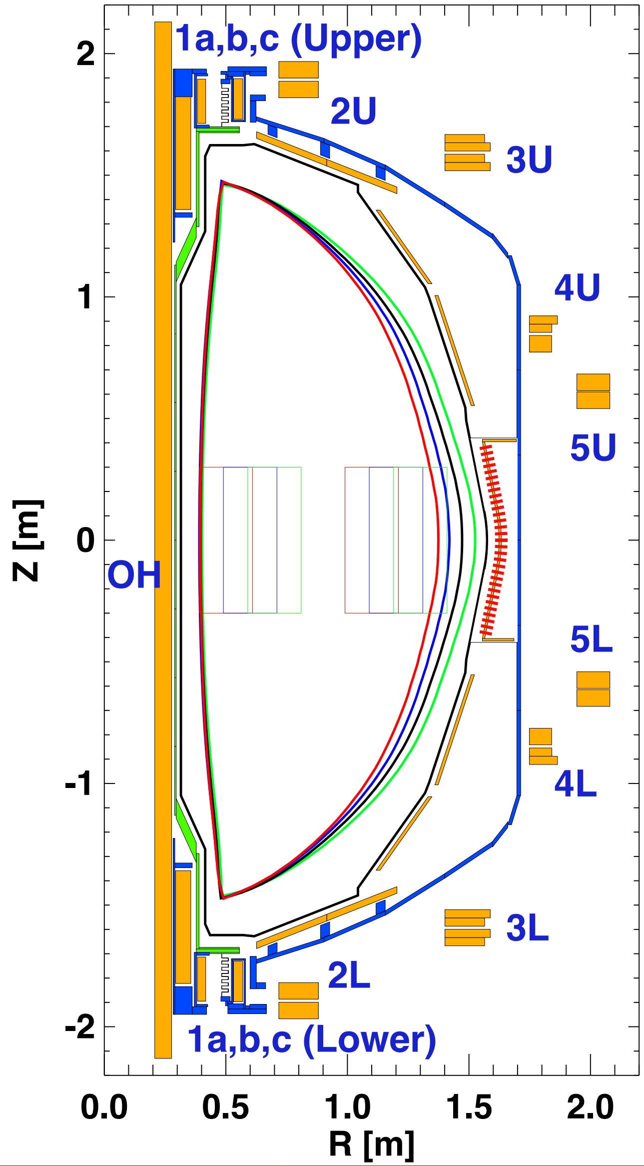
NSTX-U Coils



PF-5,4 Coils:

- Provide the vertical field,
- Upper and lower coils in series.

PF-3 Coils:

- Control the plasma vertical position by applying a radial field (up-down asymmetric currents).
- Also help in controlling the elongation, squareness, and dr-sep
- Upper and lower coils independently controlled

PF-1a,1b,1c,2 Coils:

- Control the divertor geometry, X-point and strike point locations.
- Upper and lower coils are independently controlled.

OH Coil:

- Single coil provides loop voltage to the plasma.

TF Coil (not shown)

- Makes toroidal field.

List of DCPS Algorithms

- Overcurrent
- I^2t integrals
- T_{TF}-T_{OH}
  - Must limit this due to aquapour.

Including the heating after a suppress and bypass

- Vertical and radial forces on coils
- Combinations of vertical forces
- Local stresses in OH, PF-4, PF-5
- TF Torsional Shear Stress
- TF outer leg moments

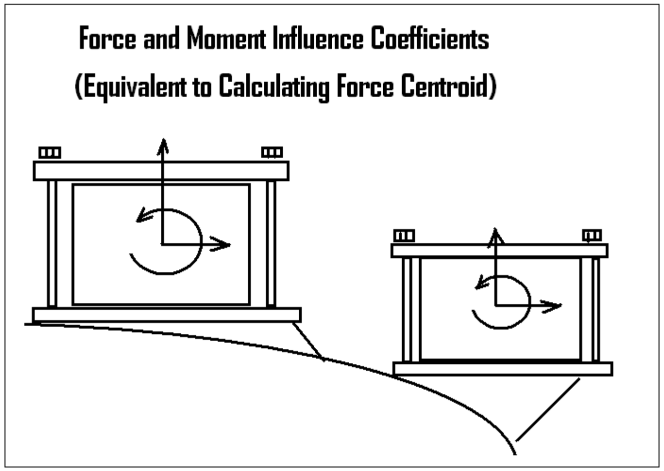
Including calculations of the forces following a disruption with a simple model for the post-disruption currents.

DCPS Has a Post-Disruption Current Algorithm And Two Plasma Shapes

- Algorithm is based on a very simple inductive coupling model.
  - The plasma current is assumed to vanish “instantaneously”.
  - The flux from the plasma is transferred to the coils, ignoring the vessel entirely
- Mathematically, it is very simple:
  - I_{coil} is a size N_{coils} vector of coil currents.
  - $I_{coil,PD} = I_{coil}+C_D I_P$, where C_D is a N_{coils} vector of coupling coefficients derived from the full mutual inductance matrix.
- At each time point, every algorithm is evaluated on both I_{coil} and $I_{coil,PD}$.
- Furthermore, many algorithms are evaluated for both a “shaped” and “circular” plasma cross-section.
  - These are generally small effects.

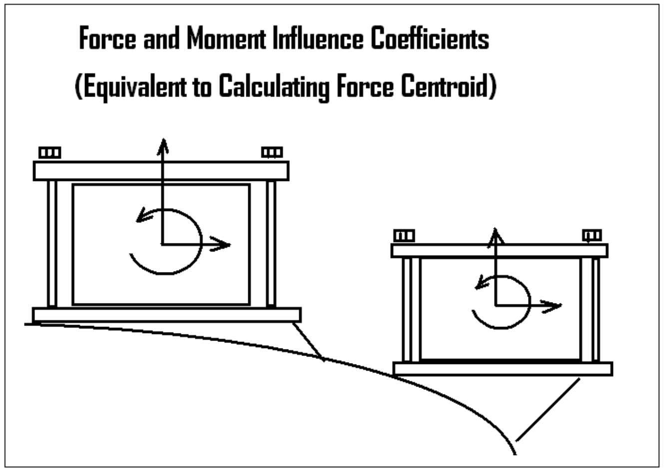
DCPS Calculates Radial & Vertical Forces on Coils, Moments

- Simple calculations of the form Force/Moment on ith coil is given by **$F_i = I_i \Sigma \alpha_{i,j} I_j$**.
  - Index j is a sum over all coils, and the $\alpha_{i,j}$ come from calculations.
  - Forces computed for all coils.
  - Asymmetric limits in many cases.
- Radial force is basically the coil hoop force (self force) + radial force due to nearby coils.
- Vertical force is that due to nearby coils…no vertical self-force.
- Moments are related to twist of the winding pack due to nearby coils



DCPS Calculates Stress on Bolts

- PF-2 through PF-5 are clamped with bolts.
- The force on these bolts is due to both:
  - Vertical force on the coil
  - “moment” about the coil centroid.
- Stress: $S_i = C_{1,i}M_i + C_{2,i}F_{1,I}$
  - i➔{PF-2U, PF-3U,…,PF-5U,…PF-3L, PF-2L}



PF2/3 DCPS Multipliers

Location/Component	Stress Limit	Fvert (lbs)	Mtheta (in -lbs)
PF2 1/2 inch Bolts	20,000 psi*	/5.23/4/.1416	/5.23/8in/2/.1416
PF2 Plate to Rib Weld			
PF3 Lower 1/2 inch Bolts	20,000 psi	/9/4/.1416	/9/8in/2/.1416
PF3 Plate to Rib Weld			

DCPS Computes Combined Vertical Forces

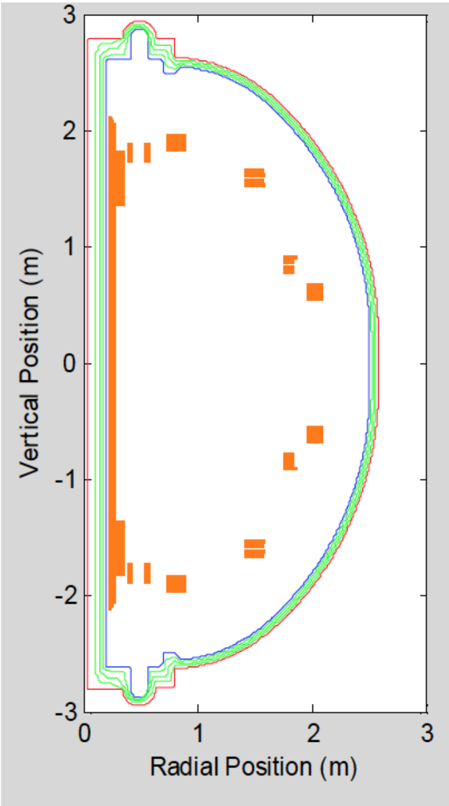
- Some forces on brackets and welds go like the sum of coil vertical forces.
- Example is the PF-4 and PF-5 mounting brackets, who's load scales like F_Z on PF-4U +PF-4L+PF-5U +PF-5L

		Enable/Execute Options			
	[redacted]	FCC		JA	
		Enable	Execute	Enable	Execute
FZ, PF1aU+PF1bU	1	1	1	1	1
FZ, PF1aU-PF1bU	2	0	1	0	1
FZ, PF1aL+PF1bL	3	0	1	0	1
FZ, PF1aL-PF1bL	4	0	1	0	1
FZ, (PF1aU+PF1bU)+(PF1aL+PF1bL)	5	1	1	1	1
FZ, (PF1aU+PF1bU)-(PF1aL+PF1bL)	6	0	1	0	1
FZ, PF1cU+PF2U	7	1	1	1	1
FZ, PF1cU-PF2U	8	1	1	1	1
FZ, PF1cL+PF2L	9	1	1	1	1
FZ, PF1cL-PF2L	10	1	1	1	1
FZ, (PF1cU+PF2U)+(PF1cL+PF2L)	11	0	1	0	1
FZ, (PF1cU+PF2U)-(PF1cL+PF2L)	12	0	1	0	1
FZ, PF3U+PF4U+PF5U	13	0	1	0	1
FZ, PF3L+PF4L+PF5L	14	1	1	1	1
FZ, (PF3U+PF4U+PF5U)+(PF3L+PF4L+PF5L)	15	0	1	0	1
FZ, (PF3U+PF4U+PF5U)-(PF3L+PF4L+PF5L)	16	0	1	0	1
FZ, PF3U+PF4U+PF5U+PF4L+PF5L	17	0	1	0	1
FZ, PF4U+PF5U	18	1	1	1	1
FZ, PF4U-PF5U	19	1	1	1	1
FZ, PF4L+PF5L	20	1	1	1	1
FZ, PF4L-PF5L	21	1	1	1	1
FZ, (PF4U+PF5U)+(PF4L+PF5L)	22	1	1	1	1
FZ, (PF4U+PF5U)-(PF4L+PF5L)	23	1	1	1	1
FZ, (PF1CU+PF2U+PF3U+PF4U+PF5U+PF5L+PF4L+PF3L+PF2L+PF1CL)	24	1	1	1	1
FZ, (PF1AU+PF1BU+PF1BL+PF1AL+OH)	25	1	1	1	1

DCPS Calculates the Torque on the TF

- Torques on the TF due to the radial part of the TF current crossing the vertical field, or the vertical part of the TF current crossing the radial field.

$$\left[\frac{\text{Net Upper Half TF System Torque}}{1\,\text{N-m}}\right] = 13563.1\left[\frac{I_{OH}}{1\,\text{kA}}\right] + 2260.9\left[\frac{I_{PF1AU}+I_{PF1AL}}{1\,\text{kA}}\right] + 1580.6\left[\frac{I_{PF1BU}+I_{PF1BL}}{1\,\text{kA}}\right] + 1851.5\left[\frac{I_{PF1CU}+I_{PF1CL}}{1\,\text{kA}}\right] + 5197.5\left[\frac{I_{PF2U}+I_{PF2L}}{1\,\text{kA}}\right] + 21915.7\left[\frac{I_{PF3U}+I_{PF3L}}{1\,\text{kA}}\right] + 56813.9\left[\frac{I_{PF4}}{1\,\text{kA}}\right] + 118636.5\left[\frac{I_{PF5U}}{1\,\text{kA}}\right] + 713308.9\left[\frac{I_{plasma}}{1\,\text{MA}}\right] \quad (2)$$

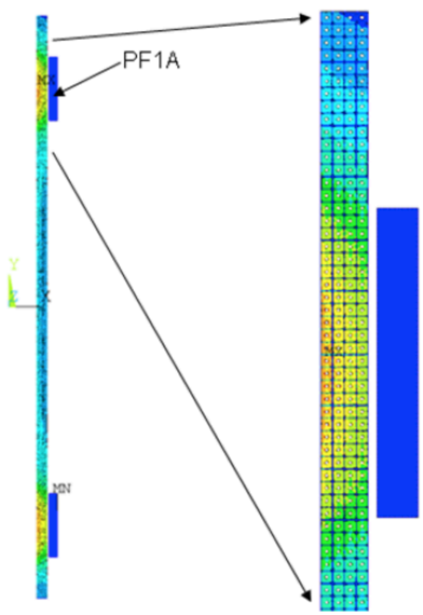


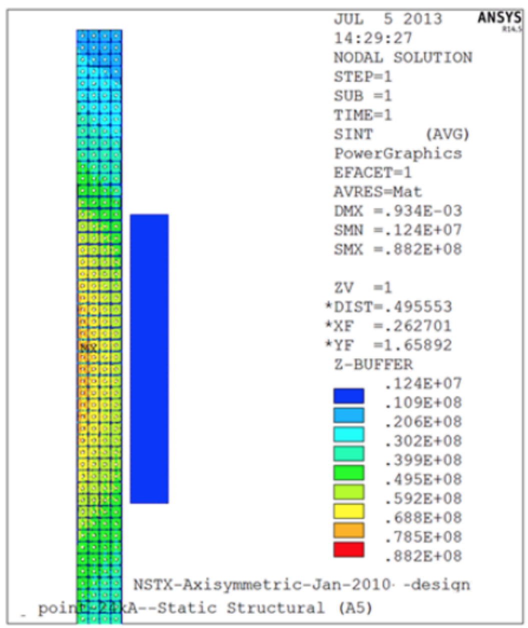
$$\left[\frac{\text{Net TF System OuterLeg Torque}}{1\,\text{N-m}}\right] = 3519.9\left[\frac{I_{PF1AU}-I_{PF1AL}}{1\,\text{kA}}\right] + 3692.0\left[\frac{I_{PF1BU}-I_{PF1BL}}{1\,\text{kA}}\right] + 4293.8\left[\frac{I_{PF1CU}-I_{PF1CL}}{1\,\text{kA}}\right] + 13191\left[\frac{I_{PF2U}-I_{PF2L}}{1\,\text{kA}}\right] + 16497\left[\frac{I_{PF3U}-I_{PF3L}}{1\,\text{kA}}\right] \quad (1)$$

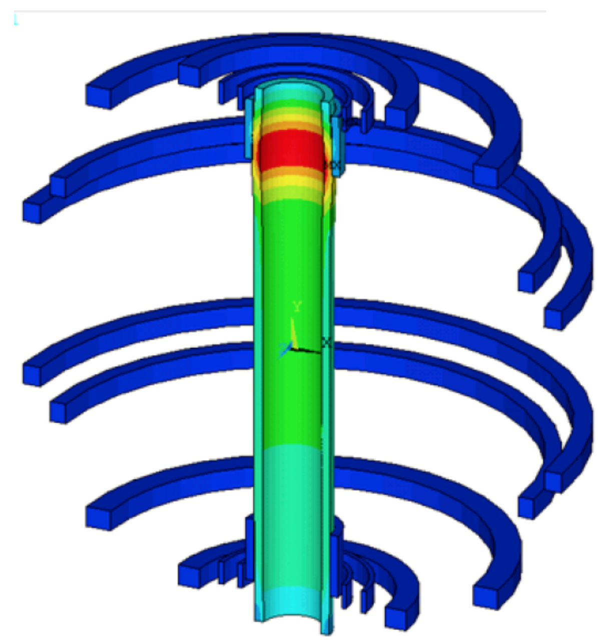
NSTXU-CALC-132-03-00

DCPS Calculates Local OH Stresses

- Basically, hoop-force is not a constant along the length of the coil.
  - Can be increased or decreased in the vicinity of a coil.
- $S_{OH}=I_{OH}\Sigma\alpha_j I_j$, with the shear stress computed at the top, middle, and bottom using this formula.

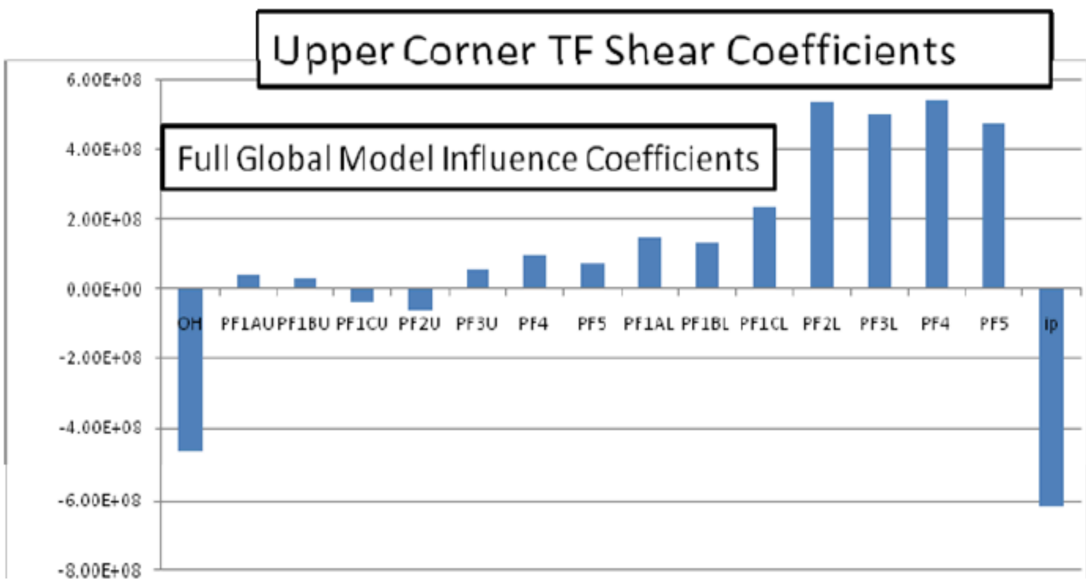


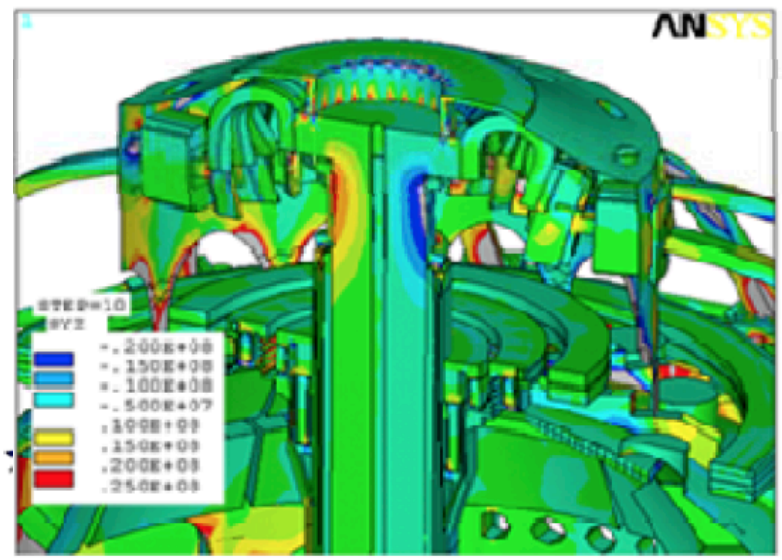




DCPS Calculates Shear Stresses on the TF Inner Bundle

- $S_{TF}=I_{TF}\Sigma\alpha_j I_j$, with the shear stress computed at the top, middle, and bottom using this formula.
- Basically, the torque on the TF flags (due to radial current and vertical field) leads to shear stress between the conductors.
  - Also the vertical radial current on the TF inner legs and the radial field from coils and plasma
- That shear stress must be taken by the CTD-425 resin system.





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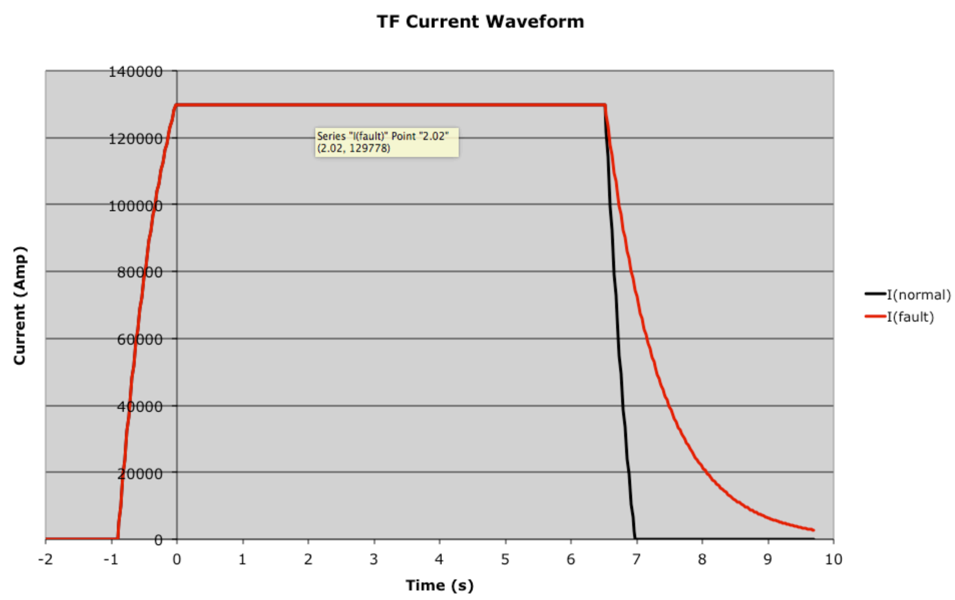
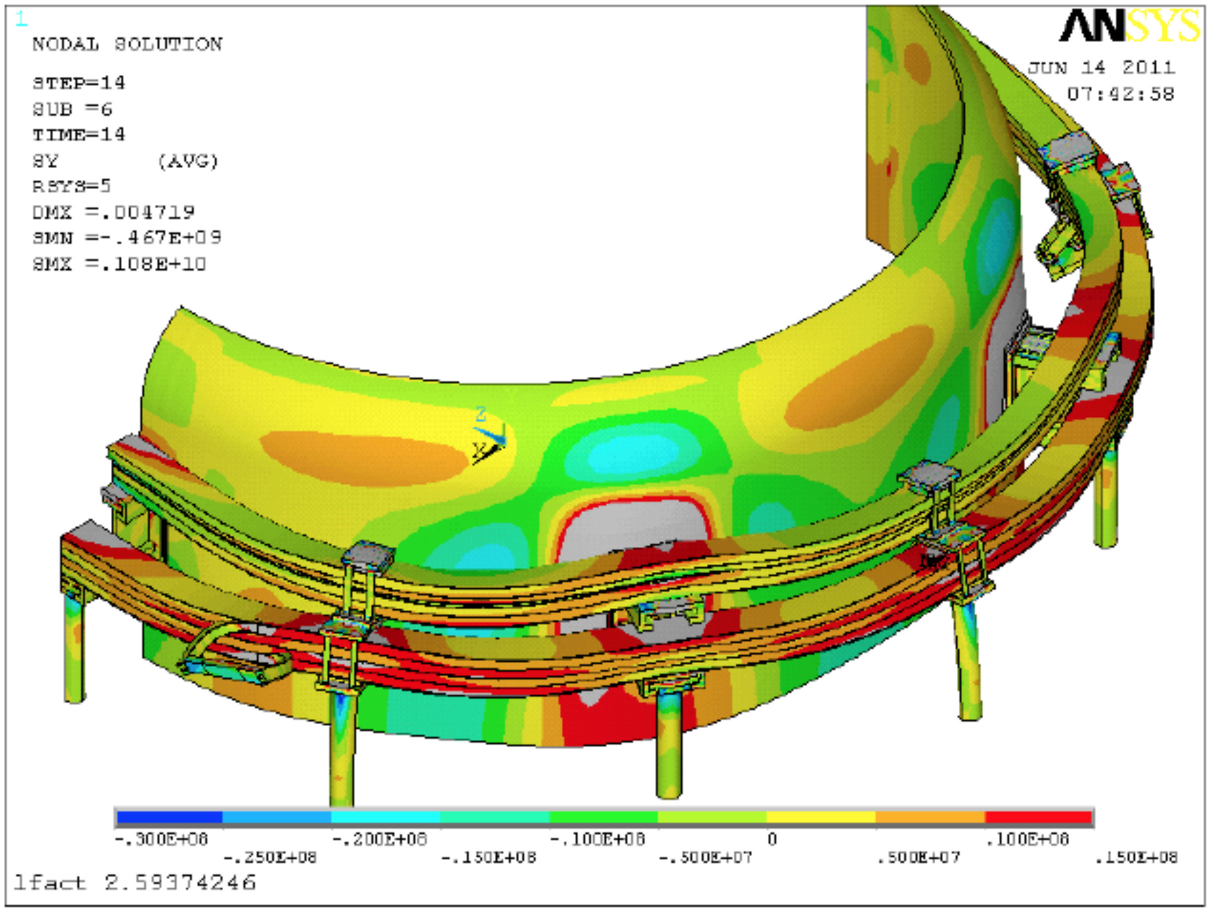
DCPS Calculates I^2t Integrals

- Computes the simple integral(I^2t)
  - This is called "action"
- Computes the action that would occur if a suppress and bypass were to happen: $\tau I_i^2/2$
  - τ is the L/R time when bypassing
- Quantity compared to limit: integral(I^2t)+$\tau I_i^2/2$



DCPS Calculates Bending Stresses on PF-4 and PF-5

- $S_{PF5}=I_{PF5}\Sigma\alpha_j I_j$ & $S_{PF4}=I_{PF4}\Sigma\alpha_j I_j$.



Basically, the brackets on the PF-4 and PF-5 coils cause local stresses where they support the coils against vertical loads

A Note on Limit Values

- All the previous mechanical things are checked against limit values to determine if there are faults.
- Different calculations have different sources of limit values.
  - Known mechanical properties and mechanical limits
    - OH vertical force, radial forces, OH stresses, TF shear stresses.
  - Qualification against 96 scenarios
    - Many vertical forces, TF torques
- Again, DCPS parameter trees created so that the FCC tree is less permissive than the JA tree.

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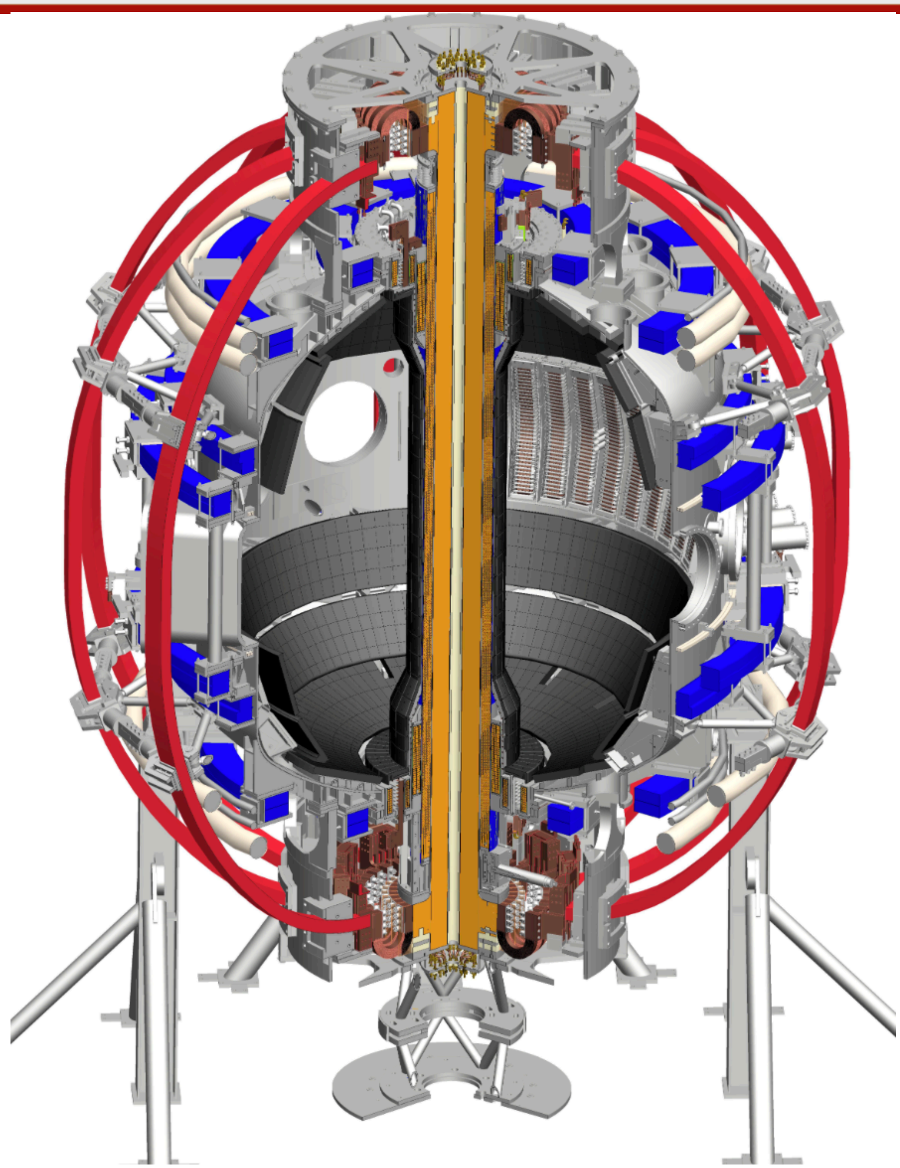
Background on Aquapoxy

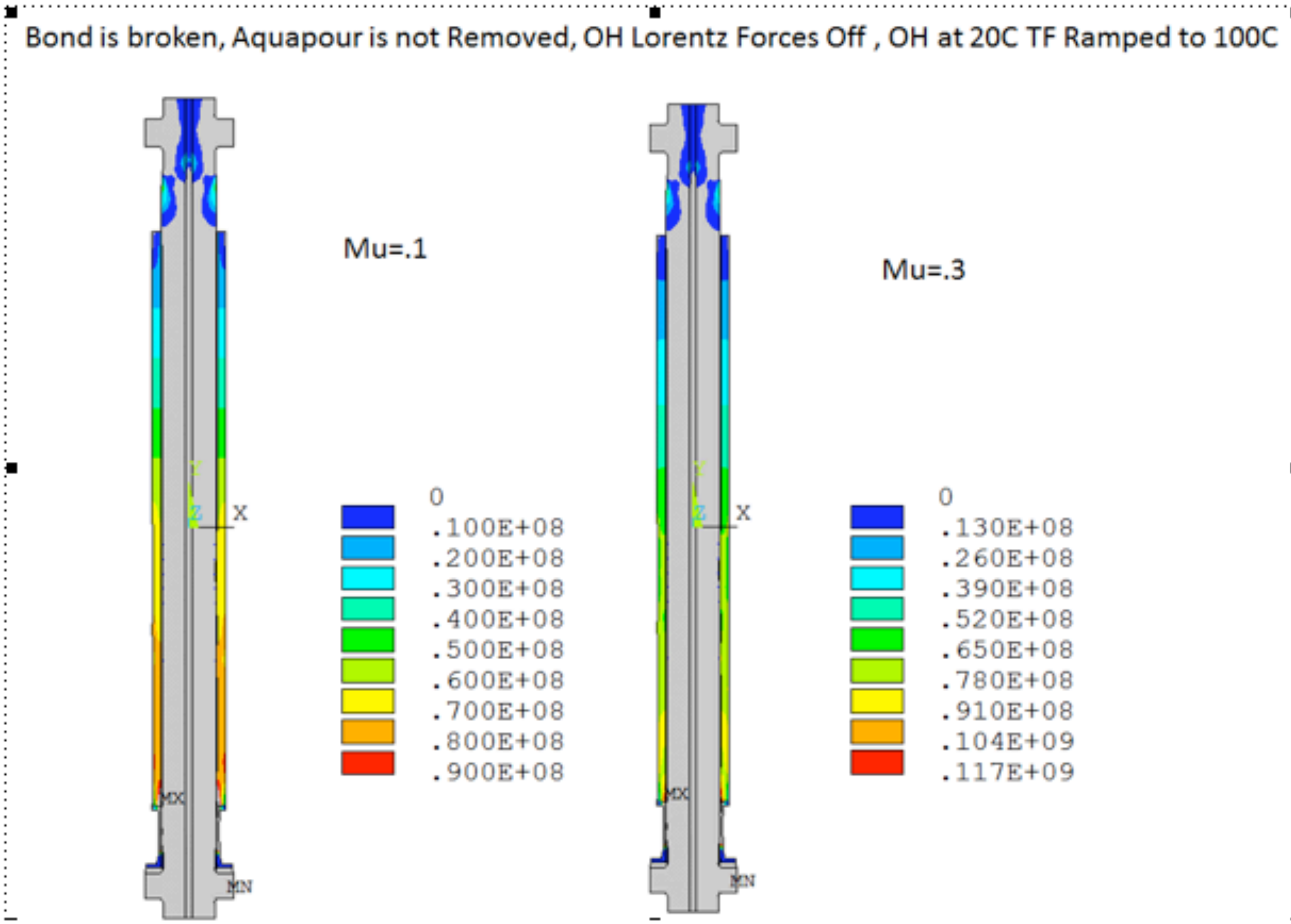
- OH coil is wound on the TF coil.
  - Intent was to have a small air gap between the OH ID and the TF OD.
  - Aquapour that was in that gap during winding was supposed to wash out.
  - It didn't wash out because it was it got inundated with CDT-425 resin (epoxy).
  - Aquapour + CTD-425+cure cycle is like concrete.

- TF coil grows axially when it gets hot.
  - With an air gap, no big deal.
  - Without air gap, it can pull on the OH coil



The TF Can Tear the Bottom of the OH Coil Apart

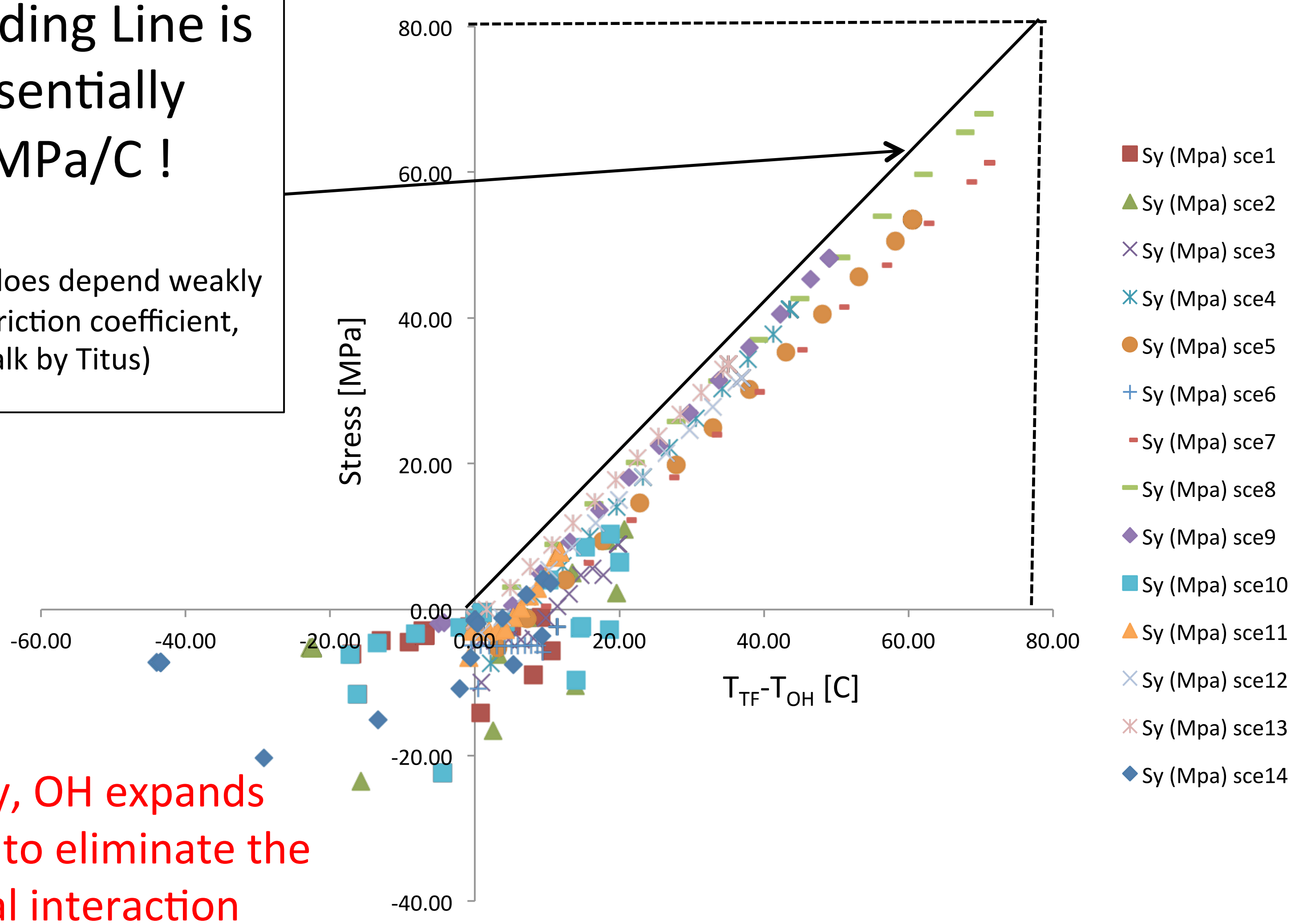
- With the TF hotter than the OH, the TF will "tug" on the OH as it grows.
- OH can slide on the TF, but there is some friction.
- Stress accumulates at the bottom of the coil.



Analysis Suggests We Can Eliminate OH Stresses by Keeping OH Hotter than TF

Bounding Line is Essentially 1MPa/C !

(Note, it does depend weakly on the friction coefficient, talk by Titus)

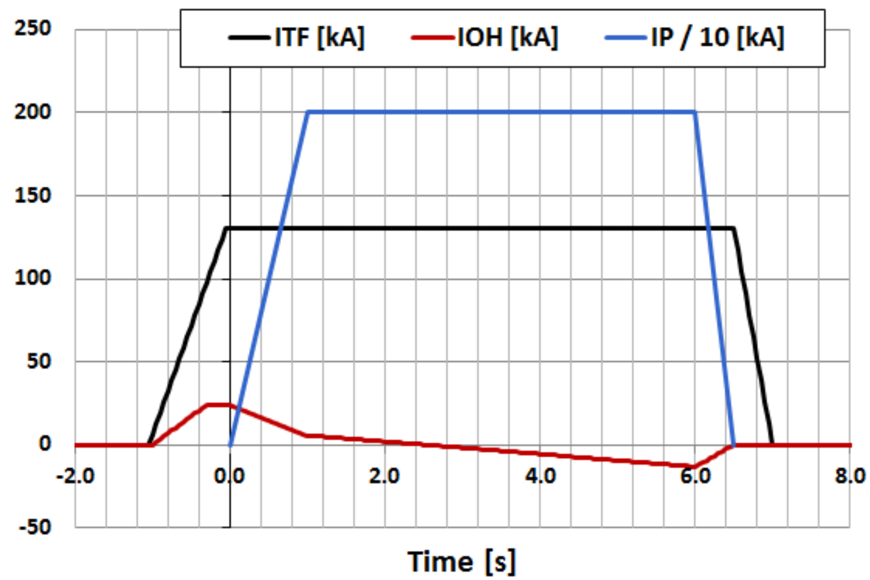


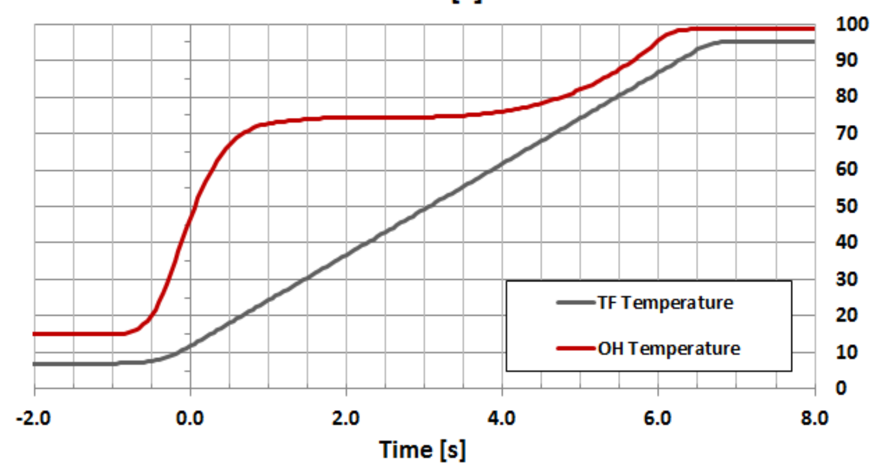
Basically, OH expands enough to eliminate the frictional interaction

Adjust the OH Waveform to Keep OH Hotter than TF

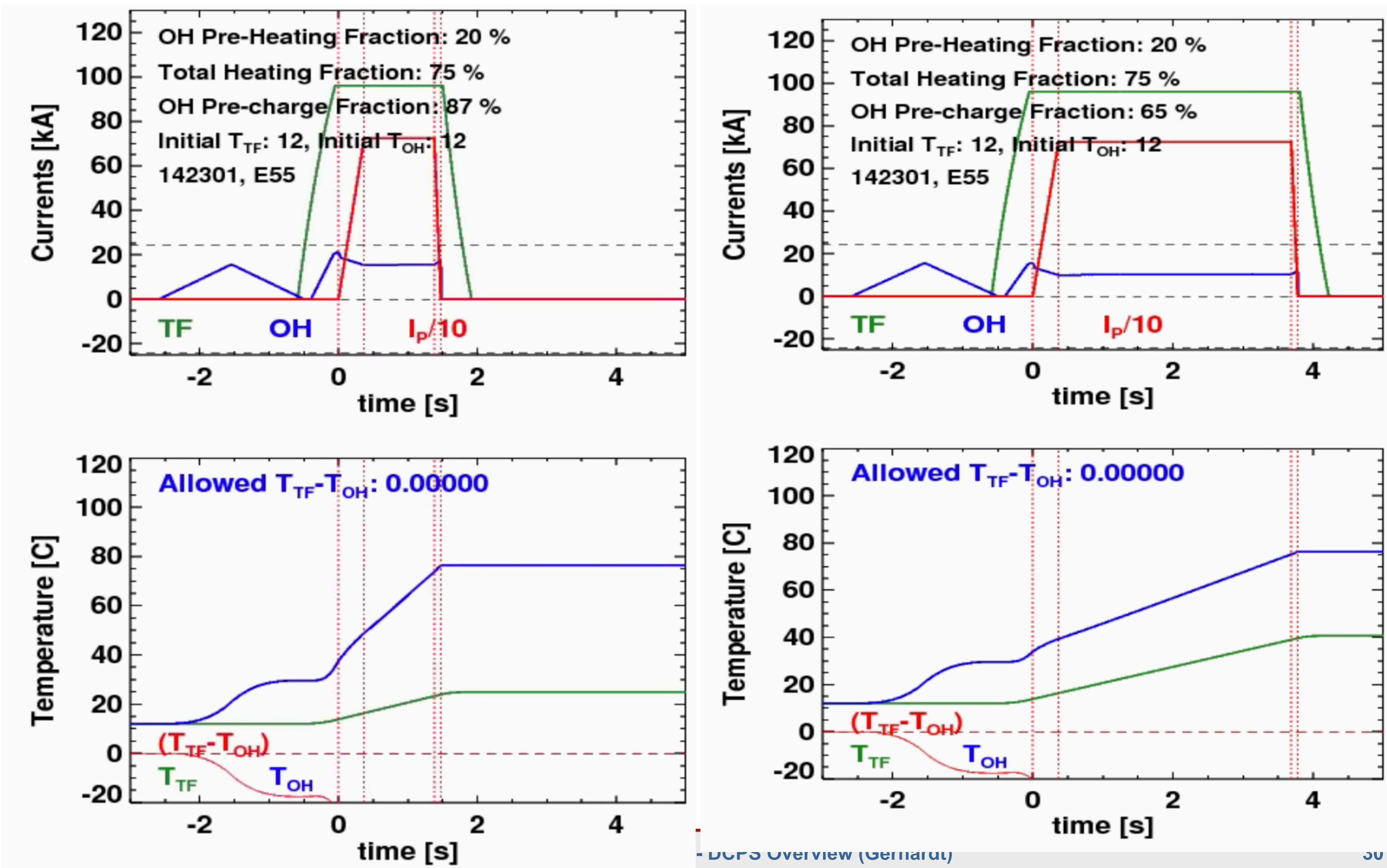
- Illustrative Example: 2 MA, 1T, 5 second.
- TF Coil:
  - Current is constant
  - Temperature is linearly increasing
- OH Coil:
  - Current has a zero-crossing
  - Temperature has an “S-Shaped” curve.
- Options for maintaining $T_{TF}<T_{OH}$.
  - ***Pre-heat the OH coil*** using currents before the TF turns on.
  - Control the shape of the OH S-curve by ***adjusting the amount of pre-charge***.
- In this example,
  - Full 24 kA pre-charge
  - Pre-charge duration is extended to provide heating.

H_{98} = 1.2, $f_{Greenwald}$ = 0.75, P_{NBI} = 8MW, β_N = 4.6





Pre-Heating/Pre-Charge Scenarios…Examples From 100% Non-Inductive Scenarios



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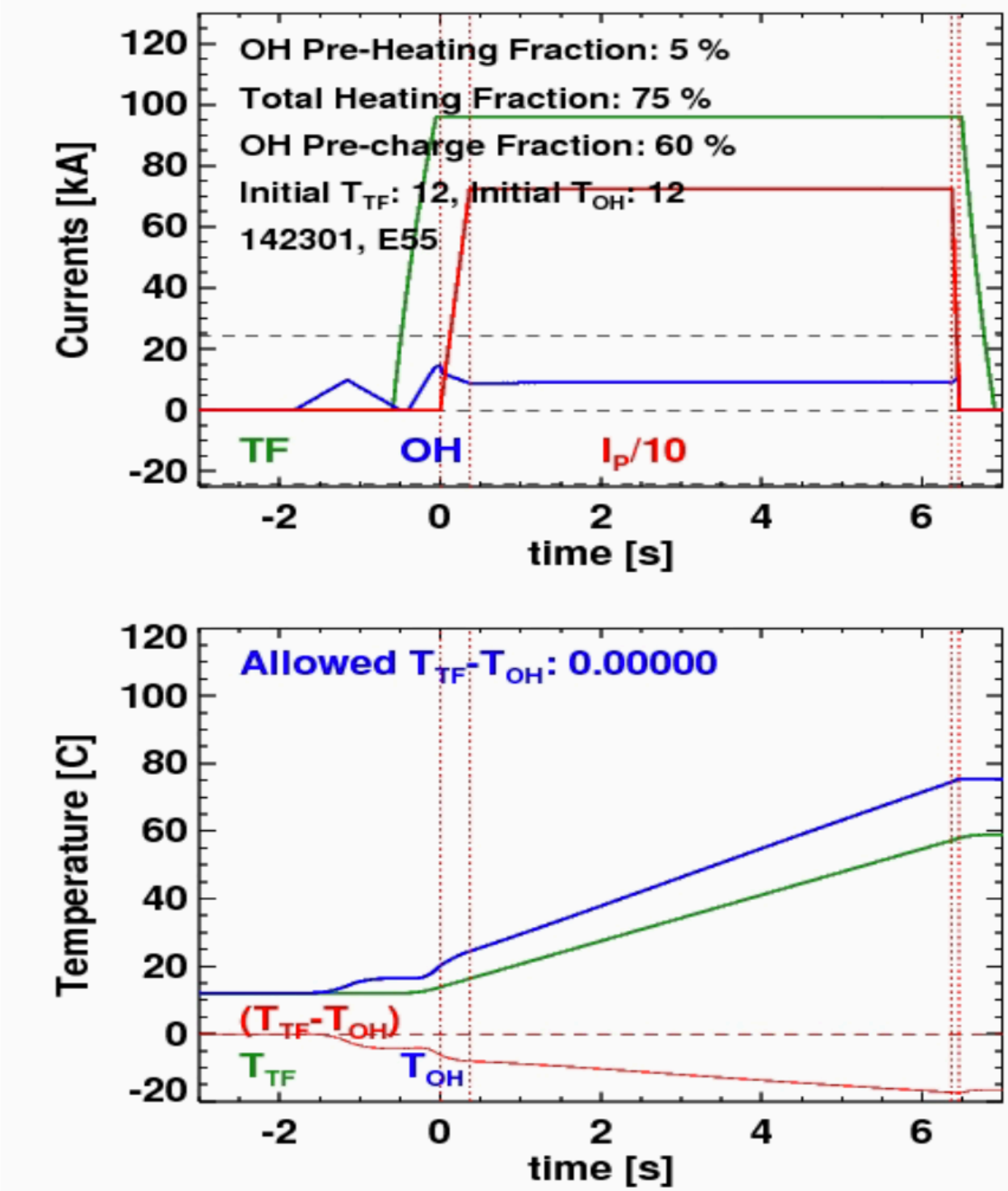


So for these 100% non-inductive plasmas, a low pre-heat and moderate pre-charge gets the longest shot.

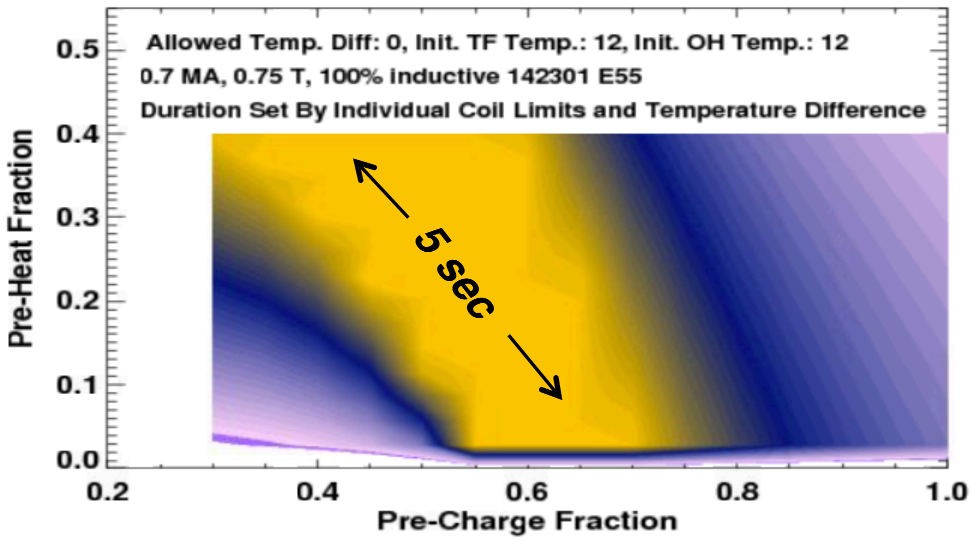
But note that this result depends on:

- TF Current
- Plasma current (flux required for ramp-up)
- Non-Inductive fraction (heating, confinement)

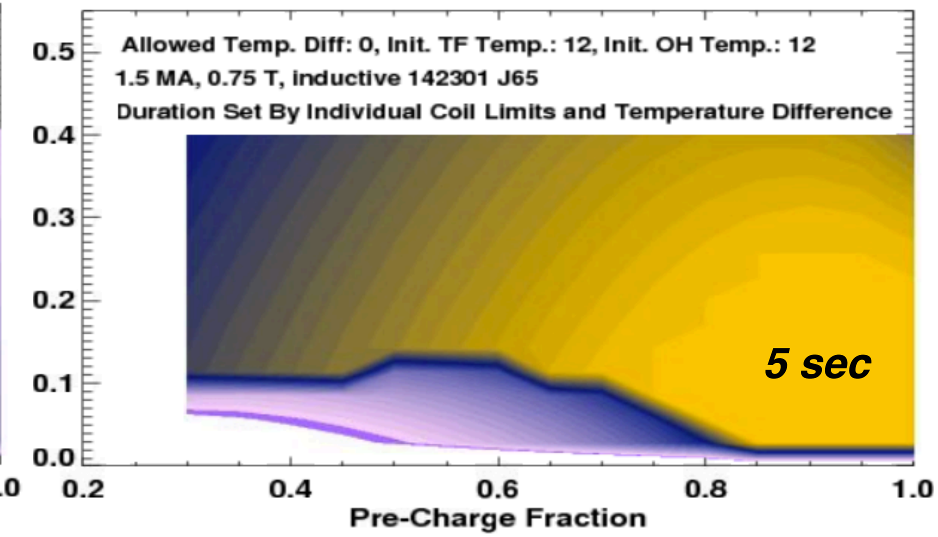
For the First Year, a 15-20% Pre-Charge Appears to be a Good Compromise

- Scan two variables in these studies:
  - Pre-heat level, quantified as the fraction of the full OH coil I^2t limit used before the shot starts.
  - Pre-Charge fraction, quantified as the fraction of 24 kA used.

0.7 MA, 0.75 T, 100% Non-Inductive



1.5 MA, 0.75 T, Partial Inductive



- Resistive pre-heat of ~15% provides operating room for 0.75 T scenarios typical of the first year.
  - Same as starting the coil at ~23 C

DCPS Will Be Used to Enforce This Temperature Difference

- Operating engineer & water-systems PLC enforce that the coils be cooled to a pre-defined set-point at the start of the discharge.

- Coil temperature evolution computed in DCPS based on I^2t integrals.
  - $T_{TF,i}=T_{TF,0} + S_{TF} \bullet dt \bullet \Sigma I_{TF}^2$ $T_{OH,i}=T_{OH,0} + S_{OH} \bullet dt \bullet \Sigma I_{OH}^2$
  - $\delta T_i = (T_{TF,i}) - (T_{OH,i})$

- Consider the heating that would occur in the event of a fault:
  - $\delta T_{TF,fault,i} = I_{TF,i}^2 C_{TF}$, $\delta T_{OH,fault,i} = I_{OH,i}^2 C_{OH}$ (OH may or may not heat up more than the TF)
  - $\delta T_{i,fault} = (T_{TF,i}+\delta T_{TF,fault,i}) - (T_{OH,i}+\delta T_{OH,fault,i})$

- At each cycle, compare both δT_i and $\delta T_{i,fault}$ to the defined limit (0 in the first year).

- Algorithm accounts for both instantaneous heating, and fault heating, while only relying on coil current measurements.

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Basic Idea is To Confirm The Grossly Proper Electrical Behavior of the Coil Systems

- When a coil has a turn-to-turn short, there is a step change in the inductance and resistance.
- Coil current evolution is generally solved by a large set of coupled 1st order ODEs

$$V_{coil}=L_{coil}dI_{coil}/dt + I_{coil}R_{tot}+M_{coil}dI_{coil}/dt+M_{plasma}dI_{plasma}/dt + \text{Vessel Coupling}$$

- Throw out many of the terms

$$V_{coil}=L_{coil}dI_{coil}/dt + I_{coil}R_{tot}+\cancel{M_{coil}dI_{coil}/dt}+\cancel{M_{plasma}dI_{plasma}/dt} + \cancel{\text{Vessel Coupling}}$$

- Algorithm:
  - Compute the expected dI/dt $\quad (dI_{coil}/dt)_{model} =(V_{coil,filter} - I_{coil}R_{tot})/L_{coil}$
  - Compute the measured dI/dt $\quad (dI/dt)_{measured} = (I_{filter,i}-I_{filter,i-1})/dt$
  - Take their difference $\quad (dI_{coil}/dt)_{error} = (dI_{coil}/dt)_{measured}-(dI_{coil}/dt)_{model}$
  - Compute the maximum dI/dt $\quad (dI_{coil}/dt)_{max} = f_{dI/dt}V_{objectiveMax}/L_{coil}$
  - Declare fault if $\quad abs((dI_{coil}/dt)_{error}) >(dI_{coil}/dt)_{max}$

Implementation Details

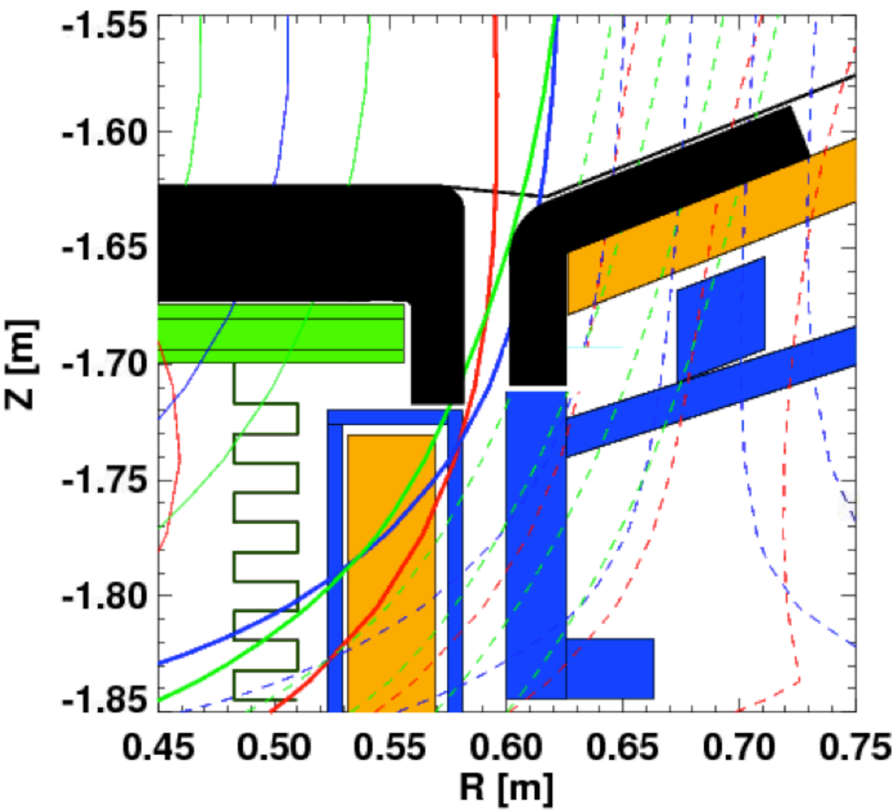
- This protection is in PSRTC, within PCS.
  - Needs to be there because PSRTC knows the coil voltage requests, while DCPS knows nothing about voltages.
- All the mutual couplings are neglected.
  - This is OK because the vessel tends to shield out most of the fast transients.
  - The term $f_{dI/dt}$ is set to 0.7 right now, which gives a big margin for error.
- When will this trip?
  - In the event of a major coil fault.
  - Possibly after fast disruptions? This is TBD.
  - If you request too much current in the wrong direction for a unipolar supply.
    - And how much is too much depends on the coil system inductance.
- How will you know it tripped?
  - You will get an un-announced suppress and bypass.
  - Look at the dedicated scope (in a few slides)
  - Does the fault indicator go high before the suppress and bypass starts?

Outline

- Overview of DCPS
- Algorithms
- Aquapour Consequences and Protection
- dI/dt protection
- PiC as a Protection System
- Demonstration of DCPS Fault Determination

PiC Will Need to Be Cognizant of Vessel/ PFC Internal Thermal Loading

- Primary concern is the PF-1c coil can.
  - TCs in the PF-1c can should be kept below 200 V to limit fatigue.
  - TCs in the tiles within the gap can also be monitored.
- Rules
  - If diverting with any of PF-1a, PF-1c, or PF-2 alone, essentially impossible to land field lines on the PF-1c coil.
    - Same conclusion when diverting with PF-1a *and* PF-2.
  - A negative PF-1c coil current can push the field lines away.
  - **Positive PF-1c current mixed with positive PF-1a can land field lines on the PF-1C coil casing!**



Note: Gap between PF-1C and IBDH tile is larger at the top.

Other concerns:
Thermal loading the RF antenna…use the cameras, does it glow after the shot.
Casing temperature…is it ratcheting?

The PiC is Often the First to Know When Something is Off

- Listen to the shots on the speakers, watch the plasma TV images.
- Be suspicious
- Don't take the next shot if you are unsure…ask Dennis/Devon/Stefan or the CoE for help.

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An idl GUI Exists to Help You Understand Why DCPS is Tripping

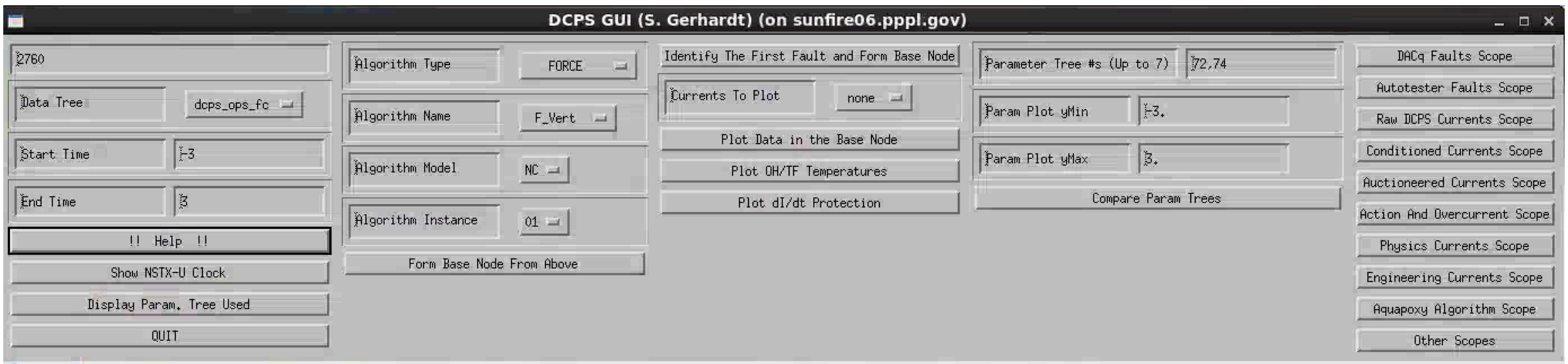
- Put the following in your .cshrc file:

```
alias DCPSGui 'idl /p/nstxusr/nstx-users/sgerhard/DCPS/GUI/GUIScript'
alias ScopeGui 'idl /p/nstxusr/nstx-users/sgerhard/DCPS/GUI/ScopeGUIScript'
module load nstx/mdsplus
module load nstx/dcps
```

- At the command prompt:

```
[sunfire06:/u/sgerhard.356]DCPSGui
```

- You should get this:



Hands on Training
Hope you brought you laptop

- Shot number…enter a number here and hit enter
- Tree: use ‘dcps_ops_fc’ or ‘dcps_ops_ja’
- “Identify The First Fault and Form Base Node”
  - Use this to identify the first fault that occurs on a shot, and then put the type, name, model, and instance in the “base node”
- “Plot Data in Base Node”…does what it says.

- Use shot 200148, find the fault that occurred (hint: dcps_ops_ja)
- Adjust limits to zoom in.
- Add a current to the plot; add two currents to the plot
- Use shot 200157 (test shot)…then “Plot OH/TF Temperatures”
- Pull up the “action and overcurrent” scope see 200148 (dcps_ops_ja) & 200049 (dcps_ops_fc).
- Use the “Aquapoxy Algorithm Scope”, look at 200157, dcps_ops_fc
  - Then 146539, tree=dcps_auto_fc
- Use the “dI/dt” protection scope from “Other Scopes”…see 201286

The end…

Stefan's Email on 3/9/13 on Magnetically Protecting the PF-1C Coils

- **Hypothesis:**
- That Kelsey's work on the gap tiles has made it much harder to put the OSP on the PF-1C casing, and that only a limited # of configurations can now cause this problem.
- That maybe NSTX-U can live without those configurations.

- **Analysis Method**
- Use isolver to solve for plasma boundaries with fixed PF-1C current. These PF-1C currents are specified as a fraction of the total plasma current.
- Provide input requests for aspect ratio, elongation, and triangularity, and allow the code to find values of currents in PF-1A, PF-1B, PF-2, PF-3, and PF-5.
- Adjust triangularity, elongation, and R0 requests to find if, for any given value of the fixed PF-1C current, it was possible to put the OSP on the PF-1C can.

- **Result**
- For PF-1A alone, essentially impossible to land the OSP on the PF-1C.
- Under this condition, no need for anything beyond Kelsey's tiles
- For PF-1A+PF-2 only, very difficult to land the OSP on the PF-1C.
- Kelsey's tile modifications appear to shield the coil for the most dangerous configurations.
- For PF-1A+PF-1B+PF-2, can once again land the OSP on the PF-1C coil
- Kelsey's tiles don't protect against this configuration...the PF-1B can push the field lines into the gap.
- For PF1A+PF-2 (+PF-1B if you want), and *positive PF-1C current* (and positive Ip)
- Tried PF-1C ratios from 0.001 to 0.007 A/A (or 7 kA at 1 MA), still could find cases with the OSP hitting the PF-1C coil with other coils currents having reasonable values
- So, adding PF-1C in the positive direction is a bad idea
- This is essentially saying that if PF-1C is used as a divertor coil (parallel to Ip) then the PF-1C must be the dominant divertor coil to be absolutely sure that the OSP cannot land on the PF-1C can.
  - May want to forbid use of PF-1A and/or PF-2 when PF-1C has current in the diverting direction.
- For a PF1A+PF1B+PF-2, and *negative PF-1C current*
- A negative PC-1C current at the level of 0.001 A/A (or 1kA at 1MA) appears to be enough "buffer" field to eliminate the tendency of the field lines to hit the 1C can when 1B is on.
- (recall), w/o PF-1B, no real problem after Kelsey's tile modifications.

- **Potential Solution**
- Never allow PF-1C to be run as a divertor coil, except when the other divertor coils are off or have very small values.
- Still need to define "very small" in this context.
- Still allows the SFD research with PF-1C "pushing"
- If PF-1B is in the circuit & control loop, and thus may turn on, then maintain a buffer field using PF-1C in the "pushing" direction of at least 0.001 A/A
- Could enforce this trivially through DCPS or PCS.