Impact of the Digital Coil Protection System and Plasma Shutdown Handler on NSTX-U Operations

S. P. Gerhardt[1], D. Battaglia[1], **M.D. Boyer**[1], K. Erickson[1], D. Mueller[1], C. Myers[1], S. Sabbagh[2], H. Schneider[1], T. Stevenson[1]

1: Princeton Plasma Physics Laboratory, 2: Columbia University

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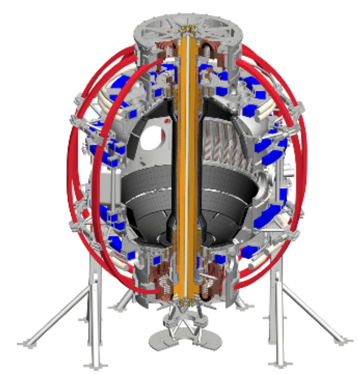


DCPS Overview

- NSTX-U power supplies can produce combinations of currents which result in forces that exceed limits on coils and their supports.
- DCPS = Digital Coil Protection System
- System → hardware, realtime software, parameter determination and archiving, testing, ops. procedures.
- Realtime software runs simultaneously in two independent locations:
  - Dedicated computer in the “junction area” adjacent to the power supply room.
  - Same computer as the plasma control system, in the FCC adjacent to the control room.
- DCPS can take only a single action…power supply crowbar that ends the shot.

DCPS Computes Four "Types" of Algorithms

- Post-Disruption Current Analysis on Current Vector I:
  - $I_{post\text{-}pis}=I-I_P P$
  - P is a vector derived from all coil-plasma mutual inductance.
  - Force algorithm evaluated on I & $I_{post\text{-}dis}$
- "Action" Integrals:
  - A_i = integral(I_i^2dt)
  - $A_{i,full} = A_i + I_i^2\tau_i/2$ ← τ_i accounts for a potential power supply crowbar
- Simple Forces:
  - $F_i=I_i\Sigma\alpha_{i,j}I_j$
  - Radial and vertical forces, internal stresses and moments
- Complex Forces:
  - $C_i=\Sigma\beta_i F_{Z,i}+\Sigma\chi\beta_i F_{R,i}+\Sigma\delta_i A_i+\Sigma\varepsilon_i A_{i,full}+\Sigma\phi_i I_i$
  - Used for combining vertical forces, bolt stresses, OH-TF interaction

Action, Simple Forces, and Complex Forces are All Compared to Positive and Negative Limits

List of DCPS Component Protection

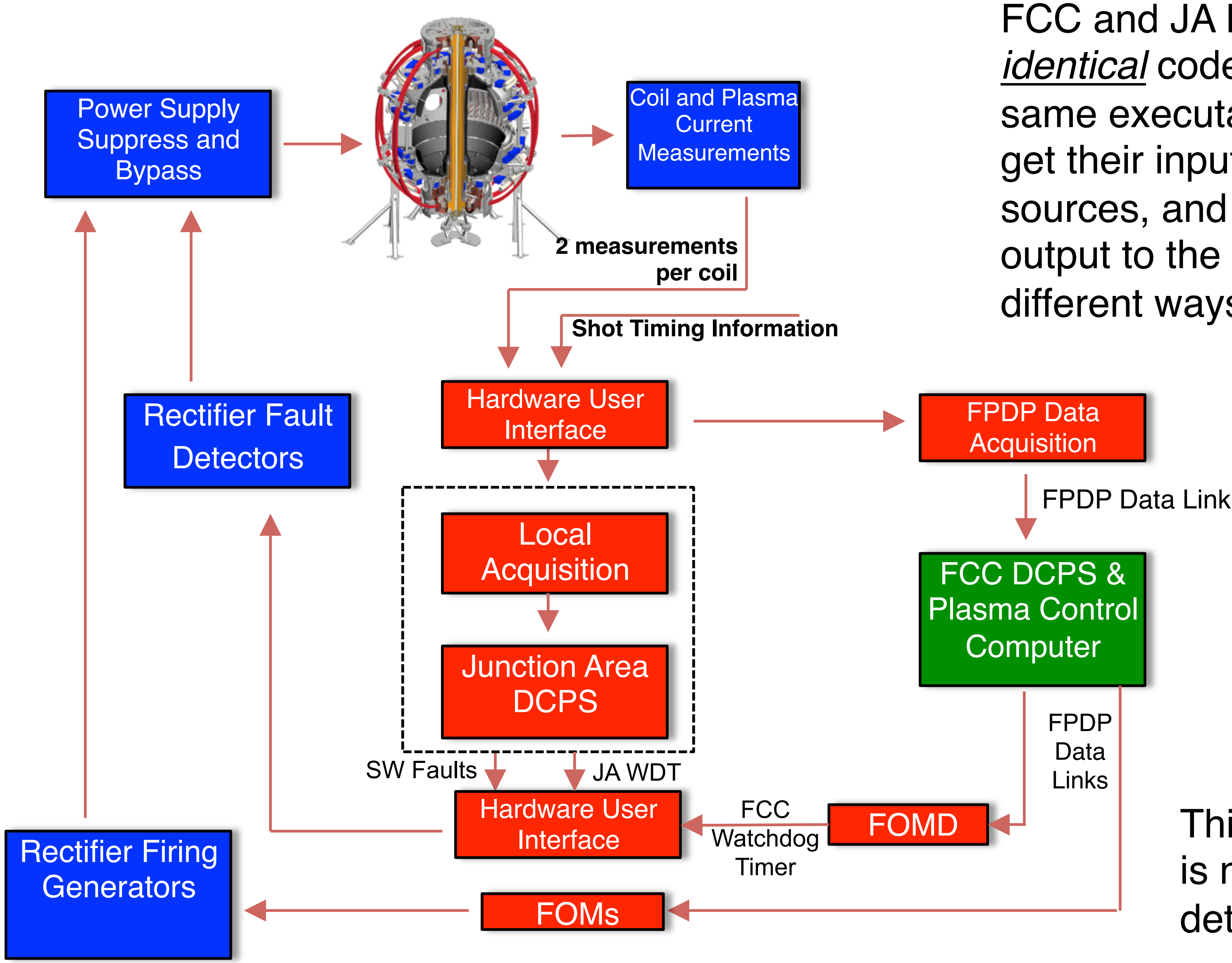
- Overcurrent
- I^2t integrals
- T_{TF}-T_{OH}
  - Must limit this due to OH-TF Frictional Interaction.

Including the heating after a suppress and bypass

- Vertical and radial forces on coils
- Combinations of vertical forces
- PF Clamp Bolt Stresses
- Local stresses in OH, PF-4, PF-5
- 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 Uses Two Realtime Computer, With a Distributed System

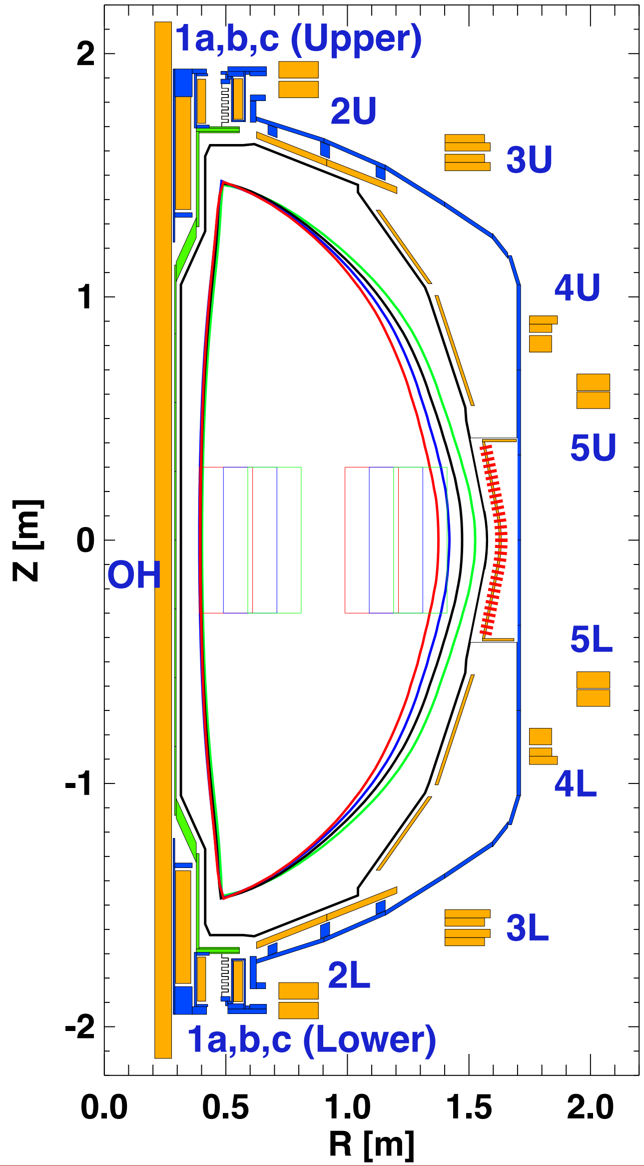


FCC and JA DCPS have *identical* code, and are the same executable file, but i) get their input from different sources, and ii) send their output to the rectifiers different ways

Red for Junction Area (i.e. Next to FCPC)
Green for FCC (i.e. Next to Control Room)
Blue for FCPC (i.e. Power Supply Room)

This block diagram is missing A LOT of details!

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.

Configuration Parameters Handled Via Excel and MDS+

Step 1:
DCPS Excel Spreadsheet

~15 Human Readable Sheets → ~8 Dense Text Sheets

Step 2: 8 Text Files

- Simple Force Parameters, FCC
- Simple Force Parameters, JA
- I^2t Parameters, JA
- I^2t Parameters, FCC
- Scaling Parameters
- Complex Force Parameters, JA
- Complex Force Parameters, FCC
- Post-Disruption Current Parameters

Step 3: C++ "Tree Builder"
Inputs: 8 Text Files
Outputs: 2 MDS+ Trees
One each for FCC & JA

Junction Area DCPS MDS+ Tree → Junction Area DCPS

FCC DCPS MDS+ Tree → FCC DCPS

One-time action (for a given set of protection parameters)

- Step 1: Input parameters in Excel spreadsheet.
  - One spreadsheet has information for both FCC and JA DCPS
- Step 2: Use AppleScript program to make 8 tab delimited text files.
- Step 3: Use C++ code to write text file content to the MDS+ tree.
  - MDS+ tree files cannot be modified, are "write-once"

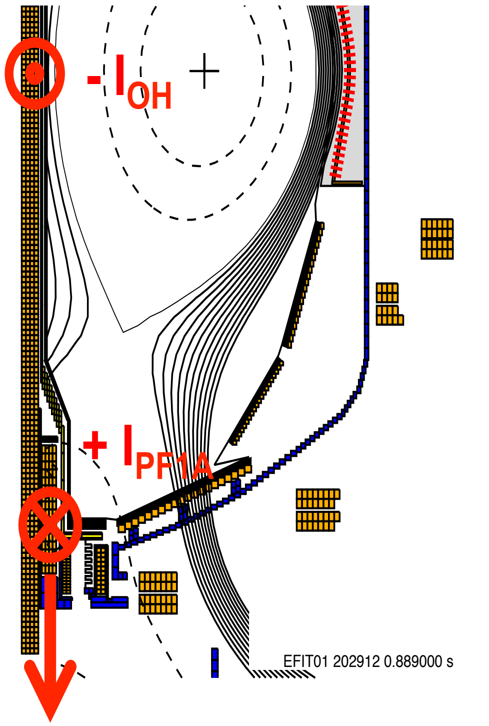
Each day

- MDS+ tree files used to provide all input parameters to DCPS

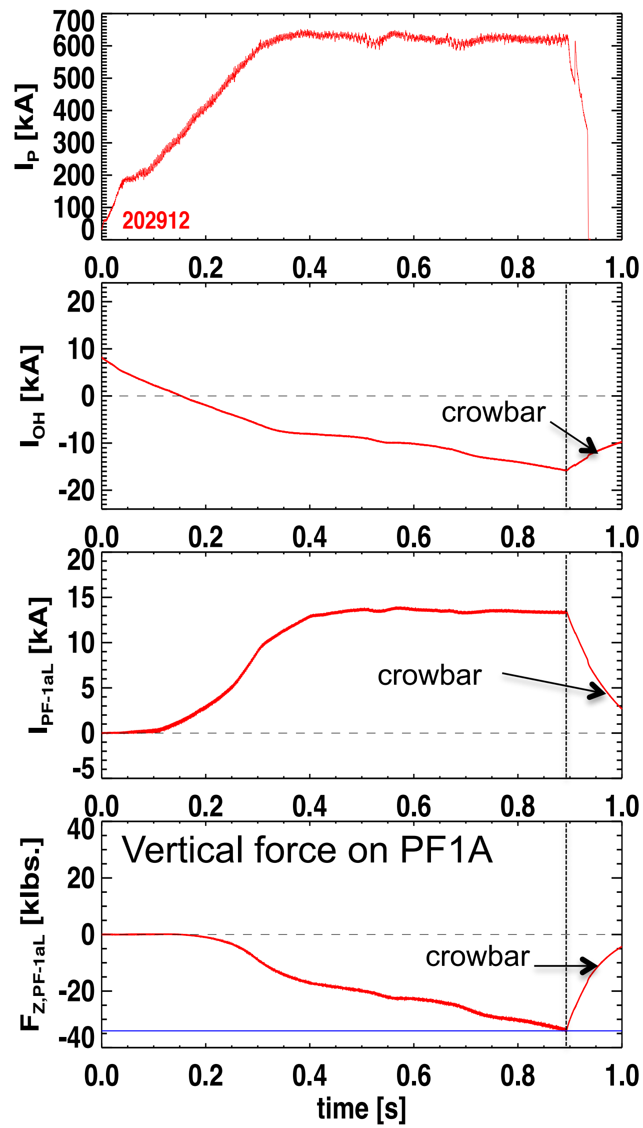
To change the protection parameters

- Make a new spreadsheet and use it to generate new trees

Example of DCPS Terminating a Shot



This sort of trip only in L-mode, which requires more divertor coil (PF-1a, PF-2) current for a given I_P.



Positive Plasma Current

OH Swinging Negative

PF-1aL Holds a Steady Positive Value

Growing negative vertical force on the PF-1aL.
Trips at ~-34 klbs.

DCPS Prevents OH-TF Frictional Interaction

- As OH coil is wound directly on the TF, must avoid the TF becoming hotter than the OH.
  - If it does, the thermal axial growth of the TF will, via friction, put an axial force on the OH coil that could damage it.
- DCPS uses the “Complex Force” algorithm to protect against this:
  - Assume the temperature rise is proportion to the I^2t integral
  - Temperature difference between coils

$$T_{TF}-T_{OH}=T_{TF,0}+\delta_{TF}A_{TF}-T_{OH,0}-\delta_{OH}A_{OH}$$

  - This fits the “complex force” algorithm template

DCPS Enforces These Quantities <1 C

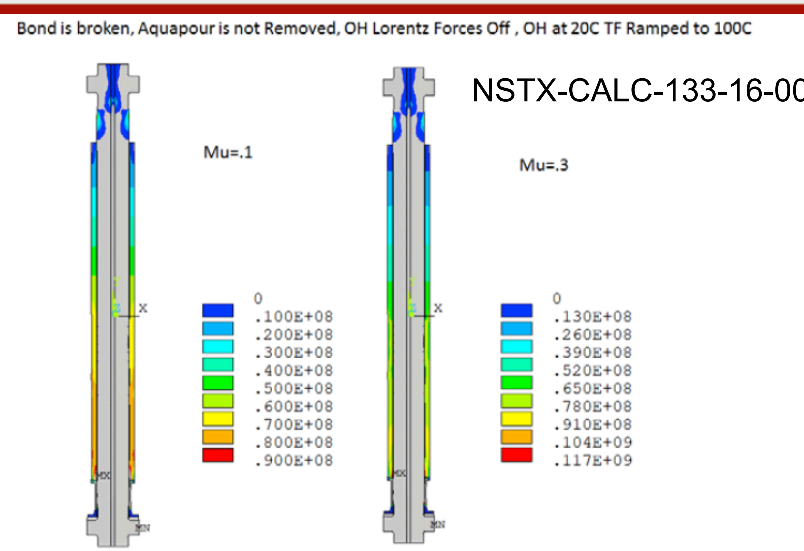
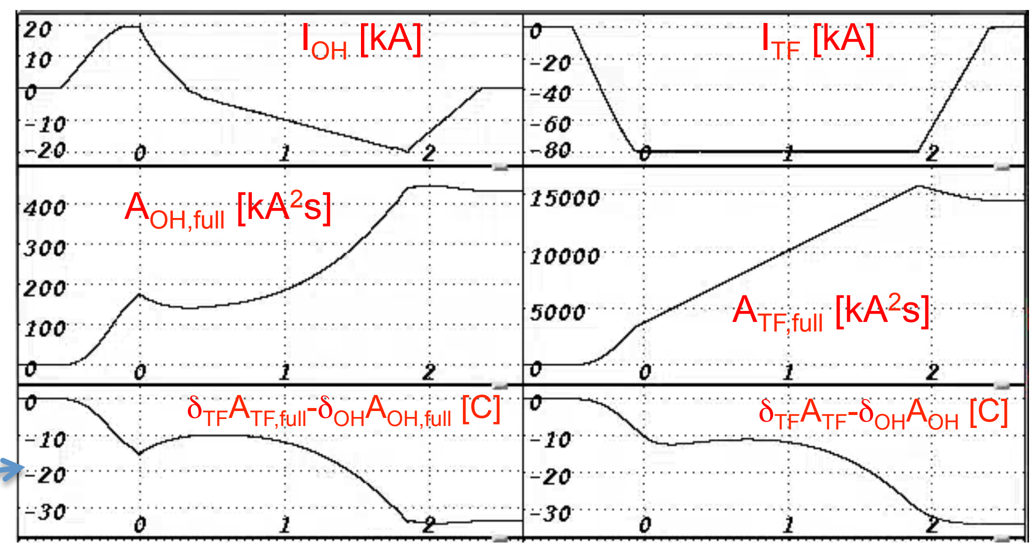


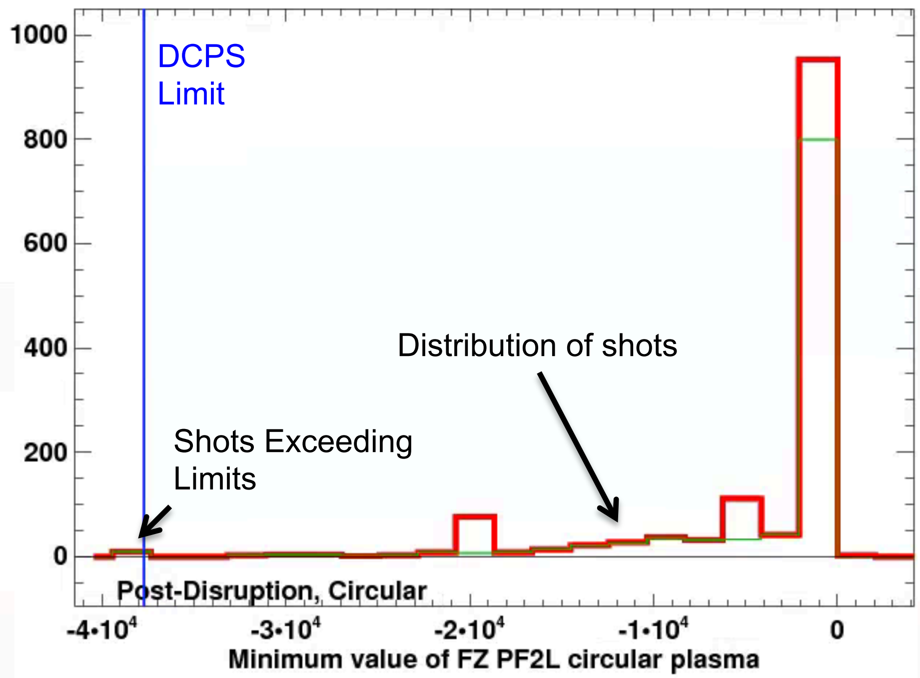
Figure 4.0-2 Showing a Worst Case Situation with the TF Hot and the OH Cold



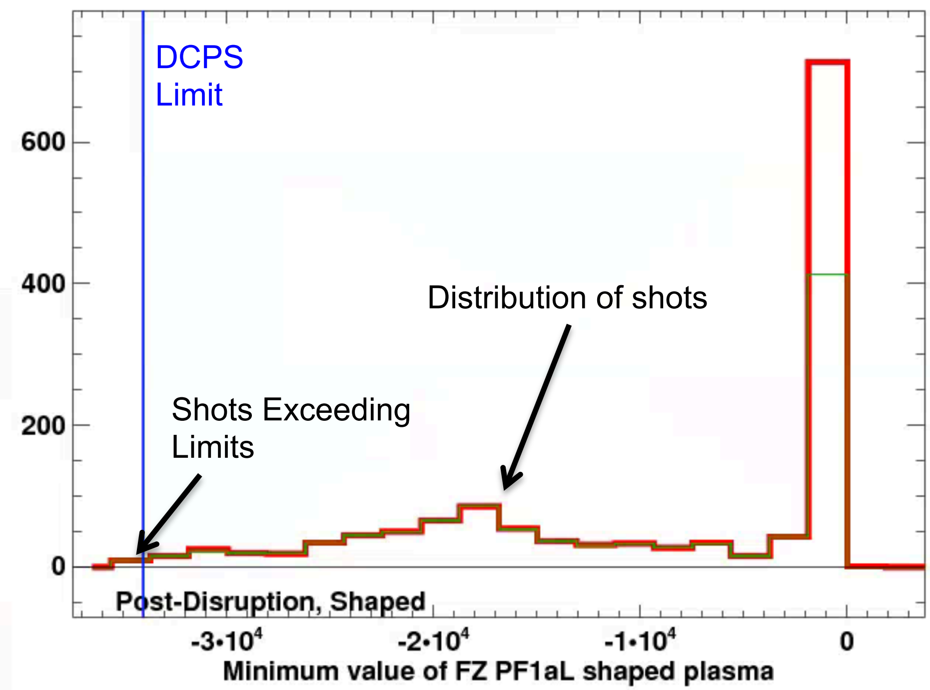
Vertical Forces on Coils Were the Primary Sources of Trips (I)

Use database that archives maximum and minimum values for each algorithm

Vertical Force on the PF-2L Coil



Vertical Force on the PF-1aL Coil



This sort of trip only in L-mode, which requires more divertor coil (PF-1a, PF-2) current for a given I_P.

Vertical Forces on Coils Were the Primary Sources of Trips (II)

- 1353 Shots & 33 Algorithm Trips
- 3 trips of the TF Total Outer Leg Out-of-Plane Moment
  - This algorithm was deemed unnecessary and subsequently disabled.
  - Instead rely on the total moments on the separate upper and lower halves of the outer leg.
- 4 spurious trips of the aquapour protection algorithm due to garbled data stream (see next slide)
- 3 I^2t trips on the OH coil during long pulse.
- 23 vertical force trips (mostly related to too-large divertor coil current in L-mode, due to higher l_i)
  - 1 on PF-1aU
  - 4 on PF-2U
  - 9 On PF-2L
  - 9 on PF-1aL

Comments on Initial Operating Experience (SPG Opinions)

- Highly reliable
  - Only frustrating day was when an arcing Penning gauge power supply was causing garbled realtime data blocks, which DCPS repeatedly noted and caused a crowbar.
- Should not have put DCPS on the control computer
  - Sharing a realtime computer with the plasma control system resulted in numerous software and hardware complications.
  - Would have been better to have two independent but identical stand-alone computers.
- Minimal number of algorithm trips
  - Only ~2.5% of shots had algorithm trips.

Shutdown Handler Designed to Gracefully End the Plasma

- Why do this?
  - Want to limit control transients at the end of the discharge.
  - Want to support critical research in disruption detection/avoidance.
- State machine implementation
- Coding of the state machine is largely free of detailed plasma physics/control.

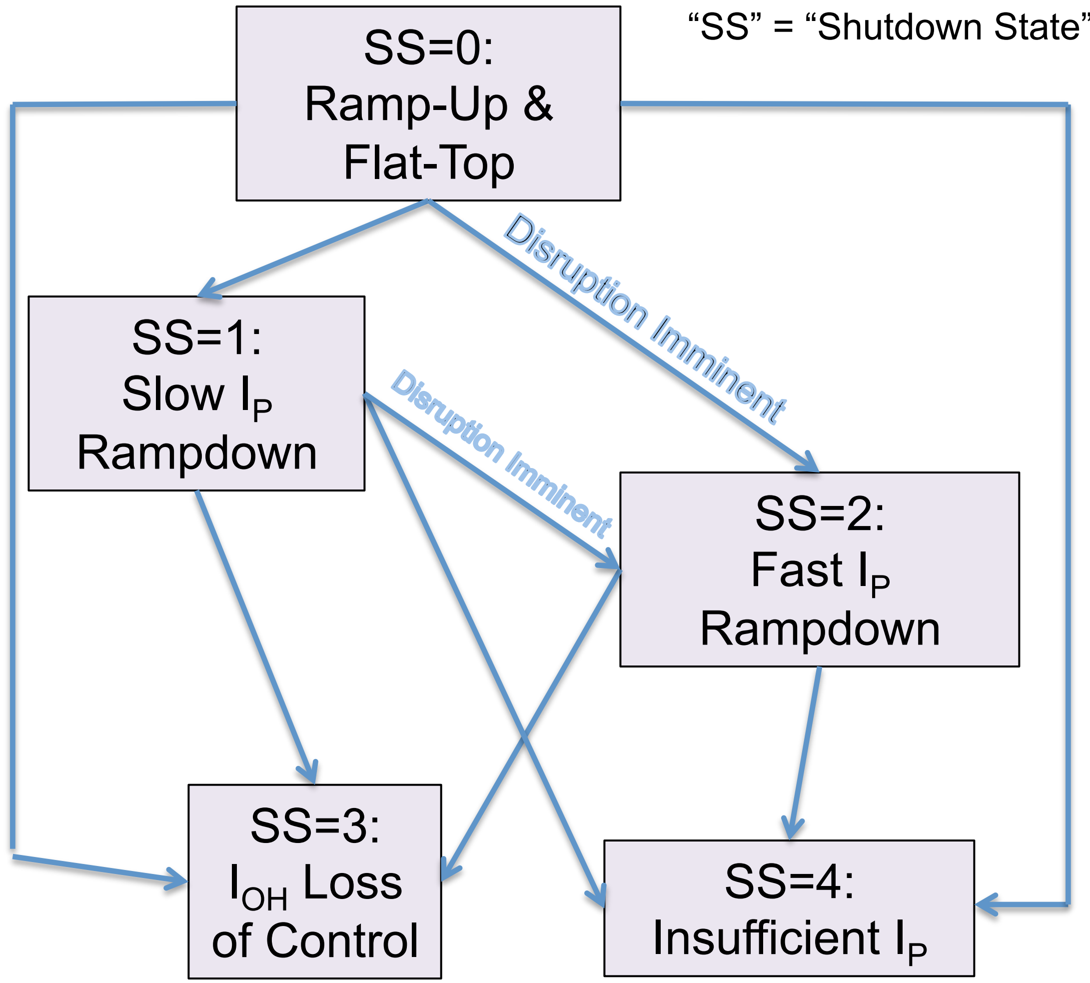


Diagram of the State Machine Presently Implemented in PCS

What Controls, and is Controlled By, the Shutdown Handler?

Controls It

- Can go into fast rampdown by:
  - Detection of large n=1 mode.
  - Detection of large loss of plasma current.
  - Detection of excessive vertical motion.
  - I_P drops beneath value required for rtEFIT while using ISOFLUX
  - Operator request
- Can go into slow rampdown by:
  - Detection that OH coil is approaching a heating limit.
  - Detection that OH coil is approaching a current limit.
  - Operator request

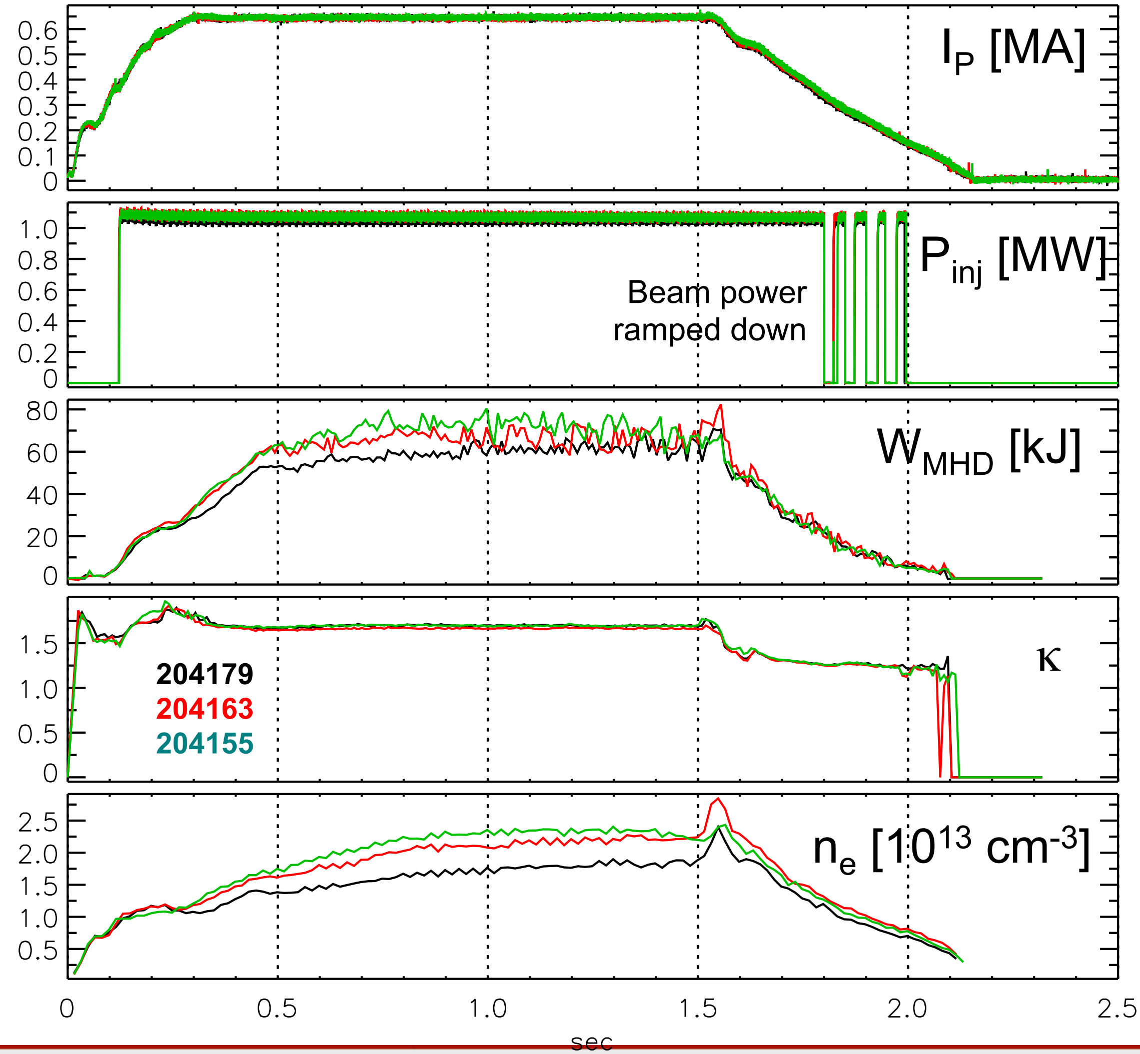
It Controls

- At each state change, switch the control algorithm used by actuators.
  - For instance, switch from diverted to inner-wall limited shape.

Shutdown Handler Used to Create Smooth L-Mode Rampdown

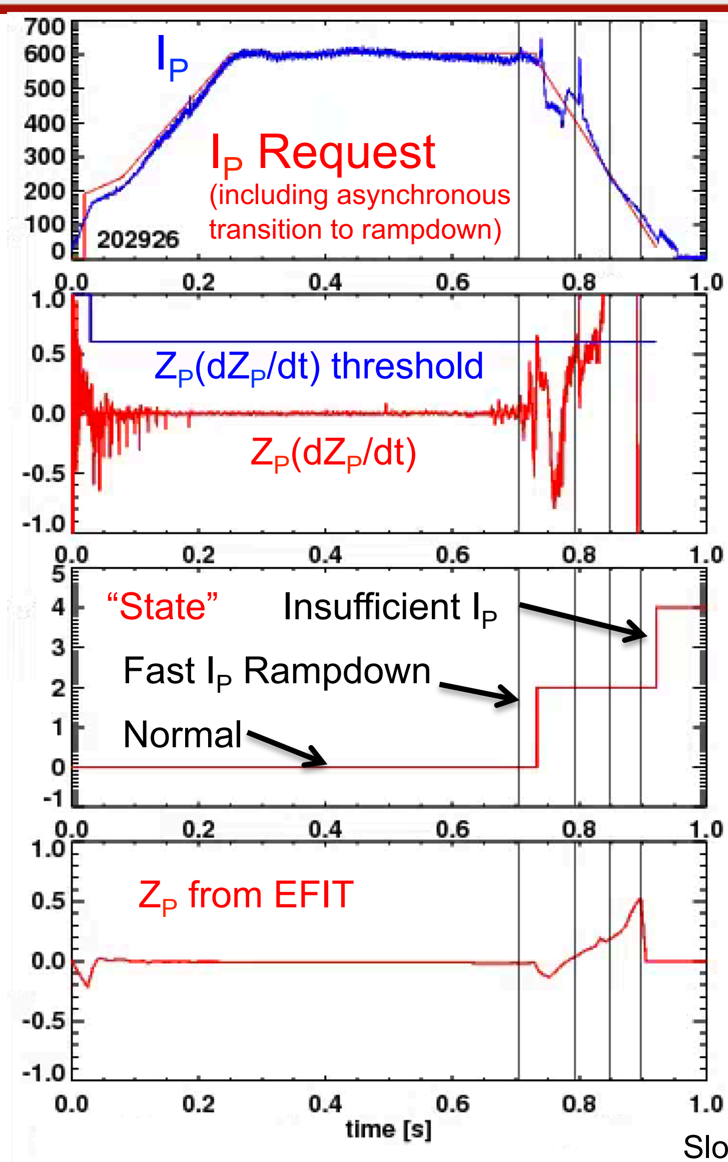
- Three AM fiducial shots from week of 4/4/2016.
- Single operator waveform modified at t=1.5 to start the rampdown.
- Rampdown is IWL, with power and I_P slowly ramped off.

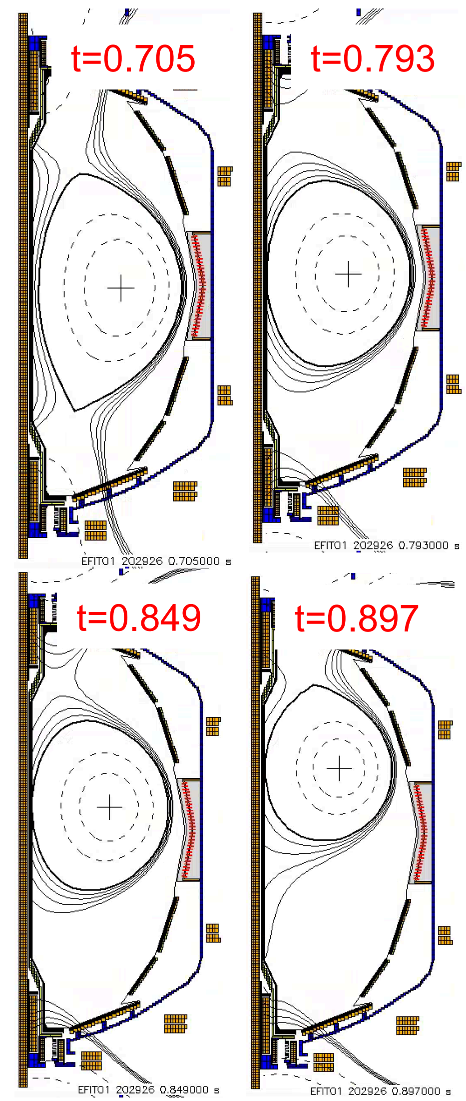
L-mode Rampdowns Triggered By a Single Switch



Shutdown Handler Also Used to End Failing Discharges

- Shot requested to go longer, but vertical motion detected.
- Rampdown initiated.
- Plasma inboard limited, only slowly drifts up.

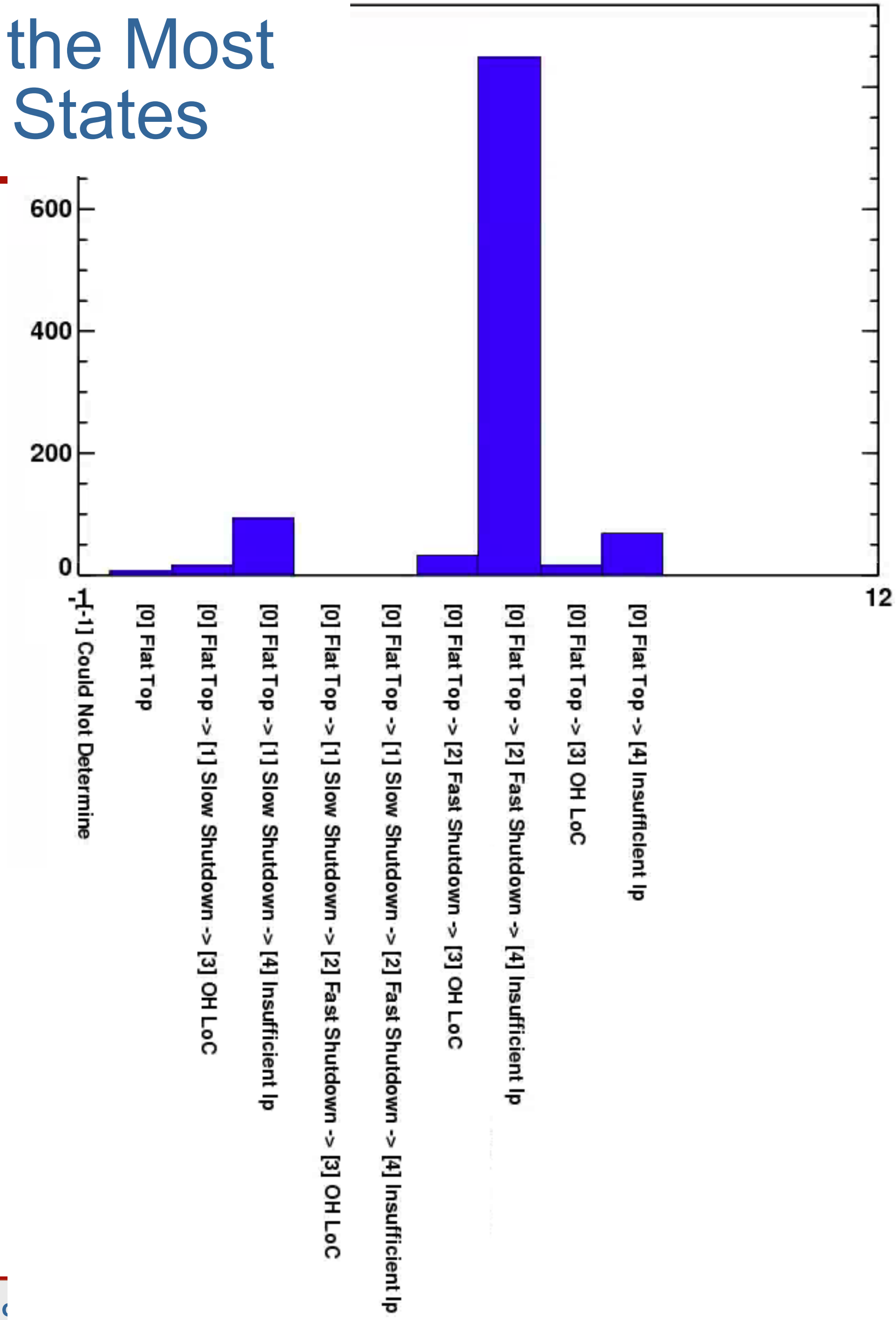




Slow Drift Up, But No VDE or Disruption

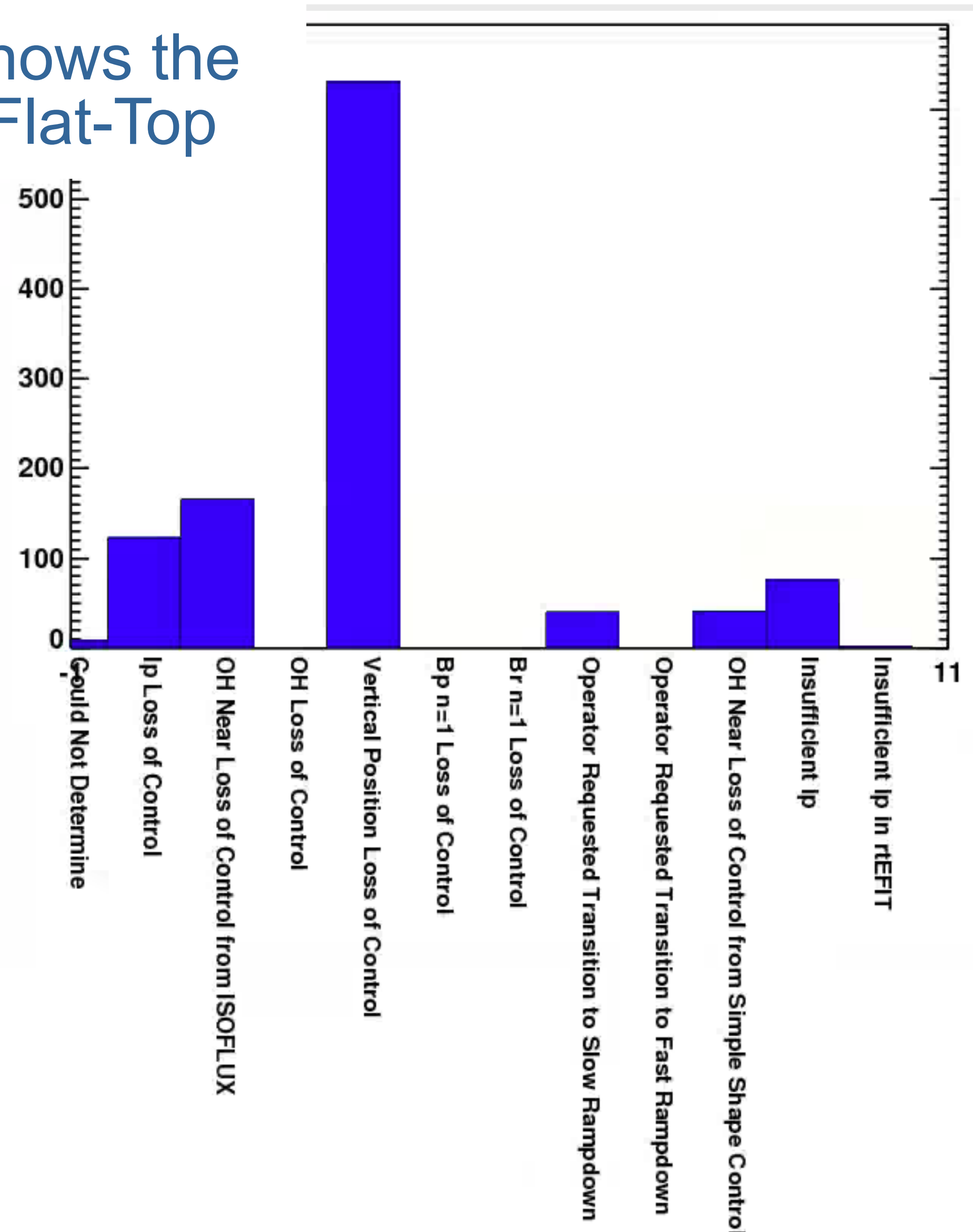
Database Analysis Shows the Most Common Path Through States

- Most likely the go from Flat-Top through Fast Shutdown to Insufficient I_P.
  - These are all the failing plasmas.
- Somewhat likely the go from Flat-Top through Slow Shutdown to Insufficient I_P.
  - These were the L-mode rampdowns.
- Last common case was Flat-Top directly to Insufficient I_P.
  - These are shots that failed to ramp-up…fizzles.



Database Analysis Shows the Causes of Leaving Flat-Top

- By far the most common is Vertical Position Loss of Control (LoC)
  - But beware, those sensors are sensitive to n=1 modes as well as n=0,
- OH Near LoC triggers shutdown based on OH current or heating limit.
- I_P LoC looks for large values of the I_P error.
- We never activated the BP & BR n=1 LoC.
  - Therefore don't read anything into its having no instances…wait till next year.



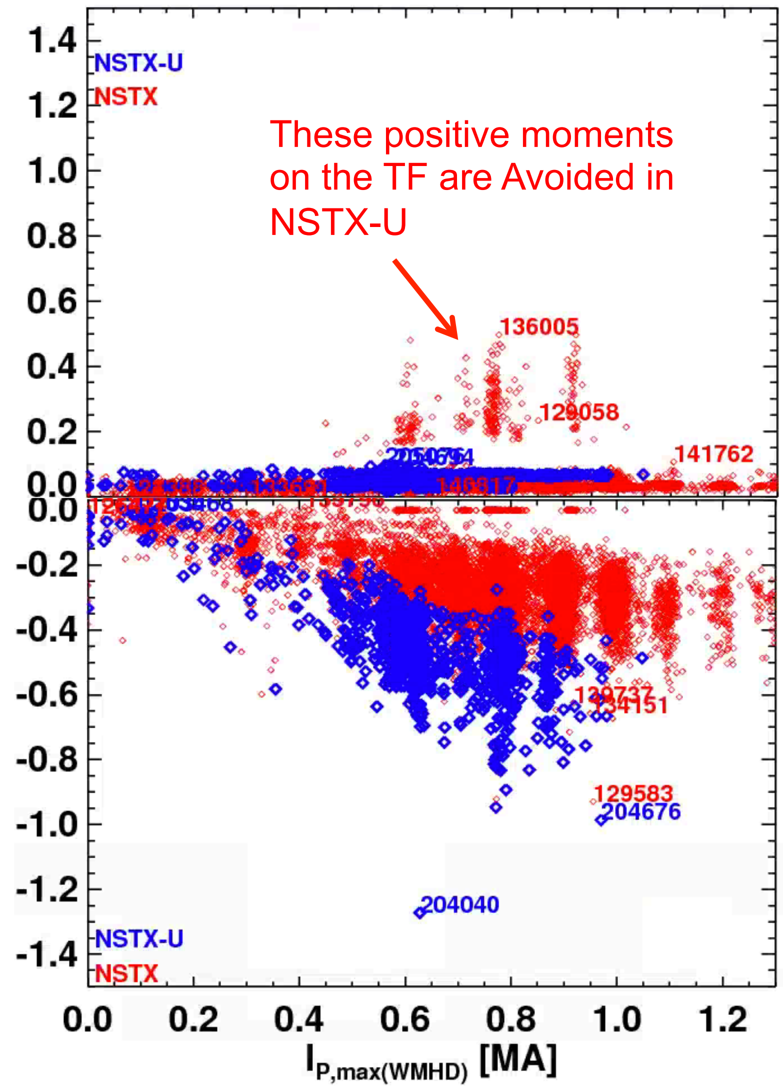
Shutdown Handler Allows Us to Reduce Stress on Components

- Consider moment on the TF outer leg due to I_{TF} crossing the poloidal field.

NSTX: Large PF transients during disruptions -> moment was both positive and negative -> more mechanical fatigue on coils.

NSTX-U: Reduced PF transients ->the moment on coils is one-sided -> reduced mechanical fatigue.

Note: The shot with the worst moment (204040) was due to a misconfiguration of the shutdown handler.



Next Steps For Shutdown Handler

- During this run, we never activated the part of code allowing a transition from slow to fast rampdown:
  - Fixed a code bug, but didn't get a chance to test it before PF coil failure.
- Need to allow the RWM sensors to trigger the rampdown
  - They were running in realtime, but never flipped the switches to enable them in this functionality.
- Need to see if some other configuration of the vertical position sensing code can be less sensitive to n=1 modes.
- Longer term:
  - Use to trigger MGI?
  - Incorporate additional tests of disruption proximity as per DECAF?