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Preparing Plasma Control and Digital Coil Protection for NSTX-U

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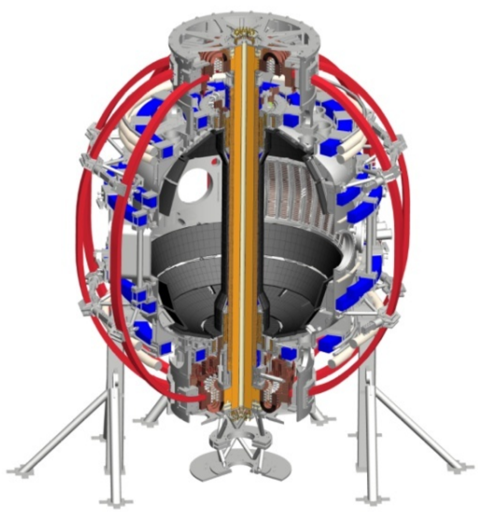

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Motivation/Outline

- NSTX-U power supplies, if unregulated, can easily make forces & torques beyond the mechanical limits of the coils and their support structures.
- A Digital Coil Protection System (DCPS) has been designed to calculate forces, stresses, and temperatures in realtime, and then to interdict the shot.

  This poster: description of some operational considerations related to DCPS.

- However, in order to avoid tripping DCPS, we would like to implement some soft-shutdown procedures.

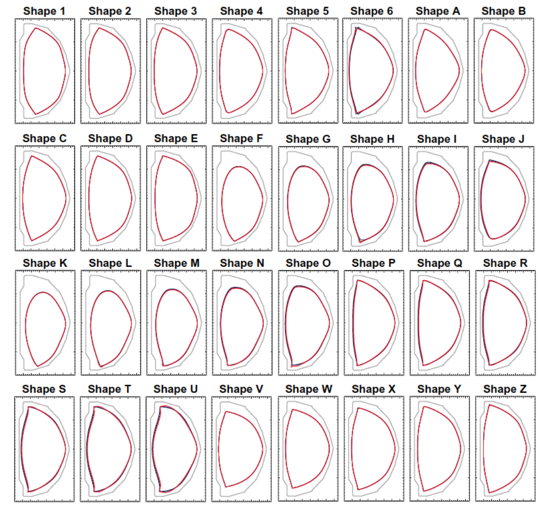
  This Poster: Some initial ideas for discharge shutdown algorithms

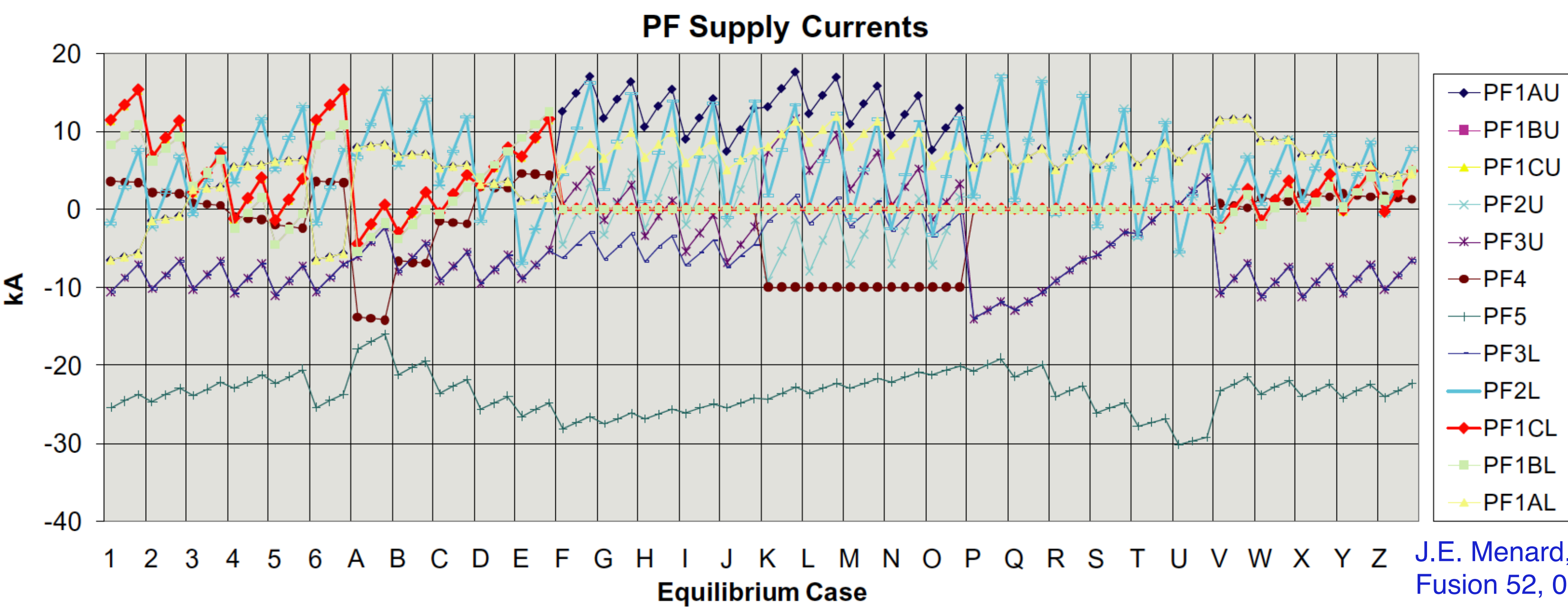
- Numerous other plasma control systems are being upgraded for NSTX-U

  This Poster: Short description of other plasma control development

Motivation For a Digital Coil Protection System (DCPS)

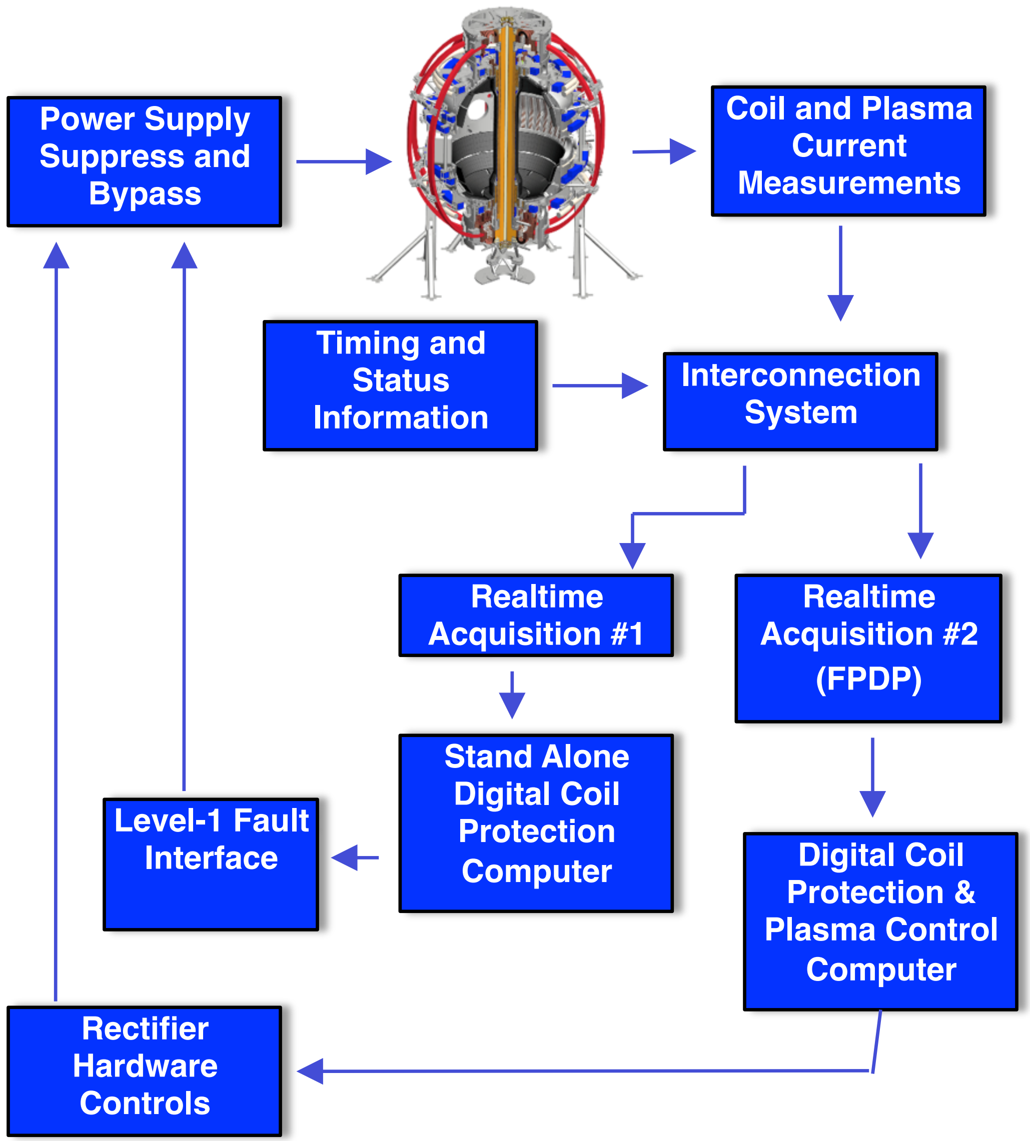
- NSTX-U PF coils, their supports, and the power supplies designed to meet the needs of 96 static scenarios with I_P = 2 MA.
- Designing a coil support structures to support large transient deviations was prohibitively difficult and expensive.
- Use a DCPS to protect against these transient and off-normal events.





J.E. Menard, et al., Nuclear Fusion 52, 083015 (2012)

NSTX-Upgrade Project is Implementing a Digital Coil Protection System (DCPS)



- Coil protection software, written in C++, to run on linux computers.
  - Operates at 5 kHz
- Only inputs are coil & plasma currents + digital timing & status information.
  - Each coil current is measured with two independent transducers
- Only outputs are the L1 fault signals, which trigger the “suppress and bypass” on ALL coil systems.
  - Sends all coils into an L/R decay through the rectifier bypass module
- DCPS trips to be reset only after forensic examination.
  - Will be time consuming, so we want to avoid this.

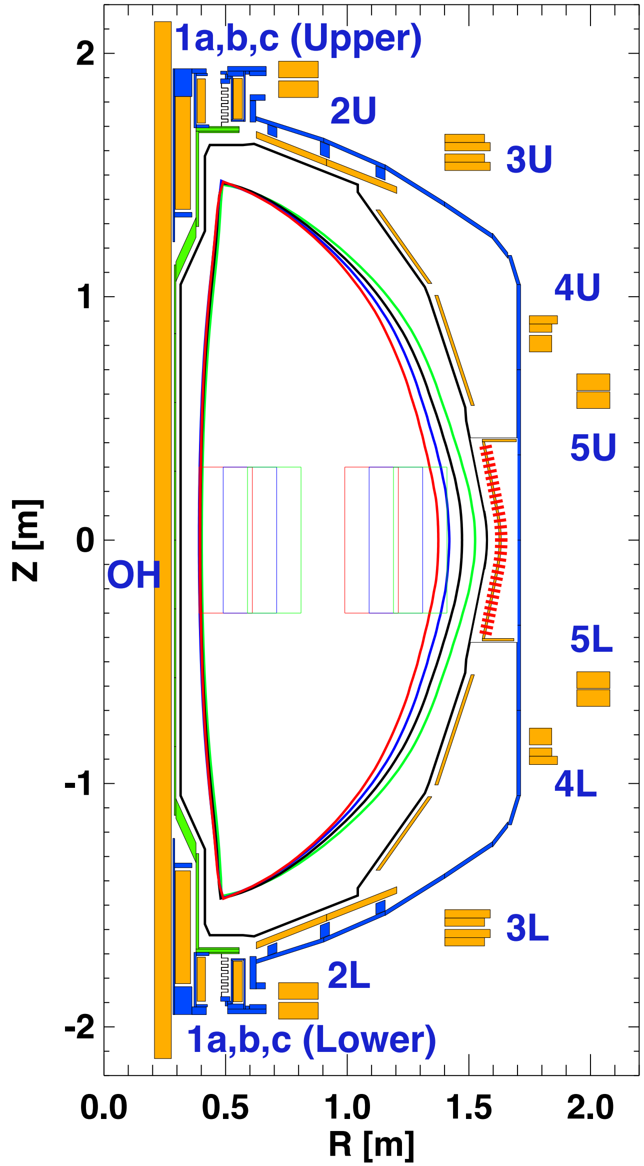
DCPS Computes Numerous Quantities in Realtime

- I^2t integrals mock up the thermal limits of the coils
- Approximately 100 forces and stresses computed with linear models of the form: $F_i=I_i\Sigma\alpha_{i,j}I_j$
  - $\alpha_{i,j}$ are coefficients derived from analysis, I_j is the current in the j^{th} coil
  - Examples include:
    - Vertical and radial forces on PF and OH coils.
    - Local stresses in the OH coil due to interactions with nearby divertor coils.
    - Local stresses in PF coils due to localized coil supports.
    - Torques on the TF conductors
    - Torsional shear stresses on the TF inner bundle.
- These forces and stresses computed for both circular and shaped plasma models, and for post-disruption currents for each shape.
  - So 4 * 100 ~400 torques and stresses for each iteration
- Calculates overcurrent protection both during and between shots.
- Limit for calculated quantities set by either detailed structural analysis or the maximum values from the 96 different NSTX-U static equilibria.
- If limit values are exceeded, then declare a fault.

How will it work in real life?

Run the NSTX shot database, and NSTX-U scenarios, through the DCPS and see what trips!!

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)

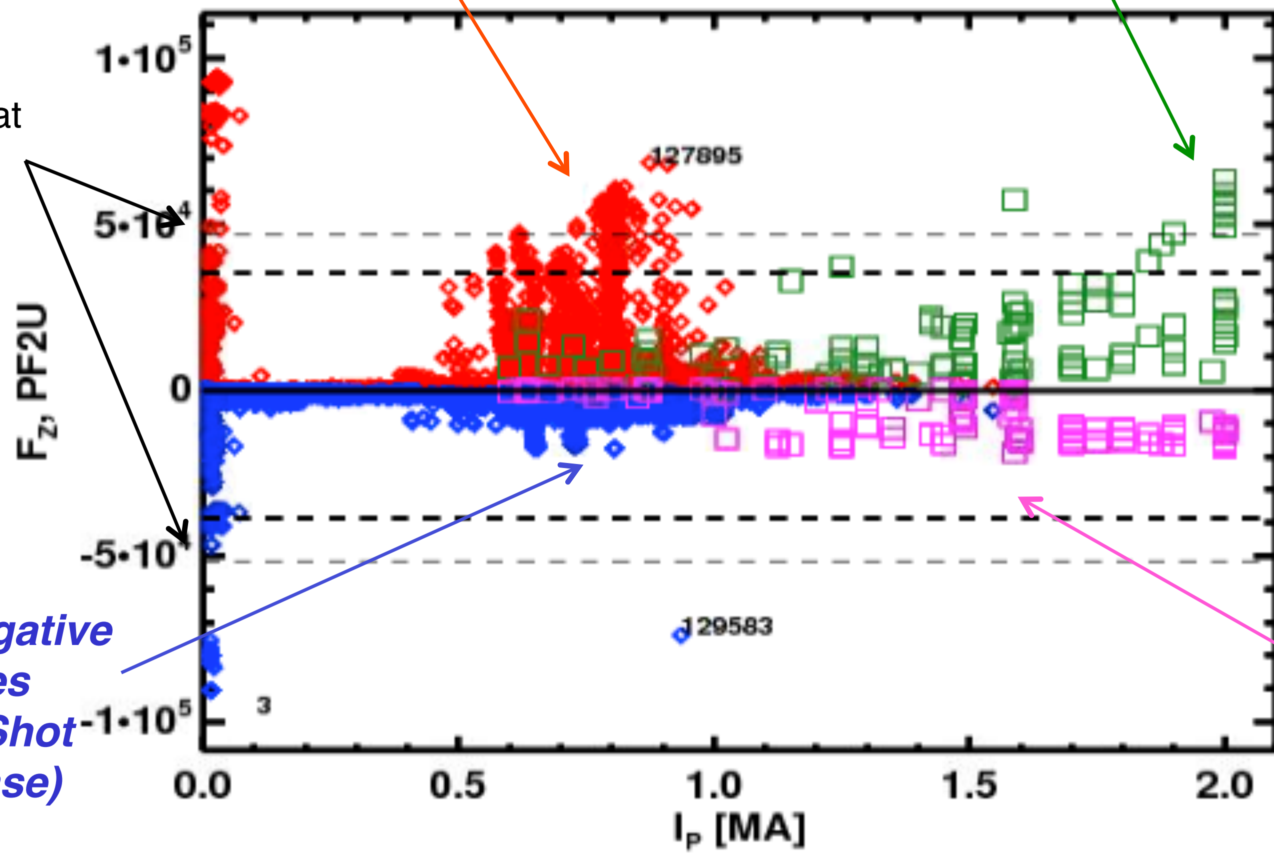
- Makes toroidal field.

Example From Study: Vertical Force on the PF-2U coil (Larger Radius Divertor Coil)

Present DCPS Limits (Set by analysis or the 96 plasma scenarios at 2MA)

NSTX Positive Forces (From Shot Database)

NSTX-U Scenarios Positive Forces



75% of Present DCPS Limits

(For forces ½ between NSTX and NSTX-U ultimate)

NSTX Negative Forces (From Shot Database)

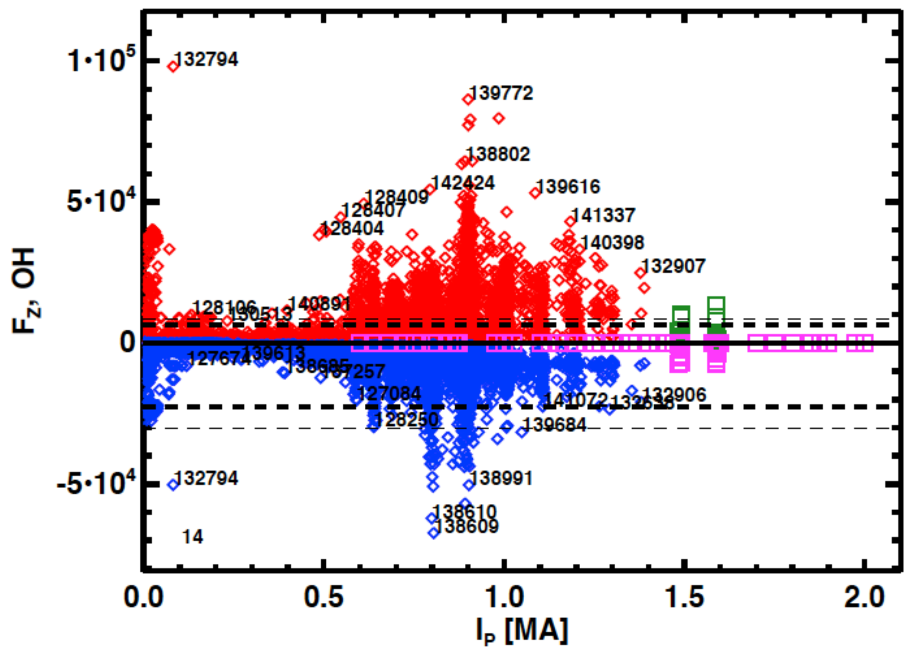
NSTX-U Negative Occurrences

To be Shown Here:

Most of these limit trips are due to large control transients, often during disruption.

Projected DCPS Impact on NSTX-U Operations

Key Constraint #1: Vertical Force on the Solenoid

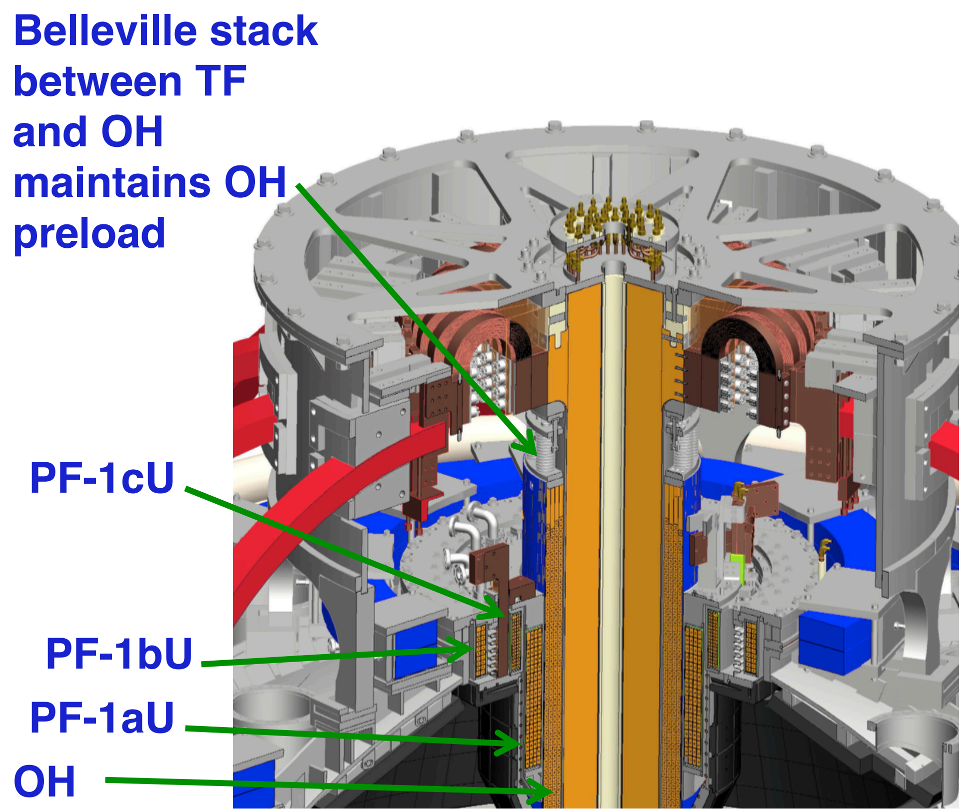


The vertical force on the NSTX solenoid (Red and Blue) often exceeded the allowable for NSTX-U

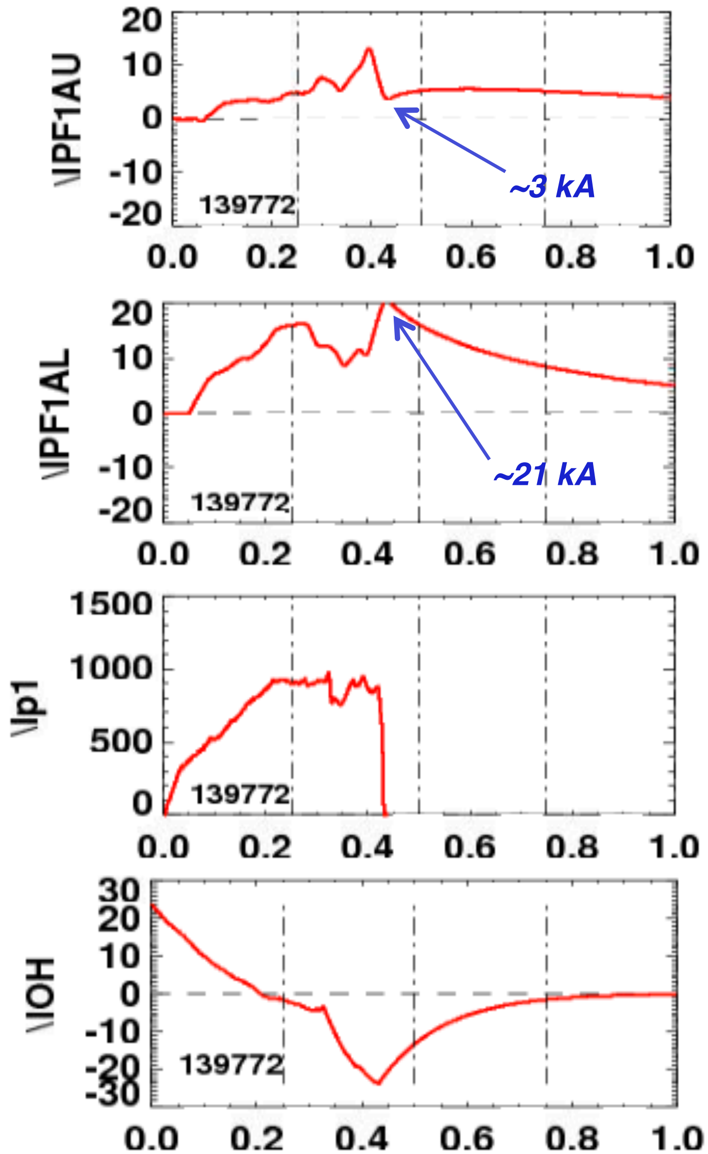
$$F_{Z,OH} \sim I_{OH}\,[154(I_{PF1aU}-I_{PF1aL}) + 171.8(I_{PF2U}-I_{PF2L}) + 86.5(I_{PF3U}-I_{PF3L}) + \ldots]$$

Allowed Vertical Force on Solenoid Depends of Temperatures due to Belleville Washer Stack Loading

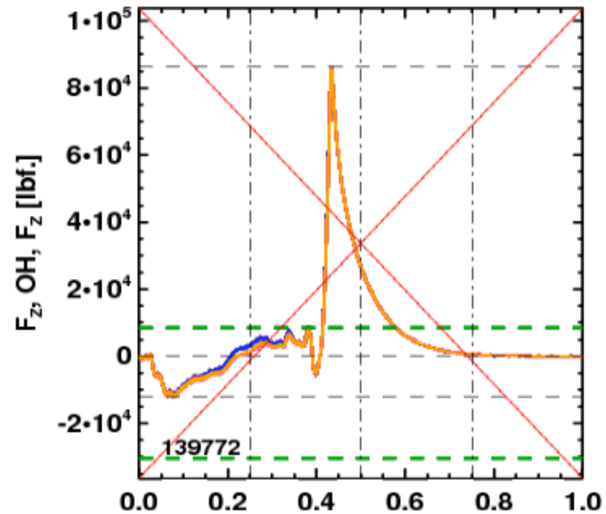
System scenario	Compression mm	Force on OH N	Force on OH lbs.*
Pre Load	17.87	162,512	36,520.
TF hot OH hot	15.47	142,268.	31,970.
TF hot OH cold	9.47	89,698.	20,157.
TF cold OH hot	23.87	211,582.	47,546.



Vertical Force on the Solenoid is Driven By Strike Point Controller During a VDE

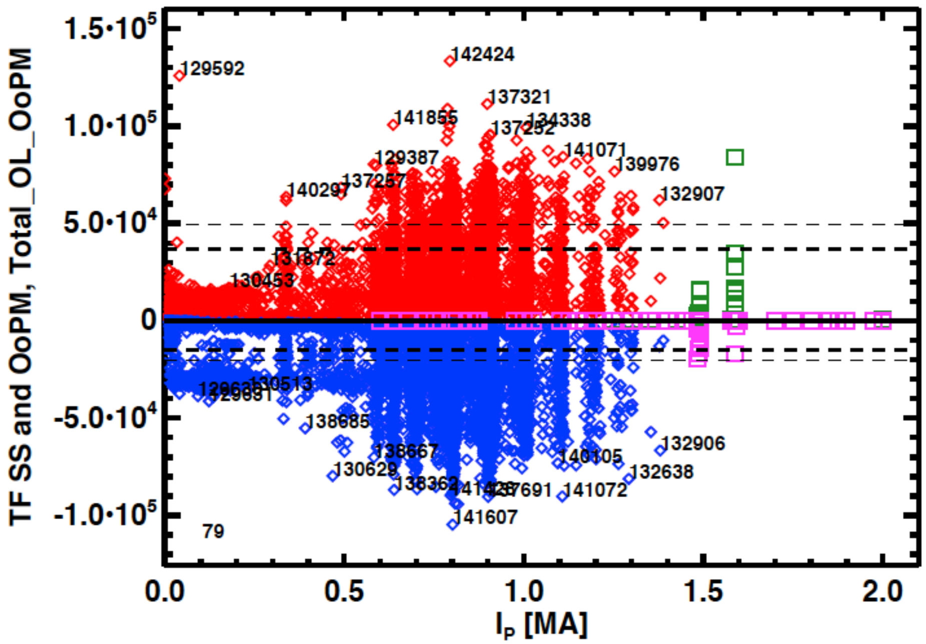


Time evolution of coil currents on left, and solenoid force below



- PF-1a coils operating under strike-point control
- Vertical instability begins, but S.P. control remains on.
- Large transient up-down asymmetry in the PF-1a current results.
  - $I_{PF\text{-}1aU}$~3 kA, but I_{PF1aL}~21 kA.
- Asymmetry results in transient large vertical force on the solenoid.

Key Constraint #2: Torque on the TF Coil

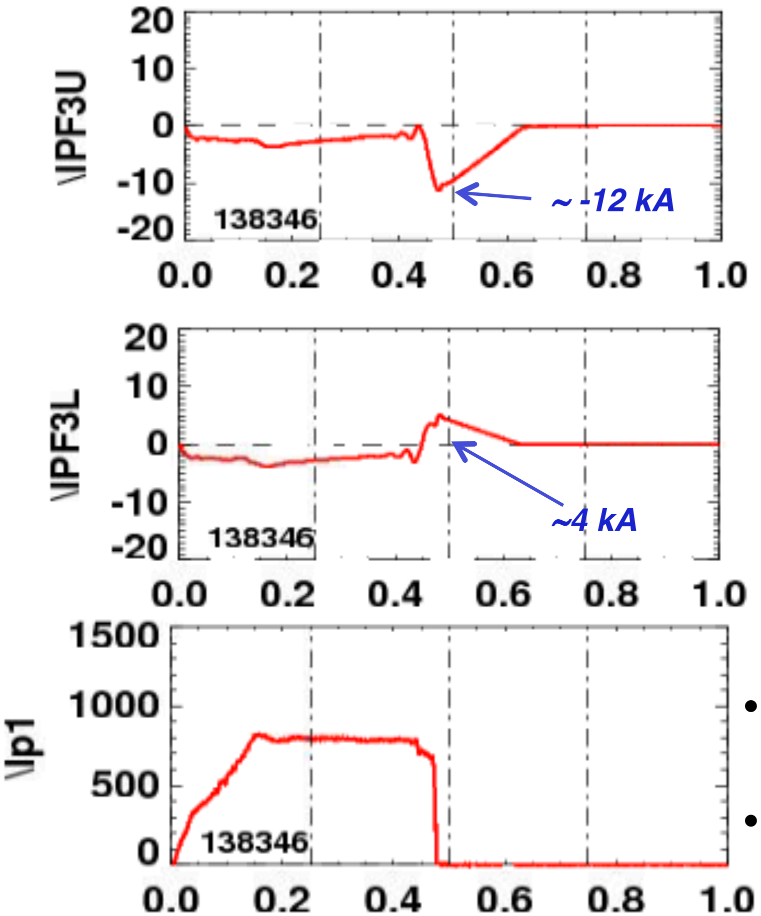


The TF out leg out-of-plane moment on NSTX solenoid (Red and Blue) often exceeded the (apparent) allowable for NSTX-U

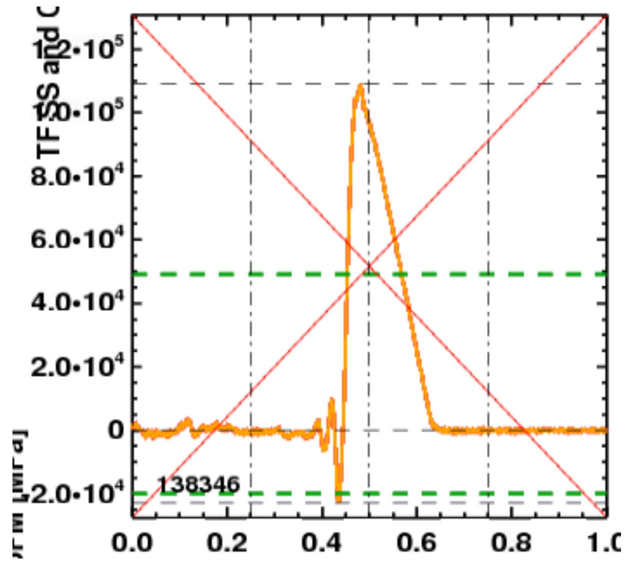
$$\left[\frac{\text{Net TF System OuterLeg Torque}}{1\,\text{N-m}}\right] = 3519.9\left[\frac{I_{PF1AU} - I_{PF1AL}}{1\,\text{kA}}\right] + 3692.0\left[\frac{I_{PF1BU} - I_{PF1BL}}{1\,\text{kA}}\right] + 4293.8\left[\frac{I_{PF1CU} - I_{PF1CL}}{1\,\text{kA}}\right] + 13191\left[\frac{I_{PF2U} - I_{PF2L}}{1\,\text{kA}}\right]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

- **Out of plane torque is driven by the up-down asymmetry in the PF coil currents.**
  - **strongest weight on the large radius PF-2 and PF-3 coils.**
- **But, up-down asymmetric currents in PF-3 are used for vertical position control!**

Large Out of Plane Moment Driven By Vertical Control Oscillations



Time evolution of coil currents on left, and out-of-plane moment below.



- PF-3 coils operating responding to a derivative term on the position
- Large up down asymmetry in the PF-3 current results.
  - $I_{PF\text{-}3U}$~-12 kA, but I_{PF3L}~4 kA.
- Asymmetry results in transient large out of plane moment on the TF outer legs.

Many Other Examples Exist of Transients Driving Conditions That Will Trip DCPS

- F_Z on OH: Forces from strike-point control, Vertical position control, CHI bias field formation.
- Aggregate load on the outer PF coils: forces dominated by the vertical position control loading.
- Net vertical load on the casing: Driven by failed strike-point control.
- Torques/Moments on the TF outer leg: Driven by up-down asymmetric currents during vertical position control.

How to Ensure that Productive Operations and DCPS Coexist?

- Continued refinement of the DCPS limits.
  - Many of the present limits defined by the calculated values of those quantities from 96 different 2 MA scenarios.
    - In some cases, the structure may be capable of tolerating larger forces.
    - However, the TF torques are at the limit of the structure for the 96 scenarios, and the allowable likely cannot be increased.
  - For cases where the limits can be increased, should do appropriate calculations to determine new allowables.
- Reduce control transients.
  - Many of the largest forces occur during transient responses.
  - Those transients are often during disruptions, long after all hope of discharge recovery is lost.
  - This motivates the development of a “shutdown handler” mechanism for NSTX-U!

Conceptual Design of Plasma Shutdown Handler

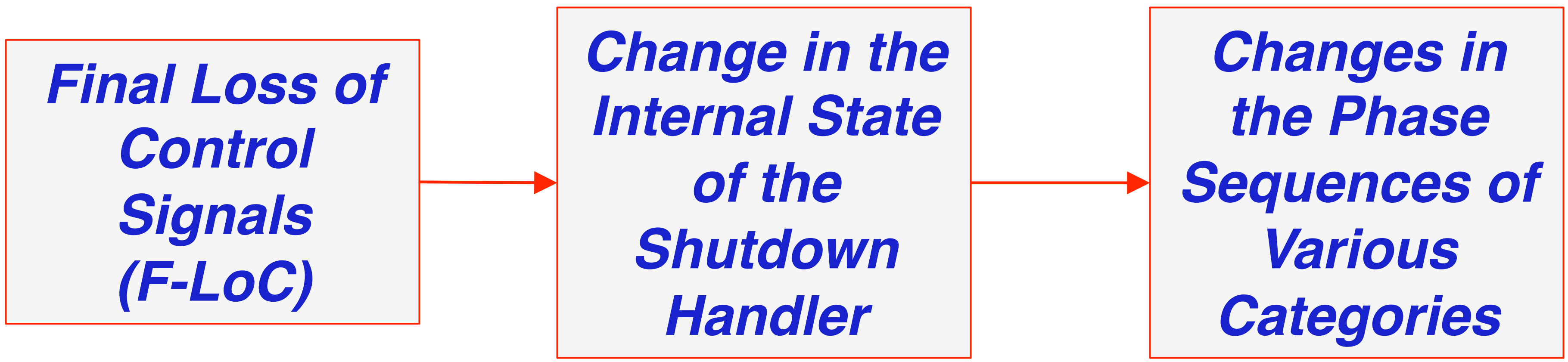
Goals for the Shutdown Handler
Modularity, Simplicity

- Should separate the shutdown “trigger” mechanism from the sequencing of actuators during shutdown.
  - Disruption detectors, detection of actuator failure, should be elsewhere.

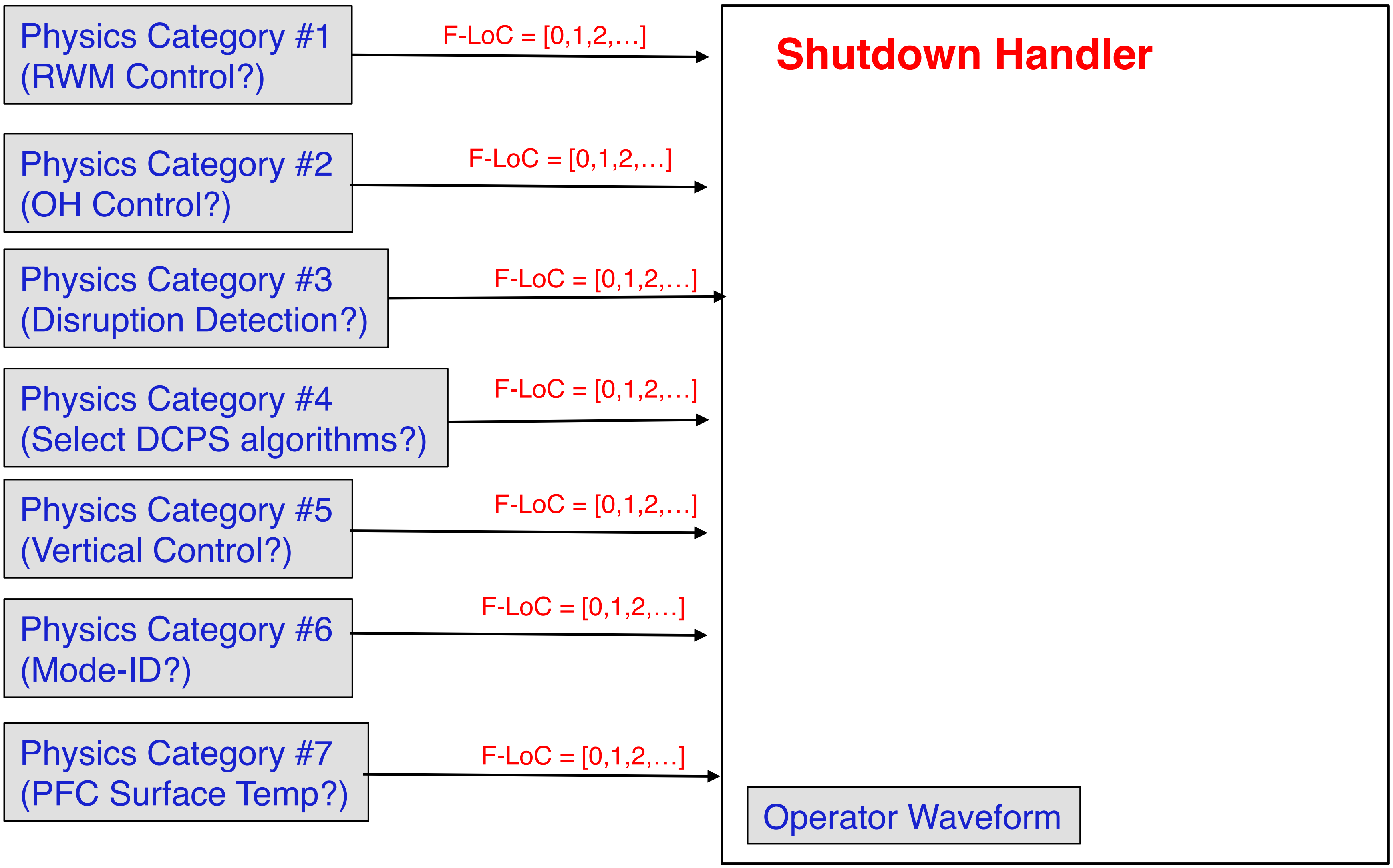
- Should be capable of handling multiple types of plasma terminations, and of switching between types semi-dynamically.
  - Should allow for closed loop MGI with NBI turning off before MGI is fired.

- Should strike the correct balance between flexibility/ generality and understandability/maintainability.

Overall Description of the Proposed “Shutdown Handler”



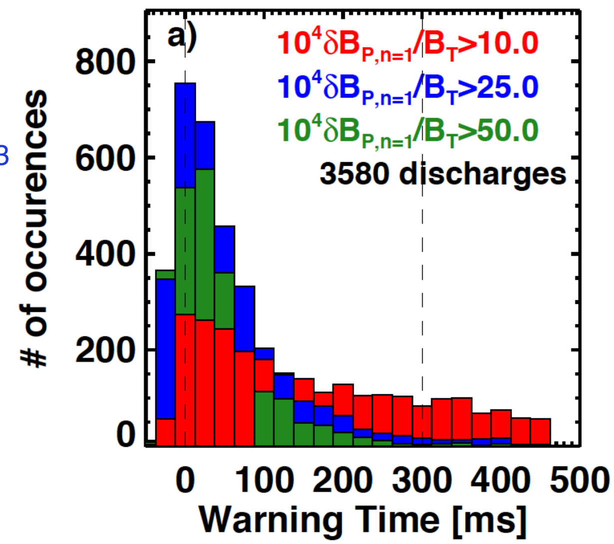
Inputs to Shutdown Handler

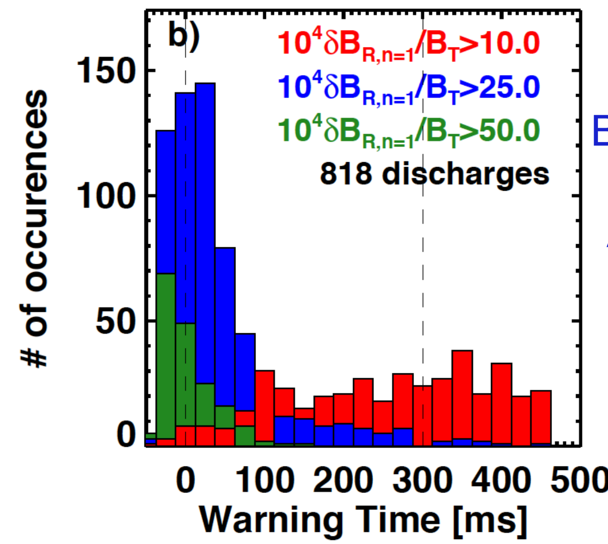


F-LoC = Final Loss of Control

NSTX Data Provides an Initial Basis For LoC Thresholds (All This Data Available in Realtime in NSTX)

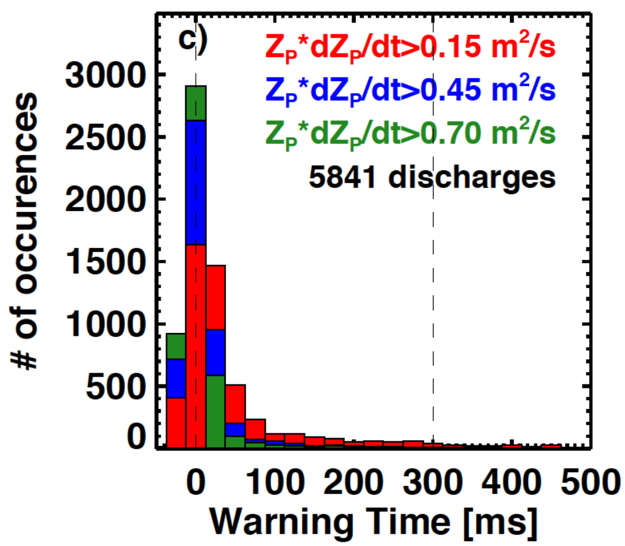
$B_{P,n=1}/B_T > 2.5\times10^{-3}$ Essentially Always Leads to Disruption

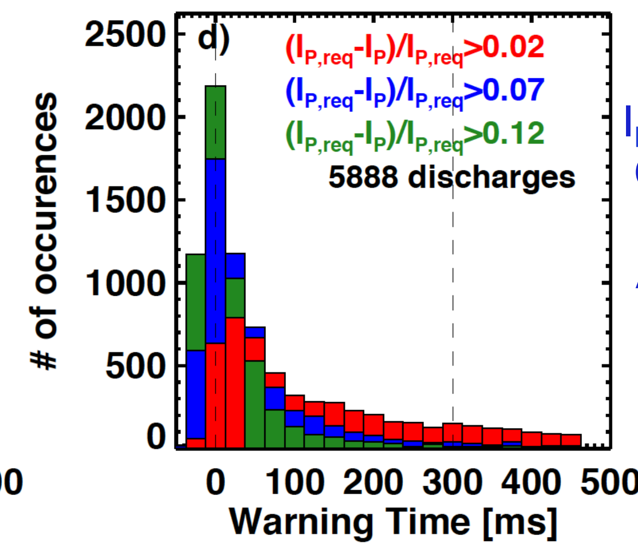




$B_{R,n=1}/B_T > 2.5\times10^{-3}$ Essentially Always Leads to Disruption

$Z_P(dZ_P/dt)$ Exceeding 0.15 m^2/s Essentially Always Leads to Disruption



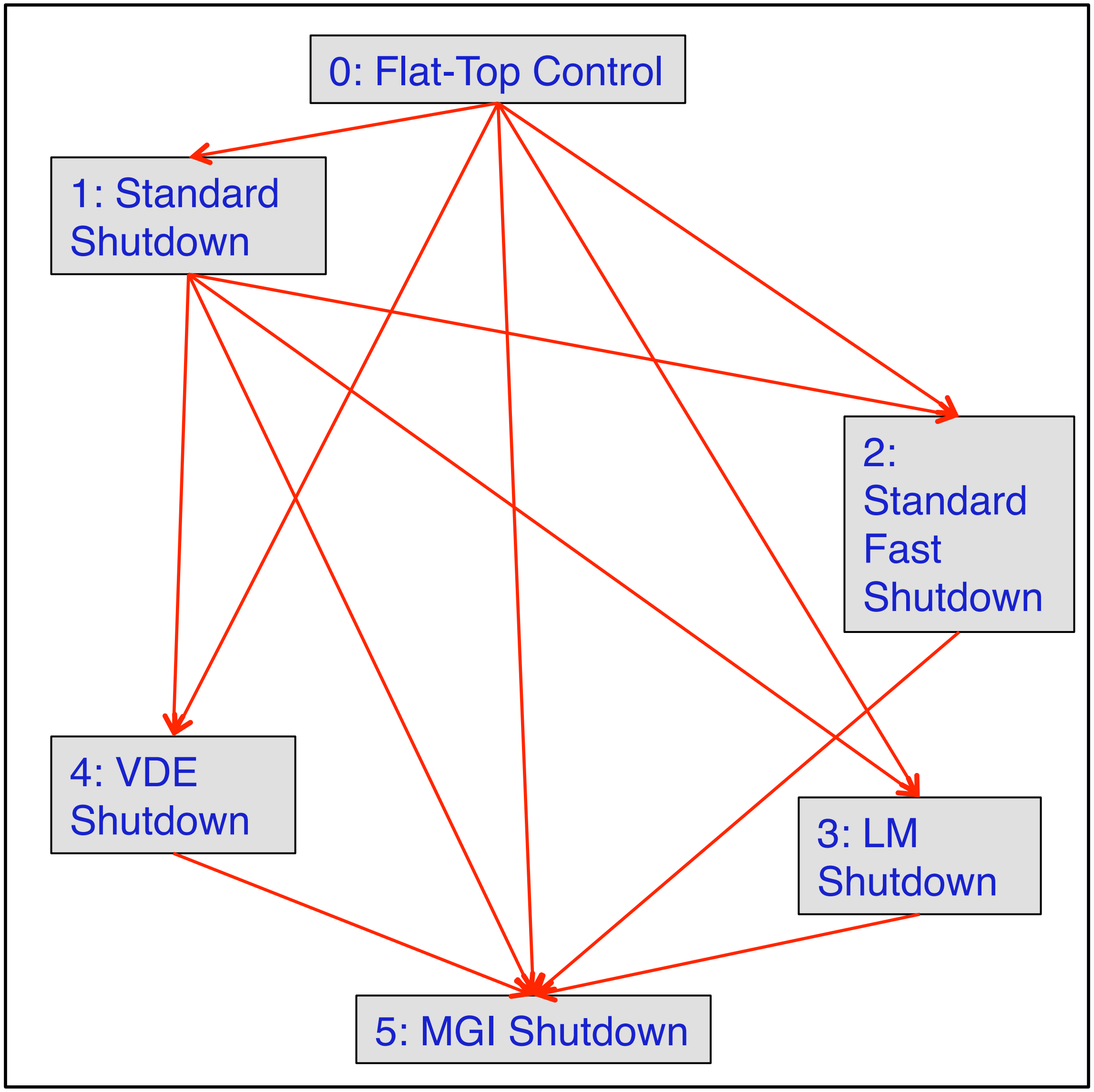


I_P Feedback Error Greater than 7% Essentially Always Leads to Disruption

S.P. Gerhardt, et al., Nuclear Fusion **53** 063021 (2013)

The Behavior of the Shutdown Handler Defined by Possible States and Transitions Between States

- Start out in Flat-Top Control state.
- Can only switch to a given state once in a discharge.
- Only certain state transitions can be allowed.
  - Can only transition to a "faster" shutdown method.
  - Example shows a potential growth of the system…not initial implementation!



Allowed States and Transitions Can Be Defined in the "Allowed Transition Table"

- Allowed states should be defined at run time.
  - By a table as below + an additional "# of states" variable on a GUI.
- Allowed transitions:
  - Also defined in the table:
- Available as a GUI
- Data reloads with the shot.

Allowed Transition Table (Example Contents)

This State	Can Transition to These States					
	0	1	2	3	4	5
0 (Flat Top Control)	no	yes	yes	yes	yes	yes
1 (Standard Shutdown)	no	no	yes	yes	yes	yes
2 (Fast Shutdown)	no	no	no	no	no	yes
3 (LM Shutdown)	no	no	no	no	no	yes
4 (VDE Shutdown)	no	no	no	no	no	yes
5 (MGI Shutdown)	no	no	no	no	no	no

Red are the inputs that the physics operator can change

PCS GUI Will Allow Mapping of Various Levels of F-LoC to the State Change.

SHS = Shutdown Handler State

This table would be a PCS GUI, for each of the potential F-LoC signals

Red numbers would be controlled by the physics operator via the PCS user interface.

One column for each available F-LoC signal

F-LoC Mapping Table

F-LoC Level	VDE F-LoC SHS Change	MID F-LoC SHS Change	Operator Waveform	…
1	1	5	1	…
2	1	5	2	…
3	2	5	3	…
…	…	…	…	…

Interpretation:

If VDE F-LoC becomes 1 or 2, then SHS goes to 1

If VDE F-LoC becomes 3, then SHS goes to 2

If MID F-LoC becomes 1-3, then SHS goes to 5

The SHS tracks the operator waveform

Also reloads with the shot

Potential Initial NSTX-U Implementation

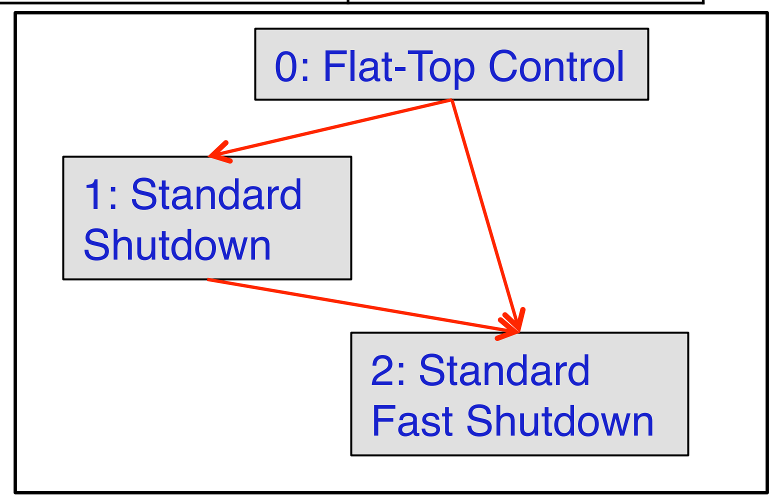
Allowed Transition Table

This State	Can Transition to These States		
	0	1	2
0	no	yes	yes
1	no	no	yes
2	no	no	no

F-LoC Mapping Table

F-LoC Level	VDE F-LoC SHS Change	MID F-LoC SHS Change	Operator Waveform	IpOH F-LoC SHS Change
1	2	2	1	1
2	2	2	2	2

Only two possible shutdown methods in this (proposed) initial implementation.



SHS Maps to the Phase Sequences in the Various Other Categories via the "Phase Transition Table"

This table would be a PCS GUI, with 1 row per shutdown handler state.
There is a column for each category whose phase sequence can be modified
Red numbers would be controlled by the physics operator via the PCS user interface.

Phase Transition Table

	Switch to Phase Sequence in Other Categories					
SHS	IpOH	NBI	Shape	VDE	GIS	RWM
1: Standard Shutdown	1	1	1	1	1	1
…	1	1	1	1	1	
5: MGI	0	1	0	0	2	4

Interpretation:

If there is a 0, then do not change from the present phase sequence
If State = 1, then all categories switch to their sequence 1
If State = 2, then NBI goes to sequence 1 and GIS goes to sequence 2
This table reloads with the shot.

IpOH Category: Potential Actions in the Shutdown Phase Sequence

- Record the plasma current at the phase change.
- Use Ip control to reduce the plasma current.
  - The exact rate of ramp-down can be an operator defined variable
  - Must make sure to carry over the same gains and integral error as during flat-top control.

NBI Category: Potential Actions in the Shutdown Phase Sequence

Note: In NSTX, the PCS is allowed to "block" a beam that would otherwise be on. This blocking can be time dependent, leading to a PCS controlled modulated waveform.

- Have the PCS actively "unblocking" the beams always, even in cases where all timing is controlled from the 138' level
  - Equivalent to running always with the "total power control" algorithm always asking for 100 MW (see beam spec.).
- Record the status of each beam at the time of the phase change.
- For the beams that are on, block them out in ~5 ms intervals.
- For beams that are not on, issue a block so that they cannot come on.

Future Work On Shutdown Handler

- Make assessment on whether this could become a more general “event handling” system on NSTX-U.
  - Must be consistent with primary goal of providing a plasma shutdown method.
- Must define a formal algorithm specification for PCS implementation.
- Implement and test simple version during the 1st year of NSTX-U operations.

Other Plasma Control Improvements for NSTX-U

Power Supply Real Time Control (PSRTC) Code Being Migrated to Reside Within the Plasma Control System

- How currents are controlled in NSTX-U:
  - Shape and plasma current control algorithms produce a voltage request for each coil.
  - Voltage requests converted to firing angles (α) for SCR rectifiers by the PSRTC code.
  - Firing angles transmitted via FPDP fiber link to hardware firing generators.
  - Firing generators generate timing pulses for each individual SCR.
- In NSTX, PSRTC was a stand-alone code.
  - First written in Fortran, then converted to C.
  - Additionally contained coil protection algorithms.
- PSRTC will be implemented as C code within the PCS framework.
  - Makes code maintenance simpler, reduces the total volume of code.
  - Allows tighter coupling to plasma control algorithms.
  - Coil protection functions all migrated to DCPS.

New Gas Control Hardware and Software Being Developed

- Some details about NSTX gas injection algorithm needed improvement:
  - Numerous generations of piezo valve driver technology.
  - Only a subset of valves controlled from the plasma control system
    - Supersonic gas injector (SGI), gas puff imaging (GPI), divertor gas controlled by PLC, and could not be restored with the shot.
  - No easy means for other algorithms to provide flow rate requests
    - For instance, for closed loop line-density of divertor radiation control
- Features of the new algorithm for NSTX-U:
  - ALL valves will be directly controlled from the PCS.
    - And waveforms will be recalled with the shot.
  - All piezo valves will have options for either i) direct open/close control, ii) direct flow rate control, or iii) control of the flow rate from other algorithms.
    - Supports closed loop control of the density and radiation when realtime diagnostics are available.
  - Massive Gas Injection (MGI) will be supported with interlocks:
    - the TF current shall not be too large (to avoid too-large torque on EM valve)
    - The neutral beam power shall be zero (to avoid reionization in the duct)

Profile Control Algorithms

- Rotation Control (see poster PP8.00053)
  - Use beam torques and neoclassical toroidal viscosity (NTV) as actuators on the rotation profile
  - Measurements from realtime toroidal rotation system via charge exchange light (M. Podesta, RSI).
  - State space controller has been developed
- Current Profile Control (see posters PP8.00051, PP8.00052)
  - Use toroidal field, plasma current, electron density, plasma shape and choice of neutral beams as actuators.
  - Use rtEFIT and/or plasma observers to determine the values of quantities to be controlled (q-profile, β_N, q_{min}, q_0, l_i).
  - Developing a suite of PID and state-space algorithms to control combinations of quantities related to the stored energy and current profile.
- Both control tasks: using TRANSP as a “flight simulator” in order to test algorithms with full-physics models.
  - See: D. Boyer, PP8.00052

Previous NSTX Capabilities Will be Restored for NSTX-U

- Shape Control
  - rtEFIT and ISOFLUX provide the basis for shape control in NSTX-U.
  - Substantial effort required to bring them back (new sensors, new coils and geometry).
  - Initial operations will rely on legacy flux-projection algorithm.
    - This algorithm is also used in first ~70 ms of every discharge, before rtEFIT is converging well.
- RWM & EF Control
  - 3D in-vessel sensors have not been modified as part of the NSTX-U construction project.
  - Will restore both PID RWM control algorithm and the state-space RWM control system.
- TF control
  - Has been upgraded to automatically ramp down the TF coil following I_P returning to zero, in order to eliminate unwarranted heating of the coil.