Initial Discussion of Soft/Hard Shutdown For NSTX-U

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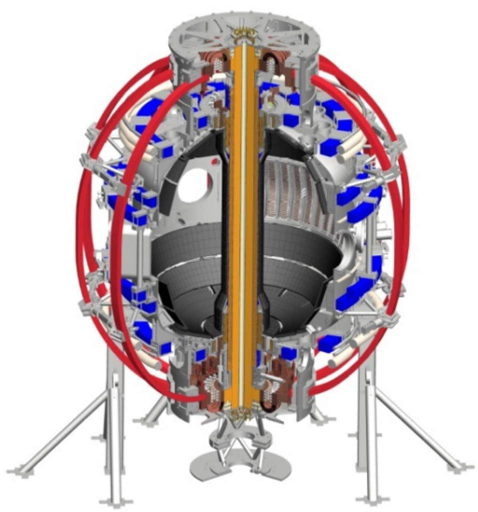

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Goal

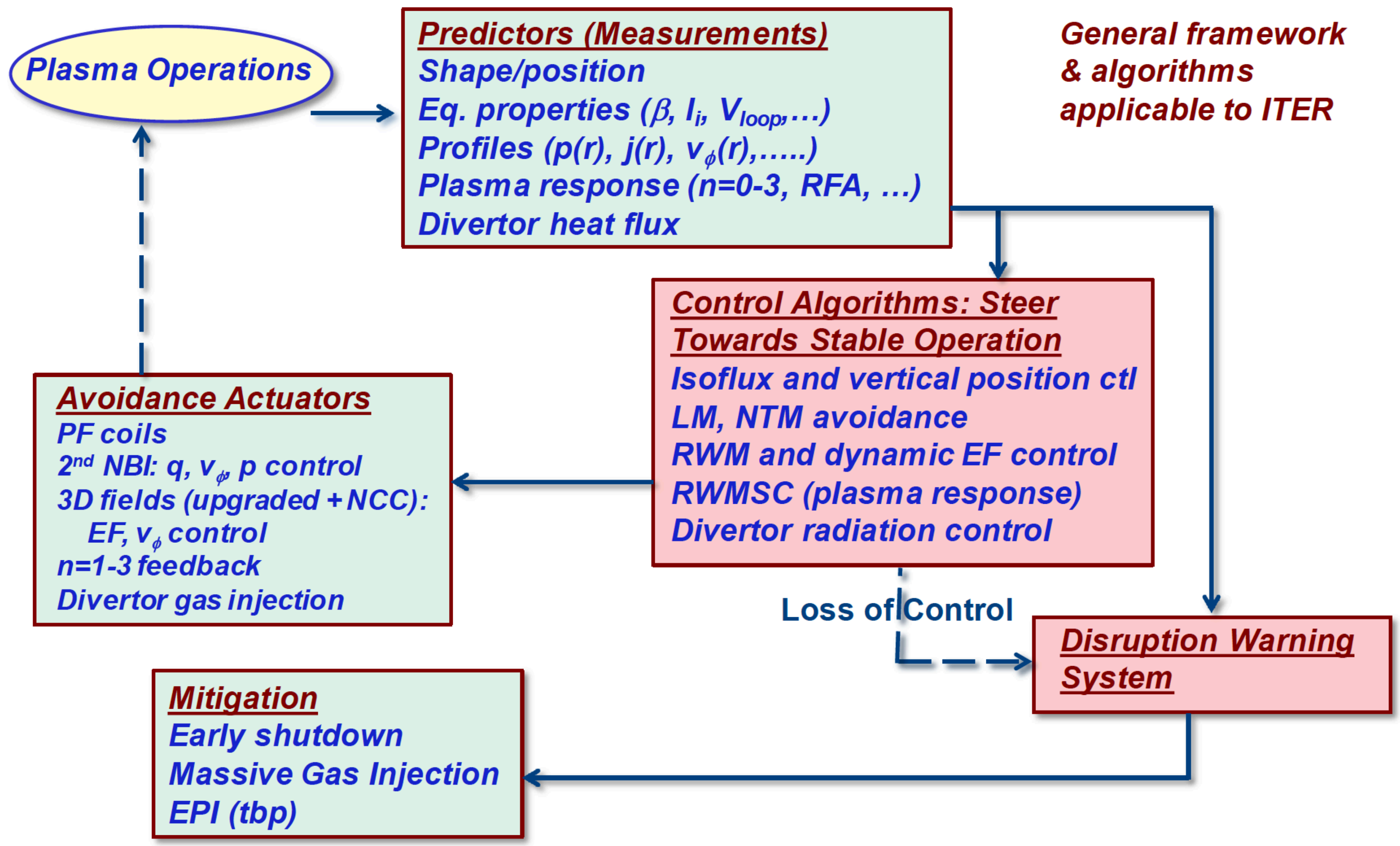
- Develop the code infrastructure to shut down the NSTX-U plasma:
  - Based on a wide range of plasma health indicators.
  - Using different actuator scenarios pending the trigger for the shutdown.

Motivation for the Goal

- Stronger Motivation: New coil protection systems are intolerant of control transients.
  - Large coil current transients occur when failing to control a VDE.
    - Leads to large torques on the TF.
    - Should stop trying once control is lost.
  - Problem is exacerbated when S.P. control is on.
    - Can lead to too much vertical load on the OH coil.
    - S.P. control should be terminated once vertical control is lost.
  - We should not be driving DCPS trips on every shot.

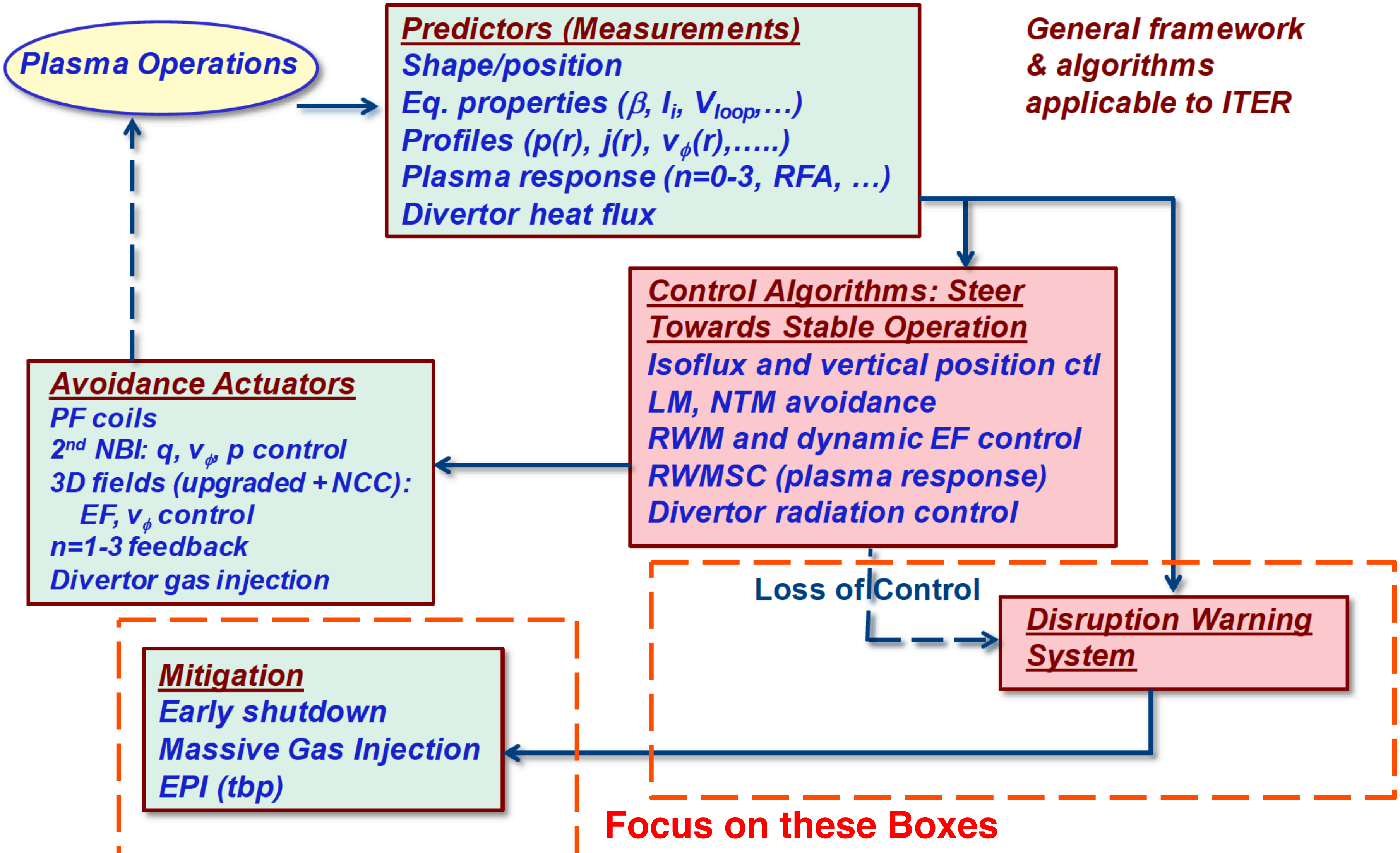
- Weaker Motivation: We promised to do this in the five year plan.
  - ITER, FNSF, DEMO,…

Physics View of the Disruption PAM System



Created/shown by S. Sabbagh at various meetings

Physics View of the Disruption PAM System



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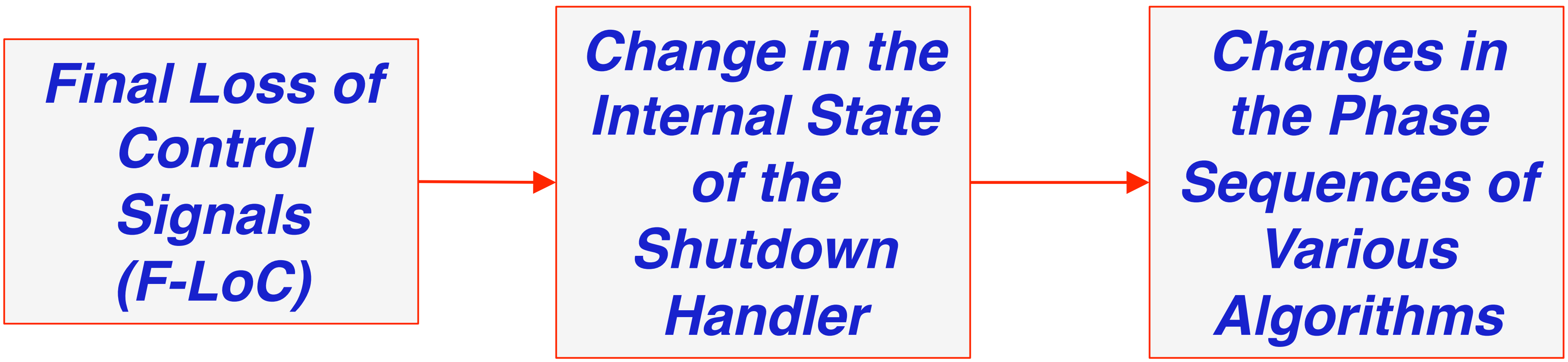
Goals for the Shutdown Handler
Modularity, Simplicity

- 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.
  - The present slides represent my judgment of the best compromise.

Overall Description of the Proposed "Shutdown Handler" (I)

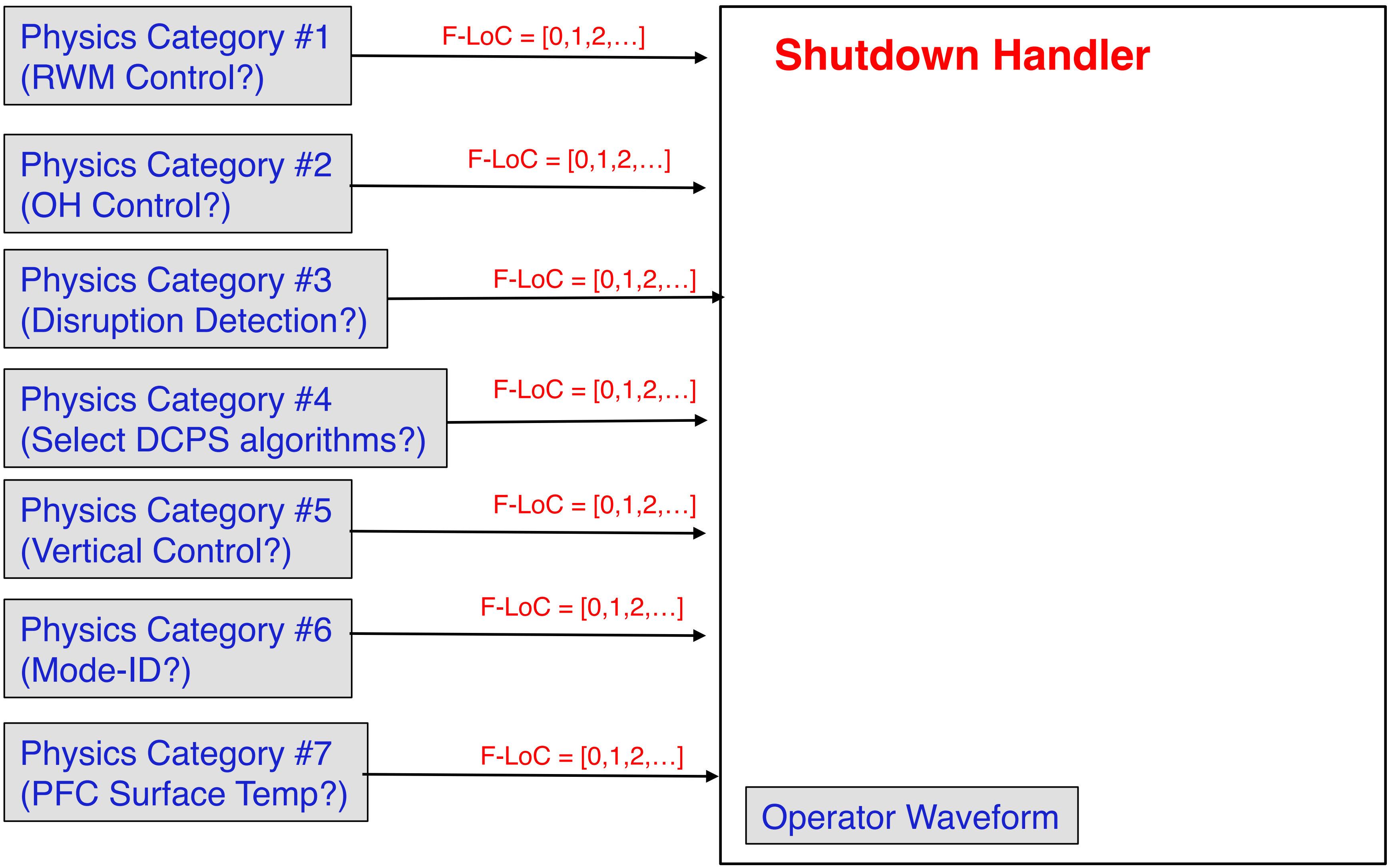


Overall Description of the Proposed "Shutdown Handler" (II)

- Piece of PCS code, likely in its own algorithm & category.
- Shutdown handler is a state machine.
- Only realtime inputs are "Final Loss of Control" (F-LoC) from other algorithm in PCS.
  - Those inputs are integers,
  - The shutdown handler has minimal information about the detailed physics and control models.
- These F-LoC signals drive changes in the internal state of the shutdown handler.
  - Allows a set of defined behaviors.
- The only outputs are imposed changes in the phase sequences of key categories.
  - Operator controlled mapping between the handler state and the various phase sequence changes.
- All physics and actuator-specific consideration are in the other algorithms.
  - The "shutdown handler" is only responsible for coordination.

1: Inputs to the "shutdown handler" from other locations in PCS

Inputs to Shutdown Handler (I)



F-LoC = Final Loss of Control

Inputs to Shutdown Handler (II)

- Each physics category is responsible for producing a “loss of control” signal.
  - RWM category: Use the SSC to determine F-LoC?
  - Mode-ID category: Threshold on the Bp n=1 magnitude?
  - VDE category: Threshold on the up-down voltage difference?
  - IpOH Category: Ip error too large, or approaching the OH current limit.
  - …
- More sophisticated disruption PAM control loops, involving multiple categories and sequences can be defined elsewhere, as long as they provide a F-LoC signal.
- Shutdown handler does not need to know any details of these systems.
  - Subject matter experts to determine how best to quantify F-LoC for each control loop.

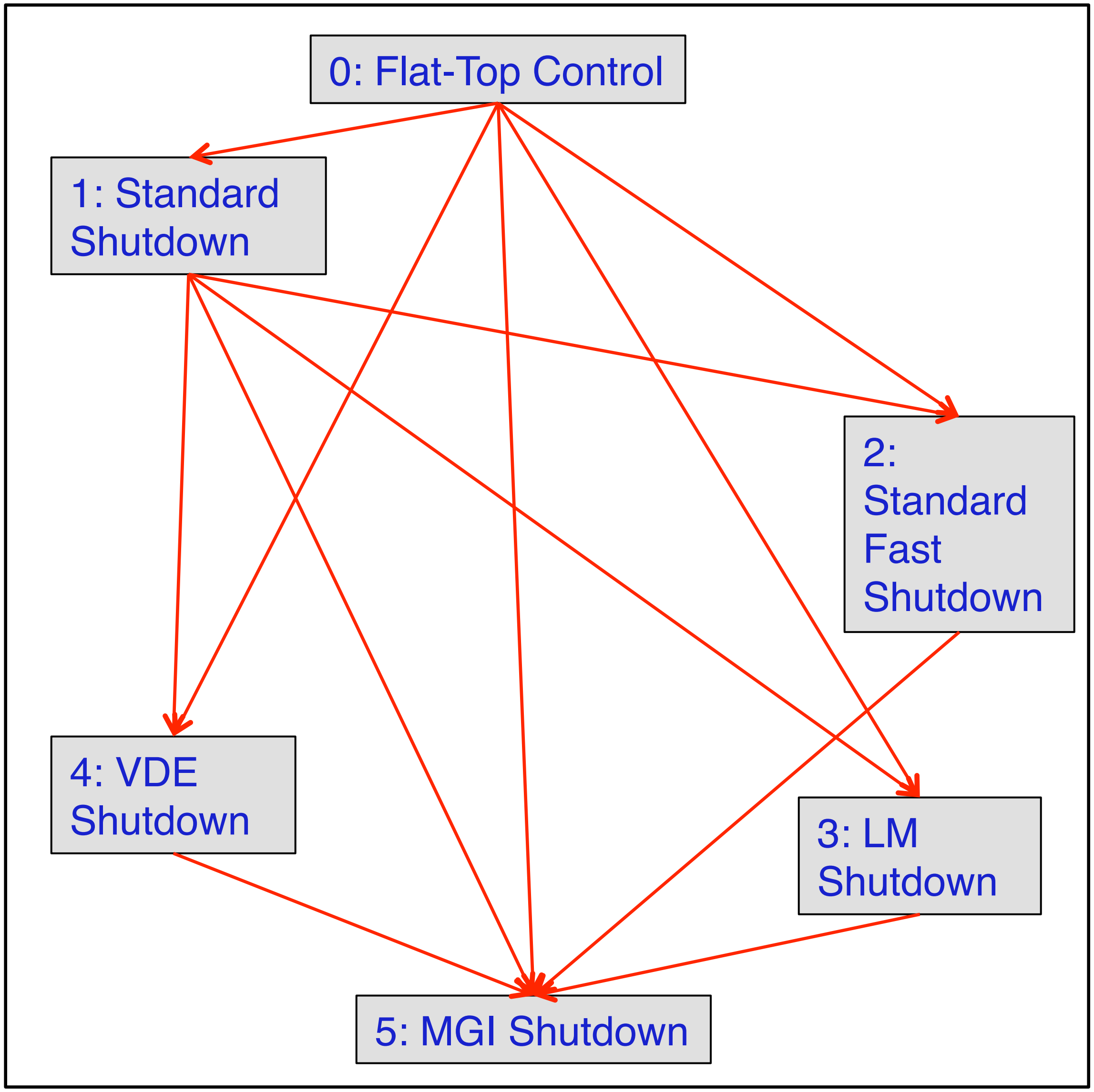
Inputs to Shutdown Handler (III)

- DCPS category:
  - The actual DCPS only declares instantaneous "global" faults, and has no mechanism for anticipating them in advance.
  - It may be advantageous to implement a few of the more touchy algorithms in PCS.
    - OH pre-load, outer-leg moment come to mind.
    - Or just implement them all, though maybe computationally expensive,
  - Can use a current predictor, based on present voltages, to determine if a trip is imminent.
  - This can all be better defined at a later date.
- Disruption Detection Category:
  - Sophisticated processing of diagnostic data does not belong in the shut-down handler.
  - Neutral networks, or semi-physics-based models like those by Gerhardt, go in this separate category.
  - They pass high-level status information to the shutdown handler.
  - This can all be better defined at a later date.

2: Inputs to the “shutdown handler” toggle the handler “states”.

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

This State	Can Transition to These States					
	0	1	2	3	4	5
0	no	yes	yes	yes	yes	yes
1	no	no	yes	yes	yes	yes
2	no	no	no	no	no	yes
3	no	no	no	no	no	yes
4	no	no	no	no	no	yes
5	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

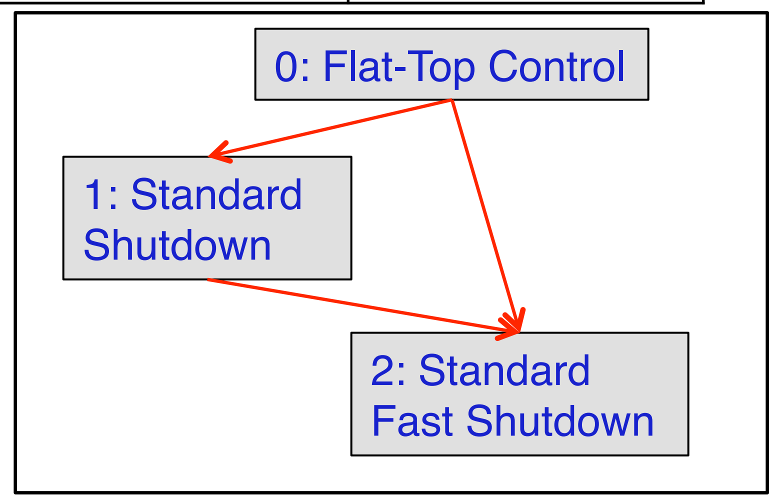
Allowed Transition Table

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.



3: A change in the SHS results in a change in the phase sequence of other algorithms.

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

<u>Interpretation:</u>

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.

Categories Must Be Able to “Lock-Out” From the SH

- Each category whose phase can be changed from the SH can issue a binary flag indicated whether their phase is allowed to be changed.
  - Call this the “PhaseTransitionLockoutFlag”
  - Allows the categories to prevent a phase change.
- Example from I_P control.
  - While during regular control, PhaseTransitionLockoutFlag = 0 (phase transitions allowed)
  - Once the OH coil reaches the current limit and enters the OH coil shutdown phase, PhaseTransitionLockoutFlag = 1 (SH not allowed to drive phase transitions).

Potential Initial NSTX Implementation

Phase Transition Table

	Switch to Phase Sequence in Other Categories				
State	IpOH	NBI	Shape	VDE	GIS
1: Standard Shutdown	2	1	0	0	0
2: Fast Shutdown	2	1	0	0	0

Both the “Standard Shutdown” and “Fast Shutdown” SHS will lead to the same rampdown sequences in this table.

First implementation will likely only impact the IpOH and NBI categories (turn off the beams and ramp down the current)

4: Phase Sequence Requirements Within the Other Algorithms

Rational: There are only two choices here.

Either

1) The shutdown handler can give detailed directions to each of the beams, plasma current, shape…the timing of all the small changes for each actuator.

- Brings all sorts of gains from disparate locations into the shutdown handler.
- Brings requirements for actuator continuity into the shutdown handler.

2) The shutdown hander can define changes in the phase sequences and leave the details in their phase sequences.

Uses the PCS infrastructure…and is what DIII-D does…

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IpOH Category
Example Actions

- 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.
    - As was done in the TF rampdown algorithm.
  - If the OH coil saturates, then the coil is ramped down and PhaseTransitionLockoutFlag = 1

NBI Category
Example Actions

- First, 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.
- Details to be defined in algorithm #3 in the beam category.
- Not any clear need to invoke PhaseTransitionLockoutFlag for this category.

Shape/ISOFLUX Category

- This is harder, but not having a perfect solution is no reason to not try.
- At the time of the phase transition:
  - Turn off SP control. Switch of simple pre-programmed PF-1A diverting as in the shape category.
    - This can be done by interfering with the system category waveforms.
  - Go to an inner-wall limit plasma shape under ISOFLUX control.
    - When the current gets so low that rtEFIT fails, this is probably sufficiently good.

- Need a bit of help understanding this step better.

RWM Category

- Sensors are not properly compensated for their pickup of nominally axisymmetric eddy currents.
  - That is, the axisymmtric plate and vessel currents during phases with rapid I_P changes lead to “random” pickup in the sensors.
  - This random pickup is interpreted as n=1 field
  - Feedback system then applies a spurious (dangerous?) n=1 field.
- So it appears that the best idea is to turn off RWM feedback of any style.
  - Or add the correct loop voltage based compensations.
- Interesting question: with the new Bay J-K cap creating a big field perturbation, will we need a special error field compensation during current ramps?

VDE Control

- VDE control is now a separate category in PCS.
  - Allows us to quickly switch in/out various new algorithms.
- Not clear at the moment that we will need to change anything in this are during the automated rampdown.

5: PCS Considerations

Total Operator Input to PCS in the Shutdown Handler Category

SHS = Shutdown Handler State

- A single floating step target that allows the operator to directly change the SHS.
- A table that describes the allowed transitions between SHS.
  - "Allowed Transition Table"
  - And also the scalar # of states
- A table that maps between the F-LoC signals and the SHS.
  - "F-LoC Mapping Table"
- A table indicating how the SHS maps to phase transitions in other algorithms.
  - "Phase Transition Table"

Inputs are only 1 waveform, three tables, and a scalar.

Everything Should Be Reloaded With the Shot

- This system implies well define interactions.
  - Need to avoid cases where the reloaded SHS calls for phase sequences that don't exist in other categories. Hence…
- All quantities in the shutdown handler need to be reloaded with the shot.

The End