Equilibrium Magnetics for NSTX-Upgrade

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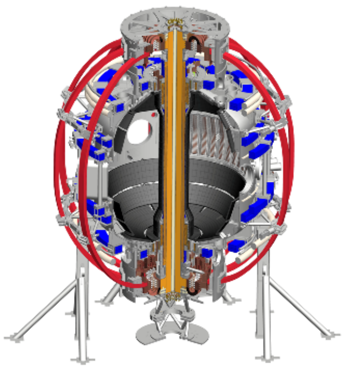
Physics Operators Course, 2015



Outline

- Uses of the equilibrium magnetics

- Locations and types of sensors
  - Mirnovs
  - flux loops
  - voltage loops & rogowskis
  - difference voltages

- Signal processing chain
  - Offline vs. online

- Diamagnetic Loop

- Magnetics in plasma control
  - I_P calculator
  - Magnetics for gap control.
  - Difference voltage for fast vertical position control.

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Uses for the Equilibrium Magnetics

- Equilibrium magnetics here are those used to define the n=0 (that is, toroidally average) quantities in the plasma.
- Offline Equilibrium Reconstruction
  - EFIT, LRDFIT, GA Kinetic EFITs
    - Thus, critical for physics analysis
  - Critical for appropriate operator decision making (EFIT)
- Online Equilibrium Reconstruction
  - rtEFIT
    - Provides the basis for nearly all shape control.
- Basic plasma position control
  - Early in the shot before switching to isoflux control
- Fast vertical position control
- Interlocks

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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 results in 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.

Naming Convention For Sensors

Locations and Orientations

PPP = Primary Passive Plate
SPP = Secondary Passive Plate
IBDV = Inboard Divertor Vertical Part
IBDH = Inboard Divertor Horizontal part.
CSC = Center Stack Casing
OBD = Outboard Divertor
EVV = External to the (Outer) Vacuum Vessel
IVV = Internal to (Outer) Vacuum Vessel
OH = On the Solenoid
U = Upper
L = Lower
M = Midplane
N = Normal
T = Tangent

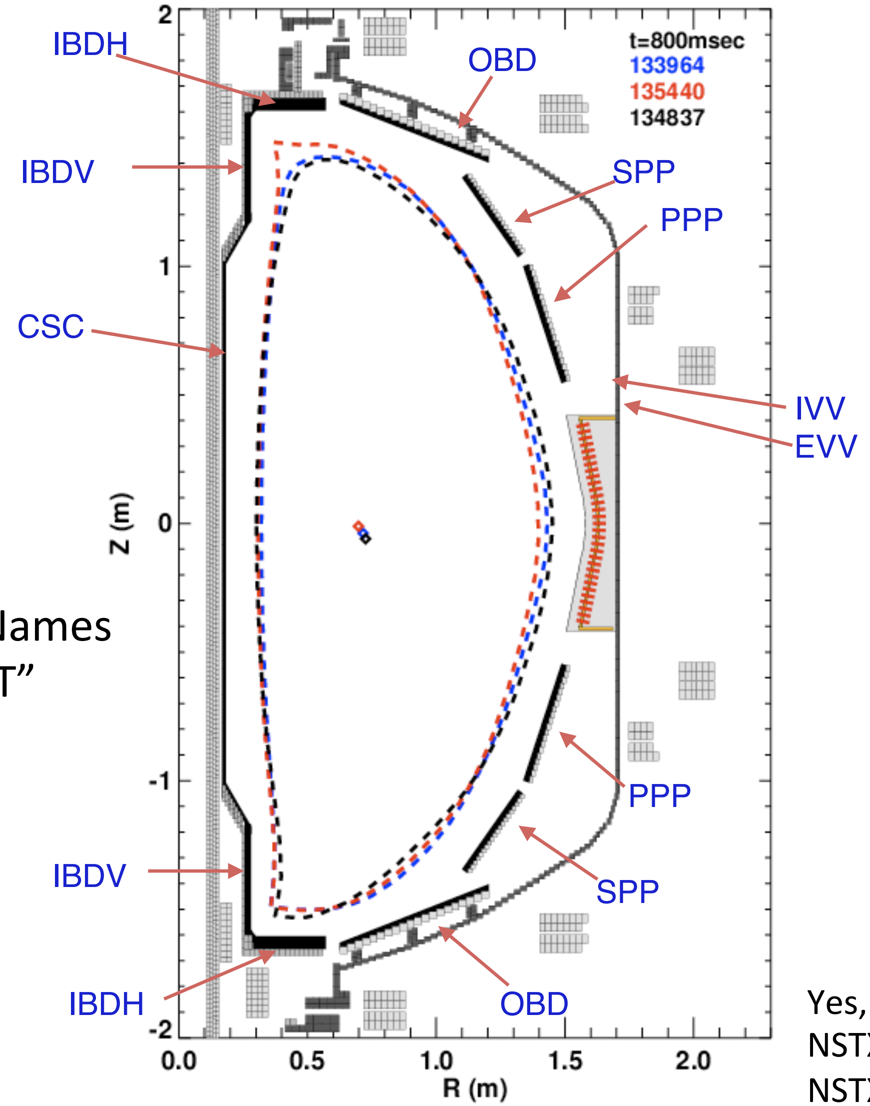
Sensor Types

1DM = One Dimensional Mirnov
2DM = Two Dimensional Mirnov
FL = Flux Loop
Rog = Rogowski

Ground Classes

Category 3 = Inner Vessel
Category 4 = Outer Vessel

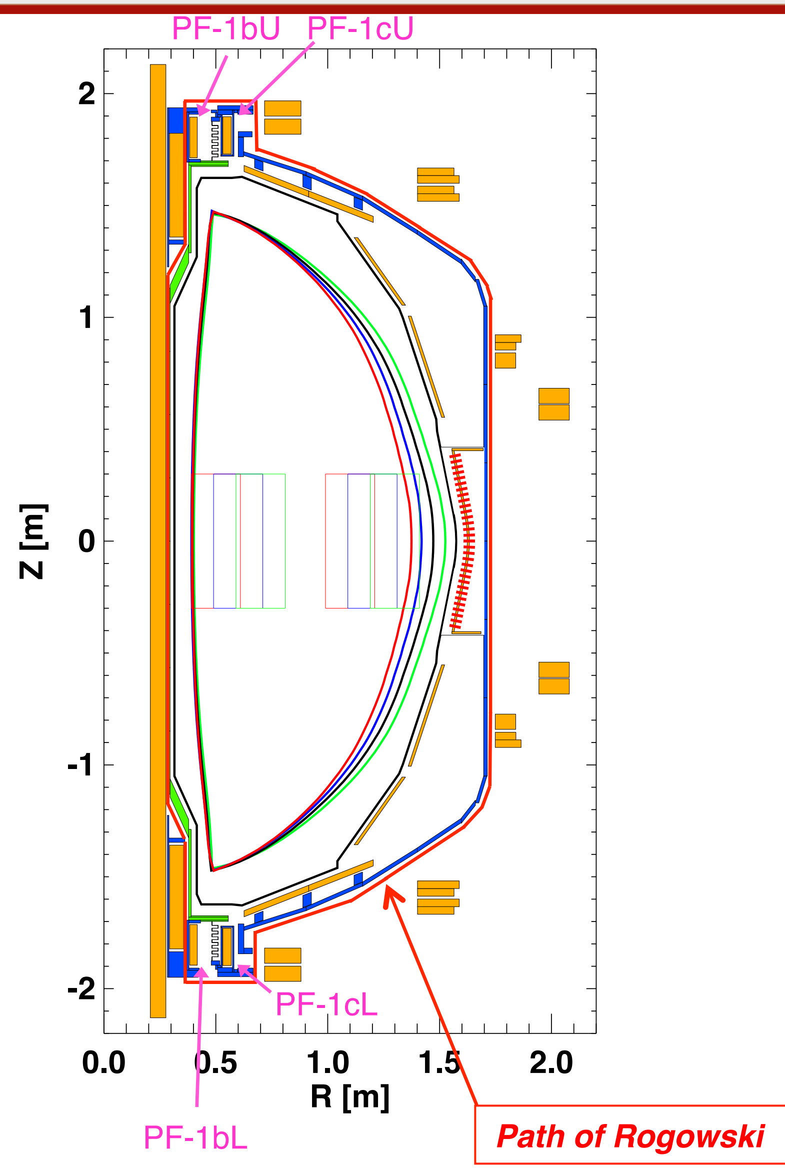
Example Sensor Names
"2DMOBDU4T"
"FLOHL2"



Yes, this in NSTX, not NSTX-U…

Plasma Current Rogowskis

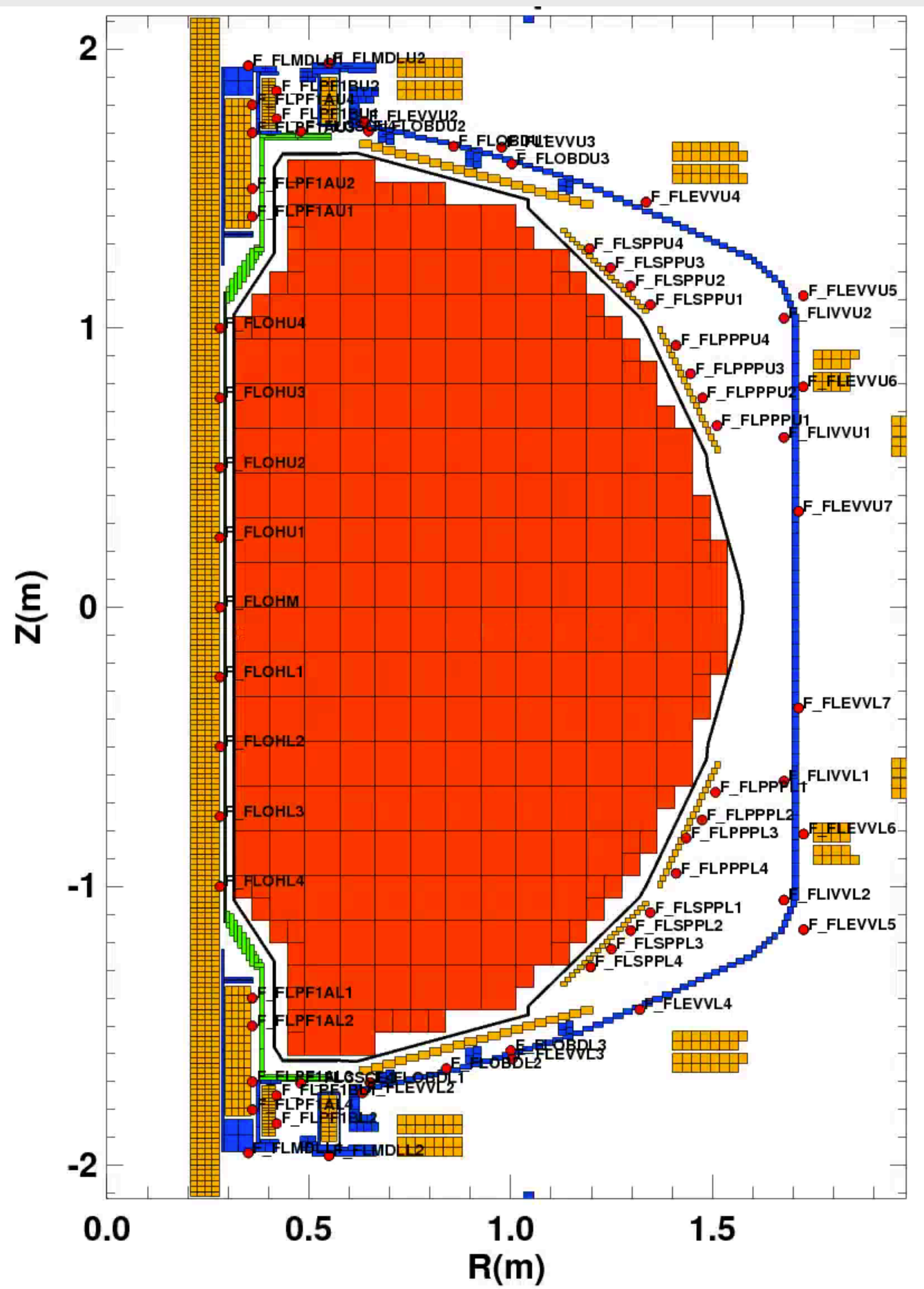
- NSTX has an “inner” and an “outer” vacuum vessel.
- Rogowski is outside the vacuum vessel
  - Allows it to cross the “CHI Gap”
  - Is on the same electrical ground as the center column.
- Rogowski Links:
  - Two divertor coils at the top of NSTX-U
  - Two divertor coils at the bottom of NSTX-U
  - Much of the vacuum chamber
  - The plasma current
- Possible to have up to 4 MA of linked current in NSTX-U.
  - 2 MA of plasma current
  - 2 MA of divertor coil current
- But also want to accurately measure 10s of kA.
  - Solution: High and low-gain channels for each of the two rogowskis



Flux Loops

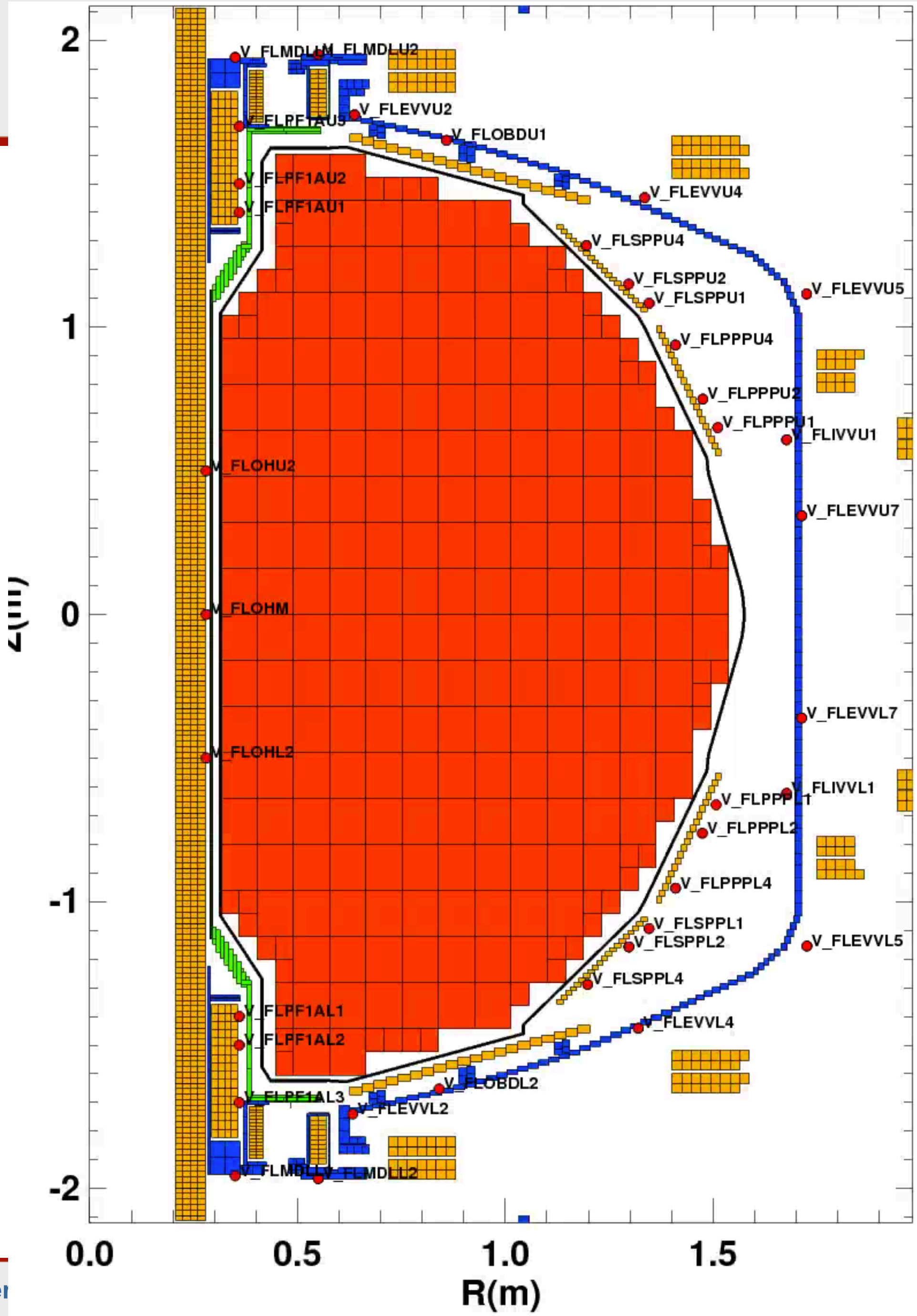
$$\psi = \iint B_Z dA = 2\pi \int_0^{R_{loop}} R B_Z dR$$

- 12 on the outside of the outer vessel (EVV).
- 10 on the inside of the outer vessel (IVV & OBD).
- 16 behind the primary and secondary passive plates (PPP & SPP).
- 9 on the OH coil
- 18 more on the divertor coils and their winding mandrels
- Not all OH and divertor coil loops instrumented with integrators right now.
  - But more integrators are being made



Voltage Loops

- Same as a “flux loop”.
  - We just don’t integrate the signal.
- 13 Measurements on the inner vessel
- 12 measurements on the outer vessel.
- 12 measurements on the plates themselves.
- Used to infer vessel currents, as described later.

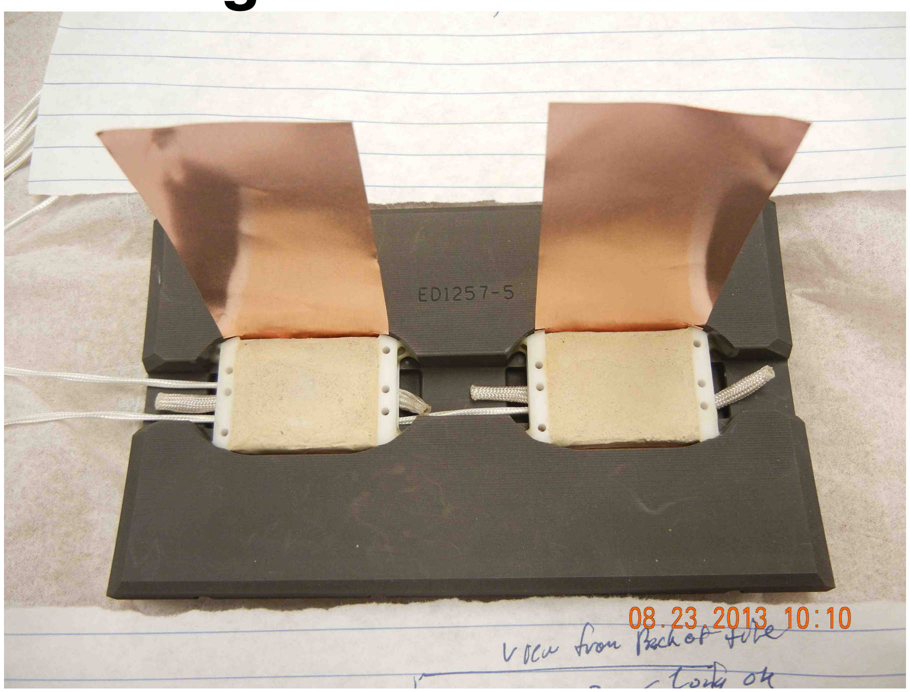


Mirnov Sensors

Detail of 2D Mirnov Installation

Tilted 1D Mirnov

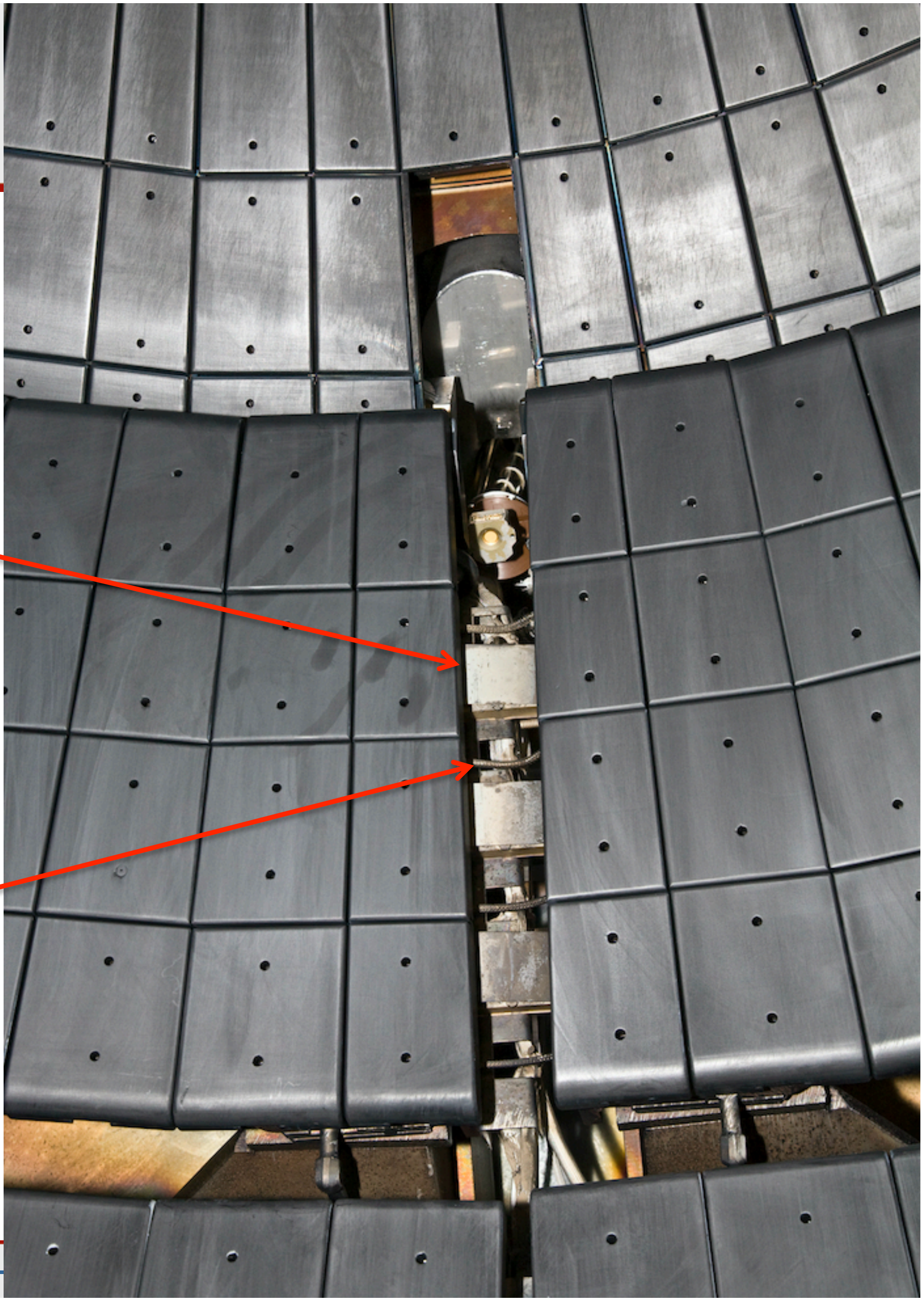
Two 1D Mirnovs in a Single Tile



Outer Vessel Magnetics

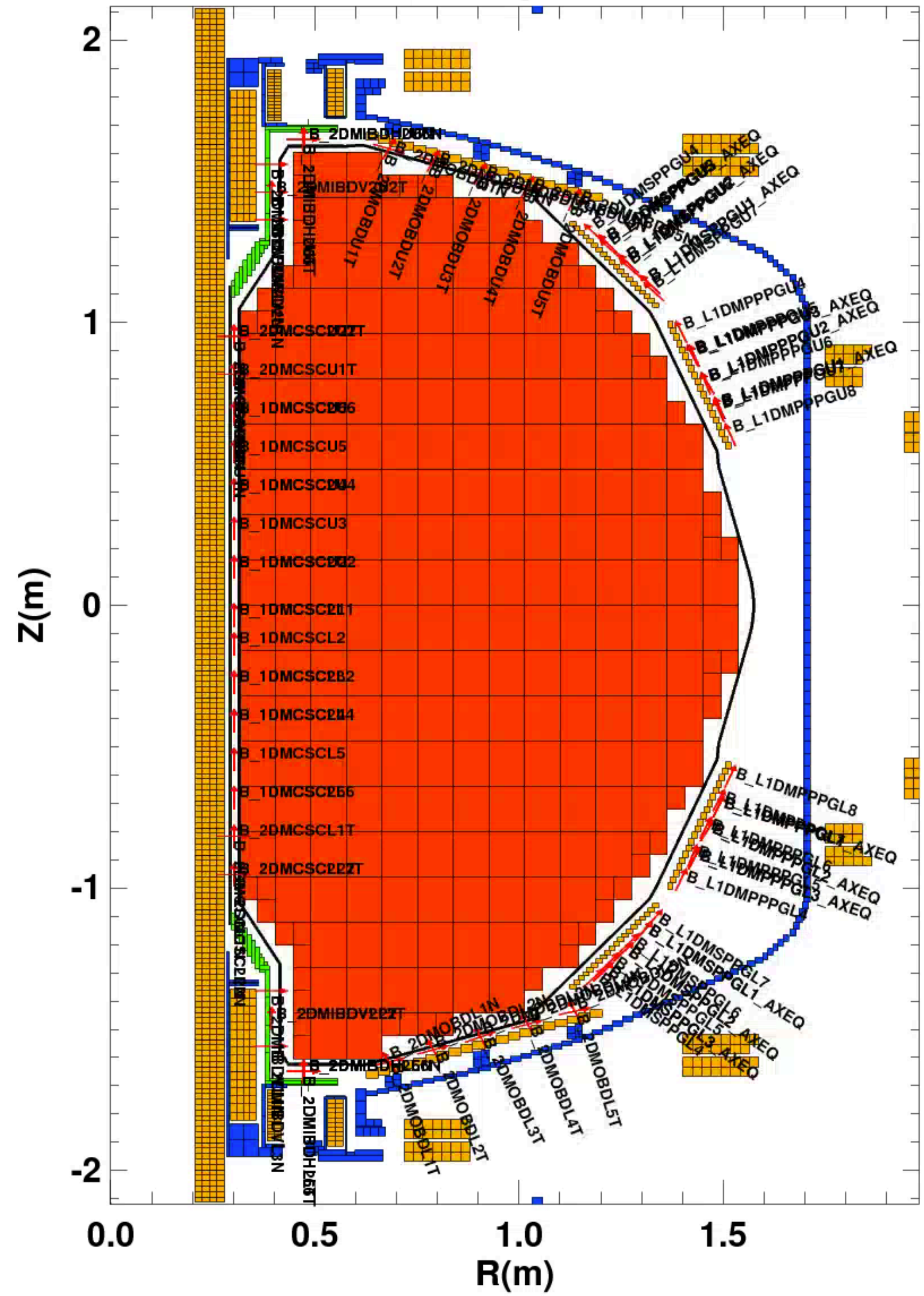
Mirnov
(3 total visible)

Flux Loops
(4 total visible)



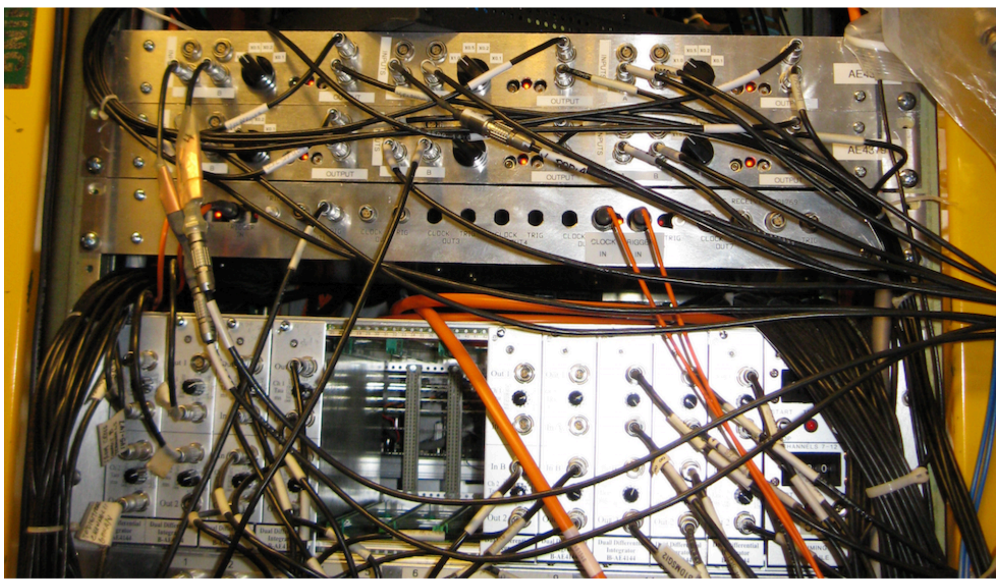
Mirnovs Sensors (small solenoids)

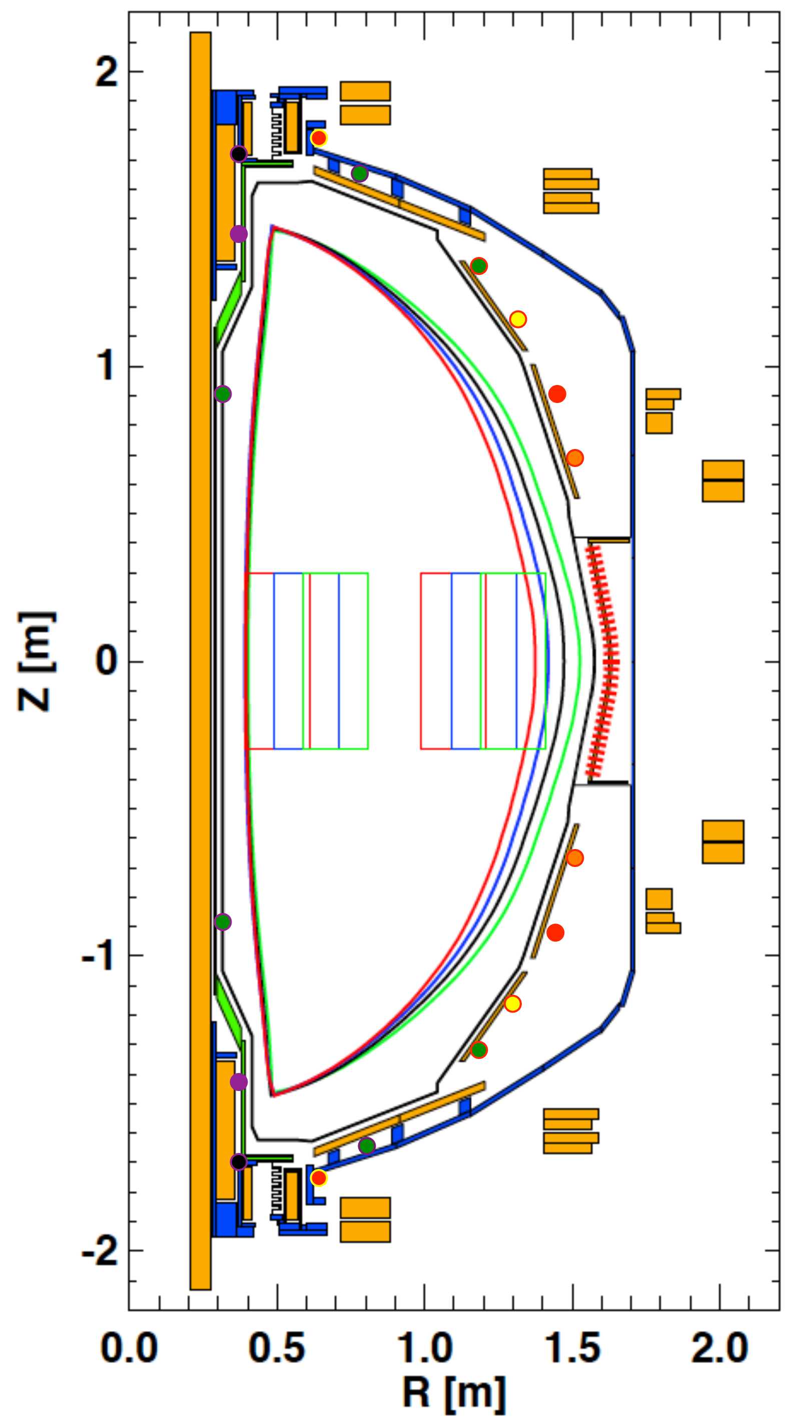
- Some have two sensors wound on the same mandrel.
  - 2D sensors mainly located in the divertor.
  - Normal to the PFC surface (N)
  - Tangent to the PFC surface (T)
- Sensors mounted:
  - Between and behind the passive plates.
  - Inside tiles on the center stack casing.
  - Inside tiles in the divertor.
    - Outer
    - Horizontal Inner
    - Vertical Inner
- Not all inner vessel sensors instrumented with integrators right now.
  - But more integrators are being made



Voltage Loop Differences

- In a few places, take analog voltage differences before digitizing the signals.
  - Allows common mode to be removed, the difference can then be amplified to higher gain if desired.
- Always take up-down symmetric pairs for this measurement.
  - 6 pairs on outer vessel, 3 pairs on inner vessel.
- Used to infer the vertical motion of the plasma
  - Discussed later.





Many New Diagnostics Have Been Added to the NSTX-U Center Column

Sensor Type	Purpose	NSTX Center Column	NSTX-U Center Column
1D Mirnovs	Fluctuation Analysis, Equilibrium Reconstruction	11	17
2D Mirnovs (2 sensors each)	Equilibrium reconstruction	10	20
TCs	Bulk temperature of tiles	22	47
Flux Loops	Equilibrium Reconstruction	12	27
Shunt Tiles	Currents Flowing into the tiles	0	18
Tilted Mirnovs	Currents in CS casing (measure B_T)	0	5
Langmuir Probes	Plasma density & temperature	14	23

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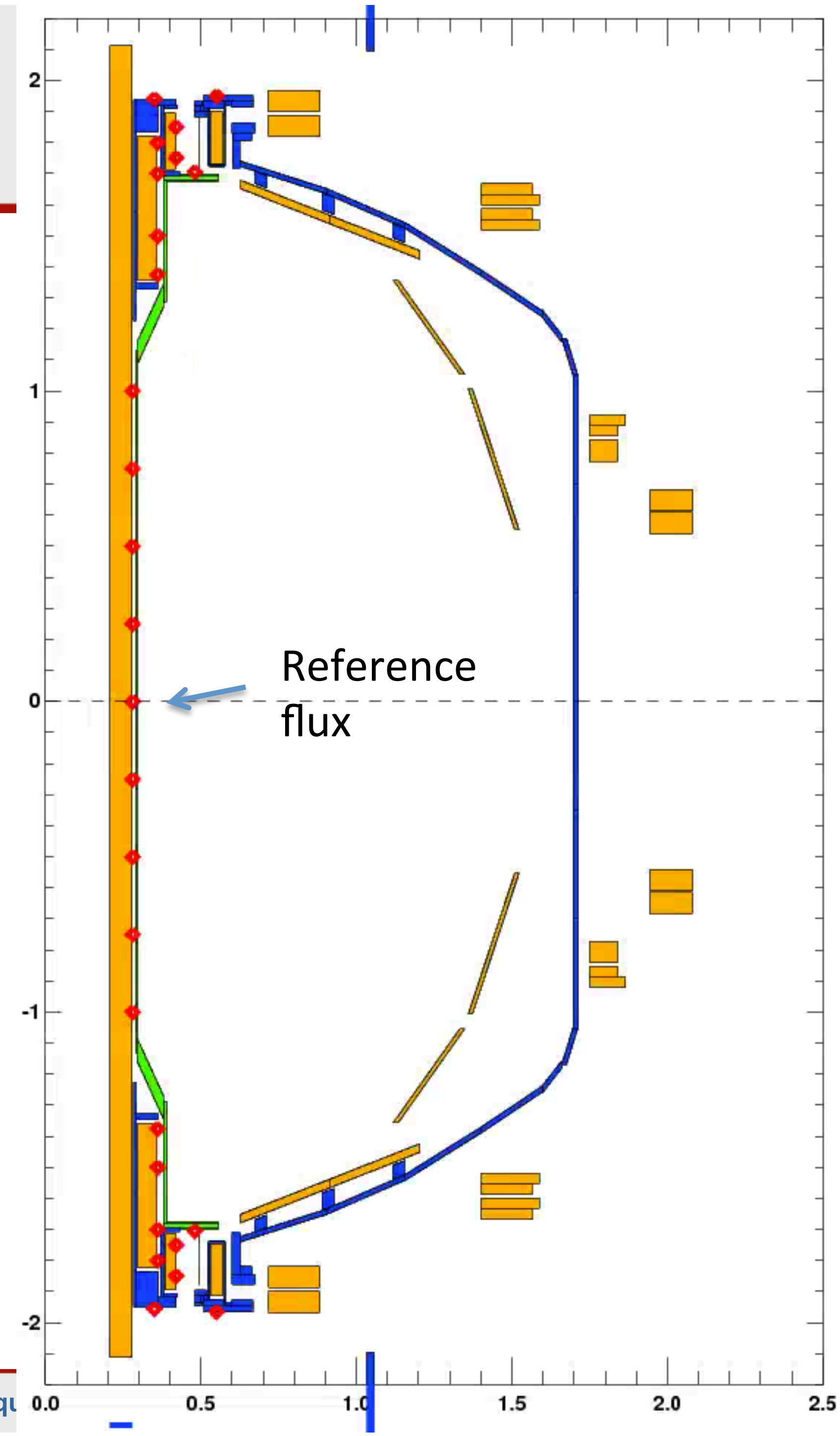
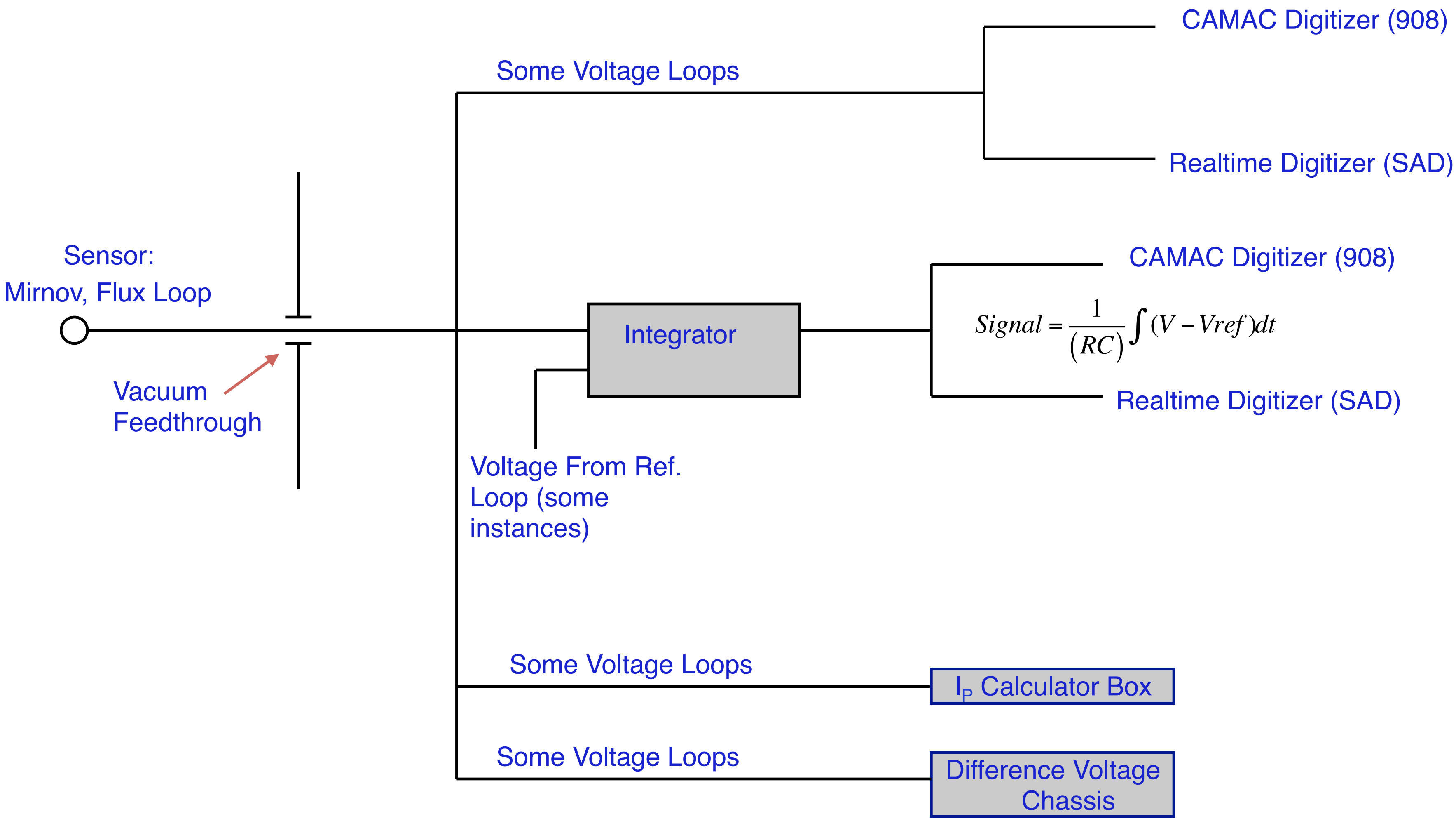
CS Loops are Actually Integrated as "Difference Fluxes"

- CS loops are dominated by the large "common mode" flux of the OH coil.
  - We want to subtract that off so that the details of the flux pattern can be seen.
- Reference flux is the midplane loop.
- For all other loops, quantity that is integrated is V_{loop}-$V_{midplane}$.
- So the digitized quantity is proportional ψ_{loop}-ψ_{ref}.
- From the operations tree, nodes like \cal_flohu3 are the difference flux, while nodes like \f_flohu3 have had the reference flux added back (in tdi).
- This only applied to the CS loops…all outer vessel loops are digitized directly.

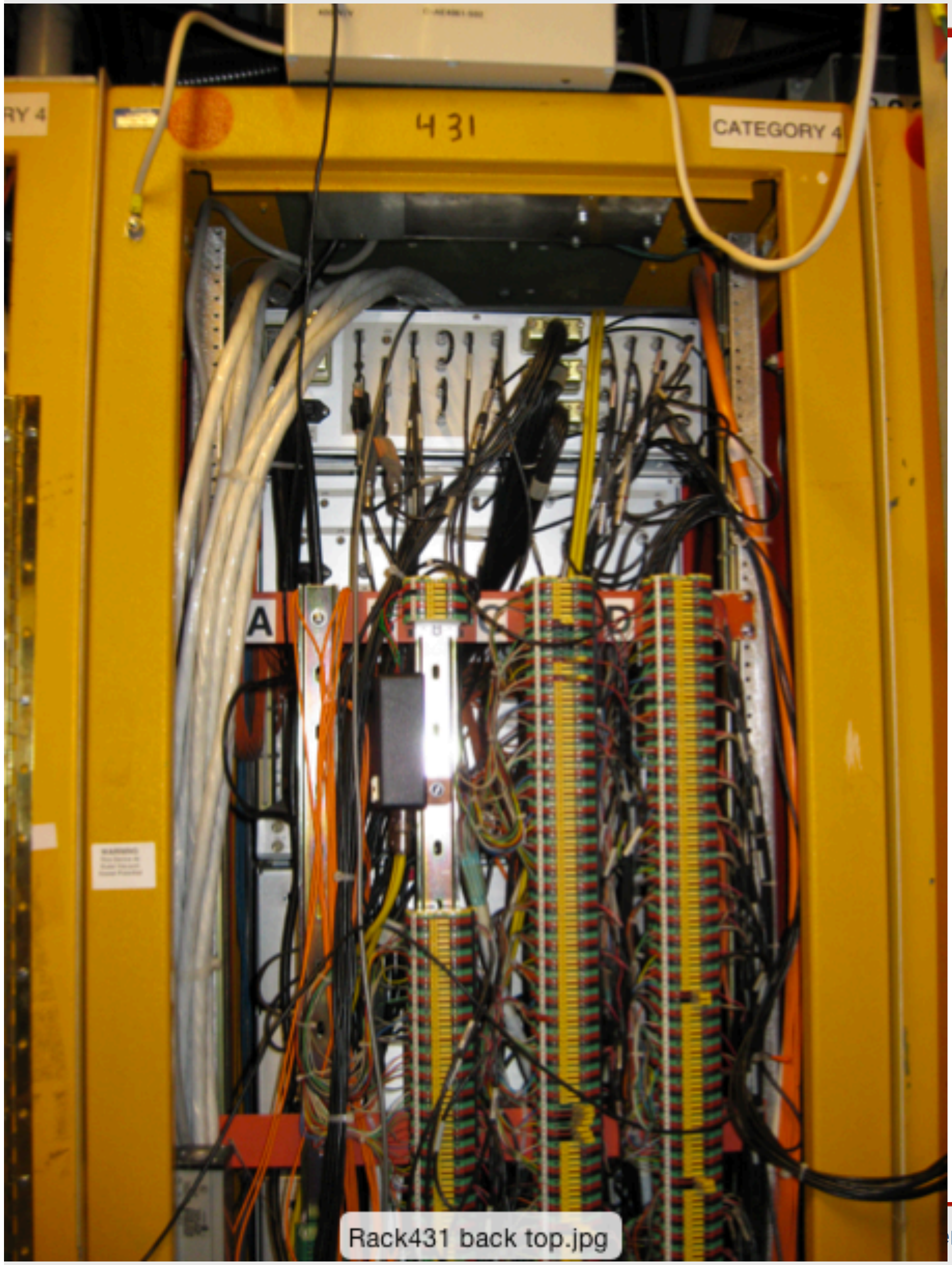


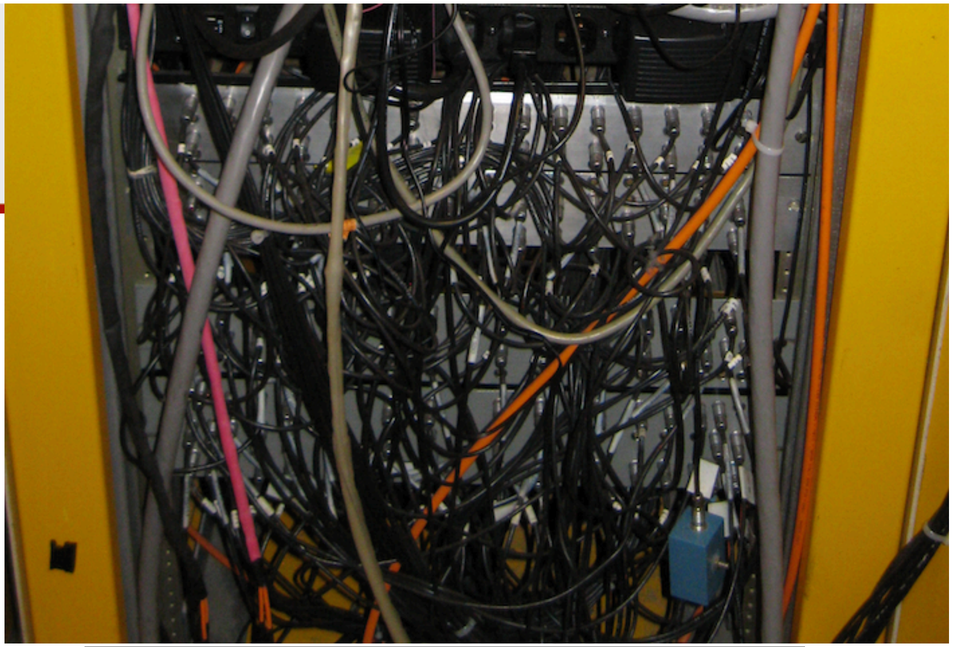
Hardware Signal Processing Chain For Mirnov Sensors and Flux Loops

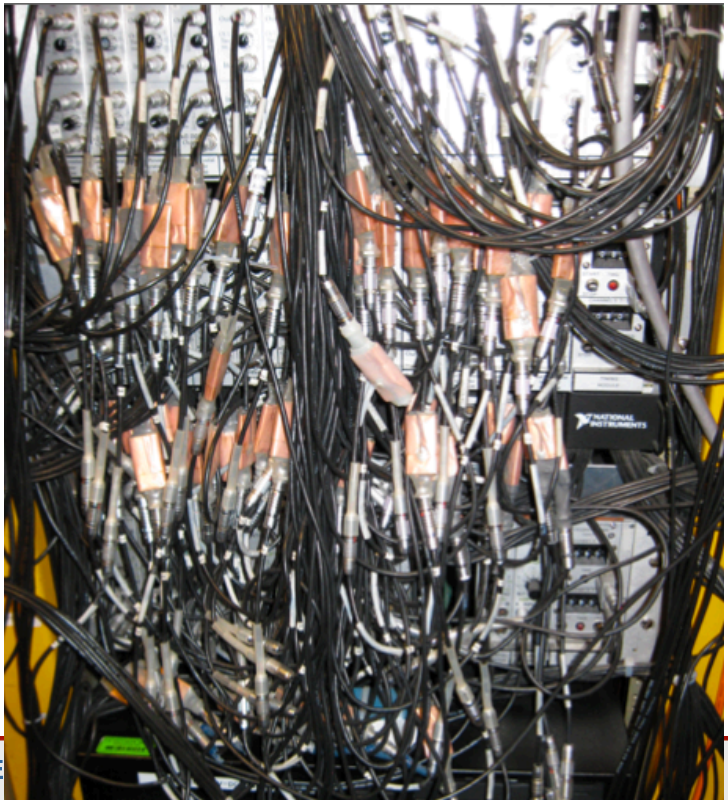


Conceptual Only

Real life is a bit uglier







Signal Calibrations Follow Similar Paths in "operations" and Realtime Versions.

- Nearly all off-line magnetic diagnostic signals are in the "operations" tree.
- First subtract a (linear sloping) baseline from the signals.
- Each sensor has many calibration coefficients.
  - Effective area
  - Integrator time constant RC ("Gain" = 1/RC)
  - Pickup coefficient for TF & other sources.

$$B = \frac{(RC)}{A} B_{Volts} - \sum_{i}^{i=NumCoils} p_i I_i$$

- Same calibration coefficients (with minor exceptions) are used off- & on-line.
  - Offline: Used in tdi function calls.
  - Online: Done in PCS.
- All of these coefficients are stored in the MDS+ model tree.
  - The "tree" is the database structure where all NSTX data is stored.
  - Some of the data in the tree is known before the shot starts.
    - Calibration coefficients, digitizer timing,…
  - Model tree contains all calibration data, places for shot-specific data.
  - Before each shot, the model tree is copied over to the shot-specific tree.

Timing Counts…

- Integrators are triggered at "T-N", which is SoP-1, or about -6 seconds.
- PCS does baseline subtraction at about -5.9 seconds.
- PCS starts control at SoP = -5 seconds.

- We have enough memory on the CAMAC digitizers to run for ~6.7 seconds.
- Those digitizers start at -3 seconds, running till 3.7 seconds.
  - I need ~0.5 seconds of that before any coil is turned on, for base lining.
- You need to make sure that you never turn on a coil before t=-2.5 seconds.
  - There is a note to this effect on the white-board

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About Diamagnetic Loops on NSTX-U

- NSTX used the TF coil as the sensor for the diamagnetic flux measurement.
  - Complicated hardware, measuring voltage in the TF SDS cabinet.
  - Complicated software, with modeling for the resistive flux consumption in the buss work, coil, including temperature dependent effects.
  - M. Bell did analysis and decided it would be even harder to make this work in the upgrade.
- Trying a new system
  - Use the spare return lead of the plasma current rogowski to measure the $d\psi_T/dt$.
    - This will of course measure dominantly the field from the TF coil
  - Use a rogowski on the TF outer leg to measure dI_{TF}/dt
  - Integrate their difference: F_{dia}=integral($d\psi_T/dt-C_{dia}dI_{TF}/dt$)
  - Once additional pickup is corrected, this should be the diamagnetic flux.
- System is in place, was tested, are now optimizing the setting for C_{dia} (potentiometer setting), will let you know how it goes.

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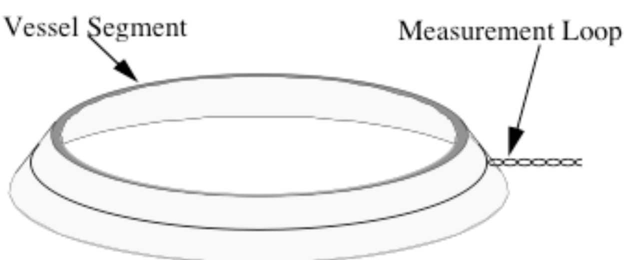
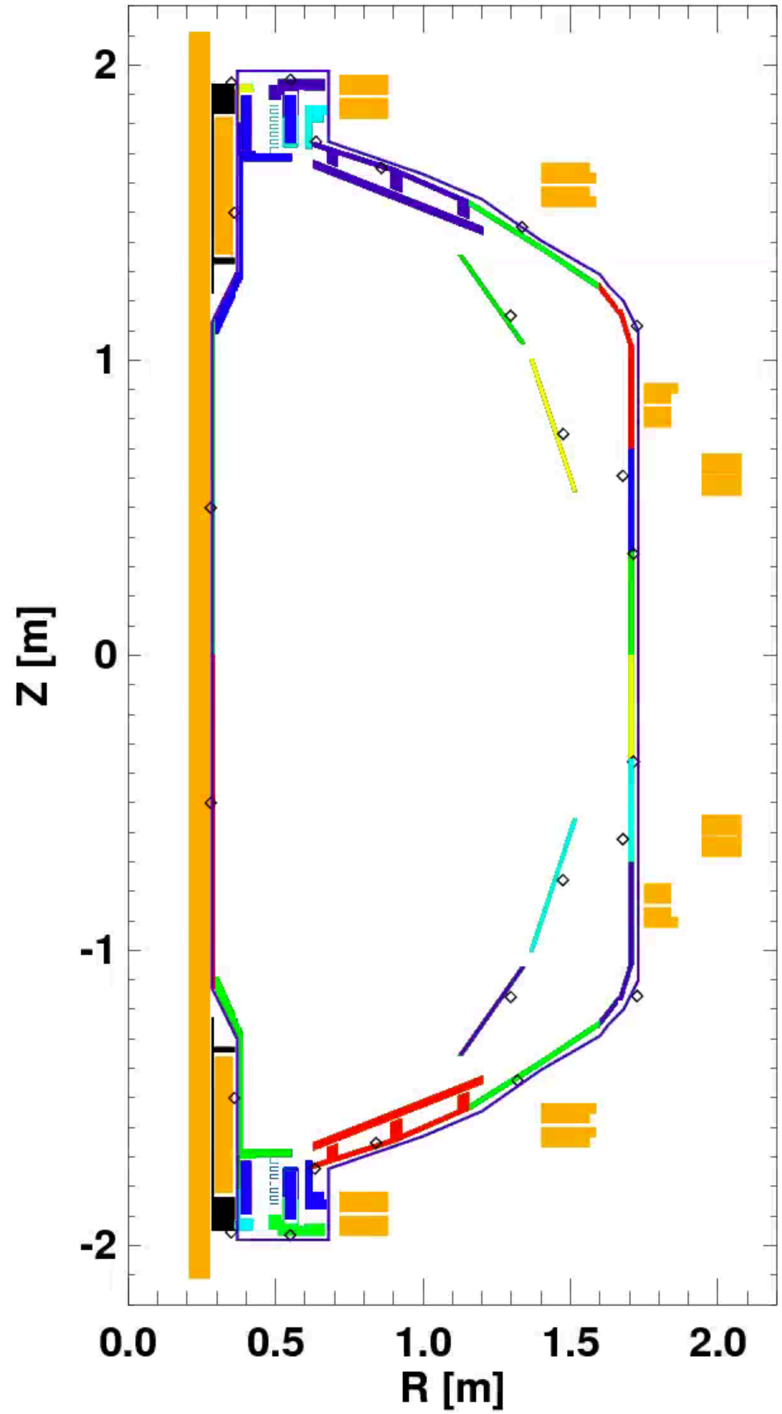
Vessel Currents Are Inferred from Loop Voltages

- Rogowski links plasma, vessel PF-1bU, PF-1bL, PF-1cU, PF-1cL coils.
- Need to know the plasma current in realtime for some interlock applications.
  - Interlock on neutral beams.
  - This is what we feed to PCS & DCPS
- Need realtime subtraction of all currents that are not the plasma.
  - Not "stray pickup", but rather real current.
  - Need to measure vessel currents in real-time.
- Break the vessel into segments, compute effective toroidal resistances, and use loop voltages to infer currents

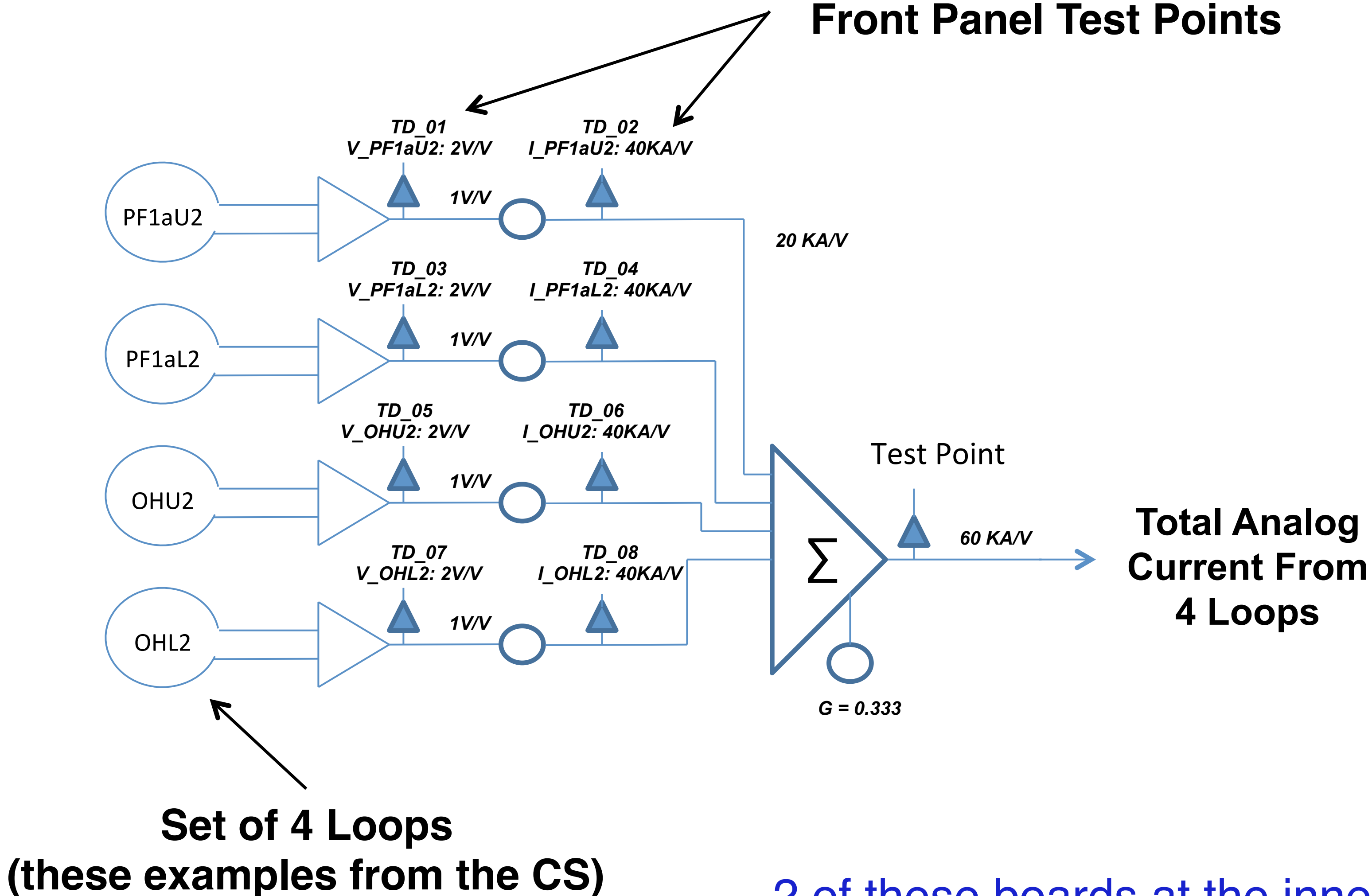


$V_{loop}=R_{segment}\times I_{Segment}$

D. Gates et al., Rev. Sci. Instrum

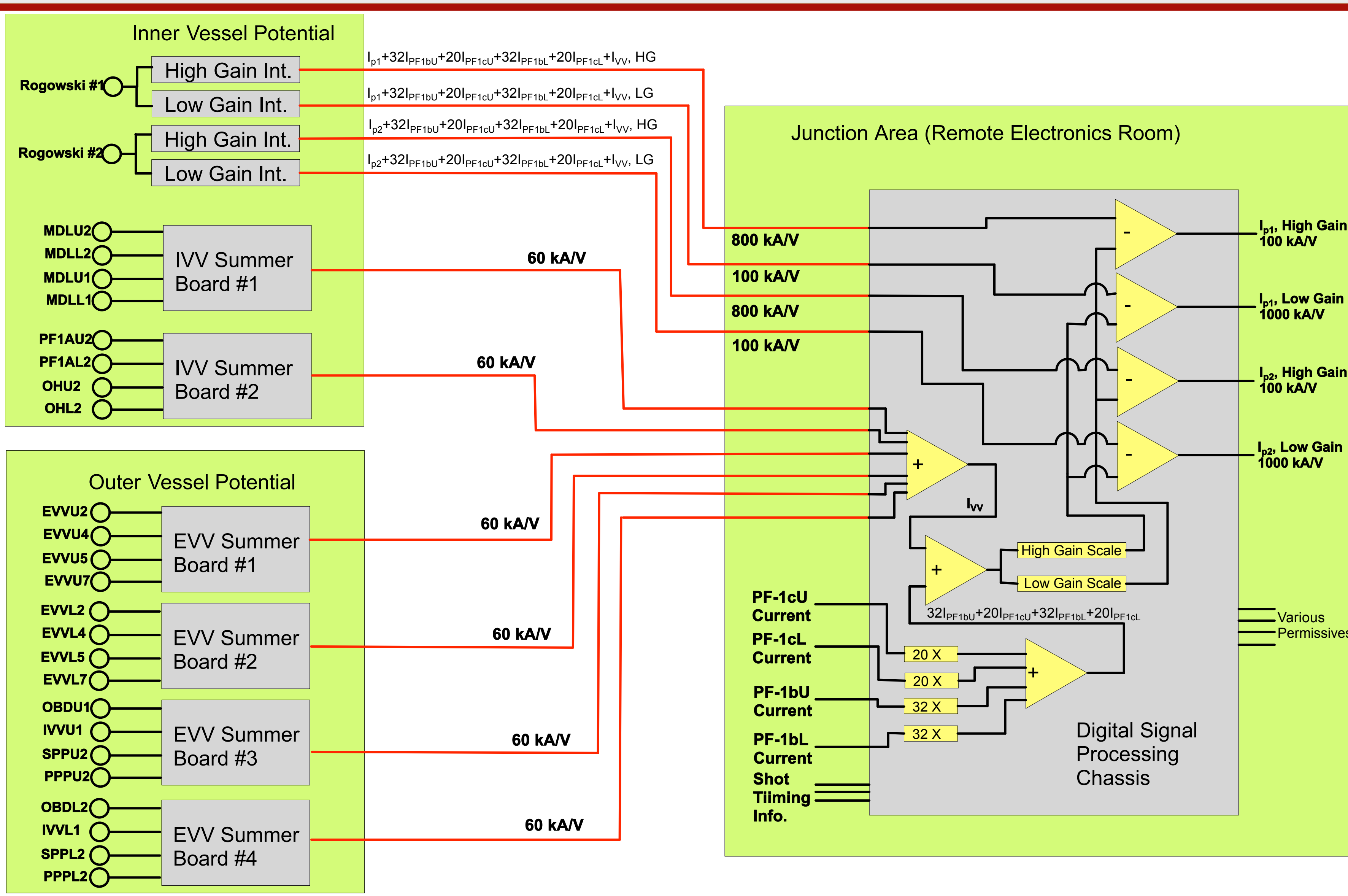


Standard Analog Circuit Board Sums The Currents From Sets of 4 Loops



2 of these boards at the inner-vessel potential, and 4 at outer-vessel potential

I_P Calculator Block Diagram
(there are released engineering versions, but those are way complicated)



Magnetics For Early Position Control

- "Early" = first ~90 ms of shot.
- Postulate that you know the poloidal flux and field at in-board and outboard midplane points.
- Taylor expansion of the flux on the outboard side:

$$\psi_{out}=\psi_{in}+2\pi R_{out} g_{out} B_{out}$$

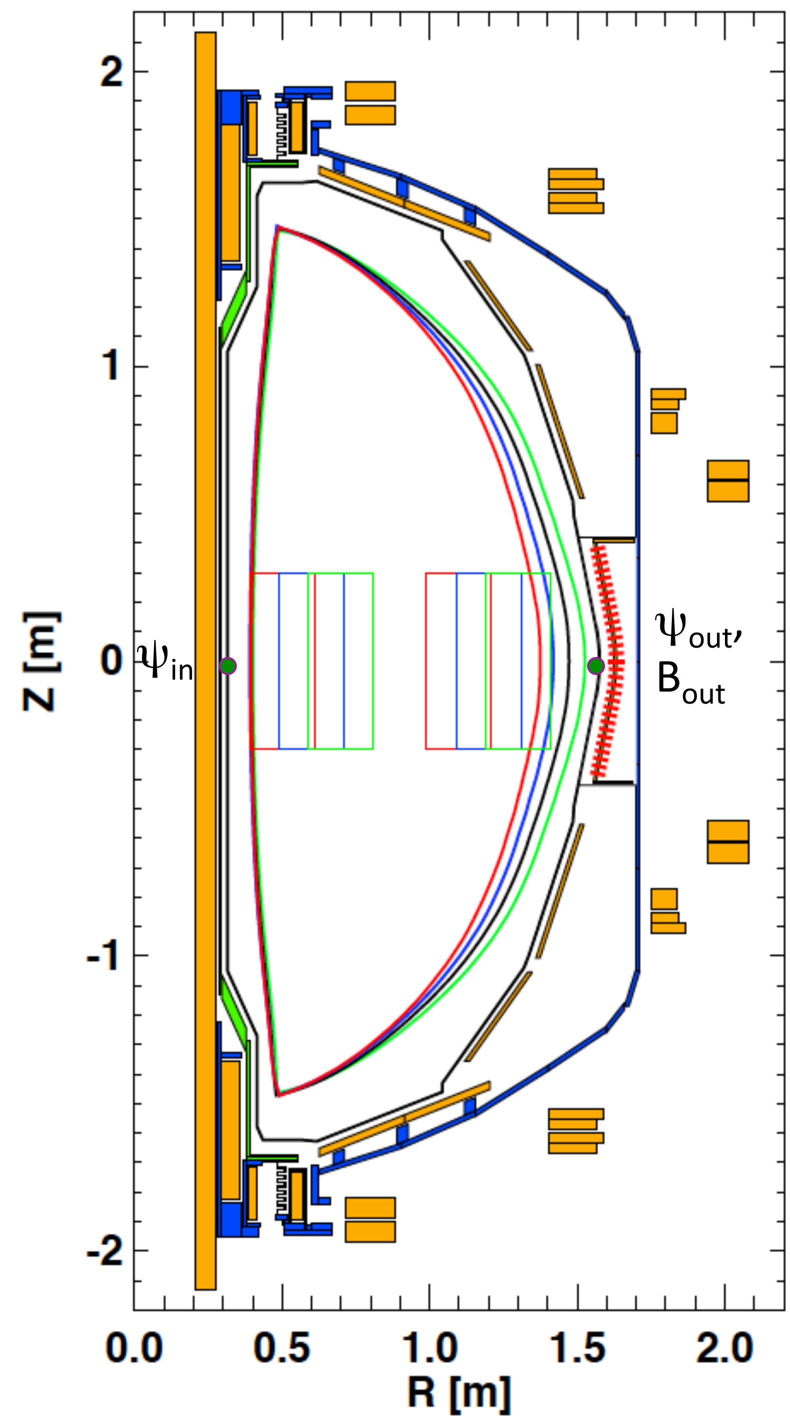
  - We neglect the small and uncontrollable inner gap
  - Note that g_{out} is a positive number in PCS
- Convert that to a control law for a given outer gap

$$\delta\psi=\psi_{out}-\psi_{in}-2\pi R_{out} g_{out} B_{out}$$

- And use this to adjust the PF-5 current

$$\delta I_{PF\text{-}5}=PID(\delta\psi)$$

- Actual algorithm has filters, other complications
- So how to we get ψ_{in}, ψ_{out}, B_{out}?



See D. Gates et al, Nuclear Fusion 46, 17 (2006)

Flux Quantities ψ_{in} and ψ_{out} are Based on a Weighted Sum of Flux Loops

$$\psi_{in}=\Sigma\gamma_i\psi_{hfs,i}$$

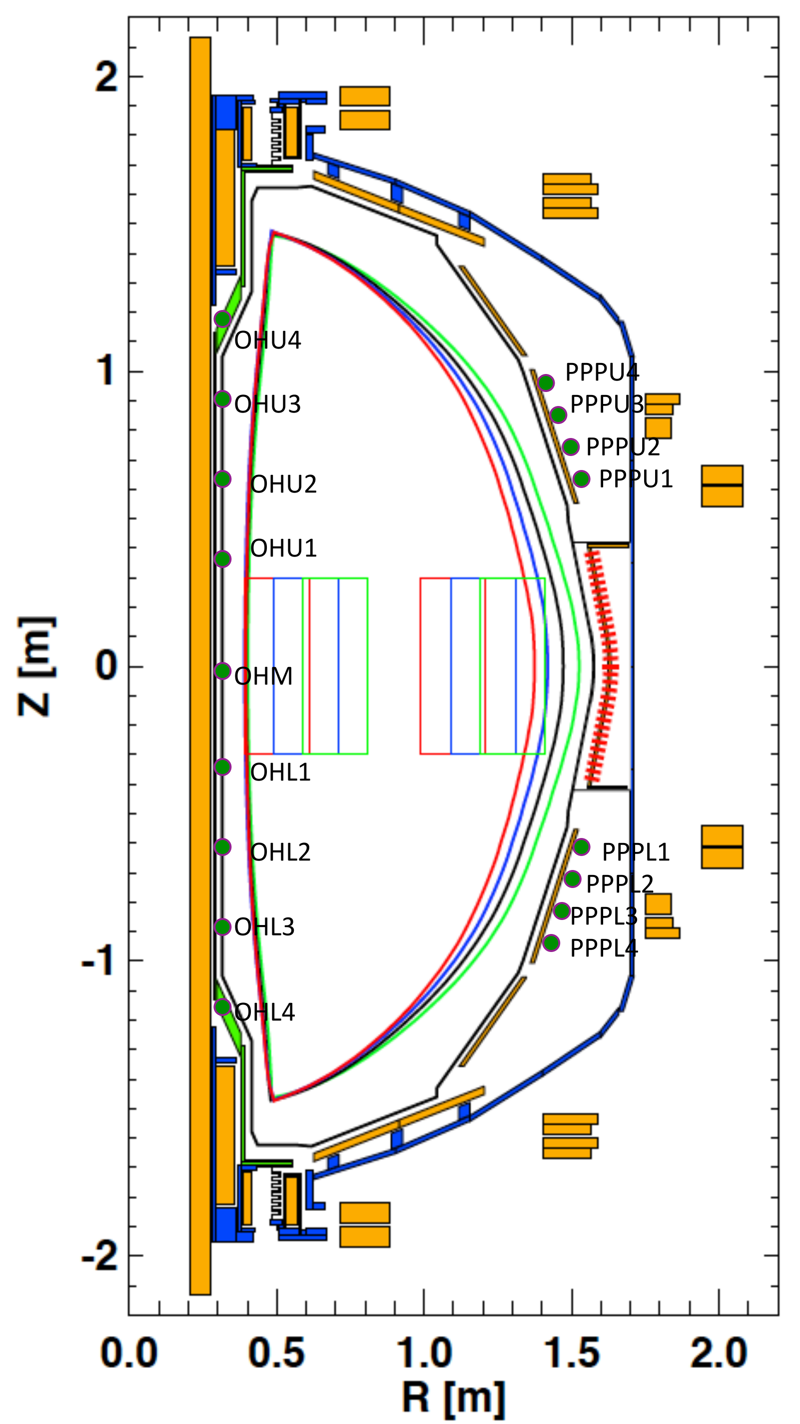
$$\psi_{hfs}=[\psi_{OHu4}, \psi_{OHu3},\ldots\psi_{OHM},\ldots\psi_{OHl3}, \psi_{OHl4}]$$

$$\psi_{out}=\Sigma\delta_i\psi_{lfs,i}$$

$$\psi_{lfs}=[\psi_{pppu4}, \psi_{pppu3},\ldots\psi_{pppu1}, \psi_{pppl1},\ldots\psi_{pppl3}, \psi_{pppl4}]$$

- Allows the user to change which loops are used for control, w/o having to recompile the code.
  - Arrays γ, δ are editable from the PCS GUI
- Software requires:

$$1=\Sigma\gamma_i \qquad 1=\Sigma\delta_i$$



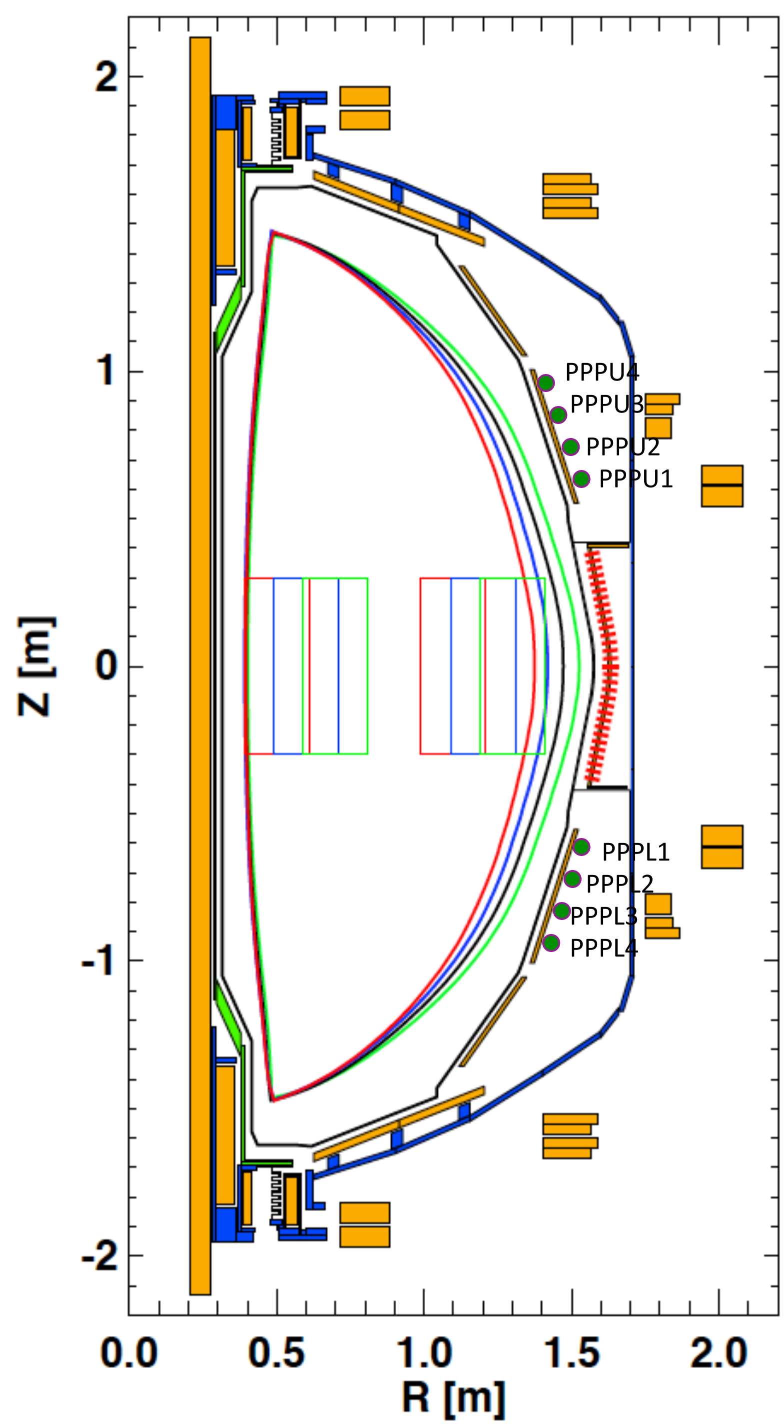
Field Quantity B_{out} Based on a Weighted Sum of Mirnov Sensors

$$B_{out}=\Sigma\beta_i B_{lfs,i}$$

$$B_{lfs}=[B_{pppu4}, B_{pppu3},\ldots B_{pppu1}, B_{pppl1},\ldots B_{pppl3}, B_{pppl4}]$$

- Allows the user to change which sensors are used for control, w/o having to recompile the code.
  - Array β is editable from the PCS GUI
- Software requires:

$$1=\Sigma\beta_i$$



Fast Vertical Position Feedback: Basic Idea

- Shape control algorithms are not fast enough to stabilize plasma against vertical instability… need a measure of the vertical velocity.
- Take the difference in flux between two up-dowr symmetric loops.
  - If the plasma is centered, then the flux difference will be zero!

$$\psi_U-\psi_L=0$$

  - If the plasma is off the midplane, then the flux difference wil be non-zero:

$$\psi_U-\psi_L=CI_PZ_P$$

- Velocity is the time derivative of position

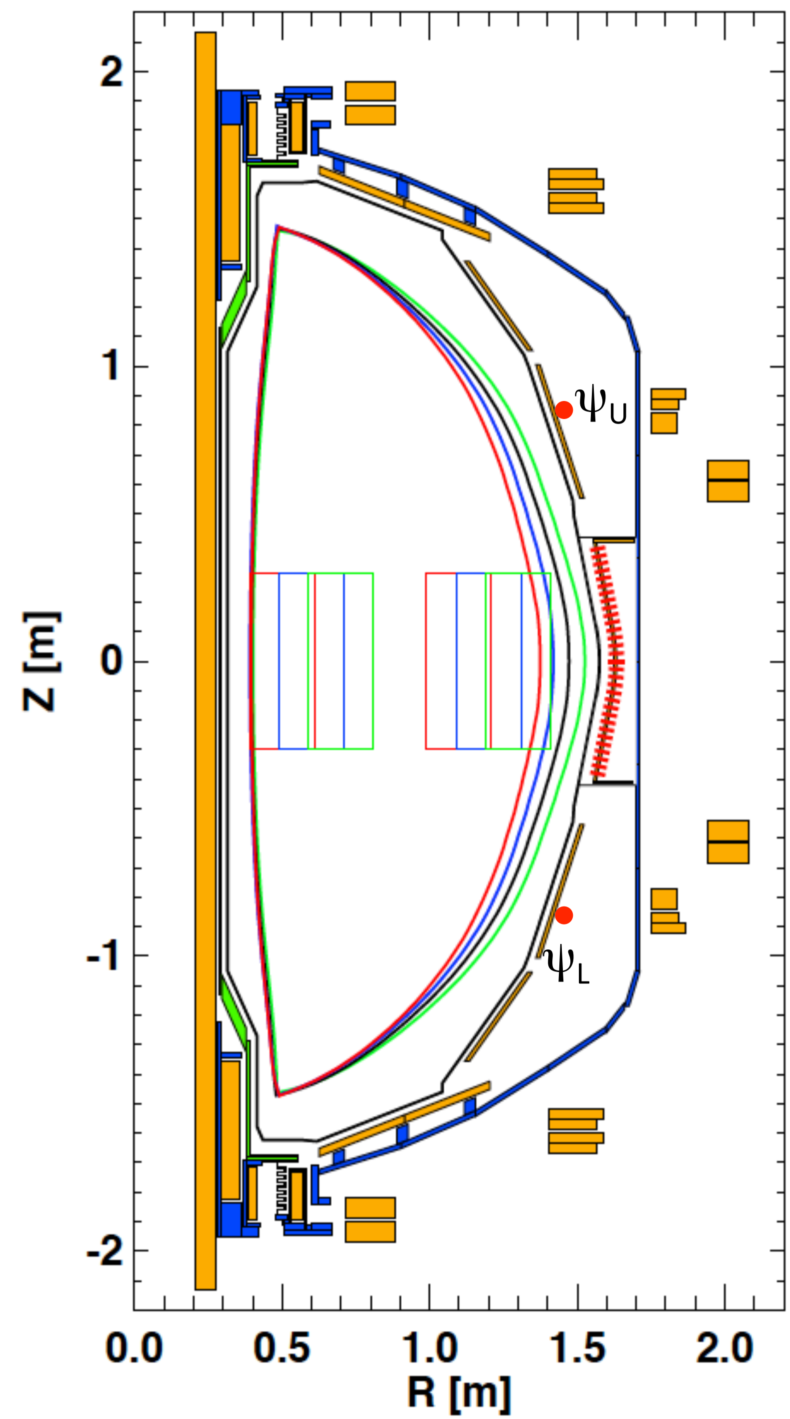
$$d\psi_U/dt-d\psi_L/dt=Cd(I_PZ_P)/dt$$

- Time derivative of a flux is a voltage, so for constant I_P:

$$dZ_P/dt \sim V_L-V_U$$

- Then you get the control law for the coil voltage request used on NSTX:

$$V_{PF-3U}=V_{PF-3U,shape} + P^*(V_L-V_U)$$
$$V_{PF-3L}=V_{PF-3L,shape} - P^*(V_L-V_U)$$



System on NSTX-U Uses 9 Voltage Difference Pairs

- 9 voltage difference pairs brought into the realtime system.
- Control law:

$$V_{PF\text{-}3U} = V_{PF\text{-}3U,shape} + Dd(I_P Z_P)/dt \ + P\delta\psi_V + Ix_{int}$$
$$V_{PF\text{-}3L} = V_{PF\text{-}3L,shape} - Dd(I_P Z_P)/dt \ - P\delta\psi_V - Ix_{int}$$

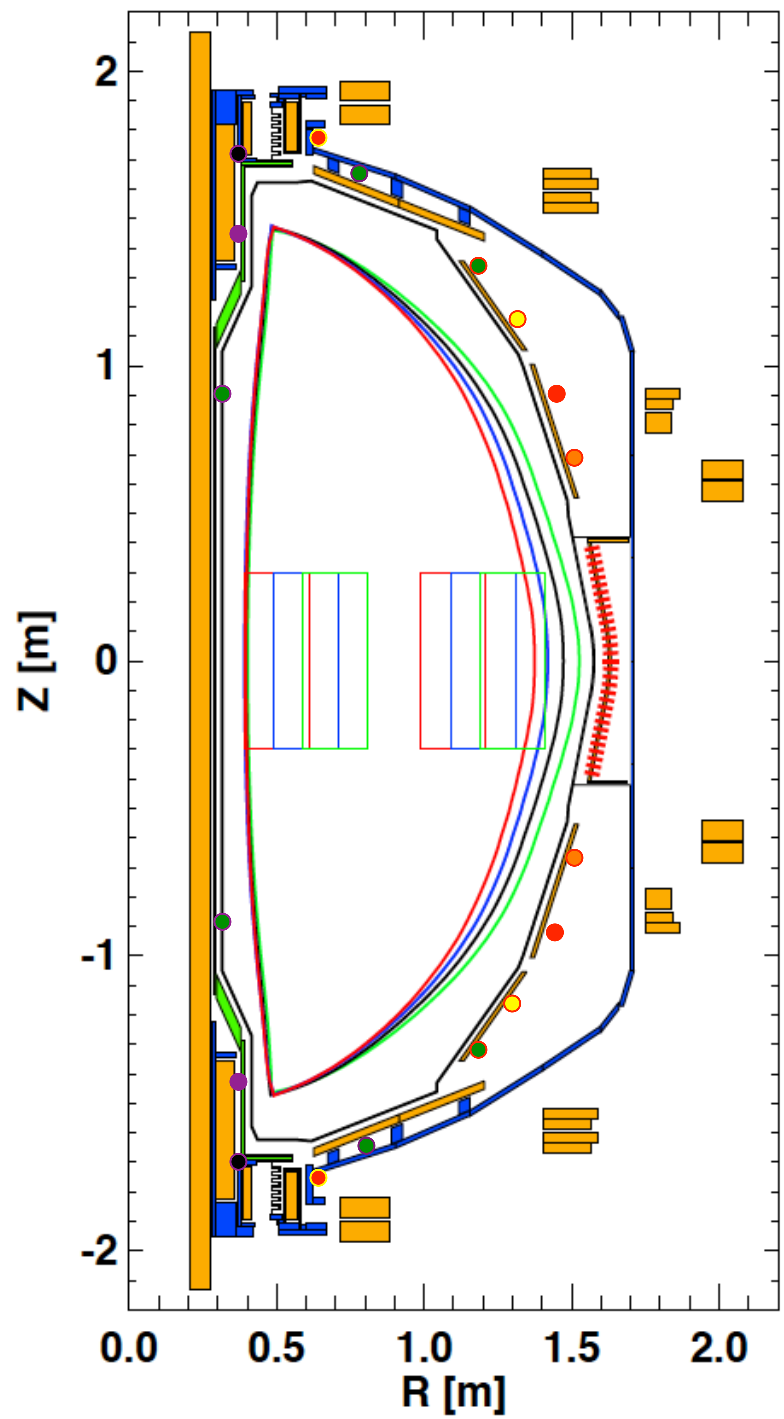
- Where the terms are

$$I_P Z_P = \Sigma\alpha_j(\psi_{UL,j} - \psi_{C,j})$$

$$\delta\psi V = I_P Z_{P,request} - I_P Z_P$$

$$d(I_P Z_P)/dt = \Sigma\alpha_j(V_{UL,j} - V_{C,j})$$

- The terms $y_{C,j}$ and $V_{C,j}$ are more sensor corrections based on coil currents and their time derivatives



Potential Magnetics Problems That Impact Plasma Control

- Individual sensor fails
  - May cause rtEFIT to behave oddly…check the χ^2.
    - Would be the case for Mirnov, flux loops, voltage loops
  - May cause vertical control to fail
    - Failed voltage loop.
  - Can cause errors in the plasma current measurements
    - Failed voltage loop
- Electronics failures
  - Full integrator crate fails (bad power supply, no trigger,…)
    - 12-24 signals will fail at once, operation with rtEFIT will fail catastrophically
  - Voltage difference amplifier fails
    - Vertical control will be fail.
  - Any electronics in the I_P calculator chain
    - FO TXs and RXs
    - DSPs in JA

Who's Who in the Magnetics

- For sensors, integrators, and basically the first level of troubleshooting: Stefan and Clayton
- For integrator hardware: Ed Lawson
- For the I_P calculator hardware: Bob Mozulay
- Realtime code: Keith Erickson
- Gap control algorithm: Devon Battaglia
- Vertical position algorithm: Dan Boyer