Introduction

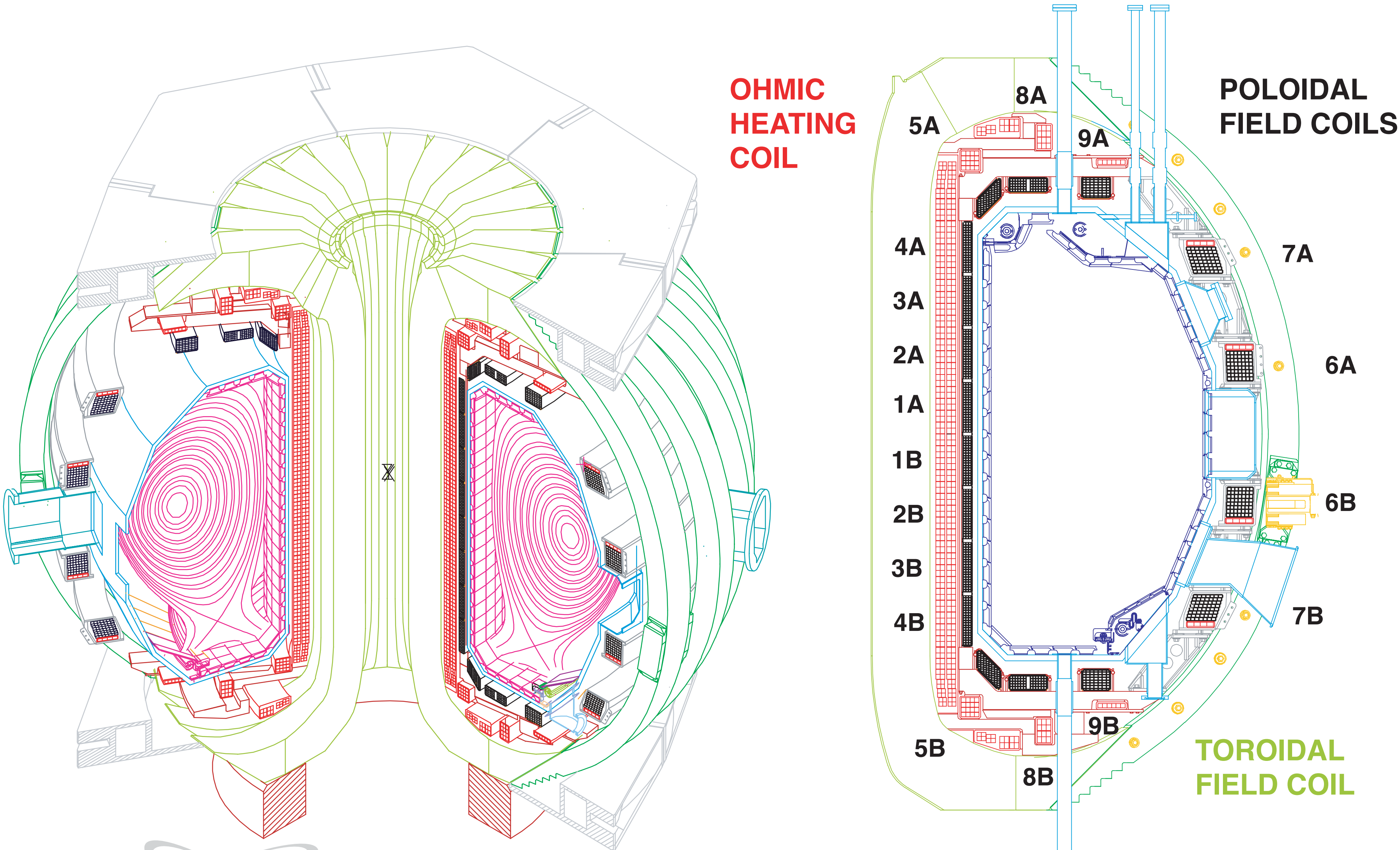
The "VFI Constraint" is a generic term used to describe the way DIII-D's Poloidal Field (PF) coils are configured in a way that provides (a) PF system safety, (b) an automatic minimization of PF coil currents consistent with the desired plasma shape, and (c) a hardware based reference flux constraint.

It is necessary to constrain the reference flux in DIII-D, though it is not in general necessary for all tokamaks. The difference is that the currents in DIII-D's extensive PF coil set can be specified to very effectively mimic an inductive current drive solenoid. The PF coil set can independently do both inductive drive and plasma shaping. The poloidal "reference flux" generated by the PF coils in Volt-secs measures the current drive done by the PF and must be specified. We show that the VFI constraint naturally sets the value of the reference flux for any given plasma shape, and sets it in such a way as to minimize the PF coil currents.

The hardware based VFI constraint is only one way to specify the reference flux. We discuss a software based constraint that specifies the reference flux in a way that provides more flexibility and a broader operating space while avoiding some of the problems that arise when the VFI constraint concept meets hardware limitations and less-than-perfect plasma control.

We show results from successful preliminary DIII-D operation utilizing a new software based constraint.

18 Poloidal Field Coils Shape The DIII-D Plasma



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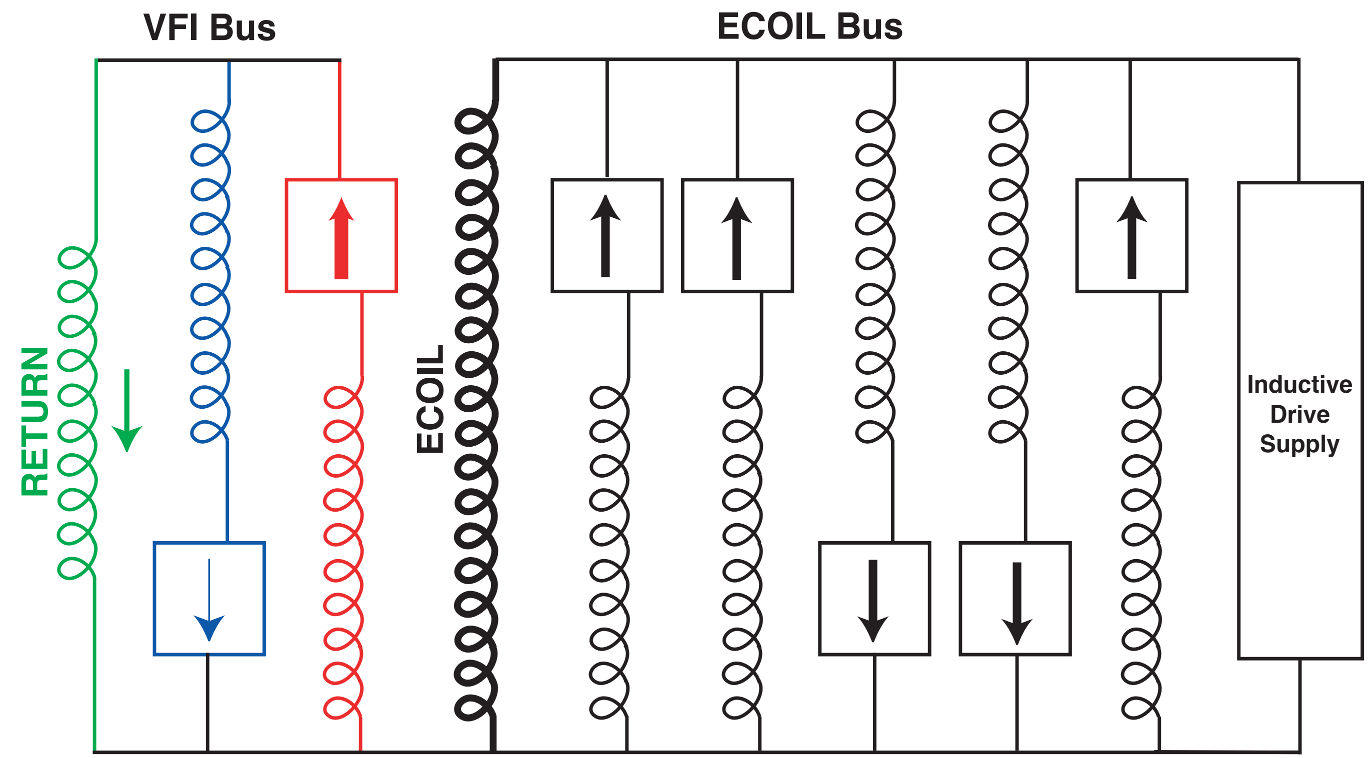
A Simplified Schematic Of The Hardware Based VFI Constraint

Each PF coil is closely coupled to the 12 V-s capable Inductive Drive coil (the 'ECOIL') with about equal mutual inductance. For safety reasons each PF coil MUST be connected across the Ecoil or a common 'VFI' bus. Connected this way potentially damaging inductively coupled Ecoil voltage can't drive current in any PF coil.

The RETURN current makes up the difference between total POSITIVE and NEGATIVE currents.

The PF supply driving the larger of the two currents (the 'dominant' supply) ALSO drives the RETURN current.



The PF coils' currents connected to the VFI bus MUST sum to zero. THIS IS THE VFI CONSTRAINT. One or more coils must be an uncontrolled RETURN coil.

Benefits of The VFI Constraint

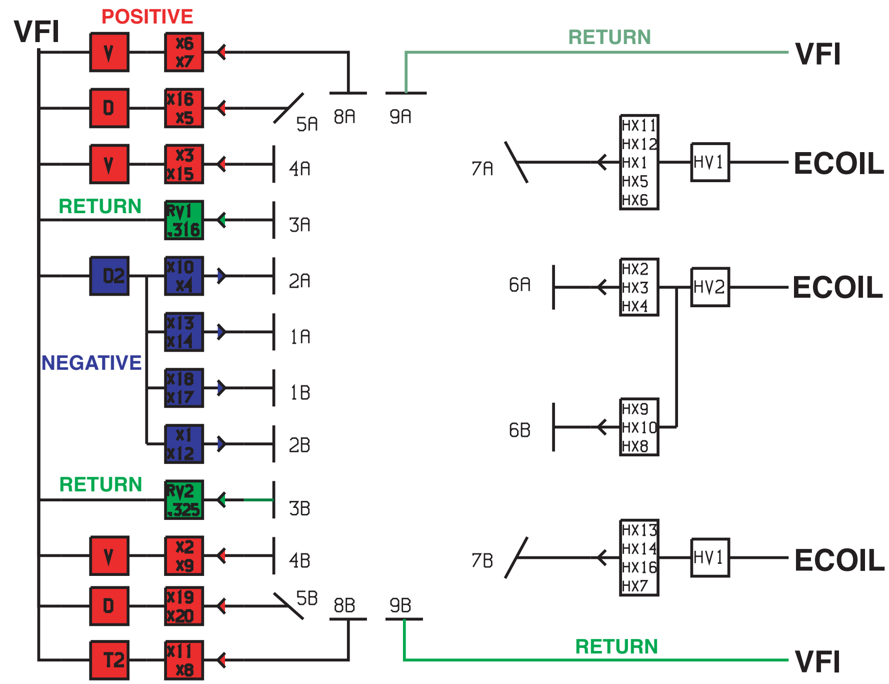
The VFI Constraint...

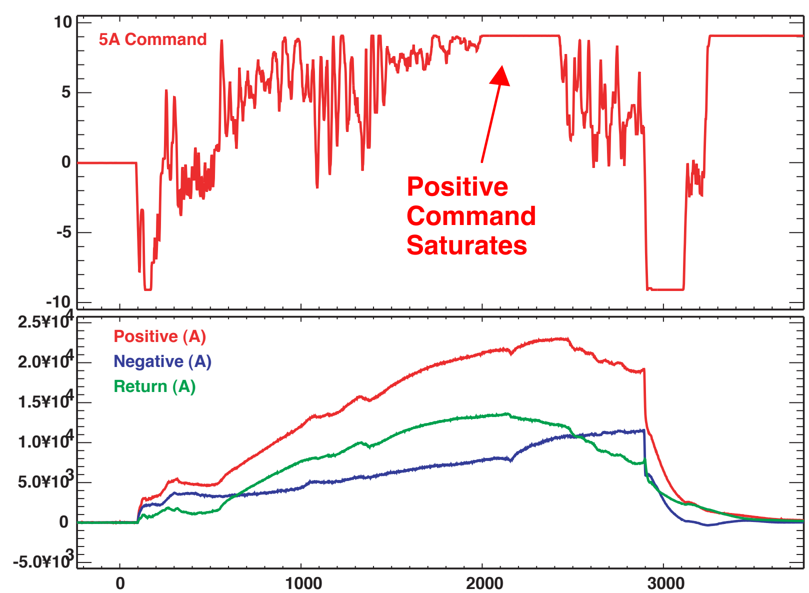
- **Provides PF system safety to off-normal Ohmic Heating Coil events.**
- **Supplies the additional constraint necessary to specify the PF coil currents.**
- **Forces equal positive and negative currents which tends to minimize the PF coil currents.**
- **Minimizes the number of PF supplies needed by driving the return coils' current without requiring dedicated PF supplies. This reduces the number of PF supplies needed, but requires some of them to have extra voltage capability.**

Problem: Saturated PF Supply Voltage Degrades Control

- **PF supply voltages can saturate trying to drive a large amount of return current.**

In the example at right the positive PF currents dominate the negative PF currents so the positive PFs also drive the return current in series. When the return current gets large enough the positive PF supply voltages saturate, and no more current can be driven. At this point shape control degrades.

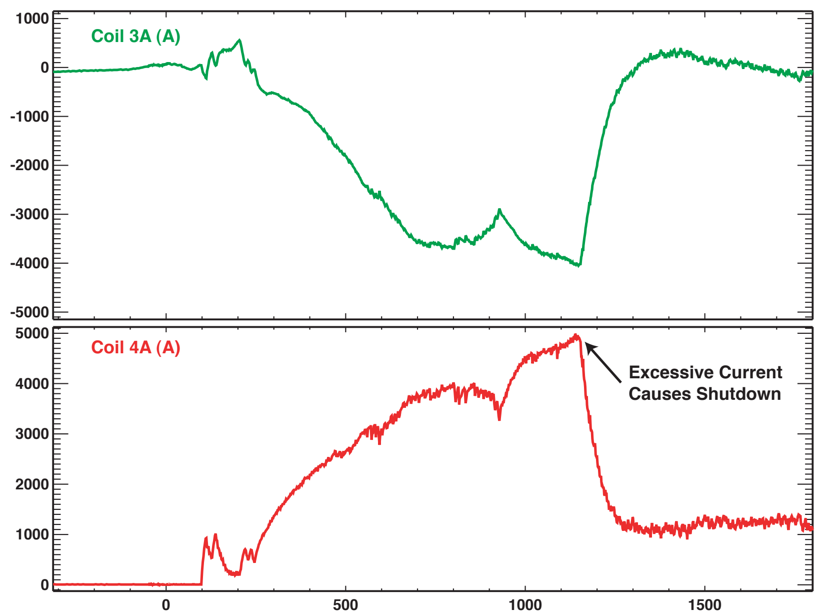


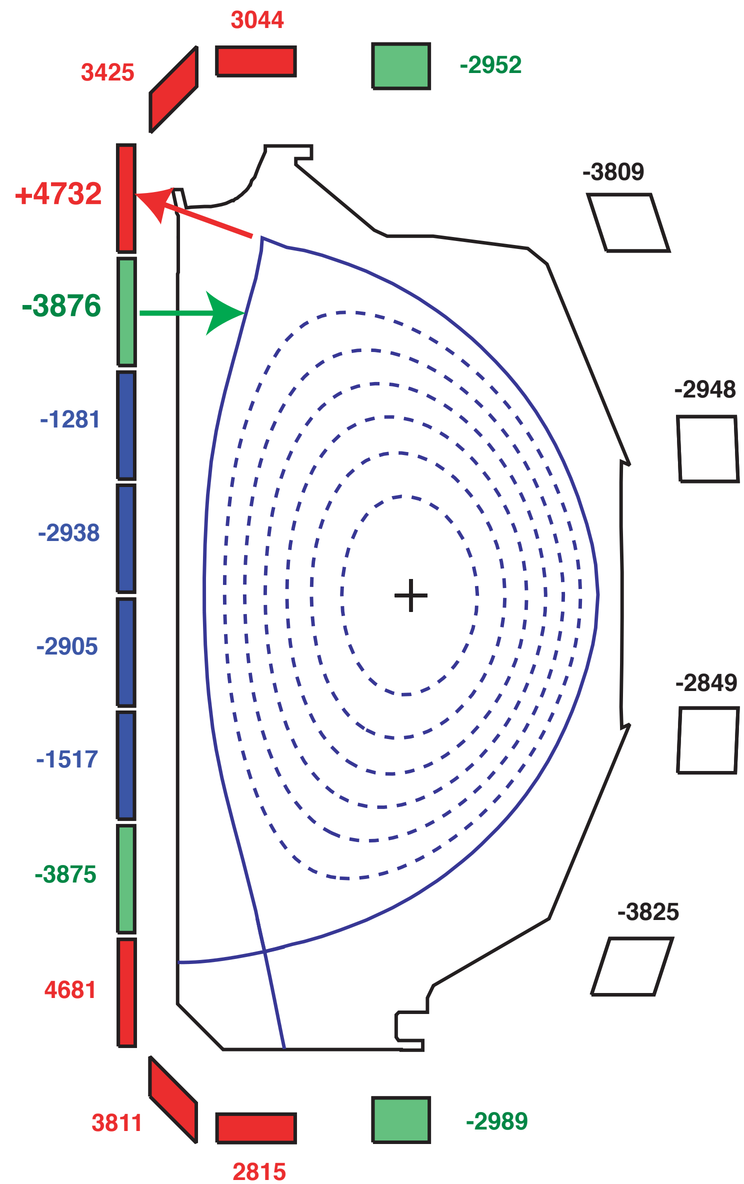


VFI Problem: Local Recirculating Current Instability

- **A return current coil next to a dominant current coil can cause a positive feedback loop that ends with command saturation or coil overcurrent shutdown.**

  This is the case here, where the dominant 4 coils drive more and more return current in the 3 coils.

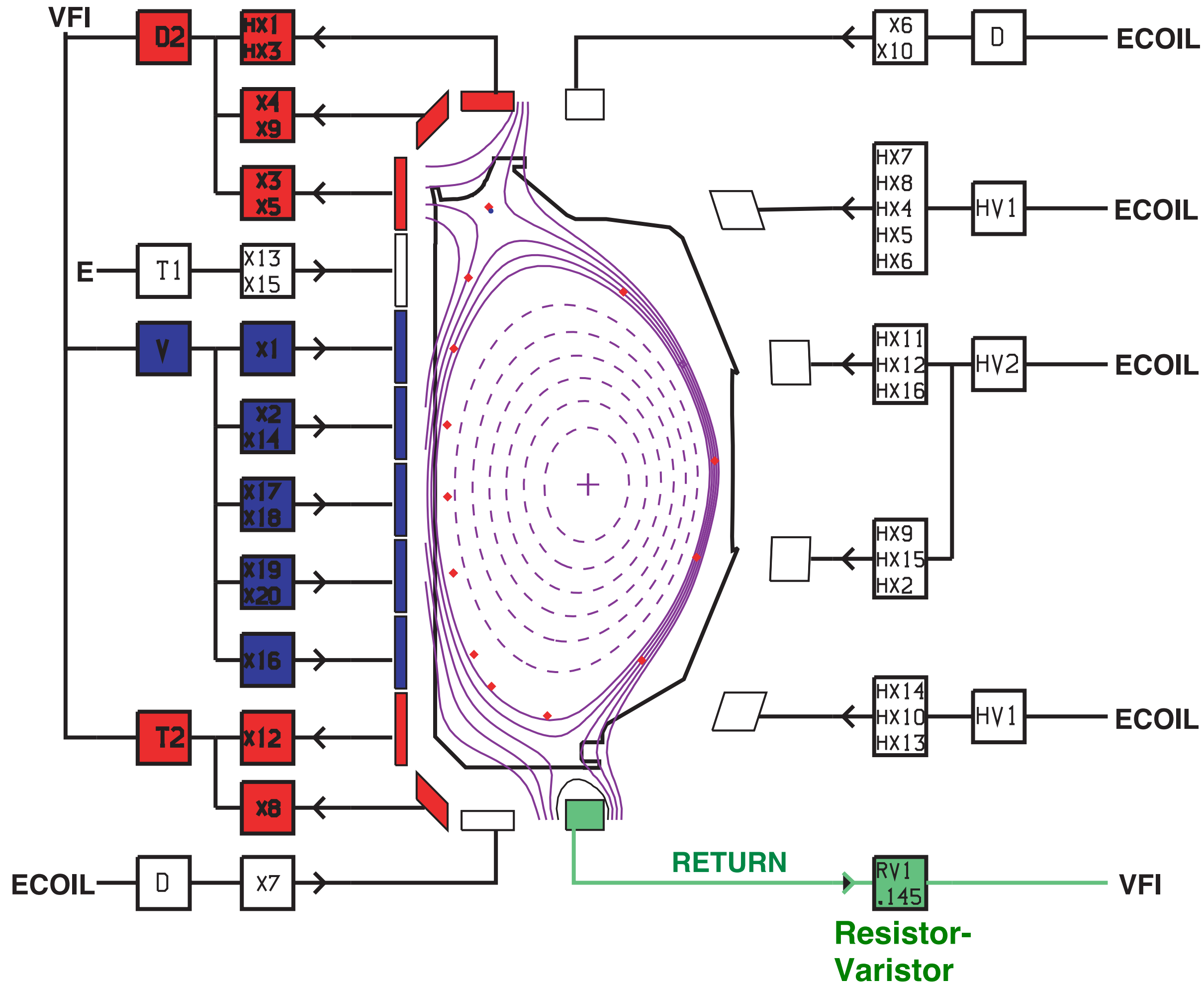




VFI Problems Lead To Decreased Productivity

- **The wrong choice of VFI configuration for the desired shape and plasma parameters together with a non-ideal control system can lead to extended experiment development time and loss of productivity.**

In the extreme example shown at right the sole return coil is connected in series with a resistor-varistor. This combination raises the VFI voltage too far. The inner coils saturate, the plasma limits on the inner wall, and the control system loses track of the plasma boundary flux. A different VFI configuration was needed to make the shape.



Defining The Reference Flux, ψ_V And The Shaping Flux, ψ_S

First consider any tokamak and its set of PF coils. These PF coils produce the poloidal flux, $\psi_{PF}(R,Z)$, that hold the plasma in equilibrium in shape S.

$\psi_{PF}(R,Z)$ can always be broken into two parts:

$\psi_V = \psi_{PF}(R,Z)$ averaged over the plasma cross-section, and

$\psi_S(R,Z)$, the remainder:

$$\psi_{PF}(R,Z) = \psi_S(R,Z) + \psi_V$$

ψ_V can't contribute to plasma shaping since it is spatially uniform, so it generates no poloidal magnetic field components $B_R = -\partial_Z\psi_V = 0$ and $B_Z = \partial_R\psi_V = 0$. ψ_V only drives plasma current and is termed the 'Reference Flux'. All shaping is done by $\psi_S(R,Z)$. The average value of ψ_S over the plasma cross-section is zero.

In DIII-D, ψ_V Is Independent Of ψ_S

- **The PF coil set in DIII-D has sufficient flexibility to produce a [nearly] uniform $\psi_{PF}(R,Z)$ across the plasma cross-section.**

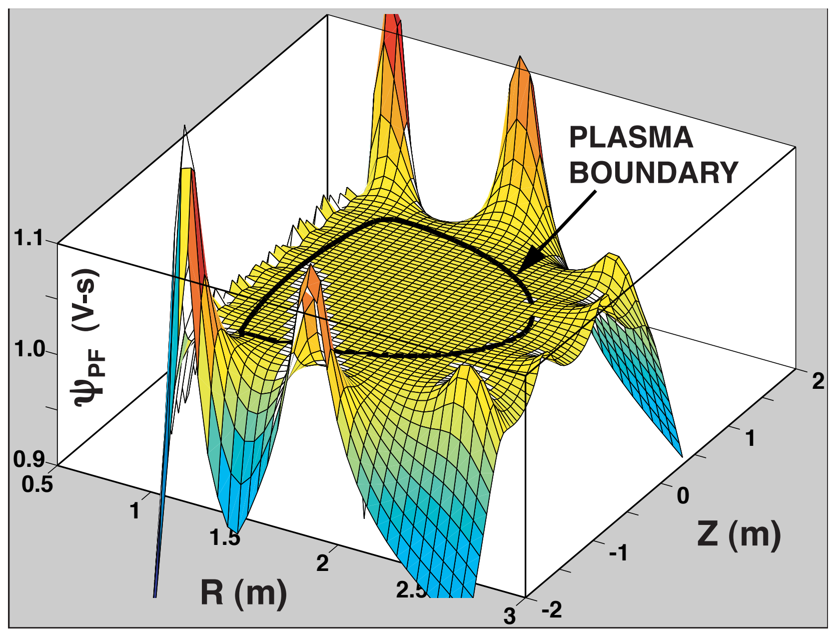
DIII-D's coil set is sufficiently flexible so that the flux $\psi_{PF}(R,Z; \vec{f}_V)$ generated by an appropriate PF coil current distribution $\vec{f}_V$ is uniform over the plasma cross-section to good enough approximation that the residual deviations are insignificant to shaping control. $\vec{f}_V$ is an eighteen element vector of PF coil currents. So $\psi_{PF}(R,Z; \vec{f}_V) \cong$ Const $= \psi_V$

$\vec{f}_V$ is additive with $\vec{f}_S$, the current distribution that generates the plasma shaping flux ψ_S. Denoting the total PF coil current distribution as the vector $\vec{f}$

Total PF current: $\vec{f} = \vec{f}_V + \vec{f}_S$

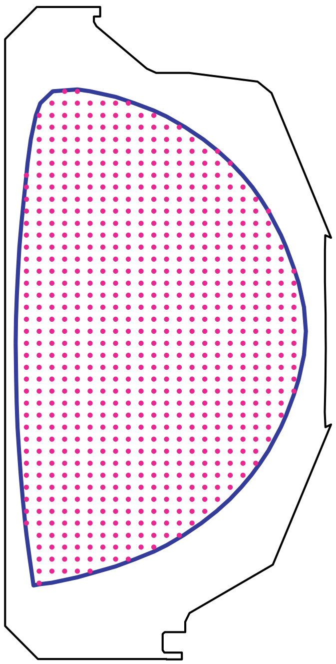
$$\psi_{PF}(R,Z; \vec{f}) = \psi_V(\vec{f}_V) + \psi_S(R,Z; \vec{f}_S)$$

Nearly Uniform ψ_{PF} = 1.0 V-s Over Plasma Cross-section



The Reference Flux Current Distribution $\vec{f}_V$

Consider a regular grid of N points located inside the plasma boundary.



At any point R, Z on the grid

$$\psi_{PF}(R,Z) = \sum_{PF} G_i\,(R,Z)\,f_i$$

where $G_i\,(R,Z)$ is the i[th] PF coil Green's Function flux response at grid location R,Z

The vector equation for all grid points is

$$\vec{\psi}_{PF} = \overleftrightarrow{G}_N \bullet \vec{f}$$

$\overleftrightarrow{G}_N$ is the N x 18 element flux response matrix, $\vec{f}$ is the 18 element PF current vector and $\vec{\psi}_{PF}$ is the N element flux vector

We find $\vec{f}_V$ from this overdetermined equation for a uniform $\vec{\psi}_{PF} = \psi_V \vec{1}$ using Singular Value Decomposition (SVD) to calculate $\overleftrightarrow{G}_N^{-1}$.

$$\vec{f}_V = \psi_V \overleftrightarrow{G}_N^{-1} \bullet \vec{1}$$

$$\boxed{\vec{f}_V = \psi_V \vec{\alpha}}$$

Let $\vec{\alpha}_N = \overleftrightarrow{G}_N^{-1} \bullet \vec{1}$ and let $N \rightarrow \infty$

note $\vec{\alpha} = \vec{\alpha}_{N \rightarrow \infty}$ is determined by PF coil set geometry and the plasma boundary.

The VFI Constraint Sets The Reference Flux

Summing over all coils on the VFI bus, The VFI constraint is

$$0 = \sum_{VFI} f_i = \sum_{VFI} f_{Vi} + \sum_{VFI} f_{Si}$$

The reference flux current distribution elements f_{Vj} are simply given by

$$f_{Vj} = \psi_V \alpha_j \quad \text{so} \quad 0 = \psi_V \sum_{VFI} \alpha_i + \sum_{VFI} f_{Si}$$

Then the VFI constraint can be rewritten as

$$0 = \psi_V + F_\alpha(VFI) \sum^{VFI} f_{Si}$$

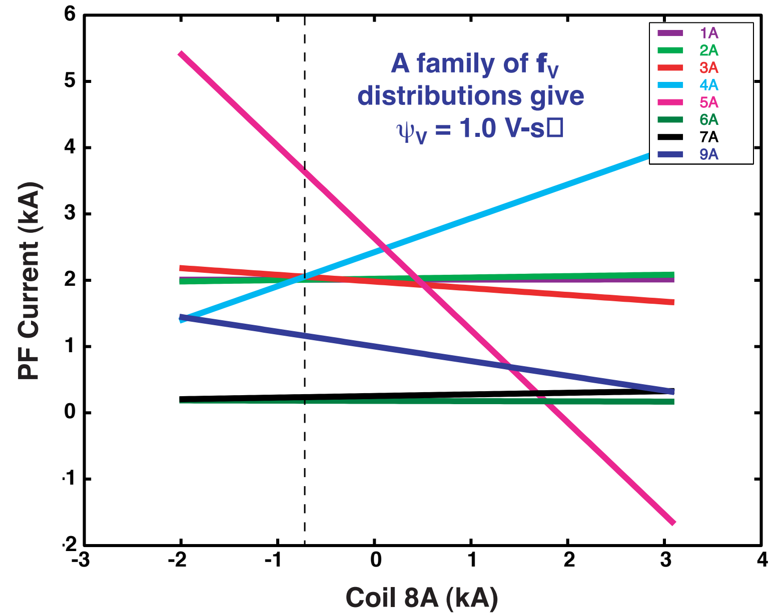
where the discrete function $F_\alpha(VFI) = (\sum_{VFI} \alpha_j)^{-1}$ is fixed by the subset of PF coils on the VFI bus, and the sum of shaping currents $\sum_{VFI} f_{Si}$ is fixed by the plasma's shape and parameters

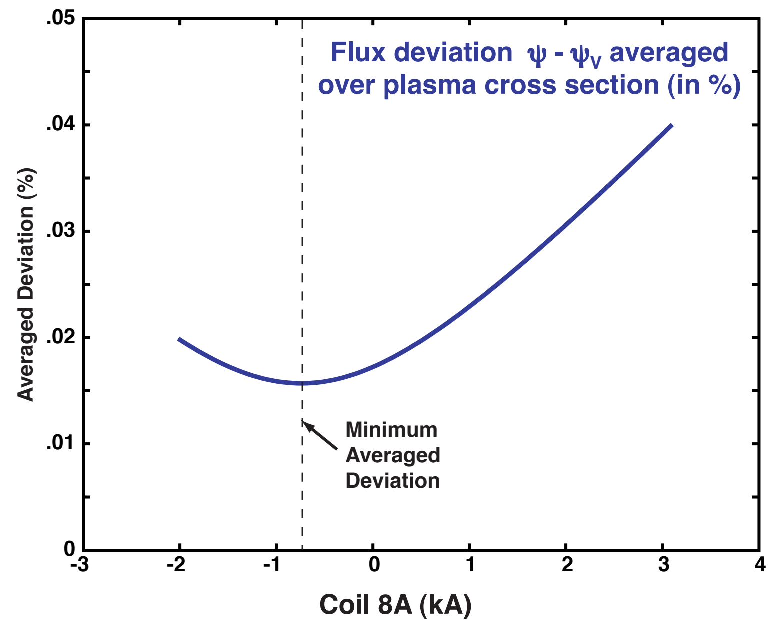
The VFI constraint then just sets ψ_V to counter the summed shaping currents.

The Current Distribution $\vec{f}_V$ That Generates ψ_V is NOT Unique

Uniform flux ψ can be produced with a broad family of PF current distributions.

Choose one PF coil and vary its current while solving the inverse equation $\vec{f}_V = \vec{\psi}_V \overleftrightarrow{G}^{-1}_N \cdot (1 - \vec{\delta})$ except $\vec{f}_V$ is now reduced to a 17 element vector with $\vec{\delta}$ the flux response of a <u>fixed current</u> PF coil. Also calculate the average flux deviation from uniformity over the plasma cross-section.





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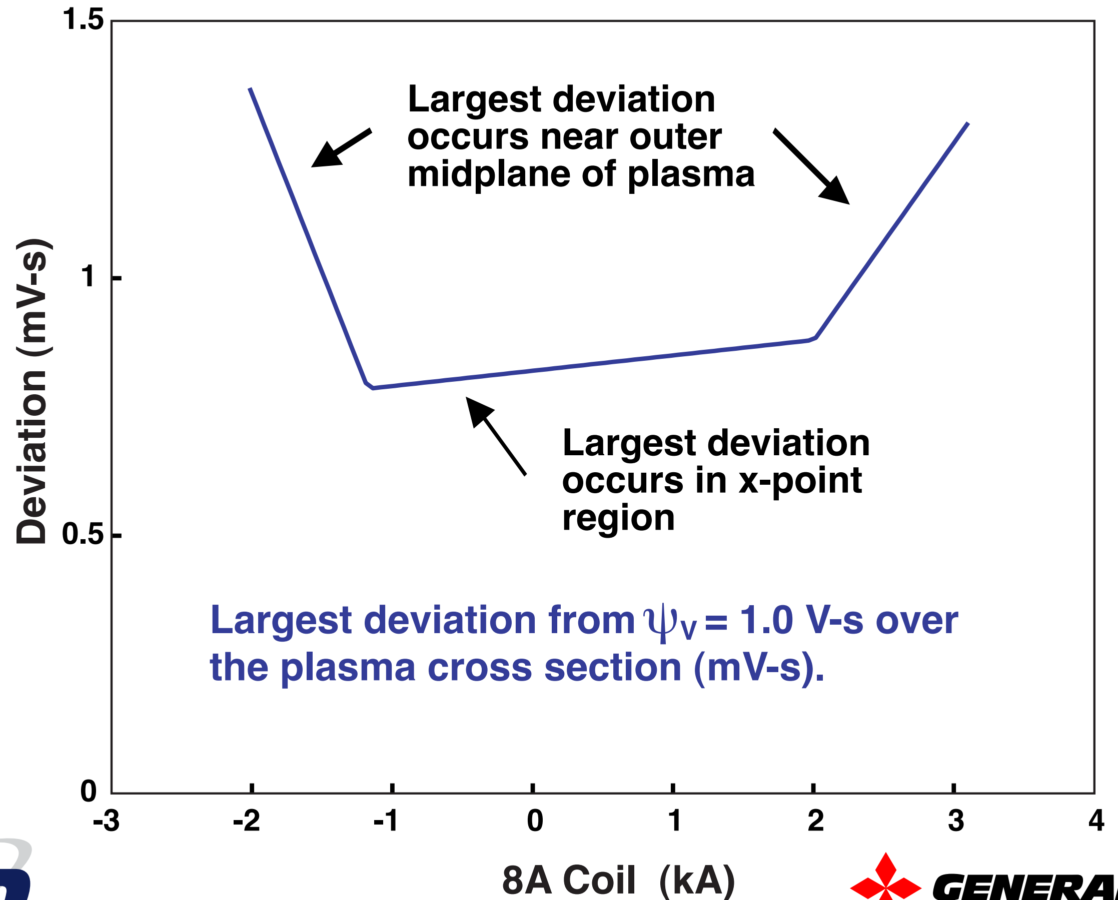
The Largest Deviation Over the Plasma Cross-section Is Small For A Large Spread In 8A Coil Current

The 8A coil current can be varied by kiloamps and still maintain the same ψ_V with essentially uniform flux over the plasma cross-section. The abrupt change in slope for the worst case deviation occur as the worst case location moves from the outer midplane region of the plasma boundary to the x-point region.



A Software Based Constraint That Specifies ψ_V

1. Connect ALL PF coils across the Ecoil and power/control them.

2. Choose one coil to act as the analog of the VFI's 'unpowered' coil and drive it with one of the following error signals:

Specify ψ_{REF} directly: $\text{Error} = \psi_V - \psi_{REF} = \Sigma\gamma_j f_j - \psi_{REF}$

Specify a VFI-like current sum: $\text{Error} = \Sigma f_j - \text{Const}$

Specify the chosen coil's current: $\text{Error} = f_C - f_{REF}$

The coefficients γ_j are calculated from proper averaging of the j^{th} coil's Green function responses on the grid. The coefficients γ_j are precalculated using the plasma cross section. (In practice it is easier to precalculate γ_j using the limiter cross section. This method calculates ψ_V to better than 1% and can be used for any plasma.)

HOW IT WORKS: Driving one coil to produce a current NOT specified by the shape forces the Plasma Control System to drive all other coils with currents compatible with the desired shape and required reference flux. This is exactly what the system does with the VFI constraint: coils are controlled to make the desired shape compatible with the current in the 'Return' coil, which specifies the reference flux ψ_V.

Benefits And Costs Of A Software-Based ψ_V Constraint

- Eliminate VFI voltage induced PCS nonlinearities (command saturation) for better shape control over a wider range of shapes/parameters during a shot.
- Increased operational productivity - eliminate stops to change an inappropriate VFI configuration. More good shots over the course of a year. Should reduce the learning curve for creating new shapes.
- Possibly relieve specific coil current limitations by adjusting ψ_V up or down. A little bit wider range of plasma shapes/parameters become available.
- Increase pulse length capabilities of PF supplies by operating at lower voltages.
- In general requires more PF supplies, though at lower voltage capability.
- It will take a while to recalibrate physics operations' intuition, so productivity may initially drop.
- Some uses may require a couple of 4 quadrant PF supplies; they are more expensive.
- Another feedback loop may introduce new control instabilities.

Initial Software-Based Operation at DIII-D

A simple VFI-like constraint (Error = Σf_j - Const) was tried in DIII-D in 1997. A simple plasma control algorithm using ratios of fluxes measured at PF coil locations was used to control a Double Null Divertor plasma. This attempt clearly showed operation with a software based constraint is possible. But it also lead to questions that eventually revealed that a broad family of PF current distributions can lead to approximately the same shape but very different total current distributions.

What we learned

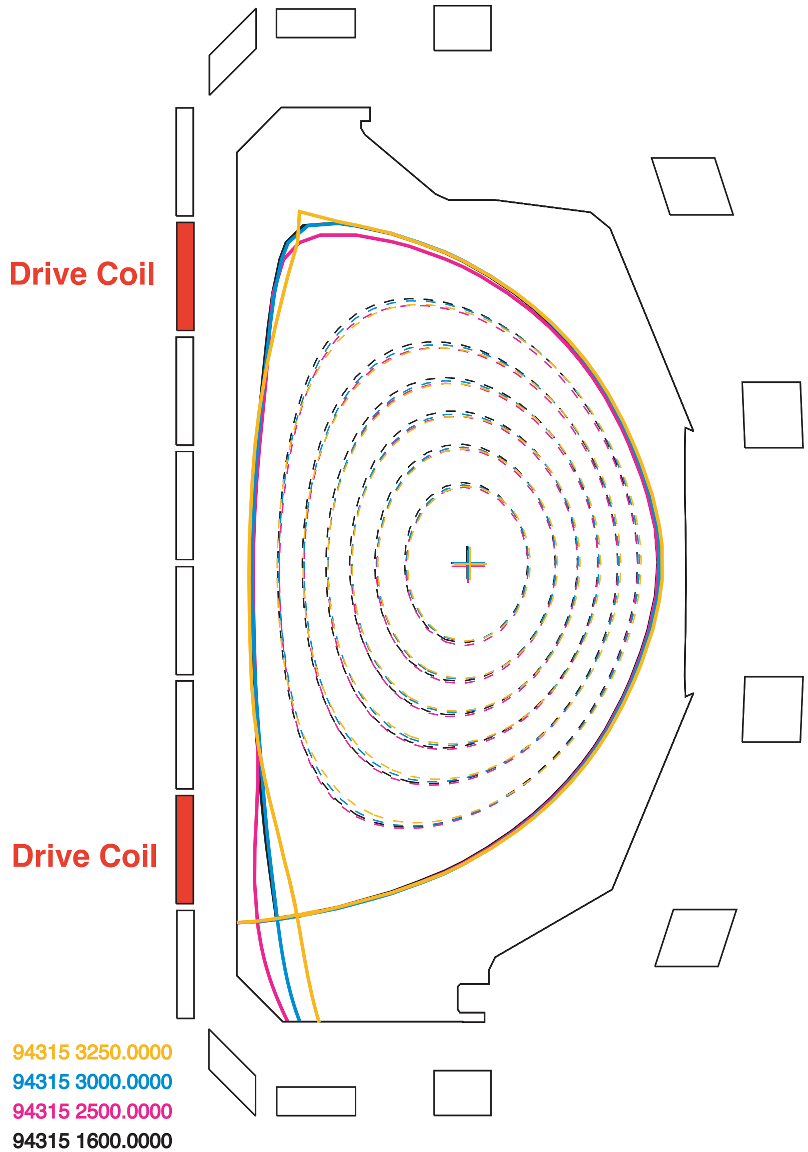
- **Shape control can be maintained while ψ_V is controlled and varied. Shot termination was due to exceeding the 'Return analog' drive coil's PF current limitations while changing the regulated VFI-like constraint.**

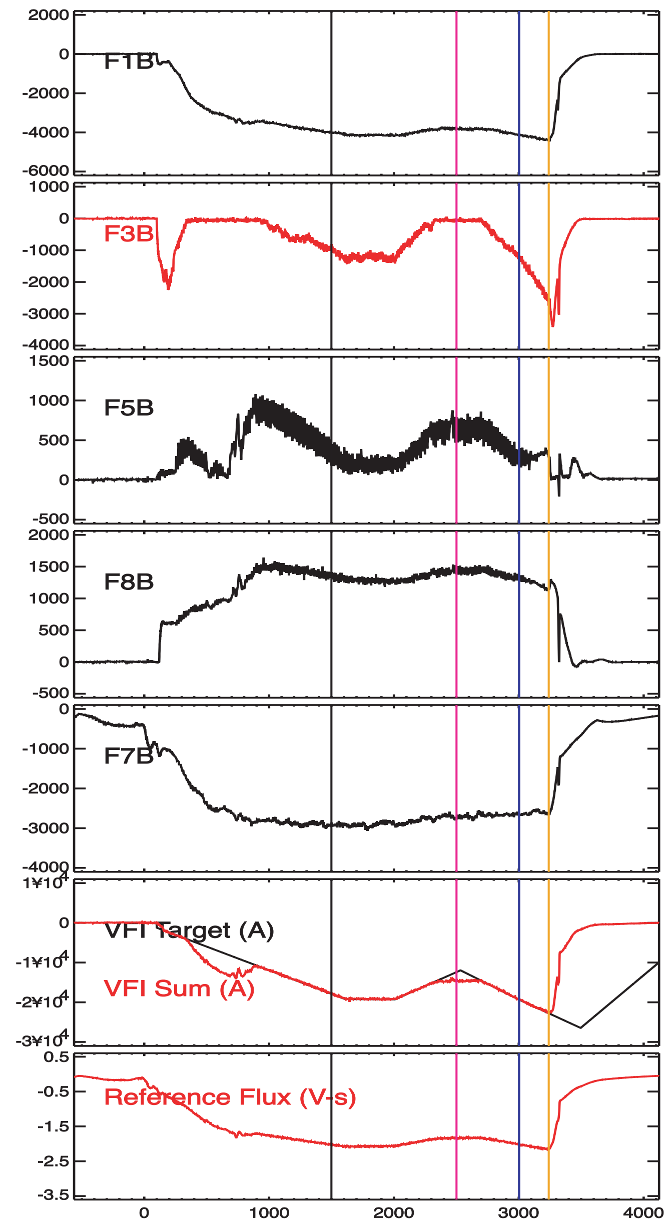
- **If the Return analog drive coil current goes to zero the rest of the coils may display some current drift. Small or zero current in the drive coil means the plasma shape can't 'feel' it's effect. To the plasma control system that coil doesn't exist, so the reference flux is no longer specified.**

- **The simple flux ratio control we used is NOT ideal in this application as it depends on fluxes and their ratios as measured very close to the PF coils. The more sophisticated equilibrium reconstruction based ISOFLUX control essentially measures flux on the plasma boundary and should work well.**

Initial Software-Based Operation Demonstrates ψ_V Control

All Coils Connected Across The Ecoil





Conclusions

The hardware based VFI constraint provides a necessary reference flux constraint, but PF supply limitations and interactions with a non-ideal plasma control system sometimes lead to undesired effects. Understanding and correcting these effects in the control room can impact productivity by extending physics operations' learning curve for a given experiment.

A software based reference flux constraint can eliminate some of the problems caused by PF supply limitations and still effectively set the reference flux, but at the cost of additional PF supplies. Software based reference flux control promises increases in productivity, but there are at present unknowns, such as newly introduced control instabilities.

In addition, software based reference flux control offers a wider range of plasma parameters and shapes by utilizing flexible control of the reference flux to relieve hardware limitations.

Initial DIII-D operation utilizing one form of software based reference flux constraint has been tried in a limited manner with some success, but more work is needed to resolve remaining questions and problems.