Agenda

- Motivation & Background for XP-1106
- Summary of XMP-77 (n=0 Control Software Checkout)
- XP-1106 shot list
- Summary of XMP-72 (RWM Control Software Checkout)

Supported by U.S. DEPARTMENT OF ENERGY Office of Science

NSTX

Development of Improved Vertical Position Control

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Colorado Sch Mines
Columbia U
CompX
General Atomics
INL
Johns Hopkins U
LANL
LLNL
Lodestar
MIT
Nova Photonics
New York U
Old Dominion U
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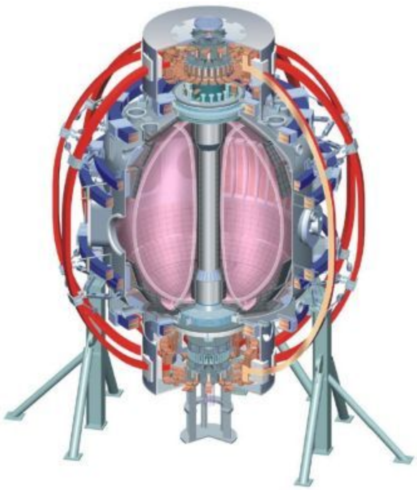
NSTX Team Review



Culham Sci Ctr
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U Quebec

Strategy To Improve Vertical Position Control

- Improve the detection of small vertical motion.
  - "dZ/dt Observer"

- Utilize improved observer in optimization of control with PF-3 as the actuator.

- Utilize improved observer in optimization of control with the RWM coils as the actuator.

- From group review…E. Kolemen examined the problem for improvements to the underlying architecture of the controller.
  - Found that there were no simple ways to improve control, due to the somewhat nonstandard coupling of ISOFLUX & Z_P control.

Vertical Position Controller is a PD Controller Using Loop Voltages for dZ/dt Measurement

- Proportional controller is simply the Isoflux shape control algorithm:

$$V_{PF-3,P} = M \times PID(\text{segment error})$$

- Fast derivative controller is based on the up-down loop voltage difference.

$$V_{PF-3,D} = D \times \left(\dot{\psi}_{Upper-Loop} - \dot{\psi}_{Lower-Loop}\right)$$

- The underlying assumption is that the plasma vertical position can be measured by only 2 loops:

$$I_P Z_P = C \times \left(\psi_{Upper-Loop} - \psi_{Lower-Loop}\right)$$

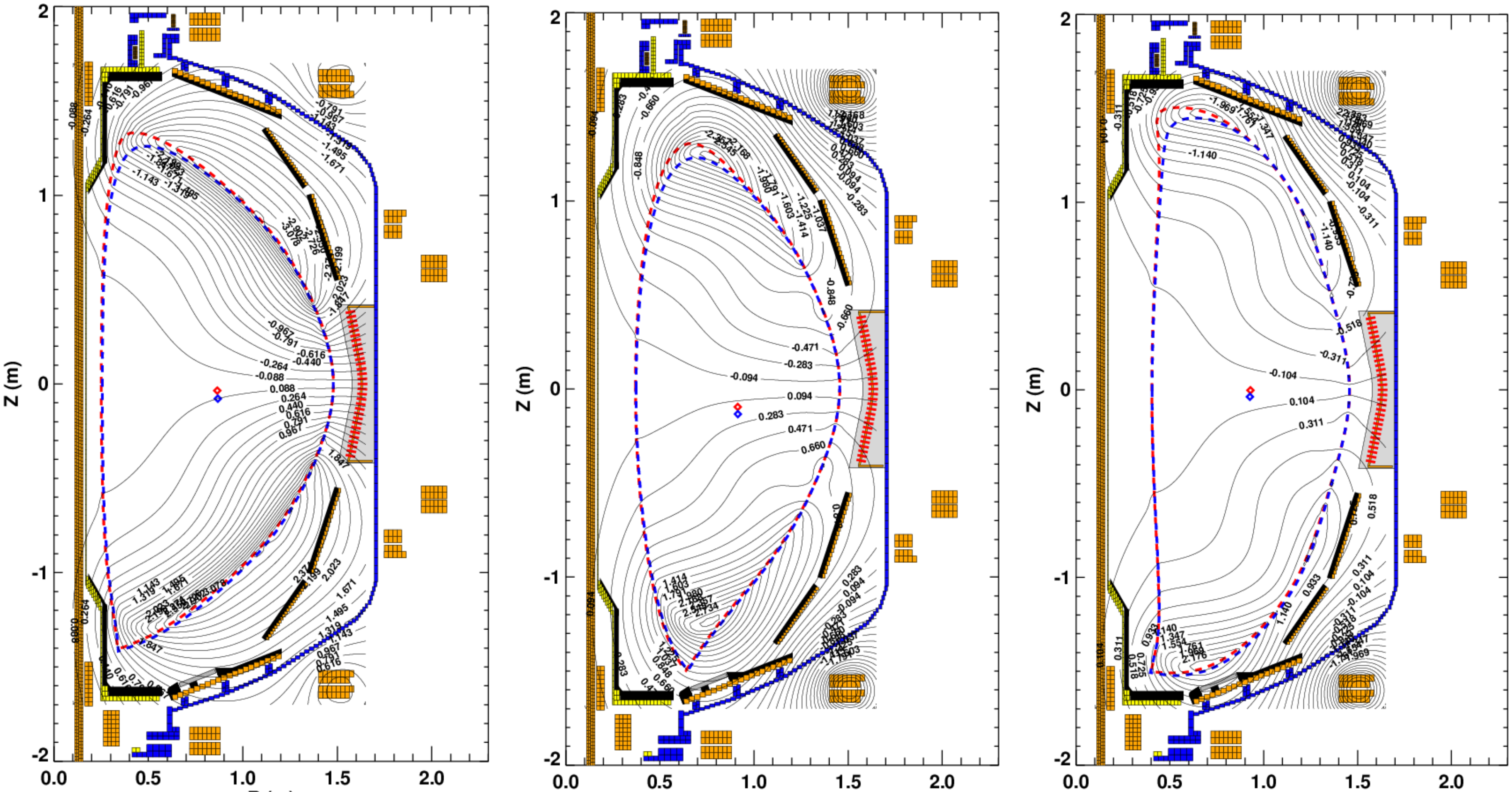
- Thesis: Using more/different loop voltages will lead to a better estimation of the plasma position.
  - Eliminate n=1 pickup from random loop orientation problems.
  - More information for shapes that are distorted.
- Proper selection of measurement loops has been emphasized in the literature:
  - Ward & Hofmann, Nuclear Fusion 34, 401 (1994)
  - Pomphrey, Jardin, and Ward, Nuclear Fusion 29, 465 (1989)
  - Albanese, Coccorese, and Rubinacci, Nuclear Fusion 29, 1013 (1989)
  - C. Kessel, et al., Nuclear Fusion 41, 953 (2001)

Plasma Equilibrium Determines the Most Sensitive Loop Pair

Compute pairs of equilibria displaced by 2 cm: ψ_1 *and* ψ_2

Subtract them from each other (Surrogate for the voltage.): $\delta\psi = \psi_1 - \psi_2$

Compute the expected flux difference: $\delta\psi_{UD} = \delta\psi - \delta\psi(z=-z)$



No single pair is optimal for detecting vertical motion.

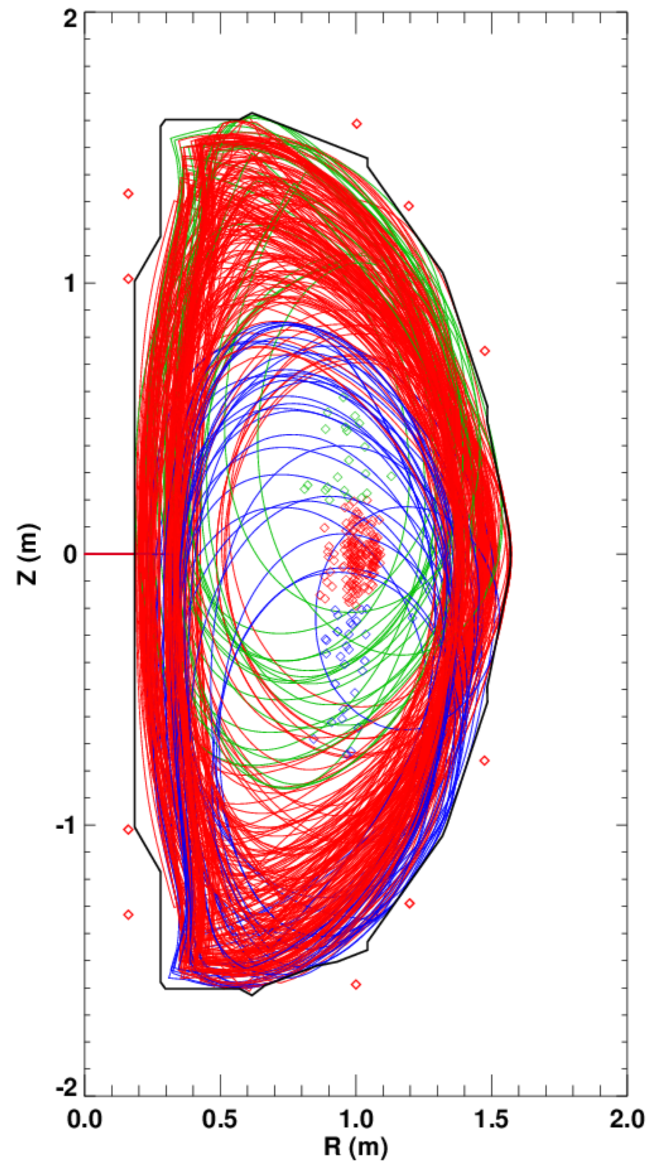
Use a Database of Equilibria to Determine Which Loops are Best For Detecting Vertical Motion

- Consider ~590 NSTX equilibria.
  - Majority from LRDFIT and EFIT reconstructions
    - Include currents in the passive plates, mode non-rigidity.
  - Minority generated with ISOLVER
- Computed the flux at the various flux loop locations.
- Fit the magnetic axis location to a function:
  - Only use equilibria with $|Z_P|<20$ cm

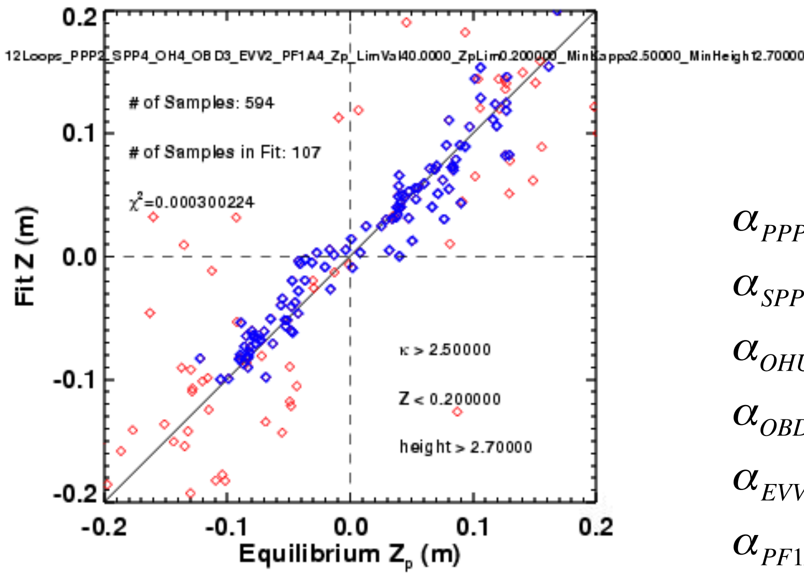
$$I_P Z_P = \sum_{i=1}^{NumLoopPairs} \alpha_i \times \left(\psi_{Upper-Loop,i} - \psi_{Lower-Loop,i}\right)$$

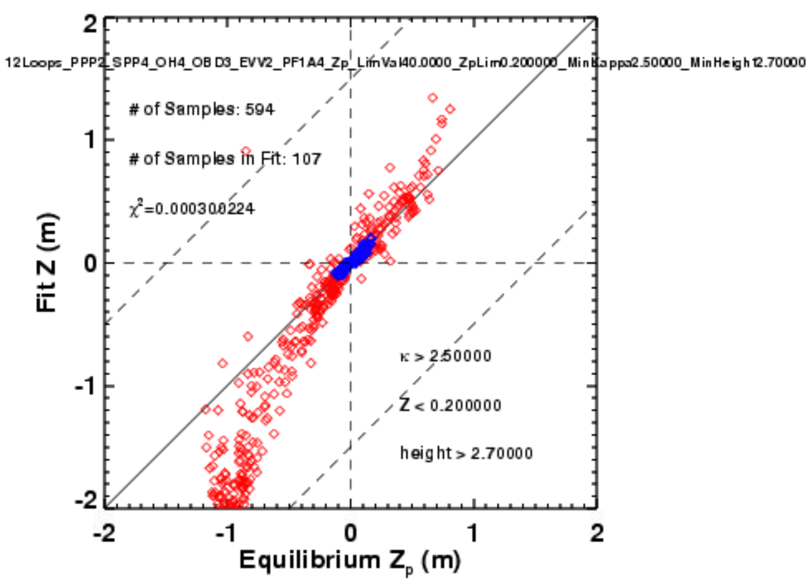
$$Z_P = \frac{\max(Z_{boundary}) + \min(Z_{boundary})}{2}$$

- Find coefficients α from:
  - linear SVD solution, or
  - constrained optimization
    - Prevent any single value α from becoming too large.

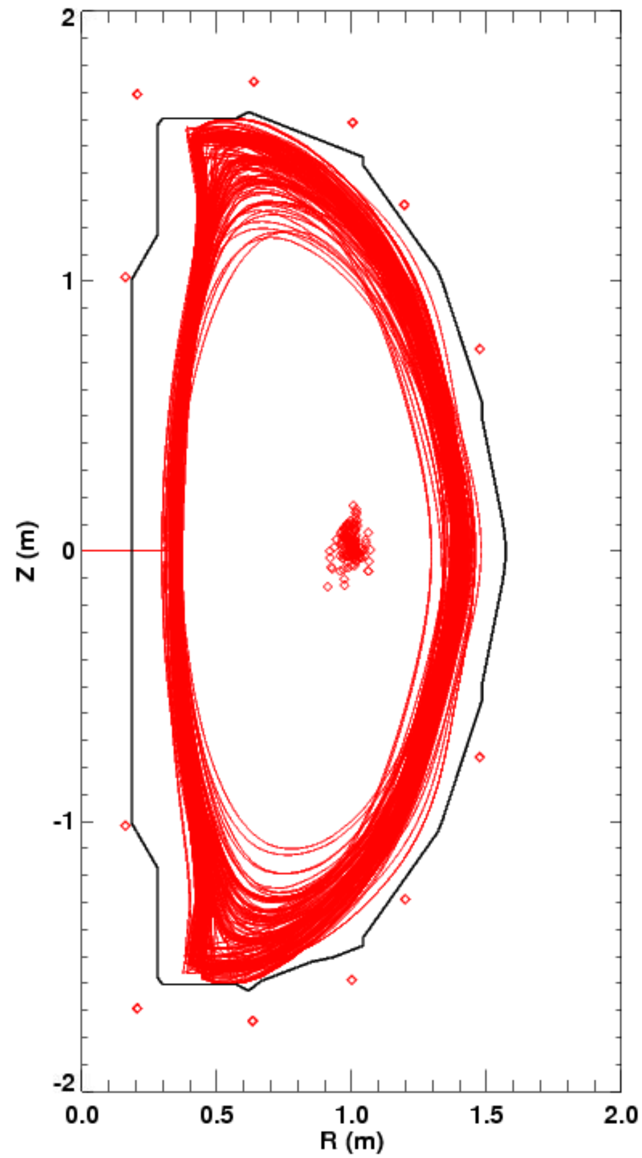


Example: Constrain to Only High Elongation Plasmas

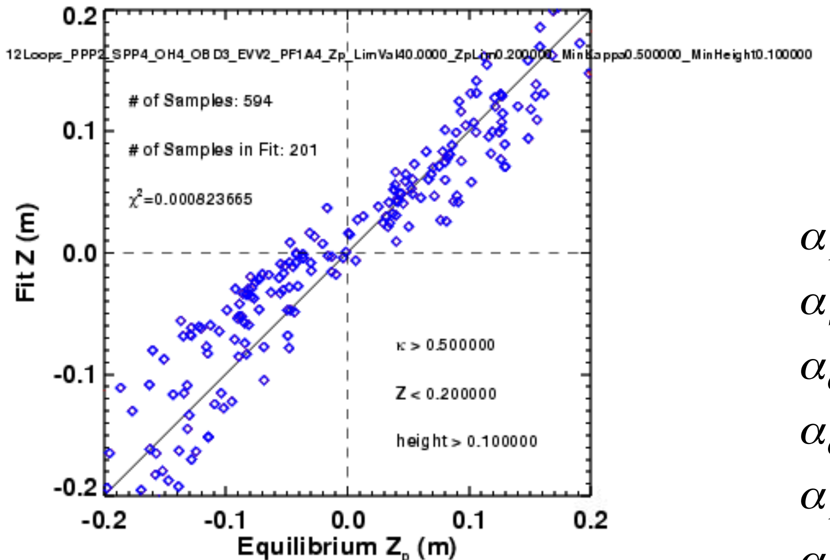




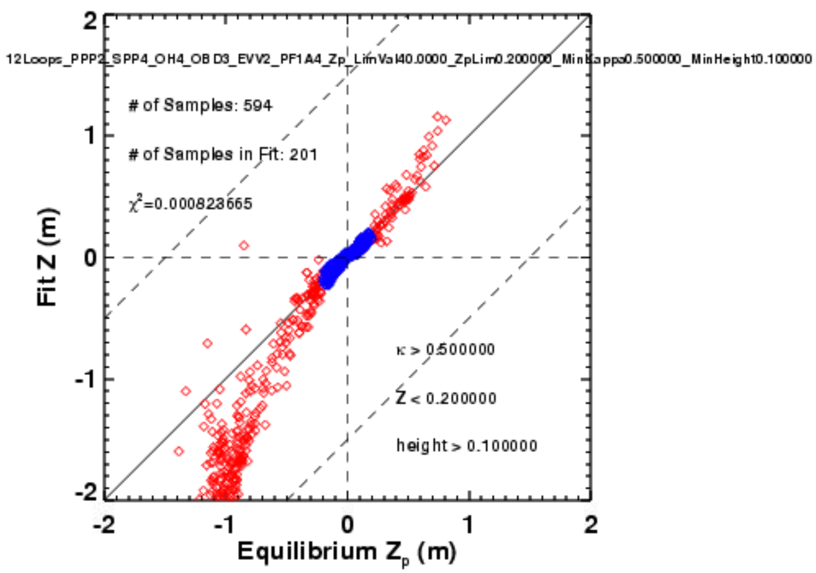
$$\alpha_{PPP2} = -0.204$$
$$\alpha_{SPP4} = 0.262$$
$$\alpha_{OHU4} = -16$$
$$\alpha_{OBD3} = -1.82$$
$$\alpha_{EVV2} = -2.89$$
$$\alpha_{PF1A2} = -5.45$$

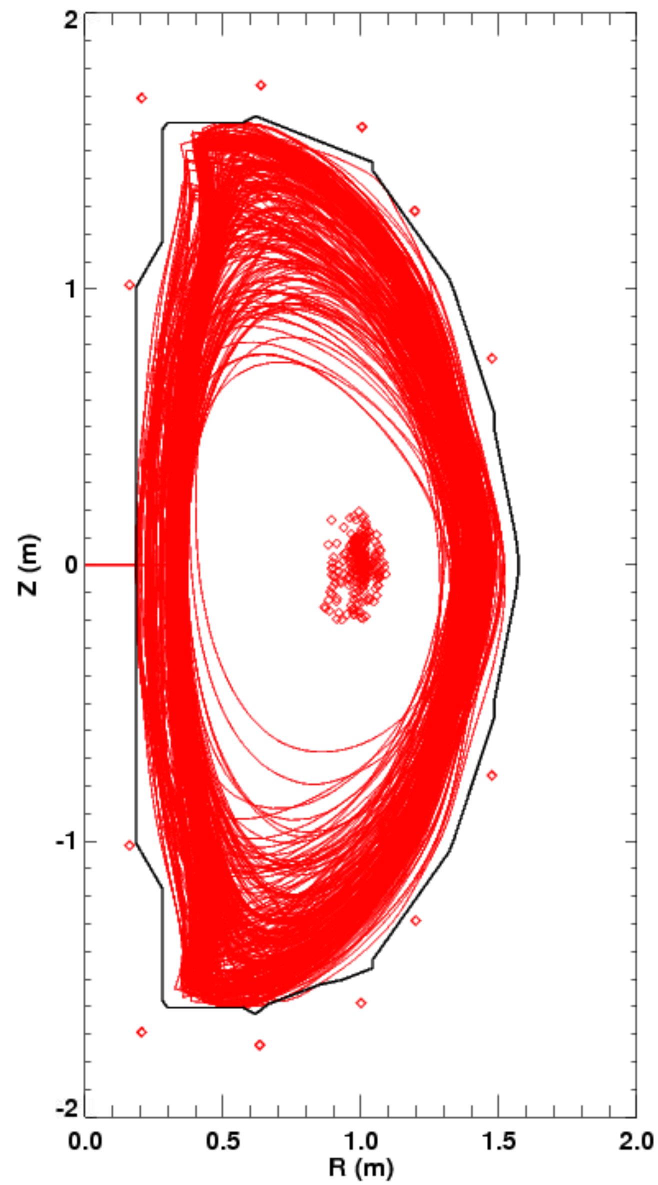


Example: Constrain to Also Sorts of Plasmas

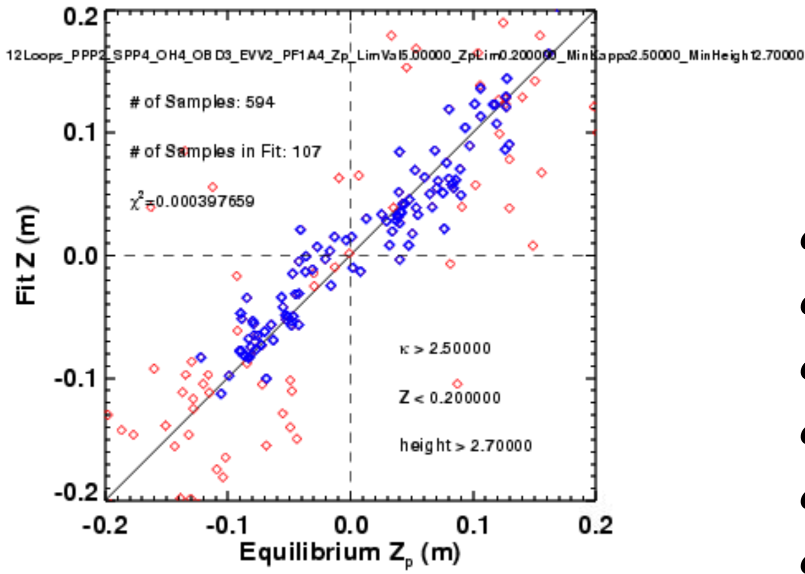


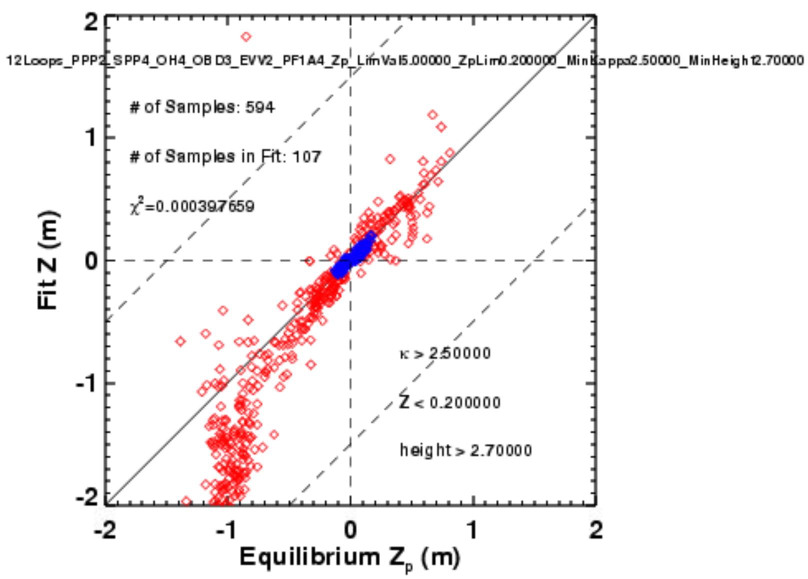
$$\alpha_{PPP2} = 0.285$$
$$\alpha_{SPP4} = -0.624$$
$$\alpha_{OHU4} = -21.3$$
$$\alpha_{OBD3} = -0.44$$
$$\alpha_{EVV2} = -1.039$$
$$\alpha_{PF1A2} = -0.9$$



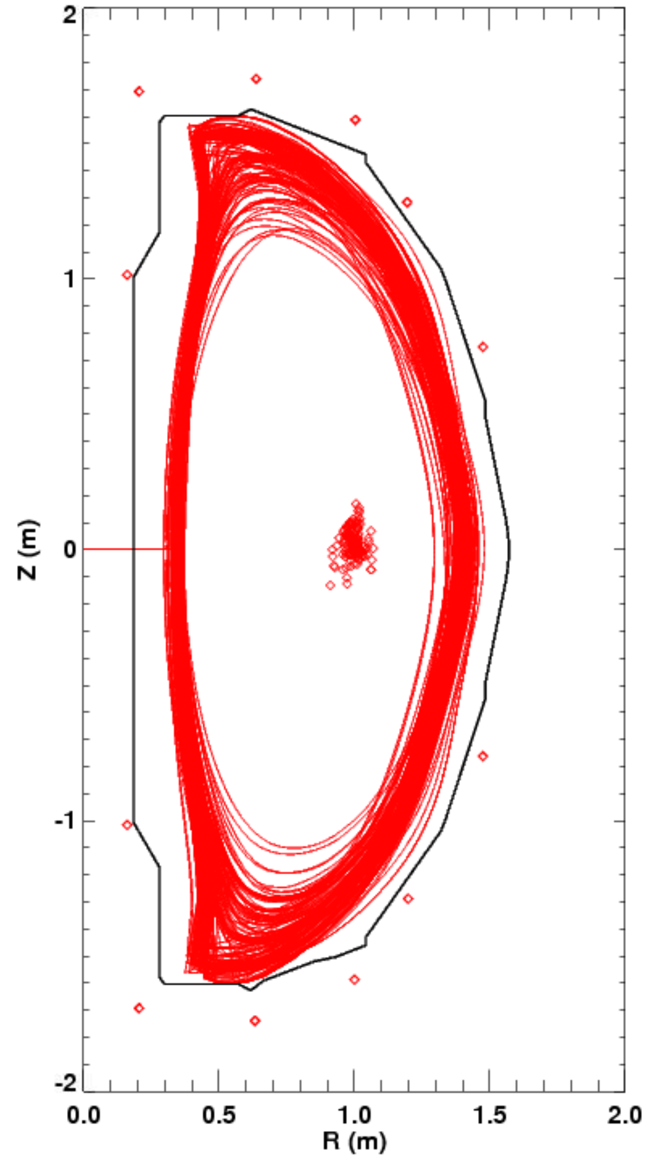


Example: Only High Elongation, But With Limits on the Size of Any Individual Weight





$$\alpha_{PPP2} = -0.707$$
$$\alpha_{SPP4} = -0.379$$
$$\alpha_{OHU4} = -5.0$$
$$\alpha_{OBD3} = -0.342$$
$$\alpha_{EVV2} = -5.0$$
$$\alpha_{PF1A2} = -4.287$$



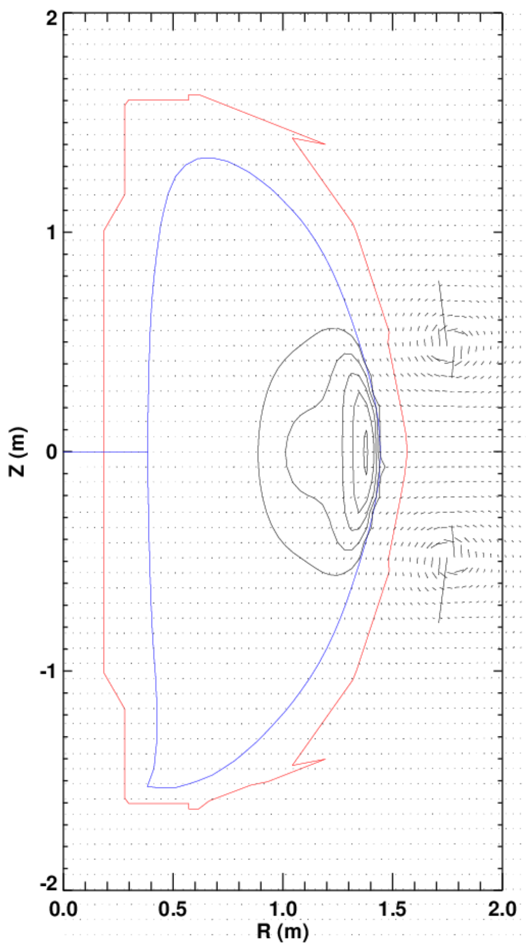
Strategy For Determining Loop Weighing

- There is a balance to be struck:
  - Linearity: Put all weight on inner flux loops
  - Noise immunity: Distribute weight across loops
- n=1 pickup (tearing and kink modes) will be stronger in some loop pairs than others.
  - Won't really know this until we see the data.
- Will pick final weight coefficients based on actual difference voltage signals.
  - Use actual voltage differences (including any noise).
  - First use coefficients from previous analysis, compare reconstructed and estimated $d(I_P Z_P)/dt$ *(will need fast EFITs/LRDFITs).*
  - May need to further adjust weights.
  - Will require a week or so of operation will all loop voltage differences functioning and data being collected.

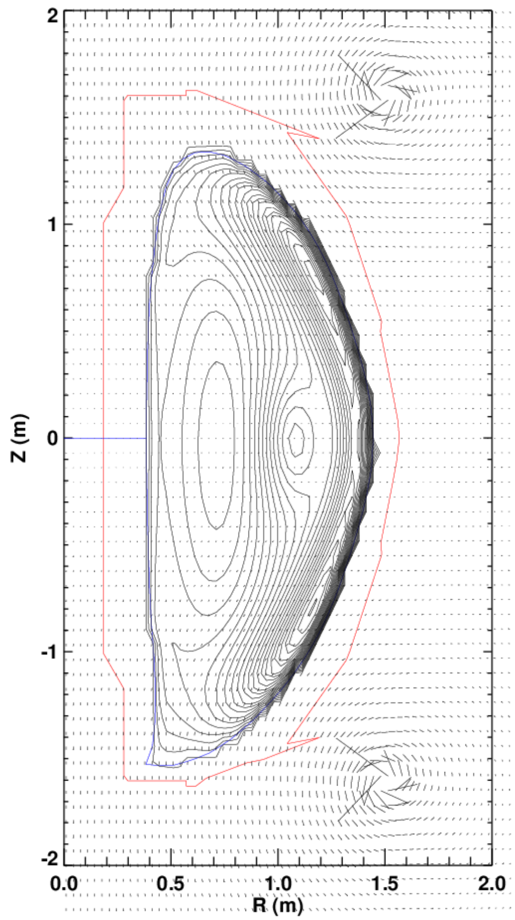
Vertical Position Control May Be Possible With the RWM Coils

Calculate force assuming 1 amp of power supply currents $F_Z = \sum J_\phi B_R$

RWM Coils: F_Z=78



PF-3 Coil: F_Z=1500



RWM Coils make far less force for the same power supply current.

(ratio is not as bad for lower-elongation plasmas)

However….

1) SPA are very fast (0 to 3 kA in 1-2 msec)

2) Latency in that system is smaller

3) RWM coil field may not couple as strongly to the passive plates.

Formulation of the PCS Code

- Estimate of $d(Z_P I_P)/dt$: $$\frac{d\left(I_P Z_P\right)}{dt} = \sum_{j=0}^{8} \alpha_j V_{UL,j}$$
- Form the SPA current request:

$$I_{SPAi}^{req}(t) = I_{SPAi}^{OHxTF}(t) + I_{SPAi,B_R}^{RWM}(t) + I_{SPAi,B_P}^{RWM}(t) + I_{SPAi}^{pre}(t) + I_{SPAi}^{VDE}(t)$$

$$I^{VDE}(t) = -D_{RWM}^{VDE} \times LPF\left(\frac{d\left(ZI_P\right)}{dt}, \tau_{VDE}\right)$$

$$I_{SPAi}^{VDE}(t) = I^{VDE}(t)$$

- How big should D be?
  - Take a 1 MA plasma, moving 10 cm in 10 msec:
    - $d(Z_P I_P)/dt$ =1*0.1/0.01=10 MAm/sec
  - We want 3000 A of current for this feedback.
    - D=3000/10=300 Asec/MAm

Hardware and Software Status

- dZ/dt Observer
  - Complete specification has been written, implemented in PCS
  - Electronics for voltage differences are finished, installed in NTC, and fully cabled in.
  - Changes to MDS+ tree for additional channels have been made.
  - Offline IDL code written for comparison to archived realtime data.
  - Testing is making good progress.
    - And has been a good (& painful) learning experience for those involved…
- RWM coils for Z_{axis} control.
  - Specification has been written.
    - Relies on the improved dZ/dt observer for the measurement.
  - Code has been implemented as part of the 6 subunit proportional control algorithm.
- XMP written for testing of these software changes.

Backup

Note on Gain Equivalences

- Present system uses a gain of 80.
  - i.e.: $V_{VDE} = 80V_{PPP2}$
- New system will use a formulation: $V_{VDE} = D\sum \alpha_i V_i$
- For observer with PPP2 loops only, α=2.5.

$$V_{VDE} = D \cdot 2.5 \cdot V_{PPP2}$$

- So, equivalent derivative gain is now 80/2.5=32.

Run Plan (I)

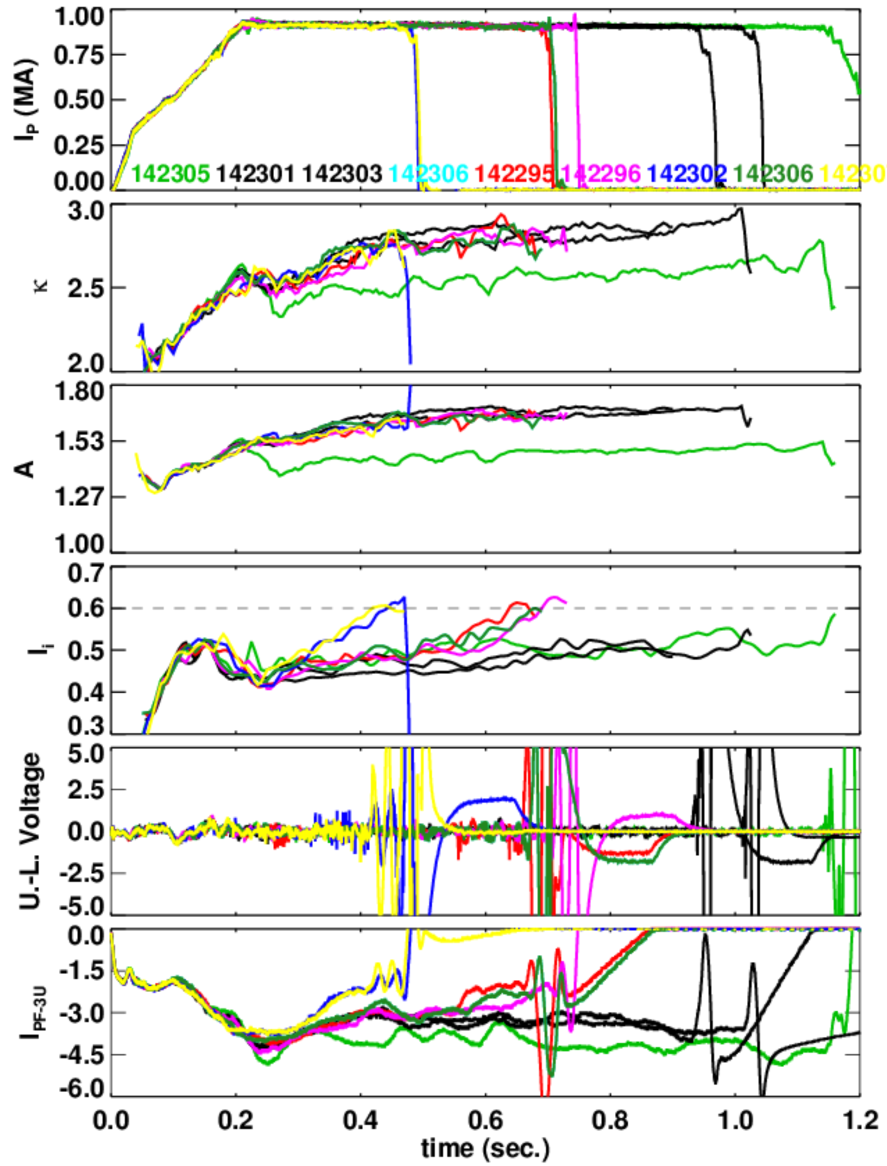
- Debugging: Compare PCS calculations to identical off-line versions.
- XMP (?): Test that system is correctly coupled to the PF-3 coils.
  - Switch to new controller formulation (the αs), use the same single loop pair and value of gain (27) that reproduces the old system.
  - Show that vertical controller still works.
- Day 1: Optimize gains with PF-3 as actuator, new $d(I_P Z_P)/dt$ observer.
  - Reload vertically unstable target, A~1.75, κ=2.9. Show a VDE. (3 shots)
    - Potential reload is 142301.
    - Use divertor gas injection to drive l_i up?
  - Transition to new $d(I_P Z_P)/dt$ observer, same overall gain. Repeat. (4 shots)
    - If no VDE, then increase κ until a VDE occurs.
  - Scan control gain for optimum stability. (5 shots)
    - (or oscillation develops).
  - Contingency, do one of: (5 shots)
    - Test a second combination of loops.
      - Repeat gain scan
    - Use same combination of loops, change the shot and demonstrate benefits.
      - For instance, lower-delta target with reduced beam heating.

Run Plan (2nd ½ day, using RWM coils, if necessary)

- Turn off PF-3 vertical control and see plasma drift. (3 shots)
  - Use fiducial like target
  - Shot to reload: 141640
- Add n=0 control with RWM coils. (7 shots)
  - Scan gain using value 0.5, 1.0, 1.5, 2.0, 2.5
  - Stop scan when coil currents become too large, or VDE is stabilized.
- If VDE is stabilized, then increase inner gap until instability is achieved. (4 shots)
- Test combined PF-3 and RWM coil control to determine the new limit on aspect ratio and l_i. (4 shots)

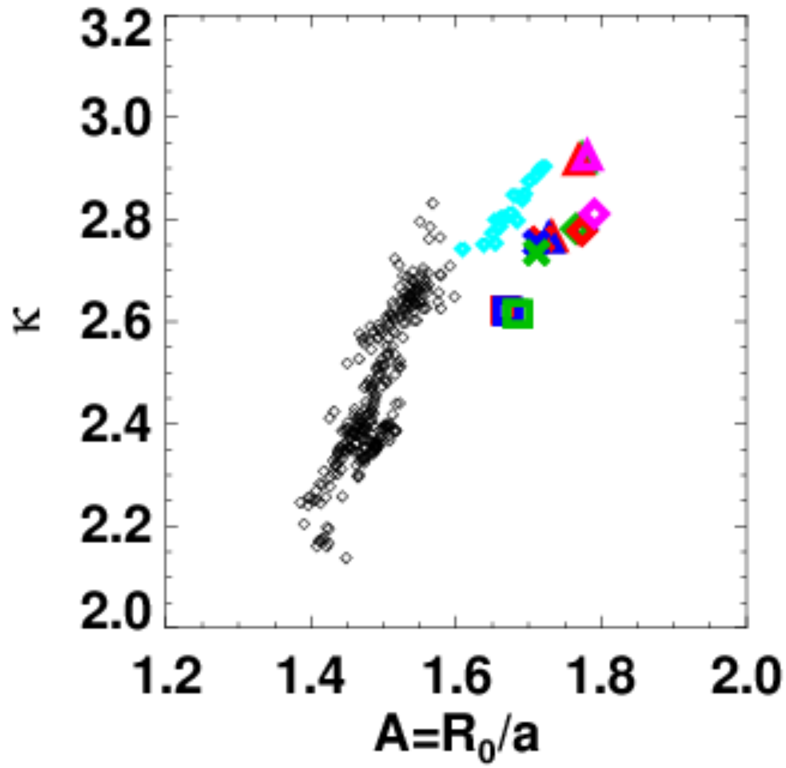
XP in 2010 Showed that Vertical Position Control can be Lost at Higher Aspect Ratio

- 1 Fiducial (green) and 8 shots at higher aspect ratio.
  - Black cases vertically stable, the colored ones have VDEs.
- *VDE is always triggered when l_i=0.6.*
  - This is not a particularly high value.
  - Would preclude use of the scenario for many XPs.
- Other instances of vertical stability problems.
  - Egemen's squareness XP.
  - Ron Bell's DIII-D comparison XP.
  - After every nearly every locked mode and RWM.
- *Motivates improvements to the n=0 controller.*

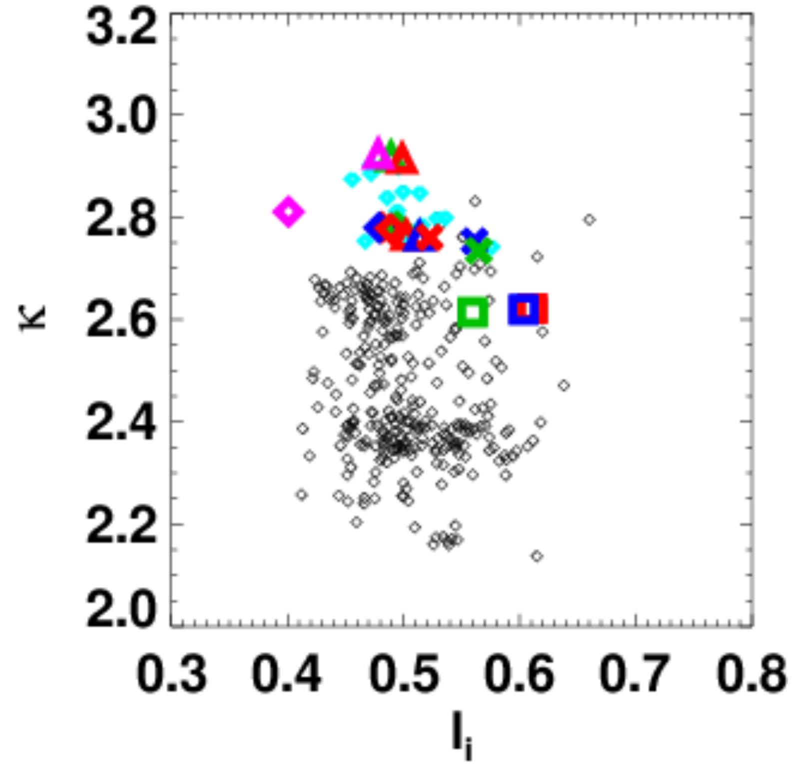


Interesting Scenarios for the Upgrade Will Push Against These Limits

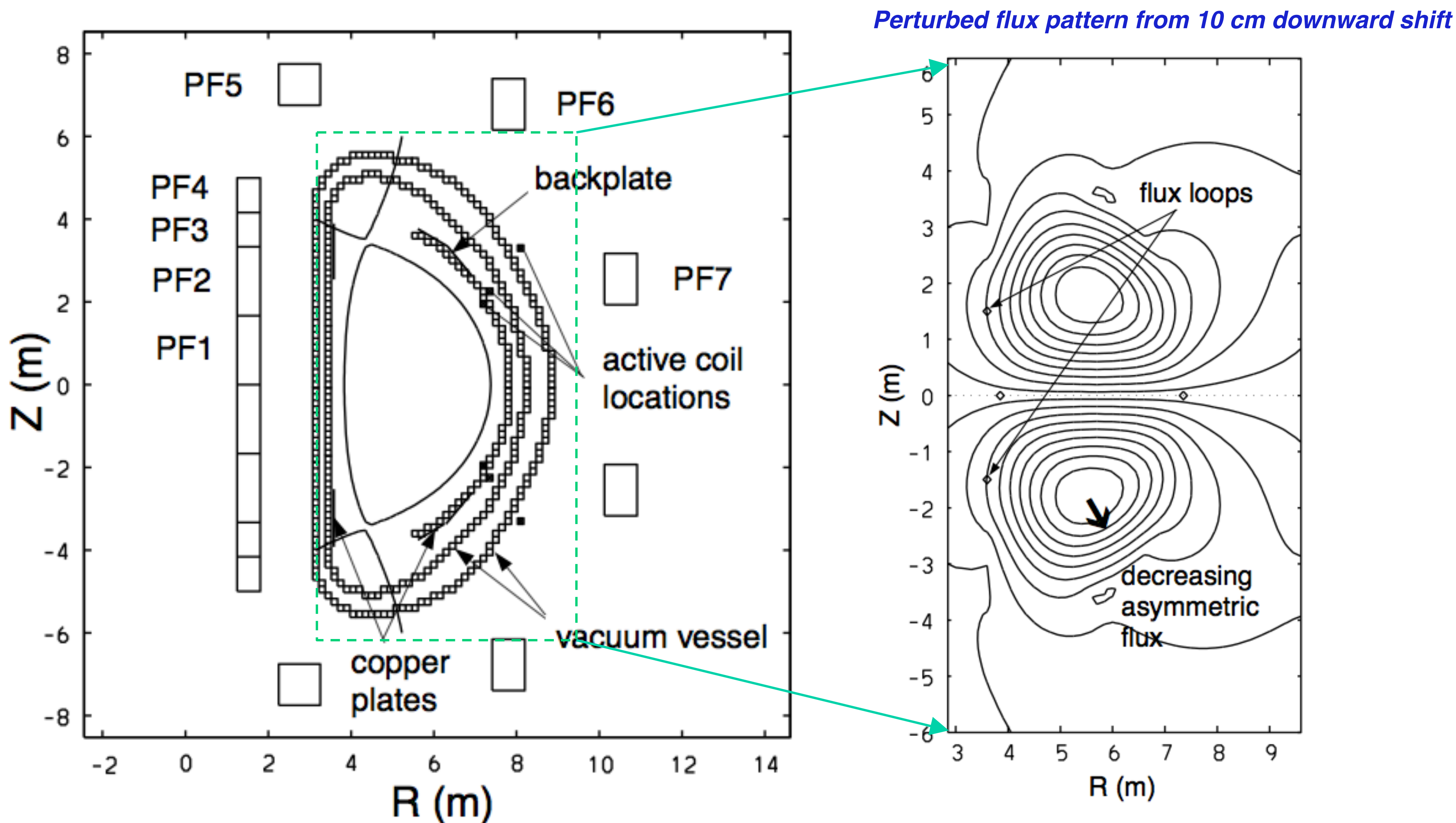
Ask for high-kappa at even larger A.



Ask for high-kappa at values of l_i comparable to present values.



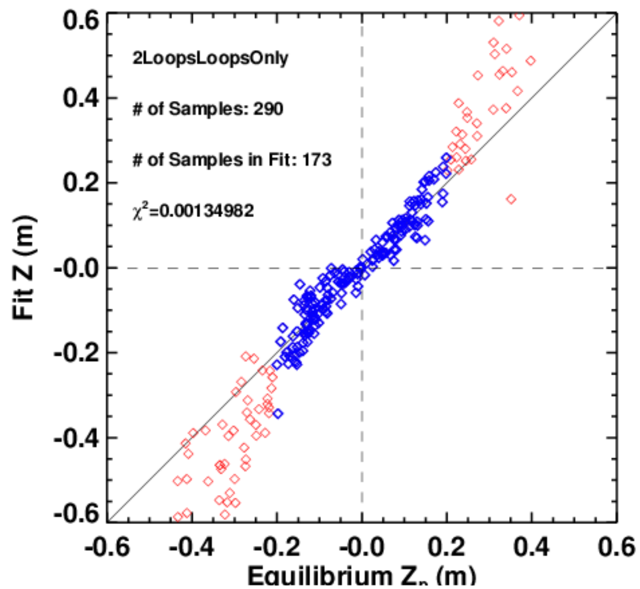
Inboard Side Loops Were Chosen in a Study for ITER Control in Kessel, et al.



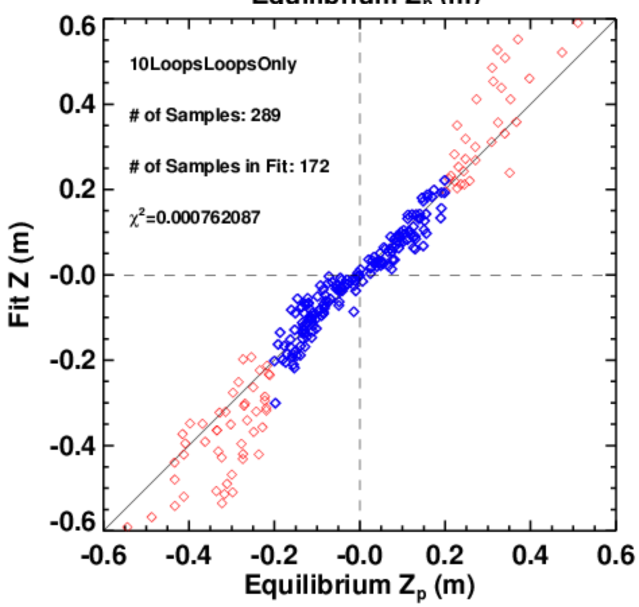
What is the common perturbed flux pattern for NSTX cases?

C. Kessel, et al., Nuclear Fusion **41**, 953 (2001)

Adding More Loops With Unconstrained Fitting Allows Further Reduction of χ^2, Keeps Weight on CSC Loops

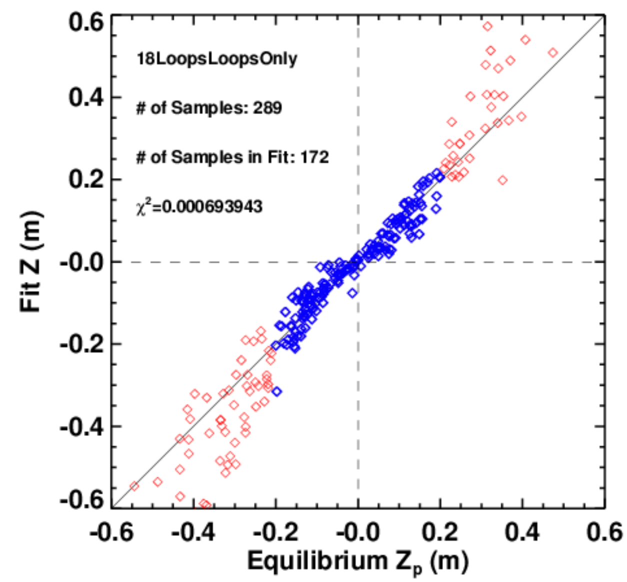


$$\alpha_{OHU4} = -34.5$$
$$\chi^2 = 1.35 \times 10^{-3}$$



$$\alpha_{OHU4} = -33.3$$
$$\chi^2 = 7.6 \times 10^{-4}$$

$$\alpha_{OHU4} = -29.48$$
$$\chi^2 = 6.9 \times 10^{-4}$$



Constrained Optimization Can Balance Sensitivity Against Linearity

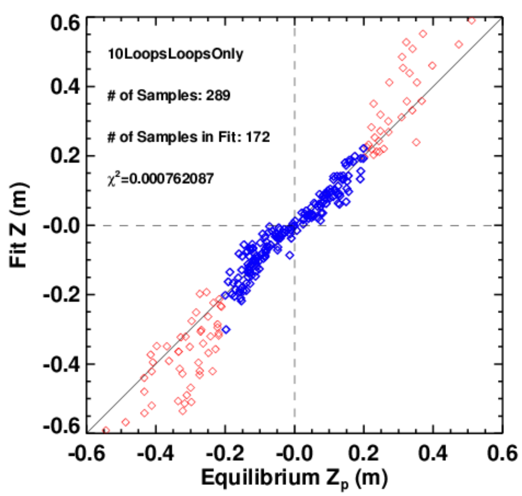
Scan of the maximum allowable weight on a single loop (40, 5, 2.5)

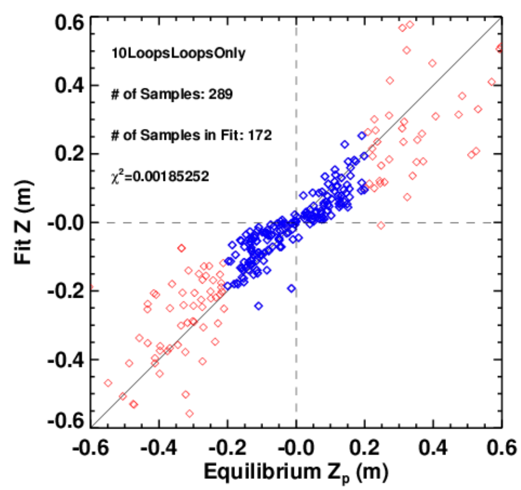
$$\alpha_{PPP2} = 0.122$$
$$\alpha_{SPP4} = 0.169$$
$$\alpha_{OHU4} = -31.4$$
$$\alpha_{OBD3} = -0.52$$
$$\alpha_{PF1A2} = -0.29$$
$$\chi^2 = 7.6 \times 10^{-4}$$

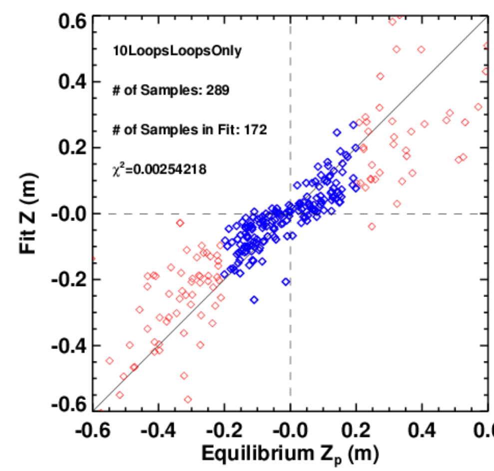
$$\alpha_{PPP2} = -0.743$$
$$\alpha_{SPP4} = -0.107$$
$$\alpha_{OHU4} = -5.0$$
$$\alpha_{OBD3} = -0.694$$
$$\alpha_{PF1A2} = -5.0$$
$$\chi^2 = 1.85 \times 10^{-3}$$

$$\alpha_{PPP2} = -0.845$$
$$\alpha_{SPP4} = -0.408$$
$$\alpha_{OHU4} = -2.5$$
$$\alpha_{OBD3} = -0.436$$
$$\alpha_{PF1A2} = -2.5$$
$$\chi^2 = 2.5 \times 10^{-3}$$

About 2.5 x better than present system





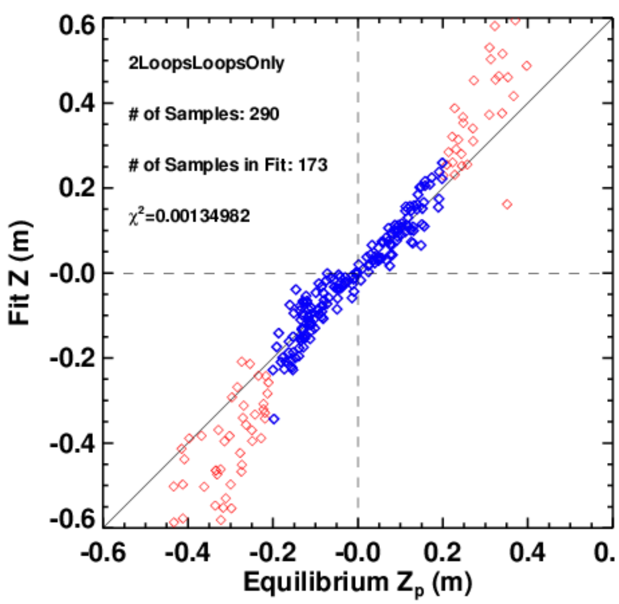


Study neglects any benefits that might come from elimination n=1 pickup.

Studies Show That Loops on the Center Column are Most Linear...But Least Sensitive

- CSC loops have less relative coupling to plates, are more linear.
  - But are much less sensitive (34 vs 2.53).
- Compromise between linearity and sensitive has not been discussed in the literature (to my knowledge)

$$\alpha_{OHU4} = -34.5$$
$$\chi^2 = 1.35 \times 10^{-3}$$



$$\alpha_{PPP2} = -2.53$$
$$\chi^2 = 6.6 \times 10^{-3}$$