Plasma Modeling Results, Control Improvement for NSTX*

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NSTX

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Strike Point Control with LLD: Transport Model Calculations

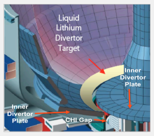
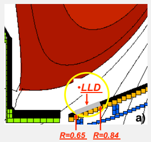
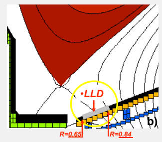


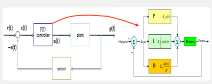
Illustration of LLD inside NSTX

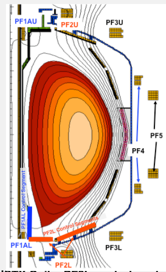
Simulations a) High δ: %25 n_e reduction b) Low δ: %50 n_e reduction

- Liquid lithium divertor (LLD), was installed on NSTX, enables experiments with the first complete liquid metal divertor target in a high-power device in 2010.
- Expected reduced recycling with LLD depends on proximity of the outer strike point (SP) to LLD.
- To get better and consistent density reduction and to avoid contact with the LLD and the CHI gap, the most important parameter is SP position and it needs to be closely controlled.

2009 Run: Design a Real Time Controller for the SP Motion



- Design a Proportion-Integral-Derivative (PID) controller to keep the SP at the center of LLD, with ~1 cm variation from the reference value.
- Currently PCS only accepts PID controller.
- s=measured position and r=requested position of the SP.



NSTX Coils: PF2L controls outer SP, and PF1AL controls inner SP

2009 Run: Lower SP Control Results

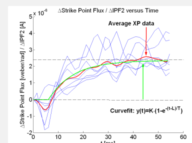
- The outer SP predominantly depend on PF2L. Use it as the sole controller for outer SP.
- System identification (ID) is achieved via "Open Loop Reaction Curve" where the response of the system to step control inputs is measured.

$$\Delta y(t) = K \cdot \left(1 - e^{-(t-L)/T}\right) \Delta u$$

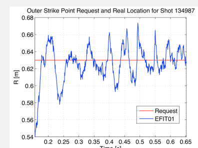
- where:
  - L = "apparent" lag in time response;
  - T = the time taken for change to occur

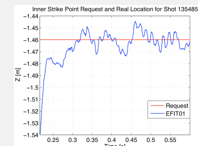
	K_p	K_i	K_d
P	1.0 T/(K L)	-	-
PI	0.9 T/(K L)	0.27 T/(K L^2)	-
PID	1.2 T/(K L)	0.6 T/(K L^2)	0.5 T/K

- Tuned PID based on these parameters as shown in Table.
- Achieved stable control of the SPs.
- RMS values of <1 cm error in $r_{st\text{-}i}$, <1.5 cm error in $r_{st\text{-}o}$ on the inner divertor, and <2 cm error in $r_{st\text{-}i}$ on the outer divertor



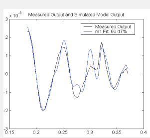
System ID experimental data via Open Loop Reaction Curve





Strike point control examples from 2009

2010 Run: Offline System ID via ARMAX model



Measured error in OSP [Webers/rad] vs time [s]: black line shows the XP data and blue line the simulation

- To reduce the RMS error of OSP, dynamics modeling was used.
- To maximize the proportion of this process that is conducted offline the 2009 XP data was analyzed and an offline system ID based on ARMAX (AutoRegressive Moving Average with eXogeneous inputs) was developed. Assuming a system of form:

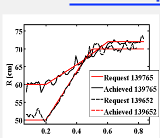
$$x_{k+1} = Ax_k + Bu_k + Gw_k$$
$$y_k = Cx_k + v_k$$

- Find minimal-state realization for A, B and C given y_k and u_k for Δt

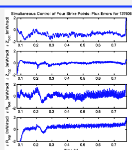
$$C(z^{-1})\epsilon_k = A(z^{-1})y_k - B(z^{-1})u_k$$

- The matrices are parameterized by A(θ) and B(θ) $\hat{\theta} = \arg\min \frac{1}{2}\sum_{k=1}^{K} \epsilon_k^2$
- Using ARMAX model, solve the minimization problem

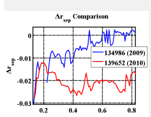
2010 Run: Improved SP Control for Upper/Lower/Outer/Inner SP



Examples of lower OSP evolution with the improved control.



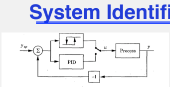
Simultaneous control of the four strike points.



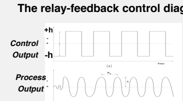
Δr_{sep}, a measure of vertical position, drift is avoided.

- Control four SP control with PF1AU, PF1AL, PF2U, PF2L
- Optimize/tune PID gains.
- Added integral gain for PF3U/L.
- Scanned lower OSP 45-80 cm.
- Achieved smooth PF coil current.
- Used the control successfully in more than 100 experiments.
- Avoided vertical position drift.

System Identification: Auto-tuning with Relay Feedback



The relay-feedback control diagram.



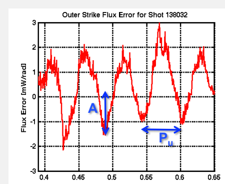
Closed-loop plant response pattern and the oscillation period (Pu) and the amplitude (A) of the plant response.

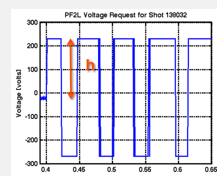
- Advantage
  1. Enabling the controller to be tuned in one shot.
  2. More robust to errors in modeling due to its closed-loop nature, improving the XP system ID and optimal control tuning.
- Isoflux algorithm has been upgraded to include relay-feedback tuning capability.
- Use Ziegler-Nichols PID Tuning where the ultimate gain of K_{cu} =4h/(πA)

	K_p	K_i	K_d
P	0.5 K_{cu}	-	-
PI	0.45 K_{cu}	0.54 K_{cu}/P_u	-
PID	0.6 K_{cu}	1.2 K_{cu}/P_u	0.075 K_{cu} P_u

Ziegler-Nichols PID tuning rules

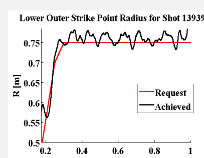
Combined X-point Height and OSP Control

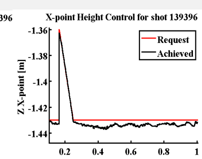


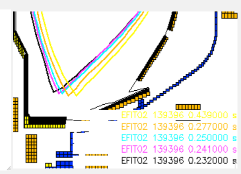


A relay-feedback system identification example for Combined X-point height OSP control.

- The relay-feedback is used to tune the combined X-point height, SP radius via the Sequential Single Input Single Output method:
  1. OSP control tuned while X-point not controlled.
  2. X-point height control was tuned while the SP used the control tuned in the previous step.
  3. SP was tuned again while the X-point height is controlled with the control tuned in the previous step. This procedure was repeated until the PID parameter designs between the steps are close to one another.
- For the combined X-point height and SP radius control, two iterations were used.





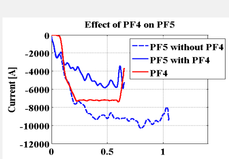


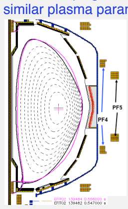
Performance of the combined X-point height, SP radius control

- The obtained control achieved <1 cm X-point height error and <2 cm SP radius error.
- The developed control algorithm was used for LLD experiments.

Combined Operation on PF4 and PF5

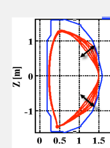
- NSTX will be upgraded with a larger center stack and an additional neutral beam, which will allow a higher B_T = 0.55T → 1T, I_P = 1MA → 2MA, P_{NBI} = 5MW → 10MW, and τ_s 1s → 5s.
- Upgrade aims 3-5 times lower collisionality with fully equilibrated profiles in full non-inductive operation.
- Some scenarios require PF4 and PF5 coils have to operate simultaneously in a roughly one-to-two ratio.
- The combined operation has hitherto not been part of the normal operations.
- To prove the concept, a feed-forward PF4 input was implemented, keeping the PF5 for outer gap control and manually tuning the operation of other coils to achieve similar plasma parameters.



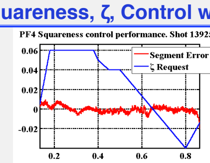


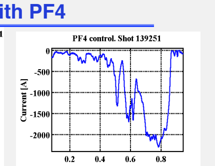
The effect of simultaneous operation of PF4 and PF5. PF5 only shot 139482 compared to PF4/PF5 shot 139484.

Squareness, ζ, Control with PF4



The ISOLVER simulated effect of varying PF4 from -10 kA to +10 kA on the plasma boundary.





Outer bottom ζ control via PF4. Shown on the left are the ζ request and the segment error. Shown on the right is the PF4 coil current.

- ζ defines how similar the boundary of the plasma is to a square: for triangle ζ=0 and rectangle ζ=1.0.
- Spherical Tokamaks operate at high elongation, κ, in order to maximize the bootstrap fraction and q*.
- OSP fixed during LLD operation. Thus, neither the κ nor the triangularity, δ, change. Leaving ζ.
- Changing the ζ could modify the global stability, edge stability, or overall transport at constant κ, δ.
- PF3/PF4 effect ζ most. PF3 used for vertical stability. PF4 best ζ control candidate minimal side effect.
- In order to control squareness, control of the plasma boundary via PF4 employed.
- The error along this segment was fed to the PF4 voltage request with a PID control.
- Achieved stable tracking of ζ request with minimal error using PF4 control.