Optimizing Plasma Boundary Control in Superconducting Tokamaks

S.B. Ballinger,[1] N.W. Eidietis,[2] M.J. Lanctot[2], D.A. Humphreys,[2] A.S. Welander,[2] and S.H. Hahn[3]
[1]Applied Physics and Applied Math., Columbia University, USA. [2]General Atomics, San Diego, USA. [3]NFRI, South Korea

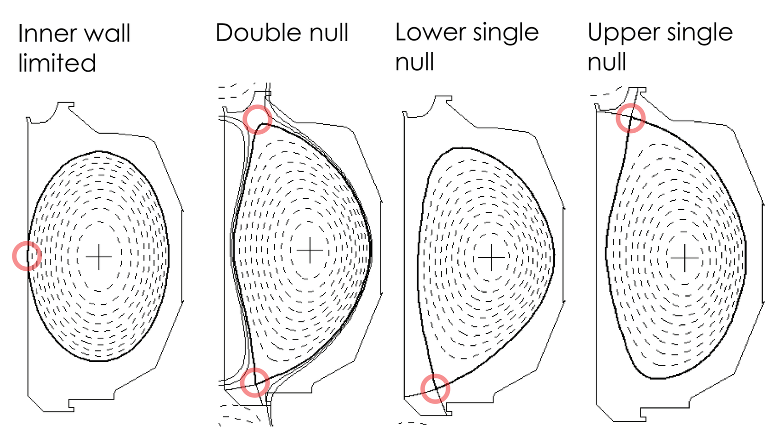
DIII-D NATIONAL FUSION FACILITY

COLUMBIA | ENGINEERING

Understanding shape control

Plasma shaping is an important aspect of tokamak operations

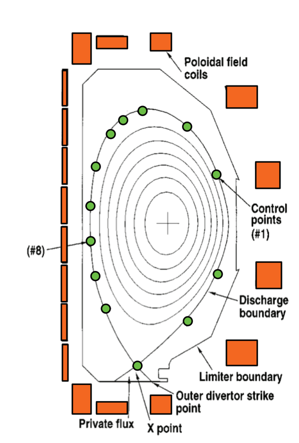
- Plasma does not fill the entire vessel
- Plasma can have x-points (nulls)
- Multiple shapes are possible:



- Plasma shape significantly impacts tokamak performance
- Feedback control via plasma control system (PCS) is necessary to maintain desired shape
- Superconducting tokamaks like KSTAR, EAST, and ITER present a more difficult control problem than DIII-D
  - Can we quantify the ability to control plasma shape by defining a new metric?
  - How do we optimize controllers in a highly coupled system?

DIII-D PCS uses poloidal field coils to control plasma boundary

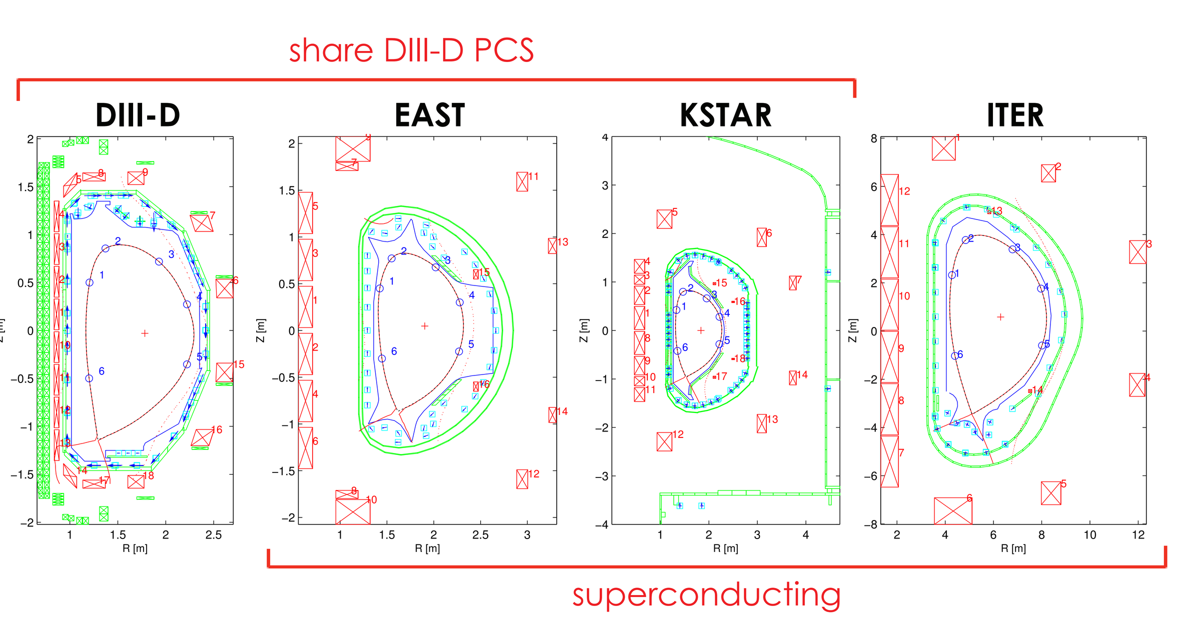
- rtEFIT/Isoflux algorithm:
  - Pick a reference flux (at limiter or x-point)
  - rtEFIT calculates flux at control points on the shape we want the outermost flux surface to have
  - Control plasma using poloidal field coils to eliminate differences in flux
  - We obtain a flux surface that has the shape we wanted
- Defining boundary points:
  - Limiter is in contact with wall
  - X-points have no vertical magnetic field



KSTAR and other superconducting devices present a more challenging shape control problem than DIII-D

- Control coils are placed farther away from plasma → less independent control of shape
- Slow power supplies limit coil response speed
- No dedicated solenoid → shape and I_p control highly coupled

Surveyed tokamak geometries



Quantifying controllability

Identifying the problem

- Need a metric to quantify control capabilities of PF coils
- Should use known operation parameters for each tokamak
- Example: ΔZ_{max} is successful in quantifying maximum controllable vertical displacement
- Use metric to compare control capabilities of DIII-D, KSTAR, EAST and ITER

Creating a controllability metric

- Shape parameter ξ describes variation in control point position
- Relate natural rate $d\xi/dt$ to ability of each coil to produce $d\xi/dt$
  - Define controllability $C_\xi \equiv \left(\left.\frac{d\xi}{dt}\right|_{\text{control}}\right)\left(\left.\frac{d\xi}{dt}\right|_{\text{natural}}\right)^{-1}$
- Value of 1 would be nearly perfect, values below 1 indicate controllability is poor
- $\left.\frac{d\xi}{dt}\right|_{\text{natural}} \sim \frac{\xi_0}{T_\xi}$ where ξ_0 is a characteristic value of the shape parameter (choose typical amount of gap variation $\Delta g \sim 1$ cm), and T is the characteristic time for its dynamic response (local penetration time τ_{pen} at each control point)
- $\left.\frac{d\xi_i}{dt}\right|_{\text{control}} = \frac{d\xi_i}{dI_{Cj}}\frac{dI_{Cj}}{dt} = G_{ij}\frac{I^j_{max}}{T^j_{PS}+\tau^j_{PS}+\tau^j_{pen}+\frac{L^j_C}{V^j_{Csat}}I^j_{max}}$: $d\xi/dt$ is related to the rate at which ξ changes in response to current changes and the rate at which current can be varied in coils

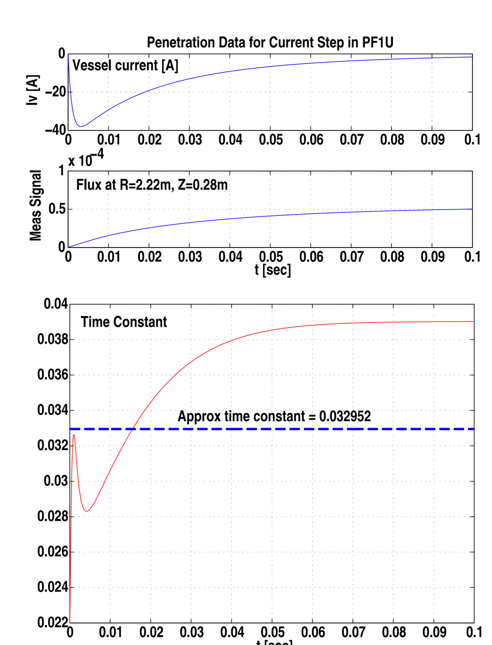
Implementation: $C_{ij} \equiv \frac{M_{ij}}{\hat{n}\cdot\nabla\psi_i}\frac{\delta I_j \tau^{ij}_{pen}}{\Delta g_i\left(T^j_{PS}+\tau^j_{PS}+\tau^{ij}_{pen}+\frac{L^j_C}{V^j_{Csat}}\delta I_j\right)}$

- M_{ij}: mutual inductance from PF coil j to control point i
- $\nabla\psi_i$: gradient of poloidal flux at control point i
- I_{max}: maximum current in PF coil j
- τ_{pen}: wall penetration time constant
- T_{PS}: power supply startup time for coil j
- τ_{PS}: power supply time constant for coil j

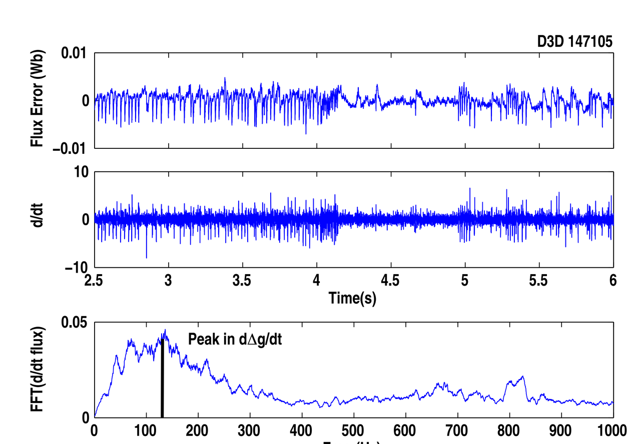
$$C = \begin{bmatrix} C_{1,1} & C_{1,2} & \cdots & C_{1,n} \\ C_{2,1} & C_{2,2} & \cdots & C_{2,n} \\ \vdots & \vdots & \ddots & \vdots \\ C_{m,1} & C_{m,2} & \cdots & C_{m,n} \end{bmatrix}$$

\# control points

\# coils



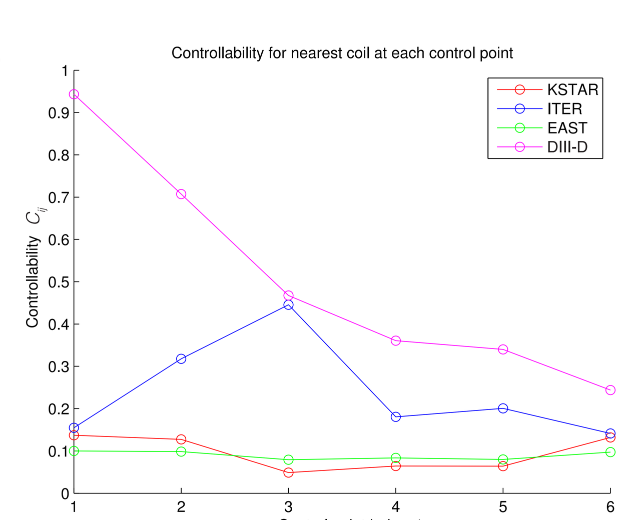
τ_{pen} obtained by driving PF coils with current to produce wall currents and calculating the field at the point of measurement (left)



Fluctuations in the gap distance are shown in the above-right figure, and are used to calculate $\delta I = \frac{\Delta g}{M/\nabla\psi}$

Results

The controllability metric was calculated at each control point using the nearest PF coil. We observe that there are consistent differences in controllability between the evaluated devices.

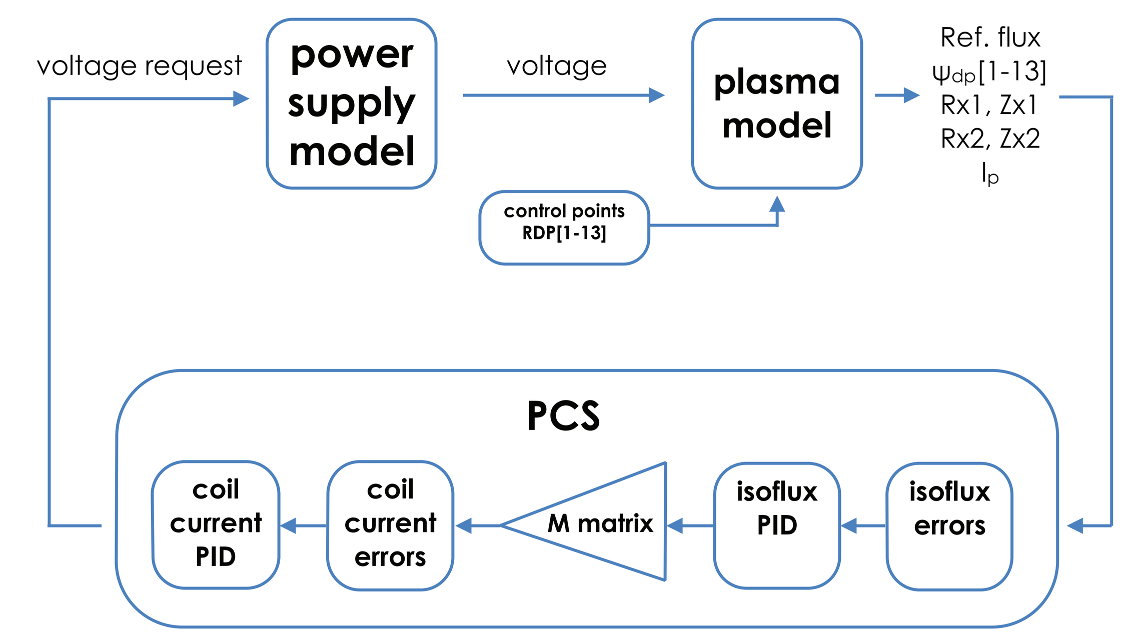


Offline optimization of strongly coupled shape control

The state of control design

- Currently, control design is done using an offline simserver
  - Saves physical machine time
  - Uses trial and error to find the "sweet spot" in the control using many simulations
- Automated tools should be more efficient to determine robust PID feedback and M-matrices
  - Simulink model of the plant (tokamak system) exists
  - Need to create the controller module (PCS)
  - Use Matlab's Robust Control Toolbox to optimize gains

A simplified model of the simulation



Plan: Leverage Matlab control tools for automated tuning of shape control system

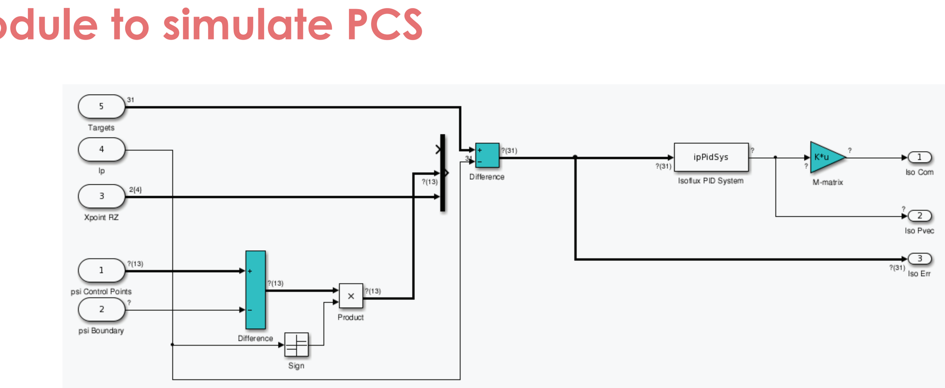
- Isoflux control algorithm contains many free parameters:
  - 18 errors (13 segment errors, 4 x-point, I_p) * 3 PID gains/error = 54 PID gains to set
  - 13x18 decoupling "M-matrix" to spread commands to PF coils = 234 free parameters
- Large number of parameters makes it difficult to tune PID by hand
- Matlab/Simulink Robust Control Toolbox provides tools for automated tuning of closed-loop control systems

Testing to see if automated tools can provide more optimal control settings with far less effort than present "by-hand" approach

The Robust Control Toolbox

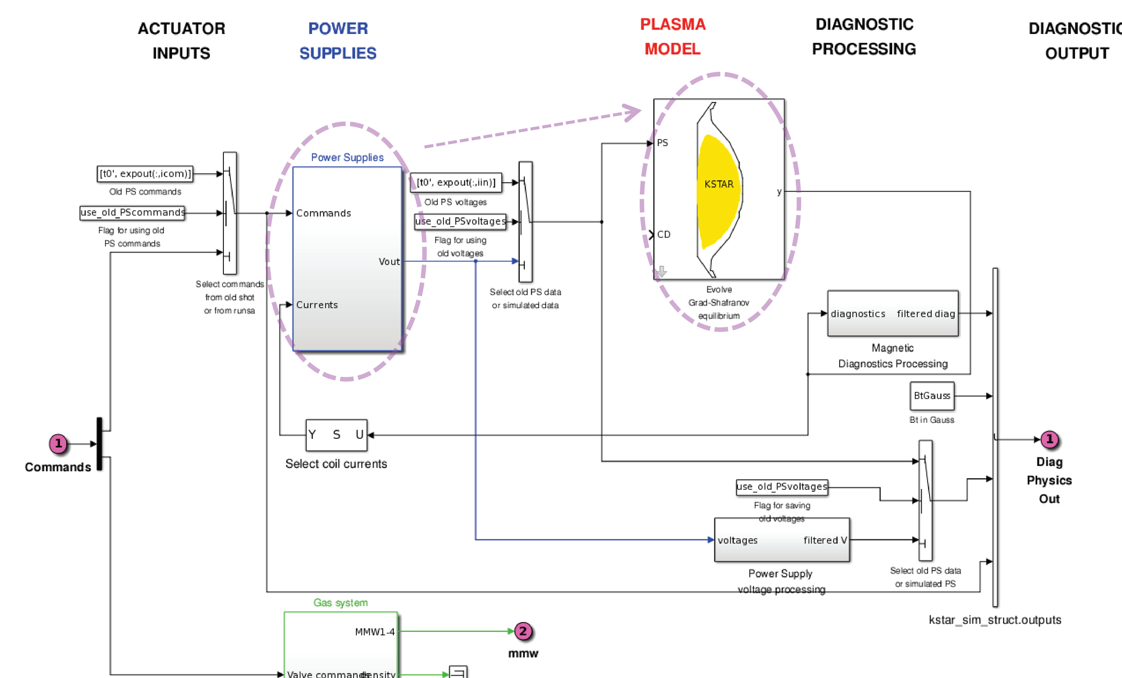
- Set PID controller gains as tunable parameters
- **Looptune:** converts target performance requirements into weighting functions which express them as an H∞ optimization problem
- **Systune:** called by looptune to optimize tunable parameters so as to minimize the H∞ norm
  - Solves minimization problem for vector of tunable parameters x, hard requirements $f_i(x)$, and soft requirements $g_j(x)$: Minimize $\max_i f_i(x)$ subject to $\max_j g_j(x) < 1$ for $x_{min} < x < x_{max}$ [1]

Module to simulate PCS

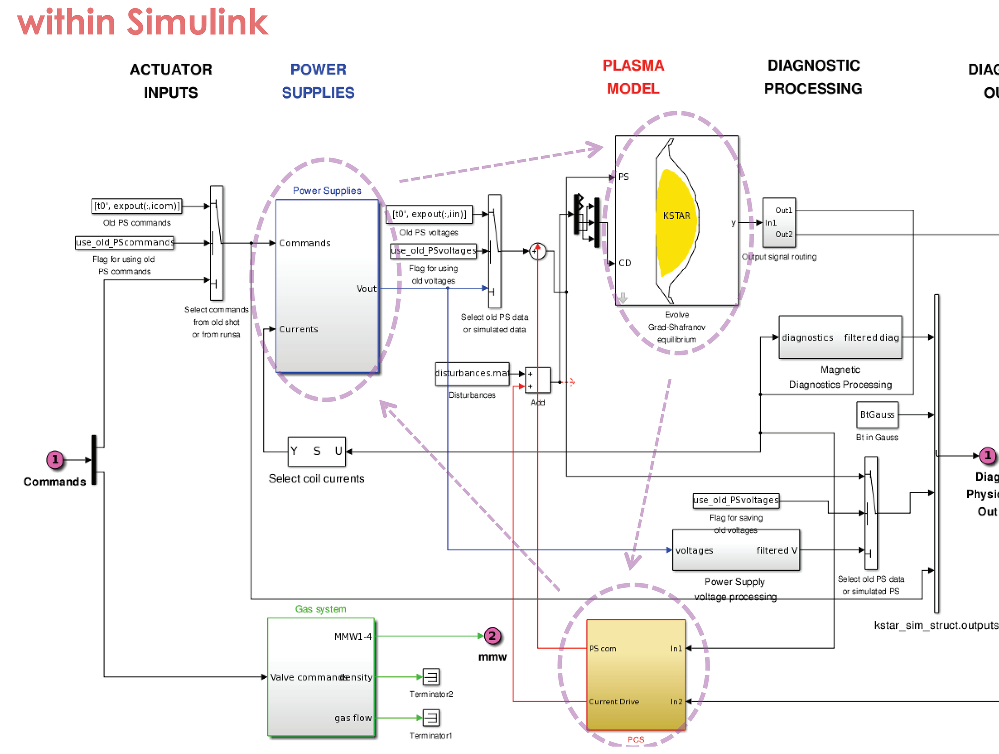


[1] systune - MathWorks Documentation Center: http://www.mathworks.com/help/robust/ref/systune.html

Matlab/Simulink models for tokamak plasma and power supplies already exist: KSTAR

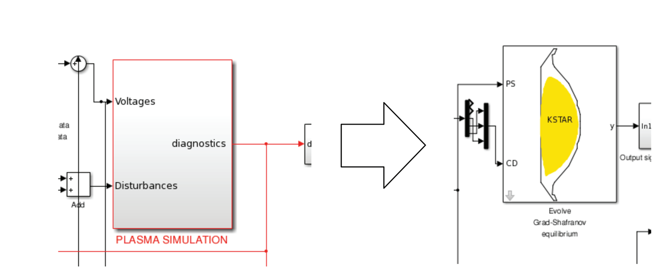


Adding PCS module to enable close-loop simulation within Simulink



Linear plasma model replaced with nonlinear gsEvolve code

- Plasma models simulate 2D Grad-Shafranov equilibrium evolution
- Comparison of models:
  - Linear → Plasma response to external fields constant as equilibrium changes
  - Non-linear → Plasma response recalculated as equilibrium changes
- gsEvolve provides flexiblity to run linear or non-linear model



Conclusions

- Framework established for automated offline optimization of shape controller (PID, decoupling matrix) using Robust Control Toolbox
- Running takes hours → use fewer adjustable parameters
- ↳ Try running simulation with optimized gains
- Controllability metric defined to quantify quality of shape control and compare DIII-D to superconducting devices
- ↳ Investigate effect of grid size on controllability metric