PRINCETON PLASMA PHYSICS LABORATORY

Plasma Control

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June 12th 2025

About Doménica

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Posdoc at PPPL since 2022 → ML, Control, Real-time

Computational Sciences Department (CSD)

Go check the CSD/PPPL webpage
https://www.pppl.gov/research/computational-sciences

Have you heard this words? Put your hand up!

PID controller

Plasma equilibrium

Magnetic Confinement

Poloidal Field Coils

Vertical Displacement Event (VDE)

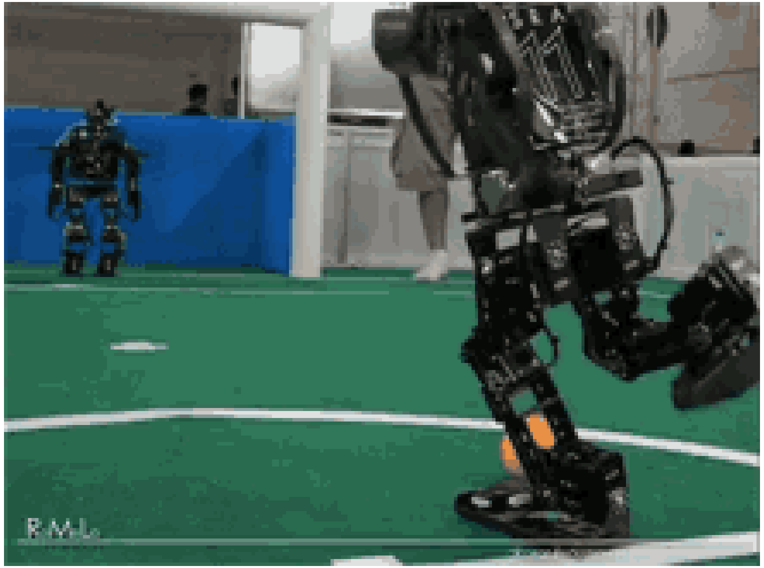
Disruption

State-Space models

Surrogate model

Sensor-Actuator

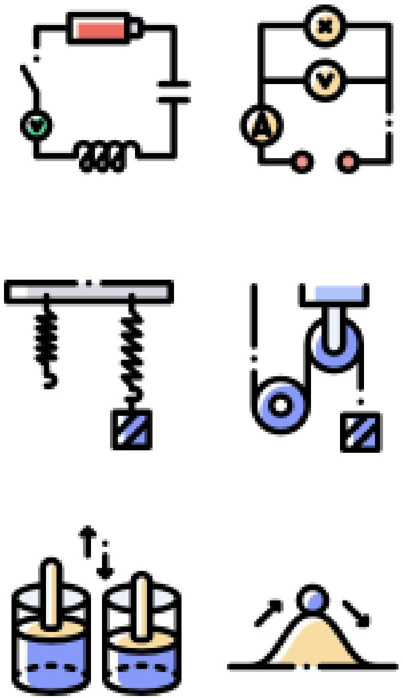
Real-time Control



Let’s get started

Just like a robot can wreck your factory floor, an uncontrolled plasma can wreck your machine

Control systems



Regulating a process or system in order to get a desired behavior.

The key components:

- Plant: The system to be controlled. The current in a circuit. The velocity of a mass. The temperature of a liquid. A tokamak!
- Sensor: Measures the plant’s outputs.)
- Controller: Computes and action to be applied
- Actuator: Applies the control signal … the voltage command to a power supply

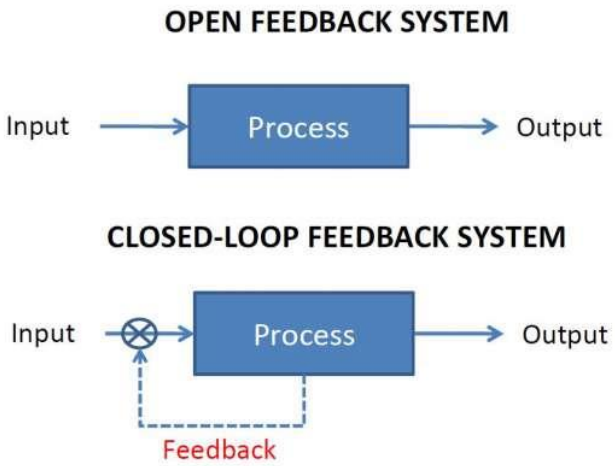
Open Loops vs Closed Loop

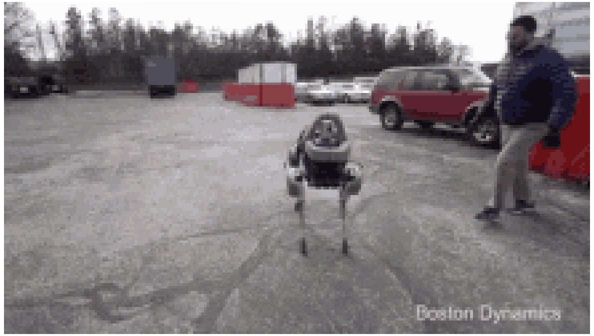
Open-Loop: Controller acts without any feedback, there is no correction of the error

Closed-Loop: Controller uses a sensor feedback to minimize the error

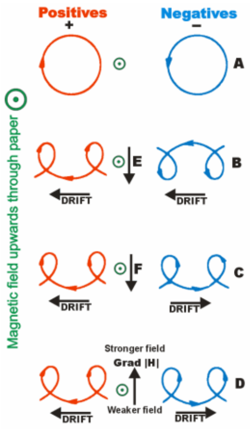
What are the control general objectives?

- **Stability**: Prevent the system from diverging and becoming unstable
- **Tracking:** Follow a reference accurately.
- **Disturbance Rejection:** Reject external perturbations





Magnetic confiment basics



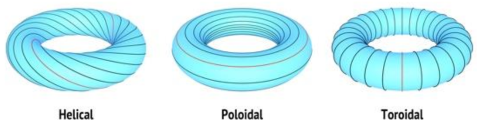
https://www.plasma-universe.com/

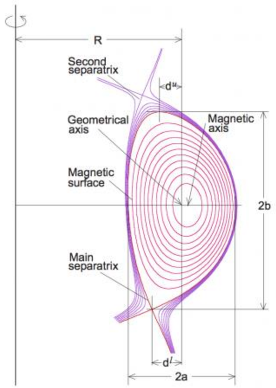
How Magnetic Fields Confine Plasma?

In a uniform magnetic field, charged particles gyrate around field lines

Without field curvature: particles drift → they need field shaping

Toroidal & Poloidal Fields



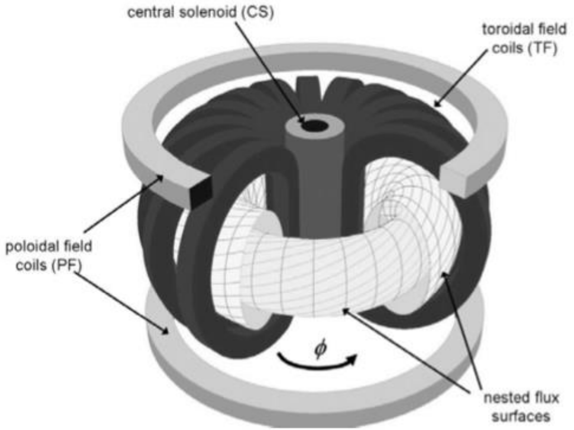


B_T from external coils keeps the plasma wrapped around the tokamak

B_P generated by the plasma current, it “twists” field lines into closed helices

Freidberg, J. P., *Plasma Physics and Fusion Energy*

Why external PF coils are needed?



Plasma-generated Poloidal Field Is Insufficient

The field from the plasma current Ip alone cannot maintain desired equilibrium and shape

Equilibrium & Control position

External PF coils supply adjustable magnetic flux to hold the plasma column at the correct major radius and vertical position.

Shape & Stability Shaping

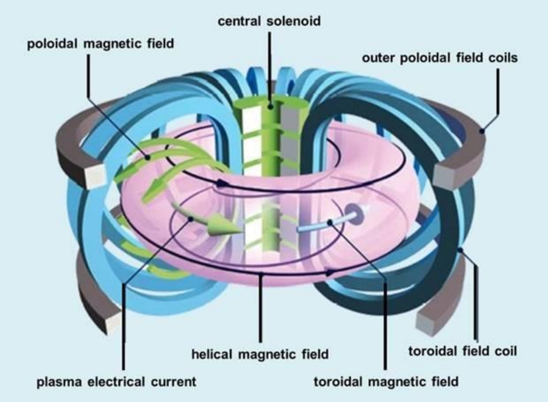
By varying PF coil currents, we can control elongation and triangularity of lux surfaces, improving confinement and suppressing instabilities

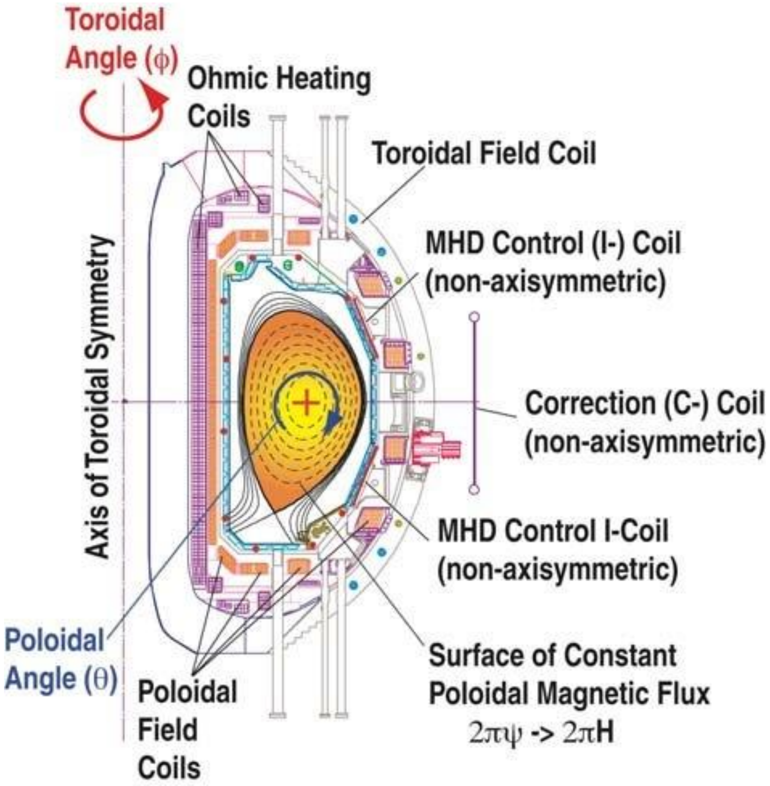
Why tokamak control matters?

Why do we need active control in a tokamak????

Plasma is confined by a combination of toroidal and poloidal magnetic fields

Small deviations in field balance can cause the plasma to drift!





•DOI: 10.1142/9789812818805_0011

Why tokamak control matters?

What are the risks of having an uncontrolled plasma?

The so famous Vertical Displacements Events (VDEs) → Fast upward/downward drifts leading to a wall contact

Disruptions → Sudden loss of confinements, it causes thermal and electromagnetic loads on the vessel
Wall damage and lost of operations → Damage in the tiles, overstressing of the coils and time of our machine not operating

Small deviations in field balance can cause the plasma to drift!

Why is vertical position critical?

Vertical instabilities grow very fast → they must be detected almost instantly

Without stabilization, the plasma touches the top or bottom of the vessel → aborted discharge

Vertical Instability in a tokamak

Inherent Unstable Equilibrium

An elongated plasma column has no natural restoring force in the vertical direction

Small vertical displacements grow exponentially without feedback

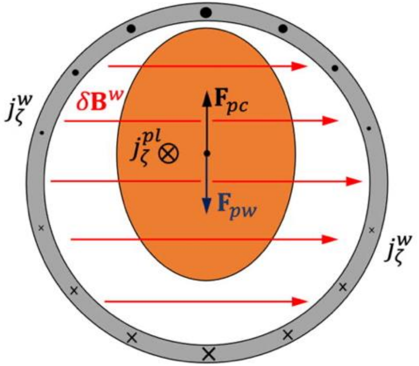
Requires detection and correction on less than one millisecond timescales

Dependence on Plasma Shape

Higer elongation κ → faster vertical growth
Triangularity δ and plasma current profile also influence stability

Need for active feedback

External PF coils + real-time controller can avoid the instability



Analytical estimates of the vertical displacement growth rate in tokamaks with a resistive wall," *Physics of Plasmas* **32**, 032511

Magnetic Control of Tokamaks via Deep Reinforcement Learning

So.. What's now the problem? 😥

Traditional controllers struggle with complex, time-varying plasma dynamics and MHD instabilities, engineers needed to tune a lot during operations

Reinforcement Learning solution 🧐

An agent "learns" coil-current policies by trial in a high-fidelity simulator, optimizing position & stability objectives.

Results

Tested on real-time achieving a faster suppression of the vertical drifts

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Article | Open access | Published: 16 February 2022

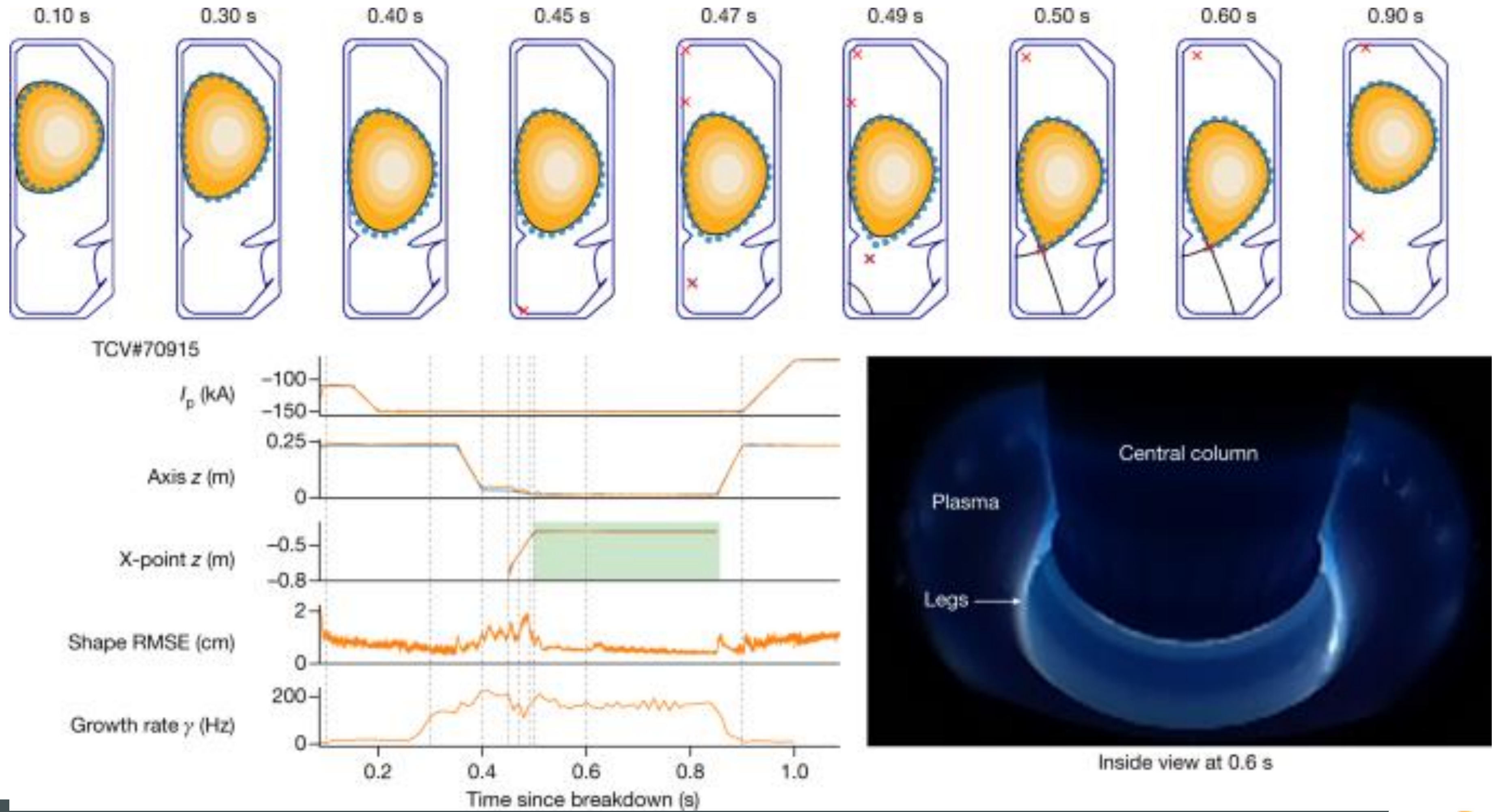
Magnetic control of tokamak plasmas through deep reinforcement learning

Jonas Degrave, Federico Felici, Jonas Buchli, Michael Neunert, Brendan Tracey, Francesco Carpanese, Timo Ewalds, Roland Hafner, Abbas Abdolmaleki, Diego de las Casas, Craig Donner, Leslie Fritz, Cristian Galperti, Andrea Huber, James Keeling, Maria Tsimpoukelli, Jackie Kay, Antoine Merle, Jean-Marc Moret, Seb Noury, Federico Pesamosca, David Pfau, Olivier Sauter, Cristian Sommariva, ... Martin Riedmiller + Show authors

Nature **602**, 414–419 (2022) | Cite this article

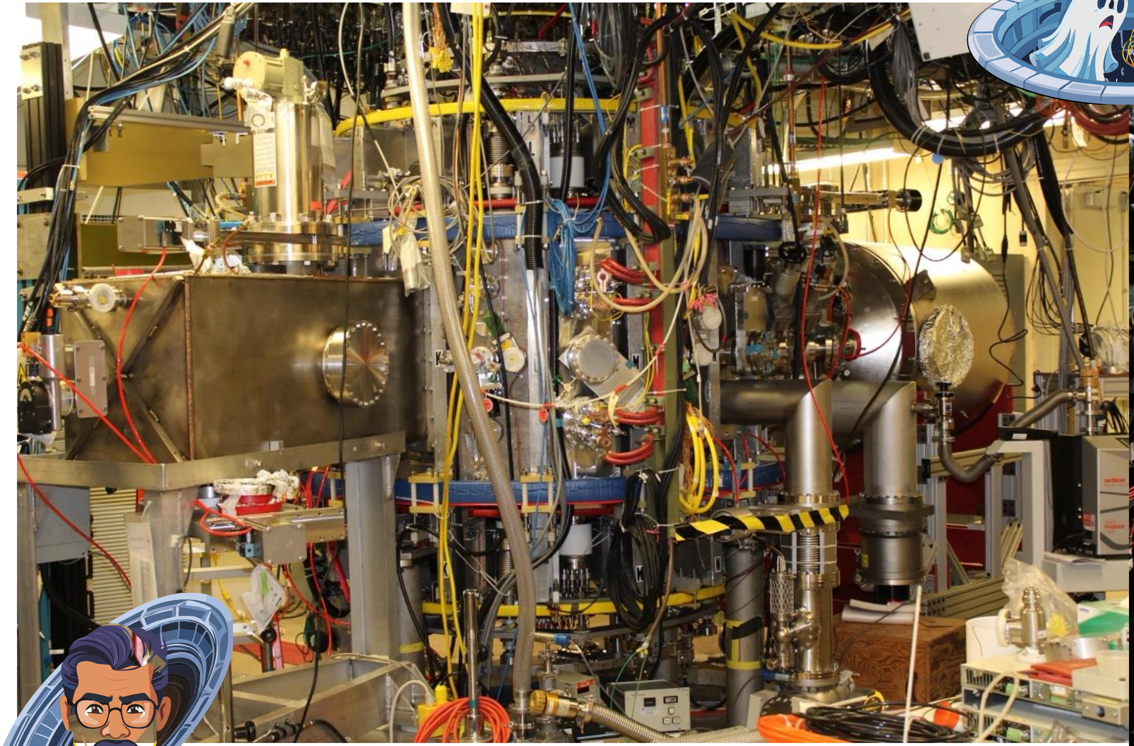
plasma current, all of which must be designed to not mutually interfere[6]. Most control architectures are further augmented by an outer control loop for the plasma shape, which involves implementing a real-time estimate of the plasma equilibrium[9,10] to modulate the feedforward coil currents[8]. The controllers are designed on the basis of linearized model dynamics, and gain scheduling is required to track time-varying control targets. Although these controllers are usually effective, they require substantial engineering effort, design effort and expertise whenever the target plasma configuration is changed, together with complex, real-time calculations for equilibrium estimation.

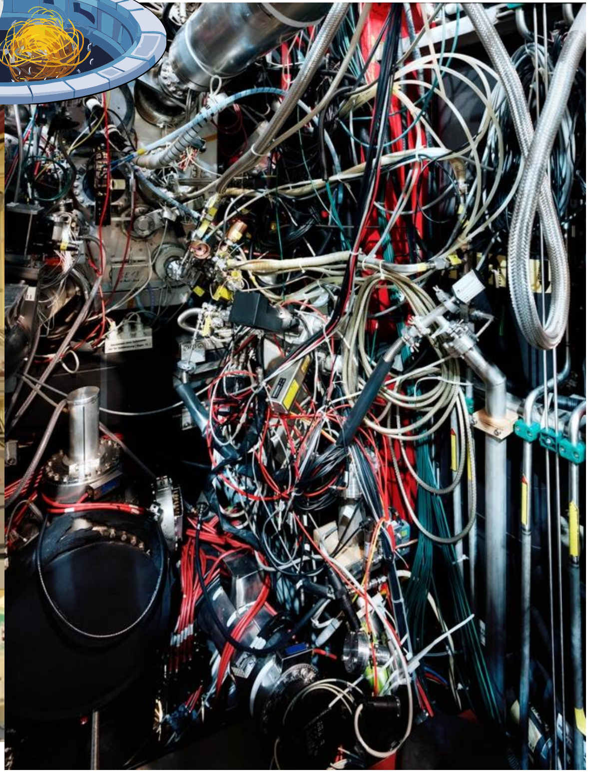
A radically new approach to controller design is made possible by using reinforcement learning (RL) to generate non-linear feedback controllers. The RL approach, already used successfully in several challenging applications in other domains[11–13], enables intuitive setting of performance objectives, shifting the focus towards what should be achieved, rather than how. Furthermore, RL greatly simplifies



0.10 s
0.30 s
0.40 s
0.45 s
0.47 s
0.49 s
0.50 s
0.60 s
0.90 s
TCV#70915
I_p (kA)
−100
−150
0.25
Axis z (m)
0
−0.5
X-point z (m)
−0.8
2
Shape RMSE (cm)
0
200
Growth rate γ (Hz)
0
0.2
0.4
0.6
0.8
1.0
Time since breakdown (s)
Central column
Plasma
Legs
Inside view at 0.6 s

Engineering & Control approaches





When they talk about control in tokamak ....

Density control

Fueling and pumping

Magnetic Control

PF coils and plasma stabilization

Whenever someone says “control”, they really mean ” magnetic control”, density folks are a silent majority 🤭

The PF coils … again 🙄 in case we forgot it

Equilibrium and position Control

Adjust coil currents to maintain the plasma major-radius and vertical position

Fast feedback loop: position → PF coils drive

Shaping & Stability Shaping

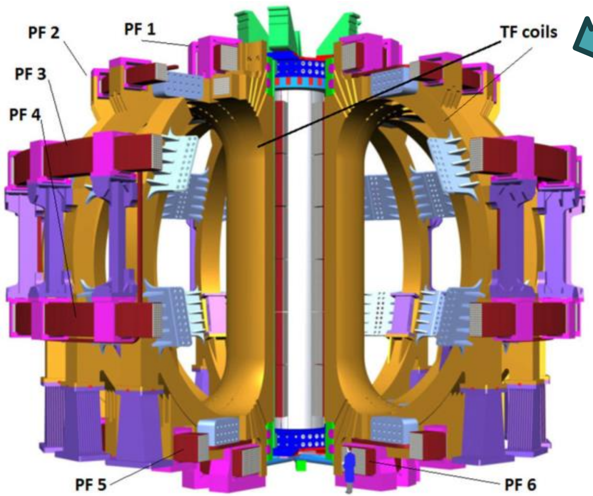
Vary coil currents to control elongation κ and triangularity δ

Tailor flux-surface geometry to suppress MHD modes

Inductive support & Ramp-rate

During current ramp-up/down, PF coils provide changing flux to drive plasma current too
Ensures smooth transition without large loop-voltage spikes

ITER coils



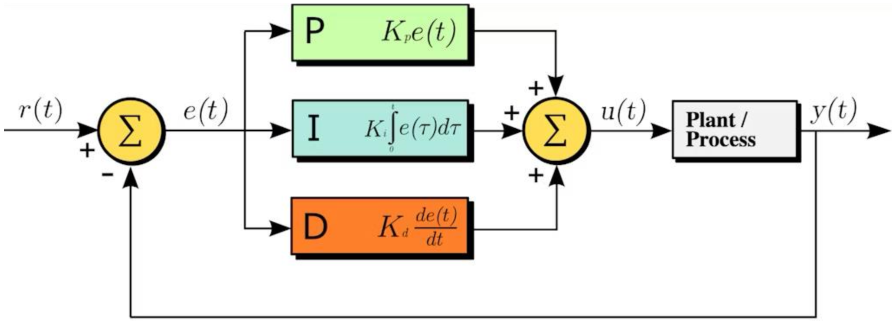
PID Controller

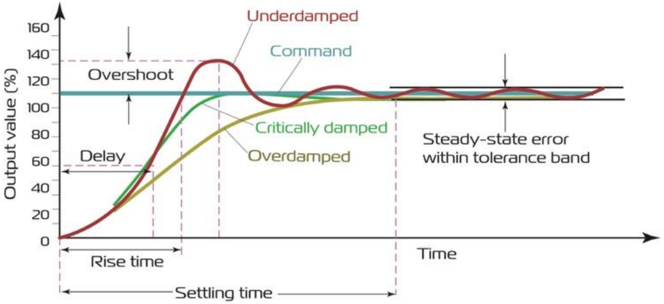
What is a PID controller?

Proportional: acts on current error
$e(t) = r(t) - y(t)$

Integral: eliminates steady-state error by accumulating $\int e(t)dt$

Derivative: predicts future error via $\frac{d}{dt}e(t)$



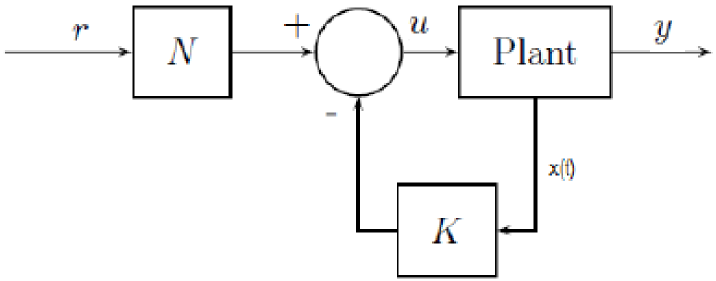


State-Space Feedback & MIMO control

Why State-Space?

Captures multi-variable dynamics in the matrix form:

$\dot{x} = Ax(t) + Bu(t) \quad y = Cx(t) + Du(t)$



Full state feedback

Control law: $u(t) = -Kx(t) + r$

Places closed-loop poles for desired speed & damping

State-Space Feedback & MIMO control

Design Methods

LQR: solves $min \int (x^T Q x + u^T R u) dt$

Kalman filter: estimates the states (x) from noisy sensors

Implementation in PCS

On a Real-time set up: state estimation → Gain x State → coil commands

But wait … what is a ”pole” what is a "PCS" ??? 🤨

Poles and Zeros

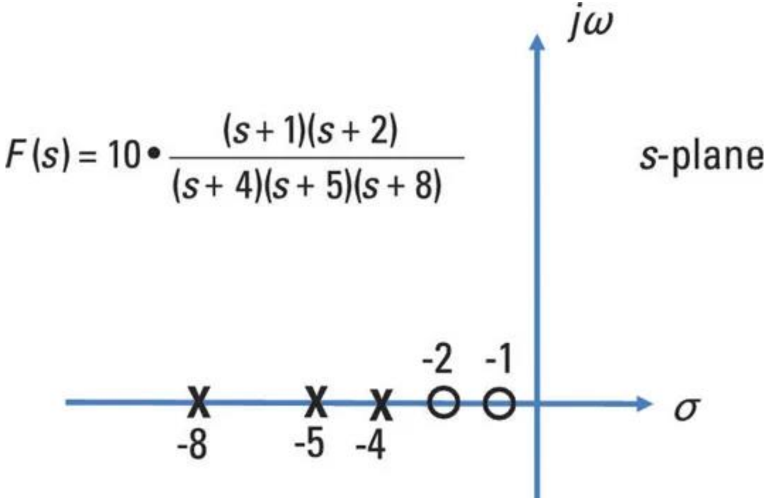
Transfers function Basics

Any linear system can be written as:

$$H(s) = \frac{N(s)}{D(s)} = \frac{(s - z_1)(s - z_2) \ldots}{(s - p_1)(s - p_2) \ldots}$$

Where z are the zeros (roots of numerator)

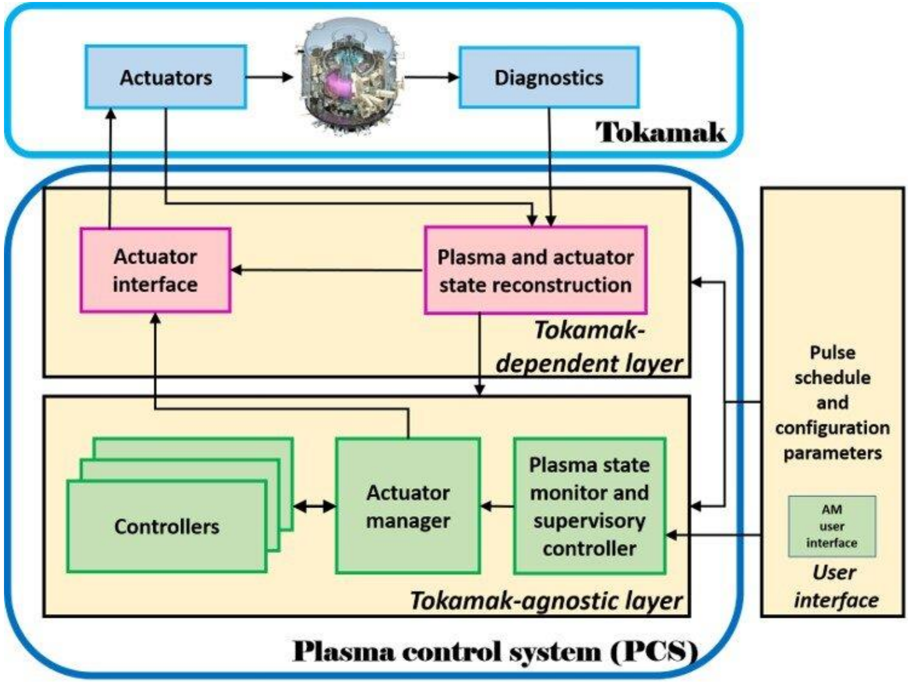
P are the poles (roots in denominator)

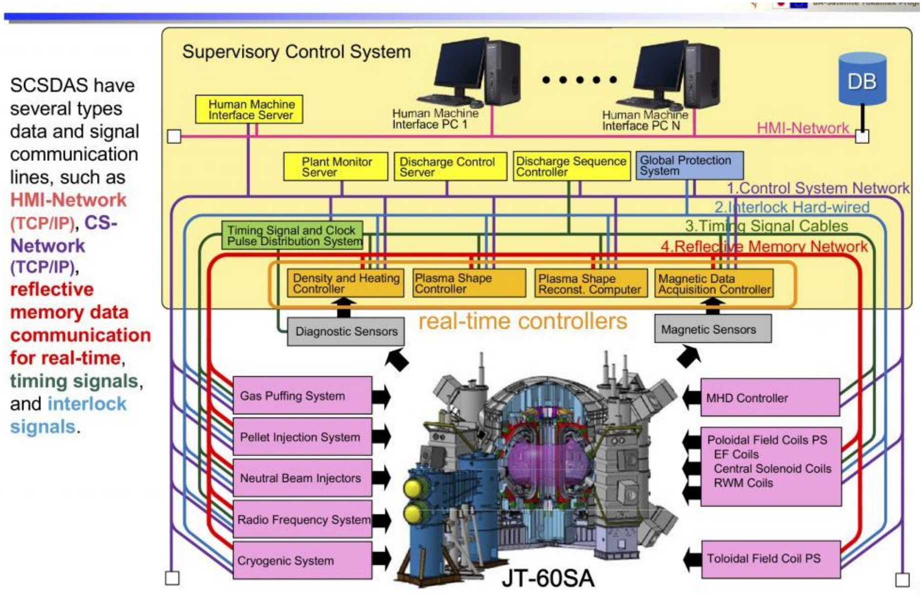


Zeros→ Act like "notches" to the response, they block certain behaviors
Poles → Natural modes of the system, determine how fast or slow the system responds

Stability → If all poles lie in the left half of the s-plane $(Re\{p_i\} < 0)$

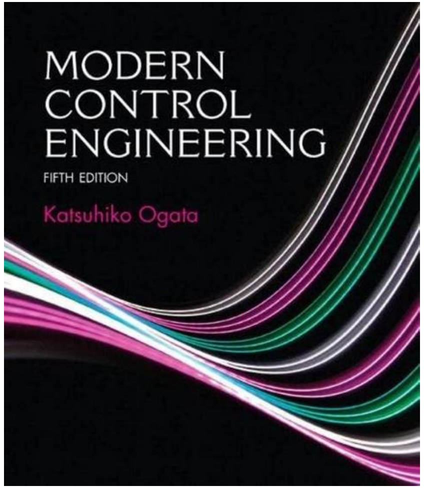
The plasma control systems

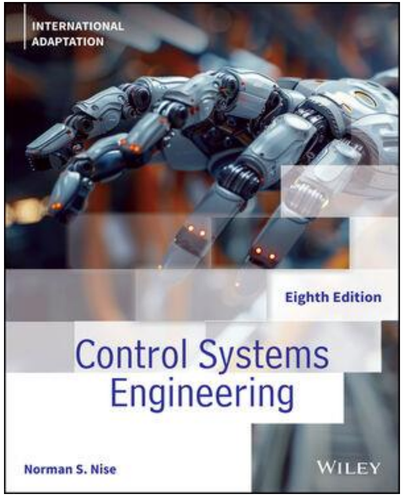


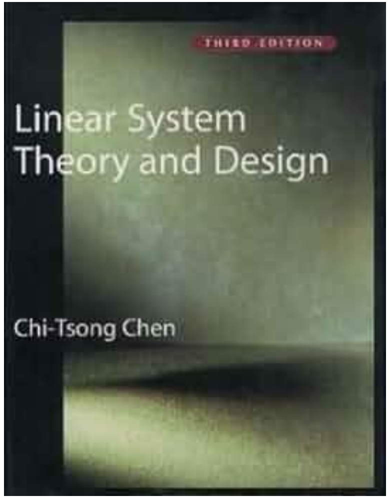


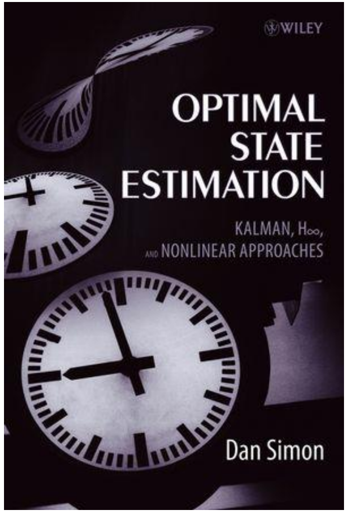
•DOI: 10.48550/arXiv.2010.16145

Control books:

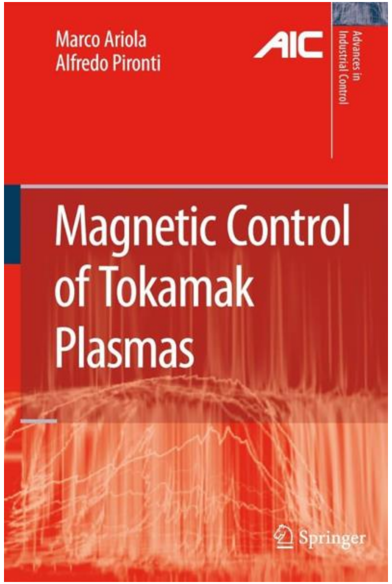


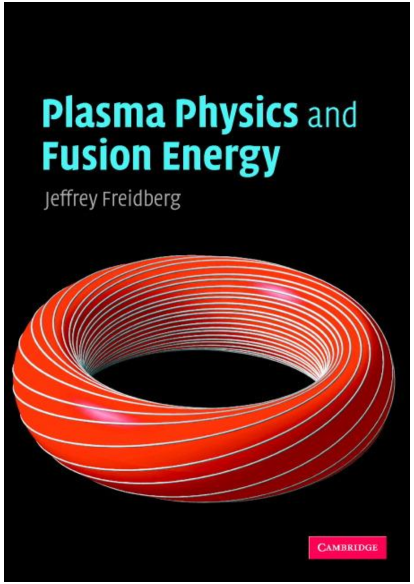


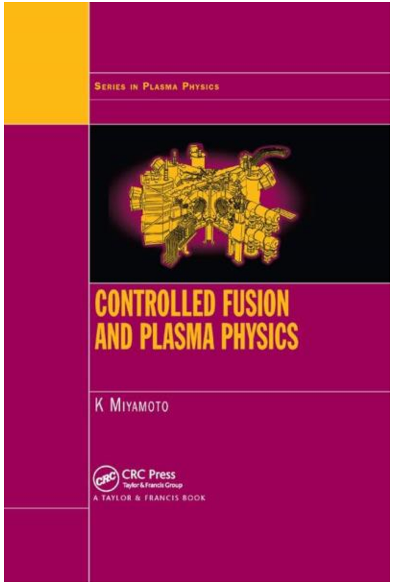


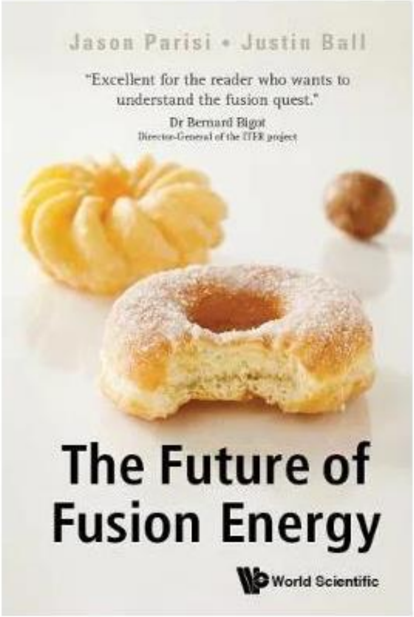


Personal favorite:









Wrote by PPPL folk 👆

Question, comments , thoughts …..