# Plasma Control

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# About Doménica

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

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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)

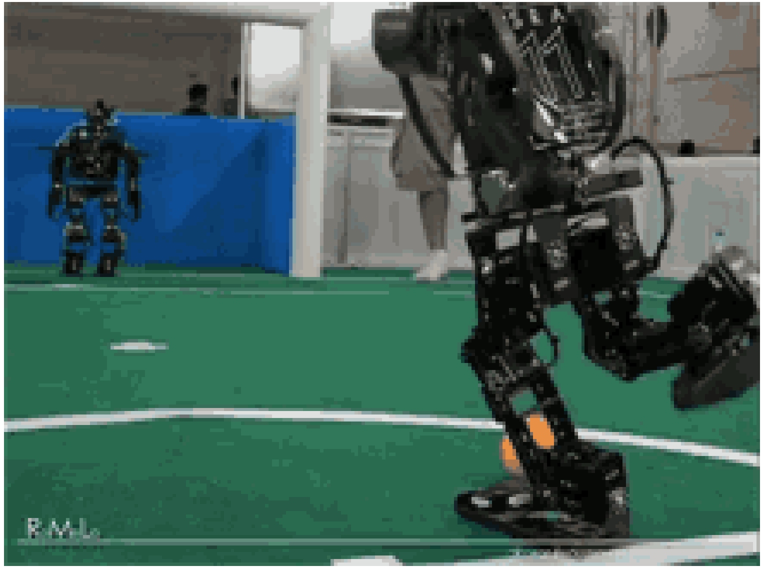
Disruption

State-Space models

Surrogate model

Sensor-Actuator

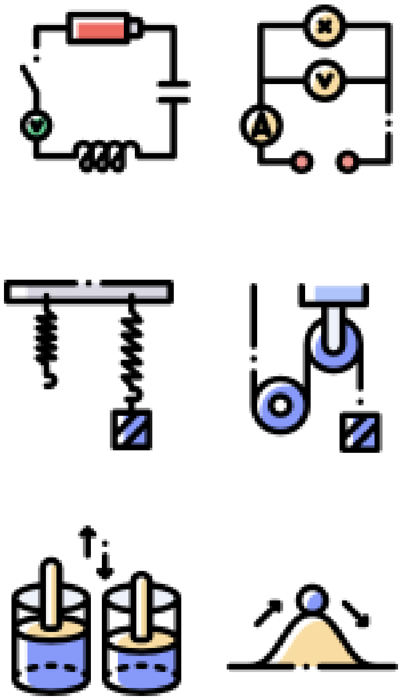
Real-time Control




# 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

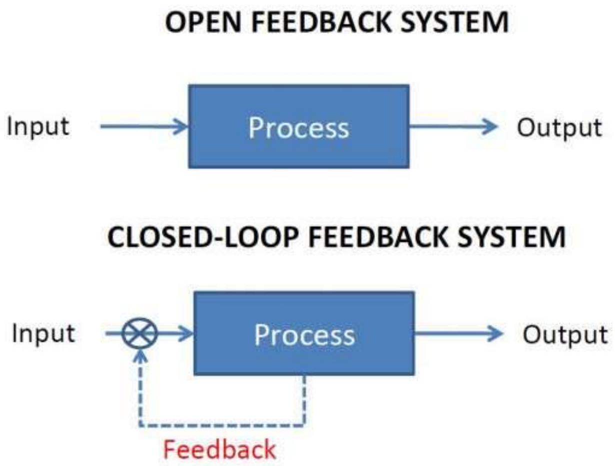
# Open Loops vs Closed Loop

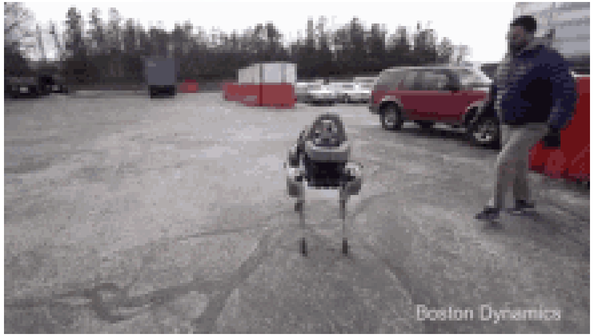
**Open-Loop:** Controller acts without any feedback, there is no correction of the error

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

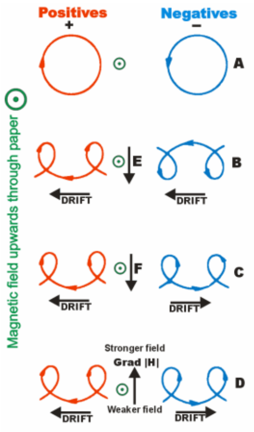
What are the control general objectives?

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



# Magnetic confiment basics



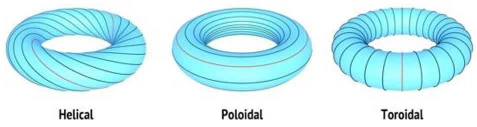

https://www.plasma-universe.cor

### How Magnetic Fields Confine Plasma?

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

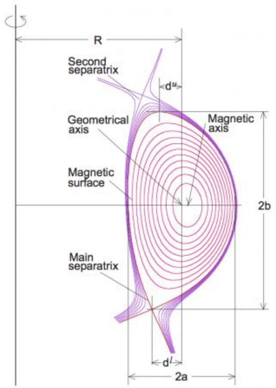
Without field curvature: particles drift → they need field shaping

### 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

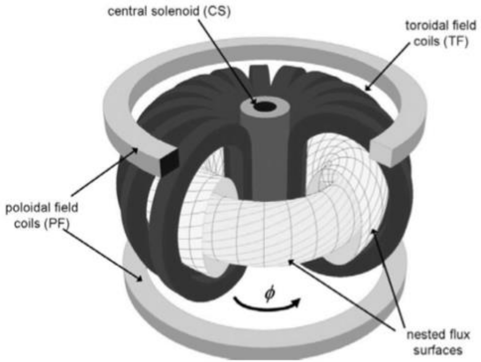



Freidberg, J. P., *Plasma Physics and Fusion Energy*

# 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**

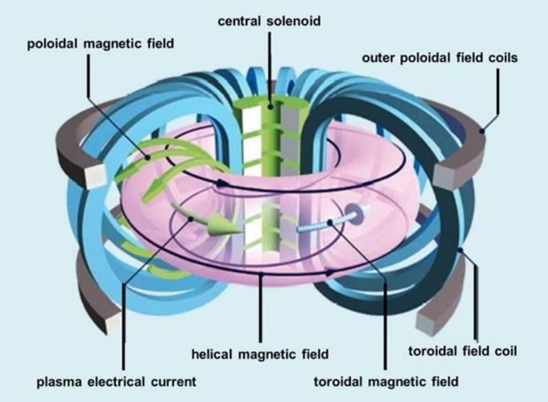
By varying PF coil currents, we can control elongation and triangularity of lux surfaces, improving confinement and suppressing instabilities

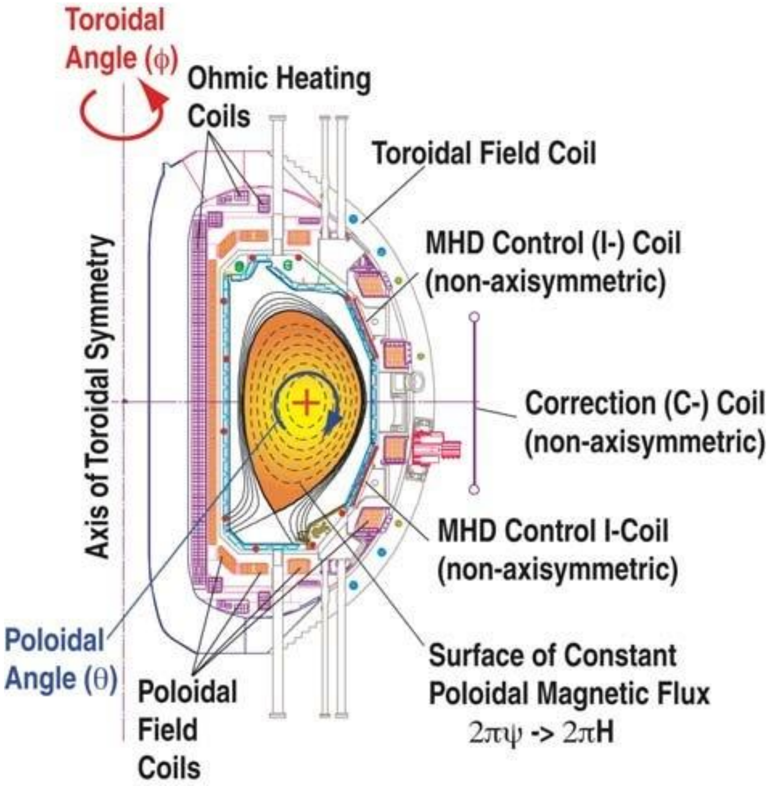
# Why tokamak control matters?

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

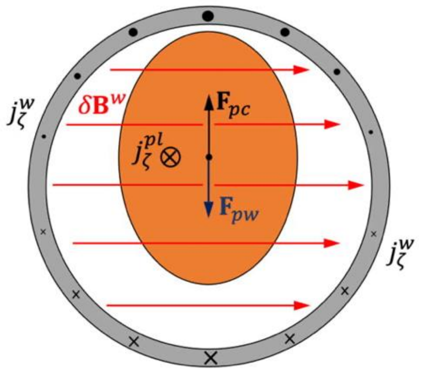
Requires detection and correction on less than one millisecond timescales

**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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**Magnetic control of tokamak plasmas through deep reinforcement learning**

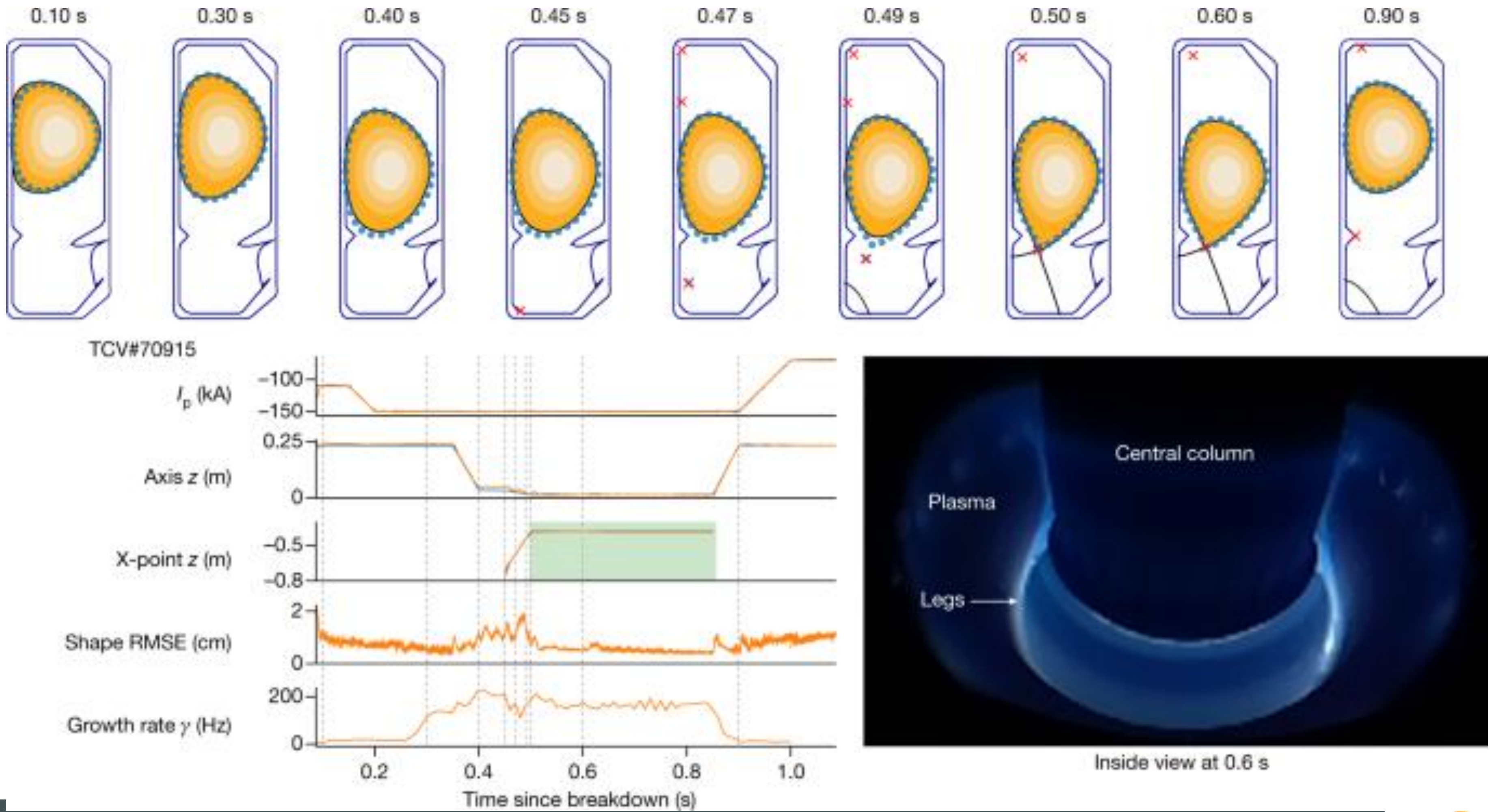
Jonas Degrave, Federico Felici, Jonas Buchli, Michael Neunert, Brendan Tracey, Francesco Carpanese, Timo Ewalds, Roland Hafner, Abbas Abdolmaleki, Diego de las Casas, Craig Donner, Leslie Fritz, Cristian Galperti, Andrea Huber, James Keeling, Maria Tsimpoukelli, Jackie Kay, Antoine Merle, Jean-Marc Moret,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

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

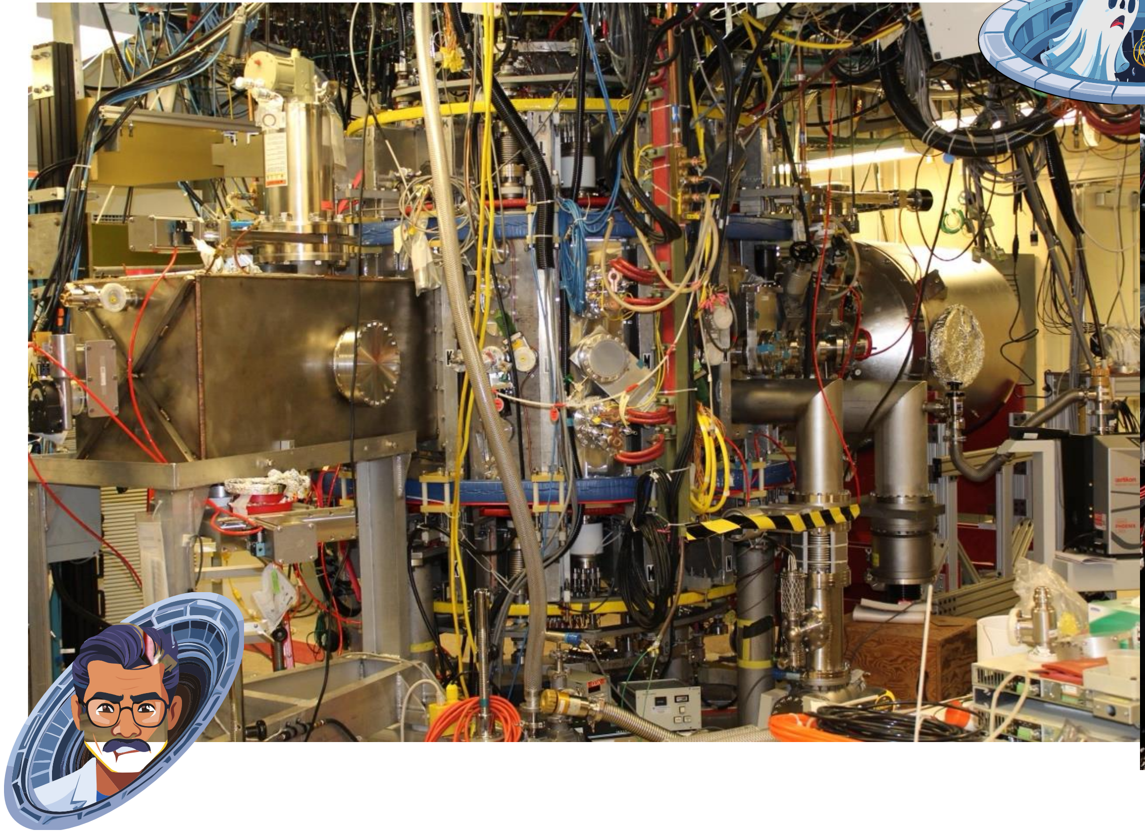


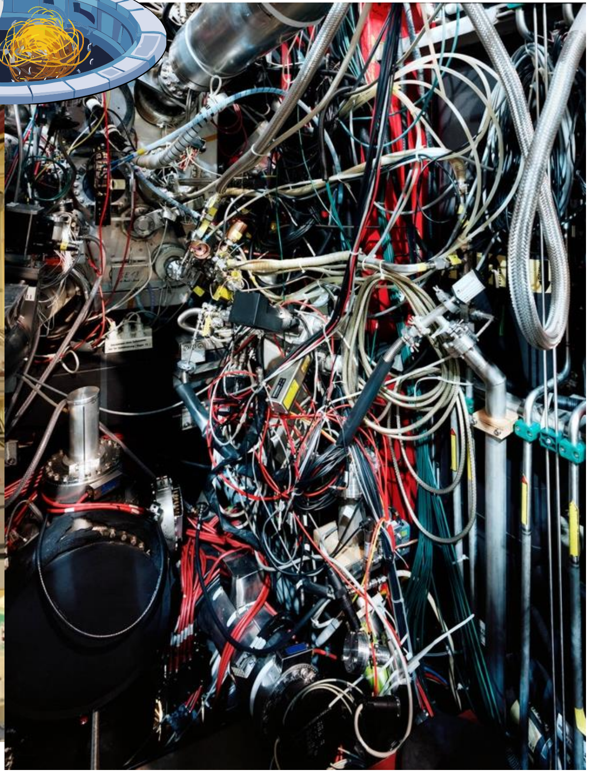
plasma current, all of which must be designed to not mutually interfere[6]. Most control architectures are further augmented by an outer control loop for the plasma shape, which involves implementing a real-time estimate of the plasma equilibrium[9,10] to modulate the feedforward coil currents[8]. The 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
Axis $z$ (m)
0.25
0
X-point $z$ (m)
−0.5
−0.8
Shape RMSE (cm)
2
0
Growth rate $\gamma$ (Hz)
200
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 🤭

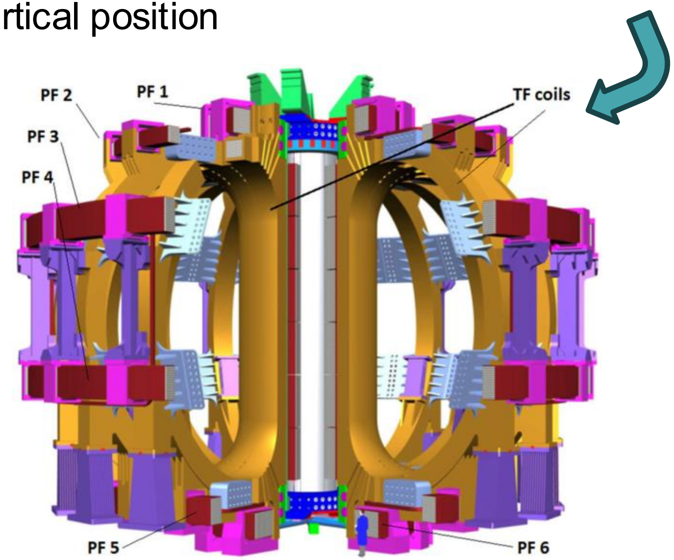
# The PF coils … again 🙄 in case we forgot it

**Equilibrium and position Control**

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

Fast feedback loop: position → PF coils drive

ITER coils




**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

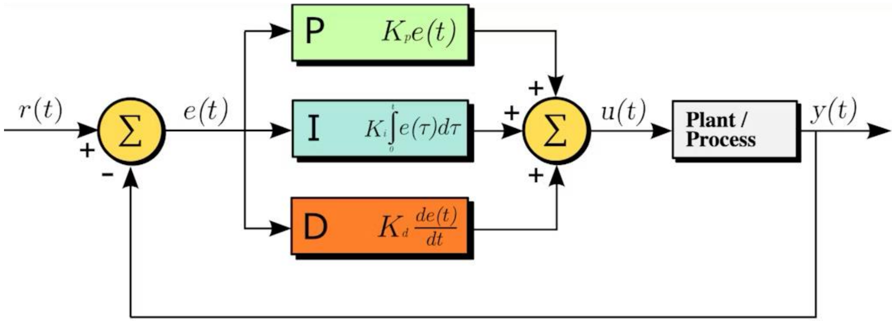
# PID Controller

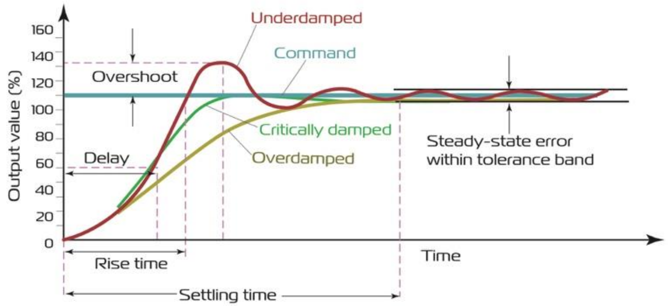
**What is a PID controller?**

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 $\frac{d}{dt}e(t)$



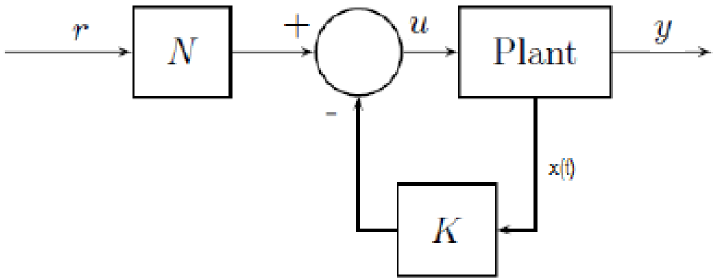



# State-Space Feedback & MIMO control

**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 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

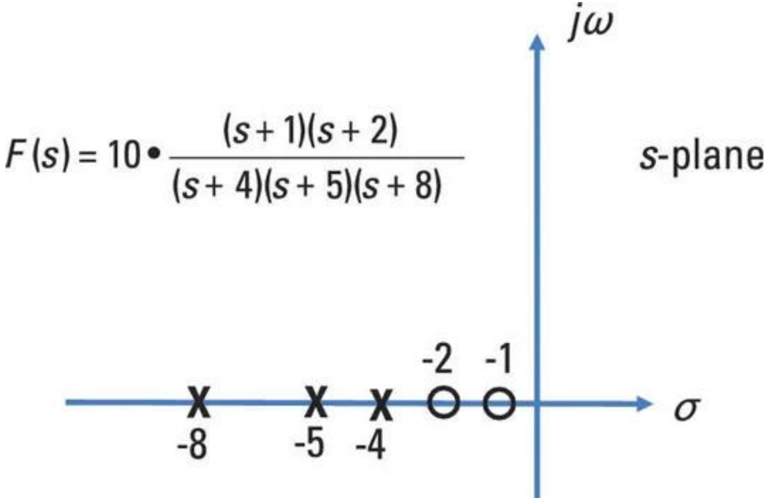
**Transfers function Basics**

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)

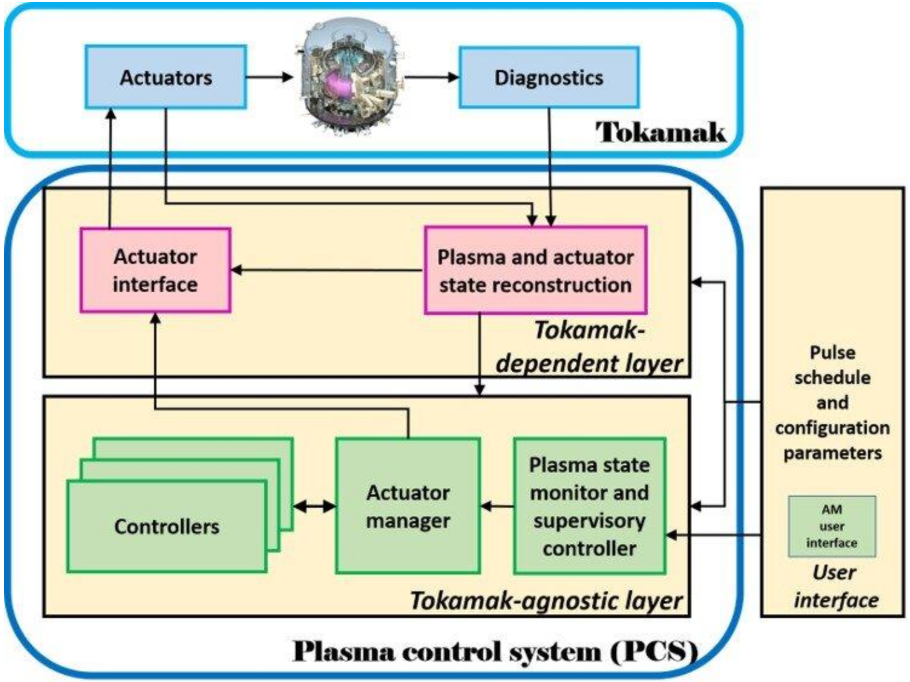
P are the poles (roots in denominator)

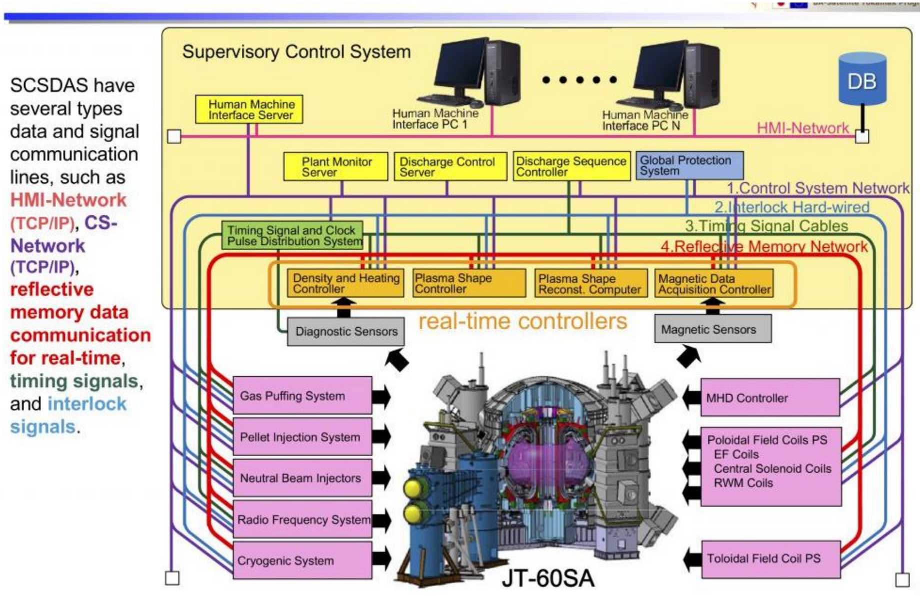



**Zeros→** Act like “notches” to the response, they block certain behaviors
**Poles →** Natural modes of the system, determine how fast or slow the system responds

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

# The plasma control systems

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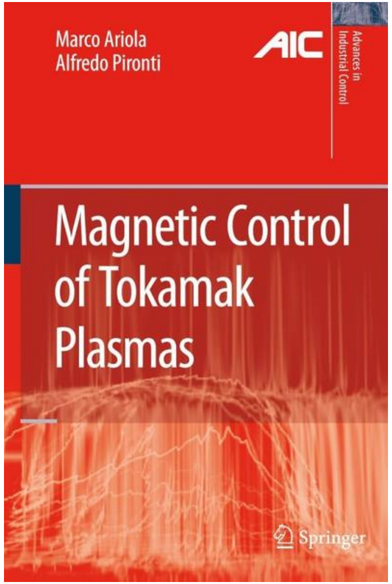
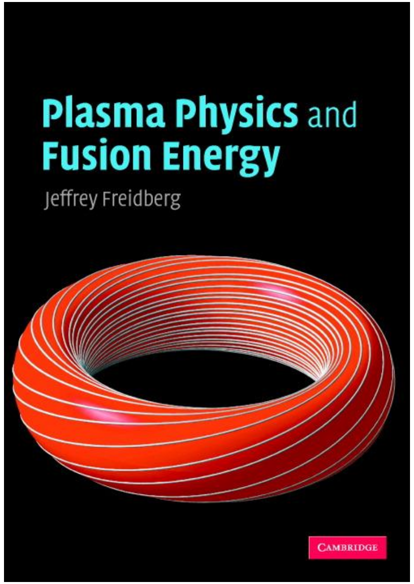
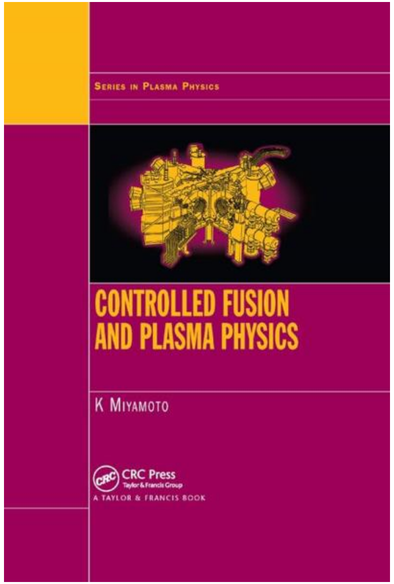
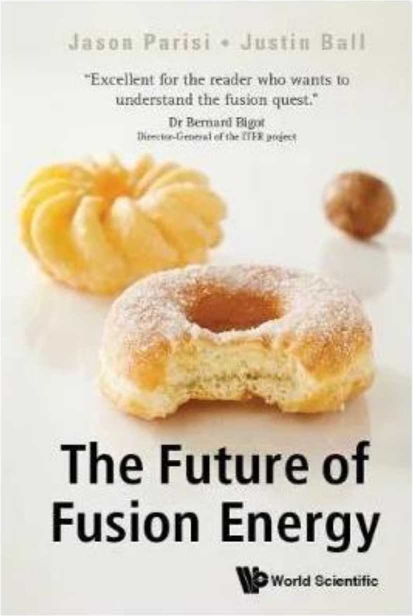
# Personal favorite:



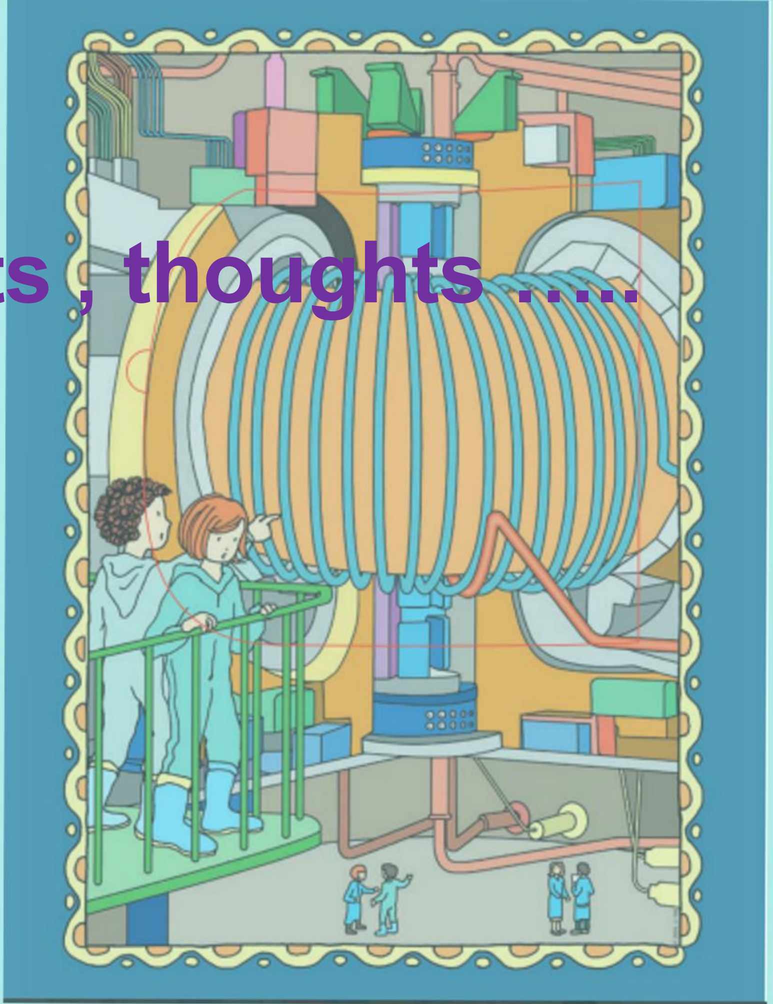




Wrote by PPPL folk 👆

# Question, comments , thoughts …..



$$L\frac{dI_{MEAS}(t)}{dt} + RI_{MEAS}(t) = V_{COMMAND}(t)$$

$$I[k+1] = I[k] + \frac{T_s}{L}(V_{COMMAND}[k] - RI[k])$$

$$V_{COMMAND}[k] = K_p e[k] + K_I T_s \sum_{j=0}^{k} e[j]$$