Overview of Topics in Tokamak Control

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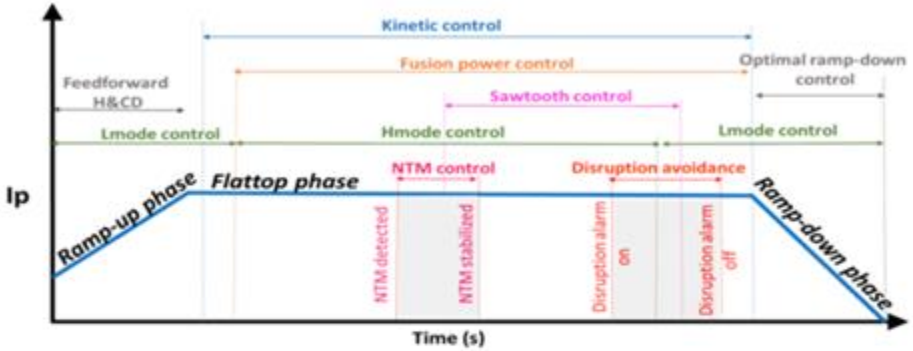
Credits to EPFL Tokamak Control Course

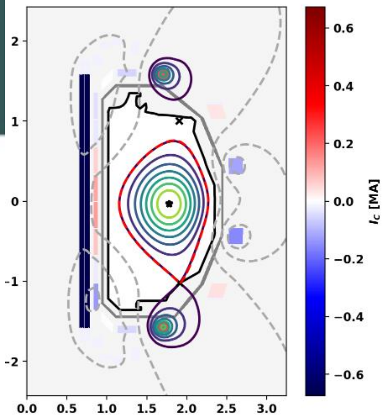
Plasma Control

Key topics relevant to our work

- Rampup control (heating trajectories)
- Safe rampdown control
- <u>Magnetic shape control</u>
- <u>MHD control (sawteeth, TMs and ELMs)</u>
- <u>Kinetic profile control (eg density control)</u>
- Fusion power control (alpha particles)
- Heat flux control (detachment)
- Impurity control (tungsten, wall conditioning)
- Disruption control (everything)

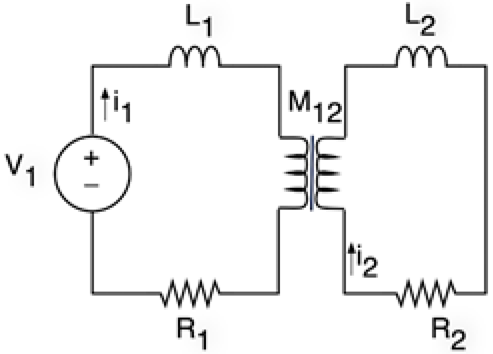


Magnetic shape control



- **Everything is a transformer circuit!**
- **L is self inductance, R is resistance/how 1 affects 1**
- **M is mutual inductance/how 1 affects 2**
- **V is actuation**
- **We want to put everything in state-space f** $\dot{x} = Ax + Bu$

$$
\begin{aligned}
V_1 &= L_1 \dot{i}_1 + M_{12} \dot{i}_2 + R_1 i_1 \\
0 &= L_2 \dot{i}_2 + M_{12} \dot{i}_1 + R_2 i_2
\end{aligned}
\longrightarrow
\begin{pmatrix} L_1 & M_{12} \\ M_{12} & L_2 \end{pmatrix} \begin{pmatrix} \dot{i}_1 \\ \dot{i}_2 \end{pmatrix} + \begin{pmatrix} R_1 & 0 \\ 0 & R_2 \end{pmatrix} \begin{pmatrix} i_1 \\ i_2 \end{pmatrix} = \begin{pmatrix} 1 \\ 0 \end{pmatrix} V
$$

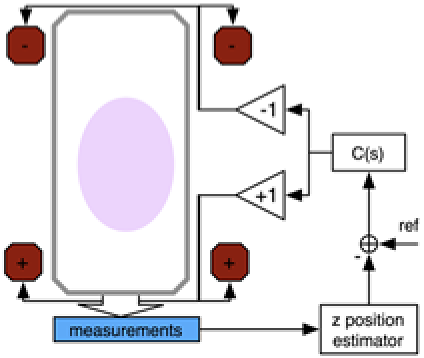


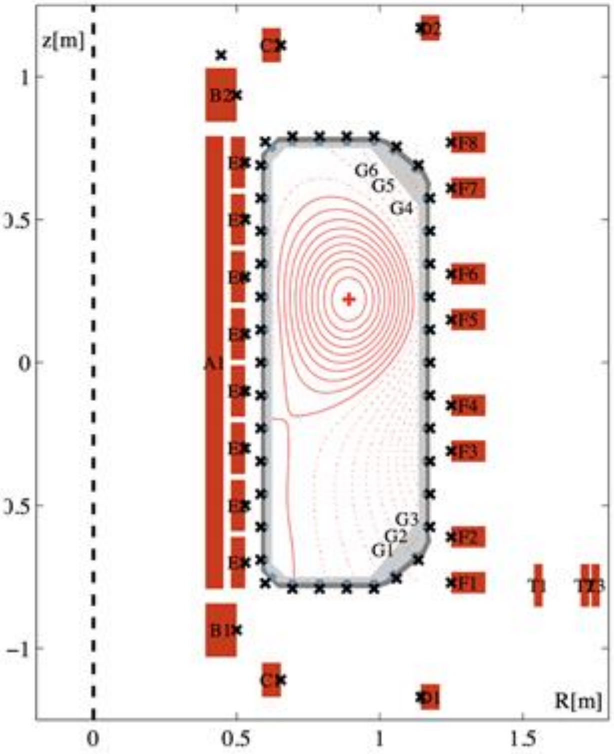
You can add more coils, add vacuum vessel eddies, add a (simple) plasma, still applies! Can solve this analytically with least squares…

Plasma Control

Vertical control

- Elongated plasmas (high performance) are vertically unstable, causing disruptions
- Growth rate is slowed down by vacuum vessel eddies, but still needs extra coil control (G1-6)
- This is generally solved with a physics model and PID control below, but harder for ... d shapes





Plasma Control

Grad-Shafranov for plasma equilibrium

$$\Delta^* \psi = -4\pi^2 \left(\mu_0 r^2 p'(\psi) + TT'(\psi) \right)$$

Flux function (plasma shape)

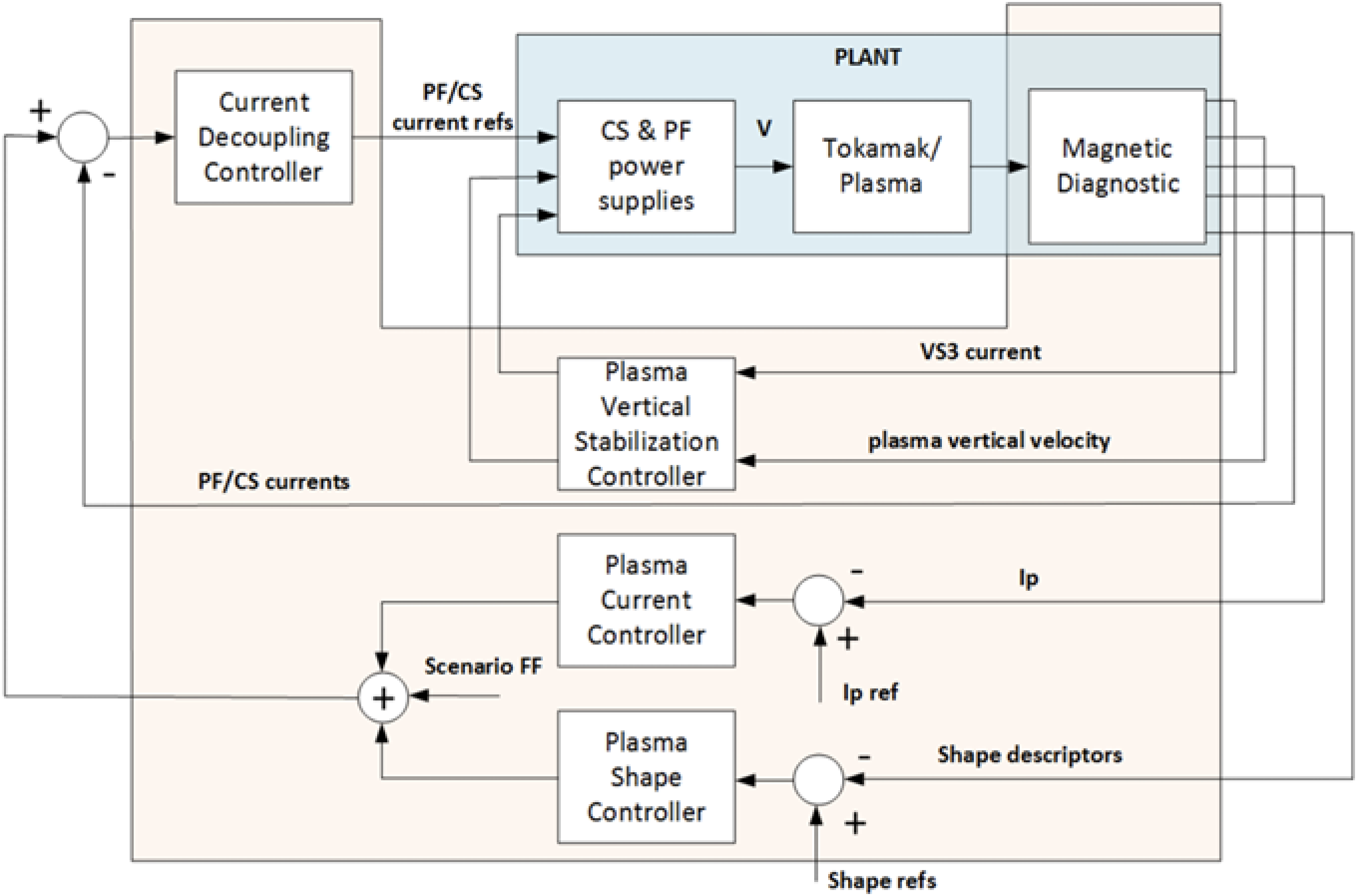
Pressure gradient

T=r*B_pol

- What it solves as an inverse problem: given coil currents and magnetic measurements which tell us the vacuum flux, find the plasma internal flux by guessing p, T and iterating. This is done by EFIT1,2, LIUQE, Tokamaker
- If we have pressure = density * Temperature from Thomson Scattering and other diagnostics, we get kinetic EFITs (EFIT3,4…, CAKE)
- Eternal question: what i o??? We normally use rho.

$$\psi_N = \frac{\psi - \psi_{axis}}{\psi_{edge} - \psi_{axis}}, \rho = \sqrt{\psi_N}$$

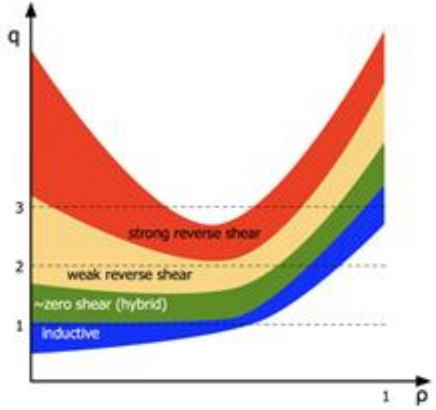
Overview of magnetic control



Plasma Control

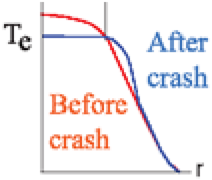
MHD control

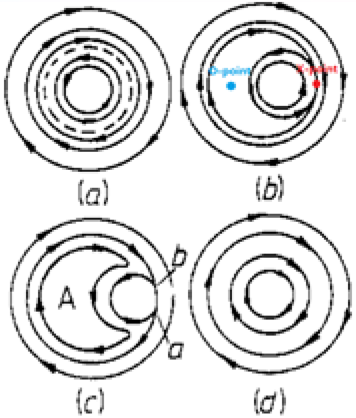
- The q profile, q(rho) = toroidal turns/poloidal turns = m/n, is fundamental to MHD instabilities.
- Low m, n numbers have lower energy so easier for islands to form and often more problematic
- Sawteeth are m=1, n=1 (1/1) islands, so only appear when q=1 surface exists.
- Tearing modes can have other mode numbers, but mainly 2/1, 3/2, and can go arbitrarily high

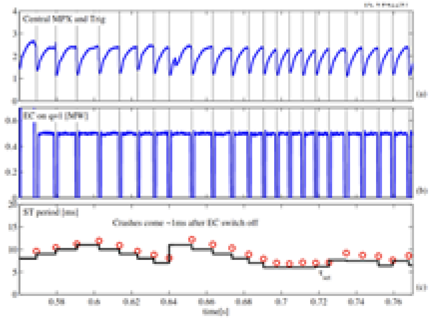


Sawteeth

- When q profile drops below 1, m=1/n=1 core islands form periodically, spitting out core energy to edge
- Core Te drops, edge Te rises, and at q=1 nothing changes! Good way to measure q=1 location
- Slow period sawteeth get bigger, and they can trigger tearing modes and ELMs
- We can control frequency of sawteeth using ECCD



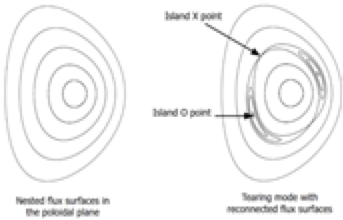




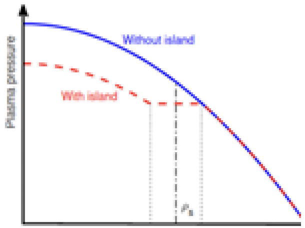
Plasma Control

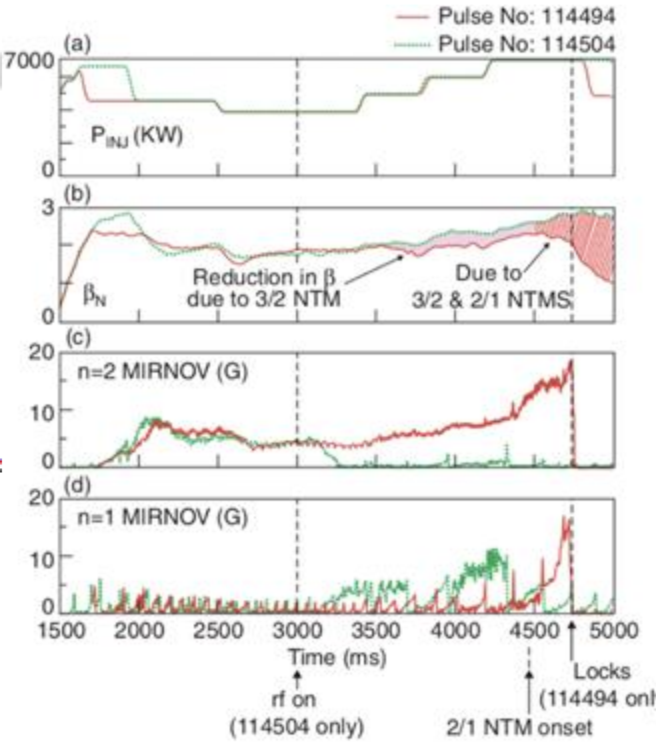
Tearing modes

- Islands form at rational surfaces
- Higher q tearing modes have bigger radii, so reduce confinement more
- Low m and n numbers require less energy to reconnect, so these modes are more likely.
- Therefore 2/1 modes are common and most damaging
- Islands rotate at plasma rotation speed so n numbers can be detected with mirnov coil oscillations (n1,2,3rms)
- As islands grow, they can stop rotating (lock)due to vacuur vessel eddies, leading to



[F. Felici, PhD thesis, 2011]





Controlling tearing modes

- The cause of tearing modes is complicated and isn't well modelled with state of the art physics (modified rutherford equation) but can be decently predicted using data-driven models
- Tearing modes are strongly correlated with beta, so reducing heating can reduce tearing modes. But we want to maximize beta!
- They are also correlated with rotation, but FPPs will have low rotation and no control, so not super relevant
- Sawteeth can trigger NTMs, so pacing sawteeth with ECH can help
- Finally, ECH at TM location has shown the most promise and is the current plan for ITER.

Actuators for profile control

Typically we want to control density, Te and Ti profiles in flattop

We have many FPP-relevant actuators for profile control:

- **NBI provides localized ion heating, torque, current drive and some fuelling for density**
- **ECH provides localized steerable electron heating, current drive and density pumpout**
- **Gas valves provide slow edge density**
- **Pellets provide core density**
- **Coils to change shape, Ip and Bt**
- **RMP does many things…**

So we have many actuators to control profiles… but where is the model???

Controlling profiles

Profile dynamics models include

- ASTRA/TRANSP for medium fidelity physics-based profile evolution
- RAPTOR for low fidelity physics-based profile evolution with real-time capable speed
- TORAX for a phyics/ML hybrid where equation free parameters can be learned
- Pure ML dynamics models

But none of these are perfect, and none of these are linear!

We can use these to design feedforward trajectories, as RAPTOR has been used with TCV, or linearize and use MPC (which is the LRAN design). These can also be fed into an RL using RAPTOR data (like Takuma) or ML model (like CMU).

Overall, this is a very new field and very difficult. Will FPPs use simple PIDs and feedforward trajectories, or model based profile control???

Plasma Control

Many more topics remain!

- ELM control
- Detachment/heat flux divertor control
- Optimizing rampup and rampdown trajectories
- Impurity control such as tungsten and wall conditioning
- In future, alpha pumpout and heating control
- Finally, all the above can cause disruptions! And that can’t happen in FPPs

Plasma Control