Enhanced plasma shape and vertical stability control in TCV

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Outline

Introduction

Controlled thermonuclear fusion

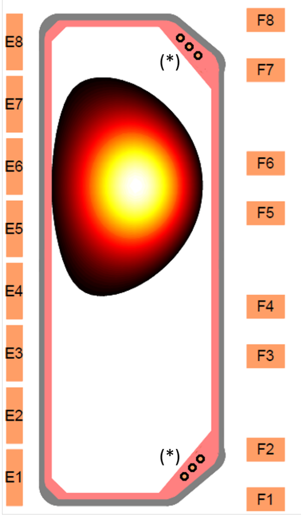
- $D + T \rightarrow {}^4He + n + 17.6$ MeV
- $nT\tau_e \geq 8.3\,\text{atm s}$ ($T_{min} = 15$ keV)

In a tokamak, plasma cross section shape influences

- energy confinement time τ_e
- pressure and current limits

Plasma shaping is performed through a set of dedicated poloidal field coils

The TCV tokamak is particularly suited for shaping ($\kappa < 2.8 \; -0.7 < \delta < 1$)



(*) fast internal coils

Introduction: shaping and force balance

Radial force balance

Vertical B_z required to compensate radial forces (tyre tube + hoop) .

Elongation

Curvature of B_z allows varying κ .

Vertical instability

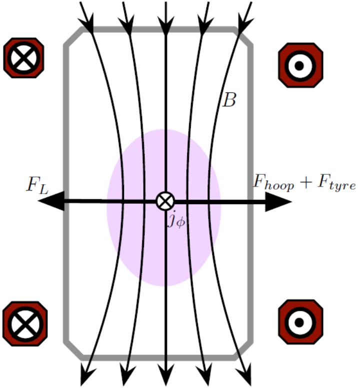
The equilibrium position (at $B_R = 0$) is unstable for elongated plasmas, thus requiring a corrective B_R.

Instability growth rate

$\gamma = f(\kappa, \beta_p, \dots) \sim 300\ \mathrm{s}^{-1}$

where

$\beta_p = \frac{\text{plasma thermal energy}}{\text{magnetic pressure (poloidal)}}$



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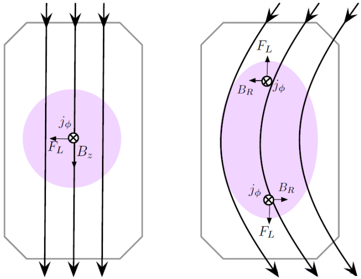

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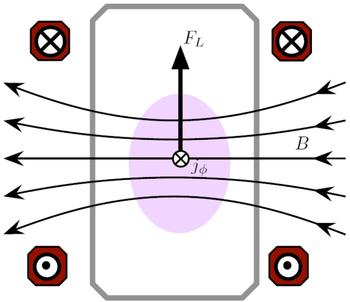

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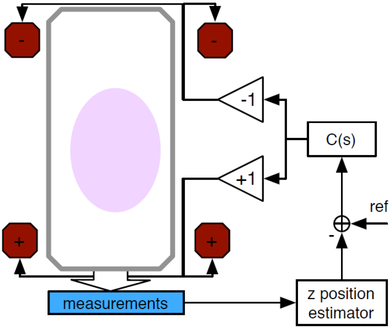


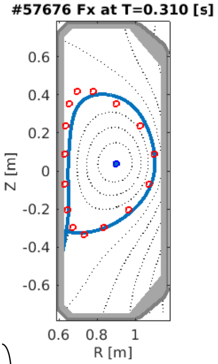
Integration of feedback control

- **stabilize** the vertical instability
- track reference plasma position
- reject disturbances

Introduction: TCV magnetic control

TCV position and shape control involves

1. real time identification of plasma boundary and position
2. comparison of actual condition with desired (isoflux control scheme)
3. adjustment of coils currents for error correction: power supply request



Three main control loops exist when using shape control

1. legacy analog observer emulator: controlled variables are obtained from **linear** combination of magnetic measurements (flux loops, magnetic probes)
2. digital position and shape controller: controlled variables are obtained from real time equilibrium reconstruction (solving **nonlinear** Grad-Shafranov eq)

$\Big\}$ actuate external coils

3. analog controller $\rightarrow$ actuates fast internal coils

Motivation

Main issues of present configuration of shape and position control

- shape control and vertical stabilization share a set of actuators (PF coils) but have different time scales ($\tau_{VS} \sim 3$ ms VS $\tau_{SC} \sim 0.1$ s)
- vertical position control relies on real time eq. reconstruction
- online tuning of the controllers is required over multiple discharges

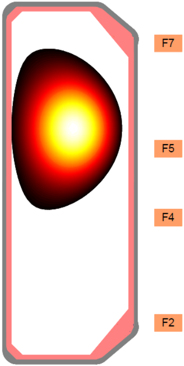
A simplified dynamical model for plasma dynamics + feedback loops can be used to optimize the control strategy allowing **offline** design and tuning of controllers.

Outline

Modelling: the plant

A linearized model is derived for plasma dynamics describing the coupled evolution of vertical position along with vessel and active coils currents.

$$\begin{cases} m_p\ddot{z} + m_p\omega_1^2 n\, z - I_{p0}\dfrac{\partial M_{pa}}{\partial z}I_a - I_{p0}\dfrac{\partial M_{pe}}{\partial z}I_e = 0. \\ L_e\dot{I}_e + R_eI_e + I_{p0}\dfrac{\partial M_{ep}}{\partial z}\dot{z} + M_{ea}\dot{I}_a = 0 \\ L_a\dot{I}_a + R_aI_a + I_{p0}\dfrac{\partial M_{ap}}{\partial z}\dot{z} + M_{ae}\dot{I}_e = V_a \end{cases}$$



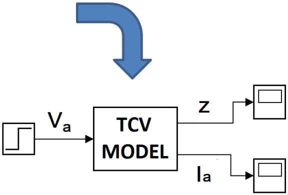
Assumptions:

- fixed shape (elongation κ)
- fixed plasma current I_{p0}
- radially constrained
- coil in series

Modelling: the plant

Application of instantaneous force balance and Laplace transform allows using block diagram algebra to model feedback loops

$$\begin{cases} m_p\ddot{z} + m_p\omega_1^2 n\, z - I_{p0}\dfrac{\partial M_{pa}}{\partial z}I_a - I_{p0}\dfrac{\partial M_{pe}}{\partial z}I_e = 0. \\ L_e\dot{I}_e + R_eI_e + I_{p0}\dfrac{\partial M_{ep}}{\partial z}\dot{z} + M_{ea}\dot{I}_a = 0 \\ L_a\dot{I}_a + R_aI_a + I_{p0}\dfrac{\partial M_{ap}}{\partial z}\dot{z} + M_{ae}\dot{I}_e = V_a \end{cases}$$



It is possible to extract the transfer functions for a voltage input V_a featuring one unstable mode (vertical instability)

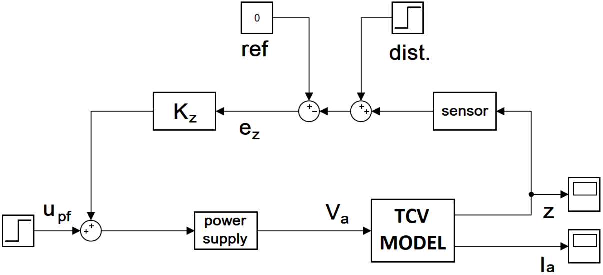
$$\text{TCV model} \ : \ V_a \rightarrow \begin{bmatrix} z \\ I_a \end{bmatrix}$$

Modelling: feedback

TCV position control is modelled reproducing two loops:

I control loop: fast but inaccurate z linear estimate

FAST



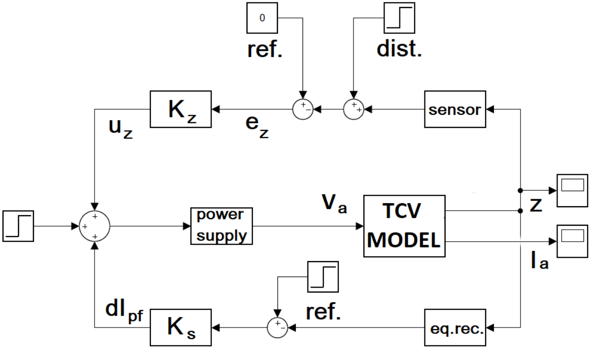
- noise and disturbance introduced by the sensors
- transmission delay of the power supply (1 ms) is included
- controller K_z ideally used for **stabilization** only and should avoid tracking low frequency disturbances

Modelling: feedback

II control loop: slow but accurate reconstruction (shape and position)

FAST

SLOW



- further introduction of delay (0.6 ms) due to eq. reconstruction
- second controller K_s is responsible for **tracking** the reference

Modelling: feedback

The dynamic response is studied using the model for tuning controllers.
Present architecture features a differentiator in the fast loop and a proportional-integral controller in the position control of the SC

$$u_z(t) = D_z \frac{d}{dt} e_z(t) \xrightarrow{\mathcal{L}} K_z = \frac{u_z(s)}{e_z(s)} = sD_z$$

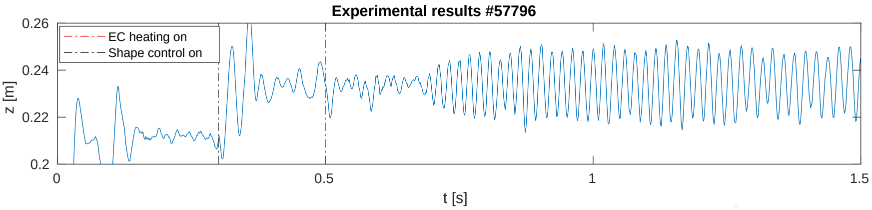
$$dI_{pf}(t) = P_s \left(e_s(t) + I_s \int_0^t e_s(t)\, dt \right) \xrightarrow{\mathcal{L}} K_s = \frac{dI_{pf}(s)}{e_s(s)} = P_s \left(1 + \frac{I_s}{s}\right)$$

Main consequences:

- $K_z = sD_z$
  - rejects low f disturbances
  - K_z alone can't stabilize but simply slows down the unst. mode
  - allows the shape control to prevail at low f
- $K_s = P_s \left(1 + \frac{I_s}{s}\right)$
  - responsible both for reference tracking **and** stabilization
- transmission delays $\rightarrow$ $\exists$ maximum value of the gains D_z P_s (destabilizing)

Outline

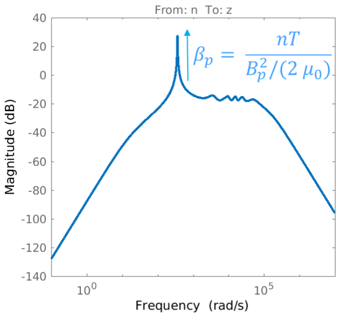
Preliminary results: slow vertical oscillations



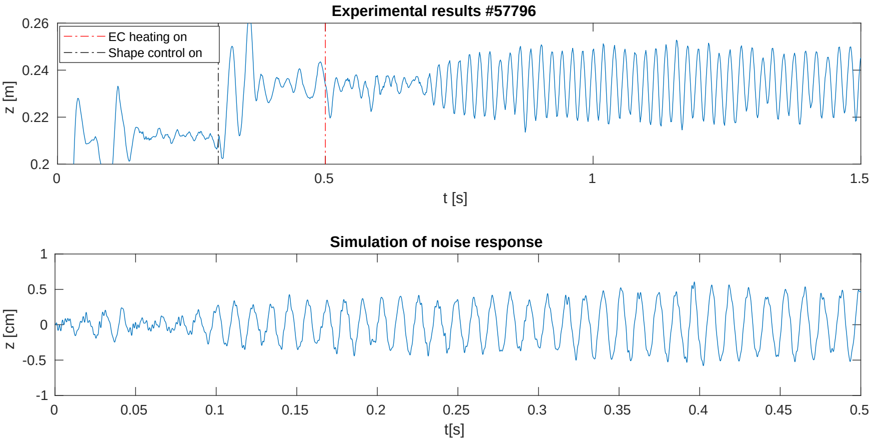
Following injection of EC heating, slow (50 *Hz*) vertical oscillations are observed.

For the model:

- instability growth rate $\sim \sqrt{\beta_p}$
- EC heating $\rightarrow T \uparrow \rightarrow \beta_p \uparrow$
- Bode plot: amplification of low f n

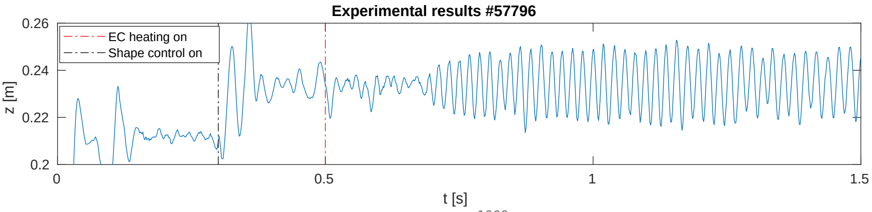


Preliminary results: slow vertical oscillations



The model is able to reproduce vertical oscillations from white noise amplification. Excessive increase of β_p can destabilize the system.

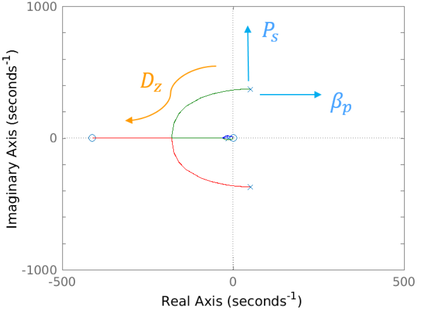
Preliminary results: slow vertical oscillations



Loop shaping techniques allow to determine the effect of controllers gains variation on poles position (Re(p) Im(p))

- $Kz(s) = sD_z$
- $K_s(s) = P_s + I_s/s$

Increasing the D_z is stabilizing until max differential gain (due to delay)



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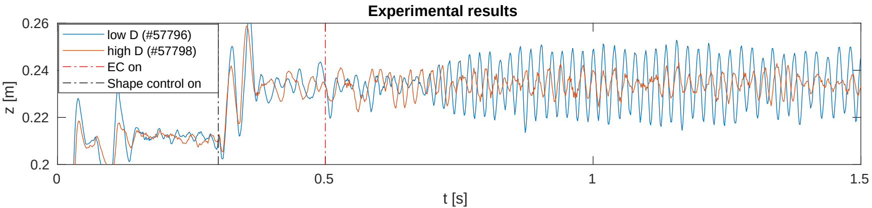
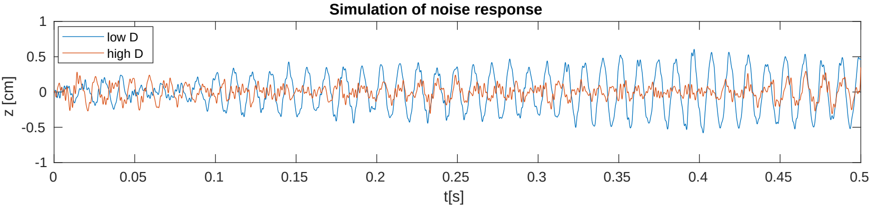




Increasing D_z gain allows to reduce the vertical oscillations amplitude, as is confirmed by experimental results. The presence of a minimum differential gain is also justified.

Outline

Ongoing study

By using the simplified model, it is not only possible to reproduce the existing control architecture but also to study the application of different linear controllers in order to find an optimal configuration

Kz	D	PD	...
vertical stabilization	×	✓	...
low f noise rejection	✓	×	...

- example: $Kz = P_z + sD_z$ instead of $K_z = sD_z$ would allow using former experience on vertical stabilization but interferes with the proportional part of the shape control

Outline

Conclusions and outlook

Summary:

Reduced model for the plant and the feedback loop was derived featuring

- vertical (z) + coil (I_a) + vessel (I_e) dynamics
- controllers K_z and K_s for vertical position and shape control
- delay effects of sensors/actuators

able to predict max min gain of controllers
and motivate the vertical oscillations correction

Outlook

- inclusion of fast coils' loop
- study effect of mutual decoupling and resistive compensation
- study effect of fast disturbances (ELMs, VDEs) $\rightarrow$ need a model
- determine a **decoupling scheme** for VS and SC

Thank you for your attention!

Additional 1: vertical instability

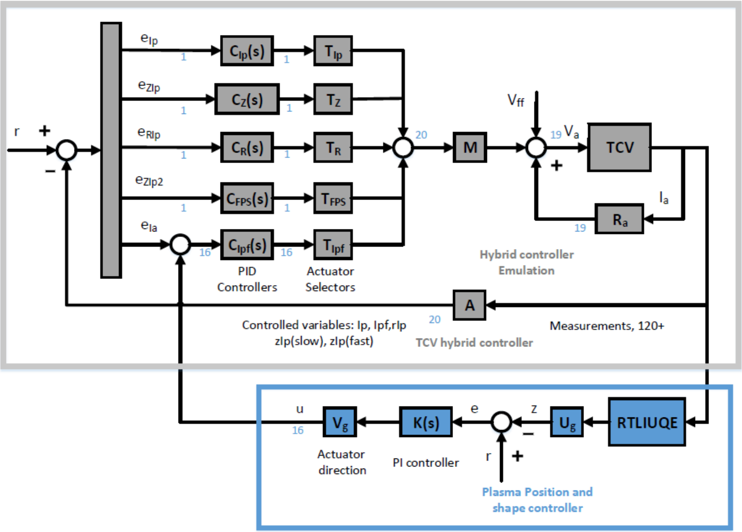
Physical sketch:
In order to obtain radial equilibrium a vertical magnetic field is required

$$B_{z0} = \frac{\mu_0 I_{p0}}{4\pi R_0}\Gamma$$

where $\Gamma = \ln \frac{8R}{a\sqrt{\kappa}} + \beta_p + \frac{l_i}{2} + \frac{3}{2}$ Shafranov parameter

Turning EC on $\rightarrow \beta_p \uparrow \rightarrow B_{z0} \uparrow$
and with the same curvature κ the Lorentz force increases, determining an increase of the instability
$p_{1,2} = \pm\sqrt{-n}\sqrt{\frac{\mu_0 I_{p0}\Gamma}{2m_p R_0}}$

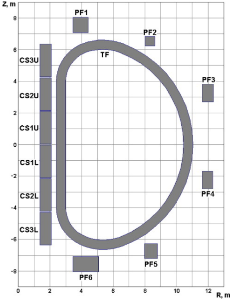
Additional 2: TCV hybrid + shape control



H.Anand, PhD Thesis, EPFL, 2017

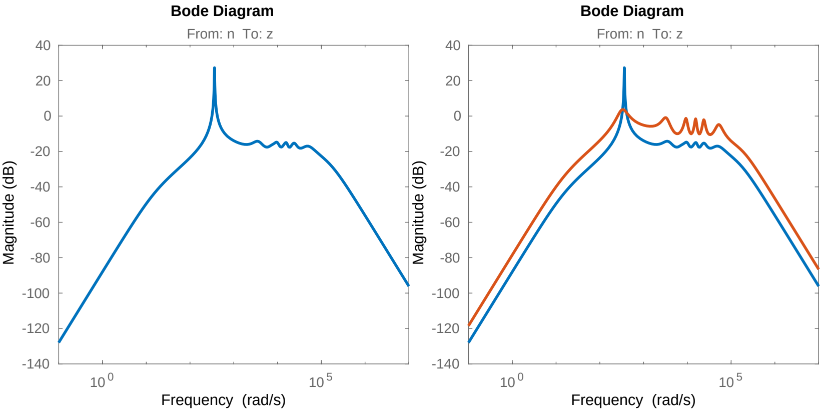
Additional 3: ITER VS

ITER PF coils superconductive $\rightarrow$ D able to stabilize plasma alone
$\tau_{VS} = 100\,ms$
$\tau_{SC} = 20\,s$



V.M. Amoskov, et al. Assessment of ITER PF coil quality from magnetic measurements, Fusion Engineering and Design, Volume 85, Issue 5, 2010

Additional 4: vertical oscillations Bodes



Additional 5: OL Bode