On plasma vertical stabilization at EAST tokamak

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Outline

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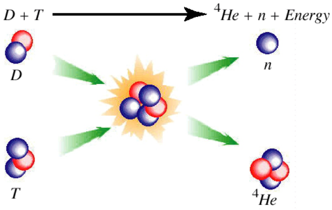
   - The plasma vertical stabilization problem
2. **Plasma-circuits linearized model**
3. **Vertical stabilization at EAST with a SISO controller**
4. **Vertical stabilization at EAST with a MIMO controller**
5. **Conclusions**

Nuclear Fusion for Dummies

Main Aim

Production of energy by means of a fusion reaction

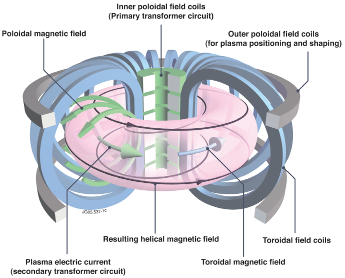
$$D + T \rightarrow {}^4\mathrm{He} + n$$

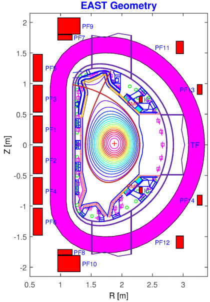


Plasma

- High temperature and pressure are needed
- Fully ionised gas $\mapsto$ Plasma
- Magnetic field is needed to confine the plasma

Plasma magnetic control





- In tokamaks, **magnetic control of the plasma is obtained by means of magnetic fields produced by the external active coils**

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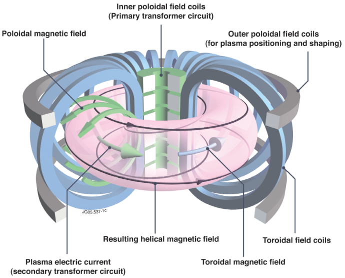

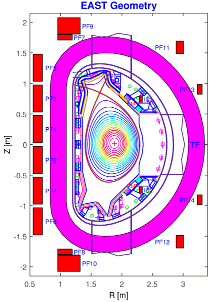

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- In order to obtain good performance, it is necessary to have a plasma with **vertically elongated cross section ⇒ vertically unstable plasmas**

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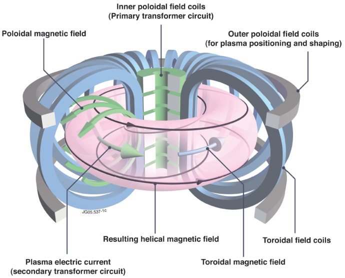

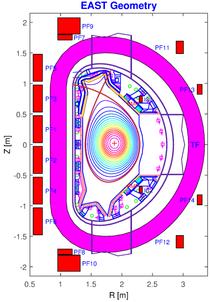

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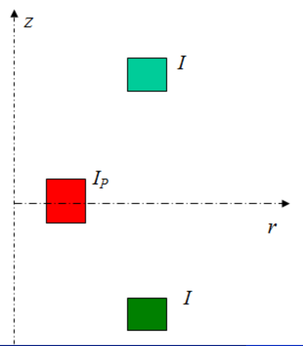
- In order to obtain good performance, it is necessary to have a plasma with **vertically elongated cross section** $\Rightarrow$ **vertically unstable plasmas**
- It is important to **maintain adequate plasma-wall clearance during operation**

The plasma vertical instability

Simplified filamentary model

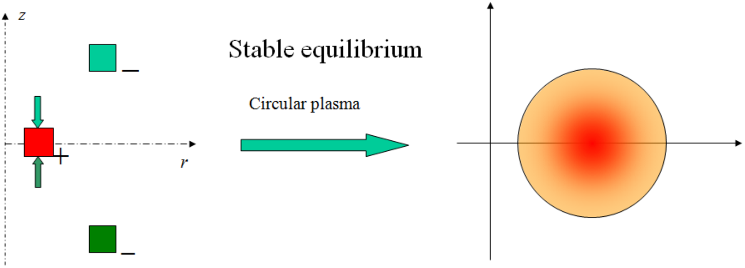
Consider the simplified electromechanical model with three conductive rings, two rings are kept fixed and in symmetric position with respect to the r axis, while the third can freely move vertically.



If the currents in the two fixed rings are equal, the vertical position $z = 0$ is an equilibrium point for the system.

Stable equilibrium - 1/2

If $\mathrm{sgn}(I_p) \neq \mathrm{sgn}(I)$



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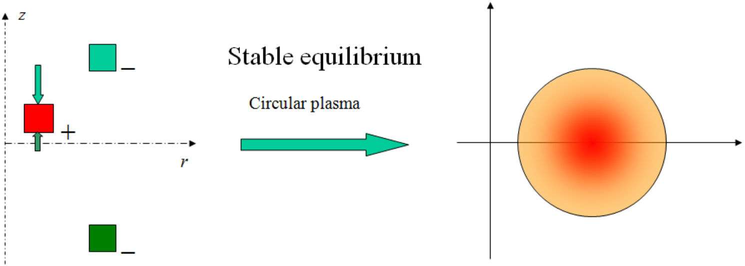

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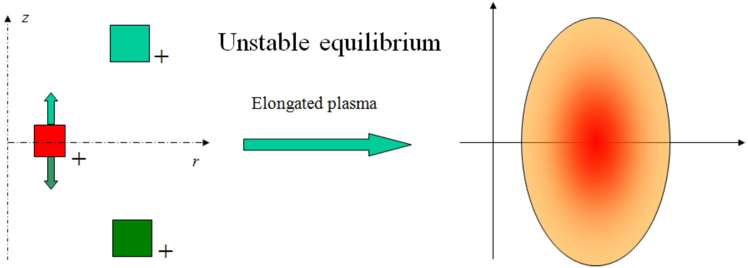

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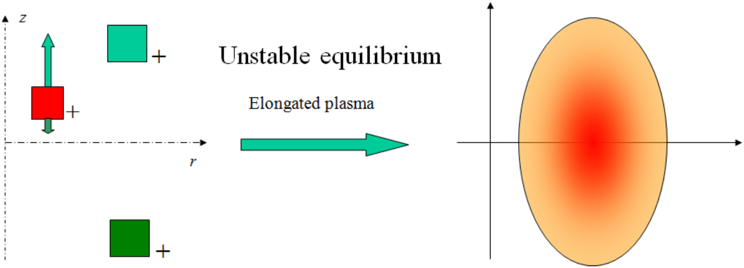

Vertical stabilization problem

- The plasma vertical instability reveals itself in the linearized model by the presence of an unstable eigenvalue in the dynamic system matrix

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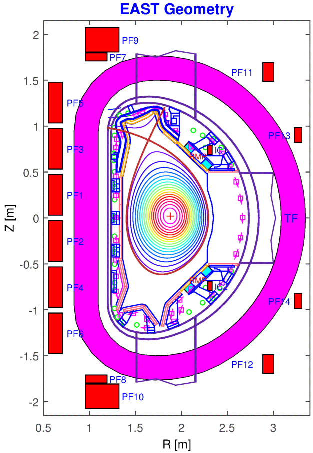
Objectives

- **The VS is the essential magnetic control system!**
- Vertically stabilize elongated plasmas in order to avoid disruptions
- Counteract the effect of disturbances
- **It does not necessarily control vertical position but it *simply* stabilizes the plasma**



Plasma-circuits linearized model

Starting from the nonlinear lumped parameters model, the following plasma linearized state space model can be easily obtained:

$$\delta\dot{\mathbf{x}}(t) = \mathbf{A}\delta\mathbf{x}(t) + \mathbf{B}\delta\mathbf{u}(t) + \mathbf{E}\delta\dot{\mathbf{w}}(t), \quad (1)$$

$$\delta\mathbf{y}(t) = \mathbf{C}\,\delta\mathbf{I}_{PF}(t) + \mathbf{F}\delta\mathbf{w}(t), \quad (2)$$

where:

- $\mathbf{A}$, $\mathbf{B}$, $\mathbf{E}$, $\mathbf{C}$ and $\mathbf{F}$ are the model matrices
- $\delta\mathbf{x}(t) = \left[\delta\mathbf{I}_{PF}^T(t)\ \delta\mathbf{I}_e^T(t)\ \delta I_p(t)\right]^T$ is the state space vector
- $\delta\mathbf{u}(t) = \left[\delta\mathbf{U}_{PF}^T(t)\ \mathbf{0}^T\ 0\right]^T$ are the input voltages variations
- $\delta\mathbf{w}(t) = \left[\delta\beta_p(t)\ \delta l_i(t)\right]^T$ are the β_p and l_i variations
- $\delta\mathbf{y}(t)$ are the output variations

The model (1)–(2) relates the variations of the PF currents to the variations of the outputs around a given equilibrium

Stabilizing the EAST plasma using a SISO controller - 1/2

$$\Sigma : \begin{cases} \dot{\mathbf{x}}(t) = \mathbf{A}\mathbf{x}(t) + \mathbf{B}u(t)\,, & \mathbf{x}(0) = \mathbf{x}_0 \\ \mathbf{y}(t) = \mathbf{C}\mathbf{x}(t) \end{cases}$$

- From Σ it is possible to derive the input-output relationship between the vertical speed $V_p(s)$ and the voltage applied to the in-vessel coil $U_{IC}(s)$ (the plasma)

$$W_p(s) = \frac{V_p(s)}{U_{IC}(s)}$$

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$$U_{IC}(s) = \frac{e^{-\delta_{ps}s}}{1 + s\tau_{ps}} \cdot U_{IC_{ref}}(s)\,,$$

with $U_{IC_{ref}}(s)$ the voltage requested by the controller, $\delta_{ps} = 550\ \mu s$, $\tau_{ps} = 100\ \mu s$

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- At EAST the plasma vertical speed $V_p(s)$ is estimated by means of a derivative filter applied on $Z_p(s)$, i.e.

$$V_p(s) = \frac{s}{1 + s\tau_V} \cdot Z_p(s)\,,$$

with $\tau_V = 1$ ms.

Stabilizing the EAST plasma using a SISO controller - 2/2

- Putting everything together we get

$$W_{plant}(s) = \frac{s}{(1 + s\tau_v)(1 + s\tau_{ps})} \cdot W_p(s) \cdot e^{-\delta_{ps}s} \,,$$

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- The 550 μs time delay of the IC power supply can be replaced by its third order Padé approximation

$$\frac{-(s-8444)(s^2-1.34\cdot 10^4 s+8.54\cdot 10^7)}{(s+8444)(s^2+1.34\cdot 10^4 s+8.54\cdot 10^7)}$$

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- **The only way to vertically stabilize EAST with a SISO stable controller (SISO strong stabilizability) is to include an integral action on the vertical speed (i.e., the vertical position z_p should be fed back**
- The reason is that the plasma unstable pole is *trapped* between two non minimum phase zeros

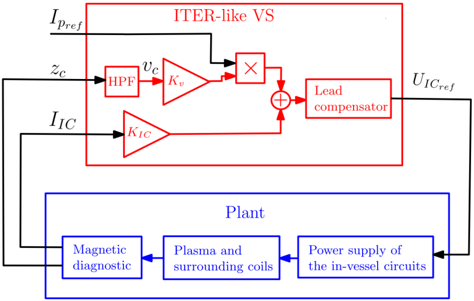
Parity-Interlacing-Property (PIP)

Theorem

A linear plant $W(s)$ is strongly stabilizable if and only if the number of poles of $W(s)$ between any pair of real zeros in the right-half-plane (RHP) is even.

D. C. Youla, J. J. Bongiorno Jr., C. N. Lu
Single-loop feedback stabilization of linear multivariable dynamical plants
Automatica, vol. 10, no. 2, pp. 159–173, Mar. 1974

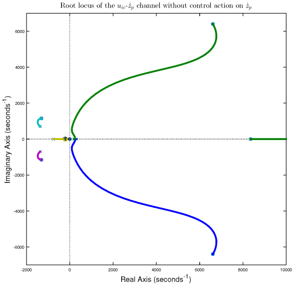
Stabilizing with a MIMO controller - 1/3



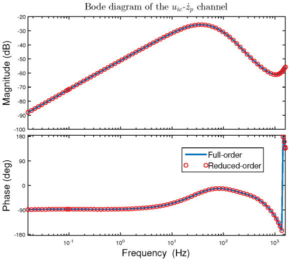
$$U_{IC_{ref}}(s) = \frac{1 + s\tau_1}{1 + s\tau_2} \cdot \left(K_v \cdot \bar{I}_{p_{ref}} \cdot \frac{s}{1 + s\tau_z} \cdot Z_c(s) + K_{IC} \cdot I_{IC}(s) \right)$$

Stabilizing with a MIMO controller - 2/3

By closing the loop on $I_{IC}(s)$ we introduce another unstable pole in the $u_{ic} - \dot{z}_p$ channel



(a) Root locus of the $u_{ic} - \dot{z}_p$ channel, when the loop on the IC current is closed.



(b) Bode diagrams of the full-order and reduced-order versions of transfer function for the $u_{ic} - \dot{z}_p$ channel, when the loop on the IC current is closed.

Stabilizing with a MIMO controller - 3/3

Closing a stable controller on the vertical speed is now possible to stabilize the EAST plasma

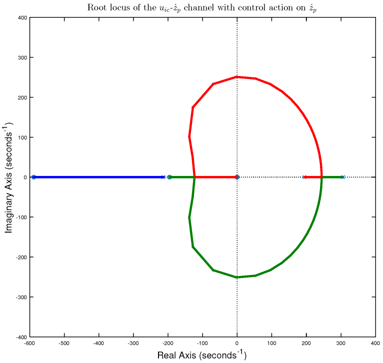


Figure : Root locus of the $u_{ic} - \dot{z}_p$ channel, when the loop on the IC current is also closed.

Experimental results - Dec 2016

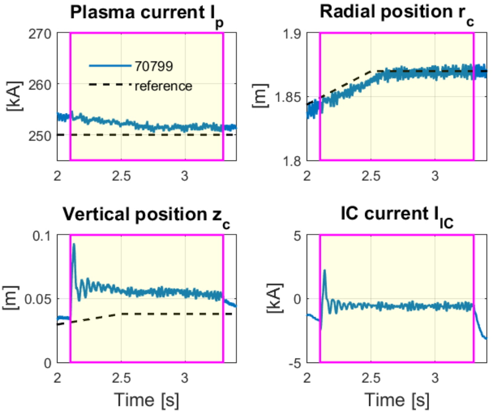


Figure : EAST pulse #70799. During this pulse the *ITER-like* VS was enabled from $t = 2.1$ s for 1.2 s, and only I_p and r_c were controlled, while z_c was left uncontrolled. This first test confirmed that the ITER-like VS vertically stabilized the plasma by controlling $\dot{z}_c$ and I_{IC}, without the need to feed back the vertical position z_c.

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Thank you!