Robust Plasma Vertical Stabilization in Tokamak Devices via Multi-objective Optimization

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Outline

Introduction

The plasma vertical stabilization problem

A multi-objective optimization approach

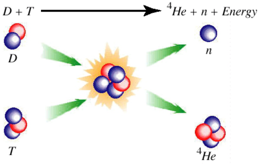
Conclusions

Nuclear Fusion for Dummies

Main Aim

Production of energy by means of a fusion reaction

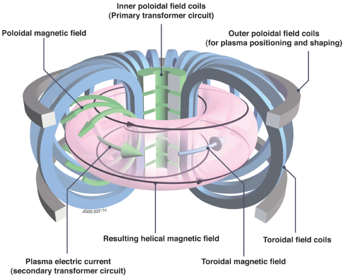
$$D + T \rightarrow {}^4\mathrm{He} + n$$

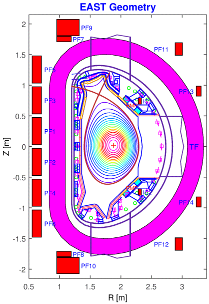


Plasma

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

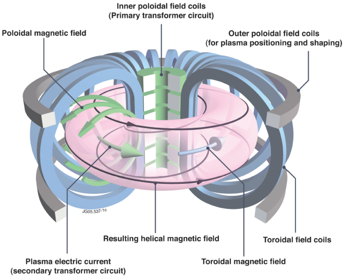
Plasma magnetic control

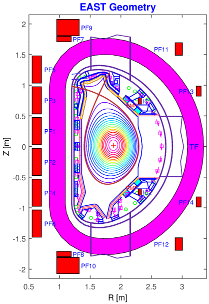




- In tokamaks, **magnetic control of the plasma is obtained by means of magnetic fields produced by the external active coils**

Plasma magnetic control





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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**

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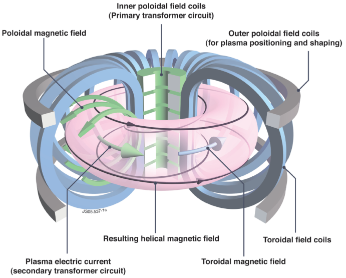

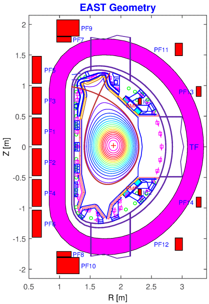

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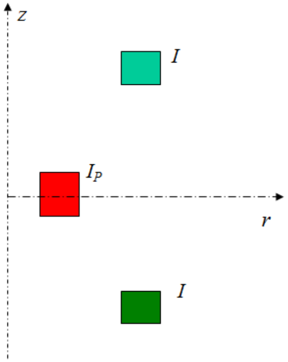
- In order to obtain good performance, it is necessary to have a plasma with **vertically elongated cross section** $\Rightarrow$ **vertically unstable plasmas**
- It is important to **maintain adequate plasma-wall clearance during operation**

The plasma vertical instability

Simplified filamentary model

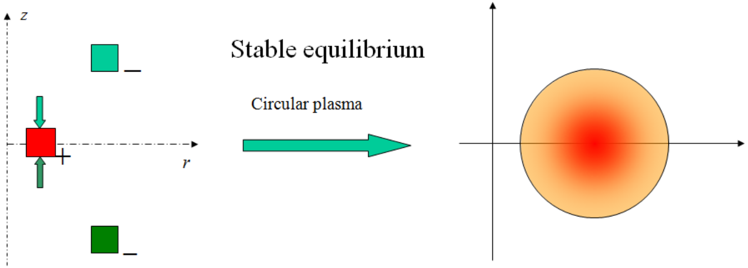
Consider the simplified electromechanical model with three conductive rings, two rings are kept fixed and in symmetric position with respect to the r axis, while the third can freely move vertically.



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



Stable equilibrium - 2/2

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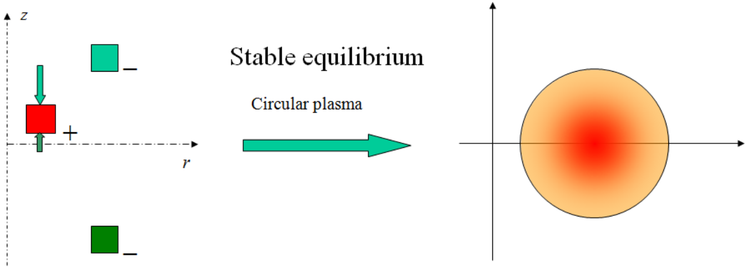

Unstable equilibrium - 1/2

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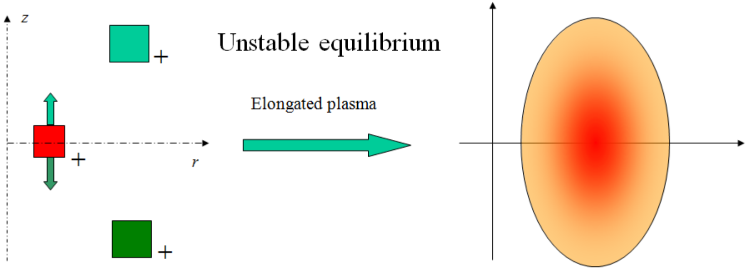

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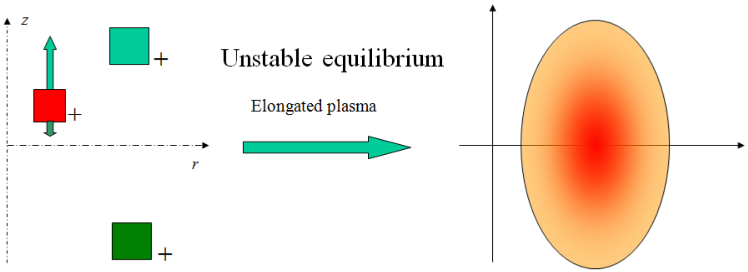

Vertical stabilization problem

- The plasma vertical instability reveals itself in the linearized model by the presence of an unstable eigenvalue in the dynamic system matrix
- The vertical instability growth time is slowed down by the presence of the conducting structure surrounding the plasma
- This allows to use a feedback control system to stabilize the plasma equilibrium, using for example a pair of dedicated coils

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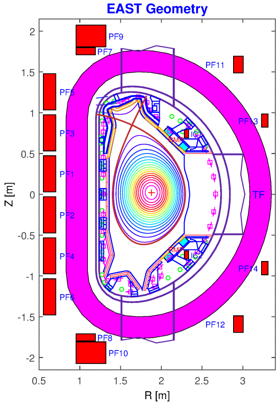
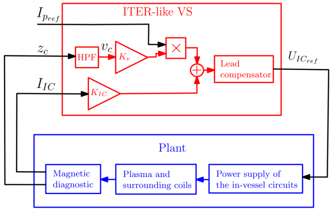
Objectives

- Vertically stabilize elongated plasmas in order to avoid disruptions
- Counteract the effect of disturbances
- **The VS is the essential magnetic control system!**

ITER-like VS for the EAST tokamak

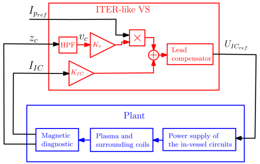




$$U_{IC_{ref}}(s) = \frac{1+s\tau_1}{1+s\tau_2} \cdot \left(K_v \cdot \bar{I}_{p_{ref}} \cdot \frac{s}{1+s\tau_z} \cdot Z_c(s) + K_{IC} \cdot I_{IC}(s) \right)$$

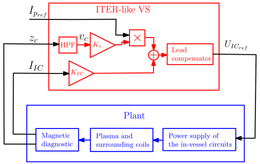
R. Albanese et al.
ITER-like Vertical Stabilization System for the EAST Tokamak
Nucl. Fus., vol. 57, no. 8, pp. 086039, Aug. 2017

SISO stability margins



- The single-input-single-output (SISO) transfer function obtained by opening the control loop in correspondence of the control output is exploited to compute the stability margins (gain and phase margins)

SISO stability margins



- The single-input-single-output (SISO) transfer function obtained by opening the control loop in correspondence of the control output is exploited to compute the stability margins (gain and phase margins)
- Given the i-th plasma linearized model, it is possible to define the objective function

$$\mathcal{F}_i = c_1 \cdot (PM_t - PM(K_v, K_{IC}, \tau_1, \tau_2))^2 + c_2 \cdot (UGM_t - UGM(K_v, K_{IC}, \tau_1, \tau_2))^2 + c_3 \cdot (LGM_t - LGM(K_v, K_{IC}, \tau_1, \tau_2))^2 ,$$

- where
  - PM is the phase margin
  - UGM and LGM are the upper and lower gain margins
  - c_1, c_2 and c_3 are positive weighting coefficients
  - PM_t, UGM_t and LGM_t are the desired values (*targets*) for the stability margins

Multi-objective optimization

Given N (different) plasma equilbria, it is possible to design the VS gains by solving the following multi-objective optimization problem

$$\min_{K_v, K_{IC}, \tau_1, \tau_2} \mu \qquad (1)$$
$$\text{s.t. } \mathcal{F}(K_v, K_{IC}, \tau_1, \tau_2) - \mu \cdot w \leq 0,$$

where $\mathcal{F}$ is a vector function

$$\mathcal{F}(K_v, K_{IC}, \tau_1, \tau_2) = \left(\mathcal{F}_1(K_v, K_{IC}, \tau_1, \tau_2) \;\ldots\; \mathcal{F}_N(K_v, K_{IC}, \tau_1, \tau_2)\right)^T,$$

where w is a vector of weights.

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Problem (1) can be solved using a sequential quadratic programming method (matlab function `fgoalattain`)

The considered case study - 1/3

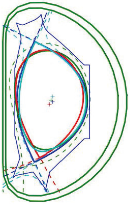

Table : Main plasma parameters of the considered EAST equilibria.

Equilibrium	Shape type	$I_{p_{eq}}$ [kA]	γ [s^{-1}]
46530	Double-null	281	137
52444	Limiter	230	92
60938	Upper single-null	374	194
64204	Lower single-null	233	512

The considered case study - 2/3

Table : Maximum real part of the closed loop eigenvalues computed by applying to the j-th equilibrium the gains obtained with the single-objective approach for the i-th one, with $i \neq j$.

	46530	52444	60938	64204
single-objective #46530	–	-0.365	-0.088	255.99
single-objective #52444	-0.360	–	-0.358	897.01
single-objective #60938	-0.360	-0.364	–	153.57
single-objective #64204	-0.360	-0.365	-0.358	–

The considered case study - 3/3

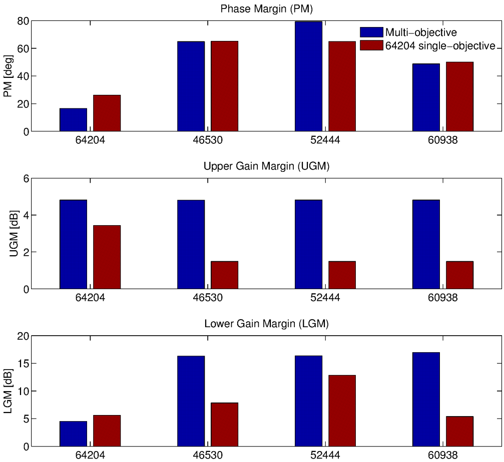

Figure : Comparison of the stability margins obtained by using the multi-objective approach and the ones obtained by using the VS parameters given by the a single-objective approach for the EAST pulse #64204.

Conclusions

- A robust design procedure for VS systems based on multi-objective optimization has been presented in this paper
- The proposed approach can be effectively used to vertically stabilize tokamak plasmas under different scenarios, without the need of online adaptive algorithms

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Thank you!