Model-based vertical position control design and optimization for CFETR tokamak

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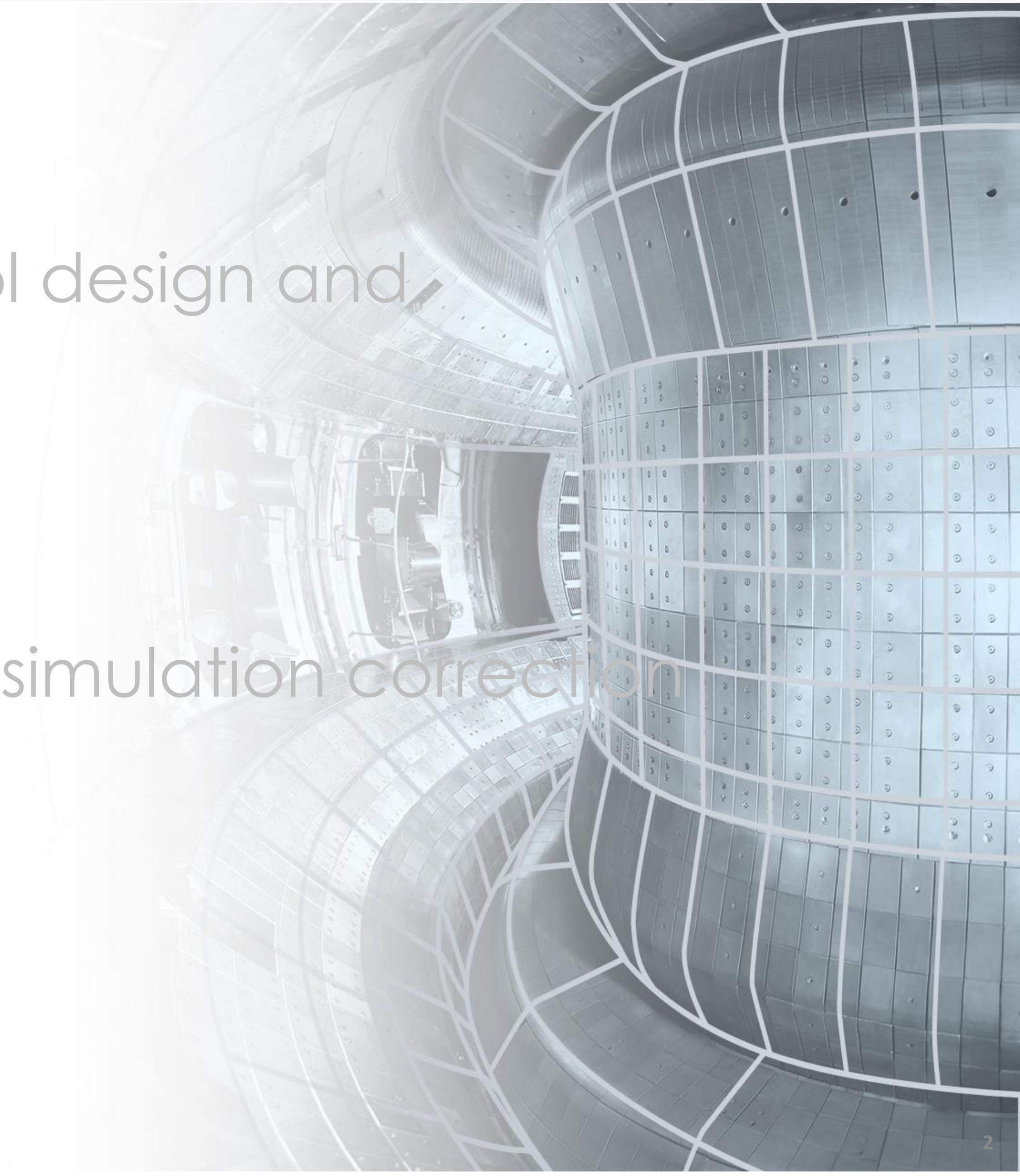
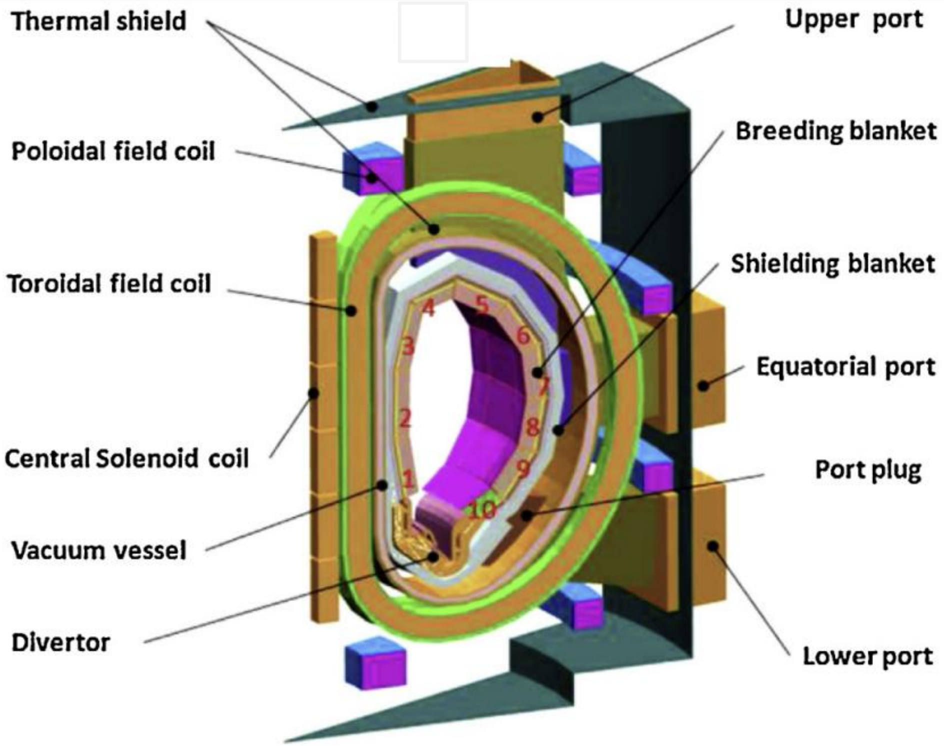
Outline

- ☐ Introduction
- ☐ Linearized modeling for control design and optimization
- ☐ Passive stabilization analysis
- ☐ Feedback control design and simulation correction
- ☐ Summary



Introduction

- Chinese Fusion Engineering Test Reactor (CFETR) is the next generation superconducting device in the roadmap for fusion energy in China, aiming to bridge the gap between ITER and DEMO
- Compared to ITER, the similar Ip, higher κ, and wider blanket result in a significantly higher power supply requirement for vertical position control
- A vertical position control design approach based on a simplified physical model was applied to the design to achieve a reduction in PS requirements and rapid iteration with engineering group



	ITER	CFETR
Plasma current (Ip)	15MA	14MA
Major radius (R)	6.2m	7.2m
Minor radius (a)	2.0m	2.2m
Toroidal magnetic field (Bt)	5.3T	6.5T
Elongation (κ)	1.7/1.85	2.0
Triangularity （δ）	0.33/0.48	0.4~0.8

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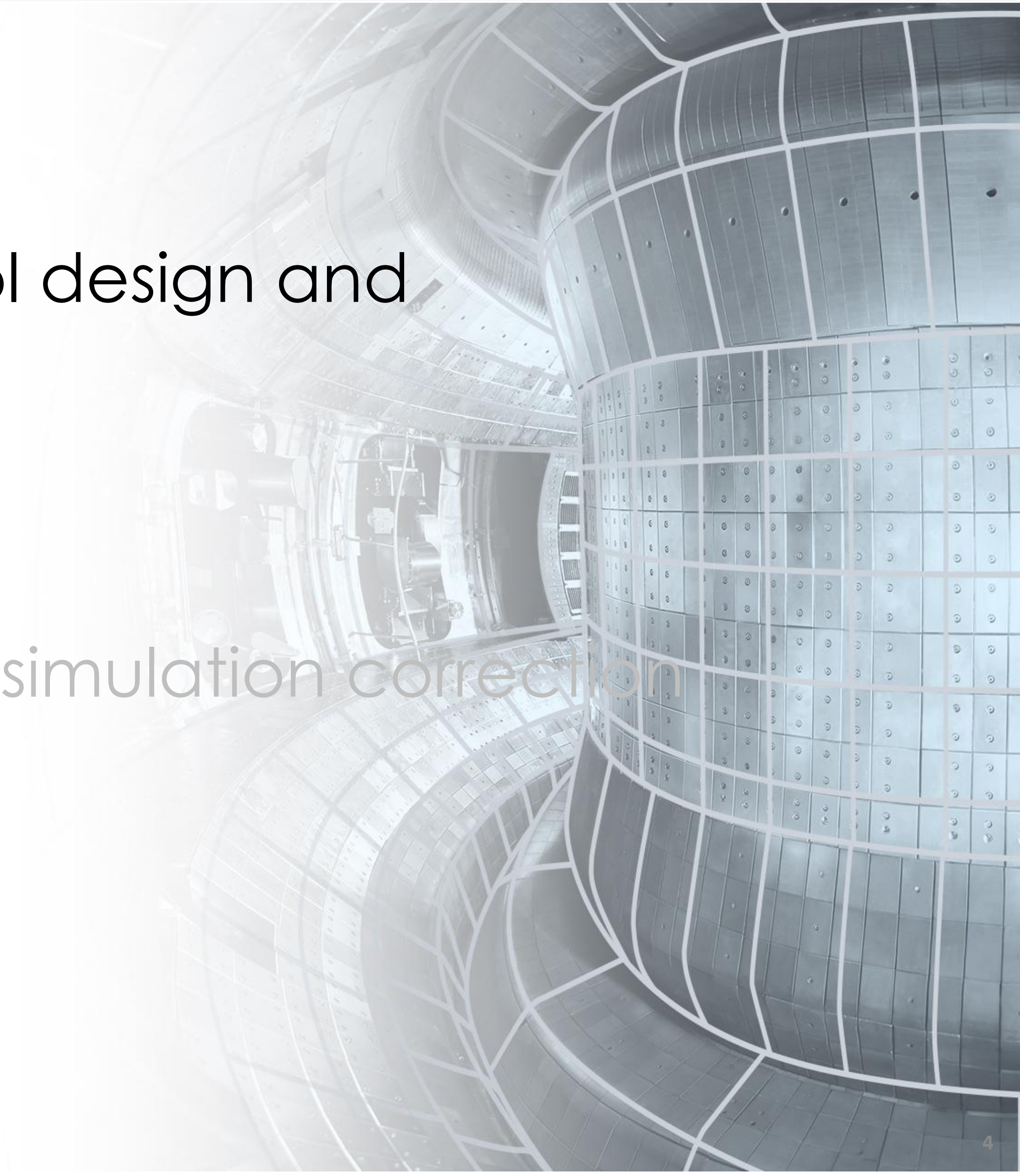


Linearized modeling for control design and optimization

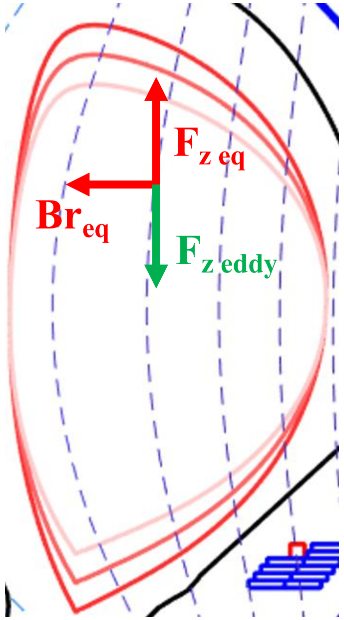
ASIPP

- Design of control systems to stabilize the axisymmetric vertical instability requires sufficiently accurate modeling of the electromagnetic characteristics of the conducting structure and active coils. For conductors, the circuit equation becomes:

$$M_{ss}\dot{I}_s + R_{ss}I_s + \frac{\partial \psi_{sp}}{\partial z}\frac{\partial z}{\partial I_s} = V_s$$

- The massless plasma assumption has also been used which will leading a requirement of the force balance:

$$\frac{\partial F_z}{\partial z}\dot{z} + \frac{\partial F_z}{\partial I_s}\dot{I}_s = 0, \frac{\partial z}{\partial I_s} = -\frac{\partial F_z}{\partial I_s}/\frac{\partial F_z}{\partial z}$$



- Combine the two equations can have:

$$\left(M_{ss} + \frac{\partial \psi_{sp}}{\partial z}\frac{\partial z}{\partial I_s}\right)\dot{I}_s + R_{ss}I_s = V_s \Rightarrow \dot{I}_s = AI_s + BV_s$$

Linearized modeling for control design and optimization

- The complexity of the above state-space equations depends on the number of conductor structures divided during modeling, which is usually more than a hundred. According to the eigenvalues properties*:

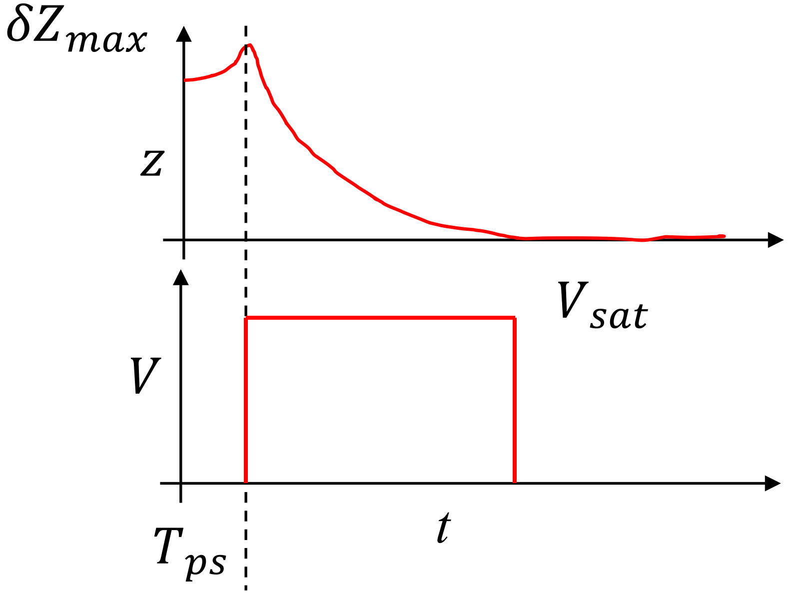
$$VA = V\Lambda,\ I_s = Vw$$
$$\dot{w} = V^{-1}AVw + V^{-1}BV_s = \Lambda w + V^{-1}BV_s$$

- For further simplification, only the influence of the dominated eigenvalue (the only positive one) is considered

$$\dot{w}_z = \gamma w_z + v_z^{-1}BV_s$$

- Considering the ideal case, the solution can be given as:

$$w_z = w_{z0}e^{\gamma t} - v_z^{-1}B\gamma^{-1}V_s(1 - e^{\gamma t})$$



- The ideal control case simplified the output into the maximum voltage or 0
- Considering the pure power supply delay T_{PS}, which will result the $\delta Z_{ctrl} = \delta Z_{max}e^{\gamma T_{PS}}$

Linearized modeling for control design and optimization

- The vertical position can be given by:

$$z = \frac{\partial z}{\partial I_s} I_s \approx \frac{\partial z}{\partial w_z} w_z = \frac{\partial z}{\partial w_z}\left(w_{z0} e^{\gamma t} - v_z^{-1} B \gamma^{-1} V_s (1 - e^{\gamma t})\right)$$

- The marginal vertical displacement will lead to $\frac{\partial^2 z}{\partial t^2} = 0$, which means:

$$\delta Z_{ctrl} + \frac{\partial z}{\partial w_z} v_z^{-1} B \gamma^{-1} V_{sat} = 0,\ \delta Z_{ctrl} = \frac{\partial z}{\partial I_s} v_z u_z B \gamma^{-1} V_{sat}$$

- Considering the delay of power supply and current limit, the estimated marginal vertical displacement can be given as:

$$\delta Z_{max} = \left(1 - e^{-\frac{I_{max} L_c \gamma}{V_{sat}}}\right) \frac{\partial z}{\partial I_s} v_z u_z \left(M_{ss} + \frac{\partial \psi_{sp}}{\partial z} \frac{\partial z}{\partial I_s}\right)^{-1} V_{sat} e^{-\gamma T_{ps}}$$

- For CFETR design, the requirement is not to estimate the maximum vertical displacement with given the parameters, but to evaluate the required parameters with given vertical displacement. Based on this goal, the first step is to determine the current demand:

$$I_{max} = -\frac{V_{sat}}{L\gamma} \ln\left(1 + \frac{\Delta Z_{max}}{V_{sat} \frac{\partial z}{\partial I_s} v_z u_z \left(M_{ss} + \frac{\partial \psi_{sp}}{\partial z} \frac{\partial z}{\partial I_s}\right)^{-1} e^{-\gamma T_{ps}}}\right)$$

Linearized modeling for control design and optimization

- It can be concluded that the power requirement for the specified vertical displacement under different control voltages is:

$$V_{sat} * I_{max} = -\frac{V_{sat}^2}{L\gamma} \ln\left(1 + \frac{\Delta Z_{max}}{V_{sat}\frac{\partial z}{\partial I_s} v_z u_z \left(M_{ss} + \frac{\partial \psi_{sp}}{\partial z}\frac{\partial z}{\partial I_s}\right)^{-1} e^{-\gamma T_{ps}}}\right)$$

- The minimum value of the above equation can be obtained through numerical calculation, which is:

$$\frac{V_{pmin}}{\;} = 1.398 \frac{\gamma}{\;}$$

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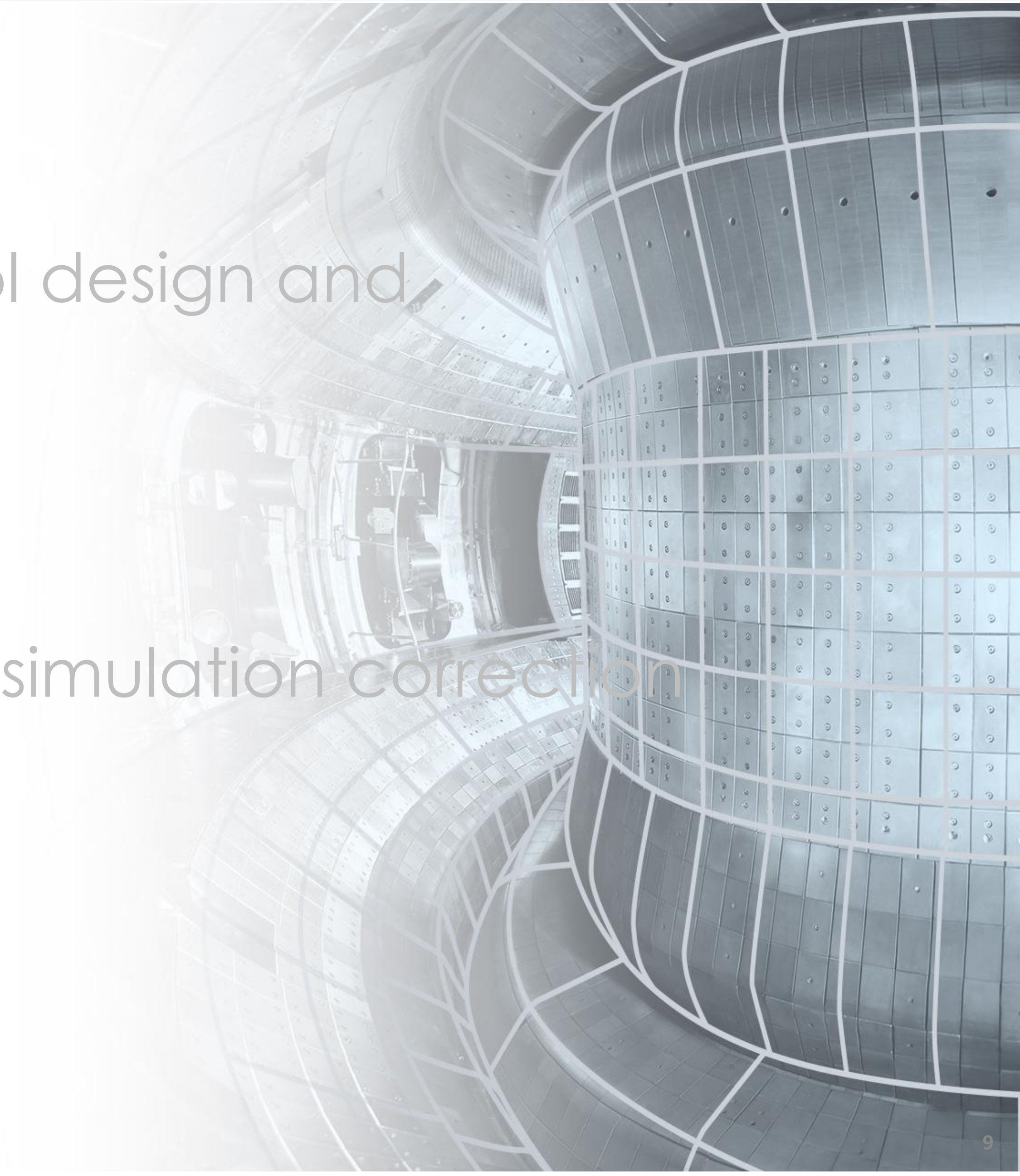
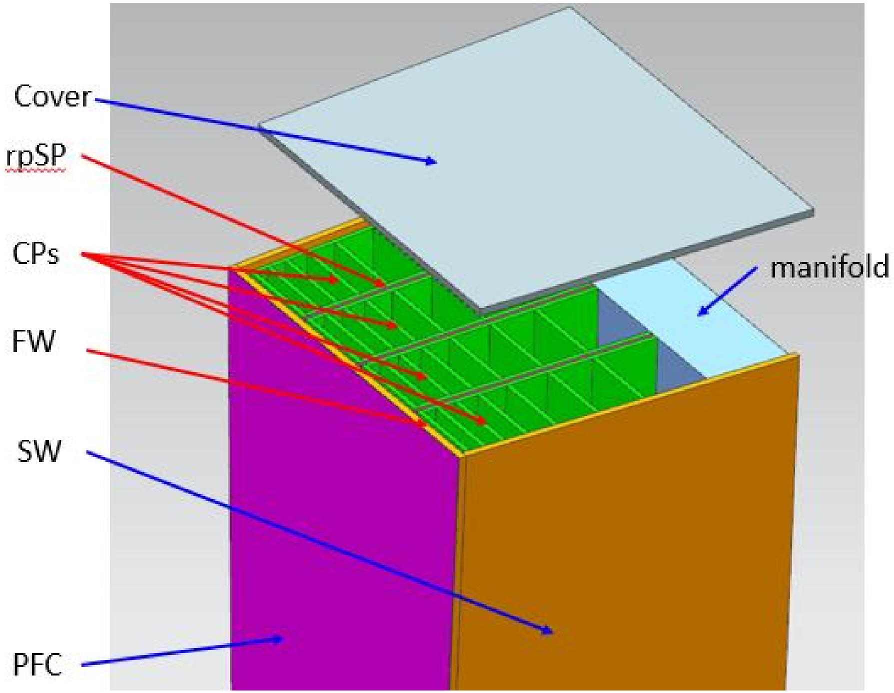
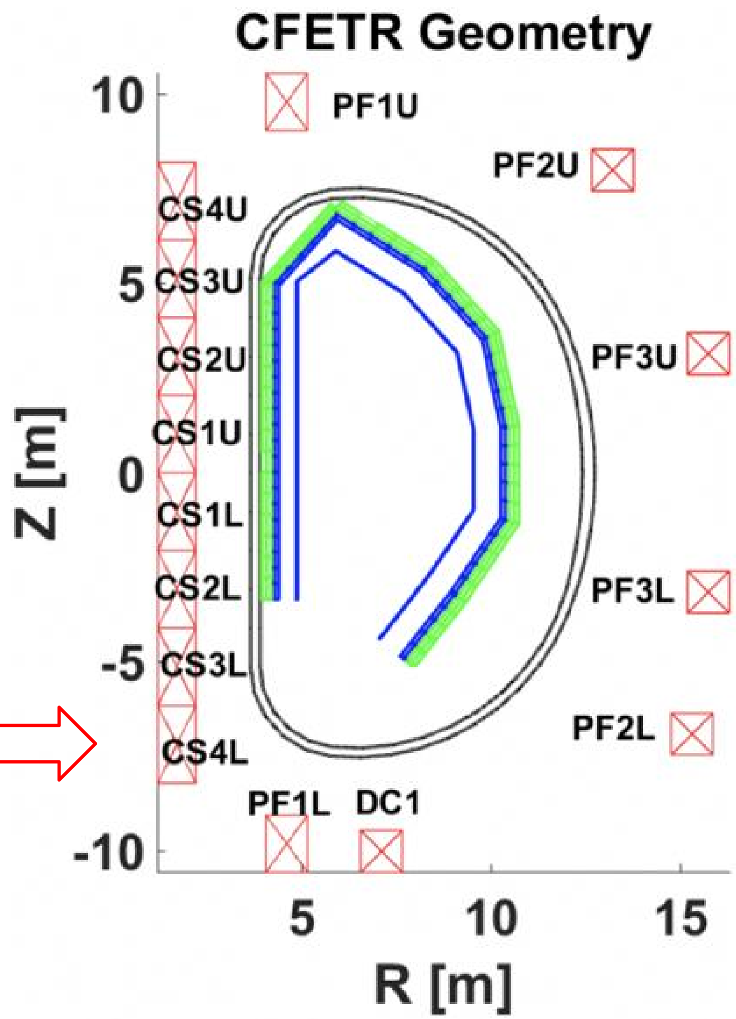


Passive stabilization analysis

- Due to the weak coupling between the vacuum vessel and plasma in CFETR, the passive stabilization effect of the blanket structure must be considered
- Based on the structure of the blanket and the composition of different materials, the resistivity was determined, and a two-dimensional equivalent modeling was performed
- Using the reference L-mode equilibrium, the growth rate was scanned under different resistivities factor

Resistivity ohm-m	Growth rate （s^{-1}）
7.62×10^{-7}	2.2
7.62×10^{-7}*2	4.1
7.62×10^{-7}*3	6.1
7.62×10^{-7}*5	9.6
7.62×10^{-7}*10	18.1
Without blanket	unable





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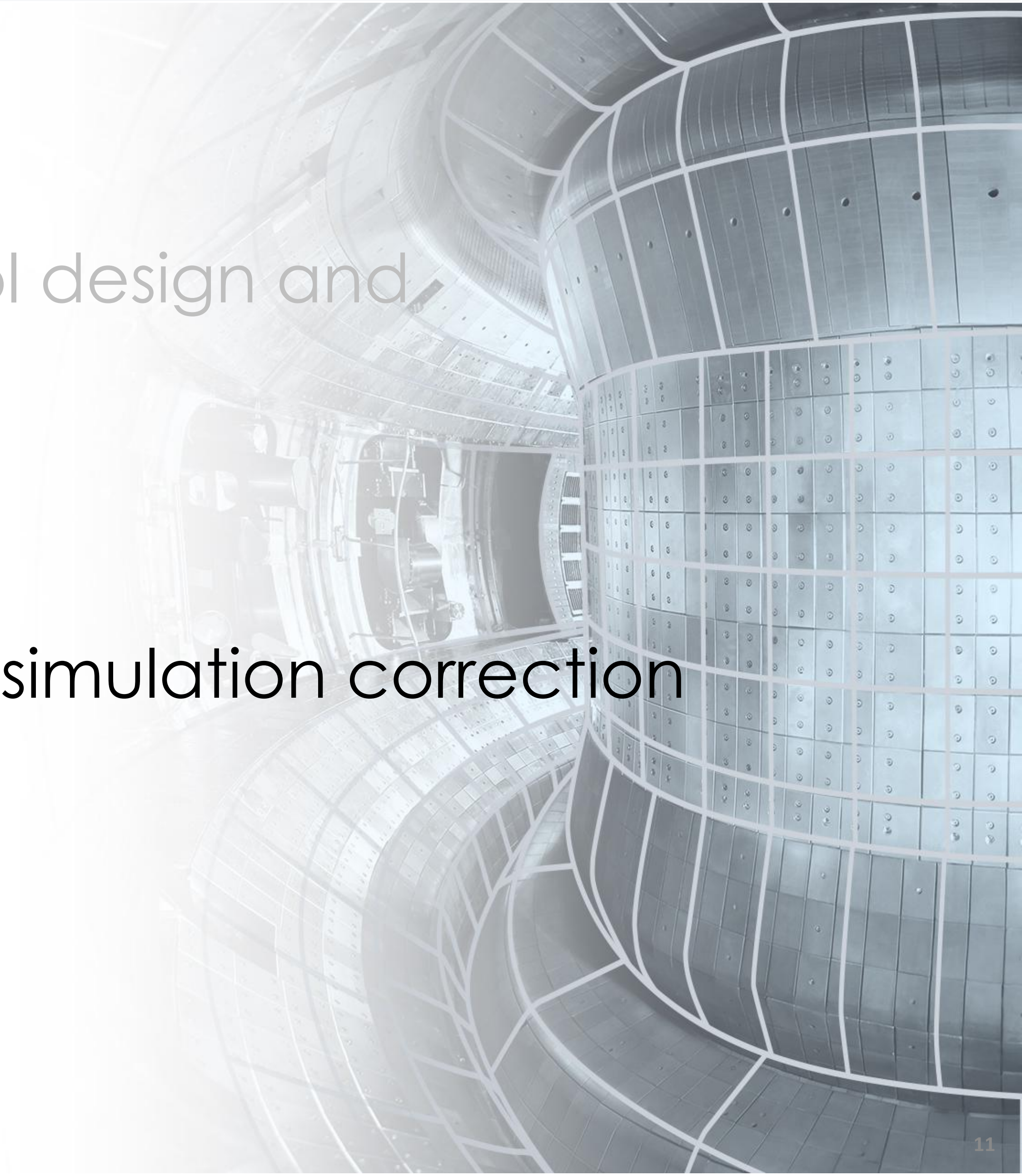
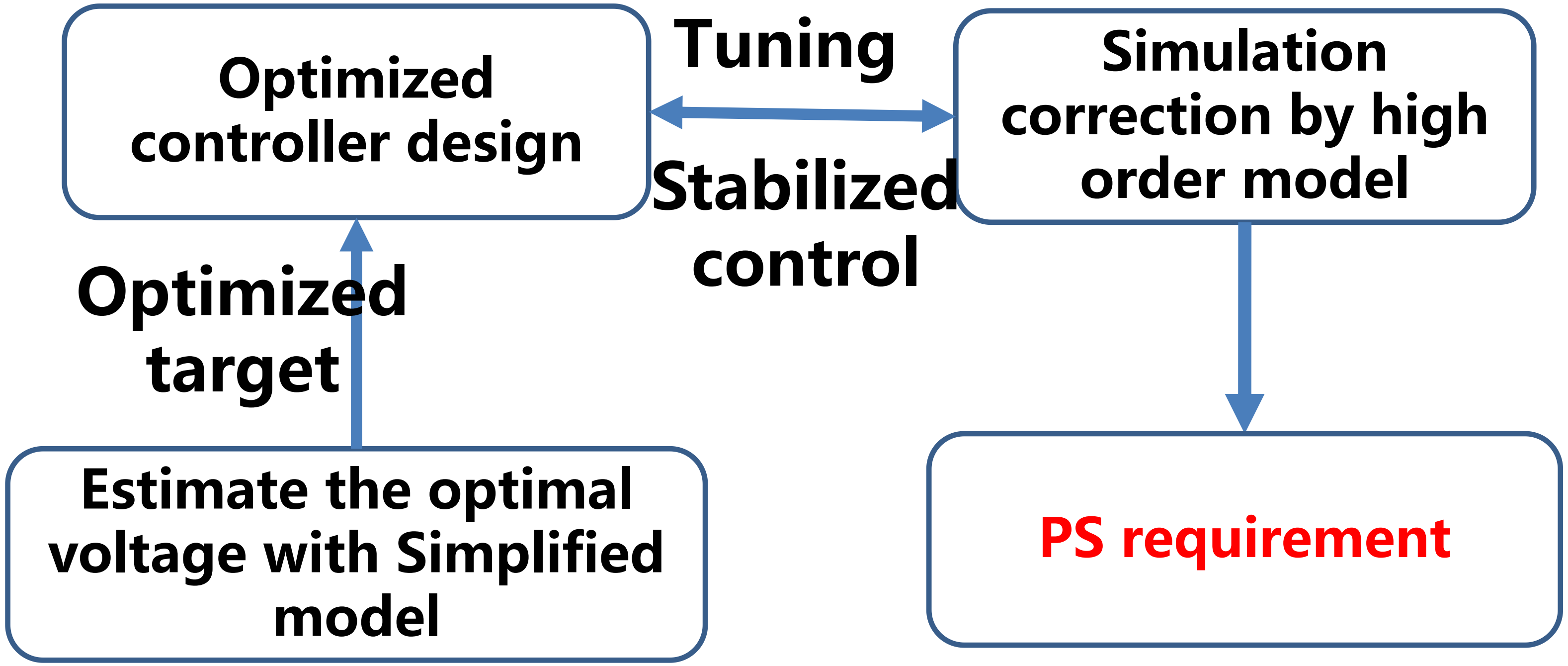


Feedback control design

- Using a linear model to estimate the optimal voltage based on a given passive structure and coil position
- Design controllers using optimal control algorithms
- Simulate verification using a rigid model



- Using Velocity controller：

$$V_{vs} = k_1 \frac{s\tau_d}{1 + s\tau_d} z + k_2 I_{vs}$$

- Combined with maximum voltage limit:

Simulation correction

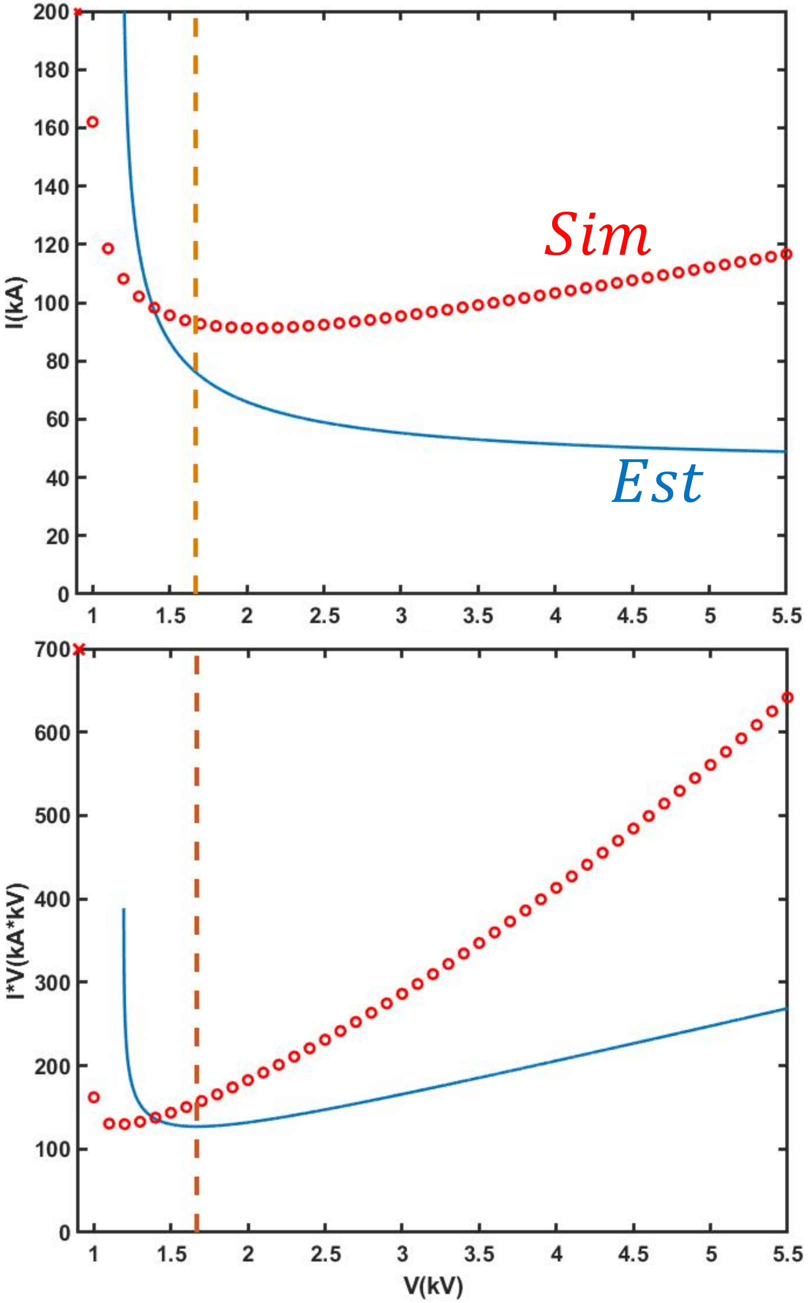
- Using the high-order rigid model and free drift recovery method for controller correction
- $T_{ps} = 1ms,\ \ \delta Z_{max}$ requirements following the ITER robust control requirements:

$$\delta Z_{max} > 10\% * a$$

- The simplified model enables a sufficient accurate assessment of control requirements at lower voltages

	Opt. Est.*	Opt. Sim.*	Early design
V_{sat}(kV)	1.668	1.2	5.32
I_{max}(kA)	76.13	108.2	112.5

*minimize the $V_{sat} * I_{max}$



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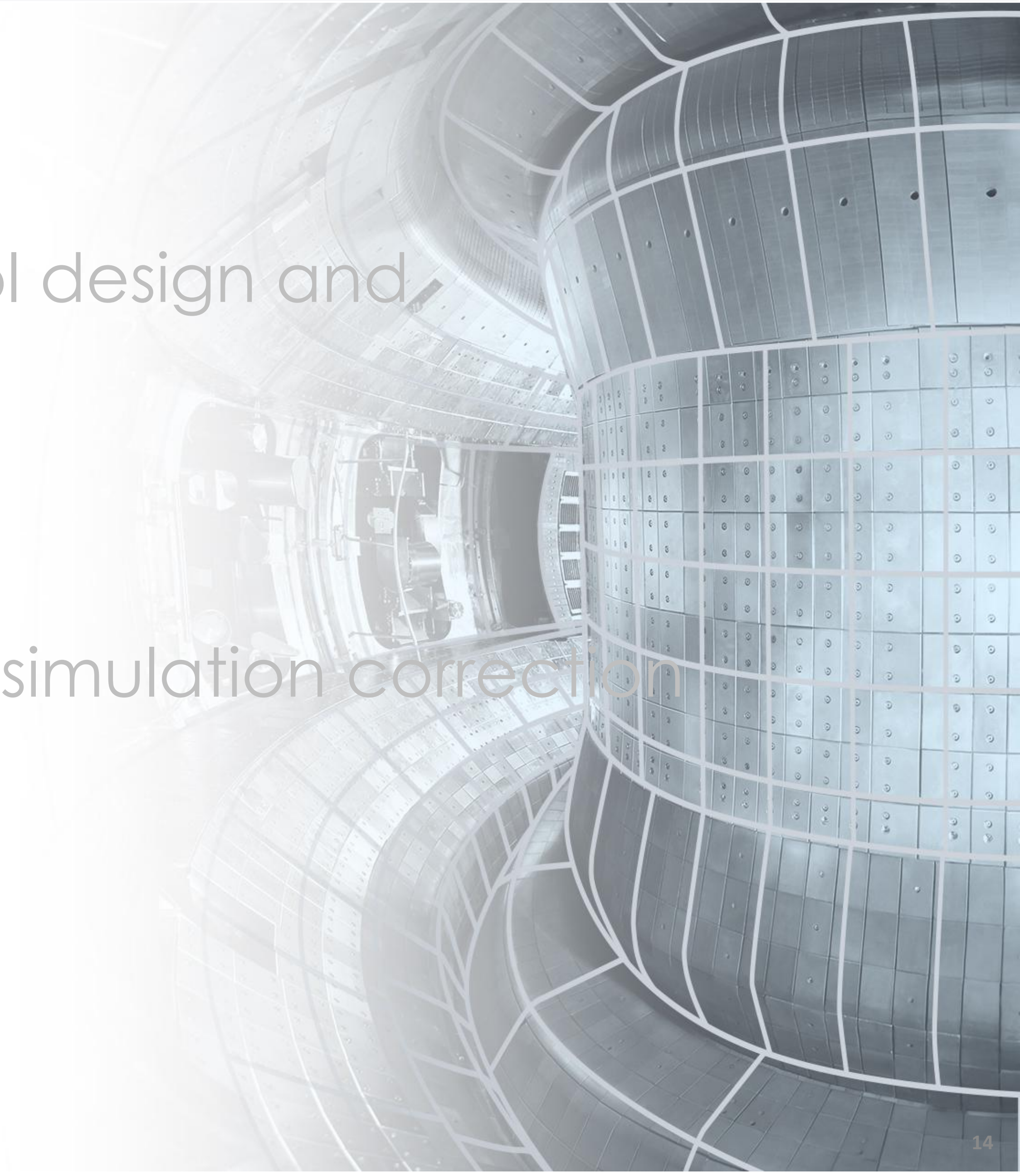

Summary

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- A vertical position control design approach based on a simplified physical model was applied to the design and achieve a reduction in PS requirements
- The simplified model enables a sufficient accurate assessment of control requirements, especially at lower voltages
  - Free-drift recovery simulation results in an inconsistency initial state between the estimation
  - Partial differences come from the overshot of the controller
  - High-order stable modes need to be considered under high-voltage

Thank you !