OPTIMAL DESIGN OF FAST PLASMA BOUNDARY CONTROL CONSIDERING VERTICAL INSTABILITY FEATURES USING IN-VESSEL COILS IN JT-60SA

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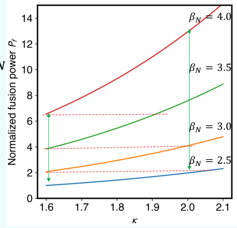
Introduction: *High elongation is one of the keys for Fusion*

- By increasing plasma elongation κ, the fusion power can be significantly improved.
  Higher κ amplifies the fusion power from an increase in β_N

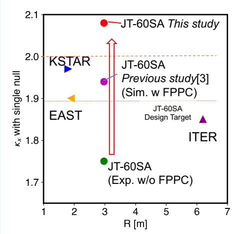
  $P_f \propto (nT)^2$ [1] $\quad$ Troyon and bootstrap fraction scaling [2]

  $P_f \propto \beta_T^2 B_T^4 \quad \beta_T \sim A^{-1/2}(1+\kappa^2)\beta_N^2/f_{BS}$
- However, an increase in plasma elongation raises the growth rate of vertical instability, causes a VDE.
- Especially, a superconducting tokamak is difficult to sustain high elongation. Larger tokamak results in slower coil current change due to large inductance, I = (V*t)/L.
- To control vertical displacement, fast control by normal-conducting coils is implemented (KSTAR, EAST, JT-60SA, ITER)



Target

Demonstration of high elongation (κ > 2) with a single-null (SN) configuration in MECS simulation



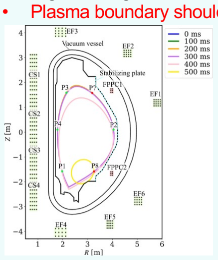
Upper Divertor: 0.45 MW/m^2 for 100 s [4]
Lower Divertor (water-cooled CFC tiles): 10 MW/m^2 for 5 s
Lower Divertor (water-cooled CFC monoblocks): 15 MW/m^2 for 100 s

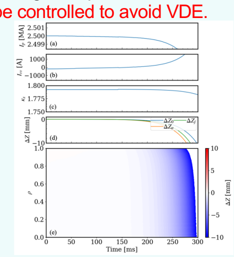
Approaches

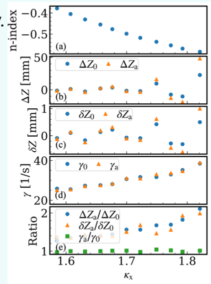
- *Reconsider the physics for the vertical instability.*
- *Design to control a single null configuration.*
- *Design to coordinate in-vessel coil control and SC coil control.*

Plasma boundary should be controlled

- Examined the natural VDE in the MECS simulation.
  → Plasma boundary moves faster than the center. $\quad \Delta Z = \delta Z e^{|\gamma|\Delta t}$
- The growth rate and amplitude of VDE are investigated for varying elongation levels.
- The reason for the faster displacement at the plasma boundary is the larger amplitude at the boundary [3].
- Higher elongation results in larger amplitude at the boundary.
- Plasma boundary should be controlled to avoid VDE.







SC coils control: *DCP scheme is applied*

Plasma current control

Control input

$$\delta\psi_X = -L_p(I_{p\_ref} - I_{p\_mes})$$

Control flux

$$\delta\psi_{Xcont} = G_{X,AVA}\left\{G_{PX}\delta\psi_X + G_{IX}\int\delta\psi_X dt + G_{DX}\frac{d\delta\psi_X}{dt}\right\}$$

Position/Shape control

Control input

$$\delta\boldsymbol{\psi}_{S\_SC} = \boldsymbol{\psi}_{surf.} - \boldsymbol{\psi}_{cont.}$$

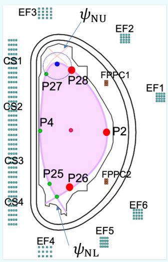
Control flux

$$\delta\boldsymbol{\psi}_{Scont} = G_{PS}\delta\boldsymbol{\psi}_{S\_SC} + G_{IS}\int\delta\boldsymbol{\psi}_{S\_SC}dt + G_{DS}\frac{d\delta\boldsymbol{\psi}_{S\_SC}}{dt}$$

- Conventional method:
  Control points are pre-programmed at fixed points.
  → It cannot directly control κ & δ.
- Dynamic Control Point (DCP) scheme [5]:

→ Control points are arranged based on κ, δ.

- Upper and lower control points are arranged at the intersections of LCFS and a circle.



Cont. point	Location	R	Z	FPPC
P2	Outer-most	Fixed	Dynamic	○
P4	Inner-most	Fixed	Dynamic	-
P28	~ Upper-most	Dynamic	Dynamic	○
P27	~ Upper-most	Dynamic	Dynamic	-
P26	~ Lower-most	Dynamic	Dynamic	○
P25	~ Lower-most	Dynamic	Dynamic	-

+ Null configuration control

To keep a single null (SN) configuration,

$$\psi_{Diff} = \psi_{NL} - \psi_{NU} > 0$$

The applied ISO-FLUX scheme can be used to sustain SN configuration.

Control input

$$\delta\psi_{Null} = \psi_{Diff\_ref} - \psi_{Diff} \quad \text{when,} \quad \psi_{Diff\_ref} > \psi_{Diff}$$

Controlled flux for the formation control is modified.

$$\delta\boldsymbol{\psi}_{S\_Mod} = (\delta\boldsymbol{\psi}_{S\_SC}\ \delta\boldsymbol{\psi}_{Null})^T$$

Control flux

$$\delta\boldsymbol{\psi}_{ScontMod} = G_{PS}\delta\boldsymbol{\psi}_{S\_Mod} + G_{IS}\int\delta\boldsymbol{\psi}_{S\_Mod}dt + G_{DS}\frac{d\delta\boldsymbol{\psi}_{S\_Mod}}{dt}$$

FPPC coils control

Fast position control

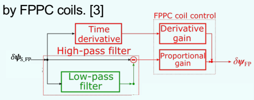
Control input

$$\delta\boldsymbol{\psi}_{S\_FP} = \boldsymbol{\psi}_{surf.} - \boldsymbol{\psi}_{cont.} \quad \leftarrow \text{Outer 3 points}$$

Control flux

$$\delta\boldsymbol{\psi}_{FPcont} = G_{P\_FP}\left(\delta\boldsymbol{\psi}_{fast} + T_{D\_FP}\frac{d\delta\boldsymbol{\psi}_{S\_FP}}{dt}\right)$$

Higher-frequency part, which cannot be controlled by SC coils is controlled by FPPC coils. [3]



Coils current change → Coil voltage command

$$\delta\boldsymbol{I}_{SC} = \boldsymbol{M}^{\dagger}(\delta\boldsymbol{\psi}_{Xcont.} + \delta\boldsymbol{\psi}_{Scont.}) \qquad \delta\boldsymbol{I}_{FP} = \boldsymbol{M}^{\dagger}(\delta\boldsymbol{\psi}_{FP})$$

$$\delta\boldsymbol{I}_{coil} = (\delta\boldsymbol{I}_{SC}\ \delta\boldsymbol{I}_{FP})^T \longrightarrow$$

Control output

$$\boldsymbol{V}_{com} = \boldsymbol{M}_c\frac{d\boldsymbol{I}_{coil}}{dt} + \frac{d(\boldsymbol{M}_{pl}I_p)}{dt}$$

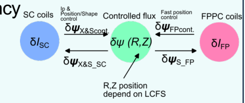
Summary & Future work

- ✓ *Reconsider the physics for the vertical instability.*
  → Plasma boundary, which has high amplitude, should be controlled.
- ✓ *Design to control a single null configuration.*
  By applying the ISO-FLUX scheme to sustain the flux gap between the upper and lower null-points, a lower single null configuration is sustained at κ=2.05.
- ✓ *Design to coordinate in-vessel coil control and SC coil control.*
  Not only the frequency separation technique, using the KKT system, the SC coil current change is calculated while fixing the FPPC coil current change for fast plasma control.
  → Control interference is avoided & the controllability is improved.
- ✓ **High elongation κ>2 with SN can be stably controlled in JT-60SA.**

- Development of a long pulse 5.5MA scenario with κ>2.0 is challenging.
  Issues: FPPC coil current is saturated due to the small and fast oscillations of the control points by DCP control, around 5MA.
  Solutions: Low-pass filtering for locations of control points / Adaptive dumper for FPPC coil current

KKT system: *Avoiding control interference*

- Conventional approach:
  Frequency separation worked to focus the variable frequency of coil current change by SC coils and FPPC coils.
  → Less coupling issues between SC and FPPC coils.
- DCP control: Control points are moved.
  Controlling magnetic flux gap $\delta\boldsymbol{\psi}_{FP}$ directly affects on magnetic flux gap $\delta\boldsymbol{\psi}_{SC}$ controlled by SC coils.
  → Control interference.



Fixed control points: Plasma motion does not affect the magnetic flux gap at the location of control points.
Moving control points: Plasma motion affects both controls.

- The Lagrangian function with the constrained least squares problem is applied.

$$\mathcal{L} = \underbrace{\|\delta\boldsymbol{\psi} - \boldsymbol{M}_{coil}\delta\boldsymbol{I}_{coil}\|^2}_{\text{Control flux gap}} + \underbrace{\lambda\|\delta\boldsymbol{I}_{coil}\|^2}_{\text{Minimize coil current change}} + \underbrace{\Lambda^T(\boldsymbol{C}\,\delta\boldsymbol{I}_{coil} - \delta\boldsymbol{I}_{FP})}_{\text{Fix FPPC coil current change for fast position control}}$$

Conditions

$$\frac{\partial\mathcal{L}}{\partial\,\delta\boldsymbol{I}_{coil}} = 0 \quad \text{Minimize flux gap} \qquad \frac{\partial\mathcal{L}}{\partial\Lambda} = 0 \quad \text{Fix FPPC coil current change}$$

(Karuch-Kuhn-Tucker) KKT system

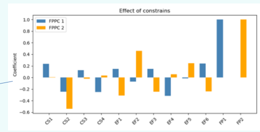
$$\begin{bmatrix} 2\boldsymbol{M}_{coil}^T\boldsymbol{M}_{coil} + 2\lambda\boldsymbol{E} & \boldsymbol{C}^T \\ \boldsymbol{C} & \boldsymbol{0} \end{bmatrix}\begin{bmatrix}\delta\boldsymbol{I}_{coil} \\ \Lambda\end{bmatrix} = \begin{bmatrix} 2\boldsymbol{M}_{coil}^T\delta\boldsymbol{\psi} \\ \delta\boldsymbol{I}_{FP}\end{bmatrix}.$$

$$\boldsymbol{H} = 2\boldsymbol{M}_{coil}^T\boldsymbol{M}_{coil} + 2\lambda\boldsymbol{E}$$

$$\boldsymbol{M}_{KKT}^{\dagger} = (\boldsymbol{H}^{-1} - \boldsymbol{C}_{cons}\boldsymbol{C}\boldsymbol{H}^{-1})\,2\boldsymbol{M}_{coil}^T \qquad \boldsymbol{C}_{cons} = \boldsymbol{H}^{-1}\boldsymbol{C}^T\left(\boldsymbol{C}\boldsymbol{H}^{-1}\boldsymbol{C}^T\right)^{-1}$$

$$\delta\boldsymbol{I}_{coil} = \boldsymbol{M}_{KKT}^{\dagger}\,\delta\boldsymbol{\psi}_{SC} + \boldsymbol{C}_{cons}\,\delta\boldsymbol{I}_{FP}$$

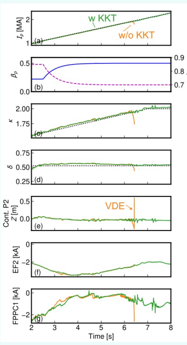
Example

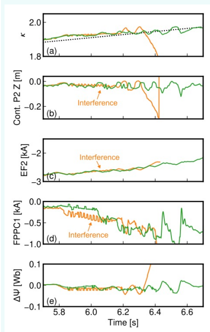


- FPPC coil current change by the fast position control can be incorporated.

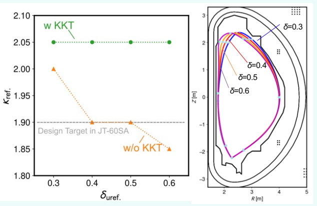
DCP + KKT: *Controllable region is expanded κ>2.05*

- DCP control without KKT system causes the control interference triggering VDE. Elongation is limited to κ~1.9.
- DCP control with KKT system avoids the control interference resulting in κ>2.0.



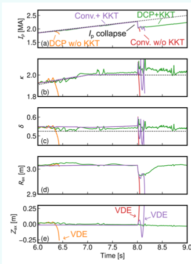


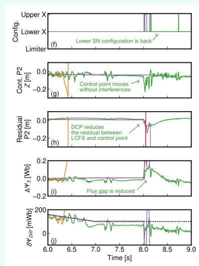
- With KKT system, high elongation κ=2.05 in wide triangularity δ=0.3-0.6 is controllable.

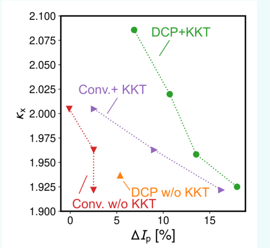


DCP+KKT: *Stable Control for disturbance*

- A minor I_p collapse causes VDE due to reduced wall stabilization.
- Conventional control using pre-programmed control points also demonstrates the effectiveness of using the KKT system.
- The influence of KKT is significant in DCP control, with or without it.
- DCP control with KKT system can avoid VDE, even with 8% of Ip collapse at κ=2.08.







References

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[3] Kojima, Shinichiro, Shizuo Inoue, Yoshiaki Miyata, Hajime Urano, et al. 2025. "Effects of Non-Rigidity on Fast Plasma Boundary Control Using in-Vessel Coils in JT-60SA." Nuclear Fusion 65 (8): 086003.
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[5] Inoue, S., S. Kojima, Y. Miyata, H. Urano, et al. 2024. "Adaptive Tikhonov Regularization and Dynamic Control Points for Accurate Shape Parameter Control of Plasmas." Nuclear Fusion 64 (1): 016014.