A POSSIBLE METHOD TO IMPLEMENT PASSIVE 3D COILS FOR RUNAWAY ELECTRON SUPPRESSION IN FUTURE REACTOR-SCALE TOKAMAKS

B. RAO, Z.Y. CHEN, Z.H. JIANG, Y.H. DING, S.N. LIU, J.H. YANG, Y.B. LI

International Joint Research Laboratory of Magnetic Confinement Fusion and Plasma Physics, State Key Laboratory of Advanced Electromagnetic Engineering and Technology, School of Electrical and Electronic Engineering, Huazhong University of Science and Technology, Wuhan, China

Email: borao@hust.edu.cn

1. INTRODUCTION

In future large-scale tokamak devices, the effective suppression of runaway electrons remains a critical challenge. In recent years, a passive 3D coil scheme has been proposed and attracted significant attention due to its self-activating capability without relying on the accuracy of disruption predictions. Key factors for its practical application include the magnitude and response time of induced currents in passive coils, as well as their engineering feasibility. Over the past few years, studies based on simulations and conceptual designs for devices such as DIII-D and SPARC have yielded promising results. However, in future fusion reactors, the vacuum vessel interior will be densely occupied by blanket modules. These thick blankets (nearly 1 m in thickness), likely constructed from metallic structural materials that may exhibit magnetic properties, introduce substantial uncertainties in the induced current magnitude, response time, and magnetic field distribution generated by passive coils.

2. METHOD TO IMPLEMENT 3D PASSIVE COILS

Recently, we analyzed the mutual coupling relationships within the poloidal field (PF) system—including PF coils, the vacuum vessel, passive coils, and plasma current—to evaluate induced currents during both normal plasma operation and disruption events. Our results demonstrate the critical role of the mutual inductance between the coil and plasma, as well as the coil resistance, in governing the current magnitude and rise time. This implies significant constraints on induced currents in large-scale reactors with blanket modules.

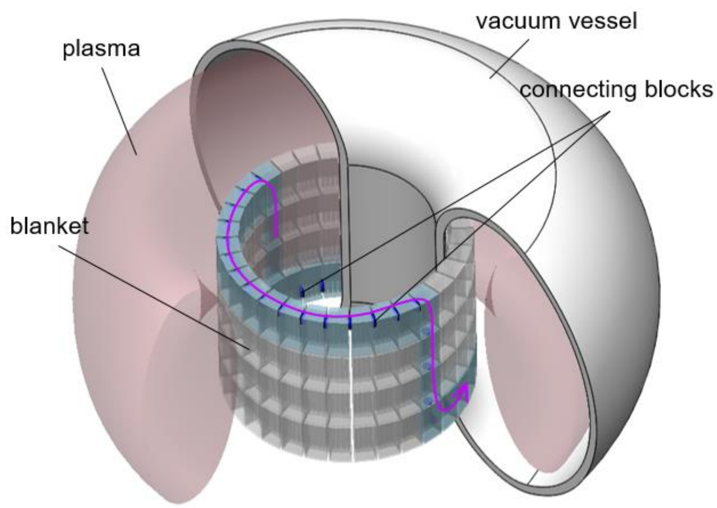

Fig. 1 Conceptual layout of a blanket coil

To address the magnetic field attenuation caused by blankets in future fusion reactors, we propose a novel passive coil implementation scheme. This involves interconnecting separated blanket modules using low-activation structural steel to form closed-loop coil circuits. Positioned close to the plasma, these loops can induce substantial currents during disruptions, generating non-axisymmetric magnetic fields of sufficient strength to suppress runaway electrons. We evaluated various coil loop configurations in terms of induced current magnitude and spatial spectral distribution of magnetic fields. Results indicate that a dual-semicircular coil structure positioned on the high-field side combines structural simplicity with high induced currents, achieving up to 8% of the plasma current in our analysis.

3. CIRCUIT LOOP AND ITS CONTROL

If the coil is a simple short-circuited conductor loop inside the vacuum chamber, it will inevitably induce currents during both the plasma current ramp-up and flat-top phases. These induced currents generate non-axisymmetric perturbing magnetic fields, which are detrimental to the control of plasma instabilities. To mitigate or minimize such induced currents, we have designed a semiconductor-switch-based switching assembly. This system prevents the coil from generating error magnetic fields that could destabilize the plasma during non-disruption operational phases, while maintaining functionality during plasma disruption events.

4. CONCLUSION

This work provides a feasible pathway for integrating passive coils with blanket systems in next-generation fusion reactors, addressing both engineering and physics challenges in runaway electron mitigation.

ACKNOWLEDGEMENTS

This work was supported by National Key R&D Program of China under Grant (No. 2024YFE03000200) and by National Natural Science Foundation of China (NSFC) under Project Numbers Grant (No. 12475223).

REFERENCES

[1] Allen H Boozer. Two beneficial non-axisymmetric perturbations to tokamaks. Plasma Phys. Control. Fusion 53 (2011) 084002

[2] R. Sweeney, A. J. Creely, J. Doody, et al., MHD stability and disruptions in the SPARC tokamak. 2020 J. Plasma Phys. 86 865860507

[3] R.A. Tinguely, V.A. Izzo, D.T. Garnier, et al., Modeling the complete prevention of disruption-generated runaway electron beam formation with a passive 3D coil in SPARC. 2021 Nucl. Fusion 61 124003

[4] D.B. Weisberg, C. Paz-Soldan, Y.Q. Liu, et al., Passive deconfinement of runaway electrons using an in-vessel helical coil. Nucl. Fusion 61 (2021) 106033

[5] A.F. Battey, C. Hansen, D. Garnier, et al., Design of passive and structural conductors for tokamaks using thin-wall eddy current modeling. Nucl. Fusion 64(2024) 016010

[6] V.A. Izzo, I. Pusztai, K. Särkimäki, et al., Runaway electron deconfinement in SPARC and DIII-D by a passive 3D coil. 2022 Nucl. Fusion 62 096029

[7] R.A. Tinguely, I. Pusztai, V.A. Izzo, et al., On the minimum transport required to passively suppress runaway electrons in SPARC disruptions. Plasma Phys. Control. Fusion 65 (2023) 034002