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

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Abstract

The suppression of runaway electrons presents a critical challenge for future reactor-scale tokamaks. This paper proposes a novel integrated passive 3D coil implementation scheme with blanket modules, aiming to fully utilize the conductive structure of blanket modules to form passive suppression circuits. The approach constructs closed conductive loops between segmented blankets, leveraging transient voltages induced during disruptions to generate strong currents, thereby creating non-axisymmetric magnetic fields capable of effectively suppressing runaway electrons. To meet fusion reactor operational requirements, a semiconductor switch-based system design is proposed to maintain steady-state plasma stability while ensuring rapid response to disruption events. Validation through electromagnetic-circuit coupling simulations on the J-TEXT device confirms the scheme's feasibility, revealing nonlinear regulatory effects of coil resistance and inductance parameters on induced currents. Results demonstrate that the dual-semicircular coil configuration achieves induced currents up to 8% of the plasma current while exhibiting favorable current induction characteristics and maintaining compatibility with blanket integration. This work provides an important technical pathway for implementing passive runaway electron suppression in fusion reactors, offering significant value in addressing key engineering challenges faced by future fusion devices.

1. INTRODUCTION

Magnetically confined fusion energy is a promising sustainable power source, but reactor-scale tokamaks face critical challenges, particularly in controlling plasma instabilities. During major plasma disruption events, the generation of high-energy runaway electron beams poses a serious threat to device safety [1]. Runaway electrons, accelerated by strong electric fields, can reach energies of tens of MeV. Their impact on the first wall materials of the vacuum vessel may cause localized melting, material erosion, and activation, which not only compromise the operational lifetime of the device but could also lead to prolonged and costly maintenance cycles.

The primary methods for runaway electron suppression currently include gas injection, shattered pellet injection [2], and the application of resonant magnetic perturbations (RMP) [3]. Although effective in devices like TEXTOR and DIII-D, these active control methods face notable limitations: high dependence on accurate disruption prediction and precise timing control—challenging in reactor-scale devices—potential induction of secondary plasma instabilities or aggravated runaway electron generation, and inconsistent suppression efficacy across different machines, indicating the lack of a universal solution.

Passive suppression technology has garnered increasing attention in recent years due to its self-triggering characteristics [4]. Specially designed in-vessel coils exploit disruption-induced voltage to generate non-axisymmetric fields that disrupt runaway electron confinement. Experiments on devices such as ASDEX-Upgrade and TEXTOR have shown that runaway electrons can be effectively suppressed [5]. Numerical simulation studies from DIII-D [6] and SPARC [7] have demonstrated that optimized coil configurations can achieve over 80% loss rate of runaway electrons.

Nevertheless, the integration of passive coils into future reactor-grade tokamaks—such as DEMO or CFETR—introduces new complexities. The presence of extensive breeding blanket systems, often nearly one meter in thickness and potentially constructed from magnetic materials, may significantly attenuate induced currents and alter magnetic field structures. These engineering realities necessitate innovative coil designs that operate effectively within spatially constrained and electromagnetically hostile environments.

To address these challenges, this study proposes a novel implementation scheme for passive 3D coils integrated within blanket modules. The design forms closed conductive loops between segmented blankets, aiming to utilize the substantial currents induced during disruptions to generate non-axisymmetric magnetic fields for runaway electron suppression. To validate the physical basis and engineering feasibility of this scheme, the study incorporates preliminary analysis of reactor-scale characteristics and establishes a detailed electromagnetic-circuit coupling model on the J-TEXT device for systematic verification. The research focuses on a dual-semicircular coil configuration, analyzing its electromagnetic coupling characteristics and induced current behaviour. Concurrently, the concept of active switching control is explored to address compatibility between normal operation and disruption suppression.

2. PRINCIPLE AND DESIGN OF PASSIVE 3D COILS

The core principle of this technology utilizes specially designed conductive connecting blocks to link discrete blanket modules into a complete toroidal loop, which form closed upper and lower semi-circular paths between the inner blanket segments, as illustrated in Fig. 1.

The operational process is as follows: When a plasma disruption occurs and the toroidal current decays rapidly, the changing magnetic field intersects the area enclosed by this conductive loop. According to Faraday's law of electromagnetic induction, a powerful transient current is induced within the loop. This induced current subsequently generates an intense localized non-axisymmetric perturbing magnetic field in the surrounding space, primarily within the plasma region bounded by the blanket modules.

The conductive loop is positioned on the inboard blanket to maximize coil-plasma coupling, generating strong local non-axisymmetric magnetic fields essential for runaway electron deconfinement. This configuration yields higher mutual inductance (M), producing larger induced currents during disruptions. As the plasma contracts inward during current quench, the inboard-mounted loop maintains effective coupling and preferentially excites low-order (n=1) perturbations that efficiently disrupt magnetic flux surfaces.

Using discrete connecting blocks to integrate segmented blanket modules into a conductive loop offers notable advantages over installing separate suppression coils. This approach eliminates the need for additional in-vessel coil hardware or penetrations, saving space and simplifying remote handling. Since the loop is formed on the plasma-facing surface, the generated magnetic field does not require penetration through the massive bulk of the blanket modules, avoiding eddy current-induced attenuation and spectral distortion. Additionally, it circumvents lifetime, erosion, and impurity issues associated with mounting independent coils on the plasma-facing side.

The loop geometry comprises two semi-circular runs joined into a single closed path, with the semi-circular portions lying immediately adjacent to the plasma’s top and bottom edges. This arrangement promotes a strong low-order multipole ($m \approx 1$) and the desired poloidal spectrum to efficiently break edge flux surfaces and deconfine runaway electrons. Compared with complex continuous helical or large-curvature coils, this configuration is simpler to form, assemble and integrate with existing blanket support structures, reducing manufacturing cost and risk.

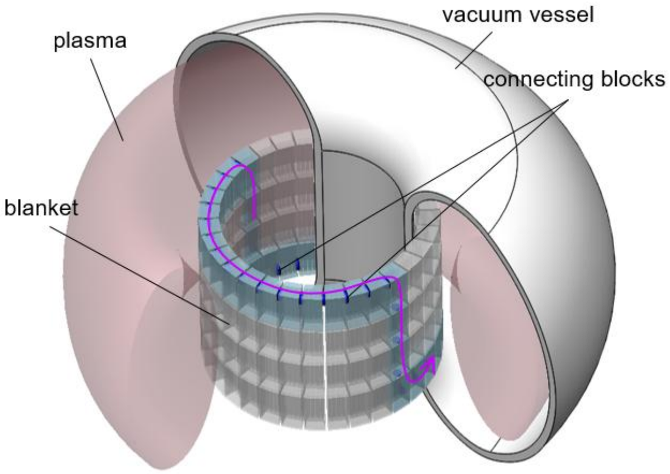

FIG. 1. Coil Design Diagram.

3. ELECTROMAGNETIC SIMULATION AND CONTROL SYSTEM ANALYSIS OF INTEGRATED PASSIVE COILS FOR FUSION REACTORS

This study aims to evaluate the applicability of passive coils to reactor-scale devices, for which preliminary integrated simulations based on CFETR parameters were conducted. Simulation of a 10 MA plasma disruption shows that a peak induced current of approximately 71.7 kA can be generated in a toroidally connected blanket, confirming the scheme's capability to excite effective magnetic perturbations. The obtained electromagnetic circuit parameters (self-inductance 16.4 μH, equivalent resistance 128 μΩ) provide critical input for subsequent system-level circuit simulations.

Even when the conductive loop is placed directly on the plasma-facing side of the blanket, the magnetic fields it creates are still affected by the entire blanket system in complex ways. Nearby blanket modules can bend and weaken the magnetic fields in their local area. At the same time, during a sudden disruption, the whole blanket structure can produce large, complex swirls of electrical current (3D eddy currents). The magnetic fields from these currents interfere with the original intended magnetic disturbance pattern. This could not only reduce its strength in important regions but, more crucially, change its detailed structure (poloidal and toroidal mode spectra), which may lower its effectiveness at scattering runaway electrons. Therefore, for the final reactor design, it is essential to treat the passive coils and the entire blanket as one interconnected electromagnetic system. A key focus must be on understanding how this network of 3D eddy currents weakens and distorts the 3D magnetic fields. Solving this will be a central challenge in future integrated design and optimization work.

To ensure the effective operation of passive coils in reactor-grade devices, a supporting circuit control system must be established. In this system, the passive coils are mechanically secured to the blanket structure via connecting blocks but are specially designed electrically: the blanket modules remain insulated from each other, with electrical lines extended only from connecting blocks at specific positions to feedthrough electrodes at the vacuum chamber windows, ultimately forming a closed loop externally. The system implements differentiated control based on the operational state of the plasma: during the steady-state flat-top phase, the external switch remains open, keeping the entire circuit electrically isolated to avoid generating static error fields that could disrupt plasma equilibrium; when the disruption prediction system detects precursor signals, the switch closes rapidly within a millisecond timescale, establishing a complete conductive path, enabling the coils to leverage the high loop voltage generated during current quench to induce non-axisymmetric magnetic fields sufficient for suppressing runaway electrons.

The implementation of this scheme primarily faces the following challenges: in terms of timing control, the switch system must complete the closing operation within an extremely short response window, as any delay would significantly weaken the suppression effect on runaway electrons; in terms of electromagnetic characteristics, the elongated connecting lines increase the equivalent inductance of the loop, potentially affecting the amplitude-frequency characteristics and dynamic response performance of the induced current, necessitating targeted compensatory measures during the electromagnetic design phase. In terms of current handling, the switch must be capable of carrying the induced current, which can reach hundreds of kiloamperes, and must reliably interrupt this current before the onset of the next steady-state phase to re-isolate the circuit.

Based on the parametric analysis using a generic model presented in this chapter, which provides a key theoretical basis for the passive coil design, the next chapter will further validate the feasibility of this scheme under the complex environment of a real tokamak. This will be achieved by constructing a detailed model incorporating the specific structure, materials, and typical discharge parameters of the J-TEXT device. The simulation-based feasibility study aims to assess the coil's performance in a scenario that closely approximates real-world conditions.

4. PASSIVE LOOP FEASIBILITY STUDY ON J-TEXT

Based on the J-TEXT device, a feasibility validation of passive coils was performed. J-TEXT offers realistic device geometry, disruption waveforms, and plasma displacement data, enabling model validation under practical conditions. Its comprehensive magnetic diagnostics allow direct comparison with simulation results, enhancing reliability. As an existing facility, J-TEXT facilitates concept verification with reduced engineering risk and enables rapid design optimization.

The specific validation approach employs a circuit-coupled simulation based on the J-TEXT device. First, a J-TEXT simulation model incorporating the iron core, passive coils, ohmic field coil set, and vacuum vessel was established in ANSYS, with the passive coils configured on the high-field side near the central column region. The specific geometric layout is shown in Fig. 2.

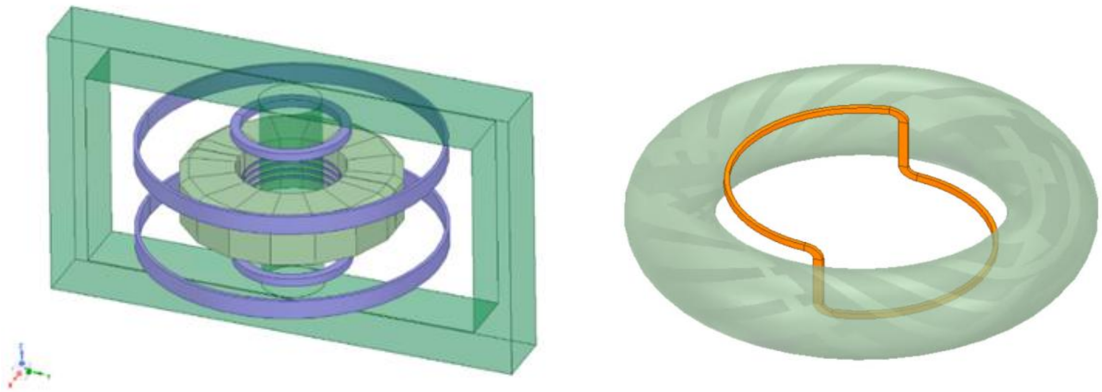

FIG. 2. J-TEXT device model and geometric layout of passive coils.

This finite element model accounts for magnetic field disturbances and eddy current effects in the vacuum vessel, enabling the extraction of self-inductance and mutual inductance parameters among the plasma current, ohmic field coils, and passive coils through simulation. These parameters, together with resistance values determined from engineering practice, were then embedded into a Simulink model whose schematic is shown in Fig. 3, constructing a system for studying the induced current characteristics in the passive coils during the plasma current decay phase.

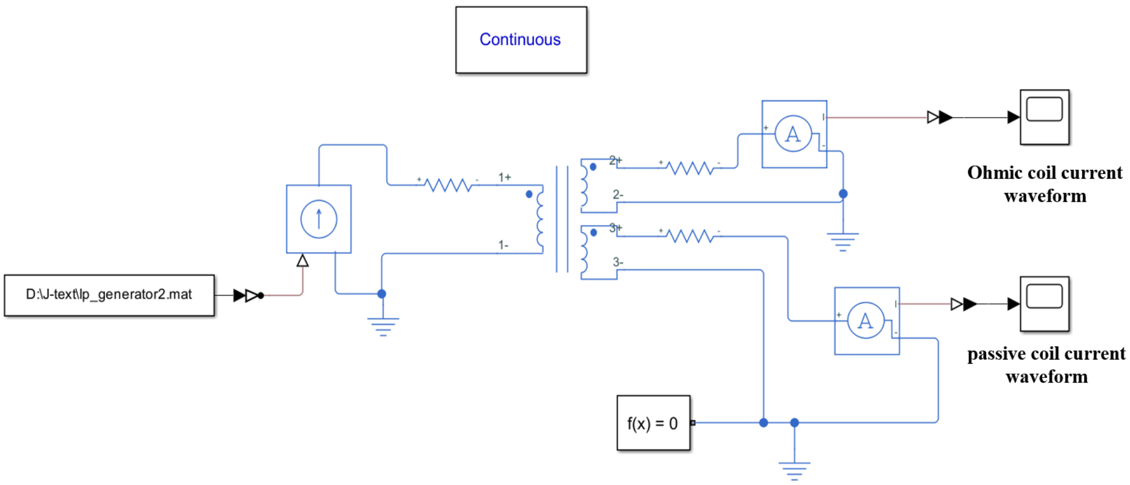

FIG. 3. Schematic of the coupled circuit model.

This study systematically investigates the electromagnetic characteristics of passive coils through dual-parameter analysis, focusing specifically on the current induced during the plasma current decay phase. The research examines both resistive and inductive parameters to comprehensively understand the system behaviour.

First, the influence of passive coil resistance variations on induced current characteristics was investigated. Analysis of the current waveforms (Fig. 4) demonstrates that reducing coil resistance effectively increases the induced current amplitude while prolonging its decay time, thereby enhancing non-axisymmetric magnetic field perturbation. Further examination of the resistance-current relationship (Fig. 5) reveals a distinct nonlinear characteristic: while high resistance maintains minimal current, resistance reduction triggers accelerated current growth, with particularly pronounced enhancement below a specific threshold. This relationship confirms that resistance optimization can significantly improve magnetic perturbation capability for runaway electron suppression.

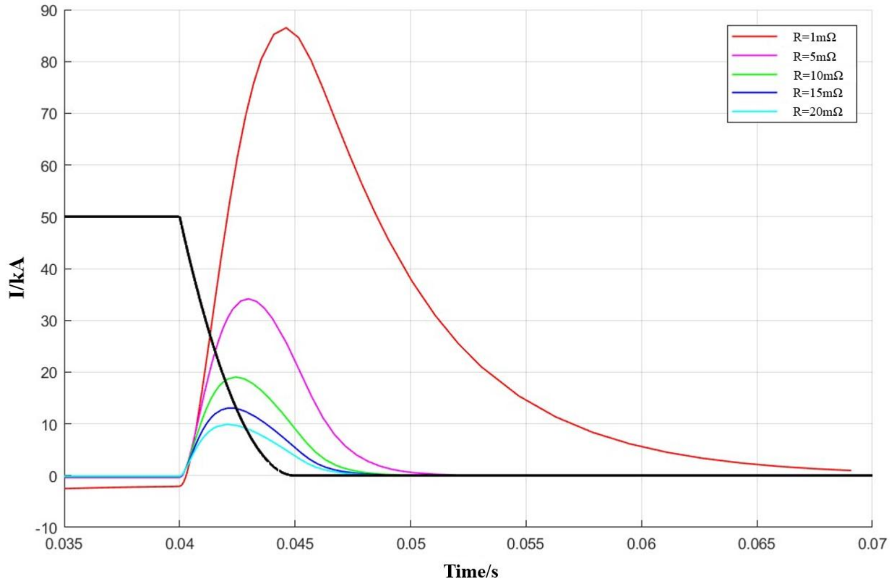

FIG. 4. Waveforms of the plasma current and induced currents in the passive coil with different resistances. The black curve (10% Ip) shows the plasma current decay.

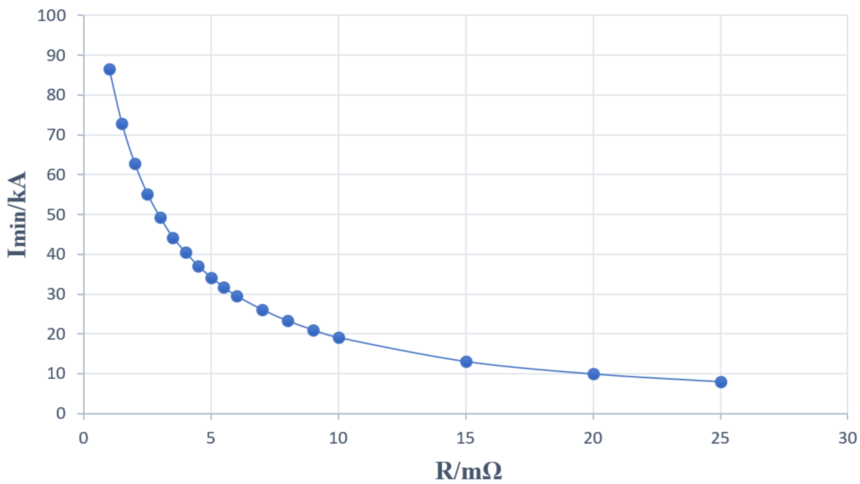

FIG. 5. Relationship curve between the passive coil resistance and the minimum value of the induced current.

Complementing the resistance analysis, this study investigated the influence of inductive parameters through relative permeability scanning using three methods: direct computation, polynomial fitting, and dense parametric sampling. The results (Fig. 6) demonstrate a clear nonlinear dependence of the minimum induced current on the inductive parameters, with a well-defined sensitivity threshold. Specifically, when the equivalent inductive parameters exceed a critical value (corresponding to $\mu r > 300$), the current stabilizes with minimal variation, indicating response saturation under strong-coupling conditions. In contrast, under weak-coupling conditions ($\mu r < 300$), the current decreases sharply with reduced coupling strength, exhibiting high parametric sensitivity.

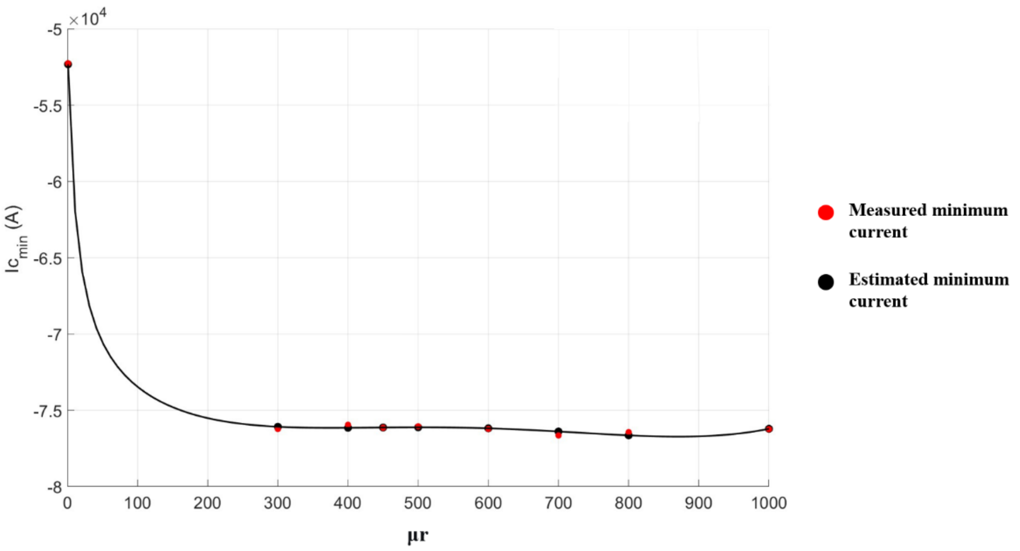

FIG. 6. Variation of minimum induced current with inductive parameters (represented by relative permeability). Red markers show measured current values, the black curve represents polynomial fitting results, and the solid line connects dense parametric sampling data.

Based on electromagnetic analysis of passive coils, this study examines induced current behaviour during plasma current decay. The results demonstrate that reducing the passive coil resistance enhances both the amplitude and duration of the induced current, thereby improving the perturbation effect of non-axisymmetric magnetic fields. In terms of inductive properties, when the system coupling strength exceeds a specific threshold, the induced current exhibits saturation behaviour, with diminishing returns from further increases in coupling strength. By coordinately optimizing these parameters of the passive coils, significantly enhanced induced current can be achieved during the plasma current decay phase, providing a reliable technical approach for runaway electron suppression.

5. SUNMMARY

This study proposes a passive 3D coil integration scheme for future fusion reactors, aiming to address magnetic field attenuation caused by thick blanket structures and the suppression of runaway electrons. The scheme constructs conductive loops between blanket modules and incorporates a semiconductor switch control system that maintains an open circuit during steady-state operation to avoid plasma disruption, while rapidly closing during disruption transients to utilize induced voltage for generating effective non-axisymmetric magnetic field perturbations. Simulations based on fusion reactor parameters demonstrate the design's potential application under reactor-level conditions, though considerations must be given to magnetic field attenuation and spectral distortion during penetration through the blanket.

To validate the feasibility of the scheme, an electromagnetic-circuit coupling model based on actual geometric parameters was established on the J-TEXT device. Simulation results demonstrate that coil resistance and inductance parameters exhibit a clear nonlinear regulatory effect on the induced current: appropriately reducing resistance helps enhance current amplitude, while optimizing coupling strength within specific ranges improves current response. Based on current research progress, future work will focus on analyzing the spatial distribution characteristics of the magnetic fields generated by passive coils, with experimental investigations planned on the J-TEXT device. By measuring magnetic perturbation signals and runaway electron behavior, a preliminary assessment of the scheme's suppression effectiveness will be conducted. Concurrently, further research will be carried out to examine the engineering feasibility of the switching control scheme.

This study provides preliminary research concepts and experimental foundations for passive suppression technology of runaway electrons in fusion reactors. The methodologies and findings offer certain reference value for the design of future fusion devices.

ACKNOWLEDGEMENTS

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