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Experimental Verification of Al_2O_3-Insulated Non-inductive REBCO Coil Array in Quench Detection for Central Solenoids of Tokamaks

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Abstract

High-temperature superconducting (HTS) central solenoid (CS) coils, while pivotal for compact fusion reactor architectures, face heightened risks of irreversible magnet degradation and catastrophic system failures under dynamic operating scenarios involving rapid current changes. Conventional voltage monitoring in HTS magnets suffer from inherent electromagnetic noise susceptibility and limited spatial discrimination, necessitating high robust quench detection methods to ensure stable and safe operation in HTS fusion system. This work experimentally demonstrates a 6-channel Al_2O_3-insulated non-inductive Rare-earth Elements Barium Copper Oxide (REBCO) REBCO coil array for quench detection through controlled quenching processes on a 1:10 scale Central Solenoid prototype at 12 T/20K operating conditions. The detection scheme combines three synergistic elements: (i) anisotropic heat transfer through Al_2O_3 insulation, (ii) induced voltage from magnetic field changes cancellation via non-inductive design, (iii) enhanced signal-to-noise ratio (SNR) and spatial resolution through voltage differential analysis across the multi-coil array. This technological framework directly supports critical objectives in quench protection system development , significantly advancing the operational reliability and engineering implementation pathways for fusion energy systems.

Keywords: REBCO, quench detection, HTS, fusion magnets

Introduction

The pursuit of compact fusion reactors as a sustainable energy source has driven significant advancements in high-temperature superconducting (HTS) magnet technology. Among these, the central solenoid (CS) coil plays a pivotal role in initiating and sustaining plasma currents, enabling efficient reactor operation. However, the integration of Rare-earth Elements Barium Copper Oxide (REBCO) HTS coils into fusion systems introduces critical challenges under dynamic operational conditions. Rapid current changes during plasma control cycles expose these coils to substantial thermomechanical stresses and localized heat generation, heightening risks of irreversible magnet degradation and catastrophic quench events. Such failures not only jeopardize reactor integrity but also hinder the scalability of fusion energy systems.

Conventional quench detection strategies, which rely on voltage monitoring across superconducting windings, face inherent limitations in HTS environments. Electromagnetic noise from time-varying magnetic fields and plasma interactions severely compromises signal fidelity, while the sparse spatial resolution of existing sensors often delays detection until thermal runaway becomes uncontrollable. These shortcomings underscore the urgent need for robust, noise-resistant diagnostic frameworks capable of preemptively identifying quench precursors with high spatial and temporal precision.

This work addresses these challenges through the experimental validation of a novel 6-channel Al_2O_3-insulated non-inductive REBCO coil array (as illustrated in Fig.1) integrated into a 1:10 scale CS prototype operating at 12 T and 20 K. The proposed detection scheme synergizes three key innovations: (i) anisotropic heat transfer modulation via Al_2O_3 insulation to localize thermal transients, (ii) cancellation of inductive voltage artifacts through a non-inductive coil design, and (iii) enhanced signal-to-noise ratio (SNR) and spatial discrimination via voltage differential analysis across the multi-channel array. By isolating resistive voltage signals from electromagnetic interference and lacating the quench area of the main coil at sub-coil resolution, this approach enables early-stage quench identification, a critical requirement for activating protective measures before irreversible damage occurs.

The successful demonstration of this framework marks a significant leap toward operational reliability in HTS-based fusion systems. It not only mitigates risks associated with rapid current ramping but also establishes scalable engineering pathways for real-time quench management in next-generation reactors. These advancements directly align with global efforts to accelerate fusion energy deployment by ensuring the safety and longevity of HTS magnet infrastructures.

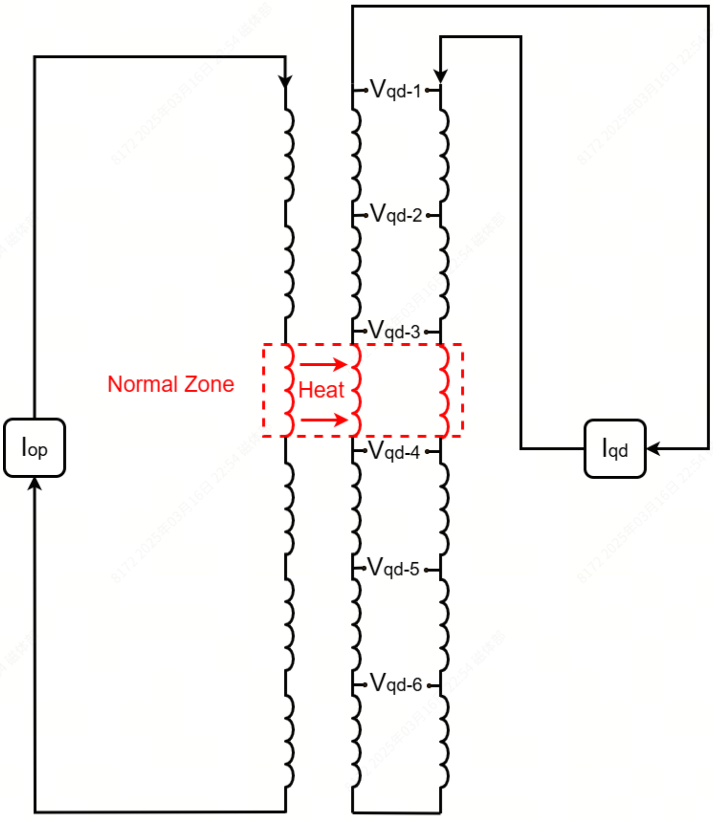

Fig .1. Quench detection scheme for 6-channel Al_2O_3-insulated non-inductive REBCO coil array