Zhang-TEC-FNT

Experimental and Numerical Research on High-Temperature Superconducting Demountable Joints for Toroidal Field Coils of Tokamaks

Authors: Zhang Chi, Qin Lang, Yang Yongqi, Wu Run, Jiang Lele, Yin Zhengxin, Chen Rui, Wang Shouzhi, Wang Binbin, Tan Yi

Corresponding Author: Qin Lang (qinlang@startorus.cn), Tan Yi (tanyi@tsinghua.edu.cn).

Zhang Chi, Qin Lang, Yang Yongqi, Wu Run, Jiang Lele, Chen Rui and Wang Shouzhi are with the Shaanxi Startorus Fusion Technology Co., Ltd., Shannxi, China.

Yin Zhengxin, Wang Binbin and Tan Yi are with the Department of Engineering Physics, Tsinghua University, Beijing, China.

Abstract

In conventional tokamak architecture, the integrally constructed toroidal field (TF) coils circumferentially enclose central solenoid (CS) coils. This configuration categorically prevents vacuum vessel replacements without through-wall disassembly of TF coils—a process fraught with excessive downtime and maintenance costs that render such systems impractical for DEMO-stage accessibility. To address this critical bottleneck, contemporary initiatives within the nuclear fusion research community have prioritized the development of demountable toroidal field (TF) coil systems, with the principal engineering challenge residing in the comprehensive design optimization and experimental validation of demountable joint interfaces. Our technical approach involves two synergistic innovations:(1) Damage-resistant copper cladding on Rare-earth Elements Barium Copper Oxide (REBCO) tapes for cyclic assembly robustness, (2) Solder hierarchy-differentiated joints combining Sn63Pb37-encapsulated HTS strands with In foil interlayers. The devised joints exploit themelt differential between indium (156.6°C) and Sn63Pb37 alloy (183°C), enabling pressure-regulated detachment via melt viscosity modulation. Experimental validation confirms stable contact resistance (<100 nΩ · cm²) through thermal-mechanical cycles, with Ic@77K, self-field retaining 98% of initial value. This work establishes a critical prerequisite for industrial-scale implementation of demountable TF systems and provides quantitative design criteria for next-generation tokamaks.

Keywords: Tokamak, REBCO, Demountable TF coil, Demountable joints

Introduction

The tokamak, a leading magnetic confinement concept for achieving controlled nuclear fusion, relies on a complex integration of toroidal field (TF) coils and central solenoid (CS) coils to generate and stabilize the plasma. In conventional tokamak architectures, the TF coils are integrally constructed as a continuous toroidal structure that fully encloses the CS coils and vacuum vessel. While this configuration ensures mechanical integrity and electromagnetic performance, it imposes a critical limitation: the vacuum vessel—a component subject to neutron-induced degradation and frequent maintenance—cannot be replaced without disassembling the TF coil system. Such disassembly necessitates cutting through structural components, resulting in prolonged downtime, exorbitant maintenance costs, and cumulative damage to superconducting materials. These constraints render traditional tokamak designs economically and operationally impractical for DEMO-stage reactors, where rapid component replacement and high availability are paramount.

To overcome this bottleneck, recent fusion engineering efforts have focused on developing *demountable TF coil systems* that enable non-destructive disassembly and reassembly. The principal challenge lies in engineering robust, high-performance demountable joints capable of sustaining extreme thermal, mechanical, and electromagnetic loads while maintaining ultra-low electrical resistance and minimal critical current (I_c) degradation across repeated assembly cycles. Existing solutions, such as bolted joints or soldering-bonded interfaces, suffer from irreversible mechanical wear, resistance instability under cyclic loading, or incompatibility with high-temperature superconductor (HTS) materials.

This work introduces two synergistic innovations to address these limitations. First, we encapsulate the rare-earth barium copper oxide (REBCO) side of HTS tapes with copper strips of equal width using Sn63Pb37 solder. This approach transforms the original superconducting-superconducting interface into a copper-copper contact during disassembly, significantly reducing the risk of HTS material degradation during repeated assembly cycles. Second, we propose a hierarchical soldered joint architecture: by integrating the Sn63Pb37-encapsulated REBCO-copper composite from the first innovation, the construction of superconducting joints now only requires connecting the pre-clad copper strips. To achieve this, indium (In) foil is employed as the interfacial medium between copper strips. Leveraging the melting point differential between In (156.6°C) and Sn63Pb37 (183°C), the joints enable pressure-regulated detachment through selective melting of the In layer, preserving the structural integrity of the REBCO tapes. Experimental validation demonstrates stable contact resistance ($<85\ n\Omega \cdot cm^2$) over multiple assembly cycles, with I_c@77K, self-field retaining 98% of its initial value—a milestone achievement for HTS-compatible demountable magnet systems.

This study not only resolves a critical engineering barrier for DEMO-reactor maintainability but also establishes quantitative design criteria for joint geometry, solder hierarchy, and operational temperature windows. By bridging the gap between theoretical concepts and industrial-scale feasibility, our work advances the realization of practical, high-availability tokamaks for commercial fusion energy.