Qin-TEC-FNT

A Novel High-Temperature Superconducting Cable Design for Compact Tokamaks

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

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

Qin Lang, Wu Run, Jiang Lele, ZhangChi, Yang Yongqi, Yi Wenqing, Tan Kan, Wang Pengjie, 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

With the increasing demand for high-field, large-sized magnets in compact tokamak devices, high-temperature superconducting (HTS) cables with high current-carrying capacity, small bending radius, and low AC loss have become a critical technical challenge. Existing HTS cables struggle to meet the requirements of such magnets due to their relatively large critical bending radius and high AC loss. This study proposes a novel HTS cable design, termed the STAR (Stacked, Twisted, Askew tapes, and Rectangular shape) cable, which achieves a critical bending radius of 400 mm through a twisted stacked structure and an external cooling channel. The STAR cable exhibits a cross-sectional utilization rate of 21% and an engineering critical current density of 98 A/mm^2 at 20 K under an 8 T background magnetic field. Benefiting from its twisted structure and cable skeleton design, the STAR cable demonstrates an AC loss of less than 30 W/m under a high magnetic field ramp rate of 40 T/s, indicating its potential for use in the magnets of compact tokamak devices.

Keywords: HTS cable, compact tokamak, critical bending radius, AC loss

Introduction

In compact tokamak fusion devices where the central solenoid (CS) magnet operates at current ramp rates reaching tens of kiloamperes per second (kA/s), the optimal solution for reducing alternating current (AC) losses in high-temperature superconducting (HTS) CS magnets lies in employing transposed-structure HTS cables. The VIPER cable configuration, currently recognized as highly promising for practical applications, features (1) grooved slots along a cylindrical core skeleton to accommodate stacked superconducting tapes with twisting transposition, and (2) an internal hollow channel enabling coolant flow through the conductor. This structural design ensures uniform thermal management across the magnet, effectively addressing challenges associated with non-homogeneous cooling in high-field applications. The core contradiction of the VIPER cable lies in the following: if a central dielectric flow channel with a small aperture is used, the flow resistance of the cable will be too large, and almost the only available cooling medium is the expensive superfluid. On the other hand, if the aperture is increased, the strain of the external superconducting tapes will increase during twisting and bending, reducing the cable's bending radius.

This report proposes a STAR (Stacked, Twisted, Askew, Rectangular - shaped) cable, which has more advantages in design compared with the VIPER cable. It has a high space utilization rate, not only realizing the transposition of superconducting tapes and high current density, but also having a smaller bending radius and lower flow resistance.

The design parameters of the STAR cable are shown in the table, and the structural parameters are presented in the figure. A single STAR cable consists of 5 groups of stacked high - temperature superconducting tapes, each group with a width of 3 mm and a thickness of 3 mm, totaling 150 superconducting tapes. Considering the self-field, it can carry a current of 8.1 kA in liquid nitrogen. Under an external field of 8 T at 20 K, it can carry a current of 34.4 kA. A 1.55 - mm circular hole in the middle can accommodate fiber - optic sensors, which are used to monitor real - time operating status information such as the cable temperature.The overall cross - sectional utilization rate of the STAR cable is 21.5%, and the engineering current density is 98.42 A/mm^2, which is at the leading level among all cable designs worldwide.

Item	Parameter
Width	13.18 mm
Height	15.88 mm
Inner Cable Diameter	11.98 mm
Area of Flow Channel	33.06 mm^2
Width of Tape	3 mm
Area of Tape	45 mm^2
Utilization Rate	21.5%
Critical Current @ 77K	8.1 kA
Critical Current @ 20K, 8T	34.4 kA

Engineering Current Density	98.42 A/mm^2
Twist Pitch	500 mm
Bending Radius	400 mm