CONFERENCE PRE-PRINT

A NOVEL HIGH TEMPERATURE SUPERCONDUCTING CABLE DESIGN FOR SPHERICAL TOKAMAKS

Wu Run
Shaanxi Startorus Fusion Technology Co., Ltd.
Shaanxi, China
Email: qinlang@startorus.cn

Tan Yi
Department of Engineering Physics, Tsinghua University
Beijing, China

Abstract

With the growing demand for large-scale magnets featuring rapid magnetic field variation for plasma control in spherical tokamak devices, the development of high-temperature superconducting (HTS) cables—characterized by high current-carrying capacity, small bending radius, and low AC loss—has become a critical technical challenge. Existing HTS cables fail to meet the requirements of such magnets, primarily due to their relatively large critical bending radii. To address this issue, this study proposes a novel HTS cable design, termed the STAR (Stacked, Twisted, Askew, Rectangular-shaped) cable. By adopting a twisted stacked architecture and an external cooling channel, this design achieves a critical bending radius of 400 mm. At 20 K under a 2.2 T background magnetic field, the STAR cable exhibits a cross-sectional utilization rate of 21% and an engineering operating current density of 50 A/mm². Moreover, benefiting from its twisted structure and integrated cable skeleton design, the STAR cable demonstrates an AC loss of less than 800 W/m even under a high magnetic field ramp rate of 24 T/s—thereby highlighting its significant potential for application in the magnet systems of spherical tokamak devices.

1. INTRODUCTION

In spherical tokamak devices, the poloidal field (PF) magnet operates at magnetic ramp rates of up to tens of Tesla per second (T/s). For mitigating alternating current (AC) losses in high-temperature superconducting (HTS) PF magnets under such extreme conditions, the optimal strategy resides in the use of HTS cables with a transposed structure. Among transposed-structure designs, the VIPER cable configuration is currently regarded as one of the most promising for practical deployment [1]. Its core structural features include two key elements: (1) grooved slots machined into a cylindrical core skeleton, which accommodate stacked superconducting tapes with twisted transposition; and (2) an internal hollow channel that facilitates coolant circulation through the conductor. Notably, this integrated design ensures uniform thermal management across the entire magnet, effectively addressing the longstanding challenge of non-homogeneous cooling in high-field operational scenarios.

However, the VIPER cable faces a critical trade-off rooted in a key dilemma: If a central flow channel with a small aperture is adopted, the cable's flow resistance becomes excessively high—leaving superfluid helium (an expensive cooling medium) as nearly the only viable option. Conversely, increasing the channel aperture elevates the strain on the outer superconducting tapes during the twisting and bending processes, thereby compromising the cable's critical bending radius.

This study presents a novel STAR cable design, which offers distinct advantages over the VIPER cable in terms of structural and functional performance. Specifically, the STAR cable achieves high spatial utilization while simultaneously enabling superconducting tape transposition, maintaining a high current density, and featuring a smaller critical bending radius and lower coolant flow resistance.

The design parameters of the STAR cable are summarized in Table 1, with its structural details illustrated in Figs. 1 and 2. A single STAR cable comprises 5 stacked high-temperature superconducting (HTS) tape assemblies, where each assembly consists of HTS tapes with dimensions of 3 mm (width) × 3 mm (thickness). The total number of HTS tapes per cable is 150. The cable case is made of stainless steel, and the body is made of aluminum alloy. Considering the self-field effect, the cable exhibits a current-carrying capacity of 8.1 kA when operated in liquid nitrogen (77 K). Under an external magnetic field of 2.2 T at 20 K, this capacity increases to 63 kA. Notably, the STAR cable incorporates a central 1.55-mm circular bore that accommodates fiber-optic sensors—these sensors enable real-time monitoring of critical operating parameters, such as the cable's temperature. Additionally, the

STAR cable achieves an overall cross-sectional utilization rate of 21.5%, with an engineering current density of 50 A/mm^2 at a current operating point of 0.17 (relative to its critical current).

TABLE 1. STAR Cable Parameters

Item	Parameter	Item	Parameter
Width	13.2 mm	Utilization Rate	21.5%
Height	15.9 mm	Critical Current @ 77K	8.1 kA
Inner Cable Diameter	12.0 mm	Critical Current @ 20K, 2.2T	63.0 kA
Area of Flow Channel	33.1 mm²	Operating Point	0.17
Size of Tape	3.0*0.1 mm	Twist Pitch	500 mm
Number of Tape	150	Critical Bending Radius	400 mm

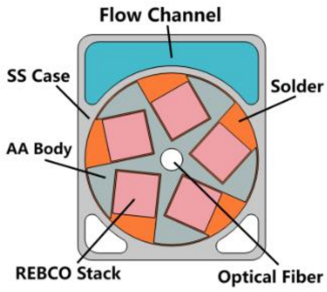

Fig 1. Cross-Section of STAR

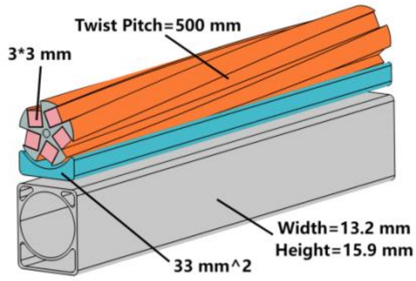

Fig 2. 3D Schematic Diagram

2. TWIST AND BENDING PERFORMANCE

For the HTS tapes within the STAR cable, the maximum distance from the cable center is 5.6 mm. Based on strain analysis by Makoto Takayasu et al. [2], calculations indicate that at a twist pitch of 86 mm, the maximum strain in the STAR cable reaches 0.4%–a value approaching the critical strain of the HTS tape. In contrast, when the twist pitch is designed to 500 mm, the maximum strain is reduced to 0.012%. For practical STAR cable applications, a 500 mm twist pitch ensures that the cable completes more than one full twist within a single coil turn, thereby fully realizing the AC loss reduction effect associated with tape transposition. It is important to note that further decreasing the twist pitch would not only increase the mechanical strain on the HTS tapes but also elevate manufacturing complexity, making it impractical for engineering applications.

As illustrated in Fig. 3, maximum strain calculations for the STAR cable using two analytical models yield distinct results at a bending radius of 400 mm: the Perfect-Slip Model (PSM) predicts a maximum strain of 0.4%, while the No-Slip Model (NSM) predicts a higher maximum strain of 1.4%. Given that the PSM result aligns with the HTS tape' s critical strain, the critical bending radius of the STAR cable is determined to be 400 mm. To ensure compliance with this strain limit during manufacturing, two key steps are required: (1) inter-tape slip must be guaranteed during cable fabrication to mitigate excessive strain accumulation; and (2) subsequent to coil winding, the cable assembly undergoes solder vacuum impregnation to enhance structural stability and mechanical integrity.

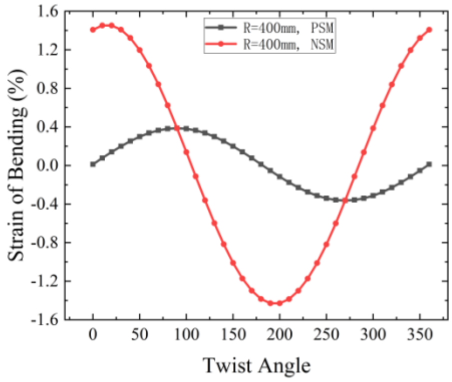

Fig 3. Maximum strain of the STAR cable at a bending radius of 400 mm

As shown in Fig 4, the feasibility of the STAR cable's twist pitch and bending radius was verified by fabricating a 150 mm-long short sample. This sample contained a ribbon stack composed of one superconducting tape and 29 copper tapes placed in each groove. The superconducting tapes were positioned at the 2nd, 8th, 16th, 22nd, 28th layers of the stack. The cable body and case were replaced with 3D-printed epoxy resin.

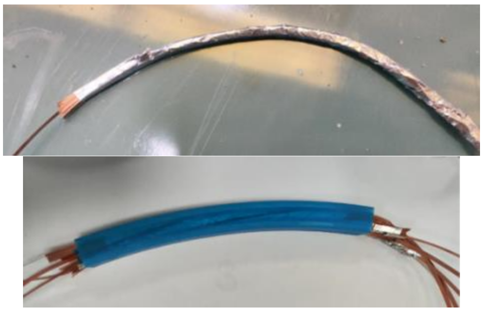

Fig 4. Short Sample of STAR cable

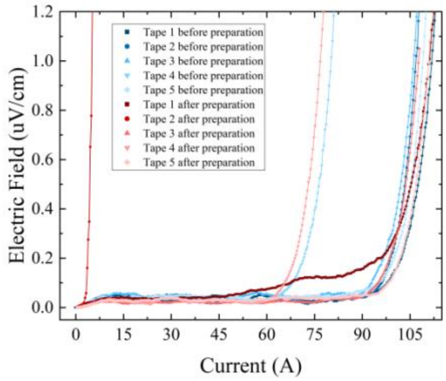

Fig 5. I-V Curves Before and After Preparation

As shown in Fig. 5 and Table 2, four of the HTS tapes in the short sample remained intact, whereas one tape incurred damage. Notably, the damaged tape was located at the stack’s center. Further analysis suggested this damage stemmed from localized bending at the end of the short sample during testing, rather than from the torsion or bending of the cable. This outcome confirms the high feasibility of the STAR cable design when operated under the optimized 500 mm twist pitch and 400 mm critical bending radius.

TABLE 2. Critical Current and n value of the tapes Before and After Preparation

Layer of HTS	Critical Current before preparation (A)	Critical Current after preparation (A)	n value before preparation	n value after preparation
2	112	111	19	17
8	107	5	22	5
16	106	108	19	19
22	80	77	16	16
28	109	111	22	21

3. CRITICAL CURRENT

Using the uniform H method and critical current data for the HTS tape from the Robinson Research Institute [3], the I-V curve for the STAR cable is calculated as shown in Fig 6, with critical current values listed in Table 3. The operating current of the STAR cable under 20 K, 2.2 T conditions is 10.5 kA, with a temperature margin of

40 K at this point. The cable's engineering current density is 50 A/mm ^{2}. The current density distribution at 10.5kA under 20K, 2.2T conditions is shown in Fig 7.

TABLE 3. Critical Current of STAR cable

Temperature (K)	Magnetic Field (T)	Critical Current (kA)
77	Self-Field	8.1
60	2.2	10.7
20	2.2	63.0
20	8	34.4

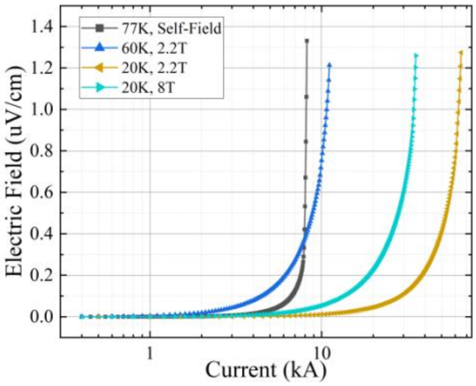

Fig 6. I-V curves of STAR cable by H method

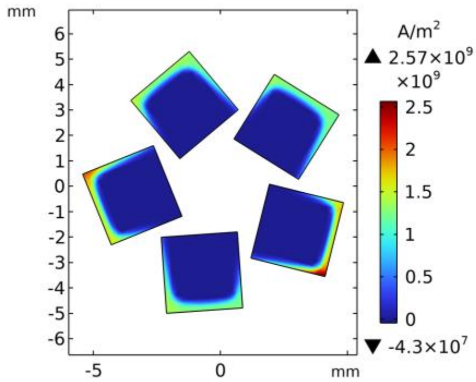

Fig 7. Current density distribution of 10.5 kA at 20K, 2.2T

4. EXAMPLE OF APPLICATION ON THE PF4 COIL OF THE SPHERICAL TOKAMAK CTRFR-1

To further demonstrate the engineering applicability of the STAR cable, it was evaluated for use in the PF4 coil—a key component of the CTRFR-1 spherical tokamak. The PF4 coil has a central point radius of 580 mm, a total ampere-turns of over 0.5 MA, and a maximum current change rate of 5.6 MA/s. This rapid current variation requires the coil to complete excitation and demagnetization in as little as 1.8 seconds. Additionally, AC losses induce temperature rises in the coil during discharge cycles, necessitating that the PF4 coil cools down to its operable temperature within 10 minutes post-discharge.

Fig. 8 illustrates the magnetic field distribution of the PF4 coil when wound with the STAR cable, with a maximum magnetic field of 2.11 T. Detailed coil parameters are provided in Table 4. The coil adopts a layer-winding configuration, where the maximum length of the STAR cable in a single layer is 31 m. Hysteresis loss simulations of the STAR cable under the PF4 coil's magnetic field (Fig. 9) yielded results of 57 J/m at 20 K and 73 J/m at 60 K.

TABLE 4. The STAR Cable Scheme of CTRFR-1 PF4 Coil

Parameter	Value	Parameter	Value
Maximum Magnetic Field	2.11 T	Maximum Magnetic Field Change Rate	24 T/s
Number of turns	7*8	AC Loss	~800 W/m
Operating Temperature	20 K	Helium Flow	0.5 g/s@5 bar
Operating Current	10.5 kA	Helium Flow Resistance	4.2 kPa
Maximum Voltage	5.92 kV	Repeated Discharge Time	6 min
Inductance	50.7 mH	Amount of HTS Tapes Used	31 km*3 mm

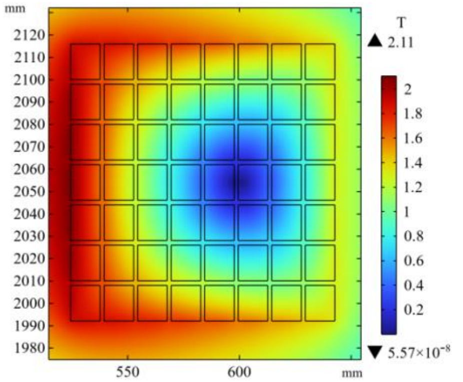

Fig 8. Magnetic Field Distribution of PF4 Coil

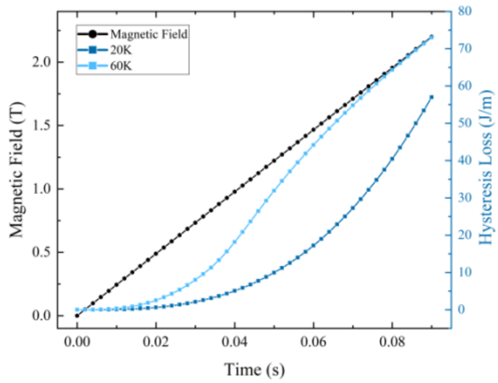

Fig 9. Hysteresis Loss

A 31 m-long STAR cable model was developed to evaluate its thermal and fluid dynamic performance under operational conditions. For this simulation, a heating power of 800 W/m was imposed on the HTS tapes, with a single discharge cycle having a duration of 0.2 s. The helium gas was supplied at an inlet flow rate of 0.5 g/s, under operating conditions of 20 K and 5 bar. As presented in Figs. 10 and 11, the simulation results indicate the following key outcomes: the maximum temperature of the cable reached 29.7 K during discharge; the maximum helium flow resistance was 4.2 kPa. And subsequent to the discharge, the cable temperature decreased to below 20.5 K within 6 minutes of cooling.

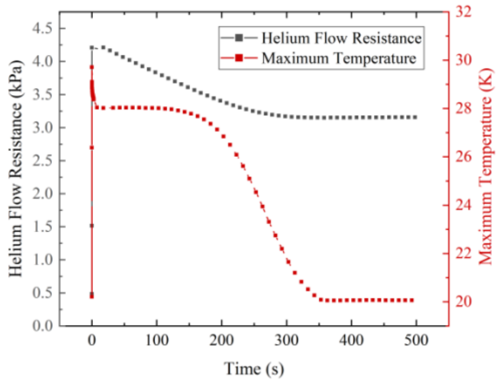

Fig 10. The Maximum Temperature of the Cable and the Helium Flow Resistance

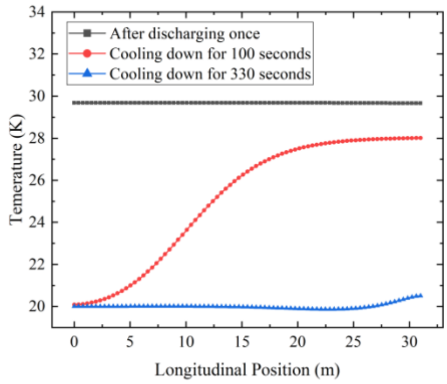

Fig 11. Temperature Distribution Along the Cable Length Direction

5. CONCLUSION

This work presents a novel high-temperature superconducting (HTS) twisted cable design. A key innovation of this design lies in the external placement of cooling channels, which enables a minimum bending radius of 400 mm—performance validated through short-sample tests. Additionally, the STAR cable achieves a high HTS tape utilization rate, with HTS tapes accounting for 21.5% of the total cable cross-section, which translates to a critical current density of 38.6 A/mm² at 77 K. Given that the cooling channel area constitutes a substantial 15.7% of the cable structure, the STAR cable is well-suited for poloidal field (PF) coils operating under rapid magnetic field variations. To demonstrate its engineering applicability, a cable scheme was tailored for the PF4 coil of the CTRFR-1 spherical tokamak. This coil operates at a maximum magnetic field of 2.11 T, with the STAR cable configured to carry 10.5 kA at 20 K. During the coil's discharge process, the STAR cable exhibits an average AC loss power of approximately 800 W/m. Post single discharge, the cable's maximum temperature remains below 30 K—well below its critical temperature of 60 K. Furthermore, under a cold helium flow rate of 0.5 g/s (at 5 bar), the cable cools to below 20.5 K within 6 minutes, enabling minute-level repeated discharge operations. Collectively, these results confirm that the STAR cable addresses key technical challenges of HTS cables for spherical tokamak PF coils, providing a reliable and high-performance solution for plasma control systems requiring rapid magnetic field variation and efficient thermal management.

REFERENCES

[1] Sanabria, C., et al., Development of a High Current Density, High Temperature Superconducting Cable for Pulsed Magnets, Supercond. Sci. Technol (2024) 37 115010.

[2] Makoto, T., Luisa C. Analytical investigation in bending characteristic of twisted stacked-tape cable conductor, IOP Conf. Ser.: Mater. Sci. Eng (2015) 102 012023.

[3] Robinson Research Institute, High-Temperature superconducting wire critical current database(2022), https://htsdb.wimbush.eu/dataset/5331145.