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Elaboration of a Promising Design of the HTS Conductor for the Central Solenoid of a Compact Thermonuclear Reactor TRT

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Abstract

The results of the preliminary development of the HTS conductor based on the VS-type design and parallel stacks for the central solenoid of the compact thermonuclear reactor TRT are presented. One of the main problems that need to be solved for the successful implementation of such projects is the creation of high-current high-temperature superconducting (HTS) conductors for Toroidal Field coils (TF) and Central Solenoid (CS) sections. The conductor must have a high engineering current density of at least 90 A/mm^2. The induction of the magnetic field in the central solenoid reaches 14 T, which leads to the occurrence of large mechanical stresses due to the influence of Lorentz forces. Like many large magnets, CS has a lot of stored energy. For the safe withdrawal of stored energy from the magnet, it requires the inclusion of elements in the conductor that provide an acceptable level of electrical voltage and heating of the conductor insulation. Thus, a sufficient amount of stabilizing and reinforcing materials should be placed in the conductor. In addition, the "cable-in-conduit" type of conductor must have channels for pumping the refrigerant. Two fundamentally different versions of the conductor based on radially arranged REBCO tapes and on the basis of pre-assembled tape packages are considered. Based on the analysis of the magnetic field distribution in the conductor by finite element method, the design characteristics of the proposed conductors under various operating modes of the electromagnetic system (EMS) of the tokamak TRT was evaluated. The results of the evaluation of the current carrying capacity of the conductor and the estimation of energy losses in a changing magnetic field in comparison with known methods are also presented.

Keywords

Central Solenoid, Conductor Design, Operating Current, HTS Tapes, Magnetic

Field Distribution

1. Introduction

Thermonuclear energy is a fundamental step towards a clean, greenhouse gas-free energy source. Thermonuclear fusion is safe, has an unlimited fuel source, high power density and does not produce significant radiation waste. In recent years, a great interest has arisen worldwide in designing of relatively compact facilities with a high magnetic field [1] [2] reaching 7 - 12 T on the plasma axis. In this case, the maximum field on the coil conductors will be within 14 - 21 T. Modern HTS materials are considered as a key element of such facilities. Remarkable progress with high temperature superconductor provides possibility to design compact quasi-stationary Tokamak with Reactor Technologies (TRT) with high magnetic field on the plasma axis [3]. The general view of the TRT electromagnetic system (EMS) is shown in **Figure 1**. Tokamak EMS includes: 16 HTS toroidal field coils, 6 HTS poloidal field coils and 4 HTS sections of the central solenoid.

Cable-in-conduit type HTS wire will be used for winding the sections. REBCO tape is used as the base material. Thus, the problem arises from aggregating a large number of superconducting tapes into a single current-conducting system. At the same time, it is necessary to achieve an even current distribution between all the tapes, which is not a trivial task due to the fact that the ohmic resistance of the HTS tapes in the operating mode equal to zero. In addition to HTS tapes, reinforcing and stabilizing materials, as well as channels for pumping refrigerant,

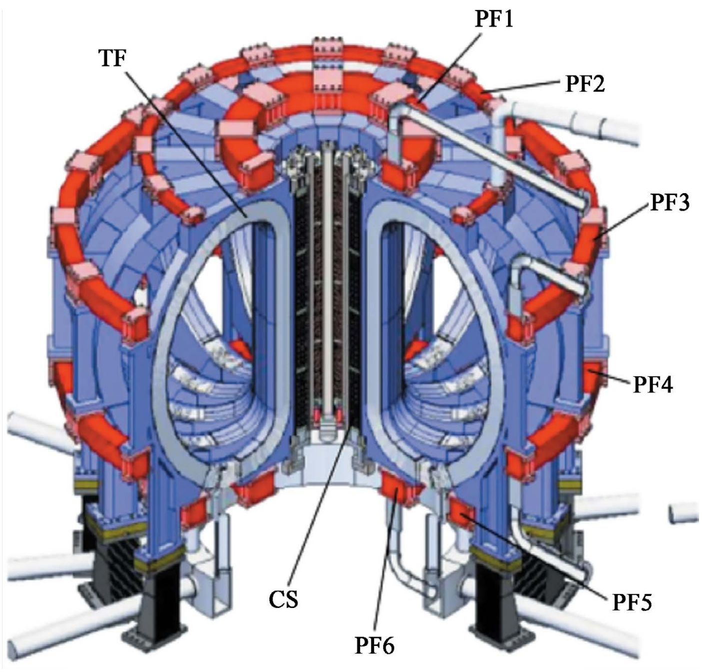


Figure 1. General view of the TRT EMS.

must be included in the conductor design in the required amount.

It should be noted that the central solenoid is the most stressed element of the EMS TRT in terms of maximum operating temperature, magnetic field induction and mechanical stresses. That is why the development of a HTS conductor for the CS TRT is one of the most important tasks of the project. In order to solve this problem, theoretical and technological research is being carried out to develop conductors that meet the specifications of the CS.

2. Requirements for the Winding Wires for Large Scale Magnets

The basic requirements for conductors for the TRT EMS were formulated in articles [4] [5]. On the basis of these requirements for CS windings, the proposed conductors were developed. A cable-in-conduit type conductor design in a stainless steel reinforcing shell was selected for the winding wires of the CS sections. As a basic superconducting element, the second generation HTS tapes, manufactured by SuperOx [6], were adopted, which are today among the best for use in strong magnetic fields at temperatures of 4.2 K - 20 K. Typical characteristics of the tapes are shown in **Figure 2** and **Figure 3**.

Based on the data for HTS tapes with a width of 4 mm, shown in **Figure 2**, the average calculated value of the critical current of the tapes for wires of the TRT can be assumed as

$$I_C\,(14\text{ T, }4.2\text{ K}) = 600\text{ A;}$$

$$I_C\,(14\text{ T, }20\text{ K}) = 320\text{ A.}$$

Depending on the thickness of the tape, the design current density can reach 1000 A/mm^2 in the transverse field of 20 T (**Figure 3**).

HTS tapes are characterized by a high level of heat generation due to energy losses in a changing magnetic field. To reduce the hysteresis losses in the tape, the possibility of filamentation of tapes can be also foreseen, that is, the division

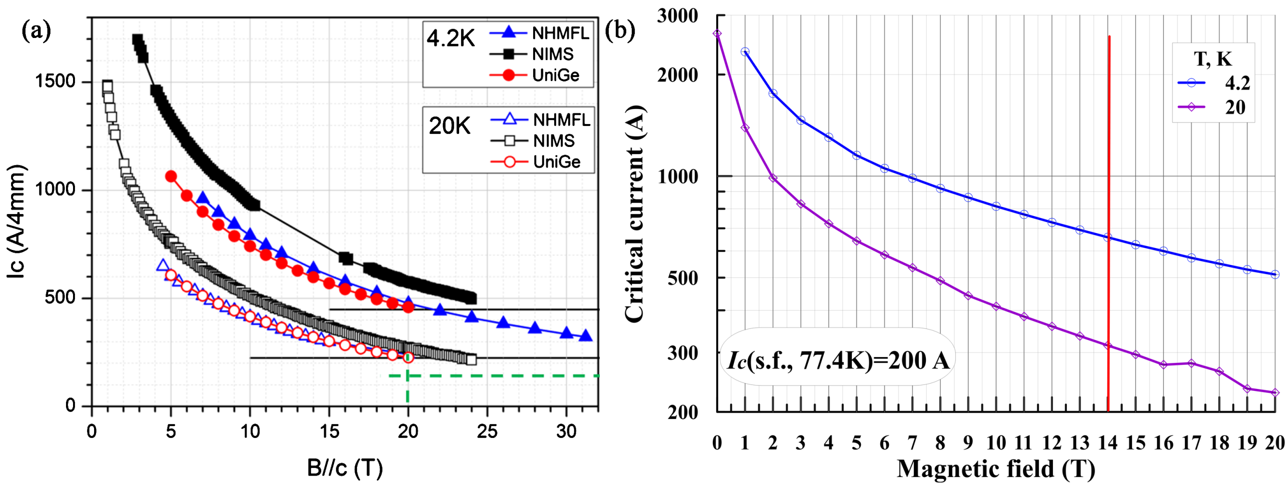


Figure 2. The critical current versus the magnetic field for HTS tapes (wide 4 mm) at different temperatures, measured in various laboratories (a) and the detailed curves (b).

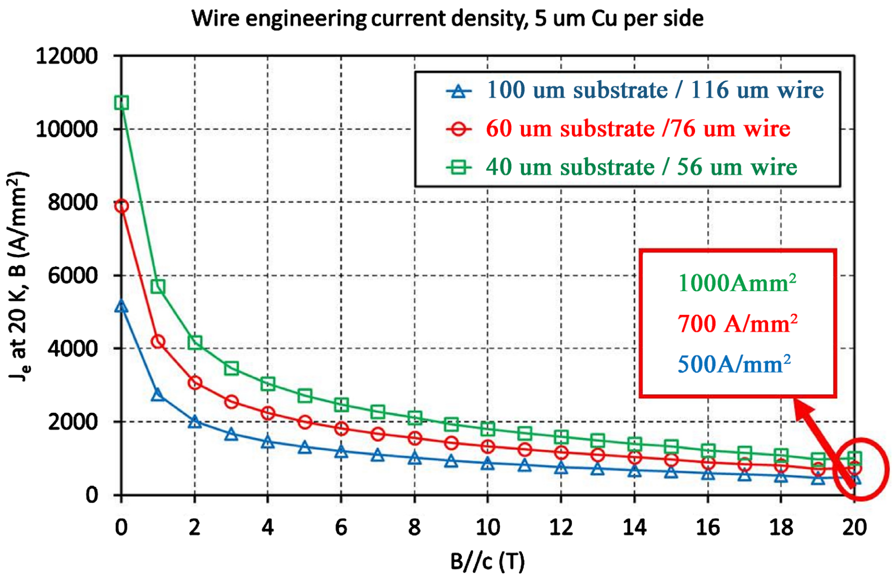


Figure 3. Engineering current density of tapes with different thicknesses.

of the superconducting layer into several thin parallel stripes on a common substrate [7] [8]. However, this issue requires additional study in terms of manufacturability and efficiency of the filamentation process.

3. The Main Directions of Development of HTS Wires for Magnets of Thermonuclear Installations

At present, the development of wires for compact magnetic systems generating strong magnetic fields is very topical [9] [10]. Mostly, conductors based on second-generation HTS tapes are considered, which makes it possible to increase the operating temperature in comparison with magnets made from low-temperature conductors. In addition, the critical magnetic fields of HTS materials are significantly higher than in low-temperature superconductors. The operating currents in such magnets are tens of kilo amperes in magnetic fields with an induction of 12 - 20 T and temperatures of 5 - 20 K. In this condition, the wire is affected by strong mechanical loads caused by Lorentz forces. The big stored energy requires the presence of elements in the winding that provide emergency energy output in terms of voltage and winding temperature. Thus, in a superconducting high-current wire of the "cable in conduit" type, there must be reinforcing elements, a stabilizing metal, electrical insulation and channels for refrigerant. As a rule, it is planned to use tapes 2 - 4 mm wide and 30 - 100 µm thick in almost all HTS wire projects. By design, conductors can be divided into two main groups, shown in **Figure 4**.

The largest numbers of developments are devoted to wires made from pre-assembled stacks of tapes—Stacked-Tape Conductor. The conductive part of the wire is assembled in two stages. The primary element in such wires is a stack of tapes, which are either located in the plane [11] [12] (**Figure 4(a)**), or twisted along the longitudinal axis [13] [14] (**Figure 4(b)**). At the second stage, several

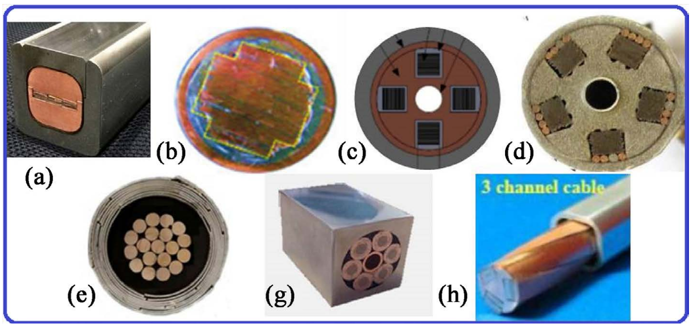


Figure 4. Cross sections of various HTS high-current wires.

stacks of tapes are assembled into a conductive wire core, either by twisting around the normal conductive core [12] [15] [16], (Figure 4(c), Figure 4(d), Figure 4(h)), or by placing them in parallel [11] (Figure 4(a)).

Constructions based on compact strands of HTS tapes are also very popular.

The primary element is the multi-layer stranding of tapes that are twisted around a small diameter core (Figure 4(e)). The primary multilayer strand was called CORC wire [12] [13] [14] and, accordingly, the wires are called CORC type wires [16] [17] [18]. In the second step, the primary elements are twisted around the longitudinal axis of the conductor (Figure 4(g)).

To circulate the refrigerant and provide mechanical strength and stability, superconducting core are enclosed in a special stainless steel conduit.

The primary elements in Stacked-Tape Conductors and CORC conductors are not transposed, which leads to different inductance of individual tapes. As it known, in parallel superconducting circuits, the current is distributed inversely proportional to the inductance of the circuits. Consequently, the current in the primary elements is distributed unevenly between the HTS tapes, which lead to a decrease in the critical current of the conductor and an increase in energy losses in changing magnetic fields. In addition, CORC design is very loose and very sensitive to transverse loads, what was shown in the paper [18].

There are several technical solutions that allow to create transposed primary sub-elements with a uniform current distribution between the HTS tapes. First is the multi-layers designs of the superconducting transmission cables cores, in which it is possible to align the inductance of the layers [19] [20] and achieve a uniform currents distribution. However, in such constructions, originally designed to work in weak magnetic fields, it is not possible to obtain a high engineering current density in strong magnetic fields. Second is Roebel cable [21] [22]. However, this option has not yet received sufficient development, due to the low mechanical characteristics and high cost of the Roebel cable, in the manufacture of which a significant part of the expensive HTS tape goes to waste.

4. Transposed Conductors of Type VS and VSS

A wire of the "cable-in-conduit conductor" type with a current-carrying core of the VS (V-Shape) is a fully transposed construction [23] (Figure 5 and Figure 6).

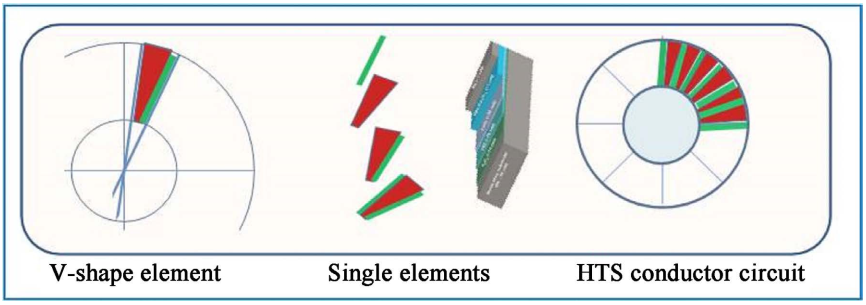


Figure 5. New VS type conductor concept. Superconducting tape is shown in green.

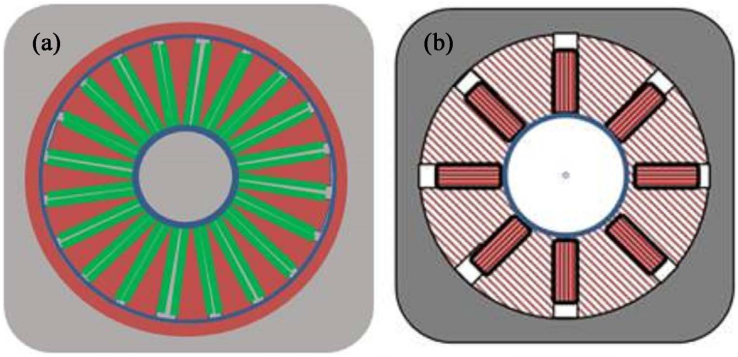


Figure 6. VS type conductor design. Single assembly (a), double assembly (b).

The general concept of the VS conductor design was described earlier [24]. The main items are:

- HTS tapes are twisted only in one layer;
- HTS tapes are located radially.

The HTS tape and wedge-shaped inset made of a normally conducting metal can be pre-soldered or connected directly during the first stage of twisting the core. The element boundaries are strictly defined by radial lines. The number of VS-elements in the structure is determined as follows:

$$N = 2\pi r/(2a + b)k \quad (1)$$

where r is the radius of the central support; a is the thickness of the HTS tape; b is the width of the bottom part of the trapezoidal element; k is the stranding coefficient.

The main advantage of the VS conductors is transposition of all superconducting tapes. Another advantages and disadvantages were discussed in [5] [23] [24].

Figure 6(a) shows design options of single-twist VS wires. Stainless steel is used as a reinforcing material, and copper or a copper-niobium composition in the form of a cylinder is used as a stabilizing material. **Table 1** shows the design characteristics of one stage conductor core. The tape characteristics on a substrate 40 μm thick with a linear critical current density of 150 A/mm width in the field of 14 T at 4.2 K are assumed as original ones. We consider structures with a critical current of up to 120 kA in a field of 14 T at 4.2 K and the engineering current density in the CS conductor at the dimensions of 26 × 26 mm^2

up to 178 A/mm^2 that is twice the required operating value of 89 A/mm^2. This means that single-twist conductors with a maximum current of 120 kA at 4.2 K provide the required double current margin at 4.2 K. The critical current of the wires at 20 K is 64 kA, and the current margin is only 1.067.

This is slightly less than the required value. Taking into account that the maximum winding temperature is reached at the end of the charging cycle and the beginning of the cooling cycle, such a small current margin may be acceptable.

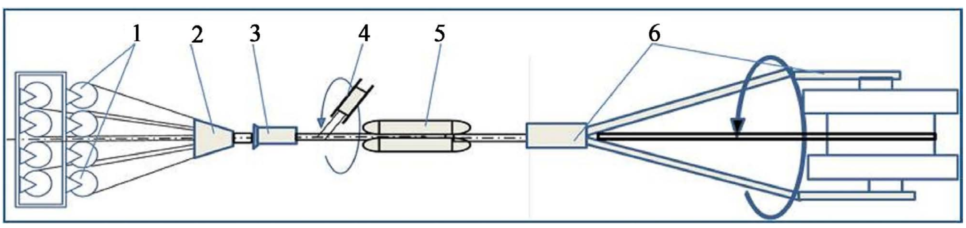
It follows from **Table 1** that the most suitable for transposed single-twist wires are the VS1$_0$-4, VS2-4 and VS2$_0$-4 designs. The total cross section of superconducting elements in conditional constructions shown in [4] is 127 mm^2.

The VS1-4 and VS1$_0$-4 designs are also of interest; however, they consist of a very large number of elements, which can present certain difficulties when twisting an HTS core. As can be seen from **Table 1**, a large number of primary elements (67 - 200 pcs) are used in the fabrication of the VS core. To twist so many elements, the use of classical twisting machines is impractical. This is due to the fact that in such machines, twisting is performed by rotating the pay-off coils located in the rotating cage [25]. It seems more rational to use machines of the Dram-Twister type. In such machines, the pay-off reels are located on fixed stands, and the core twisting occurs due to the rotation of the take-up drum **Figure 7**.

The technological operation of twisting can be significantly simplified by grouping a part of the HTS tapes into packages as shown in **Figure 6(b)**. In this design, tapes are grouped, e.g., into eight packages wrapped in titanium or stainless

Table 1. Estimation of the maximum calculated critical current and current density in the VS wire of the central solenoid at 4.2 K and 14 T.

Order number	Tape width mm	Thickness of tapes and inset ($a + b$) μm	Mandrel diameter, mm	Number of VS elements	Max. current, kA	Max. wire Jc, A/mm^2
VS1-4	4	56 + 56	5.7	160	96	142
VS1$_0$-4	4	56 + 0	3.6	200	120	178
VS2-4	4	2 × 56 + 56	5.4	100	120	178
VS2$_0$-4	4	2 × 56 + 0	3.4	100	120	178
VS2-3	3	2 × 56 + 56	3.6	67	60	89
VS2$_0$-3	3	2 × 56 + 0	3.6	100	90	133



1—pay-off reels on fixed stands, 2—forming device, 3—caliber, 4—wrapper, 5—caterpillar, 6—rotating take-up drum.

Figure 7. Drum-Twister type winding machine diagram.

steel metal tapes. The total number of tapes is the same as in VS2-4 and $VS2_0$-4 designs. In this design, there is no transposition of tapes inside the packages with respect to their self field; however, the arrangement of the tapes radially in one layer ensures the transposition of the packages with respect to the external field.

Thus, the proposed designs of VS-type wires make it possible to achieve the characteristics required for the TRT EMS. Until now, a completely transposed construction for such magnetic systems has been proposed neither in Russia nor in the world.

5. Magnetic Field Distribution and Estimation of Hysteresis Losses in a VS Type Conductor

TRT EMS consists of a large number of electromagnetic coils that can affect the field in the volume of CS. The conductor in the CS winding is subject to the influence of the conductor's own magnetic field and the external field of the solenoid (Figure 8).

The maximum field reaches 14 T. At the same time, taking into account the dimensions of the CS winding indicated in Figure 8, the maximum current density in the winding pack should be at the level of 70 A/mm^2. Along the length of the conductor, the induction in the middle of the tape varies within 2.5 T, and the orientation of the tape to the magnetic induction vector also changes. Magnetic field can vary by about 2 T across a HTS tape width. Under these conditions, an accurate calculation of energy losses is very difficult. As a first step, let us estimate the influence of the tape orientation and transport current on the

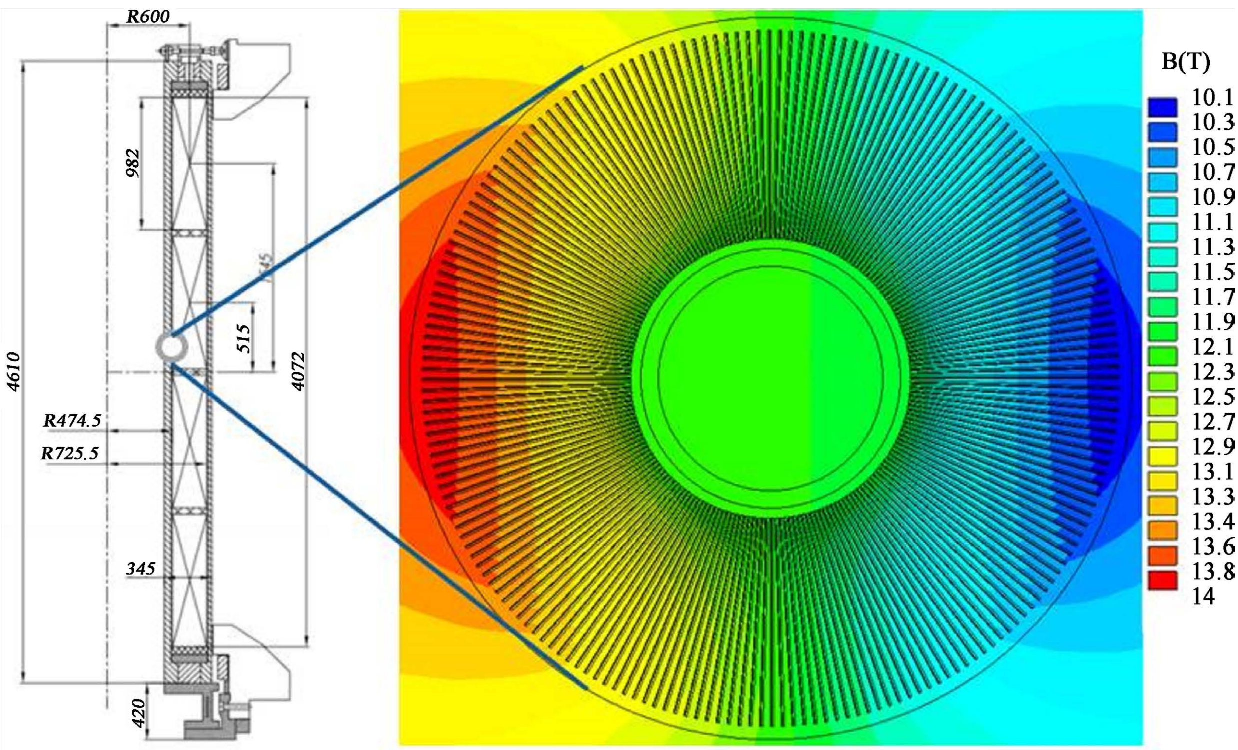


Figure 8. Magnetic field distribution in the central turn of the solenoid at an operating current 60 kA.

hysteresis losses in it.

It should be noted that Y. Mawatari [26] considered the issue of calculating alternating current losses in radially arranged HTS tapes. However, the consideration was carried out only for small magnetic fields with parallel and opposite currents in neighboring tapes, that is, for conditions characteristic of power cables.

The FEM model for calculation of transport ac losses using the finite-element ANSYS code (A/A-V formulation) had been developed recently [27]. Now the model was modified for 2 G HTS tape carrying AC transport current I_{tr} at synchronous external alternative high magnetic field B_a. This study will help to understand the role of the angle between magnetic field and the tape surface when B_a and I_{tr} are applied. The current amplitude in the tapes varies from 0 to 300 A and the amplitude of the external field from 0 to 14 T. The influence of poloidal fields changing on coupling losses was not taken into account here due to their smallness. A variant of finding a tape carrying current in an external uniform magnetic field is considered.

Figure 9 illustrates the calculated results. Calculations are compared with known analytical models. The external ac field is applied perpendicular to wide surface of the tape at zero transport current (Brandt model [28]) and the AC transport current is applied at zero external field (Norris models [29]).

The results obtained demonstrate a strong dependence of hysteresis losses in the tape on its orientation to the vector of magnetic induction. The influence of the transport current on hysteresis losses is practically absent, which is not surprising, given that the maximum tape operating current of the 300 A is only 50% of the critical one. In this regard, when estimating energy losses, it should be expected that the calculation according to the Brandt model will give more realistic results.

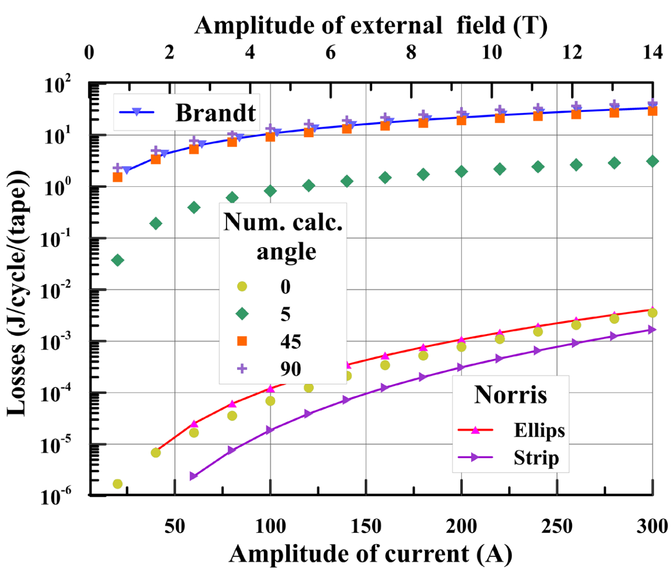


Figure 9. Calculated by the FEM model losses for different angle between the magnetic field direct to the wide surface of the HTS tape, only transport AC losses by Norris models, and magnetization losses by Brandt model.

6. CS Conductor of PaST Type, Based on Stacks of Tapes

Figure 10(c) shows a magnetic field distribution in the CS winding for the moment of reaching the maximum magnetic field induction on the winding equal to 14 T, corresponding to the end of the plasma combustion cycle. The distribution of the axial and radial components of the magnetic induction vector on the inner turn of the winding is shown in Figure 10(d) and Figure 10(e). On the upper and lower turns of the winding, the axial component of the field is at the level of 8 T, while the radial component does not exceed 10 mT. Consequently, the current carrying capacity of the conductor is determined only by the axial component of the magnetic field. Taking into account the dependence of the current-carrying capacity of the tape on the orientation of the magnetic field induction vector [5] [6], it seems advisable to use a conductor with the arrangement of the tapes parallel to the induction vector.

We call this design PaST (Parallel Stacked Tapes) conductors [30]. The idea of using several parallel, untwisted stacks of HTS tapes as a core of a high-current conductor for toroidal field coils was announced at ASC14 [31]. Later [20] [32] [33] these ideas were developed and basic recommendations of the conductor design were presented.

A variant of the PaST conductor design adapted for use in CS sections is shown in Figure 11. The rectangular conductor has a strong steel shell welded from two rolled profiles. The internal current-carrying part has the shape of a circle with the side chamfers removed. This is done to ensure the orientation of

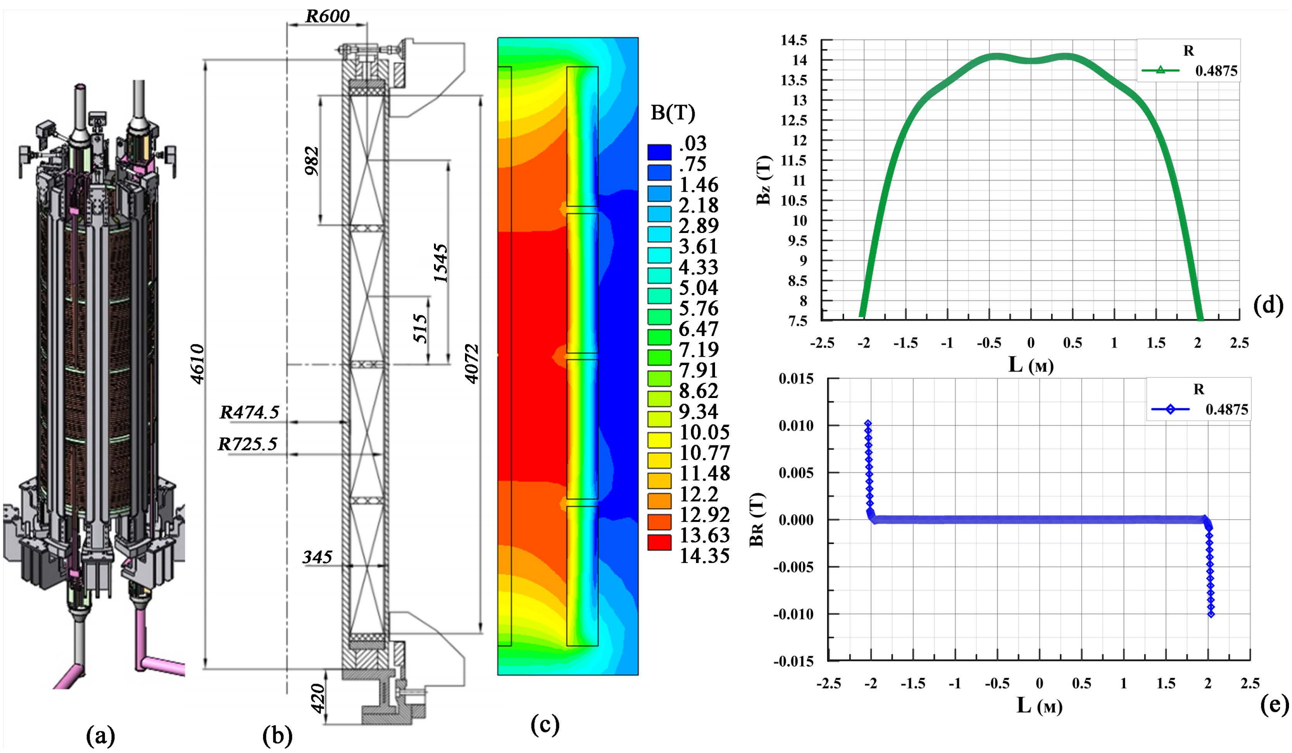


Figure 10. The central solenoid. General view (a), sketch (b), distribution of the magnetic field (c) and distribution of the axial (d) and radial (e) components of the field on the inner layer of the solenoid.

the tape packages parallel to the axial field of the solenoid.

The Lorentz force on the conductor is directed in the most favorable (perpendicular to the plane of the tape) direction and reaches 84 tons/m. The local pressure on the stack is about 3.3 kg /mm^2. The central steel insert prevents the accumulation of pressure on two adjacent stacks. A polyimide film is glued to the side surfaces of the central insert to reduce electromagnetic coupling between adjacent stacks and energy losses. As a stabilizing material (shown in **Figure 6** in red), a copper-silver alloy or an anisotropic high strength high conductivity copper-niobium microcomposite material is used. HTS tapes with a width of 6 mm are grouped into four stacks, tightly wrapped with thin titanium or steel tape. The operating current is distributed between the tapes in the stack almost evenly according to the estimates made in [11].

To achieve the same current carrying capacity of the conductor as in the VS 2 - 4 design, there should be 34 tapes with 6 mm width in each stack.

However, when calculating the VS 2 - 4 design, the critical current of the tape was determined for the transverse orientation of the magnetic induction vector to the plane of the tape. As follows from **Figure 11** when the tape is oriented parallel to the field vector, as in PaST conductor, the critical current of the tape increases 4 - 5 times. Consequently, the number of tapes in the PaST conductor can be reduced by 2 - 3 times to 12 - 17 tapes in a package.

Each section of the central solenoid is connected to a separate power supply. Therefore, it is possible to use different conductor designs in different sections of the CS, optimized in accordance with the operating mode of the section. For example, the conductor Post will have a larger margin for critical current in the central sections of the solenoid in which the field is oriented strictly parallel to the surface of the tapes.

During the cycle of plasma ignition and combustion, energy losses occur, leading to heating of the conductor from the initial temperature to 20 K. In addition, radiation heating of the conductor takes place. The calculated energy losses are taken into account when choosing the cooling conditions, which are provided by pumping helium in the conductor channels at a flow rate of 840 kg/h. It should also be taken into account that with a rapid change in the field, induced currents are generated in the tapes, which are closed through the transverse resistance of

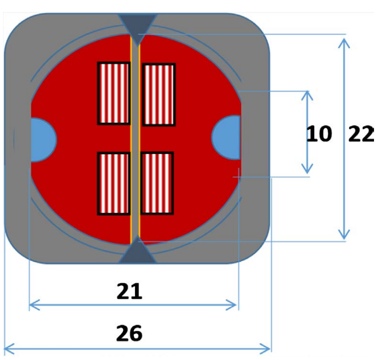


Figure 11. PaST conductor.

the circuits. The induced currents must not exceed the critical value. The maximum amount of induced currents can be limited by inserting resistive laying between the tapes if necessary.

Making a final decision on the conductor design requires comprehensive theoretical and experimental studies, taking into account the operating modes of both the entire tokamak electromagnetic system and the sections of the central solenoid. It is planned to manufacture and first experimental studies of samples of both types.

7. Conclusions

The cable-in-conduit conductor for the central solenoid of the TRT reactor is the most stressed conductor of the reactor electromagnetic system. Despite the large amount of conductor's development and research for similar systems carried out in the world, conductors that fully meet the requirements of the CS TRT have not yet been developed.

The proposed design of wire based on HTS tapes with the high performance at low temperature allow us to hope for meet specification of wires for the sections of CS TRT. A feature of the VS and VSS type conductors has a high degree of transposition, which ensures a uniform currents distribution between the tapes. PaST type conductors are characterized by high current carrying capacity in a parallel magnetic field. The versatility of VS, VSS and PAST conductors makes them promising for further development as material characteristics or TRT EMS requirements change.

The main task at present is to conduct comprehensive theoretical and technological researches of the experimental samples proposed conductor.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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