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Equivalent electromagnetic model for current leads made of HTS tapes

Streszczenie. *W niniejszym opracowaniu został przedstawiony elektromagnetyczny model przepustów prądowych wykonanych z taśm nadprzewodnikowych HTS drugiej generacji. Model opiera się na fizycznej strukturze i zachowaniu taśmy HTS. Dzięki temu było możliwe obliczenie rozkładu pola elektromagnetycznego w przepuście. Uzyskane wyniki mogą być bardzo przydatne w analizie stanów przejściowych przepustów HTS oraz optymalizacji budowy przepustu ze względu na wydzielane w nim dodatkowe straty mocy.* ***(Model polowy przepustów prądowy wykonanych z taśm nadprzewodnikowych HTS drugiej generacji)***

Abstract*. An equivalent electromagnetic model that describes the behaviour of a current lead build of HTS tapes has been proposed. Electromagnetic filed analysis of HTS lead using FEM environment was made. The model is based on the physical structure and behaviour of HTS tapes. It was possible to calculate the magnetic filed distribution in the lead. Obtained results can be very useful in the analysis of quench states of the superconducting current leads.*

Słowa kluczowe: model taśmy HTS, analiza taśm HTS drugiej generacji, modelowanie przepustów prądowych HTS
Keywords: HTS tape model, superconducting tapes analysis, quench state, HTS current leads modelling

Introduction

The development of the HTS tape manufacturing technologies leads to evolution of many superconducting devices. It is possible to build the current lead based on the high temperature superconducting tapes (Fig. 1). For this kind of current leads it is very important to keep the heat sources on the very low level (even 1 Joule).

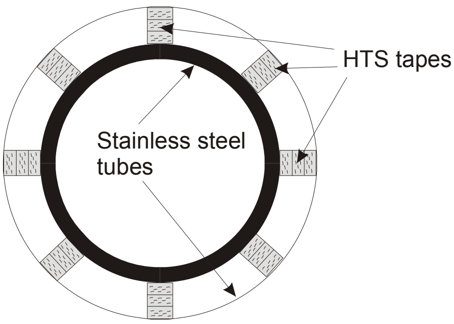

Fig. 1. Idea of current lead build of HTS tapes

In this paper the authors showed the researches of the electromagnetic model of second generation superconducting tapes and their utilization in building the HTS current leads.

Tapes made of High Temperature Superconductors

Discovery of the HTS materials was the first step in development of new generation superconducting applications. Many of HTS materials are superconductors and carry significant current above the boiling point of liquid nitrogen at 77.4 K.

High performance high temperature superconductor wire underlies the worldwide opportunity to revolutionize the electric power grid, transportation, materials processing and many other industries, with a new generation of high efficiency, compact and environmentally friendly electrical equipment. Rapid progress in commercializing these many applications has been enabled by an HTS wire known as first generation (1G) [1].

This wire is a composite structure consisting of number of filaments of HTS material embedded in a silver alloy matrix. First generation HTS wire is characterized usually by low critical current, therefore many companies are making researches on improved performance of HTS wires.

Second generation wire has quite different architecture compared with first generation wire. The 2G HTS wire comprises multiple coatings on a base material or substrate. This architecture is designed to achieve the highest degree of alignment possible of the atoms in the superconductor material. The reason of such construction is reaching the highest possible electrical current.

Second generation (2G) HTS wire consists of a tape-shaped base, or substrate, upon which a thin coating of superconductor compound, usually $YBa_2Cu_3O_7$ ("YBCO"), is deposited or grown such that the crystalline lattice of the YBCO in the final product is highly aligned, creating a coating that is virtually a single crystal. The superconductor coating in this coated conductor wire architecture typically has a thickness on the order of one micron (Fig. 2) [1-5].

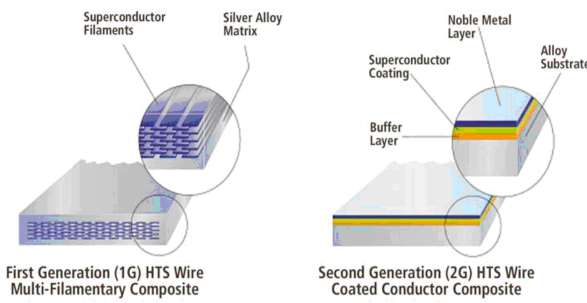

Fig. 2. First generation (1G) versus second generation (2G) HTS tape [1]

Another important aspect in HTS wire is the value of the critical current in external magnetic filed. When the magnetic flux increases the critical current decreases rapidly, even 10 times in some cases. To counteract this disadvantage the HTS wires are produced with special defects, so called pinning centres. Pinning can be achieved by introducing defects into the HTS material on a nanometer scale, comparable to the diameter of the flux lines passing through the HTS surface. While tubular defects can match the flux line geometry most optimally, a more practical approach is to find ways to introduce a high density of very fine particles called nanoparticles or nanodots. Particles of yttrium oxide (Y_2O_3) and yttrium cuprate ($Y_2Cu_2O_5$) are dispersed throughout wire's YBCO superconductor layer (Fig. 3). The effect of the dispersion is that nanodots become pinning centres of magnetic vortices associated with current flow in the superconductor.

As the result the improvement of current carrying capability of the HTS wire can be observed.

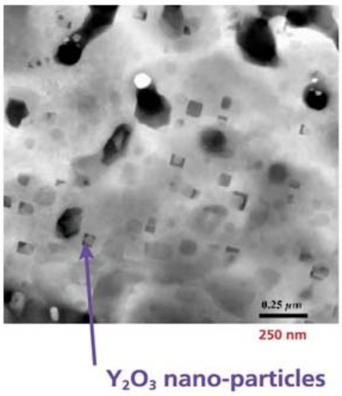

Fig. 3. Transmission electron micrograph of yttria nanodots in the YCBO matrix [2]

The AMSC is the company with the most experience in the production of 2G HTS tapes. The wire manufacturing process has been based on long, 40 millimeter wide strips of superconductor material that are produced in a high-speed, continuous reel-to-reel deposition process. [3-5]

This process is similar to the low-cost production of motion picture film in which celluloid strips are coated with a liquid emulsion. The wires are laminated on both sides with copper, stainless-steel, or brass metals to provide strength, durability and certain electrical characteristics needed in applications. Finally the tape is formed into standard wires with a width of 4.4, 4.8 or 12 mm (Fig. 4). [2]

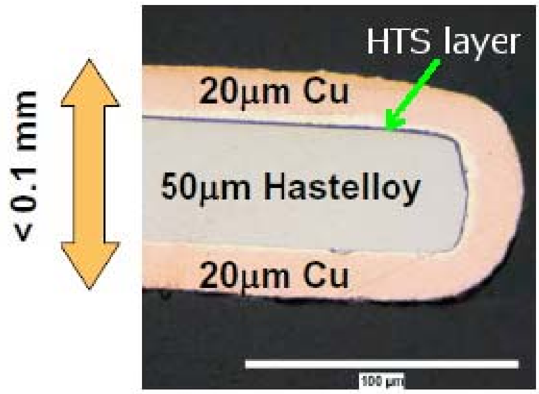

Fig. 4. Crossection of the HTS 2G YBCO tape [2]

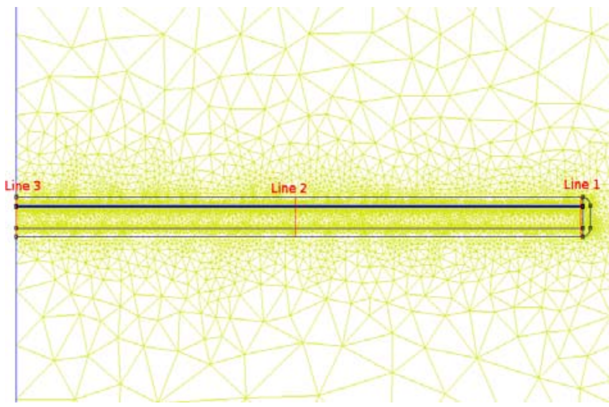

Fig. 5. FEM model of the second generation HTS tape

Electromagnetic Model of the Second Generation High Temperature Superconductor Tape

First step for constructing the current lead model is the suitable analysis of HTS 2G YBCO tape. To complete this task the appropriate FEM model of HTS 2G tape should be built. Modelling of the second generation HTS wire is a difficult task, because of the large disparity of thickness to width of the tape.[6-8] The width of the tape is at least 30 times bigger then thickness and the ratio of thickness of superconducting layer to overall width of tape can be as high as 1:10000. The first step of the simulation was the construction of the 2G HTS tape FEM model (Fig. 5).

Model is based on the SCS3050 tape produced by the SuperPower company. Model consists of: thin layer of (RE)BCO superconductor (thickness 1 μm), substrate made of hastelloy (50 μm), silver overlayer (2 μm) and copper stabilizers (20 μm each). Width of the tape is 3 mm.

Building the mesh it is very important to obtain good quality elements in HTS layer, this will get the correct results. The value of the current is 50 A and it is less then critical current for this tape equal I_c=60 A. The tape was modelled in superconducting state. After the solution the flux distribution was obtained (Fig. 6).

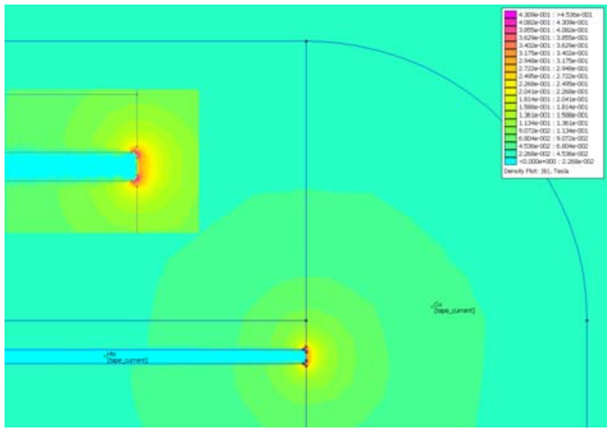

Fig. 6. Distribution of the flux density in the model (self field)

One can notice that the ends of the strips are inhomogeneities in the distribution of magnetic flux.

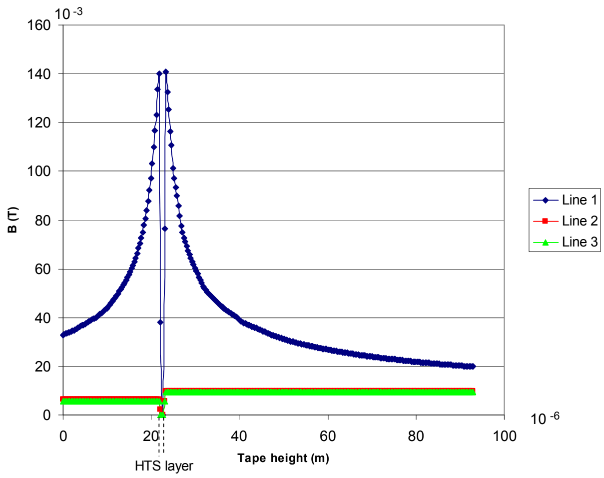

Fig. 7. Flux density versus height of tape

The flux highest values were obtained in hastelloy substrate, silver overlayer and copper stabilizers near the end of HTS layer (Fig. 7).

Transport current flows mostly in HTS superconductor layer as shown in figure 8.

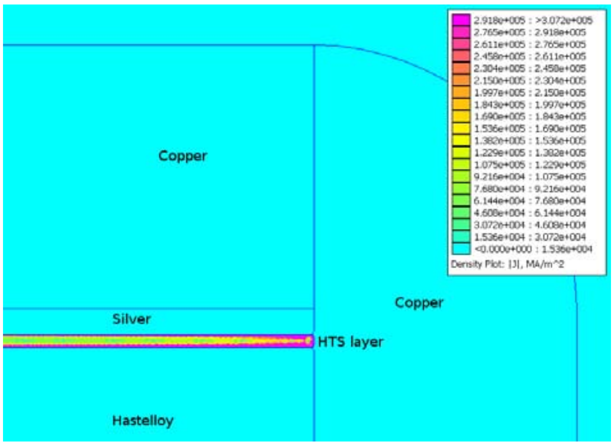

Fig. 8. Distribution of the current density in HTS tape model

In the model total power losses were calculated. The highest values were obtained in the copper laminations as shown in figure 9.

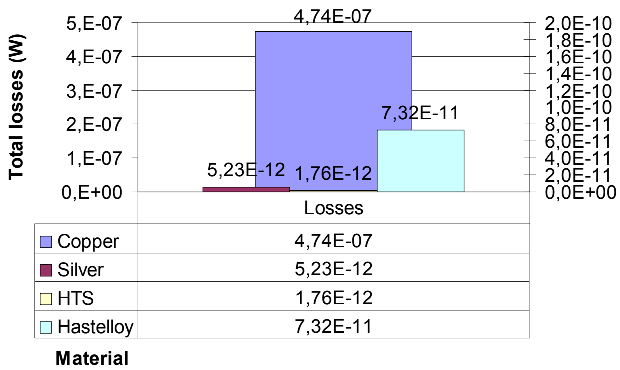

Fig. 9. Total power losses in SCS3050 tape model

Electromagnetic Model of the Current Lead made of HTS tape

The authors built the numerical model basing on existing HTS current lead design.

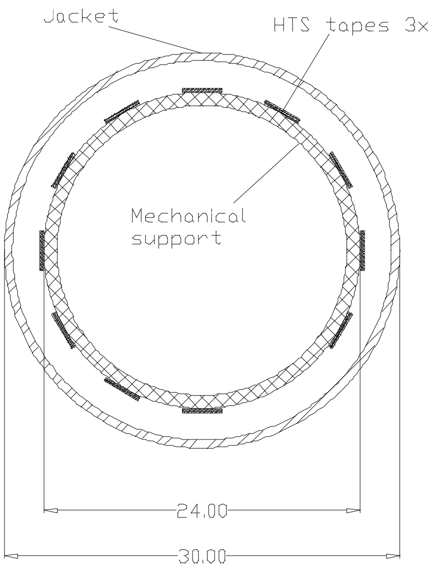

Fig. 10. Current lead supplying the LHC superconducting magnets

Current lead is made of HTS tapes connected together as shown in figure 10. HTS tape pieces are placed on tube support made of copper or stainless steel.

The outer jacket performs a function of electrical insulation and mechanical protection. Mechanical support usually is made of stainless steel or other nonferromagnetic material. [6]

The current lead consists of HTS tapes placed by few at a time on facets of polyhedral stainless steel tube of length 350 mm (Fig. 10).

For modelling of the current lead the symmetry of the geometry was assumed and quarter of the lead was considered. Because of large disproportion of the HTS superconducting layer to other dimensions of the current lead (thickness of HTS layer is 1 μm and inner diameter of the lead is 24000 μm) the magnification of the model part was shown in figure 11.

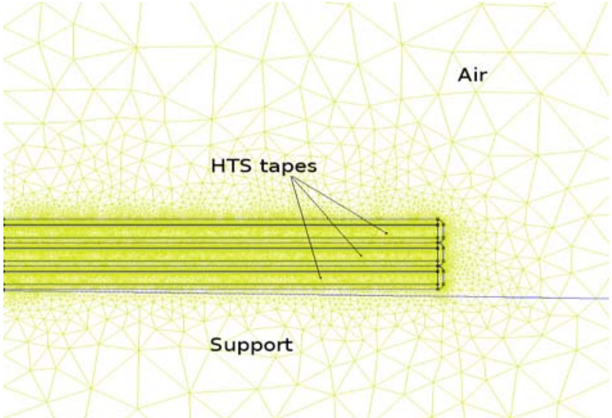

Fig. 11. Magnification of the HTS current lead tapes placed on the mechanical support

The flux highest values (similarly like in HTS tape model) were obtained in hastelloy substrate, silver overlayer and copper stabilizers near the end of HTS layer (Fig. 12).

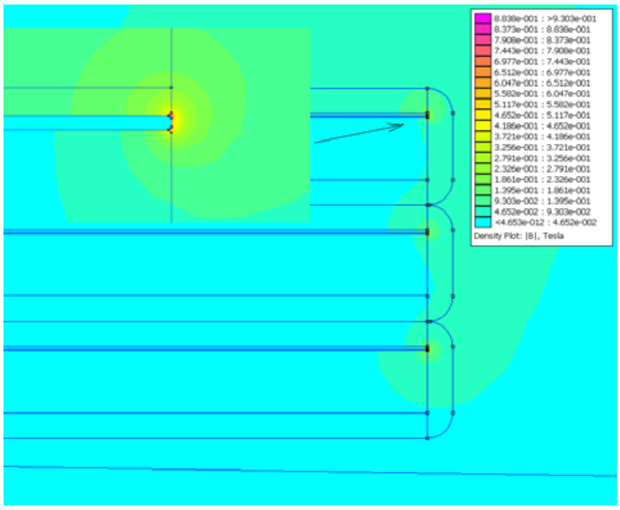

Fig. 12. Distribution of the flux density in the current lead model (self field)

Analysing the flux density distribution along the analysis lines it can be noticed that the largest inhomogeneities are present at the ends of the HTS layer (Fig. 13).

Comparing the values of magnetic flux density obtained in current lead model to a single tape model, it can be noticed that the maximum value is at least twice higher in the current lead (Fig. 7 and Fig. 13).

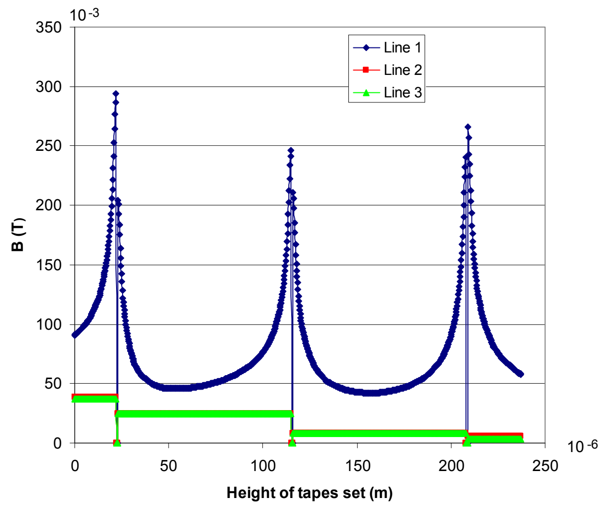

Fig. 13. Flux density versus height of tapes set along the analysis lines

Total losses (AC and resistive) in the current lead were calculated. The highest value of power losses was obtained in the copper stabilizer and is equal to about 0.12 mW (Fig. 14).

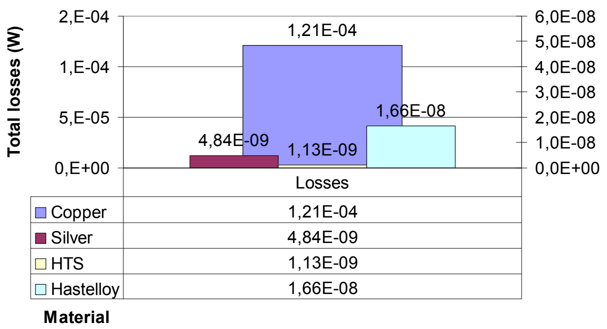

Fig. 14. Total power losses in HTS current lead model

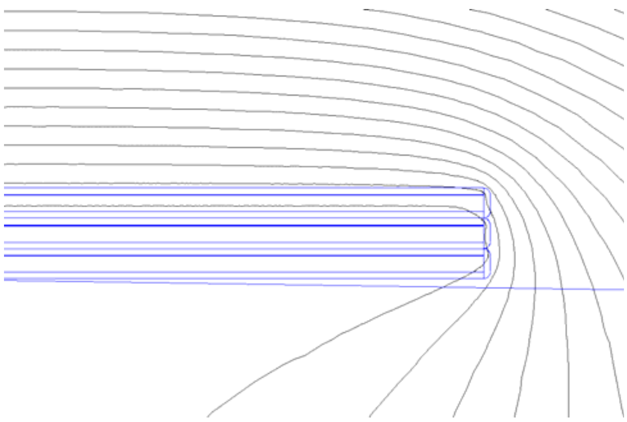

Fig. 15. Magnification of the magnetic field lines surrounding the HTS tapes of current lead

It seems that this value should not be too much problem for cooling system, however in the case of liquid nitrogen or liquid helium cooling this value is negligible but in the case of contact cooling, where cryocoolers are used, this value may be about 0.1% of the power capacity of the second stage of cryocooler.

When designing the current leads for contact cooling it is very important to minimize generated additional power losses and heat sources and keep them even on the level of 0.1 W.

Distribution of the magnetic field lines in and around the HTS tape set was obtained (Fig. 15). The higher density of the magnetic filed lines at the ends of the HTS tapes can be noticed.

Conclusion

Physical properties of HTS superconductors vary in a wide ranges and their relation to the temperature, current and magnetic filed is very difficult for implementation in electromagnetic model representation.

Other difficult task during modelling is the large disproportion of the superconducting layer thickness to overall dimensions of the current lead model.

The highest values of flux density and AC losses were obtained in the copper stabilizer of HTS tape.

Too large values of magnetic flux and current density at the ends of the tape can cause resistive zones.

Resistive zone appearance may cause unstable operation of current leads build of HTS tapes.

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