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Status of
High Temperature Superconducting
Magnet Development

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ABSTRACT

Since the discovery of high temperature superconductors more than 2 decades ago, there has been interest in their use for future fusion machines. Lack of performance of commercially available materials, however, dampened the initial optimism. However, recent advances in HTS materials, mostly second-generation tapes, open attractive topologies. In addition to reduced cryogenic loads and increased superconducting stability, the HTS tapes may allow demountable magnets that could be very helpful in the long term (for reactor maintenance) and in the intermediate term, for component-testing machines which require large access. Tests on joints have demonstrated that the thermal load due to the Joule dissipation in these joints is small, allowing operation with very long pulses without restrictions on cost of electricity or power availability.

There are challenges in the use of HTS in magnets in general, and fusion specifically. The excellent properties of HTS materials, e.g., YBCO operating at elevated temperatures (> 30 K), also offer operational advantages for fusion machines, but there are challenges, such as the manufacturing of high current cables and methods of quench protection.

In addition to tapes, HTS can be fabricated as monoliths. These monoliths offer the possibility of field control for complex geometries, such as generating stellarator-like fields from simple toroidal-fields.

The talk will summarize work at MIT and elsewhere on concept development and testing, as well as challenges ahead.

I. INTRODUCTION

New HTS materials offer a revolutionary path forward in the design of magnetic fusion devices that could lead to very high performance in compact devices, with simpler maintenance methods and enhanced reliability. The HTS materials are already sufficiently advanced to be considered for next-step fusion applications. The HTS superconductors have the ability to optimize the magnetic fusion device for very high field operation and/or relatively high cryogenic temperatures. They can be used with any magnetic field configuration including 3-D shaped devices. Since these materials can operate at cryogenic temperatures approaching that of liquid nitrogen (77K), one can consider as realistic the option to build electrical joints into the winding cross-section that can be connected, unconnected and reconnected in the field. A fusion device with HTS magnets could be disassembled and reassembled to allow for maintenance and change of internal components.

Magnetic field strength limits the achievable plasma pressure needed for fusion — higher B would allow more compact devices, or significantly ease control requirements. Superconducting magnets are required for almost any magnetic configuration of a practical fusion reactor, and the SC magnet system of large-scale fusion devices is about one-third of the core machine cost. Today's experiments, including ITER, utilize SC magnet technology that is decades old. Accurate fabrication of complex magnets is also a crucial cost and performance issue for stellarators.

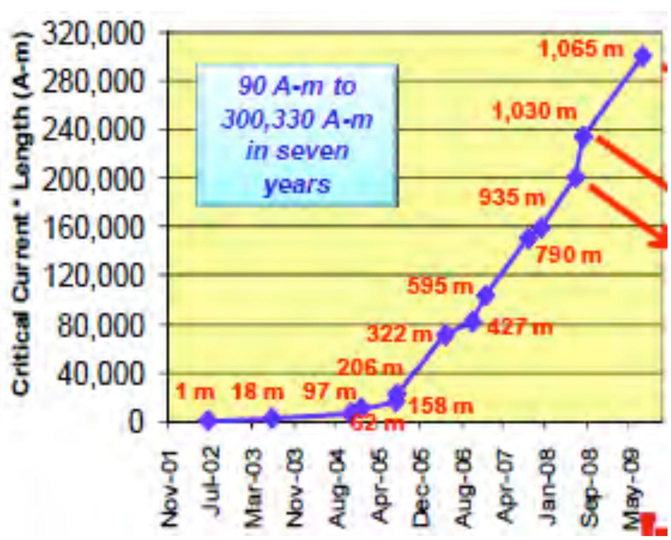

Fig. 1. Progress in manufacturing HTS tapes.

There has been substantial R&D investments in HTS by DOE Office of Electricity Delivery and Energy Reliability and high energy physics. The industry is at present providing substantial quantities of HTS tapes. In the US, all production has moved to the 2^{nd} generation materials, using YBCO and ReBCO superconductors, away from BSCCO material that were used in 1^{st} generation. These materials are available from 2 suppliers in the US, at an approximate cost (2010) of $40/m for 100 A tapes at liquid nitrogen temperature, or about $40/kA m. Figure 1 shows the progress in manufacturing tapes by Superpower Inc [Superpower]; the progress is indicated as a product of the length of the tape times the current carrying capability at 77 K and self-field.

The demands for fusion applications require investigation beyond those of existing programs.

II. FUSION REQUIREMENTS

Robust, steady state, high field magnets is a critical component of magnetic fusion devices. High fields are attractive for plasma physics reasons, such as good wave accessibility and in order to achieve high absolute performance in a beta-limited compact device. They are also essential to tokamak fusion reactors in order to reach high fusion power density [ARIES-AT], allowing the device to integrate important aspects of sustainment and plasma physics.

Demountable joints could facilitate the assembly, maintenance and repair of fusion reactors not only of the magnet system, but also of the blankets and the Plasma Facing Components (PFC). In commercial fusion reactors, these components may require periodic maintenance every few years because of damage from the 14 MeV neutrons. A fusion nuclear science facility, which is designed to test multiple designs for internal components, likely to have more failures, will need even more frequent access. By disassembling of the magnets and the shield, easy access can be provided to the blanket and PFCs. The demountable magnet concept opens the possibility for novel options for fusion reactors. For Vulcan design [VULCAN], the demountability would allow for assembly and maintenance of the machine. Because one of its main missions is to investigate the long term performance of the plasma facing components, and test difference configurations and materials, the ability to periodically update and repair the PFCs is needed. Demountability requires joints between sections of the magnets. If the joints can be manufactured with low enough resistance, then the power dissipated in the joints can be kept low.

Demountable coils could also be used to place the poloidal field coils internal to TF coils.

Demountable superconducting coils were originally proposed for the fusion program by the Powell group [Hsieh]. They proposed low temperature tape-like superconductors (thick films). The problem with this approach is that the superconductor would be prone to flux jumping and quenching, and the joints themselves are generators of heat. The joints would therefore be unstable. Another issue is the large refrigerator power required for the demountable joints. For stellarators, demountable magnets (mostly for assembly) have been suggested by Uo. [Uo]

A possible configuration of the machine can be modeled after the Alcator C-Mod sliding joints [CMOD] concept or the D-IIID machine with bolted joints [Puhn]. In CMOD the contact across plates is made with a complaint metallic shunt electroplated with silver. The joints have been in the past a source of failure in C-Mod but have proven highly reliable in recent years.

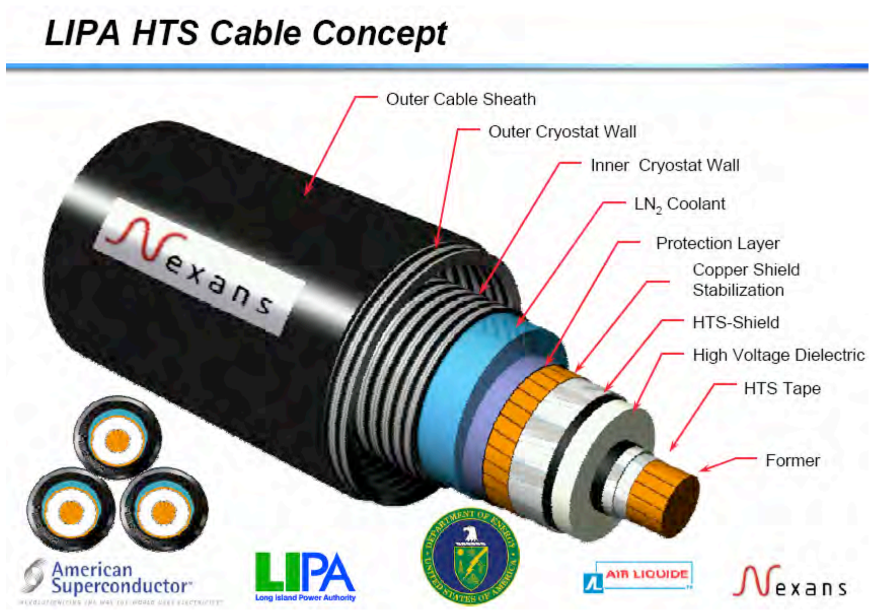

Fig. 2. Typical construction of HTS cables for electricity transmission/distribution applications.

When used for regular maintenance, demounting the magnets requires coil warm up and recooling which could negatively affect the availability. It is thus important to determine means of quickly warming/cooling of the magnets. For conventional LTS magnets, the cool down time to liquid nitrogen temperature is about the same as the cooldown time from liquid nitrogen temperature to 4 K. Faster means of uniformly heating the magnet to prevent large thermal stresses can be employed. Thus, the time to warm-up and recool the magnet can be reduced to about ¼ that of conventional LTS magnets, such as ITER. In ITER the cool down time is about 2-3 weeks, thus the time to warm-up and recool a demountable magnet may be as short as 1 week, faster for smaller machines. Better means of warming/cooling the magnets are being investigated, including the possibility of relatively large temperature gradients along the coils, so that only the regions of the magnet close to joints are warmed up.

Today high quality thick film YBCO tapes are produced. Eventually, the HTS material could be directly deposited on the structural plates. [Bromberg]

III. HTS CABLES

Because of the unconventional shape of the HTS materials, new methods of making high current cables are required. Several teams are developing cables, and some of those efforts will be summarized below.

The application of delivery of electricity with HTS, funded by the US Department of Energy, resulted in the development of cables where one or more layers of superconducting tapes are wound over a former with a round cross section, separated by dielectrics, shown in Figure 2. The magnetic field is mostly parallel to the tapes; however, the cables have low average current density, which is required for high field magnets.

Shown in Figure 3 is a cable as a stack of HTS tapes, developed by Takayasu [Takayasu]. The stack is twisted to provide better AC performance,. Although the magnetic field is not parallel to the tapes, it has higher average current density than that shown in Figure 2.

Fig. 3. Schematic illustrations of twisted stacked-HTS tape conductor.

At NIFS, Yanagi and Mito have been developing an alternative, where the tapes are not twisted, shown in Fig. 4. The stack of HTS tapes are placed in a copper sheath. [Yanagi]

In order to minimize AC losses and to obtain good current distribution amongst the tapes, KIT has been developing Roebel cables using HTS tapes. The Roebel technology provides good transposition of the conductors, minimizing the differential in inductances between different tapes in the cable and eliminating loop currents that decrease the current capacity of the cable and increase the AC losses. For fusion applications, it is important to prevent excessive heating during transients (field ramp up or ramp down), as well as improve the DC performance of the cable.

IV. DEMOUNTABLE JOINTS

Several groups have investigated demountable joints with HTS materials. At MIT we have experimented with both butt joints and lap joints for low current applications. [Dietz] Yanagi at NIFS have investigated lap joints [Yanagi] for high current. And Hashizume and Ito have investigated butt joints. [Hashizume, Ito]

Figure 4. Untwisted cable developed at NIFS.

Dietz reported joint resistance as low as 0.1 μΩ with contact areas as little as 0.15 cm^2 with resulting surface resistivities on the order of 1.5 10^{-8} Ω cm^2 at temperatures below liquid nitrogen. [Dietz]

The results obtained by Dietz are shown in Figure 5, as a function of the load applied to the joint section. The contact areas were controlled. Resistances about 200 nΩ were obtained for YBCO tapes

Butt joints with 1st generation tapes were also investigated by the MIT group. At liquid nitrogen temperature with very light pressure the resistance was ~ 10 μΩ). With increasing pressure the resistance dropped monotonically to 1.7 μΩ at the highest applied pressure.

A computational model was made of the lap joints in the test piece. We evaluated the case of 1st generation tapes which included a brass sheath. It was assumed that the overlap region is 5 mm, the thickness of the brass is 0.1 mm (10 mils), and that the brass resistivity is $4.7\ 10^{-8}$ Ωm. The model indicates a minimum resistance of 4 μΩ, with a large voltage drop across the brass. The achieved contact resistances with this material were similar to those measured.

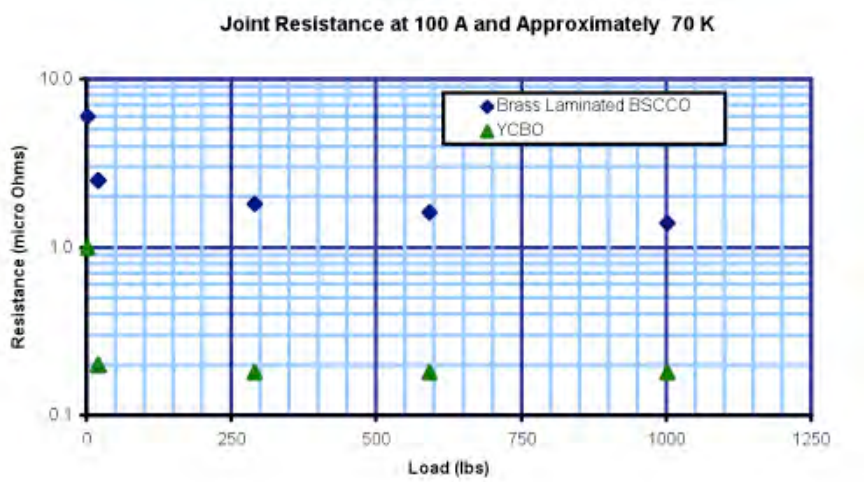

Figure 5. Contact resistance as a function of the applied load for the cases of BSCCO and YBCO shunts.

A similar joint has been developed by Yanagi for high current cables, shown in Figure 5. Yanagi obtained a joint resistance, with 16 tapes, of 0.06 μΩ. Referred to a single tape, the joint resistance is about 1μΩ. [Yanagi] In their case, the joints are soldered. Their purpose is ease of assembly, rather than maintenance, so there is no need for demountability.

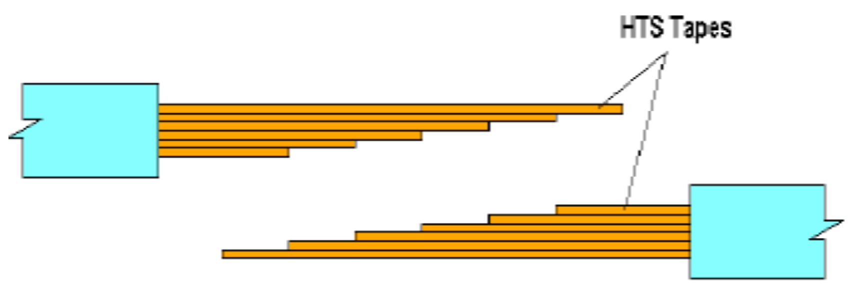

Figure 6. Joint concept being investigated by Yanagi

The butt-joint concept of Hashizume, Ito and colleagues is shown in Figure 7. Ito obtained the best results for the butt joint with dry interface, with a joint resistance 0.14 μΩ for 1 kA class stacked HTS cable at liquid nitrogen temperature. In the case of silver-electroplated joint surfaces and thin indium foil inserted across the interface, joint resistances were higher, about 0.2 μΩ. Their results over a decade are summarized in Figure 8 [Hashizume, Ito1, Ito2, Ito3]

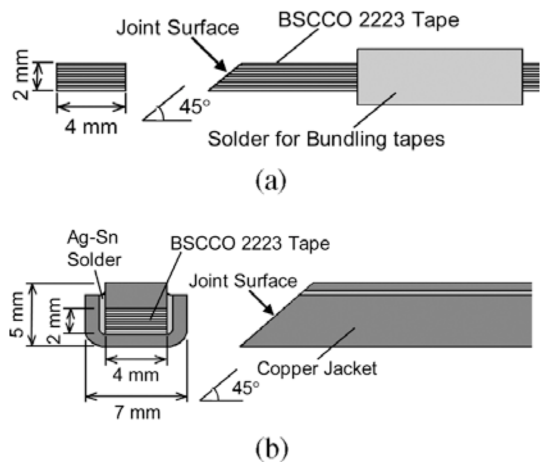

Figure 7. Test cable investigated by Ito. (a) Conventional stacked BSCCO 2223 cable; (b) stacked BSCCO 2223 cable with copper jacket.

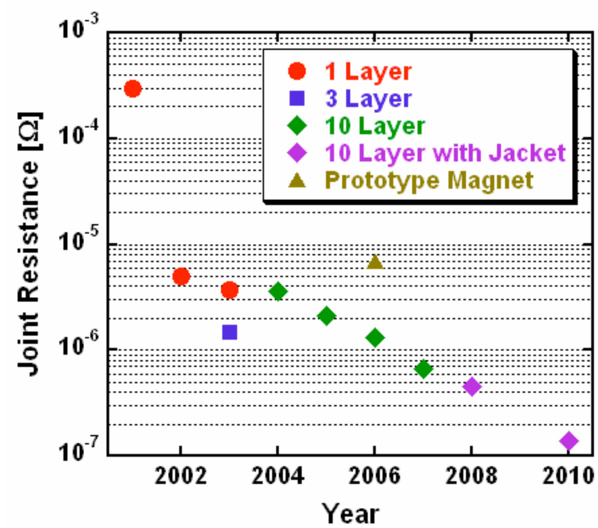

Fig. 8. Progress in performance of butt joint.

V. DEMOUNTABLE MAGNETS

Conceptual designs for a demountable magnet with HTS have been proposed. [Bromberg] The HTS thick film or tape is deposited on structural plates, covered with a normal conducting film (silver) in the region of the joint. This region is mated to a similar one in the adjacent plate. In between the two normal films, an insert is placed to transfer the current from plate-to-plate. In order to minimize the losses and to increase the joint compliance, the proposed shunt is made from a superconductor material covered with silver. The silver forms a bladder. The coolant flows through gaps in the superconductors and cools both the partially exposed silver bladder as well as the superconductor.

A near term method to enable this concept is to attach multiple layers of presently manufactured tapes on the structural tapes. This approach avoids the need for developing long lengths of tapes/conductor or to deposit HTS films over the large structure of the TF coil. The maximum length of the HTS tape would be the size of the vertical/horizontal legs.

One of the drawbacks of the use of demountable coils is that the electromagnetic loads need to be supported by external structures. Since the purpose of the structure in the superconducting plates is to carry the loads to the external structures, they should be as small as possible.

The method described above can be used to provide multiple turns per plate by patterning the thick films into strips or applying multiple tapes to the structure. The number of tapes in a given turn can be adjusted to provide the require current carrying capability; the number of tapes is determined by the magnetic field magnitude and direction at the worst point along the conductor.

Although operation at 77 K is feasible, operation at lower temperatures results in most of the same objectives with higher current densities. The difficulty of operation at lower temperatures is the cooling. Options are the use of subcooled nitrogen (down to about 65 K), the use of a eutectic mixture of nitrogen and oxygen (down to about 55 K) or the use of high pressure gaseous helium. Conduction cooling (at least in parts of the magnet) also needs to be explored.

V.A. TF magnets for tokamaks: VULCAN

If the tapes in a TF magnet are oriented so that the main toroidal magnetic field is mainly parallel to the tape the critical current density capability is maximized. This approach has the advantage that the tapes/conductor can be easily shaped to follow the desired contour, as the bending is in the thin direction of the tapes. This orientation of the tapes has the difficulty that the poloidal field is perpendicular to the tapes, and the field is more difficult to calculate, as it varies in time, is very inhomogenous and depends on the details of the scenario. Alternatively, the tapes can be oriented so that the toroidal field is perpendicular to the tapes, with the thin direction of the tapes in the toroidal direction. In this orientation the current carrying capability does not have a large dependence on the poloidal field. The toroidal field can be calculated in a straightforward manner.

The cable used for the illustrative design is shown in Figure 9. The tapes are shown in red/white lines, to indicate the arrangement of the tapes with respect to the structural plates. The tapes may be soldered after being bent in their final geometry, as a soldered set of tapes is not easily bent, and may result in overstraining of the tapes (limiting their radius of curvature). The solder can be applied around the cable with the 40 tapes, with little solder going in-between tapes. Because of the built-in insulating layer, solder between turns serves little for tape-to-tape current transfer.

For illustrative purposes, it is assumed that there are 180 plates in the magnet, each plate is 2 degrees. Each cable carries 12 kA and there are 20 cables per plate. Figure 10 shows the arrangement in the tapered plates that make the inboard region of the TF coil. Figure 10 shows the same cable characteristics for all the turns. The proposed construction method allows grading of the cables. The outer layers may not need to have as many HTS tapes as the inner ones, as the toroidal field decreases from the inside of the coil to the outside. This is true as long as the poloidal field is small compared to the toroidal field. For the inner leg of the tokamak magnet, with an internal OH transformer (as in Alcator C-Mod), the PF field is comparable to the peak TF field and relative constant over the cross section, so high degree of grading is not possible in this section of the magnet. However, in the outer section grading can substantially reduce the amount of superconducting tape required.

The structure could be made out of a structural material, such as Inconel 625, or stainless steel. Or it can be made of a highly conducting material, such as copper or a copper alloy (such as GLIDCOP).

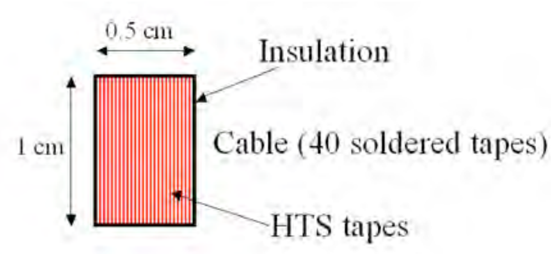

Figure 9. Cable used for the illustrative design of VULCAN.

The cooling channels can be imbedded in the plates, with appropriate manifolding at region of easy access. For the inboard leg, which is the one with less access, the manifolding can take place at the bottom and top of the legs. This provides cooling of the magnets. The same arrangement can be used for the non-tapered section of the magnets (the horizontal legs and the outermost vertical leg).

Figure 10 Illustrative diagram of the tapered TF plate in the inboard side of the magnet.

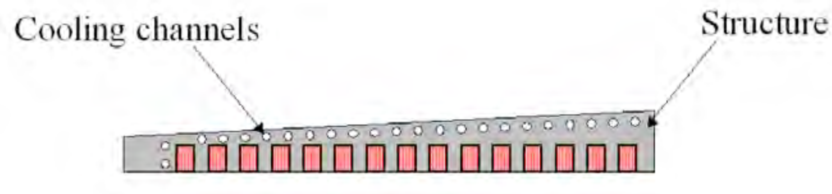

Figure 10. Illustrative diagram of the tapered TF plate in the inboard side of the magnet

I.A. Joints

Providing joints for high field magnets geometry is challenging. In Alcator C-Mod and DIII-D magnets, there is a single conductor per plate, and the current distributes in the plate depending on temperature, inductance (that is, skin-current effects), and defects of the joints. If a region of the joint does not provide good electrical contact, the current flows elsewhere across the joint.

In the long term, methods of applying the HTS films on the surface of the structure can be developed [see, for example, the discussion in Bromberg]. However, for near term machines, as in Vulcan, an approach based on the use of commercially available tapes with a set of turns in series is being investigated. In the case of HTS tapes, there is a large number of joints that need to work.

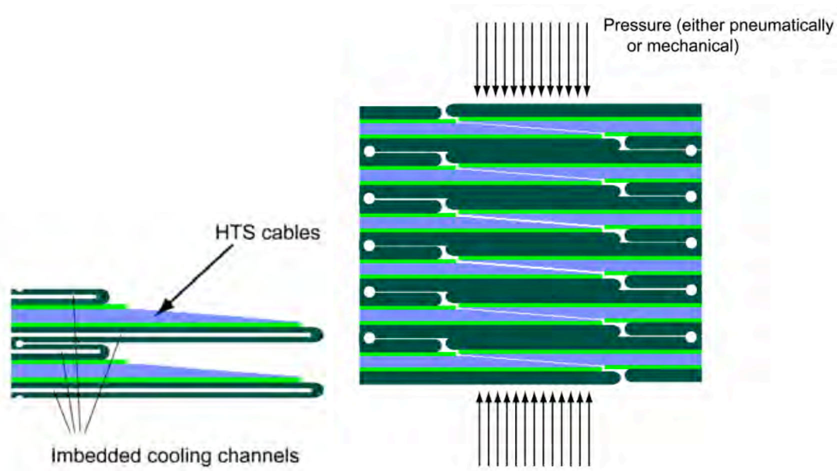

Figure 11 (a) Schematic diagram of the joint region in a section of a toroidal field segment; (b) Illustrative design of joint during operation, with pressure applied for current transfer between cables in different section of the TF coils

A section of the joint at the end of one of the toroidal field plates is shown in Figure 1l. The tapes are exposed on one side, and are supported by the structure that also serves as cooling channels, for cooling the joint. Alternatively, a high conductivity material can be used, and the cooling occurs through thermal conduction to the region away from the actual joint.

V.B. HTS magnets for stellarators: FFHR

The use of HTS tapes for stellarators is actively being investigated in Japan. In the US, the potential of HTS in stellarators has been limited monolithic HTS materials, to provide field shaping [Bromberg1]

Figure 12 shows the concept of application of jointed HTS coils for stellarators in Japan. The concept is very promising for manufacturing. For regular maintenance, however, as indicated above, the time for warm-up and recool may have large negative implications to availability, although once removed, large sections of in-vessel components (plasma facing components, blanket and shield) can be removed. [Yanagi]

Yanagi determined that the additional refrigerator power is about 300 kW. The refrigerator power is a function of the dissipation per joint, the number of joints, and the refrigeration temperature. For reference, the estimated nuclear heating to the magnets in typical fusion reactor designs is about 50 kW. However, the temperature of the magnets is higher than in those designs, thus the total electrical power may be smaller.

Fig. 12. Demountable (or segmented) HTS coils for helical devices.

Yanagi uses temperatures on the order of 20 K. At MIT we have tried to make designs operating at higher temperatures, cooled with gaseous helium.

A different approach is being taken by a team from MIT and PPPL. Because of their high critical temperatures, and consequently, high energy margins, HTS materials are not as prone to flux jumping as low temperature superconductors. Thus, they can be used to replicate fields or to exclude (shield) magnetic fields. There have been discussions of their use of bulk materials in fusion applications, including stabilizing "perfectly" conducting walls in tokamak. More recently, M. Zarnstorff (PPPL) suggested their use to provide complex field shaping required for stellarators. A stellarator configuration has been developed based on this concept, using the ARIES-CS design point and component features as a point of departure. [Bromberg1] A small number of toroidal field coils may be sufficient to create the background toroidal field. Discrete HTS monoliths ("pucks" or "tiles") are placed on a shaped structure that can be split in the poloidal direction at arbitrary locations. This allows the stellarator to be designed with large openings that provide access to remove interior plasma facing components, no longer restricted by highly shaped back legs of the modular coil winding. Unlike a coil, the structure can be assembled and disassembled in pieces of convenient size, facilitating maintenance.

The calculations are complex, and to-date the team has only determine characteristics of simpler geometry, such as shown in Figure 13. They have analyzed the implication of HTS monoliths for ripple cancellation in tokamaks, as well as shaping in linear stellerators. There are challenging issues that need to be investigated, such as mechanical support and cooling of the monoliths, performance and lifetime limitations in the fusion environment, field creep, superconducting stability of the monoliths, and cryostat design.

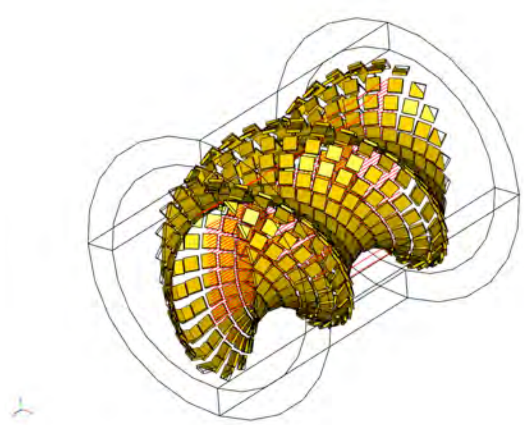

Fig. 13. HTS tiles, submerged in a solenoid field for generating a helical stellarator like geometry.

VI. SHUTING OF CABLE/CURRENT SHARING

At the present time, tapes manufactured commercially have non-uniform properties. In particular, there may be small sections of the coils that have substantially lower current density than the rest of the tape. This is illustrated in Fig. 14 from Superpower. It would be attractive to provide a cable that has means of bypassing a bad region of one or more tapes. This option is possible in HTS because of the higher thermal stability of the conductor. The 2^{nd} generation HTS coated conductors do not have the brass layer. There is an insulating layer beneath the superconductor that prevents current transfer through the bulk of the tape. In this section, a preliminary study of means of bypassing this insulating layer is presented that allows the investigation of current distribution (or redistribution after an event) across the many tapes of the cable.

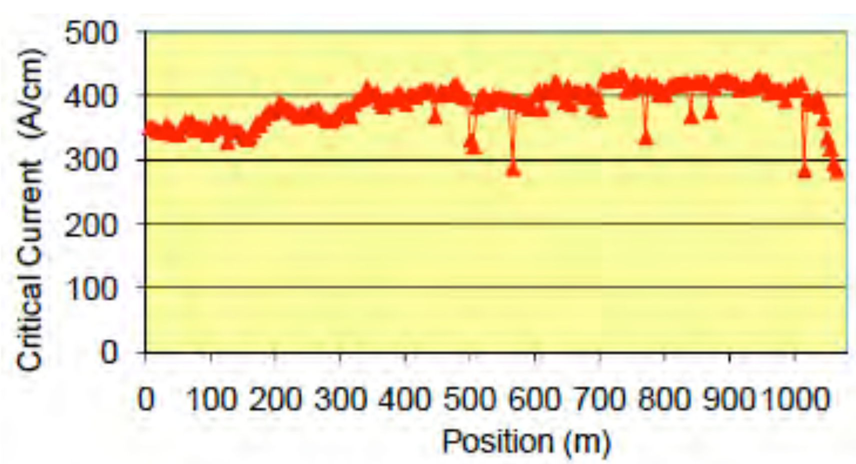

Fig. 14 Critical current density along a 1000 m tape. Note the local sudden drops in current density.

Potential methods of fabricating the cables to enable current redistribution among the multiple tapes are being investigated. Three cases are analyzed: 1) no side tape, all conducting through edges of the tape; 2) side tape, no solder, 3) side tape, with solder.

The resistance per tape period for case 1 is ~ 8 μΩ. Most of the voltage drop is across the solder (two thirds). For 40 tapes, the maximum resistance (from the bottom to the top tapes) is 0.3 mΩ.

In case 2, the voltage drop is decreased to 73 μV, and the resistance per tape period is 0.7 μΩ., with a total resistance of 1.4 μΩ, (a factor of 2 larger), about 3 orders of magnitude lower resistance than in case 1.

In case 3, the single voltage drop is 162 μV (from one of the tapes to the side shunting tape), with a shunting resistance of about 1.6 μΩ. Thus, the presence of the solder increases the resistance by about a factor of 2, as the current density at that location has been substantially decreased.

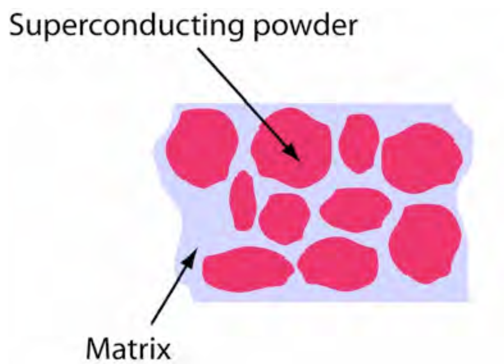

Fig. 15. Schematic diagram of hyperconducting material

By using distributed shunts in HTS cables, it is possible to achieve a high certainty in the parameters required for appropriate current redistribution in the case that the individual tapes have local defects. Further analytical studies, including multiple loops with different inductances and resistances should be investigated using conventional design tools (such as SPICE) and other tools that will also evaluate normal zone dynamics. Experiments will be required to benchmark the codes. Protection of HTS magnets remains an active area of investigation.

Fig. 16. Levitating coil for the LDX device, at MIT

VII. HYPERCONDUCTING MATERIALS

For applications where the joint is not metallurgical, as in the case of remakable (demountable) joints, it is useful to have compliant materials that can serve to transfer the current over relatively large areas that are closely, but not exactly, conforming. This is the case when it is desired to make a joint between multi-tape cables, with substantial areas and possibly multiple surfaces. The use of a compliant material that can deform under relatively low pressure can provide good current transfer between cables that are not soldered together.

A simple method is being investigated to substantially decrease the resistance of solders or compliant layers. The hyperconducting concept is illustrated in Figure 15. [Bromberg2] A soft matrix is used to serve as electrical shunts for HTS powders. The soft matrix could be a conventional solder, or it could be a soft material that can easily deform. Several options exist, such as indium, annealed silver, and even high purity aluminum. As indicated in the figure, it is best to have high fill fraction of the superconducting powder, in order to decrease the distance between superconducting elements and to increase the area of near contact between the different elements, both effects decreasing the average resistance of the material.

The random close packing for monodispersive elements is about 2/3. To achieve high fill fraction, it is best to have powders of different sizes (polydispersive). It is expected that by using a polydispresive powder, it would be possible to have fill fractions of ~80%. The corresponding decrements in resistivity of the complaint layer is on the same order as the filling fraction.

Fig. 17. Levitated coil in mini-RT experiment at the University of Tokyo.

VI. HTS IN FUSION

Because of its cost and limited availability, HTS has yet to be used in large coils in the fusion program. However, two coils have been built from HTS materials, both of the levitated dipole concept.

At MIT, the Levitated Dipole Experiment (LDX) built a coil to produce levitation of a larger, LTS coils. Fig. 16 shows the coil. The coil operated with conduction-cooling at temperatures lower than 77 K. [LDX]

The use of the HTS for the floating coil in the RT-1 experiment at the University of Tokyo resulted in long operating times. The levitated coil is shown inside the vaccum chamber in Fig. 17. The HTS coil in RT-1 has very high temperature margins. [Ogawa]

II. CONCLUSIONS

Progress in High Temperature Superconducting materials and applications has potential in fusion. The decrease in power requirement by operating at higher temperature is a minor improvement. However, potential new topologies could be enabled, including demountability and segmentations (for assembly). In addition, monoliths could also find uses in field shaping for complex magnetic topologies.

Substantial work need to be done in order to realize the vision using HTS in fusion. In addition to the issues covered in this document, quench detection/protection is an area not discussed in this report that needs substantial research.

ACKNOWLEDGMENTS

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