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Options for the use of high temperature superconductor in tokamak fusion reactor designs

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Abstract

The use of high temperature superconductors (HTS) in long term tokamak fusion reactors is analyzed in this paper. The well-documented physical properties of high temperature superconductors are used in the evaluation. Short-sample wires and tapes of $Bi_2Sr_2Ca_nCu_{n+1}O_y$ materials, with $n = 1$, 2 (referred to as BSCCO), and YBCO (YBa_2CuO_{7-x}) tapes approach their single-crystal performance limits. They provide a useful reference frame as well as a starting point of what may be possible in the future. In this paper, the design issues that arise when this technology is used in tokamak magnet applications will be investigated by extrapolating the properties of short sample YBCO thick films and BSCCO tapes to longer lengths. The properties of YBCO operating at elevated temperatures (> 10 K) will also be summarized. The limitations imposed on the performance and lifetime of the HTS materials because of the fusion environment will be reviewed. The consequences of implementing an HTS configuration in a fusion environment will then be described. The use of HTS material may offer an opportunity for a fundamentally different approach to magnet design and construction leading to either lower cost or reduced maintenance. Reduced cost magnets requiring decreased shielding, with better access and easier maintenance may be feasible. © 2001 Elsevier Science B.V. All rights reserved.

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1. Introduction

High temperature superconducting (HTS) materials are ceramic and therefore brittle in nature. The production of long lengths of wires or tapes suitable for winding magnets has limited the application of high-temperature superconductors. The solutions developed for manufacturing high performance A-15 superconductors (such as Nb_3Sn) are being used in the fabrication of HTS wires. Filamentary wires or tapes (of $Bi_2Sr_2Ca_nCu_{n+1}O_y$ materials, with $n = 1$, 2, referred at BSCCO) and thick-film tapes (of

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$YBa_2Cu_3O_{7-x}$ compounds, referred as YBCO) have been manufactured with properties that approach the ideal limit (highly textured or nearly single crystal) using this approach.

BSCCO 2212 shows good intergrain current transfer even though the intragrain current density is substantially smaller than that in the YBCO compound or for BSCCO 2223 [1,3,4,14,15,17,20,21]. Although the properties of BSCCO (2212 and 2223 compounds) are exceptional when compared to low temperature superconductors, the properties of YBCO are even better [3,12,15,17,23,28]. Indeed, if the magnetic field direction is nearly parallel to the YBCO tapes (the ab plane of YBCO is parallel to the tape), then the current density of YBCO at high fields (>10 T) and at 77 K approaches that of Nb_3Sn at 4 K and 0 T.

BSCCO wires and tapes require a large silver fraction, increasing the cost of the conductor and decreasing the engineering current density. Unless higher critical currents can be obtained from the wires and tapes, the cost of the silver may prevent their implementation in tokamak reactors. The large amount of silver that is used in the conductor results in a minimum cost for the conductor of about \$300 kA m^{-1}, or about a factor of 10 higher than the cost of the low temperature superconductors.

The use of silver in the BSCCO wires and tapes not only increases the cost of the conductor, but will also result in substantial radioactivity once the silver has been activated in the reactor environment. It may be necessary to increase the shielding to reduce the silver activation. With conventional shielding (i.e. similar to that required for Nb_3Sn magnets), the activation of the silver, which represents only 1% of the coil cross section, dominates the activity of the magnet.

Depending on the thickness of the substrate, the non-superconducting fraction of material can be made substantially smaller for YBCO than for BSCCO. However, the thickness of superconducting YBCO films that can presently be deposited is very small, being only on the order of a few μm.

The transient behavior of high critical temperature (T_c) materials differs from that of A-15 superconductors. This is due to the much higher thermal capacity of the materials, which increases as the cube of the temperature at low temperatures. At 20 K, metals and compounds have 2 orders of magnitude larger thermal capacity than at 4 K. This is comparable to the thermal capacity of liquid helium at 4 K. The absence of flux jumping in HTS was investigated using bulk materials (without normal conducting shunts). The tests were performed with BSCCO 2212 and YBCO, as a function of temperature. Instead of flux jumping, the HTS superconductor reaches a critical state, without flux pinning, and the field moves in and out of the superconductor without quenching. These tests were performed at the Francis Bitter National Magnet Laboratory at MIT [10].

Flux jumping phenomena slowed down the application of low temperature superconductors for many years. To solve this problem, the low temperature superconductor (LTS) were manufactured as thin filaments in a metallic matrix. Flux jumping does not occur with HTS materials operating at elevated temperature. Other constraints, such as brittle fracture and other issues having to do with the ease of manufacture, may still require that practical BSCCO conductors are manufactured as thin filaments in a silver composite, and YBCO tapes be manufactured as thick films.

The results of replacing low T_c material with high T_c material, without a full understanding of the properties of the high T_c materials has been studied in the past (Ehst; [13]. Recently a study that provided a roadmap for the use of high temperature superconductors in fusion was published [16]. The purpose of the present investigation is not to see how high temperature superconductors can be introduced into the fusion program, but rather what the options are for their eventual use in tokamak reactors.

In this paper, the design restrictions imposed on YBCO tapes used for tokamak fusion reactor magnets operating at elevated temperatures are discussed. The properties and behavior of YBCO are described. Design options for using HTS conductors in toroidal field coils for tokamaks are investigated.

2. YBCO properties

2.1. Superconducting properties

The physical properties of the YBCO compound have been measured by several teams. The most impressive results have been obtained by the teams in Texas [25] and in Japan [21].

The measurements of YBCO-123 performance at several temperatures as a function the magnetic field are shown in Fig. 1 [19]. These results were obtained for highly textured tapes, and show the difference in the behavior of these highly anisotropic superconductors to magnetic fields that are applied either perpendicular or parallel to the main plane of the crystal.

The performance of YBCO at liquid nitrogen temperature and 10 T is comparable to that of non-copper current density of Nb_3Sn superconductor, at 4 K and 0 T. Indeed, once the structure and stabilizer/quench protection is included in the Nb_3Sn designs, the average current density in the Nb_3Sn conductor is substantially lower than that for YBCO at elevated temperatures.

A large amount of anisotropy exists in the superconductor, depending whether the field is aligned with the c-axis or perpendicular to it. The difference is especially large at the higher temperatures. For YBCO thick film conductors, the c-axis is perpendicular to the tape. The superconductor is not single crystal but single domain. It is highly textured with the ab plane parallel to the surface of the tape.

A design that minimizes the normal field can be used to increase the operating temperature of the superconductor. The performance of the YBCO superconductor is optimized when the tape is oriented so that the ab plane of the superconductor (which is the same as the plane of the tape) is locally parallel to the magnetic field, which in a tokamak is mainly toroidal. For YBCO, it is not necessary for the magnet to be force-free, when the direction of the current is aligned with the magnetic field (J||B). Instead, only the plane of the

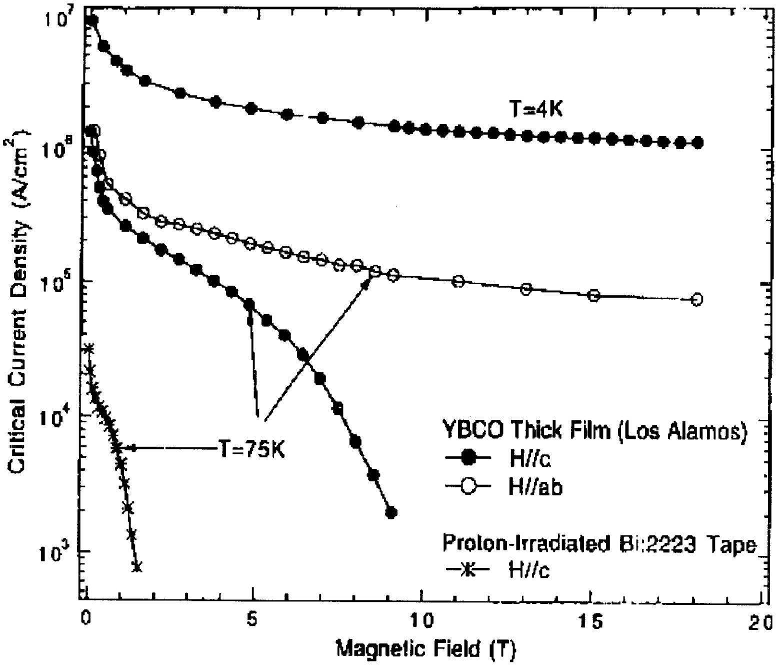

Fig. 1. The critical current density for YBCO-123 as a function of magnetic field, for several temperatures and for different field orientation with respect to the crystal.

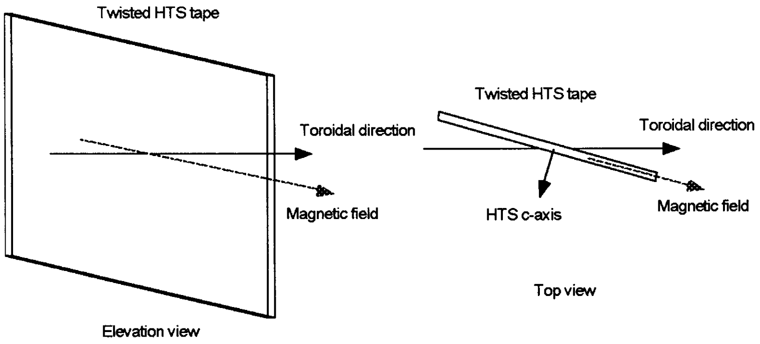

Fig. 2. A design that may be used to minimize the field normal to the tape.

tape has to be aligned with the local magnetic field. Small twists of the tape orientation away from purely toroidal can minimize the normal magnetic field. This is shown schematically in Fig. 2.

Having the magnetic field direction parallel to the surface of the tape limits the operation of the device, since the ratio of toroidal to poloidal field needs to be relatively constant. If it is necessary to tolerate normal magnetic fields that are larger than a few Tesla, it is necessary to operate the superconductor at slightly reduced temperatures (<60 K, depending on the field).

2.2. Stability and quench protection

For low temperature superconductors, stability and quench protection is as much a property of the superconductor as it is of the metallic matrix. This is not necessarily true for high temperature superconductors. As mentioned above, at temperatures higher than about 10–20 K, the superconductor materials do not flux jump. This results in conductors that are easier to fabricate. It can also result in the possibility of using tapes with thick HTS films.

The previous discussion does not mean that the high temperature superconductors do not quench. The superconductors can quench when the operating current is larger than the current-sharing current. This could happen when the temperature of the material increases beyond normal operating conditions. Because of the much larger thermal capacity of the HTS conductors at the higher temperatures, the normal zone propagation velocity is very small, and quench conditions could be very difficult to detect. Quench behavior in HTS materials is an area that requires much additional work.

For the present study, three options for use in quench protection are being considered. The first option provides an energy margin that exceeds the energy released in identifiably off-normal events, so that the current sharing condition is not reached. Since the thermal capacity of the structural material is on the order of 300 kJ K^{-1} m^{-3} and it is possible to design with 10–15 K temperature margins, then the energy margin is on the order of 3–5 J cm^{-3}. The energy margin of HTS is about four orders of magnitude larger than it is for LTS (without helium).

A second defense against quenching is the use of aggressive cooling of the superconductor, so after the heat has been released, it is quickly transferred to the cooling media. Again, this is possible because the coolant can locally remove large amounts of heat. This is the case of using liquid nitrogen, for example. BSCCO has a low resistive voltage in the normal phase, since the index n of the superconductor is relatively low ($n_{2212} \sim 5$–9 at 75 K), while YBCO has a much larger value of n_{YBCO}.

A third approach against quenching is described in Section 4 and has to do with providing alternative paths for the current to flow when a local section of the magnet has reached current sharing conditions. This approach has been tested by the authors [9] (see Section 5.2 below).

2.3. Reliability

The results of using HTS for reactor magnet applications should in principle be at least comparable to, and maybe even better, than that obtained using LTS because of the higher energy margins at increased temperatures. The use of tape magnets with conductors attached to the structure should increase reliability by immobilizing the conductor and increasing the thermal capacity of the system.

The magnet reliability, in a 10th-of-a-kind fusion reactor, is assumed to be 100%, i.e. there are no unscheduled shutdowns that are associated with magnet failures. Present day accelerators that use LTS have a reliability approaching 100%.

3. Design requirements for high temperature superconductors

Low temperature superconductors have four design requirements that that must be considered when they are used in tokamak reactor applications. These are: survival of the insulation; the stabilizer and the superconductor under irradiation; and removal of nuclear heating. In this section, these requirements are summarized and their impact on the high temperature superconductor options reviewed.

3.1. Insulation

Organic as well as inorganic materials are under consideration for use as insulation material. Most superconducting magnets are presently manufactured using fiber-reinforced epoxy that imposes a relatively low limit on the allowable irradiation.

The radiation limit for organic insulators is on the order of 10^8 rads for fiber-reinforced epoxy and 10^9 rads for polyimide based insulation. These limits are for the case when the insulator needs to withstand substantial shearing forces. In the absence of shear, it is possible to increase these limits, by as much as a factor of 10.

The fluence limit for inorganic insulators is determined by swelling. For practical insulators the maximum irradiation ranges from 10^{11} rads to 10^{14} rads depending whether the insulator is in sheets or in powder form. The corresponding neutron fluence (>0.1 MeV neutrons) is 10^{24}–10^{27} neutrons m^{-2}.

In the case of YBCO, an insulator is used in the manufacturing process, as a compliant buffer layer between the thick YBCO films and the Ni substrate. There may be no need for an organic-based insulator. It may be assumed that the irradiation limit of the insulators for HTS magnets can be increased from 10^{11} to 10^{14} rads, depending on whether or not the insulator experiences shear loads.

3.2. Stabilizer

High temperature superconductors do not suffer from flux-jumping when operated at temperatures higher than about 10–20 K, because of the very high thermal capacity of the metals at these temperatures (about two orders of magnitude higher than at 4 K). As a result, there is no need for a substantial fraction of normal conducting material, in contrast with LTS materials. The only normal conducting material required is whatever is needed to manufacture the superconductor. In the case of YBCO, it is a Ni tape. For BSCCO, the filaments are likely to be placed in a silver matrix.

The high thermal capacity of high T_c materials increases the difficulty of quench-detection, mainly because the quench-zone propagates very slowly in high-T_c superconductors. A very large source of energy is required to start a quench. For active magnet protection, novel methods of quench protection and quench detection are required if the applications of high-T_c superconductors at high temperatures is to become a reality.

For the present applications, it is assumed that all of the stabilizer and quench protection normal conductor could in principle be eliminated from the coil.

3.3. Superconductor

There has been a large amount of interest regarding the effect that irradiation has on the performance of high temperature superconductors. The present day research goal is not to identify the irradiation limits, but rather to investigate the beneficial effects that irradiation has on the performance of high temperature super conductors.

At the present time, the threshold fluences for damage of the superconductors have not been reached. Published data in the high fluence regime are scarce. Kuepfer quotes T_c's for a flux of 10^{23} neutrons m^{-2} ($E > 1$ MeV). Sauerzopf [24] gives results for fluxes of up to 1.2×10^{22} neutrons m^{-2}. His group also has two data points at a higher dose (Weber, 1999). The highest neutron fluence to-date was 2.8×10^{22} neutrons m^{-2} and T_c was 81 K. Both results were obtained without annealing.

The group at the Atominst Ostereichen University in Vienna is presently (May 1999) exposing melt-textured samples of YBCO to fast neutron fluences in the range of interest, i.e. 10^{22}–10^{23} neutrons m^{-2} ($E > 0.1$ MeV). This will take a while, in particular, since the 'as-irradiated' result would not be the final answer because annealing steps must be included.

For Nb_3Sn, the neutron fluence beyond which critical current degrades is about 3×10^{22} neutrons m^{-2}. The irradiation resistance of YBCO is at least as good as, and could be better than that of Nb_3Sn.

For the present study, YBCO tapes were chosen as the conductor, because of its ability to operate at much higher current density at 77 K. YBCO tape operating at 77 K tolerates moderate magnetic fields that are perpendicular to the tape, as long as they are not larger than ~ 5 T.

3.4. Nuclear and AC losses heating

By operating at 50–77 K it is possible to remove the same thermal power by using a refrigerator that is ~ 40 times smaller than if the same thermal power is removed at 4 K. Therefore, neutron, gamma and AC loss heating of the cryogenic environment ceases to be a constraint for practical designs when high temperature superconductors are used at these temperatures.

The refrigeration power requirements for conventional tokamak fusion reactors designs, even inductively driven pulsed reactor ones [5], are on the order of about 10 kW. This power is much smaller than that required for ITER due to the fast transients and short pulse length in ITER. Referred to room temperature, removal of 10 kW at 4 K requires a refrigerator that consumes about 3 MW. The power savings because of operation at higher temperature, in a 1 GW electric plant, are small.

The choice of operating temperature is important because it impacts the coolant choice. For temperatures lower than about 66 K, the only practical coolant is high pressure He gas. For higher temperatures, liquid nitrogen is the coolant of choice.

For YBCO, operation at temperatures lower than about 50 K does not provide much of a benefit (if the fields that are perpendicular to the tape are moderate). For BSCCO materials, and in particular for the 2212 compound, operation at lower temperature is desirable (20–40 K). The possibility of using liquid nitrogen with YBCO is another reason for picking it over the BSCCO alternatives.

3.5. Summary of comparison of LTS and HTS requirements

When compared to LTS materials, HTS materials have the potential of substantially relaxing the design restrictions placed on the material by irradiation damage to insulation, the stabilizer and nuclear and AC heating of the cryogenic environment. However, the irradiation damage limits of HTS material itself is comparable with the LTS material.

4. Replacement of LTS with HTS with conventional magnet design

The magnet cross section in most reactor design is dominated by the support structure. The composition of the toroidal field magnet used for a recent fusion tokamak study, ARIES-RS [11] is shown in Table 1. The ARIES-RS magnet design had four grades of conductor, three of Nb_3Sn and one of NbTi. The fraction of support structure in the magnet is around 70%.

As discussed above, the copper in the coil, used for stabilizing the superconductor and for quench protection, can be decreased or even eliminated if HTS magnets are used. The cross section for coolant can also be decreased, if larger temperature excursions are allowed and if the coolant is liquid nitrogen. As a consequence, the copper and coolant fraction can be decreased from about 25% in ARIES-RS [11] to about 5% if HTS is used instead of LTS, especially since the coolant can have substantial ΔT. The structural fraction can therefore be increased to close to 90%.

The superconductor fraction is small, and therefore the higher current density of HTS does not affect the overall composition of the TF coil by much.

Because the cost of the poloidal field system increases rapidly for aspect ratios lower than that for ARIES-RS [2], it is unlikely that the system will optimize at magnetic fields that are substantially higher than those of ARIES-RS. ARIES-RS optimized at about 16 T, even though the conductor was capable of operating at higher fields [20].

If LTS coils are replaced by HTS coils, the systems will look similar, with the exception of the increased structural fraction in the TF coil. The effect of the increased structural fraction in the TF coil is being addressed within the framework of the ARIES study. Preliminary results from this effort are presented in Section 4.1. However, to utilize the relaxed constraints of HTS, novel magnet configurations are required. Two innovative designs are described in sections V and VI.

4.1. HTS versus LTS implication using the tokamak systems code

The ARIES-AT conceptual design study is examining a tokamak power plant with high beta normal and beta toroidal ($\beta_N = 5.43$ and toroidal $\beta_T = 9.2\%$) with plasma vertical elongation greater than 2, and a high-efficiency thermal conversion cycle ($\eta_{th} = 0.59$) resulting from a high-temperature SiC–SiC blanket cooled by a LiPb eutectic. Access to these favorable parameters, in contrast to previous ARIES designs, relaxes the need for high-field magnet technology even as the tokamak is reduced in size (major radius). With a peak magnetic field strength lower than the ~16 T of the ARIES-RS design, the cost-of-electricity improvement anticipated from the substitution of HTS for Nb_3Sn is small, even after allowing for a factor of 2 improvement in unit cost ($ kg^{-1}).

Table 2 shows results from the tokamak system code. R_p is the plasma major radius, B_c is the peak field at the coil, cost of electricity (COE) is in $0.001 kWe h^{-1}), I_n represents the neutron wall loading, and P_E is the net electrical power output. Results for various values of I_n and P_E are given in the table. There is a very small difference in the minimized value of the COE, on the order of 2%. Although 2% is a large value for commercial units, the likely error in the calculation of the COE is larger than the 2% difference. This is especially the case when comparing the HTS and LTS magnet systems, since they invoke substantially different magnet systems whose effect of other systems, including reliability, can not be precisely determined at the present time.

The differences in COE in Table 2 is due to the reduction of the cost of the magnet system. The postulated decrease in magnet system cost is due

Table 1
Fraction of cross sectional area of toroidal field coil in ARIES-RS

Grade	Copper	SC	Helium	Insulation	Structure
4	0.142	0.05	0.123	0.025	0.659
3	0.136	0.033	0.119	0.025	0.685
2	0.125	0.012	0.108	0.025	0.728
1	0.126	0.007	0.108	0.025	0.735

Table 2
Results from tokamak systems code, when LTS is replaced with HTS, for various values of neutron wall loading and net power output (P_E) Nb3Sn magnet

R_p (m)	B_c (T)	COE (ml kWe^{-1} h^{-1})*	avgerage peak I_n (MW m^{-2})	P_E (GWe)
Nb3Sn				
5.2	11.13	53.7	3.2/4.8	1
5	11.63	53.2	3.5/5.2	1
4.84	12.03	52.7	3.7/5.5	1
5	12.86	43.1	5.2/7.7	1.5
HTS magnet				
5.2	11.12	52.7	3.2/4.8	1
5	11.64	52.3	3.5/5.2	1
4.84	12.09	51.8	3.7/5.5	1
5	12.89	41.7	5.2/7.7	1.5

to decreases in manufacturing cost of coils using printed-circuit techniques for depositing the conductor and insulation, plus decreased magnet mass. The cost of high T_c magnets that need to be manufactured using the same process as low T_c superconductors (as is the case for BSCCO wires and tapes, with separate conductor manufacturing, insulation, and then winding in the structure) is expected to be similar or higher than for the low-T_c superconductors (mainly due to the higher cost of the conductor).

If full utilization of either higher beta or higher thermal conversion efficiency is not possible, the leverage provided by B_c is greater and the advantage of HTS would be greater.

5. Novel design of toroidal field coil with cryogenic radiation shielding

As discussed above, it would be possible to substantially decrease the shielding requirement for the toroidal field coil if it were not for the fact that the high temperature superconductor has a comparable irradiation limit to the A15 low temperature superconductor (particularly Nb_3Sn).

It is possible to place the HTS superconductor in regions of substantially lower radiation flux than the peak flux in the toroidal field coil. This can be achieved by placing materials that serves the dual purpose of shielding and structural elements between the superconductor and the blanket/shield. Such a scheme is shown in Fig. 3. It is necessary to utilize radial plates as in the ARIES-1 design [6], as opposed to shells as in the ARIES-RS design [7,11]. The magnet region closest to the plasma experiences substantially higher fluxes than in the region where the superconductor is located. If radiation limits of the superconductor are one-order of magnitude lower than at the edge of the cryogenic shield region, then it is possible to place the superconductor 12–24 cm away from the plasma facing edge of the toroidal field coil. Only if the space that not occupied by superconductor can be used for structure is this a good approach. The cryogenic shield is used only in the inboard leg, as the space in top/bottom and outer legs is not as valuable as in the inboard region.

If steel is exclusively used in the cryogenic shield region, the radiation flux at the superconductor would be only a factor of 2–4 lower, as shown in Table 3. Preferred shielding elements are W, B and H. Of these materials, only W alloys could be used as structural elements. Unalloyed W, and even alloyed W, has poor manufacturing properties. A practical approach is to use W as heavy metal, in which tungsten powder is mixed with nickel, iron or copper powder, using power metallurgy (PM) techniques, and is a commercial product [22]. The powders are compacted and liquid phase sintered. The result

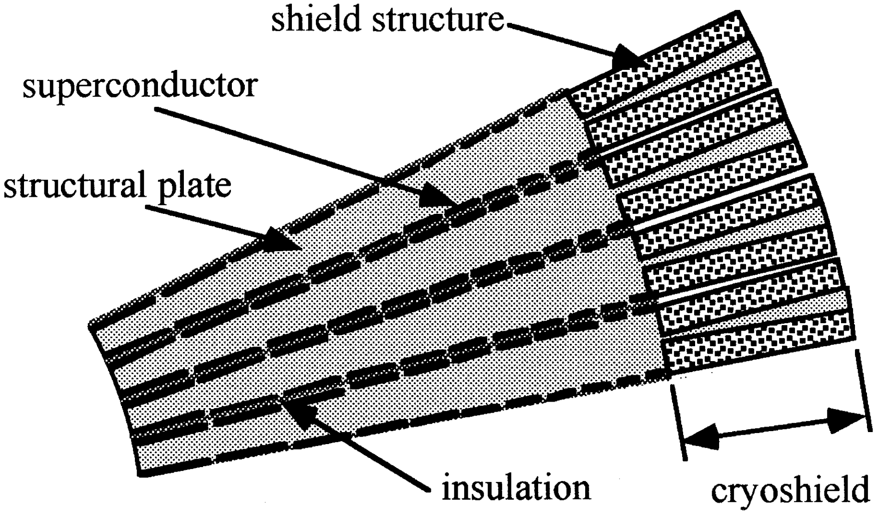

Fig. 3. A schematic diagram showing the method of inner leg coil manufacturing with cryogenic support structure in regions of higher irradiation that have no insulation nor superconductor. The cryogenic temperature shield region is also indicated.

is a very high-density machinable material having a homogeneous structure with no grain direction. This provides a material with unique physical properties and applications. The physical properties of heavy metal are: density of 17 000 kg m^{-3}, a tensile and yield stresses of 750 and 600 MPa, respectively, a Young's modulus of 250 GPa (similar to steels) and high elongation to fracture (6%). Heavy metals are either non-magnetic or slightly magnetic, depending on whether Fe is used in the liquid-phase sintering material. The material can be machined and brazed to a multitude of substrates.

Because of the good physical properties of heavy metal, it is often used as structural member. Weights and counterbalances for aircraft control surfaces and rotor blades, guidance platforms, balancing of flywheels and crankshafts, vibration damping governors, and fuse masses and weights for self-winding watches are typical applications.

The cryoshield design in Table 3 has not yet been optimized to include other elements. It is possible to mix small amounts of boron during PM manufacturing of the heavy metal (as an alloying element during the liquid phase sintering). Alternatively, boron carbide powders (with a melting temperature of 2300°C) can be added to the powder mix prior to sintering. Another approach is to use boron carbide coatings (< 10 μm thick).

The cryoshield can be used to react either the in-plane loads, or the in-plane and out-of-plane loads. For the case of outer plane, the plates need to make direct contact in the region of the cryoshield (i.e. they have to be wedged), or they need to have rivets or similar structures between them.

For fixed field at the superconductor, it is possible to increase the thickness of the cryogenic shield further (and decrease the conventional shield), at the expense of increased nuclear heating to the cryogenic environment. This tradeoff is presently being explored.

Table 3
Fast fluence (n cm^{-2}) at the conductor, for both stainless steel and tungsten cryoshields

	SS cryoshield	W cryoshield
No cryoshield	1.00E+19	1.00E+19
12 cm cryoshield	5.40E+18	3.20E+18
24 cm cryoshield	2.60E+18	6.70E+17

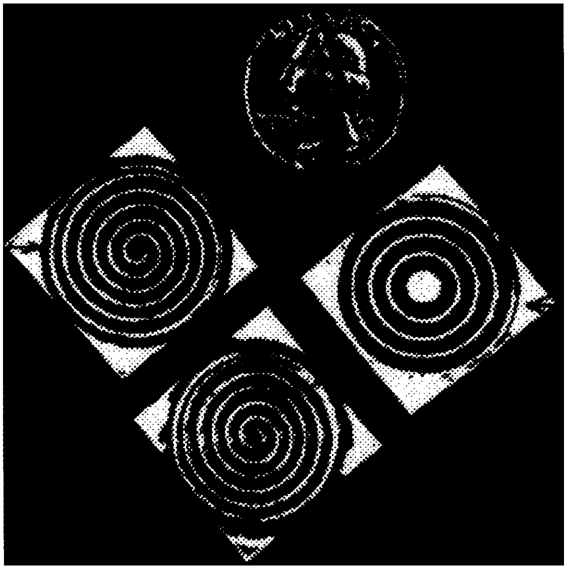

Fig. 4. Single sided samples made of BSCCO 2212 applied on a squared-silver substrate. An American quarter dollar is shown for comparison.

In Fig. 3, the cryogenic shield has been left electrically uninsulated. Ideally this region should be insulated. If a high radiation tolerant insulator can be developed, such as spinel, then it should be possible to insulate the plates in the region of high flux and eliminate the gap between the radial plates at the plasma facing edge of the magnet. Boron carbide is electrically conducting, and therefore can not be used as the electrical insulator.

The proposed approach results in a small increase in the peak field at the superconductor. For a cryogenic temperature shield of 24 cm, with a toroidal field coil at 3 m, the field increased by about 10%, easily accommodated by the HTS material.

5.1. Magnet costing of epitaxially made magnets

The unit-cost of the toroidal field can also be substantially decreased by utilizing the magnet topology described above (with or without the cryogenic shield). Instead of the complex manufacturing processes used for today's LTS magnets, modern rapid-prototyping techniques could be used [27]. The plates can be manufactured from either powders (as in the ARIES-ST reactor) or from raw stock. They can then be coated with the different layers to manufacture the superconductor, in a process similar to that used in printed circuits and that is very easily automated. Presently Ni is being used as the substrate for tapes. It is not clear whether Inconels (Ni-based steels) could be used instead. If not, then the steel would have to be coated with a layer that serves as a diffusion barrier, onto which Ni is deposited. Alternatively, tapes can be used, which after they are manufactured can be soldered onto the structural plates. However, the use of tapes may increase the cost of the magnet, due to increased number of processes involved.

It is estimated that the cost of the raw superconductor material is on the order of \$200 kg^{-1} which comparable to NbTi, but is cheaper than Nb_3Sn. Since the superconductor is such a small fraction of the cross sectional area, the cost of the magnets will be determined by the cost of the structure. The cost of the structure is being determined. It is being assumed that modern manufacturing techniques will be used. Cost as low as \$50 kg^{-1} for the magnet could be feasible.

The use of epitaxial methods of fabricating the magnet allows great flexibility in the choice of the cross section of the magnet. It is possible to vary the TF coil cross section as a function of the the poloidal angle. Thus the cross section of the coil can be chosen locally to match the local stress condition, minimizing the amount of material required. In addition, it is possible to vary the coil radial and toroidal widths to facilitate access. The option of increasing the radial width and decreasing the toroidal extent of the TF coil in the outboard side eases access restrictions.

5.2. Quench protection of multiple connected turns

It is possible to separate individual turns by leaving gaps between multiple 'ribbons' of HTS films deposited on the surface of the structure. Fig. 4 shows a photographs of multiple printed-circuit HTS pancakes, manufactured by the authors [8]. The superconducting material is BSCCO 2212, deposited in a grooved silver substrate.

As mentioned above, the present method of manufacturing YBCO involves a thin CeO_2 layer between the Ni substrate and the YBCO thick film. Therefore, these ribbons are already insu-lated from one another. Because of this, they resemble multiple turn superconducting plates [9], and therefore the current per plate is the current in each ribbon times the number of ribbons. In this case, either or both of the thickness of the film or the radial dimension of the ribbon can be used to grade the conductor along the poloidal direction. The current density in the superconductor can be adjusted by varying the radial extent or the thickness of the HTS film. Unlike the ARIES-RS magnet, with four grades of conductor, the ribbons in this case can be continuously graded.

A single ribbon, or a small number of multiple ribbons can offer additional protection against quench. If the current in one region of the ribbon exceeds the critical condition, then as long as the entire ribbon is not critical, the current will displace away from the resistive region into the superconducting one. The time constant for this process can be estimated, and is only fractions of a second, depending on the size of the perturbation [9].

In the case when the entire pancake is a single turn (single ribbon), the pack current would be very large.

The transients during charging and discharging of the 'ribbons' were investigated by the authors using inductive charging and discharging of bulk high temperature superconductors. The process is described very well by the Bean critical model. It results in current that during charging 'hugs' the inner-most region of each ribbon. The superconductor is at critical condition at the innermost region of the ribbon, and no current flows in the outer region of the ribbon until the critical current of the ribbon has been reached. During discharging, the outermost of the ribbons carry critical current in the opposite direction, and that region continues until the net current in the ribbon is zero. Therefore, there are currents that flow in the superconductor, even though they have no net currents. The above description applies even in the case of a single turn pancake.

6. Demountable high temperature superconducting toroidal field coils

Demountable superconducting coils were originally proposed for the fusion program by the Powell group [16]. They proposed using 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. It would therefore be unstable.

The difficulties with LTS are eliminated with the use of HTS. It is possible to make high quality thick films with these materials, specifically with YBCO compound, as described in Section 2. The HTS material can be directly deposited on the structural plates.

If the joints can be manufactured with low enough resistance, then the power dissipated in the machine can be kept low. A possible configuration of the machine can be modeled after the ALCATOR C-MOD [21] concept. In the ALCATOR C-MOD device, the joints where made from a complaint metallic sponge that shunts across plates. The region of the plate that is in contact with the metallic shunt was electroplated with silver. The joints have been a recurring source of failure in C-MOD.

The use of silver contacts is being pursued for BSCCO as well as YBCO applications. Silver-based contacts for YBCO are being developed for tapes as well as for bulk YBCO material used in Fault Current Limiters (FCL). Joint surface resistivities as low as $0.1\ \mu\Omega\ cm^{-2}$ have been obtained. The contact between the HTS and the normal material is an active area of research.

To minimize power dissipation, the shunts can be made superconducting, using BSCCO materials. Silver is compatible with BSCCO material, and it is used as the matrix metal for making both wires and tapes, or for contacts, as in current leads.

A possible design for the joint is shown in Fig. 5. The HTS thick film in the plate is covered with a normal conducting film (silver) in the region of the joint. This region is mated with a similar one in the next 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 shunt is made from a superconductor material covered with silver. BSCCO 2212 has been used to make superconducting leads in a similar manner. Although BSCCO 2212 has substantially lower critical current density than YBCO, it is still adequate for this application since the shunt is designed with much lower current density than that in the plate superconductor. 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. Preliminary calculations of the dissipated power and the capability of liquid nitrogen and high-pressure helium to remove the dissipated power from the joint region have been performed. The power, referred to room temperature, is on the order of a few MWs.

This approach avoids the need for developing long lengths of conductor, since the maximum length of the HTS tape would be the size of the vertical/horizontal legs.

One of the drawbacks of this approach is that the 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 narrow as possible.

The same method described in the previous section can be used to provide multiple turns per plate.

7. Poloidal field systems

In this section, only a few brief comments will be made regarding the use of HTS materials for the poloidal field system.

As with the toroidal field system, the use of HTS as a replacement of LTS in the poloidal field system does not change the tokamak concept. Higher current densities could be used to increase multipole fields, such as those needed for shaping. Higher current density also decreases the distance between the plasma and the coil centroid, therefore offering possibilities of decreasing shaping currents. However, both of these effects are small and will only have a small impact on the PF system as in the TF, for conventional tokamak fusion designs.

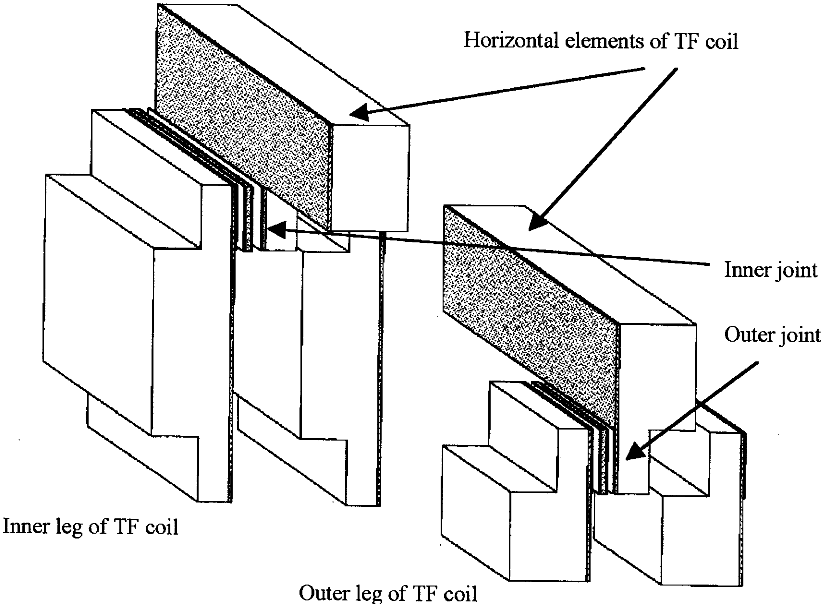

Fig. 5. A schematic diagram of a section of an inner leg, a section of a top leg and a section of an outer leg of a high temperature superconductor, de-mountable toroidal field coil. The shaded region indicates the presence of an HTS film.

For pulsed tokamaks, it is possible to practically eliminate the effects of pulsed fields on the structures and the conductor, but if necessary, the effect of transients can be accommodated with LTS [5].

As with the toroidal field coil, the HTS is an enabling technology that could change the way magnets are manufactured and maintained. Plate superconducting poloidal field coils could be much cheaper than LTS, since constant thickness plate material could be used as the structure, with HTS deposited on the surface. Therefore, the cost of the PF system could also be substantially decreased.

The concept of demountable poloidal field coils was used in the HFCTR design [13] with resistive coils. Demountable poloidal field coils enable the location of internal poloidal field coils in the case of non-demountable toroidal field coils. However, since the technology requirements for demountable PF coils are comparable to the required joints in demountable TF coils, it is likely that the PF coil would be made non-demountable in a demountable TF coil.

8. Summary and conclusions

The use of high temperature superconductors for tokamak fusion reactor designs has been evaluated. It has been shown that with conventional magnet manufacturing technologies using wound conductor, high T_c superconductors offer only a marginal improvement in the tokamak concept. Using high T_c tapes in conventional tokamak designs, results in a marginal improvement due to possibly cheaper coils and an increase in the structural fraction of the cross section of the toroidal field, with a limited reduction in the cost of electricity and no improvement in maintenance.

The use of high T_c materials, however, may be enabling technologies that spur qualitative changes in the tokamak system. Two possible design changes have been described in this paper. The first one utilizes thick films deposited directly on the structure. Besides improved performance, by decreasing the required nuclear shielding by 5–15 cm, it leads to decreased system cost because simple manufacturing techniques can be utilized for both the TF and PF coils. The second option, in addition to the above advantages, offers the potential for access comparable to that available in normal conducting machines, such as ALCATOR C-MOD and in designs such as ARIES-ST.

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