Superconducting Magnets Research for a Viable US Fusion Program

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Executive Summary

Magnet systems are the ultimate enabling technology for magnetic confinement fusion devices. Powerful magnets are required for plasma confinement, and, depending on the magnetic configuration, dc and/or pulsed magnetic fields are required for plasma initiation, ohmic heating, inductive current drive, plasma shaping, equilibrium, and stability control. Almost all design concepts for power producing commercial fusion reactors rely on superconducting magnets for efficient and reliable production of these magnetic fields. Superconducting magnet technology is a powerful knob for significantly enhancing the feasibility and practicality of fusion reactors as an energy source.

A *new "game changing" opportunity* that could significantly advance the economic and technical status of superconducting magnets is now viable, namely the use of so-called **High Temperature Superconductors (HTS)**. The use of these materials enables an attractive fusion development path because high magnetic field operation of a tokamak leads to smaller size, increased margin to operational limits with lower risk of disruptions, and efficient RF current drive for steady state operation [1]. **HTS** can be used with any magnetic field configuration including 3-D shaped devices.

These HTS materials have been used for a small-bore superconducting solenoid at > 30T. Recent studies indicate that demountable HTS magnets can be feasible for future devices. Demountability would have large impact on fusion reactor operation due to improved ability to maintain the machine, increasing reliability and availability. An integrated program of advanced HTS magnet R&D should focus on developing innovative approaches to the toroidal magnetic confinement concept that would substantially improve and accelerate the path to practical fusion reactors.

The state of the art in fusion superconducting magnet systems is ITER. The Low Temperature Superconductor (LTS) technology for ITER was developed in the 90's, and although there are still remaining issues with the superconductor cable, the technology has been used successfully in model coils and in smaller fusion experiments. In fact, all superconducting fusion systems in operation or under construction (EAST, KSTAR, LHD PF coils, Wendelstein 7-X, ITER) [2-6] use the Cable-in-Conduit-Conductor technology invented and developed in the US.

Future superconducting magnets for fusion applications require improvements in materials, topologies and components to enhance the feasibility and practicality of magnetic fusion reactors as an energy source. The only way for the U.S. fusion program to realize the potential benefits of HTS superconductors is to revitalize the magnet technology program with a ten-year development program focused on bringing HTS conductor and magnet technology to a readiness level that can then be applied to building and operating the next generation of fusion reactors such as FNSF or DEMO.

Background

Although the majority of past and present magnetic fusion experimental devices use normal resistive magnets, almost all design concepts for commercial fusion reactors rely on superconducting magnets for efficient and reliable operations. The overall electrical power requirement, including refrigerators to maintain the cryogenic temperatures, is small compared with power dissipation of resistive magnets (though superconductors would dissipate a small amount of power in transient magnetic fields). The electrical power difference between superconducting and resistive magnets increase with increasing magnetic fields and magnet size, or where long pulse length or steady state operation is required. Since the magnetic system forms the core of the fusion device, the magnet technology defines the operational limits of the plasma, as well as the core machine size and cost. Magnet limitations constrain the design of new experimental facilities as well as the design and evaluation of commercial reactors. For magnetic fusion to be attractive as a clean and efficient power source, the magnet systems, both normal and superconducting must offer very high performance, acceptable first cost, low operating and maintenance costs, and high reliability.

LTS magnets are operational or under construction for fusion devices throughout the world, but not in the USA. In fact, all recent superconducting fusion systems (EAST, KSTAR, LHD PF coils, Wendelstein 7-X, ITER) use the Cable-in-Conduit-Conductor technology invented and developed in the United States. Yet, we remain the only major country with a fusion program that has no operating superconducting fusion experiment (the exception is LDX, the Levitated Dipole Experiment at MIT, but it has been terminated as a fusion experiment and is operated minimally as a "space weather " experiment.)

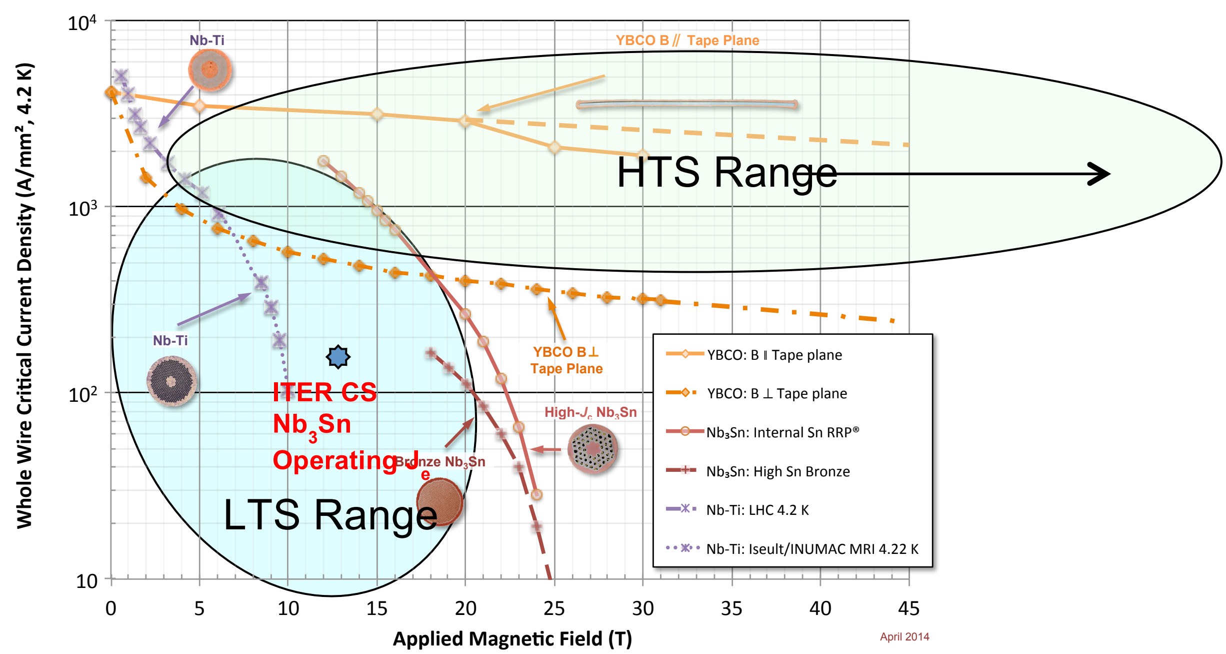
Since, ultimately, cost is the primary criterion for acceptance of a demonstrated technology, the US fusion program should lead an effort to leapfrog the last decade's LTS technology (which will not be State-of-the-Art by the time we embark on the next device, be it FNSF or DEMO) and initiate a vigorous domestic program in HTS development. While the US could maintain leadership of fusion physics based on medium scale domestic experiments as well as through a strong theory and computational physics program, supplemented by international cooperation, including that on ITER, the knowhow to build the components of a fusion power plant will rest with the teams that develop them, including domestic industrial partnerships. Since the foremost requirement for an attractive reactor (high performance, high reliability and availability, and acceptable cost) is an advanced superconducting magnet system, it is imperative that we commence a vigorous HTS magnet development program in FY 2015.

Magnet design for fusion applications requires multidisciplinary engineering skills including superconductivity, mechanical engineering, electrical engineering, materials science, and engineering design. It encompasses electromagnetics, cryogenics, structural analysis, power systems and circuits, specialized instrumentation, and complex magnet system modeling. If the U.S. is to be an active participant in a fusion energy future beyond ITER, it is imperative that it remains a leader in fusion reactor design, engineering, construction, and operation. To do so it must reestablish and maintain a solid base of scientists and engineers with the necessary skills and experience, and at the same time educate and train the next generation who will be needed to carry on the fusion program.

- **Revolutionary new HTS materials such as Yttrium-Barium-Copper-Oxide (YBCO) are sufficiently advanced for next-step fusion applications**

New Magnet Innovations

The use of HTS could significantly change the economic and technical status of superconducting magnets. Some types of HTS materials, in particular YBCO and similar Rare Earth compounds (REBCO) exhibit very high critical currents at temperatures well above that of boiling liquid nitrogen at 77 K as compared with the commonly used LTS (NbTi and Nb_3Sn), which must operate at temperatures near that of liquid helium. More importantly, if operated at lower temperatures, HTS exhibit critical current density much higher than the LTS conductors at extremely high magnetic fields making them feasible for use in magnetic fields even much higher than 20 T, as shown in Fig. 1 and Fig. 2.



All data at 4.2K.

Fig. 1 Critical current density as a function of magnetic field. At magnetic fields above 20 T The critical current density of YBCO exceeds that of the best performing LTS materials. Plot courtesy of Peter Lee (http://magnet.fsu.edu/~lee/plot/plot.htm).

YBCO is a material of enormous promise for high temperature and high field applications. *This is a revolutionary material with the potential for raising field, current density, and operating temperature simultaneously, while lowering refrigeration requirements.* Achievement of these goals would offer a realistic vision for making an economical future commercial fusion reactor.

YBCO has already been used for demonstration at fields > 30 T in small bore solenoid geometries. Such conductors do not yet have either the strength or the low AC loss requirements of present fusion conductors such as Nb_3Sn or NbTi but are showing significant progress in development that could make future magnetic fusion use possible. Recent demonstrations at the NHMFL-FSU showing fields of more than 35 T [8], and studies at MIT indicate that HTS magnets make demountable magnets a feasible option for future devices [9].

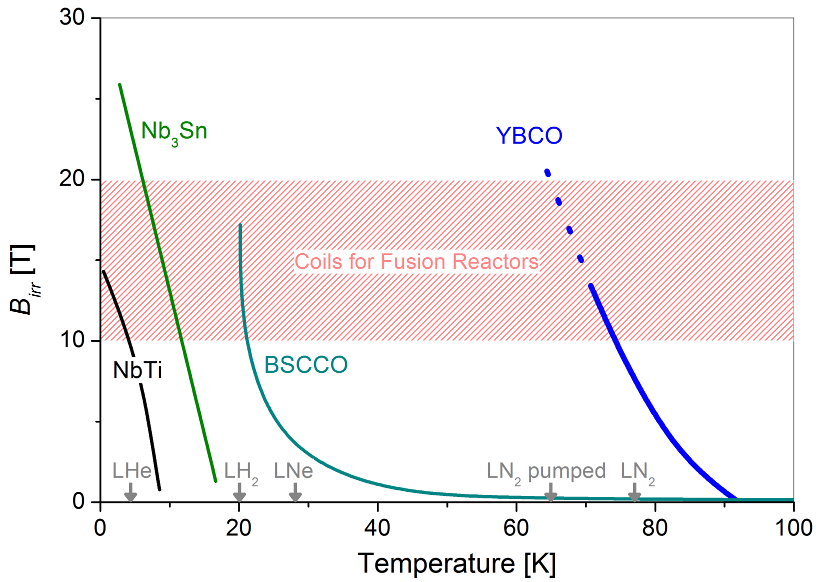


Fig. 2 Critical field as a function of temperature for several LTS and HTS materials. YBCO exhibits very high critical magnetic field when compared with the LTS conductors at temperatures between 20 K and 77 K [7].

The US fusion program should develop magnet technologies that are specifically focused on lowering the cost and increasing the availability/reliability of the magnets required in fusion power systems [10,11]. The replacement of a failed toroidal field coil or a major poloidal field coil in a fusion reactor is considered to have such a negative impact on reactor availability (several years) that coil failure should not be a credible event.

There are primarily three ways in which advances in magnet technology can lower the cost of experiments and fusion power production: 1) by providing conductor and magnet performance which substantially increases or optimizes the physics performance so as to allow a smaller or simpler device, *e.g.* increased magnetic field, 2) by lowering the cost of the superconductor and magnet components and/or assembly processes, and 3) by optimizing the configuration of the magnet systems, so that the cost of other fusion subsystems may be reduced.

- **Success in this program can potentially revolutionize the design of magnetic fusion devices for very high performance in compact devices with simpler maintenance methods and enhanced reliability.**

Scientific and Technical Approach

The focused HTS magnet development program should be a coordinated effort ranging from lab-scale R&D, prototype component development, prototype magnet tests, and eventually integration into any next-step device. The proposed program will significantly expand the fusion magnet R&D effort, which at present is subcritical, or almost non-existent, and engage fusion magnet experts across U.S. universities, national laboratories, and industries. This research will require funds for procurement of HTS materials, insulation, and structural materials as well as for fabrication of components, prototypes, and the test program.

While DOE-sponsored technology for electric power utility applications are yielding great progress, there are fundamental differences between these applications and fusion magnets. This proposed thrust would leverage ongoing R&D on HTS but would focus on HTS fusion magnet research specifically, not on the development of the superconductor tapes themselves.

HTS and advanced manufacturing techniques should be developed over the medium-term with the ultimate goal of high field operation. In the near-term, however, the properties and production lengths are now in a range sufficient for possible use in low and moderate field fusion devices, *e.g.* an ST, or even with non-planar coils, *e.g.* helical or stellarator configurations.

R&D Elements

A structured research and development program consists of the following elements:

1. HTS wire/tape characterization program
2. High current conductors/cables development program
3. Development of advanced magnet structural materials and structural configurations
4. Development of cryogenic cooling methods for HTS magnets
5. Development of magnet protection devices and methods specific to HTS magnets
6. Development of advanced radiation tolerant insulating materials
7. Integration of conductor with structure, insulation, and cooling
8. Development of joints for demountable coils
9. Coil fabrication technology incorporating the unique features of elements 1-8

Element 1- HTS wire/tape characterization program

The HTS materials characterization program goal is to measure and quantify the performance of high current tapes that can tolerate the fusion environment. The YBCO superconductor is made with thin-film technology and can only be made in long lengths as thin, flat, tapes, as shown in Fig. 3. Due to the tape geometry, the critical current density, J_c, is anisotropic, with J_c values much lower for magnetic fields perpendicular to the flat face of the tape when compared with magnetic fields parallel to the tape. Characterization of this material must be done in fusion relevant conditions of high magnetic field and current and in the temperature range 4.2 K to 77 K with emphasis in the 20 K – 50 K range.

Fig. 3 YBCO superconductor can only be made in long lengths as thin, flat tapes, with critical current density being highly anisotropic for in-plane and out-of-plane magnetic fields.

Element 2- High current conductors/cables development program

The goal of a HTS research cable program is the production of high engineering current conductors in long lengths through cabling, bundling, or stacking of a large number of tapes. For fusion applications, cables with 50-100 kA are desired. Recent laboratory work has demonstrated feasibility, so far to 5 kA- 10 kA level [12], but there is a big challenge to expand this work to the 50-100 kA level. One approach being studied is Twisted Stacked Tape Conductor (TSTC) concept, illustrated in Fig. 4.

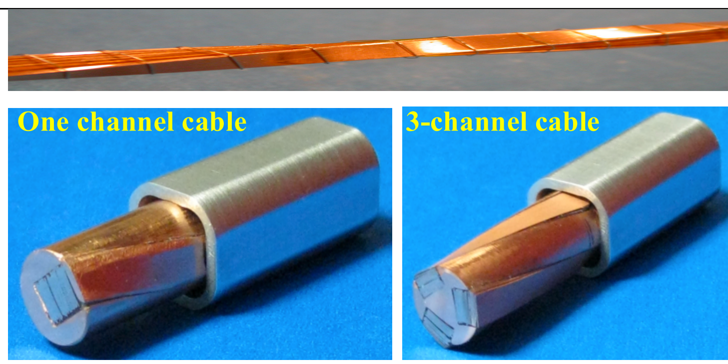


Fig. 4 Twisted Stacked Tape Conductor (TSTC) concepts.

Element 3 - Development of advanced magnet structural materials and structural configurations

Structural materials and structural concepts optimized for use with HTS material need to be explored. It is possible that conventional cryogenic materials can be used, as the heat treatment of the superconductor together with the structure is not required. For cost and manufacturing ease, the exploration of structural material improvements and of advanced manufacturing techniques will yield quantitative reductions in magnet fabrication complexity and assembly. This is an area that has received little attention and where even limited resources may yield substantial gains.

Rapid prototyping, or "additive manufacturing", can be used to create near net-shape components directly from Computer-Aided-Design (CAD) definitions. One potential use is to manufacture the structural plates of the magnet with the features needed for assembly and manufacturing. Multiple material deposition heads create the coil structure in a timely manner to near net shape such as internal coil grooves and attachment features. The fabrication cost of fusion magnet structures with this technology has been estimated to be a small fraction of traditional fabrication methods.

Flexible HTS tapes integrated into grooves in structure with complex shapes could also ease the manufacture of magnets with 3-D geometry or other alternate configurations.

Element 4 - Development of cryogenic cooling methods for HTS magnets

Cooling methods for HTS conductors need to be investigated. Present performance of HTS materials at 77 K results in critical fields that are too low for fusion applications. The critical field, however, increases very rapidly with diminishing temperature. Alternative coolants and cooling methods include flowing helium gas, single or two-phase liquid hydrogen, and sub-cooled nitrogen and nitrogen-eutectics.

Operation at higher temperatures also allows for savings in the cryostat, as higher heat loads can be accepted with a reduced (~ 1/10) refrigeration penalty. In addition, it is possible to absorb substantially higher nuclear heating. The heating constraints on the magnets can then be virtually eliminated. The problem of radiation damage to the superconductor and the insulation, however, still remains.

Element 5 - Development of magnet protection devices and methods specific to HTS magnets

Operation at relatively high cryogenic temperatures, *e.g.* 20 K - 50 K, requires reconsideration of stability, quench detection, and magnet protection as the heat capacity of the conductors, structure, and cryogenic fluid are orders of magnitude higher than those in a magnet operating in liquid helium.

Passive and active quenching methods need to be investigated. One such method is the possibility of quenching substantial sections of the magnets simultaneously through the use of eddy current heating (or hysteresis heating of the SC), using RF fields. These means are not needed at liquid helium temperature because of the fast propagation of quenches, even in the presence of helium coolant. Fast quench propagation does not occur with HTS materials.

The overall design philosophy of off-normal conditions and faults would also have to be rigorously developed, in order to guarantee protection against credible operational events. Design and analysis codes should be revised specifically for fusion magnets operating at these higher temperatures, and confirmed by comprehensive laboratory testing as has been done in the past for liquid helium (LTS) magnets.

Element 6 - Development of advanced radiation tolerant insulating materials

There has been substantial effort in the fusion community for the development of radiation resistant insulators. Progress has been made in the development of both organic and hybrid insulators. The main characteristic of these insulators is the presence of a liquid phase that can penetrate through the coil winding, filling the voids, and impregnating the coil elements and the insulation sheets. The use of HTS can substantially change the direction of this work, opening new avenues for development of superior insulation systems. For the case of HTS material directly deposited on the substrate, it would be possible to deposit thick layers of ceramics that can serve as insulation. Ceramic insulators should survive ~100 times higher doses than organic insulators. Means of transferring loads between plates of the magnet need to be investigated, in order to take full advantage of this structural potential, since the plates cannot be resin impregnated. The use of large plates eases the application of the ceramic insulation, with insulated windings on the plates, and planar insulation between plates. Alternatively, the conductors could be encased or wrapped in a ceramic insulation material.

It should be noted that, although radiation damage to the magnet insulation presently limits the operating service life of the magnet system, there is reason to predict that improvements in organic and inorganic (including ceramic) insulating systems could extend the damage limit beyond that of the superconducting material, whether low temperature or high temperature superconducting material. At this time there does not seem to be any physical path to extend the radiation damage limit for the superconductor.

Element 7 - Integration of conductor with structure, insulation, and cooling

The options described above need to be integrated into a fabrication technique that takes into consideration the requirements of the superconductor, coolant, structure, insulation and assembly. There are synergisms between these requirements that can substantially benefit fusion plasmas, as described above. The possibility of additive manufacturing, with HTS deposited on the structure, using ceramic insulation and built-in coolant passages, can substantially decrease the magnet cost while also allowing operation at higher performance (field, fusion power, pulse length). Alternatively, methods of winding HTS in grooves on plates, and insulating them, need to be developed. The coolant geometry may be different, in that the conductors may be able to carry the coolant themselves, as is the case with CICC.

Element 8 - Development of joints for demountable coils

The ability to operate at relatively high cryogenic temperatures and the use of relatively simple structural configurations provide very high stability that, in turn, allows consideration of demountable joints. Demountable high temperature superconducting coils promise unique advantages for tokamaks and alternate configurations. They would enable fusion facilities in which internal components can be removed and replaced easily and remotely, a major advantage for the difficult challenges of Reliability, Availability, Maintainability and Inspectability (RAMI).

There has been very limited investigation of demountable superconducting magnets (Fig. 5). The use of HTS allows for relatively high resistance joints with modest cryogenic power consumption when compared with joints in LTS coils. The use of tapes also facilitates certain types of joints such as lap joints, where surfaces of the tapes are pressed together for a non-permanent joint. For the case of tokamaks, two types of joints can be considered, sliding joints and finger joints (fixed). In either case, it is necessary to unload the joint region, as the joint has limited load-carrying capabilities. One additional issue that needs to be addressed is cooling of the joint region. The joint region has the largest cryogenic load of the magnet, larger than current leads or thermal radiation, and it is deposited in a small volume. The joints need to be effectively cooled. Although it is preferable to cool the joint directly, other cooling options should be studied.

Element 9 - Coil fabrication technology

Attractive solutions generated in Elements 1-8 need to be integrated and demonstrated by building prototype magnets of different configurations, e.g. planar coils, solenoids, 3-D coil geometries, etc. These must then be operated under full-scale operating conditions to the extent that they can be simulated in a prototype coil test facility. The most promising and useful magnet designs would then be incorporated into new OFES research facilities.

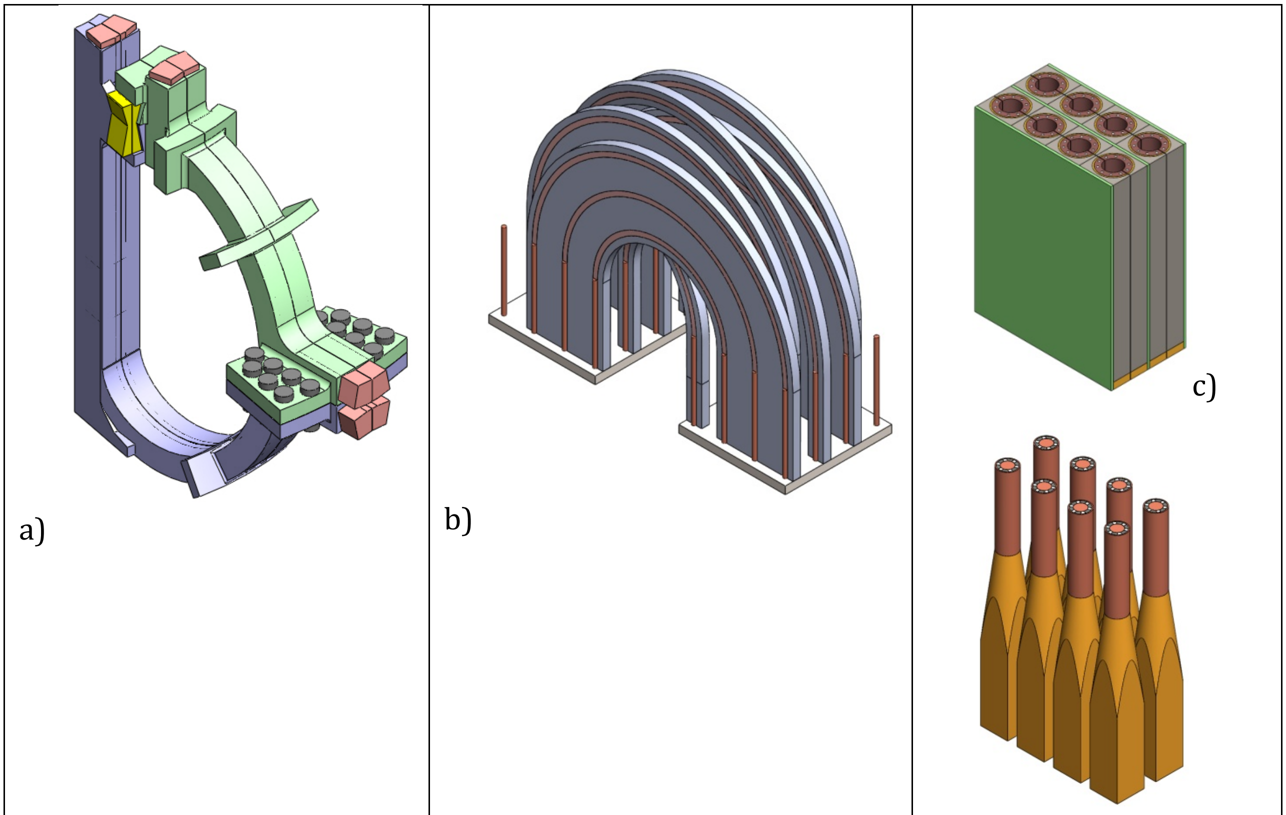


Fig. 5 a) Concept for TF coil with a demountable segment; b) Joint design to link two branches of the coil; c) Concept for pin and socket remakeable joints in the superconductor.

Benefits for Magnetic Fusion Energy

Implementation of this R&D program will result in fusion devices that have higher performance, high reliability, availability and maintainability with acceptable cost – potentially a "game changer." In the shorter term, the results of this work offer flexible steady state experimental scale devices, including tokamaks, stellarators, and other non-planar geometries for 3-D magnetic configuration devices. Thus HTS technology will enhance and accelerate the near-term scientific research needed for fusion. The U.S. would also establish a workforce knowledgeable to design, build, and operate fusion reactors of the future, by using personnel, research capabilities, and manufacturing facilities from national research laboratories, universities, and industry.

International Collaboration

Outside the United States there are teams that are beginning R&D programs to develop advanced magnet technologies for use in the next major machines to be designed and built in anticipation of a future DEMO. Most of these programs are beginning to focus on HTS magnet technology. We have started an informal group to begin to focus and coordinate our research efforts with the goal of using international collaboration to make the most efficient use of limited programmatic resources, and to share major testing facilities, which are limited in number and expensive to operate. We call this group **HTS4Fusion Working Group**, and at this time, we have about 25 participants from the U.S., Japan, England, Germany, Switzerland, Austria, India, and Russia, representing about 15 different research institutions and universities. The first workshop was held at Karlsruhe Institute of Technology (KIT) in 2011 [13] and the second was held in 2014 at EPFL/CRPP [14]. We expect to add members from Korea, China, and France shortly. The HTS4Fusion program would benefit immensely from formal sponsorship, organization, and coordination by our respective governmental funding agencies.

Required Resources

Initiation of a program of this scope will require investment of resources in funding, personnel, materials, and equipment significantly beyond those allocated to the present modest magnets base program. The HTS materials are relatively expensive at this time, and sufficient quantities of industrial quality conductor must be purchased for the lab-scale program, component development, and eventually prototype magnet development. Research and development on making advanced HTS conductors in alternative geometries requires a robust materials development program, especially for development of round YBCO wires or direct deposition of HTS materials on structures. This is also true to achieve the goals of developing structural materials with the proper alloy chemistry, shapes, and manufacturing methods. Table 1 gives a funding profile associated with the proposed R&D over a ten-year development period. After FY10 a full-scale or near-full scale prototype(s) magnet should be designed and tested to confirm the performance of this new technology on a relevant scale. Such a device may be similar to the CS Model Coil, designed and built during the ITER EDA. At this scale, a significant investment would be required in addition to the base program. If the U.S. National program is ready at this time, this coil could be the prototype for the next major nuclear science machine, and considered a part of that construction program.

Table 1 Proposed Funding Profile

Fiscal Year	Budget ($K)	Major Milestones
1	2,000	
2	3,000	
3	4,000	Full-size Conductor Samples in 50 kA to 100 kA range
4	5,000	Full-size demountable joints demonstrated
5-10	5,000	Ready to build large size prototype coil operating at high field, and to begin design of an FNSF.

Total Investment: $44,000K

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