

PSFC/RR-11-8

Magnets R&D for FNS

J.V. Minervini^a, L. Bromberg^a, J.H. Schultz^a,
M. Takayasu^a, D.C. Larbalestier^b and P.J. Lee^b

^aMIT Plasma Science and Fusion Center, Cambridge MA

^bFSU National High Magnetic Field Laboratory, Tallahassee FL

August 2011

*Sponsored by DOE-Office of Fusion Energy Sciences Grant No: DE-FC02-93ER54186

Abstract

The purpose of this paper is to review R&D requirements for magnets to be used in a post-ITER fusion machine that would have a nuclear mission. The state of the art of magnets is presented, followed by potential magnet options in the near (< 10 years) and middle term (> 10 years), followed by a description of the different components and system integration issues. The characteristics of an R&D program for investigate these issues is described, followed by a description of the present US facilities.

I. State-of-the-art

The state of the art in fusion superconducting magnet systems is ITER. The technology for ITER was developed in the 90's, and although there are still some issues with the superconductor, the technology has been used successfully in model coils and in other smaller fusion experiments in Asia (EAST and KSTAR).

The time scales of the FNS that is investigated in this R&D program are near term (design in the next 10-15 year), and longer term (> 15 year). For any machine whose design needs to be frozen in the next 10-15 years, it is likely that the ITER low-temperature superconducting technology would have to be used. Improved superconductors exist, and they may be used, especially if the machine has a limited rate-of-change of field compatible with reduced AC losses in the superconductor. For pulsed machines with a large number of pulses, the structural material of choice would be low Coefficient-Of-Expansion (COE) Incoloy 908, to reduce SAGBO (Stress-accelerated-grain-boundary-oxidation) sensitivity, but it would be necessary to restart Incoloy 908 production. In addition, structural designs could be reoptimized, for example, in the case of a long pulse machine that does not depend on inductive drive. In this case, different structural options could be more attractive than those chosen for ITER.

II. Future magnet technology: magnet technology for FNS

Future superconducting magnets for fusion applications require improvements in materials and components to significantly enhance the feasibility and practicality of fusion reactors as an energy source. The fusion program should be developing magnet technologies that are specifically focused on substantially lowering the cost and increasing the availability of the magnets required in fusion power systems. The replacement of a failed toroidal field coil or a major poloidal field coil in a DEMO or fusion reactor is considered to have such an impact on reactor down time (several years) and economics that this has to be designed to be not 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 or some special magnetic field configuration, 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.

In addition to magnet design issues, there are R&D opportunities in materials. For magnets, the insulation and structural material issues are addressed in the materials section elsewhere in this report. In this section, only magnet and superconducting issues will be discussed.

An integrated program of advanced magnet R&D focuses on developing alternative approaches that could allow for incremental improvements, or radical approaches that could substantially affect other systems. One agent of radical change could be the use of High Temperature

Superconductor (HTS) materials and magnet systems. While the materials offer the opportunity for higher, more stable magnets, they also offer enormous potential for Magnetic Fusion Energy (MFE) research experiments, and potentially transformative technological innovation, if demountable TF magnets could be developed. Accomplishment of a program which fulfills the research gaps and needs described here can potentially revolutionize the design of magnetic fusion devices for very high performance in compact devices with simpler maintenance methods and enhanced reliability.

III. Needs and opportunities for magnets for FNS

Substantial development and experimental steps must be taken to develop High Temperature Superconductors (HTS) for fusion applications. In addition to HTS, there are other magnet opportunities for improving magnets for fusion applications. We expect that it will be possible to achieve two goals:

- Halve the cost of magnet systems
- Explore alternate magnet configurations such as demountable TF magnets

Improvements can be made in the following components:

- 1) Superconducting wires and cables (both LTS and HTS)
- 2) Mechanical support structure (both for LTS and HTS)
 - (a) External
 - (b) Conductor
- 3) Insulation (see the materials section)
- 4) Structural materials (see the materials section)
- 5) Quench detection and instrumentation (both for HTS and LTS)
- 6) Demountable joints for HTS.

In item 2) above, we distinguish between external magnet structure such as a structural case or plate supporting a winding and structure integral with the conductor, *e.g.* the conduit material for a cable-in-conduit-conductor (CICC). If important quantitative and achievable goals can be realized for all of these components individually, it should be possible to reduce the cost and perhaps the complexity of fusion devices dramatically.

In the following sections we describe issues, opportunities and goals for a few of these important aspects of superconducting magnets and components. In addition, better manufacturing and system integration techniques, for example, using rapid prototyping techniques or demountable superconducting magnets, could help decrease costs through improved manufacturability, reliability and maintainability. We focus primarily on application of High Temperature Superconductors (HTS) to fusion magnets because their application is judged to have the largest future impact on machine performance and operation. However, we include some issues associated with LTS and copper machines.

IV. Superconducting materials

a. LTS

The bulk of the development of Low Temperature Superconductors has been for and been supported by the High Energy Physics community. However, HEP needs, primarily for the highest possible critical current density at the highest magnetic field, only partly overlap with the needs of the fusion community. Furthermore, as the needs of the HEP community shift to higher energies and fields, future support for LTS strand development is already showing signs of diminishing as HTS applications for high fields become practical.

For fusion applications, high current cables are needed and CICC (Cable In Conduit Conductor) have been the principal vehicle. CICC cables are complex structures, and there are still areas of their performance that are poorly understood. In particular, fatigue effects are far from being fully understood. The complex strain state of strands within the CICC are not quantitatively understood yet, as for example is clear from the degradation effects seen in the ITER test cables after multiple loading (both magnetic field loading and system warm-up and cool-down “WUCD”) cycles.

In general, the issues for Low Temperature Superconductor (LTS) conductor and magnet technology can be reduced to a few generic points: a) Cost reduction; b) Improved performance; and c) increased lifetime and reliability.

Superconducting magnets are very expensive. This is partly due to the extensive R&D normally associated with new conductor designs, raw material costs, and conductor processing costs, which are labor intensive, and sometimes of low yield. Coil fabrication costs are also high because the superconductor properties are often sensitive to handling, and the coil fabrication steps may stress or damage the superconductor. In addition, the brittle Nb₃Sn superconductor must be formed after coil winding by a long multi-step heat treatment which finishes with a high temperature reaction heat treatment (at about 650 °C for up to 200 hours) which complicates the fabrication process and extends the fabrication schedule significantly. There are other substantial costs associated with the need for cryogenic refrigeration at the 4.5 K level and nuclear shielding. Some magnetic configurations require very high field quality and therefore the conductor must be amenable to being positioned accurately.

A strong benefit results from higher magnetic field since fusion power is proportional to B^4 . Higher operating current density could reduce the size of the winding pack, as would better quench protection systems, thus reducing overall system cost. Improvements in the ability to absorb higher nuclear flux and fluence could reduce the whole machine size and cost if better insulation systems could be developed or if superconductor stability could be increased in order to reduce the size of the radiation shield protecting the magnet. Better ways of integrating advanced insulations need to be developed to decrease the manufacturing costs.

For reactor scale devices, and even for a burning plasma experiment, the size, complexity of access, and probable need for remote maintenance of the magnet system, preclude the economical exchange of coils, so the magnet coils must operate with the utmost reliability and availability. Improved performance can allow for more operating margin and thus increase system reliability. An extremely important benefit could be achieved if demountable superconducting joints could be easily and reliably made.

b. HTS

Whereas the development of high performance LTS strand has been driven by the HEP community, the development of long-length high-current HTS technology has been, until FY10, driven by the OE (Office of Electricity Delivery and Energy Reliability) of the Department of Energy with a focus on transmission-line application. However, support from OE has been dramatically curtailed, and further development needs to be performed primarily from increased industrial support and from DOE-HEP (at the expense of LTS development).

c. HTS Material and Cable Design

25 years after the discovery of HTS, the development of long-length engineering quality HTS materials now 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 magnetic fusion devices 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 some HTS materials can operate at cryogenic temperatures approaching that of liquid nitrogen (77 K), one can consider as realistic the option to build electrical joints into the winding cross-section that can be connected, unconnected and reconnected on site. 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. Recently, the NHMFL has achieved a 35 T field using HTS tapes at low temperatures. 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.

There have been substantial R&D investments in HTS by the Department of Energy Office of Electricity Delivery and Energy Reliability (OE) and high energy physics. The industry is at present providing substantial quantities of HTS tapes. In the US, all production has moved to the

2nd generation materials, using YBCO and ReBCO superconductors, away from BSCCO-2223 material that formed the basis for 1st generation HTS conductors. 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 \$400/kA·m.

Despite their great promise, high temperature superconductors are still a young technology. The demands for fusion applications require investigation beyond those of existing programs. The limits on high temperature superconductors that reflect the early stage of their development are:

1. Cost
2. Performance
3. Piece length
4. Strength
5. Production Capacity

Although high temperature superconductors are not yet a sufficiently established industry to provide conductor for the most demanding fusion applications, the rate of progress in performance has been impressive. This is especially true for YBCO which 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 temperature simultaneously, while lowering refrigeration requirements. Achievement of these goals would offer a realistic vision for making an economical future commercial fusion reactor. High temperature superconductors could be used in ultrahigh field magnets and could be developed in the moderate-term. Even now, however, the properties and piece lengths are being commercially produced in a range possible for use in even low-field fusion devices, e.g. an ST, or with non-planar coils, e.g. helical or stellarator.

Most of the commercially produced HTS tapes are made for electric power utility applications. Involvement of the fusion magnet community with the HTS manufacturers could result in wires that are more amenable to high current conductor fabrication. The goal of a high temperature superconductor research program is the production of high effective-current density strands in long lengths, the cabling of ever larger numbers of strands until the 30-70 kA levels needed by magnetic fusion are attained.

Cabling of strands or wrapping tapes about a core can increase the effective ampere-meters of an unjointed conductor by orders of magnitude, as has been demonstrated by recent high-voltage transmission line HTS cable demonstration projects, which use multiple tapes wrapped about a cylindrical former/coolant line. This approach has too low an overall current density for a fusion magnet and one central purpose of a fusion conductor/magnet development program would be to develop conductor concepts such as CICC with an adequate combination of current density, field, and cost at reasonably elevated temperature.

A round wire form of multifilamentary YBCO similar to that successfully developed for 2212 would be a better choice for a fusion conductor but would require a significant investment to address the fundamental grain boundary materials science needed to understand how to relax the present very stringent, quasi- single-crystal technology required for today's YBCO coated conductors. Although such a breakthrough seems far away at present, the resulting benefits would be so valuable that combining an effort to develop a multifilamentary round wire with the development of a reduced \$/kA·m cost would be an excellent long-term investment.

The superconducting cable design needs to address several key requirements, including (a) high engineering current density, (b) minimal strain degradation, (c) proper stabilization against quenching, (d) reduction of the maximum temperature in case of a quench, (e) low AC losses, (f) efficient cooling.

For HTS tapes, if relevant conductors can only be made as thin, flat tapes, better methods must be developed to produce compact, high current density cables, from this non-ideal geometry. Some progress has been made assembling cables using the Roebel pattern from the flat tapes. This serves to increase the overall current capacity, but still has several drawbacks. Some of the expensive superconducting material is lost in the zigzag cutting process and the cable requires development of special machinery to weave the tapes together. Although cables of several kA's can be fabricated this way, they are still about an order of magnitude too low in current for large-scale fusion magnet applications. A different approach receiving some attention is the manufacturing of the cables by stacking multiple tapes. The tapes could be twisted, providing for some transposition and to decrease loop currents. [Takayasu, L. Chiesa, L. Bromberg and J.V. Minervini, HTS Twisted Stacked-Tape Cable Conductor, submitted for publication, Superconducting Science and Technology] The tape stacks could be embedded in round copper pipes (with an appropriate groove), reducing what is a rectangular shape, difficult to wind as CICC, to a round cable. The principle has been demonstrated in short samples, with no noticeable degradation of the YBCO tapes for reasonable twisting pitches. [Takayasu, M., J.V. Minervini, L. Bromberg, Torsion strain effects on critical currents of HTS superconducting tapes, AIP Conference Proceedings 1219, p 337-44, 2010]. Another variant of this kind of cable has been proposed and demonstrated by van der Laan too.

Alternatively, better ways to integrate the HTS tapes with the structure, insulation, and cooling of the magnet should be explored. The requirements for magnet protection under those circumstances, with conductors operating at higher temperature and well cooled, needs to be determined.

d. Structural Material

The structural material issues are discussed in the materials section of this report.

e. Insulation

The insulation material issues are discussed in the materials section of this report.

f. Joints

Joints between very large, multi-strand cables of the type required for fusion applications are very difficult to make and to achieve simultaneously the conflicting goals of low resistance, low ac loss, and high stability. In order to know that a joint is "superior", it should simultaneously decrease the DC and AC losses and the size of the joint.

Although there is significant experience in the fusion magnet community with making high current, "permanent" joints with large cables made from round wires (LTS), there is no equivalent experience in joining large cables or conductors made from many thin, flat tapes (HTS).

The fabrication of high-current HTS samples should be developed in the laboratory, with a structured program for understanding joining methods, dc resistance and interface resistances, current transfer, ac losses, stability. The joint samples should be tested as hairpins and insert coils in order to establish overall properties. Simple resistance tests can be performed relatively easily with existing equipment. Full-scale prototype joint samples can be tested in the Pulse Test Facility after undergoing some modification to change the test environment from forced-flow supercritical helium, to either liquid nitrogen coolant, or intermediate temperatures by cooled helium gas.

The greatest programmatic impact will derive from developing a method of joining entire coil cross-sections as a unit while having the ability to be connected, disconnected, and reconnected multiple times with no degradation. This would enable superconducting research facilities in which major components could be readily tested and replaced, and enhance maintainability, availability and inspectability of a DEMO. This is a non-trivial task, since not only should there be excellent electrical connection, but also structural, cooling, and insulating connection. Significant resources are thus warranted to achieve this challenging goal.

Demountable (remountable, remakable) high-temperature superconducting (HTS) magnet designs have been proposed for future fusion reactors [L. Bromberg, M. Tekula, L. A. El-Guebaly, R. Miller, ARIES Team, "Options for the use of high temperature superconductor in tokamak fusion reactor designs," Fusion Engineering and Design, vol. 54, 2001, pp. 167–180.; H. Hashizume, S. Kitajima, S. Ito, K. Yagi, Y. Usui, Y. Hida, A. Sagara, "Advanced fusion reactor design using remountable HTc S.C. magnet", Journal of Plasma Fusion Research SERIES, vol. 5, 2002, pp. 532-536]. The magnet consists of sections that can be assembled and disassembled repeatedly with permanent or dismountable electrical joints. This concept could be very helpful in the long term, for improved reactor maintenance and/or construction of the large, complex superconducting magnets required for fusion reactors. In the near and intermediate term, the demountable magnet can be useful for component-testing machines which require good access. HTS has high critical current and high heat capacity at relatively high operating

temperature (>30 K), which could enable electrical joints, as opposed to low temperature superconductors, where the heat dissipated would substantially affect both the refrigerator power requirement or result in local heating leading to a quench. The use of HTS allows a practical solution to the resistive loss at the joint section, as well as provide stability to the conductor in the joint region (because of the large temperature margins).

Several groups have investigated demountable joints with HTS materials. MIT has experimented with both butt joints and lap joints for low current applications. [Dietz, A.J., W.E. Audette, L. Bromberg, *et al.*, Resistance of Demountable Mechanical Lap Joints for a High Temperature Superconducting Cable Connector, IEEE Trans Superconductivity 18 1171-1174 (2008)] Yanagi at NIFS have investigated lap joints [N. Yanagi, G. Bansal, K. Takahata *et al.*, Proposal of Large-Current Capacity HTS Conductors for the LHD-Type Fusion Energy Reactor, ASC (2010)] for high current. And Hashizume and Ito have investigated butt joints. [H. Hashizume, S. Kitajima, S. Ito, *et al.*, Advanced fusion reactor design using remountable HTc SC magnet, Journal of Plasma Fusion Research SERIES 5 532-536 (2002)]

Dietz reported joint resistance as low as $0.1 \mu\Omega$ with contact areas as little as 0.15 cm^2 with resulting surface resistivities on the order of $1.5 \cdot 10^{-8} \Omega \text{ cm}^2$ at temperatures below liquid nitrogen. The results obtained by Dietz are shown in Figure 1, as a function of the load applied to the joint section. The contact areas were controlled. Resistances about $200 \text{ n}\Omega$ were obtained for YBCO tapes

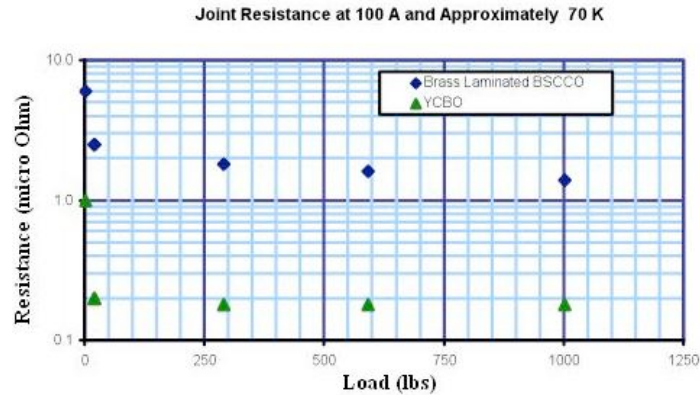


Figure 1. Contact resistance as a function of the applied load for the cases of BSCCO and YBCO shunts.

Butt joints with 1st generation tapes have been also investigated by the MIT group. At liquid nitrogen temperature with very light pressure the resistance was $\sim 10 \mu\Omega$. With increasing pressure the resistance dropped monotonically to $1.7 \mu\Omega$ at the highest applied pressure.

A similar lap-joint has been developed by Yanagi for high current cables. Yanagi obtained a joint resistance, with 16 tapes, of $0.06 \mu\Omega$. Referred to a single tape, the joint resistance is about $1 \mu\Omega$. In their case, the joints are soldered. Their purpose is ease of assembly, rather than maintenance, so there is no need for demountability.

g. Magnet protection

Quench detection is the Achilles heel of a superconducting magnet in an erratic pulsed field environment. The specific weakness of tokamak magnets is the plasma disruption, which is “unscheduled” and varying, making it impossible for its signal to be completely zeroed out predictively, since physical or computational signal balancing must know the disruption spectrum in advance. Arbitrary reliability can be built into the power supply interrupters through series connections and redundancy. However, this is much harder to do for quench detectors, which are built into the coils with signal/noise ratios that are intrinsic properties of the sensors. A simplified way of stating the problem is that the magnet voltages are on the order of 10 kV, while the quench signals one would like to detect are on the order of 100 mV, implying a need for 5 orders of magnitude in noise rejection. Various methods of quench detection needing further development including balanced voltage taps on coil segments, co-wound voltage taps for intrinsic inductive signal cancellation, and co-wound optical fibers which can sensitively measure temperature and strain over a wide range of operating conditions.

For HTS magnets operating at high temperature (but likely lower than 77 K) would require a continuous sensor, that is, one that can determine temperature along the cable either continuously

or at very short intervals, as the normal zone propagation is slow and local detection of a quench is required.

Alternative magnet protection should be investigated, especially for HTS magnets. One potential technique, used in MRI magnets, is internal energy dump, reducing the requirement for high voltages and high currents.

h. Prototype Magnet Development

Although lab scale tests and component development can lead to viable solutions to the issues discussed above, integration of these components into a magnet is non-trivial, and may lead to complications and synergistic effects which result in a magnet that is not able to achieve all its design goals. Therefore, once the OFES strategic planning process identifies a next step U.S. device, the design goals should be then focused on those required by the device concept. Then all development steps can be proven on a relevant scale prototype coil or coils, and tested under full-scale operating requirements. Depending on the scale of the magnet, existing facilities for testing should be used or modified to carry out the test program.

i. R&D Strategy

A number of critical technology areas have been identified to reduce the cost, increase the performance, and improve the reliability of superconducting magnets for fusion applications. The specific goals and criteria outlined here form the basis of an R&D program which should be supported through a significant expansion of the present, very modest, enabling technologies magnet program. This will require coordinated efforts by universities, national laboratories, and industry. A reasonable program structure would include a distribution of efforts ranging from lab scale R&D, prototype component development, full-size magnet tests, and eventually incorporation into a next-step device. By this we mean that any next-step fusion experiment constructed in the U.S. should strongly consider using the best available superconducting magnet technology as a viable option for enhancing the mission of the device.

Development of practical conductors and cables suitable for demanding fusion applications is needed for the HTS materials. The fusion program needs to determine whether and how present fragile HTS tape geometry be integrated into high current cables with the high current density needed for fusion experiments. Alternatively, the fusion program could explore whether HTS materials (and in particular, YBCO) can be made into round wires with high critical current density for easier magnet application.

Following the development of the superconductor, a program is needed to explore the integration of HTS cables into practical magnet systems for fusion experiment to address the performance, reliability and maintainability required for fusion experiments.

A program to develop HTS for fusion would incorporate:

- Fabrication of HTS wires, and integration of wires and tapes into high current density cables. A coordinated program of laboratory R&D in universities, national laboratories and industry.
- Development of magnet components, including improved structural and insulating elements, and assess performance for various fusion applications. Potential applications, which would greatly benefit FNS, include:
 - High-field SC magnets for steady-state axisymmetric facilities with demountable joints, giving flexibility to test multiple divertor and nuclear science components.
 - HTS tapes integrated into coils with complex shapes for 3-D and other alternate configurations.
 - Testing of the most promising applications in prototypes, and ultimately incorporate into new Office of Fusion Energy Sciences (OFES) research facilities.

V. R&D tasks

The following is a short description of the required tasks. The insulator and LTS structural materials are discussed in the materials section of this report.

1) SC wire and tape development program

In this task, the fusion program would undertake the development of high current superconductors that can tolerate the fusion environment. For HTS, this includes the production of high engineering current density tapes in long lengths. Another important path to explore is whether YBCO conductors could be manufactured as round, multifilamentary wires, more amenable to conventional methods of high-current cable fabrication. Although such a breakthrough seems far away at present, the resulting benefits would be so valuable that modest resources should be applied to address this issue. In addition, production of isotropic tapes with regard to orientation of the magnetic field is desirable.

One interesting possibility is to deposit the superconductor directly on the structural material. Presently, the Rare Earth-Barium-Copper-Oxide (ReBCO) materials are deposited by epitaxial means on the Ni-substrates with substantial load-carrying capability. If successful, this technique would obviate the need for cabling and winding.

The characteristics of the materials under irradiation, would have to be further explored. The present information covers mostly lower fields, higher temperature. Although informative, the effect of high levels of irradiation on the performance of these materials at high fields and low temperatures, needs to be performed. An important effect is the effect of irradiation on the anisotropy of the HTS coated conductors.

In comparison, the limits of irradiation for LTS (with neutrons) has been well documented. However, it would be of interest to explore the performance of recent high-Jc advanced ternary LTS materials.

2) High current conductors and cables development program

High current cables have been developed by the fusion community for large magnet application with LTS. High current HTS cables, with high current density and that can be incorporated in magnets, need to be developed by the fusion community, as the needs for fusion magnets in this area are unique. One of the options is to develop Cable-in-Conduit Conductors with HTS tapes. Means of cooling the superconductor, inexpensive manufacturing, high current density and operating at higher temperature than liquid helium should be developed under this task.

3) Advanced structural concepts and structural materials and structural concepts for HTS

The structural materials required for LTS applications are covered in the material section. In this R&D task, developments of advanced magnet structures are to be explored. Since it is likely that machines beyond ITER will have long pulse and non-inductive current drive, options of using bucking as a support option for the magnet should be explored. In addition, the use of external structures, such as pre-loading rings or tresses, should be investigated.

Rapid prototyping, or “additive manufacturing,” can be used to create unique shapes directly from the Computer-aided Design (CAD) models. One potential use is to manufacture the structural plates of the magnet with the features needed for operation. Multiple material deposition heads create the coil structure in a timely manner to near-net shape such as internal cooling channels, conductor 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.

If it proves too difficult to deposit directly the HTS material on the structure, an alternative approach would be to insert cables made from HTS tapes into grooved structures (plates or shells) with complex shapes. This technique would also ease the manufacture of steady-state magnets with complex 3-D geometry.

In any case, the higher temperature margins of HTS allows for different structural-cooling topologies. In particular, it may be possible to cool the superconductors through heat conduction through the structure, with cooling channels that are embedded in the plates. In addition, the use of deposited SC would allow the use of higher performance insulations, such as the built-in insulators required for the epitaxial deposition of the HTS materials. Additional ceramic insulators could be deposited on the magnet components, on top of the superconductor.

4) Cryogenic cooling methods for HTS magnets

It is unlikely that high field fusion magnets will be able to operate with subcooled liquid nitrogen. There are nitrogen-base eutectics that have substantially lower freezing temperatures than subcooled nitrogen, but even those are have temperatures of more than 50 K. Other coolants would be required, operating between 30 and 50 K. It is possible to use conduction cooling of the cable, but eventually the heat needs to be removed by a fluid, most likely a gaseous fluid (such as helium gas). Alternatively, the conductors themselves can be directly cooled by the flowing gas. Gaseous cooling for superconductors is challenging, as the heat removal rate is much lower than for liquid cooling and have much lower volumetric heat capacity. Issues of conductor stability, especially in very long conductors that are subject to nuclear heating, need to be investigated.

It is likely that much higher nuclear heating rates can be tolerated in HTS (because of the higher temperature margins), because of lower refrigeration power requirement (because of the higher temperatures). The problem of radiation damage to the superconductor and the insulation, however, still remains.

5) Magnet protection

In the case of HTS, there is the need to develop appropriate quench detection techniques. Although adequate techniques will be used in ITER, improved detection techniques could ease quench requirements, in particular the time for dump (and associated peak voltages).

At higher temperature with HTS, stability, quench and magnet protection need to be reconsidered, as the heat capacity of the conductors are orders of magnitude higher than those at liquid helium temperature. However, it is necessary to get to temperatures around 50-60 K before the heat capacity is similar to that of liquid helium. In addition, the heat removal rate, in the case of a normal zone, could be much smaller in the case of HTS with gaseous cooling, because of the poor heat surface heat transfer associated with gas cooling.

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 superconductor) using AC fields. These means are not needed at liquid helium temperature because of the fast propagation of quenches, even in the presence of helium coolant.

The overall design philosophy of off-normal conditions and faults also would have to be developed rigorously 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 cooled (LTS) magnets.

6) 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 and rigid operation which, in turn, allows for the 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 magnetic fusion machines.

There has been very limited investigation of demountable superconducting magnets. The use of HTS allows for relatively high-resistance joints, with modest cryogenic power consumption. 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 fixed (as with finger joints). In either case, it is necessary to unload the joint region, as the joints have 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 nuclear radiation, and it is

deposited in a relatively small volume (thus, high volumetric heat production). As a consequence, it will be necessary to cool the joint effectively. Although it is preferable to cool the joint directly, other cooling options (for example, through heat conduction from the joint region to channels embedded in the structure) should be studied.

Both small experiments (bench-top) and larger scale, with full current, need to be performed. Due to the large number of joints that will be required in a fusion experiment, it is important to determine the reliability of the joints.

7) Technology demonstration

The different proposed magnet improvements suited for FNS would have to be integrated and demonstrated by building prototype magnets of different configurations, e.g., planar coils, solenoids, as required by the FNS design. The size of the demonstration would be substantial, and appropriate levels of funding would be required. Design, construction of testing of these magnets would require commitment of the fusion program, as it would be relatively lengthy. These magnets must then be operated under operating conditions that are appropriate for testing the concepts and to demonstrate the technology, starting with simple small scale and ending with a near-full size prototype, as was the case with the model coils for ITER. The most promising and useful magnet designs would then be incorporated into plans for FNS.

VI. Copper machines

There is a lot experience with resistive magnets in the fusion program worldwide. However there is still some R&D that would be required for an FNS mission.

Radiation tolerate insulation is one of the R&D issues. Copper magnets allow the minimization of the thickness of the nuclear shielding, as the heating concern is very much relaxed at the operating temperatures of resistive magnets. The useful lifetime of the machine due to irradiation is thus due to the nuclear damage of the insulator. Large, flat insulators should be explored as means of increasing the machine lifetime.

Demountable joints have been made in the fusion program. However, steady state joints have not. It would be needed to incorporate steady state cooling of the magnet with the joints.

Finally, resistive magnet could allow the use of external structures or preloading rings to minimize the stresses in the inboard leg of the toroidal field coil. The means to achieve this have been proposed, but careful analysis of the options is needed, especially because FNS is likely to be steady state cooled, not “adiabatically” cooled as in other present fusion experiments.

VII. Facilities

Laboratory facilities are adequate to begin this program, including, for example, facilities at the MIT Plasma Science and Fusion Center and the National High Magnetic Field Laboratory. In

addition, we expect to collaborate with the High Energy Physics program (e.g., Lawrence Berkeley National Laboratory) and the Applied Superconductivity Group (electric grid-based HTS systems) at Oak Ridge National Laboratory. These laboratories already have complementary HTS programs supported by DOE funding, and it would be advantageous to OFES to collaborate where feasible, leveraging these efforts and facilities.

The type of facilities that would be needed for an R&D program for FNS are shown in Table 1. Table 2 summarizes the activities described in this section.

Table I.

Facilities needed in the near term (5-15 year) and longer term (>15 year) for magnet development for FNS

| 5-15 years | Beyond 15 years |
|---|----------------------------------|
| SC material research facilities | Build and test small coils |
| Lab bench testing | High field facilities |
| larger billets, scale up production | Cryogenic laboratories |
| irradiation sources (neutrons, gammas) | Concept developments and testing |
| mechanical testing laboratories | advanced manufacturing |
| magnet laboratories for making and testing SC magnets | |
| Code development | |
| Concept development | |
| High field test magnets, capable to handling irradiated samples | |
| Cryogenic laboratory for testing cooling fluids | |
| Long length, high current, high field testing facility, with cryogenic capability | |

Table 2

Detailed R&D required for near and long term R&D for FNS.

| | | 5-15 years | Beyond 15 years |
|---|----------------------|--|--|
| Materials | | | |
| | Superconductor | Nb3Sn, NbTi (for low field), HTS | HTS, high performance Nb3Sn |
| | Stabilizer | copper, protection | minimum stabilizer |
| | Insulation | better organics, inorganics | Better insulation, inorganics, alternative insulation concepts |
| | Structural materials | Incolloy other low COE materials | Advanced materials, lower cost, increased compatibility between structure and SC |
| Coolant | | liquid He, gaseous He | LHe, LH2, H2, neon |
| Protection | | external dump | advanced sensing, protection |
| Integration (demountable, configuration, costing) | | ITER like, bucking, code development, concept evaluation | |
| | | Small coil demountable testing | SC demountable, external support |
| Copper | | | |
| | Coolant joints | water, organic sliding, fixed | |
| | insulation | plate insulation, inorganic | conformal inorganic insulation |
| | integration | external support | |

VIII. Scale of Effort for FNS

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 and manufacturing methods.

Table 3 describe the costs associated with the proposed R&D for FNS.

Table 3

Estimated R&D costs for an FNS program

| | | |
|-----------------------------------|--|----------|
| Near term | | |
| High Jc LTS strands | | 500K/yr |
| Incolloy production | | 1000K/yr |
| Optimize structural design | | 2000K/yr |
| Longer term | | |
| HTS cables | | 500K/yr |
| Demountable magnet | | 2000K/yr |
| Advanced manufacturing techniques | | 500K/yr |
| Small coil construction | | 500K/yr |
| Cooling design | | 250K/yr |
| Insulation | | 500K/yr |
| Copper machine | | |
| Cooling design | | 250K/yr |
| insulation | | 250K/yr |
| integration | | 500K/yr |