US Fusion Program Issues and Requirements for Superconducting Magnets Research

Submitted by

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Abstract—**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. These improvements will derive from research and development carried out at government laboratories, universities, and industry. An R&D program carried out under the DOE Office of Fusion Energy Sciences, Enabling Technology Program for Magnets could address the needs raised in this white paper. The program should focus on developing superconductors with high critical current density at high magnetic field with low to moderate ac losses, including both LTS and HTS conductors, superconductors with both high and low stabilizer fraction, superconducting cables with high copper strand fractions, advanced conductor and structure manufacturing techniques, insulation systems that are radiation-resistant with low gas evolution and suitable for vacuum-pressure impregnation (VPI) of coils, and novel quench detectors and other types of advanced magnet system monitoring instrumentation. Component material or processing improvements that can allow a reduction in magnet fabrication complexity or improved schedule through advanced manufacturing techniques can also significantly reduce cost. These focus areas will apply to both low and high temperature superconductors so that the conductor type and magnet design for a particular future device application will be selected based on a logical evaluation of the physics, engineering, geometrical, and economic requirements of the application.**

Introduction

Magnet systems are the ultimate enabling technology for magnetic confinement fusion devices. Powerful magnetic fields are required for confinement of the plasma, 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.

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Although the majority of past and present magnetic fusion experimental devices use normal resistive magnets, almost all design concepts for power producing commercial fusion reactors rely on superconducting magnets for efficient and reliable production of these magnetic fields. Superconductors will dissipate energy in a changing magnetic field, but overall power losses, including refrigeration power required to maintain the magnets in the superconducting state are small compared with resistive magnets. This advantage grows with increasing magnetic fields and magnetic field volume, or where relatively long pulse or steady state operation is required. Since the magnetic system forms the core of the fusion device, the state-of-the-art of the magnet technology frequently defines the operational limits of the plasma performance, as well as the core machine size and cost. Limitations of the magnets impose constraints on the design of new experimental facilities as well as design and evaluation for eventual commercial attractiveness. It is clear that for magnetic fusion to be attractive as a clean and efficient source of energy production, the magnet systems, both normal and superconducting must offer very high performance, acceptable first cost, low operating and maintenance costs, and high reliability. For example, the superconducting magnets, structures, and cryogenic system of ITER comprise 33% of the core machine cost, and represent the dominant system cost.

Superconducting magnets are operational or under construction in fusion devices in many countries throughout the world to develop an energy source, but not in the USA. Since a practical cost is the primary criterion for acceptance of a demonstrated technology, it is time for the US fusion program to lead an effort to leapfrog the State-of-the-Art in magnet technology to assure that fusion provides a cost effective, reliable energy source for the future. Physics progress has been and will be impressive, but fusion is a futile effort if the required engineered systems are not available at a reasonable cost. The physics results will be shared, but the ability to build the components will rest with the teams that develop cost effective reactor technologies. Thus, the foremost requirements of the magnet systems for an attractive reactor (high performance, high reliability and availability, and acceptable cost) form the basis for the necessary magnet development program, and provide the guidelines for future research and development.

A new opportunity that could significantly change the economic and technical status of superconducting magnets is becoming visible, namely the use of so-called high temperature superconductors that have now been used for demonstration of superconducting fields > 30T 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.

Background

The U.S. 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 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. These can be addressed by defining metrics and using these metrics to set performance goals. That said, the best metrics for a magnet system aren't totally clear. For instance, one could argue that the primary virtue of a magnet is to produce a high magnetic field, since fusion power is proportional to B^4. Specific stored energy and magnetic loads, however, scale as B^2. Another virtue of a good magnet system design is the ability to tolerate high nuclear flux and integrated fluence in order to reduce the size of the neutron shield protecting the magnet system and consequently the machine as a whole. On the other hand, most conductor, structure, and insulation material properties are severely degraded by neutron and gamma radiation damage. Nevertheless, in order to create a manageable and affordable program, one has to choose the goodness parameters that are the most likely to make a difference and we propose:

1) The volume-specific stored energy (J/m^3) $\alpha = \frac{W_m}{V}$
2) The cost-specific stored energy (J/$) $\gamma = \frac{W_m}{\$}$
3) The entropy-specific refrigeration load $\delta = \frac{P_{ref}}{P_e}$

Maximizing α and γ, i.e. minimizing the specific cost and volume, requires simultaneously developing all the technologies needed for high-field operation and field configuration accuracy. Maximizing δ is done by minimizing the wall power P_e needed to remove a given refrigeration load. The most exciting and practical method of maximizing δ is through the use of high temperature superconductors that can operate from 4-65 K. The precise temperature is a tradeoff on design current and field, current density, stability and refrigeration requirements.

The clearest way of ensuring that a magnet technology will simultaneously improve α, γ, and δ is to improve the goodness factors for each of the magnet components individually. We believe major improvements can be made in the following components:

1) Superconducting wires and cables
2) Thermal stabilization
3) Mechanical support structure
    (a) External

(b) Conductor
4) Insulation
5) Thermal isolation
6) Joints
7) Leads
8) Quench detection and instrumentation
9) Isolators and feedthroughs

In item 3) above, we distinguish between external magnet structure (e.g.- a structural case 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 techniques and system integrating techniques, for example, using rapid prototyping techniques or demountable superconducting magnets, could help decrease costs through improved manufacturability, reliability and maintainability.

LTS Materials Issues

In general, the issues for Low Temperature Superconductor (LTS) conductor and magnet technology can be reduced to a few generic points:

(a) Reduce cost – Superconducting magnets are very expensive. This is partly due to high costs of the superconducting raw materials, strand processing costs, which are labor intensive, and processes that result in 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, Nb_3Sn must undergo a high temperature reaction heat treatment (about 650 C for 200 hours) which complicates the fabrication process and extends the fabrication schedule significantly. There are other substantial costs associated with low temperature operation and 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.

(b) Improve performance - 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 machine size and cost as a whole 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 needs to be developed to decrease the manufacturing costs.

(c) Increase system life and reliability - 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 the superconducting joints could be easily and reliably made to be demountable.

HTS Material Issues

Despite their great promise, high temperature superconductors are still a young technology. The limits on high temperature superconductors that reflect the early stage of their development are fivefold, including:

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

Clearly, high temperature superconductors are not yet a sufficiently established industry to provide conductor for the most demanding fusion applications, but the rate of progress in performance is 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.

Cabling of strands or wrapping tapes about a core can increase the effective ampere-meters of an unjointed conductor by orders of magnitude, as 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.

The most promising approach is the development of round strands with critical current densities comparable to those of tapes, which can be twisted into high-current cables without degradation. While cost and performance will probably continue to improve because of commercialization, the key to future use in the fusion program is the need to raise current and piece length. 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, and the development of low-cost, low-loss, high-current joints.

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

The "vision" that high temperature superconductors are primarily to be used in ultrahigh field magnets should be developed over the moderate-term. In the immediate future, however, the properties and production lengths are now in a range for possible use in even low-field fusion devices, e.g. an ST, or with non-planar coils, *e.g.* helical or stellarator configurations.

An even more important question to answer is whether YBCO conductors could be manufactured as round, mulitfilamentary wires. For example, what stands between the present YBCO tape configuration and multifilament BSCCO-2212 round wires? The underlying physics of all HTS is supposed to be similar. Although such a breakthrough seems far away at present, the resulting benefits would be so valuable that resources should be applied to address the issue.

Cable Design

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 LTS, the cable design of choice for fusion is CICC. This design provides excellent cooling and stability, low AC losses, good structural integrity of the winding pack, and high current. A major disadvantage discovered during testing of the near full-scale ITER EDA Model Coils, is the degradation of performance for Nb_3Sn cables due to the high transverse Lorentz forces for large cable cross-sections. Since those results became known, significant worldwide R&D has gone into understanding the main sources of this degradation by experiments and modeling. Although progress has been made, there is not yet definitive understanding to permit precise prediction of this effect, and thus further work is required to be able to design a high-current Nb_3Sn cable to prevent serious degradation of performance in operation. This is an important issue because, at this time, the effect can only be accounted for by designing in a large operating margin by adding extra superconducting wires, which results in very high costs.

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 by making Roebel type cables 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.

Another possible approach is the development of round strands with critical current densities comparable to those of tapes, which can be twisted into high-current cables without degradation. While cost and performance will probably continue to improve because of commercialization, the key to widespread use in the fusion program is the need to increase current and piece length. The most important goal of a high temperature superconductor research program is the development of low cost, high current superconductors in long piece lengths. This includes 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, and the development of low-cost, low-loss, high-current joints.

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.

Structural Material Issues

Structural materials are required in order to contain the Lorentz loads of the magnetic pressure vessel, to contain pressurized helium in a CICC, especially during quench, to support gravitational loads, and to maintain coil position and field accuracy.

Structural materials must also avoid excessive rigidity in the wrong locations to avoid excessive strains and stresses during assembly, cooldown, powering or quench heating. They must be compatible with coil fabrication, and, where applicable, with winding separation for adding insulation after heat treatment and compatible with conductor conduit heat treatment for CICC wind and react fabrication. Two structural materials of particular interest include the superalloy Incoloy® Alloy 908 and 300-series steels such as 304LN or 316LN. Both of these have been used for conduit material in CICC and the 300 series steels are widely used for cryogenic magnet structures.

1) Incoloy Alloy 908: A property database has been developed for Incoloy 908 base metal, welds, and transition joints that have proved to be adequate for the ITER CS Model Coil. In order to use Incoloy 908 in a burning plasma experiment or reactor and to reduce the ultimate cost of Incoloy 908, work should be completed in creating an adequate database for full ASTM code qualification. Increased Stress Accelerated Grain Boundary Oxidation (SAGBO) resistance in Incoloy Alloy 908 can be obtained by minor modifications of the alloy chemistry. The goal is to develop a modified Incoloy alloy that is simultaneously stronger and tougher than 908 at cryogenic temperature and that resists SAGBO at any stress up to an oxygen content of at least 10 ppm, or an improvement of at least 100.

2) 300 Series Steels: 300-series steels such as 304LN or 316LN are less expensive and better qualified than Incoloy 908 for most applications. However, for the long heat treatments needed for Nb_3Sn, they are actually less well characterized. The superiority of Incoloy 908 over 316LN is that it was designed to be compatible with Nb_3Sn heat treatments over a broad range of temperatures and times. Compatibility in this case means it matches the coefficient of thermal expansion (CTE) from heat treatment temperature to 4K operating temperature, while maintaining excellent mechanical properties. The toughness of 300-series base metal and welds degrades significantly during long heat treatments. In order to survive the heat treatment using 316LN, a low carbon steel, enriched with nitrogen is needed.

3) Special Alloys: Several other specially developed structural alloys have been proposed for use in fusion magnets using Nb_3Sn conductor, such as JK2LB and Haynes 242. These alloys may eventually provide some advantage, but the technology program must have sufficient resources to develop a credible materials properties database for use in this application.

For cost and manufacturing ease the exploration of the above material improvements and of advanced manufacturing techniques will yield quantitative reductions in magnetic fabrication complexity and schedules. This is an area that has received little attention and where even limited resources may yield substantial gains.

Insulation Issues

Electrical insulation is needed to prevent leakage current and arcs due to magnet voltages during charging, discharging, and quenching. The insulation must be able to withstand repeated voltages that for ITER have gone as high as 29 kV. The insulators must also act as a key structural element in maintaining winding pack stiffness and be compatible with local expansion, strain sharing, and load bearing in a conductor-in-plate design. Where insulators can develop tensile loads, they must have adequate shear strength to prevent tearing. In the front layers of the field magnets closest to the plasma, insulation must also be able to withstand neutron and gamma irradiation. The ability to withstand this radiation is frequently the magnet limit that determines the thickness of the neutron shield, and typically dictates the operating life of the magnet systems.

A good insulation system should exhibit four main characteristics.

1) Higher specific dielectric performance in the insulation.
2) Compatibility with heat treatment and other magnet fabrication processes.
3) Ease of application, e.g. impregnation temperature, pot life, etc.
4) Radiation resistance over the design life.

A focused development effort with coordinated activities of universities, national labs and industry should be undertaken with the stated goals above. This should include development of inorganic insulating systems and ceramic insulators.

In addition, better means of applying the insulation are required. The insulating step in conventional SC winding is tedious and needs to be carried out with a high level of inspection because of the potential for damaging the superconductor or the insulation itself being damaged during coil assembly and handling. Alternative approaches to the insulation materials such as new nano-dielectric materials and means of integrating the insulation process with the coil manufacturing should be explored.

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 a next-step device that incorporates the mission of a machine, which results from this ReNeW process. By this we mean that any next-step fusion experiment constructed in the U.S. must be based on the best available superconducting magnet technology, regardless of the machine size or plasma configuration.

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