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Superconducting Magnet Technology for Future Hadron Colliders

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Preface

The application of superconducting magnets to large-scale particle accelerators was successfully demonstrated with the completion of the Tevatron at Fermilab in 1983. This machine, utilizing dipole magnets operating at 4.5 T, has been operating successfully for the past 12 years. This success was followed a few years later by HERA, an electron-proton collider that uses superconducting quadrupoles and dipoles of a design similar to those in the Tevatron. The next major project was the ill-fated SSC, which was cancelled in 1993. However, the SSC R&D effort did succeed in demonstrating the reliable operation of dipole magnets up to 6.6 T. The LHC, now under construction, pushes the ductile superconductor, NbTi, to its limit in dipoles designed to operate at fields of 8.6 T at 1.8 K.

Several recent studies have addressed the issues involved in taking the next step beyond the LHC. The Division of Particles and Fields Workshop on "Future Hadron Facilities in the U.S., held at Indiana U. in 1994, examined two possible facilities--a 2-TeV on 2-TeV collider and a 30-Tev on 30-Tev collider. The participants arrived at the following conclusions with regard to superconducting magnets:

1. "Superconducting magnets are the enabling technology for high energy colliders. As such, the highest priority for the future of hadron facilities in the U.S. is the reassembly of a U.S. superconducting magnet R&D program."

2. "...emphasis on conductor development and new magnet designs."

3. "...goals of such a program might be 1) the development of a 9-10 Tesla magnet based on NbTi technology; 2) the development of high quality quadrupoles with gradients in the range 250-300 T/m; and 3) initiation of R&D activities aimed at moving beyond the existing technology as appears to be required for the development of a magnet operating at 12-15 Tesla."

In order to reach fields above 10 T, magnet designers must turn to new materials with higher critical fields than that of NbTi. Several candidate conductors exist; unfortunately, all of these new materials are brittle, and thus pose new challenges to the magnet designers. At the same time that the forces on the magnet windings are increasing due to the higher Lorentz force associated with the higher magnetic fields, the conductor tensile strain must be limited to less than about 0.5% to prevent damage to the brittle superconducting material. Also, coil fabrication methods must be changed. If the superconductor is in the reacted, or brittle, state, the coil winding procedure must be modified to prevent overstraining. If the alternative wind and react approach is used, new insulating materials must be used that can survive the high temperature reactions (650 to 800 C) necessary to form the superconducting compounds.

The issues associated with high-field dipole magnets have been discussed at a number of workshops, including those at DESY in 1991 and LBL in 1992. These workshops were extremely useful in defining the problems and focusing the attention of both materials and magnet experts on high-field dipole magnets; however, since neither set of proceedings was published, the information is not readily available. More recently, a workshop was held in Erice, Italy, under the sponsorship of the Ettore Maiorana Center for Scientific Culture. This international workshop was attended by 20 scientists from Europe, Japan, and the U.S., and the summary of that work, which represents the most recent and thorough assessment of the status of high-field magnets for accelerator magnets, is presented below.

1 INTRODUCTION

The physics performance of a particle accelerator is limited by energy and then either by beam intensity or by luminosity. In today's colliders, in which two counter-rotating beams are made to intersect, these characteristics are determined by the physical size of the accelerator, the magnetic field, and the ability to accelerate and store a sufficient number of particles–usually protons. The development of superconductors and magnet designs adequate for these accelerators has a long and complicated history, the highlights of which we can barely touch on here.

The year 1995 marks approximately 30 years since the advent of the earliest superconducting magnets for applications in high-energy physics, and, indeed, not many more years since the first practical Type II superconductor appeared on the scene. First among the various pioneering superconducting devices were solenoids, with their concomitant stabilizing techniques, ranging from fully ("cryogenic") stabilized conductors to "intrinsically" stable, filamentary composites. (Filamentary, twisted superconductors were first convincingly proposed at an epochal summer study on superconducting devices and accelerators organized at Brookhaven National Laboratory in 1968.) These early years also saw several innovative tape-wound superconducting quadrupole magnets (Brookhaven, 1965), the first of a long sequence of ever-larger superconducting coils for bubble chambers (Argonne National Laboratory, 1968), and the first operational superconducting beam transport dipoles (Brookhaven, 1973 and Argonne, 1976).

By about 1970, the accelerator community also sensed the need for fast ramp superconducting accelerator magnets for the next generation of particle accelerators beyond the conventional (resistive) proton synchrotrons then on the drawing board in Europe (CERN) and the U.S. (Fermilab). This need led to the establishment in Europe of the Group for European Superconducting Synchrotron Studies, (the GESSS collaboration of Rutherford Laboratory, Saclay, and Karlsruhe), for the purpose of jointly developing and exploiting ac magnet technology. GESSS resulted in the implementation of a number of innovative accelerator dipole designs in the sponsoring laboratories, but, unfortunately, proved premature with respect to the primary goal: the launching of an actual superconducting accelerator project.

The first effort toward demonstrating a working superconducting accelerator was ESCAR (Lawrence Berkeley Laboratory, 1974). Initially conceived as a test bed for a full-blown superconducting accelerator *system*, ESCAR was drastically scaled down in midstream to a test of the superconducting magnet system alone. As such, ESCAR did provide considerable operating experience with superconducting magnet and cryogenic systems. Next in the historical sequence came ISAbelle at Brookhaven, designed initially as a 200x200 GeV proton-proton collider. ISAbelle did not materialize because of several circumstances. Initially, it was plagued by excessive "training" of the full-length (5-m) dipoles; subsequently, a reconfigured version of the project (CBA) based on magnets wound from cable rather than braid, was canceled because of shifting priorities within the high-energy physics community. The machine was abandoned in 1983 in favor of an all-out push on the SSC.

As it turned out, the first true superconducting accelerator materialized at Fermilab in the waning days of the ISAbelle and the early phase of the CBA. Constructed in two stages as the fruit of a separate development effort launched at Fermilab ca. 1972, the Tevatron, a superconducting upgrade of the existing 500-GeV proton synchrotron, was completed in 1983. Today's "standard" superconducting accelerator magnet, the collared cosine theta dipole wound from the ubiquitous

Rutherford cable, is a legacy of the Tevatron project. Hard on the heels of Fermilab's collider came HERA in Hamburg, an electron-proton collider incorporating a proton ring whose superconducting magnets are refined versions of the Tevatron dipoles and the cold iron CBA geometry.

Sadly, the next stage in superconducting collider development, the Superconducting Super Collider (SSC), was terminated well into its construction and after ten years of dedicated effort by the U.S. high-energy community. The effort did, however, succeed in demonstrating the feasibility of accelerator dipoles which operate in the 6.5-Tesla range and which meet the exacting machine specifications of multi-TeV colliders. It is hoped dipoles and quadrupoles of this general type will prove their worth in the Large Hadron Collider (LHC) at CERN by the end of the decade in the 8- to 9-Tesla range.

2 Future Demands for High Field Magnets in Particle Accelerators

Future use of particle accelerators will be for a variety of practical applications and for expanding the frontiers of particle physics. Here we address the demands for high-field magnets that will be driven by particle physics. Two conceptually different types of development can be envisioned. The first is for magnets that will be used to improve or augment existing facilities, the second is for new accelerator facilities. Examples of the former are special magnets--such as high-field quadrupoles for FNAL, and high-field dipoles that could double the LHC energy. The proposed Eloisatron is the primary example of the second type. An accelerator using high-field magnets to achieve the highest possible energy on the FNAL site is intermediate between these two categories.

The choice of the appropriate field for any future magnet system is driven by physics requirements, time frame for development, existing and projected material capabilities, magnet design, and the combination of program resources and magnet costs. Magnets with unique capabilities for specific applications that will enhance the performance of existing and often expensive accelerators are likely to push high-field magnet development in the short term. The cost of these magnets, though important, will not be a major design criterion because it will be a small fraction of the cost of the total accelerator. On the other hand, the need for large numbers of high-field magnets for new accelerators will require a thorough analysis of component and system costs.

Since existing accelerator magnets operate in the 5- to 7-T range, and 9-T magnets have been made for the LHC, the appropriate field for future development should be well above this level. This workshop conducted a preliminary evaluation of existing magnet designs and materials to determine the highest field strength that could be achieved as an extrapolation of current technology. This analysis suggests that a 15-T magnet could be constructed within the next five years. We believe that this would be an appropriate development goal for the near term and have developed a program plan for proceeding

through the construction of a short-model 15-T dipole. We believe that an equivalent quadrupole could be constructed using the technology developed for the dipole.

There is reason to believe that superconducting material performance could be extended to achieve 20 T magnets in approximately 15 years. To that end, we present a program based on existing technology to develop and build a 15-T magnet in 5 years. The development of a 20-T magnet is more problematic and we propose a path of research and development that could lead to a first short-model 20-T magnet in a 10 year time frame.

The initial goal of the 15-T magnet program is the construction of a 1 meter model accelerator dipole in the next 5 years. The tentative specification of this magnet are given in Table 2-1.

The proposed 20-T magnet is a dipole, and the 10 year goal is a 1-meter model (See Table 2-1). It is realized that this is a large step in the development of magnets. Magnets of intermediate field above the 15-T design are likely to be required along the path to the development of such a high-field design.

Table 2-1 Specifications for 15-T and 20-T Magnets

	15-T	20-T
Operating field (T)	15	20
Operating temperature (K)	1.8	1.8
Magnet bore (mm)	40	40
Dynamic aperture, radius (mm)	10	10
Field quality, DB/B_0	$<10^{-4}$	$<10^{-4}$
Ramp time (s)	1000	1
Conductor J_c, non-copper (A/mm^2)	1000	1000 - 1500

3. STRUCTURE

The development of future dipoles will be based in part on experience to date. One key issue has been the overall structure. Higher-field magnets are expected to introduce new challenges.

In accelerator dipoles to date, the design of structural components has primarily addressed two key issues: (1) exerting sufficient control of global winding deflections so that field quality is not impaired, and (2) exerting sufficient control of local conductor motions that premature quenches are eliminated and reliability of operation is assured.

Points 1 and 2 remain as key issues. However, the challenge of successfully addressing both of the above issues becomes more difficult as the field strength increases

(20-T imposes a net force on the windings at least 4 times 25 great as the force in a 10-T magnet). Also, the options for addressing the second issue are further complicated by the more limited list of conductors available for the high fields and the need for special winding/processing techniques in their application.

The conductors available for application in the 10- to 20-T range can be degraded reversibly or irreversibly at modest levels of distortional strain (i.e. that part of the total strain which is not hydrostatic). This feature imposes on the overall magnet-structure design the need to management of local stresses to the degree that the performance potential of the superconductor is not intolerably compromised or lost with cyclic operation.

This third issue forces consideration of whether the structural component should be distributed within the windings, placed on the outside of the winding pack, or arrange in some variant of these two possibilities. For some conductor options where damage may be irreversible at extremely small levels of distortional strain, it will be essential to have a component of structure that is adjacent to the current-carrying element itself and is capable of shunting the local load around it. This component needs simultaneously to have high modulus, high strength, and a thermal expansion coefficient compatible with the superconductor. When the degradation with strain is reversible and gradual, the designer will have to evaluate carefully whether the potential degradation is excessive or can be reliably predicted in comparison to the effective reduction of winding-pack current density which would be required by inclusion of distributed structural elements. To put this issue in perspective, it should be noted that the local mean stress at some points in the winding will likely exceed 200 MPa in a 20 T design. Local stresses could easily exceed this level by a significant factor if care is not taken with the local stress management.

A fourth issue is impregnation vs. ventilation in the insulation matrix of the coil package. The decision whether or not to impregnate the windings must be weighed carefully. The process fits quite naturally with some conductor choices and winding techniques (e.g., the wind-react-impregnate process). It also has clear structural implications for the magnet design, as well as having an impact on the quality of electrical insulation, the character of disturbances to the windings, and the ability to stabilize against them. Impregnation can certainly help with the local management of stresses on strain-sensitive conductors. Potentially, it can also stop relative motion of conductors, thereby eliminating one source of disturbances that might lead to premature quenching. Traditionally, however, the latter has been either difficult to achieve (because of micro-cracking in the epoxy) or not entirely adequate, since it may still leave the possibility of global slippage of a winding block against structure, which can also quench the conductor. Typical design allowables for the impregnation layer are as follows: ~ 400 MPa for compression transverse to the layer, a very low value of ~ 10 MPa for tension, ~ 30 MPa for bond shear, and in the range of ± 0.3 % strain parallel to the layer.

Heat transfer is a major problem with impregnated coils: heat generated by beam losses, synchrotron radiation, and ac losses must pass through the impregnated matrix,

and could produce substantial temperature differentials. If a porous insulating matrix could be devised, helium could percolate within the coil package much as it does with B-stage impregnated NbTi coils. On the other hand, the design features that allow permeation of helium into the windings inevitably lead to local concentrations of stress on some combination of conductor, insulation, or distributed structure. Either the impregnated or the ventilated design could be successful with careful attention to the unique features of each.

The type of magnet construction selected has an impact on how these four structural issues are addressed in detail. Three construction types may be categorized:
(1) Shell or minimum-volume types (including cos q, intersecting ellipse, or similar variants),
(2) Block or racetrack type, and
(3) Other special designs created to accommodate a special class of conductors (e.g., tapes, new forms of high temperature superconductors, etc.), to address unique features of a particular type of accelerator, or some combination of these.

The shell-type winding may be the least flexible in terms of accommodating a wide variety of conductor geometries. Arguably, it may also present fewer options for incorporating a distributed structure, if needed. However, it does present a simpler external geometry (more rounded) that may have advantages for coupling to external structure. External structure for controlling deflections of the windings remains an essential need. Grading of shell-type windings can be accomplished with multiple shells, albeit with some loss of advantage in achieving minimum volume of conductor. Distribution of structure between shells may be sufficient to achieve the required level of stress management (especially if such designs are re-optimized with an emphasis on local stress management).

There is little experience with the other design types. However, the block-type designs appear to offer many options for both conductor grading and distribution of structure within the windings.

Among the special designs we have discussed, the "pipe" design and the "parallel walls" design were created primarily to accommodate the use of tape conductors, which tend to have highly anisotropic performance with respect to the relative directions of field and transport current. In addition, these designs offer novel approaches in handling or eliminating the need to preload the windings — approaches that may find application in another winding type.

4. PROTECTION

When an accelerator magnet quenches, the quench protection system triggers an active protection scheme for the magnet which forces a major portion of the coils to rapidly become resistive. The magnet's stored energy is completely absorbed in the quenching magnet. The technical constraints are given by the maximum hot-spot

temperature, the mean temperature and mean gradient in the coils, and the inter-turn voltage during the quench. Meanwhile the rest of the machine can be discharged at a lower rate by bypassing the quenching magnets with diodes. The aim is to avoid quenching the rest of the machine.

4.1 Example: LHC Protection System

Table 3-1 indicates a few parameters that have been obtained in a 10-Tesla magnet system.

Table 3-1 Protection Parameters in 10-T Magnet System

Current (A)	15,000
Inductance (mH/m)	5
Conductor width (mm)	17
Hot-spot temperature (K)	300
Internal voltage (V)	425
Voltage to ground (V)	1,000

The LHC will operate in superfluid helium and use a proven polyimide conductor insulation scheme. Quenches will be spread by quench heaters located on the perimeter of the outer coil layer in a system designed for the quenching magnet to absorb the full magnetic energy.

4.2 Hot-Spot Temperature and Copper Current Density

The basic relationship between the hot-spot temperature and the copper current density is of the type

$$\int_0^{\Delta t} j_{Cu}^2 \quad dt + j_{cu}^2 \frac{\tau}{2} = K\left(\frac{T}{To}\right)^{\frac{1}{2}}\left(1+\frac{1}{\alpha}\right)$$

where t is the decay time constant of the magnet, and Δt is the time delay for detection, firing, and thermal diffusion into the magnet windings. The parameter K depends on the conductor properties (specific heat, electrical resistivity), and α is the ratio Cu/non-Cu areas.

The main parameters to control and therefore minimize the hot spot temperature are Δt, j_{cu}, α, and t. As a starting point of any design, it will be assumed that Dt = 100 ms, t = 300 ms.

Preliminary examination indicates that the hot-spot temperature could be kept below 600 K with a current density in the copper around 1400 A/mm^2.

4.3 Stored Energy of a 15-T Dipole

The stored energy of a 15-T dipole (50 mm bore) could be as large as 1.6 MJ/m, depending on the design. Compared with that of 10-T magnets, the stored energy increases by a factor of 3. In order to reduce the mean temperature of the coils, the energy should be distributed throughout the whole volume of conductor by quench heaters located in each layer. The temperature gradient between layers should stay below 10 K, so that the inter-layer shear stress does not exceed 3 MPa, unless the layers are equipped with low-friction surfaces such that they can slide easily relative to one another.

4.4 Interturn Voltage

It is proposed that the self-inductance of a dipole should be limited to ~ 5 to 10 H/m corresponding to ~50 to 100 turns/pole. The requirements to be consistant with the stored energy and to satisfy the need for low self-inductance lead to currents per turn close to 20 kA, resulting in the voltage of the quenched coils being in the range of 400 V (8 to 10 V/turn). In these preliminary estimates, a current density of 2000 A/mm^2 in the non-Cu area of the conductor has been assumed. Concerning the ground insulation, it is reasonable to limit the voltages to ~ 1 kV. It appears then that it would be suitable to have operating currents in the range 20 to 30 kA for a 15 to 20 T accelerator dipole. These muti-ten kiloampere currents would require development of new higher-current diodes, which today operate only up to 15 kA.

4.5 Quench Heaters

The conclusion for heater feasibility is that it is clearly possible, within the parameters of the present heater development, for photoetched Kapton/copper/stainless steel heaters. The geometry of such a heater would be one in which all turns, or at least most turns of all layers, are covered at least 10 % by the heaters. The heater using 12 μm foil requires 12 to 32 J/m to switch a superconducting winding to normal in superfluid helium. Developments that would be useful but not critical are (a) 6-μm-thick stainless steel foil, (b) new glue to withstand 5 kV for 50 microns of Kapton/SS sandwich, and (c) thermal diffusion rate improvement of a factor of two (new filled polyimid films).

4.6 Computer Codes and Model Instrumentation

Computer codes exist to calculate the quench and stress development in a quenching magnet (QUABER[1]; ANSYS[2]). They need to be checked by suitable

measurements on models equipped with spot heaters to check the coil heating characteristics, and strain gauges to check stress levels between layers and the strain history during thermal cycling, aging and power sequencing for correct input parameters.

5. CONDUCTOR

5.1. General Conductor Requirements

The conductor requirement for accelerator magnets at 15-T and above are very stringent. In order to produce these fields in an efficient manner, relatively high J_c conductors must be obtained. A value of $J_c = 1000$ A/mm^2 in the superconductor at the operating field is generally accepted as a realistic starting point. This value is then diluted by a high conductivity normal metal matrix necessary for coil protection, insulation, space for cooling medium, and support structure. In terms of conductor choice, NbTi will be used at fields up to its practical limit, which is about 11-T at 1.8 K, since all practical high-field superconductors except NbTi are brittle. This also implies that conductor grading will be used wherever possible and that NbTi will be pushed to the limit by means of ternary additions, which increase the upper critical field by about 1-T.

All candidate conductors for use at higher fields are brittle materials. This means that special coil fabrication techniques must be used. These include careful handling, limiting magnet prestress, and minimizing the differential thermal expansion contraction problems. A minimum requirement is that the material be able to withstand the Lorentz force when the coil is energized, and that the material be able to survive a tensile strain of 0.5% without permanent degradation. In addition, the critical currents of many conductors under consideration exhibit strain sensitivity. The conductor most developed for use at fields above 12-T, Nb_3Sn, shows a relatively high J_c strain sensitivity. This is an intrinsic property of Nb_3Sn; however, some results indicate that certain conductor manufacturing approaches or conductor configurations produce conductors that are more sensitive to strain than others. Furthermore, the strain dependence is more pronounced at high fields. A primary driving force behind the interest in Nb_3Al as an alternative to Nb_3Sn is the lower strain dependence of J_c. This is especially important above 15-T. However, this conductor is not developed commercially to the extent of Nb_3Sn, and in any event fabrication is more difficult. (See Section 4.3).

In order to meet accelerator magnet requirements, the diamagnetic effect of the superconductor must be controlled (its value rendered small and predictable). Although multifilamentary Nb_3Sn may have a geometric filament diameter of 2 to 5 mm, the filaments grow together during the reaction and the effective filament size can become the size of the region containing the Nb_3Sn filaments, i.e., the order of tens of microns. Magnetization effects can be corrected; however, simple, low-cost correction requires a filament size less than 50 mm with a desirable value being around 5 mm.

Eddy current coupling can be present in Rutherford cables, depending on the resistance between strands and on operating conditions, such as current ramp rates. This coupling must be controlled and be reproducible. Too low a value of resistivity leads to heat deposition during ramping, and can lead to magnet quenching and can produce unwanted multipoles. Interstrand resistance must be controlled by strand coatings or by high-resistance core stripes in the cable to minimize these effects.

Strain limitations on materials other than NbTi typically lead to the use of a wind-and-react coil fabrication, which means that insulation must withstand the reaction cycle, which is several hundred hours at 650 C for Nb_3Sn. This means that the cable insulation must be fiberglass or a ceramic material. Fiberglass is abrasion-sensitive, especially after the sizing is removed from the insulation. Ceramics, such as mica, have low thermal conductivity and also poor shear strength.

In order to use any of these conductors in accelerator magnets, the operating current must be high enough to allow protection (see Section 3). This implies a conductor which is built up of multiple wires or tapes. The form most commonly used is the Rutherford cable, which has the advantages of flexibility, high aspect ratio, transposition, and relatively high packing factor, in addition to high operating current. Other configurations, such as tapes, need to be developed for use in accelerator magnets, and design features such as ends must be tailored to their use. As we push to higher fields, other conductor configurations may become important. Rutherford cable modifications with internal cores for strength, reduction of strand/strand coupling, or improved interstrand resistance, may be required.

The assumption is made that the minimum amount of Cu needed for stability and protection will be incorporated in each strand in a graded coil design. There will be a direct and optimized link between conductor I_c and J_c in the non-copper in each of the coils.

5.2 Nb_3Sn Status and Prospects for Improvement

Piece length of Nb_3Sn is all-important, as with any other practical conductor. Any increase in properties must be made without adverse effects on piece length. The other property that is intimately related to J_c is the "effective filament" diameter.

Provided that the effective filament diameter is not required to be <50-μm, the present state of the art for J_c of Nb_3Sn at 4.2-K is 1500 A/mm^2 at 12-T in the non-copper. These non-copper properties can also be produced at 14-T and 1.8-K. It is obvious that to make workable magnets in the region 10 to 20-T, the J_c in the non-copper must be increased significantly. This can be done in two main ways: (1) increasing the volume fraction of Nb and Sn in the non-copper area (i.e., increasing the cross-section of Nb_3Sn, and (2) increasing the flux pinning strength of the Nb_3Sn itself.

Method 1 tends to have an adverse effect on other properties, such as "effective filament diameter," copper purity, etc. Method 2 has received little recent attention and is not well understood. Refining the grain size is the standard method of raising J_c in Nb_3Sn. It works at lower fields but its effectiveness at fields of 15-T and above is less certain. New strategies are needed.

By incorporating these improvements it is reasonable to expect properties such as 1500A/mm^2 at 15-T and 1.8-K in the next few years. This would give ~750 A/mm^2 at 18-T and 1.8-K The next step will be to attempt to double this 18-T value in the subsequent 5 years.

One factor that must receive more attention is the stress sensitivity of the various types of Nb_3Sn that are available commercially. The view has been expressed that multifilamentary internal tin is much more sensitive than tape. The overall J_c of this in material is high, since no bronze is present to create dead spaces. Therefore, it is possible to expect J_c-values twice those of the multifilamentary material.

Although Nb_3Sn was first developed many years ago, it has received very little financial support recently. The fusion community has expressed a need for a material with moderate J_c and relatively low loss capability at 12-T for the ITER program. Moderate funding is expected to be available to expand manufacturing facilities for quantity production of Nb_3Sn required for the 15-T, and at least part of the 15-T and at least part of the 20-T accelerator magnets.

5.3. Nb_3Al Status and Potential

Several processing methods have been proposed for Nb_3Al in order to avoid the limitations due to the fact that the stoichiometric A15 phase forms only at elevated temperatures. The most direct approach, which has not yet been extended to commercial practice, consists of melt-quenching stoichiometric Nb-25% Al and then subjecting the resulting bcc phase to a "low temperature" (800-900 C) anneal to produce an ordered A15 phase. Another high temperature processing method, and one that is capable of yielding long continuous lengths of wire, is a powder-in-tube approach. After the components are drawn to near final size, the precursor powders are laser or electron-beam heated to form the desired phase. The disadvantage of this method is that it produces a monofilamentary wire which lacks the copper stabilizer.

Other methods consist of blending elemental Nb and Al components at the nanometer level, and then converting the mixture to A15 Nb_3Al by a moderate (800-900 C) heat treatment. Three promising routes using this approach are being developed: (1) a Nb tube approach being developed by NRIM in Japan, (2) a mechanically alloyed method being developed by IGC-ASI in the U.S., and (3) a jelly-roll of Nb and Al foils first developed in Italy (CNEN/LMI) and more recently in Japan (Sumitomo and Hitachi). Although none of these efforts are producing material on a commercial scale, small

quantities of wire with J_c = 800 A/mm^2 at 12 T are now available for model coil fabrication. This effort is being stimulated by the ITER fusion program, as a possible replacement for Nb_3Sn.

5.4 Potential of HTS Materials as Accelerator Conductors

Critical current values in the best short samples of HTS already exceed 10^3 A/mm^2 in fields out beyond 20-T at 4.2-K. The essential issue for conductors is therefore to develop such values in long lengths, and in accelerator conductor forms. The best properties are now obtained in high aspect ratio (~10:1) monocore tapes which might be suitable for parallel wall magnets, while multifilamentary conductors suitable for other magnet designs have J_c values perhaps a factor of two lower. All present HTS conductors are based on $Bi_2Sr_2CaCu_2O_x$ (BSCCO-2212) or $Bi_2Sr_2Ca_2Cu_3O_x$ (BSCCO-2223) and at present the J_c (4K) of BSCCO-2212 is actually greater than that of BSCCO-2223, even though the T_c of the BSCCO-2223 phase is about 20 K higher (~110 K vs. ~85 K). This apparently paradoxical difference emphasizes an important property of HTS materials in which they differ fundamentally from the low temperature superconductors (LTS). The key limit to J_c in HTS in the low temperature limit is the connectivity of the polycrystalline filaments. Weakly coupled grain boundaries, cracks and imperfect local composition all contribute to making the current path through the conductor percolative. Thus the true local J_c is often much higher than the average J_c. This is a vital fact for future accelerator use, since it means that there is great potential for further development of J_c. A gross idea of their potential is obtained by noting that the J_c of epitaxial BSCCO thin films can lie in the range of 10^4 to 10^5 A/mm^2, some two orders of magnitude above that of the best present polycrystalline conductor-like forms.

Multifilament conductors using the oxide-powder-in-tube (OPIT) process of both BSCCO compounds are being made in lengths > 1 km, with filament numbers up to about 250 and with diameters ranging upwards from 10 mm. Conductors using the metallic precursor (MP) process can achieve diameters < 1 mm but with lower present J_c. Most conductors are high aspect ratio even when multifilament, but recent efforts in making round wire BSCCO-2212 conductors look promising. Even tapes can be twisted when round so as to produce short twist pitches in tape form.

The strain tolerance of present conductors is very similar to that of MF Nb_3Sn when tested in tension. However, the performance under cyclic stress under axial compression, or under transverse loading, is less well understood; there is also concern that irreversible damage occurs much more quickly than in Nb_3Sn. This could easily be a manifestation of the fact that the present conductors contain many cracks (which also limit J_c) and that these propagate easily to produce progressively smaller limits on J_c.

Few cables have yet been made of HTS conductors, and their cabling performance is hard to assess. Conductors based on pure Ag matrices are unlikely to be suitable for

accelerator use, and the strengthened matrices that are presently being developed will be vital. Whether large aspect ratio conductors can be cables is unclear, but the potential of round wire conductors can also be explored.

6.0 HIGH FIELD ACCELERATOR MAGNET DEVELOPMENT PLANS

6.1 15T Magnets

The field range up to 15 T can be considered as a reasonable extension of the existing accelerator magnet technology, in view of recent progress on doped Nb_3Sn wires and of predictable advances in ductile superconducting materials, notably at superfluid helium temperatures. Present activities include

(1) developments for LHC dipoles and quadrupoles in the range 8-10 T using NbTi at 1.8 K; (2) a Nb_3Sn dipole model which has produced 11.2 T at Twente University; and (3) the D20 dipole model at LBL aiming to 13 T with Nb_3Sn at 4.3 K.

Other valuable experience revalant to accelerator magnets is available from developments in high-field solenoids, such as those for very high field NMR applications and for the 45 T facility at the National High Magnetic Field Laboratory, Florida. Fusion programs, particularly ITER, are also strong incentives for extremely high-field superconductors, although their requirements for high "J_c" are not as demanding as those for accelerator magnets.

The main requirements concern A-15 materials, Nb_3Sn being the most extensively developed at present. However Nb_3Al needs to be pursued in view of its lower transverse pressure sensitivity, as well as ternary alloys such as NbTiTa for grading purposes, if better than Nb_3Sn in the graded region. The general goal is for such conductors to increase the current density to the order of 1000 to 2000 A/mm^2 in non-Cu at operating field (15T), with effective filament diameters as small as possible below the present 50 um common to internal diffusion processes) in order to reduce magnetization effects. It is also important to minimize the strain sensitivity of J_c in view of large high field stresses.

Cable development must follow wire production, with specific requirements concerning cabling degradation, mechanical behavior under combined stresses, AC

losses, stability, quench behavior, etc. Particular cable structures should be investigated, such as cored cable, jacketed cable, coated strands, etc.

The main choice concerns the winding configuration, fulfilling the standard accelerator field requirements, and being compatible with other constraints, such as stress management, stability, losses, practical feasibility, and cost. At the 15 T field level, the cylindrical shell configuration, which is the universal scheme used in existing accelerator magnets, may still be the most practical structure. However, other configurations, such as racetrack block type coils, need to be further analyzed and compared with regard to performance and feasibility. In the case of the shell type configuration, a large number of parameters need to be optimized, and are subject to extensive design studies concerning mechanical and thermal behavior.

Technical areas covered in such studies are related to the mechanical support structure (external or distributed through the winding), the need and amount of prestress or preloading, the coil end design and support scheme, the insulation procedure, with or without full epoxy impregnation, depending on the wind-and-react sequence. Thermal requirements and many other fabrication items, such as conductor splices, instrumentation, and cooling channels, influence the coil design. Since single bore and twin aperture dipoles have similar yoke dimensions, it is desirable in the case of single bore magnets to reduce the yoke size by using an active flux return configuration.

6.2 20T Magnets

The field range between 16 and 20 T is very hard to reach in accelerator type dipole and quadrupole magnets without extensive research on materials, conductors and stress management. In particular, materials research to attain reasonable current densities in practical conductors at high levels of transverse stress is essential. In order to remain within the limits of what is practical and cost effective, it is believed that critical current densities in superconductors of about 2000 A/mm^2 are required — a factor 5 to 10 higher than is currently available in short pieces of experimental conductors. In order to make significant advances in this area, collaborative programs must be prosued, in which material scientists are encouraged to contribute with new or improved materials, conductor R&D teams are encouraged to make practical and stress-resistant conductors of such materials, and magnet designers are encouraged to develop novel geometries for

conductor and magnet construction schemes to handle and manage the stress levels in the magnet.

The specifications for a 20 Tesla dipole are driven by the requirements for reliable operation of an ultimate-energy collider, including: (1)central field B_0 ~ 20 Tesla; (2) harmonic content bn <10-4 cm^{-n}; (3) dynamic range Bmax/Bmin injection ~10:1; (3) active quench protection with internal unit absorption of stored energy.

These specifications result in some essential requirements and/or limits on the superconductor and its stabilizer, the configuration of the superconductor into coil elements, the adequate support of coil elements in the coil, and the overall field design of the magnet.

The various field design concepts being developed for high-field dipoles require a high-field region which is several (~2-4) times the beam tube region (ca. 4-5 cm) in each transverse direction. The total amp-turns per bore are thus $NI > \frac{B_0 2\pi a}{\mu_0} \sim 3$ Mamps. Such an immense current requires that the conductor carry a large effective current density, even at this immense field strength. The magnet operation at 1.8 K has various important advantages with respect to the vacuum conditions over 4.2 K operation. Moreover the critical current density is higher at 1.8 K, which roughly means a gain of about 2 Tesla. Therefore it is believed that a 20 T design should be based on supercritical helium. The most stringent requirement occurs for the inner coil elements, which must operate in the full central field. The conductor in these inner elements must carry a mean critical current of at leest J_c ~500 A/mm^2 (20 Tesla, 1.8 K). Optimizing such designs generally will require 1000 A/mm^2 in the practical superconductor and a critical current density of 1500 - 2000 A/mm^2 in the unstrained basic superconducting material.

The upper critical fields of HTS conductors at liquid He temperatures are beyond the range of direct measurement and can be arrived at only by extrapolation. Thus, from a critical field standpoint, HTS materials should be ideal for the high-field parts of high-field magnets.

The HTSC materials that are closest to commercialization in wire form are the two Bi-based materials Bi:2212 and Bi:2223. At the present time most attention is being given to Bi:2223 for use at temperatures approaching 77 K. Some interest is also being shown in Bi:2212, but in this case for use at 20-25 K in association with cryo-cooler-type refrigeration. In summary, the uses of both Bi:2212 and Bi:2223 require pushing the respective high-temperature limits of their ranges of applicability.

In the past, HTSC conductors have been criticized on the basis of low normal-zone propagation velocity. The existence of a "stagnant" normal zone offers the possibility of local burn-out unless local quench can be detected in time for protection to be applied. But it must be remembered that this is a "high-temperature" (77 K) property associated with a correspondingly high heat capacity. At low temperatures (< 4.2 K) the Ag (alloy)-clad HTSC conductor with its low heat capacity and correspondingly high normal-zone propagation velocity will behave much like a conventional superconductor.

At the present time the J_c of HTS materials is limited, not so much by intrinsic intragrain J_c as by the ability of the wire itself to carry such a J_c over its entire length (i.e., to attain its true potential). This represents a processing difficulty and as such is being addressed within the framework of HTS wires for use at 20 K and 77 K, respectively. However, for low-temperature applications, opportunities exist for increasing the intragrain J_c by the inclusion of flux-pinning additions to the HTS formulations. At the present time very little attention is being paid to this scenario since it has been found that flux-pinning additions result in a lowering of T_c. Once the need for maximal T_c is removed -- as it is when 1.8-4.2 K operation is being considered -- the door is opened for the possibility of engineering high-J_c flux-pinned Bi:2212.

Finally, when considering high-field insert magnets using HTS superconductors, several other requirements demand attention. These are: (1) The development of very long length processing methods (e.g., continuous processing); (2) The further development of multifilament strands and their assembly into cables; (3) The inclusion of mechanical reinforcement in the HTS strand to provide mechanical protection, both during processing and afterwards in service.

The conductor must be stabilized sufficiently to suppress micro-quenches (training), and to provide a realistic strategy for quench protection. These considerations require that the conductor contain sufficient high-conductivity stabilizer for a current density during a quench of ~1,500 A/mm^2 in the copper. The effective current density in a cable element would then be J_c ~375 A/mm^2 overall for J_c=500 A/mm^2, and J_c ~600 A/mm^2 overall for J_c =1,000 A/mm^2.

The cabled conductor should carry sufficient current to produce a fast, uniform distribution of the magnet's energy during a quench, so that no region is heated above room temperature. This requirement becomes quite severe for the immense stored energy (several MJ/m) of a 20 Tesla design. Preliminary calculations indicate that a practical superconducting cable should possibly carry a current of ~ 30 kA.

In addition, the cable must provide local support of the superconductor without exceeding the strain limit for axial as well as for transverse loads beyond which J_c is severely degraded (typically ~ 2 x 10^{-3} for Nb_3Sn in axial strain and 100 MPa in transverse strain, but even less for some superconductors).

The coil structure must distribute the Lorentz stresses, and the prestresses during assembly, so that the accumulation and concentration of stress nowhere exceeds the strain limits for the superconductor or the materials used for support and insulation. This requirement becomes a particular challenge at 20 Tesla. Extensive knowledge of strain-induced reduction and degradation of superconducting materials used is absolutely essential, and a major part of the efforts should focus on the optimization of strain management and overall magnet design.

20 T dipole magnets certainly not be built within a few years. As pointed out, extensive materials and conductor research and development are required, and have the highest priority. It is believed that when the conductor is available in terms of average current density at 20 T, and the stress levels foreseen to be manageable, the magnets can be built.

During the past few years we have seen a continuous improvement of current density and unit length, in particular of high T_c superconductors, and there is sufficient confidence that the required levels of current densities will become available. Therefore, it would be beneficial if physicists working in the high energy physics community think about the opportunities such a system offers in order to anticipate possible application requirements in the next 10 to 20 years.

Enhancement of the critical current density of superconductors at 20 T is absolutely essential. This could be achieved with improvements of the known materials as well as with presently unknown materials. For the A15 materials, such as Nb_3Sn and Nb_3Al, artificial fluxpinning at high fields and further shift of H_{c_2} by optimized doping could be the right approach. For the BSCCO and YBCO family of materials, continuous improvements are reported, but new ways of processing the materials should investigated and potential methods of technical interest should be recognized and developed in the light of 20 T, 1.8 K applications.

The development of practical conductors and cables for high fields should be stimulated. In a hybrid design both Nb_3Sn and an advanced conductor, as some form of HTS, will be present. Even with the existing types of high field A15 conductors a further push to higher critical current densities is necessary.

Moreover, in a 20 T magnet the body forces have to be decoupled from the local Lorentz forces on the conductor. To attain this decoupling, magnet designers need reinforced strands which are strain optimized cables, or fruitful combinations, to handle the enhanced stress levels in 20 T class magnets. Conductor R&D groups are invited to develop such reinforced conductors (Nb_3Sn, Nb_3Al, BSCCO) which can withstand external transverse stress levels of 200 - 300 MPa.

The number of laboratories involved in the R&D for future accelerators is limited, and on a world-wide scale only 1 or 2 costly high energy physics projects will be approved. The obvious consequence is the need for creating a world-wide network of excellence to carry out the necessary R&D in the field of superconducting materials, conductors and magnets. The efforts and partial and local funding should be made coherent and amplified to attain the long term goals of this 20 T project. Sharing of specific expertise, computer codes and testing facilities are essential elements of such a collaboration if it is to succeed.

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