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Limits of NbTi and Nb3Sn, and Development of W&R Bi-2212 High Field Accelerator Magnets

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Publication Date
2008-05-27

Limits of NbTi and Nb_3Sn, and Development of W&R Bi–2212 High Field Accelerator Magnets

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***Abstract*— NbTi accelerator dipoles are limited to magnetic fields (H) of about 10 T, due to an intrinsic upper critical field (H_{c2}) limitation of 14 T. To surpass this restriction, prototype Nb_3Sn magnets are being developed which have reached 16 T. We show that Nb_3Sn dipole technology is practically limited to 17 to 18 T due to insufficient high field pinning, and intrinsically to 20 to 22 T due to H_{c2} limitations. Therefore, to obtain magnetic fields approaching 20 T and higher, a material is required with a higher H_{c2} and sufficient high field pinning capacity. A realistic candidate for this purpose is Bi–2212, which is available in round wires and sufficient lengths for the fabrication of coils based on Rutherford-type cables. We initiated a program to develop the required technology to construct accelerator magnets from 'wind-and-react' (W&R) Bi–2212 coils. We outline the complications that arise through the use of Bi–2212, describe the development paths to address these issues, and conclude with the design of W&R Bi–2212 sub-scale magnets.**

***Index Terms*— Accelerator magnet, HTS, Bi–2212**

I. Introduction

THE superconducting material of choice for accelerator magnets has long been NbTi. The world's largest particle accelerator, the Large Hadron Collider (LHC) at CERN, utilizes NbTi technology. The record magnetic field with NbTi in a dipole configuration is 10.5 T at 1.8 K [**?**], and is approaching the intrinsic limitations of NbTi as will be discussed below. To surpass the intrinsic limitations of NbTi, a number of prototype dipole magnets have been constructed using Nb_3Sn superconductors, since Nb_3Sn approximately doubles the available field–temperature regime. Prototype dipole magnets that utilize Nb_3Sn technology reach a steadily increasing magnetic field, with the present record being 16 T at 4.5 K [**?**]. This progress resulted, for a significant part, from the increasing critical current density (J_c) in strands [**?**].

These successful prototype magnets demonstrate the feasibility of Nb_3Sn for use in accelerator magnets. This is emphasized through the U.S. LHC Accelerator Research Program (LARP) [**?**], which focuses on the development of Nb_3Sn magnets for future LHC upgrades. However, as will be shown below, due to these recent successful efforts, Nb_3Sn magnets are also rapidly approaching the material's limitations and a switch to a new material is inevitable to achieve higher magnetic fields.

Manuscript received September 1, 2006. This work was supported by the Director, Office of Science, High Energy Physics, U.S. Department of Energy under contract No. DE-AC02-05CH11231.

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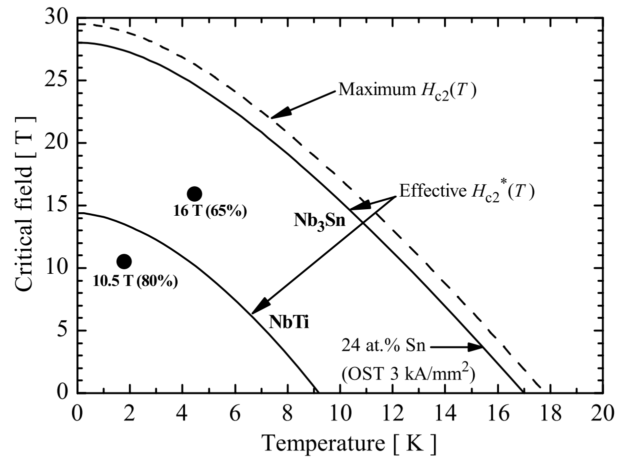

Fig. 1. Field-temperature phase boundaries and record magnetic fields in dipole magnets for NbTi and Nb_3Sn.

II. Magnetic field limits using NbTi and Nb_3Sn

To validate the use of a new material and the ensuing technology development, an accurate determination of the limitations of the present materials is required. A material's current carrying capacity is determined by its effective field-temperature phase boundary ($H^*_{c2}(T)$) and its pinning capacity. A material's pinning force (F_p) is maximized when the pinning site density is comparable to the flux-line density in the operating magnetic field range.

For NbTi, $H^*_{c2}(T)$ is limited by $H^*_{c2}(0) \cong 14.4$ T and an effective critical temperature $T^*_c(0) \cong 9.2$ K [**?**], as depicted in Fig. 1. Pinning sites can be engineered in NbTi in the form of α–Ti precipitates, with a spacing that is comparable to the flux-line spacing in the 5 to 10 T magnetic field range [**?**] (Fig. 2). NbTi is therefore, under present understanding, close to fully optimized. This pinning capacity optimization yields a parabolic-like $F_p(H)$ that peaks at about 50% of H^*_{c2} [?], and a maximum $J_c(5\ \mathrm{T}, 4.2\ \mathrm{K}) \cong 3$ kA/mm^2, or 1150 A/mm^2 at 8 T and 4.2 K [?]. Fig. 1 shows that an optimized dipole magnet, using an optimized NbTi wire, achieves about 80% of its intrinsic field-temperature limitation. 80% can thus be regarded as an optimized efficiency for dipole magnets.

Recent investigations on the capacities of Nb_3Sn superconductors [**?**], [**?**], [**?**] place well-defined practical and intrinsic limitations on its performance. For Nb_3Sn, being stable from about 18 to 25 at.%Sn (the A15 phase), $H^*_{c2}(T)$ depends on the H_{c2} averaging over the compositions that are present in a wire [?]. In Fig. 1, the maximum detectable $H_{c2}(T)$ in

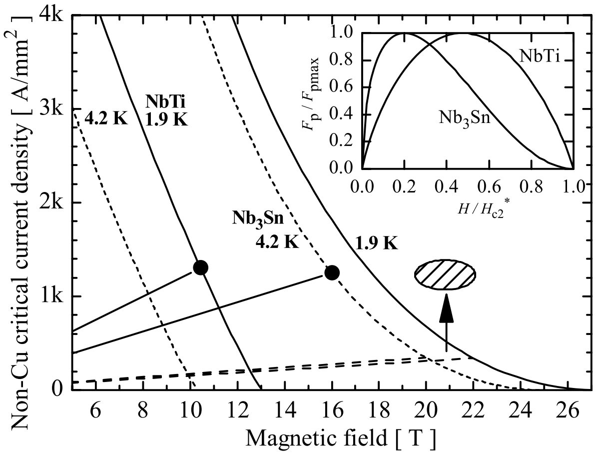

Fig. 2. Critical current density as function of magnetic field at 1.9 and 4.2 K in NbTi and Nb_3Sn. Included are the load-lines for record magnets and for a hypothetical Nb_3Sn dipole magnet achieving 80% of its intrinsic limitation. The inset shows the normalized pinning force as function of reduced magnetic field.

wires is depicted by the dashed line. Also a best estimate is given for $H^*_{c2}(T)$ for the present record Internal Tin (IT) wire ($J_c(12\ \mathrm{T},\ 4.2\ \mathrm{K}) = 3$ kA/mm^2) [?], which has an average Sn content of 24 at.%Sn [**?**]. This $H^*_{c2}(T)$ is limited by $H^*_{c2}(0) \cong 28$ T and $T^*_c(0) \cong 17$ K. Fig. 1 shows that the present record dipole magnet, using the present record wire, achieves about 65% of this $H^*_{c2}(T)$. If Nb_3Sn, like NbTi, would achieve 80% of $H^*_{c2}(T)$, it would reach a dipole magnetic field of 20 T at 4.2 K, or 22 T at 1.9 K, which forms an intrinsic magnetic field limitation for Nb_3Sn, which is closely approached in solenoids.

The main reason why a Nb_3Sn magnet does not achieve 80% of its intrinsic limitation is lack of high field pinning capacity. Grain boundaries are the main pinning centers in Nb_3Sn and the average grain size in commercial wires is between 100 to 200 nm [?]. The average flux-line spacing, in contrast, is about 10 to 15 nm. The flux-line density is therefore about one order of magnitude larger than the grain boundary density. This results in collective pinning of the flux-line lattice, described by an asymmetric $F_p(H)$ that peaks at only 20% of H^*_{c2}, i.e. at about 5 T at 4.2 K for the present record IT wires [?] (Fig. 2). This lack of high field pinning translates to the concave $J_c(H)$ curves in Fig. 2, and a reduced current carrying capacity towards H^*_{c2} [?]. The pinning curve for optimized NbTi, in contrast, translates to an approximately linear $J_c(H)$ reduction up to H^*_{c2} [?].

It has been demonstrated that the introduction of additional pinning cites in Nb_3Sn causes the maximum in $F_p(H)$ to increase and shift towards higher magnetic field [**?**]. Therefore, the only way to retain current carrying capacity in Nb_3Sn when approaching H^*_{c2} (as indicated by the hatched region in Fig. 2) is by an enhancement of the pinning site density through grain refinement or the inclusion of engineered pinning centers. Both these options, though demonstrated on laboratory samples, have not yet been validated in commercial wires. Grading and an unlimited conductor package could, in theory, generate magnetic fields approaching 20 T, but the resulting magnets would be unpractically large and expensive due to Nb_3Sn's in-efficiency at high magnetic fields. Nb_3Sn is therefore exhausted at dipole magnetic fields in the 17 to 18 T region. Even if high field pinning capacity in wires could be improved, Nb_3Sn would still be intrinsically limited to 22 T at 1.9 K as described above.

To progress towards magnetic fields of 20 T and higher, it is thus inevitable to switch to a new material with a significantly higher H_{c2} and sufficient high field pinning capacity. Of the possible candidate materials ($YBa_2Cu_3O_{7-\delta}$, $Bi_2Ca_2CuSr_2O_{8+x}$, $Bi_2Ca_2Cu_2Sr_3O_{10+y}$, MgB_2), only Bi–2212 is sufficiently developed for use in accelerator magnet applications. It has an $H^*_{c2}(4.2\ \mathrm{K})$ of about 85 T [**?**], a NbTi-like pinning curve, and is available in round wires with sufficient length. The latest generation Bi–2212 wires have already demonstrated to surpass the overall (engineering) critical current density in Nb_3Sn wires at magnetic fields of about 18 T and higher [**?**].

III. Technological Challenges with Bi–2212

Constructing a magnet using Bi–2212 is significantly more complicated than using NbTi or Nb_3Sn, as summarized in Table I. Technological challenges are related to the strain sensitivity of Bi–2212, its high formation reaction temperature in an oxygen-rich environment, and chemical compatibility of the insulation and construction materials during the reaction heat treatment. Operational challenges are related to the low normal zone propagation velocity, hindering energy dissipation and quench detection.

A. Stress and strain related issues

The critical current in Bi–2212 is, like Nb_3Sn, sensitive to strain (ϵ). A model that has been developed to describe the behavior of $J_c(\epsilon)$ in Bi–2212 in longitudinal strain experiments indicates, as with Nb_3Sn, that the highest J_c is obtained in the strain free state (Fig. 3 [**?**]). Compressive axial strain during cool-down causes, in contrast to Nb_3Sn, an *irreversible* reduction of J_c (Fig. 3: *a*). Releasing the thermal pre-compression (Fig. 3: *b*) does not, as for Nb_3Sn, recover J_c, but $J_c(\epsilon)$ shows a plateau up to an axial strain where cracks occur and J_c collapses (Fig. 3: *c*). Though $J_c(\epsilon)$ on this plateau is reversible, any additional pre-compression and relaxation causes a wider plateau at a reduced J_c value. Such a wider plateau is often misinterpreted as an indication for reduced strain sensitivity, but is in fact a result of a larger axial pre-compression in the Bi–2212. The J_c loss is on the order of 100% per % axial compressive strain [?]. Construction materials that match the thermal contraction of Bi–2212 are therefore preferred. One publication on the stress sensitivity of Bi–2212 cables indicates a broad-face load limit of about 60 MPa [**?**]. This emphasizes the need for more detailed investigations and accurate stress handling in magnets and/or new conductor reinforcement techniques.

B. Formation reaction related issues

Bi–2212 is a brittle ceramic material which is formed from precursor powders during a partial melt reaction at about

TABLE I

SUMMARY OF TECHNOLOGICAL CHALLENGES IN RELATION TO SUPERCONDUCTOR CHOICE AND ACHIEVABLE DIPOLE MAGNETIC FIELDS.

Material	Dipole limit	Reaction	Wire axial compression	Cable transverse stress	Insulation	Construction	Quench propagation
NbTi	10.5 T	Ductile: R&W	N/A	N/A	Polyimide	Stainless Steel	> 20 ms^{-1}
Nb_3Sn	17–18 T ($F_p \uparrow$: 22 T)	$\sim 675°$C in Ar/Vacuum	Reversible	200 MPa limit	S/R–Glass	Stainless Steel	~ 20 ms^{-1}
Bi–2212	Stress limited	$\sim 890°$C in O_2 ($\pm$ 2°C)	Irreversible	60 MPa limit	Ceramic	Super alloy	~ 0.04 ms^{-1}