Challenges of Unconventional Superconductors

J. Jeyabuvaneswari
Department of Physics
CK College of Engineering & Technology, Cuddalpre, Tamilnadu, India

Abstract— Since the discovery of high-Tc cuprates, the quest for new superconductors has shifted toward more anisotropic, strongly correlated materials with lower carrier densities and competing magnetic and charge-density wave orders. Although these materials' features enhance superconducting correlations, they also result in serious problems for applications at liquid nitrogen (and higher) temperatures and strong magnetic fields so that such conventional characteristics as the critical temperature Tc and the upper critical field Hc2 are no longer the main parameters of merit. This happens because of strong fluctuations of the order parameter, thermally activated hopping of pinned vortices, and electromagnetic granularity, as has been established after extensive investigations of cuprates and Fe- based superconductors (FBSs). In this paper, I give an overview of those mechanisms crucial for power and magnet applications and discuss the materials' restrictions that must be satisfied to make superconductors useful at high temperatures and magnetic fields. These restrictions become more and more essential at higher temperatures and magnetic fields, particularly for the yet-to be discovered superconductors operating at room temperatures. In this case, the performance of superconductors is limited by destructive fluctuations of the order parameter so that higher superfluid density and weaker electronic anisotropy, which reduce these fluctuations, can become far more important than higher Tc.

Keywords: high-temperature superconductivity, critical temperature, anisotropy, superfluid density, fluctuations, competing orders, vortices, critical current density, irreversibility field, grain boundaries

I. INTRODUCTION

Making predictions in superconductivity, particularly for new materials or the material require- ments for applications of existing or putative room-temperature superconductors (RTSs), has never been rewarding, reflecting the experimental fact that "doing the opposite" has often worked better than following the conventional wisdom and established models (1, 2). However, the im- portant lessons of unprecedented research and development of unconventional superconductors in the past 20–30 years have changed the perception of what is important for applications at high temperatures and magnetic fields. In this paper, I discuss some of the lessons that may be helpful in the ongoing quest for new superconductors.

Incidentally, the trend of optimistic predictions was started by Kamerlingh Onnes, the dis- coverer of superconductivity, who was the first to recognize the advantages of superconducting magnets as the only enabling technology capable of generating the DC magnetic field of 10 tesla, which could not be achieved by resistive magnets. However, this idea had to be put aside for a long time because all type-I superconductors known before 1930–1940 went to the normal state at low magnetic fields (H < 0.2 tesla) limited by the thermodynamic critical fields (Hc) of these materials. The fulfillment of Onnes's vision took nearly 50 years and many scientific and technological breakthroughs, including the discoveries of the Meissner effect and type-II superconductors as well as the development of the London, Ginzburg-Landau (GL), and Bardeen-Cooper-Schrieffer (BCS) theories, which showed that superconductivity is a phase- coherent condensate of Cooper pairs glued by phonons. These advances eventually led to the Abrikosov theory of a lattice of quantized vortices, which explained how type-II super- conductors are able to withstand high magnetic fields up to Hc2 Hc. It was then realized that the upper critical field Hc2, above which the type-II superconductivity disappears, can be significantly increased by alloying the material with nonmagnetic impurities.

By 1986, many type-II superconductors, such as NbZr, NbTi, A-15 compounds (Nb3Sn, V3Si, etc.), and Chevrel phases (PbMo6S8), with Hc2 ’ 10–60 tesla and Tc ’ 9–23 K had been dis- covered, and NbTi and Nb3Sn became the materials of choice for superconducting magnets and medical MRI machines All these materials are conventional superconductors with the s-wave symmetry of the Cooper pairs described by the Eliashberg theory, which generalized the BCS model by taking into account strong electron-phonon interaction At that time, the superconducting critical temperature Tc and the upper critical field Hc2 were regarded as the main parameters of merit for magnet applications at the liquid helium temperature 4.2 K. Making superconductors useful involved incorporation of structural defects in a material to pin vortices and prevent their dissipative motion under the action of flowing current, which otherwise caused electric resistance below Hc2 and Tc. Because stronger pinning allows a superconductor to carry larger nondissipative critical current density Jc(T, H) at high magnetic fields, materials optimi- zation involved incorporating as many extended materials defects and impurities as possible to maximize Jc and Hc2 without significant degradation of Tc . Finally, composite wires were produced by embedding thin superconducting filaments into a flexible metallic matrix to provide thermal quench stability, low AC losses, and good mechanical properties. This approach works for most conventional superconductors, including NbTi (Tc ¼ 9 K) and Nb3Sn (Tc ¼ 18 K). More recently, alloying the two-band BCS superconductor MgB2 has increased Hc2(0) from 3–5 tesla to 40–70 tesla , resulting in the development of magnet conductors

The success of this approach is based on two fundamental features of conventional super- conductors in which the symmetry of the order parameter is not lower than the symmetry of the Fermi surface. First, the coherence length j0 ’ ZvF=2pkBTc, which quantifies the size of Cooper pairs, is much greater than the mean electron spacing rs. In a good metal with a large Fermi velocity (vF), it is the strong overlap of Cooper pairs that provides the superconducting phase coherence and weak sensitivity of Tc to nonmagnetic impurities and extended crystalline defects, such as dislocations and grain boundaries (GBs). Another important feature is that fluctuations of the order parameter are negligible because of the smallness of the Ginzburg parameter Gi ¼ 0:5 kBTc=Hc2j2jc 2 proportional to the squared ratio of the thermal energy kBTc to the condensation energy Hc2j2jc=8p in the volume occupied by the Cooper pair (24). Here, j is the in-plane coherence length, jc ¼ j/g is the coherence length along the c-axis, and the anisotropy parameter g ¼ (mc/m)1/2 is defined by the ratio of effective masses along the c-axis (mc) and in the a-b plane (m) in a uniaxial superconductor (25, 26). In conventional superconductors, Gi varies from ∼10 11 for Nb (Tc ¼ 9.2 K) to ∼10 4 for a two-band MgB2 with Tc ¼ 40 K. The materials parameters that control Gi become more transparent if Hc2 ¼ f20=8p2j2l2 is expressed in terms of the magnetic London penetration depth l ¼ (mc2/4pnse2)1/2 in the clean, single-band limit, where ns is the superfluid density equal to the carrier density at T ¼ 0, and f0 ¼ pZc=e is the flux quantum superconductors with small (nanoscale) j0, non s-wave pairing, and strong vortex fluctuations in quasi-one dimensional or layered materials. These features, first regarded as exotic and not relevant to practical conductors, were eventually recognized as being among the key issues for applications at 77 K after the groundbreaking discovery of high-Tc cuprates (33). The initial enthusiasm surrounding the vision for powerful high-field magnets, motors, generators, and transmission lines working at liquid nitrogen temperatures (77 K) was based on a belief that the high Tc of YBa2Cu3O7x (Tc ¼ 92K) and (Bi,Pb)2Sr2 Ca2Cu3O x (Tc ¼ 110K) would somehow assure high field conductors.

II. PROBLEMS WITH STRONGLY CORRELATED LAYERED MATERIALS

The field dependence of Jc(T, H) is of major importance for magnet applications. The value Jcð4:2 K, 5TÞ ’ 0:5 MA=cm2 is characteristic of Nb47wt%Ti alloys with Tc ¼ 9 K and Hc2(4.2 K) ¼ 12 tesla used in magnets (19). Many superconductors have Hc2 much higher than Hc2(0) ¼ 15 tesla of NbTi because they have shorter j0 and can sustain stronger fields up to Hc2ð0Þ ’ f0=2pj20, at which the spacing between vortices (f0/H)1/2 becomes of the order of the diameter of nonsuperconducting vortex cores ’ 2j0. Very high values of Hc2s found in the cuprates and FBSs result from their small j0 ¼ ZvF=2pkBTc, either because of high Tc ¼ 90–130 K in cuprates or smaller vF in semimetallic FBSs. The values of Hc2(0) > 100 tesla extrapolated from low-field measurements near Tc often exceed the BCS paramagnetic limit Hp at which the Zeeman energy equals the binding energy of Cooper pairs with antiparallel spins, Hp[tesla] ¼ 1.84Tc[K] (43, 44). Figure 1 shows Hc2(T) and H (T) for some low-Tc superconductors, cuprates, and FBSs.

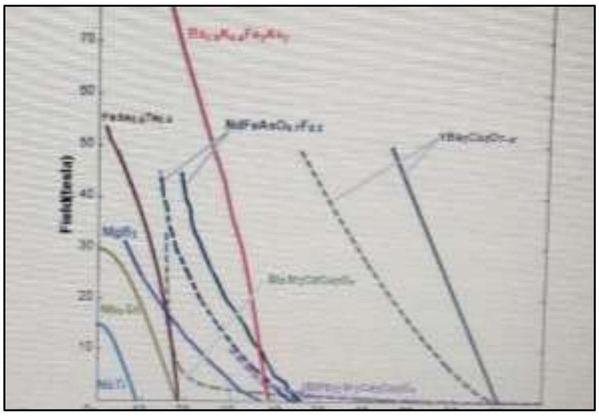

Fig. 1:

Comparative H-T phase diagram for representative cuprates, Fe-based superconductors (FBS), and conventional superconductors, where the solid and dashed lines show, respectively, Hc2(T) and H (T) parallel to the c-axis. In the range of fields 5 tesla < H < 70 tesla, which can be generated by superconducting magnets, the Hc2(T) curves for most FBS with Tc > 20 K are clustered between H (T) of the layered Bi2Sr2CaCu2Ox and H (T) for the least anisotropic YBa2Cu3O7 x. Here H (T) for the layered Bi2Sr2CaCu2Ox (Tc 75 K) and Bi2Sr2Ca2Cu3Ox (Tc 108 K) are much smaller than their respective Hc2(T), which have slopes dHc2=dT ’ 2 tesla=K at Tc (not shown here). The difference between H and Hc2 for NdFeAsO0.7F0.3 at 20–30 K is smaller than the difference between H and Hc2 for YBa2Cu3O7 x at 77 K, which reflects the diminishing role of vortex fluctuations at lower T. The less anisotropic Ba0.6K0.4Fe2As2 with 1 < g(T) < 2 and Tc ¼ 38 K has a higher dHc2/dT than NdFeAsO0.7F0.3 with g(T) 4 8 and Tc ¼ 42 K (44), so the Ba0.6K0.4Fe2As2 polycrystalline conductors that also exhibit a weaker grain boundary problem (93) could be superior at 20 K. The data are reproduced from Reference 70, with the addition of recent Hc2 data for FeSe0.5Te0.5 and Ba0.6K0.4Fe2As2

Ni alloy sub

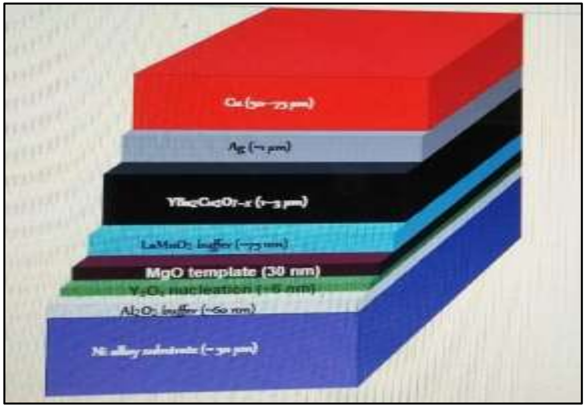

Fig 2:

A typical architecture of a coated conductor made by ion beam–assisted deposition (53). The YBa2Cu3O7 x film is grown on a textured Ni-alloyed substrate with a complex buffer layer structure, which enables replication of the low-angle grain structure of the substrate in the YBa2Cu3O7 x film and protects that film from chemical contamination. The stabilizing layers of Ag and Cu on top of the 1–2 mm thick YBa2Cu3O7 x film provide thermal quench protection of the tape, which is usually a few millimeters wide and 0.1–0.2 mm thick. The current-carrying superconducting film takes 1%–2% of the conductor cross-section, which strongly reduces its averaged current density. Reproduced from

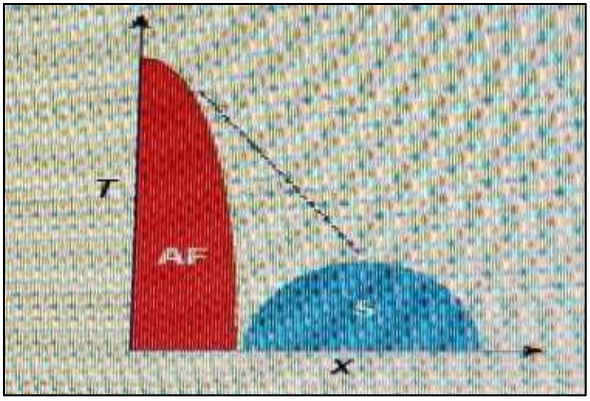

Fig. 3:

Generic phase diagram of unconventional superconductivity emerging due to doping an antiferromagnetic parent state. Here, T is temperature, and x can be proportional to either hole concentration or electron concentration, or to other external factors, such as pressure. The dashed line depicts the temperature at which a pseudogap separating Fermi-liquid from non-Fermi liquid behavior forms. AF and S refer to antiferromagnetic and superconducting states, respectively.

III. CONCLUSION & OUTLOOK

The development of high-Tc cuprates and FBSs has resulted in the evolution of parameters of merits for applications at high temperatures and magnetic fields, from the pairing-limited Tp and Hc2 to the parameters mostly controlled by thermal fluctuations and transparency of GBs. This shift of perception reflects the recognition of the importance of thermal fluctuation of vortices at high T and H in layered, strongly correlated superconductors. Those unconventional super- conductors with low Fermi energies, non-phonon pairing, and competing AF orders can have Tc up to 132 K for cuprates and up to 56 K for FBSs, and very high Hc2(0) > 100 tesla. However, making these materials useful for power or magnet applications at 30–77 K requires a lot of innovative materials tuning and expensive technological compromises.

For instance, the coated conductor shown in Figure 2 utilizes only a few percent of the current- carrying cross-section, so Jc of the superconducting film must be pushed to the limit by in- corporating dense arrays of nanoprecipitates spaced by ‘ ~ 10 nm. This does increase Jc at low T and H but not necessarily H at 77 K or higher temperatures. Indeed, because of low vortex line tension εl(T) ~1 10 K/nm, vortex segments of length ~ kBTg/ε0 ~ 10–100 nm can hop and reconnect at neighboring pins. In turn, low energy barriers Ub ~ p‘ε0g 1 ~ kBT for cutting and reconnection of soft vortex segments (26) between nanoprecipitates cause giant thermally acti- vated flux creep and electrical resistance at J < Jc, no matter how strong pinning may be. Thus, the bad combination of low εl(T) and weak-linked GBs makes it hard to develop competitive conductors for high field applications at T > 77 K, using superconductors in which εl(T) is lower than εl for YBa2Cu3O7 x.

As far as the search for new materials is concerned, mechanisms that provide high pairing temperatures may not necessarily result in RTSs that can actually be used at 300 K. In fact, it may be beneficial to explore new materials means of reducing fluctuations in cuprates or FBSs by, for example, reducing the electronic anisotropy with chemical substitutions, using contact with normal metals (130), or managing optimal inhomogeneities at the nanoscale (131). Certainly, searching for new materials with higher superfluid density and lower anisotropy than in cuprates or FBSs, even at the expense of lower Tc, could be very fruitful, as the success of MgB2 has shown. Curiously, a viable RTS may have to satisfy one of the Matthias criteria (cubic symmetry is best) but not the one that requires peaks in the density of states that would increase m and l0. The following temperature regions for applications of different materials can be identified:

REFERENCES

[1] Allen PB, Dynes RC. 1975. Phys. Rev. B 12:905–22
[2] Carbotte JP. 1990. Rev. Mod. Phys. 62:1027–57
[3] Campbell AM, Evetts JE. 1972. Adv. Phys. 21:194–428
[4] Wilson M. 1983. Superconducting Magnets. Oxford: Clarendon
[5] Gurevich A, Patnaik S, Braccini V, Kim KH, Mielke C, et al. 2004. Supercond. Sci. Technol. 17:278–86
[6] Wilke RTH, Bud’ko SL, Canfield PC, Finnemore DK, Suplinskas RJ, Hannahs ST. 2004. Phys. Rev. Lett. 92:217003
[7] Braccini V, Gurevich A, Giencke JE, Jewell MC, Eom C-B, et al. 2005. Phys. Rev. B 71:012504
[8] Flükiger R, Kumakura H. 2012. See Ref. 134, pp. 702–10
[9] Larkin AI, Varlamov AA. 2007. Fluctuations in Superconductors. Oxford: Clarendon Press
[10] Blatter G, Feigelman MV, Geshkenbein VB, Larkin AI, Vinokur VV. 1994. Rev. Mod. Phys. 66:1125–388
[11] Brandt EH. 1995. Rep. Prog. Phys. 58:1465–594
[12] Tinkham M. 2004. Introduction to Superconductivity. New York: McGraw-Hill. 2nd ed.
[13] Fischer O. 1978. Appl. Phys. (Berl.) 16:1–28
[14] Stewart GR. 1984. Rev. Mod. Phys. 56:755–87
[15] Steglich F. 2012. See Ref. 134, pp. 283–87
[16] Jerome D, Schulz HJ. 2002. Adv. Phys. 51:293–479