**Abstract**

Several future accelerators will require magnets to operate above 10 T (for example the proposed Muon and Hadron colliders). In this new domain of accelerator magnets, the pre-eminence of Nb-Ti falls away. In the time frame of new accelerator construction (10-20 years), there are strong opportunities to bring on new classes of superconductor (advanced A15, HTS), provided that serious, focused efforts start soon. Of the primary HTS superconductors, Bi$_2$Sr$_2$CaCu$_2$O$_x$, (Bi,Pb)$_2$Sr$_2$Ca$_2$Cu$_3$O$_x$, and YBa$_2$Cu$_3$O$_7$, the most promising for near-term high field magnet application is Bi$_2$Sr$_2$CaCu$_2$O$_x$ (Bi-2212). However, HTS conductors are still at an early stage of development and continued improvement over the next ten years could make other HTS superconductors available for accelerator application. Bi-2212 appears to have the highest potential today, because it can be made in round wire form with reasonably high $J_c$ values, thus permitting access to the cabling technology developed for LTS materials. Bi-2223 and YBCO are both presently limited to wide-tape designs, for which cabling is a significant challenge. Development of less aspected conductor designs might permit YBCO coated conductors to drive out 2212 as the present conductor of choice. An alternative approach is to design magnets around the use of aspected conductor forms and anisotropic properties in order to make the most of the unique properties of HTS superconductors.

**1 INTRODUCTION**

It has been 13 years since the discovery of high temperature superconductors (HTS) [1] but it is likely to be at least as long until a next generation of accelerators that might fully exploit them goes into construction. Some planning and speculation as to how HTS might enter into HEP construction plans is therefore appropriate. At this time, conductors made from HTS have made considerable progress towards viability for magnets useful for utility applications, where the essential need is that HTS replace copper and iron. This means that their main present target is dominated by lower field uses (1-2 T, occasionally higher) than most LTS applications, and by cost. Today, HTS conductors made of multifilamentary Bi-2223 ((Bi,Pb)$_2$Sr$_2$Ca$_2$Cu$_3$O$_x$) (see Figure 1) are being applied to significant prototype motors, transformers, power cables, fault current limiters, and other utility applications [2]. The principal limitation on their eventual use is now seen to be primarily economic, since most electrotechnical and utility applications are already available from conventional uses of Cu, Fe and Al. Accelerator applications are generally fundamentally different, in that superconductivity is a vital enabling technology and they are also demanding in what they expect of the superconductor. Thus the HEP view of HTS is not at all the same as the utility market view of HTS.

**2 HEP MAGNET SYSTEMS**

There are essentially two types of magnet that HEP wants, dipole and quadrupole magnets with bores of a few tens of millimeters for beam steering, and large detector magnets of many meters diameter for beam interaction analysis. Present designs of large hadron colliders (e.g. LHC) are already at 8 T for main ring dipoles and more than 10 T for specialty quadrupoles. By contrast, beam interaction analysis magnets are often meters in diameter and they continue to get bigger. However, their fields remain in the 1-2 T range, which is comfortably accessible by present day Nb-Ti conductors.

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3 HTS CONDUCTOR OPTIONS

Today there are three HTS materials from which useful conductors can be made. They are the two micaceous Bi-Sr-Ca-Cu-O (BSCCO) compounds Bi$_2$Sr$_2$CaCu$_2$O$_x$ (Bi-2212) with $T_c \sim$90 K and (Bi,Pb)$_2$Sr$_2$Ca$_2$Cu$_3$O$_x$ (Bi-2223) with $T_c \sim$107 K, and the metallic reservoir layer compound YBa$_2$Cu$_3$O$_{7-x}$ (Y-123) with $T_c$ of $\sim$92 K. However, in the context of a still great worldwide interest in high temperature superconductivity (and the very recent report of surface superconductivity [3] in the Na-doped WO$_3$), we should still admit the possibility of the discovery of new compounds that might replace the present choices. Most of us in the superconductivity community have a mindset that postulates that new superconductors of higher $T_c$ are going to be more complex than any low temperature superconductor (LTS). However, there is no firm and explicit basis for his belief, and we should remain open to pleasant surprises. Those who are optimists may be heartened by the recent interest of the popular author, Tom Clancy, in superconductivity. In his 1999 book, “Carrier”, he describes the discovery of superconductivity well above RT in wires of a Cu-Pt-Sc mix [4] in the year 2016! Apparently the simultaneous discovery of large Pt and Sc reserves in Sri Lanka also makes the material very affordable, halts a nuclear skirmish between India and Pakistan, and leads to the award of both the Physics and Chemistry Nobel prize to the discoverer and to instant widespread applications too!

Turning back to today’s conductor designs, they are either large aspect ratio multifilaments (Figure 1), round wire multifilaments (Figure 3) or monofilament tapes (Figure 2), Bi-2223 (or Bi-2212) exemplifying the first, Bi-2212 the second, and Y-123 the third. Before going into the details of fabrication that govern their availability, we first turn to discussion of the underlying properties that determine their suitability for conductors. The key issues that must be addressed in order for HTS to be made into successful conductors are:

- High critical current density.
- Temperature capability.
- Strength.
- Length availability.
- Cost and performance competitiveness with LTS conductors.

Of the above issues, only improved temperature capability by HTS conductors is fully satisfied in the competition between HTS and LTS superconductors such as Nb-Ti and Nb$_3$Sn. Attaining high enough overall $J_c$ in reasonable conductor forms is the biggest present obstacle to applications and the one that we emphasize most in the limited space available here.

4 PREREQUISITES FOR HTS USE

4.1 High Critical Current Density

The most fundamental requirement of any viable conductor is that it must have a high critical current density, $J_c$, in the field range needed for the magnet. High normally is taken to mean values of $>10^3$ A/mm$^2$ flowing in the superconductor cross-section. For low temperature superconductors, we expect that $J_c$ is primarily determined by flux pinning (filament cross-sectional variation (sausaging)) may reduce the flux pinning determined $J_c$ by factors of order 10 %, but for HTS materials this is very far from being the case. Figure 4 shows that the best HTS conductors exceed this baseline value, BSCCO at 4 K (and perhaps up to 15-20 K), while Y-123 does this comfortably at 77 K. However, a central fact of all HTS polycrystalline forms is that the supercurrent percolates, because it is im-
pered by obstacles on multiple length scales. This percolation results in loss of vital information in understanding the attainable current densities in many conductor forms, because the presence of so many barriers means that the actual cross-section occupied by transport current is a continuously varying and in general unknown quantity. What can be measured to high accuracy is the critical current, $I_c$, but the conversion to $J_c$ produced by dividing by the total cross-sectional area of superconductor contains little fundamental information.

This percolation is illustrated by representative flux penetration pictures obtained by magneto optical (MO) imaging of 2212, 2223, and Y-123 conductors in Figures 5 and 6. The image contrast comes from the non-uniformity of flux penetrating into the superconductor. Flux obviously penetrates Bi-2212 and Bi-2223 differently. The fine network in Bi-2223 has its origin in the many cracks that populate 2223 filaments. Bi-2212, being melt processed at its final stage, suffers from porosity on a larger scale, while the origin of percolation in Y-123 is less clear at the present time. The larger length scale of the granularity is important, since it means that typical Bi-2212 conductors have overall $J_c$ values 2-3 times those of Bi-2223 conductors at low temperatures, even though Bi-2212 has the lower $T_c$.

At the smallest scale, the ultimate limit to $J_c$ is defined by the depairing current density, $J_d$, the current density of the Meissner sheath or the circulating current around each vortex. Since $J_d \sim 0.5 \frac{H_c}{\lambda}$, where $H_c$ is the thermodynamic critical field and $\lambda$ is the penetration depth over which currents circulate, values of $J_d$ well exceed the needed value of $J_c$ since they reach $10^4$ A/mm² at 4 K and $10^5$ A/mm² at 77 K. The flux pinning current density, $J_{fp}$, is typically up to 10% of $J_d$. It is determined by the density of pinning sites in the microstructure and the vortex density gradient that they can support. Thus more than adequate $J_c$ is available from flux pinning too, even if the value of order $10^4$ A/mm² at 77 K must be derated somewhat to take account of flux creep, a phenomenon not normally considered in LTS materials.

The first barrier seen by these large values of local, intragranular critical current density, $J_{c1}$, are grain boundaries of arbitrary misorientation, which in general have significant local strain and disorder and depressed superconductivity, which makes the boundary a barrier to current flow. Although the magnitude of this effect is known well for special [001] tilt boundaries in Y-123 (the inter-
granular $J_c$, $J_{gb}$, is depressed by about $10^3$ [5,6] on increasing the misorientation from 0 to 45°, it is not well known for most boundaries and there are interesting signs that the doping state of the compound plays an important role in determining and perhaps ameliorating these strong barriers to current flow [7]. This strong dependence on misalignment is the reason for using texturing methods for making Y-123 coated conductors, as noted in Figure 2.

Larger scale barriers are cracks and voids, which are in these authors opinions [8-9] amongst the most serious contributors to the degradation of $J_c$ in the Bi compounds, while sausaging also contributes 20 to 100 % degradations to $J_c$. Thus the final $J_c$ determined by the measurements of $I_c$ and $A_{tol}$ is a much reduced, trickledown $J_{cr}$, in which an inherently high flux pinning $J_c$ is reduced by factors of order 10 to 100 in BSCCO and perhaps 5-10 in Y-123. This is of course also a big opportunity to improve the $J_c$ since the factors controlling $J_c$ are not fundamental ones, but rather those affected by the processing into useful conductor forms.

We finally should note that the working $J_c$ of the conductor is further diluted by the support structure (as seen in Figure 2, the superconductor cross-section in coated conductors is only about 1% of the substrate and buffer layer) and the need to add a normal metal stabilizer, typically equal to the superconductor cross-section. Thus the $J_c$ values of Figure 4 may be seriously misleading when applied to real conductors, of which in any case only BSCCO are available in lengths beyond 1 m today.

4.2 Temperature Capability

As suggested by Figure 4, it seems that only Y-123 is viable for making strong magnets at 77 K. The determining factor is the irreversibility field $H^*(T)$ at which the $J_c$ goes to zero [10]. This has typical values of 5 T (Y-123) and 0.3 T (Bi-2223) at 77 K. The BSCCO compounds do not achieve $H^*$ which exceeds 5 T until the temperature is reduced below about 25-30 K, while Y-123 has $H^*$ exceeding 20 T at such temperatures.

4.3 Strength

Pure Ag is very soft, but it can be hardened by alloying additions. Ag doped with ~0.5-2 wt.% Mg is the most favored present alloy, permitting yield strengths up to 350-Mpa which is more than 5 times the value for Ag sheathed tapes [11].

4.4 Length Availability

Today BSCCO-2223 available in 0.5-1 km lengths from several companies world wide in conductor forms such as that shown in Figure 2. Since such wide tape conductors have $I_c$ values of 100 A or less, they often need to be assembled in parallel. For magnets co-winding a stack of 3-5...
conductors is presently the most favored method, but this is rather primitive compared to accelerator demands and expectations from LTS conductors, where the fully transposed Rutherford cable is generally favored. Full (or at least one-layer) transposition can be attained in power cables by twisting the tapes around a core, since only operation in self field is required and the loss of space (often used for cooling) in the core is not material. The Pipatron concept for making a VLHC magnet is compatible with this form of cable [12]. Since the need to make aspected conductors from HTS compounds is fundamentally driven by their layered atomic structure, there is an important need to find new ways to cable HTS conductors or to use aspected conductors in new magnet designs. Recent common coil designs may be one such approach [13].

The most promising present conductor for saddle coil applications is in fact Bi-2212. The melt processing that is applied to make 2212 permits reasonable connectivity (the main factor controlling percolation and thus $J_c$) in round wire form. Scanlan’s group at LBNL have been developing this with several manufacturers and one such cable operating at ~4000 A at 4 K is shown in Figure 3. Such a cable is now being made in lengths of ~100 m and will soon be tested in coil designs common to Nb-Ti and Nb₃Sn conductors too, permitting a direct comparison of HTS and LTS performance. But LTS conductors have some way from being commodity items, because they are not yet available in more lengths and their form is that shown in Figure 2, and higher cost than competing LTS conductors. But LTS conductors have had some 35 years of development, strong improvements coming even in the last 10 years, making it not appropriate either to abandon LTS or HTS conductors. HEP magnet builders with HTS interests can now start to play an important role in developing the technology, pushing the development of HTS conductors in ways that have been so productive for LTS conductors [14]. And although not discussed here, HTS current leads are likely to be applied to all future accelerators, providing the first entry point of the new technology to HEP.

### 5 CONCLUSIONS

As this very brief review has summarized, HTS conductors suitable for HEP saddle coil applications are still some way from being commodity items, because they are still primitive, of lower working overall $J_c$ and higher cost than competing LTS conductors. But LTS conductors have had some 35 years of development, strong improvements coming even in the last 10 years, making it not appropriate either to abandon LTS or HTS conductors. HEP magnet builders with HTS interests can now start to play an important role in developing the technology, pushing the development of HTS conductors in ways that have been so productive for LTS conductors [14]. And although not discussed here, HTS current leads are likely to be applied to all future accelerators, providing the first entry point of the new technology to HEP.

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### 7 REFERENCES


