MULTI-PURPOSE FIBER OPTIC SENSORS FOR HTS MAGNETS[*]

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Abstract

Magnets using new high temperature superconductor (HTS) materials are showing great promise for high magnetic field and/or radiation environment applications such as particle accelerators, NMR, and the plasma-confinement systems for fusion reactors. The development and operation of these magnets is limited, however, because appropriate sensors and diagnostic systems are not yet available to monitor the manufacturing and operational processes that dictate success. Optical fibers are being developed to be embedded within the HTS magnets to monitor strain, temperature and irradiation, and to detect quenches. In the case of $Bi_2Sr_2CaCu_2O_x$ (Bi2212), the fiber will be used as a heat treatment process monitor to ensure that the entire magnet has reached thermal equilibrium. Real-time measurements will aid the development of high-field magnets that are subject to large Lorentz forces and allow the effective detection of quenches so that the stored energy of operating magnets can be extracted and/or dissipated without damaging the magnet.

INTRODUCTION

High energy physics (HEP) has been one of the primary drivers for the development of superconducting magnet technology for over 40 years. In this time, the HEP programs have brought NbTi to full maturity and are now seeing Nb_3Sn approach its performance limits as well [1-3]. NbTi and Nb_3Sn have upper critical fields (H_{c2}) of 14 T and 29 T, respectively, limiting magnetic field generation to about 10.5 T and 20 T. Thus, to generate the higher magnetic fields that will be required, for example, for an LHC energy tripler or a muon collider, a new conductor technology is required.

High temperature superconductors (HTS) may have significant impact on the development of high field superconducting magnets [2, 4, 5]. Significant progress has been made in HTS technology and two materials have significant potential for HEP magnets: $Bi_2Sr_2CaCu_2O_x$ (Bi2212) and $YBa_2Cu_3O_y$ (YBCO). Bi2212 is manufactured via a powder-in-tube process with Ag and AgX alloy sheathing. YBCO is manufactured using thin film deposition technologies on Ni-alloy substrates, resulting in a very thin layer of YBCO packaged with the central substrate and surrounded by Cu or other stabilizers. Cross sections of typical Bi2212 and YBCO conductors are shown in Figure 1.

Both Bi2212 and YBCO have very high critical current density (J_c) at 4.2 K in background magnetic fields of at least 45 T and have been used to generate magnet fields of at least 25 T. Thus, electrical performance may no longer be the primary limitation to high magnetic field generation. In comparing Bi2212 and YBCO, one finds that neither has a clear advantage; each has its strengths and weaknesses for HEP magnets. Bi2212 is the only HTS conductor with high J_c in an isotropic round wire; this is its primary advantage. Bi2212 is plagued, however, by relatively poor electromechanical performance and the need for a final heat treatment at about 890°C in pure oxygen. The poor mechanical properties imply that a react-and-wind magnet technology is not appropriate for high field magnets; too much of the allowed strain is "wasted" on bending strain. Thus, wind-and-react or a variant thereof is required and the final heat treatment poses significant challenges [6-8]. YBCO conductors are based upon a continuous deposition process and are fully processed before magnet construction; thus they are limited to react-and-wind magnets. YBCO conductors are only manufactured as wide, thin tapes, with significant electromagnetic anisotropy and a very low YBCO fraction within the conductor (~1%). Thus, while YBCO has significantly higher J_c than Bi2212, the engineering critical current density (J_e) ultimately may not be significantly higher.

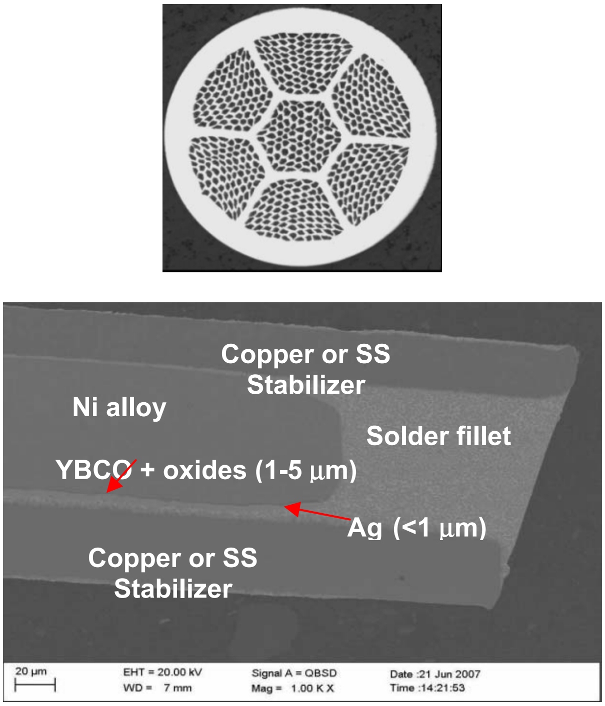

Figure 1: Typical Bi2212 (top) and YBCO cross-sections (only a portion of the YBCO width is seen).

HTS MAGNET CHALLENGES

The manufacturing of YBCO magnets is straightforward because the magnets are constructed after fully processing the conductor. For Bi2212 magnet manufacturing remains a key challenge because conductor processing is not finalized until after winding. Unlike Nb_3Sn, however, which is processed in an inert environment with a relatively temperature-insensitive heat treatment, Bi2212 requires an oxygen atmosphere and very narrow control of the peak processing temperature T_p. T_p is held for a short time; typically twelve minutes. At this temperature, the Bi2212 powder melt peritecticly. The Bi2212 phase is then recrystallized and grown during the subsequent cooling. This process results in well connected Bi2212 grains that provide the current paths. The need for peritectic melting and recrystallization in oxygen causes significant problems, including difficulty in scaling up the size of Bi2212 magnets. If the peak heat treatment temperature is too low, no liquid is formed and conductor J_e is very low. If the time at T_p is too long, then phase segregation occurs in the partial-melt and J_e is reduced. For large coils, finite thermal diffusivity implies that a significant length of time is required before thermal equilibrium at T_p is reached. Thus, if the heat treatment is not sufficiently long, then part of the coil will have very low J_e. If the time at T_p is too long then other sections will be over-processed and J_e reduced. Thus, the goal of magnet heat treatment is to remain at T_p just long enough to reach thermal equilibrium, but no longer. At present there is no effective method for identifying, real-time, when thermal equilibrium is reached.

HTS magnets face significant operational challenges that must be addressed before reliable, safe operation in large systems is realized. One issue is quench protection. In general, quench protection in large, high field magnets involves detection and protection. This has been studied extensively for LTS magnets for decades and the fundamental behaviors are well understood. Although LTS magnets do quench, they are usually well protected so conductor degradation is avoided. Qualitatively, quenching in HTS and LTS magnets is the same; the underlying electromagnetic and thermal physics is unchanged. There are significant differences, however, between LTS and HTS magnets that pose both opportunity and risk. One of the differences between HTS and LTS magnets is the large minimum quench energy; HTS magnets are significantly more stable with very large energy margins. This may be very attractive for HEP applications, particularly near the IR where large irradiation heat loads may exist. If superconducting magnets can be built with significantly larger MQE than existing magnets, then the magnet can be much closer to the IR and more effective use of the magnetic field results. Thus, in addition to the benefits of high field, HTS magnets offer the possibility of high heat load (irradiation resistant) magnets. The other key difference between HTS and LTS is that HTS magnets have significantly slower quench propagation velocity (QPV); as much as two orders of magnitude lower. As a result, quench detection is particularly difficult; this is the crux of the HTS protection challenge. In LTS magnets, typically the voltage over a length of conductor is monitored for purposes of detecting a quench. The voltage is a length-integrated electric field and a voltage measurement over a length of conductor gives no information regarding the distribution within the conductor. Note that because the electric field and voltage are a result of current sharing between the superconductor and stabilizer, there is a direct correlation between local electric field and local temperature. Because the QPV in HTS magnets is slow, by the time a detectable voltage is reached there may be a very high local temperature within the magnet which could be destructive. Thus, what is needed for quench protection in HTS magnets is a sensor capable of quickly detecting local temperature increases within the magnet.

Another operational issue that strongly influences the performance of HTS magnets is strain. Both YBCO and Bi2212 are strain-sensitive with J_e reduced and ultimately destroyed if the strain is too large. While the Ni-alloy substrate may provide sufficient maximum strain for in YBCO magnets, Bi2212 is particularly strain sensitive. Furthermore, it is possible that the quench protection limits in HTS magnets will include a strain limit. In complex magnets, load transfer between turns of conductor and between the conductor and structure is not always known as accurately as desired and stress concentrators may exist. Furthermore, the strain state of some complex windings that contain a variety of materials may not be easily calculated because of differential thermal contraction between the various materials. Lastly, it has been hypothesized that one of the underlying problems in Bi2212 processing is thermal expansion mismatch and thus strain in the Ag. Thus, to maximize usage of the allowed strain in the conductor, to ensure safe magnet operation over the desired magnet lifetime, and to qualify magnet design calculations, a detailed understanding of the conductor strain state is necessary.

FIBER OPTIC SENSORS

The development of sensors based upon fiber optics began over 30 years ago and fiber optic sensors are now commonplace in many situations [9]. Fiber optic sensors have the ability to measure strain, fatigue, temperature and pressure, often simultaneously. They are insensitive to electromagnetic interference, lightweight, compact (as small as 50 μm in diameter), available in very long continuous lengths (typically 50 km), electrically insulating and very sensitive. Fiber optics for detecting the strain state and the onset of quenches in LTS magnets has been under investigation intermittently for about 20 years and various schemes have been proposed based on different approaches. The primary focus has been on measurements of temperature, including concepts that focus on length-averaged measurements and localized measurements with various inter-measurement spacing [10-13]. With the significant progress in fiber optic sensor technology in the past ten years, and the compelling need for advanced sensors for HTS magnets, it is appropriate now to more aggressively pursue this technology.

One of the most recent advances in fiber optic sensor technology uses the Fiber Bragg Grating (FBG). The FBG is based on the more general phenomenon of the Bragg grating, whereby when a broad spectrum of light reaches a grating, all of the wavelengths will transmit, but only a certain wavelength will be reflected due to constructive interference. The reflected wavelength is the Bragg wavelength, λ_B, where the governing equation is

$$\lambda_B = 2N\lambda \qquad (1)$$

where n is the index of refraction and Λ is the spacing (pitch) of the grating. If a grating is created within a fiber and the fiber is exposed to a change in temperature or a strain, the grating pitch also changes, resulting in a change in Bragg wavelength which is found from

$$\Delta\lambda_B=\lambda_B\{[1-n^2/2(P_{12}-\nu(P_{11}+P_{12}))]\varepsilon+ [\alpha+(dn/dT)/n]\Delta T\} \qquad (2)$$

where ε is the strain, ν is Poisson's ratio, α is the coefficient of thermal expansion, and P_{ij} are the coefficients of the stress-optic tensor. This simplifies to

$$\Delta\lambda_B = \lambda_B \{[1- \rho_\alpha]\varepsilon + [\alpha+\xi]\Delta T\} \qquad (3)$$

where ρ_α is the photoelastic constant and ξ is the thermo-optic coefficient. These parameters are either known or readily measured. Thus, by measuring λ_B and $\Delta\lambda_B$ one can determine the temperature change and/or strain directly. Typical sensitivity is 1.2 pm/$\mu\varepsilon$ and 10 pm/^{o}C.

It is important to note that an individual FBG provides a local measurement at only one location along the optical fiber. There are two approaches to "multiplexing" whereby a single fiber can simultaneously provide distributed measurements along its length. The first is wavelength division multiplexing (WDM), which takes advantage of the fact that a single grating interacts only with light at λ_B, so if a broadband light source is used, all other wavelengths pass without interference. A single optical fiber is then used to measure the temperature and/or strain along its entire length by depositing gratings of varying pitch (λ_B) along the length and using a spectrometer to interpret the reflected signals. The only limitations are the need to have a few mm spacing between the gratings, and the measurement speed. Sensor and interrogator speed can be as high as 10 kHz with a minimal number of gratings, and is typically on the order of 100 Hz with a large number of gratings. Such measurement rates are sufficient for quench protection of HTS magnets. The second approach to multiplexing is time division multiplexing (TDM). With TDM, a pulsed broadband light source is used and the time required for the reflected signals to return is used to distinguish the response from each grating. This approach is much simpler and less expensive than WDM because the required hardware is less sophisticated. The sampling rate is also very high. There is a limitation to the sensor spacing, however, in that temporal separation between the returning signals must be sufficient. As a result, these systems are less common and less developed.

CONCLUSIONS

Fiber optic technology is being studied for multi-purpose sensors that are fully integrated into HTS superconducting magnets as co-wound insulation. The fiber optic sensor will serve as many as four purposes: temperature uniformity monitoring of Bi2212 magnets during heat treatment, localized temperature monitoring of Bi2212 and/or YBCO magnets during operation for quench detection, localized strain monitoring of Bi2212 and/or YBCO magnets during cool-down and operation to ensure acceptable levels are maintained and localized irradiation dosimetry within Bi2212 and/or YBCO magnets to predict magnet lifetime and to allow lifetime optimization by understanding the irradiation distribution. The successful development of a sensor that effectively serves any of these missions will be valuable to the development of HTS magnets for HEP applications, with the first two having the most potential for significant impact.

REFERENCES

[1] "Committee on Opportunities in High Magnetic Field Science: Opportunities in high magnetic field science," U.S. National Research Council, Washington, D.C. 2005.

[2] J. Schwartz *et al.*, *IEEE Trans. Appl. Supercond.* **18** (2008) 70-81

[3] A. Godeke *et al.*, *IEEE Trans. Appl. Supercond.* **18** (2008) 516-519

[4] A. Devred, S.A. Gourlay, and A. Yamamoto, *et al.*, *IEEE Trans. Appl. Supercond.* **15** (2005) 1192-1199

[5] H.W. Weijers *et al.*, *Supercond. Sci. & Tech.* **17** (2004) 636-644

[6] J. Schwartz and G.A. Merritt, *Supercond. Sci. & Tech.* **20** (2007) L59-L62

[7] X.T. Liu *et al.*, *IEEE Trans. Appl. Supercond.* **18** (2008) 1179-1183

[8] T.M. Shen *et al.*, *IEEE Trans. Appl. Supercond.* **18** (2008) 520-524

[9] B. Lee, *Optical Fiber Technology* **9** (2003) 57-79

[10] J.M. van Oort and H.H.J. ten Kate, *et al.*, *IEEE Trans. Mag.* **30** (1994) 2600-2603

[11] J.M. van Oort and R.M. Scanlan, *et al.*, *IEEE Trans. Appl. Supercond.* **5** (1995) 882-885

[12] S. Pourrahimi, *et al.*, *IEEE Trans. Appl. Supercond.* **7** (1997) 447-450

[13] J.H. Schultz, *et al.*, *IEEE Trans. Appl. Supercond.* **7** (1997) 455-460