Ultra-High Field Solenoids and Axion Detection

Mark D. Bird

Abstract High Temperature Superconducting (HTS) materials are now becoming incorporated into magnets that are being used for a variety of physics applications. Axion detection is a particularly attractive application for these conductors and there is significant promise that reliable systems can be built. However, there are still many challenges that are presently unresolved when it comes to building magnets of this scale from these materials. In particular, when a superconducting magnet quenches the energy stored in the magnetic field is converted into heat. If not controlled properly, the energy can be deposited in a non-uniform manner that results in excessive heating in some regions and damage to the magnet. For magnets using traditional Low Temperature Superconductors (LTS) methods of protecting the magnet during quench have been relatively well developed. For the HTS materials this development is presently underway, but no demonstrations protecting coils of the size needed for axion detection have yet been published.

Keywords Superconducting magnet · Axion detection · Quench protection

1 Introduction

The Axion Dark Matter eXperiment (ADMX) has been trying to detect axions for many years using an 8 T magnet with a 500 mm bore inside of which a radio-frequency resonant cavity has been installed along with various electronics. A primary parameter of interest in such searches is the square of the magnetic field integrated over the volume of the rf cavity, or approximately the square of the central field of the magnet multiplied by the volume of the detector, $B_0{}^2V$. Hence, large bore, high field magnets are vital to the search for axions. For ADMX, $B_0{}^2V$ is approximately 12 T^2m^3.

M. D. Bird (✉)
National High Magnetic Field Laboratory, Florida State University, Tallahassee, FL, USA
e-mail: bird@magnet.fsu.edu

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HTS materials were first discovered in 1986 and are also known to superconduct at higher fields than the LTS materials. NbTi is the most commonly used superconductor for magnets, being used in most magnets for Magnetic Resonance Imaging (MRI) as well as most superconducting dipole and quadrupole magnets for synchrotrons. It is also the conductor used in the present AMDX magnet. However, NbTi is limited to applications below approximately 10 T. Nb_3Sn is the other commonly used superconductor for magnets. It is frequently used in magnets for Nuclear Magnetic Resonance (NMR) or Condensed Matter Physics (CMP) having attained fields as high as 23.5 T.

The cheapest way to attain higher $B_0{}^2V$ than in the present ADMX would be to build a large bore, modest field magnet using NbTi. For example, a commercial human whole body MRI magnet has a bore of ~90 cm and can provide field up to 7 T routinely with some examples having been delivered up to 9.4 T and one at 10.5 T. A new MRI magnet in France has been delivered and energized to 11.74 T with $B_0{}^2V$ ~ 430 T^2m^3 but is not yet fully operational. Another extreme example is the Compact Muon Solenoid detector installed on the Large Hadron Collider at CERN which provides 4T in a bore of 6 m, for $B_0{}^2V$ ~ 5300 T^2m^3.

However, given the expected energy of the axion, the rf cavities must be of modest size, which would require slaving many of them together to build a next-generation axion detector based on NbTi magnets. Based on these constraints in cavity design, the bore of the magnet should be ~16 cm and the length of the rf cavity should be no more than 2.5 times the diameter. This leads us to need extremely intense magnetic fields for which HTS materials are uniquely well suited.

2 Present HTS Magnet State of the Art

There are presently three HTS conductors to be considered for this application: BiSCCO-2212, BiSCCO-2223, and REBCO. All three superconduct above 100 T, all have adequate current-density at 20–40 T for construction of an ultra-high-field (UHF) magnet. Rare Earth Barium Copper Oxide (Y or Gd being the Rare Earth component) was the first to become available in a high strength form suitable for UHF magnets. In 2007 SuperPower provided a conductor consisting of ~40 μm of Hastelloy with some buffer layers, ~1 μm of YBCO, Ag, and Cu cladding. The National High Magnetic Field Laboratory (MagLab) proceeded to build some test coils and secured funding to develop a 32 T superconducting magnet for CMP. This magnet has now reached field and is expected to start to serve the user community in the coming months [1].

In 2010 Seungyong Hahn, Yuki Iwasa, and others at MIT presented a new concept for UHF magnets: No-Insulation (NI-) REBCO. In this approach there is no insulation on the composite superconducting tape [2]. LTS magnets require insulation on the conductor. When an insulated conductor quenches (converts from superconducting to normal state), the current moves from the superconducting material to the Cu and Ag within the composite conductor. If the current-density is too high, the power density will be too high and the conductor will start to melt before the magnet is de-energized. To prevent this, a significant fraction (50–80%) of the conductor cross section is usually Cu. With HTS conductors it becomes possible to leave out the inter-turn insulation. In this case, when the conductor quenches, the current can move into Cu and Ag in adjacent turns of conductor. Less Cu is needed in individual tapes, the cross section of the conductor can become smaller, the current-density of the magnet becomes larger, and the size of the magnet becomes much smaller. The dominant stress in a solenoid is proportional to the product of magnetic field, current-density, and radius of the turn of conductor. When the size drops, the stresses reduce and less reinforcement materials are required. This results in still more reduction in size. The highest field attained purely with this technology is 26 T that was reached by a coil of only 17 cm outer diameter designed by Hahn, built by SuNAM, and tested at the MagLab in 2015 [3]. A smaller coil reached 14.4 T while operating inside a 31.1 T resistive magnet for a total field of 45.5 T at the MagLab in 2017 (see https://nationalmaglab.org/news-events/news/mini-magnet-packs-world-record-punch).

In 2013 a new ultra-high strength version of Bi-2223 tape became available from Sumitomo. It has been used by Satoshi Awaji and others at the Tohoku Magnet Lab to complete a 24 T magnet that was commissioned in early 2017 and is presently serving the CMP community [4].

Bi-2212 has been transformed in recent years into a very high current-density conductor and concepts are being developed for high-strength reinforcement to enable UHF magnets [5].

3 Proposed Magnet Concepts for Next-Generation ADMX

A number of conceptual designs have been created for magnets with 16 cm bore and fields ranging between 24 T and 30 T. One approach would be to build a system that is nearly a copy of the MagLab's 32 T magnet leaving out the innermost REBCO coil. With this approach, 24 T in 16 cm should be achieved with low risk. It should also be possible to build a 30 T, 16 cm bore magnet using this approach but using more HTS material and less LTS material than in the existing 32 T magnet. These approaches would benefit from the extensive development effort that enabled the 32 T magnet system to be completed, including extensive quench analysis and testing [6].

Another approach would be to use the newer NI-REBCO technology. This might result in much more compact coils that provide similar field in a similar bore size. However, NI-REBCO has not yet had a comprehensive analysis of behavior during quench and development of a means to prevent damage during quench.

4 Managing High Energy Quenches

During quench the energy stored in the magnetic field (½ LI^2, where $L =$ inductance and $I =$ current) is converted into heat. As mentioned above, if this heating is not uniform, it can destroy a coil. To reduce heating, most commercial magnets include resistors and back-to-back diodes across the coils or sections of coils. If a quench occurs in a coil, the voltage builds up until it reaches the diode breakdown voltage at which point the diode allows current to flow through a bypass around the coil. This allows the current in the normal zone to drop and avoid overheating. The energy is dissipated in the resistors. (Back-to-back diodes are used so the magnet can operate at either positive or negative field.)

However, the drop in current in one coil induces voltage on the adjacent coils (transformer effect) which, coupled with the diodes, results in the current in the second coil to rise. When the current in the second coil gets too high, this coil in turn will quench and decay, and current will be induced in the next coil. During this process, a coil might operate at higher current than during normal steady-state operation and be more highly stressed than intended. To avoid either overheating or overstressing the coils, the designer must consider the interaction of all the inductances, resistors, diodes, and the evolution of the resistance of the coils during the quench process [7]. Many magnets have been destroyed over the years due to insufficient attention to quench protection.

For NI-REBCO coils, the same phenomenon occurs, except on a much larger, or finer, scale. Each turn of conductor is an independent inductor and the contact area between each pair of turns is a resistive element. The turn itself has variable resistance depending on the temperature, field, and current. Instead of a few or dozens of coil sections, there are thousands or tens of thousands of turns interacting with each other.

Figure 1 shows the current distribution in an NI-REBCO coil during quench as computed by Markiewicz in 2015 [8]. All turns in the coil were originally at 200 amps. When a quench was introduced at the top of the coil (disk 1, left in the figure) current started redistributing around the resistive section. Mutual inductance between the turns caused current spikes in various turns as a quench wave passes from the top of the coil to the bottom. Computed current spikes are >3 times the normal operating current of 200 A. These current spikes can result in high hoop stresses within a coil as well as high forces between multiple nested coils.

The 32 T magnet at the MagLab stores 8 MJ of energy, ~0.3 MJ of it in the HTS coils. For comparison, 20 T LTS magnets sold by Oxford Instruments installed at the MagLab store 1–2 MJ depending on when they were built. A stick of dynamite also stores ~1 MJ of energy. Table 1 lists several HTS magnets in development worldwide over recent years with goals of reaching 24 T or greater as well as the amount of energy stored by the HTS parts of those magnets. The table does not include lower field magnets because such fields are attainable by LTS magnets and it does not include small test coils that stored <0.1 MJ of energy. Also note that Bruker does not publish anything about their progress towards 1.1–1.2 GHz NMR

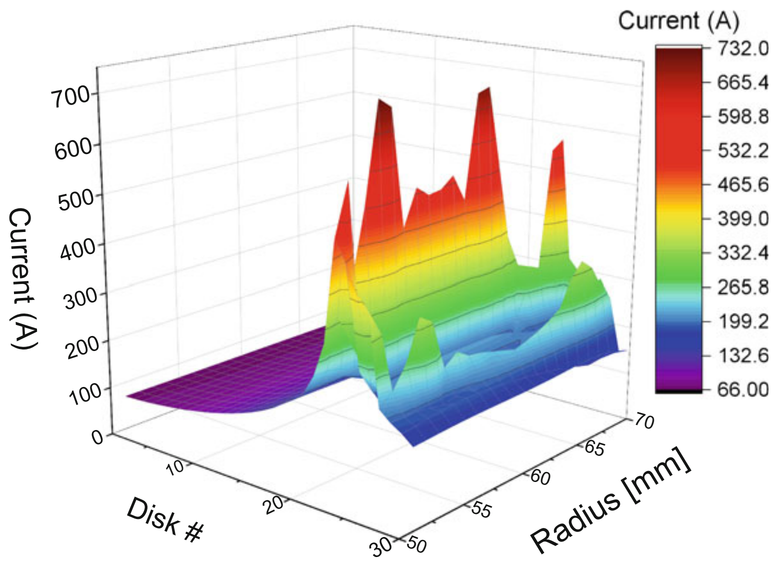

Fig. 1 Axisymmetric model of current distribution in an NI-REBCO coil during quench. Each turn has a position along the length (from disk 1 at the top to disk 30 at the bottom) and in the depth along the radius (1–20 mm from the inner radius). The current was initially 200 A in all turns. At this point 271 ms into the quench, some turns have >600 A which might lead to excessive hoop stress

magnets, so they might have destroyed coils that are not reported here. We see that only eight coils worldwide of this field and energy have been built to date and that four of those were destroyed by quench and are not expected to be put into service. The exceptions are a 24 T magnet in Sendai, Japan completed in 2017, the 32 T magnet completed in 2017 at the MagLab in Tallahassee, and the 25.8 T and 28.2 T NMR magnets by Bruker that reached performance specifications in 2019. We see that the largest amount of energy stored by a successful HTS magnet to date was 0.4 MJ. (Many smaller HTS test coils have been destroyed that stored much less than this.) Conceptual designs for axion detectors store 1.7–10 MJ.

5 Proposed Development Route

Reliable quench detection systems have been developed for LTS magnets (all commercial firms and government labs have them) and they are being developed for HTS magnets also. Doing so requires meaningful numerical modeling of quench in these magnets and benchmarking of the computational results with experimental ones. Then approaches can be proposed and modeled for protection systems which will also need to be tested. The MagLab has been performing quench analysis for

Table 1 Partial list of various HTS coils built or under development to date that were intended to reach fields >23 T

Use	Field	Cold Bore	Amount of HTS	HTS stored energy	Technology	Organization	Year
Condensed matter, other	**25 T**[a]	**4 cm**	**2.1 km**	**0.1 MJ**	**I-REBCO + Bi-2223 + LTS**	**Riken**	**2015** [9]
	28 T[a]	**4 cm**	**2.1 km**	**0.1 MJ**	**I-REBCO + Bi-2223 + LTS**	**Riken**	**2015** [10]
	25 T[a]	**5 cm**	**14 km**	**0.4 MJ**	**I-REBCO + LTS**	**Tohoku**	**2016** [11]
	24 T	**5 cm**	**11.4 km**	**0.4 MJ**	**Bi2223 + LTS**	**Tohoku**	**2017** [12]
	32 T	**3 cm**	**9.4 km**	**0.3 MJ**	**Ins-REBCO + LTS**	**MagLab**	**2017** [1]
	35 T	*4 cm*	*45 km*	*1.8 MJ*	*NI-REBCO*	*KBSI, MagLab*	[13]
	40 T	3 cm	>15 km	>2.8 MJ	REBCO	MagLab	
NMR	**25.8 T**				**I-REBCO + LTS**	**Bruker**	**2019** [14]
	28.2 T				**I-REBCO + LTS**	**Bruker**	**2019** [14]
	30.5 T[a]	**6 cm**	**12 km**	**0.3 MJ**	**NI-REBCO + LTS**	**MIT**	[15]
	30.5 T	9 cm	~30 km		Bi-2223 + LTS + misc.	RIKEN	2023 [16]
Axions	**24 T**[a]	**3 cm**	**9.4 km**	**0.4 MJ**	**NI-REBCO**	**KBSI, SuNAM, CAPP**	**2015** [17]
	25 T	10 cm	~36 km [2]	1.7 MJ	NI-REBCO	Brookhaven, CAPP	2018 [18]
	30 T	*16 cm*	*30 km*	*2.5 MJ*	*NI-REBCO + LTS*	*MagLab, ADMX*	
	30 T	*16 cm*	*40–60 km*	*6–10 MJ*	*NI-REBCO*	*MagLab, ADMX*	

Bold font indicates coils that have been tested to date
Plain font indicates coils under construction presently
Italics font indicates coils that have been proposed
[a]Indicates coil that has been damaged and removed from service

I-REBCO coils for many years as part of our 32 T magnet project and has developed a reliable protection system. A particular test coil was intentionally quenched >100 times without damage

Analysis of NI-REBCO coils has been published by a few groups (some results shown above). Improvement of modeling is underway and the development of protection systems is starting at the MagLab and elsewhere. However, there remains a significant amount of work in this field to be completed prior to having reliable magnets using NI-REBCO.

Another challenge is materials cost. Presently HTS materials are extremely expensive. However, most manufacturers claim costs can and will be reduced as volume of production increases.

6 Conclusions

While the HTS materials show tremendous potential to enable UHF magnets, there is presently only one magnet operating routinely at higher field than is available from LTS magnets. Several challenges remain to be overcome prior to reliable HTS magnets becoming widespread. Leading among these are quench protection and cost. Great progress is presently being made on quench protection. In 2017 the highest field attained by an all-superconducting magnet jumped from 27 to 32.1 T. This tremendous increase is the result of a 9-year development effort at the MagLab. While the route to still higher fields or larger bores seems much clearer than it was a few years ago, there remains a great deal of work to complete. Modeling of quenches in HTS coils is advancing quickly and reliable magnets should become routine in the coming years.

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