Stable, predictable operation of racetrack coils made of high-temperature superconducting Bi-2212 Rutherford cable at the very high wire current density of more than 1000 A/mm$^2$

Tengming Shen$^1$, Jianyi Jiang$^2$, Ernesto Bosque$^2$, Marvis White$^3$, Daniel Davis$^{1,2}$, Kai Zhang$^1$, Hugh Higley$^1$, Marcos Turqueti$^1$, Yibing Huang$^4$, Hanping Miao$^4$, Ulf Trociewitz$^2$, Eric Hellstrom$^2$, Jeffrey Parrell$^4$, Andrew Hunt$^3$, Steve Gourlay$^1$, Soren Prestemon$^1$, David Larbalestier$^2$

$^1$Lawrence Berkeley National Laboratory, Berkeley, CA 94720, USA

$^2$National High Magnetic Field Laboratory, Florida State University, Tallahassee FL 32310, USA

$^3$nGimat LLC, Lexington, KY 40551, USA

$^4$Bruker OST LLC, Carteret, NJ 07008, USA

*Email: tshen@lbl.gov

Abstract

Uncertain performance and long training with many unpredictable quenches and slowly increasing quench currents are characteristic of the accelerator magnets needed for high energy particle accelerators, particularly the Nb$_3$Sn magnets planned for future high energy proton colliders. This behavior makes high-temperature superconductor (HTS) magnets a potential option, even though there are many concerns about protection of such magnets during quench. Here we describe the performance of two recent racetrack coils made with a 17-strand Rutherford cable with state-of-the-art Bi-2212 wires capable of delivering current density up to 1000 A/mm$^2$ at 27 T. The coils carried up to 8.6 kA while generating a peak field of 3.5 T at 4.2 K, at a wire current density of 1020 A/mm$^2$. Quite differently from Nb-Ti and Nb$_3$Sn magnets, these Bi-2212 magnets showed no early quenching indicative of training, showed virtually no dependence of quench current on ramp rate, and entered the flux flow state in a stable manner before thermal runaway and quench occurred. These magnets show the huge potential of Bi-2212 as a high field conductor which is, like Nb-Ti and Nb$_3$Sn, isotropic, round and multifilament and suitable for Rutherford cable use but, unlike them, much more tolerant of energy disturbances that often lead Nb-based superconducting magnets to premature quench and long training cycles. The observation of stable voltage across the coils before thermal runaway removes one of the great concerns about being able to detect the onset of quench in a timely manner in HTS magnets, a prerequisite for triggering an appropriate quench protection strategy.
High field superconducting magnets are used in particle colliders\textsuperscript{1}, fusion energy devices\textsuperscript{2}, medical imaging devices (MRI) and ion beam cancer therapy\textsuperscript{3}. So far, virtually all superconducting magnets have been made from two Nb-based low temperature superconductors (Nb-Ti with superconducting transition temperature $T_c$ of 9.2 K and Nb$_3$Sn with $T_c$ of 18.3 K). The 8.33 T Nb-Ti accelerator dipole magnets underpin the LHC at CERN, enabling the discovery of the Higgs Boson and ongoing search for physics beyond the standard model of high energy physics, whereas Nb$_3$Sn magnets are a key to the ITER Tokamak, and a high-luminosity upgrade of the LHC that aims to increase the luminosity of the LHC by a factor of 5-10\textsuperscript{4}.

Nb-Ti and Nb$_3$Sn magnets predominately work at 1.8-5 K, generating magnetic fields seldom greater than 20 T. The superconductor and magnet communities have long sought to broaden the superconducting application space to higher fields at low temperatures (4.2-20 K) or higher temperatures (20-77 K) using high-temperature superconductors (HTS)\textsuperscript{5}. Both cuprate superconductors, discovered in the 1980s, and iron-based superconductors, discovered about 10 years ago, have upper critical magnetic fields exceeding 50 T at 4.2 K\textsuperscript{6,7}, much greater than that of Nb-Ti (~14 T at 1.8 K) and Nb$_3$Sn (~26-27 T at 1.8 K), making them potentially useful for making much stronger high-field magnets\textsuperscript{8}, like the 30 T superconducting solenoids needed for 1.3 GHz NMR spectrometers\textsuperscript{9} and 20 T accelerator dipoles for a potential high-energy upgrade of the LHC\textsuperscript{10}. Significant progress has recently been made towards making this vision a reality, particularly in solenoids made of REBa$_2$Cu$_3$O$_x$ (REBCO), culminating in a 32 T user solenoid recently constructed at the National High Magnetic Field Laboratory (NHMFL)\textsuperscript{8,11}. After three decades of arduous conductor development, high-temperature superconducting cuprate conductors, including Bi-2212\textsuperscript{12}, Bi-2223, and REBCO\textsuperscript{5}, are being commercially produced in practical forms of metal/superconductor composite conductors in lengths suitable for making magnets. These materials can deliver high critical current density in strong magnetic fields at 4.2 K or 1.8 K above 23 T, where the $J_c$ of Nb$_3$Sn wires ceases to be useful.

All superconducting magnets are susceptible to quench\textsuperscript{13,14} when local regions lose superconductivity, producing hot spots with rapidly rising temperature that may, without suitable protection, lead to local degradation or burnout. Nb-Ti and Nb$_3$Sn magnets, having low superconducting $T_c$, are comparatively unstable, relatively intolerant to small energy inputs and thus frequently characterized by premature quench, long quench training, and unpredictable performance. Long quench training is particularly an issue for the 11-16 T Nb$_3$Sn dipole magnets planned for future high energy proton...
colliders, making higher $T_c$ more stable HTS magnets a potential option. Despite frequent Nb-Ti and Nb$_3$Sn magnet quenches, protection during quench is generally not an issue because quench propagation velocities are rapid and the stored magnetic energies can be safely dissipated within the coil or transferred to an external protection circuit. By such methods, even magnets with wire engineering (i.e. whole wire) current density of 1000 A/mm$^2$ have rarely been damaged. On the other hand, the much higher stability of HTS magnets makes quench less likely but, when it does occur, a much bigger threat than in LTS magnets because normal zones are smaller, quench velocities much smaller, and the energy deposited in the normal zone much larger. Several HTS magnets systems have been degraded during quench when the small normal zones generated too little voltage for warning, making active quench protection too late to adequately protect the magnet from local overheating as the magnetic energy turned into very localized heating$^{15-19}$. A key challenge of HTS magnets is thus the timely detection of small hot spots that grow only at several cm/s, rather than the two orders of magnitude larger rate in Nb-Ti and Nb$_3$Sn magnets.

All of these concerns are much reduced in the Bi-2212 magnets we describe here. We report very high wire current density $J_E$ of up to 1000 A/mm$^2$ in an isotropic, multifilamentary HTS Bi-2212 round wire Rutherford cable$^{12}$. Optimally processed wires of the same type have shown $J_E$ up to 1000 A/mm$^2$ at 4.2 K and 27 T. We demonstrate stable operation of racetrack coils made from Rutherford cables above 8 kA, quadrupling the performance of a dozen such coils made before 2016$^{20}$. Quench protection concerns are greatly alleviated by our ability to observe stable voltages across the coil before thermal runaway and quench, an observation that allowed us to switch in a protection resistor to protect the coil during each of the many quenches that we imposed on the coils.

**Methods**

**Wire design and fabrication**

A 440 m long, 0.8 mm diameter Bi-2212 round wire was fabricated by Bruker OST LLC by their standard powder-in-tube technique using a novel, innovative precursor Bi-2212 powder made at nGimat LLC by nano-spray combustion technology. This new powder appears to eclipse the earlier industrial benchmark powder made by the melt-casting approach at Nexans, because it yields $J_E$ approximately 50% larger. The wire has an architecture of 55 x 18 (18 bundles of 55 filaments). The Bi-2212 filling factor of the as-drawn wire is ~25% and porosity occupies roughly 30% of the filament cross-section as delivered. The matrix Ag surrounding the filaments has a very high electrical conductivity of as judged by a resistance ratio >100 and very high thermal conductivity$^{21,22}$. 
Cable fabrication

17-strand Rutherford cables were made at LBNL with a width of 7.8 mm and a thickness of 1.44 mm. The cable insulation was a braided mullite sleeve with a wall thickness of ~150 μm.

Coil design, fabrication, and test

Two 2-layer, 6-turn/layer subscale racetrack coils (RC5 and RC6) were wound on an Inconel 600 pole island without any internal joints using 8 m long Rutherford cables with 140 m of 0.8 mm wire in each cable. Each coil was assembled inside an Inconel 600 structure (side bars plus top and bottom plates) and then heat treated by an overpressure processing heat treatment (OPHT) technology at the NHMFL with a gas pressure of 50 bar in flowing Ar/O2 (oxygen partial pressure P_{O2} = 1 bar). OPHT removes most of the starting porosity in the wire, increasing the filament density to >95%. The coil and its reaction structure weighs ~8 kg and measures 37 cm x 12 cm x 3.1 cm. After reaction, the coil was instrumented with voltage taps on each turn, and impregnated with epoxy resin (RC5 used the rather brittle CTD 101K epoxy adopted for High-Luminosity LHC (HL-LHC) Nb3Sn magnets, while the more fracture-resistant NHMFL “mix-61” epoxy, developed for the large-bore 900 MHz NMR magnet was used for RC6).

The coils were tested inside their Inconel reaction structure. They were powered with a 20 V, 24 kA DC power supply, and the terminal voltages monitored using a fast, FPGA-based quench detection system. Upon detecting a quench, the FPGA board sent commands to open an SCR electrical switch that inserted a room temperature dump resistor (20 mΩ) across the coils, forcing the magnet current to decay to zero within <10 ms. The magnet voltage was recorded using a 16-bit ADC system with a programmable isolation amplifier and a flexible, software-controlled measurement range that could be set from ±0.1 mV to ±5 V at both 10 Hz and 1 kHz. The best measurement resolution was 0.1 μV at 1 kHz.

Results

The high critical current density of these Bi-2212 wires

The 4.2 K wire current density J_{c} of the optimally processed strand used in this study is shown in Figure 1. J_{c} is greater than that of the HL-LHC RRP Nb3Sn strand above 11 T and it also has a much less field-sensitive characteristic, achieving 1365 A/mm^2 at 15 T, twice the target desired by the Future Circular Collider (FCC) of Nb3Sn strands\textsuperscript{23}, and 1000 A/mm^2 at 27 T, 60% better than the previous record Bi-2212 performance\textsuperscript{24}. 
**Magnet behavior no different from Nb-Ti and Nb\textsubscript{3}Sn magnets**

Ramping up the current of any superconducting magnet eventually leads to a quench, and this was no different for RC5 and RC6. The coil voltages of RC5 and RC6 shown in Figure 2 exhibit characteristic quench behavior, with \( V_{13} \) (the whole coil terminal voltage) and \( V_{13} \) (one half of the coil) going positive due to its entering the dissipative state first, while \( V_{23} \) (the second half the coil) tends negative due to its inductive response to the growing normal zone in coil 1. Despite the small coil inductance (~35 \( \mu \)H), the voltage noise is on the order of mV, making it difficult to set the quench detection voltage to be less than 10 mV. Both coils quenched above 8 kA. The peak quench current of RC6 was 8600 A, generating a peak field of 3.5 T, which quadrupled the performance of a dozen coils\textsuperscript{20} made before 2016 with less good wire and without the full densification possible with OPHT. At 8600 A, the wire \( J_e \) and the cable \( J_e \) exceeded 1000 A/mm\(^2\) and 750 A/mm\(^2\), respectively, very high values which are highly desirable for accelerator magnet applications.

**Magnet behavior qualitatively different from Nb-Ti and Nb\textsubscript{3}Sn magnets**

In strong contrast to Nb-based superconducting accelerator magnets whose \( I_q \) decreases with increasing current ramp rate \( dl/dt \) due to heating by eddy currents and hysteretic losses (e.g. \( I_q \) decreased by ~60% on raising \( dl/dt \) from 5 A/s to 200 A/s for a Nb\textsubscript{3}Sn US LARP quadrupole magnet\textsuperscript{25}), the quench current of RC5 and RC6 actually increased slightly on raising \( dl/dt \) from 30 A/s to 200 A/s (Figure 3) and they exhibited no quench training at all. Also in strong contrast, the Nb\textsubscript{3}Sn magnets being built for the HL-LHC have shown a lengthy training with only slow increase of \( I_q \), and some have also shown a detraining behavior, during which the quench current suddenly drops by 10% or as much as 1 kA. This makes the great stability of the quench current of these two Bi-2212 magnets, RC5 and RC6, very noteworthy: \( I_q \) remained nearly unchanged (average current = 8604 A, standard deviation = 4.1 A for RC6) during consecutive quenches and after thermal cycling to room temperature and back to 4.2 K (Figure 4). Thus, in strong contract to the unpredictability of Nb\textsubscript{3}Sn accelerator magnets, RC5 and RC6 showed a very stable and predictable performance.

To examine the nature of the RC5 and RC6 quenches, the magnets were powered up using a staircase scheme, during which the coil current was periodically held constant so as to zero any inductive voltages, minimize noise and allow the maximum insight into dissipation within the coils. The terminal and turn-to-turn voltages of RC5 (Figure 5) show that several turns had started to dissipate when the terminal voltage \( V_{13} \) exceeded 0.1 V, which indicates that quench was triggered by a significant length of cable entering the dissipative state, rather than being triggered by point disturbances as is generally
the case for Nb$_3$Sn magnets. The signals taken during stable-current portions of the staircase ramp show that resistive voltage signals become visible at 7000 A well below the >8000 A of $I_q$ and they steadily increase with increasing current. From $t = 447$ s to $t = 507$ s, the current was held at 7925 A and the resistive voltage of the ramp turn (a 14 cm long section that transitions between the two coil layers in the peak field region. See Figure 5c) was 3.6 $\mu$V, generating a steady joule heating of 28.5 mW. The total heat input during this hold from 447 to 507 s was $\sim$1.71 J, though significant, did not cause the coil to quench. When the coil current was held at 8130 A, the resistive voltage of the ramp turn was 9.4 $\mu$V and the joule heating 76.4 mW, which caused a thermal runaway in less than 4 seconds. Such a high thermal stability is in strong contrast to the instability that characterizes Nb-Ti and Nb$_3$Sn magnets, for which a disturbance as small as 1 $\mu$J is sufficient to cause the coil to quench.

**The global superconducting-normal transition: Coil E-I curve and $I_c$**

Figure 5 plots the E-I curve of RC5 and RC6, where the electric field $E$ is derived from the resistive signals during the current-hold parts of the staircase current ramps. Figure 5 suggests that the resistive signals were driven by the power law losses ($V \sim I^n$, where $n$ is 20-30) during the smooth transition of the Bi-2212 cable from the superconducting to the normal state. The critical current $I_c$, defined at an electric field criterion of 0.1 $\mu$V/cm, was 7550 A for RC5 and 7750 A for RC6. The $n$-values determined by the power law fitting the E-I curve were 22 for RC5 and 24 for RC6, values very similar to those obtained in short wire samples. This speaks to the excellent uniformity and current sharing of the Rutherford cables used in these two magnets.

**Discussion**

*An Achilles’s heel of Nb-Ti and Nb$_3$Sn magnets: Instability and unpredictable quenches*

Nb-Ti and Nb$_3$Sn magnets have been key to major particle physics and nuclear physics colliders including the Tevatron, RHIC, HERA, and LHC. However, an important drawback of Nb-Ti and Nb$_3$Sn superconducting magnets is their low thermal stability. Tiny, transient point disturbances as small as $10^6$ J from conductor motion are very common due to the large thermal and electromagnetic stresses and they can cause localized temperature rises sufficiently large to initiate quench of the whole magnet. The small thermal margin of Nb-Ti and Nb$_3$Sn and their low heat capacity below $T_c$ give them little protection against such energy inputs. To overcome such instabilities, the main-ring LHC Nb-Ti dipole and quadrupole magnets are cooled by 1.8 K superfluid helium that penetrates into windings and acts as a powerful coolant since its thermal conductivity and specific heat are much higher than
that of the oxygen-free-high-conductivity copper (OFHC) that thermally stabilizes and protects the Nb-Ti cable during quench. However, the quench problem is troublesome for the Nb$_3$Sn magnets being considered for future high-energy proton colliders and a high-energy upgrade of the LHC, in spite of its $T_c$ being twice that of Nb-Ti (18 versus 9 K). The reason is that Nb$_3$Sn windings cannot be permeated with superfluid helium because they must be epoxy-impregnated to protect them against the large crushing forces in the magnets. Impregnated magnets also often experience epoxy cracking and interfacial shearing and debonding. The consequence of the poor thermal conductivity of the winding and increased disturbances is long quench training, currently often as long as 30 quenches for the HL-LHC Nb$_3$Sn quadrupole magnets$^{26}$. Such training results in significant helium loss and high labor costs, significant drawbacks in considering future high-energy proton-proton colliders that need thousands of such magnets.

For other smaller scale, one-of-a-kind physics experiments, this problem can also be severe. A good example is MICE, the Muon Ionization Cooling Experiment, that selected cryocooler-cooled, epoxy-impregnated Nb-Ti construction for the coupling and spectrometer solenoids. Both MICE solenoids went through a long training despite using a highly stabilized wire with a high Cu to superconductor ratio of 3:1. Due to its high stored magnetic energy, each quench of the Nb-Ti spectrometer solenoid evaporated 800 L of liquid helium. Even worse, the MICE spectrometer solenoids had a poor memory of training and needed to be retrained after thermal cycling$^{27}$. The cost of training these magnets, despite the low cost of Nb-Ti wires, was a big financial distress.

**High stability HTS magnets: Predicting quenches from high-precision voltage measurements**

Long quench training of Nb$_3$Sn magnets is a cumbersome and costly problem but failing to detect a quench in a much more stable HTS magnet puts the HTS magnet in greater danger because the dissipative zones maybe too small to generate much voltage and they do not propagate rapidly. A key concern for an HTS magnet is thus the need to detect quench. The state-of-the-art quench detection for Nb-Ti and Nb$_3$Sn magnets relies on fast (>10 k-samples/s) but low precision (mV resolution) voltage measurements above a typical threshold in the range of 100 mV to several volts. Due to the fast quench propagation velocities (typically 10 m/s for Nb-Ti and Nb$_3$Sn magnets), 100 mV develops across growing normal zones in a negligible 0.1 ms. By contrast, at the typical 1 cm/s quench velocities of HTS conductors, resistive voltages of a localized hot spot may increase well less than 0.1 mV within 0.1 ms. At the high wire engineering current density of 1000 A/mm$^2$ safely demonstrated in these Bi-2212 racetrack magnets, hot spot temperatures can rise at hundreds of K/s, thus making
rapid detection and rapid switching of the dump resistor vital to ensure a safe quench. A detection signal that occurs at <10 ms is needed to avoid a high hot spot temperature that would render the magnet unusable after quench.

Figure 2 indeed shows that we could safely quench our Bi-2212 magnets and figure 5 shows why this is possible. The staircase ramps of the magnet show that non-localized, several-meter long Bi-2212 Rutherford cable develops stable low voltages and then enters thermal runaway nearly simultaneously as it enters the resistive transition due to its high uniformity and excellent current-sharing. Stable voltages in the µV regime appear across the coil well before thermal runaway. These voltages are stable for tens of seconds, a time scale orders of magnitude larger than quench development in Nb-Ti and Nb₃Sn. The extra thermal margin of the high-\(T_c\) conductor thus offers a new opportunity for quench detection using active, fast (1 kHz sampling rate), high precision (0.1 µV resolution) voltage measurements.

The voltages observed during staircase powering (Figure 5) reveal the µV resistive signals often covered up by the large inductive signals or noise of a fast ramp and make possible prediction of the quench currents shown in Figure 2. Reliable prediction thus enables avoidance of quenches, making RC5 and RC6 quench-free in normal operation, though we did quench it for explicit study of quench. This was demonstrated with RC6: We predicted the quench current of RC6 before driving it to quench and demonstrated that it could be ramped to and held at <8200 A without quench, even though it was in the dissipative, flux-flow state, a situation quite impossible for an impregnated Nb-Ti or Nb₃Sn magnet. This behavior points out an important potential for training-free Bi-2212 accelerator magnets. The training-free characteristics of RC5 and RC6 partly come from their simple racetrack geometry and mechanical structure but our argument is that it mostly stems from their ability to tolerate small energy disturbances produced by wire movement and epoxy cracking due to the higher thermal margin of Bi-2212. This is a highly significant result that will likely extend into the high field 10-30 T regime too because of the weak dependence of their \(J_c\) on magnetic fields.

**Conclusions**

We have demonstrated here that the exceptionally high wire current density of 1000 A/mm² can be reached in an HTS Bi-2212 magnet and that such a magnet can be safely protected against quench due to the highly uniform resistive transition of the cable that permits detection of the resistive transition voltages well before quench. This work thus shows high \(J_c\) operation and safe quench detection and protection. This high critical current density, together with new designs of magnets
such as the canted cosine theta geometry\textsuperscript{28,29}, makes it possible to envision 20-T class accelerator magnets useful for future high-energy colliders, such as a high-energy LHC upgrade. Many other magnet applications can also be foreseen, such as 30 T solenoids and \textgreater{}1.3 GHz NMR magnets due to its being the only isotropic, multifilamentary HTS round wire that permits high magnetic field quality.

Acknowledgements

Work at LBNL was supported by the Director, Office of Science of the U.S. Department of Energy (DOE) under Contract No. DE-AC02-05CH11231. Work at the NHMFL was supported by the US DOE Office of High Energy Physics (OHEP) under grant number DE-SC0010421, by the National Institutes of Health under Award Number R21GM111302, and by the NHMFL, which was supported by the National Science Foundation under Award Numbers DMR-1157490 and DMR-1644779, and by the State of Florida. Work at Bruker OST and nGimat was supported by the U.S. DOE OHEP through a SBIR award DE-SC0009705. This work was amplified by the U.S. Magnet Development Program (MDP). T.S. acknowledges support from the U.S. DOE Early Career Research Program, K.Z. acknowledges support from the China Scholarship Council, and D.D. acknowledges support from the U.S. DOE Office of Science Graduate Student Research Program. We are all grateful to our colleagues at our respective institutions for technical assistances.

Author contributions

T.S., D.L., S.G. and S.P. planned the research and T.S. supervised the research. M.W. and A.H. fabricated the powder, Y.H., H.M. and J.P. fabricated the wire, J.J. characterized the short samples, H.H. and T.S. fabricated the cable and wound the coils, E.B., U.T. and E.H. performed the heat treatment of the coils, and T.S. K.Z., D.D. and M.T. performed the high current coil measurement. T.S., D.L. and S.G. contributed to the discussion and interpretation of the results. T.S. and D.L. took the lead in preparing the paper.

REFERENCES

1 Rossi, L. Superconductivity: its role, its success and its setbacks in the Large Hadron Collider of CERN. Supercond. Sci. and Technol. \textbf{23}, 034001 (2010).
2 Mitchell, N. \textit{et al.} The ITER magnet system. \textit{IEEE Trans. Appl. Supercond.} \textbf{18}, 435-440 (2008).
3 Alonso, J. R. & Antaya, T. A. Superconductivity in medicine. Rev. Accel. Sci. Technol. \textbf{5}, 227-263 (2012).
4 Apollinari, G., Brüning, O., Nakamoto, T. & Rossi, L. High Luminosity Large Hadron Collider HL-LHC. \textit{arXiv preprint arXiv:1705.08830} (2017).
5 Weijers, H. \textit{et al.} The generation of 25.05 T using a 5.11 T Bi$_2$Sr$_2$CaCu$_2$O$_{x}$ superconducting insert magnet. Supercond. Sci. and Technol. \textbf{17}, 636 (2004).
6 Yuan, H. \textit{et al.} Nearly isotropic superconductivity in (Ba,K)Fe$_2$As$_2$. Nature \textbf{457}, 565 (2009).
7 Hunte, F. \textit{et al.} Two-band superconductivity in LaFeAsO$_{0.89}$F$_{0.11}$ at very high magnetic fields. Nature \textbf{453}, 903 (2008).
8 Markiewicz, W. D. \textit{et al.} Design of a superconducting 32 T magnet with REBCO high field coils. IEEE Trans. Appl. Supercond. \textbf{22}, 4300704 (2012).
9 Iwasa, Y. HTS and NMR/MRI magnets: Unique features, opportunities, and challenges. \textit{Physica C} \textbf{445}, 1088-1094 (2006).
Bottura, L., de Rijk, G., Rossi, L. & Todesco, E. Advanced accelerator magnets for upgrading the LHC. *IEEE Trans. Appl. Supercond.* **22**, 4002008 (2012).

NHMFL press release. https://nationalmaglab.org/news-events/news/new-world-record-magnet-fulfills-superconducting-promise. (2017).

Larbalestier, D. C. *et al.* Isotropic round-wire multifilament cuprate superconductor for generation of magnetic fields above 30 T. *Nat. Mater.* **13**, 375 (2014).

Wilson, M. N. *Superconducting magnets.* (Clarendon Press; Oxford (UK), 1983).

Iwasa, Y. *Case studies in superconducting magnets: design and operational issues.* (Springer Science & Business Media, 2009).

Awaji, S. *et al.* First performance test of a 25 T cryogen-free superconducting magnet. *Supercond. Sci. and Technol.* **30**, 065001 (2017).

Kajita, K. *et al.* Degradation of a REBCO coil due to cleavage and peeling originating from an electromagnetic force. *IEEE Trans. Appl. Supercond.* **26**, 4301106 (2016).

Kajita, K., Takao, T., Maeda, H. & Yanagisawa, Y. Degradation of a REBCO conductor due to an axial tensile stress under edgewise bending: a major stress mode of deterioration in a high field REBCO coil’s performance. *Supercond. Sci. and Technol.* **30**, 074002 (2017).

Terao, Y. *et al.* Newly designed 3 T MRI magnet wound with Bi-2223 tape conductors. *IEEE Trans. Appl. Supercond.* **23**, 4400904 (2013).

Terao, Y. *et al.* Analysis of an abnormal event in a 3-T MRI magnet wound with Bi-2223 tape conductors. *IEEE Trans. Appl. Supercond.* **24**, 4401105 (2014).

Zhang, K. *et al.* Tripled critical current in racetrack coils made of Bi-2212 Rutherford cables with overpressure processing and leakage control. *Supercond. Sci. and Technol., doi:10.1088/1361-6668/aada2f* (2018).

Li, P., Ye, L., Jiang, J. & Shen, T. RRR and thermal conductivity of Ag and Ag-0.2 wt.% Mg alloy in Ag/Bi-2212 wires. *IOP Conf. Ser.: Mater. Sci. Eng.* **102**, 012027 (2015).

Bonura, M. *et al.* Very-high thermal and electrical conductivity in overpressure-processed Bi$_2$Sr$_2$CaCu$_2$O$_{8+}$ wires. *Mater. Res. Express* **5**, 056001 (2018).

Ballarino, A. & Bottura, L. Targets for R&D on Nb$_3$Sn conductor for high energy physics. *IEEE Trans. Appl. Supercond.* **25**, 6000906 (2015).

Jiang, J. *et al.* Effects of filament size on critical current density in overpressure processed Bi-2212 round wire. *IEEE Trans. Appl. Supercond.* **27**, 6400104 (2017).

Ambrosio, G. *et al.* Test results of the first 3.7 m long Nb$_3$Sn quadrupole by LARP and future plans. *IEEE Trans. Appl. Supercond.* **21**, 1858-1862 (2011).

Chlachidze, G. *et al.* Performance of the first short model 150-mm-aperture Nb$_3$Sn quadrupole MQXFS for the High-Luminosity LHC upgrade. *IEEE Trans. Appl. Supercond.* **27**, 4000205 (2017).

Feher, S., Bross, A. & Hanlet, P. Operational Experience with the MICE Spectrometer Solenoid System. *IEEE Trans. Appl. Supercond.* **28**, 4101304 (2018).

Caspi, S. *et al.* Design of an 18-T canted cosine–theta superconducting dipole magnet. *IEEE Trans. Appl. Supercond.* **25**, 4000205 (2015).

Goodzeit, C., Ball, M. & Meinke, R. The double-helix dipole-a novel approach to accelerator magnet design. *IEEE Trans. Appl. Supercond.* **13**, 1365-1368 (2003).
List of Figures

Figure 1: $J_0(B)$ of an optimally processed sample of the strand used in this study in comparison to that of a Bi-2212 with the previous record performance, the LHC Nb-Ti strand, and the HL-LHC RRP Nb$_3$Sn strand.

Figure 2: Coil voltages (RC5) during a linear current ramp (see inset in b) that ended with a quench. a Voltage tap map. b Coil voltages $V_{13}$ (whole coil) and $V_{12}$ and $V_{23}$ (individual layers).

Figure 3: Ramp rate dependence of the quench current $I_q$ of RC5 and RC6 during linear current ramps. Inset shows a 3D display of the contours of the surface magnetic flux density generated by RC6 at 8600 A.

Figure 4: $I_q$ of RC6 for consecutive quenches before and after thermal cycling to room temperature and back to 4.2 K.

Figure 5: Voltage development of RC5 for staircase ramps of the magnet current that ended with thermal runaway and energy extraction by switching in a dump resistor. The current ramp scheme contains current holding steps during which coil inductive signals die away and noise is much reduced b. The coil and turn-to-turn voltages are shown in b and d, respectively. The ramp turn voltage is highlighted in c. The ramp turn is a 14 cm long section that transitions between the two coil layers in the peak field region. In d, L1-T1 means the turn #1 of the coil layer #1 (other turns follow the same naming method.) and it is the outermost turn in the low field region.

Figure 6: The $E$-$I$ transition of RC5 and RC6 derived from tests with staircase powering schemes.
Figure 1:
Figure 2:

(a) Diagram showing two layers, Layer 1 and Layer 2, with voltage tap points labeled 1, 2, and 3. The Bi-2212/Nb-Ti splice is indicated.

(b) Graph showing coil voltage (V) against time (sec) with energy extraction and a current rate of change (dl/dt = 30 A/s). The voltages V_{12}, V_{13}, V_{23} are indicated.
Figure 3:

![Diagram showing quench current and ramping rate with field strengths.]

- $B_p = 3.5$ T, RC6 - 8600 A
- Field strengths: 3.5 T, 2.8 T, 1.95 T
Figure 4:

- 200 A/s
- 150 A/s
- 150 A/s, after thermal cycling

\[ \frac{dI}{dt} = 200 \, \text{A/s} \]
Average = 8604 A
Standard deviation = 4.1 A
Figure 5:
Figure 6:

![Graph showing electric field vs. current with experimental data and fit lines for RC5 and RC6 ramp turns.](image)