Published in final edited form as:

Supercond Sci Technol. 2015 March 1; 28(3): . doi:10.1088/0953-2048/28/3/035015.

Magnetic field dependent stability and quench behavior and degradation limits in conduction-cooled MgB₂ wires and coils

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Abstract

Long lengths of metal/MgB₂ composite conductors with high critical current density (J_c), fabricated by the power-in-tube (PIT) process, have recently become commercially available. Owing to its electromagnetic performance in the 20 K – 30 K range and relatively low cost, MgB₂ may be attractive for a variety of applications. One of the key issues for magnet design is stability and quench protection, so the behavior of MgB₂ wires and magnets must be understood before large systems can emerge. In this work, the stability and quench behavior of several conduction-cooled MgB₂ wires are studied. Measurements of the minimum quench energy and normal zone propagation velocity are performed on short samples in a background magnetic field up to 3 T and on coils in self-field and the results are explained in terms of variations in the conductor architecture, electrical transport behavior, operating conditions (transport current and background magnetic field) and experimental setup (short sample vs small coil). Furthermore, one coil is quenched repeatedly with increasing hot-spot temperature until J_c is decreased. It is found that degradation during quenching correlates directly with temperature and not with peak voltage; a safe operating temperature limit of 260 K at the surface is identified.

1. Introduction

MgB₂ has been the subject of intense research since the discovery that it superconducts with a critical temperature of 39 K [1]. Recently, long lengths of metal/MgB₂ composite conductors with high critical current density (J_c), fabricated by the power-in-tube (PIT) process, have become commercially available. Owing to its electromagnetic performance in the 20 K – 30 K range and relatively low cost, MgB₂ may become attractive for a variety of applications, including magnetic resonance imaging magnets.

One of the key issues for large magnets is stability and quench protection. With the transition to a new superconducting conductor technology based upon MgB₂, it is important to have a quantitative understanding of the stability limits and the quench behavior so that magnets can be effectively protected. Previous quench studies on MgB₂ wires and tapes of different architectures have been performed with conduction cooling or in a cryogenic bath

[2-7]. In these studies, the minimum quench energies (MQE) ranged from 10–1000 mJ and the normal zone propagation velocities (NZPV) were on the order of 1–100 cm/s. Several computational models showed good agreement with the experimental results [3-5, 7]. The effects of different wire materials and stabilizer thickness on the quench behavior were also investigated computationally [8-10].

In this work, the quench behavior of several MgB_2 wires and coils with different architectures and performance levels are studied experimentally in a conduction-cooled environment. Previous studies of the quench behavior of MgB_2 conductors have focused primarily on self-field behavior, but magnet design requires a quantitative understanding of the effects of magnetic fields as well. Thus, the short-sample studies reported here are performed as a function of background magnetic field. Subsequently, the quench experiments are repeated on small test coils wound with one of the wires. In addition to reporting the conventional quench parameters (MQE and NZPV), two new parameters are introduced: the critical recovery voltage (CRV) and critical recovery temperature (CRT), which could provide functional reference data for the design of quench detection and protection systems. Lastly, to design an effective quench protection system, it is important to understand the conditions during a quench that permanently degrade the wire. Hence, the test coils are repeatedly quenched with the cut-off conditions systematically varied such that the conductor is permanently degraded, allowing a safe operating limit to be identified.

2. Experimental approach

2.1 MgB_2 wires

Four different MgB_2 wires are studied here; cross-sectional images of each are seen in Figure 1. Wires A, B and B* are 19-filament MgB_2 architectures; wire A has Cu laminated on both sides whereas wires B and B* are laminated on only one side. The primary difference between wires B and B* is performance; wire B* is a later evolution of architecturally similar wire. Wire C is a much smaller but has 24 filaments. Wire C is not laminated but instead has Cu filaments in the center of the wire. Geometric properties of each wire are summarized in Table 1.

2.2 Experimental Setup

2.2.1 Short samples—Short wire samples are mounted for critical current (I_c), critical temperature (T_c) and quench measurements. Each sample is 15 cm long and is pre-bent with a 30 cm diameter. After soldering the wire to the Cu sample holder, 10 cm remains available for quench propagation measurements; this section has no thermal contact other than the conduction cooling from each end via a Sumitomo SRDK-408D2 two-stage GM cryocooler. The sample holder is mounted and cooled on the second stage coldhead through a Cu extension rod, while the current leads (superconducting $\text{Bi}_2\text{Sr}_2\text{Ca}_2\text{Cu}_3\text{O}_x/\text{Ag}$ -alloy wires and Cu tape) are thermally anchored on the first stage coldhead. The mounted sample is loaded into a cryostat that is evacuated to a pressure of 10^{-5} mbar. The cryostat sits within a warm-bore superconducting magnet that generates a background magnetic field up to 8.5 T; the Cu extension rod ensures that the sample is centered in the magnet. With this setup, short samples are cooled to 20 K or below. The maximum transport current from the HP 6681 DC

current supply is 580 A. I_c is determined using a 10^{-4} V/m electric field criterion. I_c is first measured at self-field and subsequently as a function of magnetic field. The critical current density (J_c) and engineering critical current density (J_E) are then determined by dividing I_c by the MgB_2 filament cross-sectional area and wire cross-sectional area, respectively. For T_c measurements, the sample carries a constant transport current of 0.1 A and the voltage is monitored as the sample temperature gradually increases to from 20 K to 50 K and then decreases back to 20 K.

Figure 2 illustrates the wiring configuration for short sample quench measurements. A 1.2 cm long heater made of ECCOBOND 60 L A/B electrically conductive epoxy paste is attached on the sample center; the heater resistance is in the range of 0.5- 5.0 ohm below 30 K. For electrical connections, a thin Cu strip is inserted into the epoxy and the sample is used as the return path for the heater current. This approach has been shown previously to provide a more effective thermal contact with the sample than a wire heater [11, 12]. Two pairs of Cu wires are soldered to the heater; one pair serves as current leads to the heater and the other for monitoring the voltage across the heater. Along the sample, seven sections of voltage taps are soldered using Sn60/Pb40 solder. Type-E thermocouples are placed in the center of each voltage section. Each section is 1.0 cm long except the central one (1.5 cm). The readings from voltage taps and thermocouples are recorded by an array of digital multimeters (DMM) and a digital oscilloscope which are connected to a computer via GPIB for simultaneous readout. The entire experiment is controlled via GPIB using LabVIEW.

The quench measurement protocols follow those reported previously for high temperature superconductors [13-15]. After the sample is cooled to a stable operating temperature (20 K) and I_c is measured, a steady-state transport current (I_t) below I_c is established in the sample. A KEPCO BOP50 power supply is then used to generate a voltage pulse (300 ms) in the Eccobond heater. The heat pulse initiates a normal zone which either collapses (recovery) or grows (a quench); the response is monitored by the voltages and temperatures as a function of location and time. A series of measurements are performed by successively increasing the pulse voltage until a quench is observed. The quench measurements begin at self-field, and the magnetic field is increased in 0.5 T increments after completing measurements as a function of transport current.

2.2.2 Small coils—Wire B* is used for small coil quench studies. Two small coils are fabricated: coil I is a singlelayer solenoid and coil II is a pancake coil. As shown in Figure 3, both coils are wound around a Cu circular ring with a 20 cm outer diameter; 20 cm is chosen based on the limitations of the available cryostat. The Cu ring is attached to a round Cu disc which is mounted to and cooled by the second stage cold head. MgB_2 wire is wrapped by braided Dacron fibers for electrical insulation, and Stycast 2850 black epoxy is brushed on each layer during coil winding to bond the wire. Each coil has four turns of wire and a total wire length of 2.5 m. Figure 4 illustrates the wiring configuration for coil quench measurements, which is similar to the short sample measurements except that in the coils quench propagation is monitored in two directions. The Eccobond heater is attached to the turn closest to the cold head, which is the bottom turn for coil I and the innermost turn for coil II. The matrix of voltage taps and thermocouples is located around the Eccobond heater for monitoring quench propagation in the longitudinal direction, which is the same as in

short samples, and the transverse direction, which is turn-to-turn for coil I and layer-to-layer for coil II. Each section is 1.0 cm long except the heater section (1.5 cm).

In addition to the Eccobond heater, a 25 μm thick Constantan film heater is mounted on the coils. The film is cut into several 1.0 mm wide ribbons which are mounted along the MgB_2 tape surface outside the Dacron insulation by VGE-7031 varnish. The Constantan heater length is 1.2 m and has a resistance of 16.5 Ω below 30 K. The heater consists of eight 15 cm long ribbons which are evenly distributed along the coil and serially connected by Cu wires. A thermocouple is attached to the center of each ribbon to measure the temperature during heating. After attaching all of the instrumentation wiring, a thin layer of Stycast 2850 black epoxy is brushed over the entire winding to bond all of the connections. The coil is then mounted to the second stage coldhead for cooling.

Coil measurements follow the same experimental protocols as the short-sample measurements using the same equipment. Due to limitations on the superconducting magnet bore size, only self-field measurements are performed on the coils. In addition to the pulsed-heater quench measurements, the coil stability is evaluated using steady-state heating via the Constantan heater. Once the coil is carrying a steady-state transport current at a certain operating temperature, a low-level steady-state current is introduced into the Constantan heater and the temperature and voltage along the coil are monitored. If the coil reaches a stable equilibrium, the current in the heater is increased until the coil becomes unstable, thereby determining the stability limit.

Lastly, the MgB_2 wire degradation limits during a quench are determined using coil I. The same approach is used to induce a quench using the Eccobond heater with heater pulses (500 ms, 4.95 J pulses), but in this case the end-to-end voltage at which the experiment is terminated is progressively increased and I_c is remeasured after each quench; this is repeated until significant degradation is observed. This experiment follows the same experiment protocol used in a previous study of degradation in $\text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}_x/\text{Ag}$ -alloy ($\text{Bi}2212$) round wires [13].

3. Results and discussions

3.1 Short-sample experiments

3.1.1 I_c (B), J_c (B) and T_c (B) behavior—The magnetic field dependences of I_c , J_c and n -value at 20 K for the four wires are shown in Figure 5. Note that self-field values at 20 K are not reported because I_c exceeds the supply limit of 580 A. All properties decrease with increasing magnetic field; at 20 K, these wires are limited to generating magnetic fields of 3–4 T. From the perspective of magnet design and quench behavior, both J_c and I_c are important parameters; J_c describes the performance of the superconducting filaments themselves, whereas I_c influences the operating current (and thus number of turns and inductance) of a magnet. Comparing the four wires, wire C has a significantly higher J_c than the other three wires, followed by wire B*, and then wires A and B (which have similar performance). The I_c behavior of the four wires shows less variance, with wire B* having the highest I_c , followed by C, A and B. The n -value is influenced by both the wire performance and the area fraction of stabilizer. Again, wire C has the highest value,

followed by wire B*, B and A. Although wires A and B have similar I_c , wire A has lower n value primarily because it has a larger amount of Cu stabilizer, reducing the matrix resistance and thus resulting in a lower voltage for the same amount of current sharing. Lastly, the critical temperatures (T_c) as a function of magnetic field are shown in Figure 5d.

3.1.2 Stability—An important stability parameter is the minimum quench energy (MQE), which is defined as the minimum energy required to induce a quench in a conductor or magnet. Figure 6 illustrates the difference between a quench and a recovery in the voltage-time and temperature-time data in wire B* with a transport current of 400 A at 20 K, self-field. A 3.425 V voltage pulse to the heater results in a recovery, whereas a 3.450 V voltage pulse induces a quench. So, in this case, the MQE is the energy associated with a pulse voltage between these values, where the heat energy is calculated using

$$\text{Heat Pulse Energy} = \int_0^{t_p} V_h(t) I_h(t) dt \quad (1)$$

where V_h is the voltage applied to the heater, I_h is the current through the heater, and t_p is the heat pulse duration. In this example, the MQE is 0.645 ± 0.005 J. To provide more operational references for protection, two new parameters, illustrated in Figure 6, are introduced here to quantify stability: the critical recovery voltage (CRV) and critical recovery temperature (CRT), which are defined as the maximum voltage and temperature that the conductor reaches due to a disturbance but still recovers without thermal runaway. As shown in Figure 6, the CRV and CRT for this example are 2.08 mV and 28.4 K, respectively.

Figure 7a plots the MQEs for the four wires as a function of transport current (I_t) and background magnetic field at 20 K. The data at 0.5 T and 1.0 T is re-plotted as a function of the normalized transport current in Figure 7b, where I_t for each curve is normalized by the corresponding $I_c(B, 20 \text{ K})$. The dominant factors for stability are the conductor architecture and I_t . Wire A, with the largest cross-sectional area and highest stabilizer volume, has the highest MQE. Comparing wires A and B, which have similar J_c but > 50% difference in J_E , one finds that wire B has a significantly lower MQE due to its reduced stabilizer volume fraction. Wire B* has enhanced J_c , 40% higher than wire B, but with identical wire architecture. Thus, wire B* has only slightly higher MQE than wire B for the same I_t . Wire C has similar I_c as wire B* but much higher J_c and J_E due to a much smaller cross-sectional area; as a result wire C has the smallest MQE, more than an order-of-magnitude below that of wire A. To better understand the role of the wire architecture, Figure 7c re-plots the MQE data as the MQE density, defined as the MQE divided by the wire cross-sectional area, versus transport current density J_t (I_t divided by wire cross-sectional area). In this representation, the MQE density difference between wires becomes relatively small, which means that even for different types of wire, on a per unit volume basis each has similar stability when carrying the same transport current. Note that the MQE density of wire A remains slightly higher than the other wires, which implies that the larger amount of Cu stabilizer enhances the wire thermal conductivity, increasing the thermal stability. It is also evident that the stability has a strong negative dependence on J_t . This is consistent with past findings for low temperature superconductor (LTS) wires NbTi and Nb₃Sn [11, 16-19].

Figures 8 and 9 plot the CRV and CRT as a function of I_c and I_t/I_c . In general, CRV and CRT describe the normal zone created with a heater pulse just below MQE, so their values are roughly proportional to the corresponding MQE and have the same trends with I_t , B and wire architecture. More importantly, compared to MQE, the CRV and CRT parameters are relatively easy to monitor during magnet operation, and thus are potentially useful as the reference criterions for quench detection.

To understand the impact of these new parameters on stability evaluation, the CRT and CRV data are re-plotted versus the corresponding MQE in Figure 10. Figure 10a shows the effect of conductor architecture on the CRT/MQE ratio clearly: the conductor with smaller cross-sectional area has a larger temperature increase for the same disturbance energy. In Figure 10b, the data is presented in terms of effective resistance (CRV/I_t) to eliminate any influence of the transport current; here the conductor architecture effect is even stronger, since the smaller cross-sectional area and higher local temperature both increase the electrical resistivity and thus a much higher normal zone voltage is observed. From the perspective of quench detection, this is beneficial for the smaller cross-section conductor; although the MQE is lower, it will generate higher and thus more detectable voltage and temperature signals for the same disturbance energy. Hence, as with LTS magnets, there is a trade-off between stability and protection.

An important artifact of short-sample measurements that needs to be recognized is that the conductor becomes very stable at very low transport current density (e.g. $< 100 \text{ A/mm}^2$). For example, with a transport current of 100 A in self-field, wire C has an MQE of 0.6 J and a CRT of 40 K; if the current is reduced to 37.5 A, MQE increases to 5 J and the CRT becomes 90 K. For such a low current density, however, the minimum propagation zone approaches or even exceeds the sample length (15 cm), so the results are overly influenced by cooling at the ends of the conductor, and the actual stability is likely somewhat lower.

3.1.3 Quench Propagation—Typical voltage and temperature versus time and location for a quench are seen in Figure 11; this data is from the same quench illustrated in Figure 6. Note that V4 and T4 correspond to the heater location. Comparing Figures 11a and 11b indicates that there is a delay between the voltage and temperature signals. Initially, the temperature increases before the voltage; this is because there is no voltage increase until the temperature is above the current sharing temperature (T_{cs}) and because of heat conduction along the wire. After current sharing begins, however, the temperature response is delayed relative to the voltage because the thermocouples are located on the conductor surface whereas the voltage represents the average conditions within the superconducting filaments and the metal sheath. Hence, NZPV studies focus on voltage measurements, similar to previous studies on the quench behavior of HTS conductors [14, 15, 20].

To calculate NZPV directly from the voltage-time data, a voltage criterion is chosen and then NZPV is equal to the distance between voltage taps divided by the time delay between each of them reaching the voltage criterion (see Figure 11a). Figure 12 illustrates how the NZPV varies with the voltage criterion, suggesting that the voltage criterion be chosen such that the voltagetime curves are nearly parallel in order to provide the most meaningful results. Here, the voltage criterion is varied with I_t ; specifically 0.01 mV/A is used (4 mV is

illustrated in Figure 11a). Voltage taps V2 and V1 are chosen because the voltages around the heater are overly affected by the heat pulse and propagation driven by the Joule heating is most meaningful. Since the data acquisition rate of the measurement system is about 14 ms/point, the time differences measured, and thus the calculated NZPVs, have an error of about 10%. Hence, the NZPV in the example in Figure 11a is determined to be 7.22 ± 0.36 cm/s.

NZPVs for all four wires as a function of I_t , I_t/I_c and background magnetic field at 20 K are shown in Figure 13. Similar to the stability behavior, NZPV is strongly dependent upon the wire architecture. The NZPV of wire A is on the order of 1 cm/s, those of wires B and B* are about an order-of-magnitude faster, and that of wire C approaches 100 cm/s. To remove the effect of wire architecture, Figure 13 also shows NZPV versus J_t . Like MQE density, the difference between wires is significantly reduced, indicating that as with LTS wires, NZPV is strongly influenced by the current density in the normal metal matrix. This is further illustrated by the dashed line in Figure 13c which plots a simple theoretical model for adiabatic propagation [21],

$$NZPV = J \sqrt{\frac{\rho_n \lambda_n}{C_n C_s (T_c - T_{op})}} \quad (2)$$

where ρ_n is the resistivity of the normal matrix, λ_n is the fill factor, C_n and C_s are the specific heats of the normal metal and superconductor, respectively, and T_c and T_{op} are the critical and operating temperatures. According to this model, the NZPV should increase linearly with J_t , but the experimental results show that $NZPV \sim J^2$ or J^3 . This difference is related to the presence of conduction cooling in the experiment that provides too much cooling to be neglected. Thus, to drive normal zone propagation, the joule heating must also overcome the cooling, which is nearly independent of J_t . Hence, for low transport current, the joule heating is comparable to the cooling, quench propagation is more difficult, and thus the NZPV is significantly reduced relative to the ideal adiabatic model. For high transport current, for which the joule heating is large, the cooling power becomes less significant and the dependence of the NZPV on J_c is close to the ideal adiabatic model.

3.1.4 Effects of magnetic field on quench behavior—It is also important to understand the effects of increasing magnetic field on the quench behavior of wires. In general, increasing magnetic field decreases T_c , and thus the temperature margin, which should reduce MQE and increase NZPV. But increasing magnetic field also decreases J_c , increasing MQE and decreasing the NZPV. A recent study of the effects of high magnetic fields on the 4.2 K quench behavior of Bi2212 round wires with increasing magnetic field showed that the reduction in T_c and T_{cs} dominates the MQE behavior and that MQE decreases continuously with increasing magnetic fields up to 20 T. The NZPV, however, decreases with magnetic field only up to about 8 T. Above 8 T, the NZPV is independent of magnetic field up to at least 20 T. Thus, at low field, the NZPV is dominated by the decreasing J_c , whereas at higher magnetic field the competing effects of decreasing J_c and decreasing temperature margin offset [14].

Figure 14 plots J_c , the temperature margin ($T_c - 20$ K), MQE and NZPV versus magnetic field at 20 K for wire C; each property is normalized to its value at 0.5 T and the results are obtained for $I_t/I_c = 0.60$. Interestingly, the NZPV(B) curve follows $J_c(B)$ very closely, decreasing rapidly with magnetic field and not showing a plateau effect like what was reported for Bi2212 [14]. The MQE(B) curve follows $T_c(B)$ closely up to 1.5 T, showing similar behavior to Bi2212, but at higher magnetic field MQE increases dramatically. This is likely because at 20 K, above 1.5 T, I_c becomes very low; for example, $I_c(2$ T, 20 K) = 66 A, so during current sharing the joule heating is relatively low and is significantly offset by the conduction cooling. Thus, MQE becomes very high. In an adiabatic environment, it is likely that this behavior would not be observed or would be less dramatic.

3.2 Coil behavior

3.2.1 Transport properties—The temperature dependence of the end-to-end I_c for each coil and the corresponding short sample data are shown in Figure 15. The coil I_{cs} are about 10% lower than the short-sample, which is likely due to increased self-field and the smaller bending diameter in the coils (20 cm) than the short sample (30 cm).

3.2.2 Stability and quench behavior due to a heat pulse—The first coil quench scenario studied is similar to the short sample measurements in which the normal zone is induced by a heat pulse in the Eccobond heater. Figure 16 plots the MQE, CRT and CRV results as the function of I_t for both coils; the corresponding short sample data is plotted for comparison. Both coils have a higher MQE than the short sample; ~50% greater for coil I and ~100% greater for coil II, but the coil CRTs and CRVs are lower than the short sample. One reason for the significant difference in MQE between the short sample and the coils is that the heater on the short sample is more efficient than that on the coil because in the coil the heat is also absorbed by the ancillary materials, including the epoxy, insulation and coil former. Furthermore, heat propagation in the coils is two-dimensional whereas in the short sample it is only one-dimensional. Hence, an initial hotspot affects several turns or layers in a coil but is confined to the lone wire in the short sample measurements. This also implies that if a short sample and a coil each have a hotspot with the same peak temperature, the normal zone in the coil must be larger and thus likely to lead to a quench, implying that the coil has a lower CRT and CRV than the short sample, but has a larger MQE.

Figure 17 shows the voltage and temperature versus time for both coils and the short sample at 20.0 K, self-field, and $I_t = 400$ A. Data for two runs are shown: the largest heat pulse resulting in recovery and the smallest heat pulse resulting in a quench. The initial hotspot on the short sample has the slowest recovery and the fastest thermal runaway, consistent with having only onedimensional heat transfer. Comparing the two coils, coil II (pancake winding) recovers faster than coil I (layer-wound) and also shows a longer delay before thermal runaway when it quenches. These differences are likely due to better turn-to-turn heat transfer in the pancake coil as compared to the layer-wound coil, resulting in a larger effective thermal mass and thus higher MQE but lower CRT. Furthermore, the larger normal zone results in a more rapid rise in the end-to-end voltage in coil II than in coil I during a quench, even though the peak temperature in the normal zone is actually lower; this is consistent with the higher CRV for coil II.

Transverse heat conduction is expected to reduce longitudinal normal zone propagation in the coils and this is observed in Figure 18a. Comparing the longitudinal NZPV in the coils and short sample, and also considering the relative transverse propagation rates in the coils (Figure 18b, in the unit of turns/s), the short sample has the fastest longitudinal propagation because of the absence of any transverse heat conduction. Coil I has faster longitudinal propagation than coil II, whereas coil II has significantly faster transverse propagation, implying that the enhanced transverse propagation further reduces longitudinal propagation. Note that the differences in NZPV increase with I_t ; thus, as joule heating increases, so do the effects of differences in heat conduction.

3.2.3 Stability and quench behavior due to steady state heating—Figure 19 plots the voltage and temperature versus time for coil I with $I_t = 350$ A at 25 K and self-field and a steady-state voltage of 0.89 V on the Constantan heater. Since the heater covers half of the coil winding, the end-to-end voltage and the center temperature for each of the eight heater sections (labeled as T_{R1} , T_{R2} , etc.) are monitored along with the voltage and current on the heater.

In the example shown in Figure 19, the end-to-end voltage begins to increase slowly after ~30 s and then increases rapidly at ~65 s, whereas the temperatures increase slowly from the beginning of the experiment until ~65 s when thermal runaway occurs. The thermocouple nearest the coil center (T_{R5}) shows the highest temperature, so subsequent analysis of the results focuses primarily on T_{R5} . Figure 20 shows the voltage and temperature versus time in coil I for the same conditions as Figure 19 but as a function of voltage on the heater. From the end-to-end coil voltages, a voltage on the heater of 0.69 V appears to result in a thermal equilibrium whereas a heater voltage of 0.73 V results in thermal runaway. Converting the heater voltage to an input power to the coil, the stability limit is parameterized as the minimum quench power density (MQPD), defined as the power generated in the heater divided by the wire cross-sectional area. MQPD values for both coils are plotted in Figure 21 as a function of I_t . Analysis of the temperature data indicates that the coils remain stable as long as the steady-state temperature seen in Figure 20b does not exceed T_{cs} .

3.2.4 Quench induced conductor degradation—To design an effective quench protection system, it is important to understand the conditions that degrade wire performance. Hence, after completing the coil stability and propagation studies, coil I is used to determine the wire degradation limits. Thus, the coil is repeatedly quenched and the end-to-end voltage limit is increased. After each quench the coil I_c is measured again; the maximum coil temperature during each of these quenches, T_{max} , and the coil I_c after each quench, are plotted in Figure 22. Note that initially $I_t = 275$ A is used for this study. In quench #9, V_{ETE} reaches 7.1 V, saturating the power supply output voltage. Thus, to obtain higher T_{max} , subsequent quenches are initiated with $I_t = 200$ A. The power supply voltage limit is again reached in quench #16, so beginning with quench #17 I_t is reduced to 150 A.

As seen in Figure 22, in quench #14 T_{max} reaches 250 K yet there is no reduction in the coil I_c . In quench #15, however, T_{max} reaches 296 K and I_c is reduced from 395 A to 335 A (85% of the original I_c), and in quench #16 I_c is further reduced to 296 A (75%) after T_{max} reached 320 K. I_c is not reduced further due to quenches #17 and #18, for which T_{max} only

reaches 217 K. Lastly, quenches #19-22 each result in further decreases in I_c as $T_{\max}$ increases further. After the last quench (#22), for which $T_{\max}$ reaches 420 K, I_c is reduced to 143 A (36%). These results indicate a strong correlation between $T_{\max}$ and wire degradation, consistent with prior results on $\text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}_x$ wire degradation [13]. Considering the quenches with the highest temperatures that do not reduce I_c and the lowest temperatures that do reduce I_c , a degradation criterion of $T_{\max} = 261 \pm 11$ K is estimated. Analysis of the corresponding maximum V_{11} (not shown) shows no direct correlation between the maximum voltage and degradation.

Effective quench protection requires an understanding of the time-budget available to detect a quench and protect the magnet. Thus, not only is the maximum allowable temperature that can be obtained without degradation required, but an understanding of the time required to reach that temperature is also needed. The time available to protect the magnet is then the time to reach the degradation condition (less some safety margin) less the time required to detect a quench. Here we define the quench duration, t_Q , as the time from the end of the heater pulse to the time at which $T_{\max}$ is reached; t_Q is plotted as a function of $T_{\max}$ for each quench in Figure 23. As expected, $T_{\max}$ is reached much more quickly for quenches with higher I_t ; higher I_t results in higher current density in the stabilizer above T_{cs} and thus higher joule heating power. But short t_Q does not necessarily imply less time to protect the magnet, because the time-to-detect, t_D , may also be shorter. Assume, for example, that the quench detection system is triggered for $T_{\max} = 100$ K¹. In that case, $t_D = 2.4$ s for $I_t = 275$ A, $t_D = 3.9$ s for $I_t = 200$ A and $t_D = 7.0$ s for $I_t = 150$ A. For these same values of I_t , the time required for $T_{\max}$ to reach 260 K (t_{260}) is 4.2 s for 275 A, 6.8 s for 200 A and 11.6 s for 150 A. As a result, the available time budget to trigger the quench protection system, $t_{\text{prot}} = t_{260} - t_D$, is 1.8 s for 275 A, 2.9 s for 200 A and 4.6 s for 150 A. Hence, although a quench at lower I_t may be more difficult to detect, it actually provides more time budget for protection before wire performance is reduced.

The above time-budget analysis is somewhat oversimplified because it assumes that the same peak temperature has been reached when the quench detection voltage limit has been reached, independent of I_t . But the NZPV is strongly dependent on I_t as well, so higher I_t may lead to faster detection and a lower $T_{\max}$ when the detection system is triggered. Thus, more generally, both the normal zone size (e.g., minimum propagating zone) and $T_{\max}$ should be considered. The normal zone spatial size correlates directly with detection, whereas $T_{\max}$ correlates with the protection requirements.

4. Summary

The stability and quench behavior of four MgB_2 wires was studied under conduction-cooling at 20 K. Short samples were studied in magnetic fields up to 3 T. Although the different wire architectures result in widely varying MQE and NZPV, when viewed as a function of J_t the differences between wires became relatively small and the behavior was dominated by J_t . In-field measurements showed that the NZPV(B) closely follows $J_c(B)$ and

¹Typically quench detection is based on voltage measurements, but for any given magnet system there will be a corresponding peak temperature at the quench detection criterion.

did not show the plateau effect seen in Bi2212 wires, and MQE(B) closely followed $T_c(B)$ up to about 1.5 T.

Quench measurements on small coils at 20–25 K, self-field, were also performed. Compared to the short samples, the quench propagation in the coils is two-dimensional, reducing the longitudinal propagation velocity due to transverse heat conduction. One coil was quenched repeatedly with increasing hot spot temperature to study degradation in the wire. It was found that wire degradation during quenching correlates directly with peak hot-spot temperature and not with peak voltage; a safe operating limit of 260 K at the surface was identified.

Acknowledgments

The authors are grateful to Sasha Ishmael and Frank Hunte for useful discussions, and Roger Russell, Joe Matthew and Richard Lamy for technical support. This work was financially supported by the U.S. National Institutes of Health under contract 5R01EB009360.

References cited

1. Nagamatsu J, Nakagawa N, Muranaka T, Zenitani Y, Akimitsu J. Superconductivity at 39 K in magnesium diboride. *Nature*. 2001; 410:63–64. [PubMed: 11242039]
2. Fu M, Xu X, Jiao Z, Kumakura H, Togano K, Ding L, et al. Minimum quench energy and normal zone propagation velocity in MgB₂ superconducting tape. *Physica C: Superconductivity*. 2004; 402:234–238.
3. Minyi F, Zhengquan P, Zhengkuan J, Kumakura H, Togano K, Liren D, et al. Quench characteristics and normal zone propagation of an MgB₂ superconducting coil. *Superconductor Science and Technology*. 2004; 17:160.
4. Van Weeren H, Van Den Eijnden NC, Wessel WAJ, Lezza P, Schlachter SI, Goldacker W, et al. Adiabatic normal zone development in MgB₂ Superconductors. *IEEE Transactions on Applied Superconductivity*. 2005; 15:1667–1670.
5. Gambardella U, Saggese A, Sessa P, Guarino A, Pace S, Masullo G, et al. Stability Measurements in Multifilamentary MgB₂ Tapes. *IEEE Transactions on Applied Superconductivity*. 2007; 17:2937–2940.
6. Wang X, Pamidi SVPSS, Trociewitz UP, Schwartz J. Self-field quench behavior of multifilamentary MgB₂ wires in liquid helium. *Cryogenics*. 2008; 48:469–477.
7. Pelegrín J, Romano G, Martínez E, Angurel LA, Navarro R, Ferdeghini C, et al. Experimental and numerical analysis of quench propagation on MgB₂ tapes and pancake coils. *Superconductor Science and Technology*. 2013; 26:045002.
8. Glowacki BA, Majoros M, Tanaka K, Kitaguchi H, Kumakura H, Okada M, et al. Critical current and cryogenic stability modelling of filamentary MgB₂ conductors. *Journal of Physics: Conference Series*. 2006; 43:103.
9. Stenvall A, Korpela A, Mikkonen R, Grasso G. Stability considerations of multifilamentary MgB₂ tape. *Superconductor Science and Technology*. 2006; 19:184.
10. Stenvall A, Korpela A, Mikkonen R, Grasso G. Quench analysis of MgB₂ coils with a ferromagnetic matrix. *Superconductor Science and Technology*. 2006; 19:581.
11. Gosh AK, Sampson WB, Wilson MN. Minimum quench energies of Rutherford cables and single wires. *IEEE Transactions on Applied Superconductivity*. 1997; 7:954–957.
12. Martínez E, Lera F, Martínez-López M, Yang Y, Schlachter SI, Lezza P, et al. Quench development and propagation in metal/MgB₂ conductors. *Superconductor Science and Technology*. 2006; 19:143.

13. Ye L, Cruciani D, Effio T, Hunte F, Schwartz J. On the Causes of Degradation in $\text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}_{8+x}$ Round Wires and Coils by Quenching at 4.2 K. *IEEE Transactions on Applied Superconductivity*. 2013; 23:6400811.
14. Ye L, Hunte F, Schwartz J. Effects of high magnetic field on the quench behavior of $\text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}_x$ coils at 4.2 K. *Superconductor Science and Technology*. 2013; 26:055006.
15. Ishmael S, Luo H, White M, Hunte F, Liu X, Mandzy N, et al. Enhanced Quench Propagation in $\text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}_x$ and $\text{YBa}_2\text{Cu}_3\text{O}_{7-x}$ Coils via a Nanoscale Doped-Titania-Based Thermally Conducting Electrical Insulator. *IEEE Transactions on Applied Superconductivity*. 2013; 23:7201311.
16. Breschi M, Trevisani L, Boselli M, Bottura L, Devred A, Ribani PL, et al. Minimum Quench Energy and Early Quench Development in NbTi Superconducting Strands. *IEEE Transactions on Applied Superconductivity*. 2007; 17:2702–2705.
17. Trillaud F, Ayela F, Devred A, Tixador P. Investigation of the Stability of Cu/NbTi Multifilament Composite Wires. *IEEE Transactions on Applied Superconductivity*. 2006; 16:1712–1716.
18. Turowski P. The stability of Nb_3Sn -composite conductors cooled by normal and superfluid helium. *Cryogenics*. 1981; 21:533–539.
19. de Rapper WM, Dhalle MMJ, Bordini B, Ballarino A, ten Kate HHJ. Thermal Stability at 1.9 K and 4.3 K of Nb_3Sn Cables for Quadrupole Magnets for the LHC Upgrade. *IEEE Transactions on Applied Superconductivity*. 2013; 23:4702104.
20. Wang X, Trociewitz UP, Schwartz J. Near-adiabatic quench experiments on short $\text{YBa}_2\text{Cu}_3\text{O}_{7-8}$ coated conductors. *Journal of Applied Physics*. 2007; 101:053904.
21. Wilson, MN. *Superconducting Magnets*. Clarendon Press; 1983.

Figure 1.

Cross-sectional SEM images of the four MgB₂ wires. Wires A, B and B* share a similar architecture consisting of MgB₂ filaments, Ni matrix and Cu stabilizer. The only difference is that wire A has two layers of Cu stabilizer and B and B* have only one layer. Wire C has a different architecture: MgB₂ and Cu filaments surrounded by a Ni matrix and encased within a Monel sheath.

Figure 2.
Wiring diagram for short-sample quench measurements.

Figure 3.
Schematic illustrations of (a) coil I and (b) coil II.

Figure 4.
Wiring diagram for coil quench measurements.

Figure 5.
 (a) $I_c(20\text{ K})$, (b) $J_c(20\text{ K})$, (c) $n\text{-value}(20\text{ K})$ and (d) T_c versus magnetic field for short-sample wires.

Figure 6.

(a) V_{ETE} and (b) T_{heater} versus time during a recovery and a quench. Also shown are the definitions of the critical recovery voltage (CRV) and critical recovery temperature (CRT).

C

Figure 7.

Short sample stability margins for the four short-sample wires: (a) MQE versus I_t , (b) MQE versus I_t/I_c and (c) MQE density versus J_t .

Figure 8.
Critical recovery temperature versus (a) I_t and (b) I_t/I_c .

Figure 9.
Critical recovery voltage versus (a) I_t and (b) I_t/I_c .

Figure 10.
(a) CRT and (b) CRV/I_t versus MQE at 20 K.

Figure 11.

Self-field (a) voltage and (b) temperature versus time during a quench. The initial $T_{op} = 20.0$ K and $I_t = 400$ A.

Figure 12.
Normal zone propagation velocity versus voltage criterion.

Figure 13. Short sample normal zone propagation velocity for the four short-sample wires versus (a) I_t , (b) I_t/I_c and (c) J_t .

Figure 14.

J_c , $(T_c - 20$ K), MQE and NZPV versus magnetic field at 20 K for wire C; each property is normalized to its value at 0.5 T.

Figure 15.

Self-field I_c versus temperature for coil I, coil II and the corresponding short sample.

b

Figure 16.

Stability results versus I_t for coil I, coil II and the corresponding short sample at 20 K, self-field: (a) MQE, (b) CRT and (c) CRV.

Figure 17.

The (a) end-to-end voltage and (b) temperature versus time for a quench and a recovery in coil I, coil II and the corresponding short-sample at 20 K, self-field.

Figure 18.

NZPV versus I_t for coil I, coil II and the corresponding short sample at 20 K, selffield: (a) longitudinal and transverse propagation (in cm/s) (b) transverse propagation in the coils in terms of turns/s.

Figure 19.

Voltage and temperature versus time for coil I with a transport current of 350 A at 25 K, self-field and a steady-state voltage of 0.89 V on the Constantan heater.

a

b

Figure 20.

Steady-state heating quench results at 25 K, self-field, with $I_t = 350$ A and a range of voltages on the Constantan heater: (a) voltage and (b) temperature versus time.

Figure 21. Stability limit in terms of minimum quench power density versus I_t for coil I and coil II.

Figure 22.

$T_{\max}$ during each quench and the corresponding I_c measured after the quench.

Figure 23.

$T_{\max}$ versus quench duration time, t_Q , which is defined as the time from when the heater is turned off to the time when $T_{\max}$ is reached. Also shown are the degradation limits and an example of a detection criterion.

Table 1Geometric properties of four MgB₂ wires

Wire	Cross-section dimensions	Architecture	Stabilizer fraction	MgB ₂ fill factor
A	3.10 mm × 0.90 mm	19 MgB ₂ filaments / Ni matrix / Cu stabilizer	44.4% (Two 0.2 mm Cu layer)	11.2%
B&B*	3.10 mm × 0.70 mm	19 MgB ₂ filaments / Ni matrix / Cu stabilizer	28.5% (One 0.2 mm Cu layer)	16.3%
C	1.53 mm × 0.72 mm	24 MgB ₂ filaments / Monel sheath/ Ni matrix/Cu core filaments	None	11.8%