ABSTRACT

YE, LIYANG. Quench Behavior and Degradation Limit of Ag-sheathed Bi$_2$Sr$_2$CaCu$_2$O$_x$ Round Wires. (Under the direction of Dr. Justin Schwartz and Dr. Tengming Shen).

High field superconducting magnets are important for scientific research in a variety of disciplines. With nearly field-independent critical current density over a wide range of magnetic field at 4.2 K up to 50 T, Ag-sheathed Bi$_2$Sr$_2$CaCu$_2$O$_x$ (Bi-2212) round wires offer the possibility to generate magnetic fields of 30 T and above. One of the key issues in high field Bi-2212 magnet development is the quench detection and protection. A quench occurs when a part of a superconducting winding, after receiving a small disturbance, enters into the normal (resistive) state, and the event follows with significant temperature rise due to joule heating. An unprotected quench may degrade or even destruct an entire superconducting magnet system. This thesis focuses on experimentally investigating the quench behavior and degradation limit of the state-of-the-art multifilamentary Ag/Bi-2212 round wires to guide the development of Bi-2212 high field magnet, especially the quench detection and protection system.

Following an earlier work by Effio et al. that measured the minimal quench energy (MQE), a parameter that measures the stability of a superconductor, and normal zone propagation velocity (NZPV) at 4.2 K and self-field using a heater induced quench experiment, this work improved this method and extended the measurement at 4.2 K in magnetic fields up to 20 T. Due to the decreased $T_c$ and thus current sharing temperature, the increasing magnetic field resulted in a significantly reduced stability margin: the MQE measured at 20 T with the transport current density of 150 A/mm$^2$ was only ~100 mJ, which was about two orders lower than the value previously measured at self-field. Meanwhile, the in-field quench propagation was dominated by the decreasing critical current density, which drove the slow
NZPV in the order of tens of cm/s: at 20 T with the transport current density of 150 A/mm², the longitudinal NPZV was measured as 5.3 cm/s.

To further explore the quench behaviors and limits of Bi₂Sr₂CaCu₂Oₓ superconducting magnets, and to assess the impact of slow normal zone propagation on quench detection, the time evolution of the hot spot temperature and the normal zone resistive voltage was systematically measured in an epoxy-impregnated full-size Bi-2212 coil. For this coil, the hot spot temperature for the resistive voltage of the normal zone to reach 100 mV increased from ~40 K to ~80 K with increasing the operating wire current density $J_o$ from 89 A/mm² to 354 A/mm², whereas for the voltage to reach 1 V, it increased from ~60 K to ~140 K. These results highlight the difficulty of quench detection in Bi-2212 magnets, which is due to the slow normal zone propagation, and the need to allocate a more significant amount of protection time for Bi-2212 magnets when designing quench detection and protection circuitry than for conventional LTS magnets.

The heater induced quench experiment was further used to determine quench degradation limits of a large pool of commercial Ag/Bi-2212 round wires with the varied conductor designs and processing methods, and it was found that quench-induced $I_c$ degradation strongly correlated with the maximum hot spot temperature. Wires exhibit small irreversible $I_c$ and n-value degradation when the local normal zone temperature exceeds 400 K, and then large degradation when the temperature increased above 550 K. The microstructural observations of quench-degraded wires provided significant evidences for the hypothesis of a strain-driven $I_c$ degradation mechanism. Further quench degradation experiments using ITER barrel configuration quantitatively defined the dependence of the quench normal zone temperature on the pre-existing tensile strains under strong magnetic fields. The results
implied that applying a tensile axial stress decreased the quench degradation temperature limit from $>400$ K at stress-free state to $<200$ K under 130 MPa and above. A semi-quantitative model by calculating the stain state during quenching-under-tensile-stress eventually revealed the physical failure mechanism: the $I_c$ degradation in Bi-2212/Ag wire was driven by the net local strain applied on Bi-2212 filaments. During quenching, the thermal expansion difference between the Ag sheath and Bi-2212 filaments would induce the thermal tensile strain and thus cause Bi-2212 filaments cracking, while the external mechanical tensile strain could be added up to the thermal strain and then reduce the degradation limit.
Quench Behavior and Degradation Limit of Ag-sheathed Bi$_2$Sr$_2$CaCu$_2$O$_x$ Round Wires

by
Liyang Ye

A dissertation submitted to the Graduate Faculty of
North Carolina State University
in partial fulfillment of the
requirements for the degree of
Doctor of Philosophy

Materials Science and Engineering

Raleigh, North Carolina
2015

APPROVED BY:

__________________________________________  ______________________________________
Dr. Justin Schwartz                          Dr. Tengming Shen
Committee Co-chair                          Committee Co-chair

__________________________________________  ______________________________________
Dr. Carl Koch                                Dr. Frank Hunte

__________________________________________
Dr. Mohammed Zikry
DEDICATION

This thesis is dedicated to

my beloved family, Hong and Lori,

for their endless support and encouragement.
BIOGRAPHY

Liyang Ye was born in Tongcheng, Anhui, China on October 24, 1985. He received his B.S. degree in Automation in 2006 from Tsinghua University, Beijing, China, and his M.S. degree in Electrical Engineering in 2009 from Institute of Electrical Engineering, Chinese Academy of Science, Beijing, China. He was enrolled to the graduate program in Department of Materials Science and Engineering at North Carolina State University in January 2010, and conducted his doctoral thesis study at Fermi National Accelerator Laboratory since May 2013. He received his Ph.D. degree in Materials Science and engineering from North Carolina State University in October 2015.
ACKNOWLEDGEMENTS

This thesis work was performed in collaboration between the North Carolina State University (NCSU) and the Fermi National Accelerator Laboratory (Fermilab), under supervision of Dr. Justin Schwartz (NCSU) and Dr. Tengming Shen (Fermilab), with financial support from the U.S. Department of Energy, Office of High Energy Physics.

The thankful words in my mind for those who have provided invaluable help in my PhD career are beyond what this page can carry. It is therefore more than necessary to generalize these words in the following short form.

Firstly, I would like to sincerely thank my supervisor, Dr. Justin Schwartz, who brought me to the world of materials science, for his encouragements and tolerance. His valuable academic advice has guided me through my PhD life. He is strict in scientific research but very kind and easy-going in daily life. He inspired me so much to pursue a better research work and to make my graduate life more meaningful and enjoyable. Also, I really appreciate for the financial support that has permitted me and my family to live comfortably during my PhD study.

In parallel, I would like to offer special thanks to my co-advisor at Fermilab, Dr. Tengming Shen, who provided me with the chance to study and work as a Joint University-Fermilab Doctoral Program student. The work with Dr. Tengming Shen was very enjoyable and fruitful. Without the discussions with him, the ideas in my thesis would simply not exist. Both his deep understanding of our research work and fine skills of scientific writing had benefited me a lot during last two years in Fermilab.
The help from my co-workers is enormous. Among them I owe special thanks to my committee member, Dr. Frank Hunte, for his help in completing the high field experiment in Chapter 2 and his advice when I was starting my PhD study in USA. Also, I should not forget the help from Dr. Honghai Song, getting me familiar with the quench experiments and setup. I also would like to thank Dr. Pei Li, who helped me on the microstructure study in Chapter 4 with his incredible SEM skills. I sincerely thank Daniel Assell, Dr. Lance Cooley, Dr. Gene Flanagan, Allen Rusy, Daniele Turrioni and Thomas Van Raes for their invaluable help through my experimental studies at Fermilab.

I also met excellent friends in the Schwartz group at NCSU. The time spent with Dr. Wankan Chan, Davide Cruciani, Min Fan, Dr. Sasha Ishmael, Dr. Amir Kajbafvala, Dr. Quang Le, Dr. Golka Naderi, Dr. Makita Philips, Dr. Safoura Seifikar and Dr. Yun Zhang was very pleasant and memorable.

The work in Chapter 2 was performed at NCSU and supported through the VHFSMC, and the work in Chapter 3-5 was performed at Fermilab with the support from the Joint University-Fermilab Doctoral Program in Accelerator Physics and Technology, and an Early Career Award from U.S. DOE. I would like to thank the VHFSMC and Oxford Superconductor Technology (OST) for providing the superconducting wires, PMM101108-1 and PMM101108-2 and PMM080414, for my thesis study. I also appreciate Dr. Vyacheslav Yakovlev and Margie Bruce at Fermilab and Elaine Emory at NCSU who, behind the scene, help to make sure that I could get my paychecks.

Last but not the least, I cordially thank my family, especially my wife Hong Li and my daughter Lori Ye, who gave me love, appreciation and courage to enjoy my life and work.
# TABLE OF CONTENTS

LIST OF TABLES ........................................................................................................... viii

LIST OF FIGURES ......................................................................................................... ix

CHAPTER 1: INTRODUCTION ......................................................................................... 1

REFERENCES .................................................................................................................. 27

CHAPTER 2: EFFECTS OF HIGH MAGNETIC FIELD ON THE QUENCH BEHAVIOR OF Bi$_2$Sr$_2$CaCu$_2$O$_x$ COILS AT 4.2 K ........................................................................ 32

REFERENCES .................................................................................................................. 52

CHAPTER 3: HIGH-FIELD QUENCH BEHAVIOR AND DEPENDENCE OF HOT SPOT TEMPERATURE ON QUENCH DETECTION VOLTAGE THRESHOLD IN A Bi$_2$Sr$_2$CaCu$_2$O$_x$ COIL .................................................................................. 54

REFERENCES .................................................................................................................. 82

CHAPTER 4: QUENCH DEGRADATION LIMITS IN MULTIFILAMENTARY Ag/Bi$_2$Sr$_2$CaCu$_2$O$_x$ CONDUCTORS AND EVIDENCE FOR A STRAIN-DRIVEN DEGRADATION MECHANISM ........................................................................ 86

REFERENCES .................................................................................................................. 108

CHAPTER 5: DEPENDENCE OF QUENCH DEGRADATION LIMITS IN Bi$_2$Sr$_2$CaCu$_2$O$_x$ ROUND WIRE ON AXIAL STRESS AND STRAIN ................................................................ 111

REFERENCES .................................................................................................................. 136

CHAPTER 6: CONCLUSIONS AND SUGGESTED FUTURE WORK ................................. 138

APPENDICES .................................................................................................................. 142
# LIST OF TABLES

Table 2-1  Parameter summary for two test coils ...............................................................36
Table 3-1  Specifications of the solenoid sample ................................................................59
Table 4-1  Summary of properties of conductors investigated ........................................88
Table 4-2  List of samples investigated ..................................................................................91
Table 5-1  Properties of the investigated conductor ............................................................115
Table 5-2  Summary of the investigated barrel information .................................................120
Table 5-3  Summary of the quench degradation limits under varied tensile stresses ..........127
Table 5-4  Estimated strains applied on Bi-2212 filaments .....................................................130
LIST OF FIGURES

Figure 1-1 Typical superconducting magnet: (a) dipole and (b) solenoid ......................3
Figure 1-2 Nb-Ti wires and cables used in LHC: (a) cross-section image showing Nb-Ti
filaments in Cu matrix; (b) cross-section image of a 0.825 mm Nb-Ti wire; (c) a
36-strand Rutherford cable ..................................................................................4
Figure 1-3 Current evolution during a typical quench event ...........................................7
Figure 1-4 Engineering critical current density $J_E$ of major superconductors at 4.2 K.............9
Figure 1-5 Schematic diagram of PIT process ..................................................................10
Figure 1-6 A typical PIT-fabricated Ag/Bi-2212 green wire ............................................11
Figure 1-7 Generic PMP schedule for Ag/Bi-2212 round wire ........................................12
Figure 1-8 Transverse cross-section image of fully-processed Bi-2212 multifilamentary
round wire .............................................................................................................14
Figure 1-9 Cross-section images of typical Bi-2212 round wires .......................................15
Figure 1-10 Stress-strain curve of 2212 and $J_c$ dependence on strain ...............................18
Figure 1-11 $T_c(B)$ of Nb$_3$Sn, Bi-2212 and YBCO .........................................................20
Figure 1-12 Energy over volume required to induce a quench vs. operating temperature for
superconductors ......................................................................................................21
Figure 2-1 (a) Coil I after winding but before heat treatment. The Nichrome wire heaters are
seen. (b) Coil I after heat treatment, instrumentation and epoxy impregnation ..34
Figure 2-2 Instrumentation schematic for coil I. The voltage tape distance for V23 is 1.5 cm,
for all others it is 1.0 cm .......................................................................................34
Figure 2-3 (a) Coil II after winding but before heat treatment. The Ag wires attached to the
inner turns are seen. (b) A Ag wire wound around the Bi-2212 wire to be used as
a voltage tap.................................................................35

Figure 2-4 Instrumentation schematic for coil II. The black circles indicate the locations of
tap spacing in the y- and z-directions is 1.5 cm. In the
x-direction, the voltage tap spacing is 1.0 cm, except around the heater, where it
is 3.0 cm ........................................................................35

Figure 2-5 Data acquisition system schematic for the quench experiments. DMM refer to
Digital Multimeters including Keithley K2000, K2001 and K2700 and the HP
6681 is used as the transport current supply. The voltage pulse on the heater is
generated by the Kepco BOP5, with its amplitude controlled by either the
HP8112A or directly through the GPIB........................................37

Figure 2-6 $I_c(B, 4.2 \, K)$ for both coils.................................................................39

Figure 2-7 $T_c(B)$ for the witness samples measured magnetically in a SQUID
magnetometer ........................................................................40

Figure 2-8 (a) Temperature and (b) voltage versus time for both a recovery and a quench.
The heat pulse plot is shown to indicate the timing, but the magnitude is not to
scale..............................................................................41

Figure 2-9 Minimum quench energy as a function of magnetic field for each coil.........42

Figure 2-10 Voltage versus time, on each voltage tap, during a quench in coil I..............43

Figure 2-11 Temperature versus time, on each thermocouple, during a quench in coil I ......44

Figure 2-12 Current sharing temperature as a function of magnetic field for coil I ............45

Figure 2-13 Longitudinal normal zone propagation velocity versus magnetic field for each
Figure 2-14 Transverse normal zone propagation velocity versus magnetic field for each coil.

Figure 2-15 Normalized magnetic field dependence of the critical temperature, normal zone propagation velocity, minimum quench energy, critical current and current sharing temperature. All of the data are from coil II, except for the current sharing temperature which is for coil I.

Figure 2-16 Comparison between the experimental results and numeric calculation data on coil I with 60% of $I_c$.

Figure 3-1 Measured normal zone propagation velocity at 4.2 K as a function of $J_o$, the operating current density averaged over the conductor in magnetic fields up to 19 T.

Figure 3-2 (a) The epoxy-impregnated coil fabricated as mounted on the test probe, (b) the transverse cross-section of the Bi-2212 wire used to fabricate the coil, and (c) a side-view of the mullite braided insulation sleeve.

Figure 3-3 (a) Schematics of the epoxy spot heater ECOBOND 60L on the 30th conductor turn of the layer 6 (the bottom half), together with an E-type thermocouple and a voltage tap (tap length = 1.5 cm) that reads $V_{NZ}$. (b) Hot spot temperature recorded by the thermocouple for two heater input energies.

Figure 3-4 The $I_c$ of the Ø1.2 mm Bi-2212 strand at 4.2 K and in applied fields up to 14 T and the quench current $I_q$ of the test coil. The witness strand, 8 cm long, was melt processed with the coil but with its ends open during the heat treatment.
The strand $I_c$ was determined using a standard four-probe method at an electric field criterion of 1 $\mu$V/cm, whereas the coil $I_q$ was plotted against the background field only.

**Figure 3-5** Voltage-time evolution when the test coil experienced critical recovery for $I_o=100$ A, 150 A, 200 A, 250 A, 300 A, and 400 A at 4.2 K and 7 T. Signals were synchronized by placing the rising edge of heat pulses at 0.1 s.

**Figure 3-6** Evolution of (a) the hot spot temperature and (b) the layer and terminal voltage for the test coil when it experienced a heater-induced quench at 4.2 K and 7 T while carrying a current $I_o$ of 100 A. Figure (a) presents both the temperature directly measured by the thermocouple and the temperature converted from $V_{NZ}$. The insert in (b), plotted using a log 10 scale, highlights that when the terminal voltage reached 0.1 V, normal zone had propagated to the layer 3.

**Figure 3-7** Evolution of (a) the hot spot temperature and (b) the layer and terminal voltage for the test coil when it experienced a heater-induced quench at 4.2 K and 7 T while carrying a current $I_o$ of 400 A. Figure (a) presents both the temperature directly measured by the thermocouple and the temperature converted from $V_{NZ}$. The insert in (b), plotted using a log 10 scale, highlights that when the terminal voltage reached 0.1 V, normal zone had just propagated to the layer 5.

**Figure 3-8** The hot spot temperature in the test coil when it experienced heater-induced quenches while carrying an $I_o$ of 100 A, 200 A, 300 A, and 400 A, and its terminal voltage reached 0.1-1 V. The tests, results of which were presented in Figure 3-7 and Figure 3-8 for $I_o = 100$ A and $I_o = 400$ A, respectively, were
performed at 4.2 K and in a background field of 7 T. The hot spot temperature was estimated from $V_{NZ}$. 

Figure 3-9 (a) Quench integrals for commercial Ag/Bi-2212 wires ($\lambda = 0.25$). (b) Temperature rise predicted using quench integrals for commercial Ag/Bi-2212 wires. (c) Hot spot temperature rising rate $dT/dt$ when $T_{\text{max}} = 60$ K predicted by quench integral calculation as compared to experimental data. (d) Time available for forcing magnet current to go to zero and its dependence on operating current density and the quench detection temperature.

Figure 3-10 Measured minimum quench energy as a function of $J_o$, the operating current density averaged over the conductor, at 4.2 K in a magnetic field up to 20 T.

Figure 4-1 Optical cross-sectional images of the conductors investigated.

Figure 4-2 Schematic of the experimental set-up and a photograph of a wired sample.

Figure 4-3 (a) Typical voltage and temperature versus time during a thermal runaway on sample #1. (b) The local temperature rise on the central section based upon thermocouple readings and converted voltage measurements.

Figure 4-4 (a) $I_c$ after quenching normalized by the initial $I_c$ versus local peak temperature for a series of quenches on sample #1 and (b) $T_{\text{max}}$ and normalized $I_c$ versus location along the wire for the final quench on sample #1.

Figure 4-5 (a) The peak temperature and normalized $I_c$ versus location along the wires for samples #1, 2 and 3. Note that samples #2 and #3 are quenched with the longer heaters. (b) The corresponding normalized $I_c$ versus $T_{\text{max}}$.

Figure 4-6 Normalized $I_c$ versus $T_{\text{max}}$ for samples of all three conductor architectures.
Figure 4-7  (a) Normalized $I_c$, (b) $I_c$ and (c) n-value versus $T_{\text{max}}$ after quenching, comparing the wires heat treated in 1 bar and 100 bar atmospheres

Figure 4-8  Longitudinal SEM cross-sectional image of a region of a 100 bar OP processed sample that was quenched but did not degrade

Figure 4-9  Longitudinal SEM cross-sectional images of a region of a 100 bar OP processed sample that shows a 40% reduction in $I_c$ due to quenching. (a) Low magnification image; high resolution images of the areas within the ovals are shown in (b) and (c)

Figure 4-10 Longitudinal SEM cross-sectional image of a region of a 100 bar OP processed sample that shows a 80% reduction in $I_c$ due to quenching

Figure 4-11 (a) Normalized $I_c$ versus $T_{\text{max}}$ for sample #1 as in Figure 4-6 and (b) electromechanical behavior of similar wire as reported in [22, 23]

Figure 5-1  Stress-strain curve of a typical Bi-2212 round wire

Figure 5-2  $I_c$ dependence on applied axial strain for a commercial Bi-2212 round wire

Figure 5-3  Optical cross-sectional images of the investigated conductor

Figure 5-4  (a) An ITER barrel fixture made of Ti-6Al-4V alloy, (b) Bi-2212 strand with the Al$_2$O$_3$ ceramic barrel after 25 bar heat treatment

Figure 5-5  Operation procedures for transferring the Bi-2212 spiral from Al$_2$O$_3$ barrel to G-10 barrel

Figure 5-6  (a) Stress-free mode: Lorentz force pointing inward and no axial stress applied; (b) Tensile stress mode: Lorentz force pointing outward and tensile hoop stress applied
Figure 5-7  (a) Instrumentation layout for the quench degradation test on Bi-2212 barrel; (b) a Bi-2212 barrel ready for the test .......................................................... 119

Figure 5-8  $I_c(B)$ of the Bi-2212 barrel samples and 8 cm short witness samples ............ 121

Figure 5-9  $J_c$ and $n$-value re-measured after each stress cycle verse the tensile hoop stress and the corresponding transporting current for applying stress in each cycle on Barrel #2 ........................................................................................................... 123

Figure 5-10 $I_c$ after quenching normalized by the initial $I_c$ versus local peak temperature for a series of quenches on Barrel #1 ........................................................................................................... 124

Figure 5-11 $I_c$ after quenching normalized by the initial $I_c$ versus local peak temperature for a series of quenches on Barrel #3 ........................................................................................................... 126

Figure 5-12 Quench degradation temperature limits verse applied tensile stresses .......... 128

Figure 5-13 Thermal expansion on Ag/Bi-2212 round wire and Bi-2212 grain in $a,b$ plane when warming from 4.2 K ........................................................................................................... 131

Figure 5-14 Estimated tensile strains applied on Bi-2212 filaments with quench degradation temperature limits verse applied tensile stresses ........................................... 132

Figure 5-15 $I_c$ dependence on applied tensile strain from quench degradation test (black dots, retrieved from Figure 5-10) and mechanical test (red line, retrieved from Figure 5-2) ........................................................................................................... 133

Figure A-1  Schematics of the transport $I_c$ measurement on a Bi-2212 short strand ......... 144

Figure A-2  (a) Schematic of sample mounted with instrumentation wiring for a quench experiment, and (b) photograph of sample .......................................................... 145

Figure A-3  (a) Photograph of an epoxy heater mounted on the Bi-2212 and (b) schematic for
the epoxy heater circuit ................................................................. 148

Figure A-4  Thermocouple voltage to temperature conversion ............................................. 150

Figure A-5  Local temperature rise during a typical quench with the data from both
thermocouple readings and voltage converted estimations ........................................ 152

Figure A-6  Schematics for two data acquisition system used in this study ....................... 154
CHAPTER 1

INTRODUCTION

To explore the limits and guide the design of a new very high-field superconducting magnet technology based on Bi$_2$Sr$_2$CaCu$_2$O$_{8+x}$ (Bi-2212) round wires, the work experimentally investigates the behaviors of Bi-2212 wires and small coils during a quench, an event that presents significant challenges to the operation of superconducting magnets, and determines how such behaviors alter with conductor design, heat treatment, and stress/strain states of the conductor. After a brief introduction of superconducting magnets, their operations, and quenching, this introduction chapter will explain motivations to study Bi-2212 round wires, their design, fabrication, and heat treatment, then present crucial questions that drive this work and an outline of this thesis.

1. Superconducting Magnets

High field superconducting magnets are important for scientific research in a variety of disciplines. They play a key role in the Large Hadron Collider (LHC), the particle accelerator at CERN, Geneva, the largest and probably the most complex scientific instrument ever built. LHC is based on the reliable operation of almost 10,000 superconducting magnets cooled by 130 tons of liquid helium at 1.9 or 4.2 K and containing a total stored magnetic energy of about 15000 MJ. These powerful superconducting magnets in LHC enable a series of fundamental discoveries in the particle physics, highlighted with the discovery of Higgs boson in 2012. Advanced superconducting magnet systems are also crucial for nuclear physics and fusion energy technology. They play a key role in the International Thermonuclear Experimental Reactor (ITER) [1]. The central superconducting solenoid of
ITER produces a field of up to 13.5 T and the 18 toroidal coils at the maximum field of 11.8 T for exciting and confining hot plasma. Superconducting magnets were also used to achieve the world’s highest DC magnet field in the 45 T hybrid magnet at the National High Magnetic Field Laboratory, Tallahassee, FL. Its outer superconducting coil produces a static magnetic field of about 11 T, while the rest of the 45 T field is generated by water-cooled resistive insert with the bore diameter of 32 mm.

There are several important types of superconducting magnets, which differs each other in terms of the magnetic field profile generated, design, and fabrication. The 1,232 main magnets in LHC, used for bending the particle beams along the desired orbit, are dipole magnets as shown in Figure 1-1a with the dimension of 15 m in length and 30 tons in weight, whereas the superconducting magnets in the 45 T magnet are solenoids as shown in Figure 1-1b. A common feature that later on proves to be important for this research and shared by all high-field magnets are that when energized, the conductor in these superconducting windings is subjected to strong Lorentz forces and enormous amount of stresses. For more about design, fabrication, and operation of different kinds of superconducting magnets, readers are referred to an excellent monograph on basics of superconducting magnets written by Martin Wilson [2], another monograph on superconducting solenoid technology by Yuki Iwasa [3], and a book of superconducting accelerator magnet by Karl-Hubert Mess [4].
Figure 1-1 Typical superconducting magnet: (a) dipole and (b) solenoid
2. **Quench in superconducting magnet and its consequences**

Superconducting magnets are typically made from round or tape-shaped composite conductors, in which multiple superconductor filaments are embedded in a matrix consisting of a normal metal, such as Cu or Ag, or high-current cables made from them. Figure 1-2 shows the Niobium-titanium (Nb-Ti) wires and the Rutherford cables used in LHC. The cable shown in Figure 1-2c consists of 36 strands of Nb-Ti superconducting wire. Each strand is exactly 0.825 mm in diameter and houses 6300 Nb-Ti superconducting filaments, and each filament is about 0.006 mm thick embedded in a Cu matrix as shown in Figure 1-2a and 2b.

![Figure 1-2 Nb-Ti wires and cables used in LHC](image)

(a) (b) (c)

Figure 1-2 Nb-Ti wires and cables used in LHC: (a) cross-section image showing Nb-Ti filaments in Cu matrix (b) cross-section image of a 0.825 mm Nb-Ti wire (c) a typical 36-strand Rutherford cable (Courtesy of CERN)
During normal operations, transport current flows in superconducting filaments, generating no joule heating when working at steady states and a small amount of heat when either field or current is changing. However nearly all superconducting magnets may suffer from a phenomenon called quenching. During a quench, a portion of superconductor turns normal so electric current flows in the metal stabilizer, generating joule heating that drives adjacent regions to be normal and causing significant temperature rise. Simple ballpark analysis by considering the heat balance of unit volume of winding \((1 - \lambda)f_m^2(t)\rho(T)dt = \gamma C(T)dT\), where \(\lambda\) is the volumetric ratio of superconductor in the metal/superconductor composite, \(J_m\) the current density in the metal matrix, \(\rho(T)\) the resistivity of the metal matrix, \(\gamma C(T)\) the volumetric heat capacity averaged across the conductor, \(T\) the temperature, and \(t\) the time, predicts that hot spot temperature rises very fast, usually at tens of Kelvin per second for solenoids typically working with a \(J_m\) at 150-300 A/mm\(^2\) and dipole magnets working with \(J_m\) at 400-600 A/mm\(^2\).

Quenching may present catastrophic consequences to superconducting magnets. During the commissioning of the LHC, a very severe incident happened on 19 September 2008 due to a magnet quench induced by a faulty electrical connection between two magnets. The quench led to \(~100\) K temperature rise in some of the affected magnets, and around two tons of liquid helium escaped explosively before detectors triggered an emergency stop, and a further four tons leaked at lower pressure in the aftermath. A total of 53 magnets were damaged in the incident and later were repaired or replaced, with the total repair cost of €16.6 million. The incident caused more than one year of delay to restart the physics program and a minimum delay of two years to reach full energy [5]. The world-record 45 T hybrid
magnet also suffered the quench issues in its superconducting outset coil. On July 10, 2000, the outset suffered an unprotected quench (breakers not opened) about 5 minutes after reaching full current. The coil behavior suggests a thermal runaway, leading up to a quench. Following the unprotected quench, the coil was not able to perform as before; most notably, it is unable to reach the rated current after the same ramp-up scenarios as before [6].

To protect magnet from damages during a quench, it is crucial to detect a quench, and force the magnet current to go to zero quickly, before the conductor temperature goes to a dangerous level. Both of these steps need time, and Figure 1-3 gives a plot for current evolution during a typical quench event. More technical details about quench protection will be discussed later in this chapter. How fast such task can be completed depends crucially on the quench characteristics of the conductors, including the minimal quench energy (MQE) that characterizes how stable the conductor is, and the normal zone propagation velocity (NZPV) that measures how fast a normal zone travels. Both of these parameters strongly depend on temperature, magnetic field, and operating current density and will be carefully measured in this work. The time constant of the quench protection also depends crucially on the temperature at which $I_c$ of Bi-2212 wires would degrade, and this degradation limit will be carefully determined in this work.
3. Bi-2212: a very high field superconducting material

Here we will switch gear to discuss motivations for studying Bi-2212. At present, the entire present portfolio of large scale superconducting magnet technology is made up by two niobium-based low-temperature superconductors (LTS): Nb-Ti with a transition temperature \( T_c \) of 9 K and upper critical magnetic field \( H_{c2}(4.2 \text{ K}) \) of 12 T, and Nb\(_3\)Sn with \( T_c \) of \( \sim \)18 K and \( H_{c2}(4.2 \text{ K}) \) of \( \sim \)27 T. Nb-Ti was used in LHC and Nb\(_3\)Sn is being used to fabricate ITER magnets. The superconductivity boundary of these LTS limits the magnetic field reach below \( \sim \)16 T for dipoles and quadrupoles and less than \( \sim \)22 T for solenoids as demonstrated in LHC and ITER, therefore constraining the energy reach of accelerators to several TeV and restricting nuclear magnetic resonance (NMR) studies below 900 MHz. However, frontier accelerator facilities and \( \sim \)1 GHz NMR, which will enable important new physics
opportunities, demand magnets to generate high magnetic field of >22 T [7, 8]. For example, the proposed muon collider would depend on the ability to construct strong focusing magnets (30+ T) for final muon cooling [9].

Bi-2212 is one of high-temperature superconductors (HTS) that have been arduously developed into useful forms over the past two decades. Figure 1-4 compares its ability to carry current at increasing applied magnetic fields at 4.2 K (liquid Helium (LHe) temperature) with other major superconductors. Several HTS conductors, including Bi-2212, (Bi,Pb)₂Sr₂Ca₂Cu₃Oₓ (Bi-2223) and YBa₂Cu₃Oₓ (YBCO), have \(H_{c2}\) at 4.2 K up to 100 T. They offer the possibility to generate magnetic fields far beyond the maximum field with LTS, by taking advantage of their nearly field-independent current density over a wide range of magnetic field at 4.2 K up to 50 T [10, 11]. Among these materials, Bi-2212 is unique because it can be made with critical current density \(J_c\) of \(10^5\) A/cm² up to 45 T using a reliable fabrication route in round wire form, whereas Bi-2223 and YBCO need strong texture and grain alignment and they can only be made into tape-like conductor. Round wire form is important because its critical current is isotropic regards to field orientation and permits access to the Rutherford cabling technique developed for low-temperature superconducting materials.
3.1 Fabrication of Bi-2212 multifilamentary round wires

Bi-2212 is a brittle ceramic material and has been fabricated into a wire form using a powder-in-tube approach (PIT) since 1989 [13]. Figure 1-5 [14] shows the schematic diagram of the PIT process used by industry to fabricate Bi-2212 wires. The process consists of the following steps:
• Precursor powder preparation: a mixture of single Bi-2212 phase with a nominal composition of $\text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}_x$ has to be calcined to transform the carbonate into an oxide, because carbon is harmful to the following thermal processing.

• Powder packing: Pure Ag tubes are filled with the calcined Bi-2212 precursor powder by mechanical agitation. Here, Ag is specifically selected for Bi-2212 process, and the reason will be discussed in the next section.

• Tube swaging and drawing: The filled Ag tubes are sealed and cold drawn through a series of dies with gradually decreasing diameters (hex and restack technique using drawing alone without extrusion) into monocore elements.

• Restacking: A number of monocore elements are bundled and stacked into another Ag tube to form a multifilamentary green wire.
• Final drawing: The formed wire is put into Ag-alloy tube and drawn to the long length wire with the desired diameter.

Figure 1-6 [14] shows a representative commercial as-drawn, unreacted PIT Ag/Bi-2212 composite round wire conductor fabricated by the Oxford Superconducting Technology, New Jersey, a leading superconducting wire manufacturer. It has a diameter of 1.06 mm and a configuration of 85x7 filaments, whose average diameter is ~20 μm. It has a Bi-2212 filling factor of around 28%. The Bi-2212 filaments are embedded in pure Ag matrix, while there is an outer sheath made of Ag-Mg alloy surrounding the wire.

![Figure 1-6 A typical PIT-fabricated Ag/Bi-2212 green wire [14]](image)

### 3.2 Processing and microstructure of Bi-2212 multifilamentary round wires

The as-drawn PIT Bi-2212 wires need to go through a partial melt processing in order to gain capability to carry high currents. Figure 1-7 presents a schematics of the partial melt...
processing (PMP) [15]. During PMP, the green wire is firstly heated above the Bi-2212 peritectic temperature (~880 °C) where the single-phase Bi-2212 in the Bi-2212 filaments melt and decompose into a mixture of liquid, alkaline earth cuprate (AEC) and copper free (CF) phases. In the subsequent re-solidification, Bi-2212 grains form with better connectivity.

Figure 1-7 Generic PMP schedule for Ag/Bi-2212 round wire [15]

Ag, instead of less expensive Cu or Al, is used as a matrix, because pure Ag is chemically compatible with Bi-2212 during processing (many other metals such as Cu and Fe react with oxide filaments during high-temperature reactions and destroy the superconductivity), and it is permeable to oxygen. The later one is important because when melting, Bi-2212 powders release oxygen, and during solidification, Bi-2212 filaments absorb oxygen [16]. Later on,
we will see that Ag plays a role in determining the quench degradation behavior and limits of Ag/Bi-2212 wire. Compared to the well-studied Nb₃Sn and MgB₂ wires and Bi-2223 tapes which are fabricated with PIT method as well, the melt processing of Bi-2212 green wire produces substantial amount of liquid in the Bi-2212 filaments, which is very different from the solid-state reaction using for Nb₃Sn and MgB₂ and the liquid-assisted reaction used for Bi-2223, so many new microstructural features emerge. Figure 1-8 [14] shows a representative microstructure of fully-processed high $J_c$ Bi-2212 multifilamentary round wire. In contrast to the uniform and well-separated filaments of green wire as shown in Figure 1-6, the reacted filaments are very inhomogeneous and interconnected, with many filament bridges running between them. These filament bridges may form with Bi-2212 single grains growing across two filaments joined by liquid or with Bi-2212 grains penetrating into Ag matrix and touching another grain [14]. It is hitherto unknown to what degree such filament to filament bridges might affect quench behaviors of Ag/Bi-2212 wires. We will examine its role in Chapter 4.

Moreover, the Bi-2212 filaments contain many secondary phases, including Bi2201 (a low $T_c$ (~20 K) Bi-Sr-Ca-Cu-O compound), remnant AEC and CF phases [17-19] [20]. Another important feature in processed Bi-2212 round wire’s microstructure is porosity. In as-drawn Bi-2212 green wires, Bi-2212 filament density is around 70% of its theoretical density. The 30% residual void space is distributed within the filaments. During PMP, the porosity agglomerates in the melted liquid phase materials and forms bubbles within Bi-2212 filaments, which will intensively limit the current transporting capability over long length.
conductor [21-23]. Recently, the advanced processing methods to enhance the Bi-2212 filament densification and thus significantly improve the conductor’s $J_c$ are being developed, and the details will be discussed in the rest part of this chapter. In Chapter 4, we will explore potential impacts of porosity on the quench degradation behaviors.

Figure 1-8 Transverse cross-section image of fully-processed Bi-2212 multifilamentary round wire [14]

3.3 Influence of conductor design on Bi-2212 round wire

The present Bi-2212 wire architecture, which contains hundreds of fine filaments of ~20 μm embedded in a Ag matrix, is adopted from the conventional LTS composite wire fabrication. Subdividing the superconductor into multifilamentary wire with fine filament diameter has been proven to provide intrinsic stability against flux jumps in transient magnetic field, which would lead to premature quenching and poor magnet performance [2]. As described in
last two sections, the combination of melt processing with PIT fabrication yields a unique material structure-processing-properties system for Bi-2212 round wire, so the conductor design details (e.g. filament diameter, filament spacing, filament shapes, Bi-2212/Ag ratio, and filament mass density) may affect the final microstructure, $J_c$ of the conductor, and potentially affect the quench performance and quench degradation behavior of these wires. Figure 1-9 presents three double-stack Bi-2212 round wires provided by OST with the representative conductor design variations. Supercon, Shrewsbury, MA, also has developed a single-restack, high Bi-2212/Ag ratio wires [73].

![Cross-section images of typical Bi-2212 round wires](Image)

Figure 1-9 Cross-section images of typical Bi-2212 round wires (Courtesy of Pei Li and Tengming Shen)

### 3.4 The role of porosity and advanced processing method to improve the Bi-2212 densification and $J_c$

During the early development of superconducting magnet with Bi-2212 round wires, there was a ‘mysterious’ problem that the transport properties of coils with long length conductors
were typically 25–35% less than those of short samples reacted under nominally identical conditions [24-26]. Moreover, melt-processed Bi-2212 coils have often suffered from leakage, showing clear discolorations where Bi-2212 liquid leaks through the encasing metal (Ag or Ag alloy) at high temperatures and reacts with surrounding materials such as insulation [10, 24]. Since 2011, this problem has been successfully addressed: the porosity agglomeration and bubble formation within Bi-2212 filaments, which had the strongly negative impact on connectivity and current transport capability, was observed during the melt processing, and then the cause of $J_e$ degradation with length of Bi-2212 wires was identified as the wire swelling due to high internal gas pressures at elevated temperatures [21-23]. Internal gas pressure in long-length wires leads to the Ag sheath to creep during the heat treatment. Creep of Ag expands the wire with the bubbles remaining within filaments, reduces the density of Bi-2212 filaments, and therefore degrades the $J_e$ of the wire. The creep rupture of Ag sheath also causes the leakage of Bi-2212 liquid [23].

Recently, the advanced processing methods have been developed to densify Bi-2212 filaments in the as-drawn wire. OST used swaging or cold isostatic pressing (CIP) to increase the filament mass density and reduce filament porosity prior to PMP. Through 30% cross-section area reduction swaging or 1400 MPa CIPing, over 90% of the Bi-2212 theoretical density was achieved and no large bubble in the filaments was observed, and the $J_e$ of 470~480 A/mm$^2$ at 4.2 K, 15 T could be achieved on 1-m-long wires, compared to 290~320 A/mm$^2$ at 4.2 K, 15 T on as-drawn wire [27]. NHMFL also used swaging to increase the Bi-2212 filament density of the wires from 3.66 to 5.33 g/cm$^3$, and improve the $J_e$ to 808 A/mm$^2$ at 4.2 K, 5 T from 486 A/mm$^2$ at 4.2 K, 5 T on as-drawn wires [28].
Another processing method with significant performance improvement is the over pressure (OP) processing, which is essentially hot isostatic pressing (HIP) and was previously used on Bi-2223 tape processing. During the OP process, the as-drawn Bi-2212 wires are heat treated under the atmosphere pressure up to 100 bar with the oxygen partial pressure remaining at 1 bar, so that creep of the Ag is facilitated under over pressure beyond the internal gas pressure to shrink the wire diameter and fully densify the Bi-2212 filaments. A 650 MPa CIPed 1.2 m long sample processed in a 10 bar OP heat treatment gave the $J_e$ of 550 A/mm$^2$ at 4.2 K, 15 T [53]. The coil that generated almost 2.6 T in a 31.2 T background field at NHMFL was heat treated at 100 bar OP, and the $J_e$ of 252 A/mm$^2$ at 4.2 K, 33.8 T was achieved [29]. Chapter 4 will examine the role porosity and densification treatments on the quench degradation limits of Bi-2212 wires.

3.5 Mechanical properties and sheath development

The conductors within high field magnets are subjected to enormous electromagnetic stresses when the magnet is operating; the hoop stress $\sigma$ in a solenoid, estimated using $\sigma = BJR$ ($B$ is the magnetic flux density, $J=I_o/A$ in which $I_o$ is the operating current and $A$ the cross-section of the metal/superconductor wire, $R$ the radius of the solenoid insert), can well exceed 180 MPa for a 25 T magnet with a bore size of 50 mm (assuming $J=300$ A/mm$^2$). Unfortunately, Bi-2212 is brittle after reaction and its current carrying capability is sensitive to strain. Figure 1-10 shows a plot of dependence of critical current density on axial stress and strain in Bi-2212 wires. Under axial stress, the critical current $I_c$ of Ag-sheathed Bi-2212 strand is virtually insensitive to tensile strain up to a sample dependent strain limit. When this limit is exceeded, the critical current $I_c$ decreases steeply and irreversibly. Applying compressive
strain to Ag/Bi-2212 conductor causes a gradual and irreversible decrease of $I_c$. Magnetic fields have no noticeable effect on this $I_c(\varepsilon)$ dependence. For commercial Ag-0.2 wt% Mg/Ag/Bi-2212 (area ratio AgMg:Ag:Bi-2212 = 0.25:0.5:0.25) round wire, the working stress maximum is around 120 MPa at 4.2 K whereas the irreversible tensile strain is between 0.3% and 0.45% [30]. We will explore the role of strain states in determining the quench degradation limits of Bi-2212 wires in Chapter 5.

![Figure 1-10 stress-strain curve of 2212 and $J_c$ dependence on strain [30]](image)

4. Development of Bi-2212 magnets and the challenge of quench protection

A series of Bi-2212 insert coils have been made since 1994 and reached 1 T in a background of 19 T in 1997 and 3 T in a background of 19 T in 1999 [24]. In 1999 double pancake coils
were fabricated and tested in various backup magnetic fields up to 20 T by Okada et al. at the Tsukuba Magnet Laboratory of NRIM [31], and in 2000 they developed a Bi-2212 insert magnet that generates a total record magnetic field of 23.42 T (5.42 T generated by Bi-2212 magnets with a backup field of 18 T) [32]. In 2003, NHMFL in collaboration with Oxford Superconducting Technology (OST) in New Jersey, improved the record field to 25 T in a Bi-2212 solenoid insert [33, 34]. All of these coils were fabricated from flat 2212 tapes. Since 2003, great advances have been achieved in the fabrication of 2212 round-wire conductors, which is more preferred for magnet application. By 2005, Bi-2212 multifilamentary round wire can be produced with engineering critical current density ($J_c$) of 325 A/mm$^2$ at 4.2 K, 25 T and in long lengths at OST [35]. In 2006, a successful wind-and-react coil technique from Bi-2212 round wire was developed by OST and NHMFL with the capability to produce a 1 T insert in a 19 T background [36]. In 2008, NHMFL achieved a 32 T (1 T in a background of 31 T) using the Bi-2212 round-wire conductor [37], and OST created a 22.5 T (20 T generated by LTS magnets, and additional 2.5 T by a Bi-2212 insert) in 2009 [25]. In 2013, the new record field was settled at 33.8 T by a small coil that generated almost 2.6 T in a 31.2 T background field was made in NHMFL [29].

4.1 Stability and quench behavior in HTS magnet

To build and safely operate high field HTS magnets, a thorough understanding of the quench behavior of the HTS conductors is required. Although the quench behavior of LTS based magnets is well understood, HTS magnets show distinctly different stability and quench behavior due to the nature of high $T_c$ [3, 38, 39]. Figure 1-11 provided by Tengming Shen illustrates the $T_c(B)$ curve for Bi-2212 round wire and YBCO tape compared to Nb$_3$Sn round
wire. Figure 1-12 provided by Xiaorong Wang [40] shows the energy densities required to adiabatically heat a superconducting magnet from its operation temperature $T_{op}$ to its critical temperature $T_c$ estimated as a function of $T_{op}$ for both LTS and HTS conductors. Note that as $T_{op}$ approaches $T_c$ less energy is needed to induce a quench. HTS conductors require considerably more energy to induce quenching; this is a reflection of their superior stability to LTS.

![Diagram](image.png)

Figure 1-11 $T_c(B)$ of Nb$_3$Sn, Bi-2212 and YBCO (Courtesy of Tengming Shen)
Figure 1-12 Energy over volume required to induce a quench vs. operating temperature for superconductors at self field [40]

The characteristic I-V plot of any superconductor can be described by a power law of value $n$ and fit to the criterion used to determine critical current, typically $1\mu\text{V/cm}$. LTS conductors have substantially larger $n$-values than HTS [40, 41], meaning that their transition from the superconducting phase to normal phase is sharper and faster. Smaller $n$-values in HTS allow it to operate above $I_c$ and share current with the stabilizing material, but not induce excessive voltages that can create Joule heat and cause a quench. This also translates into the ability of HTS conductors to operate slightly above $T_{cs}$ without causing a quench. Vysostky et al. [42] describes a quench temperature $T_q$ and electric field $E_q$ at which HTS enter an unstable...
region for a given $J_{op}$ above $J_c$. That is to say, HTS can experience temperatures and electric fields that do not cause quench. In the absence of a constant heat disturbance these temperatures and fields will vanish and the conductor will return to normal operating conditions without changing $J_o$ [43]. This phenomenon is known as a “recovery”.

In LTS magnets, the disturbance with the energy level of mJ, such as conductor motion and epoxy cracking, could induce the magnet quenching. Although HTS intrinsically has the significantly larger stability margin than LTS, and thus the quench in HTS magnet is not as easy to occur as LTS magnet, the quench issue in HTS magnet is still a critical challenge in terms of detection and protection.

Since a superconducting magnet is expensive and quench is always possible, magnets require protection to ensure safe quenching. The speed at which the normal zone propagates, so called normal zone propagation velocity (NZPV), is a key component in quench detection and protection, because it determines the ability of a magnet to distribute the normal zone quickly through the winding and increase the area over which energy is dissipated, effectively reducing the “hot spot” temperatures experienced during a quench.

Compared to the well documented and understood LTS with NZPV of m/s [2, 3, 41], it is widely accepted that NZPV for HTS is often two orders of magnitude slower than in LTS under equal cooling conditions [3, 41, 44]. With commonly reported values for NZPV in HTS materials in the order of 1-10 cm/s, it is foreseeable that passive protection is not applicable on HTS magnets and any quench is detrimental due to potentially localized hotspot, since the detect-and-dump active protection on existing LTS magnets currently relies on measuring resistive voltage that builds up when a large size normal zone is created.
4.2 Quench-induced $I_c$ degradation

Another key factor for quench protection is to understand the conditions that degrade the wire; the ultimate goal of quench protection is avoiding such conditions, so it is essential to quantify the limits for individual wires. Qualitatively, it is known that, if a normal zone is undetected for an extended period of time during which the normal zone temperature rises above a threshold, damage will occur. Ideally, if one can keep the local temperature lower than the threshold, the conductor may safely quench. Therefore, an empirical threshold temperature was commonly determined as the degradation limit.

Previously, Imbasciati et al. studied effect of thermo-mechanical stress during quench on Cu-stabilized Nb$_3$Sn cable performance, which did not show any critical current degradation for peak temperatures up to 400 K in a heater induced quench. It also suggested that the temperature gradient between the coil and the surroundings is the most important contributor of the thermal stress on the cable [45].

Mbaruku et al. reported the effects of quenching damage on electromechanical behavior for YBCO coated conductors [46]. Samples experienced a hot-spot temperature up to 450 K along with a spatial temperature gradient as high as 150 K/cm and a temporal temperature gradient of 400 K/s and resulted in 50% loss in $I_c$. This study also observed that mechanical properties of YBCO coated conductors are degraded by partial quench damage. The yield stress is reduced and the $I_c$-strain behavior is inferior for quench damaged sample compared to the non-damaged samples. Wang et al. performed the similar quench-induced $I_c$ degradation measurement on a YBCO coated tape with a Cu stabilizer on both sides [47]. It was found that, the $I_c$ degradation initialized with a peak temperature of 490±50 K and a peak
temperature increase rate of $\sim 1800$ K/s. The author estimated the applied thermal strain on the YBCO layer developed during the quench to be $0.31\%$ applied with a strain rate of $1\%/s$, which was $\sim 60\%$ of the reported irreversible strain measured on similar samples in liquid nitrogen in mechanical tension tests applied with a rate less than $0.1\%/s$. Then, Song et al. investigated the underlying causes of degradation in YBCO CC during quenching by microstructural analysis with SEM and EDS [48]. It was found that pre-existing defects are the initiation points of subsequent degradation. These defects were mainly due to Ag delamination and/or breaches and caused high local electric field during quenching and following strong local heating, which could result in Cu etchant penetration and reaction with the underlying YBCO layer.

Effio et al. studied degradation in Bi-2212 tape conductors [49]. In this study, an experimental methodology was developed to initiate normal zone propagation in Bi-2212 tape while varying the temperature profile and then to identify the threshold quench conditions which result in conductor damage. These conditions were quantified in terms of three parameters: the maximum temperature ($T_{\text{max}}$), the maximum rate of temperature increase ($dT/dt|_{\text{max}}$) and the maximum temperature gradient ($dT/dx|_{\text{max}}$). It was found that for Bi-2212 tape, the conductor damage could be avoided under the following conditions: $T_{\text{max}} < 250$ K, $dT/dt|_{\text{max}} < 250$ K/s, and $dT/dx|_{\text{max}} < 100$ K/cm. Lately, Liyang et al. [50] used the similar methodology to study degradation limits in Bi-2212 round wires in short samples and small coils. The quench conditions are varied to identify the threshold conditions for wire degradation, which are expected to be intrinsic to the wire. It was concluded that among three quantifiable parameters considered in [49], the maximum temperature ($T_{\text{max}}$) on the hotspot is
the most critical parameter for quench degradation limit, and for two different batches of Bi-2212 round wires investigated in this study, the degradation didn’t occur until the local peak temperature rise up to 250~300 K.

5. Motivation and Outline

From the magnet quench detection and protection aspect, Bi-2212 as a typical HTS shows significant higher minimum quench energy (MQE) and a few orders slower normal zone propagation velocity (NZPV) compared to the traditional low temperature superconductor (LTS), which implies that the requirement and strategy for HTS magnet protection can’t simply follow the well-studied LTS magnets. Even though with the same protection system working for LTS magnets, the HTS magnet may still degrade because of very slow quench propagation. In general, the voltage over a length of conductor which is monitored for the purpose of quench detecting, does not provide information regarding the distribution within the magnet. There may be a very high local temperature which could be destructive by the time a detectable voltage is reached [51]. Even if the normal zone is detected, it is still challenging to spread the normal zone into a global quench in the whole magnet in a short time before local degradation occurs because the heater induced normal zone propagates very slowly.

To address the challenge of quench protection in Bi-2212 high field magnet, this thesis will focus on the following questions. (1) Compared to the previous studies on Bi-2212 shorts strands at self-field, how does the stability and quench propagation behaviors differ in large-scale coils under the high magnetic field up 20 T or even higher? (2) What are the quench degradation limits and to what degree they depend on the complex microstructure, conductor
designs, and processing details? (3) What is the physical mechanism behind the quench degradation event in Bi-2212 round wire?

Answering the first question necessitates a comprehensive experimental investigation of the quench behaviors in Bi-2212 coils under high magnetic field. Chapter 2 experimentally determines quench characteristics of small test coils and its dependence on magnetic field up to 20 T and operating current; while Chapter 3 explores the limits of Bi-2212 magnet technology through fabricating and testing various small coils, and determines the dependence of hot spot temperature on quench detection voltage criterion.

In Chapter 4, the second question is addressed through systemically characterizing the electromagnetic properties and microstructures of quench-degraded samples from a large pool of Bi-2212 round wires, which have the varied conductor designs and processing methods. A fundamental understanding for quench degradation is proposed as well.

Subsequently, Chapter 5 further expands the experiment to illustrate the degradation mechanism and provides a semi-quantitative description of the degradation event and fracture mechanics behind it to solve the third question.

Finally, Chapter 6 summaries the entire research work and proposes new design philosophy and engineering methods to guide the design of Bi-2212 high field magnets especially the quench detection and protection sub-systems.
REFERENCES


CHAPTER 2

EFFECTS OF HIGH MAGNETIC FIELD ON THE QUENCH BEHAVIOR OF Bi$_2$Sr$_2$CaCu$_2$O$_x$ COILS AT 4.2 K*


1. Introduction

The speed at which a normal zone propagates is an important parameter for designing a superconducting magnet. Earlier on Effio et al. shows that a normal zone propagates in Bi-2212 slowly at 4.2 K and self-field, at a speed of 3.6 cm/s with operating current density of 500 A/mm$^2$ [1]. Effio’s experiments were conducted using a short piece of Bi-2212 wires immersed in liquid helium, which likely plays a role in slowing down normal zone propagation speed. Here in this chapter, a series of quench experiments at high magnetic field on multilayer wind-and-react Bi$_2$Sr$_2$CaCu$_2$O$_x$ (Bi-2212) coils, which were epoxy-impregnated to better represent adiabatical conditions a quench occur in a magnet. The two- and three-dimensional quench behavior is investigated in a magnetic field up to 20 T at 4.2 K.

High magnetic field may affect the quench behavior through two opposing effects. On the one hand, high magnetic field reduces the critical transition temperature, thereby reducing the current sharing temperature, temperature margin and the MQE and increasing the NZPV. If these effects dominate, then quench detection becomes easier as the magnetic field increases. On the other hand, high magnetic field reduces $J_c$, so for constant $J/J_c$, the NZPV decreases
due to reduced operating current and thus reduced heat generation during current sharing. At present it is unclear which effect dominates. Here, a series of quench experiments on multilayer wind-and-react Bi-2212 coils investigates the effects of high magnetic field on the MQE and NZPV to address this question.

2. Experimental Approach

Bi-2212 wire is cut from a 50 m length of 0.8 mm diameter, double-restack, multifilamentary Ag/Ag-Mg sheathed RW (Oxford Superconducting Technology batch 091221-3A) insulated with braided aluminosilicate-fiber (mullite). Short samples are heat-treated using the partial-melt process (PMP) [2]; the heat treatment parameters are optimized and result in a critical current ($I_c$) as high as 580 A.

Two Bi-2212 coils are wound on Inconel 600 coil formers (outer diameter of 3.35 cm) using a Gorman Star Bobbin Winder. The first coil (coil I), designed to study two-dimensional (2D) quench behavior, consists of two layers with 33 turns per layer; the coil is seen in Figure 2-1a. Two ~1.5 cm long heaters, each made of Nichrome wire with a resistance of ~2 ohm, are wound on turns 10 and 21 of the outer layer of the coil. After winding, the coil is heat treated with the heat treatment protocol optimized using short samples. Short witness samples are heat treated with the coil. After heat treatment, the coil is instrumented with an array of Cu-wire voltage taps and Type-E thermocouples that are soldered to the outer layer. These Type-E thermocouples have been used and calibrated in the previous experiments [3, 4], and after soldered on the coil, their accuracy was double-checked at 77 K and 4.2 K with liquid Nitrogen and liquid Helium bath. The instrumented coil is seen in Figure 2-1b and a schematic of the instrumentation wiring is seen in Figure 2-2.
Figure 2-1 (a) Coil I after winding but before heat treatment. The Nichrome wire heaters are seen. (b) Coil I after heat treatment, instrumentation and epoxy impregnation

Figure 2-2 Instrumentation schematic for coil I. The voltage tape distance for V23 is 1.5 cm; for all others it is 1.0 cm

Coil II is designed to study three-dimensional (3D) quench behavior. It consists of six layers with fourteen turns per layer as shown in Figure 2-3a. During coil winding, a ~1.5 cm long Nichrome wire heater is wound around the Bi-2212 RW on the second layer. To study 3D quench propagation, it is necessary to embed voltage taps within the winding, but conventionally-used Cu wires will not survive the Bi-2212 PMP heat treatment. Thus, thin
Ag wires (0.25 mm diameter) are wound around bare Bi-2212 wire and adhered to the Bi-2212 wire surface (Ag-Mg) with Ag paste; this is seen in Figure 2-3b. The Ag wires survive the subsequent PMP, bonding to the surface, and serve as voltage taps. The Ag-wire voltage taps are arrayed around the heater to study the quench behavior; this is illustrated in Figure 2-4. The parameters for both two test coils are summarized as Table 2-1.

Figure 2-3 (a) Coil II after winding but before heat treatment. The Ag wires attached to the inner turns are seen. (b) Ag wire wound around the Bi-2212 wire to be used as a voltage tap

Figure 2-4 Instrumentation schematic for coil II. The black circles indicate the locations of voltage taps. The voltage tap spacing in the y- and z-directions is 1.5 cm. In the x-direction, the voltage tap spacing is 1.0 cm, except around the heater, where it is 3.0 cm.
Table 2-1 Parameter summary for two test coils

<table>
<thead>
<tr>
<th></th>
<th>Coil I</th>
<th>Coil II</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coil inner diameter</td>
<td>3.35cm</td>
<td>3.35cm</td>
</tr>
<tr>
<td>Layers</td>
<td>2</td>
<td>6</td>
</tr>
<tr>
<td>Turns per layer</td>
<td>33</td>
<td>14</td>
</tr>
<tr>
<td>Total length</td>
<td>~7.3 m</td>
<td>~8.2 m</td>
</tr>
<tr>
<td>$I_c$ (self-field, 4.2K)</td>
<td>360 A</td>
<td>350 A</td>
</tr>
<tr>
<td>Coil constant</td>
<td>8.40 G/A</td>
<td>13.11 G/A</td>
</tr>
</tbody>
</table>

After heat treatment and attaching the final instrumentation wiring, the coils are epoxy impregnated. No specific black stycast was used to cover the heater in this experiment, and the black part seen in the pictures was used during a previous experimental attempt and also for fix the coil edge. Each coil is then mounted between the current leads at the end of a quench probe. The probe assembly is inserted into a liquid helium bath within a cryostat that sits inside the warm bore of a magnet. Two-dimensional quench measurements on coil I are performed in magnetic fields up to 8.5 T in a superconducting magnet. Three-dimensional quench measurements are made on coil II in magnetic fields up to 20 T using the large bore resistive magnet at the National High Magnetic Field Laboratory. A schematic of the experimental set-up is shown as Figure 2-5. DMM refer to Digital Multimeters including Keithley K2000, K2001 and K2700 and the HP 6681 is used as the transport current supply. The voltage pulse on the heater is generated by the Kepco BOP5, with its amplitude controlled by either the HP8112A or directly through the GPIB.
Before beginning the quench experiments, $I_c$ is measured at several locations along the length of the coil; an end-to-end (ETE) measurement is made as well. The 4.2 K transport measurements are performed as a function of magnetic field using an electric field criterion of $1 \, \mu\text{V/cm}$ to determine $I_c$.

After electrical characterization, the witness samples are cut into short pieces ($5 \, \text{mm}$) for magnetization measurements in a SQUID magnetometer (Quantum Design SVSM). Samples are zero-field cooled to $15 \, \text{K}$ and then warmed in a magnetic field to determine $T_c$. This is repeated for increasing magnetic field to determine $T_c(B)$ for magnetic field ranging from $0.01 \, \text{T}$ to $7.0 \, \text{T}$.

In-field quench measurements are performed using measurement protocols reported previously [3-11]. Here, the transport current is varied from $40\%$ to $80\%$ of $I_c(B)$. A KEPCO
BOP50 power supply is used to generate voltage pulses (300 ms) in the Nichrome heater on the coil. The heat pulses initiate a normal zone in the Bi-2212 wire which either collapses (recovery) or grows (a quench); the response is identified by monitoring the local voltages as a function of time. A series of measurements are performed by successively increasing the pulse voltage in 0.25 V increments until a quench is observed. $I_c$ is remeasured after each quench to confirm that the coil is not degraded. The quench measurements begin at the highest magnetic field for the respective coil. The magnetic field is decreased in 1 T increments after completing measurements as a function of transport current.

3. Results and discussion

3.1 $I_c(B, 4.2 \, K)$ and $T_c(B)$

The $I_c(B, 4.2 \, K)$ results for each coil is shown in Figure 2-6. At self-field, coil I has an $I_c$ of 360 A and coil II has an $I_c$ of 350 A. The $I_c$ among the sections for quench experiment has a variation of less than ±5 %. The coil I witness samples have an average $I_c$ of 565 A and the coil II witness samples have an average $I_c$ of 559 A, confirming that the heat treatment was successful. It is typical for wind-and-react Bi-2212 coils to have lower self-field $I_c$ than their witness samples. Coil I coil has a coil-constant of 8.40 G/A, whereas that of coil II is 13.11 G/A. Thus, at 350 A, coil I generates 0.3 T of self-field and coil II generates 0.46 T. When this is taken into consideration, the coil behavior is consistent with the witness samples. During the quench experiments, no $I_c$ degradation occurred on both two test coils.
Figure 2-6 $I_c(B, 4.2 \, \text{K})$ for both coils

Figure 2-7 plots $T_c(B)$ as measured magnetically in the SQUID magnetometer. At 0.01 T, $T_c = 75$ K, but it decreases quickly at low magnetic field such that $T_c(1 \, \text{T}) = 44$ K. As the field increases, $T_c$ decreases more slowly such that $T_c(7 \, \text{T}) = 25$ K. The maximum magnetic field of $T_c(B)$ measurement is limited by the capability of SQUID, but it’s obvious that $T_c$ will keep decreasing with the field higher than 7 T.
3.2 Minimum quench energy

MQE is defined as the minimum heat pulse energy that induces a quench instead of a recovery in the coils. Figure 2-8 illustrates the difference between a quench and a recovery in the temperature-time and voltage-time behavior (this example is coil I at 8.5 T with a transport current of 118 A, which is 80% of $I_c$). A 3.50 V voltage pulse on the heater resulted in a recovery whereas a 3.75 V voltage pulse induced 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:

$$\int_{t_0}^{t_p} \text{Heat Pulse Energy} = \int_{t_0}^{t_p} V_h(t)I_h(t)dt$$

Note that $V_h$ is the voltage applied to the heater, $I_h$ is the current through the heater, and $t_p$ is the time duration of heat pulse. In this example, the MQE is 0.68 ±0.02 J.
Figure 2-8 (a) Temperature and (b) voltage versus time for both a recovery and a quench. The heat pulse is shown to indicate the timing, but the magnitude is not to scale.

MQEs of both coils as a function of background magnetic field and with constant normalize transport currents (60% and 80% of $I_c$ in coil I, and 40% and 60% of $I_c$ in coil II) are shown in Figure 2-9. As the magnetic field increases, the MQE decreases from several Joules to less than 1 Joule. Note that the energy reported here is that generated in the heater, but not all of that energy transfers into the coil winding; some is absorbed by the liquid helium and the epoxy. It is difficult to accurately determine the amount of heat into the Bi-2212 wire so the values reported here are upper-bounds for the MQE. Comparing the coil I and coil II data for 60% of $I_c$, it is interesting to note that the MQE for coil II is less than 40% of the MQE for coil I. For example, at 8 T, MQE of coil II is 1.00±0.03 J whereas for coil I the MQE is 2.65±0.05 J. Since the coils have nearly the same $T_c(B)$, are operating at nearly the same transport current, and the background magnetic field dominates the self-field, in principle the
MQEs should be nearly the same. In coil II, however, the heater is embedded between layers of the Bi-2212 winding, whereas for coil I the heater is on the coil surface. Thus, the effect of surface cooling on the MQE of coil I is very large, and coil II data is more representative of the behavior to be expected in large Bi-2212 coils.

Figure 2-9 Minimum quench energy as a function of magnetic field for each coil

Despite the uncertainties regarding surface cooling, the magnetic field dependence of MQE is the same in each coil, with the MQE decreasing significantly with increasing magnetic field and with increasing transport current. This is directly related to the reduced $T_c$ and temperature margin with increasing magnetic field. Thus, the design of high field magnets must be based upon the MQE of the highest field region of the magnet.
3.3 Normal zone propagation

More details of the voltage and temperature versus time and location for a quench are seen in Figures 2-10 and 2-11 (this is from the quench illustrated in Figure 2-8). This data is typical of the quenches in both coils studied here. Note that V23 and T23 correspond to the heater location, so the small hump in T23(t) (Figure 2-11) during the heat pulse (from t=0.375 s to 0.675 s) is an experimental artifact related to local heating due to the heat pulse and subsequent cooling at the surface by the helium and conduction along the Bi-2212 wire. The sequential rise in the voltages and temperatures in pairs of voltage taps and thermocouples illustrates quench propagation; the curves are in pairs because of symmetry in the tap/thermocouple layout. The closeness of the pairs of data (e.g., V22 and V24 in Figure 2-10 and T22 and T24 in Figure 2-11) indicates that the coil winding has a uniform and symmetric geometric shape.

![Figure 2-10 Voltage versus time, on each voltage tap, during a quench in coil I](image)

Figure 2-10 Voltage versus time, on each voltage tap, during a quench in coil I
Comparing the \( V(t) \) and \( T(t) \) data in Figures 2-10 and 2-11 indicates that there is a delay between the voltage and temperature signals in coil I. Initially, the temperature increases before the corresponding voltages; this is simply because there is no voltage increase until the temperature is above the current sharing temperature. After current sharing begins and Joule heating drives quench propagation, however, the temperature response is delayed relative to the voltage. This is because the thermocouples are located on the surface of the wire and are thus cooled, whereas the voltage represents the conditions within the wire. This is most evident when considering \( V_{23} \) and \( T_{23} \), the voltage and temperature at the heater location. Due to the heater, thermocouple \( T_{23} \) is further from the Bi-2212 wire surface than the other thermocouples. Thus it is exposed to the least Joule heating and the most helium cooling. As a result, once the heater pulse is complete, despite being at the center of the normal zone, it reports a lower temperature than the other thermocouples. \( V_{23} \), however,
consistently reads the highest voltage of any voltage tap. Figure 2-12 plots $T_{cs}(B)$ for coil I, which is obtained by replotting the data from Figures 2-10 and 2-11 as voltage versus temperature and identifying the temperature at which a reliably measureable voltage is obtained. For this purpose, a current-sharing voltage criterion of 100 µV is used. The error bar of $T_{cs}$ comes from the differences between the voltage versus temperature curves of each sections. $T_{cs}$ appears to be relatively independent of magnetic field in the range of field from 1 T to 8 T. It is likely, however, that the surface temperature is suppressed by cooling. As a result, NZPV studies focus on voltage measurements.

![Figure 2-12 Current sharing temperature as a function of magnetic field for coil I](image)

Similar to previous studies, NZPVs are calculated directly from the voltage-time data [3]. The NZPV is equal to the distance between voltage taps on the same side of the heater
divided by the time delay between each of them reaching a voltage criterion chosen such that the voltage-time curves are nearly parallel (see, for example, Figure 2-11 in [3]). Here, the voltage criterion varies from 3 mV to 10 mV due to different transport currents resulting in different signal levels. Consecutive voltage taps next to the heater 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/pt, the time differences measured and thus the calculated NZPVs have an error of about 10%.

Figures 2-13 and 2-14 show the longitudinal and transverse NZPVs in coil I with transport currents of 60% and 80% of \( I_c \), and in coil II with the transport currents of 40% and 60% of \( I_c \), as a function of magnetic field. For magnetic fields less than 8 T, the NZPVs decrease with increasing field, regardless of \( I/I_c \) or propagation direction. For magnetic fields greater than 8 T, however, the NZPV is independent of magnetic field.
Figure 2-13 Longitudinal normal zone propagation velocity versus magnetic field for each coil

Figure 2-14 Transverse normal zone propagation velocity versus magnetic field for each coil
Comparing the data in Figures 2-13 and 2-14, and considering that the diameter of insulated
Bi-2212 is \( \sim 1 \) mm, longitudinal quench propagation is more than ten times faster than
transverse propagation. This is not surprising, as both the mullite insulation and the epoxy are
thermally insulating. Furthermore, the turn-to-turn (y-direction) NZPV in coil II is about
22% faster than the layer-to-layer (z-direction) NZPV, which implies that turn-to-turn contact
between neighboring turns within a layer is better than layer-to-layer contact, also the turn-
to-turn quench propagation could be accelerated by the thermal transfer along the conductor
to a certain extent.

Figure 2-15 replots the \( I_c \), \( T_c \), \( MQE \), \( T_{cs} \), and NZPV (in all directions) data from Figures 2-6,
7, 9, and 12-14, with each curve normalized to its value at 1 T. All six NZPV curves (three
directions, two different values of \( I/I_c \) for each direction) overlap over the entire range of
magnetic field studied (self-field to 20 T). Similarly, the field-dependence of the MQE is
independent of \( I/I_c \). For low magnetic field (less than about 4 T), the MQE decreases more
slowly than the NZPV or \( I_c \), consistent with the relative slow decrease in \( T_{cs} \) at low magnetic
field. The MQE continues to decrease almost linearly for the entire range of magnetic field
studied. For magnetic fields up to 10 T, the field dependence of the NZPV and that of \( I_c \)
overlap, indicating that \( I_c(B) \) dominates the NZPV behavior. At higher magnetic field,
however, \( I_c \) continues to decrease whereas NZPV becomes field independent. Thus, the
effects of decreasing current and decreasing temperature margin offset.
Figure 2-15 Normalized magnetic field dependence of the critical temperature, normal zone propagation velocity, minimum quench energy, critical current and current sharing temperature. All of the data are from coil II, except for the current sharing temperature which is for coil I.

These results show that MQE is more controlled by the temperature margin while the NZPV is impacted by both the margin and Joule heating from the transport current. Hence, slow NZPV is likely to be intrinsic to high field Bi-2212 coils, as the effect of reduced $T_c$ at high magnetic field does not dominate. Thus, effective quench protection, and in particular effective quench detection, must overcome the challenges of slow normal zone growth. In addition, for Bi-2212 insert coils operating within a LTS outsert, the NZPV is likely to be uniform throughout the coil.
Figure 2-16 compares the experimental results of MQE and NZPV on coil I with 60% $I_c$ to the numeric calculated results according to the classic adiabatic equations shown as below [12, 13].

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

$$MQE = \pi \frac{A \sqrt{\lambda} C (T_C - T_{op})^{2.5}}{\sqrt{\rho} J_C} \left(\frac{1 - i}{\sqrt{i}}\right) \left(\frac{T_{cs}}{T_{op}}\right)^{4.5}$$

All the data is normalized by its value at 1 T, and for the numeric calculation, the magnetic field effects on the resistivity, conductivity and heat capacity are neglected, and then only left variables are $I_c(B)$, $T_c(B)$ and $T_{cs}(B)$. Unfortunately, there are significant differences between our experimental results and numeric calculated values, which indicates this model is not very suitable for our case. However, the recent simulation work on Bi-2212 round wire quench study[14] obtained a pretty similar results about the in-field quench behaviors, which also shows a stable NZPV value at the high magnetic field.
Figure 2-16 Comparison between the experimental results and numeric calculation data on coil I with 60% of $I_c$

4. Summary

The quench behavior of Bi-2212 coils was studied at 4.2 K in magnetic fields up to 20 T. With increasing magnetic field, $T_c$ decreases, resulting in reduced current sharing temperature, temperature margin and minimum quench energy (MQE). The normal zone propagation velocity also decreases with magnetic field, but only up to about 8 T. For magnetic fields 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 critical current density, whereas at higher magnetic field the competing effects of decreasing critical current density, which decreases NZPV, and decreasing temperature margin, which increases NZPV, offset.
REFERENCES


52


CHAPTER 3
HIGH-FIELD QUENCH BEHAVIOR AND DEPENDENCE OF HOT SPOT
TEMPERATURE ON QUENCH DETECTION VOLTAGE THRESHOLD IN A
Bi$_2$Sr$_2$CaCu$_2$O$_x$ COIL.*

http://dx.doi.org/10.1088/0953-2048/28/7/075014

1. Introduction
Quench protection of superconducting magnets, which must detect a non-recovery normal zone and force the magnet current to go to nearly zero within a few seconds or even some fractions of a second to prevent overheating of superconducting windings [1, 2], is nontrivial even for superconducting magnet systems made from Nb-Ti and Nb$_3$Sn [3, 4] for which abundant coil fabrication and operation experiences have been accumulated. It is especially challenging for superconducting magnet systems based on high temperature superconductors (HTS) [5, 6] because measurements in short samples of both Bi-2212 [7, 8] and (RE)Ba$_2$Cu$_3$O$_{7-x}$ (RE = rare earth) coated conductors [9] show that at 4.2 K normal zones propagate at an order of cm/s, instead of m/s for Nb-Ti and Nb$_3$Sn at 4.2 K, even in strong magnetic fields, limiting our ability to drive the resistive zone to occupy as large a fraction of the winding volume as possible for developing an internal resistance useful for active quench protection. Figure 3-1 summarizes propagation speed data of Ag/Bi-2212 round strands and coils available in the literature and measured for this study. Samples include an epoxy-impregnated coil whose specifications are presented in the table 3-1, a 13 cm long piece of
the same conductor used to fabricate this coil and a wire with a diameter of 0.8 mm and a design of 37 x 18 (reacted and tested as 13 cm long), epoxy impregnated coils tested by Ye et al. [8] and by Trociewitz et al. [7] All of these wires were manufactured by OST and have the similar Ag/AgMg/Bi-2212 ratio. For the data obtained in our test coil, the following approach was used: the transverse normal zone propagation velocity was obtained by comparing the layer voltage signals; the lower bound and the upper bound of the longitudinal normal zone propagation speed were derived by timing the transverse speed with a factor of 5 and 20, which was experimentally found by Ye et al. [8] and Trociewitz et al. [7] in epoxy impregnated Bi-2212 coils fabricated using similar strands and insulation, respectively.

![Graph showing normal zone propagation velocity at 4.2 K as a function of J_o](image)

Figure 3-1 Measured normal zone propagation velocity at 4.2 K as a function of $J_o$, the operating current density averaged over the conductor in magnetic fields up to 19 T
During a quench, conductor temperature rises quickly. Simple ballpark analysis by considering the heat balance of unit volume of winding \((1 - \lambda)J_m^2(t)\rho(T)dt = \gamma C(T)dT\), where \(\lambda\) is the volumetric ratio of superconductor in the metal/superconductor composite, \(J_m\) the current density in the metal matrix, \(\rho(T)\) the resistivity of the metal matrix, \(\gamma C(T)\) the volumetric heat capacity averaged across the conductor, \(T\) the temperature, and \(t\) the time, predicts that hot spot temperature rises to 300 K within 0.82 seconds in commercial Ag/Bi-2212 multifilamentary round wires with \(\lambda = 0.25\) when wire operating current density \(J_o = 300\ A/mm^2\) (\(J_o = 300\ A/mm^2\) is typical for solenoids), and within 0.21 seconds when \(J_o = 600\ A/mm^2\) (\(J_o = 600\ A/mm^2\) is typical for accelerator dipoles and quadruples). Experimental results that will be reported elsewhere show that a successful quench protection approach would need to limit the hot spot temperature in Bi-2212 magnets to < 300 K, beyond which conductor \(J_c\) might degrade; this has to do with the fact that inhomogeneous temperature rise introduces strains that affect the current carrying capability of brittle Bi-2212 phase (the \(J_c\) of melt processed Ag/Bi-2212 wires degrades irreversibility when the tensile strain exceeds a limit, ranging from 0.3-0.45\% depending on conductor design and fabrication, and also when a compressive strain is applied [10]). Thus quick and reliable quench detection when the hot spot temperature is low (preferred to be <50 K) is important for leaving enough time for forcing magnet current to go to zero, which is challenging and is also comprised by the slow normal zone propagation.

Active quench detection of existing Nb-Ti and Nb\(_3\)Sn superconducting magnets currently relies on measuring resistive voltage that builds up when a normal zone is created. However, a concern is that developing a detectable normal zone voltage in Bi-2212 magnets might need
a high hot spot temperature due to the slow normal zone propagation. For a Bi-2212 wire carrying $J_o = 300 \text{ A/mm}^2$ to yield a resistive voltage of 0.1 V, the hot spot temperature needs to reach 235 K and 52 K if the length of the normal zone is 2 cm and 20 cm, respectively (assuming that silver has a RRR (residual resistivity ratio) of 230 and that temperature is homogeneous within the normal zone). Assuming that the normal zone propagates only one-dimensionally along conductor, with a propagation speed of 10 cm/s (Figure 3-1), Bi-2212 would need 0.1 s and 1 s to develop a 2 cm long and a 20 cm normal zone, respectively, whereas with normal zone propagating at a speed of 10 m/s, Nb-Ti and Nb$_3$Sn would only need only 2 ms and 20 ms to develop a 2 cm long and a 20 cm normal zone, respectively. For HTS magnets including Bi-2212 coils, significant time needs to be allocated for detecting the normal zone whereas for Nb-Ti and Nb$_3$Sn magnets, primary consideration is on designing quench protection circuitry to ensure the time constant of current decay $\tau$ to be small. This change in design philosophy may limit the use of Bi-2212 conductors to low $J_o$ regions.

For designing an active quench protection system for Bi-2212 magnets, magnet designers need to know the hot spot temperature at which a detectable resistive voltage develops in a practical magnet. This knowledge is important for evaluating the effectiveness of voltage measurement for detecting a quench in Bi-2212 magnets and for determining the limits of Bi-2212 magnet technology. Measurements performed so far [7, 8, 11-13] focuses on determining minimum quench energy and normal zone propagation velocity, and some of these measurement [7] report hot spot temperature, measured by thermocouples that unlikely track temperature rises faster than 10 K/s accurately. This report will present a careful measurement of time evolution of hot spot temperature $T_{max}$ vs. $V_{NZ}$, the normal zone
resistive voltage for various $J_c$ in magnetic fields, in a Bi-2212 solenoid. We also measured the minimum quench energy and propagation speeds in this coil and compared them to those obtained in short strands of Bi-2212 multifilamentary wires. These measurements were enabled by using a small epoxy heater (1 cm long) to initiate a point-like quench and using two complimentary temperature measurement methods to measure coil temperature.

2. Experimental approach

2.1 Strand design and coil fabrication

Quench behaviors of Ag-sheathed Bi-2212 multifilamentary round wires were investigated using heater-induced experiments in both a solenoid and short length (reacted in 15 cm with ends open and tested in 13 cm) strands. The specifications of the solenoid are summarized in Table 3-1. The coil was wound on a pre-oxidized Inconel 600 coil former using wires insulated with a sleeve (~100 µm thick) braided from alumino-silicate (mullite) fibers (Figure 3-2c). The coil was reacted in 1 bar flowing oxygen by heating it from room temperature to 820 °C at 160 °C/h, holding at 820 °C for 2 hours, heating again from 820 °C to 891 °C at 48 °C/h, holding at 891 °C for 0.2 hour, cooling to 881 °C at 10 °C/h, further cooling to 835 °C at 2.5 °C/h, holding at 835 °C for 48 hour, and then quickly cooling to room temperature [14]. This is the standard partial melt processing schedule used by the National High Magnetic Field Laboratory [7, 15, 16] and Fermi National Accelerator Laboratory [17] (impacts of varying some of its important parameters on wire $I_c$ were previously investigated [14, 18-20]), and similar to those used by Oxford Instruments for making their wind-and-react coils [21, 22]. After the reaction, the reacted coil was vacuum impregnated using CTD-
101k and cured by heating it at 110 °C for 5 hours with a post cure of 16 hours at 125 °C. Figure 3-2a shows a graph of the coil as mounted on the test probe.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Winding technique</td>
<td>Wind-and-react</td>
</tr>
<tr>
<td>Conductor</td>
<td>Ag/Bi-2212 PIT wire</td>
</tr>
<tr>
<td>Wire diameter and design</td>
<td>1.2 mm; 85 x 18 filaments</td>
</tr>
<tr>
<td>Wire superconductor/Ag/AgMg ratios</td>
<td>0.25/0.5/0.25</td>
</tr>
<tr>
<td>Conductor insulation</td>
<td>Alumino-silicate braided sleeve</td>
</tr>
<tr>
<td>Insulation thickness</td>
<td>100 µm&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td>Inner diameter i.d. (mm)</td>
<td>33.40&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td>Outer diameter o.d. (mm)</td>
<td>48.10&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td>Overall winding length (mm)</td>
<td>57.80&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td>Total number of layers</td>
<td>6&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td>Total number of turns</td>
<td>244.5&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td>Central-field constant (mT A&lt;sup&gt;-1&lt;/sup&gt;)</td>
<td>4.5&lt;sup&gt;b&lt;/sup&gt;</td>
</tr>
<tr>
<td>Inductance (mH)</td>
<td>1.1&lt;sup&gt;b&lt;/sup&gt;</td>
</tr>
</tbody>
</table>

<sup>a</sup> measured value, <sup>b</sup> computed values

The PIT multifilamentary Bi-2212 round wire used to fabricate the coil was manufactured by the Oxford Superconducting Technology (OST) at New Jersey by drawing a pure Ag tube
with Bi-2212 precursor powder, then using a double restack to form 18 bundles. Its transverse cross-section is shown in Figure 3-2b. The final wire, 1.2 mm in diameter, contains filaments of ~20 µm in diameter embedded in a matrix of pure silver, which is again encased in an oxidation precipitation-hardened Ag - 0.2 wt% Mg sheath. The filaments in as-drawn wires have an oxide packing density of ~74%.

Figure 3-2 (a) The epoxy-impregnated coil fabricated as mounted on the test probe, (b) the transverse cross-section of the Bi-2212 wire used to fabricate the coil, and (c) a side-view of the mullite braided insulation sleeve

2.2 Heater-induced quench tests

The MQE and normal zone propagation velocity of short strands were measured using an experimental protocol similar to that used by Ye et al. [13]. For coils, heaters were mounted to Bi-2212 conductor sections (insulation was removed) in the test coil (layer 6, the outermost layer) to trigger a quench. The heater, together with thermocouples, was potted with the coil to minimize heat leak into helium and to better simulate a quench in an adiabatic condition. To start a quench, rectangular current pulses of variable duration of 100-
300 ms were supplied by a 200 W KEPCO power supply (KEPCO Bipolar 50-4D, 50 V/4 A).

The heater was made from graphite based electrically conductive epoxy ECOBOND 60L, previously used by Ghosh et al. [23]. This heater is 1 cm long and 4 mm in width (covering three turns), and weights ~50 mg. Heat was deposited on the strand by passing a current pulse through the heater, using the turn 30 as the current return path; heat was dominantly deposited into the turn 30, for which the mulite insulation was removed.

To observe voltage growth and to determine the propagation speed and the size of the hot zone, the coil was instrumented with voltage taps across the conductor section covered by the heater, at each of six layers, across the halves of the layer 6, and at coil terminals, and voltage signals were recorded using a National Instrument SCXI/PCI-6289 data acquisition system with a sampling rate of 1 kHz and a voltage resolution up to 0.1 µV.

For a typical quench test, the coil was maintained at 4.2 K and in a background field of 7 T and energized to an operating current $I_o$ of 100 A, 150 A, 200 A, 300 A, 350 A, and 400 A at 50 A/s and dwelled for 3 seconds before a heat pulse was applied. The heat pulse was applied with increasing amplitude until the conductor is quenched.

The minimum quench energy (MQE) is defined as the minimum heater energy, which was calculated as a product of the current and the voltage and the duration of the rectangular heat pulse, required for quenching the conductor. The coil was protected by triggering a trip of the power supply and forcing its current to go to nearly zero within 0.2 second of a bucked signal ($V_{layer123}-V_{layer456}$, the voltage differential between the layer 1 to 3 and the layer 4 to 6) exceeding a detection criterion.
2.3 Methods of determining hot spot temperature and RRR measurement

The hot spot temperature was determined by two methods. Temperature of the quench zone was directly measured using an E-type thermocouple (Lake Shore Cryogenics, Inc., Chronmel – Constantan, 36 AWG) (as shown in Figure 3-3a), following previous studies [7, 8, 11, 13]. The response time of an E-type thermocouple, confirmed by our measurements, is ~100 ms so it tends to underestimate the temperature rise if the temperature rising rate is >10 K/s.

Figure 3-3b illustrates the hot spot temperature evolutions recorded by the thermocouple for two heater input energies. When the heater energy is 0.342 J, the wire returned to superconducting state after a temperature rise to ~18 K; when the heater energy was 0.349 J, the wire experienced a thermal runoff. For this case, the minimum quench energy was defined at 0.349 J whereas the recovery case was called a critical recovery because the conductor recovered after receiving an energy that is slightly lower than the minimum quench energy and a short temperature rise.
Figure 3-3 (a) Schematics of the epoxy spot heater ECOBOND 60L on the 30th conductor turn of the layer 6 (the bottom half), together with an E-type thermocouple and a voltage tap (tap length=1.5 cm) that reads $V_{NZ}$. (b) Hot spot temperature recorded by the thermocouple for two heater input energies

Temperature was also estimated by cross-examining $V_{NZ}$, the voltage measured across the 2 cm conductor section where the heater was mounted (Figure 3-3a), with the temperature dependence of the resistivity of silver measured. Most of our measurements were made in a background field of 7 T, at which the $T_c$ of Bi-2212 is around 21-28 K so the temperature converted from the voltage was inaccurate when the actual temperature is lower than 30 K due to the uncertainty with the amount of current flowing in silver matrix. But it provides a nearly instantaneous measurement of the hot spot temperature when the temperature is above 50 K. The accuracy of the second approach was calibrated using the E-type thermocouple data when the temperature rise rate was known to be less than 10 K/s.
Estimating temperature from the resistivity measurement requires knowing the temperature dependence of the resistivity of silver, which was measured using the standard four-point technique on a wire cut from the same conductor batch but melt processed with a maximum processing temperature 15 °C lower than optimum (filaments of this sample carry nearly zero \( I_c \) so the resistivity measurement was made down to 4.2 K; current applied during the measurement is 2 A). The heat-treated wires were measured to take into consideration of potential RRR reduction due to Cu dissolving into the silver during the melt processing. The residual resistivity ratio (RRR) of silver, defined as \( RRR = \rho(293 K)/\rho(4.2 K) \), was measured to be 230. In a background field of 7 T, RRR was reduced to 30, estimated using the magnetoresistance data of silver in Iwasa et al. [24].

3. Results

3.1 Strand and coil \( I_c(B, T) \)

The magnetic field dependences of the \( I_c \) of the strand (\( \phi 1.2 \) mm, 85x18 design) studied were presented in Figure 3-4. The coil quenched spontaneously during \( I_c \) measurements. Its quench current \( I_q \) was also presented in Figure 3-4. At 7 T, the \( I_q \) of the coil is 417 A, reaching 72% of its short-sample \( I_c \) [22]. The resulted wire engineering current density \( J_e \) is about 442 A/mm² at 4.2 K and 7 T, 50% higher than the ~280-300 A/mm² in solenoids [7, 15, 16] previously fabricated from OST wires using 1 bar melt processing. Coil survived more than 20 spontaneous quenches, which likely initiated from regions around one of the current leads, and 50 heater-induced quenches without degradation, during which the highest coil temperature measured reached 280 K.
Figure 3-4 The $I_c$ of the $\phi$1.2 mm Bi-2212 strand at 4.2 K and in applied fields up to 14 T and the quench current $I_q$ of the test coil. The witness strand, 8 cm long, was melt processed with the coil but with its ends open during the heat treatment. The strand $I_c$ was determined using a standard four-probe method at an electric field criterion of 1 $\mu$V/cm, whereas the coil $I_q$ was plotted against the background field only.

### 3.2 Voltage and hot spot temperature during critical recovery

To get the first degree of appreciation of what quench detection voltage criterion should be used, Figure 3-5 examined the coil terminal voltage in cases of critical recovery [25] upon firing the epoxy heater. Coil sustained a large terminal voltage without quenching. For example, the terminal voltage reached 45 mV when $I_o=100$ A, and 4.3 mV when $I_o=400$ A. Integrating $v(t) \cdot i(t)$ from 0 to 8 s indicates that joule heating deposits heat of 24.9 J, when $I_o=100$ A, and heat of 1.18 J, when $I_o=400$ A, into the coil. The maximum voltages across the
2 cm normal zone recorded (not shown) during a recovery indicates that roughly 20% of the joule heating dissipated in the 1.5 cm heater section.

Figure 3-5 Voltage-time evolution when the test coil experienced critical recovery for $I_o=100$ A, 150 A, 200 A, 250 A, 300 A, and 400 A at 4.2 K and 7 T. Signals were synchronized by placing the rising edge of heat pulses at 0.1 s

3.3 Voltage and hot spot temperature during quenches

Figure 3-6 and Figure 3-7 present the growth of the hot spot temperature and signals of voltage taps for the test coil when it experienced a quench at 4.2 K and 7 T while carrying $I_o$ of 100 A and $I_o$ of 400 A, respectively. Voltage and temperature curves for quenches at $I_o=150$ A, 200 A, 250 A, 300 A, and 350 A were omitted for similarity. The temperature measured by the thermocouple tracked well with that converted from $V_{NZ}$ for $I_o = 100$ A ($J_o =$
88.5 A/mm², and \( J_m = 118 \text{ A/mm}^2 \) when the temperature rise rate is low \( (dT/dt = 10 \text{ K/s at 60 K}) \), verifying the effectiveness of the method of converting \( V_{NZ} \) to temperature (the error was estimated to be <10 K). The thermocouple failed to track the temperature rise for \( I_o = 400 \text{ A} \) \( (J_o = 354 \text{ A/mm}^2, J_m = 472 \text{ A/mm}^2, dT/dt = 148 \text{ K/s at 60 K}) \), significantly underestimating the hot spot temperature. When the coil terminal voltage reached 0.1 V, the normal zone propagated to the layer 3 for \( I_o = 100 \text{ A} \) whereas the normal zone didn’t even propagate to the layer 5 for \( I_o = 400 \text{ A} \), indicating the normal zone exists only in a conductor turn (the turn 30\(^{th}\) of the layer 6).

Figure 3-6 Evolution of (a) the hot spot temperature and (b) the layer and terminal voltage for the test coil when it experienced a heater-induced quench at 4.2 K and 7 T while carrying a current \( I_o \) of 100 A. Figure (a) presents both the temperature directly measured by the thermocouple and the temperature converted from \( V_{NZ} \). The insert in (b), plotted using a log 10 scale, highlights that when the terminal voltage reached 0.1 V, normal zone had propagated to the layer 3.
Figure 3-7 Evolution of (a) the hot spot temperature and (b) the layer and terminal voltage for the test coil when it experienced a heater-induced quench at 4.2 K and 7 T while carrying a current $I_o$ of 400 A. Figure (a) presents both the temperature directly measured by the thermocouple and the temperature converted from $V_{NZ}$. The insert in (b), plotted using a log 10 scale, highlights that when the terminal voltage reached 0.1 V, normal zone had just propagated to the layer 5.

3.4 Dependence of hot spot temperature on detection criterion

To quantify the difficulty of detecting normal zones of small sizes, Figure 3-8 plots the hot spot temperature when the terminal voltage of the test coil reached 0.1-1 V while experiencing a quench. Both the background field and the current of the test coil were kept roughly the same so the coil terminal voltage represents the resistive voltage of the normal zone well. At a given $V_d$, hot spot temperature rises with $I_o$, showing the increasing difficulty with quench detection with increasing $I_o$. For $V_d = 0.1$ V, $T_{max}$ was 79 K for $I_o = 400$ A and
39 K for $I_o = 100$ A, respectively, whereas for $V_d = 1.0$ V, $T_{\text{max}}$ was 140 K for $I_o = 400$ A and 64 K for $I_o = 100$ A, respectively.

![Graph showing hot spot temperature as a function of terminal voltage](image)

Figure 3-8 The hot spot temperature in the test coil when it experienced heater-induced quenches while carrying an $I_o$ of 100 A, 200 A, 300 A, and 400 A, and its terminal voltage reached 0.1-1 V. The tests, results of which were presented in Figure 3-7 and Figure 3-8 for $I_o = 100$ A and $I_o = 400$ A, respectively, were performed at 4.2 K and in a background field of 7 T. The hot spot temperature was estimated from $V_{NZ}$.

4. Discussion

We have built small insert solenoids using a multifilamentary Ag/Bi$_2$Sr$_2$CaCu$_2$O$_x$ round wire, and characterized them in background fields to explore the quench behaviors and limits of
Bi$_2$Sr$_2$CaCu$_2$O$_x$ superconducting magnets, with an emphasis on assessing the impact of slow normal zone propagation on quench detection. Quench propagation is intrinsically a thermal transport event and likely depends on the coil construction method, e.g. insulation materials and the thickness of the insulation. Our measurements were made in a solenoid wound and reacted from Bi-2212 wires insulated with mullite insulation sleeve (100 µm in thickness) and epoxy impregnated; similar construction method was used by Oxford Instrument to fabricate a 2.5 T Bi-2212 solenoid insert to achieve a total field of 22.5 T [16].

The hot spot temperature upon quench detection in our coil showed a strong dependence on the quench detection voltage threshold. The hot spot temperature for the resistive voltage of the normal zone to reach 100 mV increases from ~40 K to ~80 K with increasing the operating wire current density $J_o$ from 89 A/mm$^2$ to 354 A/mm$^2$ whereas for the voltage to reach 1 V, it increases from ~60 K to ~140 K, showing the increasing negative impact of slow normal zone propagation on quench detection with increasing $J_o$ and the need to limit the quench detection voltage to < 1 V. With increasing $J_o$, though normal zone propagation speed increases, the temperature rises more quickly and the normal zone increasingly becomes a local hot spot. At $J_o$ of 354 A/mm$^2$, the normal zone only exists in a conductor turn when the resistive voltage rose to 100 mV (we estimated the total length of the conductor in normal states to be less than 10 cm). Such a strong dependence of hot spot temperature on the quench detection voltage threshold has an important implication for quench detection and protection circuitry design, and therefore the design of the entire magnet.
The consequence of not detecting quench at low temperatures is that the time for ramping down the magnet current is reduced. The temperature rise during a quench in a metal/superconductor wire of length $\tau$, carrying a current $I_0$ normal to its cross-section $A$ can be calculated by considering the heat balance of unit volume of winding:

$$ (1 - \lambda)J_m^2(t)\rho(T)dt = \gamma C(T)dT + w $$

(1)

In which the $(1 - \lambda)J_m^2(t)\rho(T)dt$ represents joule heating, $\gamma C(T)dT$ represents the heat absorbed by the conductor volume $A\tau$, and the quantity $w$ represents the power density leaving the volume $A\tau$ through transverse and longitudinal heat transfer. On fast quenches (adiabatic condition), the last term is negligible.

Assuming adiabatic conduction and reorganizing equation (1), one arrives at [1, 2, 26]:

$$ \int_{t_0}^{t_f} (1 - \lambda)J_m^2(t)dt = \int_{4.2K}^{T_{\text{max}}} \frac{\gamma C(T)}{\rho(T)}dT $$

(2)

The quench integral on the right hand-side of the equation (2) only depends on the material properties. The temperature dependence of the quench integral of a commercial Bi-2212 wire is presented in Figure 3-9a and temperature rising rate estimated from equation (2) is presented in Figure 3-9b. The equation (2) can also be used to estimate temperature rising rate, which is presented in Figure 3-9c and agrees well with the experimentally determined values. From equation (2), one can also assume that quench detection was made at 50 K, 75 K, 100 K, 125 K, and 150 K, and derive a quantitative dependence of time remained for driving the magnet current to zero on temperature at which quench was detected. The results of such an analysis are presented in Figure 3-9d and show the importance of quench detection at low temperatures.
Figure 3-9 (a) Quench integrals for commercial Ag/Bi-2212 wires ($\lambda=0.25$). (b) Temperature rise predicted using quench integrals for commercial Ag/Bi-2212 wires. (c) Hot spot temperature rising rate $dT/dt$ when $T_{\text{max}} = 60$ K predicted by quench integral calculation as compared to experimental data. (d) Time available for forcing magnet current to go to zero and its dependence on operating current density and the quench detection temperature.

The normal zone resistive voltage can be expressed as $U(t) = I(t) \cdot R(t) = \rho_{\text{ave}}(T) \cdot J_m(t) \cdot l_{\text{NZ}}(t)$, where $I(t)$ is the magnet current, $R(t)$ the internal resistance that develops, $\rho_{\text{ave}}(T)$ the average resistivity of the normal zone, $l_{\text{NZ}}(t)$ the total length of the normal zone. When
a quench begins, the resistance is initially low, but rises steadily as the temperature increases. At the same time, the quench spreads from the point of origin with a certain velocity and new regions of conductor go normal and begin heating, developing greater resistance. This rising resistance comes from both the increase in temperature and the increase in the total length of normal zones, which is proportional to the longitudinal quench velocity along the conductor and the quench propagation velocity in the transverse direction.

The difficult quench detection shown above was clearly due to the very low quench propagation along Bi-2212 conductor and in our coil. One method to make easier the quench detection is to enhance 3-D quench propagation in Bi-2212 coil windings, through increasing normal zone propagation velocity along conductors or improving the transverse heat diffusion. The traverse quench propagation velocity \( U_t \) in a superconducting solenoid hexagonally wound from a round superconducting wire and impregnated with epoxy resin is related to the longitudinal propagation velocity \( U_l \) through this relationship [27]:

\[
\frac{U_t}{U_l} = A \sqrt{\frac{K_t}{K_l}} = A \sqrt{\frac{k_i R}{k_c t}} \tag{3}
\]

where \( A \) is a universal correlation constant to be determined experimentally, \( K_t \) the transverse thermal conductance, \( K_l \) the longitudinal thermal conductance, \( k_i \) the insulation thermal conductivity, \( k_c \) the conductor thermal conductivity, \( R \) the radius of bare superconducting wire, and \( t \) the insulation thickness. For the Bi-2212 winding tested here, \( R \) and \( t \) are 0.6 mm and 0.1 mm, respectively, and thus \( (R/t) = 6 \). Thinner insulation is desired. A thin, 15-25 mm thick TiO\(_2\)-polymer insulation coating has been developed by nGimat LLC and it yields a \( (R/t) = 24 - 40 \), which, in combination with an improvement in thermoconductivity properties
of TiO$_2$ coating as compared to mullite insulation [28], improves $U_l$ by a factor of 2 – 2.6 [29]. The nGimat TiO$_2$ insulation was applied in a NHMFL coil that generated a 2.6 T in a background field of 31 T and provides an electric breakdown voltage of 100 V [30], which is lower than that of the mullite insulation (~1679 V [31]) but should be sufficient for Bi-2212 coils. The layer-to-layer voltage and the turn-to-turn voltage, or even the maximum internal voltage in a Bi-2212 winding ($|V_{in,max}| < R_{nz}I_{op}$), shall be less than 100 V because of small $R_{nz}$ in Bi-2212 coils.

A potential second method is to increase $U_l$ along Bi-2212 conductor. Heat transfer models of quench initiation and propagation [1, 2, 26] predict that normal zone propagation velocity along a conductor can be expressed as $V_{ad} = J/\gamma C \cdot ((\rho \kappa/(T_c - T_{cs}))^{1/2}$, where $V_{ad}$ is the normal zone propagation velocity under adiabatic conditions, $J$, $\rho$, and $k$ the operating current density, the resistivity, the thermal conductivity averaged over the composite conductor, $T_c$ the superconducting transition temperature, and $T_{cs}$ the current sharing temperature. Therefore the low speed at self-field for Bi-2212 is readily explained by the large temperature margin (the $T_c$ of Bi-2212 at self-field is 82 K) and given the strong influence of magnetic field on the $T_c$ of Bi-2212, applying magnetic fields should increase the normal zone propagation velocity significantly. However, measurements by Ye et al. [8] in epoxy-impregnated showed that the highest speed obtained is 9 cm/s at self-field and it remains small in magnetic fields of up to 20 T (Figure 3-1). This propagation speed was analytically derived assuming that the voltage – current $V$-$I$ (or electric field–current density $E$-$J$ transition) of superconductor wire to the normal state is very sharp [1, 2, 26]. The $E$-$J$ characteristics of metal/superconductor composite conductors can be described using a
power-law relationship, $E = E_c \cdot (J/J_c)^n$, characterized by the parameter $n$. The $n$-value of Cu/Nb-Ti wires is $\sim$40-60 at 4.2 K and 5 T and the $n$-value of Cu/Nb$_3$Sn wires is $\sim$30-40, and therefore the assumption applied to them well. The $n$-value of Ag/Bi-2212 short wires, melt processed in 1 bar oxygen with ends open, is $\sim$15-20 at 4.2 K and self field, and $\sim$12 at 4.2 K and 12 T measured by A. Ghosh [21] and us. Long Bi-2212 strands (>30-50 cm) processed in 1 bar oxygen was known to carry lower $J_c$ than short strands heat treated with open ends and they also have reduced $n$-values (5-10) due to the negative effects of internal gases [22]. A study that will be published elsewhere shows that the low $n$-value of Bi-2212 wires reduces $U_l$ by a factor of ten at high magnetic fields. Therefore, for the overpressure processed wires that carry a $J_c$ of 700 A/mm$^2$ and have a $n$-value of $\sim$15 at 4.2 K and 20 T, the $U_l$ might be significantly increased. We are actively fabricating Bi-2212 coils using overpressure processing and testing their quench behaviors at high-fields and high current density regions. The measurement and discussions so far paint a pessimistic view of using Bi-2212 conductors to their $J_c$ limits. However, we have to caution that for our measurements, the quench was triggered at the outmost layer and the low-field region of the coils with the normal zone being point-like. Figure 3-5 indicates that the Bi-2212 coil is very stable, which shows that the total heat needed to quench Bi-2212 conductor, defined as the sum of the heater energy and the joule heating energy, is high. In the case of $I_o$=400 A for which the quench was localized in the turn 30, the heater energy is 0.3 J and the joule heating introduces additional 1.18 J. Figure 3-10 shows the measured minimum quench energy of the Ag/Bi-2212 round strands (both the Ø1.2 mm, 85x18 design wire and the Ø0.8 mm, 37x18 design wire were included).
and that obtained in epoxy-impregnated coils at 4.2 K by others and us in a magnetic field up to 20 T. Samples include the epoxy-impregnated coil whose specifications were presented in the table 3-1, 13 cm long pieces of the same conductor used to fabricated table 3-1 coil and a wire with a diameter of 0.8 mm and a design of 37 x 18 (reacted and tested as 13 cm long), an epoxy impregnated coil tested by Ye et al. [8], and an epoxy impregnated coil tested by Yang et al. [12]. Note that samples in this paper were tested using the 1 cm epoxy heater, whereas the coil of Ye et al. [8] tested by a spiral heater wound from Nichrome wire (~1.5 cm in length), and the coil of Yang et al. [12] tested by a thin film Constantan heater (40 mm x 1 mm x 20 mm x 22 cm). All of these wires were manufactured by OST and have the similar Ag/AgMg/Bi-2212 ratio.

Figure 3-10 Measured minimum quench energy as a function of $J_o$, the operating current density averaged over the conductor, at 4.2 K in a magnetic field up to 20 T
Even at 20 T with \( J = 600 \, \text{A/mm}^2 \), the plot projects that the minimum quench energy of a Bi-2212 strand will unlikely be lower than 10 mJ. Thus Bi-2212 magnets might withstand large local disturbances without quenching (the energy released in a superconducting winding by a sudden slippage of conductor and epoxy cracking, two primary sources of quenches in Nb-Ti and Nb\(_3\)Sn magnets, is in range of \( 10^{-2} \, \text{J cm}^{-3} \)), except in unusual scenarios with accelerator magnets that the particle beam is lost into a small section of the superconductor. Therefore, perhaps the best way to use Bi-2212 conductors to their \( J_c \) limits is to further stabilize it so the coil will not quench when operating standalone (it should be noted that Bi-2212 coils are often used as high-field insert coils, stacked inside NbTi and Nb\(_3\)Sn coils. The electromagnetic interactions between LTS coils and HTS coils should be considered carefully when designing quench protection systems).

However, we have to note that the MQE data summarized in Figure 3-10 were heater input energy, which was calculated as a product of the current and the voltage and the duration of the rectangular heat pulse, required for quenching the conductor. This definition ignored the heat that went into helium and might severely overestimate the stability. Second, our test coil quenched spontaneously without degradation and another 800 kJ Superconducting Magnetic Energy Storage system made from a stack of double-pancake coils wound from Bi-2212 dip-coated tapes suffered from a spontaneous quench [32, 33], which degrades the system. The source of the quench in Tixador’s system [32, 33] was proposed to originate from a conductor section with less \( J_c \) [32, 33]. Therefore, a conservative approach needs to be used, assuming that a short-section of Bi-2212 coils might quench.
Taking this conservative view, we provide several suggestions for designing the active quench detection and protection circuitry for high-field Bi-2212 coils constructed similarly to our coils. We want to caution that quench propagation in a coil depends on insulation materials and the thickness of the insulation, and therefore one need to keep that in mind when applying these guidelines to other Bi-2212 coils constructed, for example, using thin TiO$_2$ insulation coating.

1) Normal zone resistive voltage measurement should be a part of the quench detection portfolio for Bi-2212 and other HTS magnets. In spite of slow normal zone propagation, voltage measurement still allows detection of normal zones of small sizes, as shown by our data, in particularly by Figure 3-8. Other methods, such as fiber-optics sensors and acoustic emission sensors are promising and may become an auxiliary quench detection tool but so far they have not yet been fully proved in practical magnets and face issues such as making quick decision while analyzing large volume of data (gigabytes per second), taken along a long-length fiber optics sensor or by acoustic emission sensor working at >500 MHz. In contrast, data acquisition rate of >1 kHz would suffice for resistive zone voltage measurements.

2) Cautions should be taken to make sure the maximum normal zone resistive voltage to not exceed 1 V at high operating current density. Superconducting solenoids constructed from Nb-Ti and Nb$_3$Sn can afford to have quench trip voltage of several or ten volts [34]. Using such a large quench detection voltage will likely result in irreversible degradation to Bi-2212 coils because as can be seen from Figure 3-8, the hot spot temperature may well exceed 300 K before the magnet current can be ramped down. Therefore the suggestion is
that the maximum quench detection voltage shall not exceed 1 volt. This voltage is smaller than the forward voltage of cold silicon diodes (~3-10 V at 4.2 K) often used in passive quench protection circuits and therefore passive protection using a pair of diodes and resistor electrically in parallel with the superconducting coil will unlikely be effective at protecting Bi-2212 coils against quenches occurring at the high operating current density.

3) The maximum normal zone resistive voltage may be increased to several volts at low and medium operating current density, because extrapolation of data in Figure 3-8 for $I_o=100$ A to several volts shows that the hot spot temperature would likely still be less than 100 K. Quench detection at low $J_o$ benefits from transverse quench propagation to adjacent turns and layers (which is possible due to the slow temperature rise), as can been seen from voltage data of coil layers presented in Figure 3-6 and 3-7.

4) The minimum quench detection voltage shall be larger than 50 mV to not to falsely trigger quench protection. This is necessary as it can be seen from Figure 3-5 that Bi-2212 coils are quite stable against disturbances and withstood a resistive voltage of tens of mV for seconds without quenching. This will help improve the signal-to-noise ratio when a quench occurs during activation of large magnets whose inductive voltage of coils can be as large as 10-20 V. If a decision has been made to use detection voltages close to 50 mV, the ramping rate of Bi-2212 coils should be kept low and the inductance of the coil should be reduced as much as possible.

5) Determining at what hot spot temperature a quench can be detected through measurements similar to those reported here should be one of the quench protection circuitry
design steps for Bi-2212 high-field magnets as significant time would need to be allocated for quench detection.

The relatively small detection voltage suggested demands that the quench detection electronics can distinguish a real quench event from a variety of rapid voltage spikes that large epoxy impregnated superconducting coils often see during ramping tests and even occasionally in hold at constant current [35, 36]; the magnitude of these spikes can range from tens of mV to even several volts depending on the magnet construction, the inductance of the coil, and the capability of power supply and quench detection data acquisition systems. The nature of voltage spikes hasn’t been thoroughly understood due to a lack of comprehensive tests. It has been suggested that voltage spikes generated by conductor motion and epoxy cracking have a characteristic time of several ms and can be filtered whereas the voltage spikes caused by a stick-slip behavior as the coil expands and frictionally slides against its coil former can last tens of milliseconds and difficult to be filtered out.

5. Conclusion

We have reported fabrication of small-scale coils using commercial Ag/Bi-2212 strands and their quench behaviors at 4.2 K and in an externally applied field. Our experiments, for the first time, systematically measured the time evolution of the hot spot temperature and the normal zone resistive voltage using two complimentary methods in an epoxy-impregnated Bi-2212 coil. The coil was made using wires insulated with an alumino-silicate insulation sleeve with a thickness of ~100 µm. For this coil, the hot spot temperature for the resistive voltage of the normal zone to reach 100 mV increases from ~40 K to ~80 K with increasing the operating wire current density $J_o$ from 89 A/mm$^2$ to 354 A/mm$^2$ whereas for the voltage
to reach 1 V, it increases from ~60 K to ~140 K. This result highlights the difficulty of quench detection in Bi-2212 coils and the need to allocate a more significant amount of detection time for Bi-2212 coils when designing quench detection and protection circuitry than for Nb-Ti and Nb₃Sn magnets.

The difficulty of quench detection is due to the slow normal zone propagation along the conductor and between conductor turns. We have compiled master plots of minimum quench energy and normal zone propagation velocity as a function of magnetic field and operating current density for Bi-2212 wires and coils. Such plots shall be useful for predicting, at the first degree, the magnitude of the minimum quench energy and the normal zone propagation speed and their variations with magnetic field and transport current. Transverse normal zone propagation speed in our test coil was measured to increase from 1.4 mm/s to 7.5 mm/s with increasing $J_o$ from 89 A/mm² to 354 A/mm². To use Bi-2212 towards its $J_e$ limits, it is suggested that it is important to enhance the 3-D normal zone propagation using thinner insulations and to increase the normal zone propagation speed along conductor, perhaps by an order of magnitude, through understanding the effects of n-values and improving n-values.

We also presented a new method of measuring the RRR of Bi-2212 wires for numerical quench simulation. We fed the RRR value obtained into an analytical quench integral calculation to calculate temperature rises during a quench, and showed that they matched well with experimental results.
REFERENCES


1. Introduction

Quenching poses significant challenges and risks to the operation of superconducting magnets such as those in nuclear magnetic resonance (NMR) systems and particle accelerators. Without effective quench protection, magnets are at risk of permanent degradation, and the risk generally increases as the magnet current density and stored energy increase. It is therefore important to understand the quench degradation behaviors and limits of superconducting composite wires, and equally importantly, to understand degradation mechanisms in order to operate magnets within safe limits. Moreover, it is important to determine whether degradation mechanisms and limits change with conductor design and heat treatment.

During a quench, the local temperature inside a superconducting magnet winding increases at a rate $dT/dt$ roughly proportional to $J^2$, where $J$ is the operating current density of superconducting wire. For Nb-Ti and Nb$_3$Sn magnets, it has been generally advised to keep the maximum hot-spot temperature $T_{max}$ below 150 K, or more aggressively, 350 K. This criterion may not apply to high temperature superconducting materials such as isotropic, Ag-sheathed Bi$_2$Sr$_2$CaCu$_2$O$_x$ (Bi-2212) multifilamentary round wires (RW) because of intrinsic differences between Bi-2212 and Nb-Ti and Nb$_3$Sn. For example, measurements in short samples of Bi-2212 show that at 4.2 K normal zones propagate with velocities on the order of
cm/s, compared to m/s for Nb-Ti and Nb₃Sn, even in strong magnetic fields. Such slow normal zone propagation means that the local temperature gradients, $dT/dx$, in Bi-2212 would likely be much higher. In addition, while the superconducting filaments in Nb-Ti and Nb₃Sn are essentially phase-pure and ~100% dense, those in even the best-performing Bi-2212 wires are neither.

The non-uniform temperature rise during a quench induces significant strain in superconducting filaments and it is widely suspected that this strain drives degradation. While the strain dependence of $J_c$ has been well-studied, it has been hitherto unknown what portions of superconducting filaments are more prone to degradation and whether wire design and processing can be modified to mitigate quench induced $J_c$ degradation. For example, high $J_c$ was achieved by significantly reducing porosity in powder-in-tube (PIT) Ag/Bi-2212 wires, increasing the filament density to over 90%, as compared to 65-80% in previous wires [1]. Yet it is unknown if quench degradation limits increase with filament density, as porosity has been shown to serve as stress concentration sites [2]. Similar questions can be asked for other microstructural features found in Ag/Bi-2212 wires, such as Bi2201 grains and filament-to-filament bridges [3-7].

Here we study the quench behavior of a large inventory of commercial PIT Ag/Bi-2212 wires, including microstructural observations of quench-degraded wires, providing evidence that $J_c$ degradation during a quench is primarily driven by local strain in superconducting filaments. A variety of commercial wires are studied with critical current density, $J_c$, at 4.2 K, self-field, ranging from 1300 A/mm$^2$ to over 6000 A/mm$^2$, and corresponding engineering critical current density, $J_e$, ranging from 200 A/mm$^2$ to 1500 A/mm$^2$. A careful evaluation of
the importance of $T_{\text{max}}$, $dT/dt$, and $dT/dx$ using heater-induced quench experiments [8, 9] is presented.

2. Experimental Approach

Table 4-1 summarizes the commercial Ag-0.2wt%/Ag/Bi-2212 multifilamentary RWs investigated; corresponding cross-sectional images are presented in Figure 4-1. All wires were fabricated by Oxford Superconducting Technology (OST) using the powder-in-tube route. Conductor A, with a 0.8 mm diameter and a 37x18 wire architecture, is a typical wire used for high-energy particle accelerators and being manufactured into Rutherford cables and accelerator magnets at Fermi National Accelerator Laboratory [10-12]. Conductor C has a 1.2 mm diameter and an 85x18 wire architecture, typical of wire for high-field NMR solenoids. Both conductor A and conductor C contain extensive interfilamentary bridges after heat treatment. Conductor B has a 1.0 mm diameter and a 27x7 architecture. The larger interfilamentary spacing was intended to minimize interfilamentary bridging [13], so conductor B is included here to determine if such bridging influences quench-induced degradation.

Table 4-1 Summary of properties of conductors investigated

<table>
<thead>
<tr>
<th>Conductor</th>
<th>Outer diameter</th>
<th>Filaments</th>
<th>Features</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>0.8 mm</td>
<td>37x18</td>
<td>Extensive interfilamentary bridges</td>
</tr>
<tr>
<td>B</td>
<td>1.0 mm</td>
<td>27x7</td>
<td>No interfilamentary bridges</td>
</tr>
<tr>
<td>C</td>
<td>1.2 mm</td>
<td>85x18</td>
<td>No interfilamentary bridges</td>
</tr>
</tbody>
</table>
Figure 4-1 Optical cross-sectional images of the conductors investigated

Straight wires of each conductor, 8 - 16 cm in length, were heat-treated using partial-melt processing (PMP) in a 1 bar flowing pure O₂. The PMP included heating them from room temperature to 820 °C at 160 °C/h, holding at 820 °C for 2 hours, heating from 820 °C to 891 °C at 48 °C/h, holding at 891 °C for 0.2 hour, cooling to 881 °C at 10 °C/h, further cooling to 835 °C at 2.5 °C/h, holding at 835 °C for 48 hour, and then quickly cooling to room temperature. To evaluate the importance of porosity on quench degradation, conductor A was also processed using overpressure partial-melt processing (OPMP) in a mixed gas of Ar and O₂ at a gas pressure up to 100 bar. During the heat treatment, the oxygen partial pressure was maintained at 1 bar. The density of the filaments in overpressure-processed wires increased to >95% when a gas pressure was greater than 25 bar, as compared to 65-80% for wires processed at 1 bar.

The reacted straight wires were mounted on a G-10 sample holder and instrumented with heaters, Lakeshore Type-E thermocouple wires, and voltage taps using the layout shown in
Figure 4-2 or a similar pattern. The heater was made from Formvar insulated Manganin wires and had a total resistance of ~ 5.0 Ω at 4.2 K. Some samples were covered by a thin layer of Stycast 2850 blue epoxy after instrumentation wiring. The Stycast layer has a total weight of ~ 400 mg and thickness of ~ 0.5 mm. All voltage taps and thermocouples were monitored using a 24-channel high-precision data acquisition system and recorded with a data acquisition rate of 1 kHz for each channel with 0.1 µV resolution. Samples were then cooled down to 4.2 K in liquid helium and their critical current $I_c$ was measured using the four-probe method with an electrical field criterion of 1 µV/cm. $J_e$ and $J_c$ were determined from $I_c$ results divided by the whole cross-section area and the portion of Bi-2212 phase. To study the influence of $dT/dx$, the heater shown in Figure 4-2 was replaced with a longer heater that produces a smaller $dT/dx$.

Figure 4-2 Schematic of the experimental set-up and a photograph of a wired sample
Quench degradation experiments follow the protocols established in earlier studies [8, 9, 11, 14-19]. While carrying a steady-state transport current, the sample received a heat pulse of variable duration and amplitude, creating a local hotspot resulting in a maximum temperature $T_{\text{max}}$ and thermal runaway. After cooling to 4.2 K and re-measuring $I_c$, $T_{\text{max}}$ was increased gradually via increased heater pulse duration or amplitude until $I_c$ decreased. Table 4-2 summarizes samples studied with their heat treatment, heater set-up, and transport current.

<table>
<thead>
<tr>
<th>Sample No.</th>
<th>Conductor</th>
<th>Pressure during processing</th>
<th>Heater setup</th>
<th>Epoxy?</th>
<th>$J_e$ (A/mm$^2$)</th>
<th>$J_c$ (A/mm$^2$)</th>
<th>$I_t$ (A)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>A</td>
<td>1 bar</td>
<td>Standard</td>
<td>No</td>
<td>835</td>
<td>3340</td>
<td>100</td>
</tr>
<tr>
<td>2</td>
<td>A</td>
<td>1 bar</td>
<td>Long</td>
<td>No</td>
<td>835</td>
<td>3340</td>
<td>100</td>
</tr>
<tr>
<td>3</td>
<td>A</td>
<td>1 bar</td>
<td>Long</td>
<td>No</td>
<td>835</td>
<td>3340</td>
<td>10</td>
</tr>
<tr>
<td>4</td>
<td>A</td>
<td>1 bar</td>
<td>Standard</td>
<td>No</td>
<td>835</td>
<td>3340</td>
<td>200</td>
</tr>
<tr>
<td>5</td>
<td>A</td>
<td>1 bar</td>
<td>Standard</td>
<td>Yes</td>
<td>835</td>
<td>3340</td>
<td>200</td>
</tr>
<tr>
<td>6</td>
<td>B</td>
<td>1 bar</td>
<td>Standard</td>
<td>No</td>
<td>204</td>
<td>1360</td>
<td>150</td>
</tr>
<tr>
<td>7</td>
<td>B</td>
<td>1 bar</td>
<td>Standard</td>
<td>Yes</td>
<td>204</td>
<td>1360</td>
<td>150</td>
</tr>
<tr>
<td>8</td>
<td>C</td>
<td>1 bar</td>
<td>Standard</td>
<td>No</td>
<td>893</td>
<td>3572</td>
<td>200</td>
</tr>
<tr>
<td>9</td>
<td>A</td>
<td>100 bar</td>
<td>Standard</td>
<td>No</td>
<td>1532</td>
<td>6128</td>
<td>200</td>
</tr>
<tr>
<td>10</td>
<td>A</td>
<td>100 bar</td>
<td>Standard</td>
<td>No</td>
<td>1532</td>
<td>6128</td>
<td>200</td>
</tr>
</tbody>
</table>
Figure 4-3a shows typical $V(t)$ and $T(x,t)$ during thermal runaway in sample #1. The sample was heat-treated using 1 bar standard PMP and its initial self-field $I_c$ is $\sim 450$ A. With the joule heating energy from both heater pulse and transport current, the highest peak temperature is reached on the central section (V4) at 5.26 s, when thermocouple T4 reads 526 K. One experimental concern relates to the accuracy of thermocouple readings; the response time of an E-type thermocouple is $\sim 100$ ms so it tends to underestimate the temperature increase when the temperature is increasing faster than 10 K/s. Furthermore, for hotspot temperatures $> 500$ K, which is close to the melting temperature of high melting point solder used for thermocouple mounting, the bonding between the thermocouple and the wire surface may be not reliable. Hence, here the temperature is also estimated by cross-referencing the local voltage measured across each section with the temperature dependence of the resistivity of silver; this method has been proven to be more reliable for estimating the hotspot temperature during a quench in a previous study [20]. Figure 4-3b illustrates the growth of the hot spot temperature on the central section using the thermocouple data and the voltage-based approach. The temperatures measured by the thermocouple track well with that converted from voltage for $T<300$ K, but when the hotspot temperature exceeds 350 K, the results diverge. For the final peak temperature, that obtained from voltage shows 561 K, about 10% higher than the thermocouple. Thus, in this study the peak hotspot temperature will be based on the voltage method.
Figure 4-3 (a) Typical voltage and temperature versus time during a thermal runaway on sample #1; (b) The local temperature rise on the central section based upon thermocouple readings and converted voltage measurements.

After quench experiments, sample microstructures were studied using longitudinal cross-sections. The samples are mounted in a commercial electrically conductive resin and ground using SiC papers with ethanol, with final polishing in a suspension of 0.5 μm alumina in ethanol using a vibratory polisher (Buehler Vibromet). The polished samples were etched using a H₂O₂: NH₄OH: methanol solution, and examined using a JEOL-5900 scanning electron microscope (SEM).

3. Results

3.1 Quench degradation behavior

Figure 4-4a plots the normalized $I_c$ degradation as the ratio of $I_c$ after quenching to the initial $I_c$ as a function of peak temperature during the quench for sample #1. Note that the
temperature increased in each sequential quench. These results show that no degradation occurred for $T_{\text{max}}$ up to and including 439 K, and the reduction in $I_c$ was only 2.5% for $T_{\text{max}} = 466$ K, 7.5% for $T_{\text{max}} = 547$ K, and 11% for $T_{\text{max}} = 561$ K. For each of these quenches, the peak temperature was located in the central section of the wire. Figure 4-4b shows the reduction in $I_c$ versus location along the wire for the seventh (and final) quench. The degradation is highly localized, and $I_c$ is only reduced in the central section. The corresponding temperature versus location is plotted on the same graph; note that the adjacent sections only show peak temperatures in the 350 K – 400 K range, so the absence of degradation in this sections is consistent with the results in Figure 4-4a.

![Graphs showing $I_c$ and $T_{\text{max}}$ versus location](image)

Figure 4-4 (a) $I_c$ after quenching normalized by the initial $I_c$ versus local peak temperature for a series of quenches on sample #1; (b) $T_{\text{max}}$ and normalized $I_c$ versus location along the wire for the final quench on sample #1
Figure 4-5a plots the reduction in $I_c$ and corresponding $T_{max}$ versus location along the sample for samples #1-3 for their corresponding final quenches. Note that sample #2 and sample #3 use the longer heater, reducing $dT/dx$ during the quench significantly. Figure 4-5b plots the corresponding sequence of quenches in terms of the reduction in $I_c$ versus peak temperature in the central section. These results show that, despite having much smaller $dT/dx$, samples #2 and #3, like sample #1, show degradation when the local hotspot temperature exceeds 400-450 K. In fact, sample #1 appears to have maintained $I_c$ to a slightly higher temperature than samples #2 and #3; note for example that at 450 K, $I_c$ in sample #2 has clearly decreased by a few percent more than sample #1 (the temperature resolution for sample #3 is insufficient to provide a comparison).

Figure 4-5 (a) The peak temperature and normalized $I_c$ versus location along the wires for samples #1, 2 and 3. Note that samples #2 and #3 are quenched with the longer heaters; (b) the corresponding normalized $I_c$ versus $T_{max}$.
A previous study showed that the rate at which the peak temperature increased did not influence conductor degradation [9], and the results found here are in agreement with that conclusion. In this work, the temperature increases most rapidly at lower temperature, e.g. at 400 K/s for T in the range of 100-200 K, whereas $dT/dt$ is only ~50 K/s when the $T > 500$ K. While an experiment designed to vary $dT/dt$ at higher temperature is required to determine if $dT/dt$ is a secondary factor in degradation, within the range of parameters studied here, it does not play a measurable role.

The quench degradation behavior of the wires shown in Figure 4-1, as the function of the central peak temperatures, is illustrated in Figure 4-6. Only results from samples heat-treated at 1 bar atmospheric pressure and quenched using the shorter heater length are plotted, so the only variables are the wire architecture, the transport current during quenching and the presence of epoxy. Despite these differences, these samples follow a consistent trend which is illustrated by the vertical lines. In short, while the amount that $I_c$ decreases varies significantly from wire to wire, they all show no degradation until $T_{\text{max}}$ reaches ~400 K, gradual degradation for $400 \text{ K} < T_{\text{max}} < 550 \text{ K}$, and a rapid decrease for $T_{\text{max}} > 550 \text{ K}$. Furthermore, note that the only difference between samples #4 and #5, and between samples #6 and #7, is that samples #5 and #7 are epoxy impregnated whereas #4 and #6 are not. The results in Figure 4-6 indicate that the presence of epoxy increases the temperature at which degradation begins by a few degrees, and that the rate at which $I_c$ decreases may be slower in the presence of epoxy, particularly for conductor B.
Figure 4-6 Normalized $I_c$ versus $T_{max}$ for samples of all three conductor architectures

Figure 4-7 compares results from two samples processed at 100 bar using OP-PMP (samples #9 and #10) and the corresponding 1 bar PMP processed sample (#4). In Figure 4-7a the results are plotted as the ratio of $I_c$ after quenching to the initial $I_c$ as a function of peak temperature, whereas in Figures 4-7b and 4-7c the absolute values of $I_c$ and n-value are plotted as a function of peak temperature. The OP processed samples show a slightly higher temperature at which $I_c$ degradation begins, but also show a much more rapid decrease of $I_c$ with increasing peak temperature. The n-value behaves similarly to the corresponding $I_c$. 
Figure 4-7 (a) Normalized $I_c$, (b) $I_c$ and (c) n-value versus $T_{max}$ after quenching, comparing the wires heat treated in 1 bar and 100 bar atmospheres.

3.2 Microstructure of quench degraded samples

Figures 4-8 and 4-9 show SEM images of the longitudinal cross-sections from sample #9, a 100 bar OP processed conductor-A wire. Figure 4-8 is a location ~1.25 cm from the sample center within section V2, where the peak temperature reached 350 K and $I_c$ was not degraded. The Bi-2212 filaments are dense with some porosity observed. No cracking or
other evidence of quenching is seen. Figure 4-9a is from the sample center, within section V4, where the peak temperature reached 565 K and $I_c$ was reduced by 40%. Cracks are clearly seen, and their propagation was primarily perpendicular to the wire axis. Figures 4-9b and 4-9c are higher magnification images of the two large cracks circled in Figure 4-9a. In Figure 4-9b, it appears that the crack propagation direction deviates due to pre-existing defects in the filament, whereas in Figure 4-9c the deviation in direction is minimal.

Figure 4-8 Longitudinal SEM cross-sectional image of a region of a 100 bar OP processed sample that was quenched but did not degrade
Figure 4-9 Longitudinal SEM cross-sectional images of a region of a 100 bar OP processed sample that shows a 40% reduction in $I_c$ due to quenching. (a) Low magnification image; high resolution images of the areas within the ovals are shown in (b) and (c)
Figure 4-10 shows an example of more dramatic failure. Sample #10 reached a peak temperature of 635 K and had an 80% reduction in $I_c$, also has a significant rupture. The image shown was taken in the central 0.2-0.3 mm of the wire, within section V4.

Figure 4-10 Longitudinal SEM cross-sectional image of a region of a 100 bar OP processed sample that shows a 80% reduction in $I_c$ due to quenching

4. Discussion

4.1 Evidence for a strain-driven quench degradation mechanism

The experimental results imply that the local peak temperature is the primary factor influencing conductor degradation and that the temperature limit is fairly independent of the
conductor architecture and filament density. To understand the underlying mechanism, however, a thermal-mechanical analysis is necessary.

The Bi-2212/Ag composite wire has both ends mounted on the copper current leads, which fix the sample in-place and remain cooled because the Cu current leads at in liquid helium. As the temperature on Bi-2212/Ag wire increases during a quench, beginning in the central section, the Bi-2212/Ag wire wants to elongate due to thermal expansion but cannot because both ends are fixed. Thus, the wire experiences non-uniform longitudinal compression while quenching. As the thermal stress increases, and because there is no transverse support, the sample begins to buckle, deforming into an arc in order to elongate its length and release the thermal stress.

It is important to consider that the non-uniformity of the thermal stress is both longitudinal and within the wire cross-section as well. The longitudinal non-uniformity of the stress is evident from the temperature non-uniformity, and the spatial dependence on the reduction in $I_c$ seen in Figures 4-4b and 4-5a. But the non-uniformity within a transverse cross-section is also important to consider. As a ceramic-reinforced metal-matrix composite, the thermal expansion of Ag and Ag-alloy is much larger than that of Bi-2212 filaments; when cooled from room temperature, the thermal contraction for pure Ag is -0.413% whereas that of Bi-2212 in the a,b plane is -0.152%. Thus, after cooling from processing temperature to room temperature, then from room-temperature to 4.2 K, the Bi-2212 filaments are put in compression by the Ag matrix, but in this case the thermal stress is fairly uniform along the length of wire. During a quench, this process reverses but only locally and non-uniformly, so degradation is not immediate because of the pre-compression of the filaments.
The evolution of thermal stresses in Bi-2212/Ag wires is complex and dynamic, and further complicated by any non-uniformities at the Bi-2212-Ag interface and by inhomogeneities in the Bi-2212 microstructure, including porosity and secondary phases. Thus, it is challenging to develop an accurate quantitative model to describe the thermal-mechanical behavior. Yet the experimental evidence supporting a strain-driven degradation mechanism is clear. Figure 4-11a highlights the quench degradation behavior of sample #5 as in Figure 4-6, and Figure 4-11b illustrates the strain-dependence of $I_c$ measured mechanically by Lu and Cheggour [21, 22]. The similarities between the results in terms of reversible and irreversible degradation behavior support the hypothesis that quench degradation is a result of the local strain in the Bi-2212 filament and that quench degradation should be quantitatively correlated to mechanical failure. These results also imply that quench tolerance should increase as strain-tolerance in Bi-2212 increases.

Figure 4-11 (a) Normalized $I_c$ versus $T_{max}$ for sample #5 as in Figure 4-6; (b) electromechanical behavior of similar wire as reported in [21, 22]
Further evidence for strain-driven degradation is the observation of cracks in the degraded Bi-2212 filaments. Although most strain-dependence studies for Bi-2212 wires have focused primarily on the electromechanical measurements, the cracks and their propagation paths as seen in Figure 4-9 are very similar to those reported by van der Laan et al. [23] and by Lu and Cheggour [21, 22].

4.2 Role of conductor design and processing on quench limits

Bi-2212 processing studies have shown that $I_c$ depends strongly on the internal connectivity between grains within Bi-2212 filaments [3, 5-7, 13]. Recent results have shown, however, that increasing $J_c$ significantly via filament densification does not improve strain-tolerance [24], and this has been explained via microstructural-mechanical modeling as well [2]. The experimental results reported here are consistent with these other findings, in that the quench degradation behavior is weakly influenced by conductor design and processing.

Previous studies on quench degradation and mechanical failure of 1 bar processed Bi-2212/Ag wires (i.e., wires with significant porosity) found that pre-existing defects do play a role in the complex electromechanical behavior of Bi-2212 RW, and thus it was anticipated that the densification that results from OP processing would result in strain-resistant conductor [9, 21].

Yet this is clearly not the case. Furthermore, although the images in Figures 4-9b and 4-9c imply that pre-existing defects affect crack propagation, it is not possible to correlate crack nucleation to any pre-existing features within the Bi-2212 microstructure. Thus, just as an understanding of the role of microstructure in the electromechanical behavior of Bi-2212 remains elusive, so does the role of microstructure in quench degradation.
4.3 Implications for magnet design and further investigations

According to the consistent quench degradation behavior observed from the large pool of investigated conductors, a safety criterion of 300 K should be an applicable value for quench protection in Bi-2212 magnet. In the recent quench experiment on a Bi-2212 test coil running under the background magnetic field of 7 T, the conductor went through the peak temperature up to 280 K without any $I_c$ degradation [20].

As described in section 4.1, the quench degradation should be a strain-driven effect, and potentially could be associated to the mechanical failure. It will be worthy to carry on this study to the samples with different mechanical properties and varied strain states, to obtain a better understanding on the degradation limit for Bi-2212 high-field magnets which are naturally operated under high mechanical stress. The further experimental studies are in process and the coming results will be presented in a subsequent paper.

Even 300 K is not a very strict protection criterion in LTS magnet; however, considering the slow quench propagation in HTS, it would still be very challenging for quench protection in Bi-2212 magnet [20]. Although the intrinsic degradation thresholds in Bi-2212/Ag wires could hardly be improved, it is likely to increase the amount of time and the size of normal zone necessary to reach threshold conditions after the onset of a quench through improving propagation velocities, thereby facilitating detection and protection. A recently proposed method is the use of Bi-2212 conductors coated with electrical insulation materials of high thermal conductivity; this enhances turn-to-turn propagation but not longitudinal propagation [14]. Besides, these results showing highly localized degradations highlight the need for
distributed sensing within Bi-2212 magnets [25] or diagnostic tools with quench locating function [26].

5. Summary

We have studied experimentally the quench behavior of a variety of commercial Bi-2212/Ag round wires, including the effects of varying the pressure during PMP. The results show that reductions in $I_c$ due to quenching correlate primarily with $T_{\text{max}}$ rather than $dT/dx$ or $dT/dt$. Furthermore, although the amount that $I_c$ decreases varies, the general trends are independent of wire architecture, heat treatment and performance; all wires are resistant to degradation for $T_{\text{max}} < 400$ K and exhibit small irreversible $I_c$ and n-value degradation for $400$ K $< T_{\text{max}} < 550$ K. Above 550 K, the degradation is more severe. Strong evidence that $I_c$ degradation is caused by the local strain in the Bi-2212 filaments is also shown, including microstructural evidence of crack propagation and $I_c(T_{\text{max}})$ results that emulate $I_c(strain)$ results on similar wires.

These results have significant implications for developing Bi-2212 magnets. First, it is reasonable to use the maximum allowable temperature as the key physical parameter to guide the design of quench protection circuitry for Bi-2212 magnets, following the well-established methods such as using MIITs to estimate the time constant of quench circuitry, because of the dominant role of $T_{\text{max}}$ and the insensitivity of the maximum allowable quench temperature on conductor design and heat treatment. Second, our study implied that the quench degradation temperature limit would strongly depend on the strain state of Bi-2212 filaments and applying a tensile axial strain would likely decrease the quench degradation temperature limit from $>400$ K to less than perhaps 200 K. This introduces a new constraint
for developing high-field solenoids for >1.3 GHz NMR, which likely experience significant
tensile hoop strain. Therefore, the dependence of the maximum quench temperature on
tensile strains in strong magnetic fields will need to be quantitatively defined.
REFERENCES


[21] N. Cheggour, X. Lu, T. Holesinger, T. Stauffer, J. Jiang, and L. Goodrich, "Reversible effect of strain on transport critical current in Bi$_2$Sr$_2$CaCu$_2$O$_{8+x}$"


CHAPTER 5
DEPENDENCE OF QUENCH DEGRADATION LIMITS IN Bi$_2$Sr$_2$CaCu$_2$O$_x$ ROUND WIRE ON AXIAL STRESS AND STRAIN

1. Introduction

The experiments in Chapter 4 were conducted at 4.2 K and self field, with zero axial stress applied due to electromagnetic forces. However, high field magnets are subject to enormous pressures due to Lorentz force when the magnet is operating. As an example, the hoop stress $\sigma$ in a solenoid, which is estimated as $\sigma = B * J * r$ ($B$ is the magnetic flux density, $J$ is the engineering current density, and $r$ is the radius of the solenoid insert), can exceed 180 MPa for a 25 T magnet with a bore size of 50 mm (assuming $J = 300$ A/mm$^2$) [1].

In Chapter 4, we concluded that the quench-induced $I_c$ degradation in Bi-2212 wires is driven by local straining of Bi-2212 filaments and significant degradation occurs at ~500 K, a temperature limit that gives a comfortable margin for quench protection. A direct implication is that the quench degradation temperature limit would likely depend on the strain state of Bi-2212 filaments. Hence, this chapter carefully measures the mechanical limit (the amount of axial stress that Bi-2212 wires can sustain before exhibiting damages) and the dependence of the maximum allowable temperature during a quench for Bi-2212 round wire on the axial stress and strain of the conductor. This measurement was performed using a new method - the ITER barrel configuration, which could apply a tensile axial stress on the Bi-2212 strand through the Lorentz force. The experiment results show that applying a tensile axial stress/strain would decrease the quench degradation temperature limit from >400 K to less than perhaps 100 K. After quantitatively defining the dependence of the maximum quench
temperature on tensile stress in high magnetic field, a semi-quantitative model is established to analyze this crucial relationship.

Ag-sheathed Bi-2212 strand is not a kind of robust material against the tensile stress due to the limited mechanical behavior of Ag and Ag-alloy. After full processing, the yield strength of pure Ag is only ~45 MPa and the elastic modulus is ~80 GPa at 4.2 K. For industrial fabricated Bi-2212 multifilamentary round wire, some ductility could be obtained from the Ag-alloy sheath. At present, Ag/0.20wt%Mg alloy is the most common alloy used for the outer sheath of Bi-2212 round wires. Figure 5-1 illustrates the stress-strain curve of a typical Ag-0.2 wt% Mg/Ag/Bi-2212 (area ratio AgMg:Ag:Bi-2212 = 0.27:0.48:0.24) round wire at 300 K, 77 K, and 4.2 K, which shows the elastic modulus of 113 GPa and the yield stress of 131 MPa at 4.2 K [2].

![Stress-strain curve of a typical Bi-2212 round wire](image)

Figure 5-1 Stress-strain curve of a typical Bi-2212 round wire [2]
Meanwhile, Bi-2212 filaments are brittle after reaction, and the current carrying capability of Bi-2212 round wire is sensitive to strain. In general, if only considering the axial stress, $I_c$ of Ag-sheathed Bi-2212 wires is virtually insensitive to tensile strain up to a sample dependent strain limit, and then decreases quickly and irreversibly after the strain limit is exceeded. Applying compressive strain to a Ag/Bi-2212 conductor causes a gradual and irreversible decrease of $I_c$. Figure 5-2 provided by Najib at NIST illustrates the $I_c$ dependence on applied axial strain for a commercial Ag-0.2 wt% Mg/Ag/Bi-2212 (area ratio AgMg:Ag:Bi-2212 = 0.25:0.5:0.25) round wire. The working stress maximum is around 120 MPa at 4.2 K, whereas the irreversible tensile strain is between 0.3–0.45% [3], and the Bi-2212 strand densified through over pressure process hasn’t deviated the strain limit too much [4].

![Image of normalized $I_c$ versus applied axial strain](image)

Figure 5-2 $I_c$ dependence on applied axial strain for a commercial Bi-2212 round wire

(Courtesy of Najib Cheggour at National Institute of Standards and Technology)
Looking back to the study in Chapter 4, which has identified the intrinsic limit for quench degradation on Ag/Bi-2212 round wire in terms of maximum local hotspot temperature and revealed the evidence supporting a strain-driven degradation mechanism, a meaningful question for high-field Bi-2212 insert design will naturally come out: Does the temperature limit for quench degradation vary with the strain state of Bi-2212 strand, especially the tensile strains in strong magnetic fields? Hence, a new quench experiment method using the ITER barrel configuration is introduced in this chapter to quantitatively define the dependence of the maximum quench temperature on tensile strains applied through the Lorentz force under strong magnetic fields. Furthermore, a semi-quantitative model is established to combine the quench degradation limit and mechanical limit, and to reveal the driving force for the failure mechanism in Bi-2212 round wire.

2. Experimental Approaches

In this study, all the experimental investigation focuses on only one batch of Bi-2212 round wire conductor manufactured by Oxford Superconducting Technology (OST), which refers as Conductor A in Chapter 4. Its cross-sectional micrographs are shown in Figure 5-3, and specifications are listed in Table 5-1.

![Figure 5-3 Optical cross-sectional images of the investigated conductor](image)

Figure 5-3 Optical cross-sectional images of the investigated conductor
Table 5-1 Properties of the investigated conductor

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Outer diameter</td>
<td>0.8 mm</td>
</tr>
<tr>
<td>Filaments</td>
<td>37x18</td>
</tr>
<tr>
<td>Area ratio AgMg:Ag:Bi-2212</td>
<td>0.25:0.5:0.25</td>
</tr>
<tr>
<td>Self-field $I_c$ after 1 bar PMP</td>
<td>450 A</td>
</tr>
<tr>
<td>Self-field $I_c$ after 25 bar PMP</td>
<td>700 A</td>
</tr>
<tr>
<td>Self-field $I_c$ after 100 bar PMP</td>
<td>780 A</td>
</tr>
</tbody>
</table>

Instead of the short strands in Chapter 4, the Bi-2212 round wire samples are prepared in the shape of a spiral and mounted on a specific text fixture as shown Figure 5-4a, which has been widely used as the standard $I_c$ measurement protocol of Nb$_3$Sn conductors for ITER application [5, 6] and thus commonly called ‘ITER barrel’. ITER barrels could be fabricated with various materials, including Titanium Ti-6Al-4V alloy (the one shown in Figure 5-4a), Stainless steel, G-10 and so on. The quench experiments in this study are primarily applied on G-10 barrel, since the G-10 barrel body is electrically insulating whereas other barrel materials may present electrical shorts and unpredictable current sharing during a quench. Also, the thermal contraction of G-10 barrel should be close to the one of Ag-sheathed Bi-2212 round wire when cooling to 4.2 K in liquid Helium. However, the Bi-2212 spiral has to be fabricated as wound-and-react while the G-10 barrel definitely couldn’t go through the heat treatment, and thus a ceramic barrel made of 96% pure Al$_2$O$_3$ was used during the heat treatment. As shown in Figure 5-4b, the Bi-2212 green wire is wound along the pre-carved spiral groove on the ceramic barrel surface, and both of its two ends are fixed into the small
holes on the barrel body. Then, the whole barrel is heat treated using the standard partial-melt-process under 1 bar of flowing pure oxygen [7] or 25 bar over-pressing argon/oxygen mixture with the oxygen partial pressure of 1 bar [8]. Notably, the strand ends are sealed for over-pressure processing, but kept as cut for 1 bar processing.

![Figure 5-4](image)

(a) An ITER barrel fixture made of Ti-6Al-4V alloy, (b) Bi-2212 strand with the Al₂O₃ ceramic barrel after 25 bar heat treatment

After heat treatment, the Bi-2212 spiral has to be carefully transferred to the G-10 barrel for testing, and Figure 5-5 illustrates this procedure step by step: Cut off both two ends of Bi-2212 spiral, and co-axially stack the Al₂O₃ barrel with Bi-2212 spiral on top of the G-10 barrel. Since the groove size on Al₂O₃ barrel is larger than the diameter of Bi-2212 strand, the Bi-2212 spiral could be manually rotated along the groove without much resistance. After moving out of Al₂O₃ barrel, the Bi-2212 spiral is led to the G-10 barrel with two copper rings on its ends, and fits closely into the groove on the barrel surface until the whole Bi-2212 strand is transferred to the G-10 barrel. Because the Al₂O₃ barrel and G-10 barrel has the same outer diameter (31.8 mm) and their spiral grooves share the same pitch length (4.0
mm), the Bi-2212 strand should have no deformation after this transferring process. After the transferring procedure completed, the two ends of Bi-2212 spiral are soldered onto the Copper rings as current leads using low melting point indium solder, and the whole strand is wound tightly into the groove without any flexibility.

![Image](image1.png)

Figure 5-5 Operation procedure for transferring the Bi-2212 spiral from Al₂O₃ barrel to G-10 barrel

The in-field electromagnetic measurement will be performed with the background magnetic field parallel to the barrel axial and perpendicular to the current flowing through Bi-2212 strand. Through alternating the polarity of current flow, the direction of Lorentz force could be either pointing into the barrel body as illustrated in Figure 5-6a, or pointing out as Figure 5-6b. In the case of Figure 5-6a, the Bi-2212 strand is supported by the G-10 barrel and thus no axial stress would be applied on the strand, so this setup could be used to measure the in-field critical current of Bi-2212 strand without causing any damage. For the other case in Figure 5-6b, since there isn’t any reinforcement outside the Bi-2212 spiral, the Lorentz force
would generate the tensile hoop stress along the Bi-2212 strand. Because there is not interaction between each turn of the Bi-2212 spiral, the hoop stress on Bi-2212 strand could be simply estimated as $\sigma = B*J*r$. On the barrel sample with 31.8 mm outer diameter prepared for this study, 100 A transport current in the 0.8 mm-diameter round wire will generate the hoop stress of about 30 MPa in the Bi-2212 strand at the background magnetic field of 10 T. Hence, this setup could be applied to evaluate the quench degradation temperature limit of Bi-2212 strand under axial tension stress generated by the Lorentz force in high magnetic field. The tests in this study are performed at two facilitates, one is the 78 mm cold bore Oxford superconducting magnet at Fermilab that provides a background magnetic field up to 15 T, and the other one is the 50 mm warm bore conventional magnet at National High Magnetic Field Lab that provides a background magnetic field up to 31.2 T.

Figure 5-6 (a) Stress-free mode: Lorentz force pointing inward and no axial stress applied; (b) Tensile stress mode: Lorentz force pointing outward and tensile hoop stress applied

To perform the heater-induced quench degradation test, the heater made from Eccobond 60 L graphite based electrically conductive epoxy, which has been successfully applied in the
quench experiment on Bi-2212 coils in Chapter 3, is attached on the outside of Bi-2212 spiral. Then, following the same experimental preparation steps for the short strand samples in Chapter 4, the Bi-2212 barrel is instrumented with voltage taps and thermocouples as the layout shown in Figures 5-7a, and Figure 5-7b and 5-7c shows the Bi-2212 barrel ready for the test.

![Diagram of instrumentation layout](image1)

(a)

![Bi-2212 barrel ready for test](image2)

(b)

Figure 5-7 (a) Instrumentation layout for the quench degradation test on Bi-2212 barrel; (b) a Bi-2212 barrel ready for the test

The data acquisition system and test protocol for the quench degradation limit on Bi-2212 barrel sample are generally the same as the one on the short strand samples in Chapter 4. The only step specified for the barrel sample test is to distinguish the current flowing direction in
the barrel for stress-free mode when measuring its in-field $I_c$ before and after each quench run to avoid any unexpected damage on Bi-2212 strand.

Beyond determining the dependence of quench degradation limits on tensile stress, this ITER barrel setup also could be used to identify the mechanical limit of Bi-2212 strand under axial tension as well. This test could be simply performed by charging a constant transport current into the barrel as tensile stress mode and maintaining it for a certain time before shutting down the current to zero. Through this step, a stress cycle with the desired amplitude will be applied on the Bi-2212 strand, and then the barrel’s $I_c$ will be re-measured in stress-free mode with the reversed flowing direction to examine whether the Bi-2212 strand has been irreversibly degraded by the applied tensile stress.

Table 5-2 summarizes all the barrel samples studied in this chapter. Barrel #1 is heat treated at 1 bar standard PMP and tested at self-field, and all the other barrels are heat treated using 25 bar over-pressure processing and tested at in-field.

<table>
<thead>
<tr>
<th>Barrel No.</th>
<th>Pressure during processing</th>
<th>Test performed</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1 bar</td>
<td>Quench degradation limit at self-field</td>
</tr>
<tr>
<td>2</td>
<td>25 bar</td>
<td>Mechanical limit at up to 15 T</td>
</tr>
<tr>
<td>3</td>
<td>25 bar</td>
<td>Quench degradation limit at up to 15 T</td>
</tr>
<tr>
<td>4</td>
<td>25 bar</td>
<td>Quench degradation limit at up to 30 T</td>
</tr>
<tr>
<td>5</td>
<td>25 bar</td>
<td>Quench degradation limit at up to 30 T</td>
</tr>
</tbody>
</table>
3. Results

3.1 $I_c(B)$ properties of Bi-2212 barrels

Figure 5-8 illustrates the magnetic field dependence of critical currents on the Bi-2212 barrel samples and 8 cm short witness samples at the background magnetic field up to 31.2 T. Compared to the 8 cm short samples, the barrels have the consistent $I_c$ performances for both 1 Bar and 25 Bar processing, which implies that the ITER configuration and the transferring procedure could be applied on the electromagnetic measurements on Bi-2212 round wire without causing any unexpected damage. Also, the $I_c$ of 25 bar processed barrel exceeds 170 A at 30 T, and thus ensures the possibility to apply the hoop stress of up to 160 MPa on the strand when the barrel tested in tensile stress mode.

![Figure 5-8 $I_c(B)$ of the Bi-2212 barrel samples and 8 cm short witness samples](image-url)
3.2 Mechanical limit on Bi-2212 strand under the axial hoop stress

Figure 5-9 plots the $J_e$ and n-value re-measured after each stress cycle as the function of the tensile hoop stress and the corresponding transporting current for applying stress in each cycle on Barrel #2 at the background magnetic field of 15 T. In tensile stress mode, the transport current was controlled to linearly ramp up to the desired amplitude within 1 s and then maintain for 3 s before shutting down to zero. For 200 A transport current and 15 T background magnetic field, the estimated tensile hoop stress was about 90 MPa. Both the $J_e$ and n-value were re-measured as 522 A/mm$^2$ and 16.0 respectively after 90 MPa tensile stress applied, which showed no degradation from their initial values measured before stress applied. With the applied tensile stress up to 135 MPa, still no degradation occurred on Bi-2212 strand. However, after the tensile stress of 146 MPa applied, the $I_c$ decreased to 480 A/mm$^2$ and n-valued decreased to 12.5, which implies that the Bi-2212 strand had been irreversibly degraded with the $I_c$ reduction of 8.0% under such tensile stress.
Figure 5-9 $J_e$ and n-value re-measured after each stress cycle verse the tensile hoop stress and the corresponding transporting current for applying stress in each cycle on Barrel #2

### 3.3 Quench degradation limit on Bi-2212 strand using ITER barrel configuration at self-field

To verify that the ITER barrel configuration would not affect the quench degradation limit measured on Bi-2212 strand, the quench degradation experiment was firstly performed on Barrel #1 at self-field. Similar to the short strand samples in Chapter 4, the $I_c$ after quenching normalized by the initial $I_c$ is plotted as a function of the normal zone peak temperature during each quench for barrel #1 with the transport current of 200 A in Figure 5-10: no degradation occurred for $T_{\text{max}}$ up to 411 K, and the quench degradation started with the $I_c$ reduction of 2.5% for $T_{\text{max}} = 452$ K, 6.2% for $T_{\text{max}} = 477$ K, 9.8% for $T_{\text{max}} = 500$ K and 18.9% for $T_{\text{max}} = 515$ K. Compared to the 8 cm strand sample tested in Chapter 4, which is marked
as the red line in the plot, the normal zone temperature limit for quench degradation obtained from this ITER barrel configuration doesn’t show much deviation: both 8 cm strand and 1 m barrel started to significantly degrade when the local normal zone temperature exceeded 450 K - 500 K.

Figure 5-10 $I_c$ after quenching normalized by the initial $I_c$ versus the local peak temperature for a series of quenches on Barrel #1. The red line represents the results on an 8 cm strand sample from Figure 4-4

3.4 Quench degradation limit on Bi-2212 strand under the axial hoop stress

According to the stress-strain behaviors shown in Figure 5-1, the Bi-2212 strand is still in elastic deformation region with high Young’s modulus for the tensile stress under 80 MPa,
while the mechanical limit on Bi-2212 strand under the axial hoop stress has been determined as over 135 MPa. Hence, the in-field quench degradation experiments on Bi-2212 barrels were performed within the stress range from 80 MPa to 135 MPa. To generate such high tensile hoop stress, only 25 bar processed barrels were involved in this section for providing enough in-field $I_c$ performance. Figure 5-11 plots the $I_c$ after quenching normalized by the initial $I_c$ as a function of local peak temperature during the quench for barrel #3 at 15 T. During the quench runs from Q1 to Q9, the transport current of 250 A was maintained to apply the tensile hoop stress of 113 MPa on Bi-2212 strand. Under this stress/strain state, the local normal zone temperature $T_{max}$ up to 200 K didn’t result in any quench degradation, while the $I_c$ lost 2.7% with $T_{max} = 246$ K and then 6.2% with $T_{max} = 286$ K. After the $I_c$ reduction reached 13.9% with $T_{max} = 302$ K at Q7, the subsequent quench runs Q8 and Q9 with the lower $T_{max}$ (201 K and 250 K respectively) didn’t cause any further degradation. In the following quench runs from Q10 to Q13, the transport current was set as 300 A and the applied tensile hoop stress was 135 MPa. No damage on Bi-2212 strand was observed after quenching with $T_{max}$ up to 110 K under this increased tensile stress, while the $I_c$ degraded again to 81.1% of the initial value with $T_{max} = 161$ K and then 77.2% with $T_{max} = 204$ K.
Figure 5-11 $I_c$ after quenching normalized by the initial $I_c$ versus local peak temperature for a series of quenches on Barrel #3.

Following the same test protocol, the quench degradation experiments were performed on barrel #4 and #5 under the background magnetic field up to 30 T. Table 5-3 summaries the identified local normal zone temperature limits for quench degradation under varied tensile stresses. Notably, the temperature limits in this table are quantitatively determined as the least normal zone peak temperature resulting an $I_c$ reduction of 5% - 10%. As an example, the temperature limits for barrel #2 should be 286 K under 113 MPa and 160 K under 135 MPa, according to Q5 and Q12 in Figure 5-11 respectively.
Table 5-3 Summary of the quench degradation limits under varied tensile stresses

<table>
<thead>
<tr>
<th>Barrel No.</th>
<th>Background magnetic field</th>
<th>Transport current</th>
<th>Applied tensile stress</th>
<th>Quench degradation limits (Ic reduction)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>15 T</td>
<td>250 A</td>
<td>113 MPa</td>
<td>286 K (6.2%)</td>
</tr>
<tr>
<td></td>
<td>15 T</td>
<td>300 A</td>
<td>135 MPa</td>
<td>160 K (5.8%)</td>
</tr>
<tr>
<td>4</td>
<td>15 T</td>
<td>200 A</td>
<td>90 MPa</td>
<td>328 K (5.8%)</td>
</tr>
<tr>
<td></td>
<td>20 T</td>
<td>200 A</td>
<td>120 MPa</td>
<td>258 K (6.7%)</td>
</tr>
<tr>
<td>5</td>
<td>25 T</td>
<td>150 A</td>
<td>113 MPa</td>
<td>280 K (5.8%)</td>
</tr>
<tr>
<td></td>
<td>30 T</td>
<td>150 A</td>
<td>135 MPa</td>
<td>178 K (7.4%)</td>
</tr>
</tbody>
</table>

These experimental results reveal that the normal zone temperature limits for quench degradation would decrease. Figure 5-12 illustrates the quench degradation temperature limits as a function of applied tensile stress. Additional to the data from Table 5-3, the results from both the self-field quench degradation test on barrel #1 and the mechanical limit test on barrel #2 are also included in this plot. For the self-field quench degradation limit determined as 477 K with Ic reduction of 6.2%, the applied tensile stress should be zero; while for mechanical limit of 146 MPa with Ic reduction of 8.0%, no quench was involved and thus the T_{max} should be 4.2 K.
It could be clearly noticed from Figure 5-12 that all the data points obtained from the in-field quench degradation under the magnetic field up to 30 T follow a consistent behavior: the quench degradation limit on Bi-2212 strand decreases with applied tensile stress, but still above 300 K under the tensile stress up to 90 MPa; and then it reduces dramatically to less than 200 K with higher tensile stress applied up to 135 MPa.

4. Discussion

4.1 Strain analysis for the quench degradation under axial tensile stress

The previous study in Chapter 4 has concluded that the quench degradation should be a strain-driven effect, but it is still lack of a quantitative explanation; therefore, more detailed analysis for the strain state of Bi-2212 strand during quenching under axial tensile stress.
would be helpful to further understand the failure mechanism behind the quench degradation behavior.

Compared to the ends-fixed short strand sample in Chapter 4, the Bi-2212 strand using ITER barrel configuration has a simple and easy-to-analysis strain state. As described in experimental approach section, the conductor in the barrel has no constrain outside the winding, and thus would be able to freely elongate under the hoop stress due to the Lorentz force. Hence, the Bi-2212 strand’s strain state under tensile hoop stress could be determined using the stress-strain curve shown in Figure 5-1 as a reference; the Bi-2212 strand under the tensile stress up to 140 MPa should have been yielded into plastic deformation region with the axial tensile strain of above 0.4%, causing at least 5% irreversible $I_c$ degradation according to Figure 5-2. Hence, the mechanical limit determined as 146 MPa should be a reasonable value, and it is consistence with previous studies giving the stress limit range of 120 MPa to 150 MPa [3, 9, 10].

Meanwhile, when the normal zone temperature rises during quenching, the thermal expansion of Bi-2212 strand would be released through local displacement. Since pure Ag and AgMg alloy take 75% of the volume fraction in the strand and have much higher thermal expansion coefficient than Bi-2212, the thermal expansion of the whole strand is dominated by pure Ag and AgMg alloy, and thus Bi-2212 filaments will be pulled with tensile strain, which should be proportional to the local temperature rise.

Considering that the quench degradation temperature limit would be reduced upon the tensile stress applied, a reasonable model could be proposed: the intrinsic degradation limit with Bi-2212 round wire should be a constant in terms of the tensile strain on Bi-2212 filaments,
while either the applied tensile stress or thermal expansion would cause tensile strain on Bi-2212 filaments, which would be added up to share the same strain margin. To verify this model, Table 5-4 lists the total tensile strains applied on Bi-2212 filaments, which are calculated with the quench degradation temperature limits under varied tensile stresses shown in Figure 5-9. The strains due to applied stress are determined using Figure 5-1 as a reference, while the strains due to thermal expansion are estimated through the thermal expansion data on Ag/Bi-2212 round wire and Bi-2212 grain in a,b plane when warming from 4.2 K as show in Figure 5-13, and these data are previously reported in [11] and [12].

Table 5-4 Estimated tensile strains applied on Bi-2212 filaments

<table>
<thead>
<tr>
<th>Applied tensile stress</th>
<th>Strain due to applied stress</th>
<th>T$_{\text{max}}$ when degradation</th>
<th>Strain due to thermal expansion</th>
<th>Total tensile strain</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 MPa</td>
<td>N/A</td>
<td>477 K</td>
<td>0.37%</td>
<td>0.37%</td>
</tr>
<tr>
<td>90 MPa</td>
<td>0.11%</td>
<td>328 K</td>
<td>0.25%</td>
<td>0.36%</td>
</tr>
<tr>
<td>113 MPa</td>
<td>0.17%</td>
<td>286 K</td>
<td>0.18%</td>
<td>0.35%</td>
</tr>
<tr>
<td>135 MPa</td>
<td>0.30%</td>
<td>160 K</td>
<td>0.09%</td>
<td>0.39%</td>
</tr>
<tr>
<td>146 MPa</td>
<td>&gt;0.40%</td>
<td>4.2 K</td>
<td>N/A</td>
<td>&gt;0.40%</td>
</tr>
</tbody>
</table>
Figure 5-13 Thermal expansion on Ag/Bi-2212 round wire and Bi-2212 grain in a,b plane when warming from 4.2 K

Figure 5-14 illustrates the results from Table 5-4 by plotting the total tensile strain applied on Bi-2212 filaments at the degradation limits as a function of applied tensile stress, and the strain component due to the applied tensile stress is distinguished from the strain component due to the thermal expansion in the plot.
Figure 5-14 Estimated tensile strains applied on Bi-2212 filaments with quench degradation temperature limits verse applied tensile stresses

Notably, this plot strongly supports the proposed model: all the degradation limits, with either the applied tensile stress at 4.2 K or the local normal zone during quenching without external tensile stress or the combination of both, result in the same level, 0.35%–0.4%, of total tensile strain applied on Bi-2212 filaments.

Hence, when a high tensile stress applied, the strain margin left for thermal expansion would shrink, i.e., the quench degradation limits would decrease; especially for the tensile stress above 130 MPa, the Bi-2212 strand has been yielded with a comparable strain, and thus the degradation would still occur even with a low normal zone temperature as <200 K.
4.2 Implications for conductor and magnet design

The semi-quenititavie model has clearly revealed that the quench degradation in Ag-sheathed Bi-2212 round wire is driven by the net local strain state applied on Bi-2212 filaments with its intrinsic limit of 0.35%-0.40% in tension. Figure 5-15 re-plots the quench degradation results in Figure 5-10, by converting the local peak temperature $T_{\text{max}}$ into the estimated tensile strain on Bi-2212 filaments according to Figure 5-13. In terms of the $I_c$ dependence on applied tensile strain, the result from quench degradation experiment is very consistence to the one from mechanical test, which is retrieved from Figure 5-2. Hence, it implies that the quench degradation limit could be predicated directly from the mechanical behavior of Ag-sheathed Bi-2212 round wire.

![Ic-strain curve from Figure 5-2](image)

Figure 5-15 $I_c$ dependence on applied tensile strain from quench degradation test (black dots, retrieved from Figure 5-10) and mechanical test (red line, retrieved from Figure 5-2)
Although the further investigations are still needed, it seems that the tensile strain limit of 0.35\%-0.40\% comes intrinsically with the Ag-sheathed Bi-2212 round wire, regardless of the conductor architecture, the densification level of Bi-2212 filament, the way to apply the strain (thermally or mechanically). Previous studies about the mechanical behaviors of Bi-2212 have proposed that Bi-2212 filaments in a virgin sample were thermally pre-compressed after cooling and thus have a reversible region under the certain tensile strain [3, 10]. The founding in this study obviously supports this hypothesis, and further reveals that the ‘cooling’ causing pre-compression does not only mean from room temperature to 4.2 K, since the degradation temperature limit could go much beyond the room temperature and up to 500 K, but also refers to the cooling procedure from the heat treatment of Bi-2212 wire. During the heat treatment, the solidification of Bi-2212 phases start from over 800 °C and the reaction still continue during cooling procedure, so to determine the initial strain state of Bi-2212 filaments in a virgin sample is very complex and will need for a complete assessment of the thermal contraction of Ag/Ag alloy and Bi-2212 from heat treatment to 4.2 K, similar to previous study performed on Bi-2223/Ag tape [13].

Theoretically, using another metal material, with similar thermal contraction as Bi-2212 to replace Ag and Ag alloy, could improve the intrinsic quench degradation limit of Ag/Bi-2212 round wire. Unfortunately, considering the compatibility requirement during heat treatment of Bi-2212, this solution is barely applicable. However, recent studies about improving the mechanical robustness of Ag/Bi-2212 round wire [1, 14], including Young’s modulus and yield stress, will help to increase the quench degradation limit under high tensile stress as well.
From the magnet design aspect, the whole trend line shown in Figure 5-12 represents the safety operation boundary for the high-field Bi-2212 magnet, which implies the quench protection strategy must be more conservative when associated with high tensile stress. This especially introduces a new constraint for developing high-field solenoids for >1.3 GHz NMR, which likely experience significant tensile hoop stress. Hence, the reinforcement structures will be highly necessary for magnet design, and the well-developed pre-compression procedure for dipole magnet fabrication should be helpful as well.

5. Summary

In this study, the quench degradation experiments were performed on Bi-2212 round wire using the ITER barrel configuration with a tensile axial stress applied on the Bi-2212 strand through the Lorentz force. Through this setup, the experiment results showed that applying a tensile axial stress would decrease the quench degradation temperature limit from >400 K to less than 200 K.

Based on the dependence of the maximum quench temperature on tensile stress under high magnetic field up to 30 T, a semi-quantitative model revealed that the degradation in Bi-2212/Ag wire is a locally strain-driven effect and the net tensile strain applied on Bi-2212 filament is the key.
REFERENCES


CHAPTER 6

CONCLUSIONS AND SUGGESTED FUTURE WORK

To explore the limits and guide the design of a new very high-field superconducting magnet technology based on Bi-2212 round wires, this thesis experimentally investigates the stability and quench propagation behaviors in both small coils and short samples of Bi-2212 while they carry large electric current in high magnetic fields; it also determines conditions at which critical current of Bi-2212 wire degrades irreversibly and how quench induced degradation limits alter with conductor design, heat treatment, and stress/strain states of the conductor. This chapter summarizes key findings of these experimental studies, explains how they are beneficial to Bi-2212 high field magnet design, and suggests a number of subsequent works that could be performed in future.

1. Summary of Findings

This thesis aimed to answer three crucial questions: (1) Compared to the previous studies on Bi-2212 shorts strands in liquid helium and at self-field, how does the stability and quench propagation behaviors differ in epoxy-impregnated coils under the high magnetic field up to 20 T or even higher? (2) Given the complex microstructure-performance dependence in Bi-2212 round wire, can the quench degradation limits be varied through conductor designs or processing methods as well? (3) What is the physical mechanism behind the quench degradation event in Bi-2212 round wire? All of these three questions have been addressed through the study.

To answer the first question, Chapter 2 experimentally studied the fundamental quench behavior of small-size Bi-2212 test coils at 4.2 K in magnetic fields up to 20 T. With
increasing magnetic field, \( T_c \) decreases, resulting in reduced current sharing temperature and thus stability margin: the MQE measured at 20 T with the transport current density of 150 A/mm\(^2\) was only \( \sim 100 \) mJ, which was about two orders lower than the value previously measured at self-field. Meanwhile, the in-field quench propagation was dominated by the decreasing critical current density, which drove the slow NZPV in the order of tens of cm/s: at 20 T with the transport current density of 150 A/mm\(^2\), the longitudinal NPZV was measured as 5.3 cm/s.

With NZPV at 5~10 cm/s in fields up to 20 T, Chapter 3 investigates the effects of such low NZPV on quench detection of Bi-2212 coils. The study systematically measured the time evolution of the hot spot temperature and the normal zone resistive voltage in an epoxy-impregnated full-size Bi-2212 coil. For this coil, the hot spot temperature for the resistive voltage of the normal zone to reach 100 mV increases from \( \sim 40 \) K to \( \sim 80 \) K with increasing the operating wire current density \( J_o \) from 89 A/mm\(^2\) to 354 A/mm\(^2\) whereas for the voltage to reach 1 V, it increases from \( \sim 60 \) K to \( \sim 140 \) K. This result highlights the difficulty of quench detection in Bi-2212 coils, which is due to the slow normal zone propagation, and the need to allocate a more significant amount of protection time for Bi-2212 coils when designing quench detection and protection circuitry than for Nb-Ti and Nb\(_3\)Sn magnets. The result also highlights the importance of finding out the maximum allowable temperature of the conductor during a quench, so a quench protection system can be designed properly.

The studies in Chapter 4 determined the quench degradation behavior of Bi-2212 wires. It also addresses the second question through systemically characterizing the electromagnetic properties and microstructures of quench-degraded samples from a large pool of Bi-2212
round wires, which have the varied conductor designs and processing methods. Among the large pool of commercial Ag/Bi-2212 round wires investigated in this study, a consistent quench degradation behavior was observed: wires exhibit small irreversible $I_c$ and n-value degradation when the local normal zone temperature exceeds 400 K and then large degradation when the temperature increases above 550 K. The microstructural observations of quench-degraded wires provide significant evidences for the argument that $I_c$ degradation during a quench is primarily driven by local straining of superconducting filaments.

Chapter 5 takes the experiments in Chapter 4 one step further to quantitatively define the dependence of the maximum local normal zone temperature on the pre-existing tensile strains in strong magnetic fields. The measurement, for the first time, clearly shows that applying a tensile axial stress decreases the quench degradation temperature limit from >400 K at stress-free state to < 200 K under 130 MPa and above. To solve the third question, a semi-quantitative model of the stain state during quench-under-tensile-stress event revealed the physical failure mechanism: the $I_c$ degradation in Bi-2212/Ag wire is driven by the net local strain applied on Bi-2212 filaments, which could be the combination of the mechanical tensile strain and the thermal strain due to the thermal expansion difference between the Ag sheath and Bi-2212 filaments.

2. Suggested Future Work

2.1 Determining quench propagation behaviors in over-pressure processed coils that carry $J_e$ up to 600 A/mm$^2$ at high magnetic fields up to 30 T

It has been well accepted that the over-pressure processed Bi-2212 round wire can carry an engineering current density $J_e$ up to 720 A/mm$^2$ at 4.2 K and 20 T, which offers to construct
a new class of powerful superconducting magnets that generate magnetic fields of >20 T, beyond limits of Nb$_3$Sn. However, the quench experiments for OP processed Bi-2212 coils haven’t been successfully performed in this study so far, and thus it will be meaningful to continue the quench experimental study to the OP processed coils at high magnetic field, especially above 20 T. According to the $H_c2(T)$ plot shown in Chapter 1, the $T_c$ of Bi-2212 above 20 T is below 10 K, which is close to the $T_c$ of Nb$_3$Sn at lower field region, so the stability margin of Bi-2212 would be significantly reduced, and the Bi-2212 high field magnet might have the same issue of ‘training effect’ as the LTS magnet, while the normal zone propagation velocity might be enhanced to the order of m/s due to the improved current density with OP processed Bi-2212 round wires.

2.2 Investigating the fundamental fracture mechanism of Bi-2212 filaments

The microstructural study on degraded Bi-2212 samples has been introduced in Chapter 4 and successfully identified the cracks on Bi-2212 filaments as the evidence of the strain-driven quench degradation mechanism. To benefit the conductor design for a more robust Bi-2212 round wire, it is necessary to further understand the fracture mechanism on Bi-2212 filaments to reveal the following questions: Where do the fractures occur first on Bi-2212 filaments? Are they particularly associated with any features on Bi-2212 filament? How do the fractures propagate and develop into large cracks? Future studies may include both the numeric model, to analysis the stress/strain distribution and simulate the fracture initialization and development, and the advanced microstructural investigation method, to quantitatively observe the fracture inside Bi-2212 filaments and real-time monitor the fracture development.
APPENDIX A

EXPERIMENTAL METHOD FOR QUENCH CHARACTERIZE STUDY ON

Bi$_2$Sr$_2$CaCu$_2$O$_x$ ROUND WIRES

This thesis relies critically on heater-induced quench experiment on Bi-2212 round wires to establish a comprehensive understanding of the stability, quench propagation behavior and quench degradation limit. Since the detailed experimental approach details may vary upon the samples, there is a need to have this appendix qualitatively summarizing these measurement approaches for the readers’ reference.

1. Transport $I_c$ measurement

The transport critical current is the main physical parameter used to determine the quality of superconductor. The following paragraph adapted from Tengming Shen’s Doctoral thesis gives a brief introduction about the experimental method for transport $I_c$ measurement [1]. Figure A-1 illustrates the standard four-probe method used to determine the $I_c$ of Bi-2212 round wires, following protocols recommended by the International Electrotechnical Commission (IEC). The sample is mounted on the flat surface of a measurement holder and two ends of the specimen are soldered to the Cu current contact blocks. For the tests in magnetic fields, a low-temperature adhesive (such as epoxy or wax) is used to bond the specimen to the measurement holder to reduce specimen motion against the Lorentz force. After sample mounting, sample is cooled from room temperature to 4.2 K slowly to minimize the total strain induced in the specimen at the measurement temperature to be within ±0.1%. I-V characteristics of the specimen are then measured by applying an increasing current (I) to the superconductor specimen using a DC power supply and then measuring the voltage (U)
generated along a section of the specimen. During testing, the test specimen is immersed in a liquid helium bath. The $I_c$ is determined using an electrical field criterion of $10^{-6}$ V/cm at 4.2 K with the magnetic field applied perpendicular to the wire axis.

![Schematics of the transport $I_c$ measurement on a sBi-2212 short strand](image)

Figure A-1 Schematics of the transport $I_c$ measurement on a sBi-2212 short strand

2. Heater-induced quench experiments

2.1 Typical measurement set-up

Quench experiments on HTS, including YBCO, Bi-2212 and MgB$_2$, have been well developed at NHMFL [2-4], and their test protocol was adapted into this study. Figure A-2 shows a typical quench experimental setup for short samples. Compared to the standard transport $I_c$ measurement, the experiment preparation involves some additional steps, including attaching a heater on the Bi-2212 sample and connecting voltage and temperature wiring around the heater section.
Figure A-2 (a) Schematic of sample mounted with instrumentation wiring for a quench experiment, and (b) photograph of sample

2.1.1 Heater setup

Heater is the key component for quench experiment. There are several different types of heater setup involved in this study. The most common one is using metallic heating wires tightly wound around the Bi-2212 round wire as illustrated in Figure A-2(a). Two commercial heater wires from Lakeshore, AWG 32 Nichrome wire, which is made of 80% Ni and 20% Cr with Polyimide insulation, and AWG 32 Manganin wire, which is made of 83% Cu, 13% Mg and 4% Ni with Heavy Formvar insulation, are used in this study.

Both wires have a high resistivity but no strong temperature dependence, for AWG 32 wire ($\Theta = 0.203$ mm), Nichrome has the resistance of $34 \ \Omega/m$ at 305 K and $33.2 \ \Omega/m$ at 4.2 K, while Manganin has the resistance of $15.1 \ \Omega/m$ at 305 K and $13.5 \ \Omega/m$ at 4.2 K, so typically after the heater wires tightly wound around Bi-2212 round wire covering a 1-1.5 cm long section, a heater resistance of 5-10 $\Omega$ could be achieved.

For short sample test, the heater could be attached on the sample after heat treatment by gently hand winding, but for coil test, the heater has to be deployed onto the coil during the
winding process and undergo the coil heat treatment. Preliminary tests imply that Nichrome wire could survive through the heat treatment and have no negative impacts on Bi-2212’s $I_c$ performance if wound around the insulation layer of Bi-2212 round wire. However, this kind of wire-wound heater has a disadvantage of affecting the coil winding uniformity, since the heater section would have a ~0.5 mm larger wire diameter than other parts of Bi-2212 round wire in the coil.

Later in this study, another heater design using graphite based electrically conductive epoxy ECOBOND 60L was introduced for the coil quench test, which was previously used on quench experiment for Nb$_3$Sn cable [5] and MgB$_2$ short sample and coil [6, 7]. In this epoxy heater design, joule heating energy is deposited on the strand by passing a current pulse through the heater and then the superconducting strand as the current return path, and thus it is able to provide a more effective thermal contact with superconducting strand than a wire-wound heater. To apply the epoxy heater on Bi-2212 test coil, the below procedures should be followed:

- Remove the insulation of Bi-2212 round wire to expose a 5-10 cm long section for heater deployment.
- Use thin Kapton tapes (25-50 µm) to cover the conductors around the heater section so that the epoxy heater would only contact one turn of Bi-2212 round wire.
- Weigh and mix the ECOBOND 60L epoxy paste as its instruction.
- Drop a small amount (<1 mg) of mixed epoxy on the heater section and use the razor tip to slightly press the epoxy paste onto the Bi-2212 conductor.
• Place a thin Cu strip (typically 50 µm thick, 2 mm wide, 6 mm long) on the heater top surface and then drop a little more epoxy paste to cover one end of Cu strip, so that the other end of Cu strip is left outside of the epoxy heater as one lead for electrical connections.

• Use a piece of thin Kapton tape (25-50 µm) to cover the whole heater to apply a small pressure during epoxy curing.

• Leave the heater still at room temperature for 8 hrs (or at 60 ºC for 1 hr) to allow the epoxy completely cured.

• Remove Kapton tapes around the heater but keep the pieces beneath the epoxy heater, and solder a thin Cu wire right beside the epoxy heater as the other lead for electrical connections.

Figure A-3 presents the photograph of an epoxy heater mounted on the Bi-2212 and the schematics for the epoxy heater circuit. The resistance of the epoxy heater can barely be precisely controlled, since it depends on the volume and shape of the epoxy bulk and the pressure applied during epoxy curing, but in general the epoxy heater produced with the above method can behave as a constant resistance in the range of 0.5-10 Ω at 4.2 K under a current pulse with the amplitude up to 4 A and the duration up to 1 s.
2.1.2 Instrumentation wiring

After the heater deployed, the matrix of instrumentation wiring is connected on Bi-2212 conductors around the heater section to monitor the voltage and temperature evolutions during the quench test as shown in Figure A-2a.

For picking up the voltage signals along the Bi-2212 conductor, the single or twisted-pair Cu wires (AWG 32 or 36) are soldered directly on the Ag sheath of Bi-2212 conductor. Normal solder (60%Sn-40%Pb, melting point ~460 K) or high-temperature solder (1%Sn-97.5%Pb-1.5%Ag, melting point ~ 580 K) is used to solder voltage taps along the sample. Before soldering, active rosin flux (M-Flux AR, Vishay Micro Measurements) is applied on the sample surface where the solder dots are to be made.

To trace the temperature evolutions, type E thermocouple junctions, made by spot-welding the ends of thermocouple wire pairs (AWG 36, Ø 0.127 mm), are attached between the
voltage taps. During initial experiments (Chapter 3), the thermocouple junctions are mounted on the wire surface with Stycast 2850FT, but this approaches is proven not so reliable.

Thus in later experiments (Chapter 4-6), the thermocouple junctions are bonded to wire surface with a small drop of solder. The other ends of the thermocouple wire pairs are spot soldered with Cu extensions and submerged in liquid nitrogen, which provides the thermal reference points. The technical details about the thermocouples in temperature measurement will be discussed in next section.

2.1.3 Measurement of normal zone temperature

The quench event intrinsically is a thermal runway, while the local temperature may increase from 4.2 K up to several hundred K within a few seconds. A reliable measurement of the normal zone temperature must be achieved in these experiments. Regarding the selection of temperature sensor, Xiaorong Wang has presented a very comprehensive review to compare in his doctoral thesis [3] and concluded that type E thermocouples are most favorable to measure the normal zone temperature during quench experiments.

When using type E thermocouples, the temperature data has to be converted from thermocouple thermoelectric voltage (E) according to the flow chart shown in Figure A-4. The inputs are the reference temperature ($T_{\text{ref}}$) and the thermocouple voltage measured by DMMs ($E_{\text{meas}}$) in mV. The output is the temperature $T_{\text{meas}}$ in K. Because the existing standard E-T relationship for type E thermocouples has a reference temperature of 0 °C, the function $T \Rightarrow E$ is necessary to convert the liquid nitrogen reference temperature to a voltage base added to the measured thermocouple voltages to make use of the standard curve E-T data of type E thermocouple. More details about the conversion between E and T are referred to [3].
According to previous literatures[3, 8, 9], type E thermocouples have an effective range from 3.15 K to 953 K, and its error is about -2 K at 33 K (6%) and less for higher temperature. Its sensitivity (Seebeck coefficients) is 12 µV/K at 30 K, 14 µV/K at 40 K, and higher than 20 µV/K for T > 55 K, which is the highest of all the commonly used thermocouple types. With the magnetic field at 2.5 T, the magnetic error is ~1% at 10 K, while the error is ~7% at the magnetic field up to 14 T. Also, the magnetic error will decay with the higher temperature. In general, type E thermocouples are sufficient for the most quench measurements.

However, there is a concern about the accuracy of thermocouple readings; the response time of an E-type thermocouple is ~100 ms so it tends to underestimate the temperature rise if the temperature rising rate is >10 K/s. Besides, for the high normal temperature (> 400 K) which is close to the melting temperature of solder, the bonding between the thermocouple and the wire surface might be not reliable either. Hence, temperature is also estimated by cross-examining the local voltage measured across each section, with the temperature dependence of the resistivity of silver measured.

Estimating temperature from the resistivity measurement requires knowing the temperature dependence of the resistivity of silver, which was measured using the standard four-point
technique on a short strand cut from the same Bi-2212 round wire batch but melt processed with a maximum processing temperature 15 °C lower than optimum (filaments of this sample carry nearly zero $I_c$ so the resistivity measurement was made down to 4.2 K; current applied during the measurement is 2 A). The heat-treated wires were measured to take into consideration of potential RRR reduction due to Cu dissolving into the silver during the melt processing. The residual resistivity ratio (RRR) of silver, defined as $RRR = \rho(293 \text{ K})/\rho(4.2 \text{ K})$, was measured to be 230, which is consistent with the reported value [9].

Figure A-5 illustrates the growth of the normal zone temperature during a typical quench with the data both from thermocouple readings and voltage converted estimation. The temperatures measured by the thermocouple track well with that converted from voltage when it is below 300 K, but while the hotspot exceeds 350 K, these thermocouple readings start to divert from the temperatures converted from voltage. For the final temperature peak, the one converted from voltage shows 561 K, which is about 10% higher than the thermocouple readings. Therefore, in the study for quench degradation limit, the normal zone temperature often exceeds 300 K and thus mainly relies on voltage converted estimation, but the thermocouple readings are still served as a cross-check.
Figure A-5 the local temperature rise during a typical quench with the data from both thermocouple readings and voltage converted estimations

2.2 Instrumentations and LabVIEW routines

2.2.1 Main power supply

The transport current is provided by an HP 6680A direct current power supply. The maximum output voltage is 5 V and the maximum current 1000 A. During the quench experiments, the power supply operates in constant current mode. The amplitude and duration of the current output is controlled either remotely by the standard commands for programmable instruments (SCPI) over an IEEE 488.2 GPIB bus or locally by an analog voltage outputted by a NI USB-6211 card. For $I_c$ measurement experiments the ramp rate is controlled via the IEEE 488 bus and LabVIEW.
2.2.2 Heat pulse current source

Pulse voltage can be generated directly through another power supply (Kepco BOP 50-4D), which is equipped with a GPIB card and is controlled remotely by SCPI commands via GPIB bus to generate the pulse voltage across the heater. The amplitude of the pulse signal is varied with a resolution of 0.01 V limited by the Kepco power supply, and the maximum output current and voltage from Kepco are 4 A and 50 V respectively.

2.2.3 Data acquisition (DAQ) system

All data is recorded as a voltage, including the voltage along the sample and across the heater, the voltage drop across the shunt resistor which is converted into a current value, and the voltages picked up from the E-type thermocouples which are converted into a temperature. Thus, the devices needed to properly acquire data must to be able to read small voltages with high accuracy and sufficient data acquisition rate.
Figure A-6 Schematics for two data acquisition systems used in this study
Two different sets of data acquisition system are involved in this experimental study as shown in Figure A-6. Both systems could be applied in heater-induced quench experiments on Bi-2212 short strand or coils. In System (a), all the signals are read by multiple Keithley multimeters and saved into the computer through GPIB bus, while in System (b), the signals are directly connected to a National Instrument SCXI signal conditioning system and then simultaneous recorded into a computer by a PCI-DAQ card.

In System (a), most Keithley multimeters only read one signal per device with the resolution up 0.1 uV and thus the reduced noise level since the signals isolated from each other. However, the real time data recording rate is limited at ~10 Hz by the time delay during sending and receiving commands and data through GIPB bus. Even with the embedded buffer inside Keithley multimeters, the effective DAQ rate in only up to 200 Hz. Besides, for the quench experiments with multiple signal channels, especially on the coil, this system will involve a number of devices and thus become unwieldy and unstable.

According to these disadvantages, System (b) uses the SCXI plus DAQ card to replace most Keithley multimeters for signal reading and recording. The DAQ rate in this system could be maintained at 1 kHz at least, with the resolution down to 0.5 uV. Hence, System (b) is mainly applied with this study (Chapter 3-5), while System (a) is only used in Chapter 2.
REFERENCES


