Design and Analysis of the Quench Protection for the MICE Coupling Coils

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***Abstract*— Two identical MICE coupling coils have the largest diameter and stored energy, at 13 MJ each, of all coils in the MICE experiment. The coils have an inner diameter of 1.5 m and radial and axial builds of 102.5 mm and 285 mm, respectively. The coils contain approximately 15,936 turns and are wound with a single rectangular NbTi strand with a copper-to-superconductor ratio of 3.9:1. Each coil is conduction cooled using 3 cryocoolers, which maintain an operating temperature at about 4.5 K. Each coil is powered through a pair of series-connected copper and 500 A HTS current leads. The quench protection analyses described here show that subdividing the winding into 4 or more, cold-diode-protected subsections maintain hot spot temperatures below 150 K and internal winding voltages below 300 V. The superconducting subdivision interconnect loops are protected by heat sinking them to the aluminum winding housing. Stabilizing the coil leads from the winding to HTS current leads minimizes the likelihood of lead quench. The first of 3 coils will be tested at Fermi Lab and the final 2 coils will be installed in MICE at Rutherford Lab.**

***Index Terms*—cold diodes, MICE, NbTi, quench protection, superconducting magnets**

I. Introduction

Muons are produced from pion decay with a diffuse phase space, and their longitudinal and transverse emittance must be reduced within their short lifetime to produce useful beams for a muon collider or a neutrino factory. Ionization cooling, which involves passing the beam through a low Z material, reduces both the longitudinal and transverse momentum, and the longitudinal momentum can be restored by coherent acceleration [1]. One of the objectives of the Muon Ionization Cooling Experiment (MICE) is "to show that it is possible to design, engineer and build a section of cooling channel capable of giving the desired performance for a Neutrino Factory" [2]. Liquid hydrogen absorbers in MICE perform the cooling within the absorber focus coil (AFC) module, RF cavities reaccelerate the muons, and the coupling coils confine the beam in the cavities [3]. Cooling of the 200 MeV/c, 6π mm rad muon beam is expected on the order of 10% [4, 5]. Together the cavities and the coupling coil form the RFCC module. A recent update on the status of this module is provided in [6]. The MICE experiment is being installed in the ISIS facility of the Rutherford Appleton Laboratory (RAL) in UK.

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II. MICE Coupling Coil Parameters

The MICE coupling coils are wound with a single strand of rectangular NbTi conductor which is conduction cooled inside a 6061-T6 aluminum coil case. The coil case is cooled by natural circulation of liquid He through tubes welded to the case OD. The helium flowing out of the tubes is heat exchanged in a reservoir cooled by 3, 2-stage, pulse-tube cryocoolers [7]. Each terminal of the winding is powered through a copper current lead between room temperature and the intermediate shield temperature and a 500 A HTS current lead from the intermediate temperature to 4.5 K. The winding outer diameter is over-wound with aluminum banding, which shares hoop load with the conductor when the magnet carries current. At the time of this writing, one winding has already been made with eight, equally-radially-spaced subdivisions and is to be tested at Fermi Lab (FNAL). Two additional windings are to be fabricated for MICE at RAL.

MICE can be operated in either "flip" mode, where the two magnets in all of the AFC modules operate at the same current but opposite polarity, or in "non-flip" mode where the AFC module magnets operate at the same current and same polarity [8]. Since the flip mode requires higher current (210 A) and stored energy (12.9 MJ) in the coupling coils, this mode sets the design point for the coupling coil quench protection design. Other relevant parameters are given in Table 1.

III. Coil Quench Protection Analysis

With 12.9 MJ of energy in a magnet of this size, quench protection is an important design consideration. The coil cross sectional dimensions along with typical transverse quench propagation velocities in insulated NbTi coils suggest passive quench protection could be an option. In fact a previous paper [10], using a semi-empirical quench model, concluded that passive protection could be viable.

The present task is to recommend the quench protection design for the MICE coupling coils, particularly the last two, which are still in production. Results reported here are based on the application of the lead author's quench code in the evaluation of passive quench protection with subdivision, as has been previously considered for the MICE coupling coils [10, 11]. A subdivided winding is shown in Fig. 1, in which cold diodes shunt each subdivision of the winding. A diode turn-on voltage at 4.5 K of 10 V is assumed. The actual turn-on voltage will be coordinated with the coil charging voltage during the FNAL test. Once the diodes conduct, their forward voltage is assumed to drop to 1 V. Voltage taps across each subdivision will provide signals to disconnect the power supply from the magnet circuit via *S1* and *S2*.

TABLE I
DESIGN POINT PARAMETERS FOR QUENCH ANALYSIS

Parameter	Units	Value
Maximum operating current	A	210.1
Stored energy	MJ	12.9
Inductance	H	584
Number of layers		96
Peak field on conductor	T	7.37
Number of turns per layer		166 ± 3
Coil inner radius	mm	750
Coil outer radius	mm	852.5
Coil length	mm	285
Conductor width, no insulation	mm	1.65
Conductor height, no insulation	mm	0.95
Average conductor width with insulation [9]	mm	1.73
Average conductor height with insulation [9]	mm	1.06
Cu:Sc		3.9
RRR of Cu		70
Copper mass	kg	897
Joules/kg of Cu	J/kg	1.44e+04
Quench temperature if uniform energy distribution	K	113

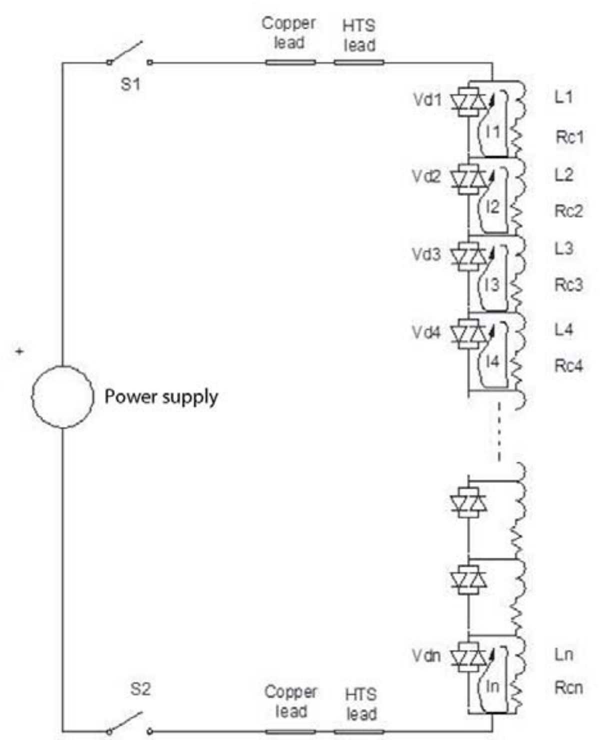

Fig. 1. General circuit diagram for coil with n subdivisions

The analyses show that hot spot temperature and peak voltage within the winding are generally lower with an increased subdivision count. The superconducting leads from each subdivision are brought out via insulated bushings through the sides of the coil housing. The benefit of reduced voltages afforded by increased subdivisions is offset by the increased risk of shorts at each subdivision lead penetration. With increasing subdivision count, there is no added net benefit of additional subdivisions once an acceptable voltage performance is achieved.

The lead author's quench code is based on a 3d finite difference model of the winding and uses temperature dependent thermal properties of the components as well as a *Jc(B, T)* characterization for the superconductor. Quench can be initiated at any location throughout the winding and results are dependent on the initiation site. The 3d temperature distribution and the circuit equations are solved at each time step, the size of which changes dynamically as the transient evolves. The time-step-size limiting thermal time constant increases with temperature, while the limiting electrical time constant decreases, and there is often a cross-over of the most limiting constraint for setting the time step size as the transient evolves. Voltages are calculated at each time step by combining the inductive and resistive components within each element and adding the element voltages in winding order. This approach differs from the semi-empirical approach in [10]. Although quench-back from the aluminum coil housing can be analyzed, it was ignored in these analyses for conservatism of the hot spot temperature calculation. Coil subdivision counts of 1, 2, 4 and 8 were considered in the analyses. Quench initiations from both the maximum and minimum locations of magnetic induction (*Bmax, Bmin,* respectively) were also considered. The objectives were to determine 1) whether quench propagation is sufficiently rapid that passive diode protection alone, without dump resistors, could be used, and 2) how many subdivisions are optimum to achieve acceptable hot spot temperature and voltage performance during a quench event.

Results of the subdivision analyses are shown in Table II. Coil hot spot temperatures decrease slowly and maximum internal coil voltages decrease significantly with increased subdivision count. Quenches initiating from the location of *Bmin* result in slightly higher hot spot temperatures and slightly lower voltages.

TABLE II
RESULTS FOR DIFFERENT NUMBERS OF SUBDIVISIONS

No. Sub-divi-sions	Initi-ation site	*Thot* (K)	Maximum ΔV in Coil (V)	Maximum Layer to Layer Voltage (V)	Maximum Turn to Turn Voltage (V)
1	*Bmax*	136	2114	155	97
2	*Bmax*	124	1074	100	58
4	*Bmax*	122	281	71	21
8	*Bmax*	122	78	68	7
8	*Bmin*	127	72	32	6

Based on the results in Table II, the team concluded that diode protection without dump resistors is sufficient for coil protection, and that 4 subdivisions achieve the coil voltage and hot spot temperature objectives. Figs. 2 and 3 plot current decay and hot spot temperature growth, respectively, for the case of 4 subdivisions and quench initiation from the *Bmax* location, which is in the innermost subdivision (Coil 1 in Fig. 2) at the axial winding center and coil ID. Fig. 4 shows the voltage distribution throughout the Coupling Coil relative to one end of the winding at 3 s, the time of maximum differential voltage (281 V) within the winding. Subdivision voltages are clearly visible as the ends of the subdivision can only be diode-forward-voltage drops away from each other.

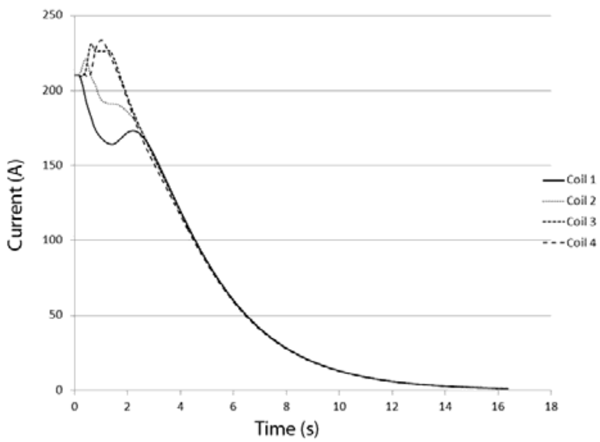

Fig. 2. Coil currents for 4 subdivisions and quench initiation from location of *Bmax*. Subdivisions are labeled as Coils 1-4, in sequence, outward from the Coupling Coil ID.

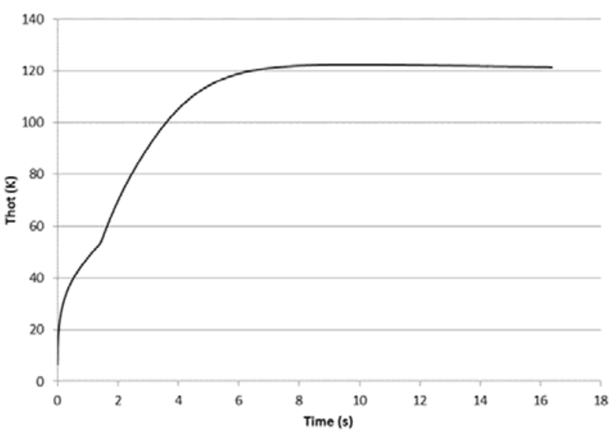

Fig. 3. Hot spot temperature for 4 subdivisions, quench initiation from location of *Bmax*

To ensure the 4-subdivision-protection approach is viable at lower operating currents, the quench program was run with quench initiation from both *Bmax* and *Bmin* locations for magnet stored energies in 10% increments over the 50-100% range of the 12.9 MJ maximum stored energy. In all cases, the hot spot temperature decreased with decreasing energy. These results, along with the times required to turn on the cold diode in the first-quenching subdivision are summarized in Table III.

IV. Subdivision Lead Protection

Each superconducting strand end of each coil subdivision penetrates the side of the coil case, forms a loop and reenters the winding pack volume to begin the next subdivision. To maximize thermal stability, these superconducting strands are soldered to a copper plate and G10-clamped to the side of the aluminum coil case through an insulating layer of Kapton, as shown in Fig. 5. A length of normal strand comprising a subdivision loop, with all current flowing through the copper stabilizer and clamped to the case, will heat exchange with the case by conduction through the Kapton and result in a loop temperature rise of only a few 10's of K. This heat from the loop outside the case, however, is conducted back into the winding through the loop end and is sufficient to initiate a normal zone quench in the winding after less than 1 s. Because the normal zone initiates from a side of the winding, the hot spot temperature for this quench is 153 K, which is higher than hot spots reported in Table II, where quenches initiate from points nearer to the axial center of the winding. In this analysis, it was assumed that the point of entry of the loop end on the axial side of the winding is at the radial location of the lowest field, and thus results in the slowest quench propagation time. Nevertheless, the above analysis confirms that these subdivision loops are protected should they go normal.

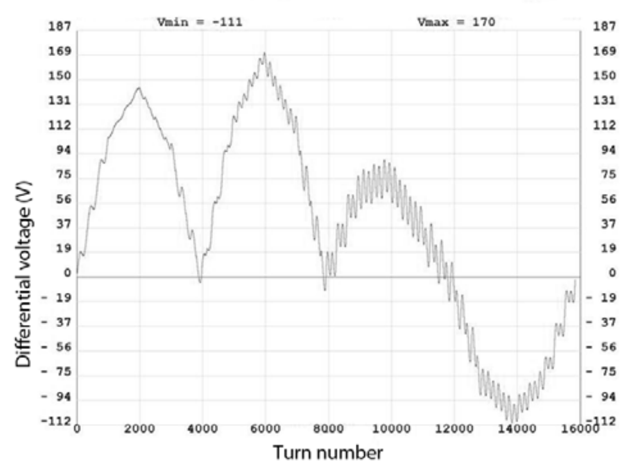

Fig. 4. Voltage distribution along the coupling coil at 3 s (time of maximum differential voltage) into the transient for 4 subdivisions, quench initiation from location of *Bmax.*

TABLE III
Quench Protection Performance at Lower Currents

Fraction of 12.9 MJ	Current (A)	Quench from *Bmax*		Quench from *Bmin*	
		Time to diode on (s)	*Thot* (K)	Time to diode on (s)	*Thot* (K)
1.0	210.1	0.068	122	0.404	128
0.9	199.3	0.087	115	0.45	122
0.8	187.9	0.106	108	0.491	116
0.7	175.8	0.139	101	0.568	109
0.6	162.7	0.196	96	0.641	101
0.5	148.6	0.396	89	0.762	93

Each of the subdivision loops contains a voltage tap whose signal can be used as added verification that a quench has occurred and, if sustained quench has occurred, to disconnect the power supply from the magnet circuit.

V. COLD DIODES AND COPPER BUSES

Diodes will be chosen from the Powerex R620 series, with which LBNL has prior experience in the MICE spectrometer magnet [12]. These diodes require clamping with forces over 4450 N and heat sinking for proper operation. The worst case I^2t is 201,000 A^2s for the case of a quench caused by a normal bus loop conducting heat back into the winding pack. The diodes are connected to the superconducting bus loops with an AWG 8 copper wire. Assuming an RRR of 50 for these copper buses, they have a safety factor of more than 10 on I^2t for a nominal 150 K temperature rise from 4.5 K.

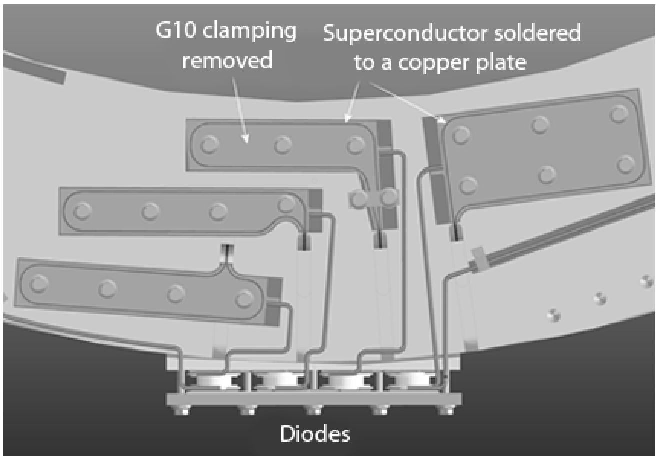

Fig. 5 Superconducting subdivision end loop penetrations are shown soldered to a copper plate on the coil housing side flange. G10 clamping is removed. Copper bus connections to cold diodes are also shown.

VI. LTS AND HTS LEAD PROTECTION

The low temperature superconductor (LTS) leads emanating from the winding pack are connected to the high temperature superconductor (HTS) leads, which are connected to the copper leads at the intermediate shield temperature. The LTS leads have been stabilized by soldering a second superconductor strand in parallel with the lead coming from the winding. Each of these pairs is clamped through a thin insulator to the aluminum structure attached to the liquid helium reservoir, as shown in Fig. 6. Both the warm and cold ends of the HTS leads are connected to their respective heat stations via low thermal resistance connections.

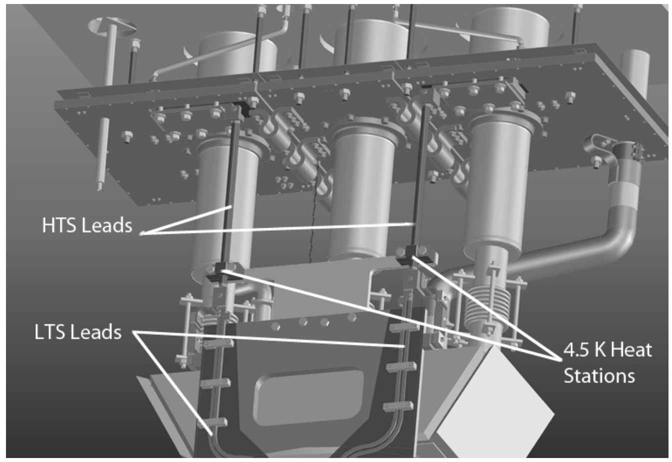

Fig. 6 shows the doubled-up LTS leads clamped through a thin insulating layer to the cold structure near the liquid He reservoir. The bottoms of the HTS leads are well stabilized and clamped to the 4.5 K structure also.

VII. CONCLUSION

Quench protection approaches for the MICE coupling coil have been analyzed for various numbers of subdivisions with shunting cold diodes using a 3d finite difference code. Dividing the coil into 4 equally radially spaced subdivisions provides a good compromise between lower hot spot temperatures with lower internal coil voltages against the higher risk of electrical shorts between the bus end loops and the coil case, particularly at the locations of their penetrations through the coil case. The bus loops are stabilized and protected by soldering them to copper plates and clamping the assembly to the coil case through a layer of electrical insulation. Copper buses connecting the diodes to the superconducting subdivision loops have a large factor of safety on their I^2t capacity requirement. LTS leads are stabilized and both the warm and cold ends of the HTS leads have low thermal resistance to their respective heat stations. The first production MICE coupling coil, including al quench protection components, will be tested in an upcoming test campaign at FNAL.

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