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Quench Analysis of an LTS Quadrupole Triplet Magnet System for the IBS RAON In-flight Fragment Separator

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***Abstract*—In this paper we present quench analysis results of a Low-Temperature Superconducting (LTS) quadrupole triplet magnet system, a part of the In-flight Fragment (IF) separator of a heavy ion linear accelerator complex, named RAON, currently being constructed by the Institute of Basic Science (IBS). This magnet system is composed of three quadrupole magnets: a triplet, surrounded by iron yokes and embedding hexapole/octupole LTS coils for field correction. The magnet will be operated at 4.2 K in liquid helium. For reliable and safe operation of this complex superconducting system, quench and protection analysis with possible failure scenarios must be performed. In this paper, we first discuss probable quench scenarios and then present results of the quench propagation analysis on: 1) coil currents and voltages by multi-coil model circuit analysis; and 2) simulated temperature distribution inside each coil. Our quench analysis results show that the maximum voltage and temperature in each coil are below safety limits, 2000 V and 150 K, respectively, and confirm that this quadruple triplet magnet system is self-protecting.**

***Index Terms*—superferric, triplet, RAON, quadrupole, quench.**

I. Introduction

Institute of Basic Science (IBS) is now building a heavy ion accelerator facility named Rare isotope Accelerator complex for ON-line experiment (RAON) for rare isotope science [1]. The RAON of IBS will use two kinds of rare isotope production system, Isotope Separation On-Line (ISOL) and In-flight Fragment (IF) separator. Total 13 Low-Temperature Superconducting (LTS) quadrupole triplet units will be used to focus and transport a beam in IF separator. A single unit of quadrupole triplet consists of three quadrupole magnets, one hexapole magnet, and one octupole magnet. The unit is to be operated in one single cryostat and each magnet is operated by the independent power supply. Thus, in total five electrically independent magnet systems will be constructed and housed in one single cryostat. Geometrically, the three quadrupoles, LQ1, LQ2, and LQ3 are aligned in a straight line with four racetrack coils for each pole. The hexapole, Lx, and the octupole, Lo, are fixed inside the pole tip of LQ1 with serpentine coil structure. An overview of the magnet configuration is shown in Fig. 1. In this paper, we present quench behaviors of quadrupole, hexapole, and octupole to confirm that the RAON IF quadrupole triplet magnet system is properly protected and that the coils are self-protecting.

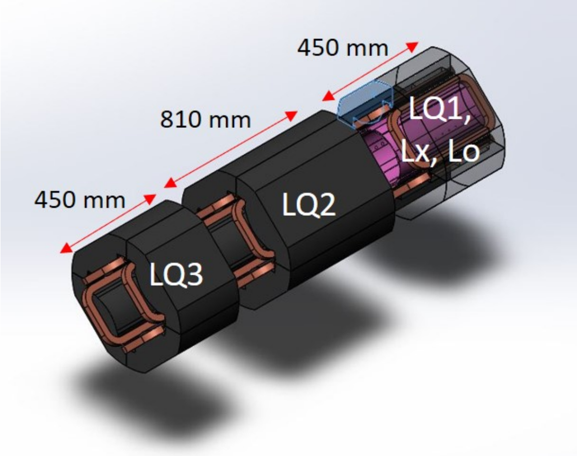

Fig. 1. Coil configuration of the quadrupole triplet magnet system. LQ1 and LQ3 are shorter, and LQ2 is longer quadrupole magnets. The hexapole (Lx) and octupole (Lo) are located inside the LQ1.

TABLE I
LTS Conductor Specifications and Properties

Physical Property	Value
Superconductor	NbTi
Bare wire diameter	1.02 mm
Insulated diameter	1.10 mm
Cu/SC ratio	4.3
RRR	120
Breakdown Voltage	2000 V
Critical current at 4.2 K, $10^{-}14\Omega\cdot$m	
at 3 T	685 A
at 4 T	570 A
at 5 T	470 A

II. The Triplet Magnet System Information

A. Conductor and Winding

The NbTi superconducting wire described in Table I is used for winding all the coils. Then each coil is impregnated with cryogenic epoxy by a vacuum impregnation method. Voids in

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TABLE II
PROPERTIES OF QUADRUPOLE MAGNET

Physical Property	LQ1, LQ3	LQ2
Effective length	550 m	900 m
Yoke length	450 m	810 m
Number of turns per each pole	1600	
Coil cross section	44 × 44 mm^2	
Operation temperature	4.2 K	
Iron pole tip radius	180 mm	
Iron yoke outer radius	420 mm	
Iron yoke material	Non-Grain-oriented Silicon Steel	
Maximum operation current	165 A	
Maximum field in the coil	3.6 T	
Transition temperature	8.6 K (at 165 A, 3.6 T)	

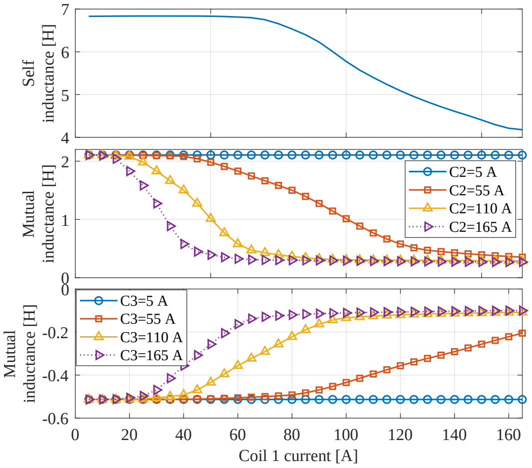

Fig. 2. Computed self-inductance and mutual inductance of LQ2 coils. The self and mutual inductance values are dependant on each coil current due to the iron core saturation. Coil 1 is the reference coil, Coil 2 (C2) is the neighboring coil, and Coil 3 (C3) is the coil across the center of the magnet.

the impregnation reduce the winding thermal conductivity that in turn adversely affects coil quench behavior. We introduce a concept of contact factor to quantify an effective winding thermal conductivity by considering unpredictable, imperfect impregnation results. The contact factor is a coefficient between 0 to 1. If the coefficient is 0, there will be no thermal contact between winding. The value of 1 means perfect contact without any void.

B. Quadrupole Magnets

Superferric type quadrupole design is used for the triplet system. The superferric type design is using a large amount of iron yoke to generate desired field [2], [3]. A single quadrupole magnet consists of four racetrack type LTS coils, one coil per one pole and a pair of back-to-back protection diodes is connected to each coil. The winding cross is rectangular. Detailed information is described in Table II. The self-inductance and mutual inductance are calculated separately with FEM simulation by using COMSOL Multiphysics. Fig. 2 shows the calculated inductance and mutual inductance values. Since the iron core becomes saturated by the operation current, the self and mutual inductance values are varied by the operation current.

TABLE III
PROPERTIES OF HEXAPOLE AND OCTUPOLE MAGNET

Physical Property	Hexapole (Lx)	Octupole (Lo)
Coil inductance	295 mH	178 mH
Conductor length	1.62 km	1.49 km
Total number of layers	4	4
Number of turns per layer	100	72
Maximum operation current	150 A	180 A

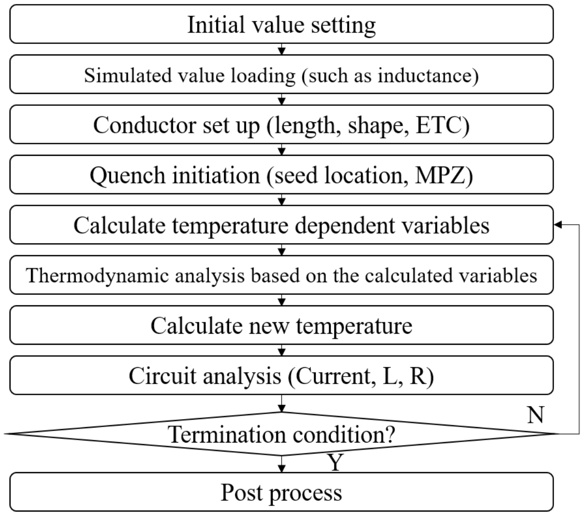

Fig. 3. Algorithm of the quench simulation program.

C. Hexapole and Octupole Magnets

The hexapole and the octupole are installed inside the LQ1 pole tip to make the system compact. The properties of the two magnets are shown in Table III. Serpentine coil winding is used because of the limited space between the pole tip and cryostat. Although the serpentine coil winding may be installed in a very compact size, however, it requires complex winding techniques [4] which may result in poor thermal contact between adjacent conductors.

III. QUENCH SIMULATION ALGORITHM

MATLAB based quench simulation code has been written to analyze the magnet quench behavior of the magnet. A flowchart of the program is shown in Fig. 3. The program aims to solve multiple differential equations that include heat transfer and electrical circuit behavior. First, the program loads initial values, pre-calculated values, the winding configuration of the magnet, and initial quench conditions such as the location of the highest field calculated by the FEM simulation. Each turn of the coil considered one segment of the calculation which has unique physical length, cross-sectional area, normal zone length, temperature, thermal connections between neighboring turns, resistivity, and thermal capacity. The program calculates quench propagation in the longitudinal and transverse directions. The quench propagates in a longitudinal direction with Normal Zone Propagation Velocity (NZPV), U_l, given by [5]:

$$U_l = \frac{J_m}{C_m}\sqrt{\frac{\rho_m k_m}{T_t - T_{op}}} \tag{1}$$

where T_{op} is the operating temperature T_t is the transition temperature, C_m is the conductor average volumetric heat capacity of the conductor over the range from T_{op} to T_t, and J_m is the current density, ρ_m and k_m are the matrix, respectively electrical resistivity and thermal conductivity. Heat transfer between two neighboring strand model is applied to calculate the quench propagation in a transverse direction. If a strand is heated over the critical temperature by joule heating from neighboring strands, the quench propagates. The governing equation is

$$A \cdot l \cdot C \cdot dT/dt = RI^2 - Q_{inter} \tag{2}$$

where A, l, and C, T, R, and I are the strand, respectively, cross-sectional area, average length, and heat capacity, average temperature, resistance of the strand, and current. Q_{inter} is heat exchange between neighbor strands. Q_{inter} is given by:

$$Q_{inter} = cf \cdot \frac{kl}{2d} \cdot [w \cdot (T - T_r + T - T_l) + h \cdot (T - T_u + T - T_b)] \tag{3}$$

where cf is a contact factor, which quantifies a degree of thermal contact between conductors, k is the insulator thermal conductivity, d is the insulator thickness, w is the strand width, h is the strand height, T_r, T_l, T_u, and T_b are the average temperature of right, left, upper, and bottom side strand respectively. The resistance, heat capacity, and thermal conductivity values are updated with calculated temperature at each simulation time.

The magnet current is calculated by:

$$\boldsymbol{V} = \boldsymbol{R} \times \boldsymbol{I} + \boldsymbol{L}\frac{d\boldsymbol{I}}{dt} \tag{4}$$

where $\boldsymbol{V}$, $\boldsymbol{R}$, $\boldsymbol{I}$, and $\boldsymbol{L}$ are all matrices represent respectively each coil voltage, resistance, current, and inductance.

IV. ASSUMPTIONS AND SIMULATION CASES

Assumptions in the analysis include the following: a quench occurs at the maximum operating current and located at the edge, where the field is highest and the temperature margin is the lowest; the whole system is adiabatic; upon quench, the power supply shuts down or the protection diode turns on immediately. The critical values of the system are breakdown voltage (2 kV) of the conductor specification and peak temperature (150 K) which has enough margin compared to the generally acceptable overstraining temperature (200 K) of a NbTi magnet [5]. LQ2, the magnet with the largest energy is analyzed for quadrupole magnet cases. The cf value is fixed to 0.9 for quadrupole quench simulation, which is experimental value based on the manufacturer specification.

We analyzed two cases of quadrupole quench scenarios. The brief concept is described in Fig. 4. The first case is the Coil 1 quench without any quench propagation to the other coils. The maximum uneven current distribution appears in this case. In the second case, the other coils are driven normal because of magnetically-coupled AC losses, or the diode turning on, which is equivalent to having quench heaters in Coils 2-4 as indicated in Fig. 4. For simulations, the quench heaters generate 1 W, activated right after the initial quench.

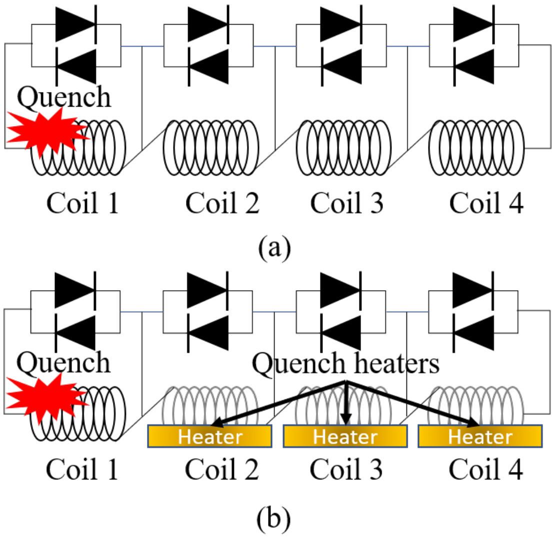

Fig. 4. Simulation cases for the LQ2 quadrupole magnet. (a) Case 1: only Coil1 quenched in LQ2. (b) Case 2: thermal interaction between coils such as magnetically-coupled AC losses modeled as built-in quench heaters.

V. SIMULATION RESULTS

A. Case 1: Single Coil Quench

When Coil 1 quenches, the magnetic coupling will charge or discharge Coils 2-4. As a result, the magnet will be subject to significantly unbalanced currents among the coils. The currents in Coils 1-4 are shown in Fig. 5. The maximum currents are 190 A for Coil 2 and Coil 4 and 153 A for Coil 3. Stress distributions under unbalanced currents are calculated with another simulation. The peak stress concentration in the yoke at the contact point with the coils is 14 MPa in the nominal operation with evenly distributed coil current. The stress is increased up to 20 MPa when the coil has unevenly distributed current regarding the simulation. However, the stress difference between the two cases is no greater than 7 MPa which has a negligible impact on the internal stress. Coil 1 voltage and temperature are shown in Fig. 6. The peak temperature (70.3 K) and voltage (266.3 V) values are not reached the critical level compared to the design limit.

B. Case 2: Multiple Coil Quench

In this case, the unbalance currents among Coils 2-4 will be decreased; however, the current decays in Coils 2-4 will energize Coil 1 to higher peak voltage and temperature. Fig. 7 shows the calculated current for each coil. Fig. 8 shows the temperature and voltage for each coil. Upon Case 2 quench, Coil 1 reaches to the highest temperature and the highest peak internal voltage because most energy is more consumed in Coil 1. The peak temperature value is 74.2 K, which is 3.9 K increased compared to Case 1, while the peak voltage

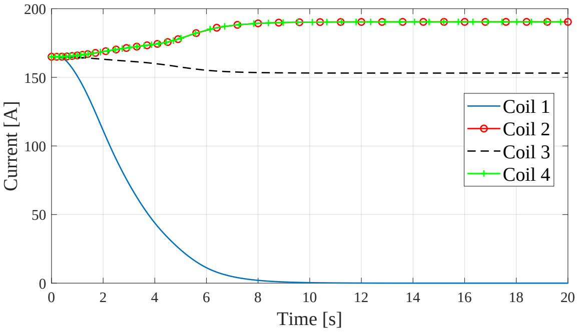

Fig. 5. Conductor current calculation result according to the time in Case 1 simulation. If there is no quench event in Coil 2-4, decreasing current of Coil 1 will charge up the Coil 2 and Coil 4.

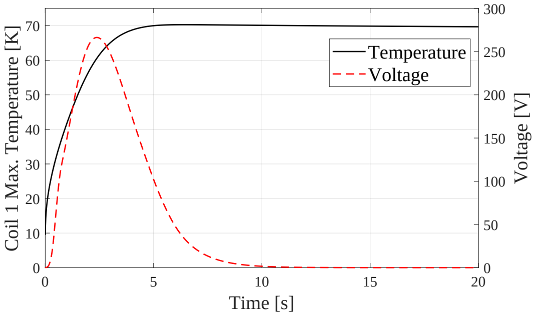

Fig. 6. Conductor maximum temperature and voltage variation in the simulation Case 1. The peak temperature is 70.3 K and the voltage is 266.3 V.

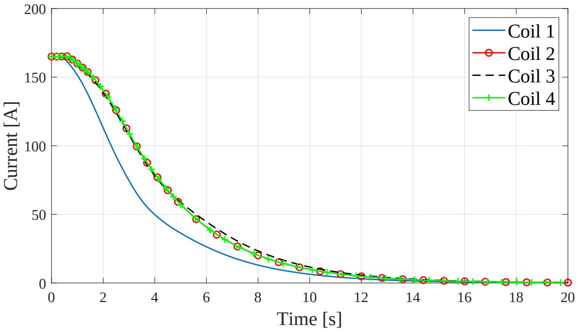

Fig. 7. Conductor current calculation result according to the time in Case 2 simulation. The quench event of Coil 1 triggers quench in Coil 2-4. As a result, every coil current almost decreased within 20 s.

is 278.7 V, which increased 12.4 V. However, these values are still much lower than the critical limits.

C. Hexapole and Octupole

Because of the complex winding process of the serpentine coil, the thermal contact between conductors in the hexapole and the octupole is not good compared with that of the quadrupole winding case. Quench behavior is simulated with different contact factors. The first assumption is only half of the contact remains after impregnation, which implies cf is 0.5. Even worse case is the half-contact epoxy has 50 % void inside, which implies 0.25 of cf value. The peak internal voltages and temperatures are shown in Table. IV. The poorer contact increases temperature and decreases peak internal voltage due to the slow quench propagation. Despite the differences, the overall values are much less than the critical limits. This is because of the stored energy in the hexapole and octupole magnet is small relative to its size.

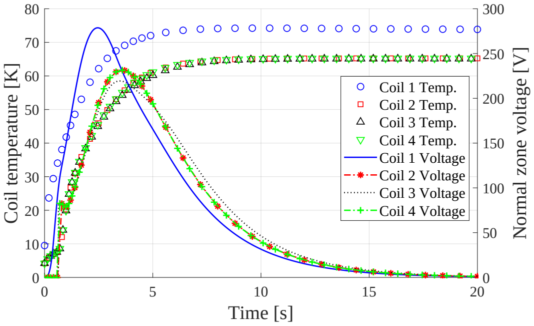

Fig. 8. Conductor temperature (Temp.) and voltage variation in the simulation Case 2. The temperature of Coil 1 is the peak conductor temperature while the other coil temperatures are average conductor temperature. The initial quench coil, Coil 1, has the highest temperature (74.2 K) and normal zone voltage (278.7 V).

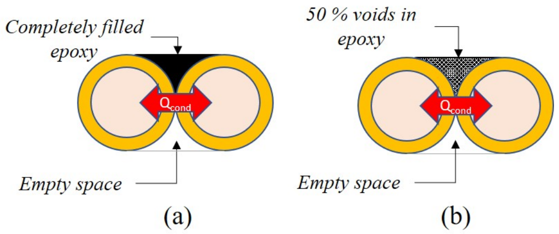

Fig. 9. The concept of poor contact in epoxy impregnation. (a) shows only half contact area (cf=0.5) with perfect epoxy impregnation, and (b) shows the half contact area has 50 % void inside in it (cf=0.25).

TABLE IV
PEAK VOLTAGES AND TEMPERATURES IN HEXAPOLE AND OCTUPOLE COIL

	Hexapole		Octupole	
Contact Factor	0.25	0.5	0.25	0.5
Peak Temperature	44.5 K	41.4 K	43.2 K	40.3 K
Peak Voltage	21.5 V	24.2 V	22.1 V	24.6 V

VI. CONCLUSION

Quench behavior of LTS quadrupole triplet magnet system for the IBS RAON IF separator is analyzed by numerical simulation. The most possible force unbalance situation was not enough to damage the quadrupole magnets. The peak temperatures and peak voltages of the quadrupole magnets in the system did not exceed the critical limits in any cases. The hexapole and octupole quench behavior may differ from the winding status. However, the temperature and voltage levels are not critical if the contact factor is higher than 0.25, which represents a very poor contact status. Based on our simulation results the magnet equipped with internal protection diodes and thus self-protected, will not be damaged in an electrical or thermal way by an accidental quench event.

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