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Quench Protection Studies of 11T 2-in-1 Nb_3Sn Dipole Models for LHC Upgrades

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Abstract
CERN and FNAL are developing 11 T Nb3Sn dipole magnets for the LHC collimation system upgrade. Due to the large stored energy, protection of these magnets during a quench is a challenging problem. This paper reports the results of experimental studies of key quench protection parameters including longitudinal and radial quench propagation in the coil, coil heating due to a quench, and energy extraction and quench-back effect. The studies were performed using a 1 m long 11 T Nb3Sn dipole coil tested in a magnetic mirror configuration.

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QUENCH PROTECTION STUDIES OF 11T Nb_3Sn DIPOLE MODELS FOR LHC UPGRADES*

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Abstract

CERN and FNAL are developing 11 T Nb_3Sn dipole magnets for the LHC collimation system upgrade. Due to the large stored energy, protection of these magnets during a quench is a challenging problem. This paper reports the results of experimental studies of key quench protection parameters including longitudinal and radial quench propagation in the coil, coil heating due to a quench, and energy extraction and quench-back effect. The studies were performed using a 1 m long 11 T Nb_3Sn dipole coil tested in a magnetic mirror configuration.

INTRODUCTION

The upgrade of the LHC beam collimation system foresees additional collimators to be installed in the dispersion suppressor areas and around the high luminosity Interaction Regions [1]. The required space for these collimators could be provided by replacing some 14.3 m long 8.33 T NbTi LHC main dipoles with shorter 11 T Nb_3Sn dipoles compatible with the LHC lattice and main systems. FNAL and CERN have been pursuing a joint R&D program with the goal of building a 5.5-m long twin-aperture 11 T Nb_3Sn dipole suitable for installation in the LHC [2, 3]. Two such dipoles with a collimator in between will generate a bending strength equal to an LHC main dipole. Due to the large stored energy (a factor of 1.5 larger than in the NbTi LHC main dipoles), quench protection of the 11 T Nb_3Sn dipoles is a challenging problem. The quench protection studies started with simulations [4, 5] and tests of short dipole models [6, 7]. This paper reports the results of quench protection studies for a 1 m long 11 T Nb_3Sn coil tested in a dipole mirror configuration MBHSM01 [8].

COIL DESIGN AND INSTRUMENTATION

The coil and dipole mirror design and parameters are reported in [8]. The two-layer coil was made of 40-strand Rutherford cable with a stainless steel core and 0.7 mm RRP-108/127 strand. The coil was installed into a magnetic mirror structure, which allows an individual coil to be investigated under conditions similar to those of an actual magnet. This structure provides the level and distribution of magnetic field and Lorentz forces close to those expected in a real dipole magnet.

The cross section of the dipole mirror structure with the coil, an iron mirror block replacing the missing coil, an iron yoke, aluminium clamps and a bolted stainless steel skin is shown in Fig. 1.

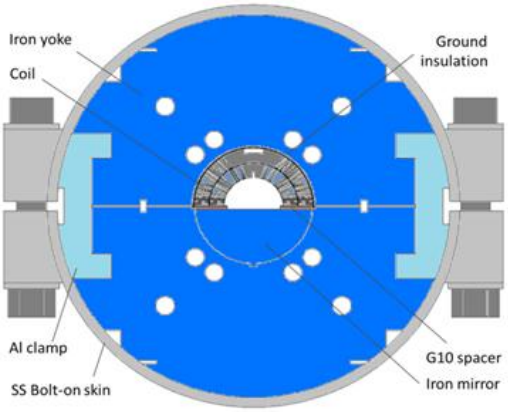

Figure 1: MBHSM01 dipole mirror cross-section.

For quench protection studies the coil was equipped with voltage taps, and protection and spot heaters. Two regular protection heaters (PH), composed of 0.025 mm thick stainless steel (SS) strips, were placed on the coil outer surface between the 1st and 2nd Kapton layers of the ground insulation [8]. The width of SS strips in the high field (HF) and low field (LF) coil blocks are 26 mm and 21.5 mm, respectively. Spot heaters (SH) made of 2 mm wide SS strip were installed on the coil inner-layer (IL) and outer-layer (OL) mid-plane turns. Each SH covers a 32 mm long by 14 mm wide area of a mid-plane turn and is surrounded by two voltage taps to measure voltage growth after a quench. Additional voltage taps were installed 10 cm from the SH to measure longitudinal quench propagation velocity. The SH position and surrounding voltage taps are shown in Fig. 2.

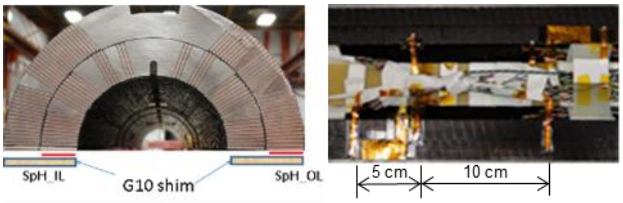

Figure 2: Spot heaters and voltage taps in coil mid-plane.

TEST RESULTS

The dipole mirror MBHSM01 was tested at FNAL Vertical Magnet Test Facility. The results of quench performance studies are reported in [8]. One of the main goals of these measurements was to complement quench protection studies in previous 11 T dipole models, including longitudinal quench propagation velocity, quench temperature, radial quench propagation from outer to inner coil layer, quench integral for different dump resistors, and quench-back effect.

Quench protection studies in MBHSM01 were

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performed mostly at 4.5 K at currents up to 12000 A. The minimum PH peak power density P_{PH} required to quench the magnet was measured at different currents. A 50-55 W/cm^2 PH peak power density is necessary to quench the magnet at the LHC injection current of 760 A. Therefore, the same average P_{PH}=50 W/cm^2 peak power density was used in the following heater tests. Unfortunately, the IL spot heater wiring was damaged during magnet assembly and only the OL spot heater was available for testing.

Longitudinal Quench Propagation Velocity

The OL spot heater induced quenches were used to measure the longitudinal quench propagation velocity. A peak power density of ~26 W/cm^2 was deposited in SH at different currents. A typical voltage growth with time in the cable segment next to the SH (SHB2-B3) at 5 kA is shown in Fig. 3. The voltage growth at $t_1<t<t_2$ corresponds to the quench propagation along this segment, while the following voltage increase at $t>t_2$ is due to increase of the cable temperature.

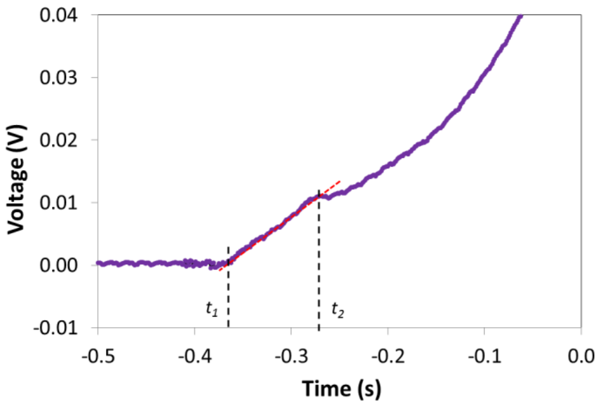

Figure 3: Voltage vs. time in cable segment SHB2-B3.

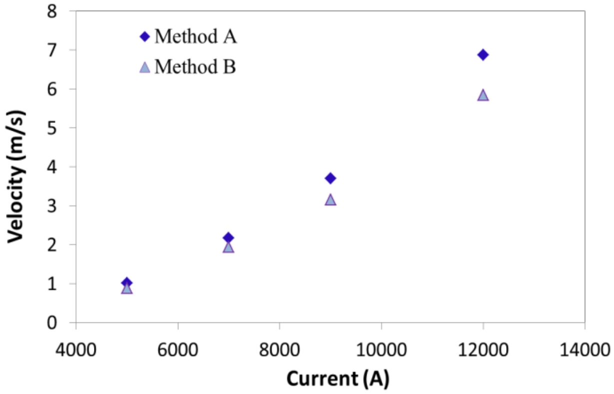

Figure 4: Longitudinal quench velocity in OL mid-plane.

The longitudinal quench propagation velocity v was determined using two different methods. In method A it was estimated using the following equation:

$$v = \frac{dV}{dt}\frac{S_{Cu}}{\rho_{Cu}(B)\cdot I},$$

where dV/dt is the slope of $V(t)$ dependence in (t_1-t_2) time interval, S_{Cu} and ρ_{Cu} are the cross-section area and the resistivity of copper matrix, B and I the average field and the current in the cable segment.

In method B the quench propagation velocity was defined as the ratio of the cable segment length L=100 mm to the measured propagation time (t_2 - t_1). The results from both methods are shown in Fig. 4.

Quench Temperature Measurements

The cable temperature growth in the coil due to a quench was also measured using spot heater induced quenches. To observe the time development of the coil resistive voltage $V(t)$, the energy extraction system was delayed for 70-250 ms at different currents. The coil temperature $T(t)$ vs. time t at fixed coil currents I is shown in Fig. 5. The coil temperature was determined from the following equation:

$$V(t) = \frac{I\cdot\rho_{Cu}\big(B,T(t)\big)\cdot L}{S_{Cu}},$$

assuming $T(0)=T_{cs}(I,B)$, where T_{cs} is the current sharing temperature.

The resistivity of the copper matrix as a function of temperature and magnetic field was approximated with an analytical formula using the measured value of coil RRR. The dashed lines in Fig. 5 connect the temperature points corresponding to the same quench integral values (QI), calculated as $\int I^2(t)dt$. Comparison of the measured cable temperatures with the adiabatic analysis in [5] confirms strong cable cooling effect in the coil.

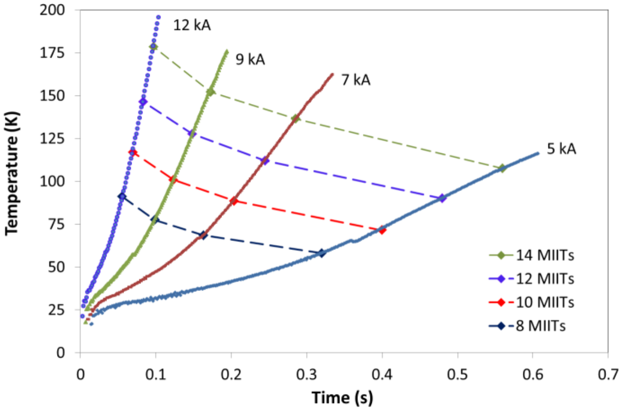

Figure 5: Quench temperature vs. time.

Radial Quench Propagation

Simulations [4] and MBHSP01-02 heater studies [5-7] demonstrated that a quench propagates quite rapidly in the radial direction from outer-layer to inner-layer coil blocks. The radial quench propagation studies in MBHSM01 were expanded to currents up to 12 kA, corresponding to 92% of SSL at 4.5 K.

To observe the radial quench propagation from the coil outer to the inner layer, the extraction dump was delayed by 1 s. The quench propagation time from OL to IL was determined as the time difference between quench initiation in the OL and IL of the coil. Fig. 6 shows this time difference vs. the magnet current at P_{PH}=50 W/cm^2.

The corresponding results for similar heaters in MBHSP01-02 dipoles are also shown, demonstrating excellent heater performance reproducibility. The short quench delay time observed at high currents improves the dissipation of stored energy in magnet coil.

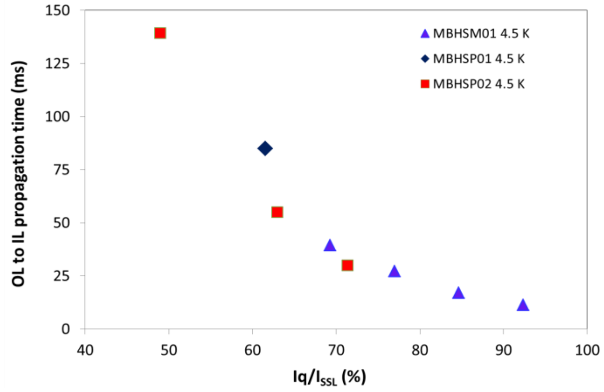

Figure 6: OL to IL radial quench propagation time.

Quench Integral Study

The goal of this study was to measure QI as a function of current for the OL PH induced quenches and for different external dump configurations. QI was measured with the dump delayed for 1 s, which is equivalent to the operation without the extraction dump (*Rd*=0 or "no dump"), or with *Rd* of 2.5, 5 and 10 mΩ without any delay. The QI was determined by integrating $I^2(t)$ over the time from 0 to 1 s. To keep the cable temperature during a quench below 400 K, the QI has to be less than 19 and 21 MIITs (10^6 A^2·s) in the HF and LF areas respectively.

QI as a function of magnet current normalized to the short sample limit is shown in Fig. 7. At 12 kA in the case of "no dump" QI reaches ~15 MIITs which corresponds to a maximum temperature of the coil outer-layer under the protection heaters of less than 250 K (adiabatic calculations [4, 5]). Therefore the estimated QI budget is ~4 MIITS in HF and ~6 MIITs in LF areas, which correspond to the quench detection time budget of 28 ms and 42 ms respectively.

Test results for different dump configurations in Fig. 7 demonstrate that even the small dump resistors help to reduce the accumulated QI.

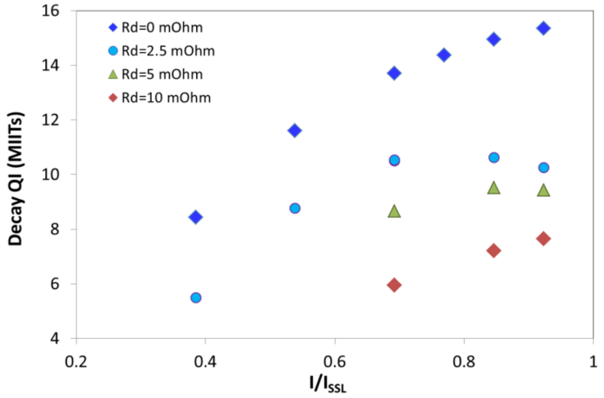

Figure 7: Quench Integral for different dump resistors.

Quench-back Effect

Coupling current losses in the conductor at very high ramp rates, which occur during the fast energy extraction, may introduce the so called "quench-back" effect in the magnet. The fast energy extraction tests in MBHSM01 were performed at different currents and without the protection heaters. No resistance increase was observed in the coil at currents up to 12 kA, which is consistent with the cored cable and small filament size in strands.

CONCLUSION

A new 1 m long 11 T Nb_3Sn dipole coil, was fabricated and tested in a dipole mirror structure MBHSM01 at FNAL. Due to the improved quench performance, quench protection studies in MBHSM01 were expanded to currents up to 92% of SSL and performed with different external dump resistors.

A minimum PH peak power density of ~50-55 W/cm^2 is required to quench magnet at the LHC injection current and above. The longitudinal quench propagation velocity was first time measured in the OL mid-plane turn at different currents. The radial quench propagation from OL to IL coil blocks was also measured showing good reproducibility with previous data. Direct measurements of the coil temperature during a quench were performed at different quench currents. Results of this study demonstrated strong cooling effect in the coil.

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