Use of High Resolution DAQ System to Aid Diagnosis of HD2b, a High Performance Nb_3Sn Dipole

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***Abstract*— A novel voltage monitoring system to record voltage transients in superconducting magnets is being developed at LBNL[1]. This system has 160 monitoring channels capable of measuring differential voltages of up to 1.5kV with 100kHz bandwidth and 500kS/s digitizing rate. This paper presents analysis results from data taken with a 16 channel prototype system. From that analysis we were able to diagnose a change in the current-temperature margin of the superconducting cable by analyzing Flux-Jump data collected after a magnet energy extraction failure during testing of a high field Nb_3Sn dipole.**

***Index Terms*— HD2, superconducting magnets, Nb_3Sn**

I. Introduction

Several improvements to magnet test and diagnostics have been made over the past year by the Superconducting Magnet program at Lawrence Berkeley National Laboratory (LBNL). The new and under development systems include: magnet voltage monitoring, magnetic measurements, magnet fault trigger, strain gauge measurements, power supply control, etc. The end purpose of all these upgrades is to better understand the magnets being developed, and in this way provide better feedback to the design and manufacturing process. This paper focus on the use of a novel magnet data acquisition system to obtain an insight on a change in performance after an energy extraction failure during the training of a high field dipole magnet called HD2b. After that, this paper will discuss on the steps being taken on studying the possibility of expanding our data acquisition system by developing a multichannel Flux-Jump antenna with high spatial resolution.

II. HD2b Test Incident

HD2a, HD2b and HD2c are part of an ongoing series of high field Nb_3Sn race track dipoles being design, assemble and tested at LBNL [2][3]. During testing of HD2b on March 30 2008, after performing 13 successful training quenches, an SCR in the energy extraction rack broke during extraction of the magnet at the end of quench 13 (Q13). After this failure, a change in the magnet performance was observed in subsequent training ramps.

Figure 1 shows the training curve for HD2b. The solid dots correspond to training quenches and the empty circles correspond to quenches due to excessive ramp rate.

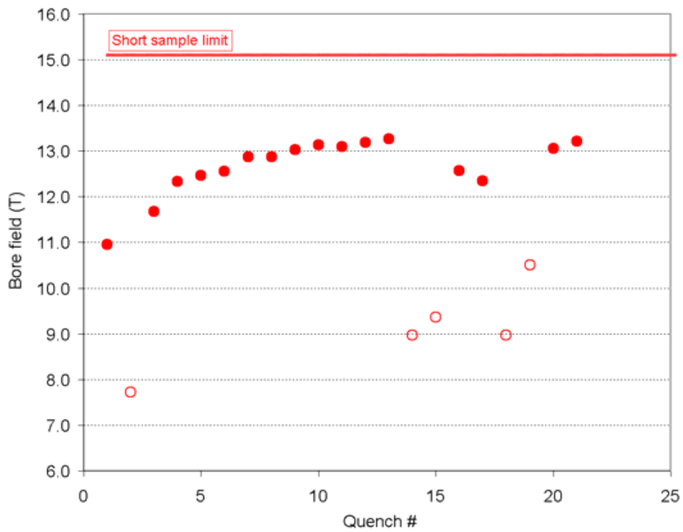

Fig. 1. HD2b training curve. Solid-dots correspond to training quenches, empty circles are quenches due to excessive ramp rate.

Q13 occurred at 15.127kA, after that, the quenching current went down to 9.928kA for Q14 and 10.393kA for Q15. The power supply ramping rate was then changed from 50A/s up to 11kA and 20A/s to quenching, to a ramping rate of 50A/s up to 5kA, then 20A/s up to 11kA and 10A/s up to quenching. Small variations of this current ramping profile were used in subsequent ramps, reaching the same level of performance than Q13 at Q21 with a quenching current of 15.059kA.

When a magnet quenches from superconducting state the extraction rack must shut down the current fast enough to avoid excess heat, but slow enough to keep the magnet from arching. Figure 2 shows the derivative of the voltage in each of the two coils in HD2b during a normal magnet extraction. Time 0 corresponds to the trigger point; at time equal -1ms the magnet started quenching; at time +5ms the protection heaters were fired; and at time +34ms the extraction system was triggered. A normal extraction time is around 6ms and afterwards the value of dV/dt becomes negative for both coils, indicating that the current in the magnet is decaying.

Figure 3 corresponds to the derivative of the voltage in each

Manuscript received August 19, 2008. This work was supported by the Director, Office of Energy Research, Office of High Energy and Nuclear Physics, High Energy Physics Division, U. S. Department of Energy, under Contract No. DE-AC02-05CH11231.

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coil during energy extraction at the end of Q13. It shows that the magnet extraction time was reduced to less than 1ms, and the value of dV/dt in coil1 remained positive and practically unchanged, suggesting persistence of the magnet current. Afterwards, the SCR in the extraction rack that failed and caused this abnormal behavior was replaced and operations resumed the next day.

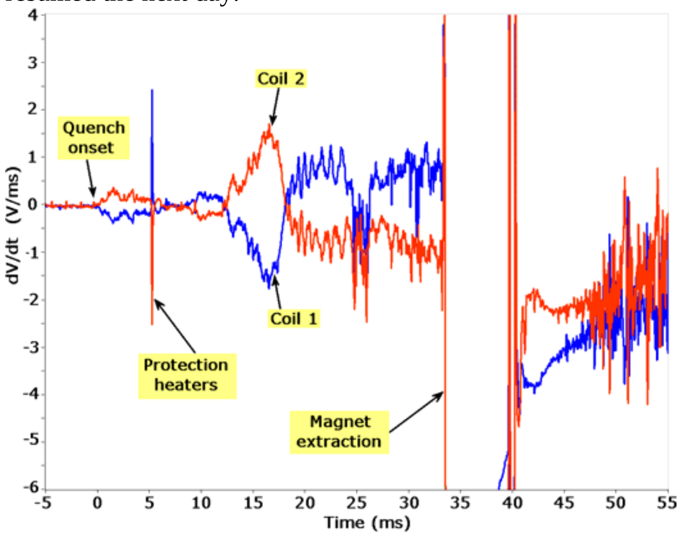

Fig. 2. Coil voltages during a normal magnet extraction. A negative dV/dt after extraction indicates decay in magnet current.

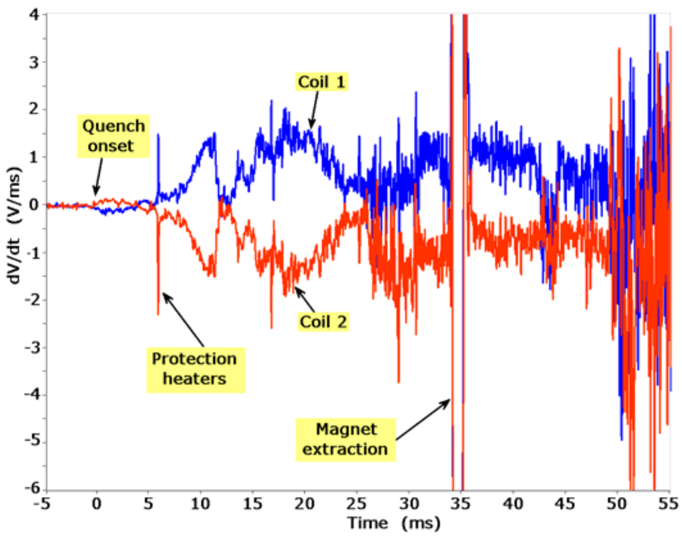

Fig. 3. Coil voltages during HD2b magnet extraction at the end of quench 13. There is no indication of current decay after extraction.

III. HD2b Energy Extraction Failure Diagnostic Approach

After the change in performance shown in figure 1, a basic question arose on whether or not the energy extraction system failure at the end of Q13 had any effect on the Jc distribution in the magnet. With the purpose of answering this question, data from a prototype high resolution Magnet Voltage Monitoring System (MVMS) [1] developed by the Superconducting Magnet Program at LBNL was used.

MVMS on its current developmental stage consists of 16 channels capable of measuring differential voltages of up to 1500V with a common mode of 1500V. Each channel has a bandwidth of 100kHz and is being used to collect data at a sampling rate of 400kS/s during a window of 100ms around a trigger point. This system was used to monitor the voltage along 8 sectors on each coil of HD2b, and it allowed us to record with unprecedented resolution the fast voltage transients that occur during the ramping of the magnet current. Two kinds of events were collected, Flux-Jumps (FJ) and Slip-Sticks (SS), named after their hypothesized process of origin.

Figure 4 shows a typical FJ collected during HD2b training. FJs are caused by loss of diamagnetism in a volume of superconductor, producing a change in B field and inducing a voltage signal across the terminals of the magnet [4][5][6].

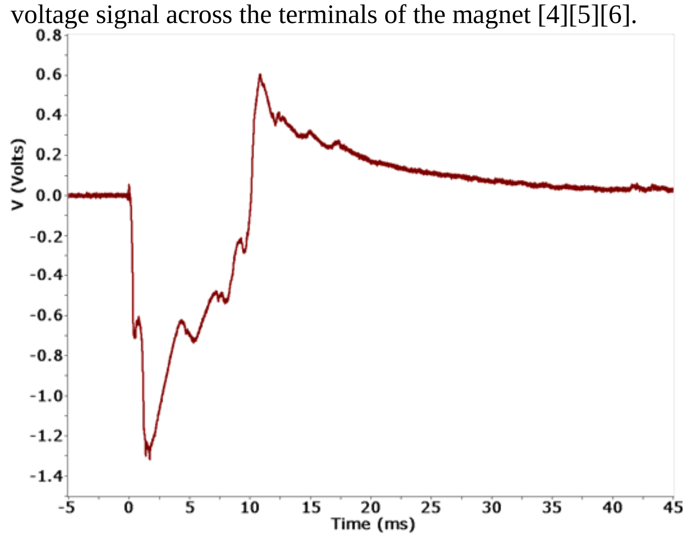

Fig. 4. Voltage unbalance induced between the two coils in HD2b by a typical Flux-Jump.

Figure 5 shows a signal from a typical SS collected during HD2b training, SS are mechanical vibrations caused when dynamic competing internal forces cause sections of the magnet to detach and release energy in the form of dumped oscillations [4].

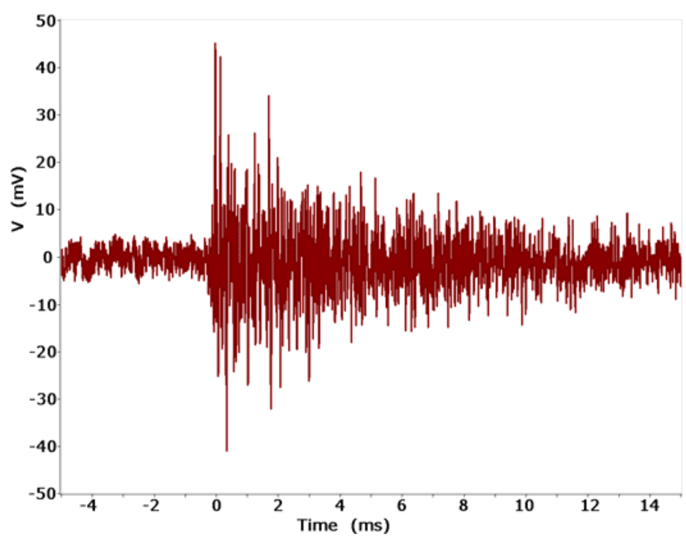

Fig. 5. Voltage unbalance induced between the two coils in HD2b by a typical Slip-Stick.

FJs are seen as an undesired effect due to the substantial amount of energy they release and its potential to quench the cable from superconducting state. However, they can also be seen as a way to diagnose changes in Jc distribution. In particular, the flux change induced by a FJ is an indication of the current-temperature margin of the volume of superconductor where the FJ took place.

To use FJs as a diagnostic tool, the distribution of integrated flux unbalance per FJ for two training ramps before and two after Q13 were compared. For that purpose a software analysis tool was developed, which allowed us to process hundreds of events in a semi-automatic way. This program runs over all events collected during a training ramp and decides whether an event is a FJ or a SS by using a Fourier filter and then setting a threshold of acceptance on the output. The program then identifies the beginning and end of the event within the 100ms window collected by the MVMS, and places a cursor at each boundary. At this point the user is given the option of rejecting the event, accepting the recognition done by the software, or changing the type of event and setting new event boundaries before going into further processing.

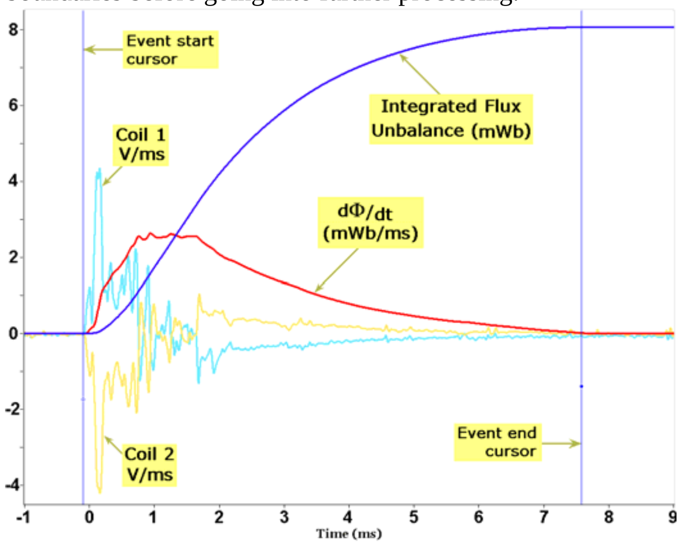

Fig. 6. Flux-Jump signal after processing by the analysis software.

Figure 6 shows a typical event after processing. The traces labeled as "Coil1" and "Coil2" represent the derivative of the voltage in coils 1 and 2 during this particular event in units of V/ms. The trace labeled as "dΦ/dt" represents the voltage induced in coil 1 minus the voltage induced in coil 2 in Volts, which corresponds to the time derivative of the integrated flux unbalance. The integrated flux unbalance is the integrated flux crossing coil 1 minus the integrated flux crossing coil 2. A coil integrated flux refers to the sum over all its turns of the flux crossing each turn in the coil, which is only a fraction of the actual flux change produced by the FJ.

The trace labeled as "Integrated Flux Unbalance" in fig 6 is the time integral of dΦ/dt in miliWebers. Multiple shapes of this parameter had been collected, reflecting the complex way flux lines go between coils and affect the instantaneous Jc margin through the cable, potentially triggering similar events in other parts of the magnet. The value of the integrated flux unbalance at the end of the event is the net integrated flux unbalance left by the event. In this manner this parameter refers to integration over area and time of the difference in flux enclosed by the coils. The cursors shown in fig 6 correspond to the start and end boundaries set for this event.

IV. HD2b Flux-Jump Observations

All events collected during training ramps Q11, Q12, Q14 and Q15 up to 9.7kA were analyzed using the analysis tool described above. Q11 and Q12 were collected before the energy extraction failure at the end of Q13, while Q14 and Q15 were collected after the failure. These ramps were chosen because they share the same ramp rate and trigger threshold. Fig 7 shows two histograms corresponding to the distribution of net integrated flux unbalance per FJ for the two ramps before and for the two ramps after Q13.

Each point making up these histograms corresponds to the net integrated flux unbalance for a particular event. A positive *(negative)* value means that the event mostly or entirely occurred in coil 1 *(coil 2)*. Thus, the histogram made up of events before Q13 suggests a symmetrical FJ activity between the two coils, while the histogram with events after Q13 suggests a FJ activity bias towards coil 1. The event count for each coil before and after Q13 is summarized in table 1.

TABLE I. FJ Event Count for Coils 1 and 2 before and after Q13

	Coil 1	Coil 2
Num Events Before	**31**	**29**
Num Events After	**47**	**16**

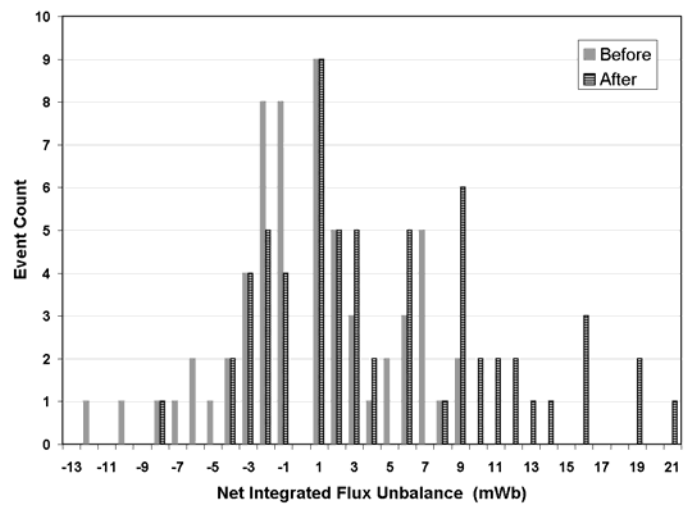

Fig. 7. Net integrated flux unbalance histogram before and after failure.

Figure 8 shows the net integrated flux unbalance before and after Q13 as a function of event count using only data from coil 1. This plot shows a significant increase on the size of FJs after the extraction failure.

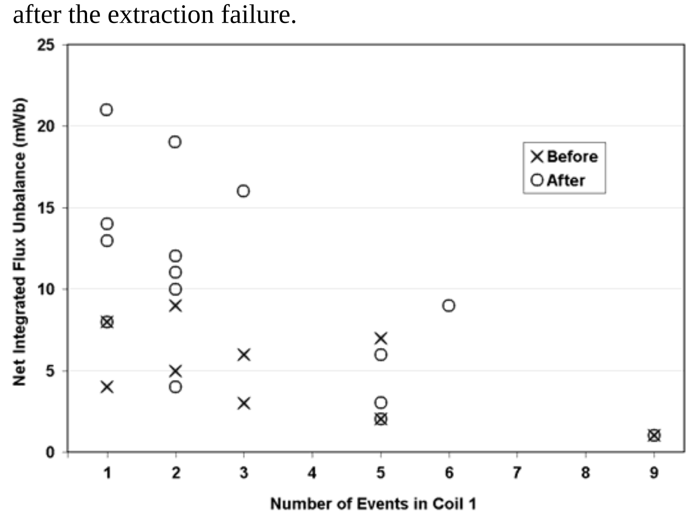

Fig. 8. Net integrated flux unbalance for events in coil 1 before (exes) and after (circles) energy extraction failure at the end of Q13.

Due to the correlation between the cable's current-temperature margin and the magnet's FJ activity, the change in FJ patterns observed before and after Q13 suggests that the energy extraction failure that occurred at the end of Q13 indeed caused a change in the current-temperature margin of HD2b.

V. Flux-Jump Antena Prototyping

Given the potential that FJ studies have on aiding magnet diagnostics, the Superconducting Magnet Program at LBNL is studying the possibility of implementing a multi-loop multi-channel FJ antenna to spatially locate FJs inside a magnet and measure their properties more precisely. For this purpose, the ability to detect a FJ using a 1-loop antenna was tested during the training of HD2b.

Figure 9 shows a schematic for the two 1-loop antennas placed on the surface of the inner face of coil 1. Voltage taps 4, 5, 6 and 7 on the inner layer monitor the voltage on the two straight sectors against the pole, however, voltage taps 4 and 7 were routed to the DAQ system through the top of the magnet, while voltage taps 6 and 5 were routed through the bottom of the magnet as depicted by figure 9.

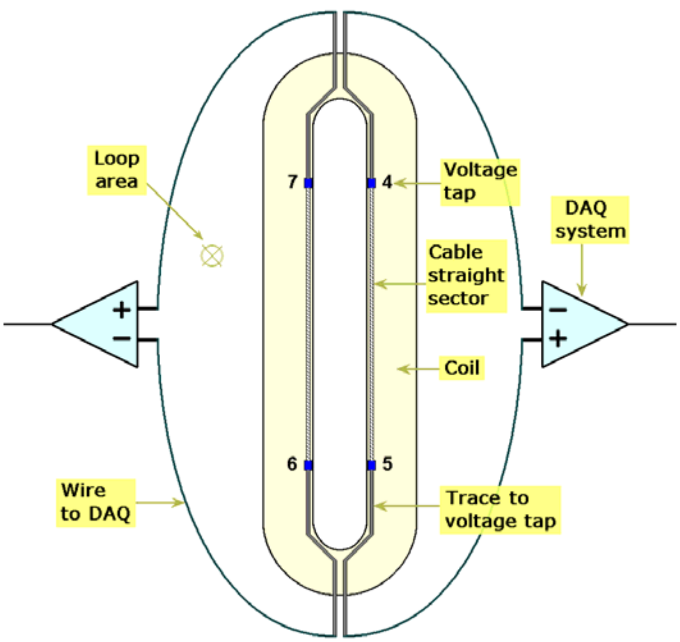

Fig. 9. Schematic for the two 1-loop antennas placed on the inner layer of coil 1 monitoring opposite sides of the coil.

If the straight sectors are not quenching, the resistive component of the voltage at the loop terminals is zero and only the voltage induced by the flux enclosed by the loop will be collected by the data acquisition system.

To further look into the effect of the energy extraction failure after Q13, the 1-loop antennas were used to locate the side of coil 1 that the 6 FJs with the highest net integrated flux unbalance collected on Q14 and Q15 were originated. These events correspond to the events making the three circular data points above 15mWb shown in figure 8. Figure 10 shows the raw signals collected from these two loops for event 142 in Q15 and the calculated integrated flux unbalance. This event corresponds to the event making the highest circular data point with net integrated flux unbalance of 21mWb.

The 1-loop antennas indicate that 5 out of the top 6 events were located in the half portion of the coil covered by sector 4-5. Understanding how this correlates to the location of quench 13 is under way. This is an important result in that it suggests that the excess FJs are grouping around one side of coil 1. This result also tells us that a 1-loop antenna can pick up the signal induced by a FJ and provide information about its location within the magnet.

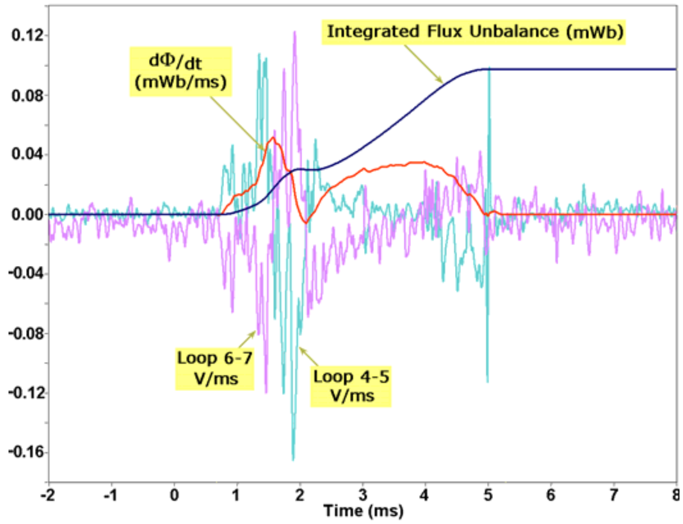

Fig. 10. Signals from two 1-loop antennas placed on each side of coil1, software reconstructed dΦ/dt and integrated flux unbalance.

VI. Conclusions

- A comparison of FJs count before and after the magnet energy extraction failure shows an increase in the magnet's FJ activity.
- A comparison of the magnitude of FJs originated in coil1 before and after the energy extraction failure shows that the net integrated flux unbalance per FJ increased.
- A change in FJ behavior suggests a change in the current-temperature margin distribution of the cable.
- Data from the 1-loop antennas placed on coil 1 suggests that the excess FJs tend to cluster in one side of the coil.
- The 1-loop antenna placed in coil 1 proved the feasibility of a FJ antenna with multiple loops and higher spatial resolution. This approach will be further studied during the following year.

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