Measurement of Fast Voltage Transients in High-Performance Nb_3Sn Magnets

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Abstract— **The Superconducting Magnet group at Lawrence Berkeley National Laboratory has been developing Nb_3Sn high-field accelerator magnet technology for the last fifteen years. In order to support the magnet R&D effort, we are developing a diagnostic system that can help identify the causes of performance limiting quenches by recording small flux-changes within the magnet prior to quench-onset. These analysis techniques were applied to the test results from recent Nb_3Sn magnets. This paper will examine various types of events and their distinguishing characteristics. The present measurement techniques are discussed along with the design of a new data acquisition system that will substantially improve the quality of the recorded signals.**

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

I. Introduction

A novel Magnet Voltage Monitoring System (MVMS) is being developed at LBNL with the purpose of probing the voltage along multiple sectors of a coil cable during magnet testing. It has been observed that small transient imbalances occur inside high-performance Nb_3Sn magnets during training [1,2]. These imbalances have different amplitudes and time profiles depending on the process that originated them.

For the most part the effect of a transient imbalance fades out and its induced voltage spike decays. However, as the current through the magnet increases, the effect of these transient imbalances becomes more relevant, especially when the magnet is approaching its short sample current and the superconducting margin is low.

The purpose of the new MVMS is to record the voltage spikes generated by magnet imbalances and the magnet quenching. This system will allow Supercon (Lawrence Berkeley Superconducting Magnet Group) to understand the origins of quenches and diagnose what is taking place inside a magnet. This diagnostic process is crucial to provide feedback for the manufacturing process.

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II. Characterization Of Fast Voltage Transients

Two kinds of fast transient events have been identified in Nb_3Sn magnets [2,3,4] and named after the suspected mechanism that originates them. The first kind is called Flux-Jump and it is usually the first kind of event observed during current ramping. It is believed that Flux-Jumps are a transient local collapse of diamagnetism in a superconductor, which generates an electric signal due to change in magnetic flux.

The second kind of fast voltage transient that has been observed is called Slip-Stick. It is believed that portions of a magnet can rearrange due to changes in magnet parameters like Lorentz force or temperature. When such rearrangements occur, a new equilibrium point is achieved with frictional forces holding the magnet at a more stable point. At the moment that a slippage occurs, energy is released and parts of the magnet experience a dumped vibration.

A. *Flux-Jumps*

Figures 1 through 3 show a sequence of Flux-Jumps captured during training of the SD01b dipole. The two traces at the top of figure 1 correspond to the voltage induced in each coil of the dipole. The signal amplitude is proportional to the change of flux through (enclosed by) the coil.

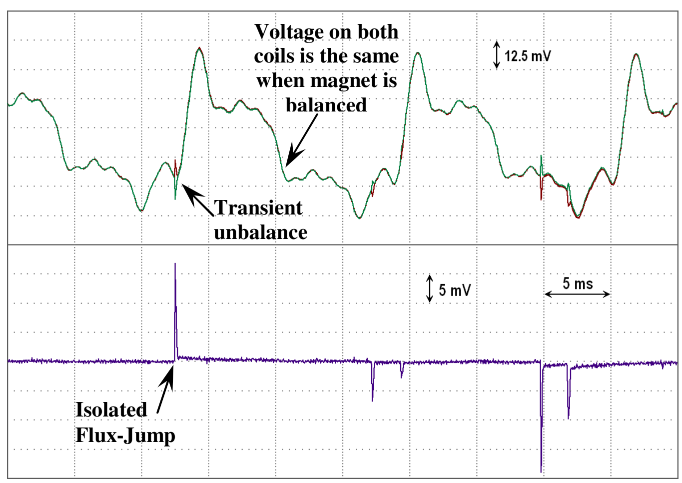

Fig 1. The two traces at the top correspond to the raw voltage across each of the two coils in a dipole magnet (SD01b) for a Flux-Jump event. The signal at the bottom is obtained after subtraction of power supply noise (differential voltage between coils), uncovering 5 single Flux-Jumps.

The plot at the bottom of figure 1 corresponds to the pure Flux-Jump event after common mode subtraction, showing 5 isolated Flux-Jumps at low field. These single Flux-Jumps are caused by the loss of diamagnetism at one single location, which did not trigger such same effect in its neighborhood.

As the magnetic field increases, the shape of Flux-Jump events becomes more complex, as shown in figure 2.

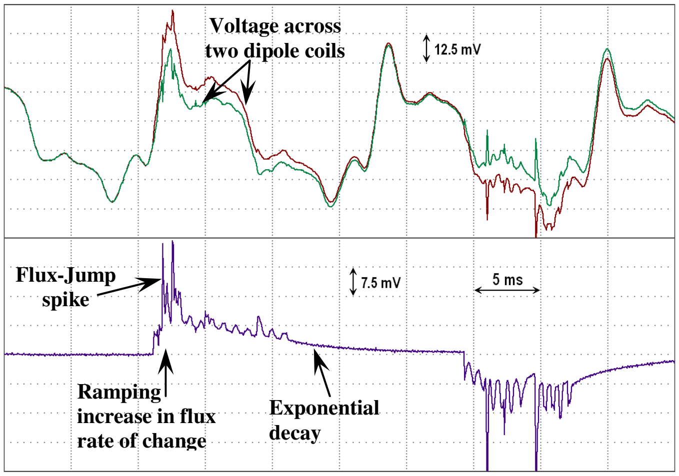

Fig 2. Double Flux-Jump event at high field. As the current in the magnet is increased, the shape of Flux-Jump events becomes more complex. Top traces are the coil's raw voltage, bottom trace is their subtraction.

Three main characteristics can be seen in the high-field Flux-Jump events: 1) A series of spikes corresponding to a train of individual Flux-Jumps; Due to their proximity in time, it is reasonable to assume that they are correlated. 2) An integrated effect showing the net magnetic flux continuously increasing at a faster rate. This could be associated to the heat released by the Flux-Jump transferring into neighboring regions reducing their superconducting margin and creating further collapse of diamagnetism. 3) An exponential decay on the magnetic flux increase rate, with a decay time of a few ms.

Figure 3 shows the Flux-Jump distribution during the first 10 training ramps in SD01b as a function of magnet current. Although the magnet current was varied from 0 to ~1800A for all ramps, most Flux-Jumps occur at around one specific value of current (~1300A) or strength of magnetic field. The width of the distribution is only ~15 seconds, ramping at 14A/sec.

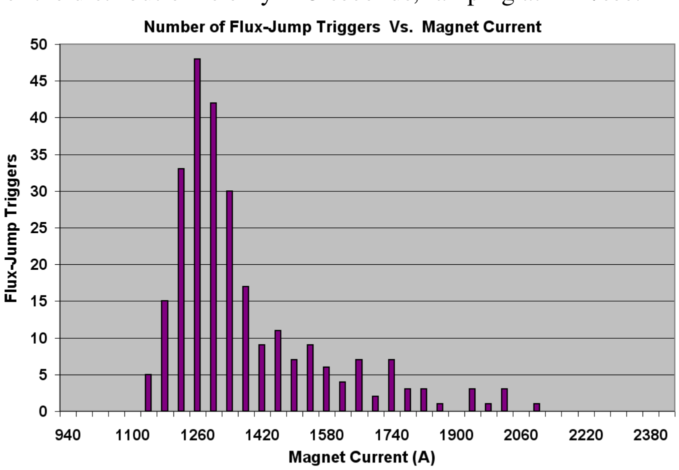

Fig 3. Flux-Jump triggers distribution as a function of magnet current for SD01b superconducting magnet. Flux-Jump event rate peaks at 1300A, with 70% of the Flux-Jumps happening within 15 seconds, between 1200A and 1400A.

Since the concept of transient magnet imbalances was first introduced in FY2000 [5] a great deal of interest aroused in trying to connect this phenomenon with a theoretical model. For this purpose accurate measurements have to be made, which is one of the goals that we hope to achieve with the new MVMS being setup at LBNL.

B. Slip-Sticks

Figure 4 shows a typical signal generated by a Slip-Stick in SD01b during magnet training. A characteristic common to all Slip-Sticks studied is the sudden start of an oscillation with frequency components in the order of several tens of kHz, and a damping factor with a time constant ~1.5 to 2ms.

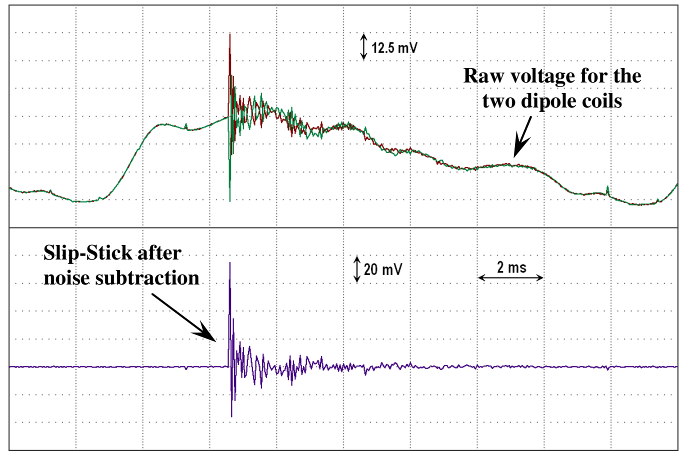

Fig 4. The two traces at the top correspond to the raw voltage across each of the two coils in a dipole magnet (SD01b) for a Slip-Stick event. The signal at the bottom is obtained after subtraction of power supply noise (differential voltage between coils), showing a ringing associated with flux change due to mechanical vibration.

Slip-Sticks start to occur at a higher field than Flux-Jumps when the Lorentz force on the coils is much higher, and becomes comparable to the force exerted on the coils by the magnet's mechanical structure [6].

While the total number of Flux-Jumps as a function of ramp number stays fairly constant, the number of Slip-Sticks rapidly decreases with ramp number. For the dipole discussed above (SD01b) there were 26 slips during the first training ramp, 7 in the second ramp, 1 in ramp 3, 6 in ramp 4, and only 1 or 2 slips in each of the subsequent 17 ramps. This data is telling us that most of the magnet's internal re-arrangement happens during the first few training ramps.

Figure 5 shows a Fourier transform for a Slip-Stick event in a large-bore quadrupole called SQ01. This distribution shows a small set of resonant frequencies that could be related to the magnet's normal modes of mechanical vibration.

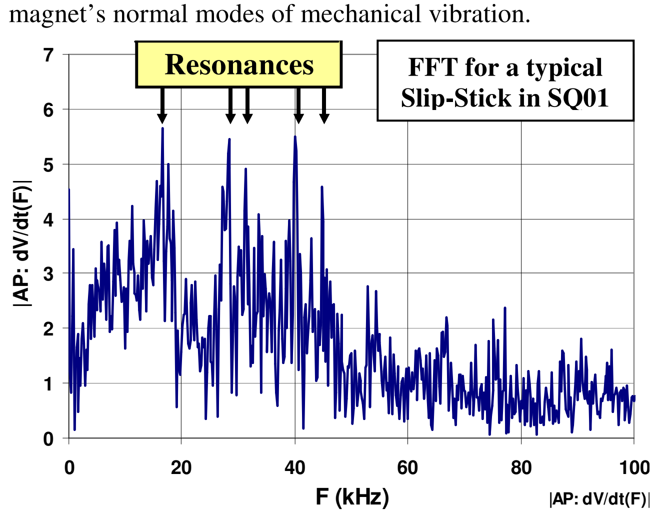

Fig 5. Fast Fourier Transform for a Slip-Stick collected during testing of a large-bore quadrupole magnet (SQ01) showing a collection of dominant frequencies [7].

The new MVMS will allow us to make more precise measurements and find correlations, if any, between Slip-Stick parameters like frequency components and decay time, to magnet parameters that determine its normal modes of vibration like stress, material Young modulus, mechanical structure, etc.

III. MVMS Functionality

Supercon's new MVMS is a custom made system to address our unique magnet testing needs. The following is a list of functionalities that the new MVMS will provide.

- Voltage monitoring of up to 136 magnet sectors including whole, half and quarter magnet. The system architecture provides easy scalability to much higher channel count.
- 1500VDC can be applied between channels or channel-to-ground, in a safe and reliable manner.
- 120 kHz analog front end bandwidth.
- 500 kS/s sampling rate.
- 16-bit digitizing resolution.
- Three modes of Vtap (probing voltage tap) connectivity: 1) Consecutive channels monitor consecutive magnet sectors. 2) Re-routing of sector reference to bypass open Vtaps. 3) Debugging and calibration.
- User can select between derivative or linear amplification.
- Variable gain over two and a half orders of magnitude.
- Automatic creation of a test setup record. A log entry is made every time a change in the system setup is made.
- Independent acquisition of Quenches and voltage spikes.
- DC voltage measurement capability. This feature allows the user to check magnet connections and find open Vtaps before and after cool-down. This is an important feature to create confidence on the magnet test.
- BNC outputs for oscilloscope monitoring and debugging.

IV. MVMS Architecture

Figure 6 shows the front view of a 3D model for the new MVMS for Supercon's magnet test facility.

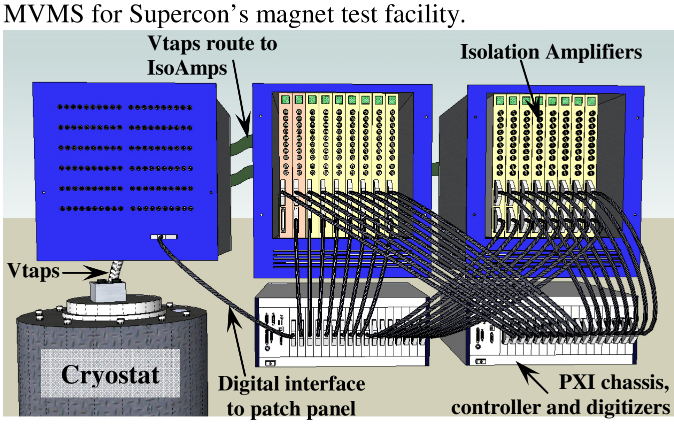

Fig 6. 3D model for Supercon's new MVMS. An electronic patch panel connects to a cryostat and routes the out-coming signals to two chassis housing a set of isolation amplifiers (IsoAmps). The signals from the isolation amplifiers are digitized by a bank of commercial digitizers.

On the upper left corner we have an electronic patch panel that routes signals into two chassis housing high-voltage isolation amplifiers (top center and top right).

At the bottom center and bottom right there are two National Instruments PXI chassis housing a PC controller and a set of general purpose digitizer modules.

The upper section of the cryostat cooling the magnet is shown in the lower left corner of this same figure.

A. Electronic Patch Panel

This component receives all Vtaps coming from the magnet and uses a set of electromechanical relays to route them into a bank of amplifiers according to a user defined setup file.

Figure 7 shows a schematic diagram illustrating how the relays are placed to bypass any number of consecutive V-taps and re-route reference signals to feed multiple consecutive channels. The state of each relay is controlled by an FPGA (Field Programmable Gate Array) inside the patch panel, which communicates to a PC using a commercial general purpose I/O module inside a PXI chassis.

The relays are rated for 3000V coil-contact and 2500V between contacts, this being the limiting factor for the patch panel voltage rating.

All relays can also be set to simultaneously connect all differential pair outputs to a test bus, which allows for easy debugging and calibration of the isolation amplifiers.

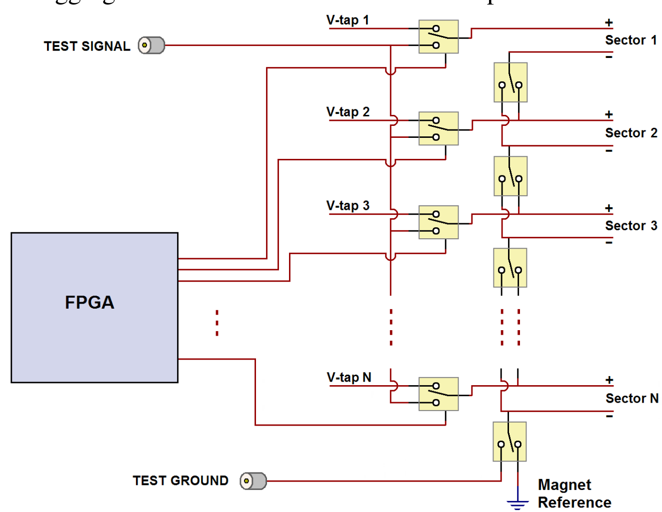

Fig 7. Block diagram for the relays inside the electronic patch panel routing probing signals from the magnet to the isolation amplifiers. An FPGA communicates to the control PC and dynamically sets the relays state.

Every time a change in the connectivity settings of the voltage taps is made, a test setup record is created in software. This record serves as documentation for the experimental setup, which builds confidence in the test and avoids manual log entries and the errors that come with them.

B. Isolation Amplifiers

The bank of isolation amplifiers is split between 2 chassis capable of housing up to 10 8-channel amplifier cards each, providing a maximum of 160 monitoring channels.

Figure 8 shows a simplified schematic of one isolation amplifier channel. A novel architecture is used to completely eliminate common mode rejection issues, without adjusting or matching any components. Our approach is to make each channel electrically floating, independent of the magnet or test facility grounds. Thus, each channel receives a pair of consecutive Vtaps and uses one of them as isolated reference.

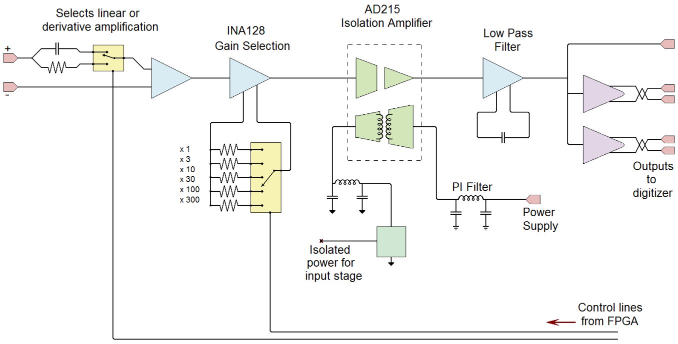

Fig 8. Single channel isolation amplifier diagram. From left to right, there are 5 stages of signal conditioning: Linear/Derivative Selection, Gain Set, High Voltage Isolation, Low-Pass Filter, Line Drivers.

The first stage of the channel is shown in figure 8 around the first Op-Amp from the input. This section brings the differential voltage of the Vtap pair to a range acceptable for commercial low-voltage devices. In addition, it allows the user to select between linear and derivative amplification. The main purpose of the derivative amplification is to provide a large signal range by measuring slew rates rather than the raw voltage from the magnet. On the other hand, the main purpose of the linear mode is to record small transient imbalances.

The second stage around the second Op-Amp from the input provides 5 gain settings for different digital resolutions. In linear mode the resolution goes from 20mV at 8 bits, to 2000V at 16 bits. In derivative mode the gain can be set to resolve from a slew rate of 10mV/ms at 8bits, to 25V/ms at 16bits.

The next device at the center of the schematic in figure 8, labeled as AD215, changes the reference of its input voltage. In our case, this device takes the voltage of the positive Vtap after the first two stages of conditioning referenced to the negative Vtap, and outputs the same differential voltage but referenced to the test facility ground. It also provides isolated power for the first two stages of signal conditioning.

The next stage in the channel's signal conditioning path is a low pass filter with frequency cutoff at ~200kHz, increasing rejection to 60dB per decade, with the purpose of providing the right Nyquist frequency to the digitizer. It also fans out to the differential line drivers and the general purpose BNC.

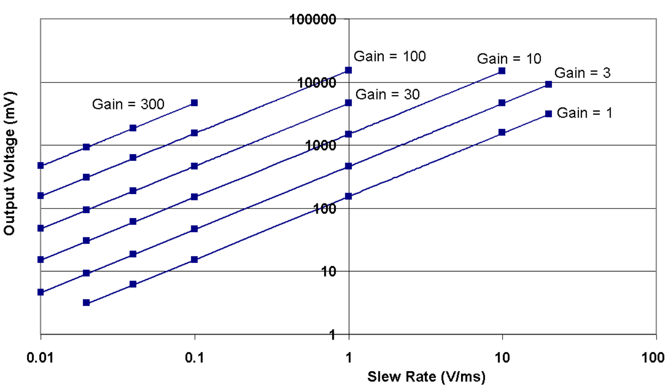

Fig 9. Measured response for a single-channel isolation amplifier working in differential mode at several values of gain and input slew rates. The amplifier shows very good linearity over 4 orders of magnitude.

Figure 9 shows the measured response of the prototype channel for several values of input slew rates and channel gains. The lines on top of the data are linear fits showing excellent level of linearity over 4 orders of magnitude.

C. Digitizers

After analog signal conditioning, a window of time around each magnet imbalance has to be digitized and recorded. For that purpose, the signals from the isolation amplifiers are duplicated and fed into two commercial digitizer modules. The two digitizers are triggered independently, such that one module only records Flux-Jumps and Slip-Sticks, while the other module only records the magnet quench.

Two PXI chassis filled each with 17 digitizer modules are needed to digitize and record all 136 analog channels. The PXI chassis shown at the bottom center in figure 6 houses the digitizers used to record voltage transients, while the chassis at the bottom right houses the digitizers that record the magnet quench. This architecture allows us to solve any issues related to digitizer dead-time after trigger.

For every trigger, each channel is digitized at a rate of 500kS/s with 16 bit resolution during a window of time defined by the user. The default window being recorded around each event is 100ms long, where 30ms are used on pre-trigger samples and 70ms on post-trigger samples. However, the system can be set to record up to 8 seconds long events.

The digital I/Os for each digitizer module are used to talk to the FPGA in each of the isolation amplifiers, and in this way read and write amplifier settings and status.

An embedded PC-controller running Windows Vista controls settings and communication with the isolation amplifiers and the electronic patch panel. This embedded PC also allows for remote-desktop connection to control the system remotely from the test facility control room.

V. Conclusions

Analysis of signals collected from recent superconducting magnets at LBNL shows that the fast transient voltages that occur before magnet quenching have the potential of providing useful information in understanding magnet behavior. For the purpose of collecting these events, a custom system is being setup and an incomplete version of it will be used for the testing of the HD2 magnet at the end of December 2007 at LBNL.

Several tests have been performed to build confidence on the data to be collected with the new MVMS. The data collected with HD2 will be analyzed and used to provide feedback for the system's final design and implementation.

References

[1] A.F. Lietzke, "Differentiation of Performance-Limiting Voltage Transients During Nb_3Sn Magnet Testing", ICMC-2005 conference proceedings.

[2] Feher, S.; Bordini, B.; Carcagno, R.; Makulski, A.; Orris, D.F.; Pischalnikov, Y.M.; Sylvester, C.; Tartaglia, M.; "Sudden flux change studies in high field superconducting accelerator magnets", *IEEE Trans. On Appl. Supercond.*, vol 15, no. 2, June 2005, p.1591.

[3] A.F. Lietzke, et al., "Test results for HD1: a 16T Nb_3Sn dipole magnet", *IEEE Trans. On Appl. Supercond.*, vol. 14, no. 2, June 2004, p. 345.

[4] A.F. Lietzke, et al., "Test results for RD3c, a Nb_3Sn, racetrack dipole" *IEEE Trans Appl. Supercond.*, Houston, 2002, pp. 1292-1296.

[5] A.F. Lietzke, et al., "Race-Track Coil Technology Validation (RT-1) Test Results",VLHC Workshop, FNAL, May 24, 2000.

[6] A.F. Lietzke, et al., "Test results for HD1: a 16T Nb_3Sn dipole magnet", *IEEE Trans. On Appl. Supercond.*, vol. 14, no. 2, June 2004, p. 345.

[7] A.F. Lietzke, et al., "Voltage-Spike Diagnostics of Under-Performing Nb_3Sn Magnets", Internal LBNL communication.