Analysis of Voltage Spikes in Superconducting Nb_3Sn Magnets

S. Rahimzadeh-Kalaleh, G. Ambrosio, G. Chlachidze, C. Donnelly, M. Tartaglia

***Abstract*— Fermi National Accelerator Laboratory has been developing a new generation of superconducting accelerator magnets based on Niobium Tin (Nb3Sn). The performance of these magnets is influenced by thermo-magnetic instabilities, known as flux jumps, which can lead to premature trips of the quench detection system due to large voltage transients or quenches at low current. In an effort to better characterize and understand these instabilities, a system for capturing fast voltage transients was developed and used in recent tests of R&D model magnets. A new automated voltage spike analysis program was developed for the analysis of large amount of voltage-spike data. We report results from the analysis of large statistics data samples for short model magnets that were constructed using MJR and RRP strands having different sub-element size and structure. We then assess the implications for quench protection of Nb_3Sn magnets.**

***Index Terms*— Niobium-Tin, Superconducting, Magnet, Flux Jump, Voltage Spike**

I. INTRODUCTION

Fermi National Accelerator Laboratory (FNAL), in cooperation with Brookhaven National Laboratory (BNL) and Lawrence Berkeley National Laboratory (LBNL), is working on a new generation of superconducting accelerator magnets intended for a luminosity upgrade for the Large Hadron Collider (LHC) at CERN under LARP (US LHC Accelerator Research Program). Since the LHC will push the current NbTi high field superconducting accelerator magnet technology close to its usable limit, another niobium alloy, Nb_3Sn, is being investigated as a possible replacement for the bending and focusing of particles in high energy physics.

Although Nb_3Sn theoretically offers a greater critical applied field at greater critical current densities than NbTi, the performance of Nb_3Sn magnets is thought to be limited by thermo-magnetic instabilities, or flux jumps, which manifest themselves as distinct transient spikes in coil voltages [1]. During a magnet test, the difference of two half coil signals, which we call the “bucked signal”, is used to detect quenches by means of a constant voltage threshold. However, the detection system often trips due to non-quenching voltage spikes that occur well below the critical current. At present, a high threshold is needed to eliminate false trips due to these voltage spikes. In light of this, the need for a better quench protection system was seen in order to better study both quenching mechanisms and thermo-magnetic instabilities while isolating true quenches from false trips.

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II. SYSTEM FOR VOLTAGE SPIKE RECORDING AND ANALYSIS

A. Present System

At Fermilab, superconducting R&D magnets are tested at the Vertical Magnet Test Facility (VMTF) [2], where coil voltage signals are recorded by the Voltage Spike Detection System (VSDS). The fast data acquisition system of the VSDS is based on a National Instruments PXI multifunction DAQ, which samples data at 100 kHz [3],[4], and software written in LabVIEW. The VSDS captures half-second snapshots of the bucked signal and saves that snapshot if any voltage value exceeds the threshold set by the user while ramping up the current. At the conclusion of a ramp, the snapshots are bundled into a single LabVIEW file and these are later converted into individual MATLAB files for analysis purposes.

B. Improvements

As the manual inspection of a single current ramp could take an excessive amount of time, a new software program, written in MATLAB, was developed by the authors to automate and accelerate the spike data analysis process. The software known as “Autonomous Voltage Spike Analysis Program” (AVSAP) relies on zero crossings of the first derivative of the bucked voltage signal to automatically detect the spikes. Furthermore, there are certain criteria an event needs to satisfy in order to be declared a spike: the width, magnitude, and slope must each exceed a certain threshold. These parameters were tuned based on manual inspection of data and identification of spikes.

Due to the large amount of noise present in the signals, a study was performed to determine the effects of various filters on the noise and on the spike peak voltages. To evaluate the former, the signal-to-noise ratio (SNR) was considered; for the latter, statistical distributions were made for each filter of the percentage reduction in the spike amplitudes. For both of these studies, data from TQS02a magnet test (see section III) were used.

Based on the amplitude threshold employed to trigger the data acquisition system at hand (the VSDS), a method to determine the SNR was developed. The procedure consisted of considering a noise "envelope," i.e. the maximum and minimum voltage values arising purely from the noise, regardless of the width and in the absence of spikes. This is motivated by the fact that any single voltage value beyond the threshold would trigger the data acquisition system. It is therefore essential to not have any value arising from the noise beyond the threshold. Table I summarizes the results of the effects of the filters on noise levels, where E_{min} is the minimum of the noise envelope, E_{max} is the maximum of the envelope, and ΔE is the total envelope size.

TABLE I
FILTERING EFFECTS ON NOISE ENVELOPE

Filter	E_{min} *(mV)*	E_{max} *(mV)*	*ΔE (mV)*
No Filter	-12	8	20
30 kHz	-12	8	20
25 kHz	-12	8	20
20 kHz	-10.5	5	15.5
15 kHz	-8.5	3.5	12

It was found that both 30 kHz and 25 kHz low-pass filters provided no improvement in noise reduction. However, it was also found that a 20 kHz and a 15 kHz low-pass filter reduced the noise levels by 25 % and 40 % respectively, which greatly enhances the effectiveness of the automation program.

To determine the effects of the different filters on the peak magnitudes of the voltage spikes, a new parameter was introduced. This parameter is called the Spike Reduction Ratio (SRR); it is given by

$$SRR = 1 - \frac{V_2}{V_1} \tag{1}$$

where V_1 and V_2 are the peak voltages of the spikes before and after the application of the filters, respectively.

SRRs for all spike events within a single current ramp were generated for all four filters shown in Table 1. It was found that in any of the filters presented, the vast majority of the spikes (> 90 %) suffered a reduction in their amplitude of less than 5 % (SRR < 0.05).

With the application of a 15 kHz filter, noise was reduced by 40 %. Moreover, the study showed that this filter led to an SRR below 0.1 for 98.5 % of all spikes, a SRR below 0.04 for 89 % of all spikes, and a SRR below 0.01 for roughly 55 % of all spikes. Based on these results, a 15 kHz low-pass filter was selected to be used by the developed software for its effectiveness in noise diminishment at an acceptable spike magnitude reduction.

III. MAGNETS TESTED

Three magnets are presented as part of this work, which are LARP technology quadrupoles; namely, TQC01, TQC02a, and TQS02a. TQC magnets, fabricated at Fermilab, are characterized by stainless steel collars supported by an iron yoke and a stainless steel skin [5]. Conversely, TQS magnets, fabricated at LBNL, are characterized by a key and bladder structure surrounded by a stretched aluminum shell [6]. TQC01 was fabricated using MJR coils while TQC02a and TQS02a were both fabricated using RRP coils. Furthermore, all magnets underwent standard testing in the VMTF at Fermilab, which includes quench training and ramp rate studies at 4.5 K and 1.9 K. The test summaries for TQC01, TQC02a and TQS02a can be found in [7], [8], and [9] respectively.

IV. QUENCH DETECTION

In the presented context, there are two main characteristics a good quench detection system should have. First, for safety purposes, it should quickly detect quenches at high current. Second, for improved efficiency of tests, the system should not trip with non-quenching voltage spikes at low current. The present quench detection system consists of a single threshold value, which is set by the user at the beginning of a test and is kept fixed throughout. Unfortunately, such a system very often compromises the second desired characteristic in order to preserve the magnet's safety. This leads into the quest for a dynamic quench detection system.

For the development of a dynamic quench detection system, the peak voltages of all spikes arising from flux jumps throughout the test need to be well known. We refer to the peak voltage of any spike as the "voltage spike magnitude", and then plot this value against the magnitude of the current at the time of occurrence; this is shown for TQS02a at 4.5 K and 1.9 K in Fig. 1 and 2 respectively, for TQC02a at 4.5 K and 1.9 K in Fig. 3, and for TQC01 at 4.5 K in Fig. 4. The data points represent the peak voltages of all spikes occurring at that particular current level. The continuous horizontal line near the top of each plot represents the minimum threshold that would need to be used in such test to avoid premature system trips due to non-quenching voltage spikes.

V. RESULTS AND DISCUSSION

A. *Current Dependent Quench Detection Threshold*

From the data presented above, a general trend in spike magnitude is observed; once a maximum value has been reached at a few thousand amps, voltage spike magnitude decreases with increasing current. This points to the feasibility of a current dependent quench detection system, the most reasonable form of which would be a step function that gradually decreases with increasing current (shown by the dotted lines in Fig. 1-4). The benefit of using such a threshold is two-fold in nature; it would allow quicker detection of quenches at high currents, while avoiding premature system trips at low currents due to non-quenching voltage spikes. Thus, both the nature of the flux jumps and quench onsets could be better studied while providing greater protection for the magnet itself.

One issue that needs to be clarified is the lack of spikes above 9 kA in Fig. 4, which is most likely due to the fact that the VSDS threshold was set at a high level to exclude trips from noise. However, when the magnitude of the voltage spikes dropped with increasing current, neither the spikes nor the noise had a magnitude great enough to trip the threshold, leading to the apparent absence of spikes. Clearly, this issue could also be solved with a dynamic threshold such as the one proposed.

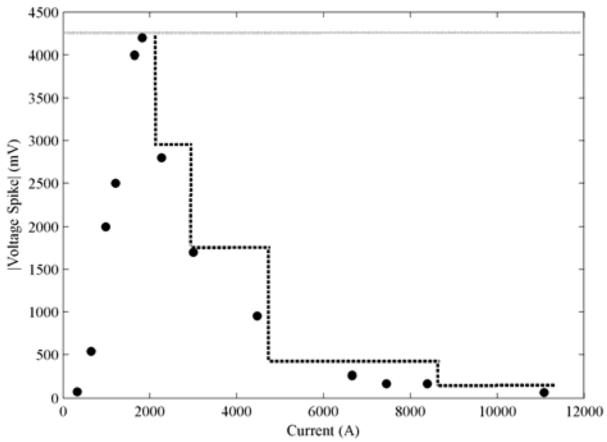

Fig. 1 Voltage spike magnitude vs. current for TQS02a at 4.5 K

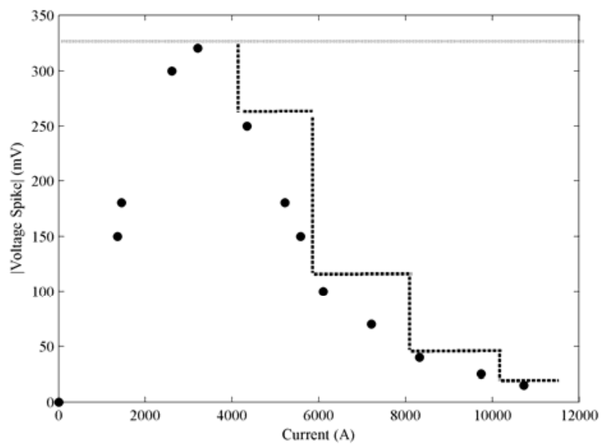

Fig. 2: Voltage spike magnitude vs. current for TQS02a at 1.9 K

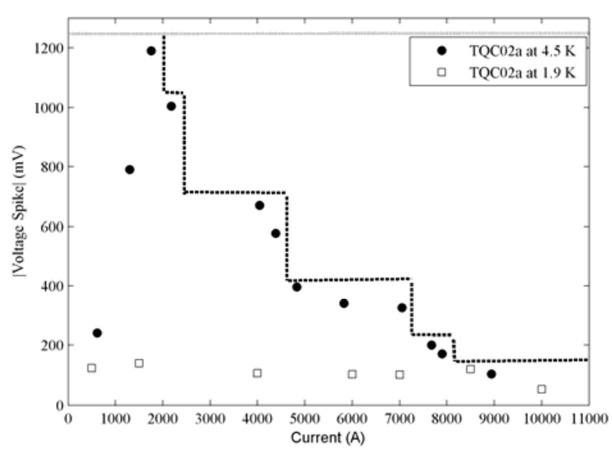

Fig. 3: Voltage spike magnitude vs. current for TQC02a at 4.5 K and 1.9 K

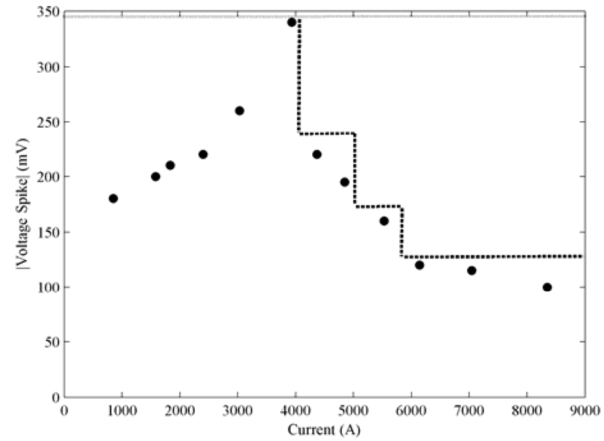

Fig. 4: Voltage spike magnitude vs. current for TQC01 at 4.5 K

B. Voltage Spike Temperature Dependence

The temperature dependence of the voltage spikes can also be seen in Fig. 1, 2, and 3. At low and intermediate currents (< 8 kA), the voltage spikes in all magnets at 4.5 K were an order of magnitude greater than those seen at 1.9 K. At high currents however, there is very little temperature dependence of the magnitude of the voltage spikes. There are at least two mechanisms which might contribute to this behavior. First, the thermo-magnetic processes that govern development of the flux jump may be influenced by the cooling conditions, as well as by the conductor critical current; additional analysis of existing (but limited) VSDS data taken at intermediate temperatures may be quite useful. Second, recalling that flux jumps may have a mechanical origin as well, the spike profiles at 1.9 K and 4.5 K are affected by any training performed on the magnet. It may be possible to differentiate the mechanical spike features by comparing distributions at the start of training, versus those in 4.5 K data recorded after training and temperature dependence.

C. Voltage Spike Conductor Dependence

The TQC01 magnet showed spikes about an order of magnitude less than the TQS02a, while TQC02a had spikes intermediate between the two. Spikes on the order of 3-4 volts were not uncommon for TQS02a at 4.5 K, spikes in the 1-1.5 volt range were seen in TQC02a, and the maximum spike seen for TQC01 was less than 0.5 volts. These differences must arise from the two major differences between these magnets. First, TQS02a and TQC02a were built from different RRP coils whereas TQC01 was comprised of MJR coils. Second, coil pre-stress variations during fabrication, cool down and excitation vary in different ways for the TQS02a shell structure, and TQC01 and TQC02a collared coil structures.

The plots in Figs. 5-8 characterize both the magnitude of the voltage spikes as well as the current at which those spikes occurred for each of the three magnets. The plots are normalized to the total number of spikes for each magnet at the specific temperature.

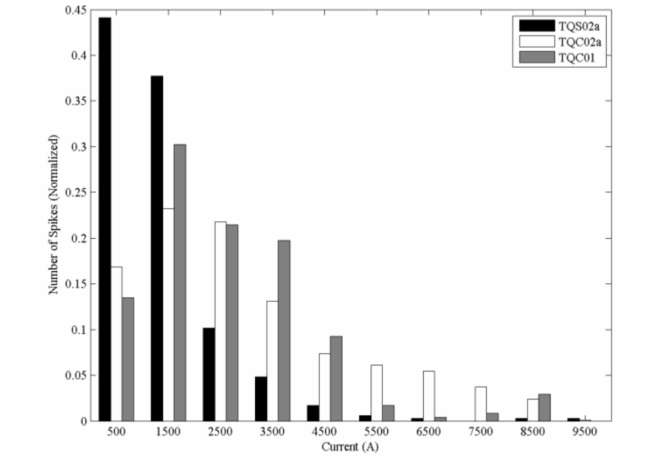

Fig. 5: Number of spikes vs. current at 4.5 K

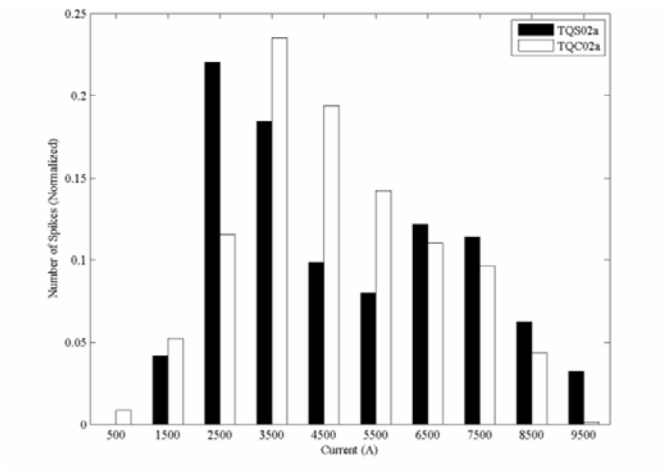

Fig. 6: Number of spikes vs. current at 1.9 K

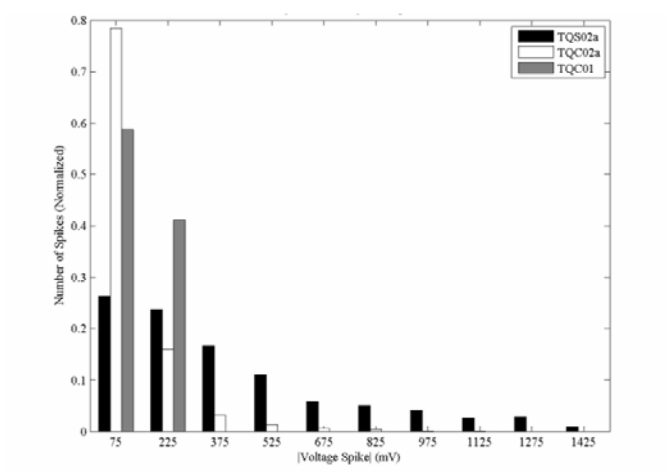

Fig. 7: Number of spikes vs. voltage spike magnitude at 4.5 K

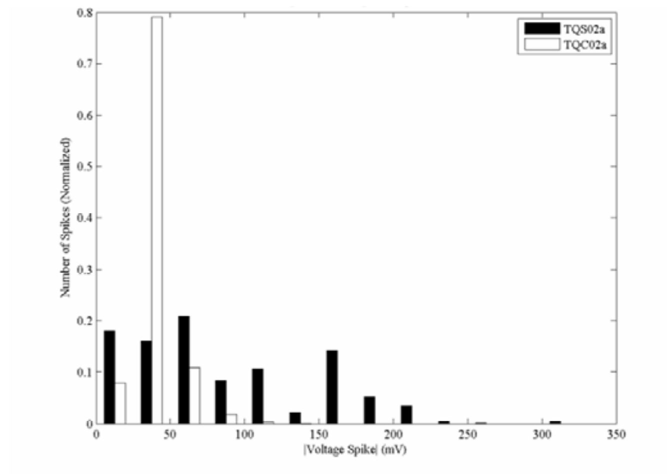

Figure 8: Number of spikes vs. voltage spike magnitude at 1.9 K

VI. Conclusions

The voltage spikes recorded for TQC01, TQC02a and TQS02a magnets were analyzed. Voltage spike dependence on temperature of the test, as well as on coil conductor type was discussed. The voltage spikes were generally an order of magnitude greater at 4.5 K than at 1.9 K, and TQS02a with the RRP coils showed spikes an order of magnitude greater than TQC01 with the MJR coils.

The feasibility of a current dependent quench detection system was shown.

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References

[1] B. Bordini et al, “Voltage Spikes in Nb3Sn and NbTi Strands,” IEEE Trans. Appl. Superconduct., Vol. 16, Issue 2, June 2006, pp 366-369.

[2] D. F. Orris et al, “Voltage Spike Detection in High Field Superconducting Accelerator Magnets,” IEEE Trans. Appl. Superconduct., Vol 15, Issue 2, June 2005 pp 1205 – 1208

[3] T. J. Peterson, K. I. Rabehl, C. D. Sylvester. “A 1400 Liter 1.8 K Test Facility” Advances in Cryogenic Engineering. Vol. 43A, New York: Plenum Press, 1998, pp. 541-548.

[4] S. Feher et al, “Sudden Flux Change Studies in High Field Superconducting Accelerator Magnets,” IEEE Trans. Appl. Superconduct., Vol. 15, Issue 2, June 2005, pp 1591-1594.

[5] R.C. Bossert et al, “Development of TQC01, a 90 mm Nb3Sn Model Quadrupole for LHC Upgrade Based on SS Collar,” IEEE Trans. Appl. Superconduct., Vol 16, Issue 2, June 2006 pp 370 - 373.

[6] S. Caspi et al, “Fabrication and Test of TQS01—A 90 mm NbSn Quadrupole Magnet for LARP,” IEEE Trans. Appl. Superconduct., Vol 17, Issue 2, June 2007 pp 1122 - 1125.

[7] S. Feher et al, “Development and Test of LARP Technological Quadrupole (TQC) Magnet,” Trans. Appl. Supercond., Vol. 17, No. 2, pp.1126-1129, June 2007.

[8] G. Ambrosio et al, “LARP TQC01b Test Summary,” Fermilab TD Note TD-07-026, found at : http://tdserver1.fnal.gov/tdlibry/TD-Notes/2007%20Tech%20Notes/TD-07-026.pdf

[9] G. Ambrosio et al, “LARP TQS02a Test Summary,” Fermilab TD Note TD-07-022, found at : http://tdserver1.fnal.gov/tdlibry/TD-Notes/2007%20Tech%20Notes/