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TQS02a Voltage Spike Analysis

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Contents

1. Abstract

This note reports the analysis of the data recorded by the VSDS (Voltage Spike Detection System) [1,2] during 68 current ramps of the TQS02a superconducting magnet (LARP Technological Quadrapole). It was found that the voltage spikes at 4.5 K were an order of magnitude larger than the spikes at 1.9 K. Moreover, the shape of each type of spike contained at 4.5 K was given a cursory analysis; four types of spikes were found at low currents, and two types of spikes were found at high currents, with some mixing of types occurring. Following the installation of a physical noise reduction system, data was analyzed and it was found that the vast majority of spikes occurred below 1500 A and had magnitudes below 100 mV. The onset of all available quench onsets was examined and is presented.

2. Quench Summary

For reference, the quench history of TQS02a is presented in figure 1 and in table form in table I.

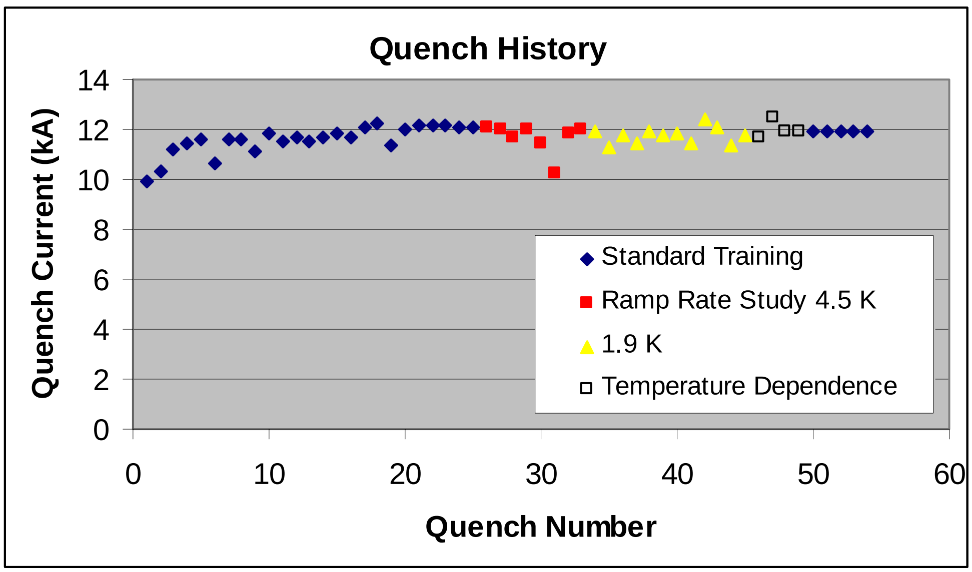

Figure 1: Quench History of TQS02a

Table I: Quench History of TQS02a

Ramp #	Quench #	Coil	Temp (K)	RR (A/s)	Current (kA)	Ramp #	Quench #	Coil	Temp (K)	RR (A/s)	Current (kA)
1	**1**	21	4.5	20	9.9017	29	**27**	21	4.5	40	11.9642
2	**2**	21	4.5	20	10.3212	30	**28**	21	4.45	80	11.714
3[a]			4.5	20	1.7366	31	**29**	21	4.45	10	12.011
4	**3**	22	4.5	20	11.161	32	**30**	21	4.5	100	11.407
5	**4**	20	4.5	20	11.44	33	**31**	21	4.5	120	10.217
6	**5**	20	4.5	20	11.575	34	**32**	21	4.5	60	11.839
7	**6**	21	4.5	20	10.634	35	**33**	21	4.5	5	11.963
8	**7**	22	4.5	20	11.637	36	**34**	21	1.9	20	11.937
9	**8**	20	4.45	20	11.5992	37	**35**	21	1.9	20	11.252
10	**9**	20	4.5	20	11.126	38	**36**	21	1.83	20	11.77
11	**10**	20	4.45	20	11.8456	39	**37**	21	1.82	20	11.439
12[a]			4.45	20	1.949	40	**38**	21	1.9	20	11.941
13	**11**	20	4.5	20	11.495	41	**39**	21	1.91	20	11.731
14	**12**	20	4.5	20	11.7	42	**40**	21	1.89	20	11.844
15	**13**	20	4.5	20	11.515	43	**41**	21	1.9	20	11.411
16	**14**	20	4.5	20	11.696	44	**42**	21	1.86	20	12.383
17	**15**	20	4.5	20	11.802	45	**43**	21	1.94	20	12.045
18	**16**	20	4.5	20	11.71	46	**44**	21	1.92	20	11.374
19	**17**	21	4.5	20	12.069	48	**45**	21	1.9	20	11.741
20	**18**[b]		4.5	20	12.269	49	**46**	21	2.08	20	11.716
21	**19**	21	4.5	20	11.378	50	**47**	20	2.17	10	12.463
22	**20**	21	4.5	20	11.97	51	**48**	20	2.95	20	11.957
23	**21**	21	4.5	20	12.162	52	**49**	21	4.42	20	11.933
24	**22**	21	4.5	20	12.146	53	**50**	21	4.44	20	11.935
25	**23**	21	4.4	20	12.139	54	**51**	21	4.44	20	11.934
26	**24**	21	4.5	20	12.11	55	**52**	21	4.44	20	11.925
27	**25**	21	4.42	20	12.071	57	**53**	21	4.45	20	11.917
28	**26**	21	4.5	5	12.0496	68	**54**	21	4.45	20	11.927

3. Voltage Spikes at 4.5 K

At currents below 2000 A, spikes on the order of a few volts were not uncommon. A maximum voltage spike of 4.2 V at 1820 A was observed during ramp 64. The general profile of the voltage spike magnitude versus current seems to show a steep increase followed immediately by a consistent exponential decay. This is shown in figure 2 below and more clearly with maximum peaks isolated in figure 3. Note that this same pattern was seen in TQC01, albeit with peaks more than an order of magnitude smaller.

[a] Ramp 3 and 12 contained spikes that tripped the QDS.
[b] Quench occurred at a coil to coil NbTi junction.

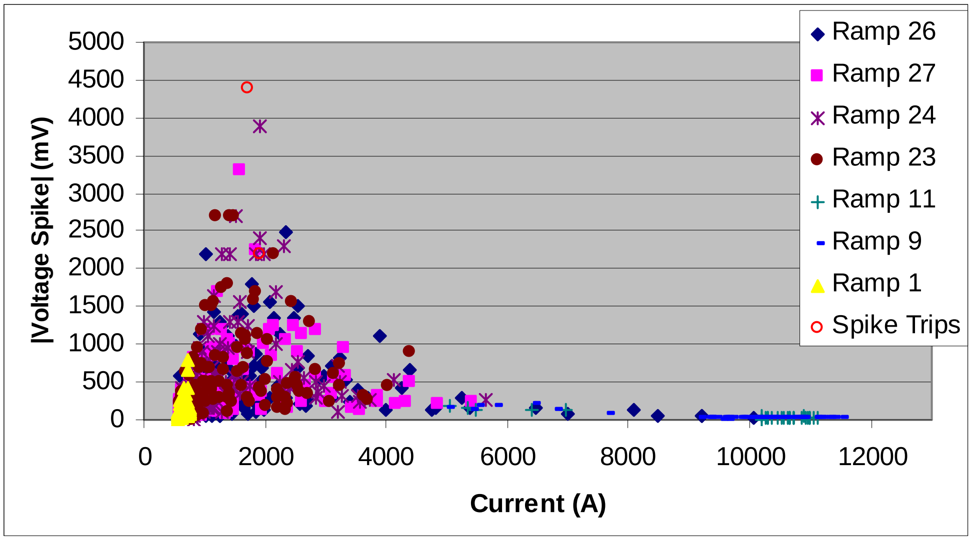

Figure 2: Magnitude of Voltage Spikes versus Current

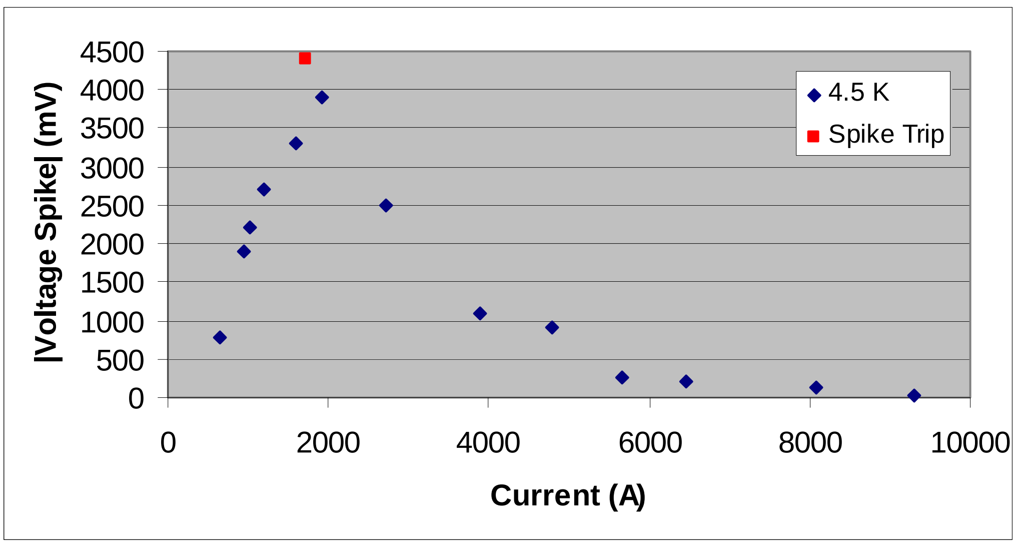

Figure 3: Magnitude of Peak Voltage Spikes versus Current

The voltage spikes can clearly be divided into 2 distinct groups based on peak voltage: above 5000 A and below 5000 A. Because of this, a graph of the spikes above 5000 A is shown in figure 4 below.

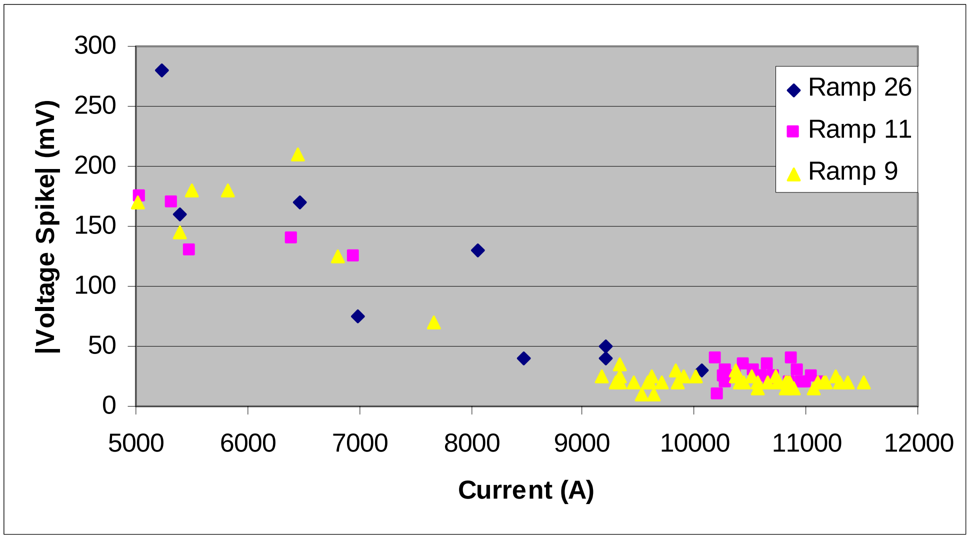

Figure 4: Magnitude of Voltage Spike versus Current for Currents Greater than 5000 A

This close up view of high current spikes shows that the trend of “exponential” decay clearly continues in the high current regime. However, there is a problem with detecting spikes at these currents prior to the installation of the noise reduction system; the noise amplitudes at these currents are typically between 75 and 100 mV with the spikes being less than half this height. The detection of spikes at these currents seems to be a result of the noise crossing the threshold of the VSDS, not the magnitude of the actual spike, so lowering the threshold of the VSDS will not aide in spike detection at these currents. Only approximately 20 % of the 240 “spikes” that the VSDS returned above 5000 A contained actual spikes. In order to confirm that the noise in the high current spikes was similar noise in low current spikes, a Fast Fourier Transform of the noise at each level was performed and the results were quite similar with peak frequencies between 45 and 50 kHz (figures 5 and 6). However, at high current, the magnitude of the peaks was roughly twice that of the low current peaks.

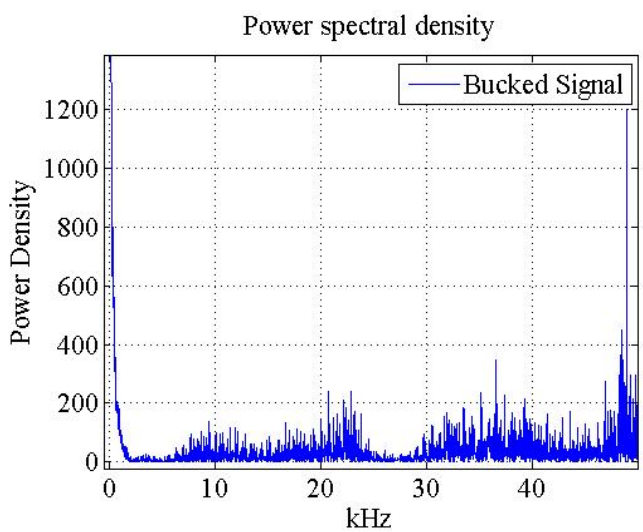

Figure 5: FFT of low current noise

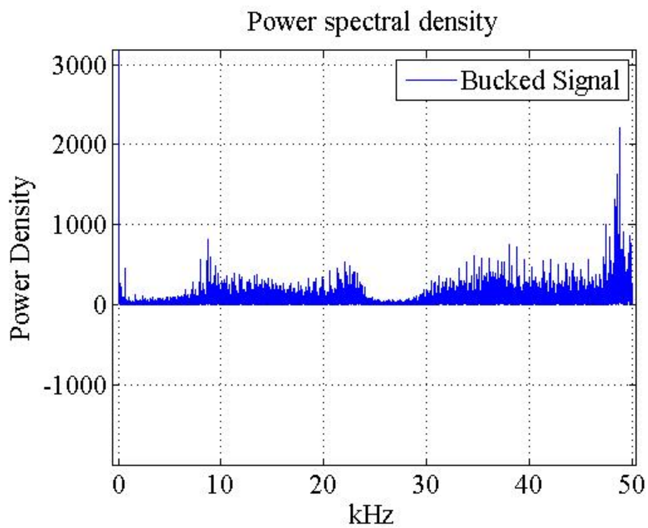

Figure 6: FFT of high current noise

The main difference in the transforms lies in the amplitude of the frequencies, with the high current amplitudes being larger. This result is expected as, visually, the high current snapshots are noisier than the low current snapshots.

4. Spike Characterization at 4.5 K

4.1 Low Current

Once again, the characterization of the spikes can be divided into those seen at low currents and those seen at high currents. At low currents, there are four main categories of spikes, including some that are combinations of two different kinds of spikes. First, the simplest spike is characterized by a linear rise and exponential decay and can occur at any current in the low current (sub 5000 A) regime. It is shown in figure 7 below.

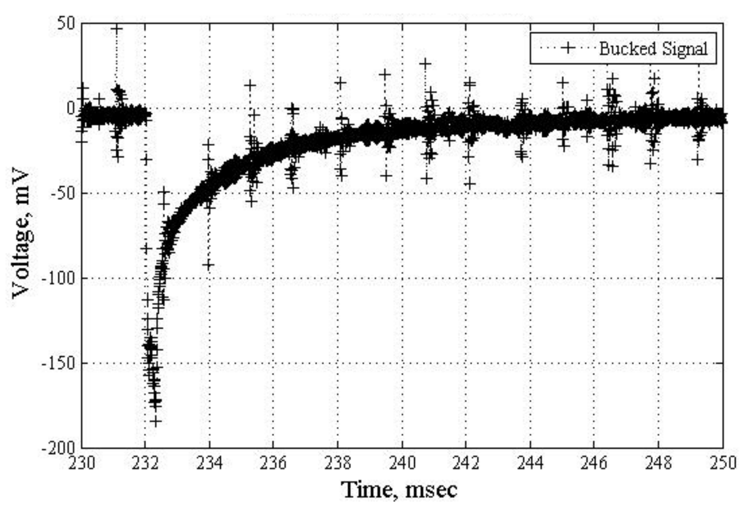

Figure 7: Typical Low Current Spike (670 A)

Notice the periodic noise that is present in each of the snapshots, such as at 238 ms in figure 7. This is the characteristic noise of the power supply and occurs about once every 1.4 ms. At very low currents, below about 1500 A, multiple distinct consecutive spikes, like those in figure 8 below, could be seen.

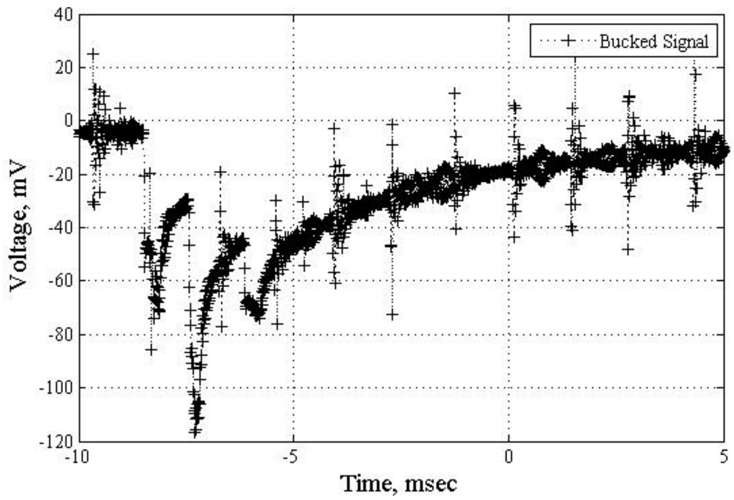

Figure 8: Distinct Consecutive Spikes (570 A)

As current is increased, the distance between distinct consecutive spikes became shorter and the signal appeared to oscillate at its peak. (Figure 9)

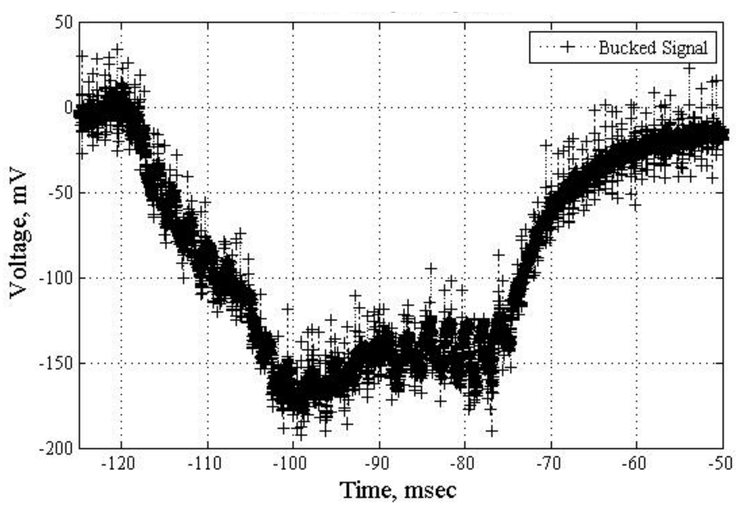

Figure 9: Spike Oscillating at Its Peak (2610 A)

The final type of spike has a portion of its amplitude both above and below the y-axis and is shown in figure 10 below.

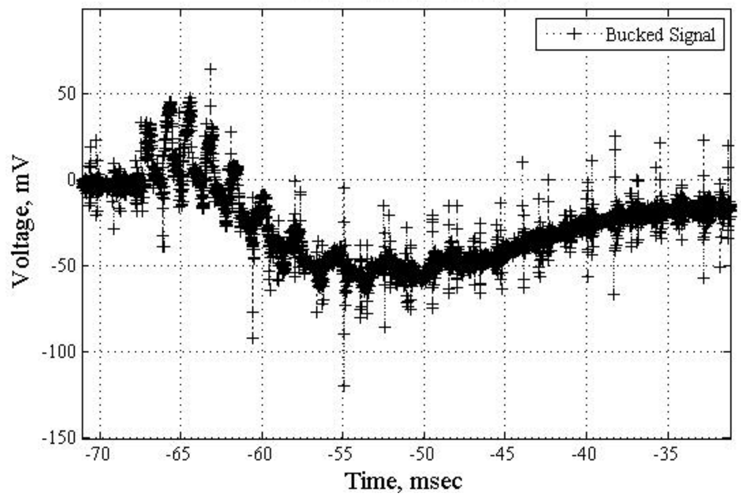

Figure 10: Spike Oscillating about Peaks and Y-axis (4790 A)

Notice how this spike contains two different categories of spikes; this is not an uncommon phenomenon to see at these current levels.

4.2 High Current

At high currents, there are only two types of spikes; however, these are present throughout the 5000 A + regime. The most common spike (Figure 11) is a scaled down version of figure 7; it is characterized by a linear rise and exponential decay.

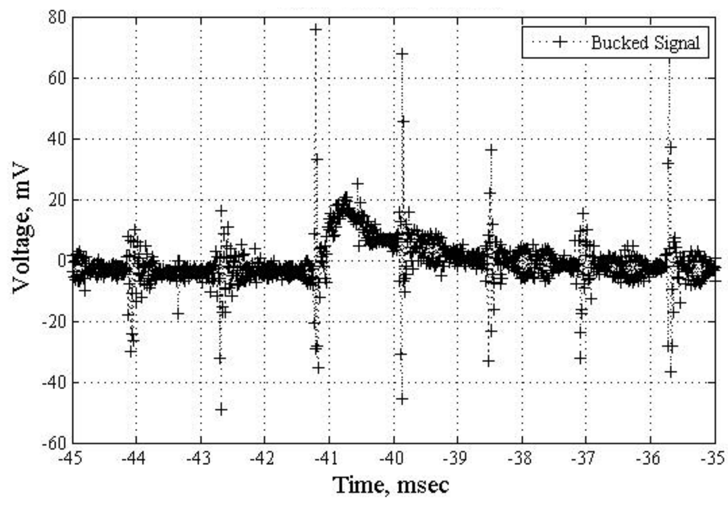

Figure 11: Typical High Current Spike (11150 A)

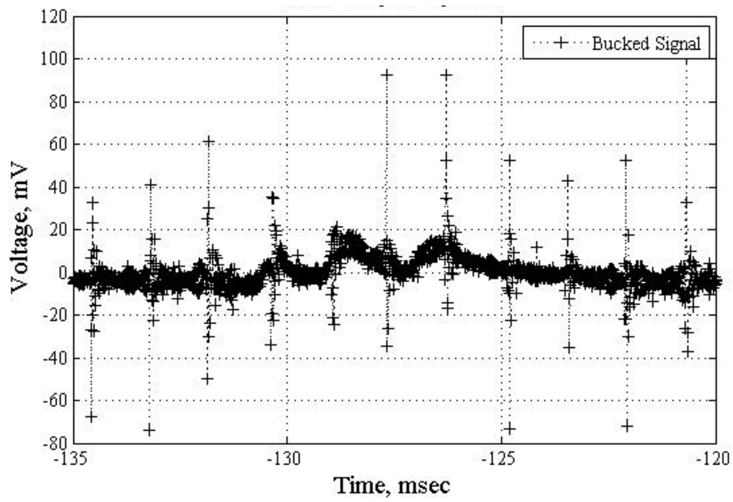

Figure 12: High Current Spike Oscillating at Peak (11120 A)

The second kind of high current spike oscillates around a value that lies above (or below for a negative spike) zero. (Figure 12)

It is also important to note that the inherent noise in the sample was greater in the high current samples than in the low current samples, as shown in figures 13 and 14.

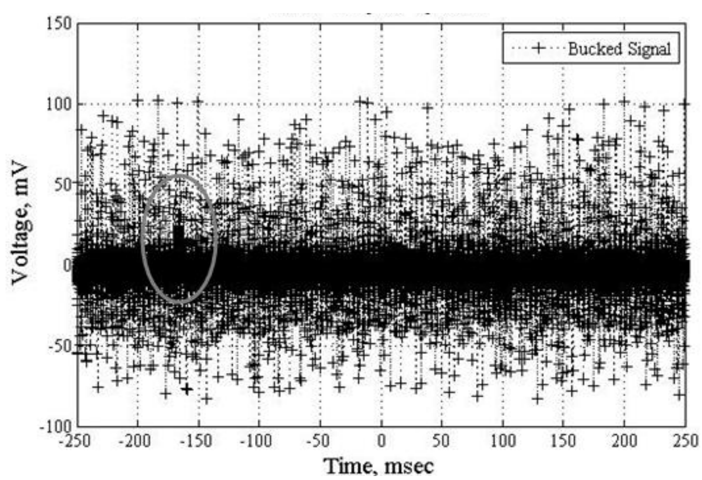

Figure 13: Typical Spike and Noise at High Currents (11050 A)

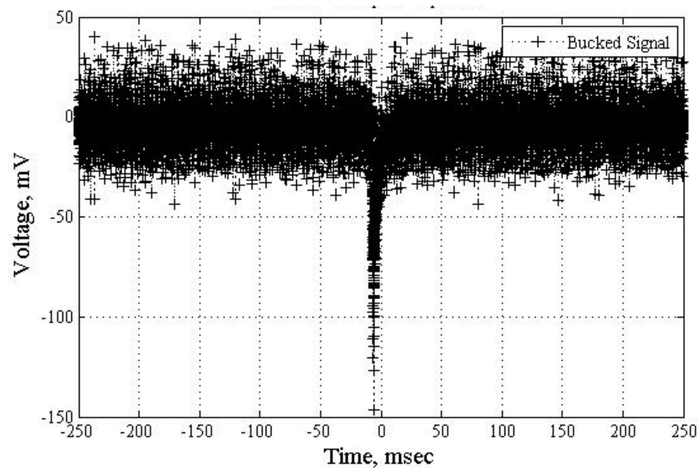

Figure 14: Typical Spike and Noise at Low Currents (1300 A)

5. Voltage Spikes at 1.9 K

As with the spikes at 4.5 K, the magnitude of each voltage spike at 1.9 K was plotted against the current at which it occurred; the result is shown in figure 14 below.

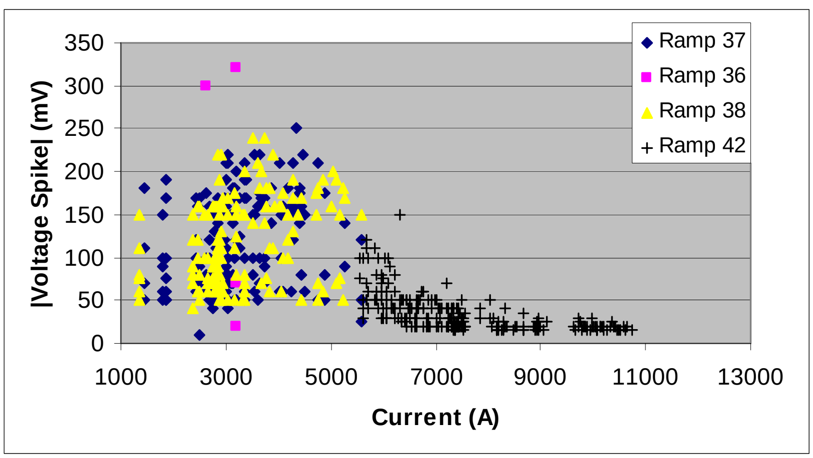

Figure 14: Magnitude of Voltage Spike versus Current Profile at 1.9 K

Once again, the trend is easier to see when the peak voltages at selected currents are isolated and plotted. (Figure 15)

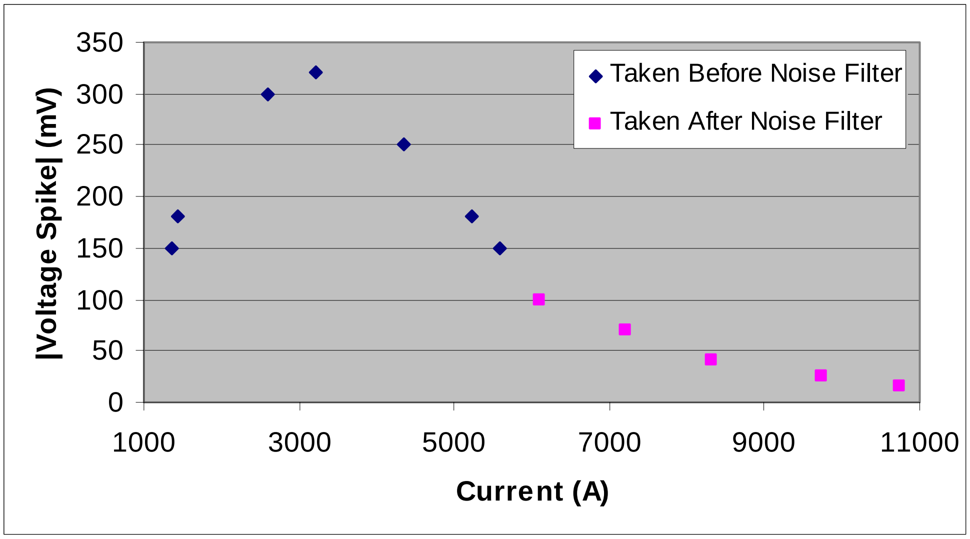

Figure 15: Peak Isolated Profile at 1.9 K

The profile stopped at about 5600 A before a noise filter was installed because, as with the high current scenario at 4.5 K, the threshold for the VSDS system was set too high for the magnitude of spikes present. After the filter was installed, it was possible to lower the threshold and therefore detect the smaller spikes at higher currents.

In order to better understand the spike behavior at high currents at 1.9 K, the VSDS threshold was lowered for ramp 42 to detect more spikes. The spike profile for ramp 42 is shown below.

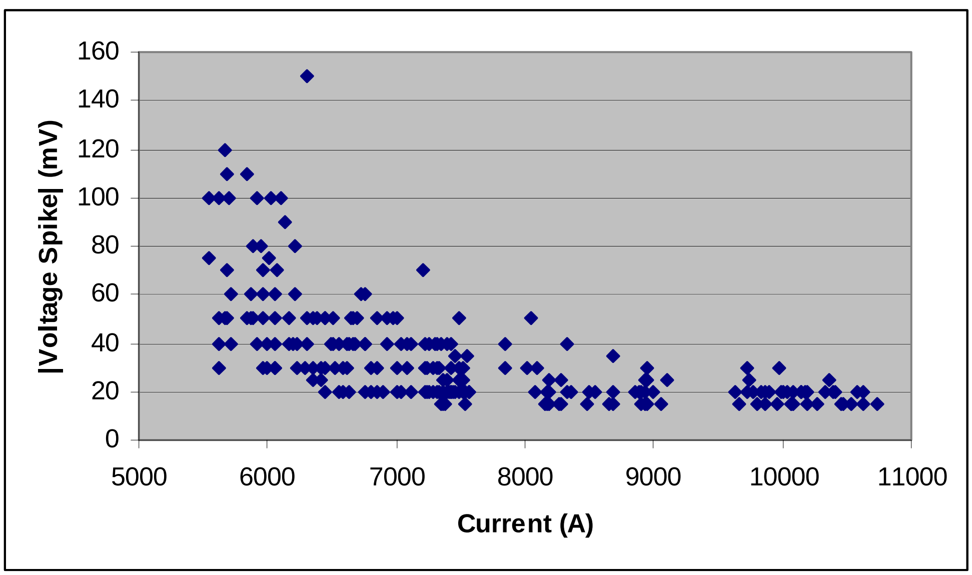

Figure 16: Profile for Ramp 42

It is clear that the exponential decay that was expected at high currents was indeed present for TQS02a. It is also important to note that above 7400 A, roughly 40 % of the events detected by the VSDS were tripped by noise and did not contain any true spikes.

This problem was remedied by the installation of the aforementioned physical noise reduction system and the results of that study are presented later in this report.

6. Comparison of 1.9 K and 4.5 K Tests

The difference in magnitude of the voltage spikes can best be seen by plotting figures 3 and 15 on the same axes: shown in figure 17 below.

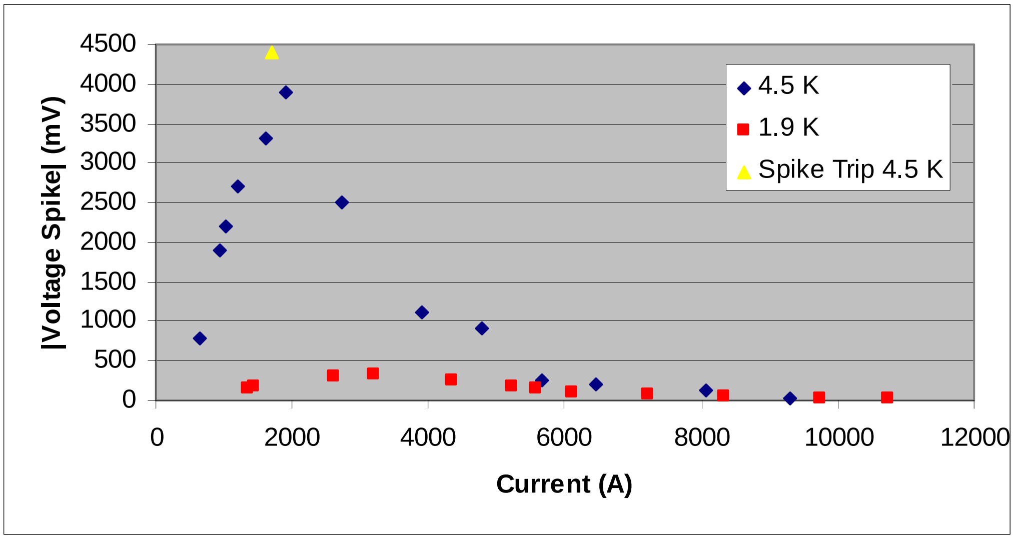

Figure 17: Magnitude of 1.9 K and 4.5 K Spikes

It is obvious that the spikes at 4.5 K are roughly and order of magnitude greater than the spikes at 1.9 K up to about 5000 A, the end of the low current regime. However, at current above roughly 5600 A, the magnitude of the voltage spikes at both temperatures was of the same order of magnitude.

8. Spike Analysis with Low Noise

On June 20, 2007, a physical noise reduction system (“noise filter” in the following) was installed on the Vertical Magnet Test Facility (VMTF) at Fermilab. The filter showed immediate improvements in the output of the VSDS as it reduced the noise at high currents to levels below the magnitude of the actual spikes. Figures 18 and 19, respectively, show the VSDS output before and after the installation of the noise filter.

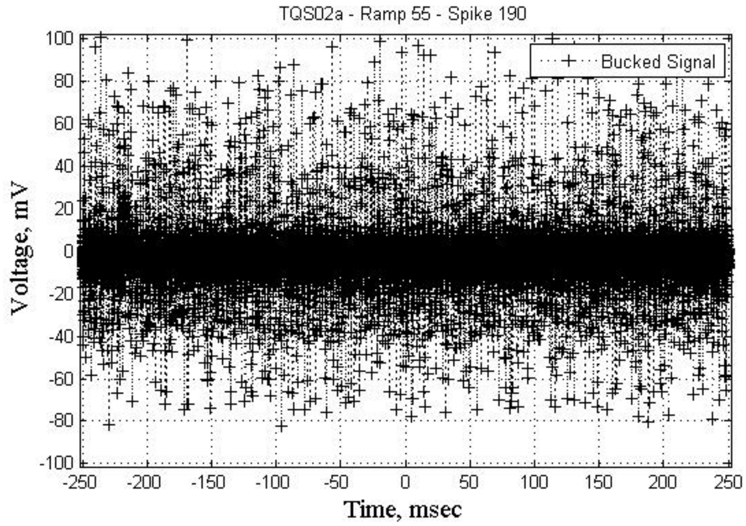

Figure 18: Typical High Current Spike (10.95 kA) Before Noise Filter

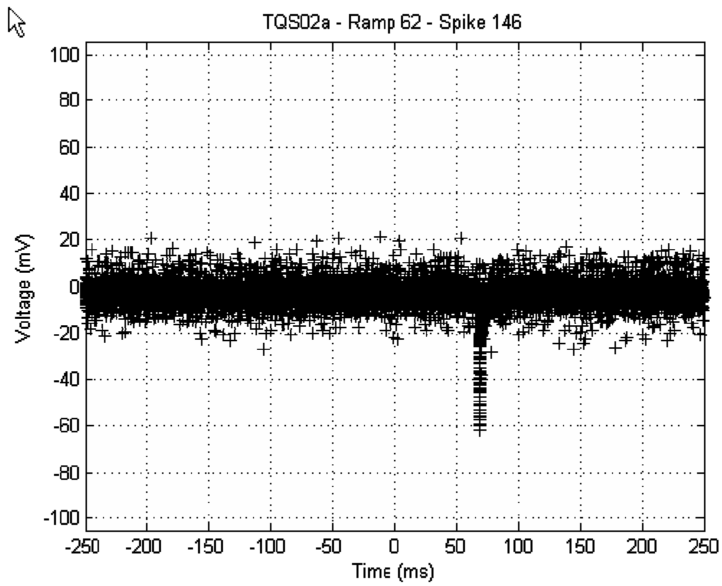

Figure 19: Typical High Current Spike (10.87 kA) After Noise Filter

After the installation of the noise filter, the magnitude of the spikes was clearly greater than the magnitude of the noise at high currents. Also, it was noticed that the overall magnitude of high current spikes became apparently greater after the noise filter was installed because the VSDS was triggered by real spikes rather than by noise.

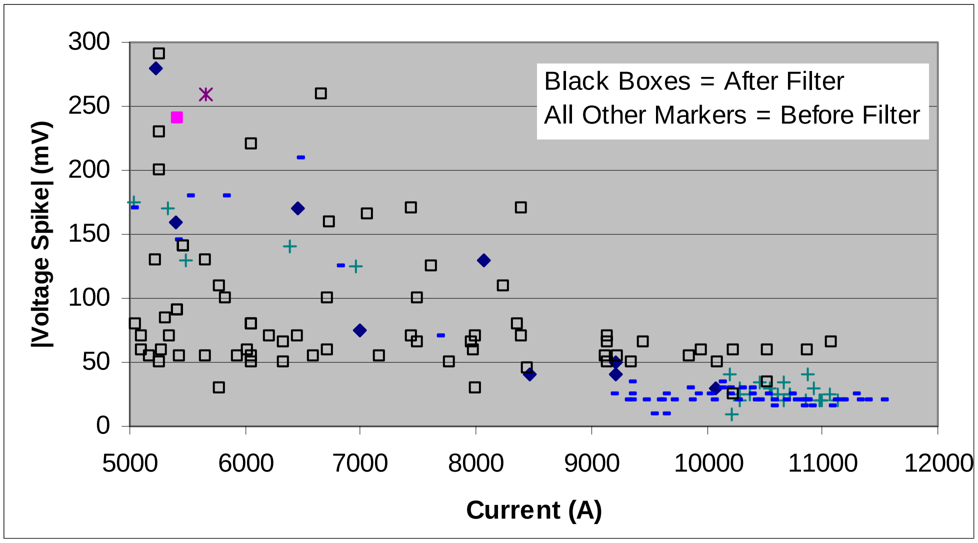

Figure 20: High Current Spikes Before and After Noise Filter Installation

The noise filter also allowed the VSDS to detect spikes at very low currents. Previously, the lowest current at which spikes were recorded was roughly 600 A; however, in the ramps with the noise filter, spikes were detected as low at 300 A (Figure 21).

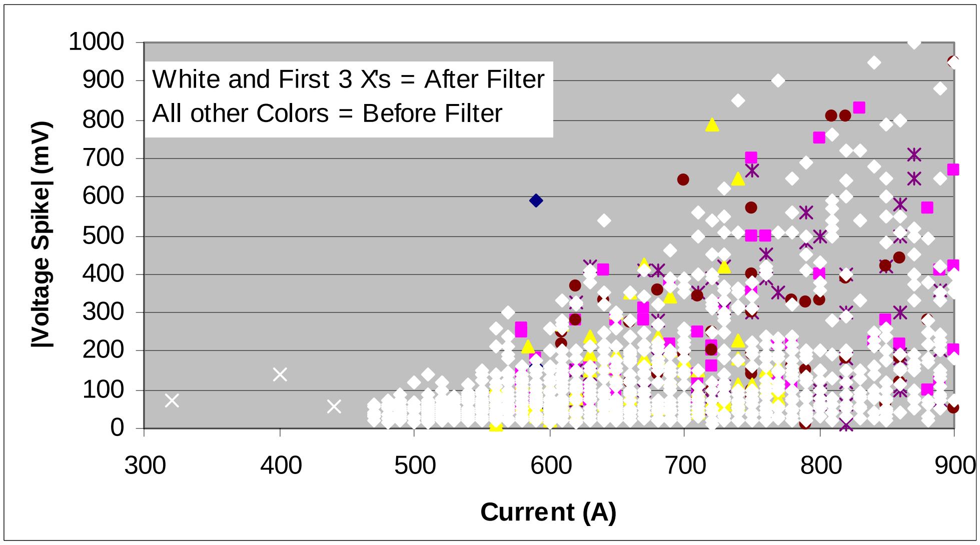

Figure 21: Low Current Spikes Before and After Noise Filter Installation

However, at intermediate currents, the I-V profile for the noise filtered spikes generally fell within the profile established by the pre-filter ramps. The profile with the filtered ramps added is presented in figure 22 below.

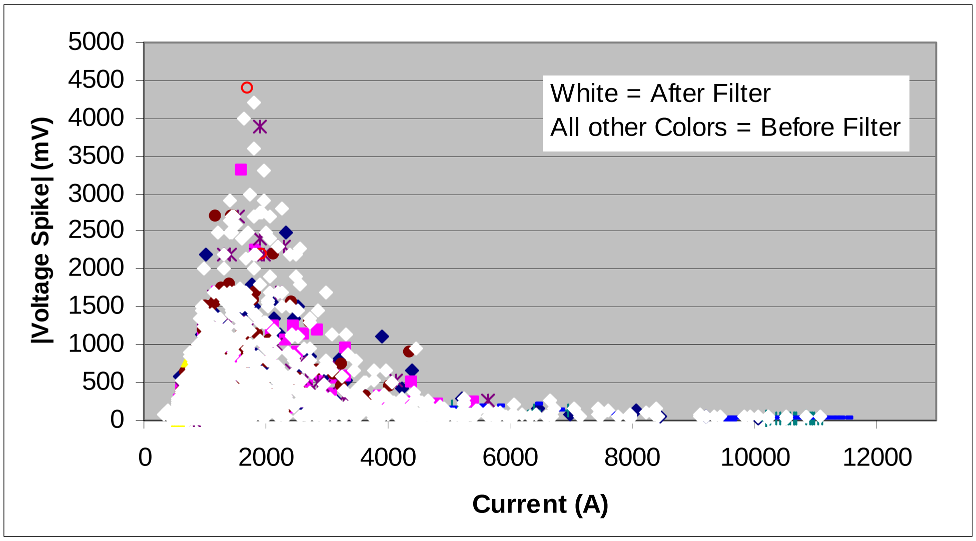

Figure 22: Voltage Spike Profile After Noise Filter Installation

When comparing figure 22 to figure 2, there seems to be a greater density of spike data after the filter was installed. This is a result of the threshold setting on the VSDS. With the high noise samples, the threshold had to be set high enough to prevent noise trips; therefore, smaller spikes were not saved by the VSDS. This led to a greater quantity of filtered spikes being saved by the VSDS.

Since the filtered data was relatively similar to the unfiltered data and since more spikes were saved in the filtered data set, statistical analysis was performed on the filtered data to better understand the voltage spikes and the currents at which they occurred. Figure 23 below is a normalized probability distribution graph, created with Matlab, of the number of spikes that occurred during a ramp versus current.

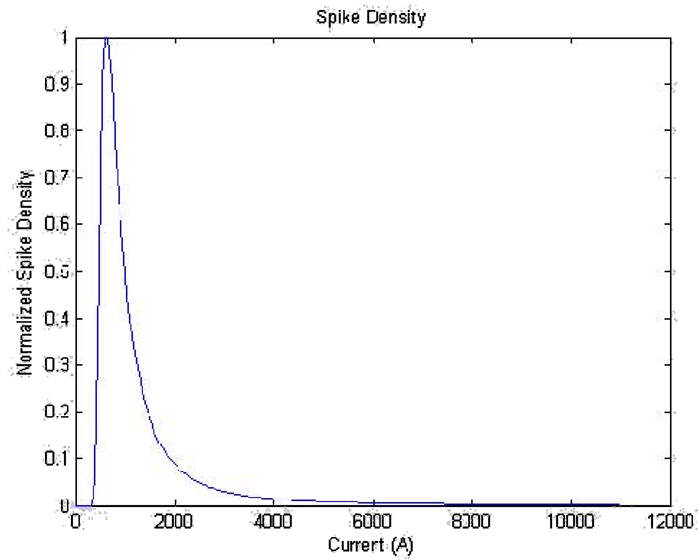

Figure 23: Number of Spikes Distribution

The most interesting point of this graph is that most of the spikes during a ramp occurred before the current reached 1500 A. A similar profile was created for the magnitude of the spikes themselves.

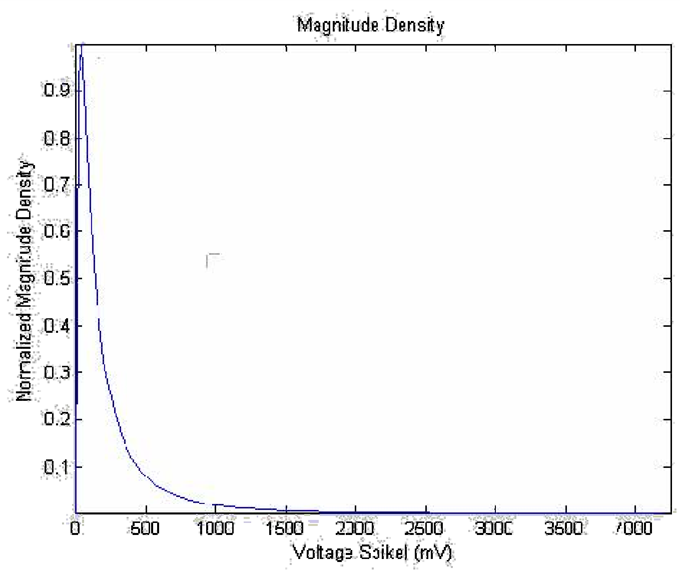

Figure 24: Magnitude of Spikes Distribution

This figure is even more definitive than the previous figure; it clearly shows that most of the spikes that occur during a ramp are below 150 mV in magnitude. Putting these two distributions together leads to the histogram presented in figure 25 below[c].

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[c] The Matlab code for this histogram was adapted from “2D Histogram” by Murphy O’Brien, which is available on the Matlab File Exchange.

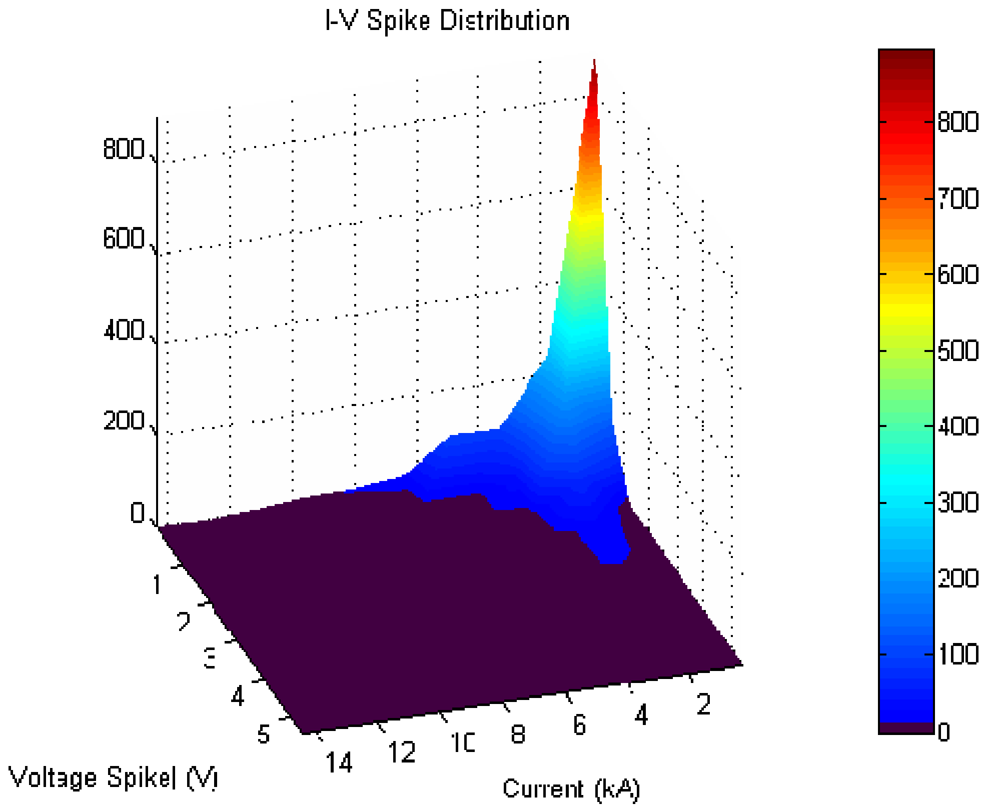

Figure 25: Histogram of Voltage Spike and Current Data

In this plot, a redder surface indicates a greater density of spikes at that current and voltage spike magnitude, a bluer surface indicates a lesser density of spikes, and a black surface indicates a density of zero. The z-axis is unitless and is normalized to the greatest spike density. This reinforces the previous two figures, as the vast majority of spikes that occur at low current have a low voltage spike magnitude.

9. Quench Onset

At this point in time, only trends can be identified with regards to characterizing the onset of the quenches. Most of the quenches from quench 4 to quench 16 occurred in coil 20 and most of the quenches from quench 17 to the conclusion of testing occurred in coil 21, specifically in B2-B3 and B3-B4 segments.

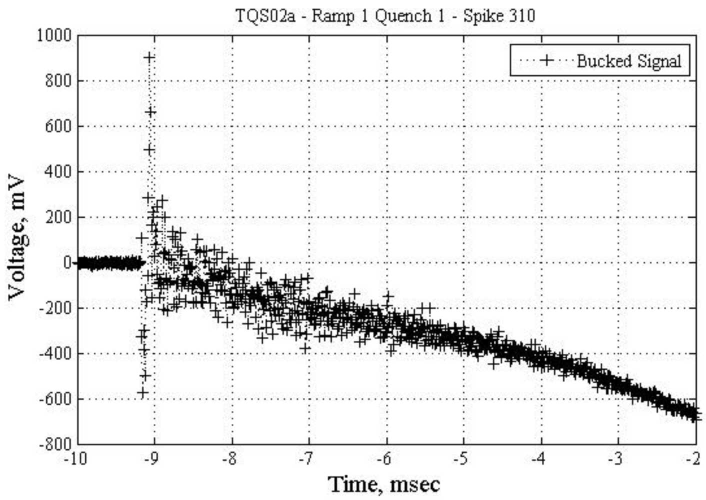

Figure 26: Quench onset of Quench 1 (99017 A)

Figure 26 shows the quench onset of the first quench. The large oscillating spike at about -9 ms (arbitrary zero) has been seen in other magnets and has been interpreted as mechanical movement. Quench 4 showed a slightly similar behavior; however, the starting spike had much smaller amplitude.

The first group of onset quenches, which are the expected form of quench onsets in the case of a normal transition, appeared in quenches 2-18. These are characterized by a generally smooth voltage increase over time; an example is shown in figure 27 below.

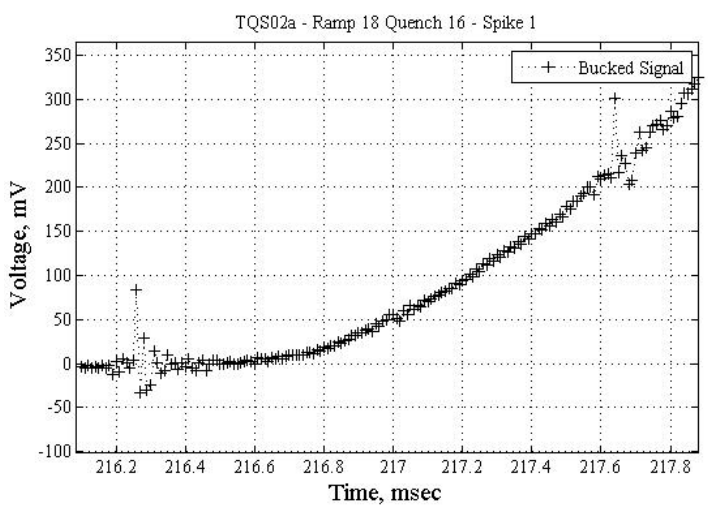

Figure 27: Quench Onset of Quench 16 (11710 A)

Note that the noise in figure 27 at 216.3 ms and 217.7 ms is characteristic of the power supply. Then, quite suddenly, the onset became irregular and also initiated in coil 21. This is shown in figure 28 below.

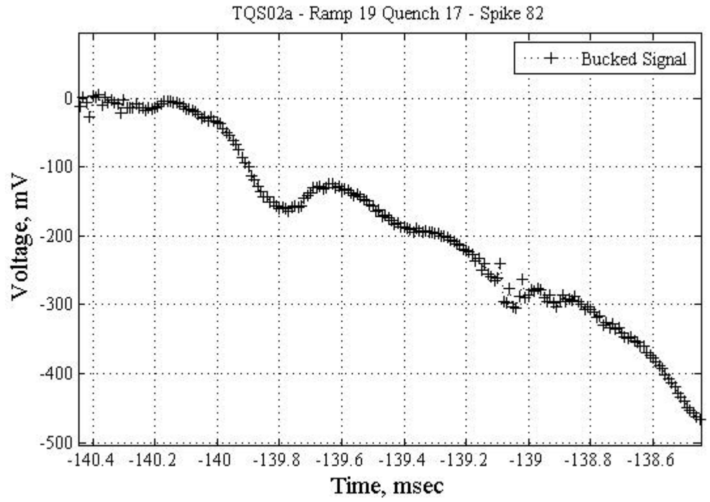

Figure 28: Quench onset of Quench 17 (12069 A)

This pattern continued until quench 21 when the shape of the irregularities changed slightly. (Figure 29) However, the quench began in the same coil and coil segments as quenches 17-20.

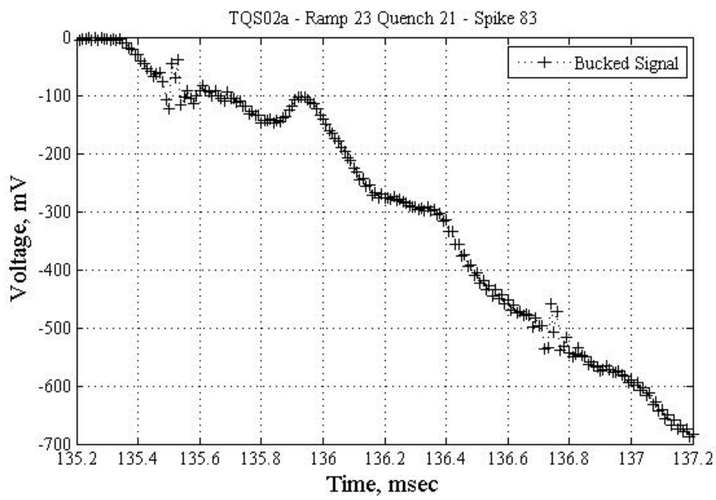

Figure 29: Quench onset of Quench 21 (12162 A)

This continued through quench 25, which ended standard training. Following a ramp rate study, ramps to quench at 20 A/s were performed at 1.9 K (Quenches 36-48). The irregularities seen at 4.5 K were again seen at 1.9 K and the magnet continued to quench in coil 21. (Figure 30)

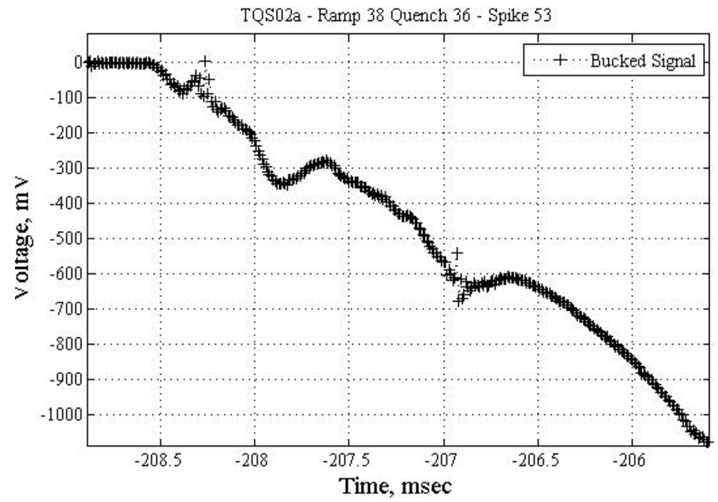

Figure 30: Quench onset of Quench 36 (11770 A)

It is interesting to note that this pattern is similar to the pattern that was seen in quenches 17-20.

This general pattern continued until quench 42, at which point the onset began to show a plateau after about 1 ms. This occurred in quenches 42-52 that began in coil 21 and an example is shown in figure 31 below.

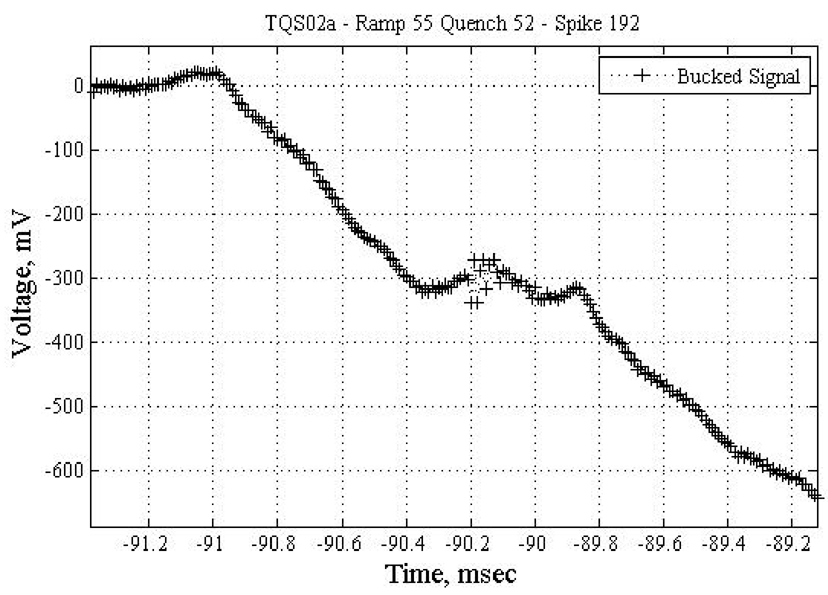

Figure 31: Quench onset of Quench 52 (11925 A)

However, between quenches 42 and 52, there were two quenches that occurred in coil 20, one of which, quench 47, reached the highest current for this magnet, 12.463 kA. These two quenches showed the standard smooth quench onset (Figure 32).

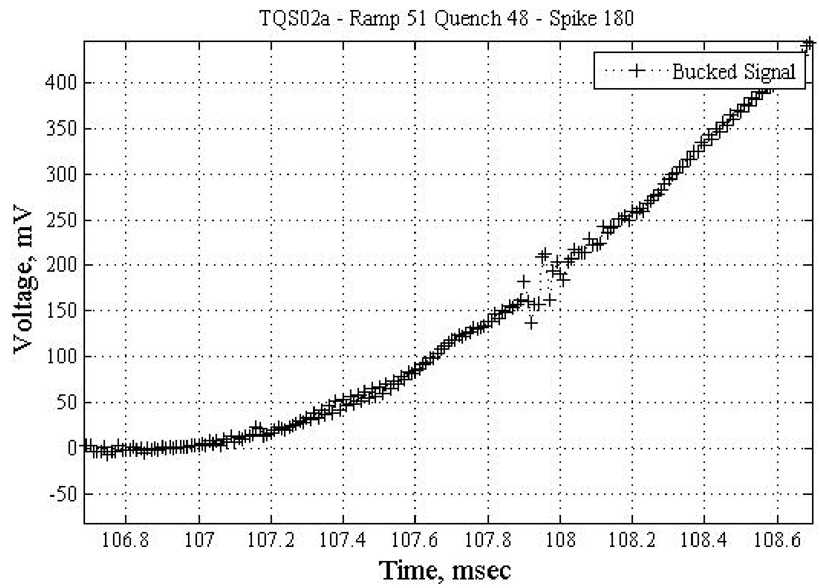

Figure 32: Quench onset of Quench 48 (11957 A)

9. Conclusions

There was a definite correlation between the magnitude of voltage spikes and the current at which they occurred at 4.5 K. The spikes at currents below 5000 A were well defined and generally less than 3 V with only two exceptions. Between 5000 A and 9000 A, the signal become noisier and the spikes less pronounced. Before the noise reduction filter was implemented, above 9000 A, the spikes were less in magnitude than the amplitude of the noise and the VSDS system was most likely tripped by the noise rather than the spike itself.

There was a similar correlation between the magnitude of the voltage spikes and the current at which they occurred at 1.9 K; however, the magnitude of the spikes was roughly an order of magnitude less at this temperature than at 4.5 K. A similar problem was experienced with VSDS threshold being too high to catch the spikes at high current.

Overall, this data is similar in shape, albeit quite different in magnitude, to the data collected for TQC01; the same general shape profile for spike height versus current was seen in both TQC01 and TQS02a.

Once the noise reduction filter was implemented at the VMTF, the clarity of the spikes was much improved. It was also shown that the vast majority of voltage spikes occurred at low currents and had low magnitudes.

The quench onset signals show unusual oscillations in quenches in coil 21 at 20 A/s starting from quench 17. However, no conclusions can be drawn as to the reason of this unusual shape. More examination is needed and will be performed.

References

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