FERMILAB-CONF-05-401-TD

Voltage Spikes in Nb_3Sn and NbTi Strands

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***Abstract*—As part of the High Field Magnet program at Fermilab several NbTi and Nb_3Sn strands were tested with particular emphasis on the study of voltage spikes and their relationship to superconductor instabilities. The voltage spikes were detected under various experimental conditions using voltage-current (V-I) and voltage-field (V-H) methods. Two types of spikes, designated 'magnetization' and 'transport current' spikes, have been identified. Their origin is most likely related to magnetization flux jump and transport current redistribution, respectively. Many of the signals observed appear to be a combination of these two types of spikes; the combination of these two instability mechanisms should play a dominant role in determining the minimum quench current.**

***Index Terms*—Magnet, Instability, Nb_3Sn, Voltage Spike**

I. Introduction

As part of its High Field Magnet Program, Fermilab has designed, built and tested many accelerator magnets which utilize Nb_3Sn superconductor. The quench performance of most of these magnets was not satisfactory. Extensive strand, cable and magnet studies indicated that the most probable explanation is conductor instability [1].

Relatively early in the program we observed that some magnets generated unexpectedly large voltage spikes. Since these voltage spikes might be related to conductor and magnet instabilities, we developed a special Voltage Spike Detection System (VSDS) [2] and tested several magnets, recording hundreds of voltage spike events [3]. Using the VSDS we were able to examine the detailed structure of the voltage spikes. Two fundamentally different signal shapes were distinguished, indicating that they are most likely generated by different mechanisms (flux jumps and conductor motion). We also observed that the spikes have substructure.

To understand the origin of these magnet voltage spikes our attention shifted toward strand studies. By studying strands, conductor motion would not be expected to play a big role in generating the voltage signal. If the substructure of the voltage signal in the magnet was related to strands, the substructure of a single strand signal would be simpler. We also wanted to study how to relate voltage spikes to thermo-magnetic instabilities.

Manuscript received September 19, 2005. This work was supported in part by the U.S. Department Energy.

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For the past year several NbTi and Nb_3Sn strands were tested using VSDS at the Short Sample Test Facility (SSTF) at Fermilab. This paper summarizes the test results of four different strand samples.

II. Test Setup

The data were collected using both the VSDS and the standard critical current readout system at SSTF (details of these systems are described elsewhere [2], [4]). The strand samples were wound and heat treated (if Nb_3Sn) on grooved cylindrical Ti-Alloy barrels in an argon atmosphere. The sample was divided into two halves with voltage taps. Each half coil voltage was monitored separately by the VSDS. The readout frequency of the VSDS was 100 kHz.

III. Samples

For this study we used four different samples listed as A, B, C, D (see Table I). Sample A was produced by SUPERCON and samples B, C and D were produced by Oxford Superconducting Technology (OST). Samples A and B are NbTi strands with different filament and copper matrix properties. Samples C and D are Modified Jelly Roll strands with almost identical strand parameters but with a significant difference in their residual resistivity ratios (RRR), 7 and 130, respectively. The different RRR values were obtained by using different heat treatments. For sample C, the reaction sequence was: 100 h @ 210 °C, 48h @ 340 °C, 180h @ 650 °C; for sample D, the last reaction step was reduced to 72 h. Although the heat treatment was different, the critical current density J_c @ 12 T was quite similar: 1830 A/mm^2 for the C sample and 2000 A/mm^2 for the D sample. The non-copper to the strand cross section ratio for both strands was 0.529. We chose this MJR strand since some of the previously tested coils, where we observed hundreds of spikes [3], were made from the same type of strands.

Sample B is a multifilamentary NbTi strand with a highly resistive matrix, CuNi (the electrical resistivity of the CuNi is higher than the resistivity of the copper at 300 K) and a

TABLE I
Tested Samples

Sample	SC	Strand diameter, mm	Number of filaments	Filament size, µm	Matrix
A	NbTi	0.3	1	185	Cu
B	NbTi	0.5	54	46	CuNi
C	Nb_3Sn	1.0	54	110	Cu
D	Nb_3Sn	1.0	54	110	Cu

moderate current density of 2600 A/mm^2 at 5 T. Sample A is a NbTi monofilament surrounded by a copper shell, with a J_c @ 5 T of 1860 A/mm^2.

IV. Test procedure

Voltage spikes were first observed on the upward current ramp during quench testing as the magnetic field in the superconductor increases. In strand studies, the current or the magnetic field can be changed independently. Ramping the strand current at a fixed external magnetic field will be referred to as a V-I measurement; if the current is fixed and the magnetic field is ramped we designate it a V-H measurement.

In addition to measuring voltage spikes, we also characterized the strand samples by measuring the V-I curve and determining the critical current (I_c) value by observing the reversible transition between the superconducting and normal states.

During these tests we observed voltage spikes and premature quenching of the strands. The frequency of the voltage spikes and the magnitude of the quench current (I_q) had a strong correlation with the prehistory of the sample. In order to systematically study instability-related premature quenching and voltage spikes, we performed the following experiments referred as **E1**, **E2** and **E3**:

*A. V-I measurement: I_c determination [**E1**]*

This measurement starts at high field values – 15 T for Nb_3Sn and 10 T for NbTi – and it is repeated at lower and lower field values down to a minimum field at which the reversible transition to the normal state is observed.

*B. V-I measurement: I_q of demagnetized strands [**E2**]*

This experiment is done at magnetic fields lower than those of **E1**. Before performing the measurement the sample has to be completely demagnetized. The magnetization due the transport current itself can be neglected considering the relatively large coil radius and distance between the adjacent turns with respect to the current that flows in the strand. Demagnetization of the sample at each field value was achieved by quenching the sample few times. The current ramp rate was 1 A per second.

*C. V-H measurement: I_q of strongly magnetized strands [**E3**]*

In order to eliminate magnetization pre-history, the sample is also demagnetized before performing the measurement. This measurement starts at higher current and it is repeated at lower and lower current values until the minimum quench current, I_{qm}, between 0 and 4 T is observed. The magnetic field ramp rate was 1 T per minute.

V. Test results

A. Critical current measurements and quench tests

Fig. 1-2 summarize the critical current measurements and quench tests of A, B and C, D samples respectively. Each sample was exposed to all three different (**E1**, **E2**, **E3**) measurement conditions described in the previous section. Each measurement point in the figure is labeled with a symbol corresponding to the type of experiment performed.

The monofilament sample (A) exhibited stable behavior under conditions **E1** and **E2**. It shows reversible transitions down to 4 T and none below 4 T. I_q had to be very close to I_c since the derivative of quench current was monotonically increasing with decreasing magnetic field as one would expect if the sample is at, or close to, its critical value.

For sample B, we observed reversible transitions down to 6 T. Further decreasing the field from 5.5 T to 4 T and performing E2 type measurements, we observed that I_q was below I_c value but it was still increasing. When decreasing the field further to 3 T, I_q started to decrease. The ratio I_q/I_c at 3 T was about 0.6. In the low field region between 0-3 T, I_q was significantly lower than I_c (see Fig. 1).

Although the critical current value of sample C was much larger than that of sample B, its quench behavior was very similar. The reversible transition was observed down to 11 T and I_q started to decrease at 7 T (Fig.2).

We were not able to perform direct comparison of sample D with the other samples. The transition was measured down to 11 T. With further decrease in the field, I_q increased until the power supply limit (PSL) was reached (Fig.2).

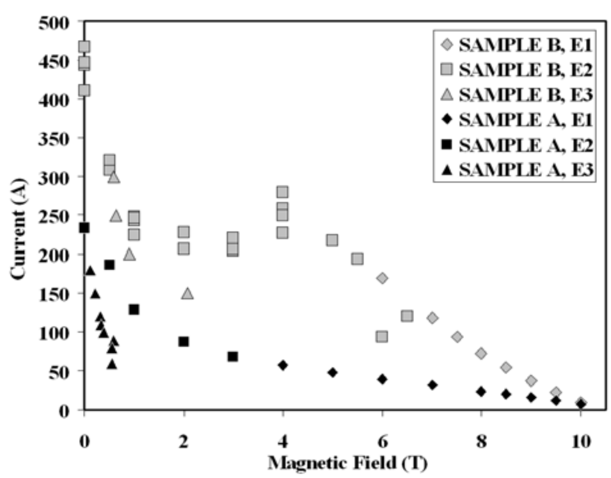

Fig. 1. Critical and quench current of the samples A and B

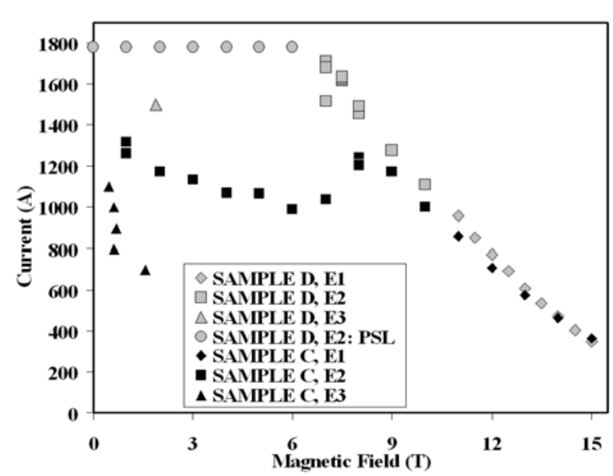

Fig. 2. Critical and quench current of the samples C and D

The lack of magnetization current in these tests (**E2**) and the fact that the strand was exposed to higher Lorentz forces during **E1** experiments, indicates that the quench mechanism should be driven by self field instability (non uniform distribution of the transport current in the strand [4] [5]). It is also interesting to note that sample D, even though it has a slightly higher J_c than sample C, is much less limited by self field instability. This is most likely due to the higher thermal and electrical conductivity of its copper matrix.

In **E3 (strong magnetization)** measurements, none of the samples exhibited stable behavior; significant quench current reduction was observed for all the samples. The I_{qm} of sample A was 60 A @ 0.5 T. The minimum quench current (I_{qm}) was about 3 times smaller than the I_q obtained at the same field value in the case when the sample was demagnetized. The I_{qm} of sample B was 150 A @ ~2 T, a reduction factor of about 1.4. For sample C, I_{qm} was 700 A @ 1.57 T and the reduction factor was ~1.8. Sample D had a I_{qm} equal to 1500 A @ ~ 2 T.

From these experiments it can be concluded that the magnetization significantly reduces I_q. Furthermore, in order to determine the I_{qm} value it is likely that both the filament flux jump and the self field mechanisms should be taken into account.

B. Voltage Spikes

The frequency of voltage spikes had a strong variation with the magnitude of the strand magnetization and the value of the transport current. The number of spikes scales with the magnitude of the magnetization. In the E2 experiments, when the sample was demagnetized, we observed no spikes even if the sample was self field unstable. In the E3 experiments, where the sample was always magnetized, we observed many spikes. The maximum number of spikes occurred in the low field region where the magnetization is expected to have a maximum. The number of spikes also increased with the magnitude of the transport current.

Based on the above observations and the shape of the spikes signals, we were able to separate the spikes into two groups. The first group of spikes can be associated with demagnetization of the strand filaments, the second group with the transport current in the strand; hence they have been named 'magnetization' spikes and 'transport current' spikes.

During an up-ramp of the magnetic field from 0 T with no transport current present in the conductor (always starting with the sample demagnetized) the voltage spikes were always negative. On the other hand, on ramping down from high field, the voltage spikes were always positive. The polarity change of the signal is a characteristic feature of 'magnetization' spikes. It is most likely that 'magnetization' spikes are related to the change of the magnetic flux in the filaments of the strand that is experiencing the demagnetization. The magnetic flux change has a different sign depending on the direction in which the strand was magnetized. We also observed that these spikes can propagate longitudinally: the voltage spike was observed to start in one half of the coil and move into the other half. This behavior has been observed in cable tests as well [6]. An example of this type of spike is shown in Fig. 3: the two curves display the voltage in the two halves of the sample. To be able to compare the two signals easily, the second signal has been offset. The signals can be divided into two parts: the first part, p1, has a sharp rise and fall; the second part, p2, has a 'smooth tail'. Comparing the two half coil signals we can clearly see the time delay between the two p1 signals (longitudinal propagation), on the other hand, the two p2 half coil signals are equal. Fig. 4 is a different example of a magnetization spike: the increase of the voltage in the coil where the flux jump is propagating, instead of being almost instantaneous, rises progressively in about 2 ms. In sample C, shown in Fig. 5, high frequency oscillations are superimposed on the same kind of signal that was observed in sample D (Fig. 4). The origin of these oscillations has not been yet investigated. Since their frequency is very high (few kHz) and no Lorenz forces are applied to the strand, a mechanical origin should probably be excluded. In the literature, there are models which predict voltage oscillations during a flux jump [7].

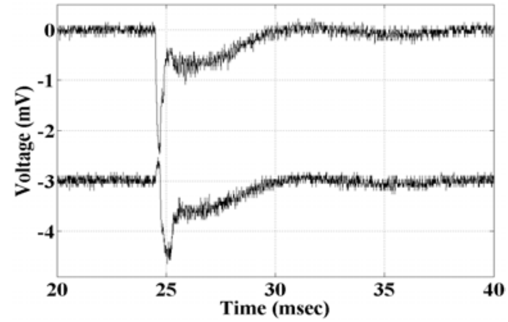

Fig. 3. 'Magnetization' Voltage Spike in sample D

'Transport current' spikes were observed in samples C and D when the filaments were magnetized and a transport current was flowing in the strand. Only one was collected for sample A. A significant feature is that the signals were positive even if the sample was negatively magnetized, hence these signals can not be associated with filament demagnetization.

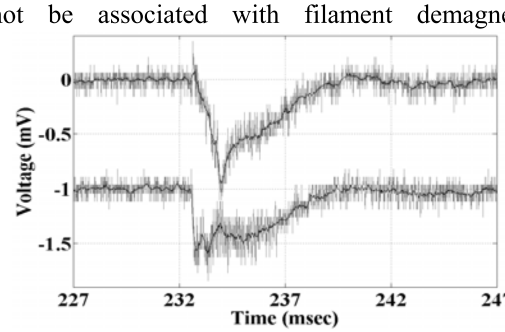

Fig. 4. 'Magnetization' Voltage Spike in sample D

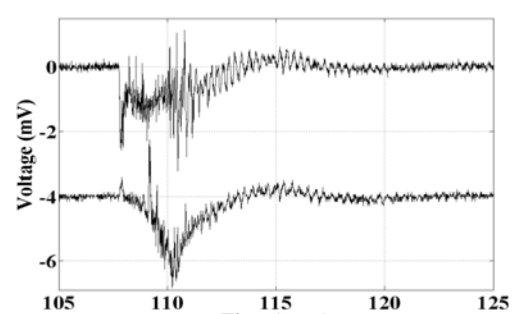

Fig. 5. 'Magnetization' Voltage Spike in sample C

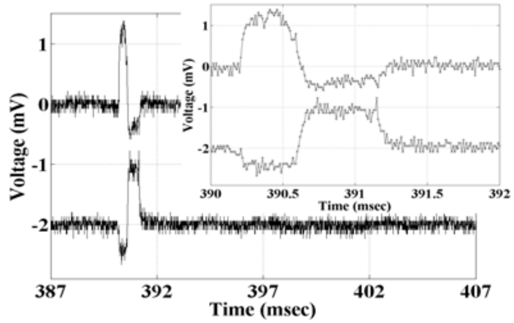

Fig. 6. 'Transport Current' Voltage Spike in sample D

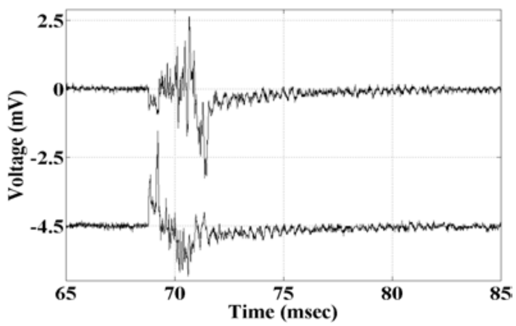

Fig. 7. Superimposition of 'Transport Current' and 'Magnetization' Voltage Spike in sample C

'Transport current' spikes are most likely related to the redistribution of the transport current within the strand. Fig. 6 displays a 'transport current' voltage spike. These spikes also propagate longitudinally, as is visible in Fig. 6. (Note: the small signals in each half coil indicate some inductive pickup, most likely due to an origin near the separating voltage tap.) The shape of these spike voltage signals is characterized by fast rise and fall times and a negligible 'smooth tail'. 'Transport current' spikes do not appear if the sample is demagnetized which probably means that these events are triggered by filament flux jumps. Superposition of the 'transport current' and the 'magnetization' spikes has been observed frequently during the E3 experiments, as shown in Fig. 7. The first part of the signal was positive due to the 'transport current' redistribution; the second part was negative due to the demagnetization process in the filaments.

The quenches observed in a magnetized strand had a spike triggering the quench, Fig. 8. In particular, samples C and D had 'transport current' spikes immediately before the quench. It is also interesting to notice that in strongly magnetized samples, when the I_q was close to the I_{qm}, many spikes were observed immediately prior the quench.

A general characteristic of the voltage spikes is that they are a local phenomenon that can propagate. Moreover, they have

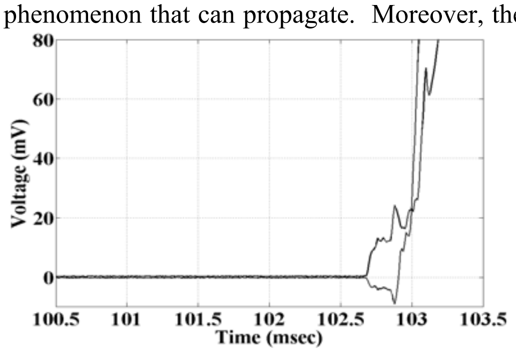

Fig. 8. Voltage spike triggering a quench in sample C

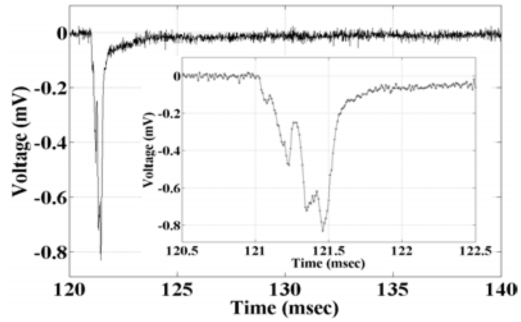

Fig. 9. 'Magnetization' Voltage Spike in sample A – bucked signal

a substructure even at the mono filament level (Fig.9). This could mean that flux penetration is not a continuous process.

VI. Conclusion

Two type of spikes, 'magnetization' and 'transport current' spikes have been identified. Their origin is most likely related to magnetization flux jumps and transport current redistribution respectively. Many of the signals observed are a combination of these two types of spikes and the combination of these two instability mechanisms is probably the cause of the minimum quench current. No spikes were observed when the sample was not magnetized even if it was self field unstable. In strongly magnetized samples, when the quench current was close to the minimum quench current, many spikes were observed right before the quench and even the quench was triggered by a voltage spike. We found that the voltage spikes are local phenomenon that can propagate longitudinally. Their development is not a continuous process and it is responsible for substructure even at the monofilament level.

Acknowledgment

The authors thank the staff of Fermilab's Technical Division for their contribution to this effort.

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