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Precursory Voltage Signals in Cosine Theta Nb_3Sn High Field Model Magnets

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Abstract— **To understand the premature quenches of the Nb_3Sn high field model magnets, we also made mirror design model magnets, and studied their quenches. With one of the mirror magnet, HFDA-03A, which had extra lead cables installed, some precursory voltage signals were observed at soldered joints in the high field region, leading to quenches at high ramp rate. These voltage signals diminish with slower ramp rate. The ramp rate dependence of the quench behaviors is experimentally studied. In the course of these quench investigation we developed a method to cancel the inductive voltage in the voltage tap signals. This method proved very effective to understand clearly how the quenches are propagating in all parts of the magnets.**

Index Terms— **Nb3Sn high field magnets, Quench, Rutherford cable**

I. Introduction

At Fermilab we are working on the development of Nb_3Sn High Field Model Dipole Magnets, trying to make model dipole magnets in the field range 10 to 11 T. In the previous years, we tested the cosine theta model magnets HFDA-03 and HFDA-04 [1]. They reached roughly the 50 (9,700A) and 60 (12,000A) percentage of the short sample data. Both of magnets showed that many of the quenches started near the power leads. As possible causes of this premature quenches, we started investigation on many causes. That includes, the mechanical damage in the Nb_3Sn cable near the splice regions, improvement of the splices, possibility of flux jumping, some possible defective Nb_3Sn cable, and the effect of BICC.

To expedite the investigation, we started the series of mirror magnets a year ago. First we made HFDA-03A, utilizing one half coil of the existing HFDA-03 magnet [1]. Most of the quenches of HFDA-03 occurred near leads. And we had some notion that the cable near the leads might have been damaged mechanically during handling the cured coil. To investigate this possibility, an additional pair of leads, which were made of NbTi Rutherford cables were added 13.5 cm inside from the ends of the existing old splices in order to bypass that suspected part of the cables. Also to study possible current redistribution, a pair of NbTi Rutherford cables, 14.9 cm long, was soldered on the same median plane at the return end side of the coil, as shown in Fig 1.

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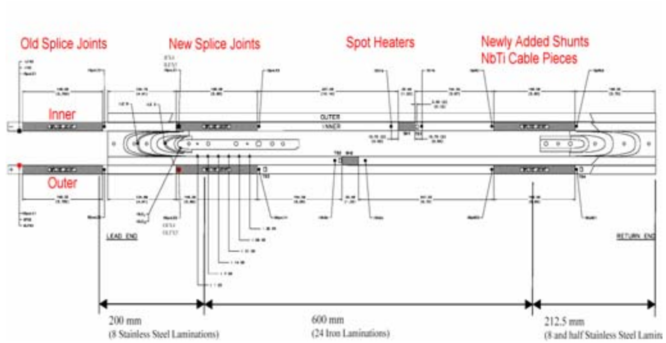

Fig. 1. Layout of Splices and Instrumentation of Mirror Magnet HFDA-03A

The mirror magnet HFDA-03A was tested on two separate occasions. The extensive test results on both runs are reported in another report on many test items, including Temperature Margin Test, Spot Heater Test, as well as on the Quench Test [2]. Its ramp rate dependence is shown in Fig.2. In the first thermal cycle TC-1 (with triangle marks), the magnet was excited with the original splices. The quench current is below 7,000 A, having a moderate ramp dependency. In the second thermal cycle TC-2 (with diamond marks) it was operated with the newly added splices. The quench current went up to 10,000 A to almost 11,700 A at the ramp rate below 140 A/sec. But above 150 A/sec, it went down drastically almost as same as that of TC-1. Both runs were tested at 4.45K.

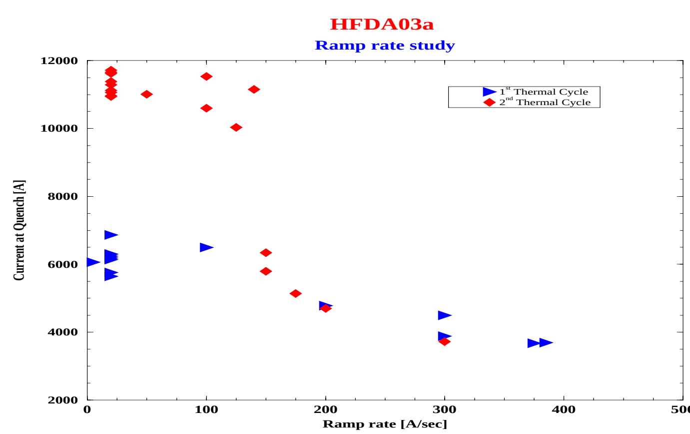

Fig. 2. Ramp Rate Dependence of Mirror Magnet HFDA-03A at 4.5 K. At 140 A/sec, there is a sharp decrease in the quench current in TC-2 run.

We pursued to investigate this ramp rate dependence with a possible relation to BICC [3, 4]. We have not achieved a clear cut relation yet, but we observed a very peculiar precursory voltage signal just before the start of quench at high ramp rate. A detailed analysis on its quench is given in another report [5].

When we are testing a short superconducting magnet, the time constant of the system is very short. This causes the rapid decay of the current, inducing large inductive voltages in the observed voltage signals, causing problems for the interpretation of the experimental data. Therefore we developed a method to correct this inductive voltage [6, 7]. The corrected voltage signals show a much cleaner quench signals. Then we are also able to study more easily the data near the quench starting points.

The HFDA-04 achieved its highest quench current, 12,199 A, corresponding to the central field B_o of 7.2 T, at the ramp rate of 20 A/sec at 2.15 K. At 4.5 K operation its highest current was 11,647 A, corresponding to B_o of 6.8 T, reaching 64% of short sample data with the assumed Jc = 1,750 A/mm^2, including degradation of 0.875, at 12 T and at 4.2 K.

II. Characteristic Structure of HFDA-03A Magnet

The Nb_3Sn Rutherford cable is made of 28 strands of 1.0 mm diameter, made by MJR method by OST. Its width is 14.24 mm, and the median thickness is 1.8 mm. Its compaction factor is 88 %, and it is keystoned with 1.02 degree angle. The cable has an annealed 316 stainless steel core, 25 μm thick and 9.5 mm wide, to reduce the crossover resistance Rc.

The strand has 54 subelements. The effective size of the filament, deff is about 110 μm, and the RRR is rather low and in the range of 4 to15. Therefore the filament coupling and hysteresis loss are quite high. The adjacent resistance Ra value of the cable with a stainless core for the HFDA-03A is reported to be about 1.8 μΩ [7].

The locations of the pair of the Old (original) set of Splices and the New set of Splices on the median plane of the HFDA-03A are shown in Fig.1, together with the added NbTi Cable Shunt Pieces on the return end.

At this coil lead end region, the boundary condition of the cable for the BICC is quite complicated. First the old splice is at the low field region. The Nb_3Sn cable is soldered to a NbTi lead cable, by extracting the stainless core locally. Then there is a cored Nb_3Sn cable, about a cable pitch length, in the high gradient field region. Next is followed the new splice, at high field region, which is soldered to the NbTi lead cable only at the top side of the Nb_3Sn cable, leaving the core inside.

III. Observation of Precursory Voltage Signals at Soldered Places at Fast Ramp Rate

With quench data of the HFDA-03A mirror magnet, we observed some precursory voltage signals, especially at fast ramp rates, ranging from 1 to 20 mV signals across the new splice at high field or across the soldered NbTi shunt piece also at high field [5]. They are estimated to generate heating power in the order of 0.1 to 2 Joules. They are preceding a few to 45 ms relative to t = 0 ms time. These voltage signals usually diminish to the order of 1 mV at the nominal ramp rate of 20 A/sec, but occasionally we observed the voltage signal at the soldered NbTi cable piece even at 20 A/sec.

A typical example is shown in Fig. 3, where the Quench No.13 of HFDA-03A is shown. It is the case with a ramp rate of 380 A/sec, and shows a voltage signal at the Inner Shunt at t = -45 ms (the bottom line), and also another voltage signal at the Inner New Splice at t = -40 ms (the 2nd line from the bottom). These voltage signals are estimated to deposit about 0.8 J and 1.5 J at their locations. These energy deposits can be considered big enough to start quenches at these points, but due to the fairly large heat capacitance of these parts and due to the well cooled outside surface, they could not propagate a quench. In the meantime the second turn under these soldered and heated parts can be estimated to get heated and start to quench at t = -25 ms (15 ms delay relative to the signal at the Inner New Splice) [10]. Actually the triggering quench is observed starting in and propagating in, QILE8-QI1CR, the Inner Coil of 2nd and 3rd turns and the one half turn of the 1st coil, at t = -25 ms, which is 20 and 15 ms later than the precursory voltage signals.

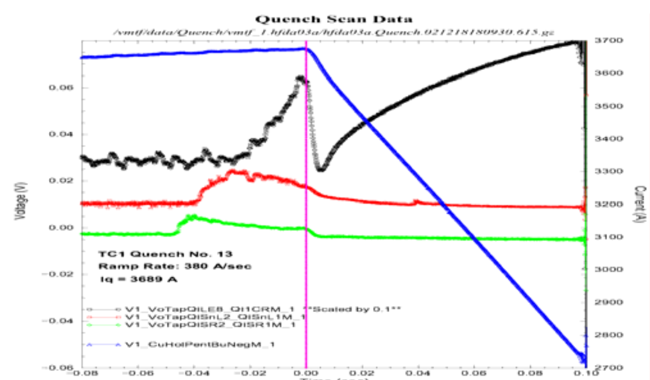

Fig. 3. Quench No. 13 of TC-1 of HFDA-03A. The highest Ramp Rate of 380 A/sec of TC-1. Iq = 3689 A. Precursory voltage signals are observed in the New Inner Splice (2nd from top) and Inner Shunt (3rd from top).

When the voltage of QILE8-QI1CRM_1 (2nd line from top, reduced by 1/10) grows to 0.5 V, it turns off the power supply. Its quench voltage is still growing due to the quench propagation. At t = 0, its voltage is shifted down inductively due to the rapid decaying current at the rate of –9,500 A/sec (top line). From the voltage drop of 0.45 V, the effective inductance of that part of the coil is estimated 0.047 mH.

IV. Quenches at Slow Ramp Rate

For the slow ramp rate range of the HFDA-03, the data of Quench No.4 with the ramp rate of 5A/sec is shown in Fig. 4. There are no clear precursory voltage signals at both New

Splices and Shunts. But the short Cable, QISnL1-QISol2, which is between two Inner Splices, starts a normal quench and completes a quench propagation cycle, as shown in Fig.4.

This phenomenon of spontaneous quenching in the cable, but not at any soldered parts, seems caused by the complicated boundary condition in this region. It seems to be not due to any mechanical damage in the local cable. It may be due to Electro-Magnetic Phenomenon.

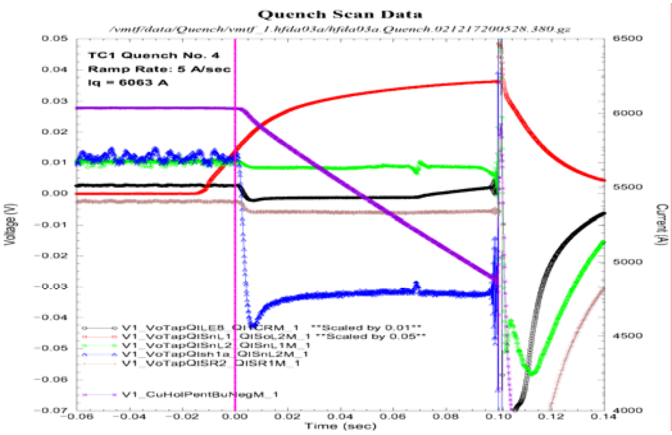

Fig. 4. Quench No. 4 of TC-1 of HFDA-03A at the slowest Ramp Rate of 5 A/sec. Iq = 6063 A. The short cable between two inner splices quenches.

During the current decay, another quench is started at t = +69 ms in QILE8_QI1CRM_1, the Inner Coil part, containing the 2nd and 3rd turns of the Inner Coil. It seems the excessive heating at the short Cable between two Inner Splices, caused lateral quench propagation to the underlining 2nd turn cable through the insulation.

Stability of the magnet depends on the thermal balance between the heating and cryogenic cooling, especially around splice and other soldered regions. The splice joint is made up by connecting the Nb_3Sn cable to NbTi cables, which has a much lower Tc(0) than that of Nb_3Sn cable.

V. Voltage Signals and Induced Voltages

After a quench starts, the voltage V(t) across two voltage taps of the coil can be expressed as follows,

$$V(t) = Rn(t) \times I + L_{eff} \times dI/dt \approx Rn(t) \times I + L_{eff}\, \Delta I/\Delta t,$$

where Rn(t) is the normal resistance of that part of the coil, and L_{eff} is the effective inductance of that part of the coil. The method to get clean signals by extracting the induced voltage is explained in another report together with magnet data [6,7].

VI. HFDA-04 Magnet and Splices

The HFDA-04 dipole magnet has two layer coils, with the inside surface of the inner coils is exposed to liquid He. The Outer Coil is covered with an insulation layer, which contains the strip heater for heating the lower two blocks of the Outer Coil. The entire coil is clamped and covered with an 8 mm thick aluminum half cylinders and an iron yoke.

The 28 strand Nb_3Sn Rutherford cable of this magnet is also made of Oxford MJR 1mm strands, but it has no stainless core inside the cable. This point is different from all other magnets, which has been tested. This means this magnet may behave, because the value of Rc is smaller than other magnet. Both Ra and Rc were measured as 19 μΩ [9].

This magnet has rather small ramp rate dependence. At 4.5 K operation the quench currents are 11,647 A at 20 A/sec, 10,111 A (-13.2 %) at 75 A/sec, and 9,692 A (-16.8 %) at 500 A/sec [11]. This is quite different from the case of HFDA-03A [2], which shows a sharp decrease at around 140 A/sec.

The splice is made by soldering the Nb_3Sn cable with a NbTi Rutherford cable only on one side. And another Rutherford cable made of copper is soldered on the outside of the NbTi cable. The other side of the Nb_3Sn cable is resting on the ceramic bar. The whole conductive region is covered with 3 mil (75 μm) thick Kapton tape, and the whole coil assembly is Epoxy impregnated.

Two lead cables, made of NbTi and Copper Rutherford cables, from the inner coils of two half magnets are used as power leads. The other pair of lead cables from the outer coil segments, 33.5 cm long, is soldered together at their ends over 13.5 cm and encased in G10 structure and attached to the magnet assembly. The measured resistances of all four splices are about 1 nΩ each.

VII. Quench Data of HFDA-04 Magnet

There are 29 quench data at 4.5 K, and 8 quench data at 2.15 K with the HFDA-04 magnet. All of quenches at 4.5 K started at the outer splice regions, between the Nb_3Sn and NbTi cables, for the ramp rate from 20 to 500 A/sec with a rather flat ramp rate, peaking 11.65 kA at 20 A/sec [11].

With 2.15 K operation, four of them quenched at the H1 Outer Coil connecting splice, one of them at the H2 Outer Coil connecting splice, one of them simultaneously at both H1 and H2 Outer Coil connecting splices, and two of them at H2 Inner Coil Lead splices. All quenches at 2.15 K were tested at 20 A/sec, and they were from 11.2 to 12.2 kA.

The H2 Inner Coil Lead splice, where 2 Quench events started at 2.15 K, is located in the inner layer of the coil, which is more directly cooled by the liquid He than the other splices. The connecting Outer Coil splices of H1 and H2, where most of the Quench Events started, are on the outer layer coil, which are less cooled because it is not directly exposed to liquid He.

In Fig. 5 and 6 are shown the original and corrected voltage signals of the individual coil segments; H1-Inner (bottom line), H1-Outer (2nd top line), H2-Outer (top line) and H2-Inner (2nd bottom line) coils, for the Quench 28 event with the highest 12,199 A at 20 A/sec at 2.15 K [12]. We can observe clear quench signals in both Outer Coils in Fig. 6.

To investigate the quench starting points, the voltage signals of the H1 and H2 Outer splice voltage signals (200 times magnified) are shown in Fig. 7 together with the H1-Outer (2nd top line) and H2-Outer (top line) coil signals. The voltage signals at two splices (across Nb_3Sn and NbTi) and their corresponding voltage signals across the Nb_3Sn cables and Cu cables are shown in Fig. 7. We can judge the quench started at t = -5 ms simultaneously at or near both Outer coil splices. There is possibility that the pieces of NbTi cable at these splices momentarily quenched first due to heating effect of BICC, and triggering off the power supply, leading a kind of quench.

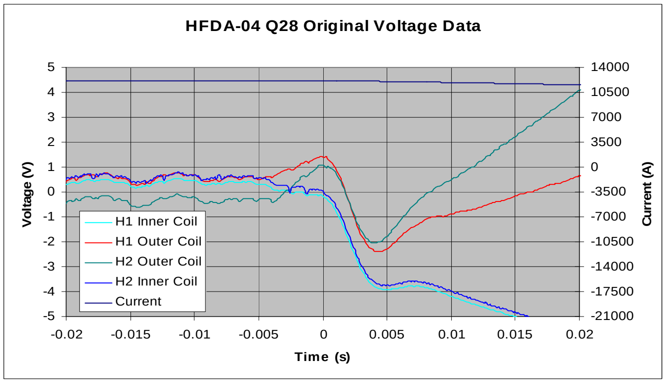

Fig. 5. Original voltage signals of four coil segments of Quench 28.

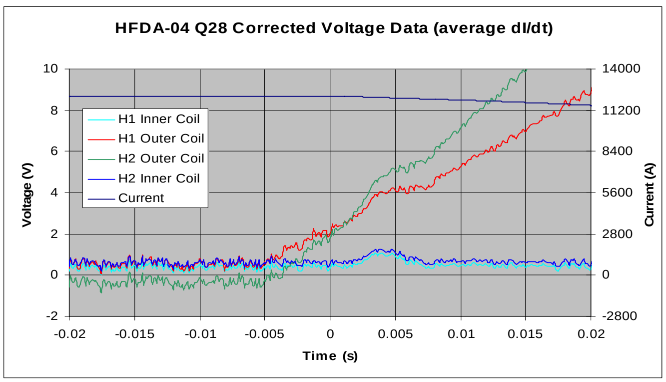

Fig. 6. Corrected voltage signals of four coil segments of Quench 28.

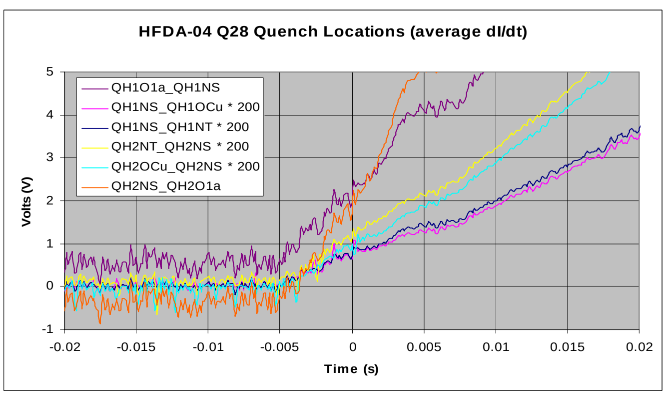

Fig. 7. Comparison for quench starting points of Quench 28. Splice voltages at H1 and H2 Outer splice voltages are shown together with H1 (2nd top line) and H2 (top line) Outer coil signals.

VIII. Conclusion

As long as we are using Rutherford cables to make superconducting magnets, we cannot avoid the effects of InterStrand Coupling Currents and BICC. Therefore we should reduce the causes of creating bad boundary conditions as much as possible to reduce the effect of them. We should avoid any extra soldered splice joints and shunts as much as possible. They especially should not be placed in high magnetic field nor in high gradient field region, unless well cooled.

It seems realized that, at high ramp rate, the effect of the BICC is enhanced. With higher supercurrents, it generates more heat at the soldered splice joints and shunts, and initiating the regular quenches, which are manifested by the precursory voltage signals. These voltage signals are reduced with the slower ramp rate, but still the effect of the supercurrent should be there with reduced magnitude, as is shown in the case of TC-2 of HFDA-03A magnet.

The problem of these ISCC and BICC is related to thermal balance between the heating due to these coupling currents and cooling by the coil structure, namely to the problem of cryostability. We should try to make the splice joint, which contains a NbTi cable, to be away from the coil body and well cooled with liquid Helium. The Nb_3Sn cable is completely epoxied, and does not have space to be permeated with liquid He, like NbTi cable. This will make a difference for the cooling and for supercurrent, even though the H_{c2} value of Nb_3Sn is higher.

With the present HFDA-04 magnet all quenches started at the splices or near splices. It seems the splices should be improved. All of the splices of this magnet are made with one NbTi cable and another Cu cable. We should use two NbTi cables and add copper heat sinks around the splice, and improve cooling of the splices by providing liquid He passage by making spiraling He passage on the inside surface of the aluminum spacers.

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