Quench Problems of Nb$_3$Sn Cosine Theta High Field Dipole Model Magnets

Ryuji Yamada and Masayoshi Wake

Abstract—We have developed and tested several cosine theta high field dipole model magnets for accelerator application, utilizing Nb$_3$Sn strands made by MJR method and PIT method. With Rutherford cables made with PIT strand we achieved 10.1 Tesla central field at 2.2 K operation, and 9.5 Tesla at 4.5 K operation. The magnet wound with the MJR cable prematurely quenched at 6.8 Tesla at 4.5 K due to cryo-instability. Typical quench behaviors of these magnets are described for both types of magnets, HFDA-04 of MJR and HFDA-05 of PIT. Their characteristics parameters are compared on $d_{eff}$, RRR, thermal conductivity and others, together with other historical Nb$_3$Sn magnets. It is suggested a larger RRR value is essential for the stability of the epoxy impregnated high field magnets made with high current density strands. It is shown that a magnet with a larger RRR value has a longer MPZ value and more stable, due to its high thermal conductivity and low resistivity.

Index Terms—Nb$_3$Sn high field magnet, Quench, PIT, MJR, RRR

I. INTRODUCTION

In the past several years we developed and tested several Nb$_3$Sn cosine theta model magnets, and their mirror magnets [1]. The earlier magnets were wound with Rutherford cable made of MJR strands, manufactured by Oxford Instruments Technology Ltd, which was the only commercially available high current density Nb$_3$Sn superconductor at that time for the high energy accelerator magnet. The quenches started prematurely mostly near or at the splice regions at the nominal operation ramp rate of 20 A/sec. With these magnets the premature quench was the main problem.

This year, using the recently improved PIT Nb$_3$Sn strands from ShapeMetal Innovation B.V., we made and tested a mirror magnet HFDM-03 and a regular cosine theta magnet HFDA-05 [2]. With these magnets, we achieved the current level of the short sample test data of the extracted strands [3]. The central field values $B_0$ of the HFDA-05 we achieved are 9.5 Tesla and 10.1 Tesla at the operation temperature of 4.5 K and 2.2 K respectively. With these magnets, the main problems are the training, probably due to the epoxy cracking and subsequent wire motion, and some degradation of the short sample data due to the cabling.

The importance of RRR for the stability of the Nb$_3$Sn magnets was reported at the Fermilab Workshop on Instability in April 2004 [4]. By comparing our results with the historically successful magnets, the causes of the quenches were investigated. The analysis of this problem is being worked out using a 3-D FEA by ANSYS.

II. BASIC PARAMETERS OF COSINE THETA DIPOLE MAGNETS

The coil cross section of the cosine theta dipole magnet is shown in Fig.1. In this figure the flux distribution at 20 kA, corresponding to $B_0 = 11$ Tesla is shown. All coils of the tested magnets were wound with Rutherford keystoned cables made of 28 strands of 1mm diameter Nb$_3$Sn strands [5], [6].

The cosine $\theta$ magnet HFDA-04 and its corresponding mirror magnet HFDM-02 are wound with MJR strand cables, and the mirror magnet HFDM-03 and its corresponding cosine $\theta$ magnet HFDA-05 are wound with PIT strand cables. The major characteristics of these strands are summarized in the Table I.

The detailed characteristics of the magnets of both types of strands, including their power lead splice structure are reported

<table>
<thead>
<tr>
<th>Deff, $\mu$</th>
<th>RRR</th>
<th>Ic (10T), A</th>
<th>Ic (12T), A</th>
<th>State</th>
<th>$T_c(0,0)$, K</th>
<th>No.of Subelements</th>
</tr>
</thead>
<tbody>
<tr>
<td>MJR</td>
<td>110</td>
<td>5</td>
<td>984</td>
<td>Virgin</td>
<td>18.3</td>
<td>54</td>
</tr>
<tr>
<td>PIT</td>
<td>50</td>
<td>89</td>
<td>825</td>
<td>Extracted</td>
<td>18.3</td>
<td>192</td>
</tr>
</tbody>
</table>

Table I. Typical Characteristics of 1 mm MJR and PIT Strands

Fig. 1. Cross section of cosine theta magnet, shown with the flux distribution at
II. QUENCH PROBLEMS WITH MJR MAGNETS, HFDA-04 AND HFDM-02

We have produced and tested several short cosine theta Nb$_3$Sn model magnets with MJR cables in the last several years. The most typical one is HFDA-04 [5] and its corresponding mirror magnet HFDM-02 [7]. Both HFDA-04 and HFDM-02 magnets were wound with keystoned MJR Rutherford cables. They have very low RRR values of 5 and 6, respectively. These magnets wound with MJR cables were quenching at a substantially low field, and showed similarly premature quenched near or at the splices at 4.5 K operation [8].

The cross section of the heat treated MJR Rutherford cable, is shown in Fig. 2, where the end of the cable is pictured. The most outside strand is pushed hard and flattened, and the next strand is really squeezed making a tear drop shape. The subelements at squeezed areas in these strands are seen damaged due to the cabling process. During heat treatment cycle, the inside pure tin melts and leaks out of the niobium mesh to the outside. The copper tubes surrounding the subelements were contaminated, and in worst case the overall copper stabilizer was contaminated, reducing the RRR to the order of 5.

In September 2004, the regular cosine theta dipole magnet, HFDA-05, (Coil-12 + Coil-13) was excited up to 16.93 kA, corresponding to $B_0 = 9.5$ T at 4.5 K, and up to 18.17 kA, corresponding to $B_0 = 10.1$ T at 2.2 K, both at 20 A/sec ramp rate. Considering the maximum field in the conductor is 5% of a Nb$_3$Sn cable, NbTi cable, and solder. The NbTi cable with a lower $T_c$ value is more susceptible for starting a quench, if the splice is not well cooled.

A. Why LBNL RD3c Magnet Achieved 13 Tesla, While HFDA-04 Quenched Prematurely?

In the past few years Fermilab group always used 1 mm MJR strands for cosine theta magnets, except for the recent magnets made with 1 mm PIT strand cables. LBNL group has used 0.8 mm MJR strands for their RD3c magnet and obtained 13 Tesla [10].

While our highest $B_0$ field achieved was 6.8 Tesla with cosine theta magnets, they achieved 13 Tesla with RD3c Race Track dipole magnet using same MJR material. The difference between HFDA-04 and RD3c are shown in the following Table II.

<table>
<thead>
<tr>
<th>Magnet type</th>
<th>$B_{\text{peak}}$</th>
<th>Strand</th>
<th>dia.</th>
<th>$d_{\text{eff}}$</th>
<th>Keystoned</th>
<th>RRR</th>
</tr>
</thead>
<tbody>
<tr>
<td>HFDA-04</td>
<td>6.8 T</td>
<td>MJR</td>
<td>1 mm</td>
<td>110 $\mu$m</td>
<td>Yes</td>
<td>5</td>
</tr>
<tr>
<td>RD-3c</td>
<td>13.0 T</td>
<td>race track</td>
<td>0.8 mm</td>
<td>88 $\mu$m</td>
<td>No</td>
<td>92/13/16</td>
</tr>
</tbody>
</table>

There is 20% difference in $d_{\text{eff}}$ and there is a substantial difference in RRR values. It is partially due to keystoning of the HFDA-04 cable. The field distribution inside the conductor of HFDA-04 is rather uniformly high except in the outer layer region. But the field distribution of RD3c is rather localized, and it is peaked to the maximum field of 13 Tesla at the inside edges. If the field distribution has a big gradient in the cross section of a cable, there might be a chance of current sharing between strands.

IV. QUENCH VALUES OF PIT MAGNETS, HFDM-03 AND HFDA-05

After two years of collaborative effort with Fermilab, SMI succeeded recently to make and supply us their PIT strands, with reasonable degradation when made into Rutherford cables. Their 1 mm strand has 192 subelements, and its $d_{\text{eff}}$ is 50 $\mu$m.

In April 2004, the mirror cosine theta magnet, HFDM-03, was excited up to 21 kA at 4.5 K and 21.8 kA at 2.2 K. This mirror magnet had a half coil (Coil-12), which was wound with a keystoned PIT Rutherford cable of 28 strands of 1 mm diameter. The peak field values in the cable were 9.75 T at 4.5 K and 10.0 T at 2.2 K respectively [2]. This mirror magnet (Coil-12) had an RRR value of 84.

In September 2004, the regular cosine theta dipole magnet, HFDA-05, (Coil-12 + Coil-13) was excited up to 16.93 kA, corresponding to $B_0 = 9.5$ T at 4.5 K, and up to 18.17 kA, corresponding to $B_0 = 10.1$ T at 2.2 K, both at 20 A/sec ramp rate.
more, both cables of these two magnets reached the same short sample limit. The RRR value of the HFDA-05 is measured 113.

These quench current values are regarded near their short sample data of PIT cables. This high RRR values have contributed to the excitation up to the short sample test data current.

The Rutherford cables for HFDM-03 and HFDA-05 are keystoned with a compaction factor of 88.5 %. The cross section of this cable after heat treatment is shown in Fig. 3. There are some slightly damaged subelements inside the strands at the edge of the cable. But this may be tolerable for the magnet operation, but it is contributing to the degradation of the $I_c$ value.

Because the PIT strand uses NbSn$_2$ power in the Nb tubes and does not have pure tin as much as the MJR strand, there is much less chance of contamination during heat treatment. This is the advantage of PIT strand over the internal tin strand when using the Rutherford cable.

V. TRAINING DUE TO EPOXY CRACKING

The training quench data of HFDA-05 are shown in Fig. 4. During the 4.5 K operation the first quench started from 14.0 kA and its 29$^{th}$ quench is in the flattened state at 16.8 kA range. It had about 17 % of excessive training range.

All of these quenches started from the inner most 3-turn block of the inner layer. The inner surface of the inner coil is directly exposed to liquid He. The inner surface showed a lot of cracking in epoxied surface even before testing. We think further cracking of the epoxy due to Lorentz force may be the main cause of the training of the magnet, thus inducing wire movement with heat generation.

To avoid the quench due to cracking of epoxy, we should avoid buildup of epoxy on the inner surface. In the future this excessive training should be eliminated. For instance, the CERN-ELIN magnet did reach 9.5 T at the second quench.

The cracking of epoxy on the inside layer surface has been observed also with our previous magnets, HFDA-04, HFDM-02 and others.
VII. DISCUSSIONS

With the cosine theta dipole magnets wound with MJR cables, we always experienced premature quenches without reaching their short sample values. With the R&D magnets developed at LBNL, RD3C and HD1, they could excite their magnets up to the short sample data limit. Our cables are keystoned, while LBNL cables are rectangular and not keystoned. Probably the difference in RRR values; ours 5 to 6, while theirs above 13, made a difference. As pointed out before we can expect the RRR value will be important for the stability.

Consideration of a minimum propagating zone, MPZ is helpful to evaluate the stability of magnet [11]. MPZ is given for a superconductor with copper ratio $r$, as,

$$MPZ = \frac{r}{r + 1} \left(\frac{2k(\theta_c - \theta_0)}{J_c^2 \rho}\right),$$

where $\theta_c$ is the critical temperature, $\theta_0$ is the bath temperature, $J_c$ the critical current, $k$ and $\rho$ are the thermal conductivity and resistivity of copper respectively. If the critical current is the same, MPZ is determined by the ratio of $k$ and $\rho$. The RRR = 80 conductor should have about 15 times larger MPZ than that of the RRR = 5 conductor. Such a large difference in MPZ can explain the difference of magnet performance.

When the RRR value of the Nb$_3$Sn is very low, less than 10, the design of the power lead should be made very conservative, by providing enough cooling channels, by using two NbTi power lead cables and adding a copper heat sink to prevent the temperature rise of that part. Otherwise that part will start a quench due to flux jump because it is in the low field region. When the RRR value is large, 80 or so, just a single NbTi cable will work well.

VIII. CONCLUSION

With the use of PIT strands, we could reach 10 Tesla field. Probably there are several reasons for this. Its small $d_{eff}$ improved the stability of the strand due to the small value of flux jump energy. But more likely its higher value of RRR did improve the cryostability.

But there are still many things are to be improved. The magnets are showing extensive training. We think it is probably due to the cracking of the epoxy and wire motion. This problem should be fixed.

Our PIT cables show a large degradation partially due to cabling and keystoning. We have to improve these techniques, as well as we have to encourage the industry to make better Nb$_3$Sn strands for Rutherford cables.

For the stability of the magnet, it is now clear to have a strand with a smaller $d_{eff}$ to prevent the effect of flux jump. At the same time we should have a bigger RRR value from the standpoint of cryo-stability. The MPZ of the conductor is strongly affected by the RRR value.

The correlation of $d_{eff}$ and RRR value is shown in Fig. 7 with our magnets and the historical Nb$_3$Sn magnets [3]. We drew a line between the stable and unstable regions. This stability region should be studied further.

References


Fig. 6. Thermal conductivity of copper with different RRR values.

![Thermal Conductivity of Copper](image-url)