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and R.M. Scanlan

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Abstract

We have observed that some of our model SSC dipoles have long time constant decays of the magnetic field harmonics with amplitudes large enough to result in significant beam loss, if they are not corrected. The magnets were run at constant current at the SSC injection field level of 0.3 tesla for one to three hours and changes in the magnetic field were observed. One explanation for the observed field decay is time dependent superconductor magnetization. Another explanation involves flux creep or flux flow. Data are presented on how the decay changes with previous flux history. Similar magnets with different Nb-Ti filament spacings and matrix materials have different long time field decay. A theoretical model using proximity coupling and flux creep for the observed field decay is discussed.

Introduction

The quality of the magnetic field in the model SSC dipoles has been a major concern in that circulating beam can be lost if field imperfections exceed approximately 10^-4 of the dipole field, especially at the injection field of 0.33 tesla or 1 TeV. Incorporated in the magnet test program has been an extensive magnetic field measurements program at all field levels. Because of magnetization currents flowing in the superconducting filaments, the exact field distribution depends on the path taken to reach a given field. We have been careful to follow a standard excitation path. An example is shown in Fig. 1, with the complete excitation and measurement cycle being from zero field to 6.6 tesla and then decreasing to zero.

Generally, it was found that the magnetic field non-uniformities repeated quite well, but sometimes there were differences that were unexpected. These differences were traced to different delay times between the magnet excitation and magnetic field measurement; since no decay was expected, there was no standard delay time. When we looked for field decay with time, we found it. Several magnets with different superconductor designs were tested for magnetic field decay and some of that data is presented here. The largest effect is seen in the normal sextupole component, although it also appears in the other multipoles allowed in a dipole. In this paper, we will focus on the sextupole.

Figure 2 shows the effect of different excitation times. In the cycle case, the magnet is ramped to 6600 A at 16 A/S, back to 50 A, and up to 320 A at the same rate for a total of about 15 minutes before the decay measurements begin. When this cycle is interrupted to make magnetic measurements on the upramp and downramp, the time is increased to about 120 minutes. We call this a "sweep". The decay after the fifteen minute cycle is roughly linear on a semi-log scale, the first three measurements which take six minutes not lying on the straight line. For the two hour sweep, the first ten measurement, which take about twenty minutes, do not lie on the straight line which applies for the next hour of decay. The straight line slopes for the cycle and sweep modes are the same. The significance of this linear semi-log behavior is discussed below in the Explanation section.

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Figure 3 shows that the decapole also changes with time. Figures 4 and 5 show the injection sextupole field decays for four different magnets at 4.3 K. The magnets are almost identical except for their superconductors, which are listed in Table I.

![Fig. 3 Decapole Decay - Four Magnets](image)

![Fig. 4 Sextupole Decay - Two Magnets, Flux Creep Only](image)

Table I. A Comparison of the Superconductor in Four LBL Dipoles in Which Long Time Constant Field Decay was Measured.

<table>
<thead>
<tr>
<th></th>
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<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Inner Layer</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Number of Strands in Cable</td>
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<td>23</td>
<td>23</td>
<td>23</td>
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<tr>
<td>Strand Diameter (mm)</td>
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<td>0.808</td>
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<td>1.35</td>
<td>1.52</td>
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<td>Filament Diameter (μm)</td>
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<td>6.0</td>
<td>5.3</td>
<td>5.0</td>
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<tr>
<td>Filament Spacing (μm)</td>
<td>0.4*</td>
<td>1.5</td>
<td>0.53</td>
<td>1.2</td>
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<tr>
<td>Material Between Filaments</td>
<td>Cu*</td>
<td>Cu</td>
<td>Cu-Mn**</td>
<td>Cu</td>
</tr>
<tr>
<td>Jc at 5 T and 4.2 K (A mm(^{-2}))</td>
<td>2600</td>
<td>-2700</td>
<td>-2700</td>
<td>2650</td>
</tr>
<tr>
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<td>2.0</td>
<td>2.7</td>
<td>0</td>
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<tr>
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<td>1.6</td>
<td>2.2</td>
<td>1.6</td>
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<td><strong>Outer Layer</strong></td>
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<td></td>
<td></td>
<td></td>
</tr>
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<td>Number of Strands in Cable</td>
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<tr>
<td>Strand Diameter (mm)</td>
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<td>0.648</td>
<td>0.648</td>
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<tr>
<td>Normal Metal to S/C Ratio</td>
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<td>1.8</td>
<td>1.35</td>
<td>1.61</td>
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<tr>
<td>Filament Diameter (μm)</td>
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<td>6.0</td>
<td>4.3</td>
<td>5.0</td>
</tr>
<tr>
<td>Filament Spacing (μm)</td>
<td>0.4*</td>
<td>1.5</td>
<td>0.43</td>
<td>1.0</td>
</tr>
<tr>
<td>Material Between Filaments</td>
<td>Cu*</td>
<td>Cu</td>
<td>Cu-Mn**</td>
<td>Cu</td>
</tr>
<tr>
<td>Jc at 5 T and 4.2 K (A mm(^{-2}))</td>
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<td>-2700</td>
<td>-2700</td>
<td>2600</td>
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<td>5.4</td>
<td>2.0</td>
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<td>1.6</td>
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<td>1.6</td>
</tr>
</tbody>
</table>

*This superconductor is quite complex. The conductor consists of 52 μm diameter bundles of superconductor with 0.4 μ spacing between filaments within the bundle. The filaments are not round. The spacing between the filament bundles is about 3.5 μm.

**The filaments are nearly round and uniformly distributed in the conductor with manganese doped copper between filaments.
dependence observed by Fennilli in the Tevatron magnets. The critical current density or filament diameter has filament spacings or 4.7 mm. filament diameters have filament spacings or 0.85 T, and there is probably no proximity coupling between bundles. If the D-15A-4F magnet conductor had spacings between the filaments of 0.4 mm throughout the conductor (instead of in 52 mm bundles), the proximity coupling magnetization would be at least an order of magnitude more than that measured in the dipole D-15A-4F conductor. The Supercon conductor used in dipole D-15A-6, which has manganese doped copper between filaments, has a uniform filament spacing throughout the conductor. Yet the measured proximity coupling magnetization is smaller than that measured in the D-15A-4F Superconductor. \(^9\)\(^10\) Magnet measurements suggest that the manganese doping does really reduce proximity coupling but enough to completely eliminate it or the resultant field decay. Calculations using the SCMAG04 program suggest that most of the proximity coupling occurs in the outer layer of the magnet (where the filament spacing is smaller and the field is lower), and that there is almost no proximity coupling in the inner layer superconductor. The filament distribution in these two magnets are displaced in Figures 6 and 7.

In Table 2, we list the slopes of the linear portions of the sextupole vs. log t curves for the four magnets shown in Figures 4 and 5. The slopes are the sum of the flux creep and proximity coupling component, if any.

\begin{table}[h]
\centering
\begin{tabular}{|l|c|}
\hline
Magnet & Slope b2 (units)/decade (time) \\
\hline
D-15A-5R2 & 0.85 \\
D-15B-1 & 0.85 \\
D-15A-6 & 1.22 \\
D-15A-4F* & 3.47 \\
\hline
\end{tabular}
\caption{Slopes of Sextupole Decay - Two Magnets, Flux Creep Plus Proximity Coupling}
\end{table}

According to E. W. Collings, one can argue for a faster rate of decay in the proximity coupling currents because the region between filaments behaves like a weakly pinned superconductor with a lower Tc than the superconductor within the filaments. The magnitude of the proximity coupling currents is related to filament spacing, the filament bundle size, and material between the filament.

To test the hypothesis of proximity coupling as one source of magnetization (which then decays away), the SCMAG04 computer code was used to estimate the effect of superconductor magnetization (including proximity coupling) on the sextupole at a control induction of 0.33 T (when the magnet has been charged to high field, brought down to 0.05 T, then brought back up to 0.33 T). If one includes the extra magnetization due to proximity coupling measured by Brookhaven National Laboratory for the Furukawa cable used in magnet D-15A-4F* one get an extra negative sextupole of 3.4 units at a central induction of 0.33 T. If one dopes the matrix material, one should also reduce the magnetization due to proximity coupling. The addition of manganese to the copper in the superconductor of magnet D-15A-6 does reduce coherence of the copper, and it appears to reduce the proximity coupling between the filaments. The extra sextupole component at 0.33 T observed in dipole D-15A-6 is also reduced.

Unfortunately it is difficult to make a direct comparison between magnet D-15A-4F and D-15A-6 because the conductors in the two magnets are quite different in their structure. The conductor in magnet D-15A-4F is complex consisting of many 52 mm diameter bundles of 4.7 mm diameter filaments spaced 0.4 mm apart with copper between the filaments. The bundles of filaments are about 3.5 mm apart, and there is probably no proximity coupling between bundles. If the D-15A-4F magnet conductor had spacings between the filaments of 0.4 mm throughout the conductor (instead of in 52 mm bundles), the proximity coupling magnetization would be at least an order of magnitude more than that measured in the dipole D-15A-4F conductor. The Supercon conductor used in dipole D-15A-6, which has manganese doped copper between filaments, has a uniform filament spacing throughout the conductor, and the measured proximity coupling magnetization is smaller than that measured in the D-15A-4F Superconductor. \(^9\)\(^10\) Magnet measurements suggest that the manganese doping does really reduce proximity coupling but not enough to completely eliminate it or the resultant field decay. Calculations using the SCMAG04 program suggest that most of the proximity coupling occurs in the outer layer of the magnet (where the filament spacing is smaller and the field is lower), and that there is almost no proximity coupling in the inner layer superconductor. The filament distribution in these two magnets are displaced in Figures 6 and 7.

In Table 2, we list the slopes of the linear portions of the sextupole vs. log t curves for the four magnets shown in Figures 4 and 5. The slopes are the sum of the flux creep and proximity coupling component, if any.
Conclusions

Slow magnetic field changes due to decay of magnetization current was observed in all of the magnets tested. The magnets with conductor which have filament spacings of 1.5 μm exhibited sextupole component decay with a log t dependence. When the filament spacing is reduced to 0.53 μm or below, the observed magnetization sextupole was increased and the subsequent decay was also increased. An explanation based on proximity coupled currents (for the cases with small filament spacings) and their decay of these currents seems qualitatively correct but quantitative predictions require more data on the candidate conductors. Doping of the copper in the interfilamentary region with 0.5% manganese does reduce the proximity effect.

References