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An Analysis of the Coil Ends for the First High Field Magnet Mechanical Model

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Abstract—*As a first step towards building a Nb_3Sn dipole magnet for a future very large hadron collider (VLHC), a mechanical model was built and tested at Fermilab to set up the equipment and tooling for magnet fabrication and to test various fabrication techniques. The coil end parts were designed using program ROXIE. After mechanical model fabrication, sectional cuts of the lead end and return end were made to see cable positioning. This note provides a brief summary of the analysis of the coil ends.*

1. **Introduction**

Fermilab, in collaboration with LBNL and KEK, is working on the design of a high field Nb_3Sn dipole magnet (of field strength 11 T) for use in future Very Large Hadron Collider (VLHC) machine. The design is based on a 2-layer $\cos\theta$ coil structure with a cold iron yoke. A mechanical model was built and tested [1], before building an actual magnet, to verify our production technology. Fig. 1 shows the cross section of the dipole model magnet, which is based on a 5-block design. The coil ends were designed using program ROXIE [2]. After epoxy impregnation, the magnet ends and the straight section were sectioned to study the cable positioning at magnet ends and in the straight section. Fig. 2 shows a representative cross-section of the straight part of the mechanical model. It should be noted that the top half of the cross-section corresponds to the designed cross-section with a nominal insulation thickness of 0.125 μm. However, due to several turn to turn shorts observed while winding the top half of the coil, it was decided to increase the insulation thickness from 0.125 μm to 0.25 μm for the second (bottom) half of the coil. This forced us to wind fewer turns for the second half of the coil, however, no turn to turn shorts were observed while winding the second half of the coil. Fig. 3 shows a micrograph of the mechanical model taken close to the coil mid-plane, which shows the regions of thick and thin coil insulation. Table I provides a summary of the geometrical data for mechanical model cross-section for the different conductor groups shown in Fig. 1.

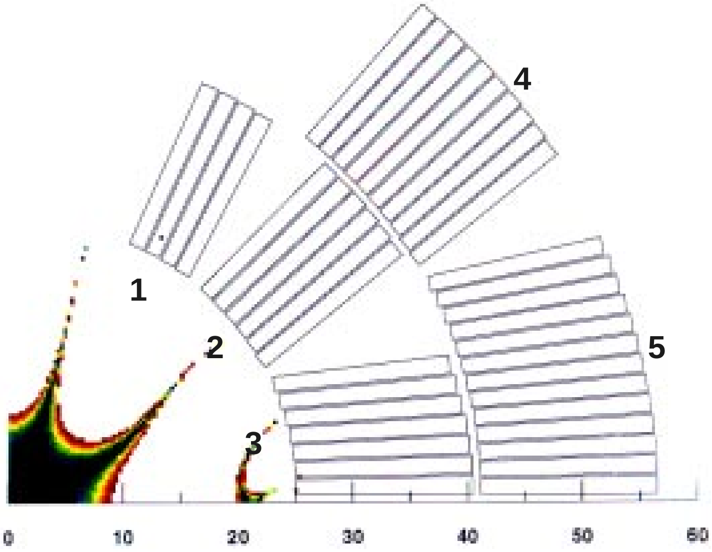

Figure 1: Cross-section of the HFM mechanical model obtained from ROXIE.

Figure 2: An actual cross-section of the HFM mechanical model.

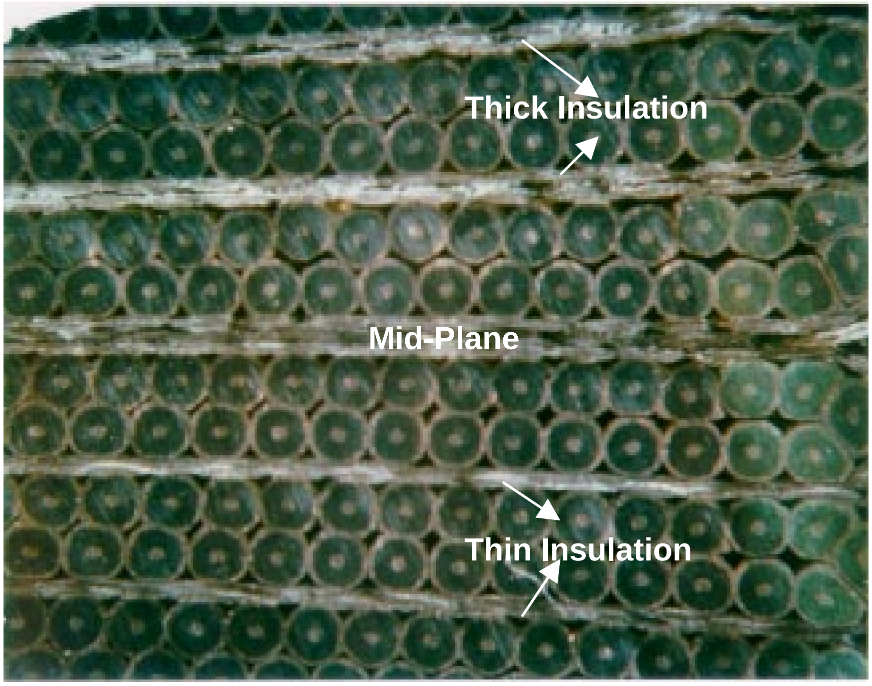

Figure 3: A micrograph of the cross-section close to the coil mid-plane (taken by D. Chichili).

TABLE I

GEOMETRICAL DATA FOR THE MECHANICAL MODEL CROSS-SECTION

Conductor Group	No. of Conductors	Positioning Angle (degrees)	Inclination Angle (degrees)	Inner Radius (mm)
1	4	51.25	62.0	25.0
2	6	27.50	39.5	25.0
3	7	1.28	0.0	25.0
4	10	29.90	39.0	41.06
5	13	0.78	0.0	41.06

2. Analysis of the coil ends

Fig. 4 shows the theoretical (design) YZ cross-section of the lead end of the mechanical model. An actual YZ cross-section for the same is presented in Fig. 5. The top half in Fig. 5 corresponds to the nominally designed section, whereas, the bottom half is the one with reduced number of turns due to thicker insulation. Figures 6 and 7 present the theoretical and actual YZ cross-sections for the return end. Since the coil ends were designed using ROXIE and not program BEND, a comparison was made between the two.

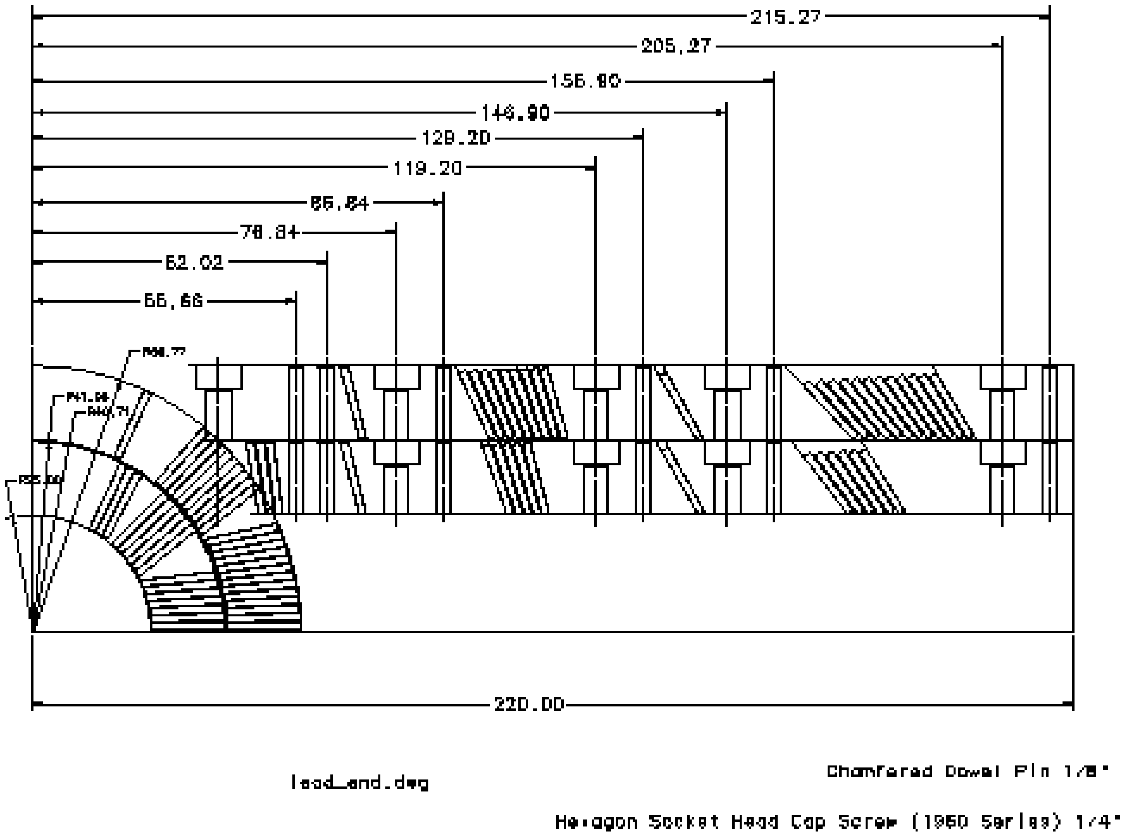

Figure 4: YZ cross-section of the lead end.

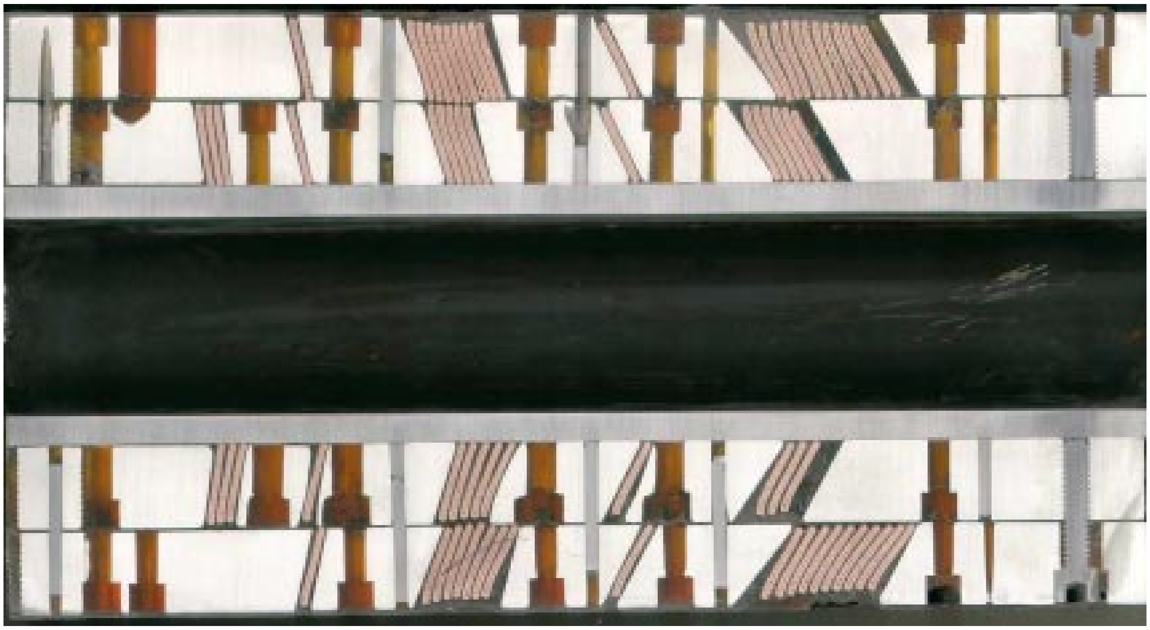

Figure 5: Actual YZ cross-section of the lead end.

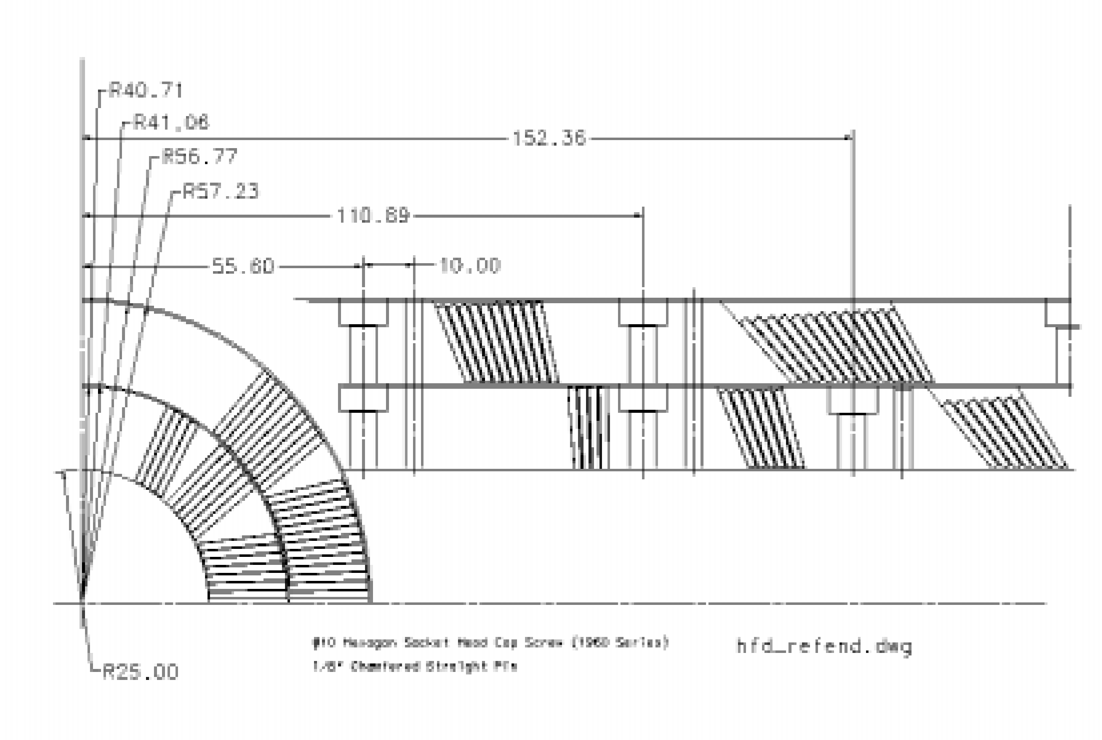

Figure 6: YZ cross-section of the return end.

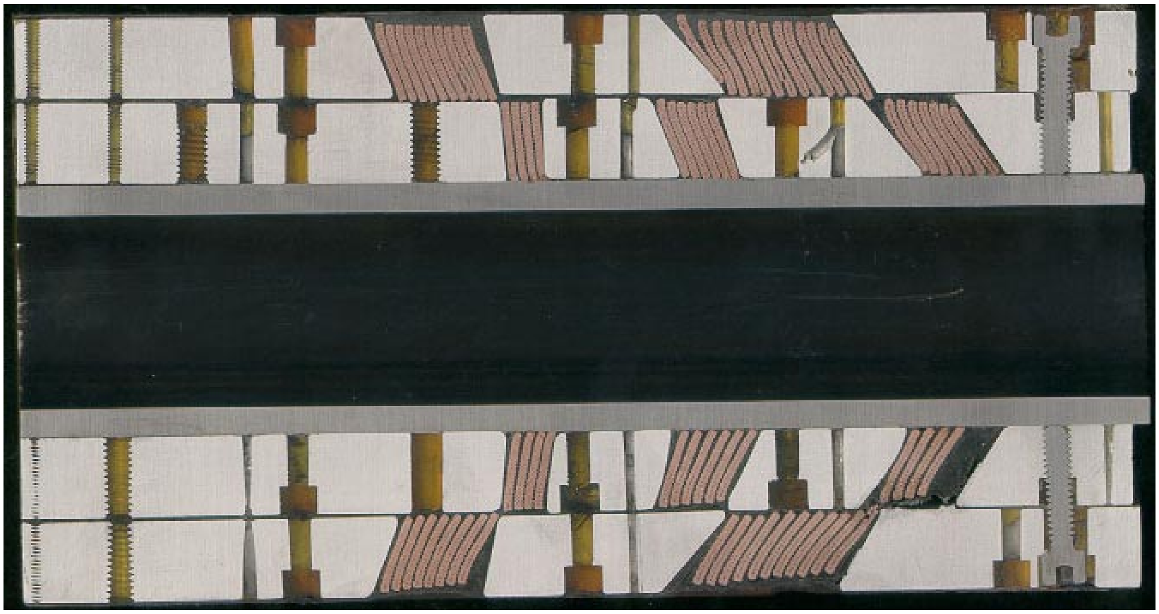

Figure 7: Actual YZ cross-section of the return end.

Table II provides the YZ inclination angles (measured from vertical) for the first conductor in each of the five conductor groups. These angles were chosen by the ROXIE user with the intent of keeping the parameter *bulge* in ROXIE less than 1.1, since a *bulge* of more than 1.1 gives rulings which make sense mathematically but not physically, and can cause lifting off the cable from the mandrel, after winding [2]. It should be noted that a large value of the parameter *bulge* could be corrected by inclining the blocks more or by adding additional spacers or inter-turn fillings. An attempt was also made to minimize the *hard way* strain in the cable and to maximize the radius of curvature in the ends. However, it was found difficult to optimize all of these parameters at the same time using program ROXIE. Also, no de-keystoning of the cable was accounted for in the ends. For a given cross-section and a fixed *A-length*, program BEND outputs a value of the final edge angle (YZ inclination angle) for a given conductor group, with the intent of minimizing the *hard-way* strain in the cable. YZ inclination angles were computed from program BEND for each of the five conductor groups, using the same value of *A-length* as was used in the ROXIE calculations. These values are also presented in Table II.

TABLE II

COMPARISON OF THE ROXIE AND BEND YZ INCLINATION ANGLES

Conductor Group	Number of Conductors	YZ Inclination Angle used in ROXIE	YZ Inclination Angle from BEND
1	4	5	19.01
2	6	22.5	29.51
3	7	40	39.38
4	10	22.5	28.18
5	13	42.5	38.62

A close up view of the lower surface of conductor group 1 is presented in Fig. 8. This conductor group was wound at a very small angle with vertical, 5 degrees as opposed to 19 degrees angle provided by BEND. A tendency of the conductors to move inside the bore was observed for this conductor group. This is possibly due to the fact that the conductor group had a very large strain energy in it, when wound, and it tends to minimize its energy by moving inside the bore when the winding tension is removed. As a consequence, no insulation is observed at the bottom surface of the conductors in this group. Some lower edge curl of the conductors is also observed which would indicate that the conductors prefer to rest at a larger angle with vertical, as indicated by the BEND output.

Fig. 9 shows a similar close up view of the lower surface of conductor group 2. When compared to conductor group 1, this group shows less of the lower edge curl phenomenon. Also, some insulation can be observed at the bottom surface of the conductors in this group. However, the conductors in this group show a curl on their

Figure 8: Close up view of the bottom surface of conductor group 1.

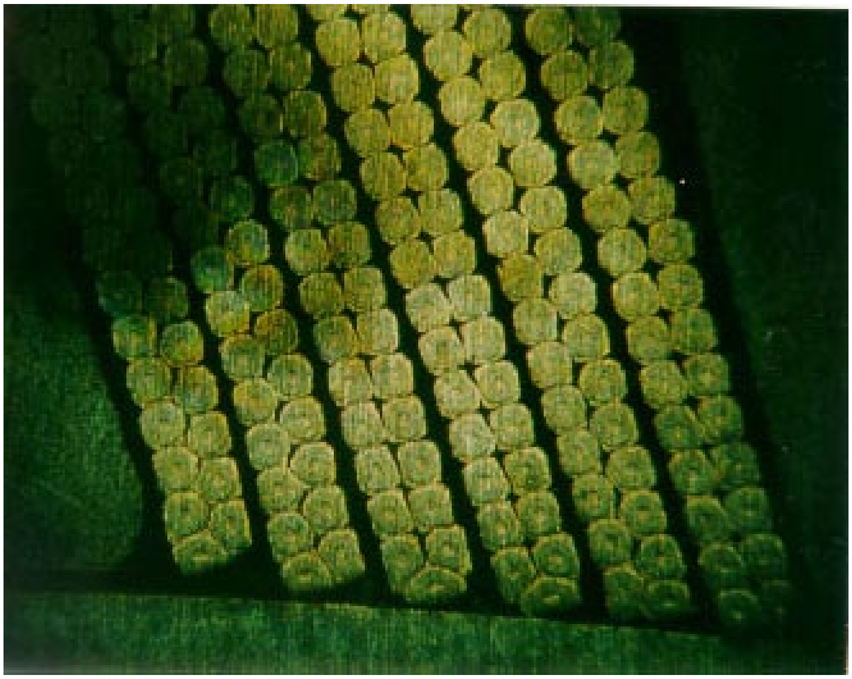

Figure 9: Close up view of the bottom surface of conductor group 2.

upper edge. This may *possibly* be due to the lack of support on the upper edge from the back surface. Figures 10 and 11 show similar close up views for conductor groups 3 and 5.

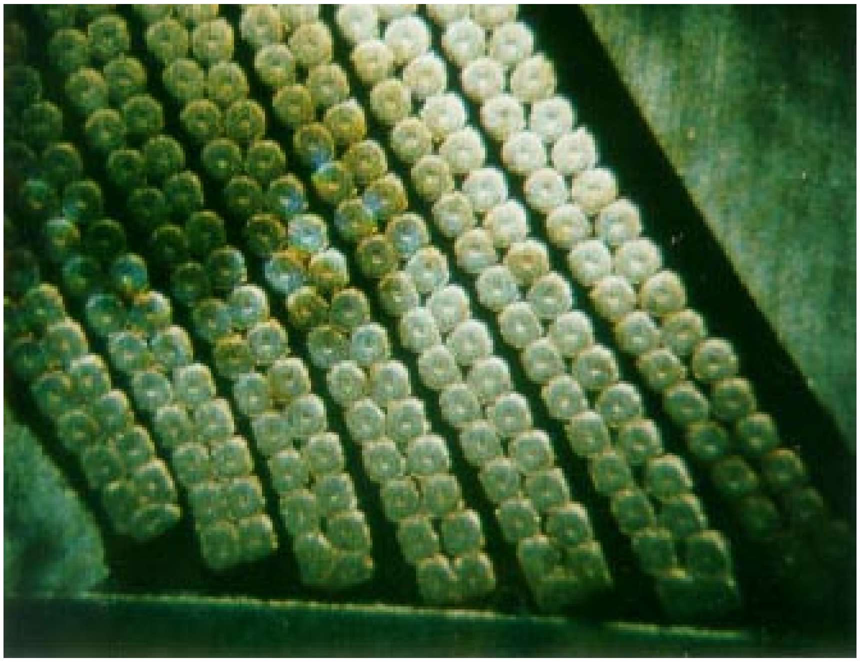

Figure 10: Close up view of the bottom surface of conductor group 3.

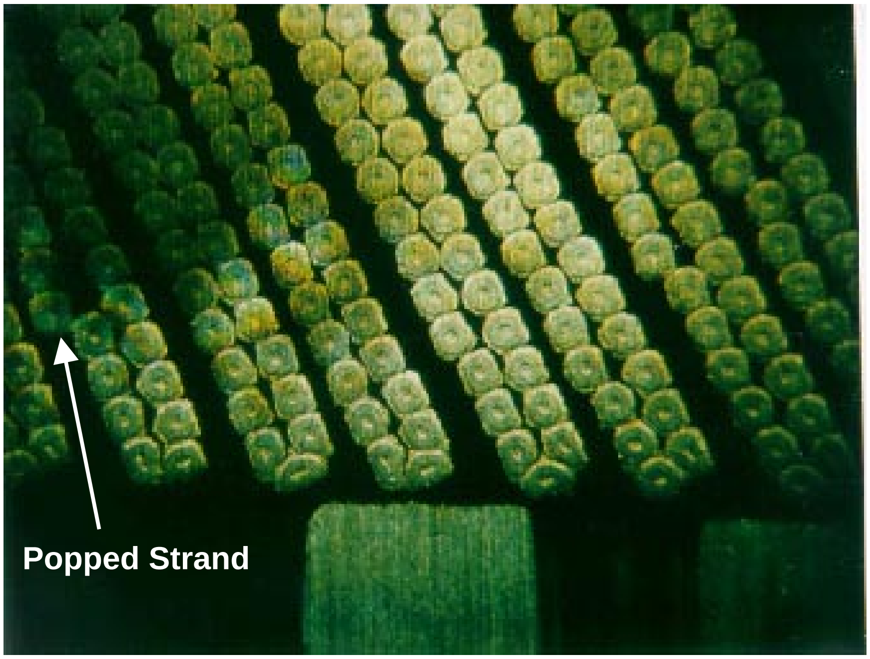

Figure 11: Close up view of the bottom surface of conductor group 5.

Some popped strands were also observed (Fig. 11) while winding the first half of the coil with nominal insulation thickness. Such popped strands did not occur for the second half of the coil which was wound with a thicker insulation. It should also be noted that the upper edge curl phenomenon is observed to be more severe for conductor groups 3 and 5 which have a large YZ inclination angle.

Note that large gaps were observed at the back surface of each conductor groups because de-keystoning of the cable was not accounted for. Table III lists the actual values of the YZ inclination angles of the back surface of the conductor groups 2 to 4 for a given front surface inclination angle. Similar values were obtained using program BEND with the inclusion of cable de-keystoning parameters, same as those used for the NbTi cable used for the LHC IR Quads. It should be noted that BEND outputs angles which are very similar to the front surface inclination angles. This is due to the fact that the cable is almost rectangular at the ends due to de-keystoning. This de-keystoning of the cable was not accounted for when using ROXIE and therefore the angles obtained from ROXIE are very different from the corresponding front surface angles. This lead to the observed *keystoned* gaps at the end of the conductor groups.

TABLE III

COMPARISON OF THE ROXIE AND BEND YZ INCLINATION ANGLES OF THE BACK SURFACE

Conductor group	YZ inclination angle of front surface used in ROXIE	YZ inclination angle of back surface obtained from ROXIE	YZ inclination angle of back surface obtained from BEND
2	22.5	16.63	21.32
3	40	33.2	38.1
4	22.5	12.72	20.54
5	42.5	29.78	39.95

3. Summary

Sections of the lead and return ends of the mechanical model have been investigated. Some gap was observed at the back of each conductor groups due to the fact that cable de-keystoning was not accounted for. Also, a tendency of the conductors to move inside the bore was observed for some conductors. Lower edge curl and upper edge curl of the conductors was also observed. This is probably due to the fact that the conductors were positioned at inclination angles which induced large *hard-way* bend in the cable.

References

[1] N. Andreev et al., "Fabrication and Testing of High Field Dipole Mechanical Model," presented at the 16th International Conference on Magnet Technology, Florida, 1999.

[2] S. Yadav and I. Terechkine, "Design and Fabrication of End Parts for the First High Field Magnet Mechanical Model," TD-99-022, FNAL, 1999.