SELECTING MAGNET LAMINATIONS RECIPES USING THE METHOD OF SIMULATED ANNEALING

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Abstract

The Fermilab Main Injector project is building 344 dipoles using more than 7000 tons of steel. There were significant run-to-run variations in the magnetic properties of the steel. Differences in stress relief in the steel after stamping resulted in variations of gap height. To minimize magnet-to-magnet strength and field shape variations the laminations were shuffled based on the available magnetic and mechanical data and assigned to magnets using a computer program based on the method of simulated annealing. The lamination sets selected by the program have produced magnets which easily satisfy the design requirements. This paper discusses observed gap variations, the program structure and the strength uniformity results for the magnets produced.

1 INTRODUCTION

The Main Injector [1] is a high performance 150 GeV synchrotron which is being built at Fermilab to provide high quality, high intensity beams. Design studies [2] from which requirements were established, assumed a magnet-to-magnet uniformity of the bend strength of 10^{-3}. Efforts to improve on that minimum goal have been directed toward minimizing commissioning and operating efforts by reducing the use of correction magnets.

The bend strength of a dipole may be characterized [3] by

$$BL_{eff} = \int B_y ds = \frac{\mu_0 L_{eff}}{g}(N_g I - \mathcal{L}\langle\mathcal{H}\rangle) \quad (1)$$

where I is the current (per turn) in the coil, N_g is the number of turns linked by a flux line which crosses the gap in the good field aperture, g is the gap height, $\mathcal{L}$ is the length of the flux path in the core, L_{eff} is the effective length of the magnet, and $\langle H\rangle$ is the average of $\vec{H}$ along the flux line in iron. The parameters which can be controlled during manufacture are the (effective) length, the gap, and $\langle H\rangle$.

The steel received from the manufacturer, LTV Steel, was of high quality and met all contract specifications. Nonetheless, there were run to run variations [4] in the properties of the sheet steel which resulted in variations in the gaps of the stamped laminations and in the magnetic properties at high fields.

To produce the half cores, laminations from different production heats and runs were mixed taking into account

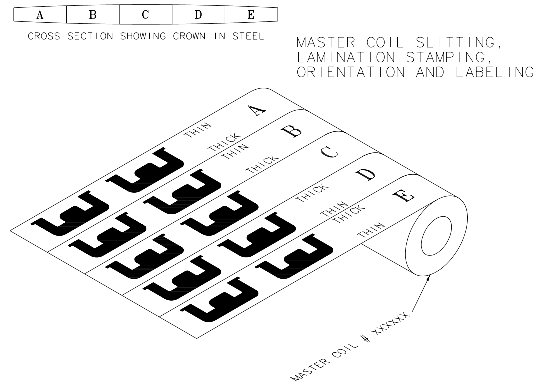

Figure 1: Master coil and slit structure.

their magnetic properties, their average gap height and their transverse taper, Figure 1. Control of L_{eff} was obtained by stacking laminations to a fixed length with a minimum pressure which was sufficient to flatten the laminations. The half cores produced had sufficiently uniform magnetic and mechanical properties that matching of half cores was not required.

2 STEEL AND LAMINATION PROPERTIES

The $55''$ wide steel master coils, Figure 1, were cut into 5 $10\frac{7}{8}''$ slit coils to minimize waste during stamping. Each slit coil yielded about 800 laminations. It was necessary, because of the crown in the master coils, to balance the amounts of A and E slits and B and D slits in each half core to insure that the core ends were sufficiently parallel.

The lamination shape is shown in Figure 2. The shape of the pole sets the high order field properties of the magnet and is quite reproducible across all steel lots. The half height of the gap is the distance of the pole feature from a reference line across the backleg features on each

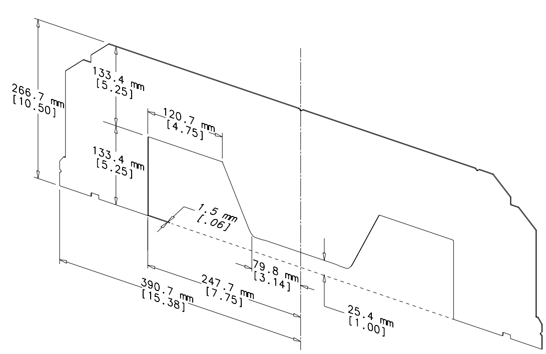

Figure 2: Main Injector dipole lamination.

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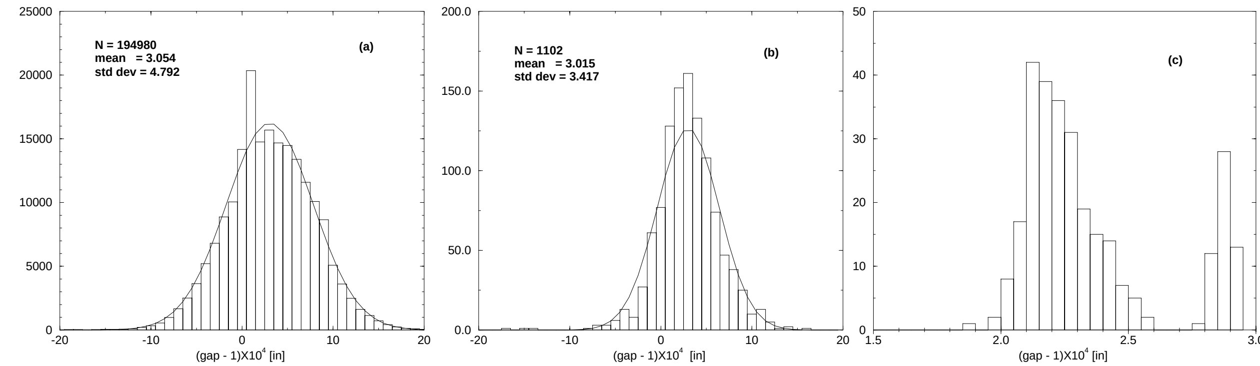

Figure 3: Measured gap (half) height distributions. (a) All measured laminations. (b) Averaged over slit coils. (c) Average gaps for half core recipes.

side. However, the half gap height created in the lamination stamping die is modified by stress relieving deformations which vary from coil to coil. Occasional die adjustments were required to maintain the required gap height by compensating for die wear.

The lamination shape was monitored by measuring a 0.2% sample of the laminations with a coordinate measuring machine (CMM) and a 2% sample with a gap monitoring system. The CMM confirmed in detail the shape of the laminations. The gap monitoring system used three mechanical sensors[1] to measure the pole position at the center and 2.00″ to either side of center. The selected lamination was placed with a reference surface supporting the back legs and the three distances to the pole were recorded.

The target range for the average gap of a half core was $1.0002''$ to $1.0003''$. Figures 3a and 3b show the measurement data for the laminations. The standard deviations of the distributions are $0.00048''$ (12μm) and $0.00034''$ (8.6μm) respectively, significantly larger than the target range. Figure 3c shows the gap distribution for a set of half core recipes generated by the simulated anneal program, some of which were eliminated on other grounds. Figure 4 shows the time sequence of the average gaps for this set of half core recipes.

3 SIMULATED ANNEALING PROGRAM

To meet the required magnet specifications it was necessary to control the average gap and average H_c for each half core. The spread in the distribution of each was several times greater than allowed. (Pre-production, it was anticipated that the spreads would be even larger than was actually realized.) As noted above, it was also necessary to compensate for the taper of the slits used to make the laminations.

A program based on the simulated annealing [5], [6] method was used to generate the lamination recipes from which the half cores were assembled. The recipes were computed in batches, typically of 20–80, depending on the inventory of laminations available. Simulated annealing is based on the observation that when a metal is heated and cooled slowly (annealed), the resulting solid is highly ordered. We can think of the available energy states in the metal as obeying a Boltzman distribution, $e^{-E/kT}$. The probability that a state with energy E_i will change to a state with energy E_j is $P_{ij} = e^{-(E_j - E_i)/kT}$ if $E_j > E_i$ and $P_{ij} = 1$ if $E_j < E_i$. The important observation is that there is a non-zero probability that the final state will have higher energy than the initial. The system can escape from a local energy minimum.

The simulated anneal program adjusted 4 parameters for each half core: the total number of laminations, the A-E and B-D slit imbalance, the average gap, and the average H_c. Each box of laminations was characterized by its slit type, A–E, the number of laminations (typically between 350 and 450), N, the average gap, $\overline{g}$, and the average coercive force, $\overline{H_c}$. The optimization specified tolerances on the total number of laminations in the half core, on the slit-type imbalance, and the deviations of $\overline{g}$ and $\overline{H_c}$ from the

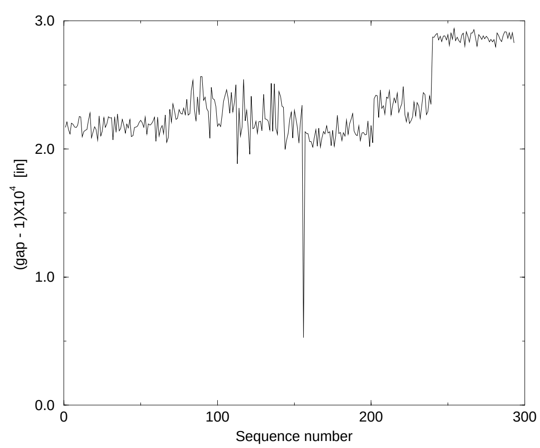

Figure 4: Time evolution of the average gaps for the same set of 6 meter half core recipes. This plot shows the improvement obtained as the cooling program was refined.

[1]Mitutoya Digamatic Indicator Model IDC112C. The sensor has a resolution of 0.0001″ (2.5 μm) with an accuracy of 0.00015″ (3.8 μm).

inventory averages. The "energy" for a half core recipe is

$$E = \left(\frac{\sum N(n) - N_{nom}}{\delta N}\right)^2 + \left(\frac{\sum b(n)}{\delta b}\right)^2 + \left(\frac{\sum \overline{g}(n) - \overline{g}_0}{\delta g}\right)^2 + \left(\frac{\sum \overline{H_c}(n) - \overline{H}_{c0}}{\delta H_c}\right)^2 \quad (2)$$

where the sums run over the boxes of laminations included in the recipe. N_{nom} is the target number of laminations and $\sum b(n)$ is the total slit-type imbalance. The quantities $\overline{g}_0$ $\overline{H_{c0}}$ are the average gap and H_c for the total inventory from which the half cores are being selected. The "cooling" is achieved by slowly reducing the denominators in each term while shuffling the box assignments to produce half cores which meet the criteria. (Before starting the program, the inventory is adjusted to ensure that the slit balance, the average gap and the average coercive force will allow the specifications to be met. Over- and undersized laminations were used to make the end packs. This helped us maintain the average gap of the pool in the target range without significant waste.)

4 MAGNET PROPERTIES OBTAINED

The magnet fabrication system has been monitored by a program of mechanical and magnetic measurements. The results are recorded in, and easily retrieved from, a comprehensive relational database. The 1.5 mm lamination thickness provides a least step size in the magnet length. Mechanical measurements of the half core lengths are consistent with having this as the dominant limitation on length uniformity. As we see in Equation 1, the strength variation due to geometry is governed by L_{eff}/g. To evaluate this we fit the low field (below 0.8 T) downramp excitation curve [3] to a linear function and multiply the inverse slope by $\mu_0 N_g$ to determine g/L_{eff}. The correction for finite μ_{dr} is expected to be less than 0.5% and nearly independent of the steel sample involved. Results are shown in Figure 5. We note that the initial production of 6 m dipoles had a larger and less uniform gap, but the late 6 m dipoles and the full production run of 4 m dipoles had remarkable uniformity. Statistics are shown in Table 1.

Series		$\langle g/L_{eff}\rangle$	σ	$\sigma/\langle g/L_{eff}\rangle$
IDA	all	0.008349	3.859e-06	4.622e-4
IDB	all	0.008347	3.476e-06	4.614e-4
IDC	all	0.012520	2.572e-06	2.054e-4
IDD	all	0.012519	2.920e-06	2.333e-4
IDA	early	0.008354	2.602e-06	3.114e-4
IDA	late	0.008347	1.544e-06	1.850e-4
IDB	early	0.008353	2.632e-06	3.152e-4
IDB	late	0.008352	2.632e-06	3.152e-4

Table 1: Average g/L_{eff}, σ, the rms spread, and the ratio for the different magnet populations shown in Figure 5.

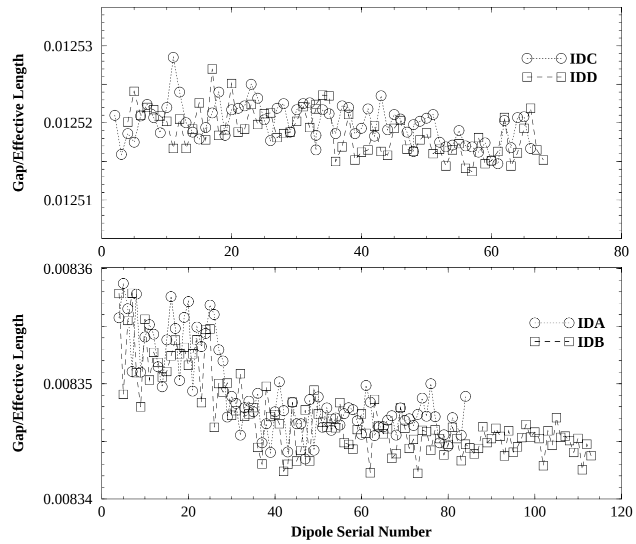

Figure 5: g/L_{eff} for 6 m (below) and 4 m (above) dipoles *vs.* production serial number. The apparent change after IDA028 and IDB025 and the subsequent improved uniformity is believed to be due to several improvements in the half core manufacture and magnet assembly procedures. The relative change in g/L_{eff} is $\approx 10^{-3}$.

5 SUMMARY

In the face of significant materials variations we have produces a remarkably uniform set of magnets. The simulated annealing method provided a very robust and efficient tool to assign laminations to magnets to obtain desired and tightly controlled properties,

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7 REFERENCES

[1] Holmes, S. D., et al. Status of the Fermilab Main Injector and Recycler, this conference

[2] Harfoush, F. A., B. C. Brown, H. D. Glass, C. S. Mishra, S. Peggs, Defining the Systematic and Random Multipole Errors For Mail Injector Tracking, Proceedings of the 1993 IEEE Particle Accelerator Conference, pp 351–353, 1993

[3] B. C. Brown *et. al.*, Results on Fermilab Main Injector Dipole Measurements, IEEE Trans. on Magnetics, **32**, 2186 (1996)

[4] Martin, P. S., D. J. Harding, E. G. Pewitt, A. D. Russell, Variations in the Steel Properties and the Excitation Characteristics of FMI Dipoles, this conference.

[5] Kirkpatrick, S., C. D. Gelatt, Jr., M. P. Vecchi, Optimization by Simulated Annealing, Science, **220**, 671 (1983)

[6] Numerical Recipes in C, 2nd ed., W. H. Press, S. A. Teukolsky, W. T. Vetterling, B. P. Flannery, Cambridge Univ. Press, 1988