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REMANENT MAGNETISM IN TOROIDS

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by

Peter Hall and S. Legvold

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Abstract

The Brookhaven Laboratories have reported that the remanent magnetism in the Cosmotron magnet decreases with increasing pulse height, and increasing pulse length (BNL-1447). A group at Iowa State College has attempted to duplicate these effects with the simple geometry of a virtually complete toroid. It was found in this case that B_{rem} is independent of the pulse length, rises and approaches a constant value as the pulse height is increased. These results confirm a previous hypothesis that the unusual behavior of the Cosmotron remanent field is due to the particular configuration of the copper and iron used in that case, and is not due to inherent properties of iron.

Introduction

During the past year, a group at Iowa State College has been investigating, for the Midwest University Research Association, some magnetic effects which were reported at Brookhaven National Laboratory (BNL-1447). The pulse applied to the electromagnets used in the Cosmotron had a linear rise and linear fall with time,

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as shown in Fig. 1. They found there that the remanent magnetism decreased with increasing pulse height, and with increasing pulse length. This report covers some work done in an investigation of these effects using toroids as samples to make the geometry simple, and using thin laminations to reduce eddy current effects to a minimum.

Apparatus

For this investigation, two toroids were made of 1/16" laminated metal. The toroids had a 1" x 1" cross section, and an 8 1/2" outside diameter, as shown in Fig. 2. One was of 1010 steel, one was of Armco iron. A 3/8" slot was cut through each of these so as to be able to pass a flip coil through the flux inside the toroid. Then a laminated "keeper" was made to fit each of the slots nearly completing the magnetic circuit again. Around each of these toroids was wound an energizing coil to which the pulse was applied. The pulse was obtained by means of an Amplidyne which was controlled by the circuit represented in Fig. 3. In Fig. 4 and Fig. 5 are shown the details of the controlling circuits. Essentially, a 10 μ f capacitor (C-201) is charged up toward +300 volts. The charging is terminated at a value designated by a potentiometer (R-201), at which time, relays K-204 and K-203 are reversed, and the capacitor finds itself being charged toward -300 volts. However, this charging is terminated at zero volts, and the pulse is complete. The rise and fall times are adjusted by varying the resistors R-202 and R-203 through which the capacitor is being charged. The pulse obtained

FIG.1 PULSE SHAPE

FIG.2 SAMPLE AND KEEPER

FIG. 3 APPARATUS FOR PRODUCING PULSE

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FIG. 4 AMPLIDYNE CONTROLLER

FIG. 5 MAGNET CHARGE CONTROLLER

in this manner is fed into "external control" of the amplidyne control unit, shown in Fig. 4. This in turn controls the field of the generator by means of a feedback loop, so as to obtain a nearly linear rise and fall curve of current through the sample. Originally, this feedback was taken from below the sample (dotted lines in Fig. 3). However, it was found that the "noise" level could be reduced, and the pulse made more linear by taking the feedback from above the sample. The magnet charge controller was designed so as to include the possibility of multiple pulse studies. However, it was not felt necessary to perform the multiple pulse studies, so the rest of the equipment, as shown inside the broken lines of Fig. 5, has not been installed.

Results

Using the 1010 steel toroid, B_{rem} was measured as H_{max} was varied, keeping the slopes constant (rise slope = 45 oersteds per sec, decay slope = -52 oersteds per sec). The results are shown in Fig. 6. As H_{max} was increased, B_{rem} increased sharply, until at about 10 oersteds, it began to level off, and finally B_{rem} became essentially constant, being 8.4 kilogauss at 18 oersted, and only about 8.6 kilogauss at 75 oersted. There was no tendency observed for B_{rem} to decrease with increasing H_{max} , at least in this range. (i.e. up to 75 oersted. This corresponds to a B_{max} of about 15 kilogauss.) The experiment was repeated with Armco, with similar results, as shown in Fig. 7. For the Armco trials, rise slope = 24 oersteds per sec, fall slope = -27 oersteds per sec. A similar curve of B_{rem} vs. H_{max} was found, with a "knee" at

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about 10 oersteds of $H_{\max}$ and B_{rem} leveled off at about 6.6 kilogauss. Again there was no tendency for B_{rem} to decrease with increasing pulse height, although we could only go up to 40 oersteds of $H_{\max}$, which corresponds to about 14 1/2 kilogauss on the magnetization curve of the Armco toroid.

Also, we varied the decay time, keeping rise time and $H_{\max}$ constant. The results, which can be seen in Fig. 8, show that in changing decay time from about 0.13 sec to 2.6 sec, the change in B_{rem} was undetectable. Comparable results were obtained by varying the rise time, as shown in Fig. 9. The greater spread of the points on the Armco curves was probably due to the wider air gap between the magnet and keeper. It seems, then, that within experimental error, B_{rem} is independent of pulse length.

Discussion

In order to assure ourselves of the accuracy of the flip coil method of measuring B_{rem} , we wound a secondary around the 1010 toroid, and plotted a magnetization curve using this secondary coil to measure ΔB . This curve was compared to a magnetization curve obtained by flipping out the pickup coil. Since we found it too difficult to remove the remanent magnetism completely, we had to take two curves, using the flip coil method, one in the direction of the B_{rem} , the other in the opposite direction. The average of these two runs was seen to coincide very closely with the curve obtained using the secondary as a pickup coil, as is shown in Figs. 11 and 11a.

Also, despite our keeper, there was a finite amount of air gap in the magnetic circuit (about 9/1000" for Armco, and about 2/1000" for steel). To get an idea of how much this air gap affected the magnetic behavior, we made two complete toroids, one of steel, one of Armco, similarly laminated, but somewhat smaller (5 1/2" outside diameter). Magnetization curves were plotted for these complete toroids, to be compared with the magnetization curves for the larger, gapped toroids with their keepers in place. The results, as shown in Figs. 7 and 8, indicate that the air gap seemed to have the effect of reducing the effective magnetomotive force, because the curves of the gapped toroids could be corrected to coincide fairly well with the true curves by multiplying H by a constant fraction. For steel, this turned out to be 0.90. For Armco, it was 0.62 (see Figs. 10, 11). The difference here is attributed to the different size of air gap. Strictly speaking, the correction factor should not be a constant, but should be a function of μ , since $\phi = \frac{\text{mmf}}{\text{reluctance}} = \frac{\text{mmf}}{\frac{\ell}{\mu A}}$ for a complete

toroid of cross section A, and circumference ℓ , and $\phi = \frac{\text{mmf}}{\frac{\ell}{\mu A} + \frac{\delta}{A}}$

for a toroid with effective gap width, δ . We see, then, that the effect of the air gap is to multiply the magnetomotive force by a factor equal to $\frac{1}{1 + \frac{\delta \mu}{\ell}}$.

However, if μ does not vary very much, one can use a nominal value for it, and arrive at a fair approximation for a correction factor. This is essentially what was done, except that we did it empirically because of the difficulty involved in determining δ .

However, using a feeler gauge to determine the order of magnitude of δ , we found the correction factors to be 0.91 and 0.55, taking μ as that value where the original normalization fits best. These are seen to correspond quite well with the empirically determined correction factors (0.90 and 0.62). We see that the corrected curves lie quite close to the true curves for complete toroids, except perhaps, toward the upper end of the magnetization curve of 1010 steel.

Another point that needs elaboration is the assigning of a $B_{\max}$ to an $H_{\max}$. We did this by extrapolating the magnetization curves obtained as above. The premise that the sample follows the magnetization curve on a pulse of this type was suggested by the rise-time independence of B_{rem} and was corroborated by an actual trial of measuring B_{rem} by flipping the coil very soon after the $H_{\max}$ had been reached, before B could die down to B_{rem} . There was a surprisingly high degree of repeatability here, and the point taken fell within experimental error of the magnetization curve, as shown in the upper right hand corner of Fig. 8.

Some other methods of getting data on this problem were considered, but discarded in favor of using a flip coil with a keeper. Among them was the possibility of using a rotating coil Rawson fluxmeter to measure B_{rem} in the gap. However, the $B_{\max}$ achieved without the keeper was far less than the 14 kilogauss which is what was used at the Cosmotron. Also, we did want to save the simple geometry. Some attempts were made, too, to use a Grassot fluxmeter around a continuous toroid, but this proved to be less accurate than the flip coil method. The only major disadvantage in using the flip coil and keeper method is the finite air gap. However,

we believe we have shown that the air gap in our samples was not large enough to invalidate our conclusions.

It should be remarked here that the accuracy of the points on the graphs is not as good as the graphs would indicate, because the day-to-day variation (say in the steel) was as much as 2% in B_{rem} , whereas for one run the mean deviation from the curve is about 1/2%. Therefore, we can say that we know the shapes of the curves better than we know the absolute values of the points on them.

Conclusion

We believe we can conclude, then, that at least in the ranges indicated above, the effects found by the Brookhaven Laboratory cannot be duplicated using 1010 steel and Armco with the simple geometry of a virtually complete toroid. We worked in the same range of B_{max} as the Brookhaven group (up to 14,000 gauss) but of course our B_{rem} was much larger (8000 gauss compared to 20 gauss). Due to this large B_{rem} , however, these effects should have been even more evident, if they are really inherent in the material. Therefore, we would suggest that the effects were probably either due to the peculiar geometry or to eddy current effects. Eddy current effects were minimized in our samples by 1/16" laminations. The Brookhaven magnets were of 1/2" laminations. We found no evidence to show that B_{rem} might decrease either with increasing H_{max} or with increasing pulse length. Our experiments would also indicate that the steel will give a larger remanent magnetism for a given B_{max} than will the Armco, as might be expected from published curves.