FERMILAB-UPC-171

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Dec. 5, 1983

SAVER DIPOLE PERSISTENT CURRENT HYSTERESIS EFFECTS

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In UPC #162, data were reported on hysteresis effects in the sextupole moments of Saver dipoles. Since that time, further studies have been carried out on both the harmonic component and the dipole hysteresis of additional magnets. These studies concentrated on two aspects of the magnet performance:

1. The general aspects of the hysteresis effects
2. Any aspects which might have special significance for Saver operation, especially as relates to injection fields.

These studies were given a preliminary analysis and no striking effects were found. A poster paper was presented at the Santa Fe Accelerator Conference but the published version was not completed. The analysis which was reported lacked the consistency of detail which would have allowed a published report. Since Saver injection works well enough to make that aspect of the study less pressing this report will consentrate on the more general issues of the hysteresis such as may be of interest for projects such as the SSC where general questions must be asked.

Data were taken on the magnets with both the harmonic analysis hardware and the standard Saver test program DCH and with the Extended Range NMR system (more flexible than the system used for Saver production measurements) with data recorded with pen and paper. I will describe elsewhere some interesting small effects which appeared as elusive dirt effects in the data I will present which would have required a more elaborate system to elicidate. In the remainder of the paper I will attempt to show a simple picture of the persistent current magnetic field as shown in these data. The data were taken only to illuminate the issues associated with Saver injection fields and the range is somewhat reduced from what would be chosen for the present purpose.

A Naive Physics Overview

One expects in the body of a Saver dipole to have magnetic fields whose magnitude and shape are dominated by the pattern of the current carrying conductors. The Sextupole moment b2 will be dominated by the placement of the conductors and that placement in the body is determined to cancel the large sextupole contributed by the end field. In Type I superconductors, the

Meisner effect excludes all field from the body of the superconductor, canceling them with a perisitent surface current and producing a corresponding effect on the external field. With the Type II superconductors used to produce magnets, the flux is excluded only for small field changes. For large fields, the flux penetrates the superconductor, reducing the persistent currents. A third contribution to the magnetic field shape comes thru the deformation of the coil at large excitation currents in response to the large magnetic forces. One might expect that the persistent current effects will be negligible at or near the "short sample limit" for magnets, however, the coil deformation effects make this limit point difficult to use.

Observation of the hysteresis effects associated with the problems studied in UPC #162 shows that there is a transition region associated with changes in the sign of dB/dt. The dB/dt electric field sets up new Meisner currents which will then cause the magnetic field to follow the curve associated with that sign of dB/dt after a transition region with a characteristic size of 100 A. The "Reset" and "Overshoot" effects reported in UPC #162 are associated with the details of that transition. I will attempt to give a picture of the overall hysteresis pattern, ignoring all but the existence of that transition.

I will attempt to find a representation of the field data in which one term is proportional to the current and represents the effects of the transport current in the magnet and with a second term which is caused by the persistent currents and by assumption is added to the field for down ramps and subtracted from the field on up ramps. With the data available, such a separation is arbitrary but possible by inclusion of an additional arbitrary offset term. I will tie to enough data make it plausible but further analysis and probably more data is needed. The coil deformation effects are expected to be important above 2000 A where there is no NMR data but the harmonic analysis would not allow this interpretation without there being such a term.

Measurements and Results

Dipole field measurements were made using the Extended Range NMR system. Data were taken with all probes available. Each probe must be inserted into the magnet attempting a best effort to achieve the same location. The data from the lowest range probe showed an offset from the higher range data which must be instrumental but has not been investigated. In Figures 1 and 2 the data are presented in a visually pleasing if arbitrary fashion. We assume, consistent with the above model, that the field measured by the NMR is the sum of a term which is proportional to current and a second term which is given by the persistent current terms.

B = (alpha) * I + dB

To produce the graphs in Figures 1 and 2, I collected data with several probes which have barely overlapping ranges. The magnet was ramped from 0 to 4000 then down to the current specified and the measurement was performed. The ramp was reversed at some current and the field value tracked through the transition region and up through the previously measured currents. The various symbols track the data through the transition region for various "Reset" currents. Both this data and the additional harmonic data are consistent within errors of finding that after a small "reset" region, the field follows the same pattern on the increasing ramp that was observed on the ramp which extended to 0 amp "reset." It appears that the data are consistent, outside the transition regions with the model above with the possible addition of an offset. The data are presented by selecting the value of alpha such that the curves are flat (dB independent of I). The magnitude of the persistent current field change is 12-14 gauss. The apparent offset term (still mystereous) is about 5 gauss.

Data with the harmonic probe can be taken with less systematic effects since one probe covers all field ranges. Unfortunately, the data was taken dominantly in order to study the transistion effects. The data in table 1 of UPC #162 are as suitable as any I have conveniently found for studying the overall magnitude of the hysteresis. In Figure 3 I present it with the suggested analysis:

dB2 = (b2 * I) - (alpha + beta * I)

where the first bracketed term converts the b2 to a field at 1" and the second accounts for the dominant field produced by the transport currents. We see that unlike the dipole field observed by the NMR, the sextupole field term decreases with increasing transport current. At low fields, however, its magnitude is similar to the dipole term.

Finally, the routine measurements of Saver magnets have included measurements of the remanent field using both the stretched wire technique and a harmonic analysis of that field in the center of the magnet using the standard probe. For magnet TC0535 for which the above NMR studies were carried out, a comparison was made of the NMR results, the sextupole and decapole hysteresis and the remanent field of the magnet. This comparison is presented in Table 1. With it we see that the remanent field is consistent with the differences seen between up ramp fields and down ramp fields. If the dipole term were independent of current, should the remanent be half of the difference?

Limitations, Conclusions, Acknowledgements

The above analysis is based on a more limited set of data than seems wise for strong conclusions. In addition, it has been prepared under less than ideal timing. I feel strongly that it provides the guidance I would use to acquire more data on both the overall shape and the nature and details of the transition regions. Probably the results are valid to the 25% level or better. I would like to acknowledge the assistance of the MDTF operations and instrumentation groups in acquiring this data.

Table 1 Summary of Hysteresis Data on TC0535

Dipole Hysteresis (central filed)

Current	gauss up ramp	gauss down ramp	gauss difference
250	2508.8	2520.8	12
500	5026.7	5042.5	15.8
1000	10069.9	10084.2	14.3
1200	12085.4	12099.80	14.4
1400	14101.95	14116.20	14.25
2000	20149.8	20163.95	14.15

Sextupole Hysteresis

Current	b2	b2	b2	
660	6.59	17.10	10.51	Standard Units
	4.35	11.29	6.94	Gauss at 1"
Decupole	b4	b4		
660	1.56	1.88	.33	Standard Units

Remanent

Dipole	17.17 g
Sextupole	7.62 g at 1"
Decupole	-0.88 g at 1"

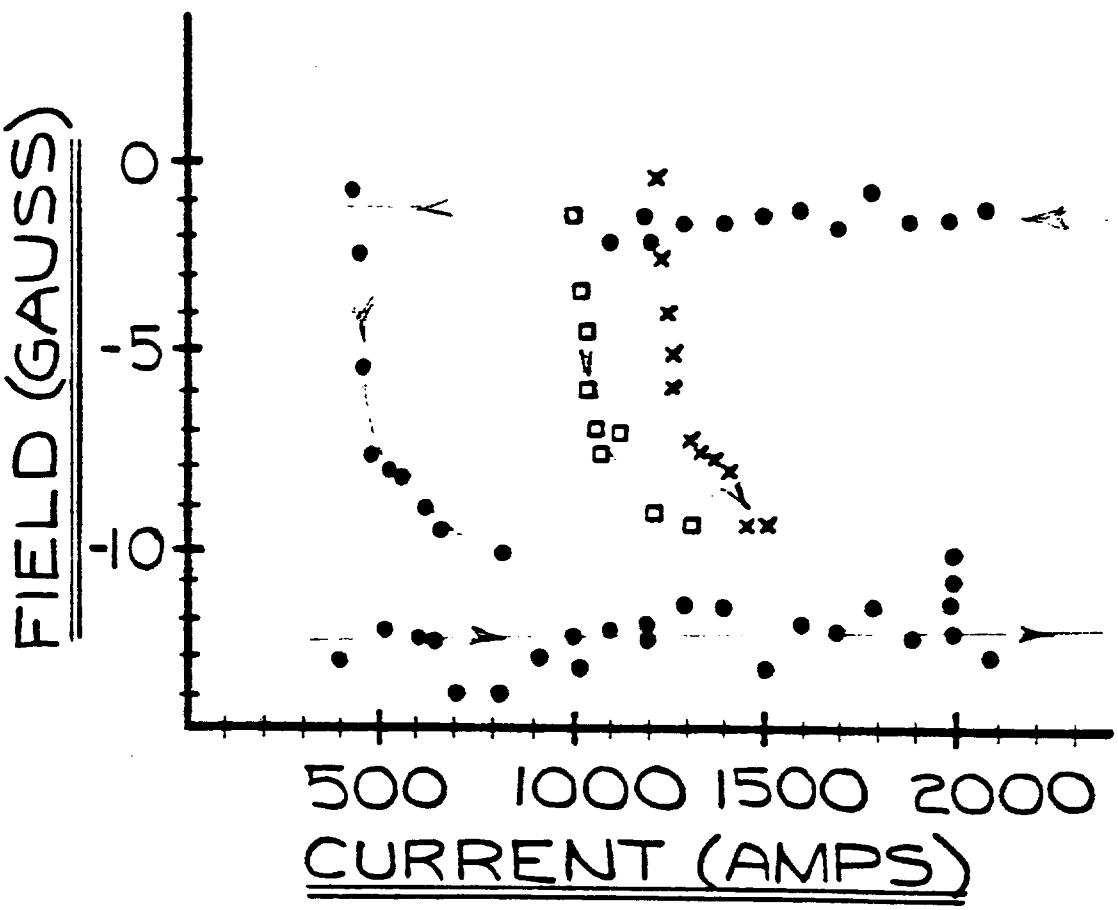


Figure 1

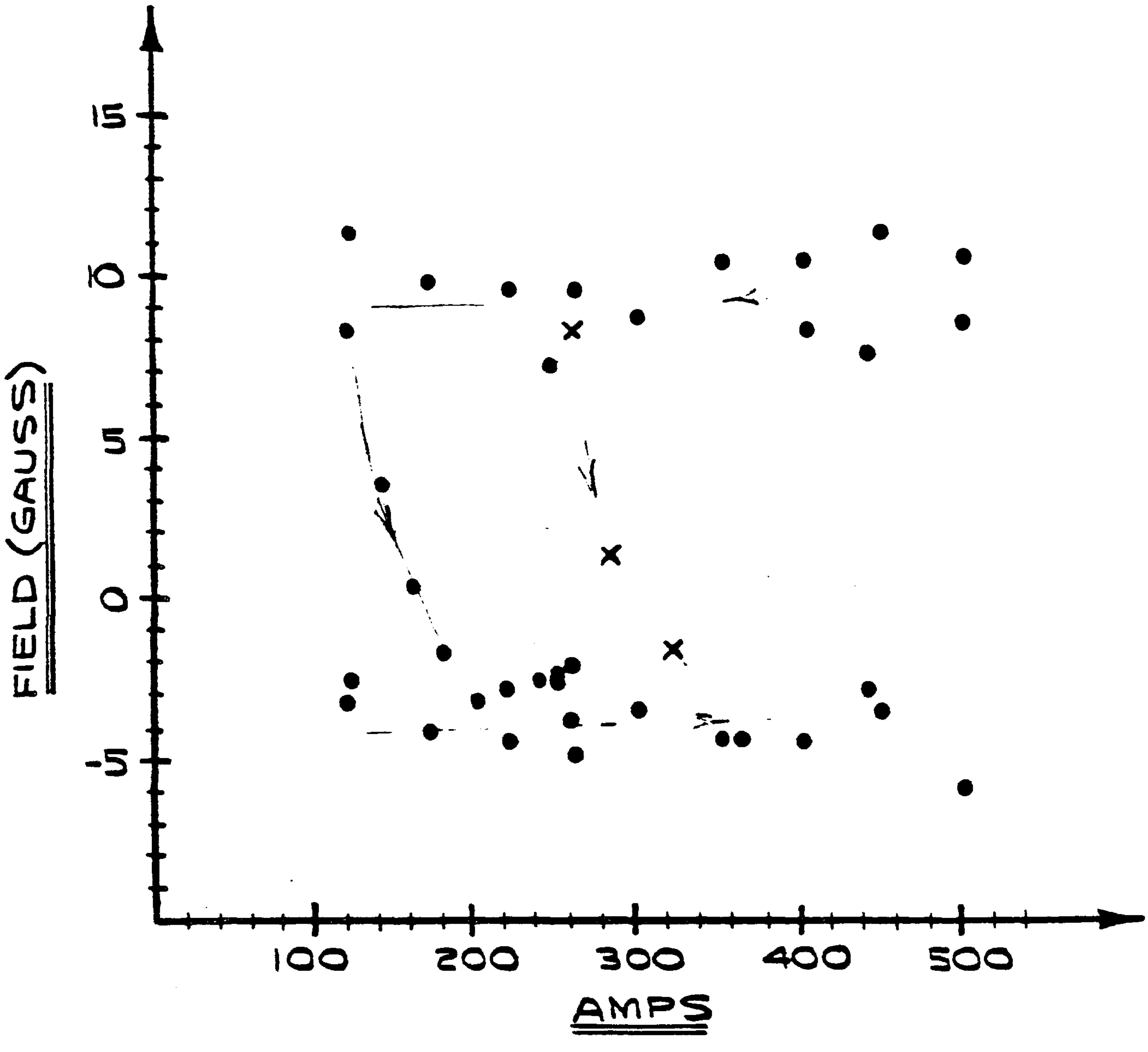
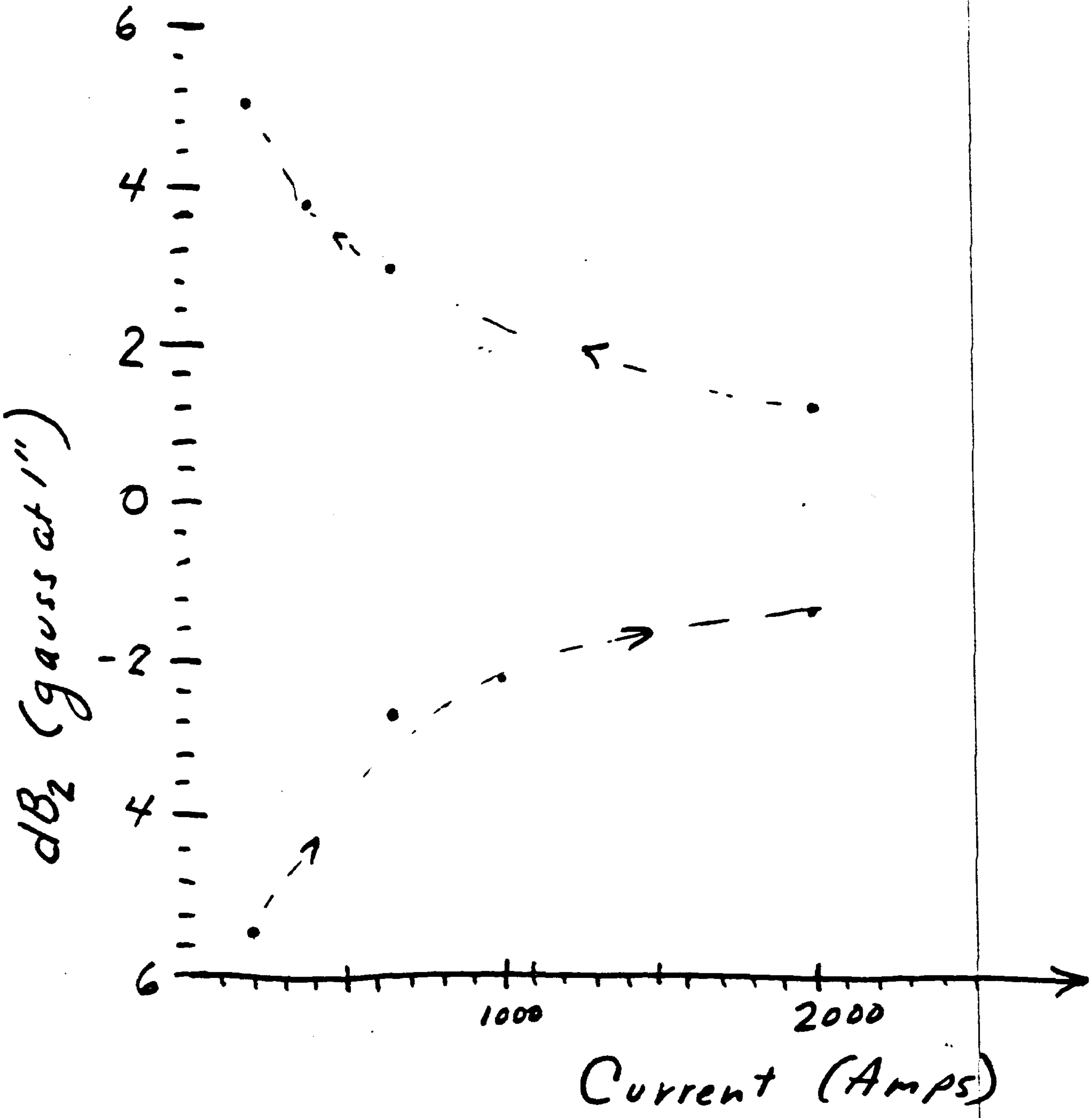


Figure 2



Persistant Current Sextupole

$$dB = b_2 * I - (\alpha + \beta I) \quad \text{gauss at } 1''$$

$\alpha = -.5 \quad \beta = .021 \quad I$ in KA

unit of b_2 are chosen to give gauss at $1''^2$ for I in KA.

Figure 3