AC LOSSES IN MAGNETS MADE OF Nb_3Sn RIBBON*

G.H. Morgan and P.F. Dahl
Brookhaven National Laboratory
Upton, New York

I. INTRODUCTION

The possible reduction of size and cost of a proton synchrotron, which can be achieved through the use of high magnetic field strength, has caused much interest in the application to this end of high field superconductors.[1] The success at Brookhaven of magnets wound from ½ in. Nb_3Sn ribbon[2] naturally led to interest in the ac loss characteristic of these ribbons. The advantages of Nb_3Sn ribbon are high current and current density, high winding density, and ease of handling. These characteristics lead to more compact magnets and higher possible field gradients. Furthermore, the superconducting layer in the commercially available ribbons is thin enough that ac losses should be low if the field were parallel to the ribbon. With this justification, the Brookhaven ac loss program began with a study of the losses in three commercially available ½ in. wide Nb_3Sn ribbons. Much of the results of this study has been reported elsewhere,[3,4] and will be summarized here.

II. APPARATUS

Heat produced in the magnet was determined by measuring the volume of helium vaporized. The magnet and a standard heat source consisting of an electrically heated resistor were enclosed in a container submerged in liquid helium. Power for the magnet was provided by either a fast-rise-time dc generator, permitting current pulses to 3000 A at 50 V with frequencies up to 3 Hz, or by the 60 Hz power line through a variable transformer.

III. MAGNETS AND MATERIALS

The tested magnets were all made of one or more spirally-wound flat coils in which successive turns of the ribbon were separated by ½ in. wide plastic (Mylar) ribbon of several possible thicknesses. The magnet form most commonly tested was a single "pancake" or circular coil having 2.5 in. i.d. and 6 in. o.d., and from 130 to 370 turns of conductor. Two such coils were combined coaxially to produce either an adjacent or a separated pair. One other magnet consisted of a pair of racetrack-shaped coils with 2 in. spacing having an 8 in. straight section. 2.5 in. i.d., and 6 in. o.d.

---

*Work performed under the auspices of the U.S. Atomic Energy Commission.

1. P.F. Smith, Nuc. Instr. and Methods 52, 298 (1967).
2. P.G. Kruger, W.B. Sampson, and R.B. Britton, Brookhaven National Laboratory, Accelerator Dept. Report AADD-104-R (1966).
3. W.B. Sampson, R.B. Britton, G.H. Morgan, and P.F. Dahl, in Proc. 6th Intern. Conf. High Energy Accelerators, Cambridge, Mass., 1967, p. 393.
4. G.H. Morgan, P.F. Dahl, W.B. Sampson, and R.B. Britton, submitted to J. Appl. Phys.

The tested materials were all Nb_3Sn composite ribbons, ½ in. wide. Type A was made by RCA by their vapor-deposition process, and types B and C were made by G.E. by a diffusion process. Some of their characteristics are shown in Table I.

TABLE I

Ribbon Type	A	B	C
Thickness (in.)	0.0051	0.0042	0.0036
I_c at 40 kG (A)	2160	1040	515
J_{eff} (A/cm^2)	21 000	40 000	35 000
Peak field at J_{eff} (kG)	24.6	47.4	39.8

In Table I, I_c is the short sample critical current, J_{eff} is the maximum over-all current density obtained in a single pancake during continuous pulsing, and the field listed is the peak field in the winding at that current density. Part of the lower performance of the A ribbon is due to the lower winding density which was used because of surface roughness.

IV. RESULTS

There are nine important results. First, the loss per cycle is independent of frequency. Since frequency variation was possible only with the generator, this was conclusively proved only at higher fields, since the lower frequencies required higher fields to produce measurable losses. The 60 Hz data, however, agree with the low frequency data if one accepts the next result.

The second result is that the losses depend on the change in current or field, and are largely independent of the magnitude of the field or current. Again, this was proved only by relatively high field results obtained with the generator, since the task of constructing a 60 Hz source with dc bias proved formidable. As stated above, however, for given peak-to-peak current, the loss per cycle at 60 Hz agreed with that caused by the unidirectional, triangular current pulses from the generator.

The third finding is that the loss per meter of ribbon depends mainly on the average of the change in component of field normal to the ribbon surface. This was proved by demonstrating that all the loss measurements can be correlated on this basis. Figures 1, 2, and 3 illustrate this point. Here are shown all the data taken using type C ribbon. In each figure, the points "G" are data using the double pancake magnet having 1/8 in. separation of the pancakes. All of the remaining points are data using either of two almost identical single pancakes. The figures show, respectively, loss per meter plotted against mean square parallel component of field B_Z, mean square total field B, and mean square radial or normal component of field B_N. The field is calculated assuming uniform current distribution in the conductor. By mean is meant the spatial average of the peak field during the cycle. As can be seen, the double pancake data merge with the single pancake data only in the plot against radial field component, Fig. 3, and the correlation is poorest in the plot against parallel component, Fig. 1. It should be noted that plotting against mean square, rather than some other power of the normal component, is not essential to obtain correlation, provided that in the case of odd powers, the absolute value of the normal component is used. Thus $|\overline{B_N}|$ gives about as good a correlation as $\overline{B_N^2}$. The correlation of loss with change in average normal field allows one not only to make accurate estimates of loss in proposed magnets, but also to predict in which part of a magnet winding the loss is greatest. Figure 4 is an example of this. Here is plotted loss per meter vs radial position in a single pancake of type C ribbon, operated at the highest current it was capable of, 500 A (35 000 A/cm^2) with a peak field in the winding of about 40 kG. The loss is least at the inner and outer turns, and greater by a factor of four or more in the middle. It is worth emphasizing that loss prediction requires calculation of the average normal component of field assuming uniform current distribution in the conductor, not the actual normal field component, a much more difficult task.

The fourth finding is that loss is essentially independent of current. Actually, this is a corollary to the third result, since the double pancake which produced the data of Fig. 3 has 51% greater average field for the same current as has the single pancake.

The fifth finding is that loss is independent of current density. This was demonstrated by splitting ½ in. ribbon, from which the edge was removed, in two to form ¼ in. ribbon. For equal average normal field component, the loss per meter in a pancake made from the ½ in. wide ribbon was twice that in a pancake made from the ¼ in. wide ribbon. If loss is presumed proportional to the width of the ribbon or to the amount of Nb_3Sn, this says that loss is independent of current density, since for given normal field component, the current density in the ¼ in. pancake is almost twice that in the ½ in. pancake.

The sixth experimental finding is concerned with the effect of winding density on loss. Three pancakes were wound with type B material and different thicknesses of Mylar interleaving to give a total pitch, or thickness per turn, of 0.005, 0.010, and 0.014 in. At low fields, the loss per meter for a given field change was the same for all three magnets. With increasing field, however, the loss curves become increasingly separated, and at the highest field common to the three magnets, the coarsely wound magnet has 4.6 times the loss per meter of the most closely wound magnet, and the medium density magnet has twice the loss per meter that the high density magnet has. This could be a current density effect in contradiction to the fifth finding, and to test this point, a bifilar magnet was wound, essentially the magnet of 0.014 in. pitch already described, with the 0.010 in. thickness of Mylar replaced by a sandwich of 0.004 in. of superconductor (more B ribbon) between two 0.003 in. thicknesses of Mylar. With only one of the windings powered, i.e., with the same current density as the 0.014 in. pitch magnet, the bifilar magnet had a loss per meter corresponding to a pitch of 0.007 in., about one-third that of the 0.014 in. pitch magnet. In fact, the total loss of the bifilar magnet was less than (77% of) the total loss of the 0.014 in. pitch magnet, at the highest field. This effect is attributed to an increasingly great reduction of the normal component of field with increasing winding density, or equivalently, increasingly great field exclusion. The fact that loss per meter is the same in the three magnets at low fields says that at low fields, exclusion is complete, so that the loss is a surface phenomenon. In fact, we find that at sufficiently low fields, the loss in all three ribbon types tends to be the same.

The seventh result is the dependence of loss on superconductor thickness, or equivalently for constant J_c, on I_c. According to theory,[5] the loss in ribbons in a field parallel to the ribbon should go as thickness or I_c squared, so using the critical currents listed in Table I, the corresponding loss ratios should be A/B = 4.3 and B/C = 4.0. The observed ratio of loss in type A to that in type B ribbon is about 3.0 at intermediate and high fields (with both materials at the same winding density of 0.010 in./turn). The observed ratio of loss in B to that in C ribbon (both at a winding density of 0.005 in./turn) is a function of field: 1.4 at intermediate field to 1.0 at high field. In both cases, increasing the Nb_3Sn thickness results in lower

---

5. R. Hancox, Proc. IEE (London) 113, 1221 (1966).

loss than is predicted by the theory. Assuming that cladding is not a factor, the discrepancy could be due to the field not being parallel to the ribbon, to the assumption that J_c is the same in all materials, or it could be that field exclusion effects are a function of superconductor thickness, or amount of superconductor per unit volume of winding.

The eighth conclusion one can obtain from the data is that the loss at high field in all materials increases as about the 2.5 power of the normal field. Since the actual normal field, in this field range, increases faster than that calculated on the basis of uniform current distribution, the true field exponent must be less than 2.5. It should be remembered that these observed losses are due to field changes in the material which range from zero (at the kernel of the magnet) up to the maximum at the innermost turn. The observed loss is thus an average over a variety of field changes, and the exponent of the loss curves is accordingly an average.

The ninth result is the finding that in all the tested magnets, the ratio of stored energy to energy loss per cycle, $E/\Delta E$, lay within a band ranging from about 100 to 250, with a generally decreasing trend at higher fields. This latter result follows from the 2.5 power dependence of loss on normal field, and the second power dependence of stored energy on field, which together imply a $1/\sqrt{B}$ dependence of $E/\Delta E$ on field. The constancy of $E/\Delta E$ from magnet to magnet is possibly a result of the relation between stored energy and length of conductor in compact solenoids.

V. COMPARISON WITH THEORY

Comparison of the results with theory is difficult for several reasons. First, some of the ribbon parameters (Nb_3Sn content) are not known accurately. Second, the contribution of the Nb substrate in the G.E. ribbon is uncertain. Third, the field direction at the ribbon surface is both complex and unknown. Eddy currents in the normal material presumably contribute to the loss, but this contribution is probably small, since we observe no frequency dependence. Using formula (9) of Hancox,[5] we compute the loss for the case of field parallel to the ribbon, which should set a lower limit to the experimental loss. The value obtained is 6.7 or 3.9 J/cycle, depending on whether the Nb substrate is or is not included. The experimental value for G.E. 150 with an average total field change of 19.5 kG was 25.6 J/cycle.

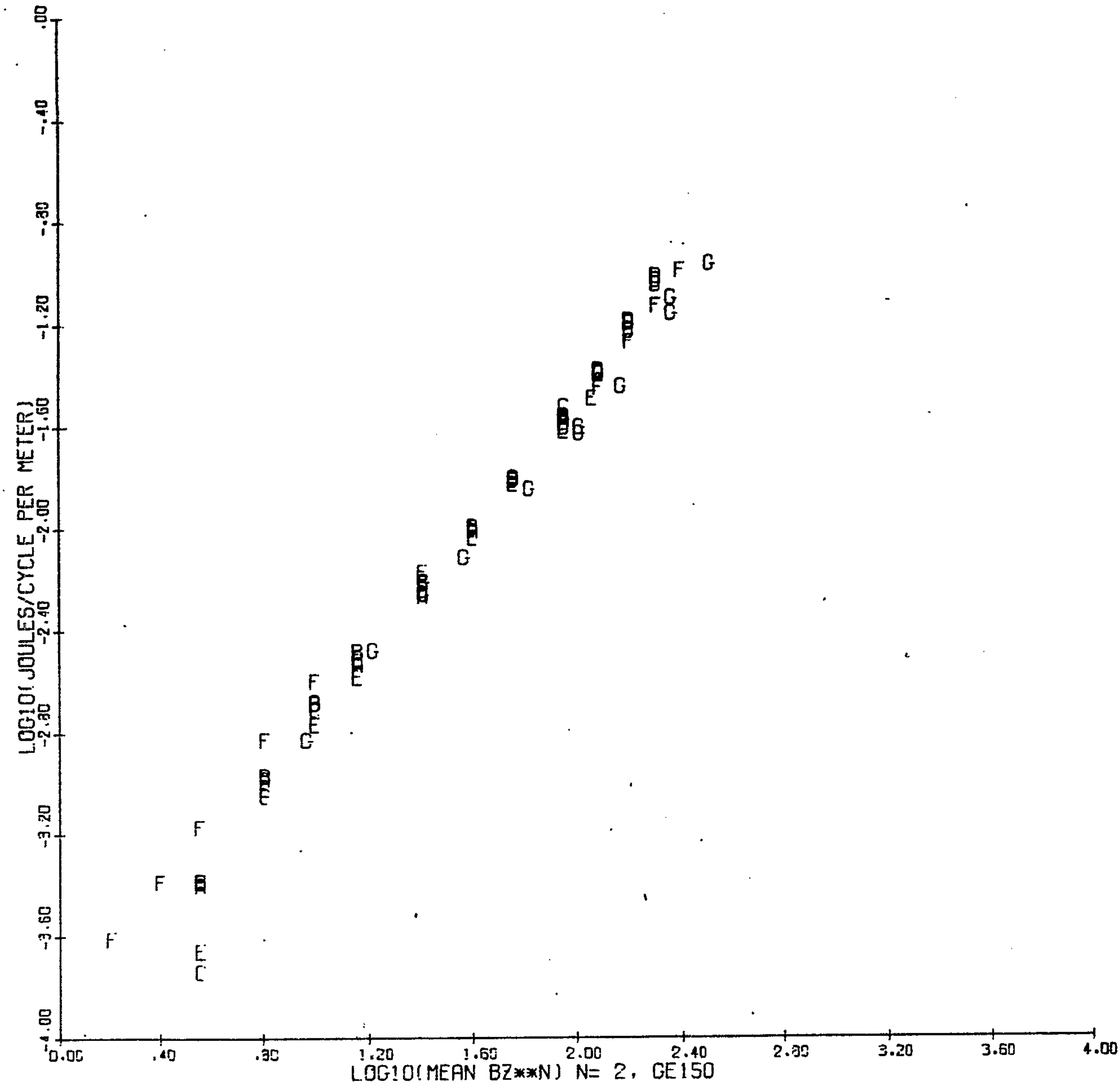

Fig. 1. Energy loss per cycle per meter vs mean square parallel component of field. The G's are from a double pancake magnet, and the remaining points from single pancake magnets.

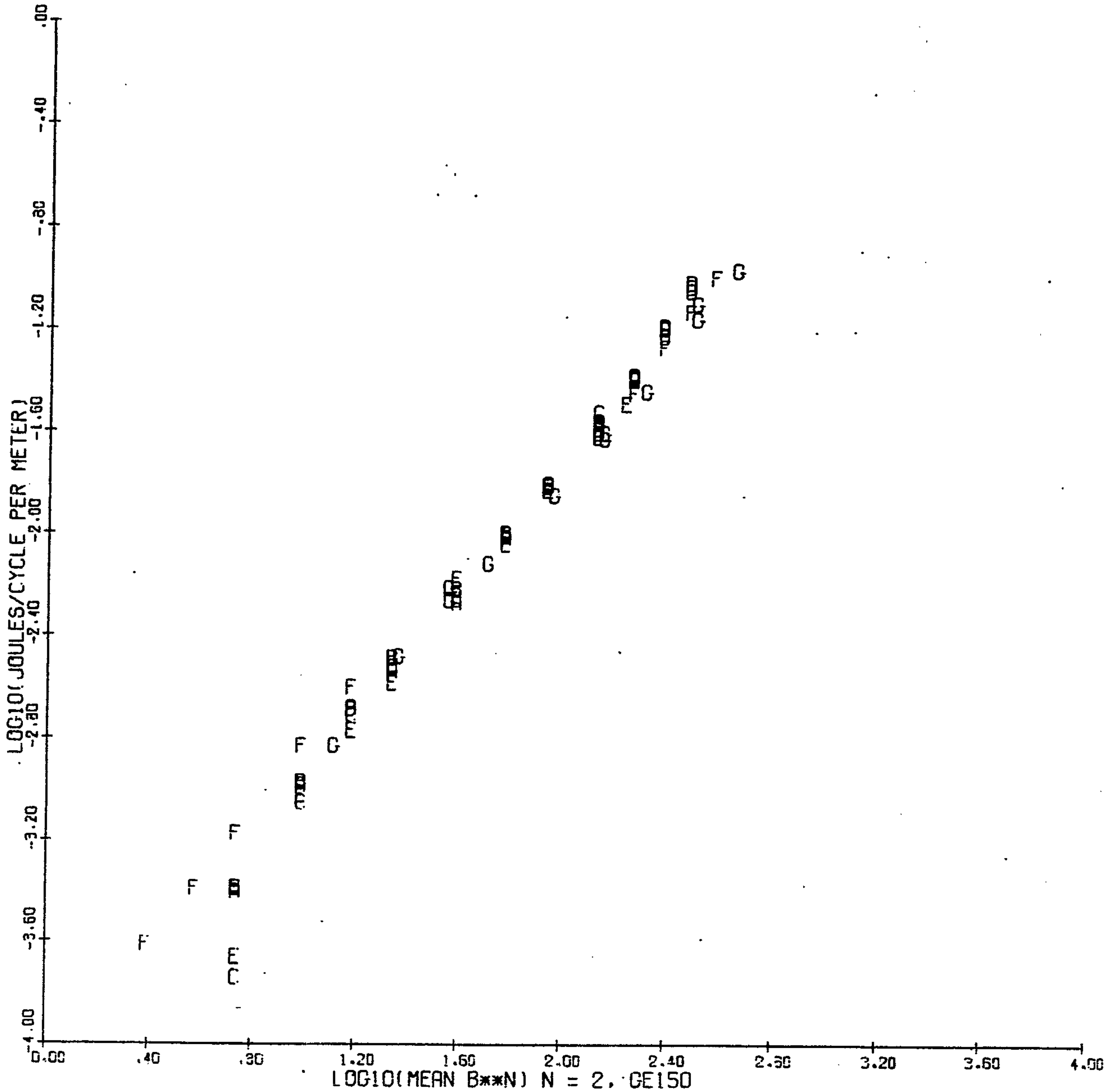

Fig. 2. Energy loss per cycle per meter vs mean square total field. The symbols have the same meaning as in Fig. 1.

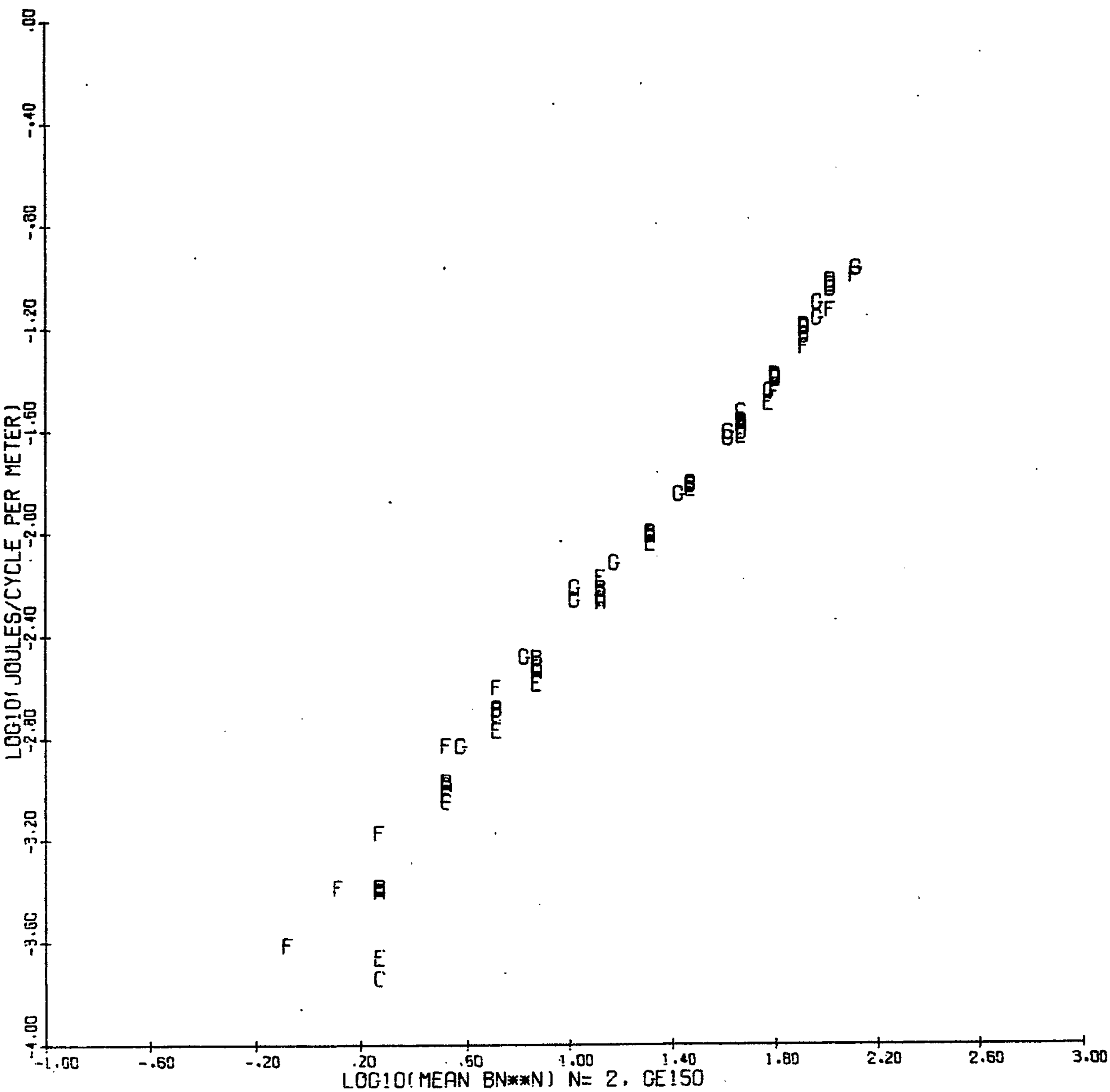

Fig. 3. Energy loss per cycle per meter vs mean square normal component of field. The symbols have the same meaning as in Fig. 1. Note that here, the G's blend in with the remaining points, especially at high field where the data are more accurate.

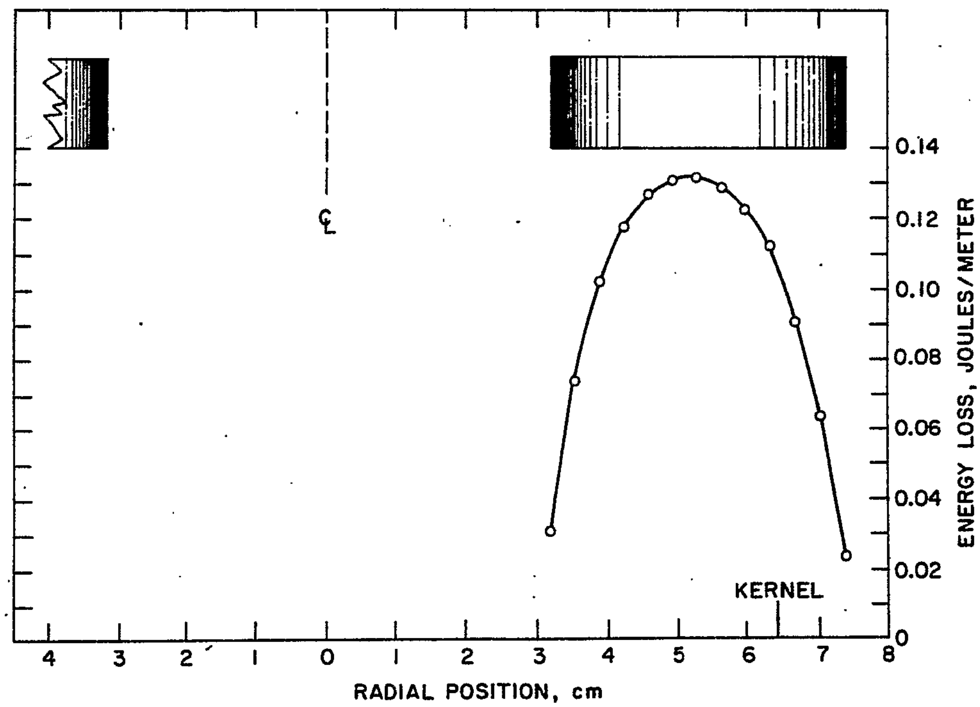

Fig. 4. Energy loss per cycle per meter vs radial position in a pancake magnet. The loss is derived from the data of Fig. 3, which are losses for entire magnets.