

Magnetic measurements of AGS experimental magnets

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ACCELERATOR DEPARTMENT

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Internal Report

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MAGNETIC MEASUREMENTS OF AGS EXPERIMENTAL MAGNETS

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December 26, 1961

This is a preliminary report on the magnetic measurements taken to date on the AGS experimental magnets. It mainly summarizes the results which were necessary for the setting up of the \bar{p} separated beam in August 1961. A few curves on information obtained since then are included. When the study is finished, a complete report on all phases of the work, including the methods used, will be forthcoming.

The experimental magnets available are:

<u>Deflecting</u>	18 D 36
(6" gap)	18 D 72
	30 D 72
<u>Circular Quadrupoles</u>	8 Q 24
	8 Q 48
	12 Q 30
	12 Q 60
<u>Rectangular Quadrupoles</u>	6 RQ 24
(36" long)	

The basic approach used is to establish the identity of all members of a given class of magnets by observing the azimuthal integral of the magnetic field as a function of current and position. Because of the high mechanical and magnetic tolerances required of the manufacturer, it is reasonable to expect this identity to an accuracy sufficient for almost all purposes, barring faulty workmanship. In cases where this was not adequate, a first order

interpolation could be made since the differences will be very small. These tests can be made rapidly on a lens, as well as a map of the horizontal plane of magnetic symmetry, which is a sensitive test of lens quality.

A detailed study of the harmonic content of only one member of a class need then be made as a function of current. From a knowledge of the symmetries involved for a given lens type, one knows the terms that can exist in a 3-dimensional expansion of the field. By judicious combinations of integrated measurements and point measurements, one can get what amounts to a complete 3-dimensional map of the field.

Optical computations can be done to a high order of accuracy by assuming the lenses to be ideal thick lenses. The separated beam at the AGS was set up on this basis, using the integrated field results. The resolution was the theoretical one, and the current settings were identical with those obtained from the results.¹

Only sufficient measurements were taken on aberrations to establish that they were small enough to ignore at this stage.

Effort was concentrated on getting absolute values of integrated field length in the work described in this report. One needs to know both the field strength and the length to write a matrix for a thick lens, but not as accurately as one needs the product. Curves are included for the "lengths" as a function of current.

Then dividing this thick lens length L_B into $\int B(s)ds$ one can obtain a thick lens field (or gradient as the case may be). It is suggested that for practically all cases one can get sufficient accuracy by assuming L_B constant and let all the variation go into the field. This appreciably simplifies manipulation of the lenses.

1. C. Baltay et al. and H.N. Brown et al. BNL Internal Report C-29

No results are available for 6 RQ 24 magnets, which are needed to complete this "first phase" of the work.

Work is in progress to get complete descriptions of the aberrations of the magnets. The two dimensional aberrations (i.e. not associated with end effects) will be measured, and then can be corrected when and if such accuracy becomes necessary.

The three dimensional terms present in the ends will also be measured.

These can be modified, but cannot be eliminated, and always will introduce some aberration. However with a description of the ends, one can find the effect of such terms using, say, many matrix intervals in a computational program. The above aberrations are only for the case of perfectly constructed magnets having the ideal design symmetry. Assymmetrical terms are also looked for. If they were not negligible, or easily corrected, such a magnet would not be used for a very precise beam, but we expect few problems from this source.

The rest of the report is a description of the curves included for the various magnets.

The $\int B(s) ds$ (azimuthal integral of the field; in this case taken at the center lines) of all 18 D 72 magnets is identical to about 2×10^{-4} parts. If we ever desire more accurate comparisons, better current regulation will be necessary.

The integrated harmonic content is shown in Fig. 1 as a function of transverse distance from the aperture centerline, with current as parameter ($1000 \cong 9.25\text{kg}$). For any given curve the values are relative ones with respect to the value at the aperture centerline. The values on the aperture centerline for different currents bear no relation one to another. Except at high fields, the aberration is very small. Because of the symmetry, it can be expressed in

even powers of X, the transverse dimension.

For small deviations, this looks like a sextupole effect primarily. Measurements on this can be made to high accuracy, when it becomes necessary to flatten this field, with shims or pole-face windings.

Fig. 2 gives the relation between p (bev/c) and $(\sin \theta_f - \theta_i)$, and $\int B(s)ds$ (k gauss - inches).

Here θ_f = angle of exit with respect to magnet axis.

θ_i = angle of entrance with respect to magnet axis.

Knowing $\int B(s)ds$ (= $B L_B$) required, Fig. 2 gives the required "current".

Here current is actually the voltage read across a (0.25%) shunt, the value being assumed to be perfect. However it will be shown later that the particular shunt value drops out, since we have a way of setting up so that the various lenses with their supplies, have their "current" scales cross calibrated so as to produce the correct field.

Then the correct voltage across the shunt of a given supply is known for a given lens to give the required $B L_B$.

Note: As indicated on Fig. 2, the value of $B L_B$ should be increased by 1.0025. This correction was forgotten when plotting the figure, and is due to the fringing field beyond the long coil used. The correction is constant to 10% over the range, and is assumed to be constant here.

The hysteresis is seen to be somewhat larger than 0.1% maximum. With cycling, the field could be held very well even without Hall probe control. The dotted and solid curves represent different runs as explained on the graph.

Fig. 3 gives L_B (magnetic length) vs I. This is the Fig. 2 values divided by the field at the center. The right hand scale gives

$\Delta L_B = L_B - L$ (L=nominal 72"). This curve is, strictly speaking, also low by 1.0025, because of Fig.2.

It should be noted that, except for the transverse variation shown in Fig. 1, the angle of bend as given in Fig. 2 is rigorously correct independent of the actual shape of the ends. There will only be a small translation due to the detailed shape. Even uncorrected, the aberration is very small in most cases, as shown in Fig. 1, and so the angle of bend should be quite accurate.

Accuracy

The accuracy of the absolute values is somewhat poorer than that of intercomparisons. The detection sensitivity is identical, but, whereas in the case of intercomparisons the two magnets "Track" at least to first order with current fluctuations, the absolute value is I dependent. Furthermore, the absolute system is more sensitive to stray noise at present. In practice, the accuracy was determined by the regulation of the magnet current. As can be seen from Fig. 2, except at very low currents, the data is better than 0.1%, because the power supplies can do better than 0.1%. The absolute calibration is probably about 5×10^{-4} parts which is better than the accuracy of the points on Fig. 2 and the corresponding quadrupole curves. It is noteworthy that this calibration is just a "bonus" because it corresponds to the absolute value of momentum of a beam transported. Since all lenses of a beam have the same calibration constants involved, an error would not affect the focal properties. However, in this case the absolute value is better than the relative values.

Quadrupole Results

The next curve, Fig. 4, gives $\int G(s) ds$ for 8 Q 24. Run 1' was on

a different magnet than the others. It was the first absolute run done. The second setup was after the other lenses were done. This shows that Q 101 and Q 108 are very close in value.

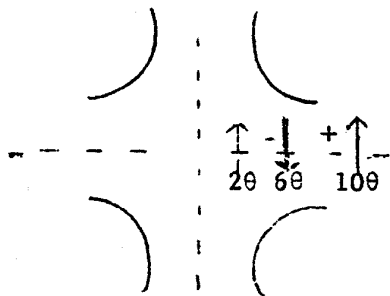
The various quadrupoles were not intercompared , for two reasons.

1) The quality of workmanship is good. The tests which will be made to "set up" the power supply I values for a given lens plus its supply will tell if there are coil shorts, or the magnetic axis is off center. Also the requirements on absolute values are not as stringent as for deflecting magnets.

2) A measuring device is now ready which will give the location of the magnetic axis, the harmonic content (including any assymetrical terms) and the integrated gradient length intercomparisons, all as a funtion of I.

Harmonic Content

The symmetrical harmonic content was observed (6θ and 10θ) in 8 Q 24 and 8 Q 48 (integrated) and also point values inside, to the best of our ability without special equipment.



Phase was defined with respect to 2θ direction of field on horizontal symmetry axis.
 (-ve is anti-||)
 (+ve is ||)

At r = 4" (The harmonic content is very insensitive to current)

$$\frac{B_{6\theta}}{B_{2\theta}} = (-0.96 \pm 0.3) \times 10^{-2} \left(\text{varies as } \frac{r}{4} \right)^4$$

$$\frac{B_{10\theta}}{B_{2\theta}} = (+0.9 \pm 1) \times 10^{-2} \left(\text{varies as } \frac{r}{4} \right)^8$$

These limits include not only measurement errors, but slight variations from internal values to the two integrated length values. However this was too small to merit further study until we have better data. Sample calculations of one 12 inch quadrupole (which should have the same harmonic content) gave similar results well within the limits of accuracy quoted. The matter was not pursued further, since other new harmonic coils will give much more precise information.

Fig. 5 is $\int G(s) ds$ vs I for 8 Q 48.

Fig. 6 is G vs I for an internal (2 dimensional) position on a 8" quadrupole.

Figs. 4 to 6 show that hysteresis is large in the quadrupoles. Furthermore, at present I control is used on quadrupoles. Thus cycling must be used for individually powered quadrupoles. As can be seen from the repeats, careful cycling should give about 1×10^{-3} accuracy.

Fig. 7 is $\Delta L_B = L_B - L_{\text{core}}$ (nominal) for 8" quadrupoles. It is obtained by dividing Fig. 6 data into Fig. 5 and Fig. 4 data. The agreement is well within the length tolerances on the magnets. This is more than adequate for thick lens calculations.

Figs. 8 and 9 give $\int G(s) ds$ vs I for 12 Q 30 and 12 Q 60 respectively. Fig. 9 shows the affect of cycling on different hysteresis loops. As can be seen it is better to cycle down from a higher current, to minimize variations with power supply conditions.

To obtain $\Delta L_B (= L_B - L_{\text{core}})$ for 12" quadrupoles, extrapolate from the 8" quadrupole data in Fig. 7. Take a current which is 0.97 times the required current in the 12" quadrupole. Read ΔL_B (8") from Fig. 7 for this corrected current. Finally, multiply by 1.50 to scale the dimensions (the almost negligible current correction scales to the same relative pole tip fields.)

In all cases use $\int G(s) ds$ values directly for the lens integrated strength.

Fig. 10 gives $\int B(s) ds$ vs I for the 18 D 36 bending magnets.

Fig. 11 gives L_B for the 18 D 36.

The above curves give adequate information for beam design for the lenses described in this report. The vertical focussing of the bending magnets has not been discussed. However, like the angle of bend, it does not depend on the details of the integral through the fringing fields, to first order, and so can be calculated for a given case from the data in the curves.

Transfer of Test Data to Calibration of Beam Lenses

The deflecting magnets will have Hall probes installed. If the Hall voltages are known that correspond to the "current" values for the curves taken on the test stand, then $\int B(s) ds$ is known independent of the particular power supply setup.

A permanent reference Hall fixture is part of the measurement equipment. It has two probes, so it can be used as a gradient pair for quadrupole calibration, in addition to dipole calibration.

The rest of this report can be ignored for beam design. It describes the actual method of calibration of a beam setup at the AGS.

The ratio of $\int B(s) ds$ to V_{Hall} was measured as a function of magnet current in a 18 D 72 for both magnet polarities and for both reference Hall plates. This was done at two values of Hall current. Graphs of $\int B(s) ds/V_{Hall}$ vs I were made. Dividing this data appropriately into $\int B(s) ds$ from Fig. 2 gives the Hall voltage corresponding to a desired $\int B(s) ds$.

To calibrate a magnet, the reference Hall fixture is placed in the center. A few "currents" are set up and the deviations of V_{Hall} from the values on the test stand observed. This gives the cross calibration of the shunt in the supply used to that in the test set-up. It also would include any leakage currents present by error, and reveal shorted magnet coils. This gives a slightly modified "current" scale so Fig. 2 applies locally. Alternatively, the local Hall can be cross calibrated against the reference, and local Hall voltage used to give $\int B(s) ds$.

To calibrate a 18 D 36 magnet plus supply setup, the same procedure would be followed.

Most data was taken with 200 ma of Hall current. (Actually 200 mv across the reference series shunt when the magnet field is zero). Data was also taken at 30 ma. The latter is included here for purposes of illustration.

Fig. 12 gives $\int B(s) ds/V_{Hall\#1}$ vs I, for both magnetic field polarities.

Fig. 13 is the equivalent for Reference #2. Both these curves are for 18 D 72 and, again, it should be noted that after all manipulations of the curves are finished, that $\int B(s) ds$ should be increased by 1.0025.

The Hall current varies with the magnet field (constant voltage source). Fig. 14 gives this variation of I_{Hall} with I magnet for the various cases. To calibrate, the Hall current is read as well as the voltage, and should agree with the data in Fig. 14. (If it were off, the ratio V_{Hall}/I_{Hall} can be extrapolated over several percent variation quite linearly, since V_{Hall} is proportional to I_{Hall} .)

Hall control is not used at present on quadrupoles. However, the Hall Reference gradient pair goes into all 8" and 12" quadrupoles on a precision locating fixture. Again, data is available on the Hall voltages of this pair as a function of "current" on the test setup.

If this fixture is tested against each quadrupole and supply setup in the beam, again one has a corrected current scale so the "currents" correspond exactly with those on the curves.

It is a pleasure to acknowledge the thoughtful efforts of those involved from the Magnetic Measurements and Mechanical Engineering groups who were responsible for the success of this program. Also, the Power Supply people, who provided the Hall probes, gave considerable assistance. I would like to especially mention Mr. Jack Weisenbloom who led the measurements crew.

Without painstaking work on the part of all concerned, a program of this type could not succeed.

Dist: B1,B2, B3
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Figs. Attached

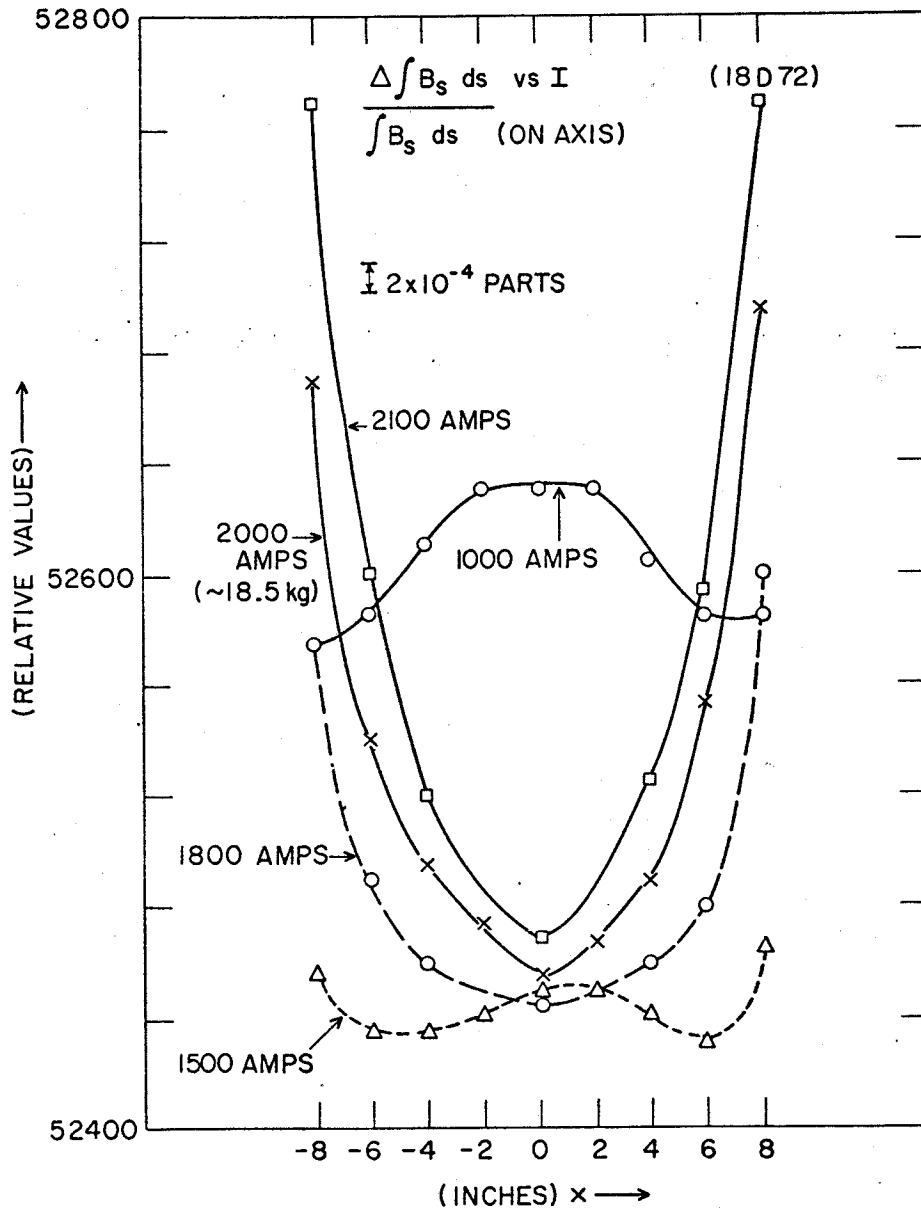


Fig. 1. Integrated nonlinearity, $\Delta \int B_s ds$, of 18D72 magnets.

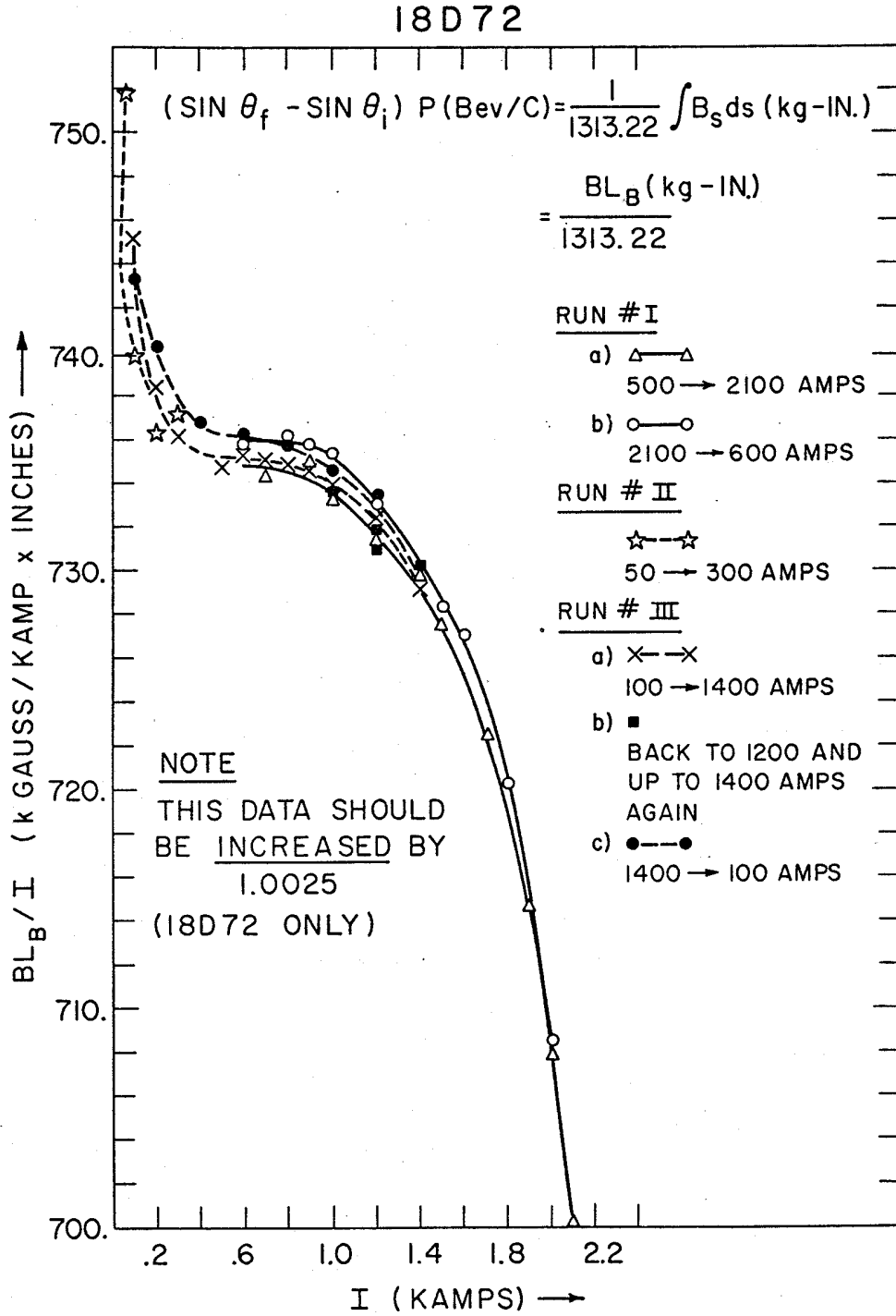


Fig. 2. $\int B_s ds$ vs I for 18D72 magnets.

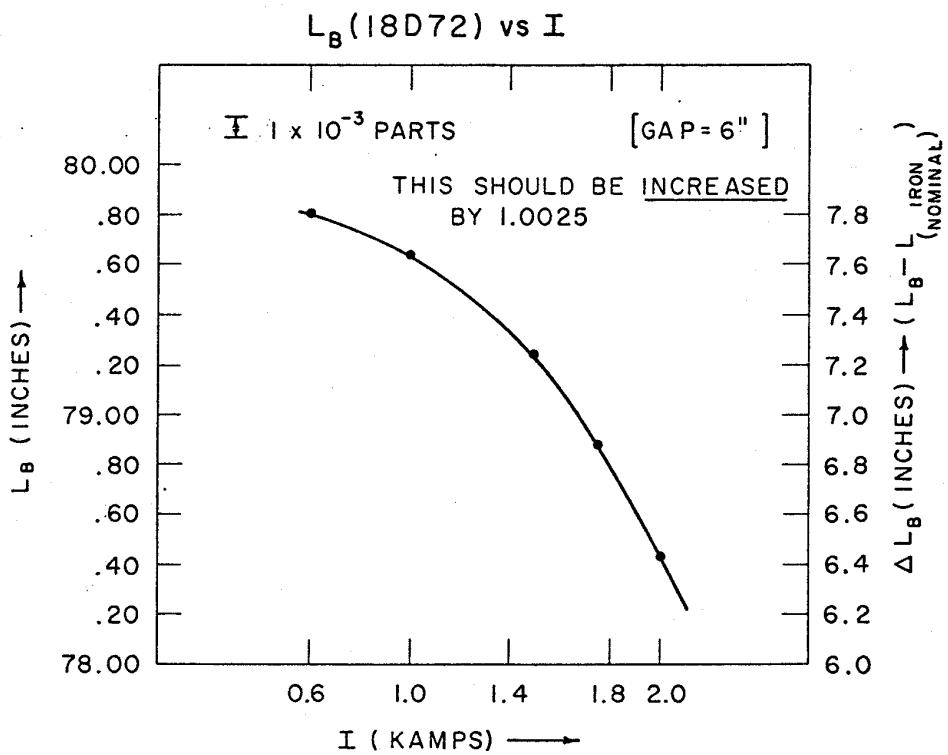


Fig. 3. Magnet length, L_B , vs I for 18D72 magnets.

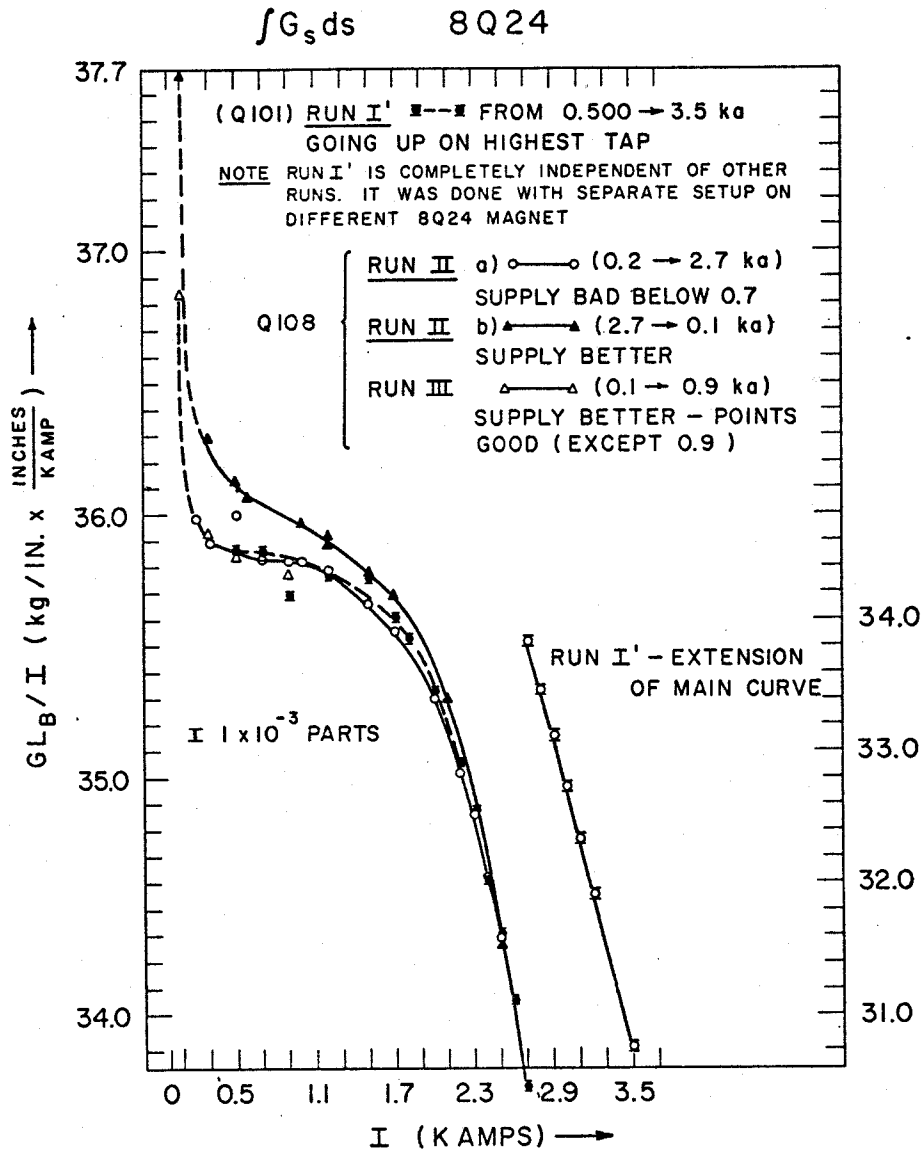


Fig. 4. $\int G_s ds$ vs I for 8Q24 magnets.

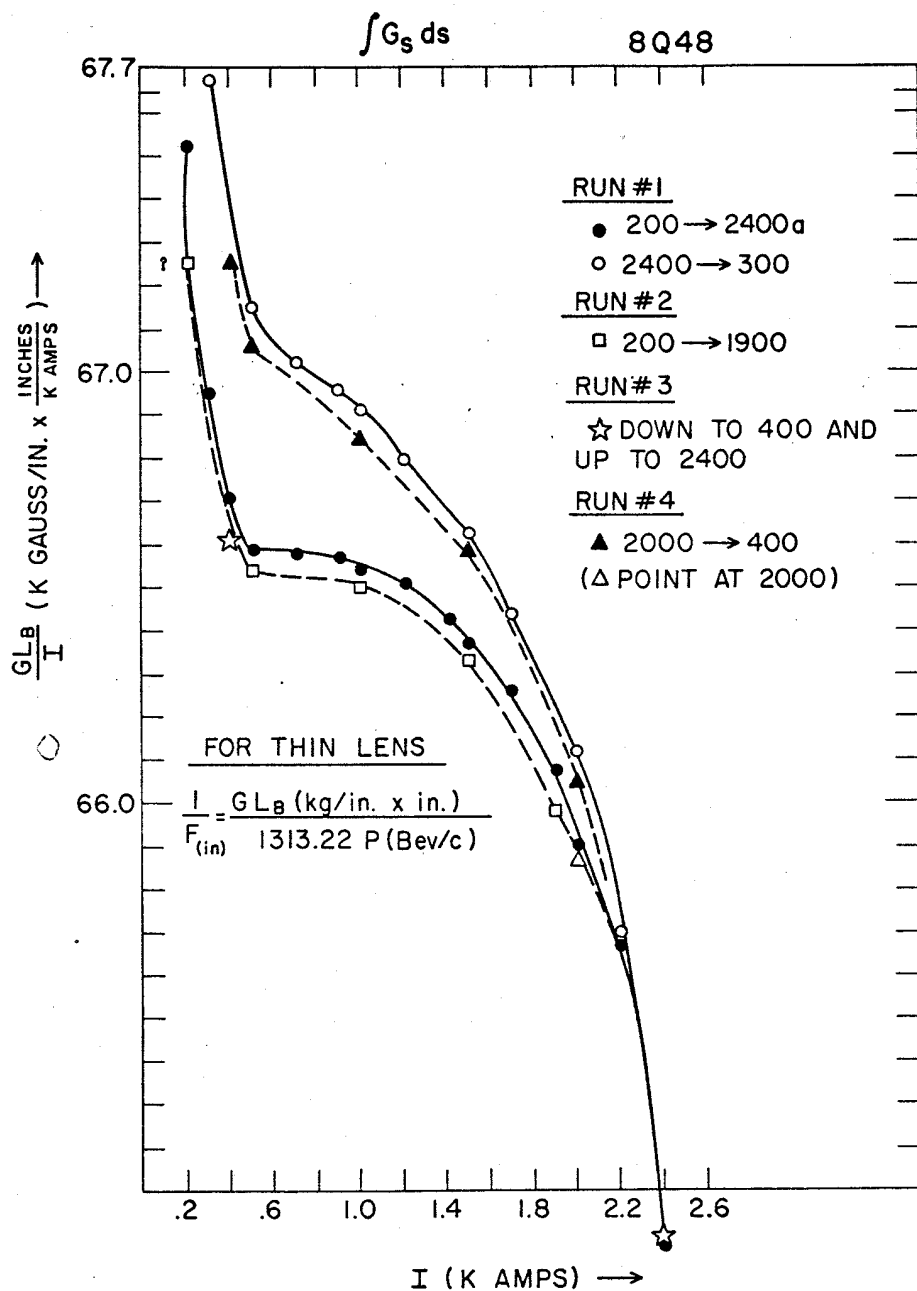


Fig. 5. $\int G_s ds$ vs I for 8Q48 magnets.

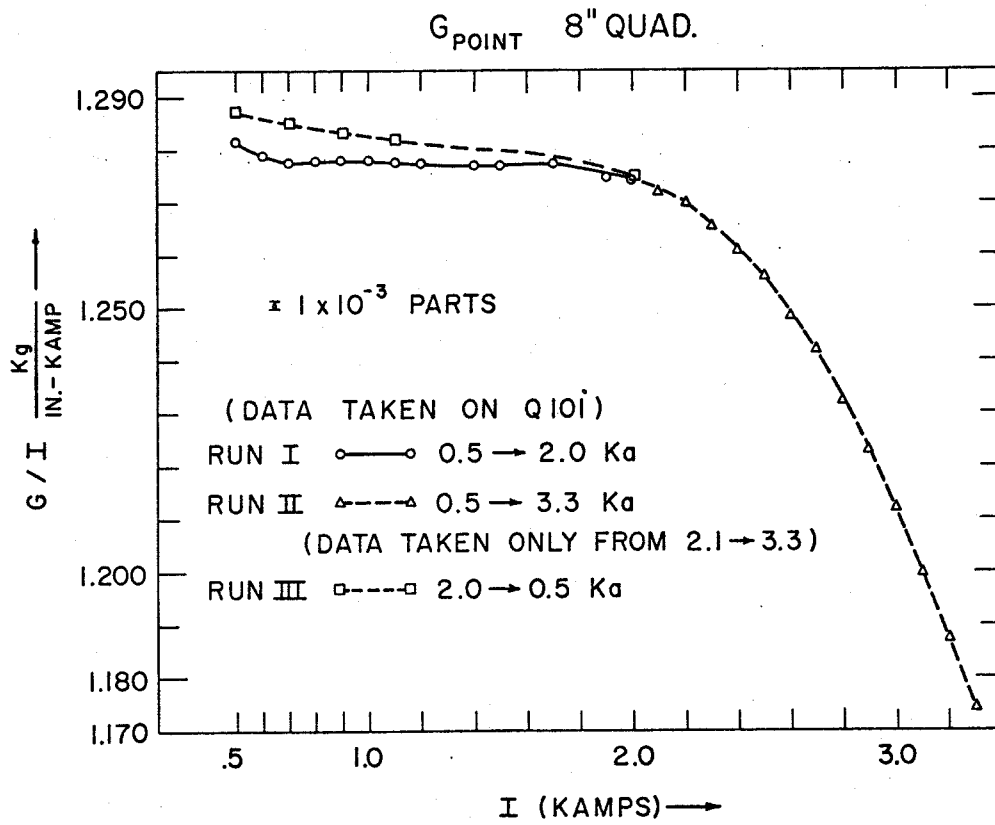


Fig. 6. Gradient, G point, vs I for 8 inch quadrupoles.

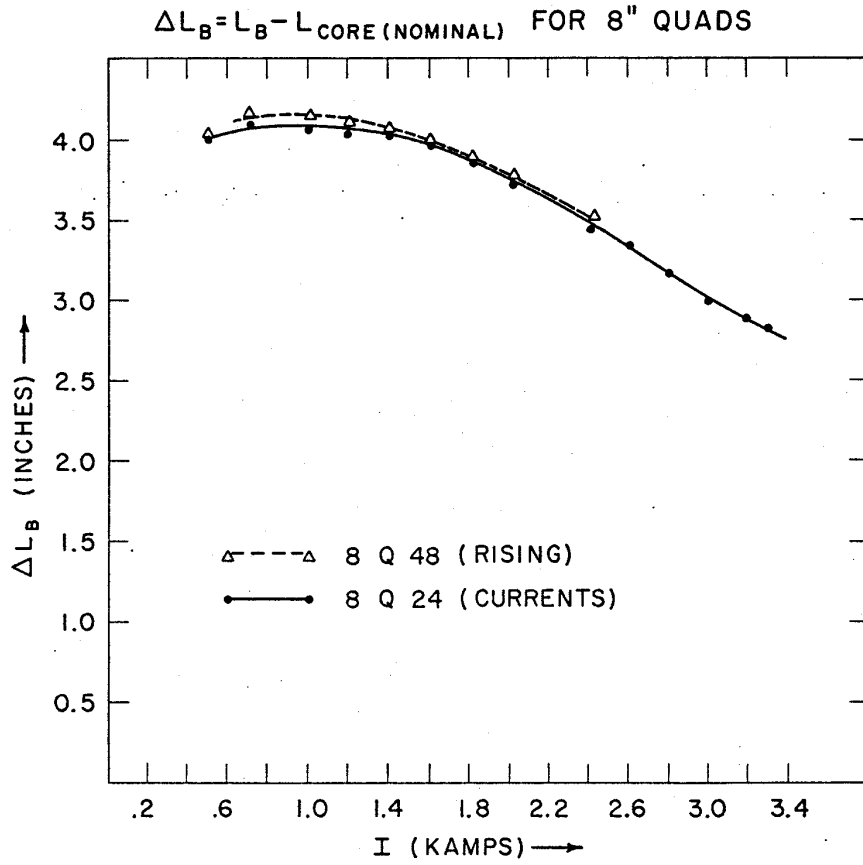


Fig. 7. Magnet length, L_B , vs I for 8 inch quadrupoles. ($L_B = \Delta L_B + L_{core}$).

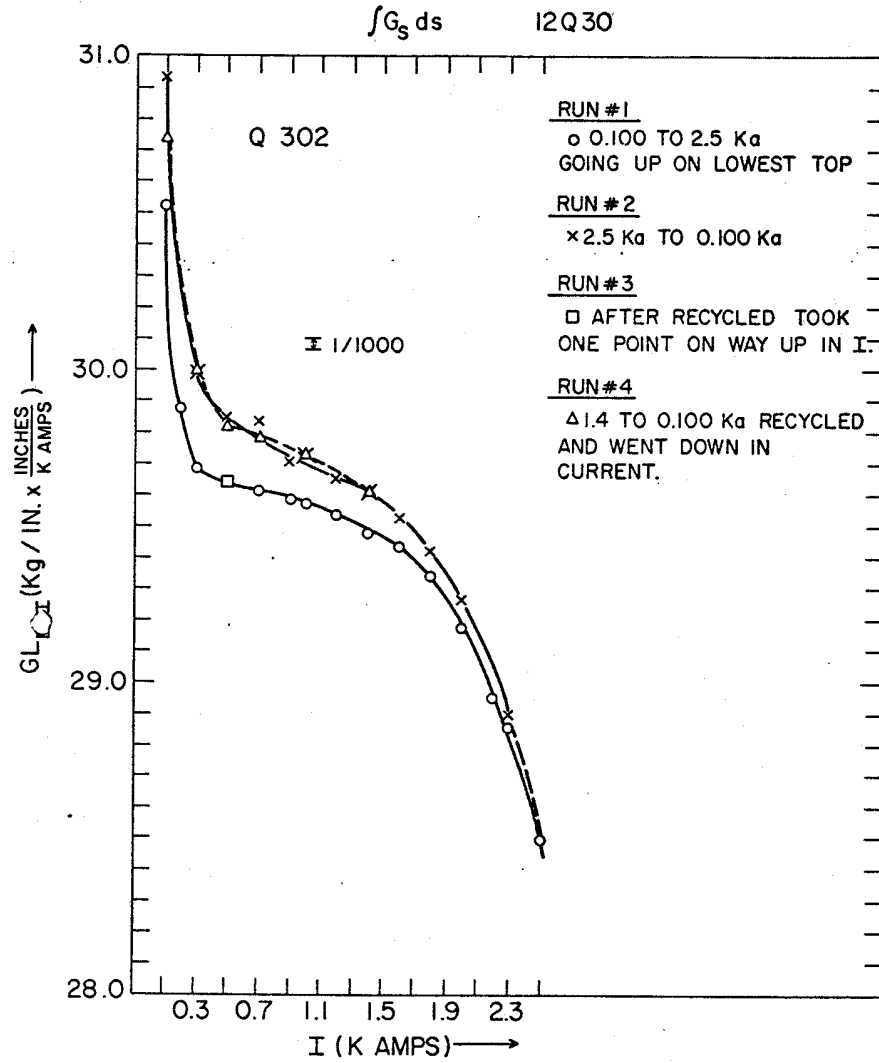


Fig. 8. $\int G_s ds$ vs I for 12Q30 magnets.

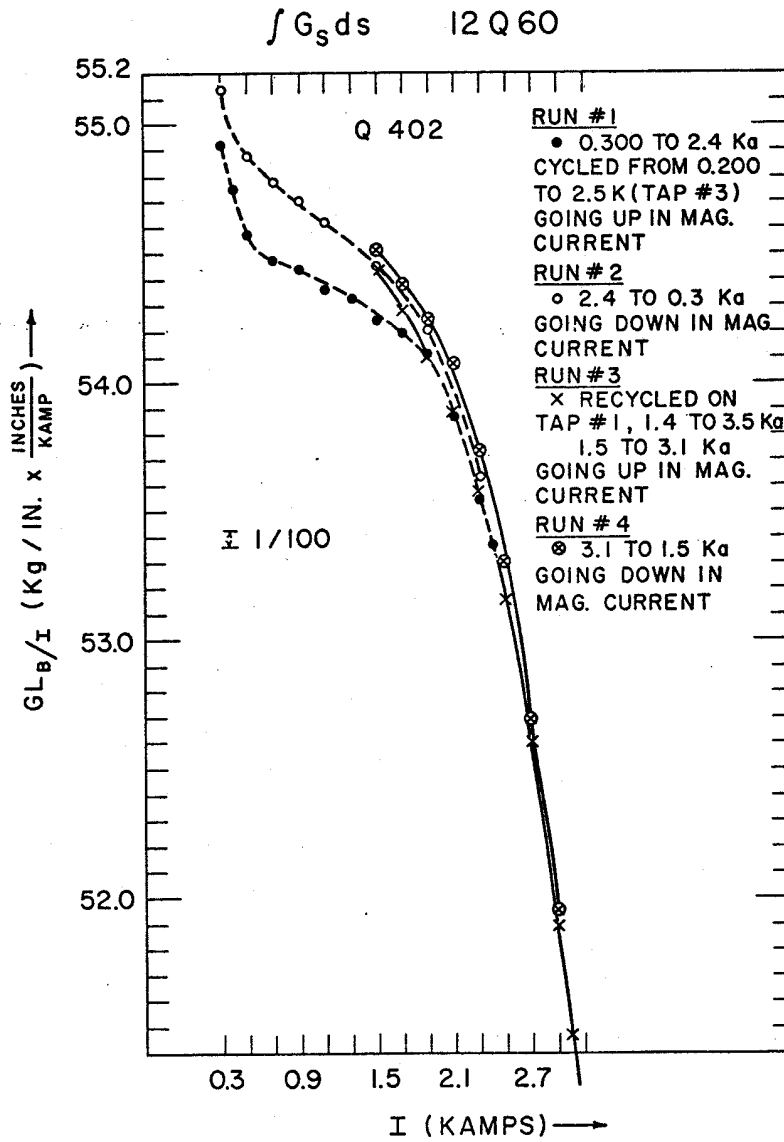


Fig. 9. $\int G_s ds$ vs I for 12Q60 magnets.

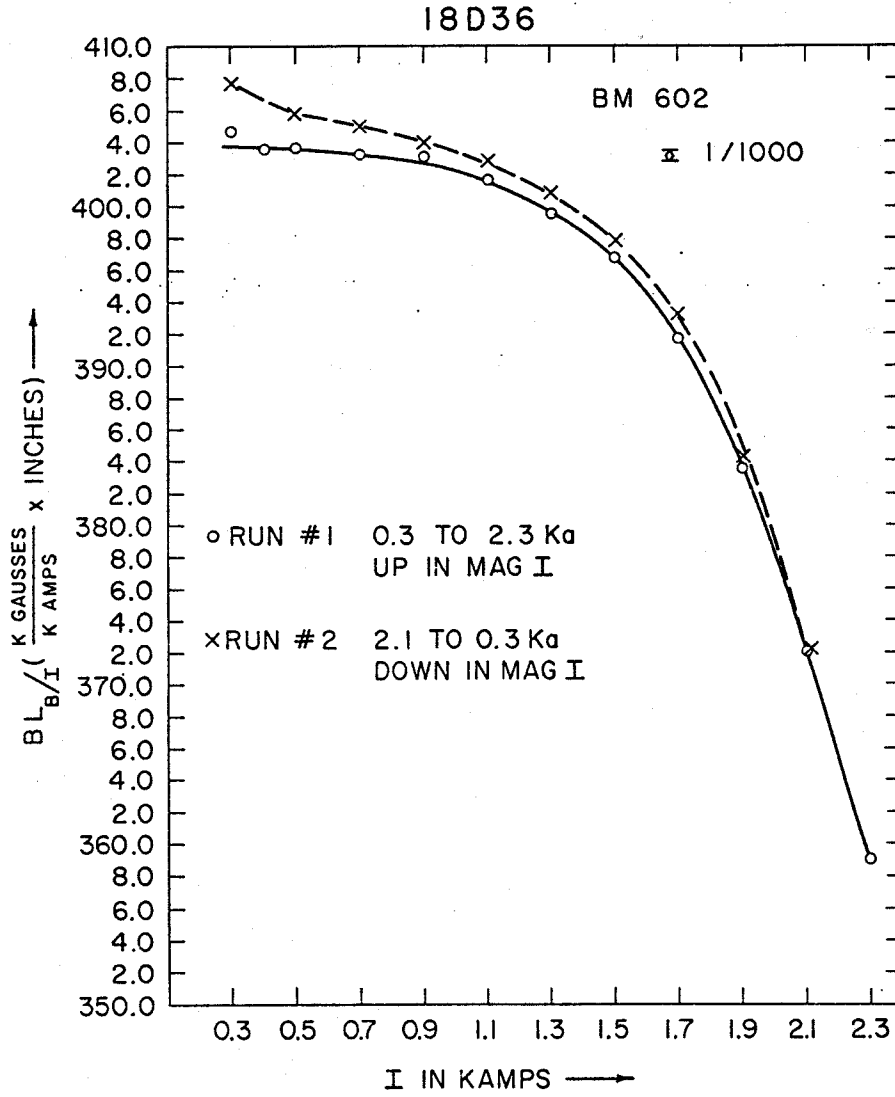


Fig. 10. $\int B_s ds$ vs I for 18D36 magnets.

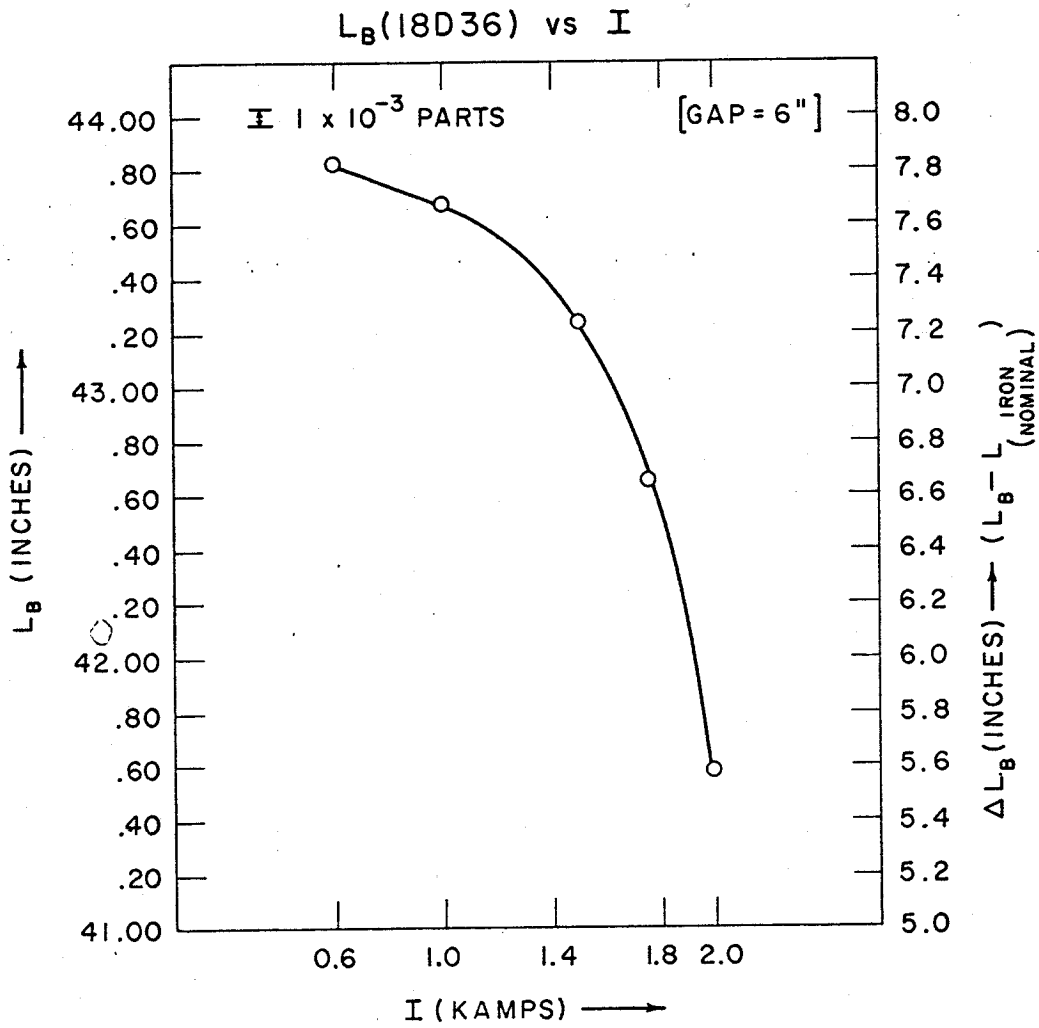


Fig. 11. Magnet length, L_B , vs I for 18D36 magnets.

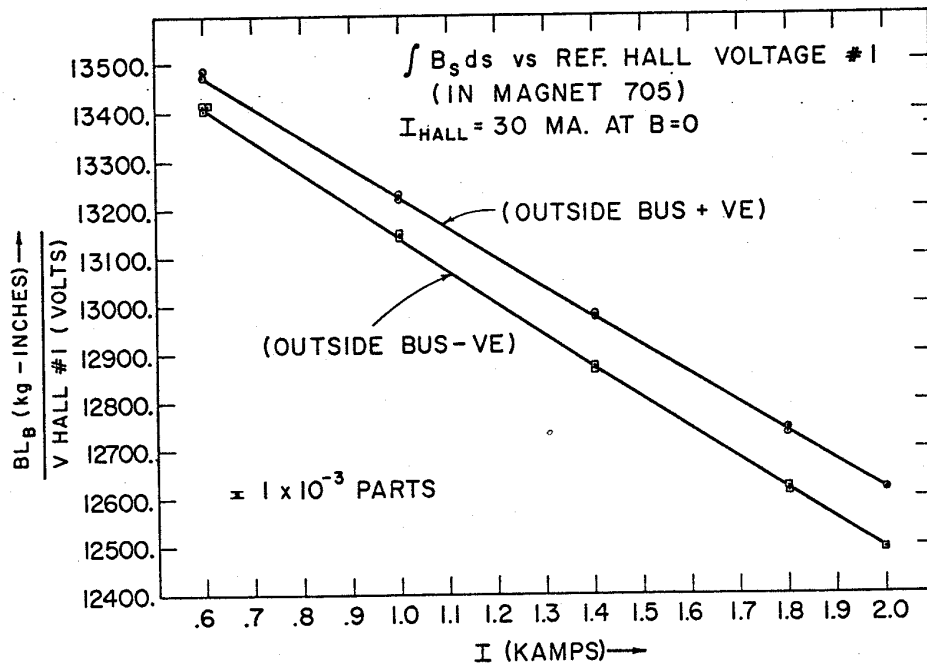


Fig. 12. $\int B_s ds$ vs Hall Ref. #1 voltage as a function of I for 18D72 magnets.

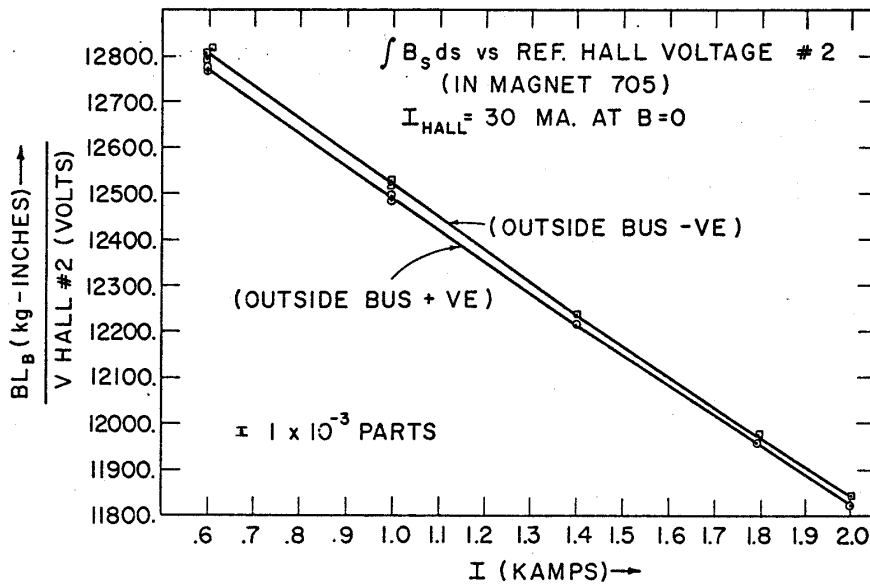


Fig. 13. $\int B_s ds$ vs Hall Ref. #2 voltage as a function of I for 18D72 magnets.

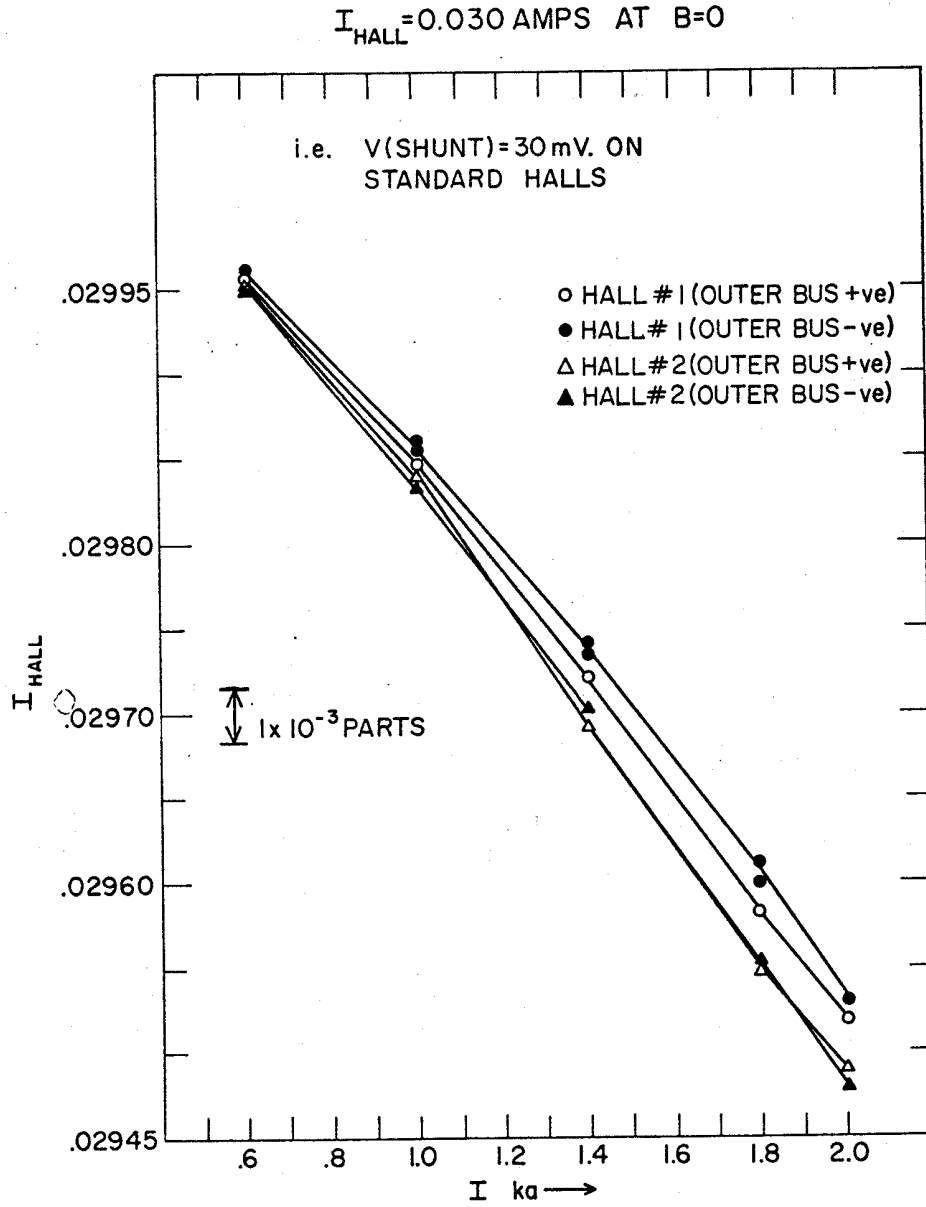


Fig. 14. Hall current vs I (magnet) for Hall probes in a 18D72 magnet.