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ESTABLISHING THE MAGNETIC FIELD OF A SOLID POLE MAGNET TO WITHIN ± 0.01%*

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Summary

The bending magnets of the Beam Switchyard (BSY) of the two-mile linear accelerator require an accuracy of ± 0.01% in the setting of the magnetic field for the proper energy definition. These solid pole magnets are located in such a high radiation field and at such a remote location that it is impractical to use a variable frequency nuclear magnetic resonance detector (NMR) in the individual magnets.

This paper deals with the problems associated with setting the fields of several magnets in series using only current as an indicator for the calibration of the magnetic field.

It is shown that the rate at which the magnet current is allowed to change, even for short periods of time, can change the calibration of the magnet by 0.3%. A fast rate of change of current during the energizing cycle results in a higher magnetic field than when the current is raised slowly.

We have not had the opportunity to compare the initial magnetization curve of several identical magnets nor have we checked how several magnets track to these accuracies when the currents through them vary in an identical pattern.

It is possible to set the magnets in the BSY to an accuracy of 0.01% by current alone, if one is prepared to carefully control the rates of current changes in the series of magnets that make up the deflection system. Based upon the results presented here and making an estimate of the difficulty of instrumenting the power supplies for a controlled rate of current change, it appears that the rate should be set at approximately 6 amperes per second. This rate is well within the capability of the power supply run-up system, and it results in a residual field of approximately 9 gauss for all current settings over ≈ 7500 gauss, thus simplifying the degaussing.

The following recommendations are made for selection of the magnets to make up the system and for setting of the system when installed in the BSY:

1. Selection:
   (a) Magnets should be selected on the basis of similar magnetization curves when gaussed at an excitation rate of 6 amperes per second.
   (b) A secondary consideration in the selection should be the degaussing characteristics, specifically the amounts of reverse field required to degauss a magnet when the residual field is a certain value.
   (c) A third consideration for selection should be the similarity of the curve of maximum field produced by a given current versus the run-up rate. This could be an important factor in selection if it is planned to have more than one rate of current change in the Beam Switchyard deflection systems.
2. Procedures to Enhance Stability
   (a) Use the 6-ampere-per-second rate for all changes in current.
   (b) Before degaussing run the magnet up to 14.5 kilogauss and then back down to zero.
   (c) Monitor at least one magnet with an NMR for a check of the high field and with a magnetometer for a check of the degaussed field. This can be conveniently done in the spare magnet.

I. Introduction

Eight 3° bending magnets located in the Beam Switchyard are used to guide the electron beam for 1,000 feet through a 24° angle from the end of the two-mile electron accelerator to the "A" End Station. Four magnets are used in a similar fashion to guide the beam through an angle of 12° to the "B" End Station.

The first four magnets in the "A" magnet group are the most critical because they are used in conjunction with a slit to precisely define the energy of the electrons. The magnetic field of these magnets must be determined to within ± 0.01%.

The energy of the beam is defined by $\int_{-\infty}^{\infty} B\,d\ell$ through which the beam travels. It can be shown that the $\int_{-\infty}^{\infty} B\,d\ell$ is independent of temperature variations for a given current for the accuracies with which we are concerned. The measurement of $\int_{-\infty}^{\infty} B\,d\ell$ cannot be made in the magnets after they are installed because a vacuum chamber is installed in the gap; however, it will be possible to measure the magnetic field with a nuclear magnetic resonance detector (NMR) at a representative point for two fixed values of magnetic field in two selected magnets. It will not be practical to measure the field with a variable frequency NMR because of the long distance (up to 400 feet) between the magnets and the Beam Switchyard Data Assembly Building (DAB) and because of the high nuclear radiation environment at the magnets.

The difficulties in making a precise magnetic field measurement in the Switchyard magnets have caused us to explore other methods of making an indirect determination of the fields in these critical magnets: First, we plan to connect all of the magnets in each of the bending groups in series so that each of the magnets will be subjected to the same history of current variations. Second, we will add an additional magnet in each group identical to those in the Switchyard but located in the DAB, where it will be available for critical magnetic field measurements. It is

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It is assumed that a magnetic field measurement made in this single magnet will prove to give reproducible data and be representative of the magnetic field ($\int B d\ell$) of the other magnets of the group in the Switchyard proper. It is upon this point of reproducibility and similarity of the magnetic fields of several magnets that this report deals.

II. Equipment

A schematic drawing of the arrangement of experimental equipment is shown in Fig. 1. The individual components are described below.

A. Magnet

The prototype Beam Switchyard 3° bending magnet was used for the tests. At the time of the test the magnet was configured with only five energizing coils instead of its normal complement of six, but this should not affect the conclusions that can be drawn from the sequence of tests described in this report. The important electrical and mechanical characteristics of the magnet are given in Fig. 2. All of the steel used was low carbon, high purity steel with the following approximate composition:

Carbon	0.10% maximum
Total Al+Mo+S+P	0.10% maximum
Total Cr+Cu+Mn+Ni+Si	0.70% maximum

B. Power Supply

The magnet was energized with a magnetic amplifier controlled, 100-kW power supply rated at 100 volts, 1000 amperes (max.) built by Litton Industries, in series with a transistor bank regulator constructed by Spectromagnetics Industries. This combination used a water-cooled shunt for regulation with a zener regulated reference voltage and held the current stable to better than ± 0.01%.

C. Current Measurement

The current to the magnet was measured with a Dymec Model #2401 C digital voltmeter, and a Leeds and Northrup Model K3 potentiometer, and a sensitive research shunt.

D. Magnetic Field Measurement

The values of magnetic field (above 1000 gauss) were read with a Varian F8A nuclear magnetic resonance fluxmeter and a Hewlett-Packard Model 5245L electronic frequency counter. The low values of field (less than 50 gauss) were measured with an F. W. Bell Model 240 gaussmeter.

E. Rate of Rise of Current Control

A Slo-Syn stepping motor control was connected to the Helipot control of the regulated current to provide for an easily controlled rate of change of current for values less than 20-amps-per-second change. The fastest rate of change, at about 100 amps per second, was accomplished by turning the power supply on when the bias to the basic power supply was set for the required output voltage.

III. Experimental Procedure

A. Dependence of Magnetic Field Attained Upon Rate of Rise of Current

Since we lacked sufficient knowledge of the various parameters that could affect the setability of the magnets to the required accuracy, we started by controlling as many different parameters as possible. The first object of the study was to find out how well the field could be set by a knowledge of the current only. The magnet was first degaussed to less than one gauss residual field and the Slo-Syn motor controller was set so that it would run the current up to 800.00 amperes (13,100 gauss) during a time period that could be controlled, thus giving the magnet a linear current increase with time but with an adjustable run-up time to reach the desired excitation current I_{max}. The time to run up to 800 amperes was varied between 6 seconds and 910 seconds; it was found that the longer the run-up time, the lower the field that was attained.

A bit more should be said about the technique used to make these measurements. Because time constants of the system were not known at the start of the measurements, a program of allowing the magnet to become stable after each change of current was adopted. This consisted of starting with a degaussed magnet, gaussing it by the controlled method of current run-up, and then waiting 10 minutes before taking a field reading with the NMR. After taking a reading at high field, the magnet was turned off abruptly by disconnecting the ac input to the power supply; it was then allowed to sit with no current for five minutes before a reading of the residual gauss was taken. (It was observed that the residual field was still changing for times less than five minutes.) After the residual field was recorded, the power supply was reversed and then run up until a current of about three-tenths of the current that was used in gaussing was reached. This was held for 3 minutes, at which time the power supply was turned off, and after ten minutes the residual field was recorded. At this point the magnet was usually degaussed and was ready to be used for another measurement of maximum field versus run-up time. In the event that the magnet had some residual field after the degaussing cycle, this field was considered to be additive to the maximum field reached. This addition assumed that the magnetization curve was shifted by the amount of residual field for all values of the field that were under study. (This is probably not an exactly accurate assumption, but it did simplify the mechanics of performing the experiment.) The corrections that were applied in this way were very small, usually less than 0.5 gauss.

Figure 3 is a graph of the field attained by the magnet as the percent deviation of maximum field versus the run-up time for the two currents, 300 amperes and 800 amperes. The curves were arbitrarily normalized to the 100-second run-up time, and it can be seen that they follow reasonably close to an exponential curve. It is also readily seen that the deviation per unit time for the 800-ampere maximum current is considerably greater than the deviation per unit time for the 300-ampere maximum current.

In Fig. 4 the deviation in percent for each rate of run-up is shown when going to a given excitation current in amperes; the various curves represent different rates of gaussing the magnet after normalizing to the 8-ampere-per-second rate which is shown as a straight line representing zero deviation. Studying Fig. 4, one can conclude that the deviation of field with various run-up rates is greatest at about 800 amperes and the deviation in field as a percentage becomes much smaller as the current gets higher than 800 amperes. At 800 amperes the deviation in field attained varies by approximately 0.2% as the run-up rate is changed from 1 to 20 amperes per second. At 1000 amperes, the total variation of the field with rate is approximately 0.05% over the same range of rates. This behavior may be expected since the incremental permeability of the magnet steel changes considerably at the 800-ampere value.

B. Methods of Degaussing the Magnet

When the magnet had been energized and the measurements of its field made, it was necessary to degauss it in such a way as to have essentially the same starting conditions for the next measurement. If the residual field was different from zero, the next run was taken just as if it were zero and the difference from zero was added or subtracted from the final field. Also, if the residual field reading indicated that the magnet was not degaussed to less than 0.1 gauss, then the reverse current used for degaussing was changed on the next degaussing cycle. Figures 5 and 6 show some typical degaussing data for degaussing when the remanent fields are 4.7 gauss and 2.5 gauss. Figure 7 shows the remanent field of the magnet after gaussing with various energizing currents (and fields) and with various current run-down rates, which were the same as the run-up rates. One can see that, in general, the slower the run-down rate, the higher the remanent field will be for a given energizing current I. It is also seen that for a given run-down rate the remanent field is generally higher for higher energizing currents than for low. Figure 8 shows the reverse current and field that are necessary to degauss the magnet for various values of remanent field. These values of reverse current and gauss are correct when one degausses using a reverse current run-up rate of 14 amperes per second, allowing the magnet to stabilize at the reverse current value for three minutes and then turning off the magnet by means of disconnecting the ac input to the power supply. The final degaussed state of the magnet was ascertained by reading the residual field 10 minutes after turn-off of the power supply.

C. Time Variance of Magnetic Field After Reaching an Equilibrium Condition with Excitation Current

An investigation of the stability of the field with time after a field had been established in the magnet was undertaken. This area of investigation was felt necessary for two reasons. First, it was hoped to learn whether the magnetic field would be stable to the required accuracy of 0.01% for long periods of time after it was once set. Second, with the results of the various run-up rates yielding different values of field, it was of interest to see if, after running in the energized condition, the magnetic field would gradually shift either upward or downward toward more stable conditions. For these reasons, several measurements were made. The magnet power supply was programmed to run up to 400 amperes in 60 seconds in one case and in 120 seconds in another, and the field was monitored with an NMR fluxmeter for several hours. During this time the magnet current was also monitored and held to a constant value within 0.01%. Figure 9 shows the results of those measurements. It is seen that the maximum field reached at 400 amperes is again higher for the faster rate of rise of current. It is also shown that the deviation of field after 10 minutes is in either case stable to better than 0.01%. (The step shown in the upper curve is thought to be a function of the line voltage into the regulator and should be ignored relative to the stability of current versus field.)

D. Field Decay With Time

It has been seen that for the magnet to reach a steady state after the power had been turned off, one had to wait at least 10 minutes. It was hard to believe that the eddy currents would require that much time to decay. An experiment was performed to determine the time constants of the magnetic field decay when the magnet was gaussed to 13 kilogauss and then the power supply was quickly turned off. The field in the gap was plotted against time after turn-off of the power supply and the curve was analyzed to find the various time constants of decay. Figure 10 is the curve of field as a percent of starting field versus the time from turn-off. It can be seen that the time constants found are approximately 2.8 seconds, 98.5 seconds, and 723 seconds. The actual equation of the field decay can be written as

$$\frac{B(\%)}{B_0} = 100e^{-t/2.8} + 0.27e^{-t/98.5} + 0.051e^{-t/723} + 0.028$$

where the 0.028 term at the end is the residual field when the turn-off is fast. To get some idea of the explanation for the various time constants of the decay of field magnitude with time, one must calculate the time constants for the various known processes that could produce the delay.

The time constant of the coils themselves can be calculated from the known inductance of 0.12 henry and resistance of 0.078 ohm as

$$\text{Time Constant} = \frac{L}{R} = \frac{0.12 \text{ henry}}{0.078 \text{ ohm}} = 1.54 \text{ seconds}$$

The approximate time constant of the eddy currents in the core can be calculated as follows: Because there are 80 turns in the winding and a total inductance of 0.12 henry, the inductance of a one-turn short around the core would be

$$0.12 \left(\frac{1}{80}\right)^2 = 18.75 \times 10^{-6} \text{ henry}$$

The resistance of a short-circuited shell of iron 1 cm thick around the poles, yokes, and legs is about 72×10^{-6} ohm. The time constant of the eddy currents in the outer shell, 1 cm deep, is approximately 0.25 seconds (5 cm deep is about 1.0 second). The time constant for current shells deeper in the core will be less because the inductance decreases faster than the resistance. The magnitude of eddy currents will be maximum in the shell on the surface of the core; the long narrow configuration of the magnet will produce eddy currents with a magnitude proportional to the distance from the center line of the pole piece. For a rate of change of field of 100 gauss per second (6.0 amperes per second), the voltage produced in the outer shell will be about 9×10^{-3} volt. This voltage corresponds to

$$\frac{9 \times 10^{-3}}{72 \times 10^{-6}} = 120 \text{ ampere-turns}$$

in the outer 1-cm shell. The current in the core will reach some steady-state value with a proportional current distribution within a few time constants (0.25 sec) after a uniform rate of change of current in the magnet has been established. The poles are 30 cm wide; therefore, the total effective eddy current ampere-turns will be about

$$\frac{120}{2} \times 15 = 900 \text{ ampere-turns}$$

at the center of the gap. This is to be compared with the 24,000 ampere-turns required to produce 5000 gauss in the gap for the five-coil configuration. The magnitude of the eddy currents will be proportional to the rate of change of the magnetic field.

The time constants found from the decay curve (Fig. 10) cannot be explained by the eddy current or by the winding time constant because it has been shown that the decay of field with time exhibits time constants of much longer duration than the winding or the eddy currents. (In one check the magnet leads were opened within 10 seconds after turn-off and no change in the flux decay rate was observed.) These long-term effects may be explained by the magnetic aftereffect sometimes called the magnetic viscosity, and the Jordan lag.

In the case of the magnetic aftereffect, Tomono[1] showed that the effect is dependent upon at least two factors, temperature and impurities in the iron. Basically, the magnetic aftereffect is a delayed change in magnetization accompanying a change in magnetic field. Eddy currents are not included in this category because they are an electromagnetic phenomenon. Magnetization changes accompanying structural changes or aging of the substance are not included because they do not permit one to return to the original state by purely magnetic means. Tomono demonstrated that if a magnetic field is suddenly changed from H_1 to H_2 at $t = 0$, the magnetization of intensity B_1 is immediately changed by the value B_i; this is followed by the gradual change B_n as shown in Fig. 11 where B_n is a function of time, or

$$B_n = B_n(t)$$

The magnitude of B_n depends not only on the magnitude of initial change of magnetization B_1 but also on the final stage of magnetization. For instance, if the final point is in the range of rotation magnetization, the value of B_n will be fairly small; if the magnetization is in the range of irreversible magnetization, this value may be fairly large.

In the simple case $B_n(t)$ is described by a single exponential function

$$B_n(t) = B_{no}(1-e^{-t/\tau})$$

where B_{no} is the total change in B_n from $t = 0$ to ∞. The time constant τ is dependent only upon temperature and the value of B_{no}/B_1 depends upon the impurities in the magnetic material. (Pure iron does not show any magnetic aftereffect.) Richter[2] showed that the time constant of the magnetic aftereffect could be expressed as $\tau = 2/3C\, e^{Q/kT}$ where Q is the activation energy for the diffusion of impurity atoms in body-centered cubic iron. For carbon atoms as the impurity, Q is ≈ 1 eV. The decay curve time constant for the magnetic aftereffect is about 3.6 seconds according to Richter, which is in good agreement with the 2.8-second time constant obtained for the first part of the field decay curve. The longer time constants in the decay have not yet been explained.

E. Variation of Ultimate Magnetic Field Reached by a Composite of Several Rates of Rise of Current

In view of the strong dependence of field attained in the magnet on the rate of rise of the current in the magnet, it was of interest to see the effect of several different rates of rise which were changed at some point in the gaussing cycle. Of special interest was the case of a controlled slow rate of rise until a current near the desired current was reached, and then a fast change or a series of fast changes to get to the exact current. Minor changes in the final field could be made fast with high rates of current change. This situation might be a practical requirement to live with for a narrow range regulator that has a controlled slow rate of change to get to the desired current value but then might have a fast rate available for small changes. Accordingly, a series of runs was made where two rates of current run-up were used and the transition from one rate to the next was at 50% of the desired maximum current in one case and at 90% of the desired maximum current in the other case. 800 amperes was selected as the maximum current and the current rates of 2 amperes per second and 8 amperes per second were chosen. In each case, the magnet was degaussed at the start and was then gaussed according to a predetermined program. The final field in the magnet which resulted from the composite of current run-up rates was also compared with the final field when the run-up rate was constant. Figure 12 depicts the various methods by which the gaussing was accomplished and the final field that resulted from each method. For ease in reading Fig. 12, the various paths are coded with a letter and one or two digits. Thus the run that was made from 0 to 0.50 I_{max} at 8 amperes per second is labeled A, and at each point where the rate change occurred the nomenclature of the run indicates a split as A1 or A2, and subsequently A1 becomes A11 and A12, etc. Thus, one can compare the final field that resulted from paths A2 and B1 and see that when the transition point is 50% of I_{max}, the run-up of 8 amperes per second and then 2 amperes per second is lower than that for the reverse order of run-up rates by 10 gauss out of 13,100 gauss, or 0.08%. Comparing runs A11 and A12, one can see that the run-up by a continuous run of 8 amperes per second is 10 gauss higher than the run-up to 90% of Imax at 8 amperes per second and then 2 amperes per second for the last 10%. This compares with only 1.4-gauss difference between a slow run-up all the way and the 90% run-up at a slow rate and then a fast run-up for the last 10%. One other run on Fig. 12 is of importance, run C. In this run, the rate selected was 3.3 amperes per second and C1 is the continuous run-up to I_{max}, whereas run C2 was run up to 50% of I_{max} and then after a wait of 2 hours the run was continued at 3.3 amperes per second until I_{max} was reached. In this case, as one can see by comparing the final field for C1 and C2, the field is in almost perfect agreement. Thus the wait of 2 hours has not affected the final field, if the overall run-up rate was the same.

F. The Effect of Run-Up Rates on the Homogeneity of the Central Plane Field of the Magnet

A series of measurements of the flatness of the magnetic field in the central plane of the magnet was made when the field had been established by several different current run-up rates. It was found that with a fast run-up rate, the resulting field in the central plane of the magnet was not as homogeneous as it was with slow run-up rates. However, the difference between the flatness was about 1 to 2 parts in 10^5 at transverse positions - 2 and + 2 inches, and was therefore not a large enough effect to worry about.

G. Offset in Magnetic Field Due to an Overshoot in Current

It has been pointed out to the authors that effects of the type that have been reported here have previously been seen, but in many cases have been traced to power supply overshoot. To check the data and to ascertain if power supply overshoot could be responsible for the observed effects, the current in the magnet was monitored carefully on both increasing current runs and also during the fast cut-offs of the supply. In neither case was any significant overshoot observed. In the case of a fast turn-off of the magnet, the leads were opened when the magnetic field had decayed to 1% of maximum and no change in the continuity of the decay curve was observed.

A measurement was made to determine the permissible amount of programmed current overshoot when the rate of change of current was held to 6 amps per second. Table I shows the errors introduced in the relationship between field and current for various fields and overshoot.

This error was determined by first degaussing the magnet, then setting the current to a given value at the specified rate of rise. Next, the current was slowly increased by the desired increment and then returned to the initial value. The magnetic field was read before, during, and after the small current change.

Similar small changes were also introduced as fast steps for comparison to a controlled rate of change, and it was found that the results were of the same magnitudes, but they were erratic.

It was interesting to note that successive small (less than 1%) changes in current after the initial overshoot measurements shown in Table I did not cause any significant additional hysteresis error in field.

TABLE I

Magnetic Field Change Due to Overshoot of Current at a Rate of Change of Current of 6 Amps Per Second

Initial Set Value of Current I_1 (amps)	Initial Field Gauss	Percent Increase Current
301.59	4998.4	0.24
599.95	9939.3	0.24
920.02	14,593	0.23
920.05	14,598	0.62
899.97	14,373	2.2

Percent Increase in Field	Percent Change in Field When the Current is Returned to I_1
0.24	0.01 to 0.02
0.235	0.01
0.16	0.013
0.40	0.04
1.5	0.09

List of References

1. Tuzo Tomono, "Magnetic After Effect of Cold Rolled Iron (I)," Journal of the Physical Society of Japan, 7, No. 2 (March-April 1952).

2. G. Richter, Ann. Physik 29, 605 (1937).

3. J. Cobb and C. Harris, "Establishing the Magnetic Field of the 3° Bending Magnets to Within ± 0.01%," SLAC Internal Report, Stanford Linear Accelerator Center, Stanford, California (1965).

For further information, see references on page 320 of the chapter on "Magnetic Aftereffect," in Physics of Magnetism by Sōshin Chikazumi, QC-753-C45.

Discussion

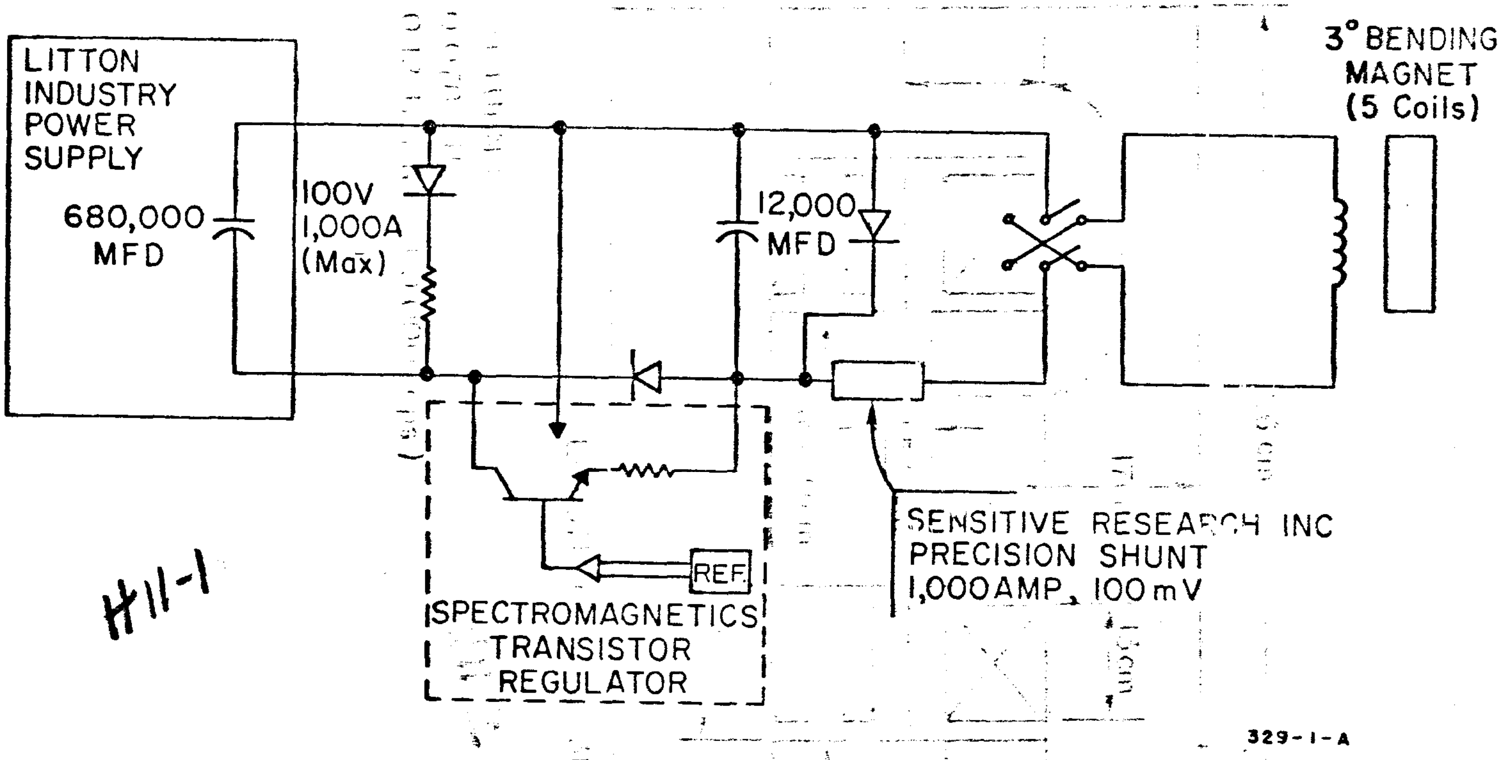
Alec Harvey, Atomic Energy of Canada, Ltd.

Q. How reproducible are the fields which you get? If you increase your current to 3.3A/sec right up to 800 A several times, you quote a number for the field to 6 significant figures. Is this reproducible to the sixth significant figure every time?

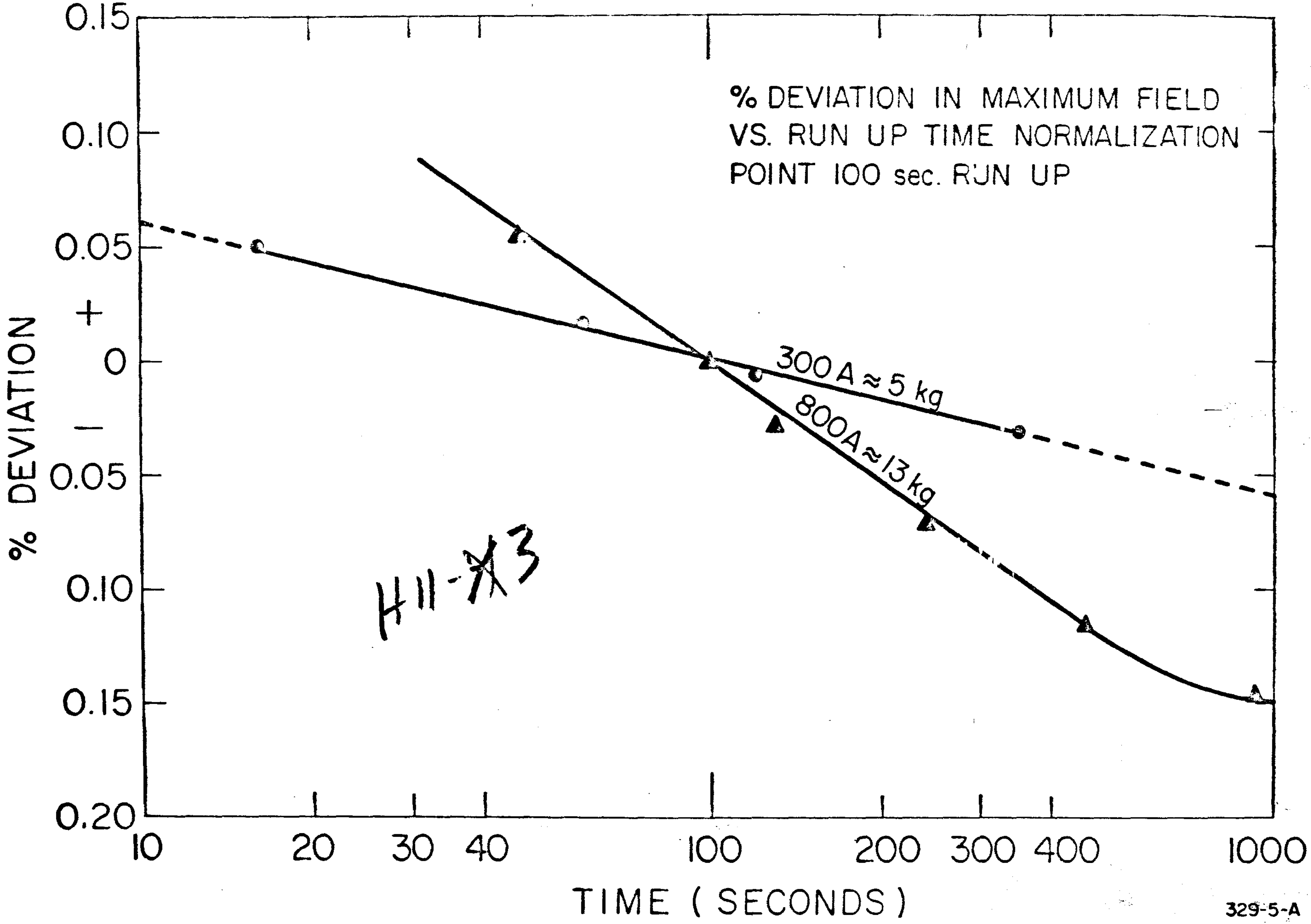
A. To the 0.01% value the measurements are reproducible measured over a time period of 24 hours.

FIGURE CAPTIONS

1. Schematic diagram of experimental apparatus
2. 3° bending magnet characteristics
3. Percent deviation in maximum field versus run-up time for two maximum fields
4. Percent deviation in maximum field versus maximum currents for different run-up rates
5. Residual field after a single-step degaussing cycle for different reverse currents (maximum field 13,100 gauss)
6. Residual field after a single-step degaussing cycle for different reverse currents (maximum field 4,976 gauss)
7. Residual field versus peak forward current for different run-up rates
8. Reverse field required to degauss the magnet for different maximum forward fields
9. Magnetic field long time stability for constant magnet current and two different run-up rates
10. Magnetic field decay versus time after turn-off
11. Time change in magnetization on the occurrence of sudden change in the magnetic field (Tomono[1])
12. Deviation in maximum field with different combination of run-up rates and delays

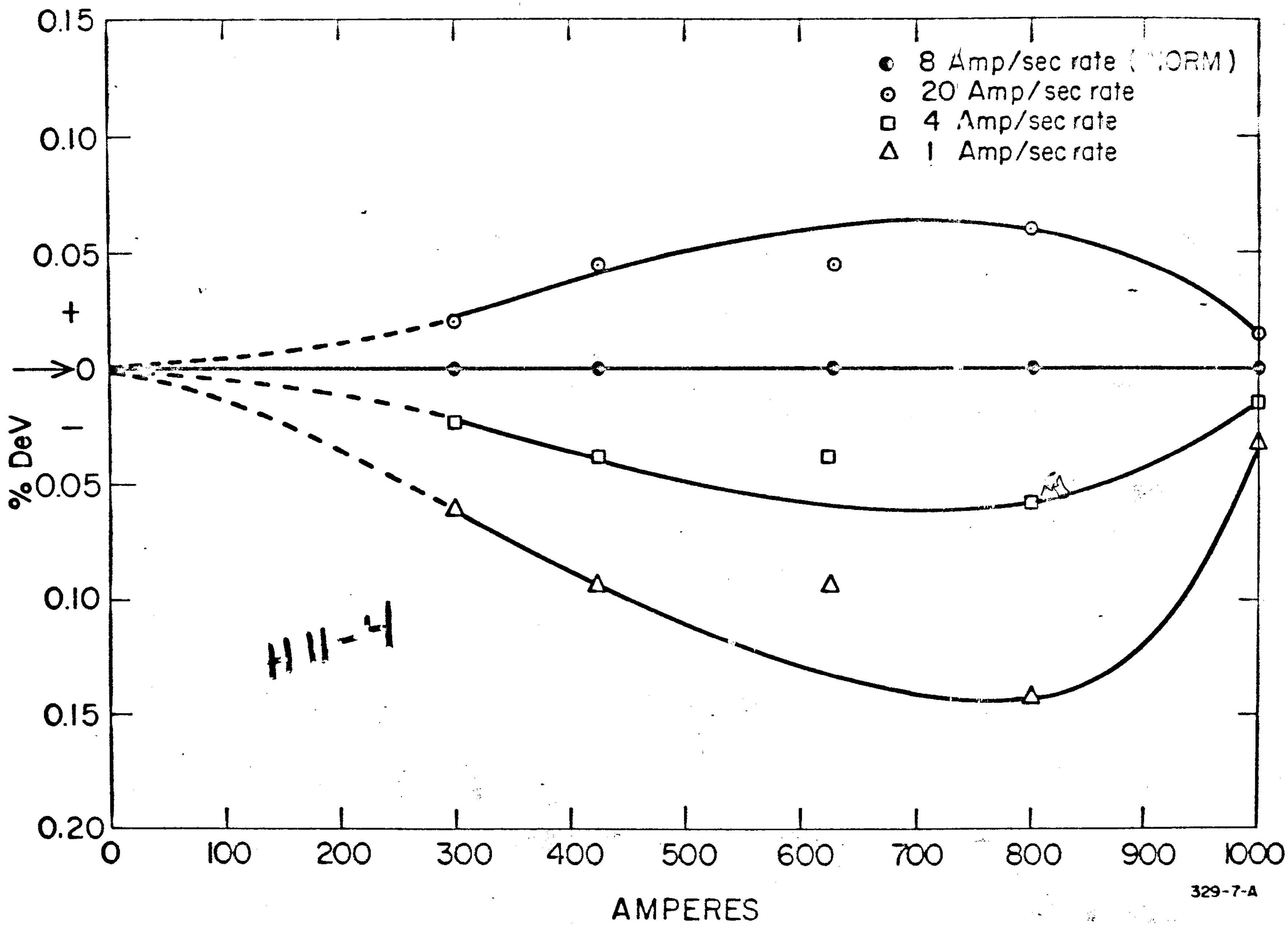

LITTON INDUSTRY POWER SUPPLY
680,000 MFD
100V
1,000A
(Max)
12,000 MFD
3° BENDING MAGNET (5 Coils)
REF.
SPECTROMAGNETICS TRANSISTOR REGULATOR
SENSITIVE RESEARCH INC PRECISION SHUNT 1,000 AMP, 100 mV
329-1-A

#11-1

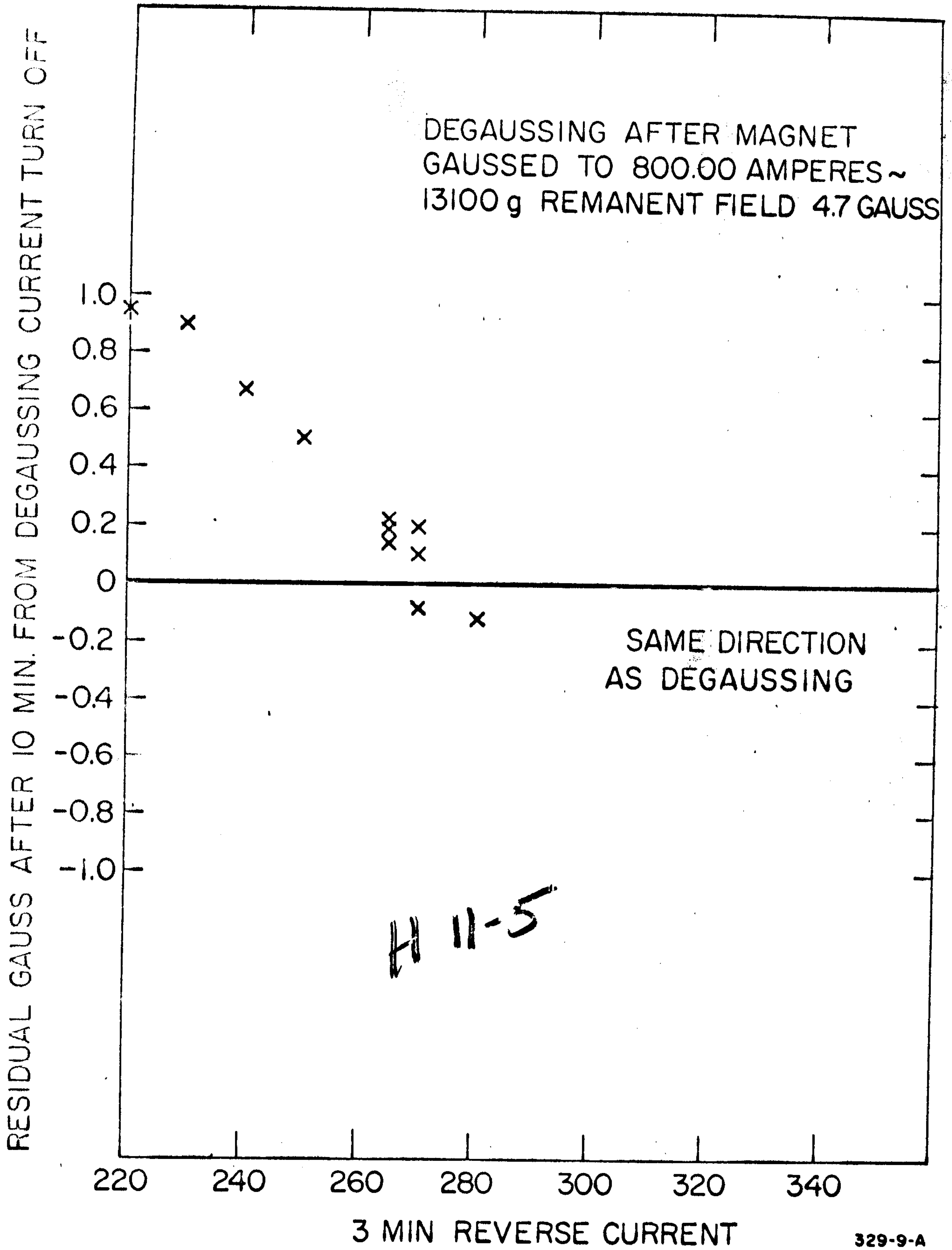


% DEVIATION IN MAXIMUM FIELD
VS. RUN UP TIME NORMALIZATION
POINT 100 sec. RUN UP
300 A ≈ 5 kg
800A ≈ 13 kg
% DEVIATION
+
−
0.15
0.10
0.05
0
0.05
0.10
0.15
0.20
10
20
30
40
100
200
300
400
1000
TIME (SECONDS)
H11-X3

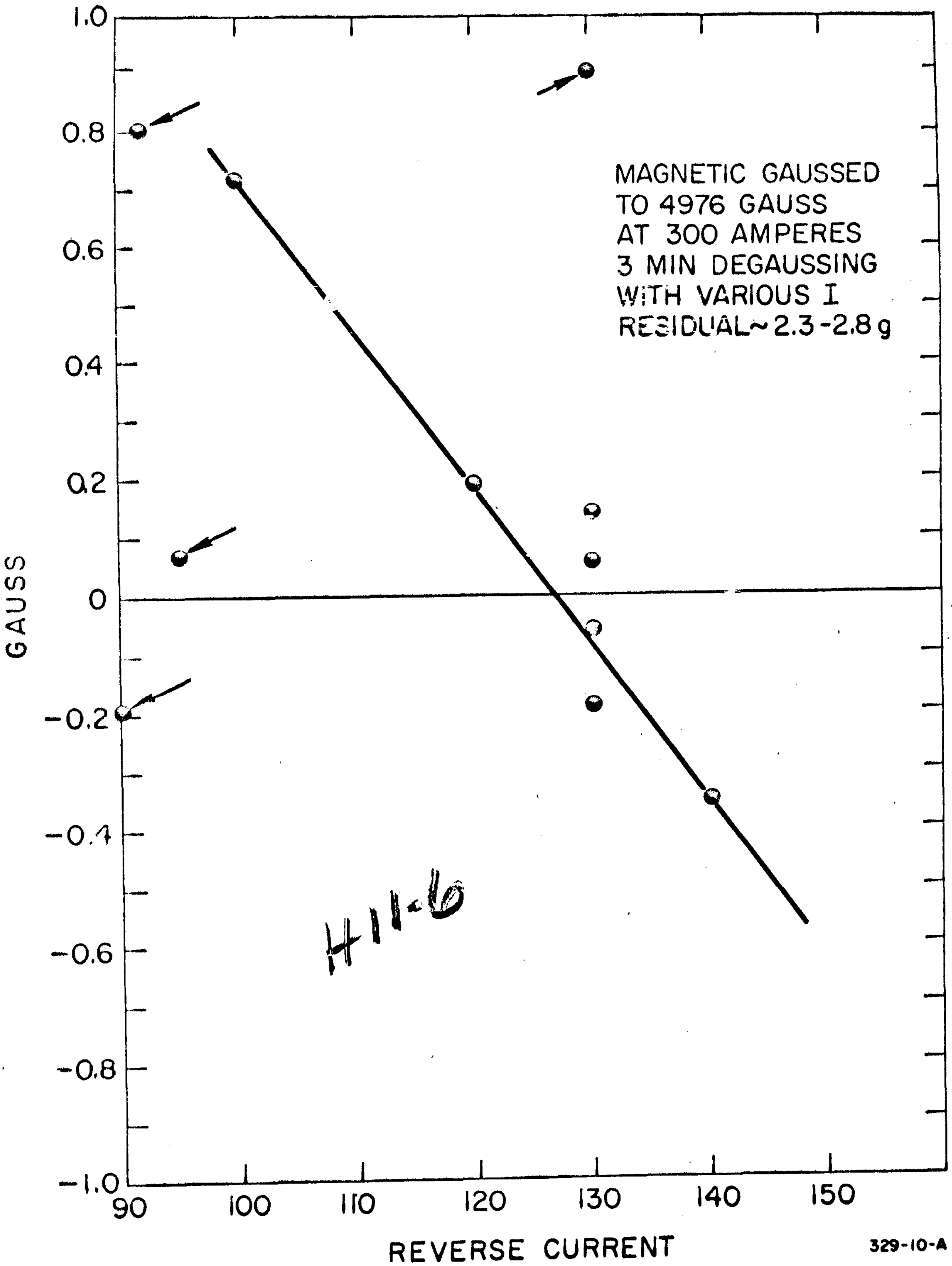
329-5-A

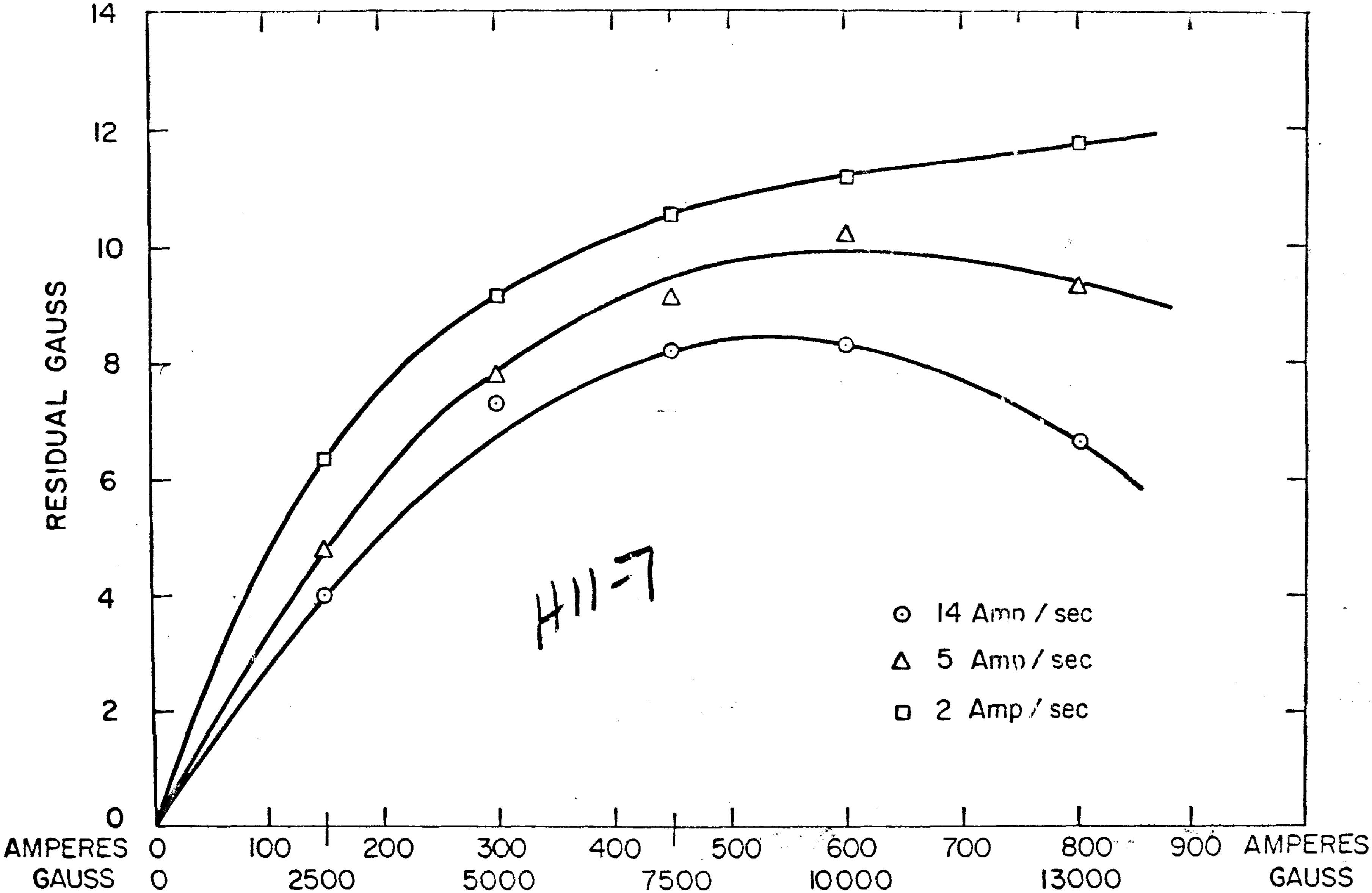


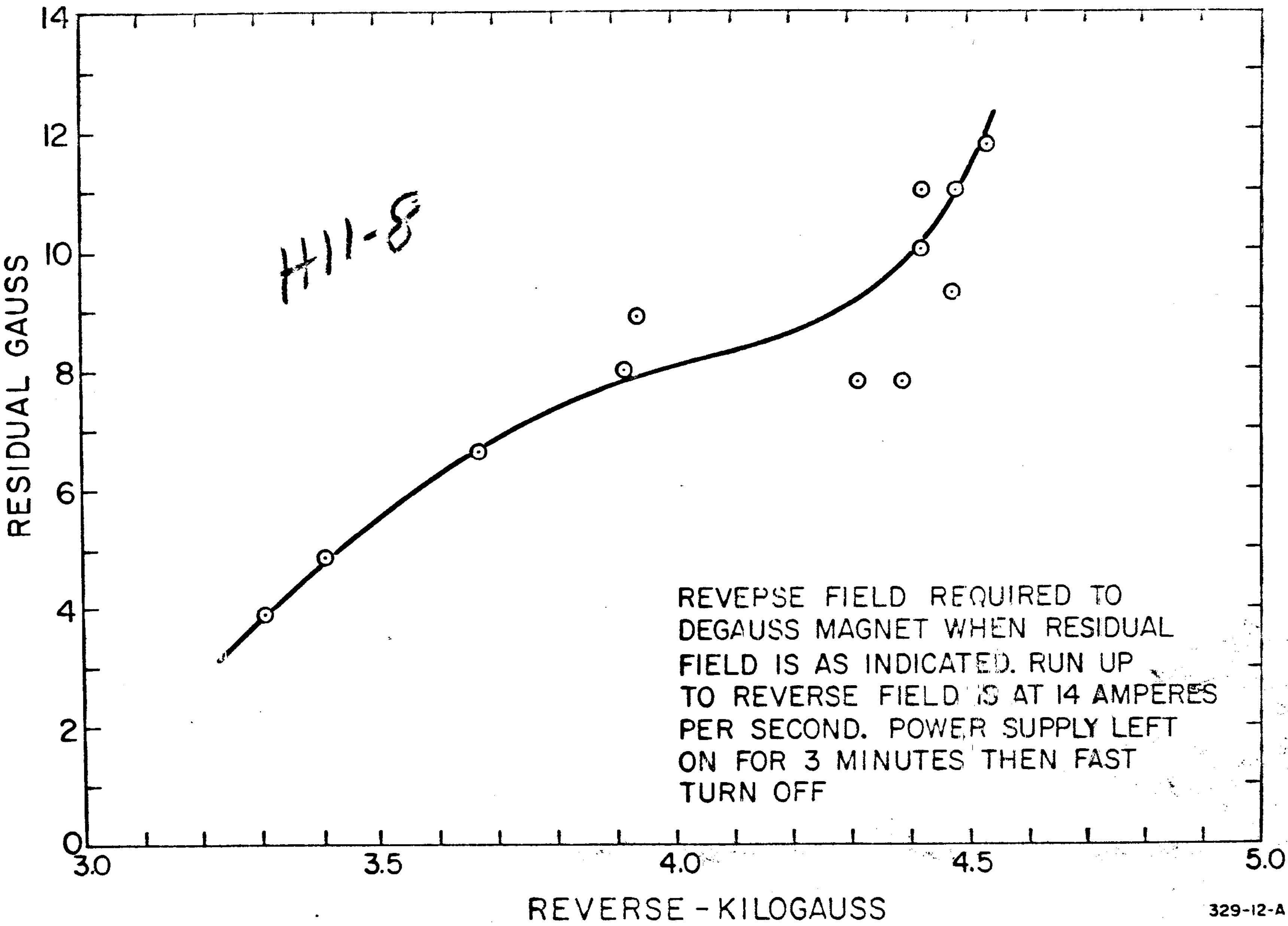
8 Amp/sec rate (NORM)
20 Amp/sec rate
4 Amp/sec rate
1 Amp/sec rate
0.15
0.10
0.05
+
0
−
0.05
0.10
0.15
0.20
% DeV
0
100
200
300
400
500
600
700
800
900
1000
AMPERES
329-7-A
H11-4

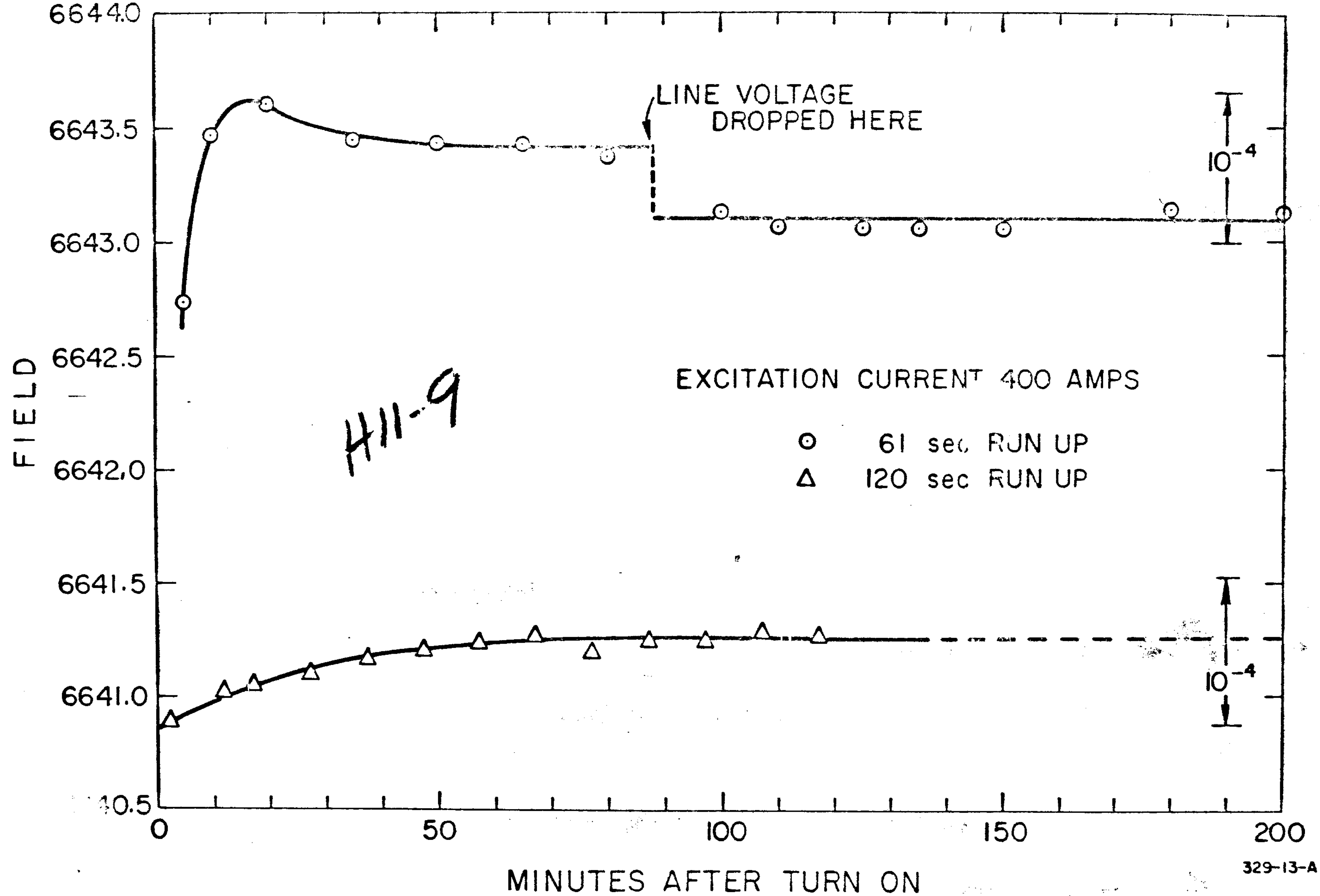

DEGAUSSING AFTER MAGNET GAUSSED TO 800.00 AMPERES ~ 13100 g REMANENT FIELD 4.7 GAUSS
SAME DIRECTION AS DEGAUSSING
RESIDUAL GAUSS AFTER 10 MIN. FROM DEGAUSSING CURRENT TURN OFF
1.0
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8
-1.0
220
240
260
280
300
320
340
3 MIN REVERSE CURRENT
H 11-5

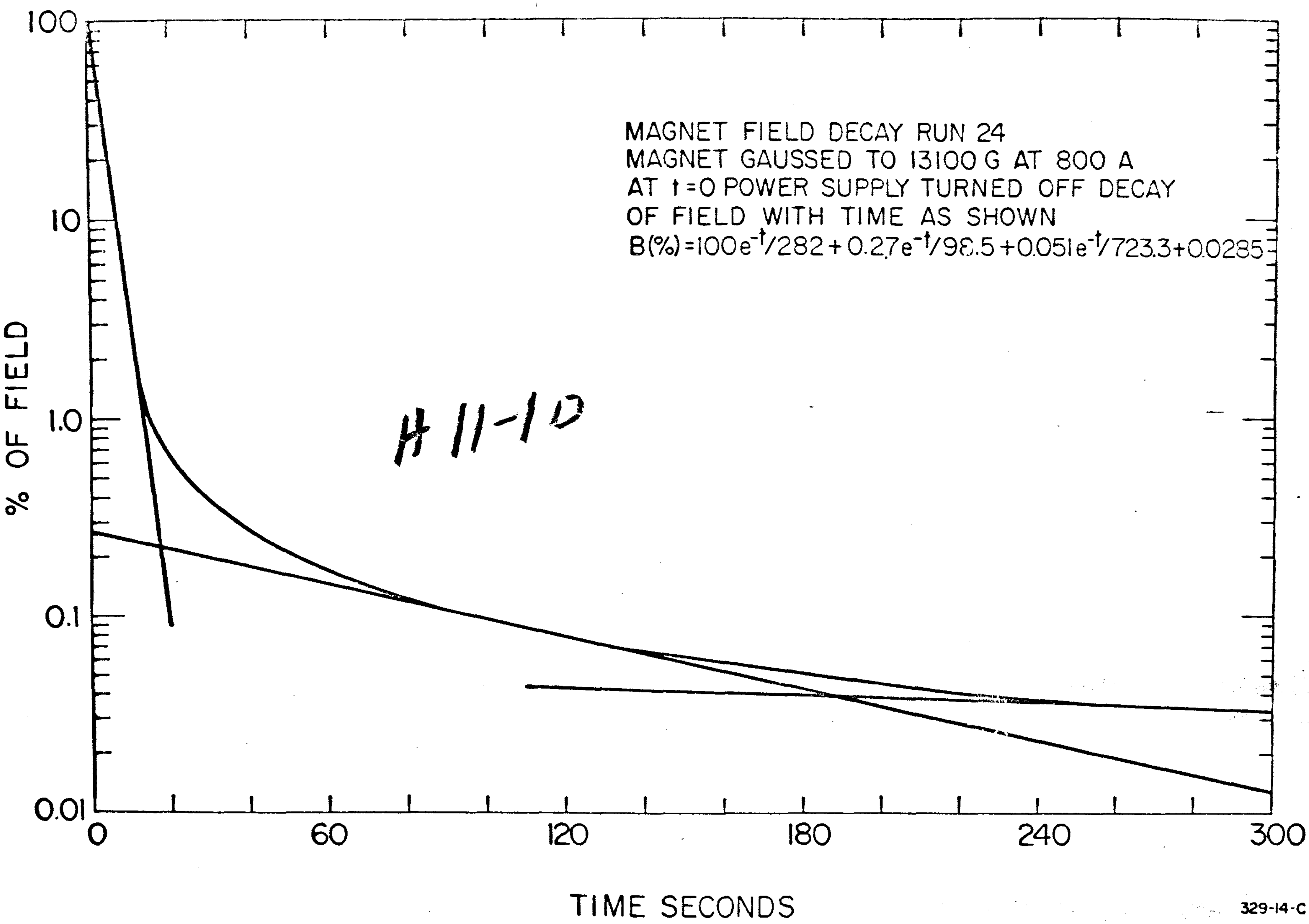
329-9-A


MAGNETIC GAUSSED
TO 4976 GAUSS
AT 300 AMPERES
3 MIN DEGAUSSING
WITH VARIOUS I
RESIDUAL~ 2.3 - 2.8 g
GAUSS
1.0
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8
-1.0
90
100
110
120
130
140
150
REVERSE CURRENT
H11-6
329-10-A

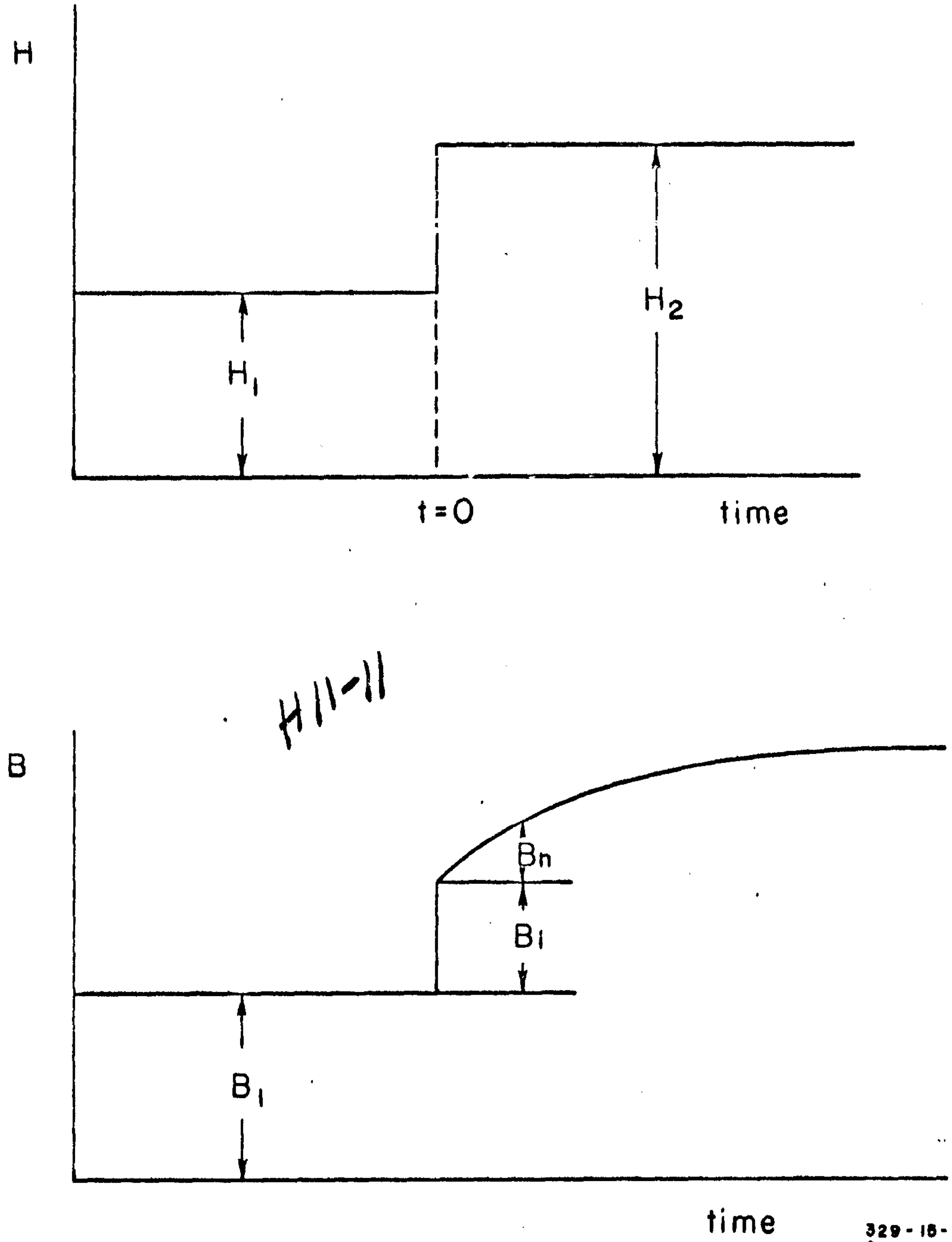

RESIDUAL GAUSS
14
12
10
8
6
4
2
0
AMPERES 0 100 200 300 400 500 600 700 800 900 AMPERES
GAUSS 0 2500 5000 7500 10000 13000 GAUSS
14 Amp / sec
5 Amp / sec
2 Amp / sec
H11-7
329-11-A


H11-8
RESIDUAL GAUSS
0
2
4
6
8
10
12
14
3.0
3.5
4.0
4.5
5.0
REVERSE - KILOGAUSS
REVEPSE FIELD REQUIRED TO DEGAUSS MAGNET WHEN RESIDUAL FIELD IS AS INDICATED. RUN UP TO REVERSE FIELD IS AT 14 AMPERES PER SECOND. POWER SUPPLY LEFT ON FOR 3 MINUTES THEN FAST TURN OFF
329-12-A

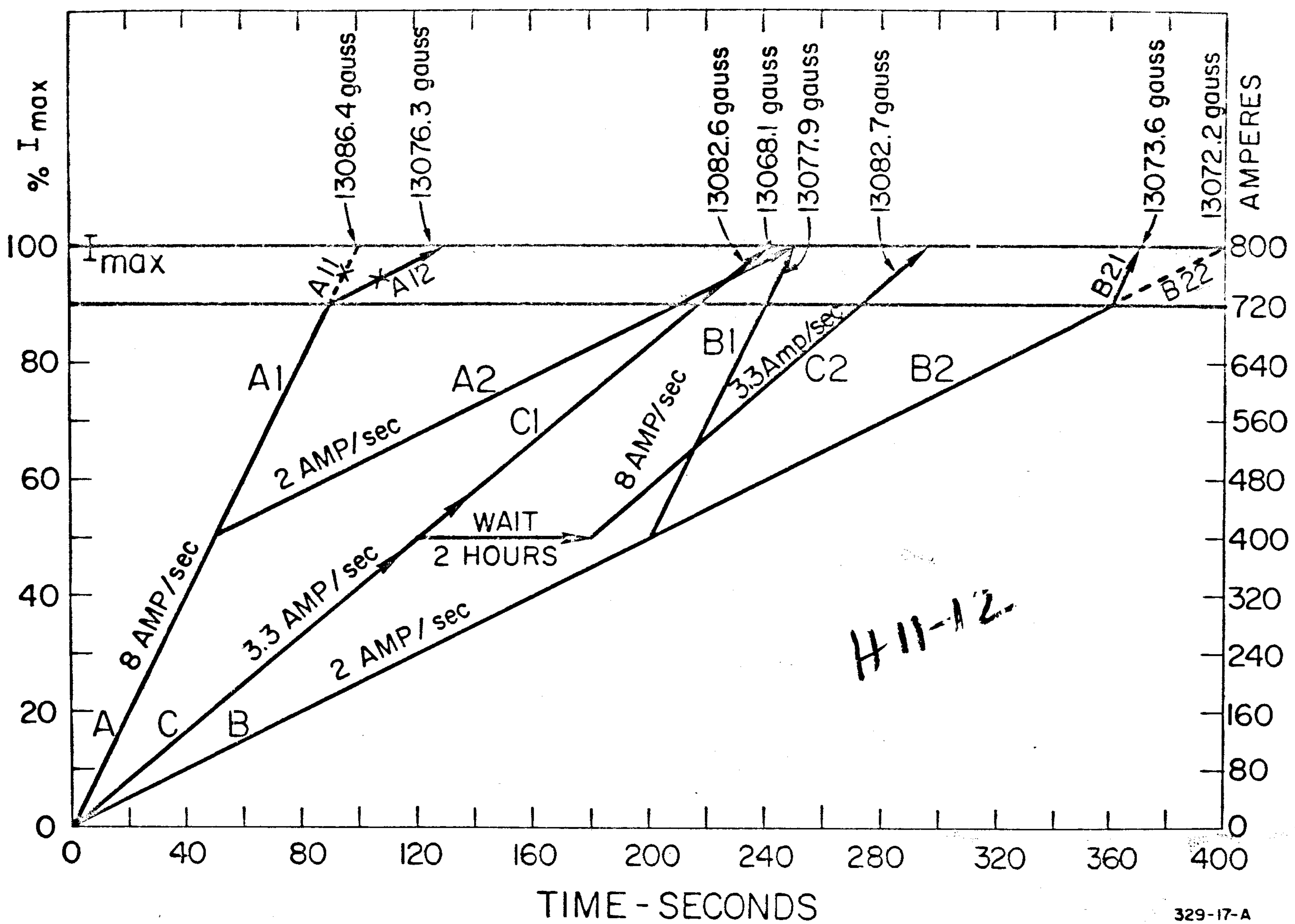

6644.0
6643.5
6643.0
6642.5
6642.0
6641.5
6641.0
6640.5
FIELD
0
50
100
150
200
MINUTES AFTER TURN ON
LINE VOLTAGE DROPPED HERE
10^{-4}
10^{-4}
EXCITATION CURRENT 400 AMPS
61 sec RUN UP
120 sec RUN UP
H11-9
329-13-A


MAGNET FIELD DECAY RUN 24
MAGNET GAUSSED TO 13100 G AT 800 A
AT t = 0 POWER SUPPLY TURNED OFF DECAY
OF FIELD WITH TIME AS SHOWN
B(%) = 100e^-t/2.82 + 0.27e^-t/98.5 + 0.051e^-t/723.3 + 0.0285
H 11-1D
% OF FIELD
100
10
1.0
0.1
0.01
0
60
120
180
240
300
TIME SECONDS

329-14-C



329-15-A



% I max
AMPERES
100
80
60
40
20
0
800
720
640
560
480
400
320
240
160
80
0
I max
13086.4 gauss
13076.3 gauss
13082.6 gauss
13068.1 gauss
13077.9 gauss
13082.7 gauss
13073.6 gauss
13072.2 gauss
A11
A12
B21
B22
A1
A2
B1
C1
C2
B2
8 AMP/sec
2 AMP/sec
3.3 AMP/sec
WAIT
2 HOURS
8 AMP/sec
3.3 Amp/sec
2 AMP/sec
A
C
B
H11-12
0
40
80
120
160
200
240
280
320
360
400
TIME - SECONDS
329-17-A