national accelerator laboratory

TM-677
1600.000

AC LOSS OF ONE FOOT DIPOLE MAGNETS

H. Ishimoto, R. Yamada and R. E. Pighetti

17 June 1976

AC loss of several D and E series one foot dipole magnets were measured in the past year using DPO-PDP11 system.[1] Their data are collected and summarized in this report. They were made of various kinds of cables. For checking internal consistency, the magnetization curves were obtained for some magnets.

The main items are the ramp rate dependence at constant maximum field, and the maximum field dependence at constant ramp rate. The specifications and the data summary of these magnets are listed in Table I.

The ramp rate dependence of the magnets with soldered cables is much stronger than those magnets with unsoldered cables. This fact arises from the eddy current coupling between strands through solder. The doubling $\dot{B}$ ($\dot{B}_d$), where the ac loss goes twice as much as the hysteresis loss ($\dot{B}$ = 0), is also shown in Table I.

The maximum field dependence curves have two bending points: One corresponds to complete flux penetration field (B_s), which is primarily determined by the effective filament diameter. The other at high field is related to mechanical movement of the wire and/or distortion of the coils. Above it, the loss increases nearly quadratically in most cases, and more drastically in some cases. The magnetization curve is also distorted at high field, which suggests a small change of inductance at the normal state. Such a break is not observed in the short sample magnetization measurements[2] and it is peculiar to these magnets. For the Dl-10 made of the soldered cable, the breaking point is higher than those of the other magnets. With cold iron lamination, the coil was more tightly compressed and the breaking point seems to have disappeared. Judging from these situations and the strain gauge measurement by the Energy Doubler Group, the wire movement due to the magnetic force is a most probable cause for such a break. In Table I, the extrapolated ac losses at 45 kG with a ramp rate of 4.5 kG/s (100 GeV/s) are listed for both cases, with and without the break.

References:

[1]R. Yamada et al., Superconducting Wire Test at Fermilab, TM-598, July 1975.

[2]H. Ishimoto et al., AC Loss in Flat Transposed Superconducting Cable, TM-636, October 28, 1975.

TABLE I

	Cable	Solder	Iron	$\dot{B}_d$ (kG/s)	B_s (kG)	B_m (kG)	B:0→45 kG E_{est} at 4.5 kG/s (J/cycle)	B:0→45 kG E_{est}^* at 4.5 kG/s (J/cycle)
D1-4	MCA17	Yes	No	0.8	1.6	-	-	(92)
D1-7	MCA17	No	No	>8	2.2	23	(84)	(33)
D1-10	MCA23	Yes	No	0.8	3.4	34	(618)	(488)
			Yes	-	-	-	(~500)	(~500)
E1-2	MCA23	No	No	5.1	2.0	16~20	88	49
			Yes	-	-	16~20	~90	~51
E1-3	MCA23	No	No	-	-	17	95	60
E1-10	MCA23	No	No	6.5	2.2	16	90	64

E_{est} - Estimated values for 0 → 45 kG in actual case

E_{est}^* - Estimated values for 0 → 45 kG in case of no break at B_m

( ) means some ambiguities in the values

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MAGNET MEASUREMENT REPORT

AC Loss Test of D1-4 and D1-7 Magnets

H. Ishimoto, R. Yamada and R.E. Pighetti

October 30, 1975

These magnets were made with MCA 17 cable: D1-4 with soldered cable and D1-7 with unsoldered one. Measurements were made without iron at the earliest stage of AC loss test from September 5 to September 29.

The ramp rate dependence of these magnets exhibits a remarkable difference among them as shown in Figs. 1 and 2. D1-4 has a strong dependence on $\dot{B}$, but D1-7 has a weak one. This fact is attributed to a large eddy current loss of the soldered cable. For D1-7, another magnetization method was also used to check an internal consistency. Agreement between both methods is fairly good.

The maximum field dependences of AC loss are given in Figs. 3 and 4. Both magnets were measured from zero field, and only D1-4 was measured also from 9 kG field. D1-4 could not be excited up to the high field, because of the absence of the safety device at that time. Both of them have a bending point at around 2 kG, which corresponds to the complete penetration field.

D1-7 has another breaking point at about 23 kG. Below this field down to 2 kG, the dependence is nearly linear. Above that, it seems to be quadratic. The similar behavior was observed for D1-4 at the first cool down, but it disappeared the next day.

It may be due to training. The magnetization loop of the D1-7 (Fig. 5) also drastically varies above the upper bending point. We have no definite verification, but it seems to arise from the wire movement. The absolute values may have an error factor of about two.

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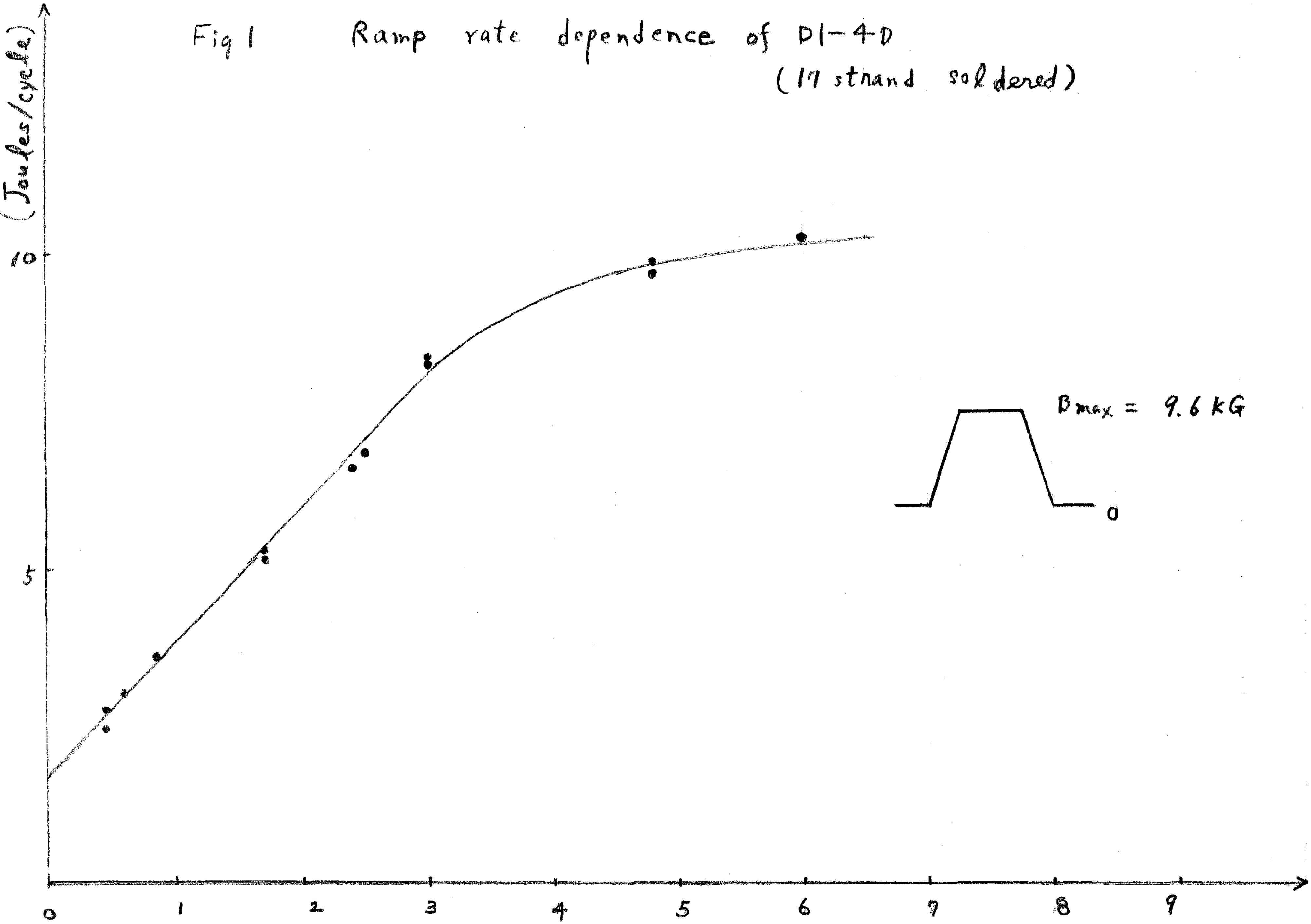
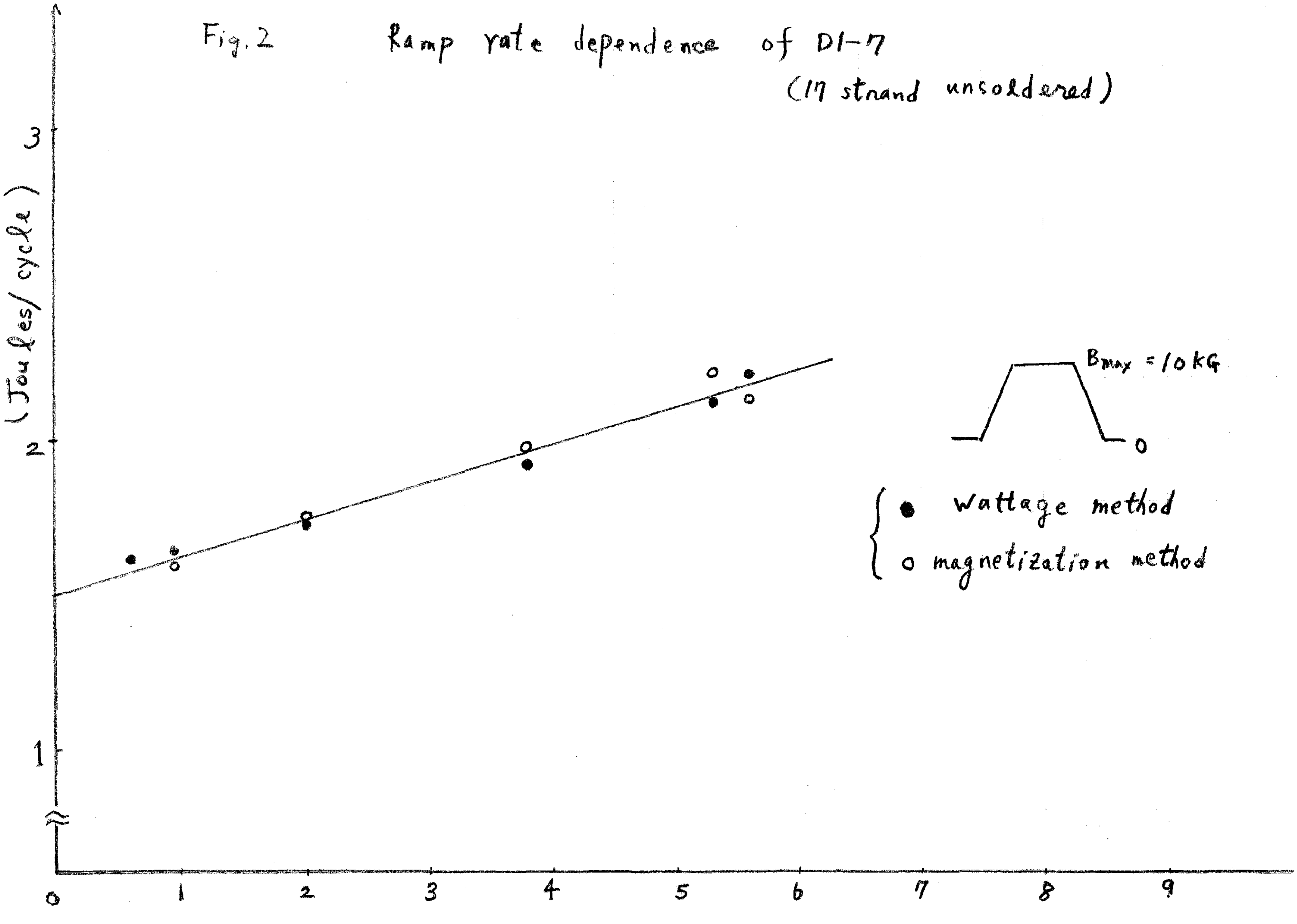


Fig 1 Ramp rate dependence of D1-4D
(17 strand soldered)
(Joules/cycle)
10
5
Bmax = 9.6 kG
0
0
1
2
3
4
5
6
7
8
9

9/10/95

Fig. 2 Ramp rate dependence of D1-7
(17 strand unsoldered)



9/5/75

Fig 3. Maximum Field Dependence of

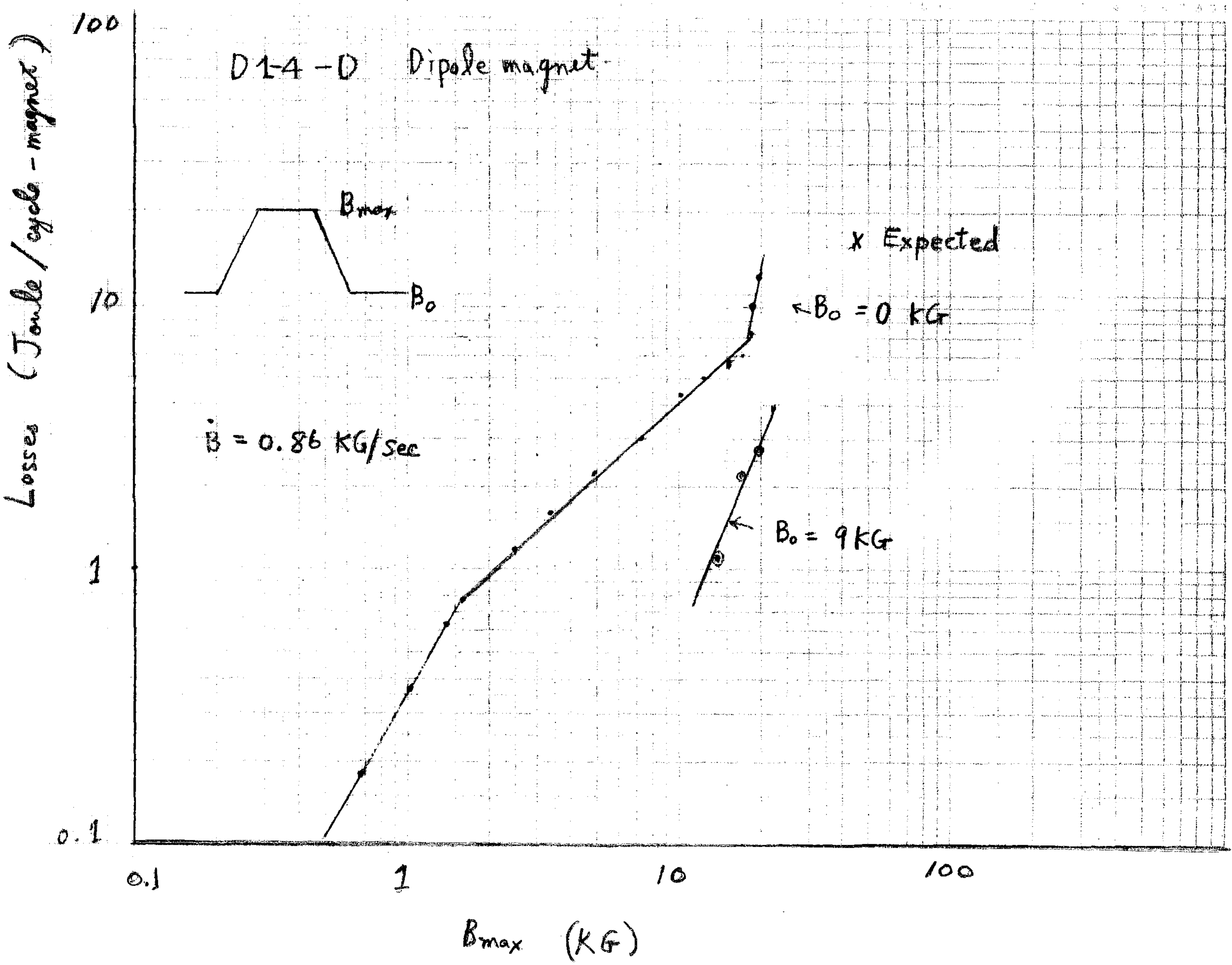


Fig 4 Maximum Field Dependence of D1-7 Dipole magnet

9/29/75

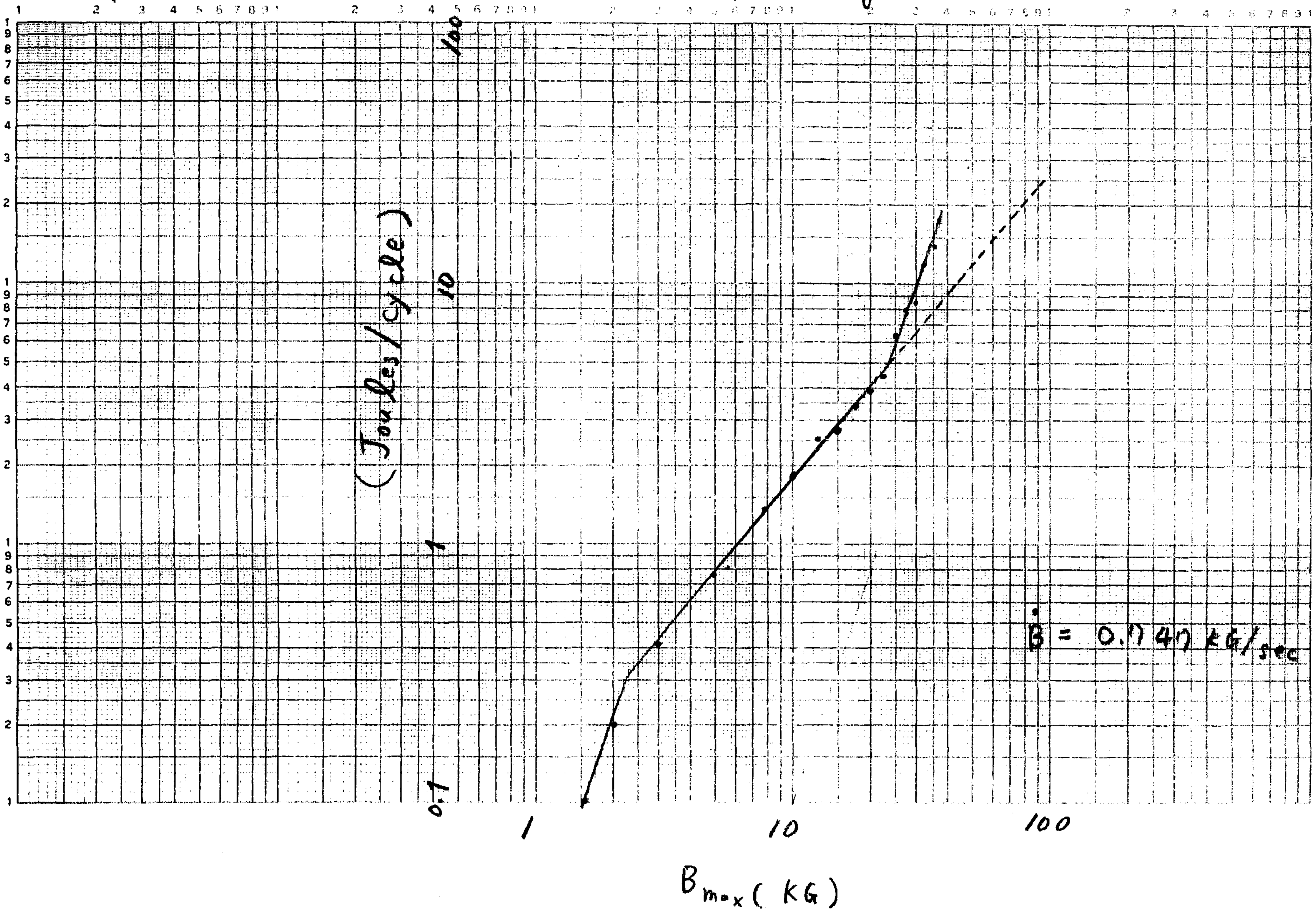
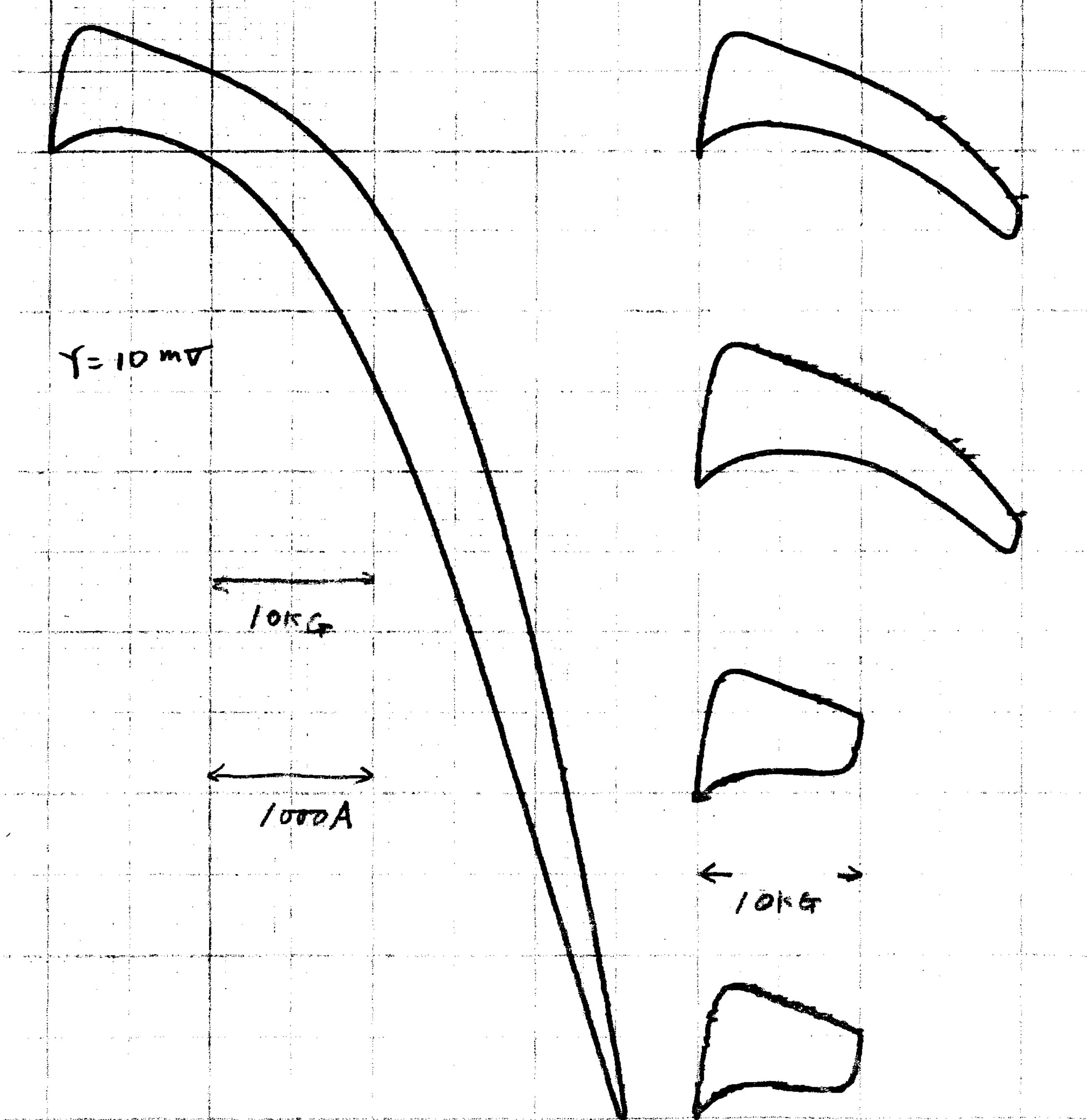


Fig.5 Magnetization Loop of

DI-7 dipole magnet

9/29/75



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MAGNET MEASUREMENT GROUP

AC Loss Test of D1-10 Magnet

H. Ishimoto, R. Yamada and R. Pighetti

October 30, 1975

This magnet was made with MCA 23 soldered cable and tested from Sep. 20 to 26. The ramp rate and maximum field dependence of AC loss, and the quenching current were measured with iron or without iron. The results are given in Fig. 1 ~ Fig. 4. In Fig. 5 summarized data for D-series magnets are shown.

The ramp rate dependence seems to vary with maximum field values. But the normalized one is almost the same as each other, which agrees with the theoretical estimation. This dependence is much steeper than that of E1-2, as was expected from the magnetization measurement of short sample.

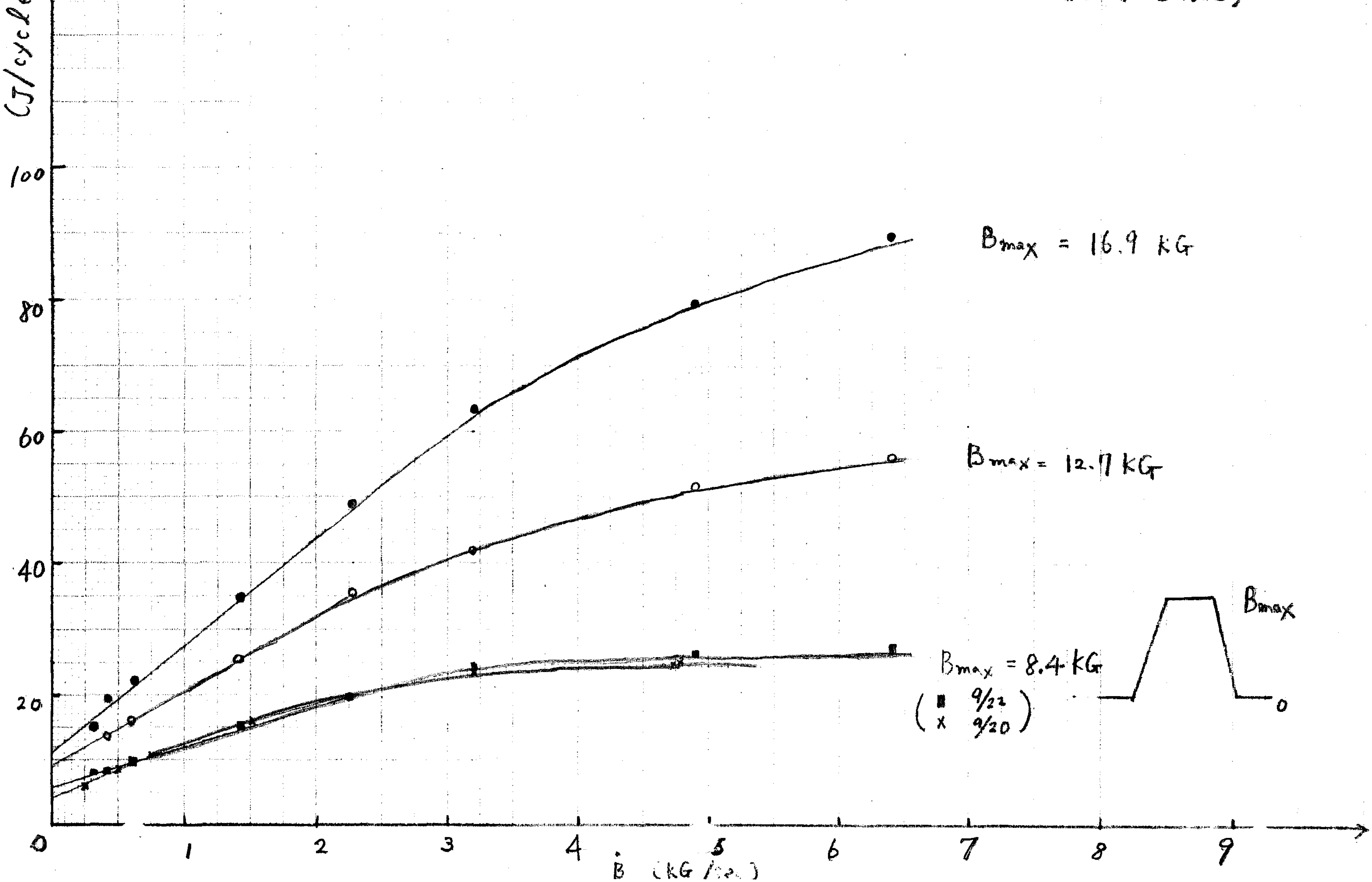
The maximum field dependence curve has two bending points; one corresponds to what is called saturation field, and the other is not clearly understood. However at this field the wire movement seems to begin. The upper bending point occurs at a higher field value than that of E1-2. This fact may be attributed to the fact that a soldered cable is more restricted as far as movement of single strands is concerned. The cable may move as a rigid unit at high field.

The large absolute values of AC loss, compared with those of E1-2, is due to coupling between strands through solder. Existance of long magnetization decay at flat top also confirms the above mentioned coupling.

To investigate the relation between premature quenching and AC loss, the magnet was quenched many times. The training curve is shown in Fig. 4. After many quenchings, the maximum current hit 4640A without iron and 4460A with iron. But these values are about 94% of those expected from the short sample data. We think this large AC loss, which is about five times bigger than that of an unsoldered wire magnet is preventing us from reaching 100% of short sample data. These measurements were made using the bucking coil inside the magnet. The absolute values in these data may have an error factor of about two.

9/22/75

Fig. 1 Ramp rate dependence of D1-10 dipole magnet (23 strand soldered cable)



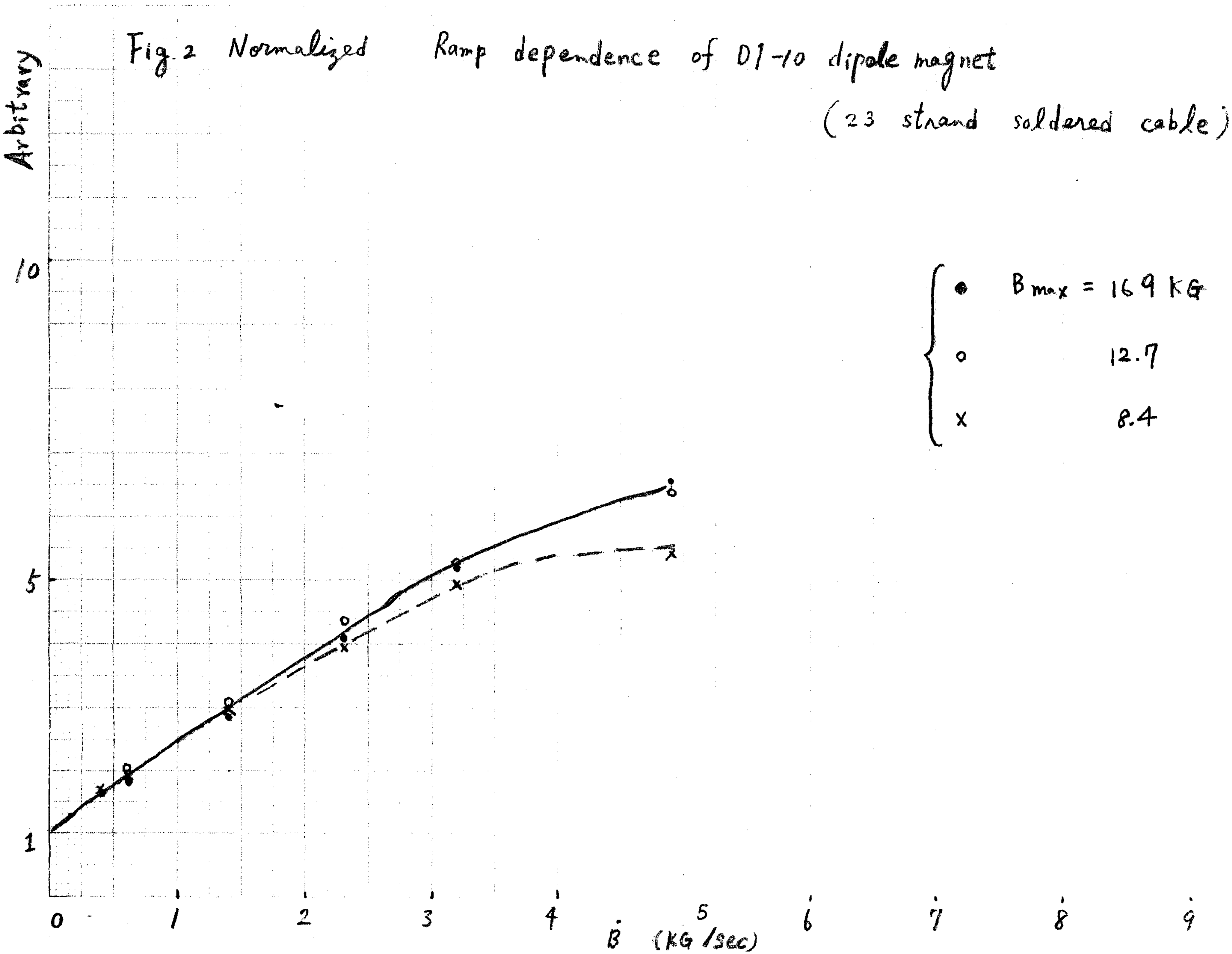
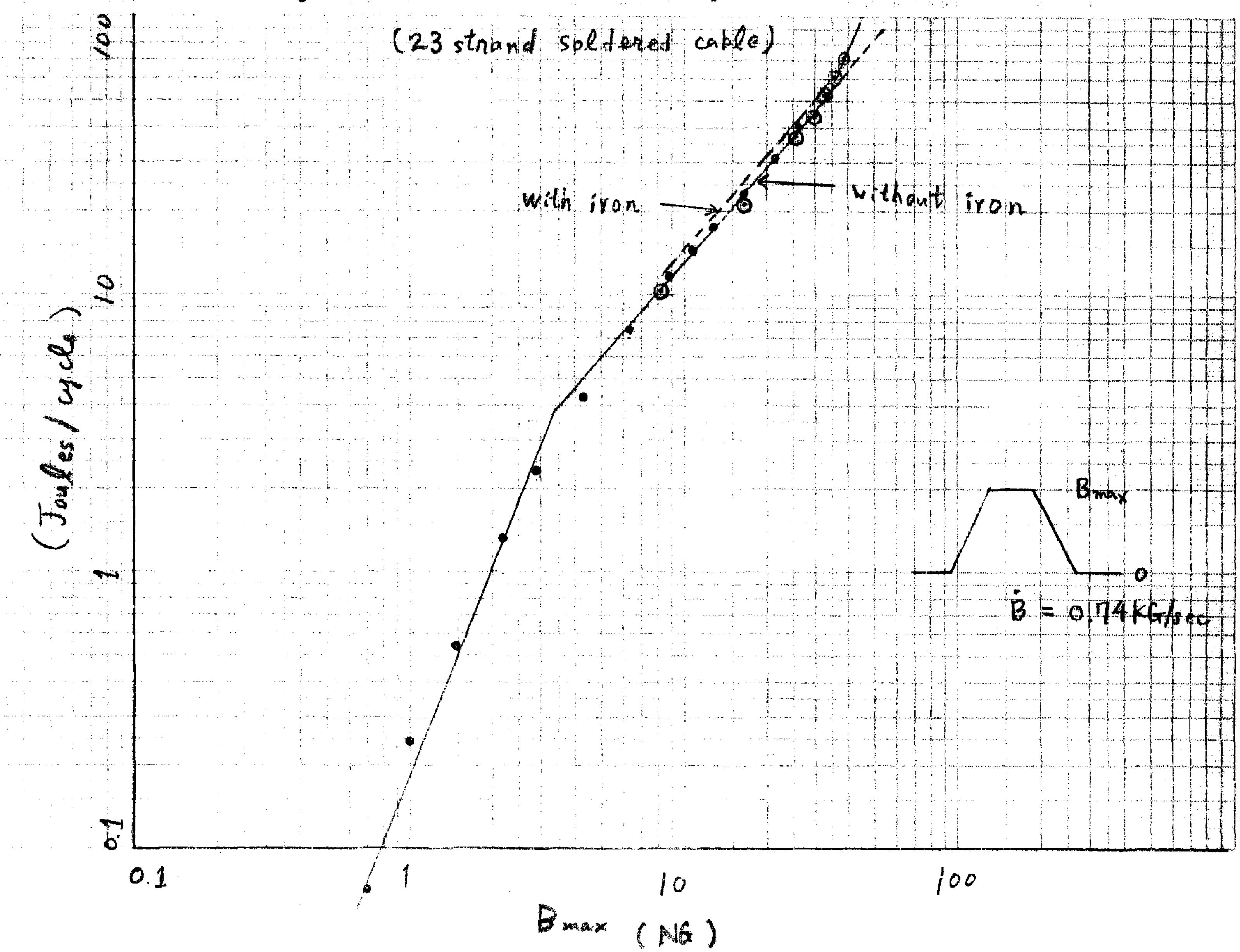


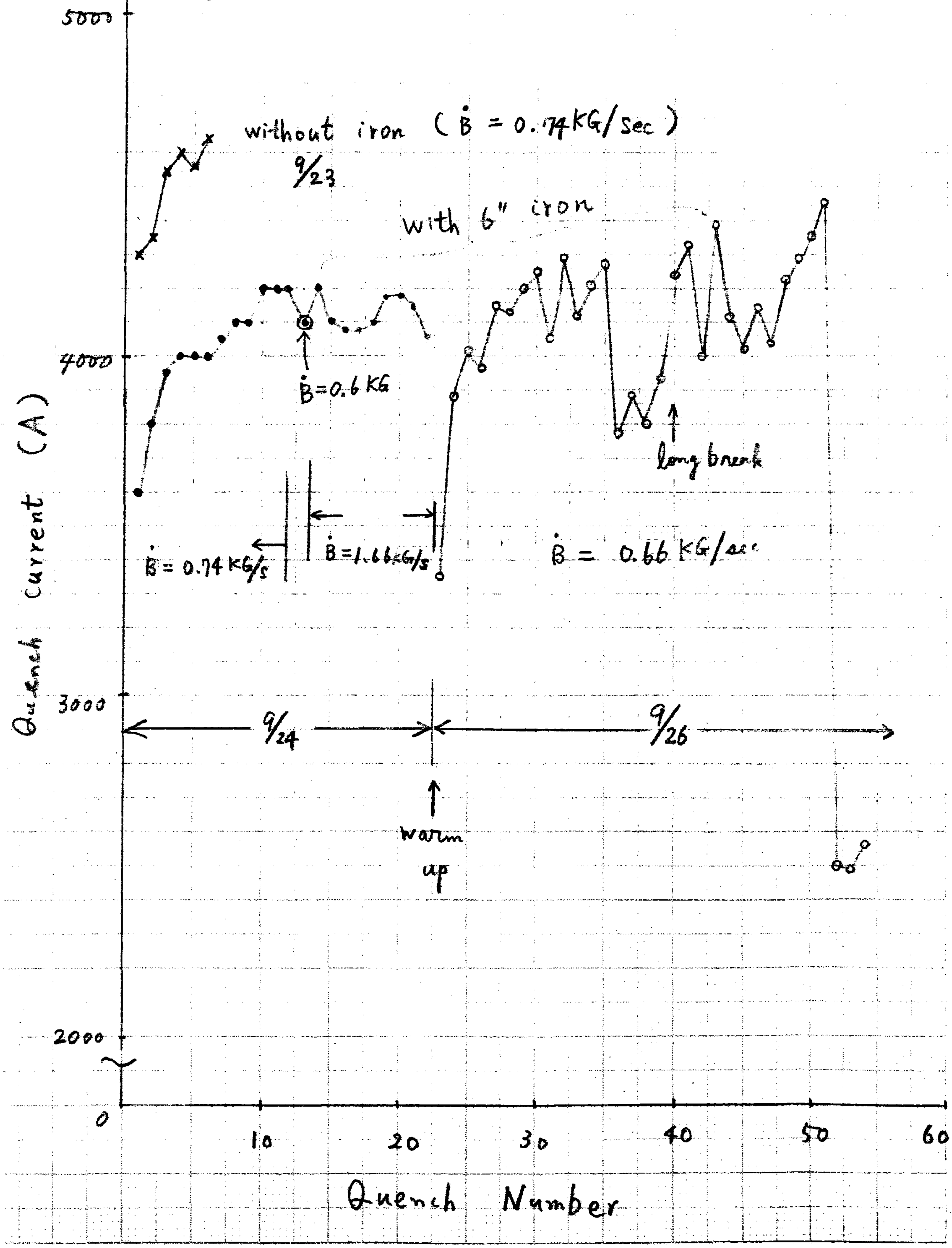
Fig. 2 Normalized Ramp dependence of D1-10 dipole magnet
(23 strand soldered cable)

Fig. 3 D1-10 dipole magnet



D1- 10

Fig. 4


without iron ($\dot{B}$ = 0.74 KG/sec)
9/23
with 6" iron
$\dot{B}$=0.6 KG
long break
$\dot{B}$ = 0.74 KG/s
$\dot{B}$=1.66KG/s
$\dot{B}$ = 0.66 KG/sec
9/24
9/26
warm up
Quench Current (A)
Quench Number
5000
4000
3000
2000
0
10
20
30
40
50
60

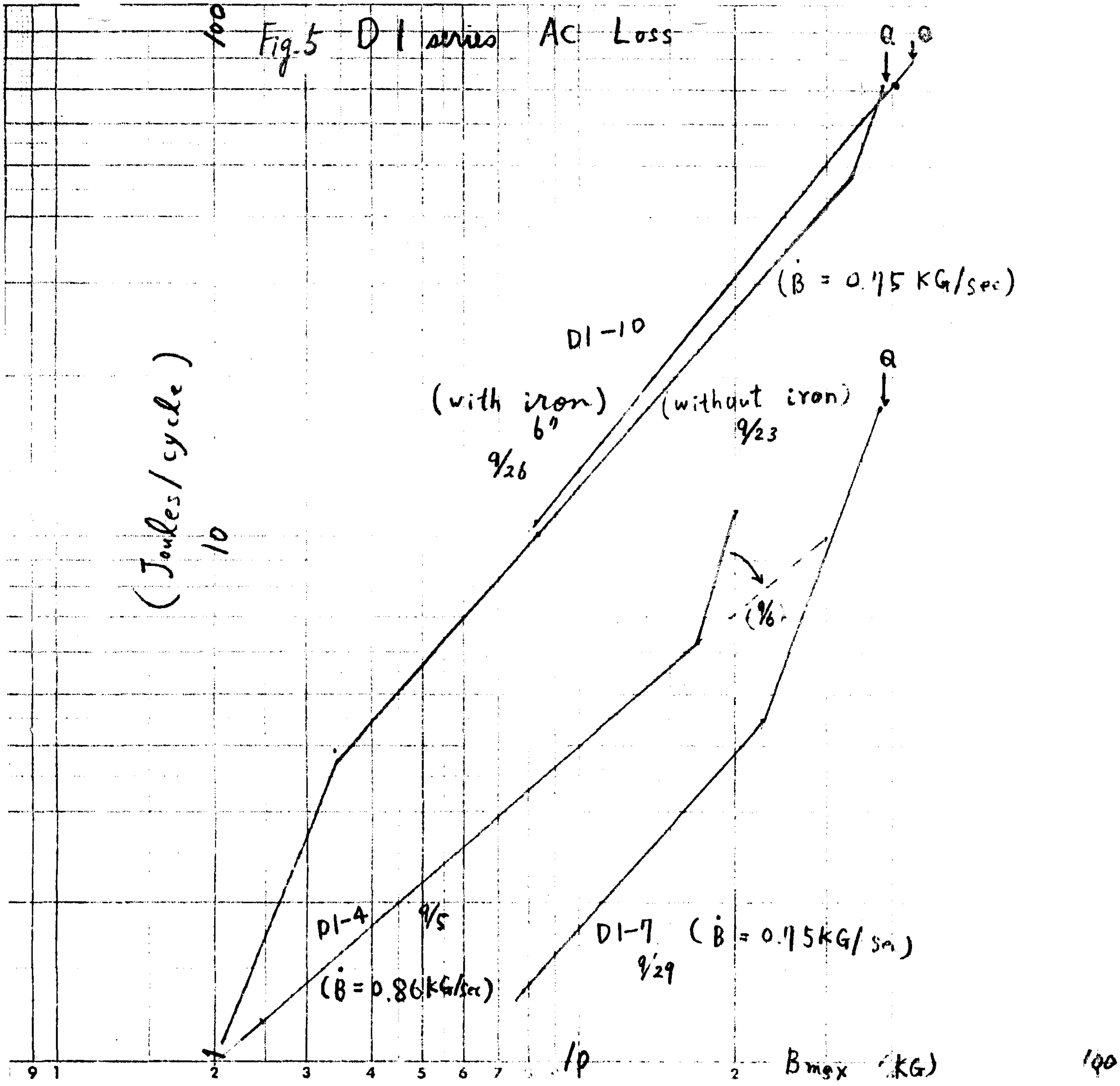


Fig. 5 D1 series AC Loss

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MAGNET MEASUREMENT GROUP REPORT

AC Loss Test of E1-2 Magnet

H. Ishimoto, R. Yamada and R. Pighetti

October 30, 1975

This magnet is made with the MCA 23 unsoldered cable, which is barber-poled with B stage fiberglass tape. The test was done without iron and with iron in the vertical dewar from Oct. 16 to 23. The measured items are as follows:

i) Ramp rate dependence of AC loss at constant maximum magnetic field,

ii) Maximum field dependence of AC loss at several different contstant ramp rates,

iii) Effect of iron.

The results are given in Figure 1 to Figure 7.

The ramp rate dependence of this magnet is roughly four times less than that of D1-10, as expected from the short sample magnetization measurement.

The maximum field dependence over the whole field region is shown in Figure 2. It has two bending points. One, which is at low field, corresponds to the saturation field where the flux completely penetrates into the filament. But the other is not observed in the magnetization measurement of short sample wire. Therefore this is peculiar to the magnet. The wire movement is the most probable explanation. To pursue this problem the maximum field dependence were investigated, in detail, at high field. As shown in Figure 3, the dependence is nearly quadratic and the increase of loss is independent of $\dot{B}$ after subtracting the extrapolated conductor losses. Especially at high field, the obtained values seem to depend on the history of magnet as shown in Figure 4.

The magnetization curve of the magnet without iron is also distorted at high field, which suggests the small change of inductance at the normal state.

From the above mentioned results and the report in B.N.L., we guess that the wire movement, which includes that of single strands inside the cable, occurs.

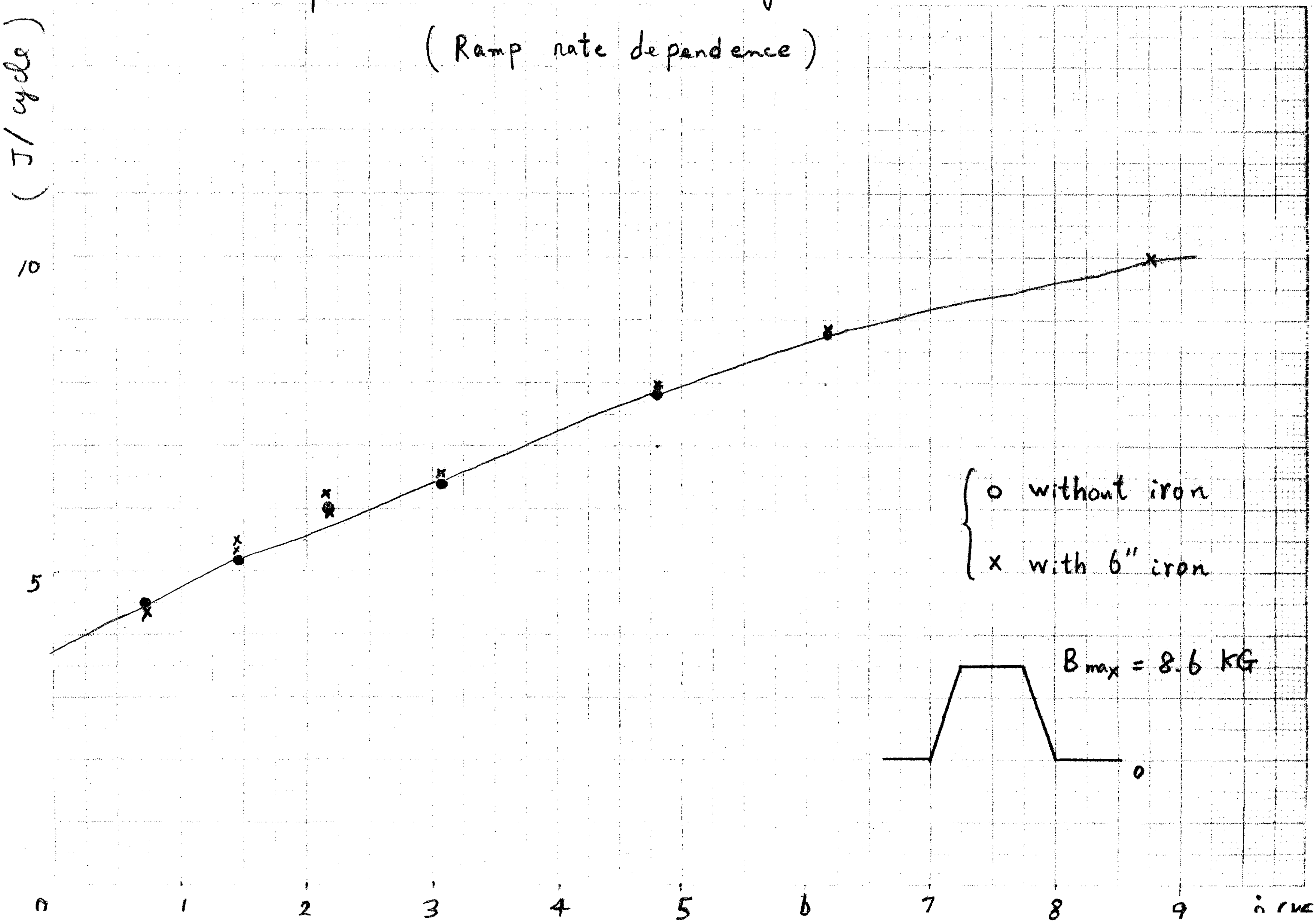
The effect of iron is not so large as shown in Figure 3. Unfortunately, at high field, it is buried under another effect mentioned above. But the increase of loss due to iron is not so unreasonable judging from the rough calculation.

The magnetization loop with iron is quite different at high field from that without it (Figure 6). We have no other information, but the local saturation of iron may be happening somewhere. Training curve is shown in Figure 7. On the first test without iron no quenching was done.

All of the measurements were taken using an air core inductor put at room temperature. So there is no ambiguity with the absolute value except the experimental errors. The future measurement will be made using this new system.

Fig. 1 E1-2 dipole magnet 10/17/75

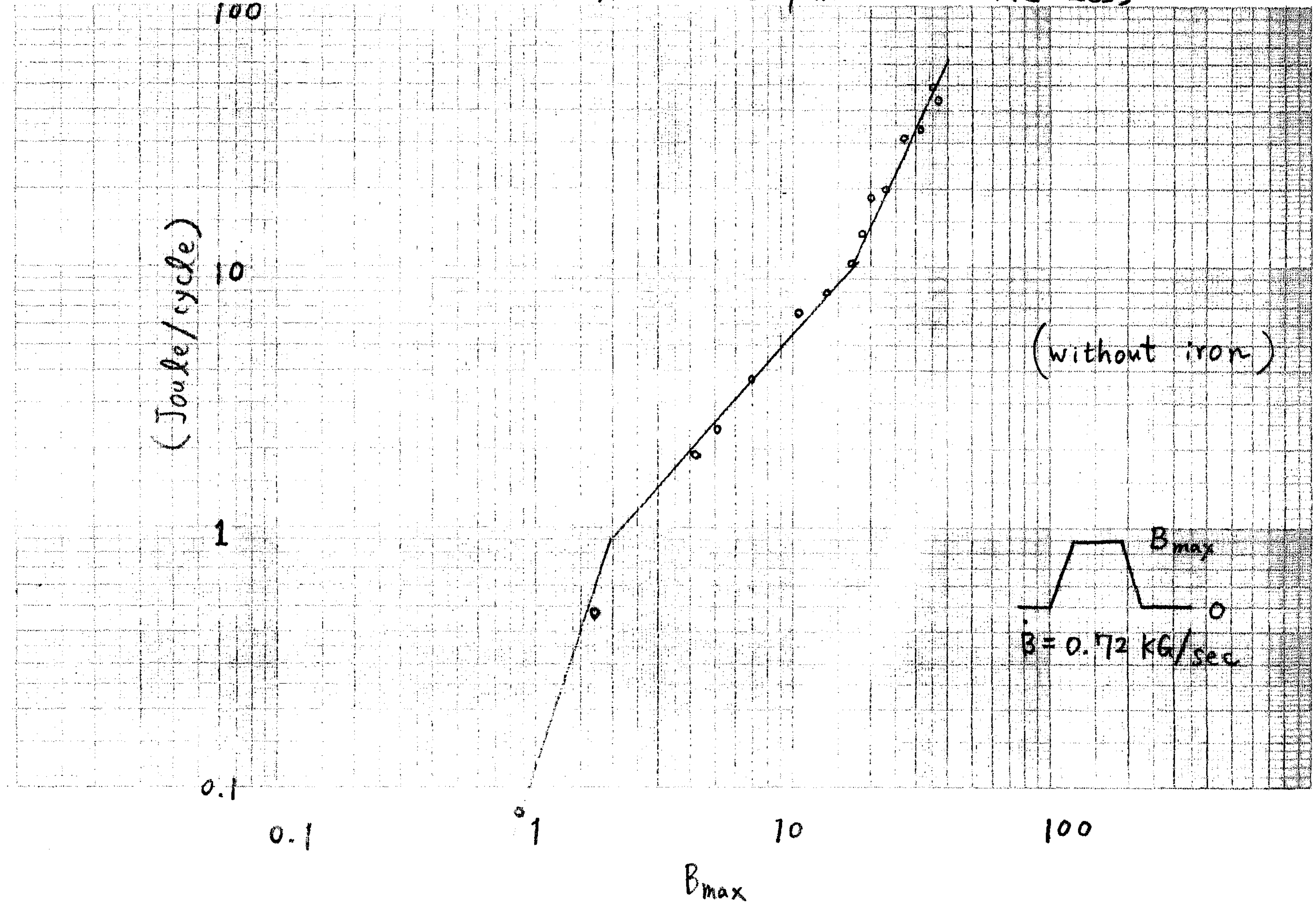
(Ramp rate dependence)



10/17/75

Fig. 2 E1-2 Dipole magnet

Max. Field Dependence of AC Loss



E1-2

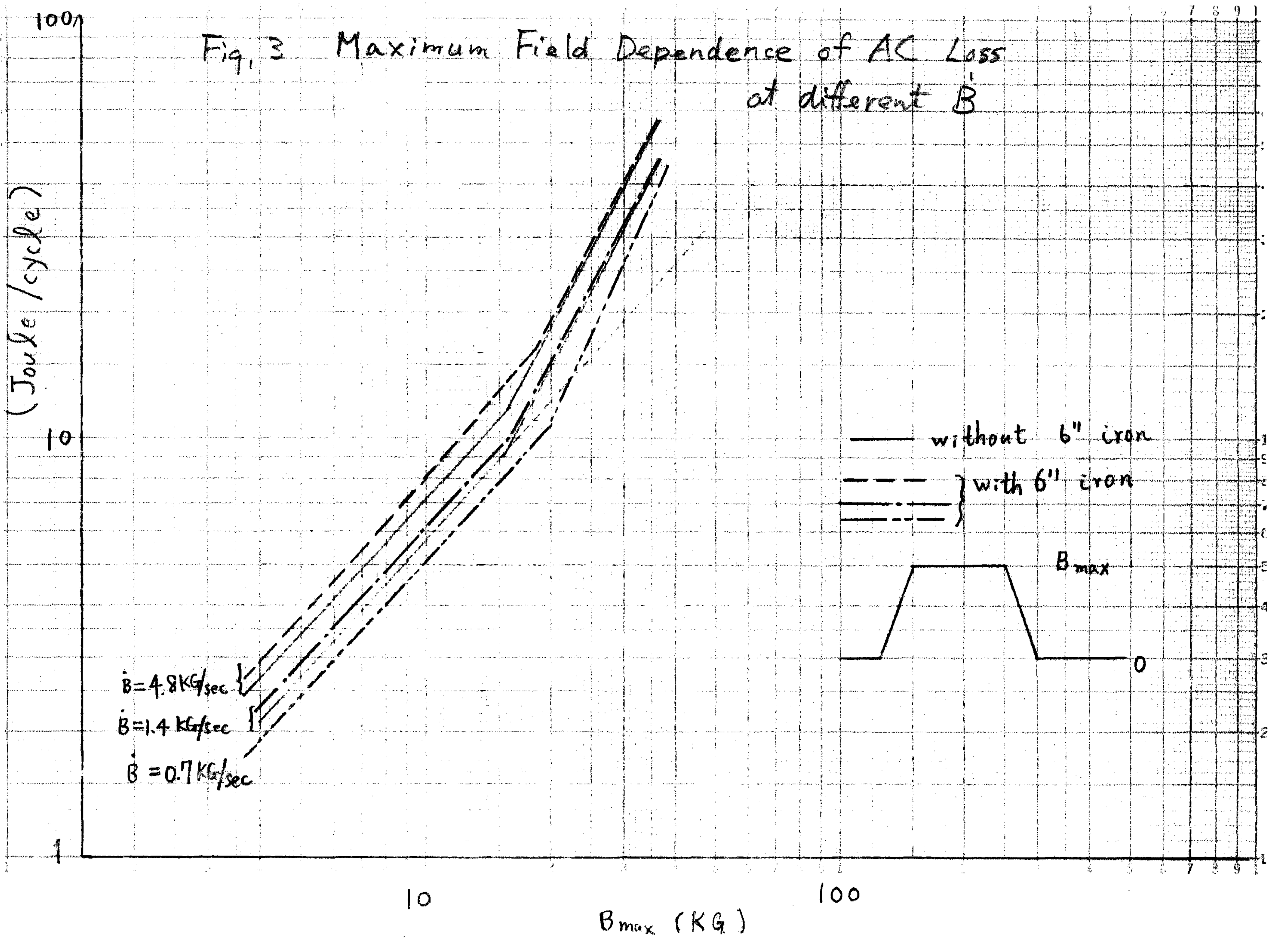


Fig. 3 Maximum Field Dependence of AC Loss at different $\dot{B}$
(Joule /cycle)
100
10
1
10
100
B_{max} (KG)
$\dot{B}$=4.8 KG/sec
$\dot{B}$=1.4 KG/sec
$\dot{B}$=0.7 KG/sec
without 6" iron
with 6" iron
B_{max}
0

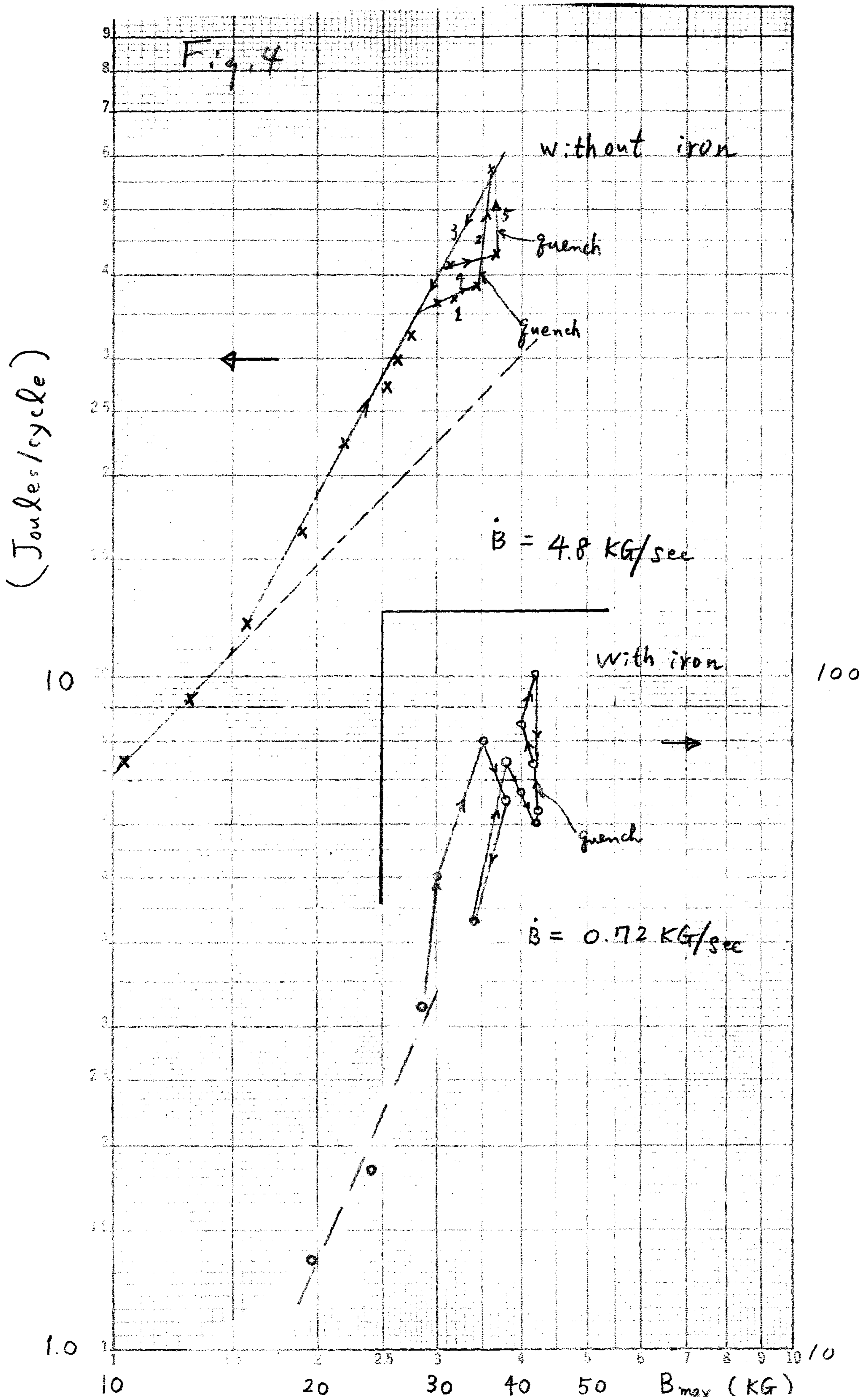


Fig. 4
without iron
quench
quench
Ḃ = 4.8 KG/sec
with iron
quench
Ḃ = 0.72 KG/sec
(Joules/cycle)
10
1.0
100
10
10
20
30
40
50
Bmax (KG)

Fig. 5

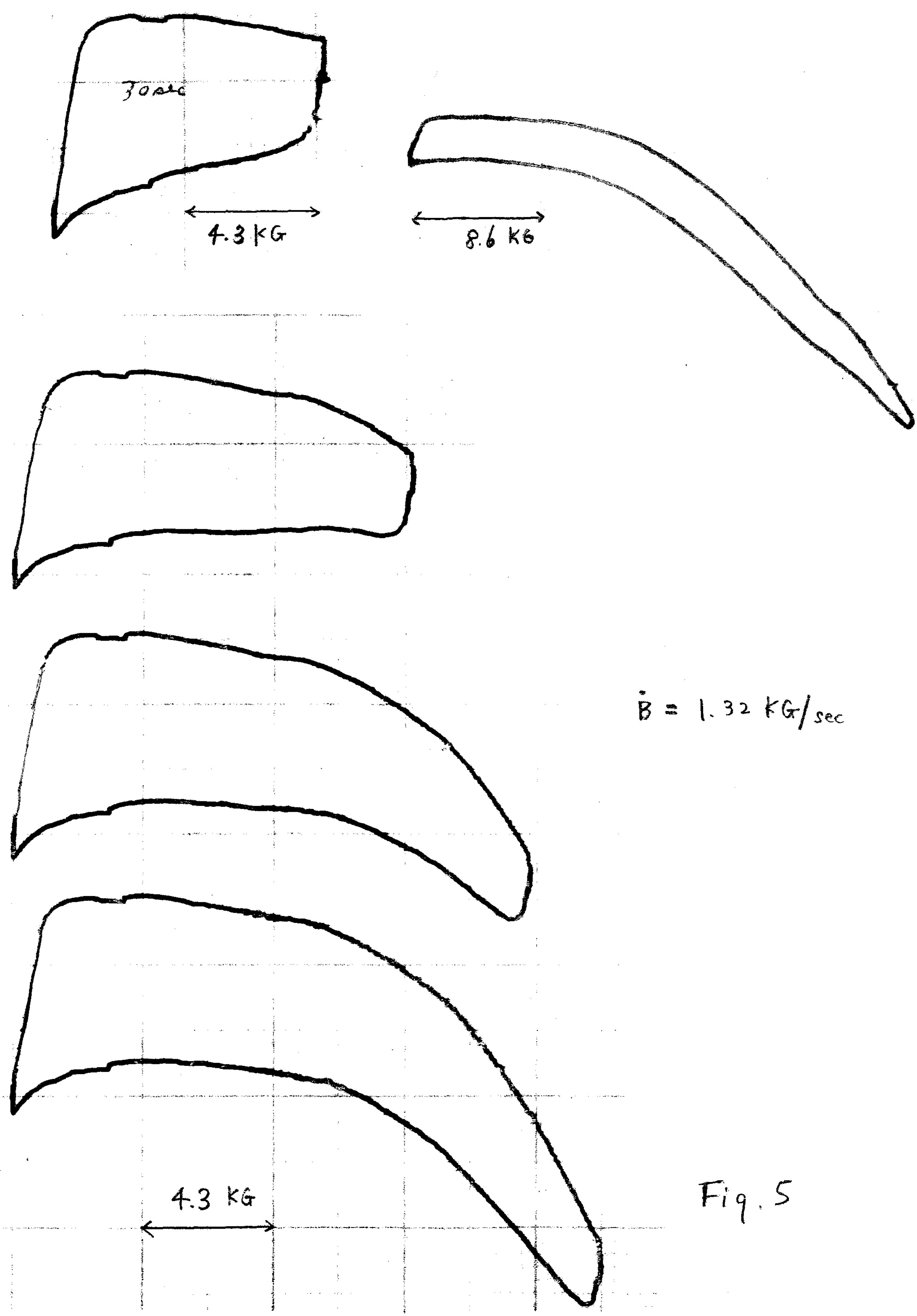
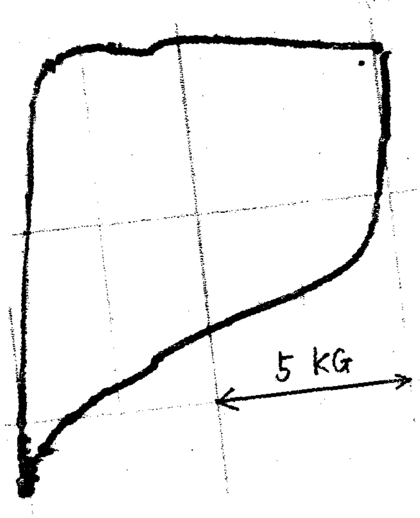


Fig. 5

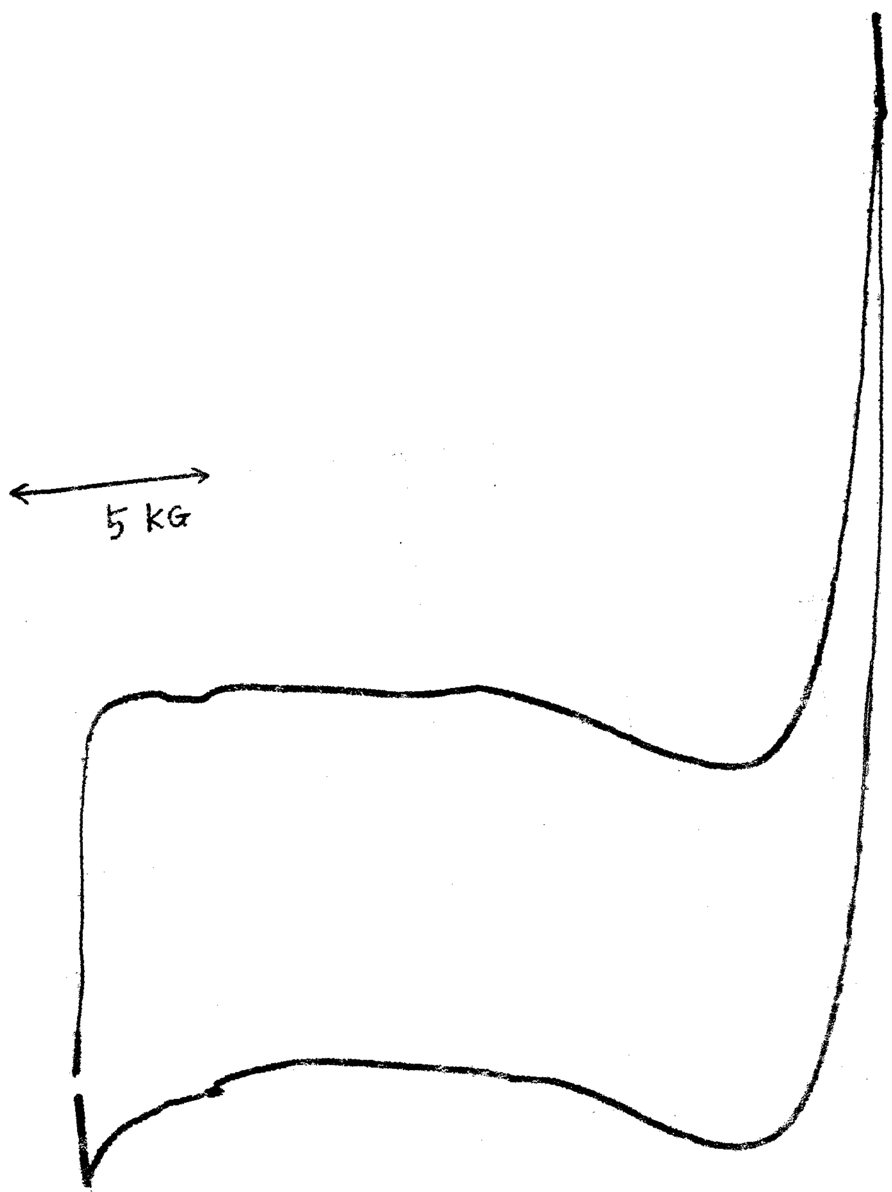
Magnetization loop of E1-2 without iron

6 Magnetization loop of E1-2 dipole magnet with iron

Fig. 6



$\dot{B} = 1.44$ kG/sec



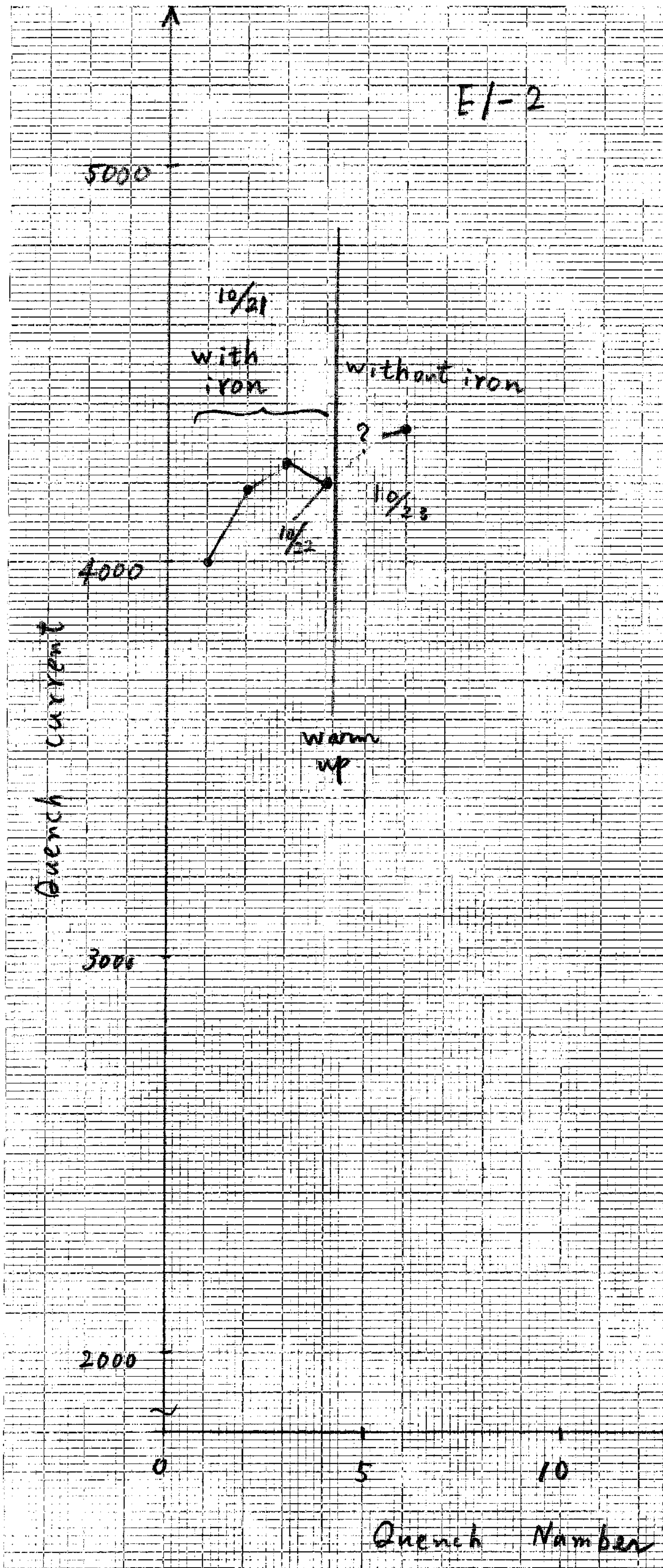


Fig. 7

Training curve of E1-2

Before these runs there was test without iron, but we did not quench the magnet during that test.

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MAGNET MEASUREMENT GROUP REPORT

AC Loss Test of E1-3

H. Ishimoto, R. Yamada and R. Pighetti

November 11, 1975

Magnet E1-3 is constructed using the same design and the same cable as E1-2. But in this case, both sides of the cable (MCA 23 unsoldered) are painted with 1 mil thick epoxy.

The main purpose of this experiment was to investigate the behavior of loss at high field. All measurements were made without iron and the maximum field dependence at high field was mainly taken at various ramp rates. The results are given in Fig. 1 - Fig. 6.

The maximum field dependence has a bending point at around 20 kG, which hardly depends on $\dot{B}$. However, in one run at $\dot{B}$ = 4.4 kG/sec, this behavior temporarily seemed to have disappeared after quenching. Sometimes the values at field higher than the bending point fluctuate and seem to depend on the experimental history (Fig. 1). Top and bottom halves were individually measured to see if there was any difference. As we can see in Fig. 2 there was no difference between them.

The wire movement is most probable cause. To verify this, the magnet was vacuum impregnated first slightly with epoxy and in the following test it was soaked with Vaseline. The results are shown in Figs. 3 and 4. We could not see a drastic change as expected. This fact suggests that to suppress the wire movement completely, we should be careful in choosing an impregnation material and its way of potting.

While measuring the AC loss, the magnet quenched often. Its training curve is given in Figs. 5 and 6. The quenching current of the potted magnet is much smaller than that of the unpotted one. It is interesting to note the first several quenches in this run were just above the bending point of the field dependence curve.

This magnet needed much more training than El-2 magnet, and still the final values were much lower. These final values are affected very much by the way of potting.

Transfer function is 8 kG per kA for this magnet without steel core.

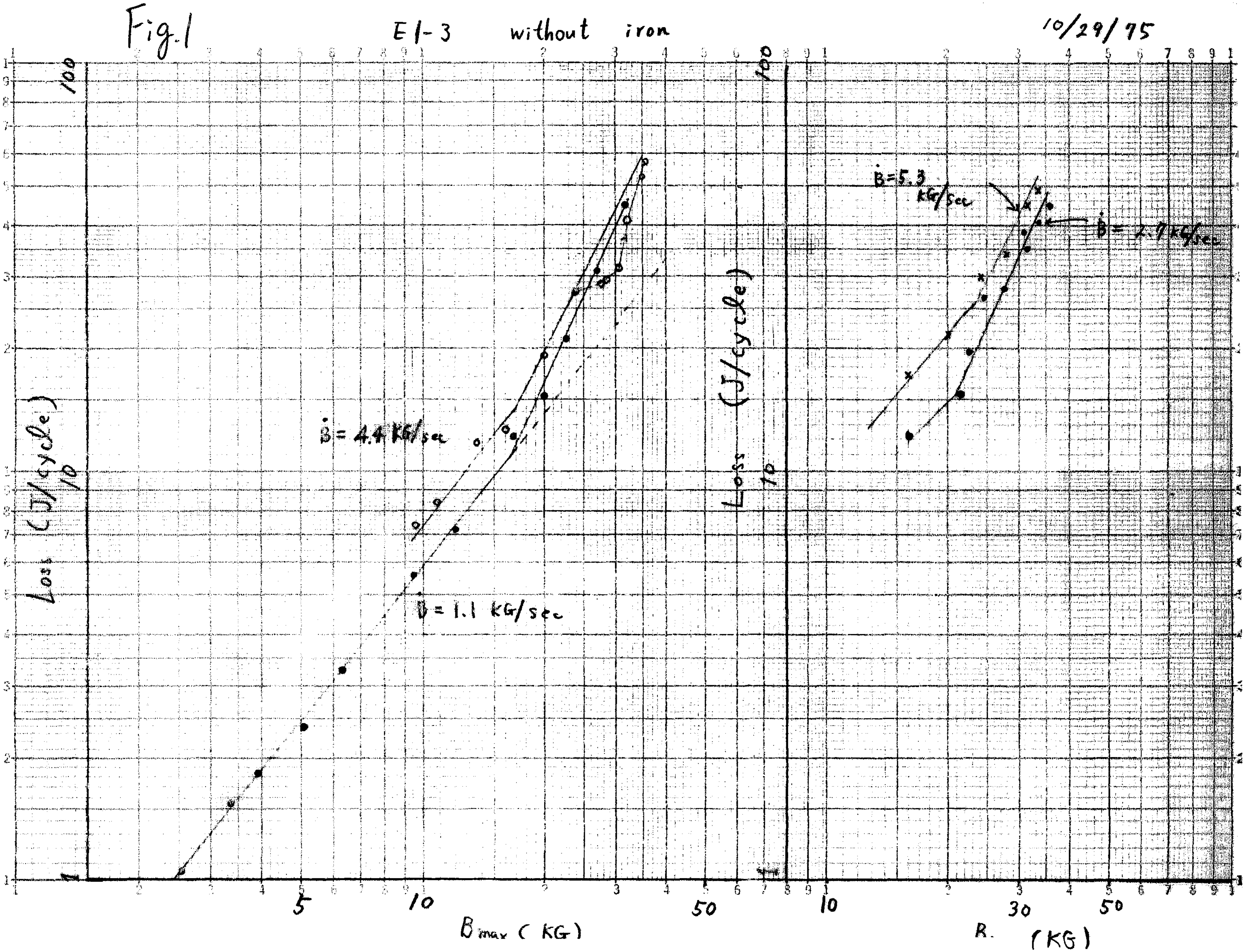


Fig. 1
E1-3 without iron
10/29/75
Loss (J/cycle)
$\dot{B}$ = 4.4 KG/sec
$\dot{B}$ = 1.1 KG/sec
B_{max} (KG)
$\dot{B}$ = 5.3 KG/sec
$\dot{B}$ = 2.7 KG/sec
B (KG)
100
10
1
5
10
50
30

Fig. 2

10/29/75

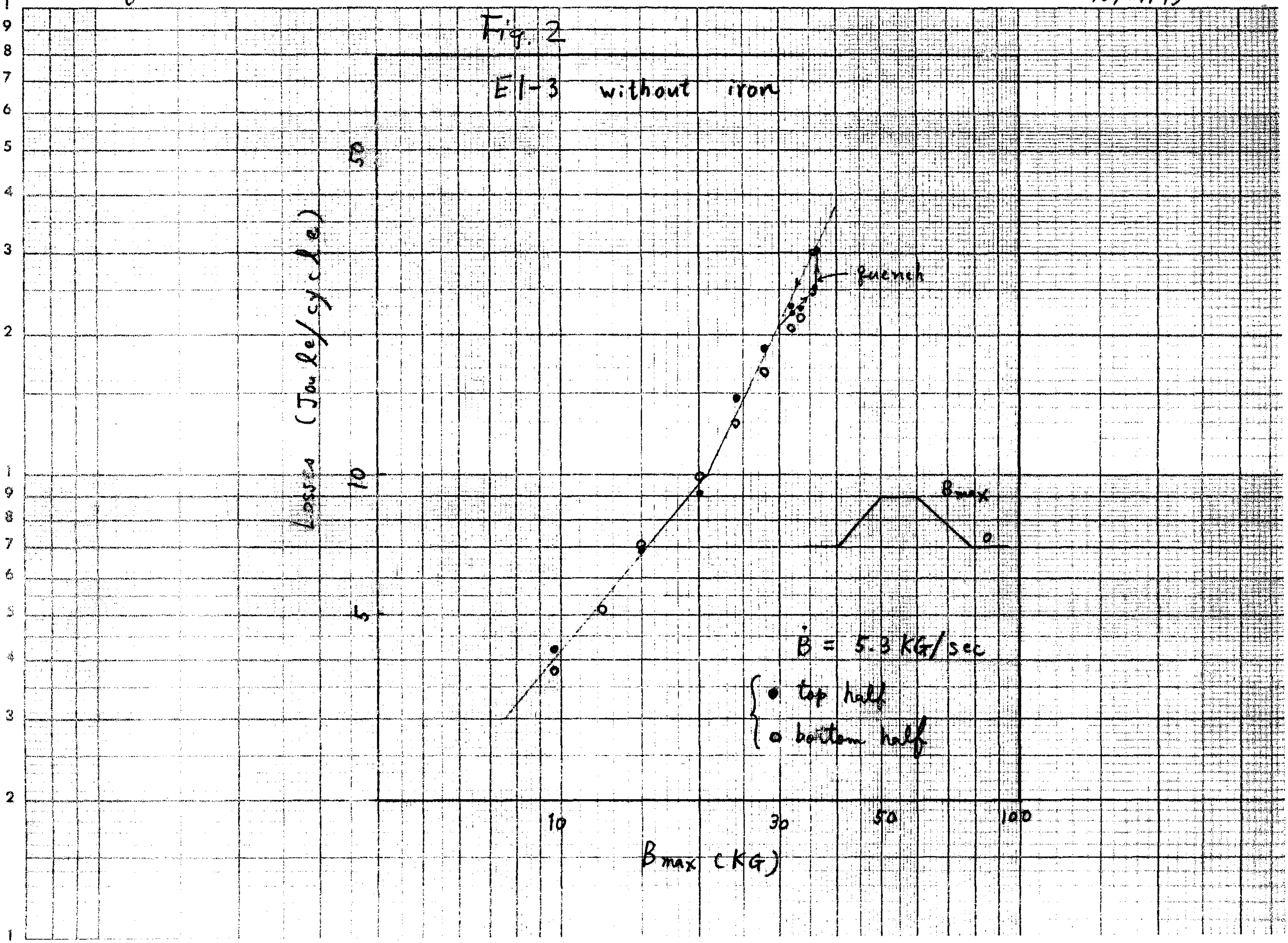


Fig. 2
E1-3 without iron
Losses (Joule/cycle)
50
10
5
quench
Bmax
Ḃ = 5.3 KG/sec
• top half
o bottom half
10
30
50
100
Bmax (KG)

Fig. 3

E1-3 potted slightly with epoxy 10/31/75

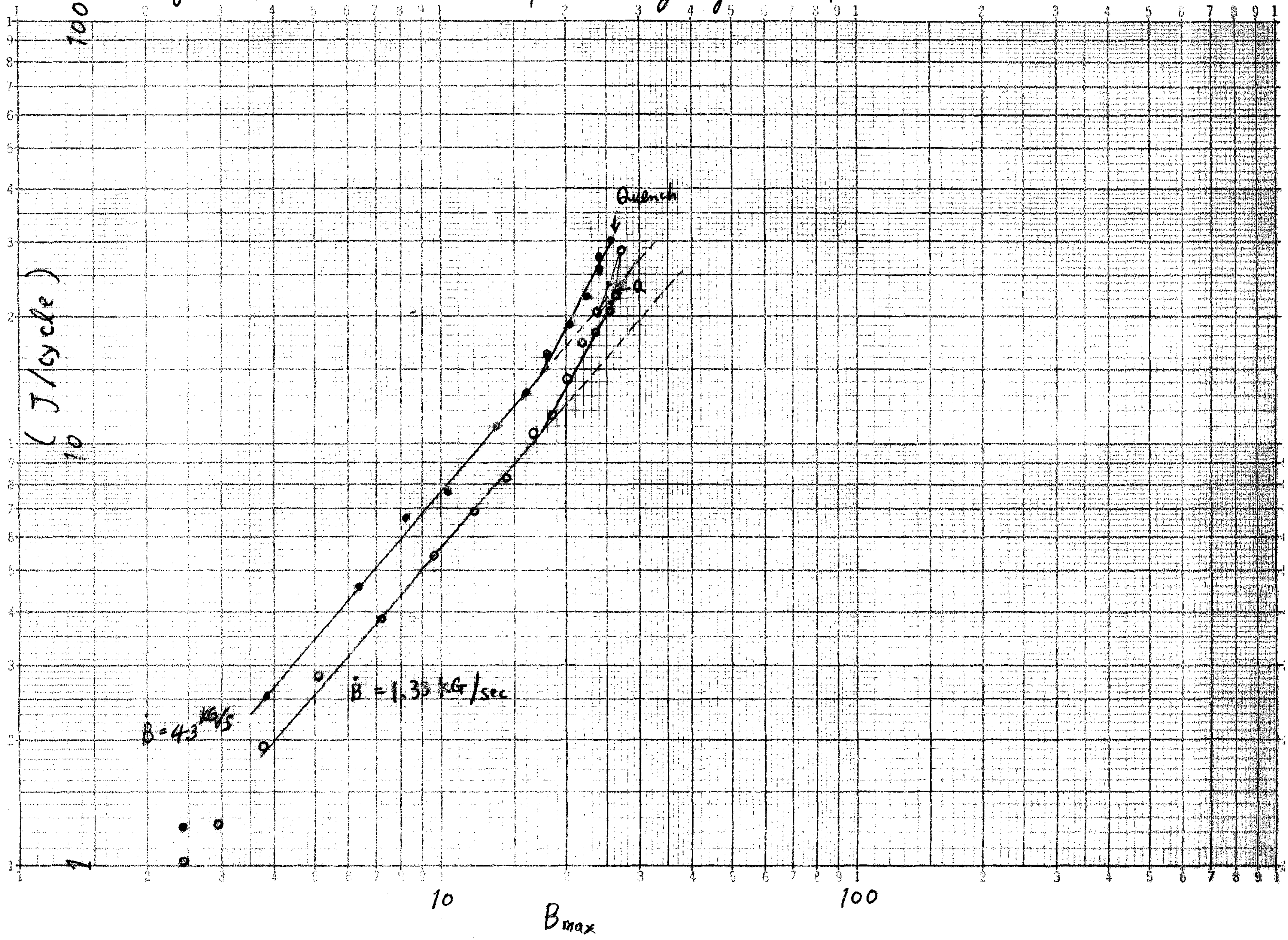
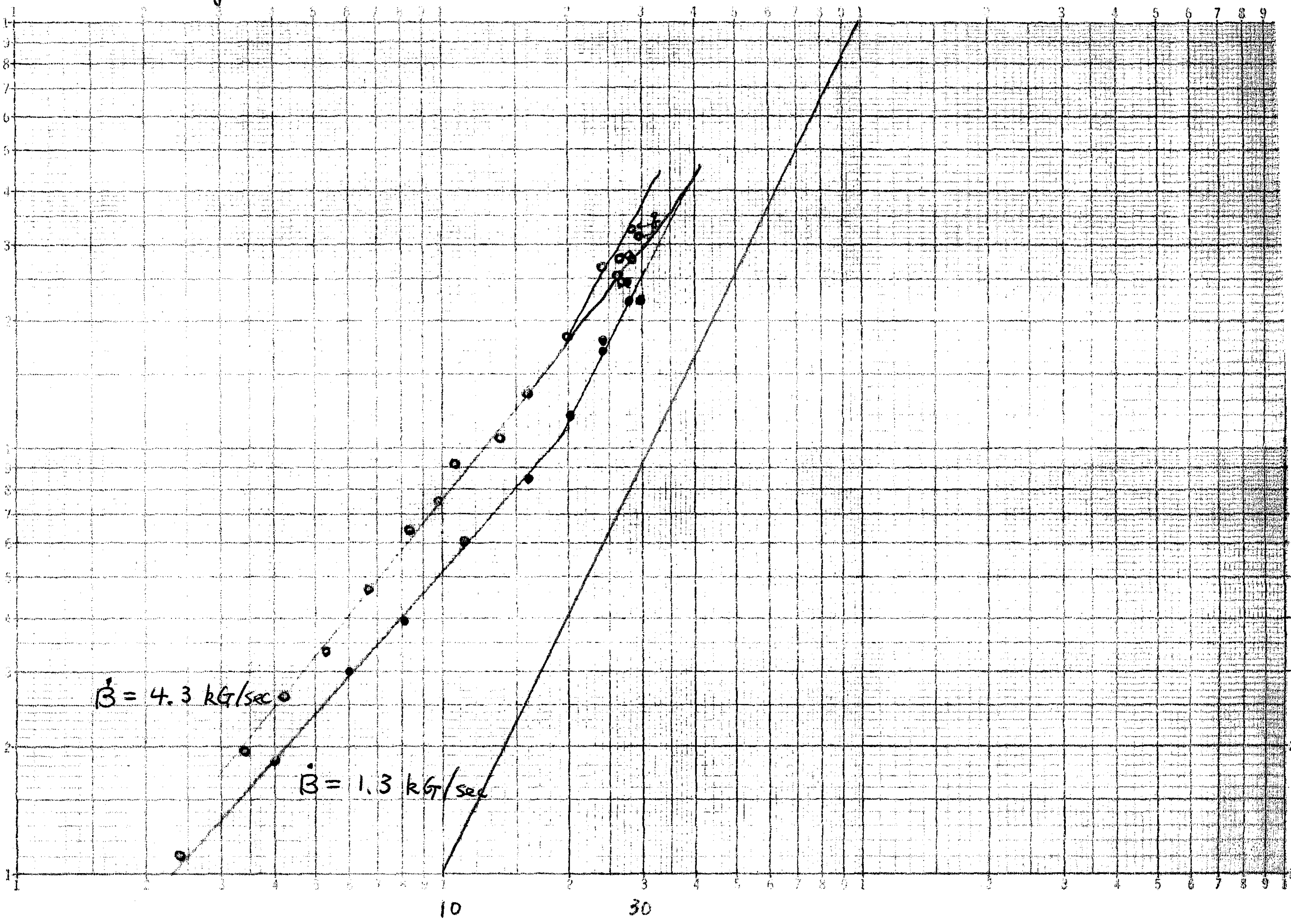
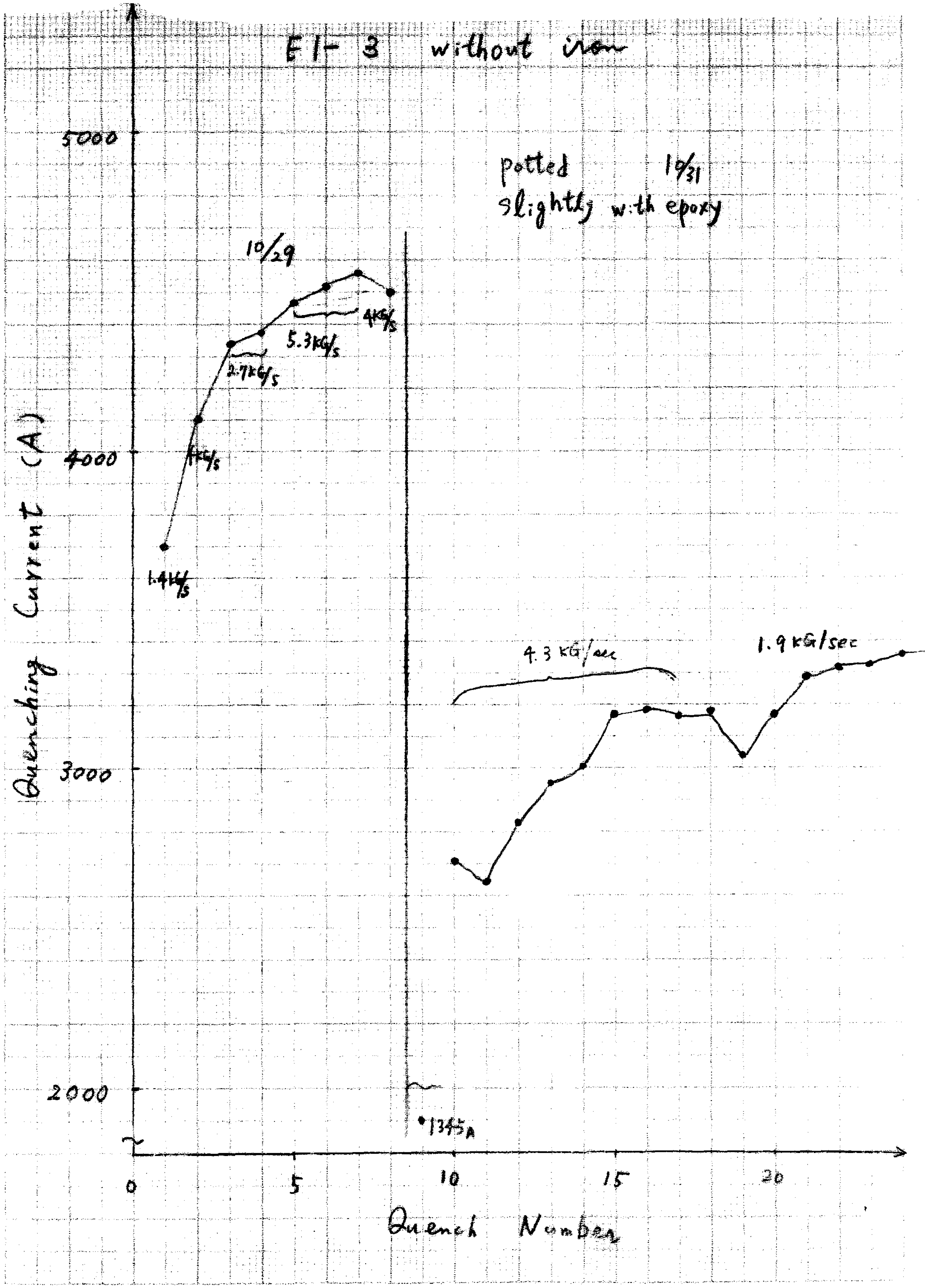


Fig. 4 El-3 potted with Vaseline 11/5/75





E1-3 without iron
potted 10/31
slightly with epoxy
10/29
5000
4000
3000
2000
Quenching Current (A)
1.4kG/s
1kG/s
2.7kG/s
5.3kG/s
4kG/s
4.3 kG/sec
1.9 kG/sec
1345A
0
5
10
15
20
Quench Number

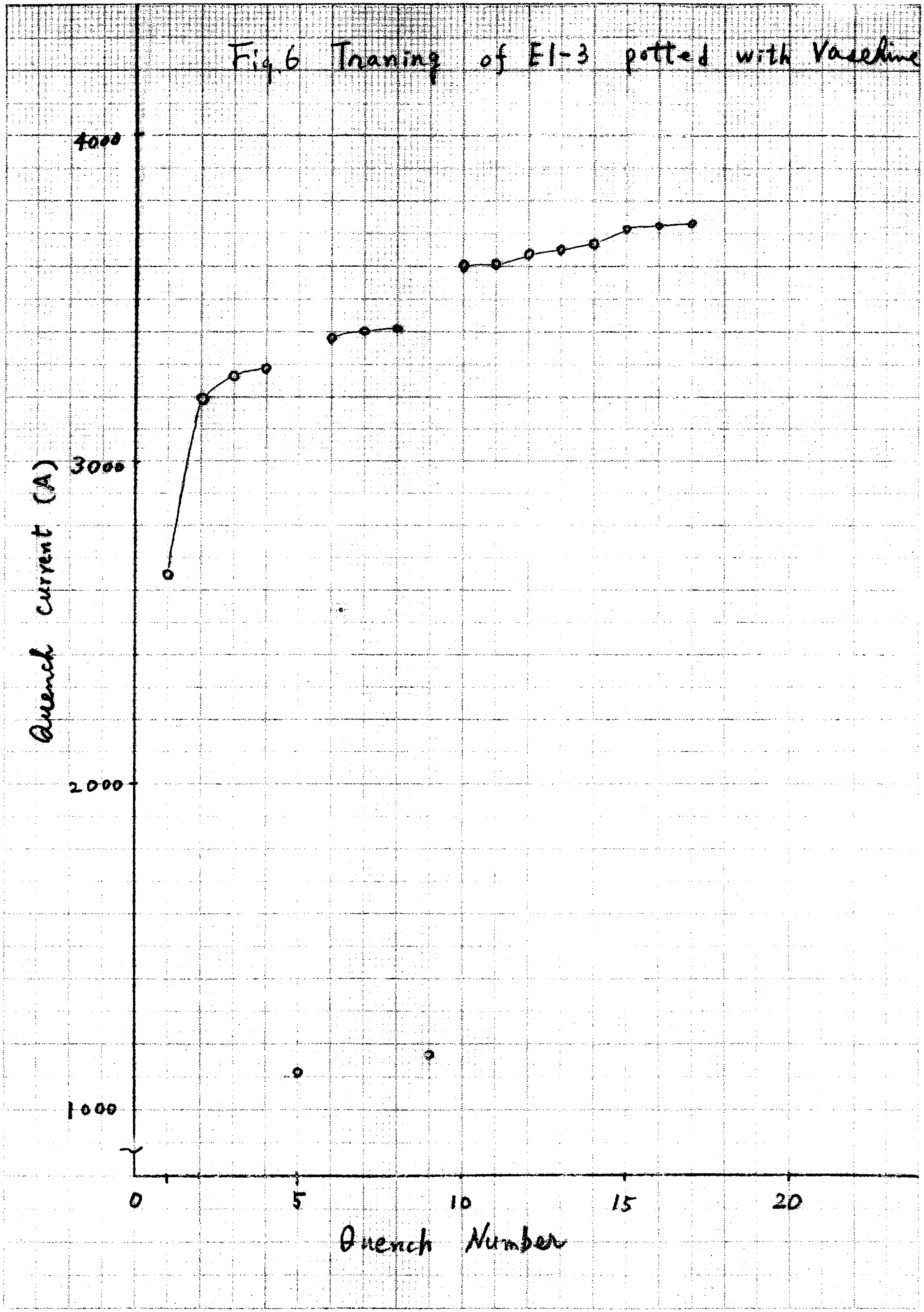


Fig. 6 Traning of E1-3 potted with Vaseline
4000
3000
2000
1000
Quench current (A)
0
5
10
15
20
Quench Number

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MAGNET MEASUREMENT GROUP REPORT

H. Ishimoto, R. Yamada, and R. E. Pighetti

December 9, 1975

AC Loss Test of E1-10 Magnet

This magnet is made with MCA23 unsoldered cable, but according to the measurement of the Superconductor Group, the ramp rate dependence of quenching current exhibited a very different behavior from those of any other magnet ever made.

We expected the ac loss might behave differently from E1-2, etc. The test was done without iron from December 5 to December 8. At first cool down, the quenching current did not go higher than about 2800A. We guessed moisture inside the magnet might have caused the quenching at lower current. We dried it up in the oven at 150°F overnight, and tried again. One of the power lead bolts might not have been tight enough.

The obtained results are given in Figures 1 - 4. The ramp rate dependence is quite similar to that of E1-2. The maximum field dependence in the whole field region has two bending points as the other magnets, contrary to our expectations. Further we investigated this dependence mainly at high field, and at high ramp rates we have never tried. The obtained values are almost the same as those of E1-2, and the ac loss increases in proportion to $\sim B_{max}{}^2$ at high field. The upper bending points seem to shift to the low field side with increase of the ramp rate.

As we pointed out before, the very small wire movement may cause the extra loss at high field. The quenching currents during measurements are shown in Figure 4.

12/5/75

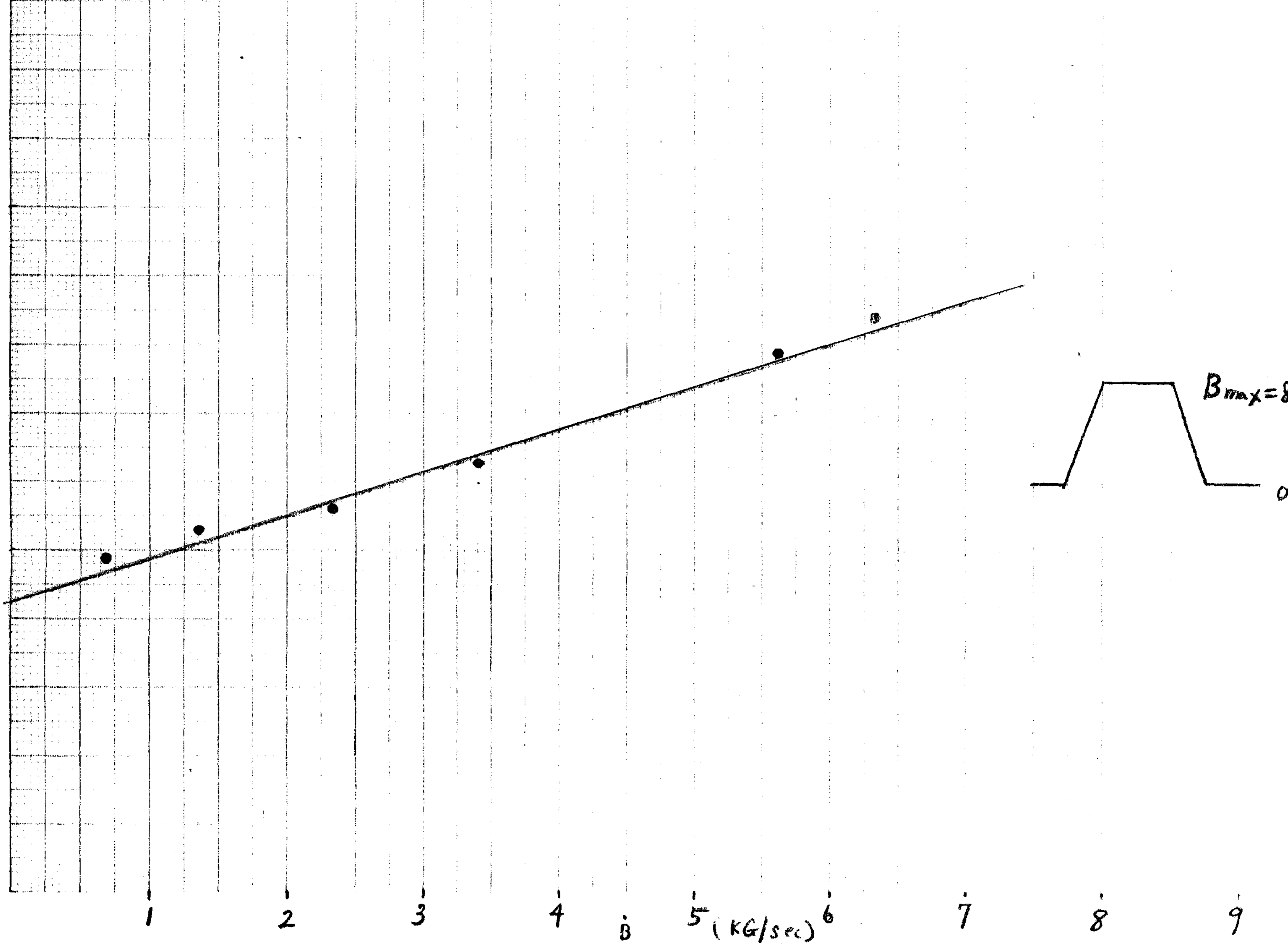


Fig 1 Ramp rate dependence of E1-10 without iron

Fig. 2 Maximum field dependence of E1-10

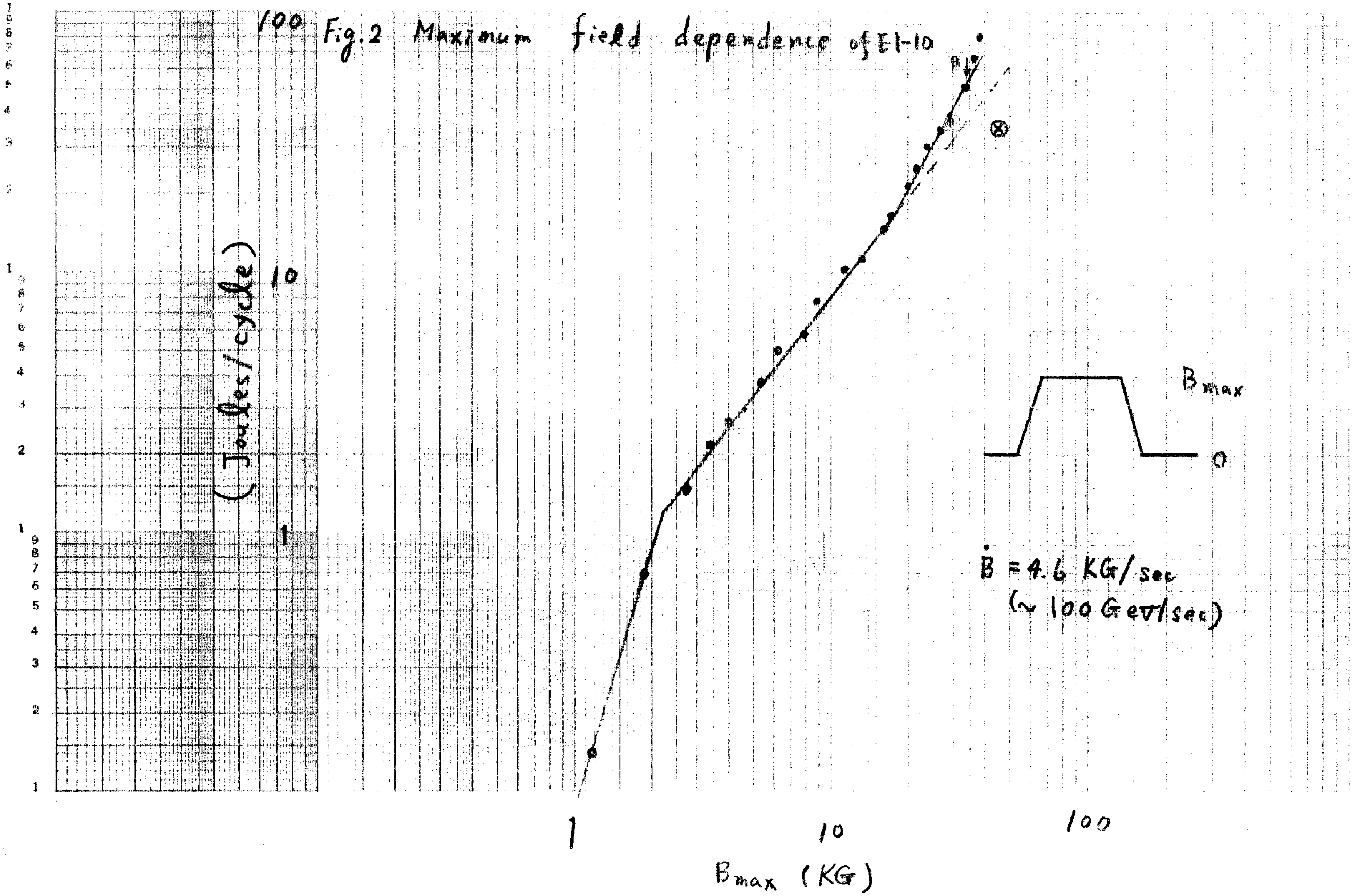
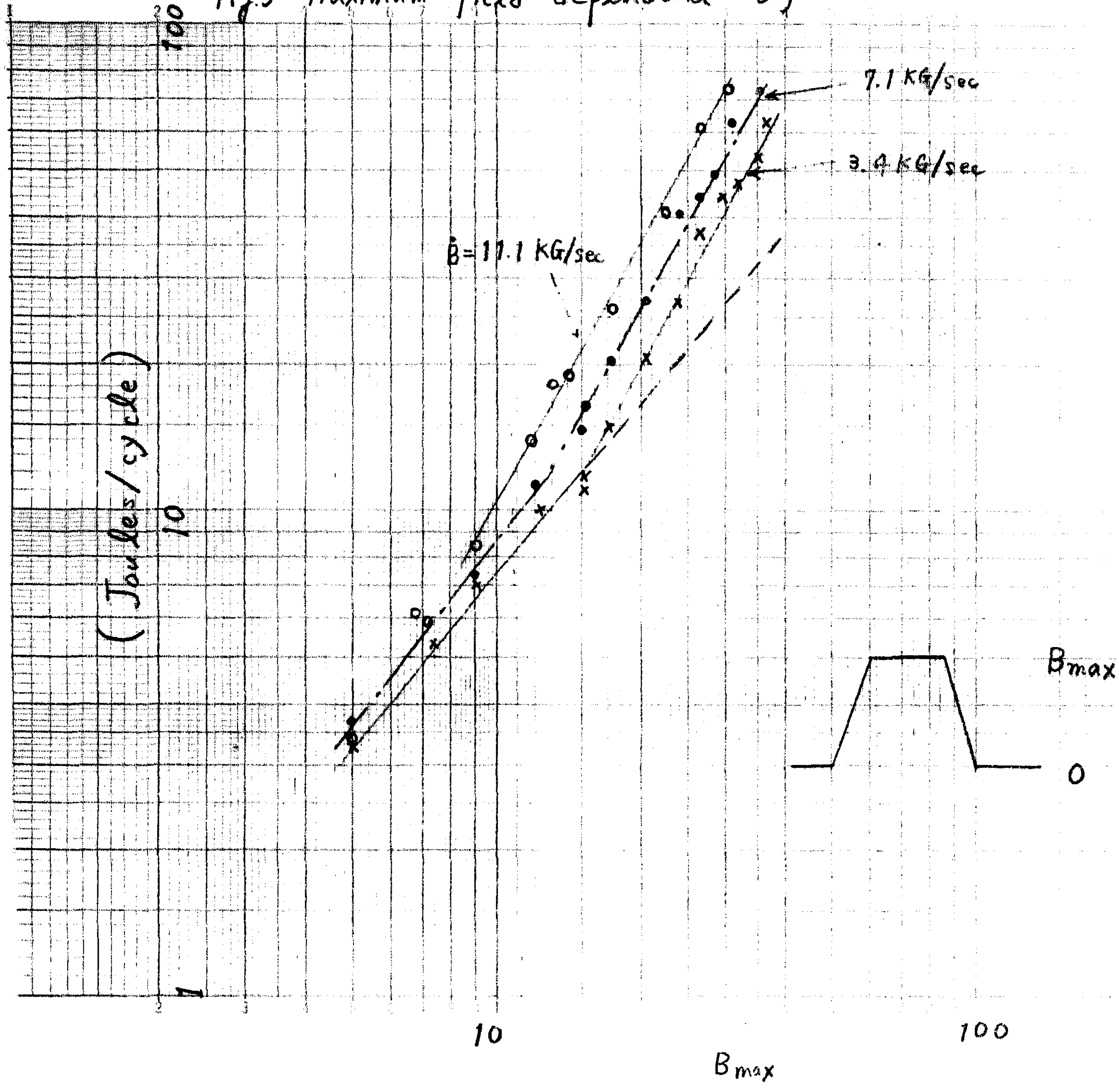
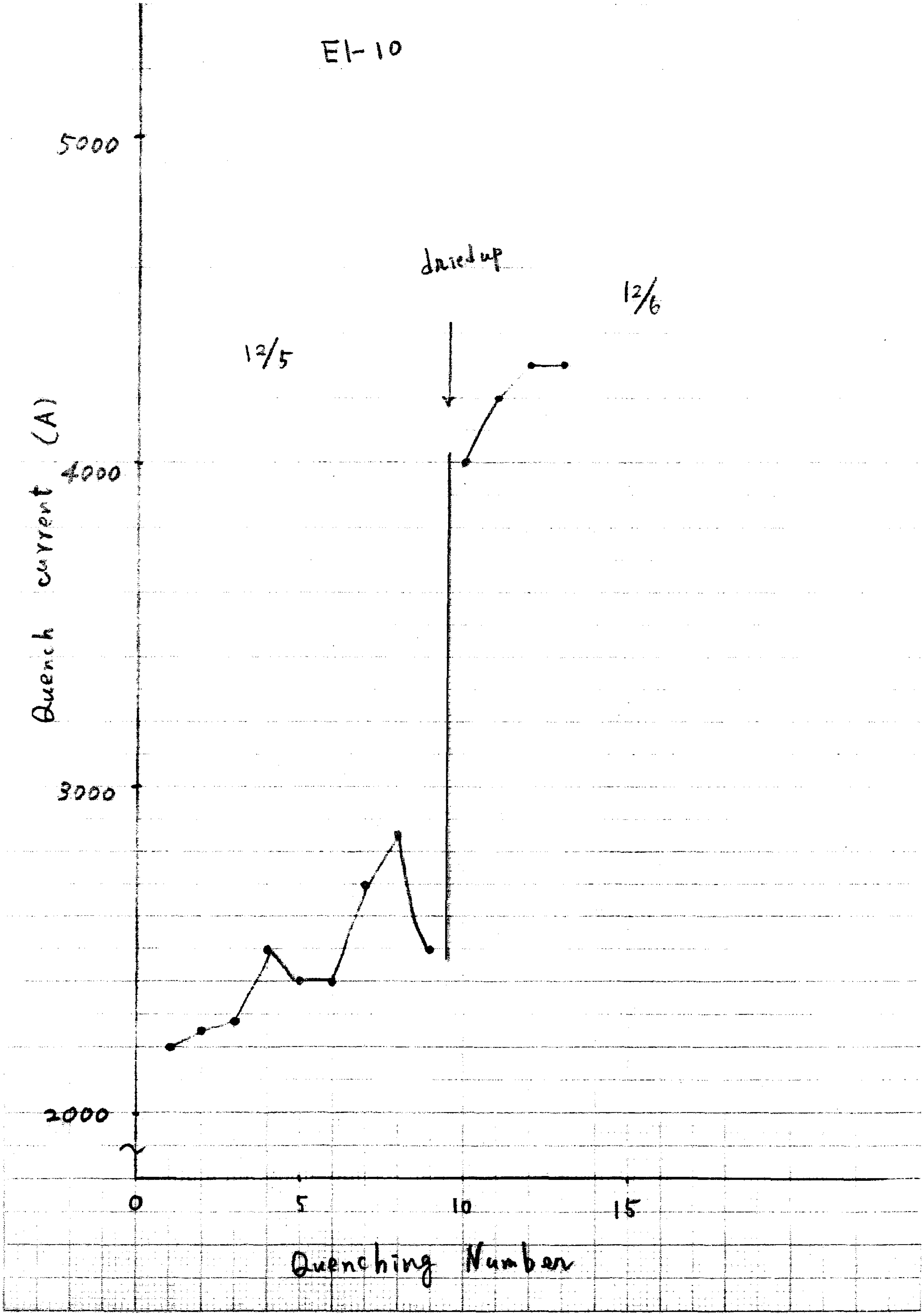


Fig.3 Maximum field dependence of E1-10

12/8/75




El-10
5000
4000
3000
2000
Quench current (A)
dried up
12/5
12/6
0
5
10
15
Quenching Number