Fermilab

PBAR #431

3Q120 LOW GRADIENT BEHAVIOUR -- COMPANION REPORT

A. WEHMANN

OCTOBER, 1985

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Introduction

Three 3Q120 magnets--representative of those in the AP 1 line-- have been measured with a harmonics probe at MDTF at both low (0-48 A) and high (to >= 400 A). The intent of the measurements was to learn their behaviour at the low gradients necessary to transport 8 Gev antiprotons back through the AP 1 line for injection into the Main Ring. This paper describes some aspects of the measurements that were not included in the main paper, in order to keep the size of the main report reasonably small. It includes as Appendix I a chronology of the measurements made and significant changes made to the measurement apparatus and analysis programs.

Degaussing Procedure and Remnant Fields

The first 3Q120 magnet measured in this series was QQQ004. It had not been excited by current and it was judged unnecessary to degauss it to remove excessive remnant field before making the first round of studies. The remnant field value ($\int$ G dL) before any excitation was 1.2721 * 10**-3 tesla. For comparison, the first excitation to 400 amperes gave 27.5 tesla gradient strength. Excitation to 24.4 amperes after a set of three biasing ramps to 405 A gave a result of 1.85 tesla.

Table 1 shows the remnant field gradient strength measured after three ramps to the bias currents shown. Where available, several representative values are shown to indicate the repeatability of the measured value. After one of the 405 A bias runs, the remnant field was measured with a Hall probe at a pole tip and was 45 gauss when the Hall probe was oriented for a maximum reading. Measurement data exists for pole strengths of the remnant field for pole numbers besides four, but they have not been analyzed.

Magnet QQQ004 was degaussed four times. The value of ($\int$ G dL) after these four was 5.96 * 10**-3, 1.80 * 10**-2, 4.31 * 10**-3 and 6.37 * 10**-3. The first of these used the degaussing sequence (+405), -405, +300, -225, +169, -125, +94, -70, +50, -37, +20, -10, and +5 A (May 13 sequence). The second degauss used the sequence (+405), -148, +126, -94, +71, -53, +40, -30, +22, -17, +12, -9 A (July 15 sequence).

When magnet QQK013 was first mounted on the measurement stand, its remnant field quadrupole gradient strength was 1.32 * 10**-4 tesla. The corresponding value for magnitude of the magnetic field at the pole tip was measured as 1 gauss with a Hall probe. Magnet QQK013 was degaussed a total of five times; the corresponding gradient strengths for the remnant field were 9.58 * 10**-3, 1.76 * 10**-2, 1.48 * 10**-2, 1.48 * 10**-2, and 2.05 * 10**-2 tesla. The current sequence used was that of May 13 for the first three. For the fourth, the sequence was -148, +120, -80, +50, -30, +20, -10, +5 A (July 28 sequence). The fifth used the July 15 sequence.

The QQK012 remnant field quadrupole gradient strength before excitation was 5.11 * 10**-2 tesla (10 gauss at the pole tip with Hall probe). It was degaussed once to 1.02 * 10**-3, using the May 13 sequence.

For QQK012 and QQK013 I would expect to see similar remnant field values in Table 1. Given the size of the signal being measured, I think that the remnant field values for both are in reasonably good agreement. The values are certainly systematically different from those for QQQ004.

The degaussing process was necessary at certain times during the measurement of these magnets in order tc reduce the remnant field sufficiently low to ensure that the biasing ramps used in the following sequence of measurements set the remnant field to a fixed value. Three different sequences were used, which represent a small attempt to find a sequence which minimized the number of steps necessary.

Slope of $\int$ G dL vs I & Saturation Effects

As discussed in the main paper, slopes of $\int$ G dL vs I could be obtained from a linear regression fit such as that shown in Fig. 4a. An offset value was also obtained. Tables 2-4 are tables I made for my own use and are included here for completeness and so that I may refer to the values of slopes recorded there. I decided not to try to redo these tables to make them more intelligible.

For QQQ004 the slope value for the low current measurement ranged from 0.068769 to 0.06967431 tesla/A. By looking at the plot of residuals (e.g. Fig. 4b in main paper) and putting a lower limit of ≈30A on the current, the "linear", rising part of the curve could be selected and the slope values rose as shown in the table to 0.0712999 .

For the high current measurements the slope values ranged from 0.0683695 to 0.0727697 . The 0.0704329 value for the May 20 & 23 set could be boosted to 0.0731466 by removing the I> 260 A values (that show saturation effects) and currents at and below 40 A. The process of doing this is shown in Figs. 1 & 2. Fig. 1a shows the initial plot, which includes 0 and 400 A values. The linear regression slope and offset are shown. In Fig. 1b the linear regression line has been subtracted. One sees saturation effects starting at about 260 A and a non-linear behaviour at and below 40 A. There is a linear portion between. Fig. 2a shows the result of the cut 40 < I < 260 and then subtracting the resulting line. The residuals in Fig. 2b show a somewhat random pattern and therefore the linear regression line slope of 7.31466 * 10**-2 is not subject to further modification.

Tables 3 & 4 show the slope and intercept results for QQK012 and QQK013. Taken together there is a range of slope from 0.0711352 to 0.071913 tesla/amp for the low current measurements and a range of 0.0696735 to 0.0723568 for the high current points. As shown, the Aug. 30 low current measurement slope could be raised from 0.0717396 to 0.0724849 by imposing I > 29. For the Aug. 30 - Sep . 3 high current points, the slope value could be raised from 0.0712563 to 0.0733418 by imposing 10 < I < 200. Fig. 3a shows the ∫ G dL vs I data and Fig. 3b shows the result of subtracting the linear regression line. Fig. 4 shows the effect of imposing a cut of 10 < I(nominal) <= 200, redoing the linear regression line, and plotting the residuals. I don't recall why the slope is shown as 0.0731084 in Fig. 4 and as 0.0733418 in Table 3, but I don't regard the discrepancy as significant.

For QQQ004 the low current data slope variation was +/- 0.7%; for QQK012 the variation was +/- 0.5%. The slope difference between the two magnets is 3.2%, for the low currents. When the non-linear portions of the high current results are removed from each magnet's data, the high current slopes differ by only 0.3%. The difference in slope at the low currents, together with the difference between the values discussed above and that of 0.0744 in reference/remark #13 in the main report, led me to investigate possible systematic errors contained in the measurements and the analysis. As part of doing so, I reviewed the history of the calibration constants being used for the transducers in the database and when changes were recorded between power supplies. My understanding is that the high current transducers have been calibrated against a precision shunt and this is the source of the current vs voltage calibration constants that MDTF is using. Similarly, the ADC being used has been calibrated. The shunts being used at the low current region are associated with the Hewlett Packard supply that was in use for most measurements below 50 amperes (see Figs. 5,6 & 7). I did not succeed in getting any calibration or accuracy data for these two shunts, but when compared against one another I saw no systematic error that alarmed me.

As part of my search for systematic error, I had a special measurement done at the high currents in which the shunt voltage was connected to the DVM that the Vax computer read out (instead of having the transductor voltage displayed there). I found no significant source of systematic error in that data. I had the three different people who had inserted the probe over the course of the measurements reinsert the probe one after the other, with a set of runs between 0 and 375 A taken after each insertion. There was no significant disagreement in the results (resulting from differences in probe insertion). A special measurement request still pending at the time of writing this report was one where the other quadrupole winding on the probe would be used--as a check on consistency with the results all done with one quadrupole winding. I did not personally verify the dimensions being used for the effective area of the winding; instead I rely on the belief that the MDTF group has a good set of parameters in the database. In summary, I found no systematic errors in the measurement or analysis that resulted in the values of slopes & therefore left the values as they were.

Appendix I

Chronology of measurements and changes

1. QQQ004 on stand A, PEI power supply, transductor CS05, shunt MTFSNT02, station A electronics

   The PEI supply has the capability to go to 5000 A, at 30 volts. When tapped for 1250 amperes, the voltage capability is 120 volts.

   The transductor has an output of 10 volts for 4000 amperes. The shunt has an output of 100 mv for 2000 A. April 8-10, 1985 Individual unnormalized measurements done with the quadrupole, sextupole,octapole,decapole, & duodecapole windings on the probe--prior to any excitation.

   Excitation sequence of 400,0,150,30,50,0 amperes. At each current the different probe windings were used, with the higher pole results normalized to the quadrupole reference amplitude.

2. May 3, 1985 Two measurements at zero excitation

3. May 8 & 10, 1985
   Cross calibrations of shunt and transductor

4. May 15-20
   Exploration of hysterisis loops with excitation to 100, 200, 300, 400 amps (step sizes 20 & 25 A). Each loop preceded by 400 A.

5. May 23 - 24
   Remnant field biasing ramps of 405 A, followed by studies between 0 and 35 A, with occasional excursions to 100 A.

   400 A biasing ramp, followed by study between 0 to 50 A, study between 0 and 100, & study between 0 and 200.

6. May 30
   Study of degaussing QQQ004, using polarity reversal and steps of 25% reduction in excitation for each reversal

7. May 30 - June 3, 1985
   No biasing ramp, study between 0 and 100 A, study between 0 and 295 A

   Biasing ramp to 295 A, studies between 0 and 100 and 0 and 200 A.

8. June 3 - July 1
   Interruption to study Main Ring quadrupole for Chuck Schmidt (Ref. 1)

9. July 1
Installation of capability of using Hewlett Packard 50 A supply and its associated shunts for imprcved accuracy in 0-50A region. The internal shunt on the HP supply gave 100 mv for 50 A. An external shunt was used also, which gave 50 mv for 50 A. The voltage from the external shunt was amplified by a factor of 100 and fed to the Kinetic Systems 12 bit ADC as the current measurement to be recorded for each of the ~1036 angular positions of the probe during its rotation.

10. July 9
QQQ004 on stand B, HP power supply, Station A electronics, biasing ramps supplied by PEI power supply via transfer switch

11. July 10 - 11
Studies in 0-48 A range with biasing ramps of 405 A

12. July 12
QQQ004, 405 A biasing ramps, excitation study to 400 with spaced intermediate steps

13. July 15
Degauss of QQQ004 using polarity reversals and 20% reduction in amplitude each step. Short sequence starting with -148 A.

14. July 16
Upgrade of "HARMONICS" measurement program to dispense with hysterisis ramp prior to each measurement. This allowed studies of excursions of current in small steps around likely operating points with the magnet current set by a digital to analogue converter controlled by the computer--instead of using a manual potentiometer setting and a DVM readout of the transductor voltage. The upgrade also provided for recording the value of the "CURRENT" digital voltmeter before and after the rotation of the harmonics probe.

Switch to remnant field biasing using three ramps instead of one. This was found necessary to "set" the remnant field to a new value (e.g. after degaussing).

Studies in 0-48 A range, with biasing ramps of 295 A.

15. July 17
biasing ramps of 148 A, studies between 0 and 48 A (4 A steps, using HP supply)

16. July 18
Discovery that probe was inserted 42" instead of 60" (since July 9).

Excitation sequence 295,0,295,0,295,0,400,0,400,0,400,0,405,0,405 before adjusting probe position; sequence 0,405,0,405 after correcting probe position.

17. July 19
QQK013 mounted on stand B

full set of harmonics measured before exciting magnet

pole tip field was 1 gauss (Hall probe)

18. July 22
QQK013 degaussed using same currents as on May 30 (for QQQ004)

remnant field at 0 excitation was measured

Excitation sequence: 0,405,0,405,0,405,0,10,24,200,390,400,390, 200,24,10,0,500,0,500,0,500,0

19. July 23
QQK013 again deguassed

295 A bias ramps, followed by 0-48 A study

20. July 24 & 25
QQK013 again degaussed using May 30 sequence

148 bias ramps, followed by 0-48 study

270 A bias ramps, followed by 0-48 A study

21. July 25
Switch to EMI supply, transductor CS15, shunt MTFSNT01 for excitations above 50 A. The PEI supply was needed for measurements of Main Ring overpass magnets. It was because of this impending switch that QQK013 was first measured with a bias current of 405 A on July 22 (instead of starting with a 148 A bias after the initial degaussing).

The EMI supply was capable of supplying 375 A DC current. It could supply more current for short periods, but after a while the AC fuses supplying it with AC power would blow. With sufficient AC power connected, it is capable of 600 A. Its rated DC voltage is 80 volts.

22. July 28
QQK013 degaussed using ~40% reduction in current each reversal

23. July 30
QQQ004 remounted on Stand B

magnet degaussed using May 30 sequence

bias ramps to 148, followed by 0-48 A study

24. July 31

295 A bias, 0-48A study

25. August 1
measurement of remnant field after ramps to 405 A

QQK012 mounted on Stand B

remnant field 10 guass (Hall probe) at pole tip, prior to any excitation

degauss QQK012 using May 30 sequence

26. August 2 & 19
148 A bias, 0-48 A study

27. August 20 -26
Special studies due to inconsistencies in data

28. August 26
Realization that EMI biasing supply and HP 50 A supply had been delivering opposite polarities to magnet.

Repeated QQK012 with 148 A bias

29. August 29
QQK012, 148 bias, check for measurement stability with 9 repeated measurements at 24 A, then at 48 A, & then back at 24 A

30. August 29 & 30
0-48 measurements with bias of 270, 295 and 405 A

31. September 3
405 A bias & then study of 0-4C0 in 25 A steps

study from 300 to 400 in 10 A steps

32. September 4
QQQ004 mounted on stand B, degaussed using May 30 sequence

33. September 5 & 6
0-48 study with bias of 270 and 295 A

34. September 9
295 A bias, stability study, 9 measurements each at 24,48, 24

repeat of stability study with zero current intersperset between each

35. September 10
Morgan coil probe removed from QQQ004 to check wiring against another probe. A wiring error was found, but not corrected (the Q1

and Q2 windings were interchanged). This error did not affect our amplitude measurements, but it would affect the measurements done of the harmonic content of the remnant fields and the field at at 24 A (most of these have not been listed in this chronology, since they have remained unanalyzed).

Probe returned to QQQ004

36. September 11
295 A bias, further stability studies with current sequence 0,48, 0,48,etc.

37. September 12
QQQ004, check on probe insertion technique by three different people, meaurement of 0-375 A in 50 A steps (last step 25 A).

38. September 13
QQQ004 degaussed using May 30 sequence

39. September 17
QQK013 remounted on stand B

3 bias ramps to 375 & then 0-375 A sequence taken

40. October 4
Changed input to "CURRENT" DVM to be the voltage from shunt MTFSNT01--instead of transductor voltage. Ran 0-375 A sequence as a check of focusing strength vs current as reported by the shunt (instead of current as read by the transductor).

References and Remarks

1. "Hysterisis Measurements of a Main-Ring Type Quadrupole", Accelerator Exp. # 127, Charles Schmidt, July 25, 1985

REMNANT FIELD

$\int G\, dl$ (TESLA)

Bias Current (A)	QQQ004	QQK012	QQK013
148	.158, .150 (.74)	.0636 (.73)	.0685, .0683 (.86)
270	.183 (.87)	.0803 (.92)	.0769 (.97)
295	.199, .195, .204 (.95)	.0811 (.93)	.0769 (.97)
405	.218, .204, .206	.0874	.0795

Numbers in parentheses are the values represented as fractions of the value at 405 A

QQQ.004 (Type III 3Q120, serial #004)

Date	slope	offset	Stand	TDR	ADC	Probe length (in)	peak I	bias	1.42361 * Slope (where applicable)
May 17+20	.0726522	.0195073	A	CS05	22[illegible]	60	300		
May 20+23	.0727697	−.0114942	A	↓	↓	"	300		
" "	.0704329	.23185	A	↓	↓	"	400		I=0 + 2-400 A points included
July 18	.0683695	.186475	B	↓	22330	"	405		
"	.0485176	.176290	B	↓	↓	42	405		.0690714
July 10	.0483059	.129182	B	SNT06	22330	42	48	405	.068769‡
July 8	.0483658	.127902	B	SNT06	22330	42	48	295	.0688540‡
July 17	.048565	.10066	B	↓	↓	42	48	148	.0691376‡
Sept 5+6	.0696743‡	.160922	B			60	↓	270	
Sept 5	.0696831‡	.163655	B			60		270	
Sept 6	.0695685‡	.171296	B	↓	↓	60	↓	295	
Sept 5	.0712835	.0995414	"	↓	↓	↓	↓	270	I_nom > 30
Sept 6	.0712999	.105338	"	↓	↓	↓	↓	295	cur > 29
May 20+23	.0731466	−.0688415	A	CS05		60	260†		40<cur<260
Sept 12	.0731884	.04794	B	CS15	22330	60G	250		50<I_nom<250
"	.073181	.055356	B	↓	↓	60B	"		"
"	.072946	.055713	B	↓	↓	60D	"		"

† lower points excluded also cur > 40

July 8 ‡ Av of 6 slopes marked = .069281

60/42 = 1.4286

1.4286 * .0483059 = .06901

Table 2

page 2

QQK012 (Type II 3Q120, Serial #12)

Date	slope	offset	Stand	TDR	ADC	Peak I	bias	
Aug 26	.071913†	.0445546	B	SNT06	22330	48	148	
Aug 27	.0718826†	.0562716	B	↓	↓	48	148	
	.0718037†	.0585533	B			48	148	
Aug 29	.0717818†	.06199	B			48	270	
Aug 30	.0717396†	.06513	B			48	295	
"	.0724849	.0374236	↓	↓	↓	"	"	cur>29
Aug30-Sep3	.0712563	.26118	B	CS15	22330	400		
"	.0733418	.0255968	B	"	"	200‡		10<cur<200
Aug 30	.0724376	.039487	B	SNT06	2230	48	295	cur>25

‡ current >10 also

† Av of 1st 5 slopes .071824 σ = .000072

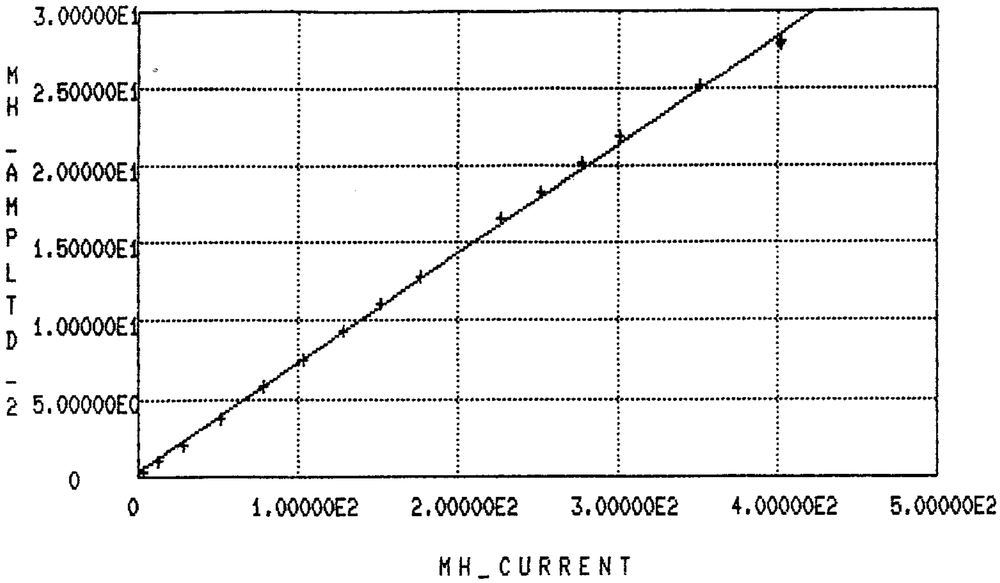
Table 3
page 2

QQK013 (type II 3Q120, serial #13)

Date	slope	offset	stand	TDR	ADC	peak I	bias
July 23	.0711352	.0713149	B	CS05	22330	48	295
July 25	.0712036	.07164	B	CS05	22330	48	270
July 24	.0712613	.061619	B	CS05	22330	48	148
July 22	.0696735	.128017	B	CS05†	22330	400	
"	.0723568	.0043	B	"	"	202	I_{min} = 24.7 only 2 pts

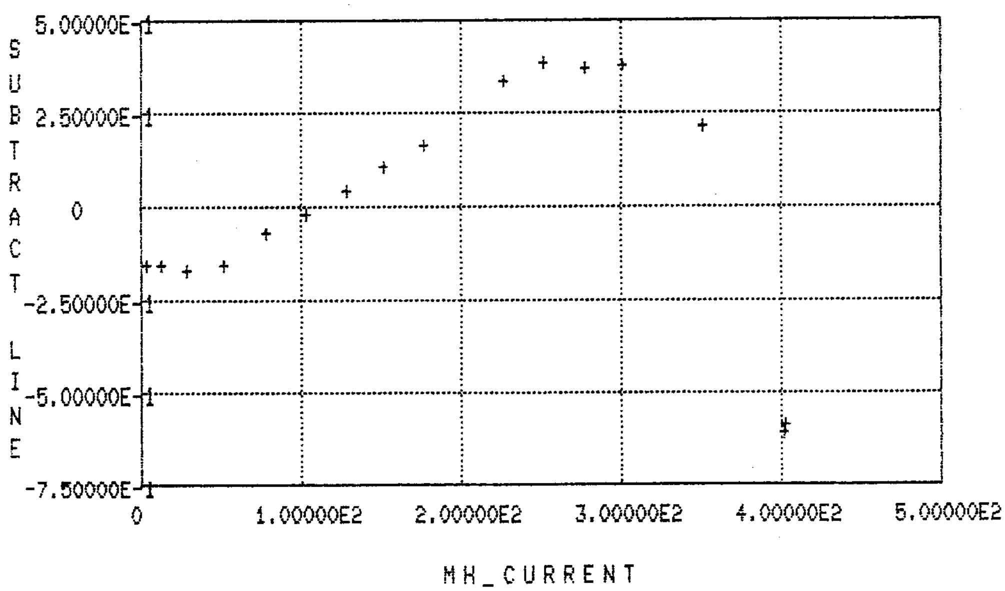
† I think that this is really CS15

Table 4
paper 2



7.04329E-2   2.31851E-1

171 - 187 Local run #'s

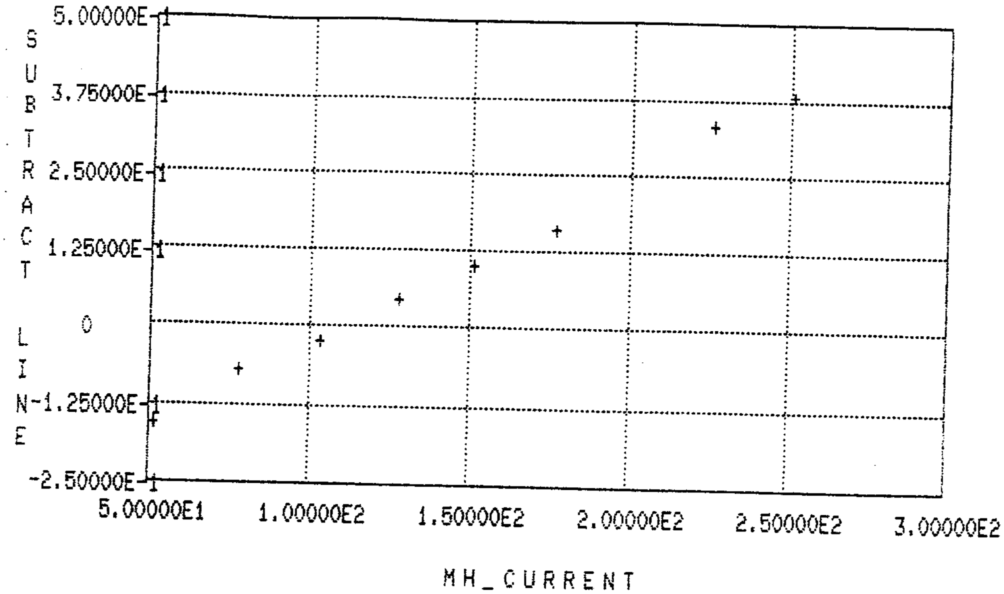


Slope 7.04328E-2
Offset 2.31874E-2

QQQ004

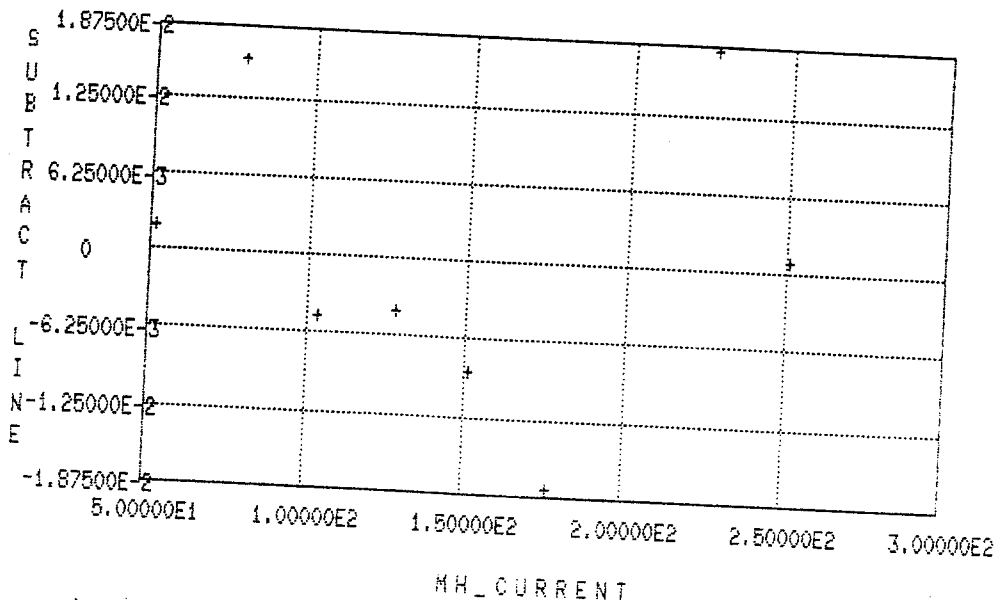
2nd page

Fig 1



40 < cur < 260

slope, off as above

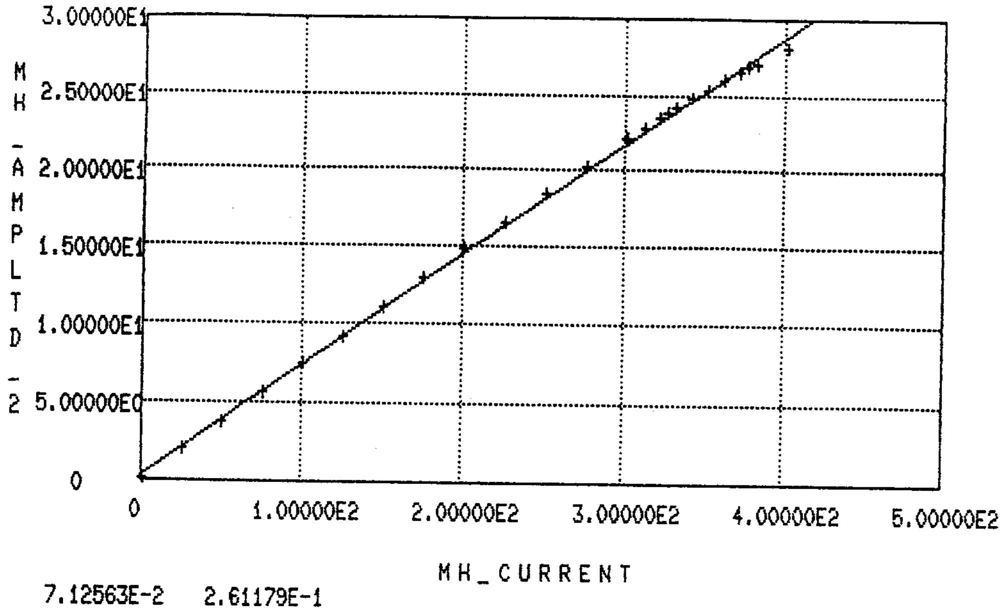


slope = 7.31466E-2
off = -6.88415 E-2

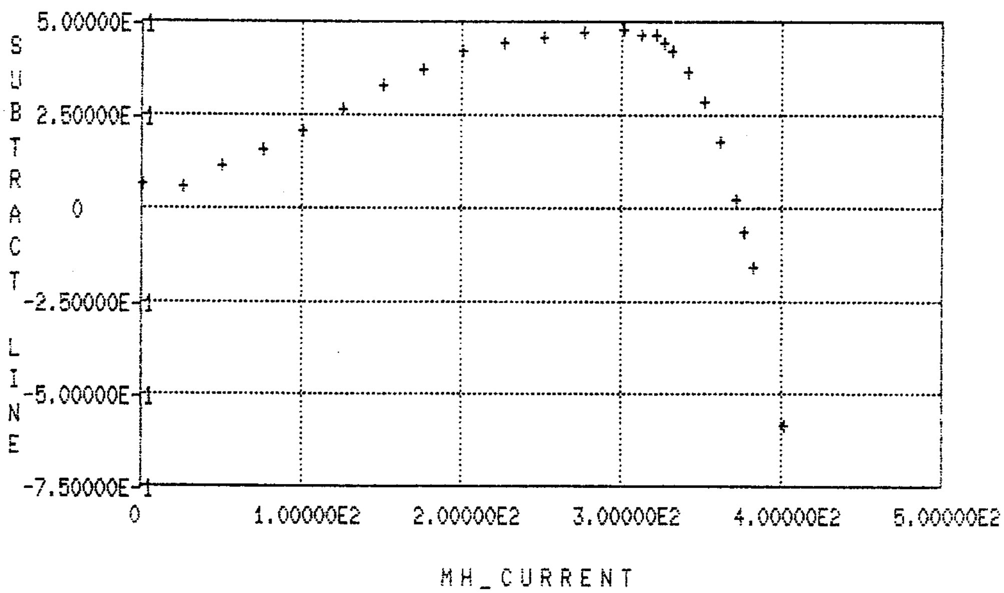
2nd page

Fig 2

000004



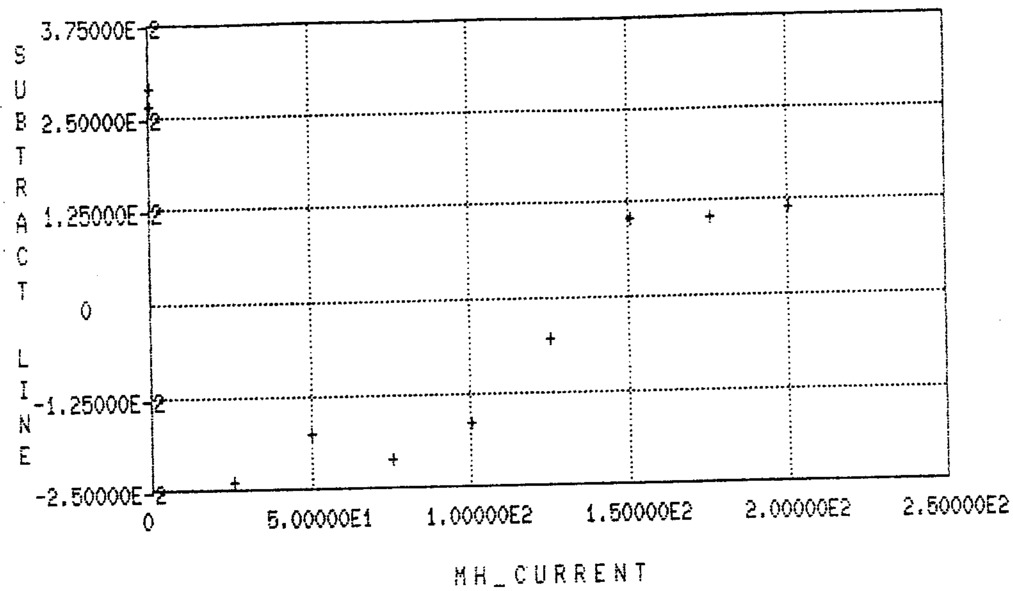
Aug 30
+ Sep 3
0 - 400
300 - 400
data
combined



Slope = 7.12563E - 2
offset = 2.61179E - 2

518 → 545
QQK012 0-400, 300-400 runs
see saturation effects

2nd paper
Fig 3



slope = $7.31084 \cdot 10^{-2}$ I_nom LE 200 of last set

of = $5.87023 \cdot 10^{-2}$ QQK012

2nd page
Fig 4

SUBJECT

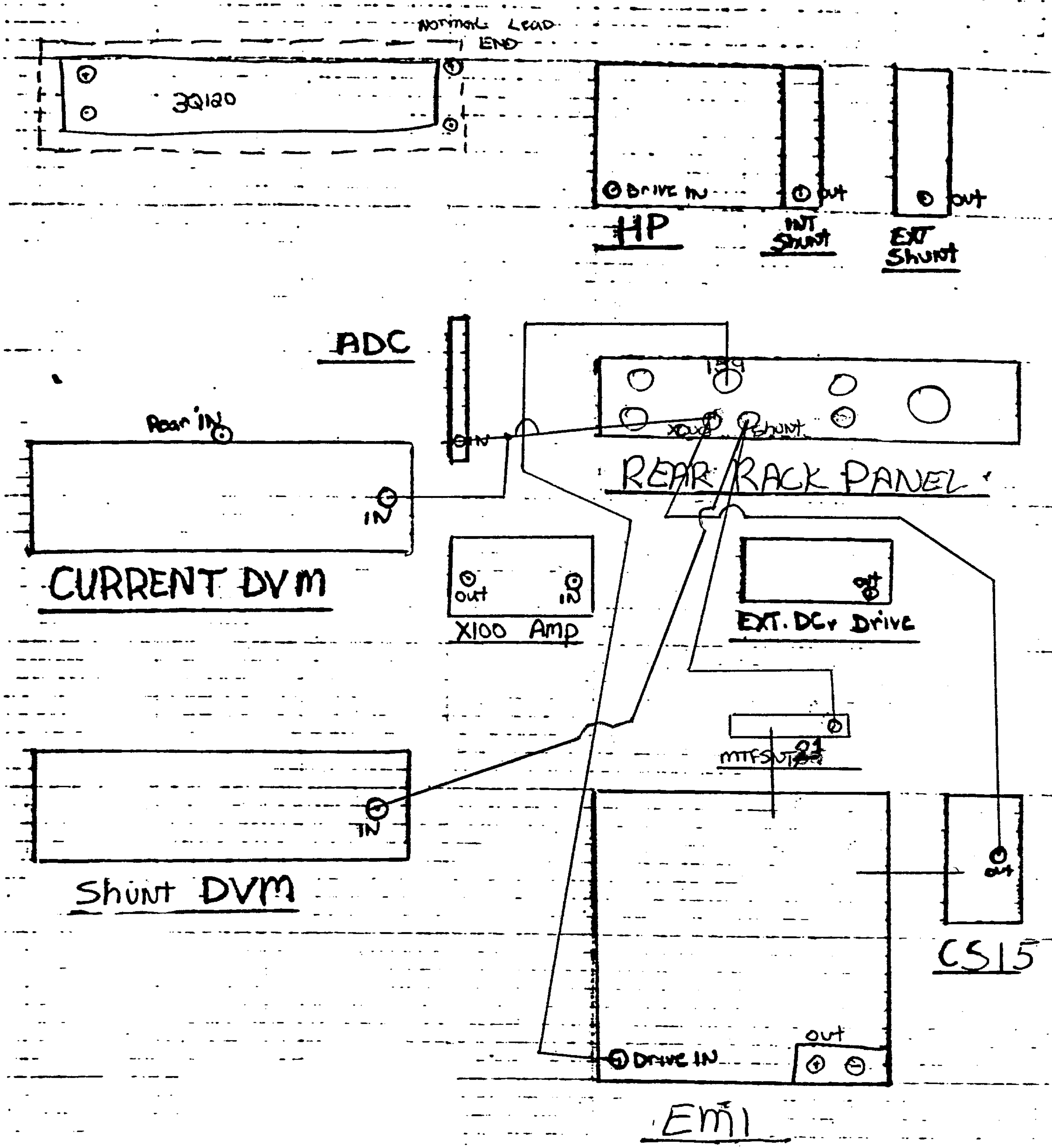
EMI Powering 3Q120
RACK "A3" STAND "B"

NAME

Greg Cisko

DATE

REVISION DATE



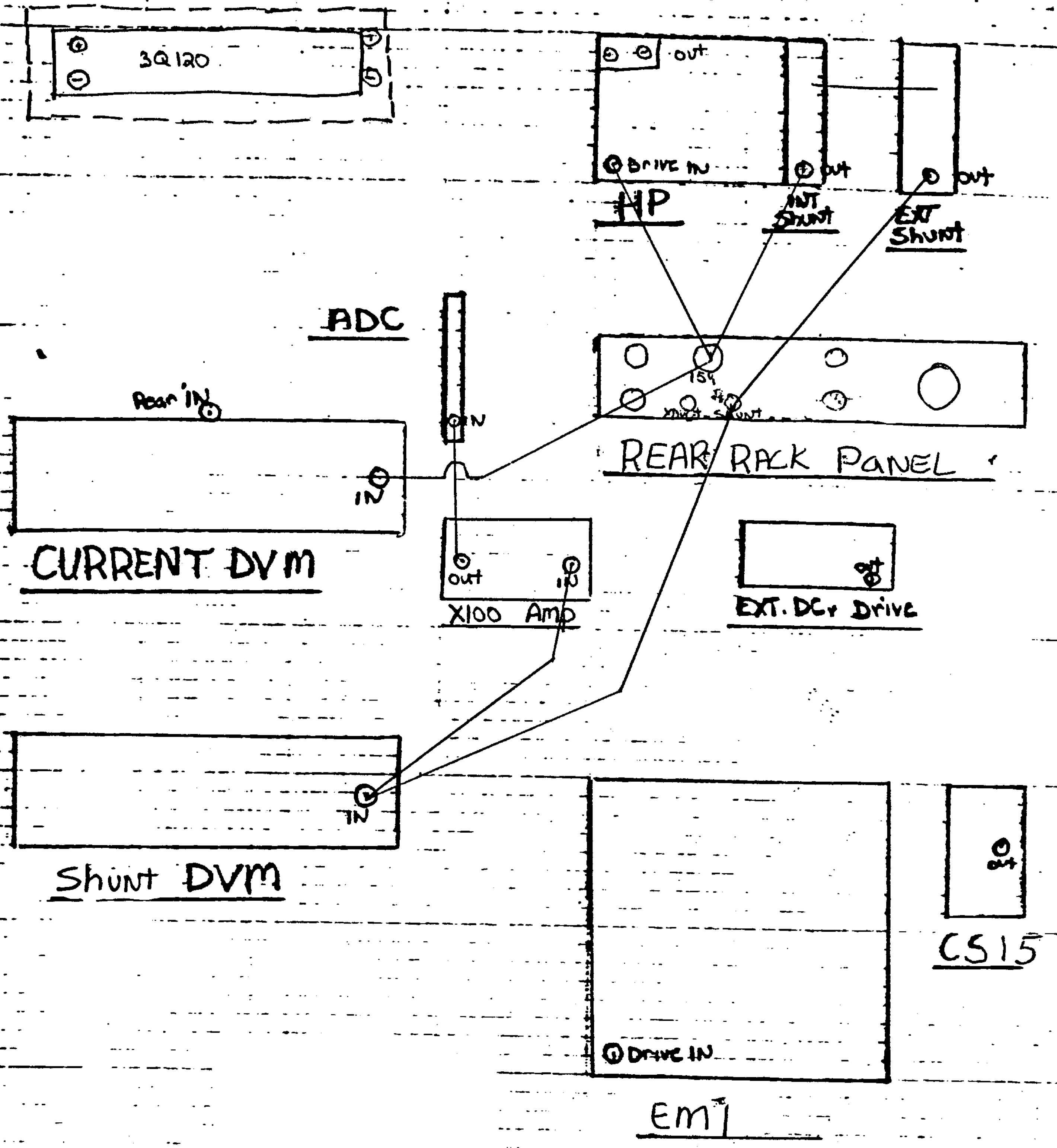
second page
Fig 5

SUBJECT: H.P. Powering 3Q120 RACK "A3" STAND "B"

NAME: Greg Cisko

DATE

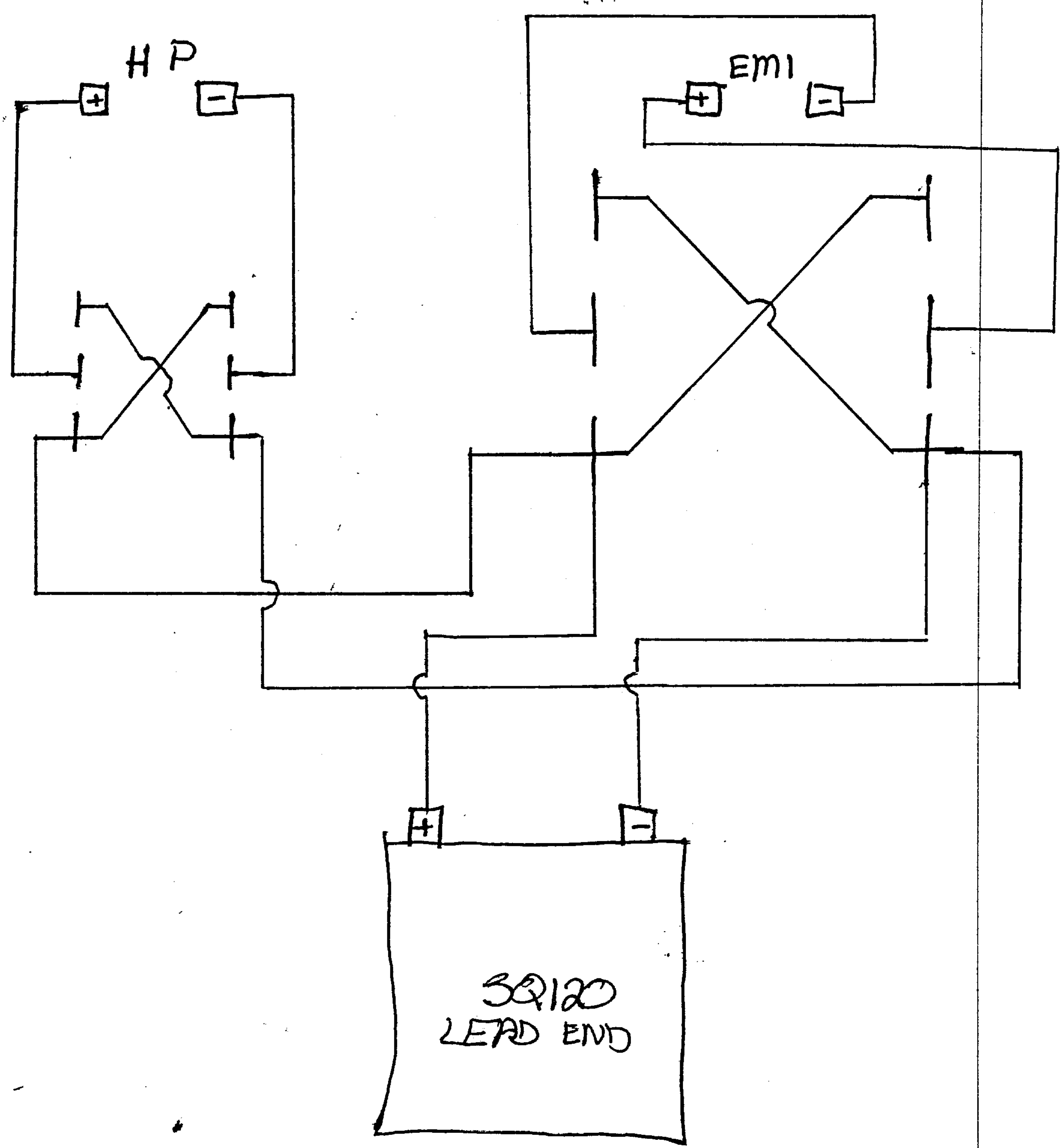
REVISION DATE



2nd page Fig 6

21 Sept 85

POWER CONNECTIONS OF 3Q120 ON STAND "B"



2nd figure

Fig 7