Fermilab

PBAR #430

3Q120 LOW GRADIENT BEHAVIOUR

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 (and subsequently the superconducting ring--see Ref. 1).

Many of the measurements have been preceded by remnant field biasing ramps to 148, 270, 295, or 405 amps to set the remnant field to a standard value. The measurement sequence is then 0,4,8, . . . 48 amperes (in 4 A steps). The amplitude vs current graph for 0-48 A is visually a straight line and can be fitted via linear regression to a straight line--obtaining a slope and intercept. The residual differences from a straight line can again be plotted vs current and can be reasonably well fit to a second degree polynomial.

The smallest set of information that is necessary to tabulate for the operation of AP 1 quadrupoles is the set of currents that correspond to the desired focusing strengths as stipulated by the beam design. Given the parametrization described above, it is straightforward to extract a current corresponding to a given gradient strength for either of the two types of 3Q120.

A companion report has been prepared simultaneously with this one (Ref . 2). To it have been relegated discussions (of the measurements) that seemed secondary.

Magnet Description

The three magnets measured represent the two latest designs of 3Q120 quadrupoles. Both designs have water-cooled copper coils that can be driven to 400 A and above; they differ in the amount of steel in a cross section of the magnet. The later design (referred to as Type III) has additional steel added to reduce saturation effects and has a better water cooling circuit. The earlier design (Type II) has the same steel shape as the earlier, fin-cooled 3Q120 design (Type I) that was used in the switchyard beam transport and elsewhere back in the early 1970's.

	magnet	cable type	max cable I (A)	Est. resist. (Ω)	I 120 GeV (A)	V max P.S. (V)	I max P.S. (A)	R magnets (mΩ)	grad. (kG/m)
type II	PQ 1	#1	140	.155	135	70	200	160	4.84
	PQ 2	#1	140	.090	99	70	200	160	3.57
type III	PQ 3	350 mcm	325	.020	248	100	500	160	8.89
	PQ 4	500 mcm	405	.0108	340	100	500	160	11.73
	PQ5A+B	500 mcm	405	.0097	400	200	500	320	13.46
	PQ 6 A+B	350 mcm	325	.0123	278	100	500	320	7.096
type II	P 7 A+B	250 mcm	270	.0129	217	100	500	320	10.630
	PQ8 A+B	350 mcm	325	.0138	255	100	500	320	—
	PQ9 A+B	350 mcm	325	.0169	278	100	500	320	—

AP1 LINE QUAD INFO

Table 1

The probe used to make the measurement is of the Morgan coil type. The quadrupole reference winding was used; it had a coil radius of 1.089 inches (Ref. 8). The probe was centered in the magnet's vacuum tube in each case.

The quadrupole winding was 84" long and therefore was not sufficiently long to extend throughout the quadrupole; for this reason it has been inserted so that the end of the winding was at the center of the magnet. The measurement was made by rotating the probe and digitizing the integrated voltage with a Kinetic Systems 12 bit ADC at each of ~1036 positions on a rotary encoder attached to the probe. The voltage from a current-reading device was fed to the other channel of the ADC and was digitized at the same time. The "raw" results went to one file on the Vax 730 disk and the "reduced" results went to another. The data reduction consists of removing the effects of drift in the integrator, making a Fourier transform of the voltage vs angle readings to extract the quadrupole amplitude, averaging all the current readings, and converting to "engineering" units. In doing this, a large data base of auxiliary information is accessed via DATATRIEVE (Ref. 9). The probe radius is divided out (with the proper power) and the amplitude is quoted directly as

$$\int_{-a}^{60''} G \; dL$$

in Tesla, where "a" corresponds to a 8' long winding inserted half way into a 120" long quadrupole.

Description of Analysis

The chronology in Appendix I in the companion paper (Ref. 2) attempts to give an overview of the measurements made and lists significant occurrences and changes. In the series of measurements shown there, 928 probe rotations were made for QQQ004 and 585 probe rotations were made for QQK012 and QQK013 lumped together. The method of analysis is described in the following. Each probe rotation resulted in a "reduced" data file on the Vax 730 disk (also called a "run"). As needed, all the "reduced" data files of a particular ilk were combined into a single data file that could be accessed as a data base by DATATRIEVE. DATATRIEVE could then be used to form a subgroup (a "collection") by selecting on date and time of measurement, nominal current, and/or other properties. An example of a subgroup is a single 0-48 A sequence, in 4 A steps, with a particular bias current for a selected magnet. If desired, DATATRIEVE could write selected information from the subgroup to a file on the disk for later perusal. DATATRIEVE plotting features could be used to examine aspects of the collection (Ref. 10).

An example of this process using DATATRIEVE is given in Figs 3 to 5 (Ref. 11). Fig. 3a shows the excitation of QQK013 vs local run number for July 25 (Ref. 12). There are several measurements at 24 A, interspersed with 0 A, and with excursions to 26 A and 22 A. Then there is a 0-24 A sequence of 4A steps, followed by a set of full harmonics (windings other than the quadrupole winding on the probe) at 24 A, and finally a sequence from 28 to 48 A in 4 A steps. At the end there is a repeat of the 24 A measurement. Fig. 3b shows the quadrupole amplitude for each of these.

Local run numbers 138-144, 154-159 were selected to get the 0-48A sequence isolated and Fig. 4a shows the plot of quadrupole amplitude vs current for that sequence. A linear regression fit is also shown, together with the values of slope and intercept. Fig. 4b shows the result of subtracting the linear regression line from the points in Fig. 4a. The values plotted in Fig. 4b could be printed, as shown in Table 3 (Ref. 13). They were also stored in a log file that kept track of the DATATRIEVE session and were later extracted from that file, together with other information, to make plots that DATATRIEVE couldn't make--as well as for other purposes. Fig. 6 shows an example of such later use; it shows the result of a three-parameter polynomial fit to the values of Table 3. The parameter values from the polynomial fit were saved in a separate data base that DATATRIEVE could access, together with the slope and offset of the linear regression line fit to the amplitude vs current values (e.g. Fig. 4a) and identifying information.

Although not seen in Fig. 4b, some other 0-48 A sequences that were interrupted for a full harmonics set (as in Fig. 3a) showed a break at 24 A (or 12 A) when a plot similar to that of Fig. 4b was made. Repeated runs were made at one current (e.g. 9 in a row) to try to understand these breaks. Although the results of these "stability" runs were interesting in their own right, the break was never understood and was removed by smoothing it away (again by the use of DATATRIEVE). A few other unexplained local "glitches" in a set of points such as those see in Fig. 4b were similarly smoothed out.

Results of Analysis

Because of the differences in the steel laminations between the Type II ("QQK") and Type III ("QQQ") 3Q120 magnets, I decided not to combine them in any way. For the two examples of Type II magnets (QQK012 & QQK013), I did not keep them separate in the final averaging of multiple sequences. Where multiple sequences existed for the same bias current for each of the two 3Q120 types, I chose to combine the polynomial fit parameters and slopes and intercepts of the linear regression fit by simply averaging them. Figures 7 through 13 show the results of this averaging process and the individual sequences (actual values--not the results of polynomial fitting) at different dates and times that were used. The points with the dashed line in each figure are the results of the averaging. These figures serve to show the sequence to sequence stability of the data and the quality of the averaging.

Table 4 gives the individual parameters, slopes, and intercepts--as well as the averaged ones. Those marked with penetration being 42" were not included in the averaging, since their values were increased by the factor 1.42361 (Ref. 14) and were re-entered in the data base with a penetration value of 60".

The averaged parameters, slopes and intercepts were used to calculate operating currents for the AP 1 quadrupoles, using Newton's method to solve for the current--given the desired strength. The result of this calculation is given in Table 5. Also shown in Table 5 are four values of percentage deviation, marked % Dev 1,2,3, & 4--together with the values of current from p-bar note # 384. The percentage deviation values show the difference between various possibilities for the current and the calculated result. The first possibility is

$$I_1 = \frac{\int_{-a}^{60} G \; dL \; - \text{OFFSET} - A}{\text{SLOPE} \; + B}$$

This was the actual starting value used in the Newton's method solution. The second possibility is

$$I_2 = \frac{\int_{-a}^{60} G \; dL \; - \text{OFFSET}}{\text{SLOPE}}$$

The third is

$$I_3 = \frac{\int_{-a}^{60} G \; dL}{(1.24*10**-2) * 60. * 0.1}$$

(Ref. 15). The fourth percentage deviation compares the p-bar note # 384 values and the Newton's method result.

Acknowledgements

It is a pleasure to acknowledge the help of all the people at MTF for their help in making these measurements. In addition to those whose names appear elsewhere in this report, I feel I must mention Bill Lord--who made the bulk of the actual measurements.

References and Remarks

1. See "Design Report, Tevatron 1 Project", September, 1984, Fermilab. See also various papers at Accelerator conferences up to and including the conference in Vancouver, March, 1985.

2. Pbar Note, "3Q120 Low Gradient Behaviour--Companion Paper", A. Wehmann, October, 1985

3. There has been some discussion of raising the energy of the AP 1 line above 120 Gev.

   The design of the AP 1 line is discussed in p-bar note # 384, "Recent Changes to the Design of the AP 1 Beam Line", G. Dugan & D. Johnson, 4/27/84.

4. G. Dugan, private communication

5. For example, after excitation of QQQ004 to 405 A, the remnant field at the pole tip (3" diameter) was measured with a Hall probe to be 45 gauss.

6. Since the bias current is on for only a short time, it is safe to exceed the cable ratings in Table I by 10% for a few minutes. R. Oberholtzer, private communication.

7. B. C. Brown, D. J. Harding, M. F. Gormley, M. E. Johnson, A. J. Lennox, K. J. McGuire, J. E. Pachnik, J. K Plymale, R. A. Shenk, A. A. Wehmann, "Data Acquisition System Design for Production Measurement of Magnets for the Fermilab Anti-Proton Source", IEEE Transactions on Nuclear Science NS-32, 2050 (1985)

8. The harmonic probe that was used has MTF identification code MH850326. It has one dipole winding, two quadrupole windings, and the following higher order windings: sextupole, octapole, decapole, duodecapole, and twenty pole.

   After completing the 3Q120 series of measurements in October, a wiring error on this particular probe was corrected. Our series of measurements used quadrupole reference winding 2; in the future this will be known as reference winding 1. Some measurements were done with other windings besides the those with quadrupole symmetry, in order to have on file the harmonic content of the remnant field and to have the harmonic content of the field at representative currents of 12 and 24 amperes. The measurements with other windings have not been analyzed. They are not always listed in the chronology of measurements in Appendix I in the companion paper (Ref. 2).

9. DATATRIEVE is a Digital Equipment Corporation software product that has an extensive series of query language commands for

manipulating data in a data base and making inquiries about values of variables in the data base. It has been adopted for use extensively at MDTF and its use is woven throughout the MTF data acquisition and data analysis programs. One of its virtues is that it can share a data base with FORTRAN. No "interface" is necessary for FORTRAN to read or write to the data base (if it is in the form of a RMS file).

10. DATATRIEVE comes with a plotting package that has some limitations. Paul Banks spent a summer at MTF and, among other things, modified some of the plotting package to remove some of the limitations. When the operating system on the lab's Vax computers was upgraded from VMS 3 to VMS 4, Rick Shenk and I had to delve into the subtleties of the plotting package and what Paul had done in order to keep the features he had introduced--at least for the plots I wanted to use. It was worthwhile to spend the necessary time, because being able to plot from within DATATRIEVE was a great virtue over having to exit from DATATRIEVE each time a plot was desired.

    Because DATATRIEVE uses DEC's plotting package called REGIS, the plotting terminal must support that convention. The set of terminals one can use is much more limited than if using the Tektronix 4010 convention (which has a much wider use).

    Many of the early results of 3Q120 measurements were plotted by Julian Plymale of MTF by using a Tektronix 4105 terminal and the "QUICK DRAW MCGRAW" package originally obtained from the Computing Department. Hard copies could be made on a Printronix line printer.

11. Figures 1 and 2 do not exist. To save work, the figures were not relabelled.

12. The local run number was something that DATATRIEVE was instructed to create in order to label runs conveniently, after sorting by date and time of the measurement, and to provide for a run number for selecting runs and plotting results vs run.

13. Table 3 is to be found on the same page as Figure 5.

14. As indicated in the Chronology in Appendix I in the companion paper (Ref. 2), the probe was inserted incorrectly in QQQ004 when that magnet was transferred from Stand A to Stand B. It therefore had a penetration of 42", instead of the desired 60" (half the magnet). The factor of 1.42361 was obtained by analyzing the results of measurements taken with the probe in both positions in the same magnet.

15. The value of 1.24*10**-2 kg/(inch*ampere) is one that was obtained from Hall probe measurements of the AP1 magnets in

Spring, 1984 (G. Dugan, private communication). The effective length used to convert this to integral strength in p-bar note # 384 is 120 inches. If we multiply 1.24*10**-2 by 6 (using a half-magnet effective length of 60" and 0.1 to go from kg to tesla), this value converts to 7.44*10**-2 when compared to the slope values in Table 4. A number of checks were made to look for possible sources of error in the slopes obtained different ways from the integral measurements made between May and October, 1985 and are discussed in a companion report (Ref. 2). No reason was found to correct the slope values given in Table 4.

The values of current from Table 5 were used during the transport of antiprotons from the accumulator to Main Ring and Tevatron in October, 1985. The images seen on beam line instrumentation were of reasonable size (private communication, G. Dugan).

	magnet	cable type	max cable I (A)	Est. resist. (Ω)	I 120 Gev (A)	V max P.S. (V)	I max P.S. (A)	R magnets (mΩ)	grad. (kg/m)
type II	PQ 1	#1	140	.155	135	70	200	160	4.84
	PQ 2	#1	140	.090	99	70	200	160	3.57
type III	PQ 3	350 mcm	325	.020	248	100	500	160	8.89
	PQ 4	500 mcm	405	.0108	340	100	500	160	11.73
	PQ5A+B	500 mcm	405	.0097	400	200	500	320	13.46
	PQ 6 A+B	350 mcm	325	.0123	278	100	500	320	7.096
type II	f 7 A+B	250 mcm	270	.0129	217	100	500	320	10.630
	PQ8 A+B	350 mcm	325	.0138	255	100	500	320	—
	PQ9 A+B	350 mcm	325	.0169	278	100	500	320	—

AP1 LINE QUAD INFO

Table 1

magnet string	$I_{120\,GeV}$ (A)	I_{bias} (A)	$I_{bias} \div I_{120}$
PQ 1	135	148	1.10
PQ 2	99	148	1.49
PQ 3	248	295	1.19
PQ 4	340	405	1.19
PQ5 A+B	400	405	1.01
PQ6 A+B	278	295	1.06
PQ7 A+B	217	270	1.24
PQ8 A+B	255	295	1.16
PQ9 A+B	278	295	1.06

AP1 LINE QUAD INFO

Table 2

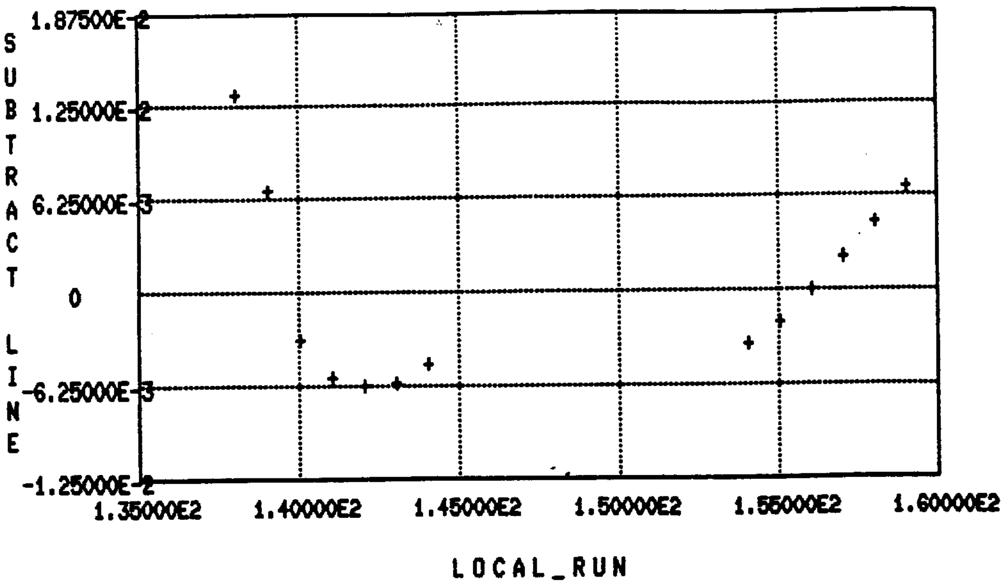


Fig 5

QQK013, 270 A bias, July 25

DTR> :PRINT_LINE

LOCAL RUN	MH CURRENT	AMP - LINE
138	-1.1423E-01	1.3130E-02
139	4.0350E+00	6.6007E-03
140	8.0451E+00	-3.3468E-03
141	1.2127E+01	-5.7985E-03
142	1.6147E+01	-6.4081E-03
143	2.0278E+01	-6.1389E-03
144	2.4401E+01	-4.9138E-03
154	2.8526E+01	-3.6766E-03
155	3.2645E+01	-2.2796E-03
156	3.6748E+01	-1.6897E-04
157	4.0896E+01	2.0480E-03
158	4.5056E+01	4.2517E-03
159	4.9185E+01	6.7034E-03

Table 3

DTR> !This is for QQK013, bias current of 270 amperes
DTR>

MAGNET ID	BIAS CURRENT	DATE	SET	PENETR	PAR A	PAR B	PAR C	SLOPE	OFFSET
QQK	148	915	1	60	1.0323E-02	-1.3489E-03	2.7969E-05	7.1715E-02	5.5250E-02
QQK012	148	826	1	60	9.1753E-03	-1.3580E-03	2.8236E-05	7.1913E-02	4.4557E-02
[illegible]013	148	724	1	60	9.1708E-03	-1.0930E-03	2.4158E-05	7.1261E-02	6.1619E-02
QQQ	148	915	1	60	2.3654E-02	-2.9765E-03	6.3249E-05	6.9138E-02	1.4330E-01
QQK012	148	827	2	60	1.0022E-02	-1.3418E-03	2.7350E-05	7.1883E-02	5.6272E-02
QQQ004	148	717	1	42	1.6616E-02	-2.0908E-03	4.4429E-05	4.8565E-02	1.0066E-01
QQK012	148	927	1	60	1.2120E-02	-1.6235E-03	3.3094E-05	7.1804E-02	5.8553E-02
QQQ004	148	717	1	60	2.3654E-02	-2.9765E-03	6.3249E-05	6.9138E-02	1.4330E-01
QQK	270	915	1	60	1.0722E-02	-1.4352E-03	2.9240E-05	7.1493E-02	6.6817E-02
QQQ	270	915	1	60	2.0376E-02	-2.9138E-03	5.9283E-05	6.9679E-02	1.6229E-01
QQK012	270	829	1	60	1.2076E-02	-1.6143E-03	3.2883E-05	7.1782E-02	6.1995E-02
QQK013	270	724	1	60	9.3683E-03	-1.2562E-03	2.5598E-05	7.1204E-02	7.1640E-02
QQQ004	270	906	2	60	2.1803E-02	-2.9161E-03	5.9412E-05	6.9683E-02	1.6366E-01
QQQ004	270	905	1	60	1.8950E-02	-2.9115E-03	5.9154E-05	6.9674E-02	1.6092E-01
QQK012	295	830	1	60	1.2607E-02	-1.6885E-03	3.4460E-05	7.1769E-02	6.3863E-02
QQK013	295	723	1	60	8.3454E-03	-1.1137E-03	2.5662E-05	7.1135E-02	7.1315E-02
QQQ004	295	709	1	42	1.6074E-02	-2.1408E-03	4.3551E-05	4.8366E-02	1.2790E-01
QQQ004	295	708	1	60	2.2883E-02	-3.0476E-03	6.2000E-05	6.8854E-02	1.8208E-01
QQQ004	295	906	1	60	2.4582E-02	-3.2689E-03	6.6408E-05	6.9569E-02	1.7130E-01
QQK	295	915	1	60	1.0284E-02	-1.3754E-03	2.9537E-05	7.1437E-02	6.8220E-02
QQQ	295	915	1	60	2.3732E-02	-3.1582E-03	6.4204E-05	6.9211E-02	1.7669E-01
QQQ	405	915	1	60	2.0365E-02	-2.9070E-03	6.1687E-05	6.8769E-02	1.8391E-01
QQQ004	405	710	1	42	1.4305E-02	-2.0420E-03	4.3331E-05	4.8306E-02	1.2918E-01
QQQ004	405	710	1	60	2.0365E-02	-2.9070E-03	6.1687E-05	6.8769E-02	1.8391E-01

/EOP
19.12.41.UCLP, QQ, TB10, 0.109KLNS. ** END OF LISTING **

I. Results of polynomial fit of data to

$$A + B*I + C*I^2$$

for individual measurement sets

II. Results of averaging parameters & slopes & offsets, when combining sets (for 60" penetration)

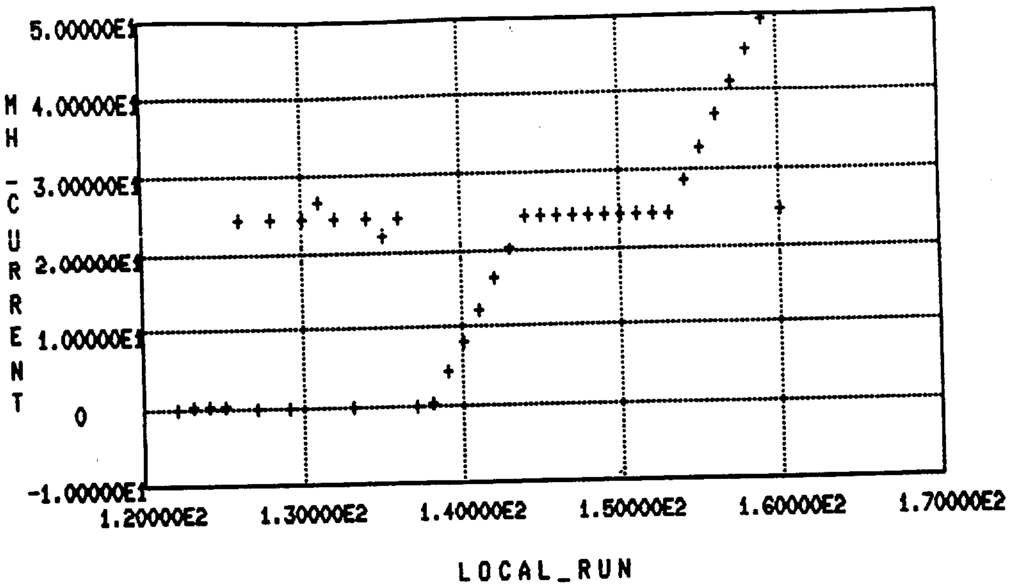
Table 4

MAGNET	3Q120 TYPE	BIASING CURRENT	DESIRED Gradient Kg/m for 120" length	current predicted (A)	% Dev 1	% Dev 2	% Dev 3	current from P note 384 (A)	% Dev 4
PQ1	II	148	4.84	9.515	0.0	0.4	4.2	9.92	4.2
PQ2	II	148	3.57	6.782	0.5	0.3	7.8	7.31	7.2
PQ3	III	295	8.89	17.190	-1.0	1.7	5.9	18.2	5.9
PQ4	III	405	11.73	23.523	-0.9	2.2	2.1	24.0	2.0
PQ5A+B	III	405	13.46	27.344	-0.7	2.6	0.8	27.6	0.9
PQ6A+B	II	295	7.096	14.229	-0.3	0.6	2.1	14.82	2.1
7A+B	II	270	10.630	21.819	-0.4	0.9	-0.2	22.2	-0.6
PQ8A+B	II	295							
PQ9A+B	II	295							

II "QQK"
III "QQQ" (more steel, better cooling)

API LINE QUAD INFO

Table 5



QQK013, 270 A bias, July 25

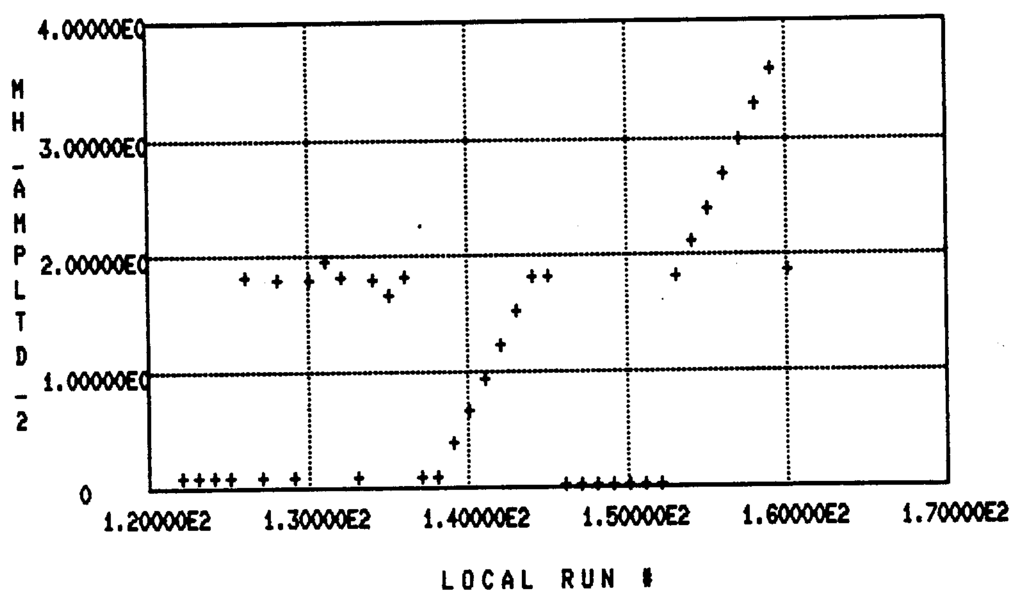
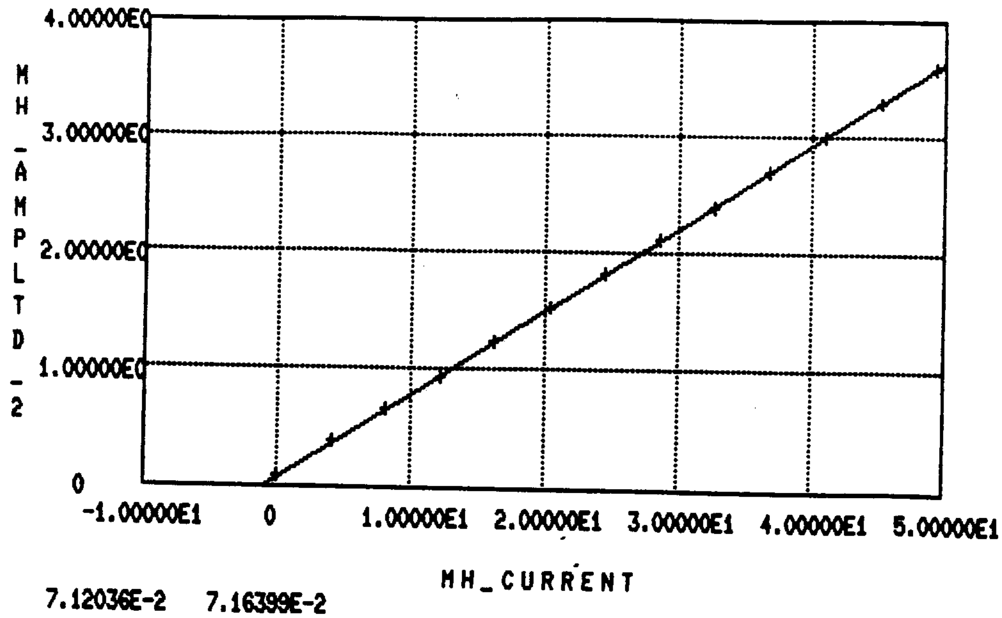


Fig 3



QQK013, 270 A bias, July 25

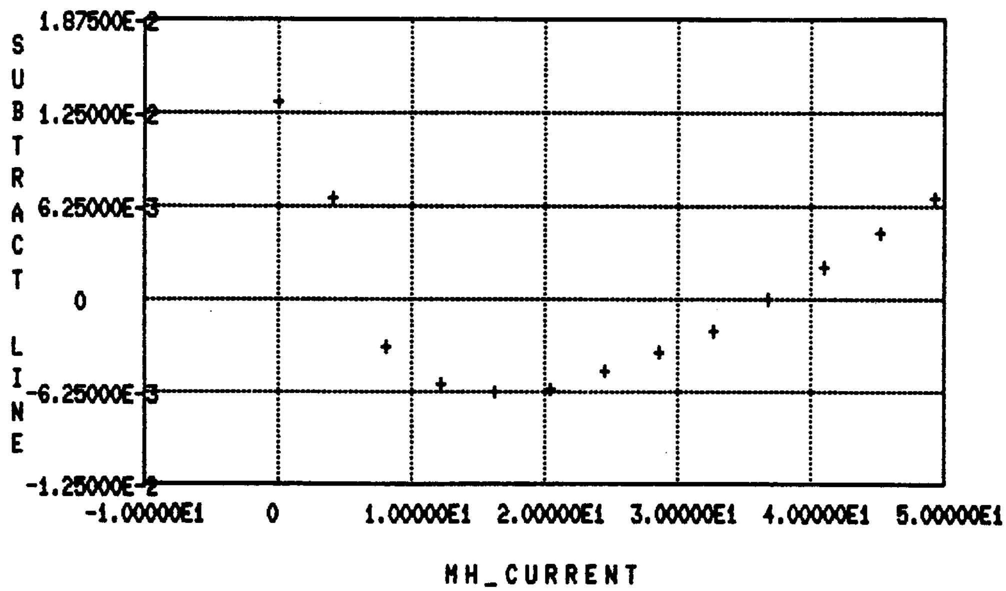
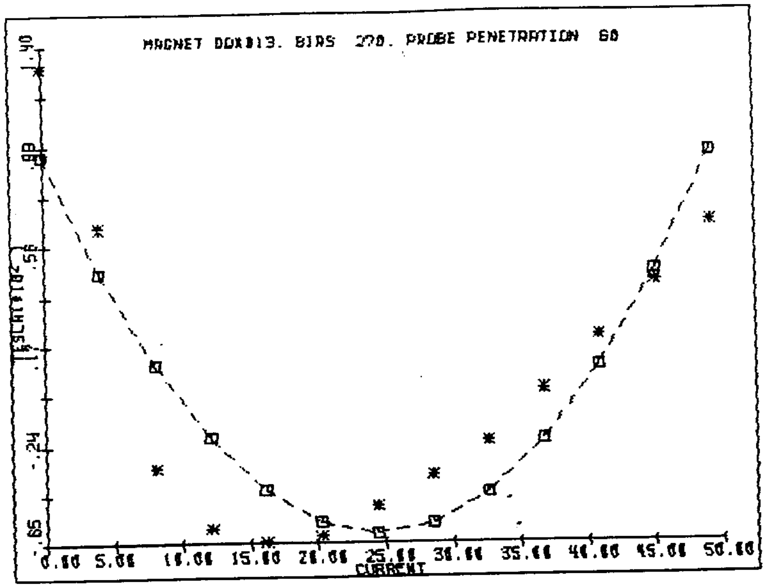


Fig 4



QQK013, 270 A bias, July 25

* = values from datatrieve

□ = results of 3 parameter polynomial fit

Fig 6

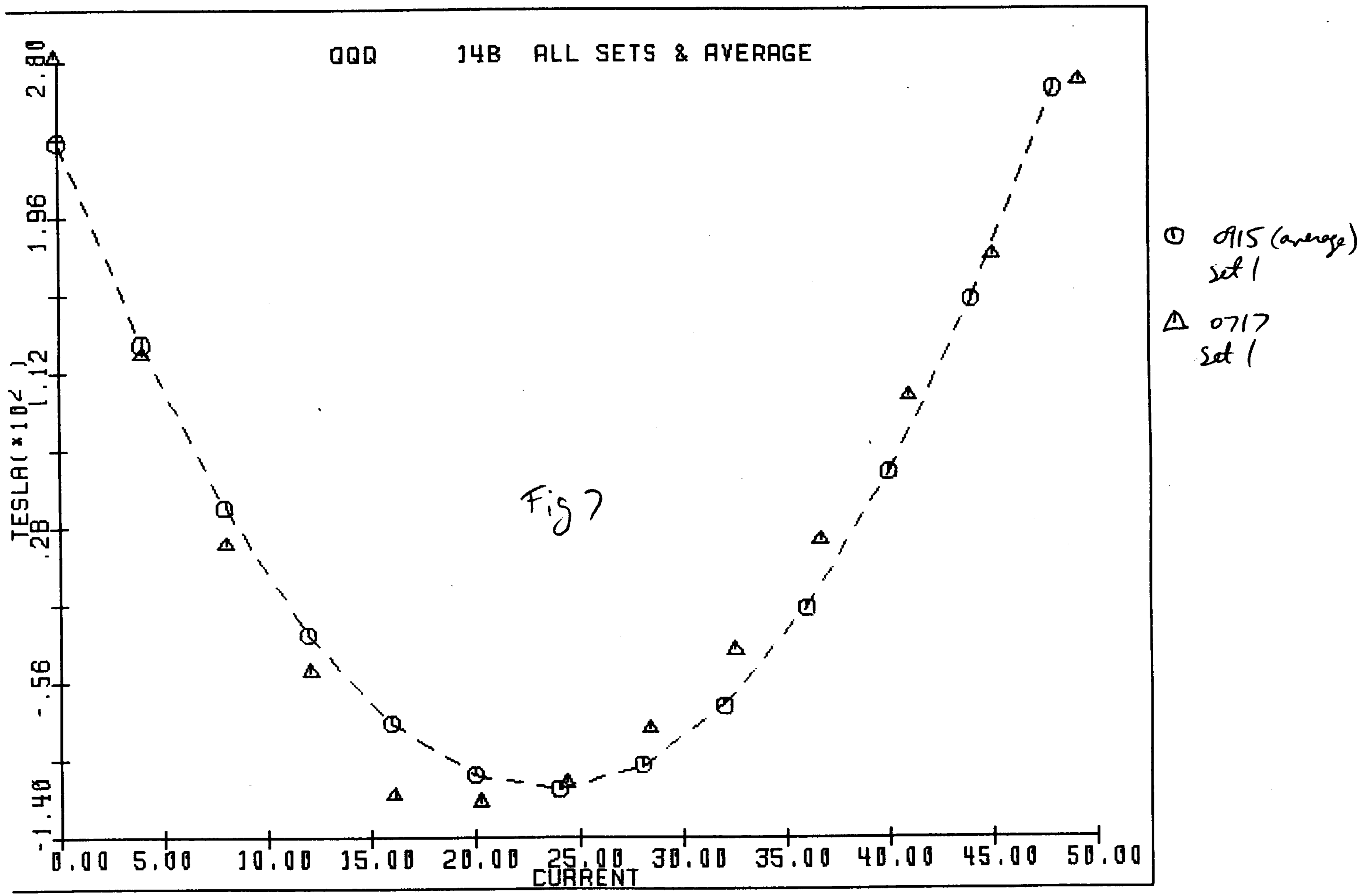

QQQ 14B ALL SETS & AVERAGE
TESLA(×10²)
2.80
1.96
1.12
.28
-.56
-1.40
0.00
5.00
10.00
15.00
20.00
25.00
30.00
35.00
40.00
45.00
50.00
CURRENT
0915 (average) set 1
0717 set 1

Fig 7

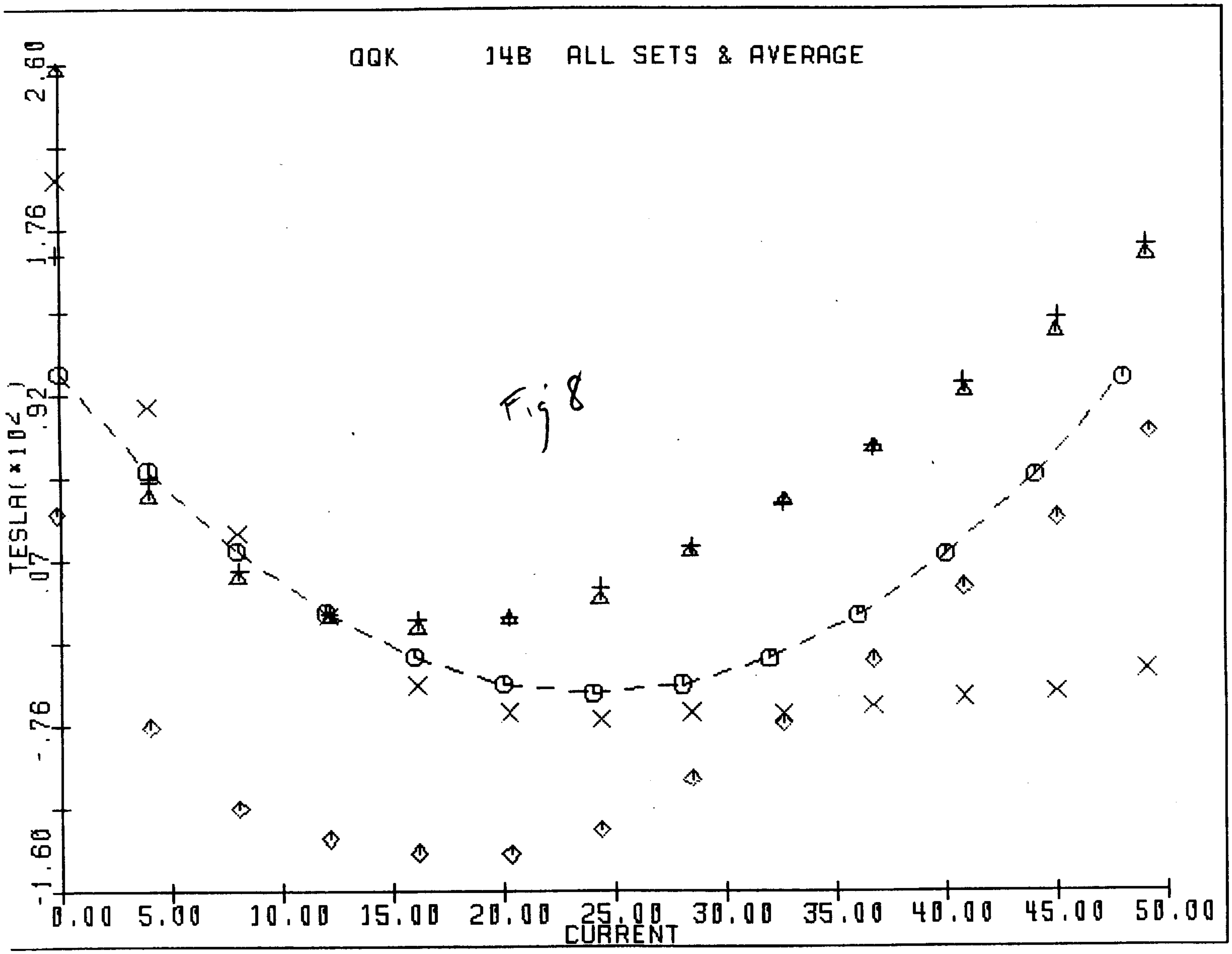
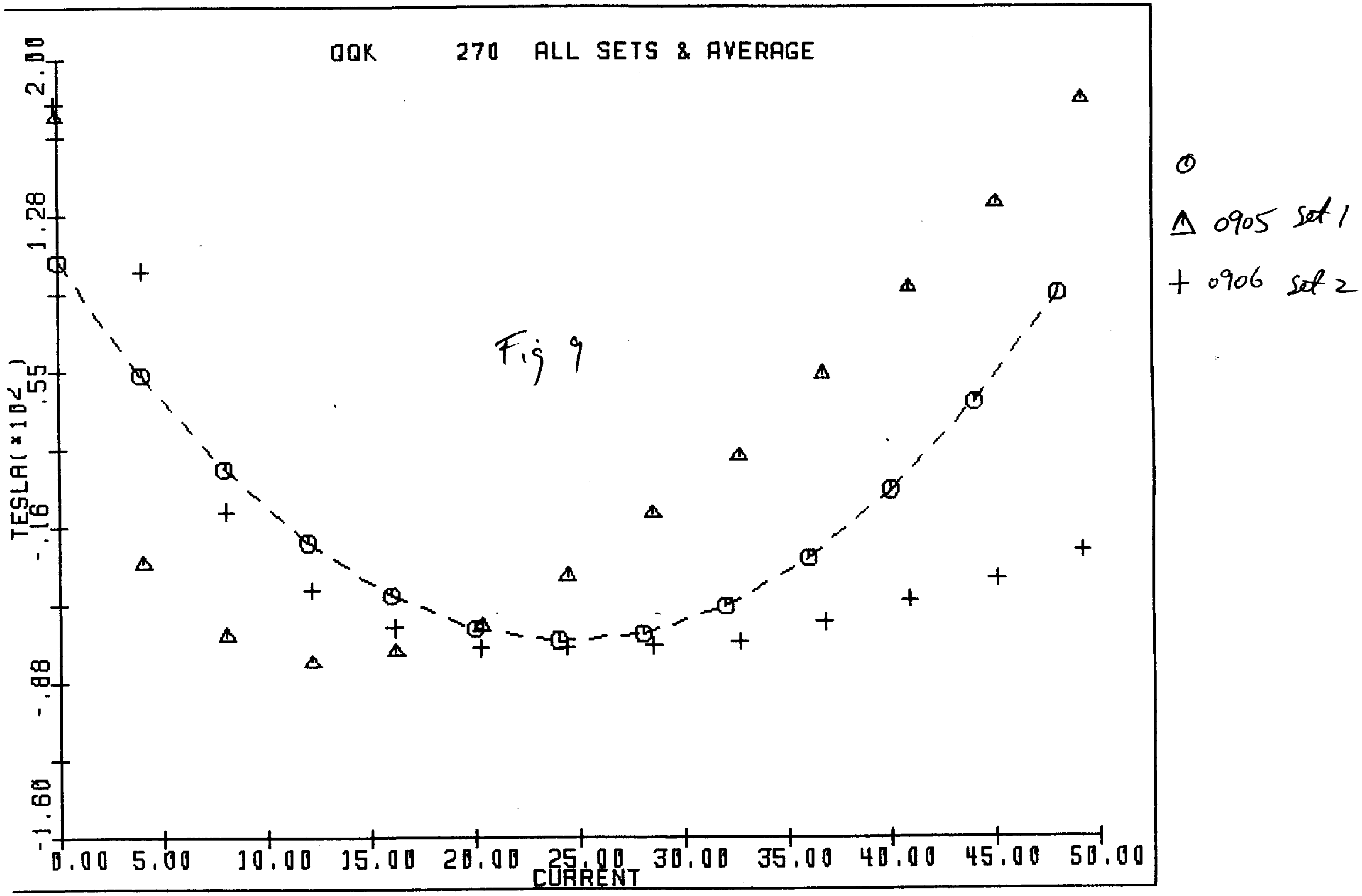

QQK 14B ALL SETS & AVERAGE
TESLA(×10²)
2.60
1.76
.92
.07
-.76
-1.60
CURRENT
0.00
5.00
10.00
15.00
20.00
25.00
30.00
35.00
40.00
45.00
50.00

Fig 8


QQK 270 ALL SETS & AVERAGE
TESLA(×10²)
2.00
1.28
.55
-.16
-.88
-1.60
CURRENT
0.00
5.00
10.00
15.00
20.00
25.00
30.00
35.00
40.00
45.00
50.00
Fig 9
0905 set 1
0906 set 2

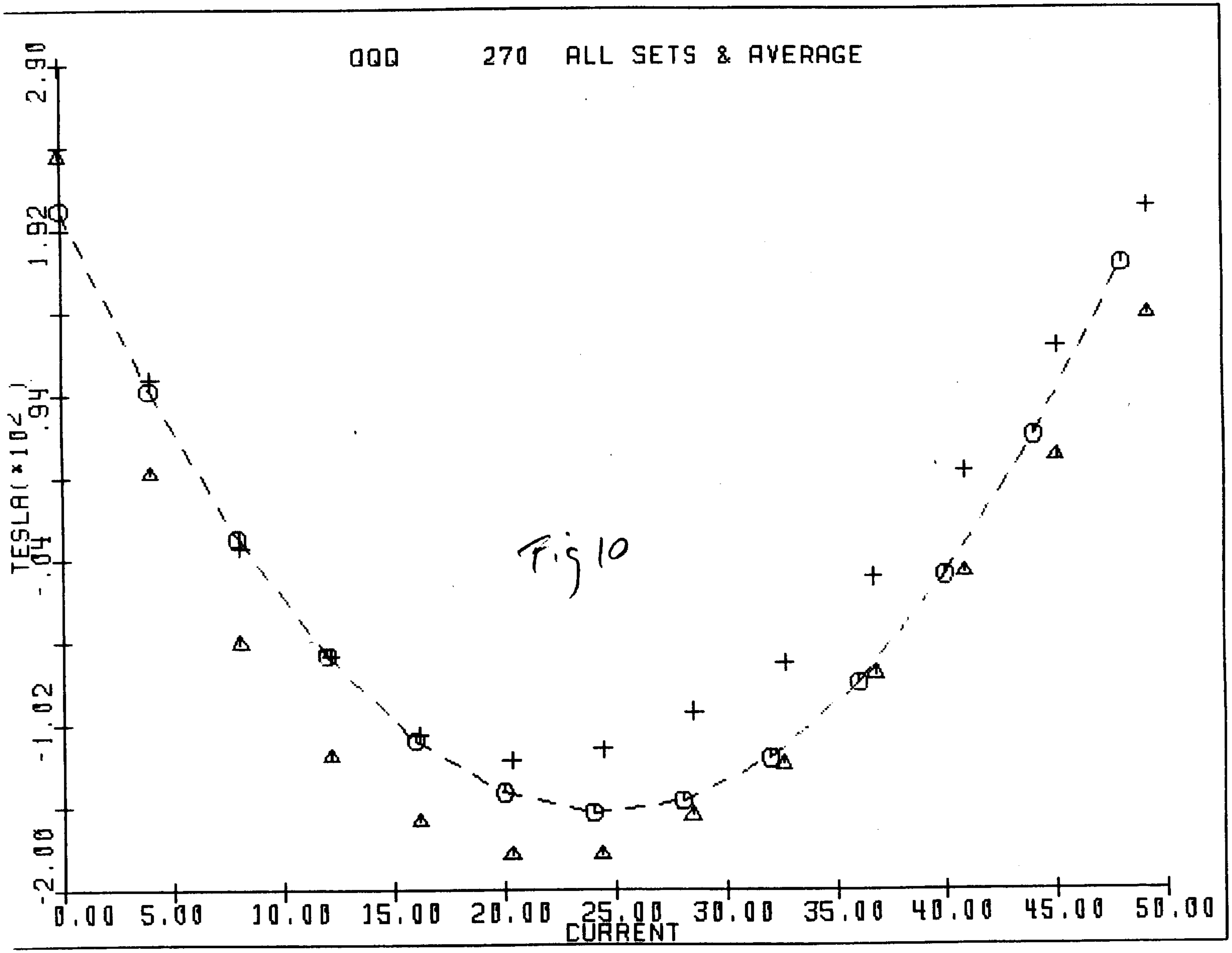
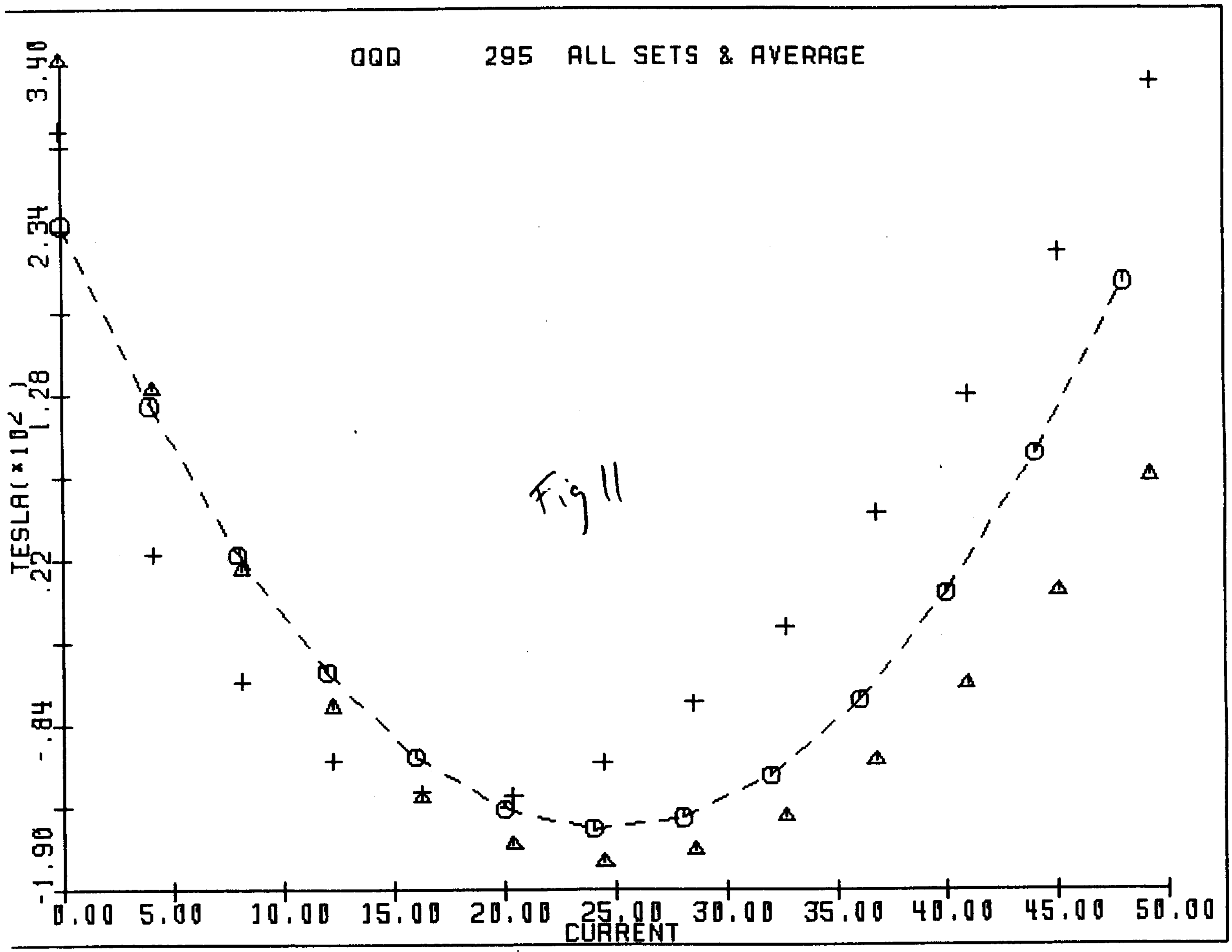
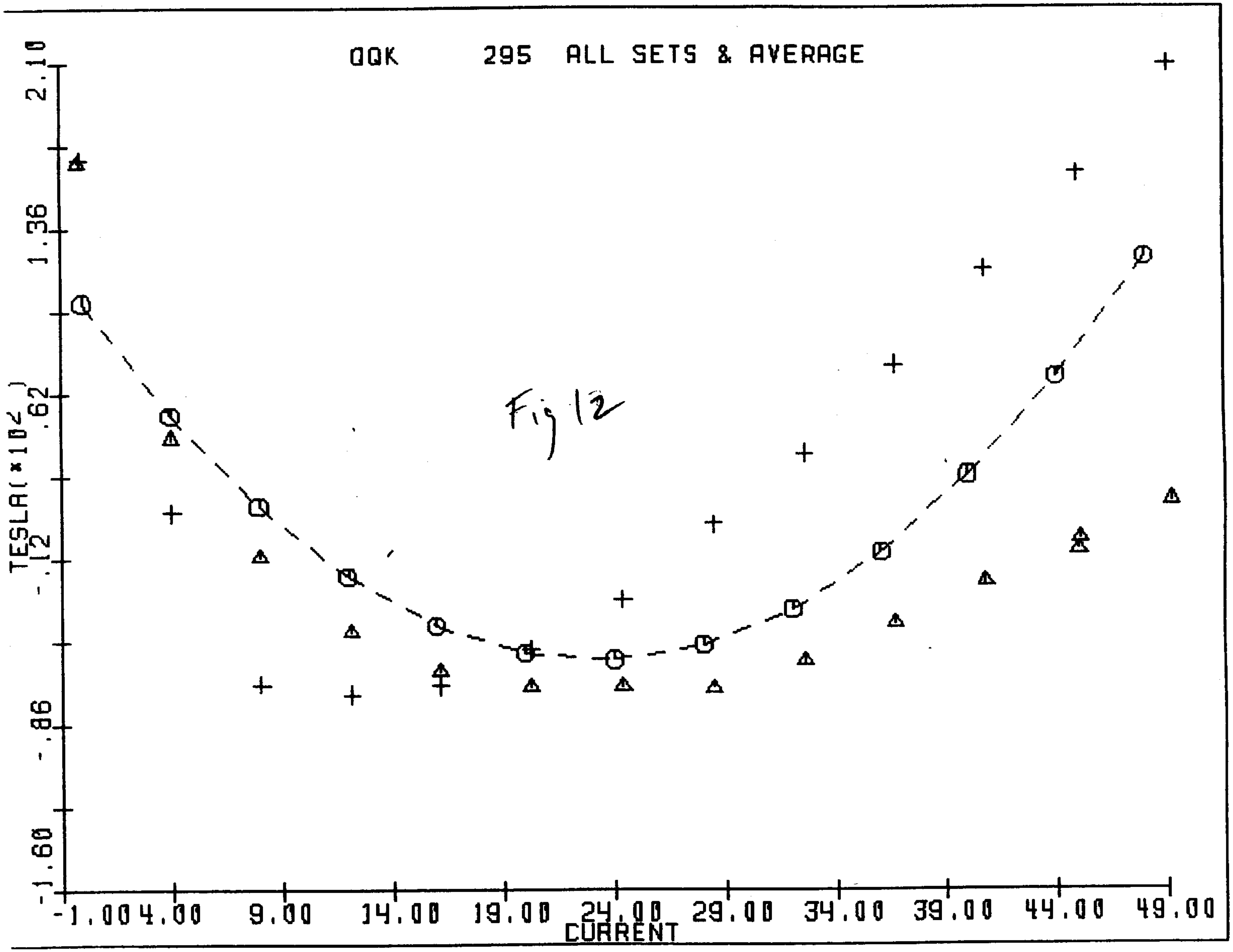

QQQ 270 ALL SETS & AVERAGE
TESLA(×10²)
2.90
1.92
.94
-.04
-1.02
-2.00
0.00
5.00
10.00
15.00
20.00
25.00
30.00
35.00
40.00
45.00
50.00
CURRENT

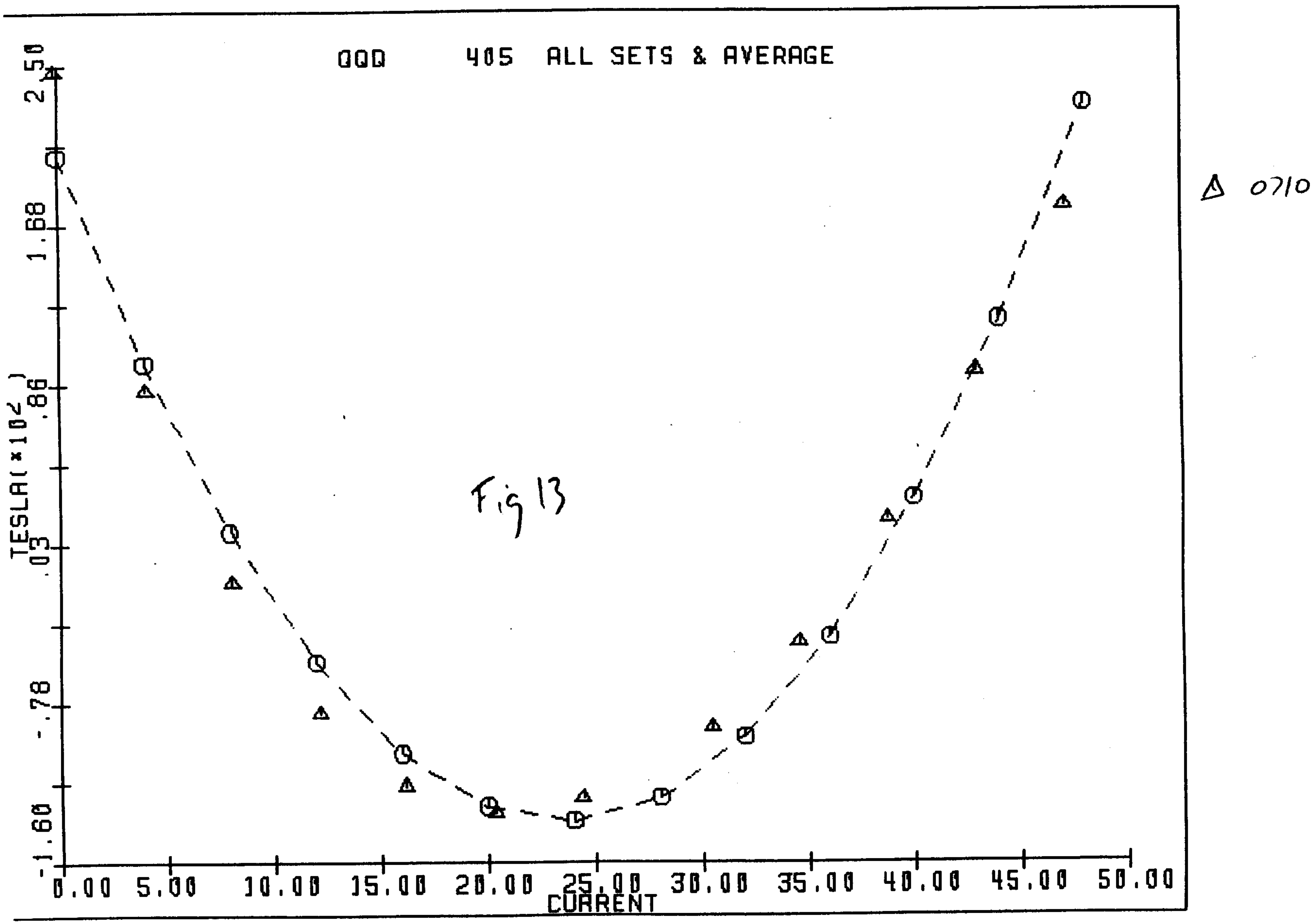
Fig 10



QQQ 295 ALL SETS & AVERAGE
TESLA(×10²)
3.40
2.34
1.28
.22
-.84
-1.90
0.00
5.00
10.00
15.00
20.00
25.00
30.00
35.00
40.00
45.00
50.00
CURRENT
Fig 11



QQK 295 ALL SETS & AVERAGE
TESLA(×10²)
2.10
1.36
.62
-.12
-.86
-1.60
-1.00
4.00
9.00
14.00
19.00
24.00
29.00
34.00
39.00
44.00
49.00
CURRENT
Fig 12


QQQ 405 ALL SETS & AVERAGE
Δ 0710
Fig 13
TESLA(×10²)
2.50
1.68
.86
.03
-.78
-1.60
0.00
5.00
10.00
15.00
20.00
25.00
30.00
35.00
40.00
45.00
50.00
CURRENT