Fermi National Accelerator Laboratory

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Measurements of the Fermilab 200 MeV Transfer Line Quadrupole Magnets

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This report presents the results of measurements of two quadrupole magnets that are used in the 200 MeV transfer line. The measurements were performed to obtain data to evaluate the suitability of these magnets for use in a 400 MeV transfer line once the Linac Upgrade is complete. In order to provide a basis for comparison, data were obtained from Fermilab's Magnet Test Facility of measurements of magnets of similar size and strength that were built for the Loma Linda project. These Loma Linda magnets are possible replacements for the ones presently in the 200 MeV transfer line.

The Fermilab Linac Upgrade includes the reconfiguration of the transfer line that runs from the linac to the booster in order to handle the higher beam energy. Nominally, the quadrupole strengths will need to be 1.5 times their current operating points. This report will use a value of 1.7 to allow a tuning range to account differences in geometry between the old and new lines. Another goal in the design of the new transfer line is to produce a non-steering line. A complaint about the current line is that steering results from any attempt to re-tune the line.

The present transfer line magnets are 10" long with an aperture diameter of 3.25". Each coil has 121 turns and carries between 6 and 50 amps. Most of the transfer line quads have a solid yoke with removable pole pieces. These pole pieces are 3.75" diameter iron bar with two notches cut in them (see Figure 1). The magnet of this type that was measured has been designated TQT002. A few magnets in the transfer line are of a different design (Figure 2). In these the yoke is made in four pieces that bolt together. The pole has a constant thickness and is welded to the yoke. The magnet of this type that was measured was designated TQT001. The two Loma Linda quads (Figure 3) whose data are presented here for comparison were designated LQL001 and LQL004.

Measurement Procedure

The magnets were measured at Fermilab's Magnet Test Facility using a rotating Morgan Coil. This coil was 2.6" in diameter and had windings of N = 1, 2, 3, 4, 5, 6, & 10. The software of the measurement facility can a perform a harmonic analysis on the data from each coil. The harmonic analysis produced 30 harmonic components, n = 1 - 30, for each N.

One concern with the TQTxxx magnets is whether of not the geometric center of the magnet coincides with the magnetic center. Unfortunately, the measurements in this report can not answer this question. The measurement setup does not provide a relationship between the two coordinate systems. The centering of TQT002 was checked with a plastic ruler and was centered to +/- .5 mm.

Questions to be Used for Evaluation

The following questions will be used to determine the suitability of the present magnets for use in the upgrade.

1) While the physical position of the magnetic center cannot be measured, does it move as a function of current?
2) How much saturation occurs at the field strengths needed for 400 MeV beam?
3) Is there a significant amount of hysteresis?
4) How good is the field quality in terms of harmonic content?

These questions will be used to determine the "quality" of the present magnets and to compare them to the newer (i.e. better design?) Loma Linda magnets.

In order to determine the effects of hysteresis, the excitation history of the magnet has to be controlled. The magnet needs to be energized from 0 amps to a maximum current and then back to 0 with measurements taken at various currents along the way. The measurements of the Loma Linda magnets, LQLxxx, were conducted as part of their manufacturing program, not as a part of this investigation. Therefore their excitation history is unknown. Also, no 0 amp measurements were made of the LQLxxx, limiting the answer to question 1.

Results

Table 1 compares the data from the four magnets for questions 1 - 3, saturation, hysteresis, and motion of the magnetic center.

The Ampfac measures the saturation. It is defined as the deviation from a linear correspondence between current and field. Figures 4 - 7 show the determination of the Ampfac for the four magnets. The horizontal axis in these figures is the current. The vertical axis is the quadrupole field strength minus the product of the current and a constant. If a magnet of the type represented by TQT002 were to be used in a position that required high current, it would require 17% more current at 80 amps than an unsaturated magnet. Since the current - field relationship is not linear at this point it could make tuning more difficult. The Ampfac starts to vary from 1 at approximately 50 amps. As can be seen in Table 3 many quads will need to run above 50 amps at 400 MeV if they are of the TQTxxx type.

An example of hysteresis is shown in Figure 8 for TQT001. This data is a subset of that shown in Figure 4. The current is plotted along the x axis and the y axis shows the quadrupole strength with .05 times the current subtracted. The arrows on the line show the excitation history. Hysteresis is defined here as the difference between two measurements of the field strength at a given current divided by the total field strength, where the difference in the two values is due to the excitation history.

Figures 9 - 14 show the measurement of the dipole field normalized to the quadrupole field as a function of the current. The product of the dipole field strength and the probe radius gives the offset between the probe center and the magnetic center. Figures 9 and 11 show a large movement (1 - 2 mm) that occurs when the magnet is first turned on. The LQLxxx magnets did not have a 0 amp measurement. Ignoring the 0 amp values, the motions for all 4 magnets are less than 250 microns (10 mills). Ten mills is approximately the accuracy to which the magnets can be aligned in the beam line. The only way there could be a problem with the TQTxxx magnets would be if the 0 amp value represented the true physical center of the magnet. However, since an attempt was made to align the magnets in the measuring apparatus and the 0 amp values are large relative to the energized values, one can conjecture that the 0 amp values are due to asymmetries in the remnant fields. The large variations in Figure 13, for LQL001, are

presumably due to the fact that the measurements were taken over a period of months, with the measuring system dismounted each time. Within each of the five sets of data, the stability as a function of current is similar to that in Figure 14 even though one of the sets has a systematic 1 mm offset.

Table 2 presents the results of the harmonic analysis. The analysis software uses a fast fourier transform algorithm to break the measurement from a coil down into 30 components. Due to the symmetries involved only those that correspond to N(2m+1), where 2N is the pole number of the coil and m is an integer ranging from 0 to infinity, have physical significance. The values have been normalized by the main quadrupole field and multiplied by 10**4. Comparison of the results for TQTxxx with LQLxxx shows no significant advantage of one design over the other. Figures 15 - 18 show the data for the harmonic analysis for each magnet. The x axis is the current and the y axis is the field strength for a given harmonic measured by a given coil normalized to the quadrupole field.

Some Discussion

As mentioned above, the pole pieces on most of present transfer line quads are removable to enable servicing of the coils. Any asymmetry in the gap between opposite pole faces will generate a shift in the magnetic center. The effect of the removal and replacement of the pole pieces was not investigated for this report. Another possible complication could be the fact that the pole pieces are just steel bar and therefore do not have the precision of machining or stamping (for laminated magnets). There could be variations in the harmonic content along the length of the magnet.

Conclusion

Nine of the magnets in the current 200 MeV transfer line will have to operate above 50 amps if they are to be used at 400 MeV. The saturation effects shown in TQT002 indicate that some other magnet may need to be used. Magnets of the design represented by LQLxxx should provide an adequate replacement. The design provides a gradient of 11.8 T/m which covers all the requirements of the line except for Q8, Q20, and Q25. However, the measurements of the LQLxxx show little sign of saturation at 260 amps, so, barring cooling problems, they should be able to handle these higher gradients.

The parameters listed in Table 3 assume that the present transfer line configuration will be used. A number of elements will differ in the new line, such as the chopper position, the debuncher, and the injection girder. The final composition of the new transfer line may have fewer magnets and/or better matching of the required gradients. This will need to be better defined before a decision about replacing the magnets can be made.

A final concern in the decision of whether to replace the present magnets could be time. The TQTxxx magnets do not have good reference markings and take a long time to align. Given the short period of time available to install and commission the Upgrade and the large amount of work involved in the installation, it may be necessary to acquire new magnets mainly for ease of installation.

Table 1

	TQT001	TQT002	LQL001	LQL004
Ampfac	1.10	1.16	1.02	1.02
Hysteresis	.01	.01	N/A	N/A
Magnetic Center Motion				
5 - 80 Amps (75 - 250 Amps, LQL)	125μm	200μm	20μm	12μm
0 - 5 Amps	1mm	2mm	N/A	N/A

Table 2

N	Harmonic	TQT001	TQT002	LQL001	LQL004
		(in units of 10^{-4} relative to main quadrupole field)			
2	6	40	40	50	30
2	10	15	20	25	20
2	14	10	5	4	20
2	18	25	10	5	10
2	22	20	15	5	40
2	26	20	15	5	10
2	30	25	15	5	20
3	3	8	15	3	6
3	9	<1	2	<1	<1
3	15	<1	1	<1	<1
3	21	<1	<1	<1	<1
3	27	<1	<1	<1	<1
4	4	1	<1	2	2
4	12	<1	<1	<1	<1
4	20	<1	<1	<1	<1
4	28	<1	<1	<1	<1
5	5	<1	2	2	2
5	15	<1	<1	<1	<1
5	25	<1	<1	<1	<1
6	6	36	32	10	5
6	18	<1	<1	<1	<1
6	30	<1	<1	<1	<1
10	10	22	24	5	5
10	30	<1	<1	<1	<1

Table 3

Magnet (Transfer Line ID)	Gradient for Upgrade (T/m)	TQTxxx Current at Gradient (Amps)	TQTxxx Current + 20% (Amps)	LQLxxx Current at Gradient (Amps)	LQLxxx Current + 20% (Amps)
Q6	7.5	42	48	141	160
Q7	11.2	63	74	211	239
Q8	12.3	69	78	232	263
Q9	8.0	45	51	151	171
Q10	5.9	33	40	111	126
Q11	5.4	30	34	102	116
Q12	6.4	36	41	120	136
Q13	3.9	22	26	73	83
Q14	8.0	45	51	150	170
Q15	8.6	48	54	162	184
Q16	3.6	20	22	68	77
Q17	1.6	9	10	30	34
Q18	9.3	52	60	175	198
Q19	10.2	57	65	192	218
Q20	11.8	66	75	222	252
Q22	11.1	62	70	209	237
Q23	10.0	56	63	188	213
Q24	5.9	33	37	111	126
Q25	13.4	75	85	252	286
Q26	10.2	57	65	192	218

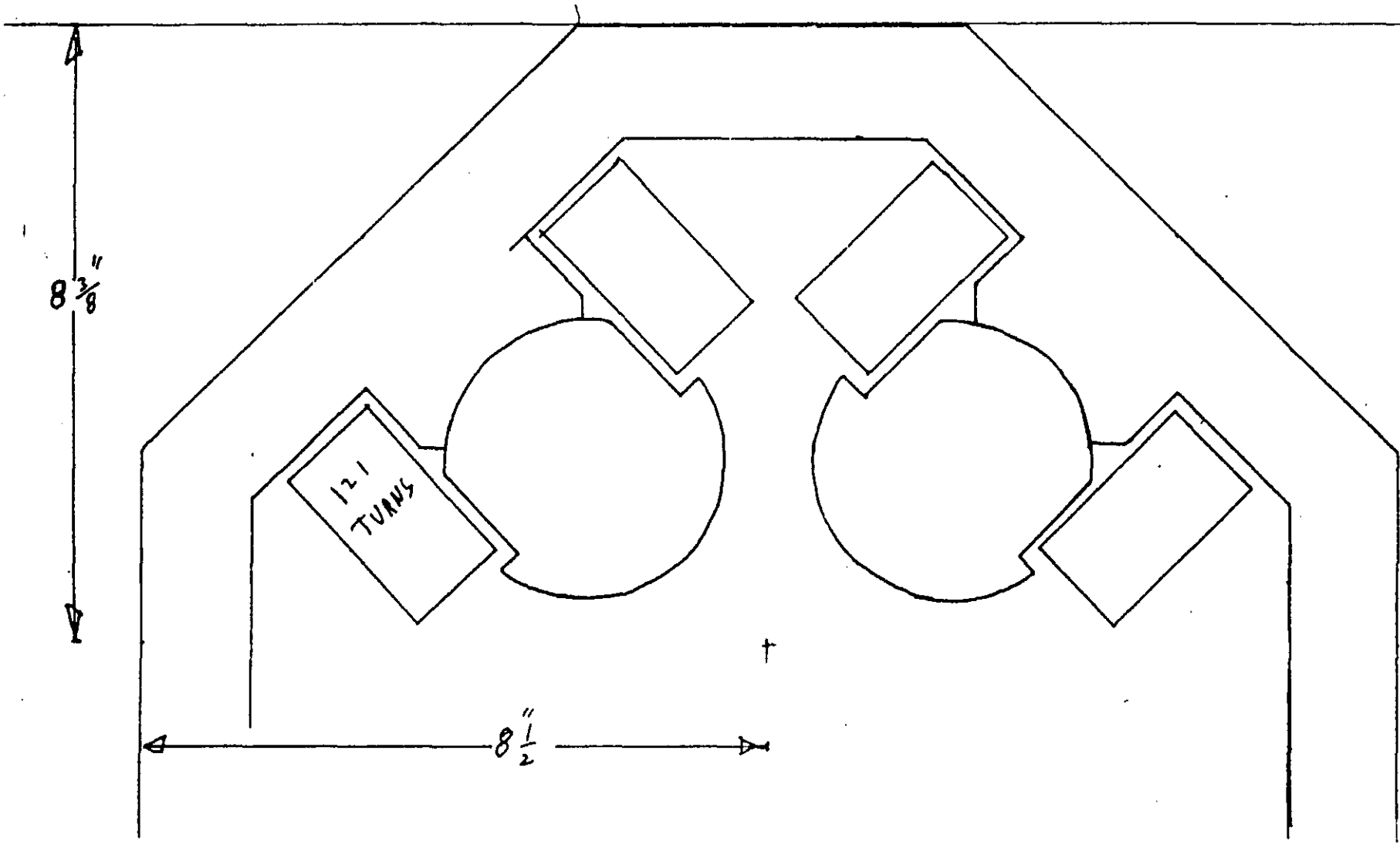


Figure 1, TQT002

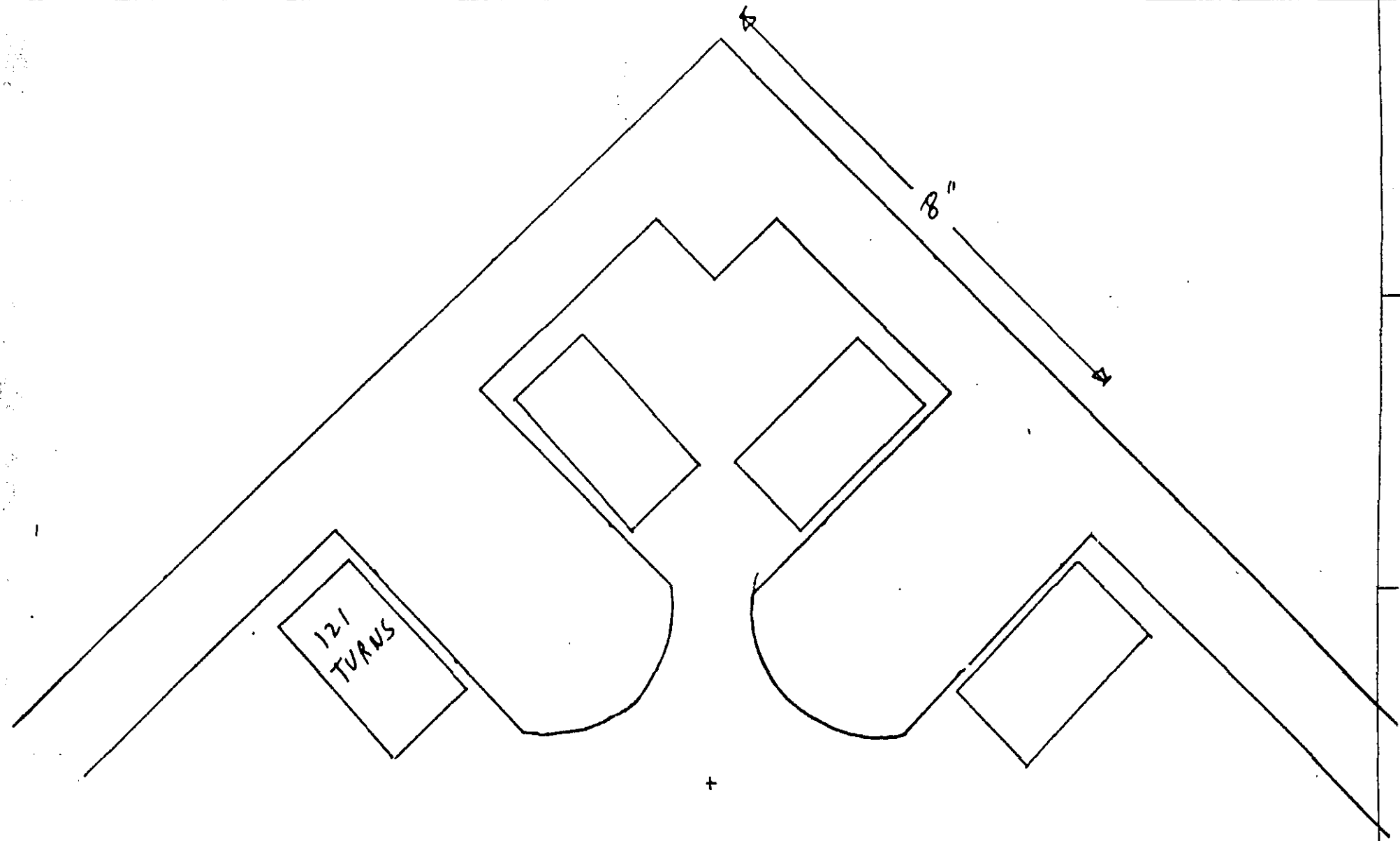


Figure 2, TQT001

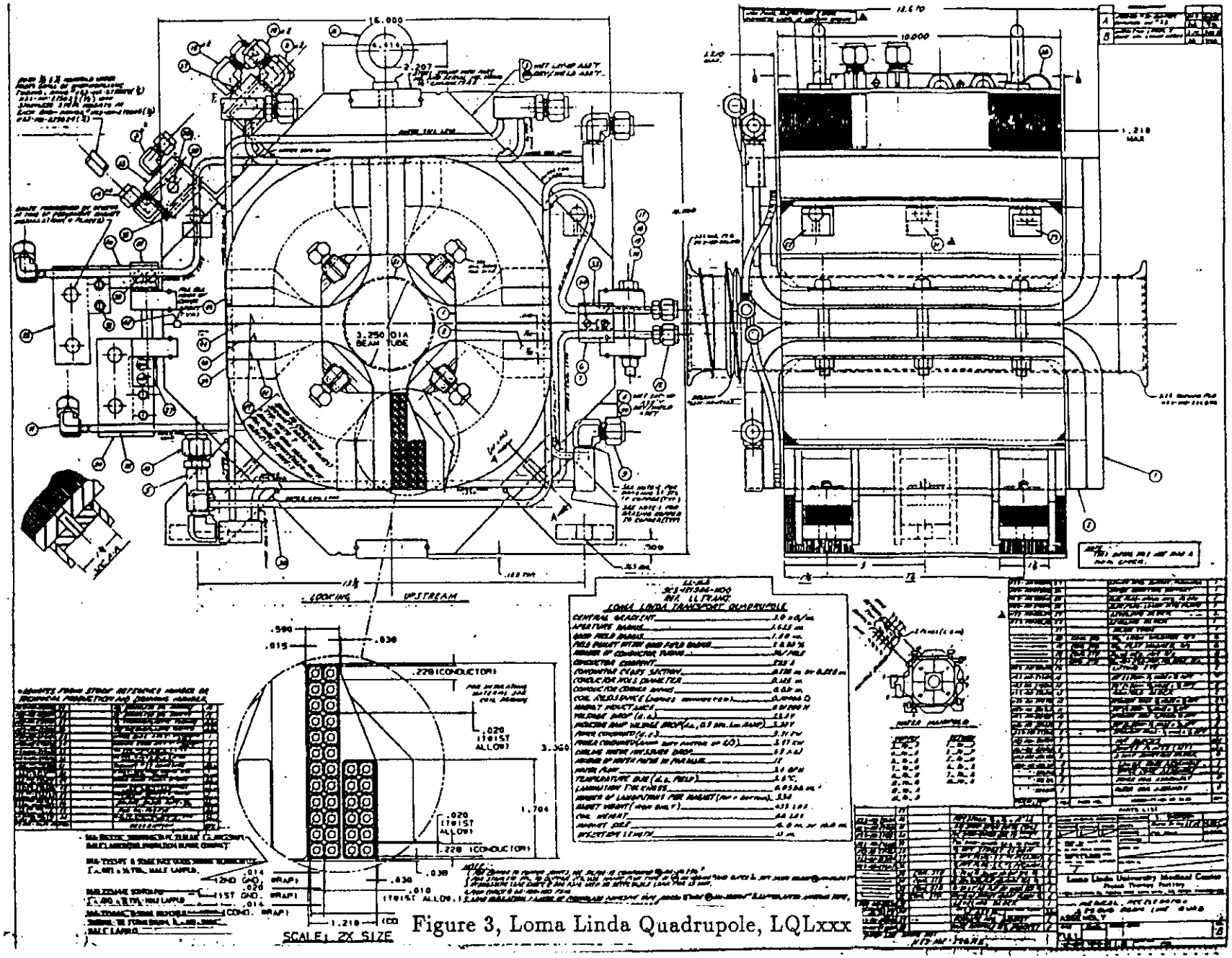
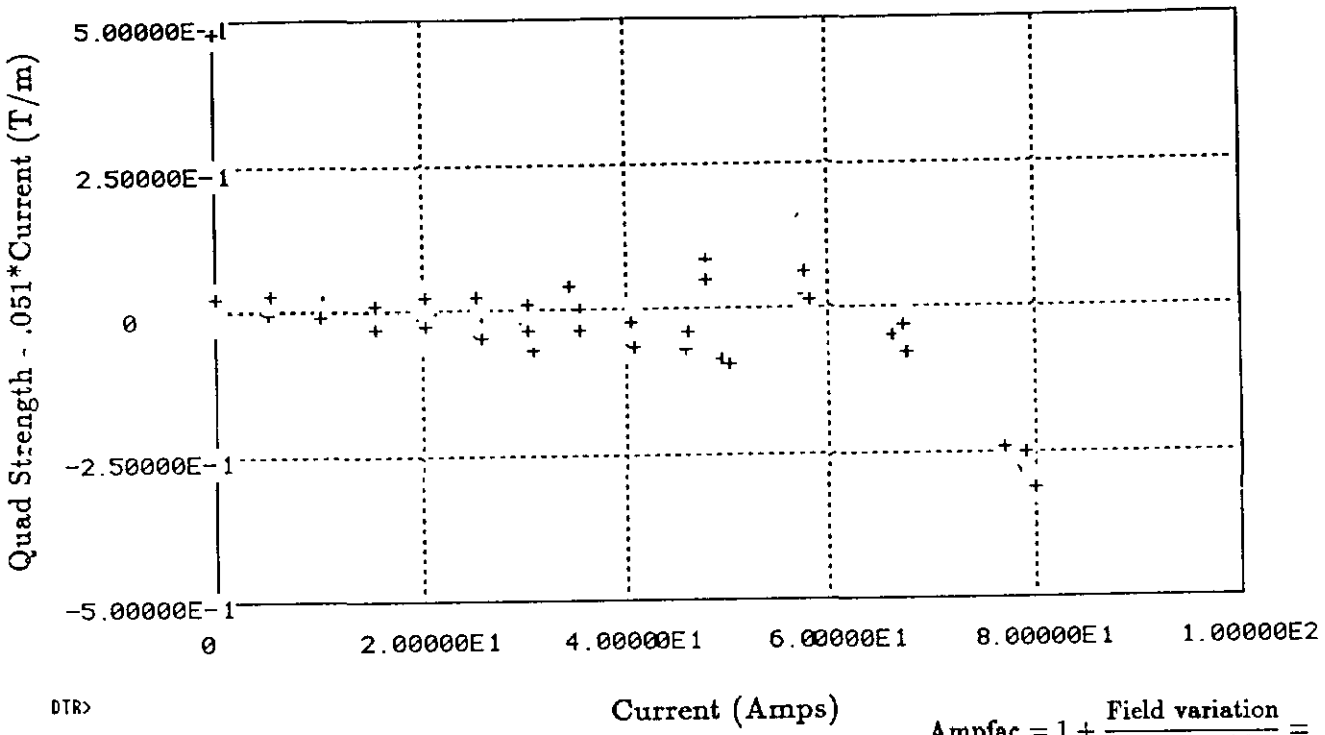
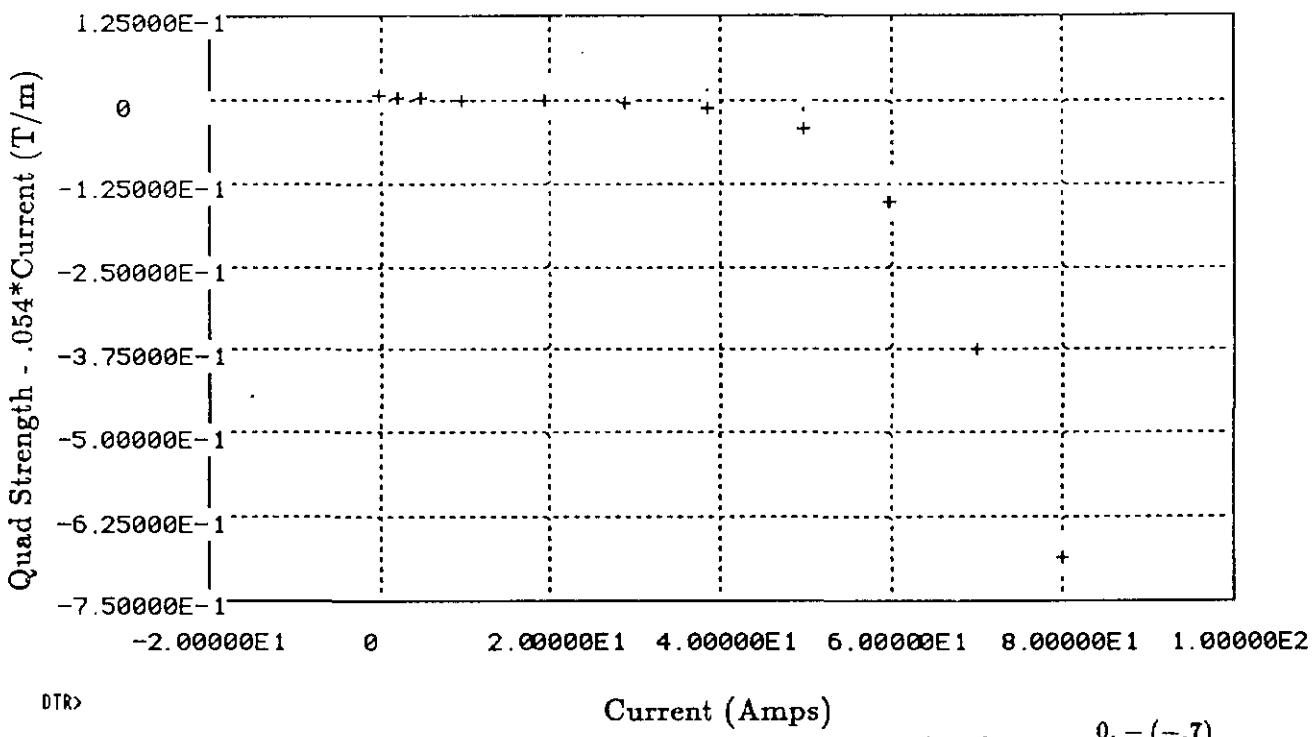


Figure 3, Loma Linda Quadrupole, LQLxxx



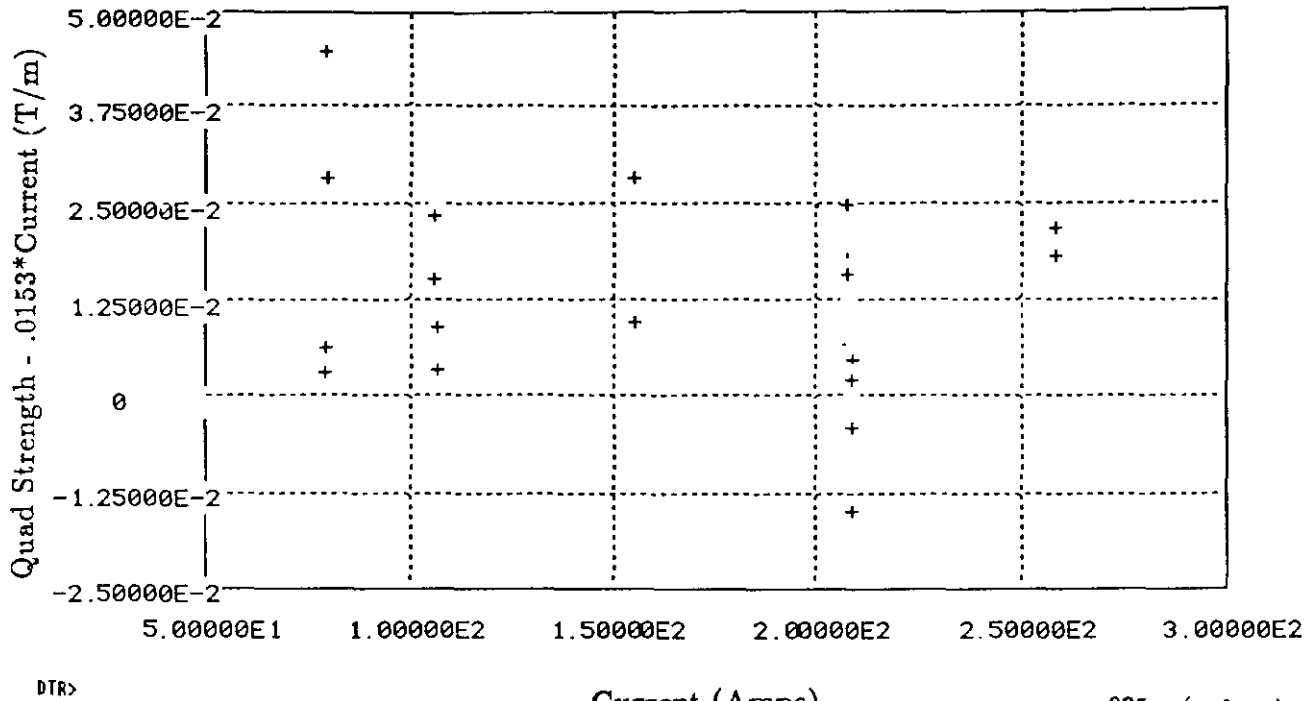
$$\text{Ampfac} = 1 + \frac{\text{Field variation}}{\text{Total field}} = 1 + \frac{.1 - (-.3)}{80(.051)} = 1.1$$

Figure 4, Ampfac TQT001



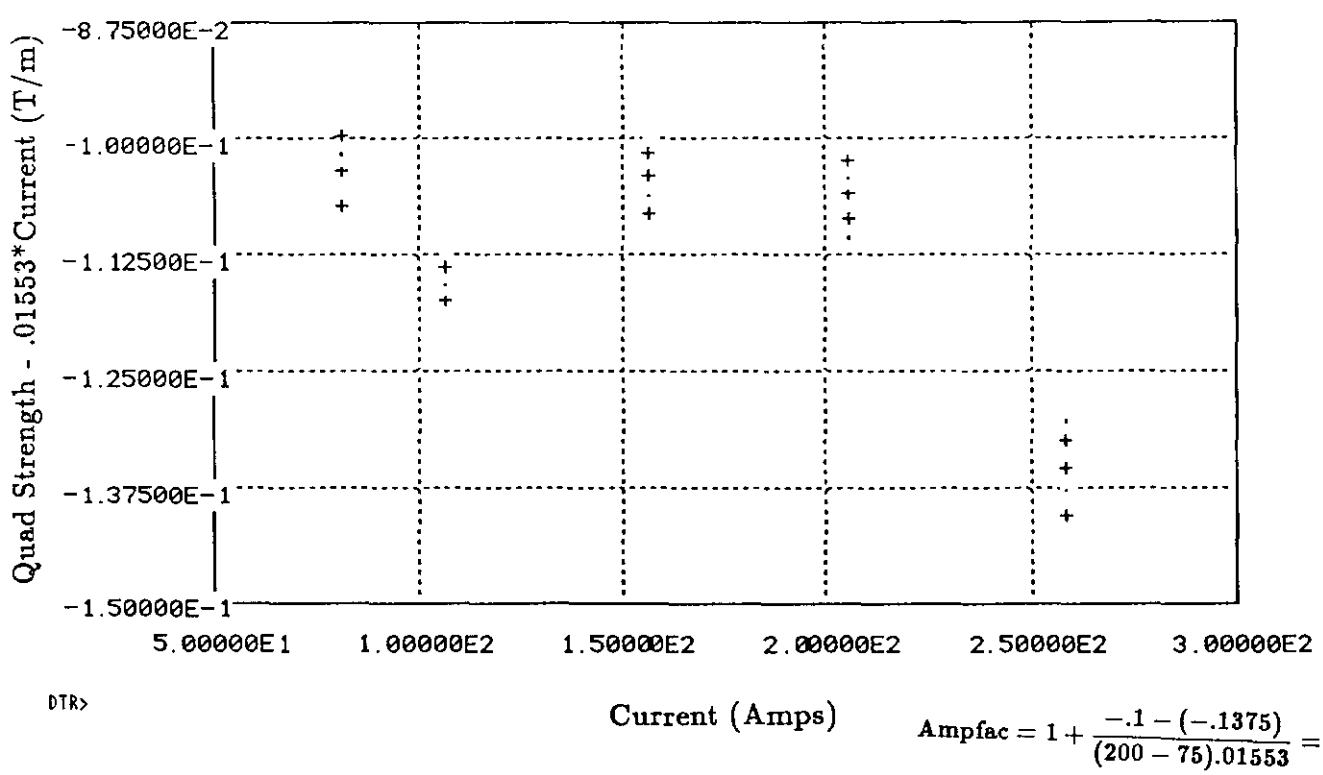
$$\text{Ampfac} = 1 + \frac{0. - (-.7)}{80(.054)} = 1.16$$

Figure 5, Ampfac TQT002



$$\text{Ampfac} = 1 + \frac{.025 - (-.0125)}{(200 - 75).0153} = 1.02$$

Figure 6, Ampfac LQL001



$$\text{Ampfac} = 1 + \frac{-.1 - (-.1375)}{(200 - 75).01553} = 1.02$$

Figure 7, Ampfac LQL004

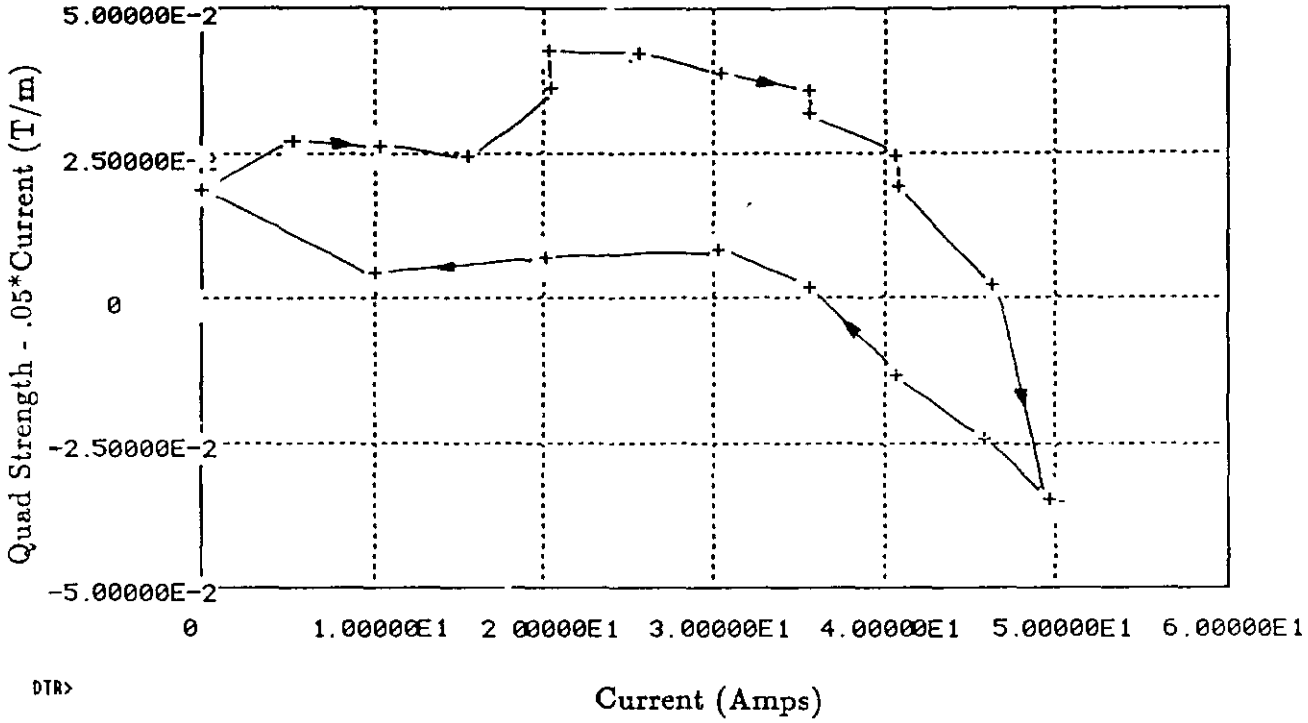
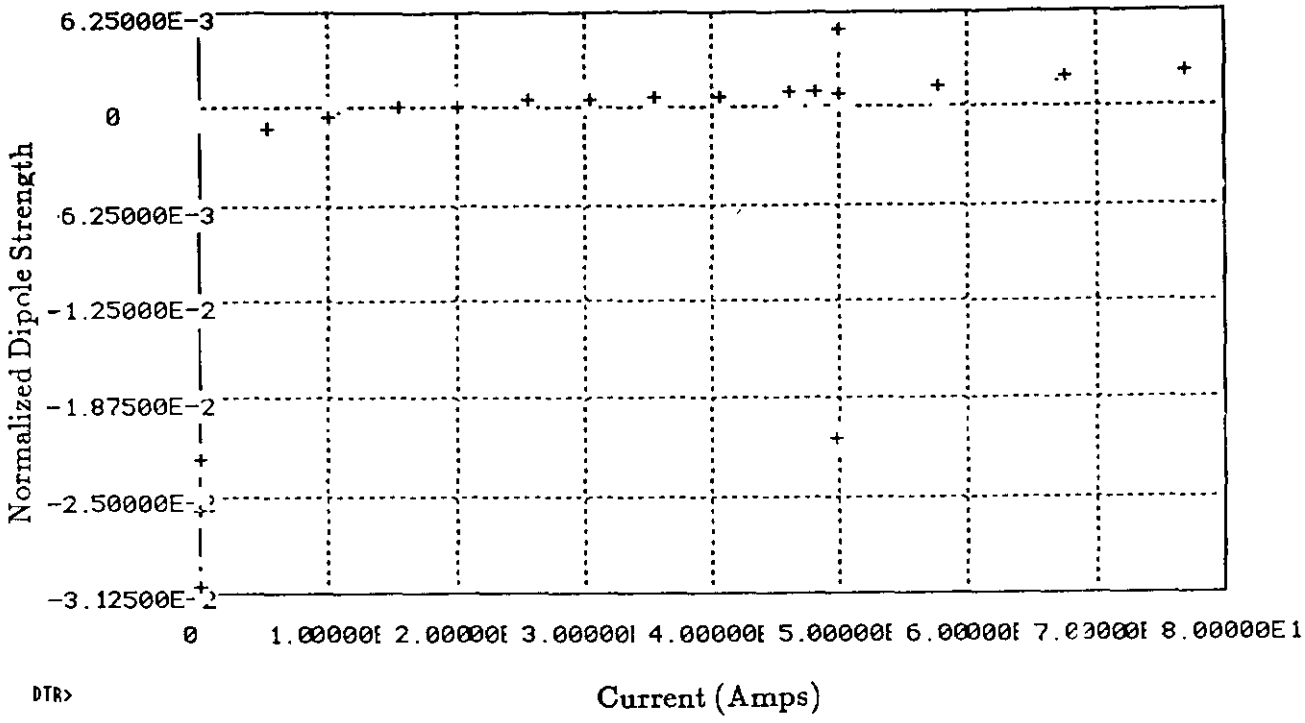


Figure 8, Hysteresis TQT001

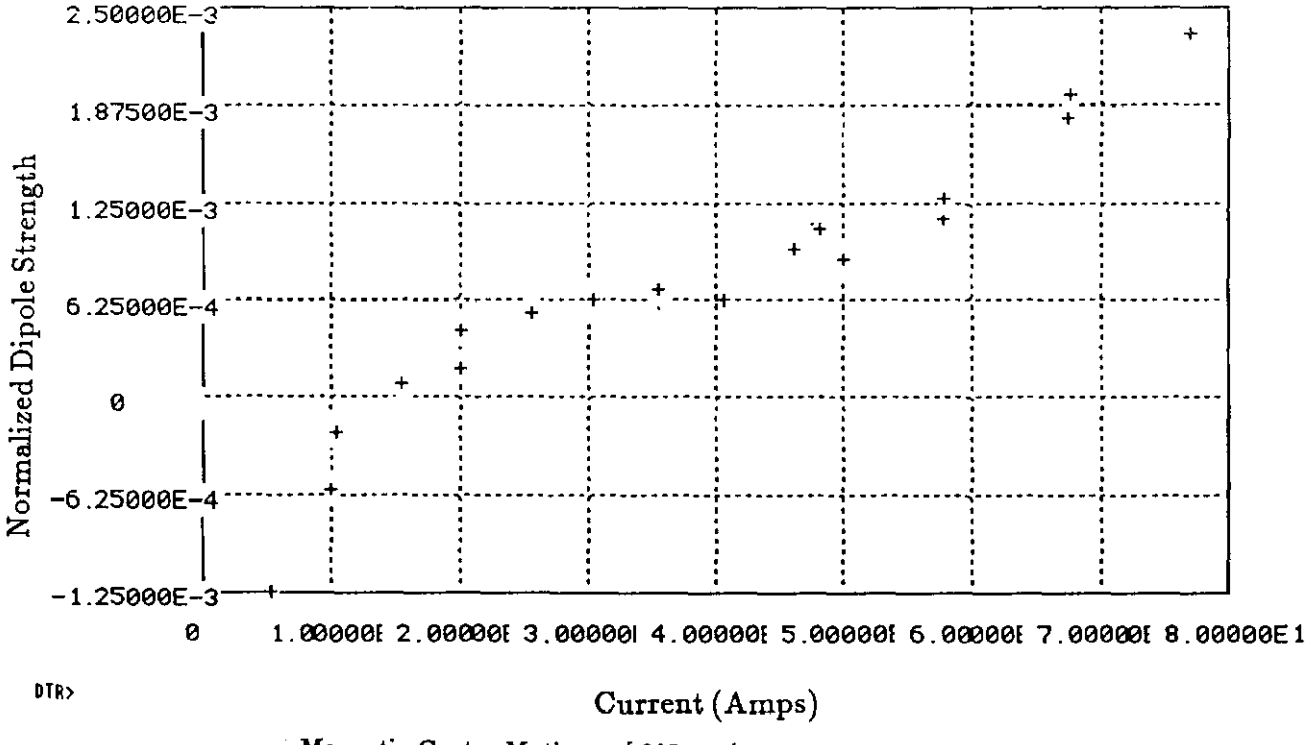
$$\text{Hysteresis} = \frac{\text{Maximum variation at a single current}}{\text{Total field range}} =$$

$$\frac{.04 - .005}{50(.05)} = .01$$



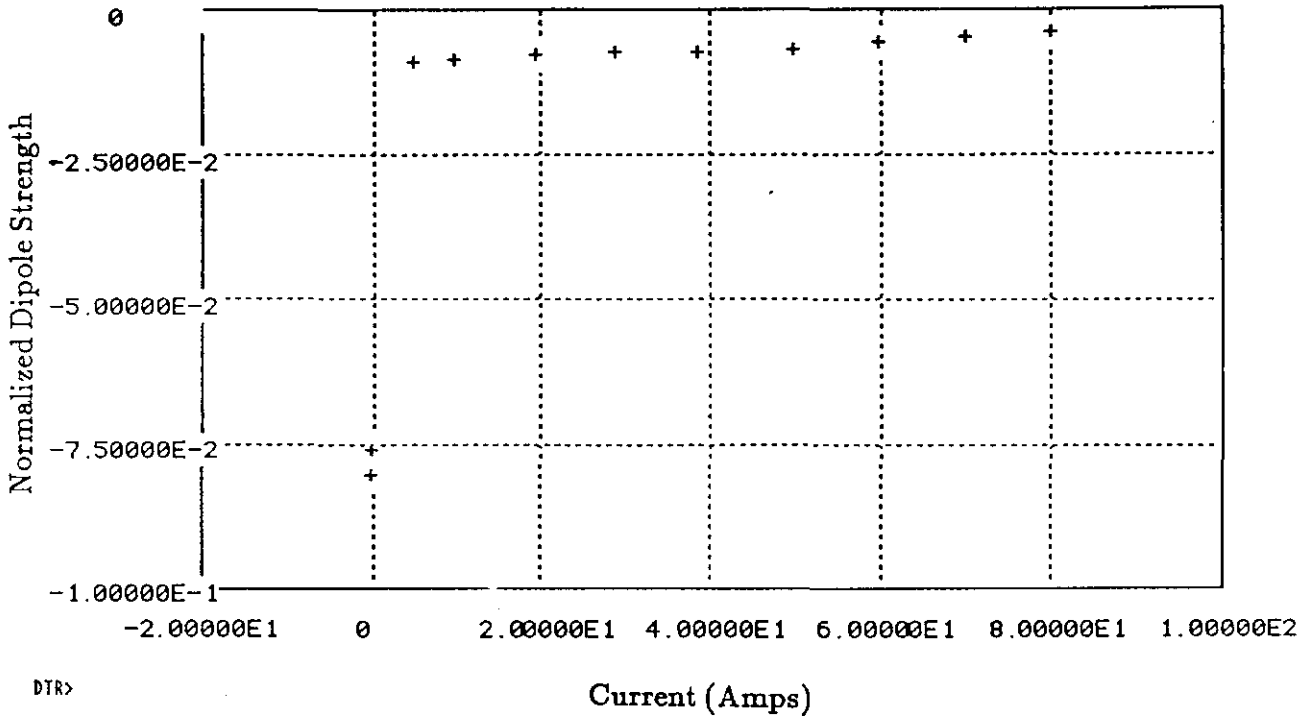
Magnetic Center Motion =
Variation of normalized dipole field × Probe radius =
$-.03125(1.3")(.0254) = .001\text{m}$

Figure 9, Magnetic Center Motion TQT001



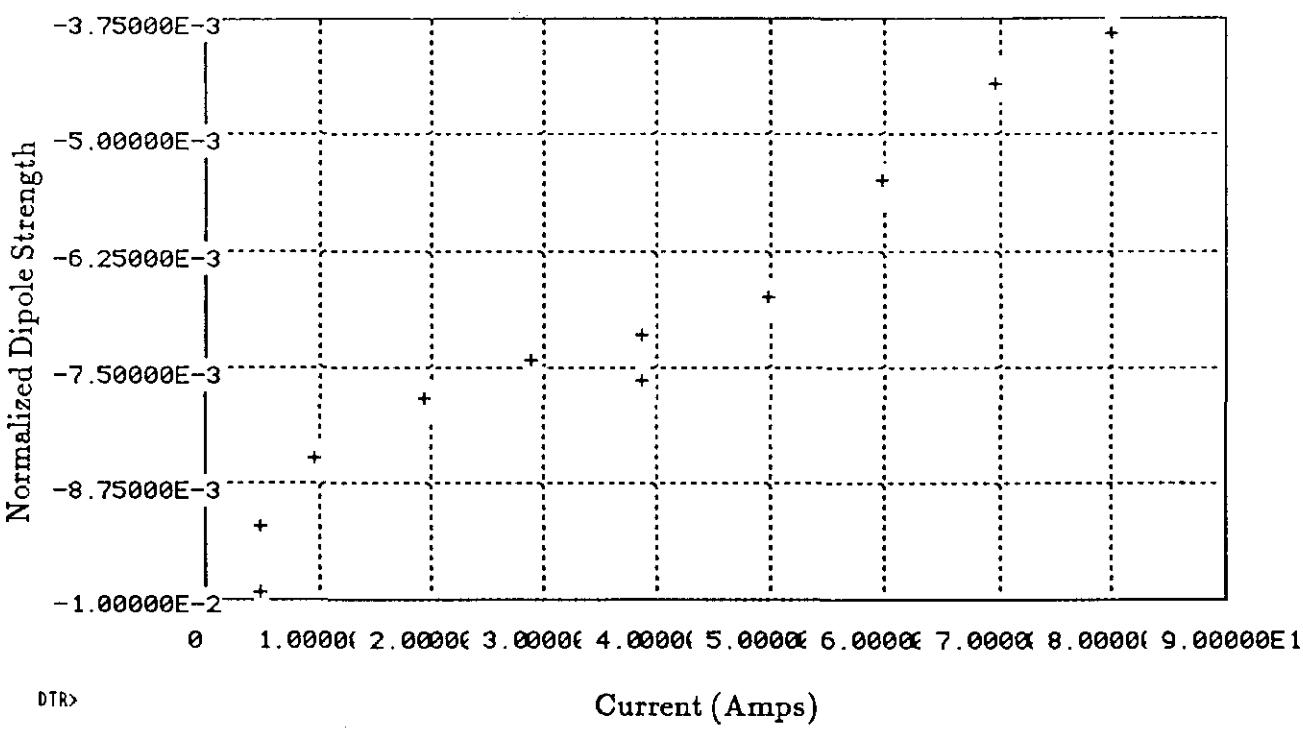
Magnetic Center Motion $= [.0025 - (-.00125)](1.3")(.0254) = 125\mu\text{m}$

Figure 10, Magnetic Center Motion TQT001



Magnetic Center Motion = $[-.01 - (-.08)](1.3")(.0254 = .002\text{m}$

Figure 11, Magnetic Center Motion TQT002



Magnetic Center Motion = $[-.00375 - (-.01)](1.3")(.0254 = 200\mu\text{m}$

Figure 12, Magnetic Center Motion TQT002

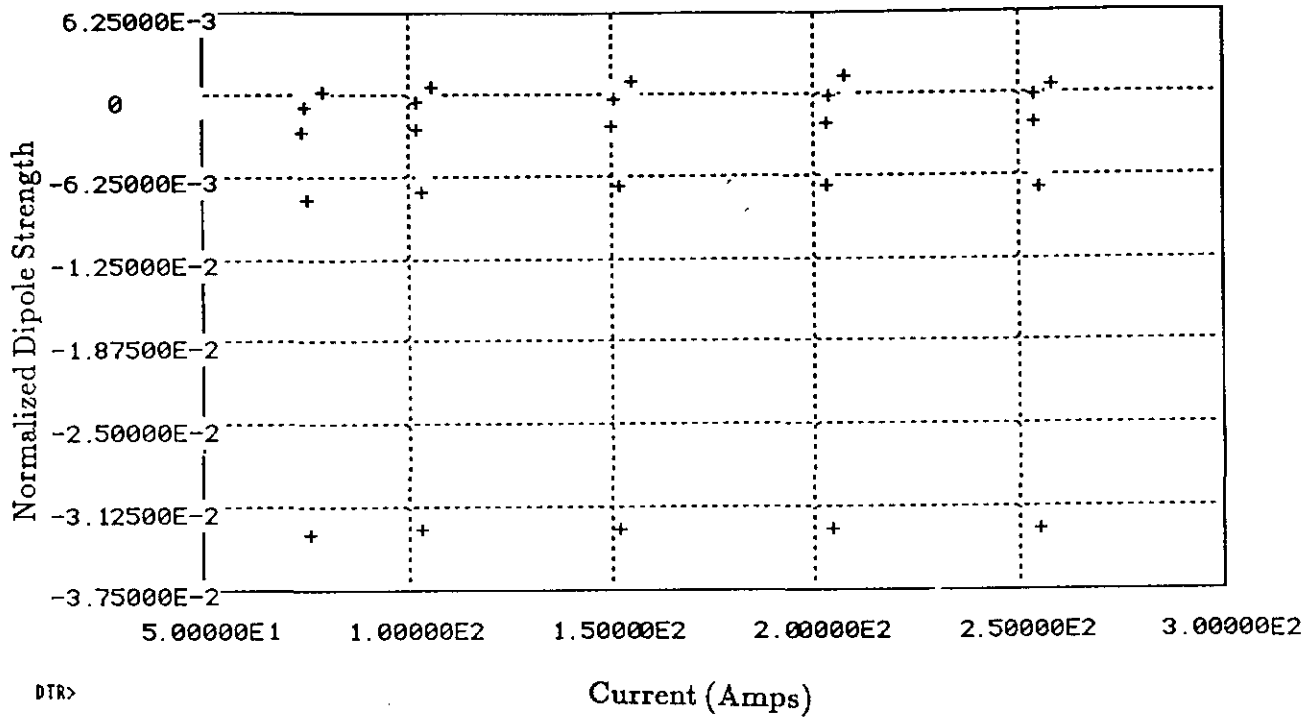
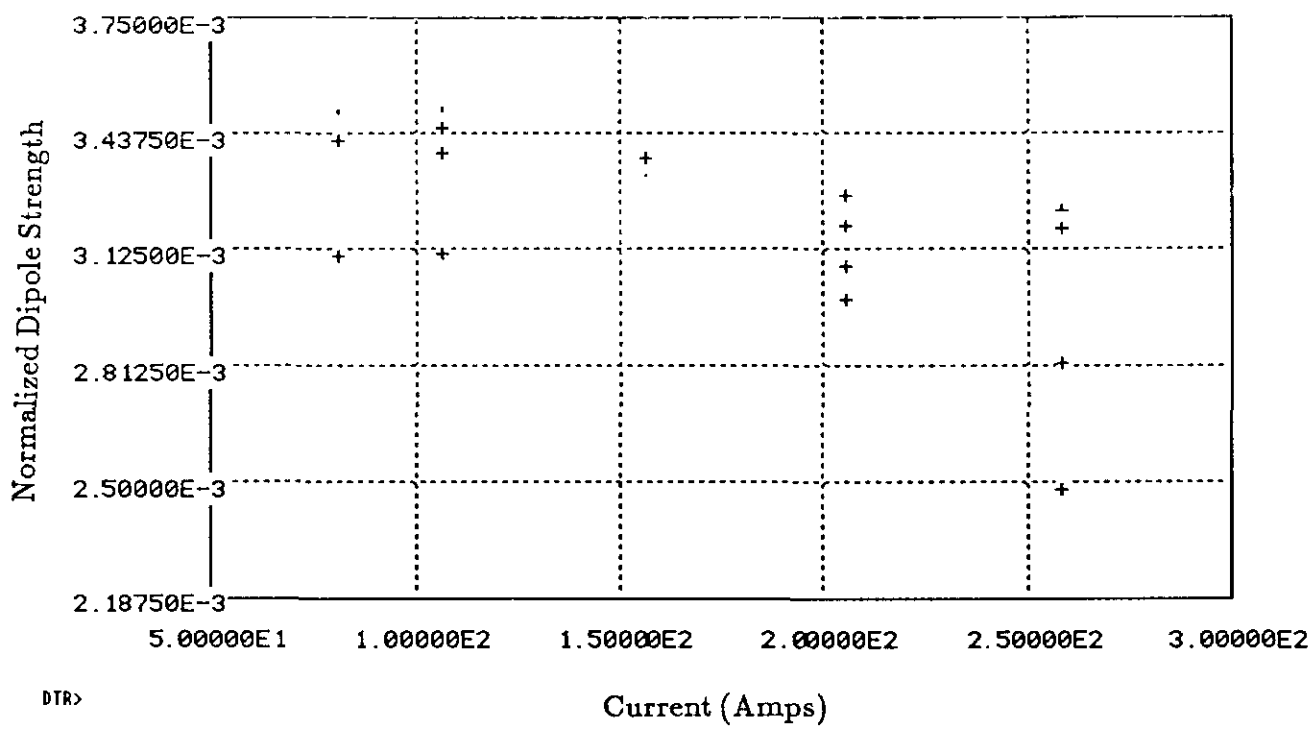


Figure 13, Magnetic Center Motion LQL001



Magnetic Center Motion $= (.0035 - .003125)(1.3")(.0254 = 12\mu m$

Figure 14, Magnetic Center Motion LQL004

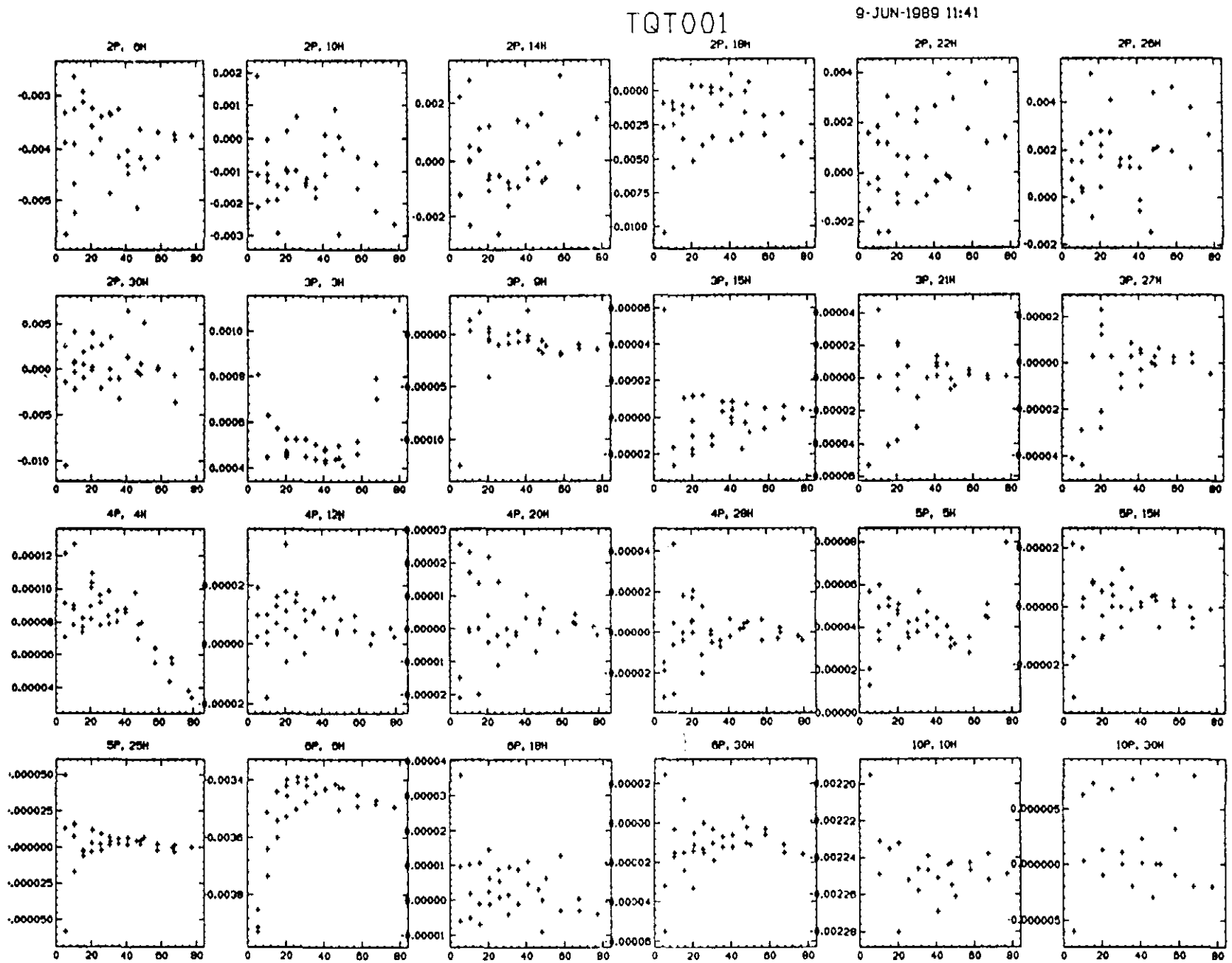


Figure 15, Harmonic Analysis TQT001

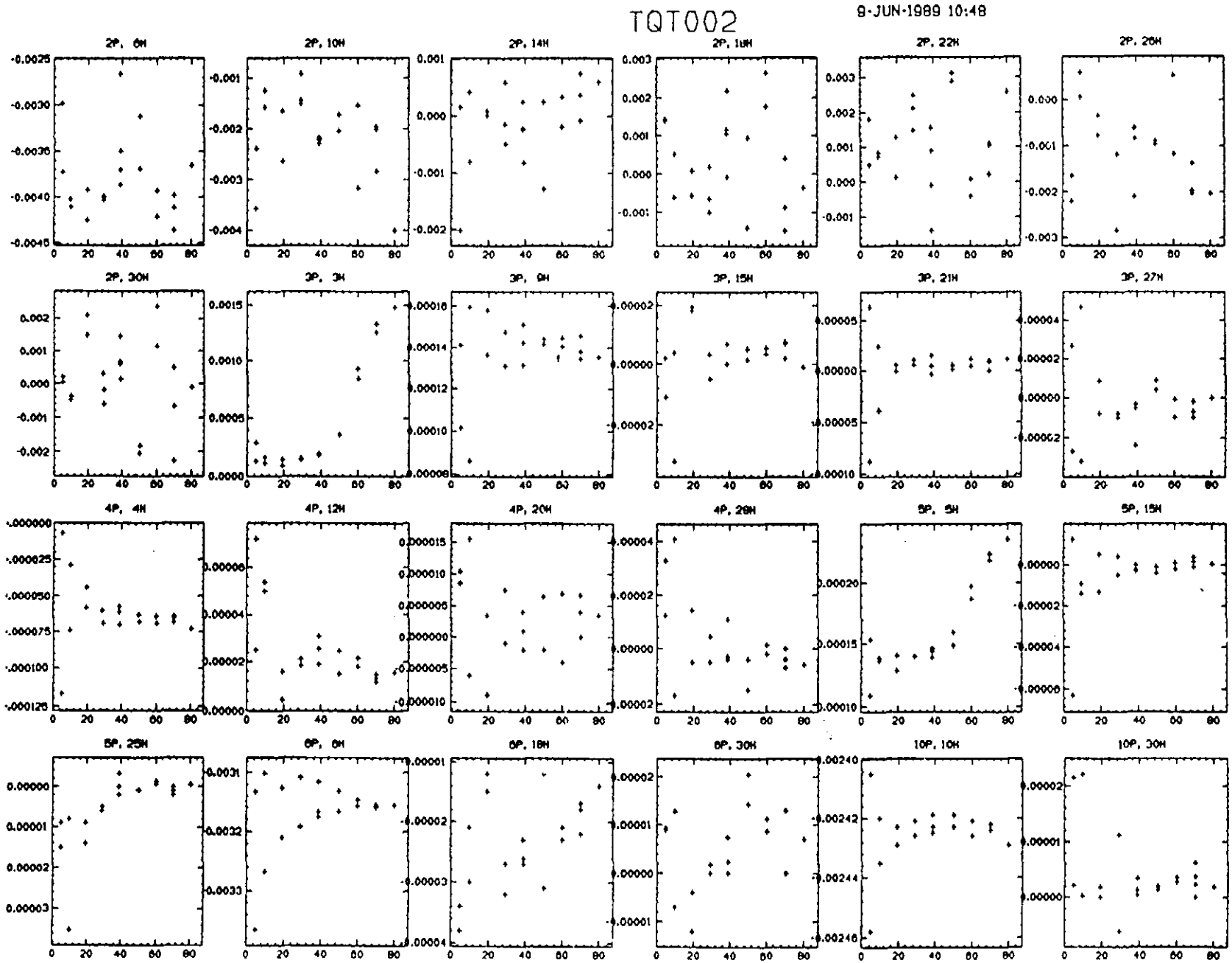


Figure 16, Harmonic Analysis TQT002

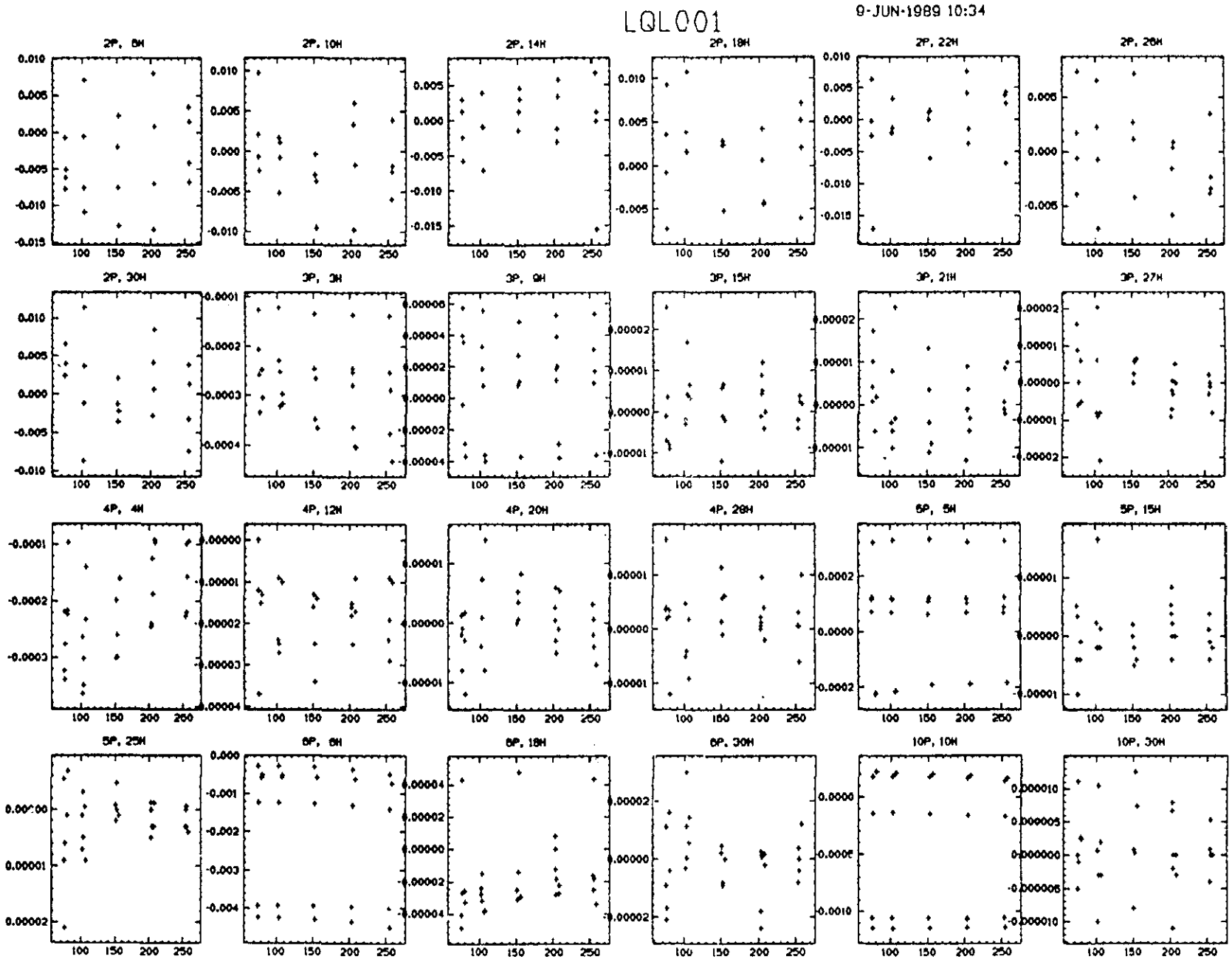


Figure 17, Harmonic Analysis LQL001

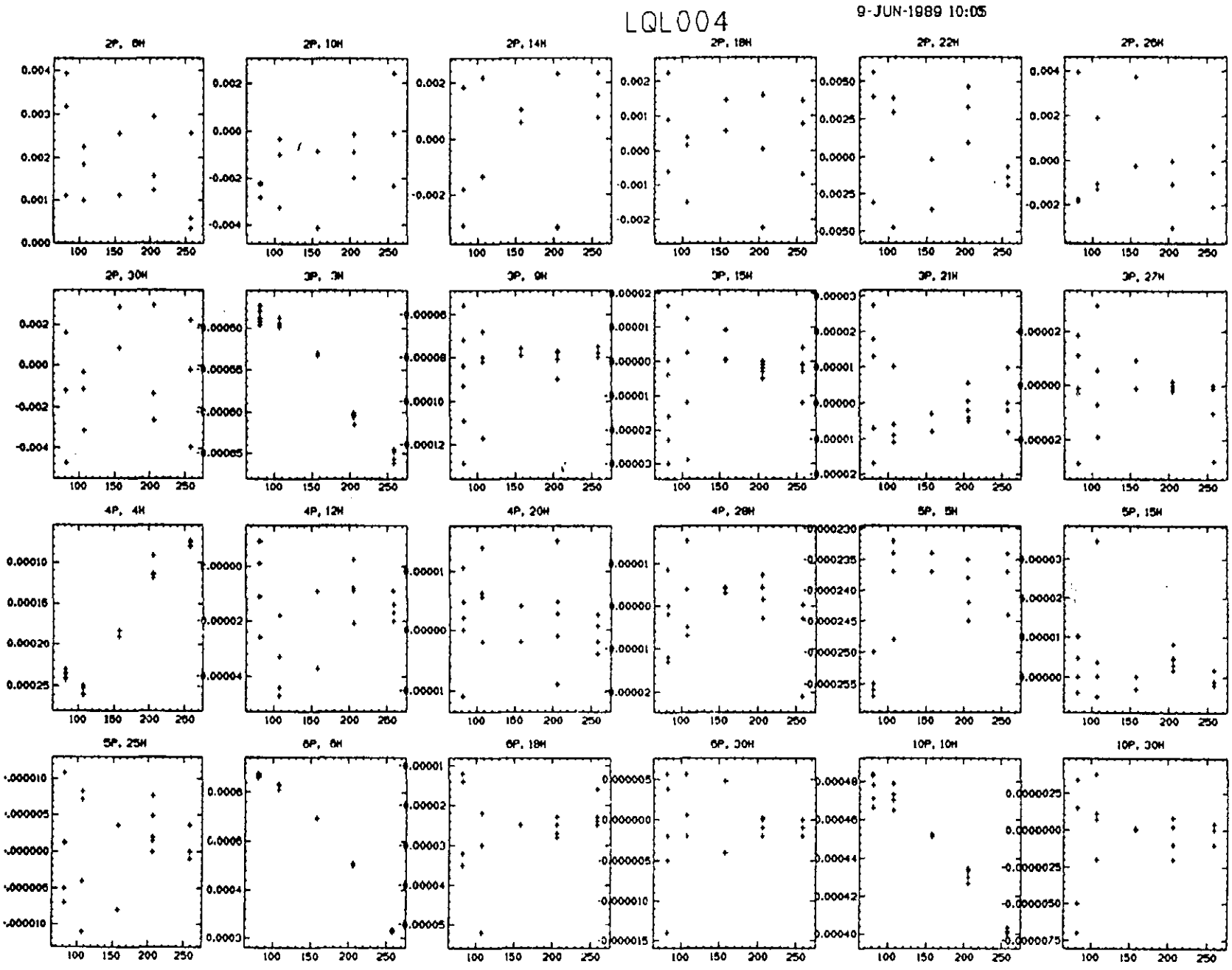


Figure 18, Harmonic Analysis LQL004