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Observation and Correction of Resonance Stopbands in the AGS Booster: 1992

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1 Introduction

During the 1992 Physics run, resonance stopbands were observed and studied for the first time in the AGS Booster, and the system developed to correct the resonances was tested with beam for the first time. The resonances were studied at low intensity on two flat porches—one at 1.0 GeV/c and the other at 1.7 GeV/c—during the study portion (user 3) of the Booster supercycle. The effects of the stopband corrections during the Physics portion (user 1) of the supercycle were also studied. In this report we summarize our observations and discuss some of the questions they raise.

2 The Second and Third Order Resonances

The Booster operates in a region of tune space for which the horizontal and vertical tunes (Q_x and Q_y) are between four and five. Following is a list of the second and third order resonance lines which cross this region.

Second order (excited by quadrupole fields):

$$2Q_x = 9, \quad 2Q_y = 9 \tag{1}$$

Second order (excited by skew quadrupole fields):

$$Q_x + Q_y = 9, \quad Q_x - Q_y = 0 \tag{2}$$

Third order (excited by sextupole fields):

$$3Q_x = 14, \quad Q_x + 2Q_y = 14 \tag{3}$$

$$3Q_x = 13, \quad Q_x + 2Q_y = 13 \tag{4}$$

$$2Q_y - Q_x = 5, \quad 2Q_y - Q_x = 4 \tag{5}$$

Third order (excited by skew sextupole fields):

$$3Q_y = 14, \quad Q_y + 2Q_x = 14 \tag{6}$$

$$3Q_y = 13, \quad Q_y + 2Q_x = 13 \tag{7}$$

$$2Q_x - Q_y = 5, \quad 2Q_x - Q_y = 4 \tag{8}$$

The parenthetical remarks serve to remind the reader of the type of multipole field which excites each resonance. We should also add that the resonances containing a minus sign, i.e. the difference resonances, produce only bounded betatron oscillations when excited, while those containing no minus sign, i.e. the sum resonances, can produce unlimited growth of betatron oscillations. Resonances containing both tunes generally involve the exchange of energy between the two planes of oscillation. A brief summary of the basic results of the theory of sum and difference resonances is given in the appendix. A tune diagram containing the second and third order resonance lines is shown in Figure 1.

3 The Resonance Correction System

The resonance correction system designed for the booster is discussed in Refs. (1–4). It is capable of correcting resonances (1–4) simultaneously—i.e. it can correct each of these resonances without affecting the correction of the others. (This is necessary because the space-charge detuning of the beam particles spreads their tunes over several of the resonance lines.) The remaining resonances (5–8) are either difference resonances or resonances excited by skew sextupole fields. These were not considered in the development of the correction scheme for the booster (because the difference resonances produce only limited growth of betatron oscillations and the skew sextupole fields are generally relatively small) but may require correction in the future. During the course of our studies, in fact, beam losses due to the first of resonances (5), and the second of resonances (6) were observed. These observations and those of resonances (1–3) are discussed in the subsequent sections.

4 Observation and Correction of the $2Q_x = 9$, $2Q_y = 9$, and $Q_x + Q_y = 9$ Resonances on the 1.7 GeV/c Porch

To observe these resonances, a low intensity beam was injected into the booster on the study cycle (user 3) and the tunes were programmed to pass through the resonances on the 1.7 GeV/c porch. The vertical tune was held fixed at 4.59 while the horizontal tune went from 4.62 to 4.38 as indicated by the line connecting points A and B in Figure 1. Figure 2 shows the beam loss as the tunes first cross the $2Q_x = 9$ and then the $Q_x + Q_y = 9$ resonance. Here no stopband corrections have been applied and the upper and lower traces show the circulating beam current (unnormalized) and the current in the horizontal quadrupoles. In Figure 3 the $2Q_x = 9$ resonance has been corrected and beam loss is seen only as the tunes pass through the uncorrected $Q_x + Q_y = 9$ resonance. Conversely in Figure 4 the $Q_x + Q_y = 9$ resonance has been corrected and beam loss is seen only as the tunes pass through the uncorrected $2Q_x = 9$ resonance. Figure 5 shows only a small beam loss with both resonances corrected.

The tunes were also programmed to follow the line connecting points A and C in Figure 1 thereby passing through the $2Q_y = 9$ and $Q_x + Q_y = 9$ resonances. Both resonances were corrected so that no beam loss occured and it was verified that the correction required to correct $2Q_x = 9$ did not depend on the amount of correction applied to correct $2Q_y = 9$ (and vice versa).

The corrections required to correct all three resonances are summarized below:

Resonance	Correction Required
$2Q_x = 9$	$\cos 9x = 350$ $\sin 9x = 300$
$2Q_y = 9$	$\cos 9y = 400$ $\sin 9y = 50$
$Q_x + Q_y = 9$	$\cos 9xy = 290$ $\sin 9xy = -90$

The corresponding currents in the four strings of quadrupoles and four strings of skew quadrupoles are (in Amps): QVSTR1 = 0.9, QHSTR1 = 0.4, QVSTR2 = −0.6, QHSTR2 = −1.4, and QSSTR1 = 2.8, QSSTR2 = −2.3, QSSTR3 = −2.8, QSSTR4 = 2.3.

5 Observation and Correction of the $Q_x - Q_y = 0$ Resonance on the 1.7 GeV/c Porch

To study this resonance, the horizontal and vertical tunes were programmed to be equal on the 1.7 GeV/c porch and the beam was kicked in the horizontal plane with the tune meter kicker. The amplitude of the peak in the vertical FFT spectrum was then recorded for various settings of the $Q_x - Q_y = 0$ resonance correction, $\cos 0xy$. These amplitudes are a measure of the coupling between the two planes and are plotted in Figure 6. Here we see that the coupling reaches a minimum (i.e. the resonance is corrected) near $\cos 0xy = 500$. The corresponding currents in the four skew quadrupole strings are (in Amps): QSSTR1 = 2.8, QSSTR2 = −0.5, QSSTR3 = 2.8, QSSTR4 = −0.5.

6 Observation of the $3Q_x = 14$, $Q_x + 2Q_y = 14$, and $2Q_y - Q_x = 5$ Resonances on the 1.0 GeV/c Porch

These resonances were observed at low intensity on the 1.0 GeV/c porch, where the tunes were programmed to follow the lines connecting points A, B, and C as indicated in Figure 7. The beam losses as the tunes pass through the $2Q_y - Q_x = 5$ and then the $3Q_x = 14$ resonance are shown in Figure 8. (The tune meter was used to verify that the tunes were passing through each resonance.) It was found that excitation of the $3Q_x = 14$ resonance required that the correction, $\cos 14xy$, for the $Q_x + 2Q_y = 14$ resonance be nonzero. This presumably means that the matrices used in the correction program are not quite right. Steve Tepikian has supplied a new set of matricies which hopefully will solve this problem. The loss due to the $2Q_y - Q_x = 5$ resonance, which requires a 5θ harmonic in the sextupole fields around the ring, was not affected by the corrections for the $3Q_x = 14$ and $Q_x + 2Q_y = 14$ resonances, which produce no 5θ harmonic. Although the present correction system has no provision for correcting the $2Q_y - Q_x = 5$ resonance, the corrections for the $3Q_x = 13$ and $Q_x + 2Q_y = 13$ resonances do produce a 5θ harmonic in addition to the desired 13θ harmonic and therefore could excite the $2Q_y - Q_x = 5$ resonance. This possibility has not been investigated and could be a problem if, in the future, one wishes to correct all three resonances simultaneously. We should also mention here that the corrections for the $3Q_x = 14$ and $Q_x + 2Q_y = 14$ resonances produce a 4θ harmonic which can excite the $2Q_y - Q_x = 4$ resonance. Further analysis and/or studies are required to determine whether or not, or under what conditions the difference resonances $2Q_y - Q_x = 5$ and $2Q_y - Q_x = 4$ are harmful.

The tunes were also programmed to follow the line from point E to point D in Figure 7 thereby passing through the $3Q_x = 14$ resonance. The beam loss due to this resonance is shown in Figure 9 where the $\cos 14xy$ correction has been set to 500. With all corrections set to zero, the beam passes through the resonance with no loss as shown in Figure 10.

Finally, the tunes were programmed to follow the line from point E to point G thereby passing through the $Q_y + 2Q_x = 14$, $2Q_y - Q_x = 5$, $Q_x + 2Q_y = 14$, and $3Q_y = 14$ resonances. (As before, the tune meter was employed to verify that the tunes were passing through these resonances.) The first loss seen in Figure 11 is due to the $Q_y + 2Q_x = 14$ resonance which is excited by skew sextupole fields and is discussed in the next section. The second loss is due to the $Q_x + 2Q_y = 14$ resonance with the $\cos 14x$ correction set to 800. Figure 12 shows that this loss disappears when all corrections are set to zero. There appears to be no loss as the tunes pass through the $3Q_y = 14$ resonance. This is somewhat puzzling because this resonance should be excited by the same fields which produce the loss seen as the $Q_y + 2Q_x = 14$ resonance is crossed.

7 Observation of the $Q_y + 2Q_x = 14$ and $2Q_x = 9$ Resonances on the 1.0 Gev/c Porch

These resonances were observed at low intensity on the 1.0 GeV/c porch as the tunes (which were, as before, verified with the tune meter) followed the line from point E to point F in Figure 7. The beam losses seen as the tunes first pass through the $Q_y + 2Q_x = 14$ and then the $2Q_x = 9$ resonance are shown in Figure 13. The loss due to the $Q_y + 2Q_x = 14$ resonance (which is excited by skew sextupole fields) was not affected by any of the available corrections, and in fact can not be corrected until skew sextupole correctors are put in the Booster ring. Further analysis and/or studies are required to determine whether or not, or under what conditions this resonance is harmful. In the meantime, it has been recommended that skew sextupole correctors be put in the ring during the current shutdown period, and various experts have been consulted about possible sources of skew sextupole fields in the Booster. It should be noted here that the resonance line $Q_y + 2Q_x = 14$ is equivalent to the line $2Q_y + 4Q_x = 28$ which is excited by dodecapole (i.e. 12-pole) fields. These fields can be produced by quadrupole magnets, but experts claim they are very small for the booster quadrupoles.

The loss due to the $2Q_x = 9$ resonance could not be eliminated completely with the corrections for this resonance. The loss was minimized with settings of $\cos 9x = 50$ and $\sin 9x = 50$ which correspond to currents of less than a tenth of an Amp in the quadrupole strings. Since the power supplies provide a maximum of 50 Amps, which corresponds to a setting of 2048 counts, the ability to completely correct the resonance may be limited by the least-count resolution in the setpoints for the currents.

8 The Effect of the Corrections during the Physics portion of the Supercycle

During the HEP portion (user 1) of the supercycle, the beam intensity in the Booster was 7.5×10^{12} protons at injection and 5.0×10^{12} just before extraction. A favorable operating point was found near $(Q_x, Q_y) = (4.8, 4.8)$, and the corrections for resonances (1–3) were tuned to see if they had any effect on the intensity. Only the corrections for the $Q_x + 2Q_y = 14$

resonance were found to have a significant effect. Figure 14 shows the normalized beam current and the current in a sextupole string during one of the user 1 booster cycles. The machine operators found that they could increase the intensity by about 5% with these corrections ramped to a value of 200 shortly after injection. Figure 15 shows that this ramp coincides with the transition from low to high B-dot during the magnetic cycle. Here the lower trace is the main magnet power supply voltage and the upper trace is the sextupole current, which reaches 20 Amps on the high B-dot portion of the cycle. This suggests that eddy currents in the vacuum chambers may be the source of the sextupole fields which excite the resonance. Since the effects of these currents are supposed to be compensated by the passive correction windings on each vacuum chamber, this may be an indication that one or more of the windings is not connected properly.

9 Concluding Remarks

The studies indicate that the corrections for the second-order resonances $2Q_x = 9$, $2Q_y = 9$, $Q_x + Q_y = 9$, and $Q_y - Q_x = 0$ are basically functioning properly. However there is some evidence that the ability to correct the $2Q_x = 9$ and $2Q_y = 9$ resonances may be limited by the least-count resolution in the correction current setpoints. It has been recommended that the maximum currents for these corrections be reduced from 50 to 12.5 Amps, thereby increasing the setpoint resolution by a factor of four.

The studies of the third-order resonances have raised questions about which of these resonances need to be corrected. As pointed out by Y.Y. Lee, and as discussed in Ref. (6), the effect of a given resonance depends on the machine operating point and on the location of a particle in the bunched beam. Particles near the longitudinal center of a bunch, where the current density is highest, experience the largest tune shift due to the space-charge force, and this places their tunes furthest from the operating point. They also have the largest amplitude-dependent tune shift which means that if they do cross a resonance they will move out of the stopband as the resonance is excited. The space-charge force therefore stabilizes and limits their oscillation amplitudes. Particles near the ends of a bunch, on the other hand, experience little or no space-charge force and their tunes remain near the operating point. If they cross a resonance here, they experience very little of the stabilizing effect of the space-charge force and are therefore susceptible to resonance blow-up. It follows that the resonances near the operating point are the ones that need to be corrected; those further away are not so important because of the stabilizing effect of the space-charge force.

For an operating point near $Q_x = Q_y = 4.8$, the third-order resonances $3Q_x = 14$, $Q_x + 2Q_y = 14$, $3Q_y = 14$, $Q_y + 2Q_x = 14$, and possibly $2Q_y - Q_x = 5$ and $2Q_x - Q_y = 5$ are potentially harmful. Of these, only the $3Q_x = 14$ and $Q_x + 2Q_y = 14$ resonances can be corrected with the present correction system. Correction of the $2Q_y - Q_x = 5$ resonance with the existing sextupoles is being investigated. The correction of the $3Q_y = 14$ and $Q_y + 2Q_x = 14$ resonances would require four skew sextupoles appropriately placed in the Booster ring. Gordon Danby and John Jackson are investigating how these magnets could be made with additional windings placed on the existing correction dipoles.

If the operating point is near $Q_x = Q_y = 4.4$, as may be required for the acceleration of gold in the booster, then the resonances $3Q_x = 13$, $Q_x + 2Q_y = 13$, $3Q_y = 13$, $Q_y + 2Q_x = 13$, and possibly $2Q_y - Q_x = 4$ and $2Q_x - Q_y = 4$ are potentially harmful. Of these, only the $3Q_x = 13$ and $Q_x + 2Q_y = 13$ resonances can be corrected with the present correction system. Correction of the $2Q_y - Q_x = 4$ resonance could be accomplished with existing sextupoles, but correction of the $3Q_y = 13$ and $Q_y + 2Q_x = 13$ resonances would require skew sextupoles.

The fact that the corrections for the second-order resonances (1–2) had little affect on the beam intensity (7.5×10^{12} protons at injection) during the HEP portion of the supercycle, is consistent with the operating point, $Q_x = Q_y = 4.8$, and a space-charge tune shift of at most -0.3 in each plane. It would be useful to confirm this with a careful calculation of the space-charge tune shift for the Booster. Such a calculation has been carried out for the AGS and is discussed in Ref. (7).

10 Appendix: Sum and Difference Resonances

A detailed discussion of the theory of sum and difference resonances may be found in Ref. (5). Following are some basic results.

The resonance is defined by the equation

$$mQ_x + nQ_y = N, \tag{9}$$

where Q_x and Q_y are the horizontal and vertical tunes, and m, n, and N are integers. If m and n have opposite signs, the resonance is called a difference resonance; otherwise it is called a sum resonance. The order, l, of the resonance is

$$l = |m| + |n|. \tag{10}$$

If the tunes are sufficiently close to the resonance, i.e. if they are within the resonance stopband, and if n is even (odd), the resonance will be excited by the Nth harmonic, in azimuth θ, of the normal (skew) $2l$-pole fields present in the machine. The resonance condition (9) arises from the first-order perturbation treatment of the vector potential terms $x^{|m|}y^{|n|}$ associated with the $2l$-pole field. The width of the stopband is proportional to the strength of the $2l$-pole field, and for resonances of order 3 and higher also depends on the amplitudes, J_x and J_y, of the betatron oscillations. If the tunes are near the resonance, and if $m \neq 0$, $n \neq 0$, then the quantity

$$C = nJ_x - mJ_y \tag{11}$$

is a constant of the motion. For the case of the difference resonances this implies that the amplitudes are bounded; for sum resonances the amplitudes can increase without bound. In the presence of space-charge forces the amplitudes are generally bounded as discussed in Ref. (6).

11 References

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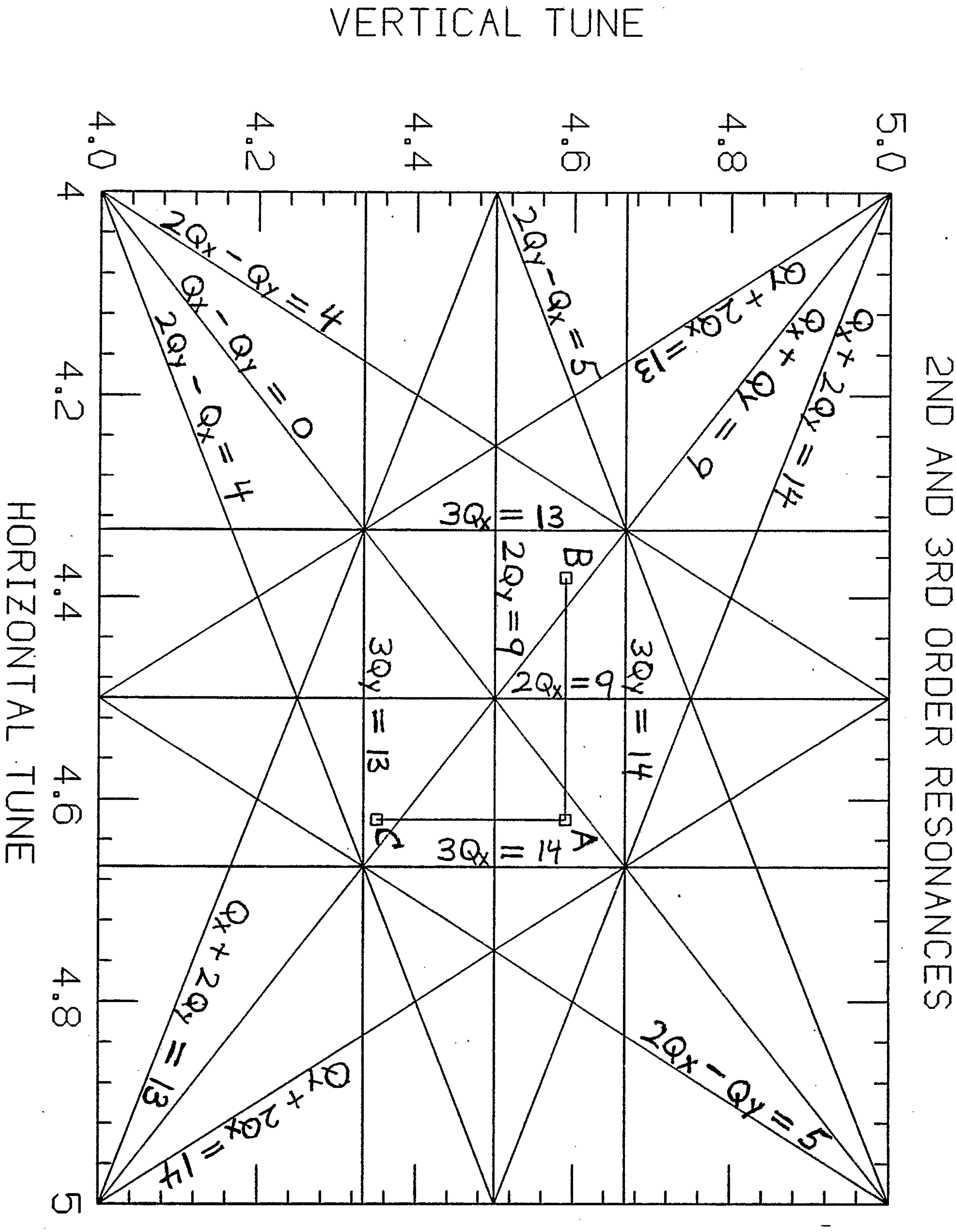
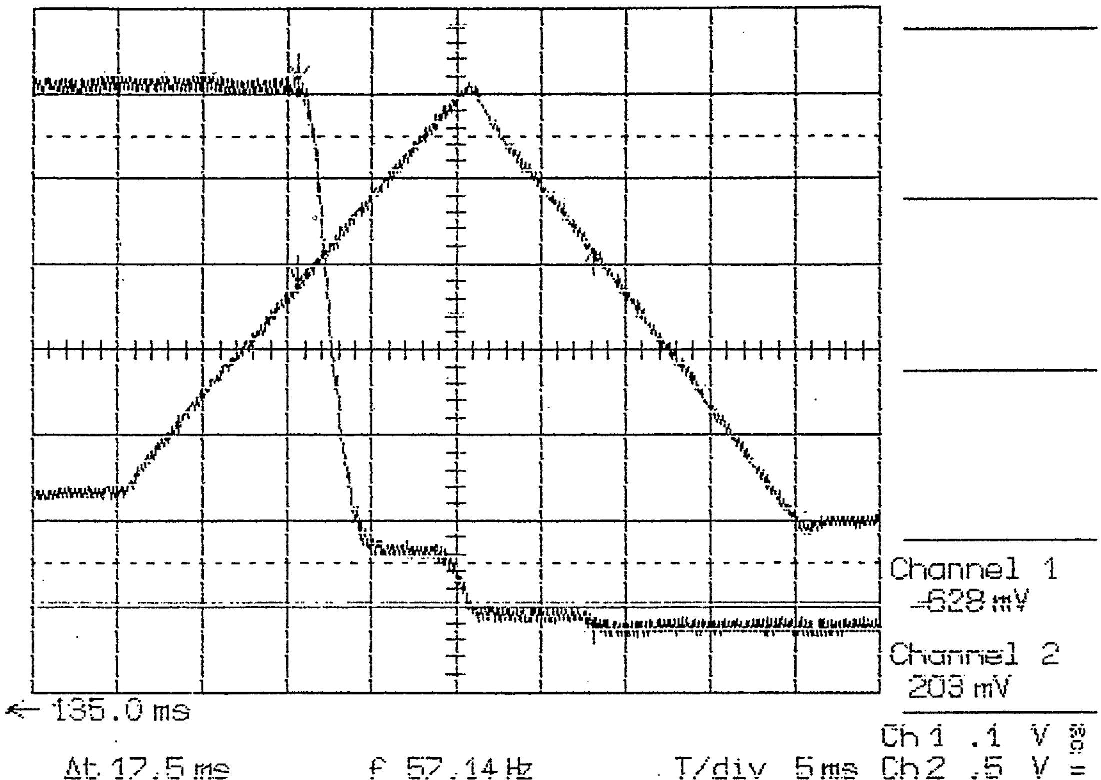
6. W.T. Weng, Space Charge Effects—Tune Shifts and Resonances, Physics of Particle Accelerators, AIP Conference Proceedings 153, American Institute of Physics, New York, 1987, pp. 348–389.

7. E. Raka, et al., Increased Intensity Performance of the Brookhaven AGS, IEEE Trans. Nucl. Sci., NS-32, No. 5, 3110 (1985).



VERTICAL TUNE
HORIZONTAL TUNE
2ND AND 3RD ORDER RESONANCES
4.0
4.2
4.4
4.6
4.8
5.0
4
4.2
4.4
4.6
4.8
5
2Qx − Qy = 4
Qx − Qy = 0
2Qy − Qx = 4
2Qy − Qx = 5
Qy + 2Qx = 13
Qx + Qy = 9
Qx + 2Qy = 14
3Qx = 13
2Qy = 9
2Qx = 9
3Qy = 13
3Qy = 14
3Qx = 14
A
B
C
Qx + 2Qy = 13
Qy + 2Qx = 14
2Qx − Qy = 5

Figure 1


Channel 1
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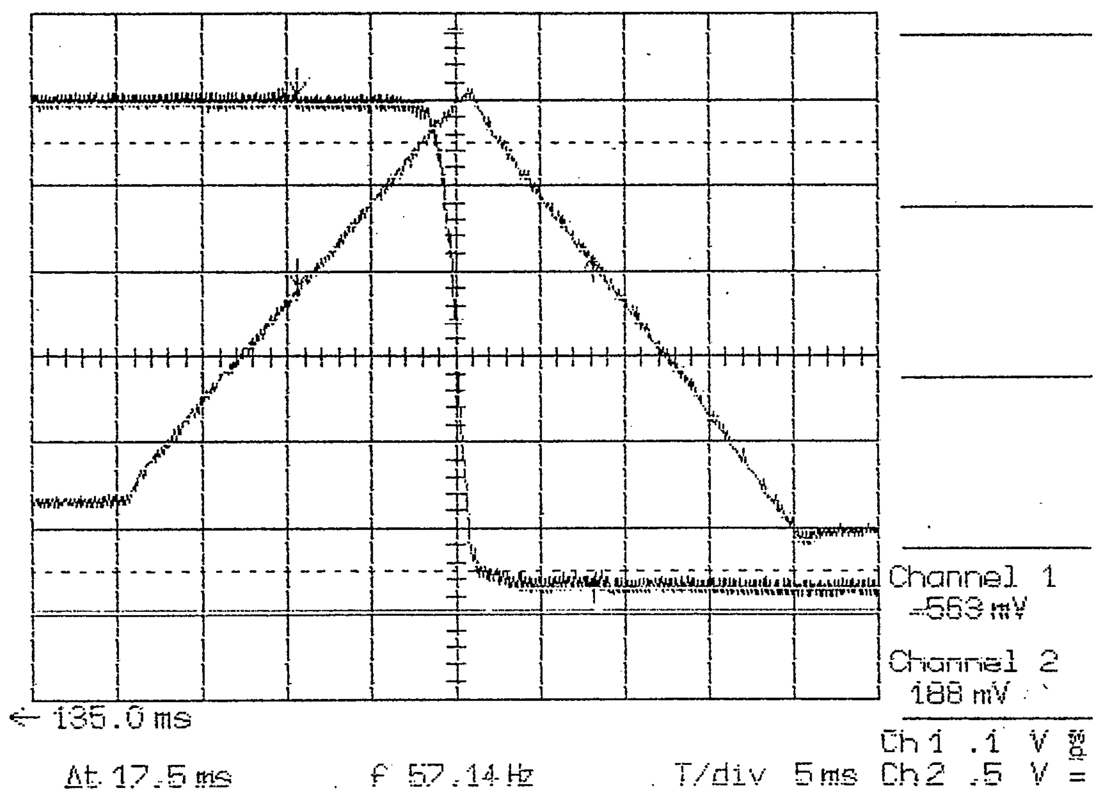
Channel 2
203 mV
← 135.0 ms
Δt 17.5 ms
f 57.14 Hz
T/div 5 ms
Ch1 .1 V
Ch2 .5 V =

Fig. 2


Channel 1
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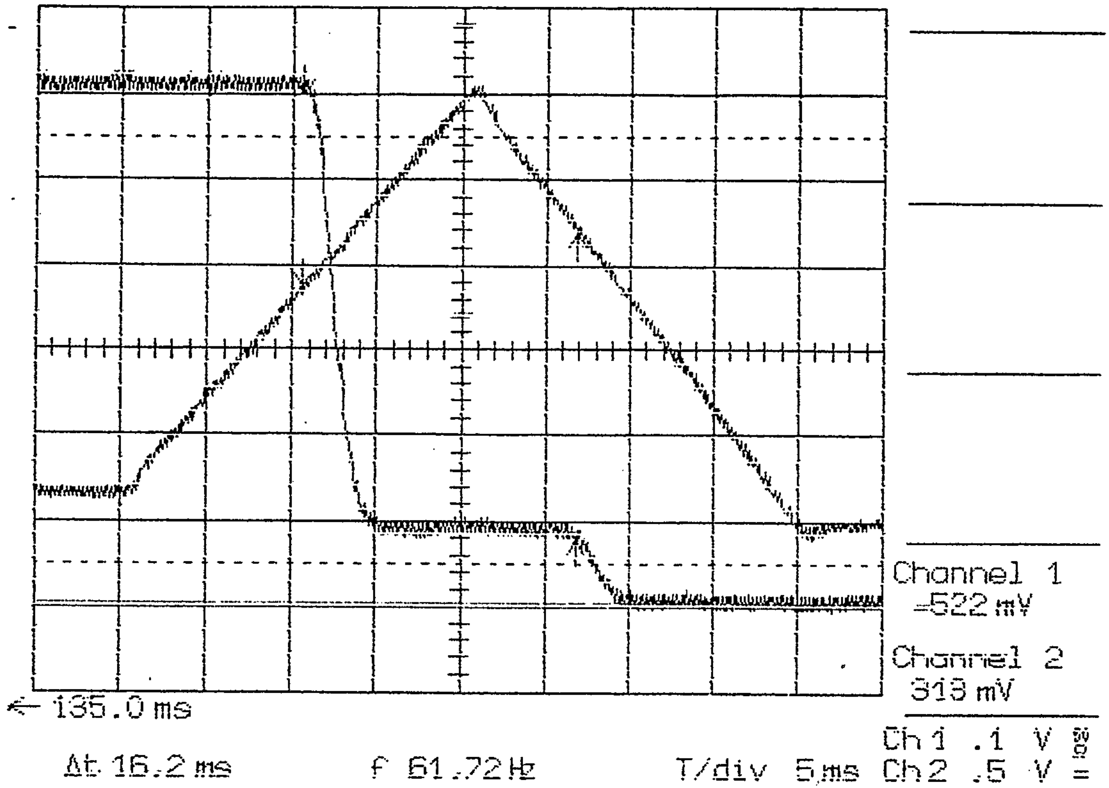
Channel 2
188 mV
← 135.0 ms
Δt 17.5 ms
f 57.14 Hz
T/div 5 ms
Ch1 .1 V
Ch2 .5 V =

Fig. 3


Channel 1
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Channel 2
318 mV
← 135.0 ms
Δt 16.2 ms
f 61.72 Hz
T/div 5 ms
Ch1 .1 V
Ch2 .5 V

Fig. 4

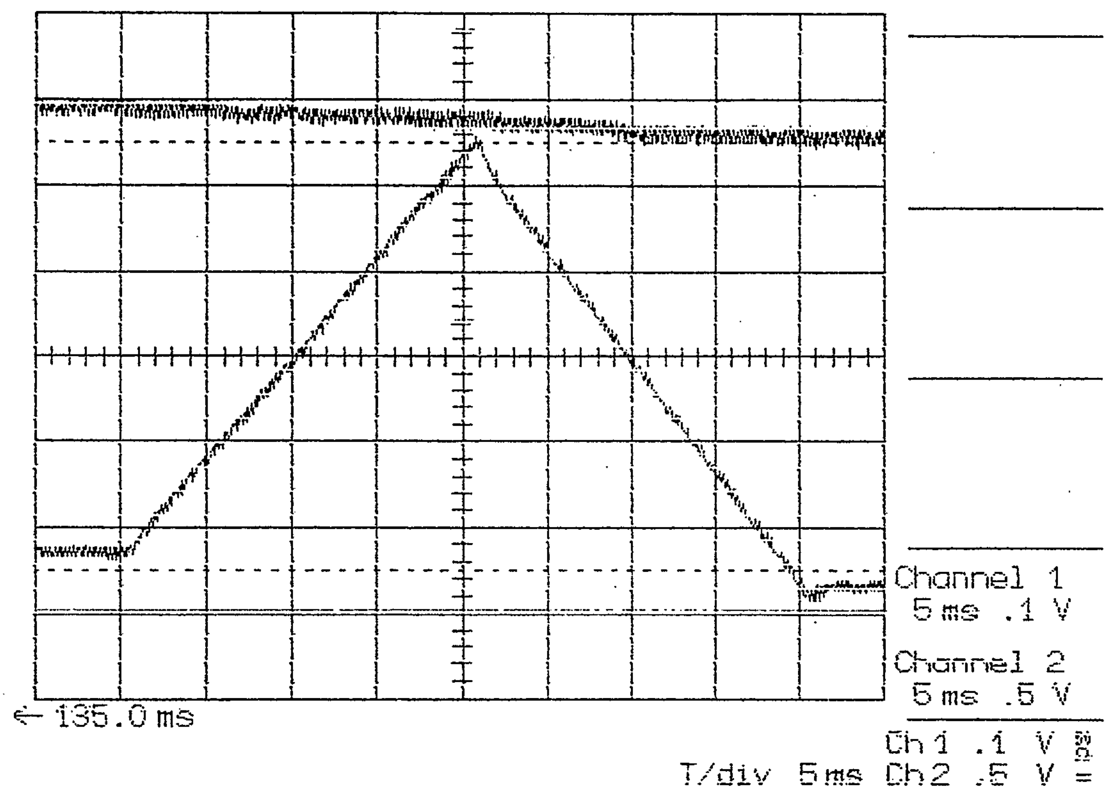

Channel 1
5 ms .1 V
Channel 2
5 ms .5 V
← 135.0 ms
T/div 5 ms
Ch1 .1 V
Ch2 .5 V

Fig. 5

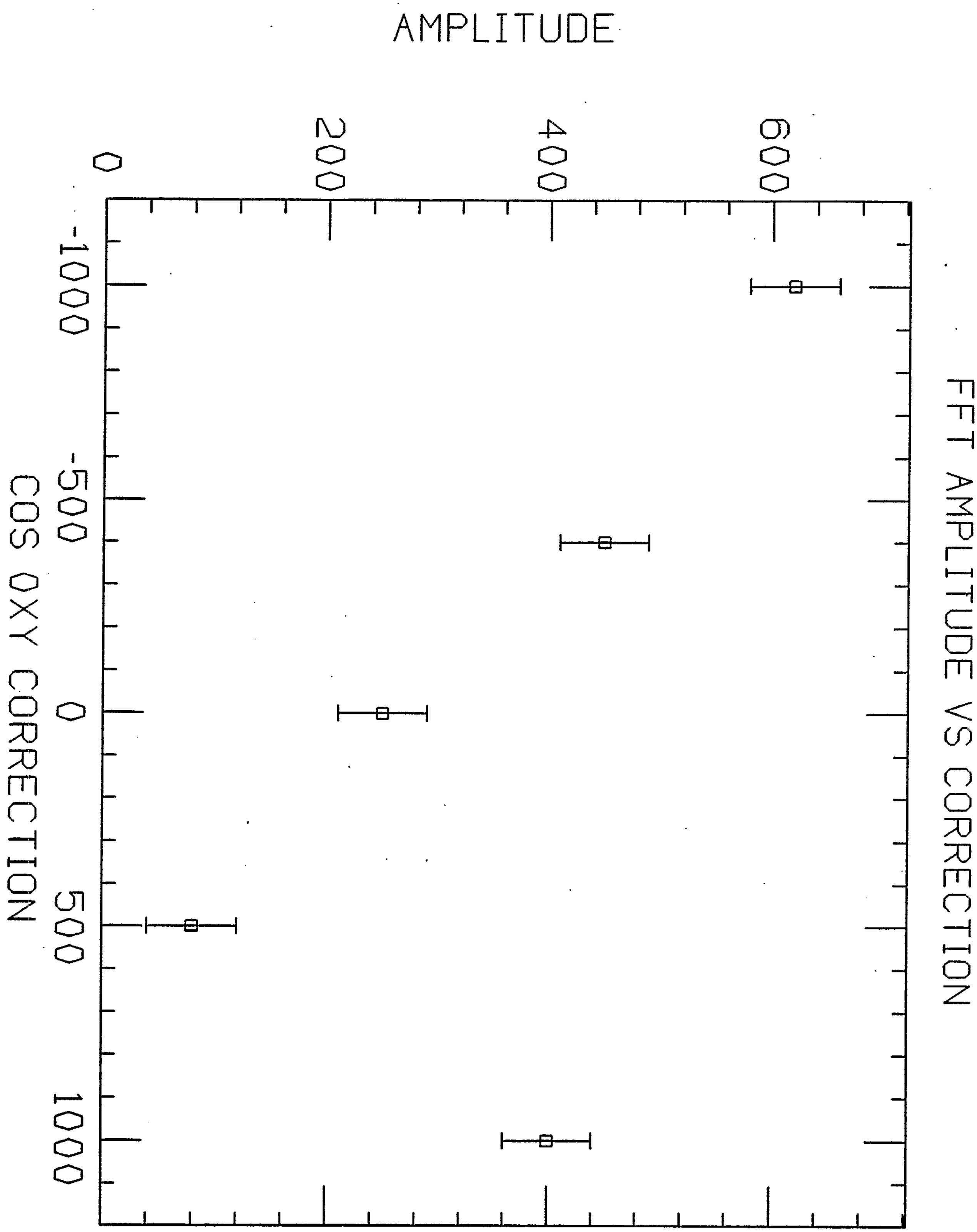

FFT AMPLITUDE VS CORRECTION
AMPLITUDE
0
200
400
600
-1000
-500
0
500
1000
COS OXY CORRECTION

Fig. 6

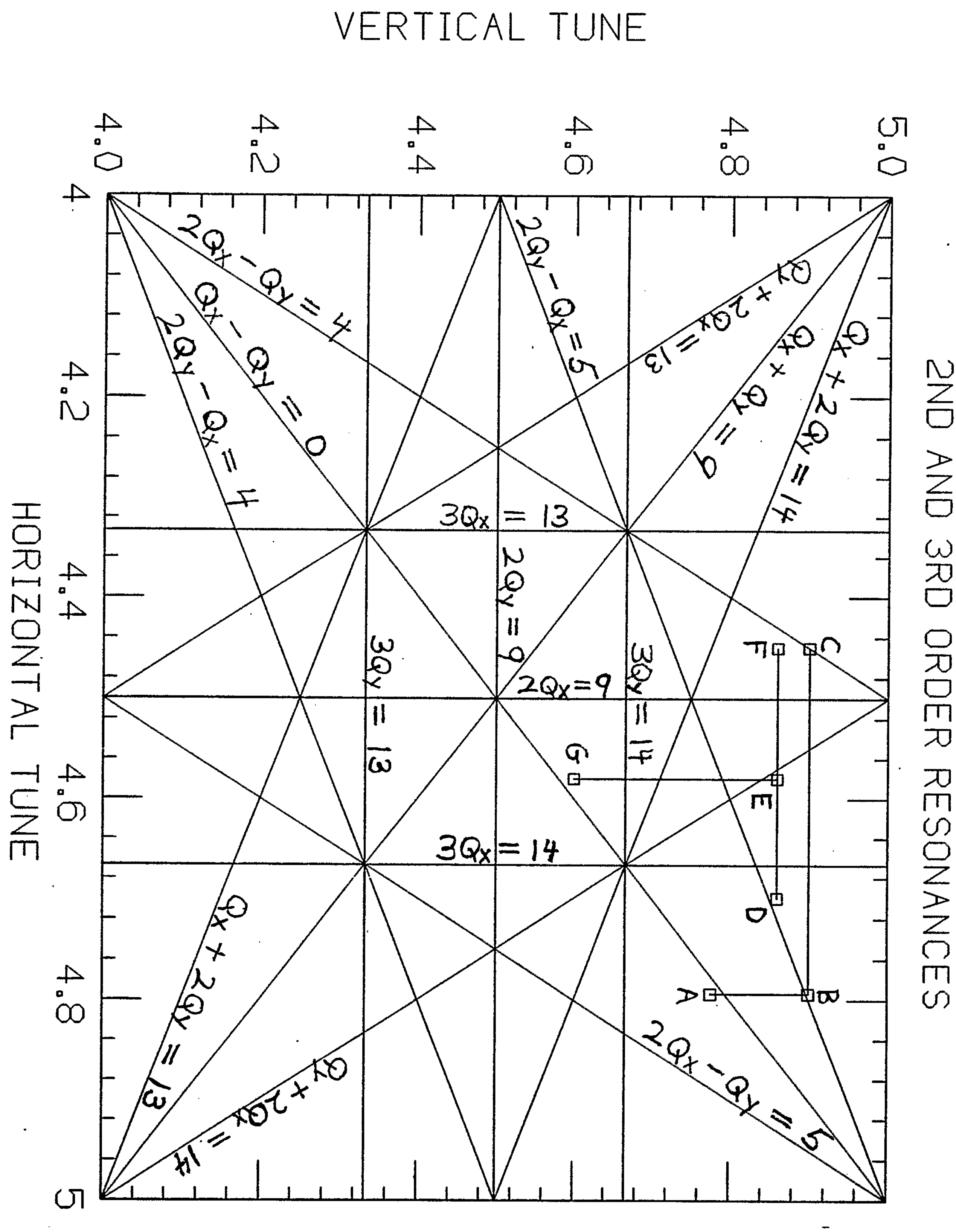
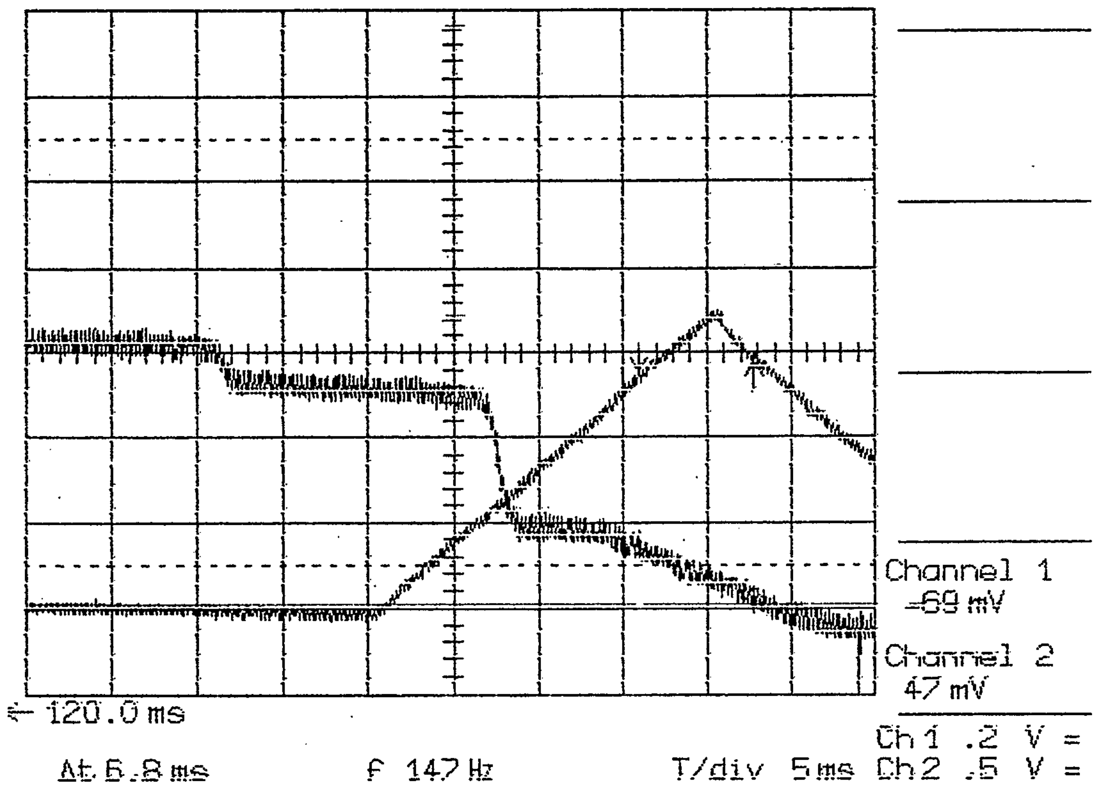
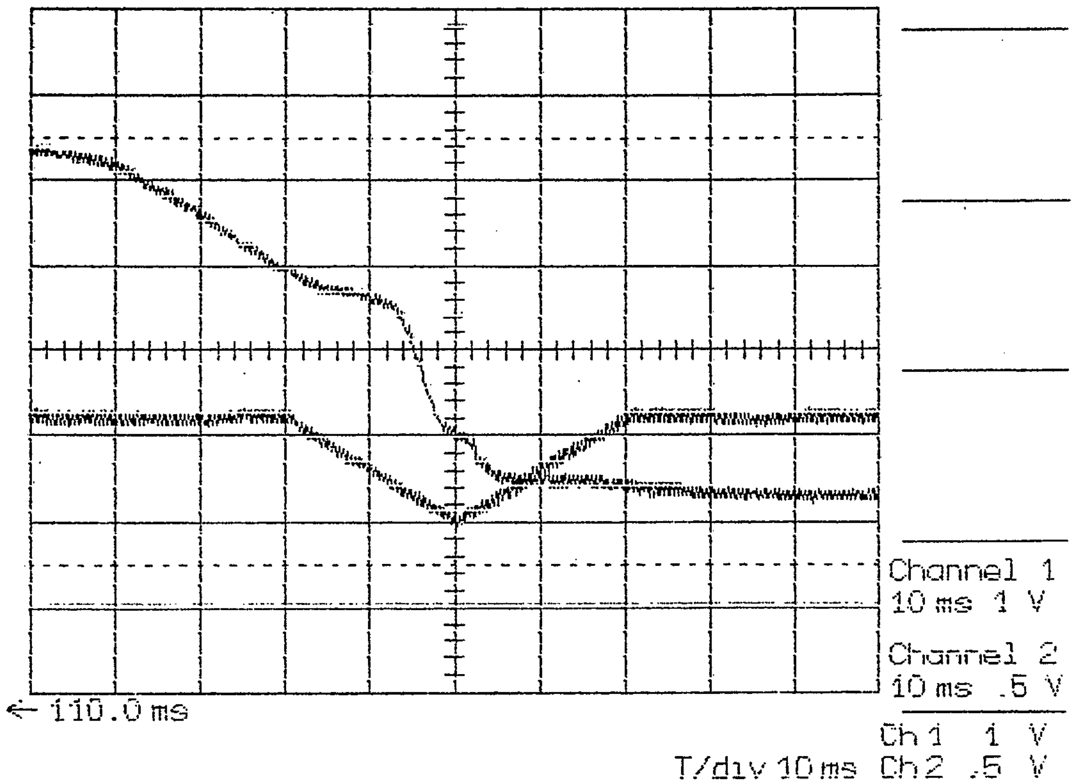

VERTICAL TUNE
HORIZONTAL TUNE
2ND AND 3RD ORDER RESONANCES
4.0
4.2
4.4
4.6
4.8
5.0
4
5
2Qx - Qy = 4
Qx - Qy = 0
2Qy - Qx = 4
2Qy - Qx = 5
Qy + 2Qx = 13
Qx + Qy = 9
Qx + 2Qy = 14
3Qx = 13
2Qy = 9
2Qx = 9
3Qy = 13
3Qy = 14
3Qx = 14
Qx + 2Qy = 13
Qy + 2Qx = 14
2Qx - Qy = 5
A
B
C
D
E
F
G

Figure 7



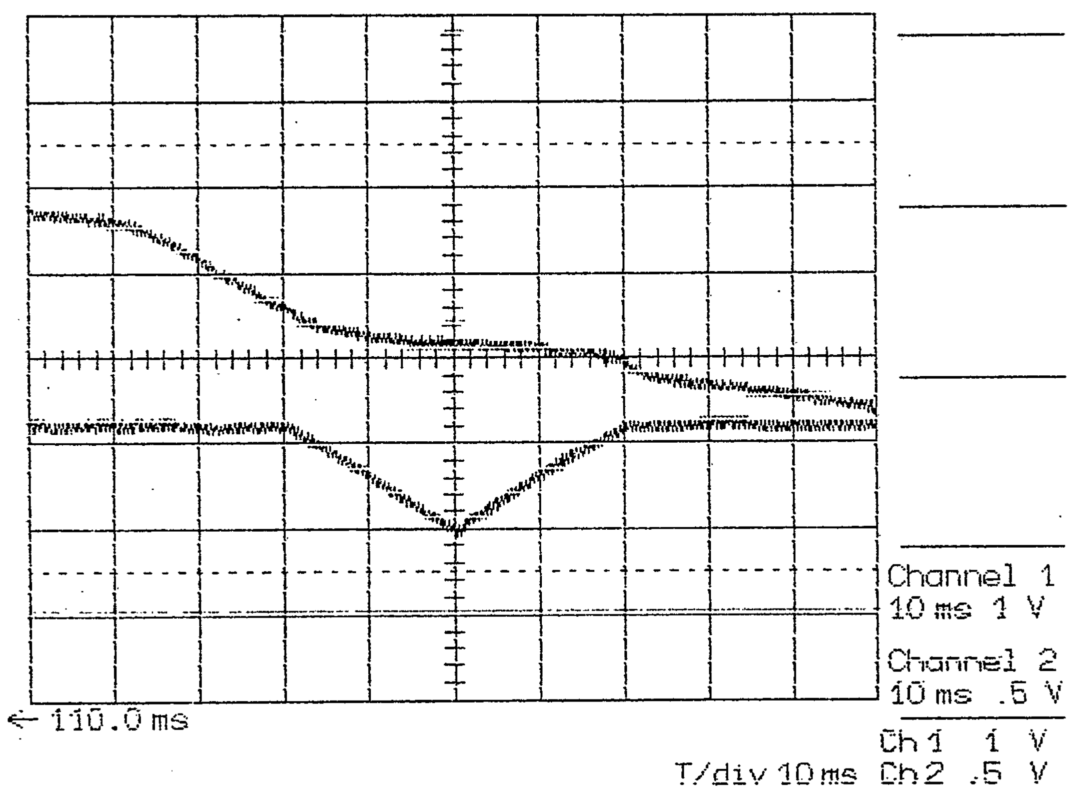
Channel 1
-69 mV
Channel 2
47 mV
← 120.0 ms
Ch 1 .2 V =
At 6.8 ms
f 147 Hz
T/div 5 ms
Ch 2 .5 V =

Fig. 8



Channel 1
10 ms 1 V
Channel 2
10 ms .5 V
← 110.0 ms
Ch 1 1 V
T/div 10 ms Ch 2 .5 V

Fig. 9



Channel 1
10 ms 1 V
Channel 2
10 ms .5 V
← 110.0 ms
Ch 1 1 V
T/div 10 ms Ch 2 .5 V

Fig. 10

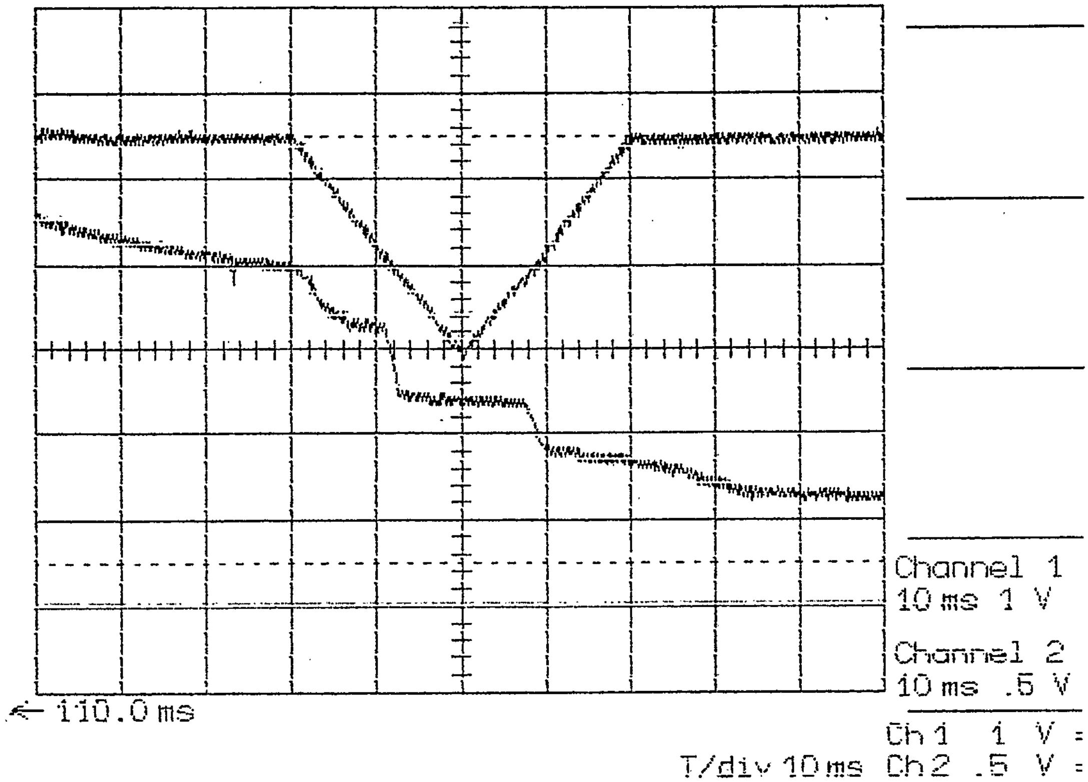

Channel 1
10 ms 1 V
Channel 2
10 ms .5 V
← 110.0 ms
Ch1 1 V :
T/div 10 ms Ch2 .5 V :

Fig. 11

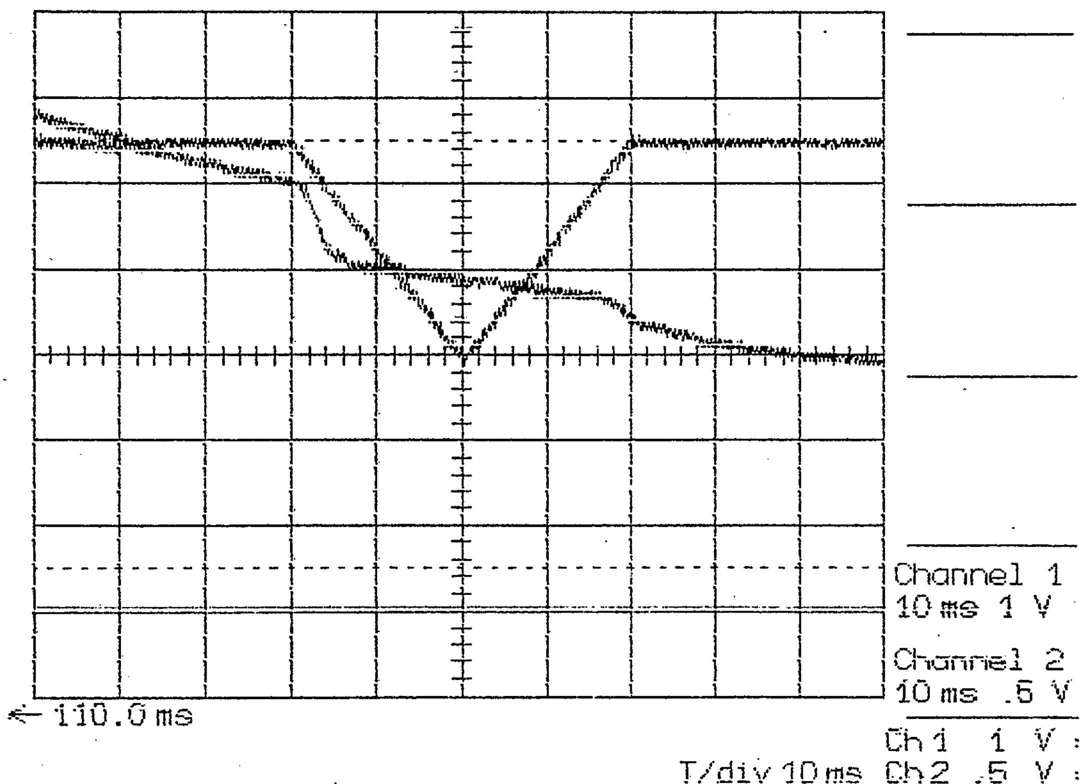

Channel 1
10 ms 1 V
Channel 2
10 ms .5 V
← 110.0 ms
Ch1 1 V :
T/div 10 ms Ch2 .5 V :

Fig. 12

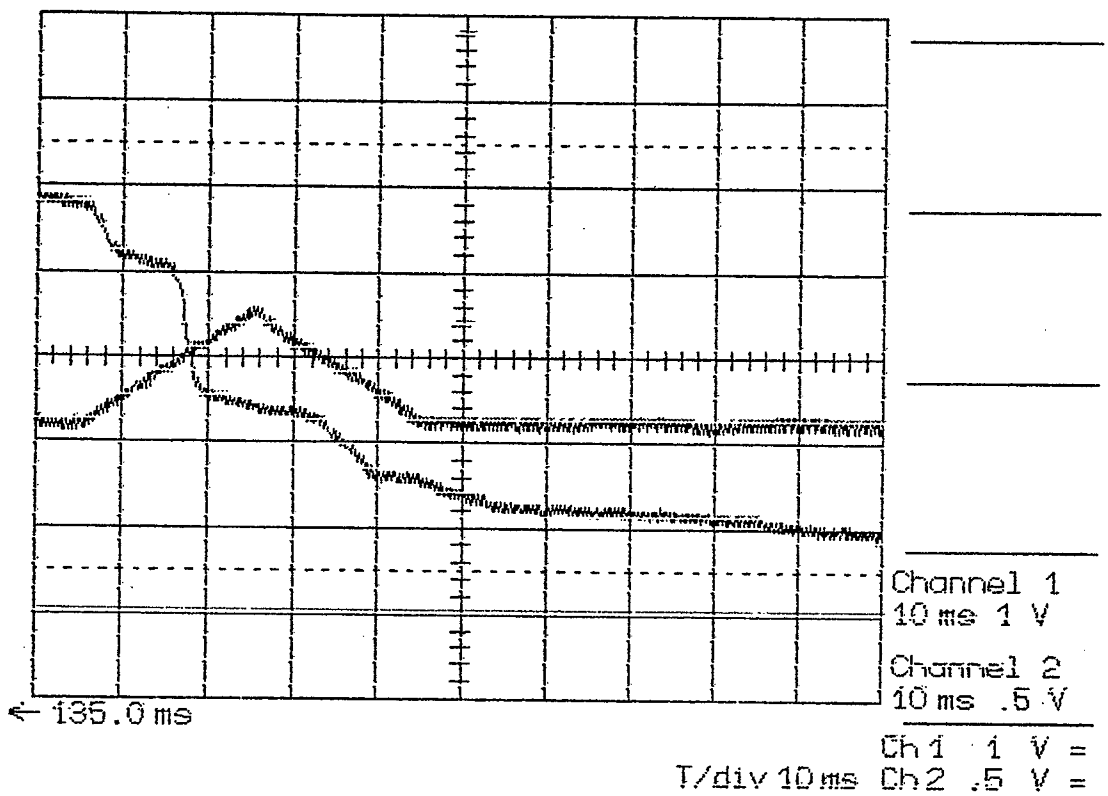

Channel 1
10 ms 1 V
Channel 2
10 ms .5 V
← 135.0 ms
Ch 1 1 V =
T/div 10 ms Ch 2 .5 V =

Fig. 13

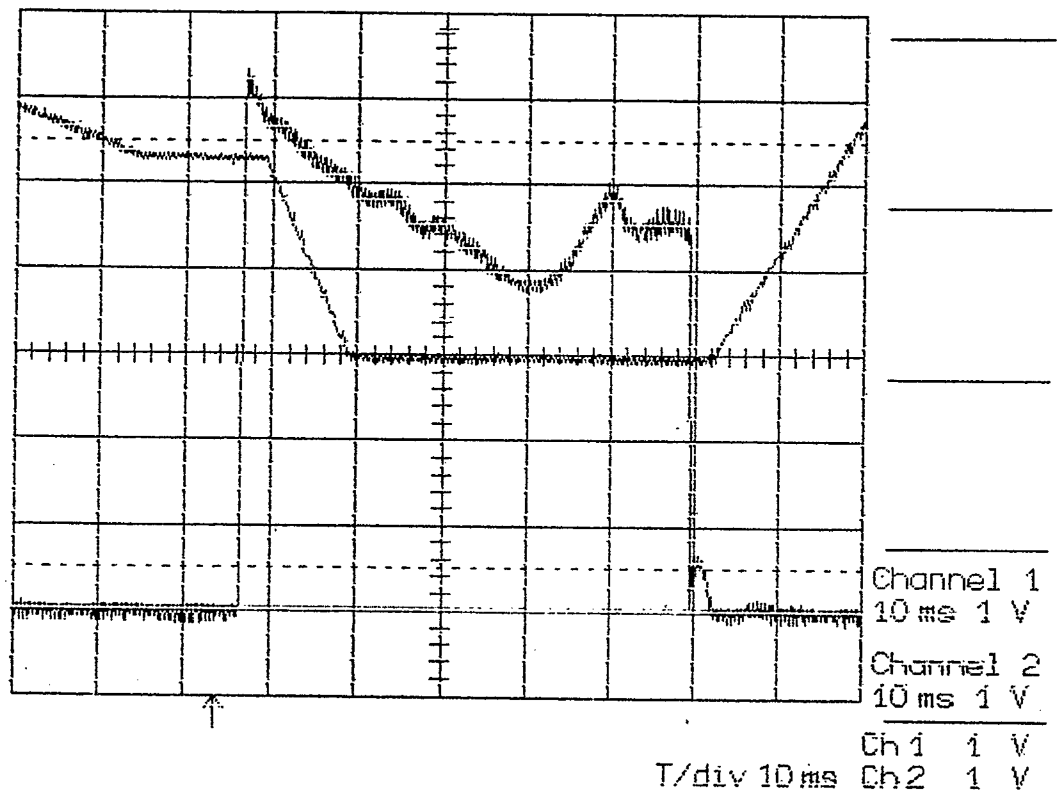

Channel 1
10 ms 1 V
Channel 2
10 ms 1 V
Ch 1 1 V
T/div 10 ms Ch 2 1 V

Fig. 14

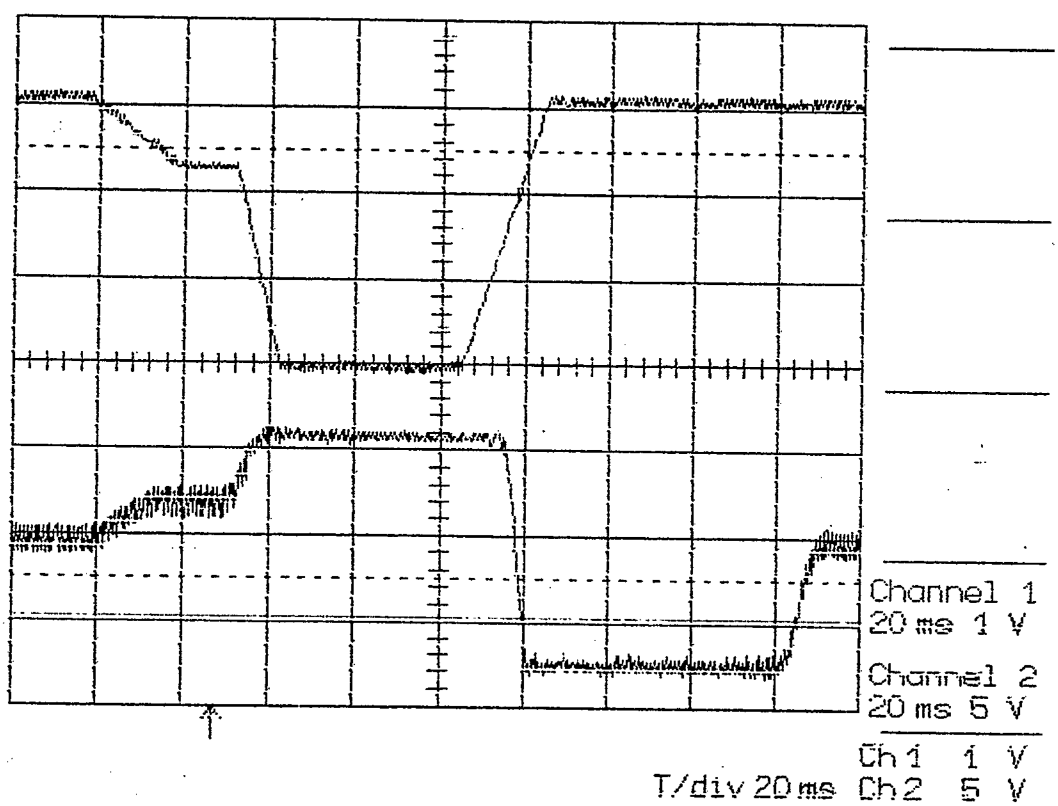

Channel 1
20 ms 1 V
Channel 2
20 ms 5 V
Ch 1 1 V
T/div 20 ms Ch 2 5 V

Fig. 15