BNL-104170-2014-TECH

AGS.SN297;BNL-104170-2014-IR

Stopband Correction of the AGS Booster Intensity Dependence of Resonances

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May 1993

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U.S. Department of Energy

USDOE Office of Science (SC)

AGS Complex Machine Studies (AGS Studies Report No. 297) Stopband Correction of the AGS Booster Intensity Dependence of Resonances
Study Period: May 28-June 4, 1993
Participants: C. Gardner and Y. Shoji
Reported by: Y. Shoji
Machine: User3; MMPS: high intensity 30 G/ms injection; intensity variable (5-200 turns, 110 degrees); chromaticities $\xi x=-0.5$, $\xi y=-0.75$
Aim: To study high intensity effect in the tune space.

I Motivation

In a previous report we confirmed that there were no strong resonance in the designed working area in the tune space; $4.5<Qx<5$, $4.5<Qy<5$ [Shoji & Gardner, SR-296]. As the next step we surveyed the tune space for different beam current. The intensity dependence would give us answers to some questions, which we have had about the high intensity operation. These questions are:

1. How much is the tune spread by the space charge ?
   And how much is the space charge limit at the present ?
   We have many calculations but we don't have had any experiment.
2. How does a resonance depend on beam current ?
   Does it become broader and shallower in the tune space by the space charge tune spread?
   Is there any change of resonance strength like that observed at the KEK-PS MR? [Shoji, AGS/AD/TN-373]
   Are weak resonances still weak with high beam current?
   Especially how does the structure resonance change to beam current? Space charge can induce structure resonance.
3. Is it necessary or effective to cancel higher order resonances?
4. Why is the optimum working point in the tune space depend on the beam current?
   [Bleser, Thern and Luccio, Booster/Proton Book IX, 1993, p.7] And where is the best?
   Why does the working point have to be changed during the acceleration to obtain the highest intensity ?

II Tune Space Survey

The machine parameters were almost the same as those at the previous measurement on May 20 [Shoji and Gardner, SR-298] except the radial steering function of the rf control; dRset. The set function is shown in Fig.1. That difference of the dRset function would not be matter because the function parameters of stop band correction were measured with constant dRset [Shoji & Gardner, SR-286 and SR-295], which was much closer to the present function than that was on May 20. And the corrections were fine on May 20.

The LINAC beam was injected into 110 degrees of rf bucket. Number of injection turn was changed from 5, 50, 100 and to 200. The beam current was measured on two lines in the tune space; Qy=4.78 and Qx=4.78 (except the measurement with 5 turns injection). The horizontal and vertical tunes were measured and adjusted to be constant from the injection to 50ms after T0. The fluctuation of tunes were reduced to 0.004.

The results are plotted in the following figures.

Fig. 2	5 turns;	(a) Qx=4.86, (b) Qy=4.78
Fig. 3	50 turns;	(a) Qx=4.78, (b) Qy=4.78
Fig. 4	100 turns;	(a) Qx=4.78, (b) Qy=4.78
Fig. 5	200 turns;	(a) Qx=4.78, (b) Qy=4.78

III 5 Turns Injection

1. Fig. 2 is expected to be almost the same as that measured on May 20. The resonance 3Qy=14 looked stronger than that was before. Maybe this difference would have come from the difference of the emittance. But the skew sextupole coupling resonance 2Qx+Qy=14 was still weak enough. As mentioned in the previous report the skew sextupole correction strings were adjusted for 2Qx+Qy=14 not for 3Qy=14.

IV 50 Turns Injection

1. At the 50 turns injection, the resonance structure changed from the 5 turns injection. The dips (beam loss structure in the tune space) of half integer resonances shifted to higher tunes by the space charge tune shift. They shifted by about 0.05 in both Qx and Qy direction. And as can be predicted from the theory, the shift was larger at just after the injection. The shift of dips of the half integer resonances at 2ms after the injection were dQx=0.04 and dQy=0.07. Obviously the vertical tune shift and tune spread were larger than those of horizontal axis because the vertical beam size was smaller than the horizontal beam size.

2. If the LINAC emittances were conserved, the space charge tune spread should have reached to dQx=0.3 and dQy=0.5 at just after the injection [Shoji and Gardner, AGS SR-296]. We could not measure that tune spreads. Because a fine resonance structure disappeared from the maximum intensity plot. But we observed movements of tail parts of 2Qx=9 and 2Qy=9 at 2ms after the injection. The tails reached to Qx=4.68 and Qy=4.64, which corresponded to the tune spread of 0.12 and 0.18, respectively. The observed spread was about half of the expected one. (Of course locations of the tail end were not clear. Then this is a very rough result.) An emittance blow-up or re-arrangement of the beam shape could have happened. We will discuss about it in section VII.

3. The sharp edges at the lower side of the integer tunes (Qx=5 and Qy=5) moved a little bit to higher side. The hard edge of the integer resonance did not move like those of the half integer resonances. The coherent resonance blew the coherent betatron oscillation up and killed the beam. As described in many textbooks, the coherent tune shift was much smaller than the incoherent tune shift.

4. The shape of the dip by these half-integer resonances was not symmetric to the tune. The lower tune side was sharper than the higher tune side. This can be explained qualitatively as the following. Suppose that the tune is set at the lower tune side of a dip. That means that the tune is set at a little bit higher than the coherent resonance. The space charge pushed down the incoherent tune and the incoherent tune of the most dens part goes over the resonance. When some part of the beam is lost by this resonance the tune shift will decrease. Then the incoherent tune of the most dens part comes up to the resonance and more beam will be lost. Once the beam loss starts it induces more beam loss. On the other hand if the tune is set at the lower tune side of the dip the incoherent tune goes away from the resonance.

5. The dips by the third resonances became broader and shallower with more beam current. The consequence of 'broader' is that it becomes difficult to avoid this resonance. The consequence of 'shallower' is that the effect of the resonance become weaker. These were theoretically expected change. The dip by 2Qy=9 just after the injection (maximum current) became broader and shallower. The dip by 2Qy=9 at 2ms or 19ms became broader but not shallower. Was this the effect of 4th structure resonances?

6. There existed the flat area at 2ms after the injection. The ratio of survived intensity in this flat area; 4.6<Qx<4.8, 4.65<Qy<4.85 was roughly the same as that with 5 turns injection. The total effect of small higher order resonances was not changed against the beam current.

7. There appeared unknown resonances at Qx=4.84 and Qy=4.9 (Qy=4.9 appeared as a shoulder of the integer resonance). These resonances were stronger than 3Qy=14. But we didn't have observed such a strong resonance with a low beam current. In the two-dimensional tune space survey, which will be explained in the next section, the resonance at Qx=4.84 of Fig.3(b) appeared parallel to Qx=5. The space charge tune shift of the most dens part was estimated to be dQx=0.04 from the shift of 2Qx=9.

Then this resonance was identified to be 5Qx=24. And probably the other resonance in Fig.3(a) was 5Qy=24. These were decapole structure resonances. The structure is strong because the number 24 is identical to the number of FODO cells in the Booster. But a symmetric beam would not produce any decapole field. Then we cannot say it is natural. The beam loss occurred mainly later than the 2ms after the injection. It suggested that it was a higher order resonance which needed much time to kill the beam.

8. As mentioned previously, we surveyed the area near Qx=4.84 to identify the unknown resonance. The result is shown in Fig.6. It was obvious that the unknown resonance was parallel to Qx=5 (Qy axis). We also observed the other inclined line, which was thought to be the integer coupling; Qx-Qy=0. At the intersection of these resonances, the beam loss was not simply additive but was enhanced.

V 100 Turns Injection

1. The 5th structure resonance 5Qx=24 did not become stronger than that was at 50 turns. The decapole field produced by the space charge strongly depends on the shape of the beam.

2. The new resonance appeared at Qy=4.42 in Fig.4(a). This resonance was thought to be the integer coupling; Qx+Qy=9, which looked stronger than 2Qy=9.

3. There was no flat area in the tune space. The tail parts of the 5th resonance and the half integer resonance overlapped in both Qx and Qy axis. But the ratio of survived intensity at 2ms after the injection was even improved from the 50 turns injection at the optimum tune point.

VI 200 Turns Injection

1. The 5th resonance; 5Qy=24 completely went out from the working area to behind the integer resonance; Qy=5.

2. We cannot identify each resonances any more. They were connected to a broad dip.
3. The optimum vertical tune was just below the integer at just after the injection. This is the best point to avoid the coherent integer resonance and minimize the effect of the half-integer resonance; 2Qy=9 and the integer coupling; Qx+Qy=9. But as the beam was accelerated, the space charge effect decreased, the 5th resonance; 5Qy=24 appeared from behind the integer resonance. Then the vertical tune had to be changed to the lower as the beam was accelerated. The survived beam current was much lower in Fig.5 than that was in the normal high intensity operation. Because the tune was always constant throughout the cycle.

4. We are not sure whether the broad peak came from 2nd order resonances; 2Qx=9, 2Qy=9 and Qx+Qy=9 or 4th order structure resonances; 4Qx=18, 4Qy=18, 2Qx+2Qy=18. It may be natural to think that ' When the space charge produces such a strong quadrupole field (about 10% of the lattice quadrpole field), the same space charge could have produced also a strong octupole field '.

5. Although the tune spread became very large, a fine adjustment of the tune (by 0.05) was effective to minimize the effect of the resonance. Then we have enough reason to think about the correction of integer resonance group; Qy=5, 2Qy=10, 3Qy=15. If we correct these resonances, the stop band width of Qy=5 becomes smaller, then it can help to reduce the beam loss. But obviously the correction of 2Qy=9 and Qx+Qy=9 is more effective to improve the beam current and emittance.

6. During the injection the beam intensity was changing from 0 to $2X10^{13}$ppp in about 0.2ms. The resonances in the tune space should have changed drastically during this 0.2ms. And because the Booster has injection bump during this period, the stop band corrections was thought to be worse. If we assume the maximum tune spread as 1.0, the beam crossed some resonances with the crossing speed of 5. That speed was very fast and not slow enough to produce a beam loss at any resonances except the integer resonances. Injection bump can be one reason why the resonance Qx=5 looked much stronger than Qy=5.

7 At this intensity we attempted an two-dimensional tune survey. The ratio of the beam current at 2ms after the injection to the maximum current are shown in Fig.7. The best working point in the tune space just after the injection was Qx=4.8, Qy=4.96. The differential coupling resonance; Qx-Qy=0 or 2Qx-2Qy=0 had small effect in the tune space.

8. At that time the correction function of Qx-Qy=0 was not correct at just after the injection. Because at near the injection the corrections didn't have been measured. [W. van Asselt, private communication].

VII IPM

We also measured the beam profile by the IPM at 4 kinds of situations:

(a) 50 turns injection, tunes are fixed to Qx=4.78, Qy=4.80
(b) 100 turns injection, tunes are fixed to Qx=4.82, Qy=4.86
(c) 200 turns injection, tunes are fixed to Qx=4.84, Qy=4.92
(d) 200 turns injection, tunes follow the programmed function [file name; june1_u3]

The fixed tunes of (a), (b) and (c) were set at the optimum position, which were obtained from the tune space survey. Then they were different for the different beam current. At the situation (d) the tunes were not fixed but followed the programmed functions shown in Fig.8, which had been adjusted for the high intensity operation. At which the tunes were about Qx=4.82 and Qy=4.956 just at the injection.

The beam current normalized with number of injection turn is shown in Fig.9. The beam current was improved by changing tunes with time.

Bias voltage of the IPM was 1200V. The automatic analysis of beam size and intensity was injured by the noise. Then only the beam profiles are shown in Fig. 10.

As the increase of the beam current the beam emittance grew and shapes of the beam profiles changed from Gaussian to trapezoid like shape. The typical change of the shape was observed in the vertical shapes of Fig.10 (c). At just after the injection (profile at 28.1ms) the shape was close to Gaussian. But during the successive several ms (profiles at 32.1ms and 36.1ms) the beam center decreased its particle density and the shape went close to a trapezoid. And after that the shape comes back to Gaussian. This can be understood schematically as follows:

(1) At just after the injection the beam had large tune spread and the incoherent tune of a particle at the center of the beam reached to the 2nd order resonances; 2Qy=9 and Qx+Qy=9.

(2) The particle at the beam center grew its betatron amplitude and went out of the beam center and became stable.

(3) Then the beam profile changed its shape. And with the new beam shape the form factor of the space charge tune spread became small. The tune spread itself became smaller.

(4) As the beam was accelerated further the space charge effect decreased. Then other kinds of disturbances, such as higher order resonances, shook the beam and the beam profile came back to Gaussian.

The change of beam profile with the beam current like this was observed also at the KEK-PS Booster [Shoji, AGS/AD/TN-373].

The second important result was the dependence on the tunes. The difference of (c) and (d) was only tunes. At (c) the vertical beam profile was close to Gaussian just after the injection. But at (d) the vertical beam profile was close to the trapezoid from the first. The beam was vertically painted by the integer resonance. This could be the other reason why such a high vertical tune was favorable for a high intensity operation. But we are not sure if that painting took place in a normal high intensity operation. The electric field of the IPM could have produced that effect especially near the integer tune. After all the beam current of the Booster decreases to the bias voltage of the IPM [Blesser, Thern and Luccio, Booster/Proton Book IX, 1993, p.7; Thern and Zeno, Booster/Proton Book IX, 1993, p.84]

FIGURE CAPTIONS

Fig. 1 RF radial steering function used through the measurement.

Fig. 2 Tune space line survey with 5 turns injection;
(a) Qx=4.86, (b) Qy=4.78

Fig. 3 Tune space line survey with 50 turns injection;
(a) Qx=4.78, (b) Qy=4.78

Fig. 4 Tune space line survey with 100 turns injection;
(a) Qx=4.78, (b) Qy=4.78

Fig. 5 Tune space line survey with 200 turns injection;
(a) Qx=4.78, (b) Qy=4.78

Fig. 6 Two dimensional survey in the tune space with 50 turns injection. The beam current at 18ms after the injection.

Fig. 7 Two dimensional survey in the tune space with 200 turns injection. The ratio of the beam current at 2ms after the injection to the maximum beam current.

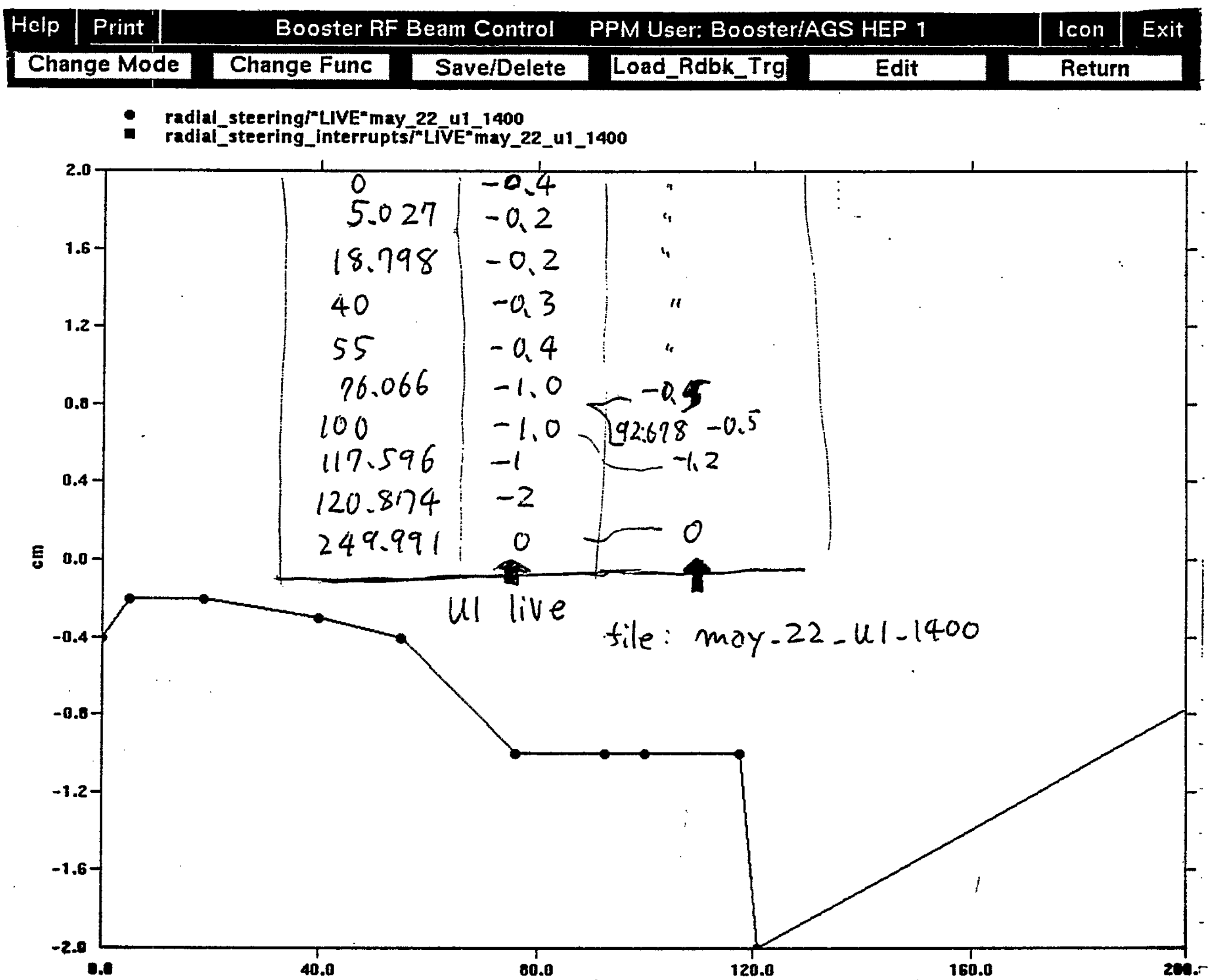
Fig. 8 Programmed tunes for the high intensity operation.

Fig. 9 The beam current to time. Ten times averaged. The bias voltage of the IPM was turned off.

(a)	50 turns	Qx=4.78,	Qy=4.80
(b)	100 turns	Qx=4.82,	Qy=4.86
(c)	200 turns	Qx=4.84,	Qy=4.92
(d)	200 turns	function (LIBRARY FILE; june1_u3)	

Fig. 10 The beam profiles measured with IPM.

(a)	50 turns	Qx=4.78,	Qy=4.80
(b)	100 turns	Qx=4.82,	Qy=4.86
(c)	200 turns	Qx=4.84,	Qy=4.92
(d)	200 turns	function (LIBRARY FILE; june1_u3)	



Help
Print
Booster RF Beam Control
PPM User: Booster/AGS HEP 1
Icon
Exit
Change Mode
Change Func
Save/Delete
Load_Rdbk_Trg
Edit
Return
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radial_steering_interrupts/*LIVE*may_22_u1_1400
0 -0.4
5.027 -0.2
18.798 -0.2
40 -0.3
55 -0.4
76.066 -1.0 -0.5
100 -1.0 92.678 -0.5
117.596 -1 -1.2
120.874 -2
249.991 0 0
U1 live
file: may-22-U1-1400
cm
2.0
1.6
1.2
0.8
0.4
0.0
-0.4
-0.8
-1.2
-1.6
-2.0
0.0
40.0
80.0
120.0
160.0
200.0

Fig. 1

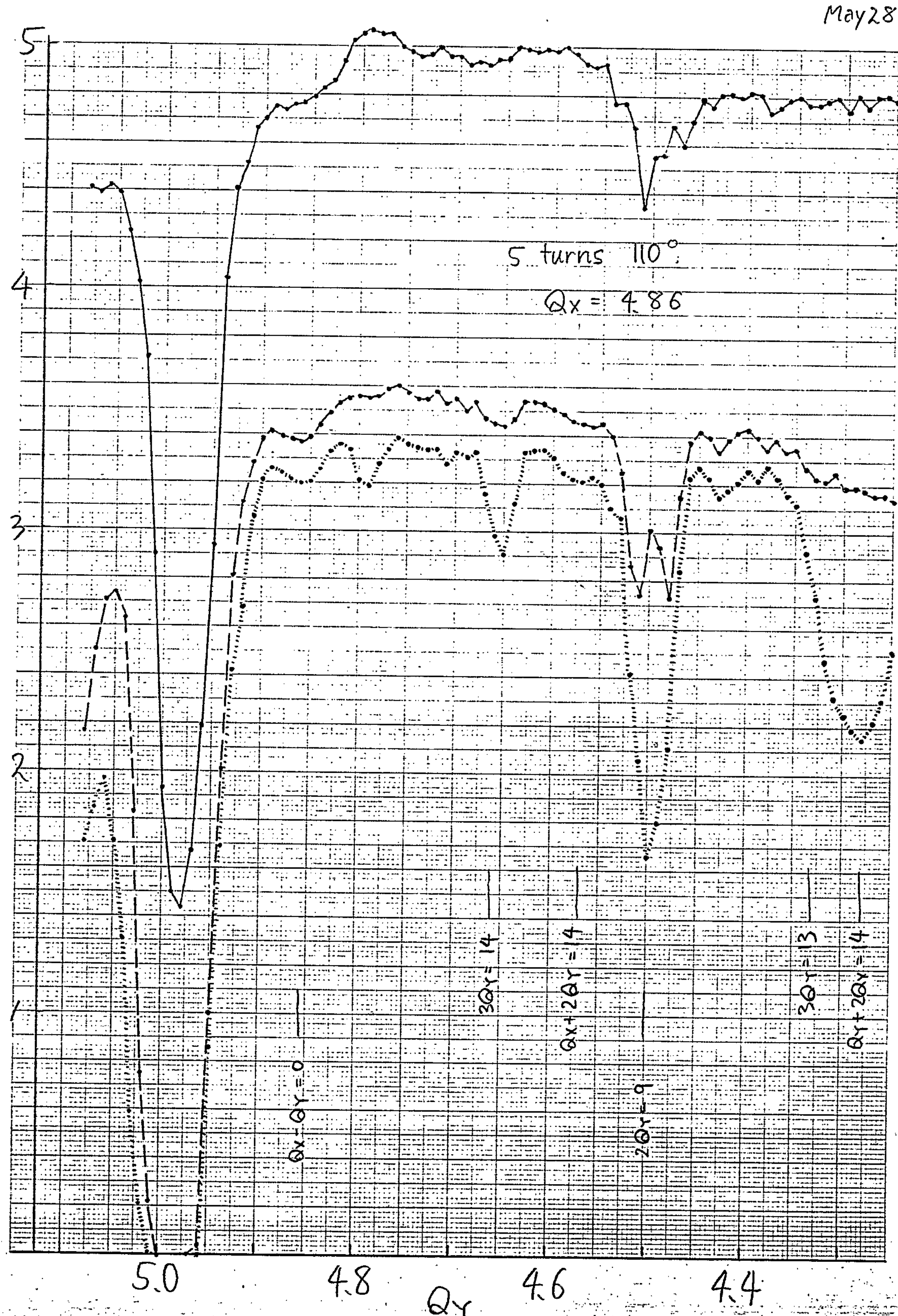
May28
5 turns 110°
Qx = 4.86
5
4
3
2
1
Qx-QY=0
3QY=14
Qx+2QY=14
2QY=9
3QY=13
QY+2QY=14
5.0
4.8
4.6
4.4
QY

Fig. 2 (a)

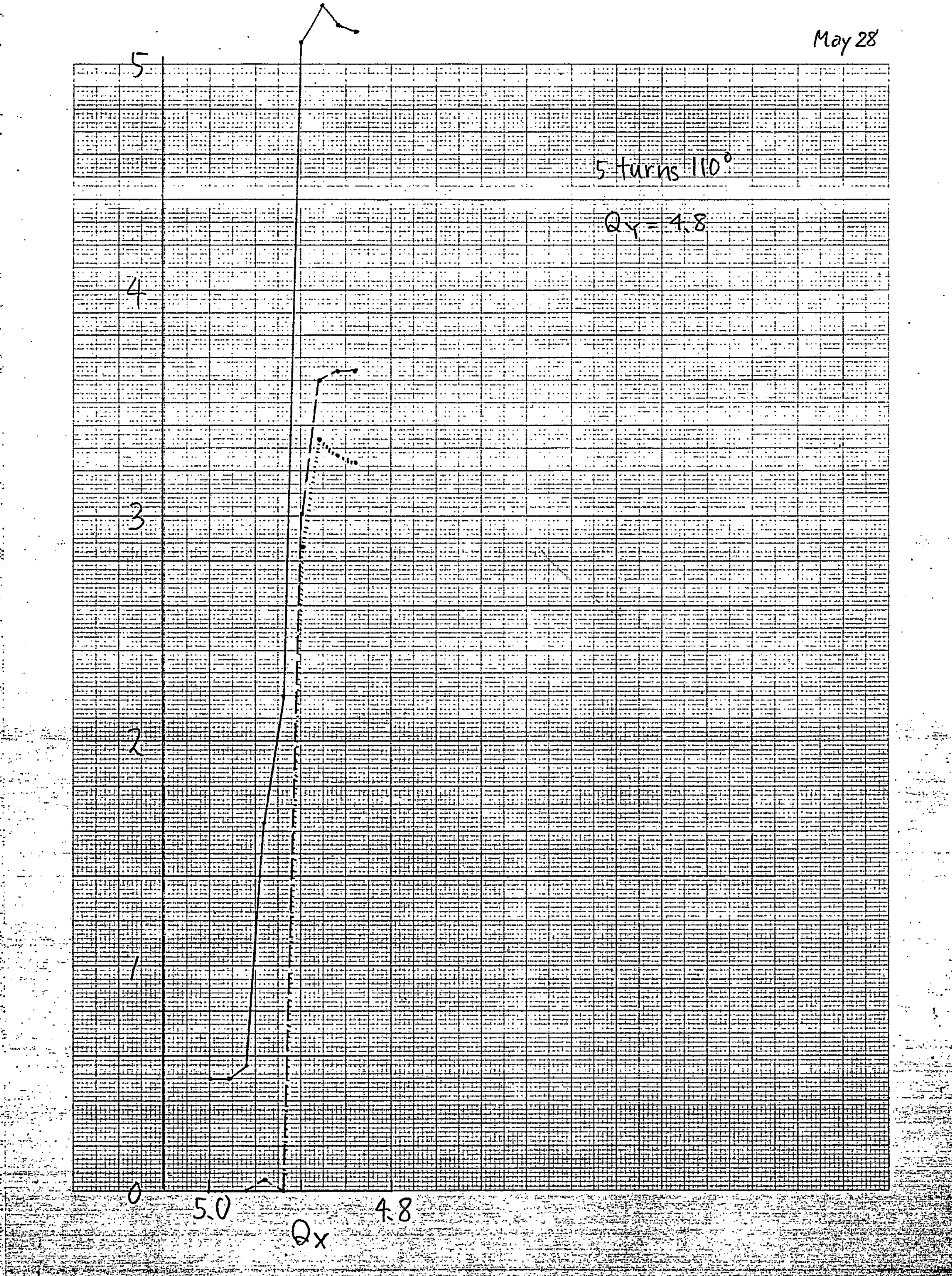

Fig. 2 (b)

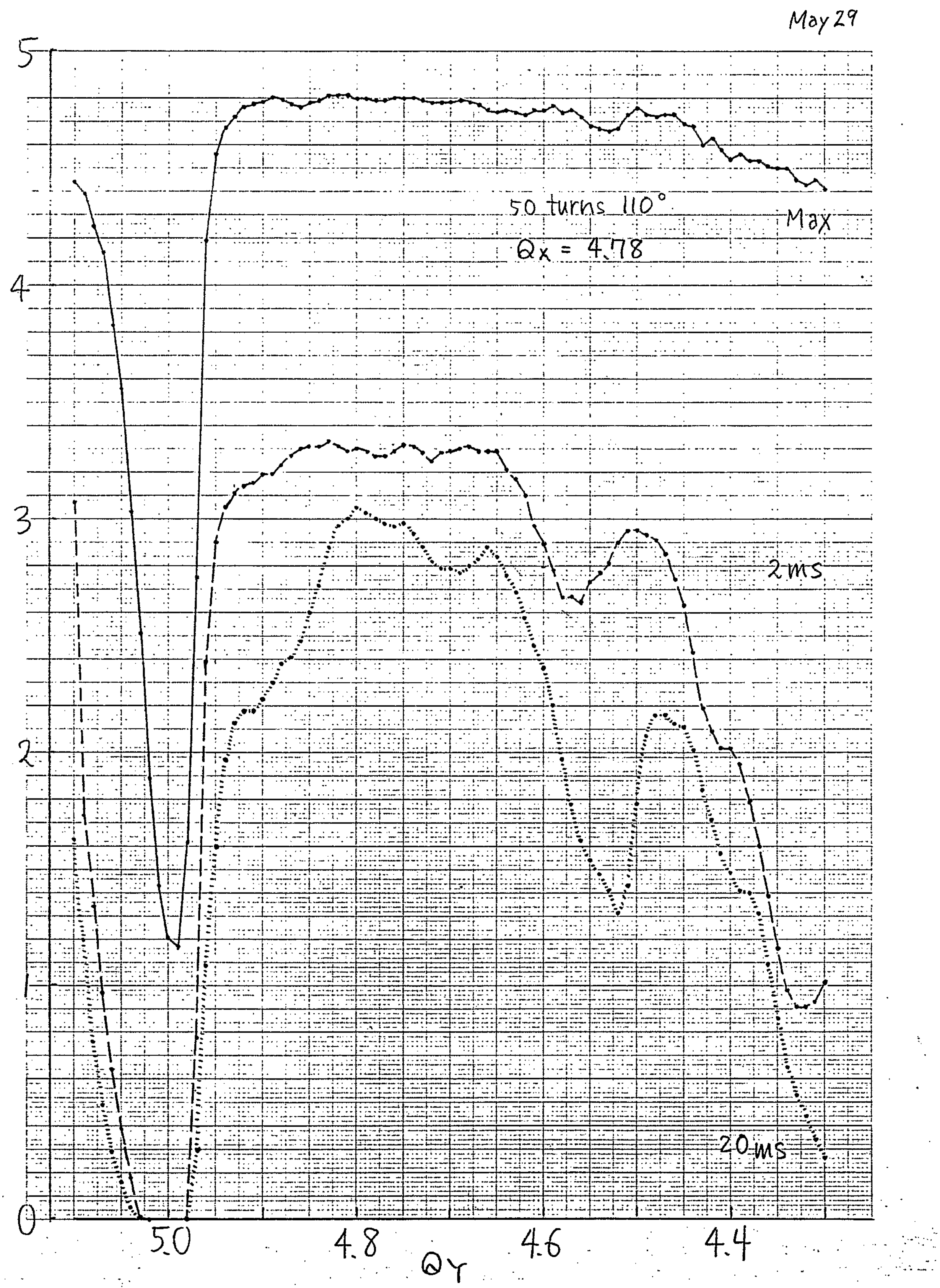

Fig. 3 (a)

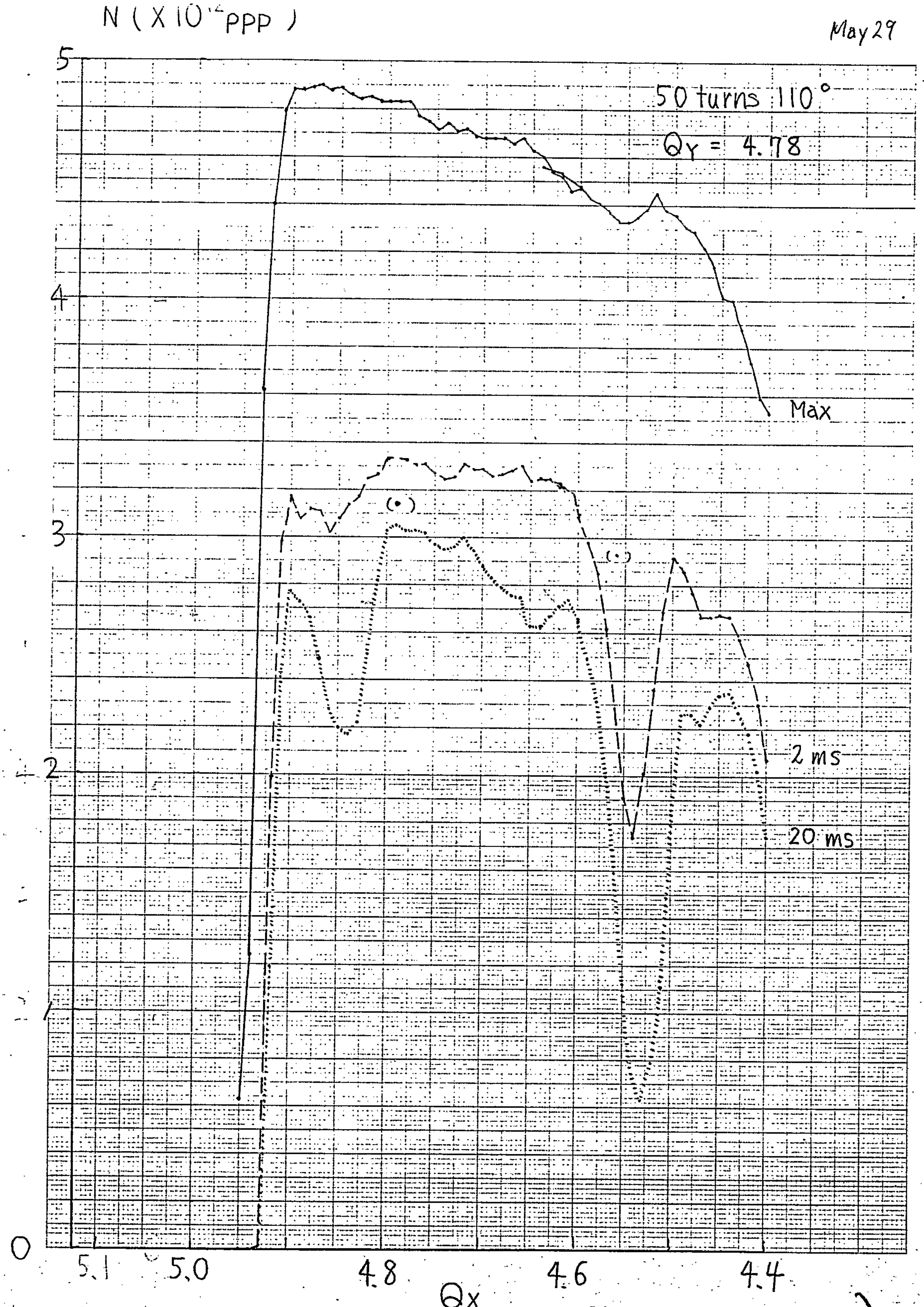
N (X 10^{12} ppp)
May 29
50 turns 110°
Q_Y = 4.78
Max
2 ms
20 ms
5
4
3
2
0
5.1
5.0
4.8
4.6
4.4
Q_X

Fig. 3(b)

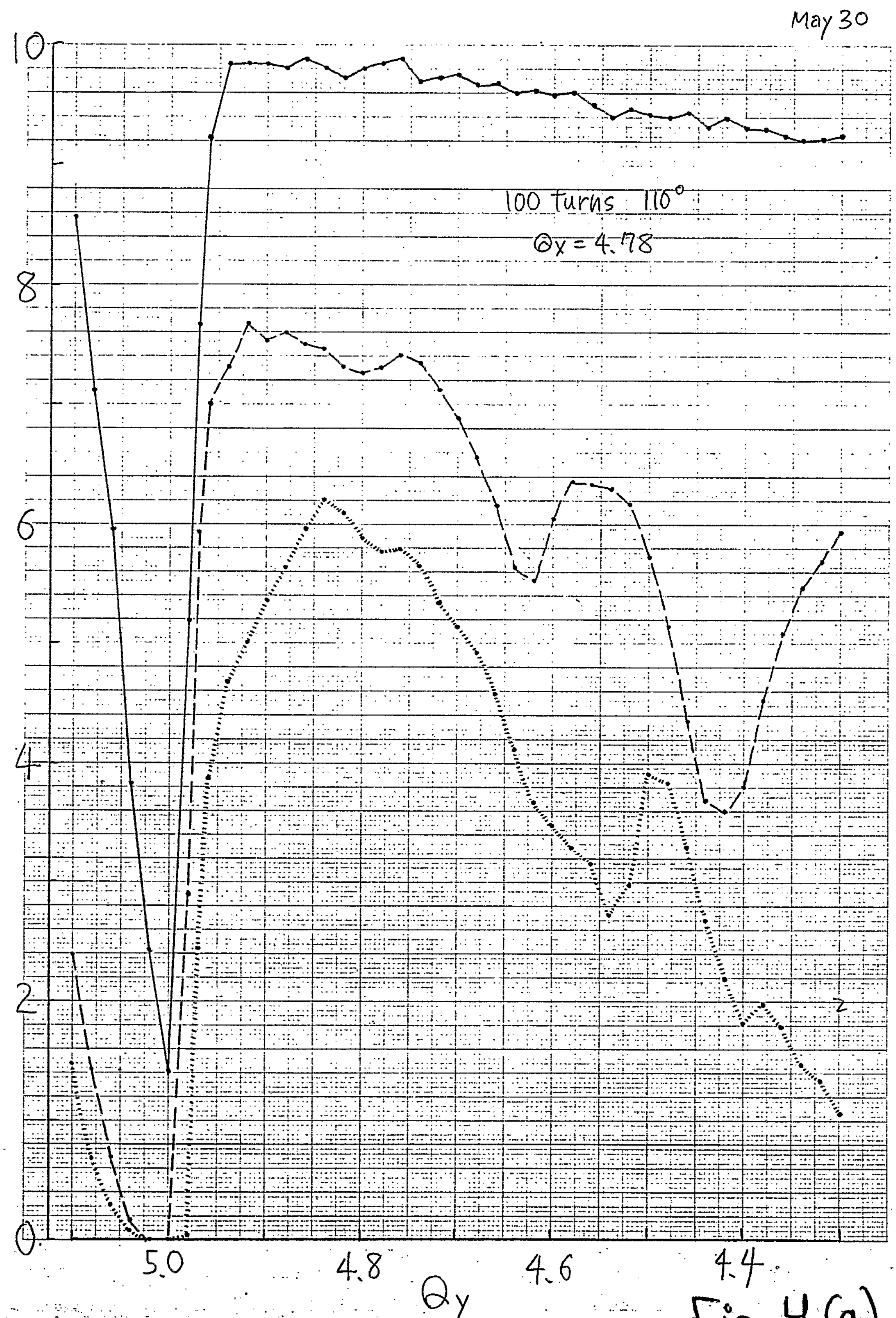

Fig. 4 (a)

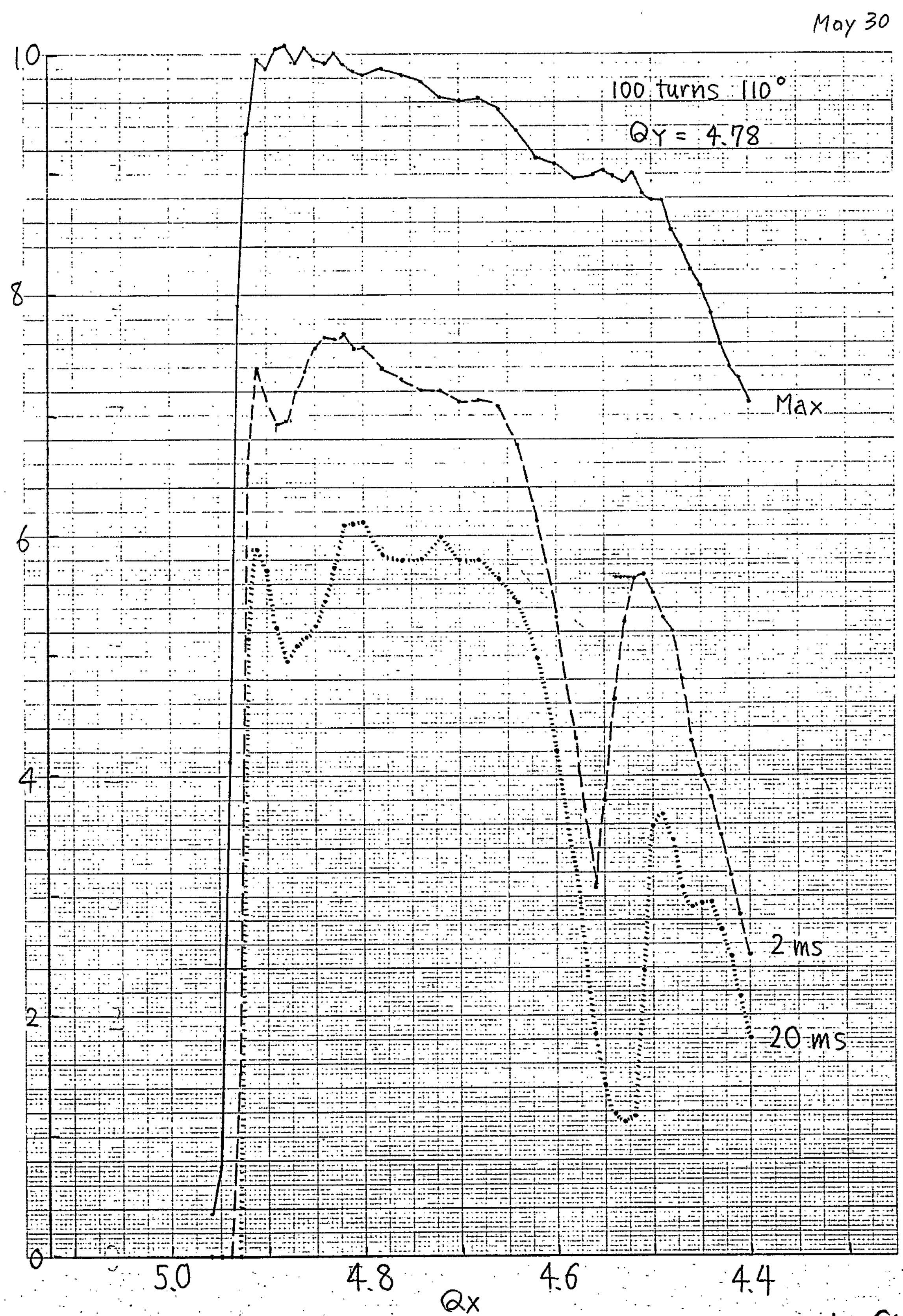

Fig. 4(b)

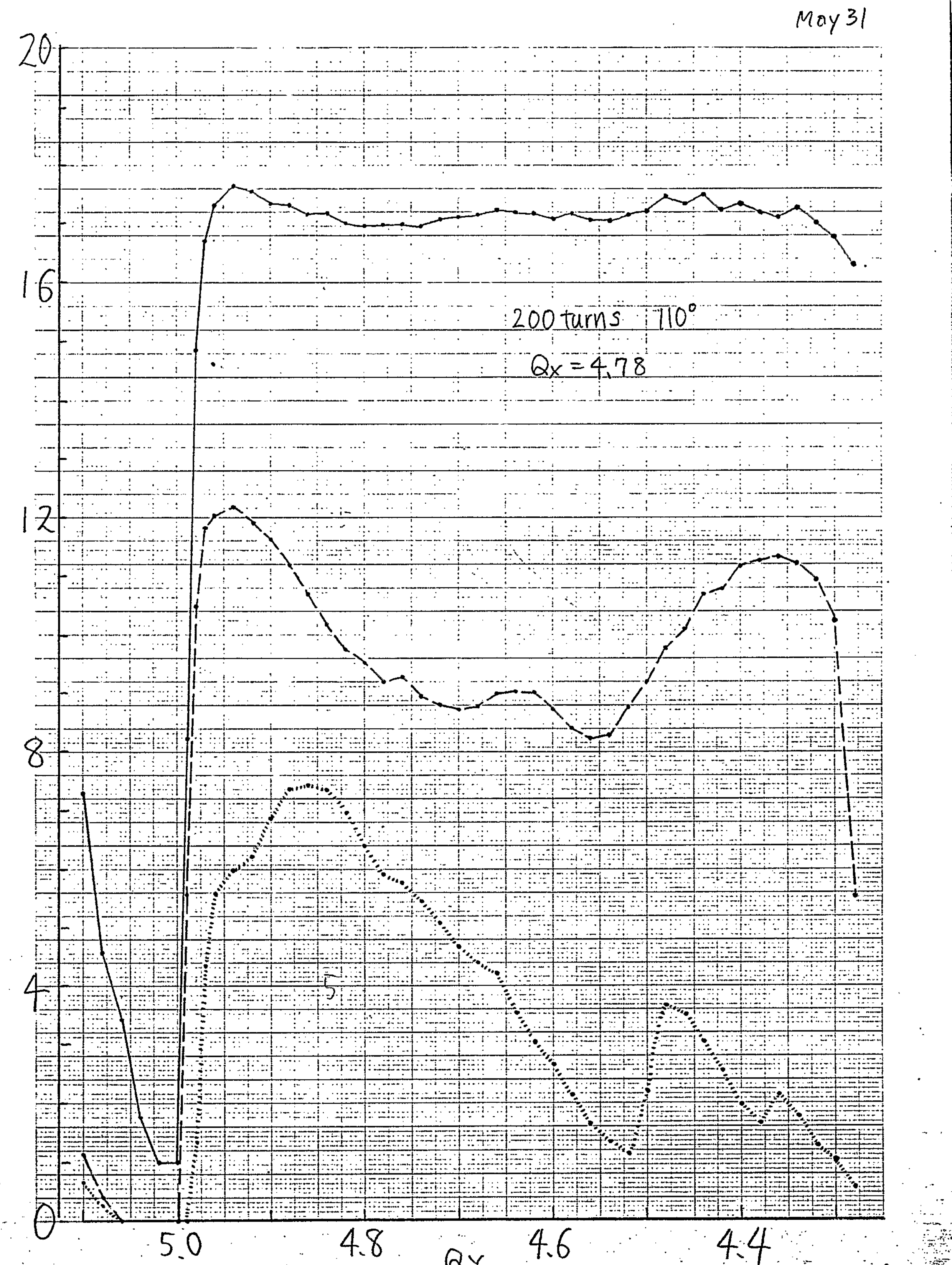

Fig. 5 (a)

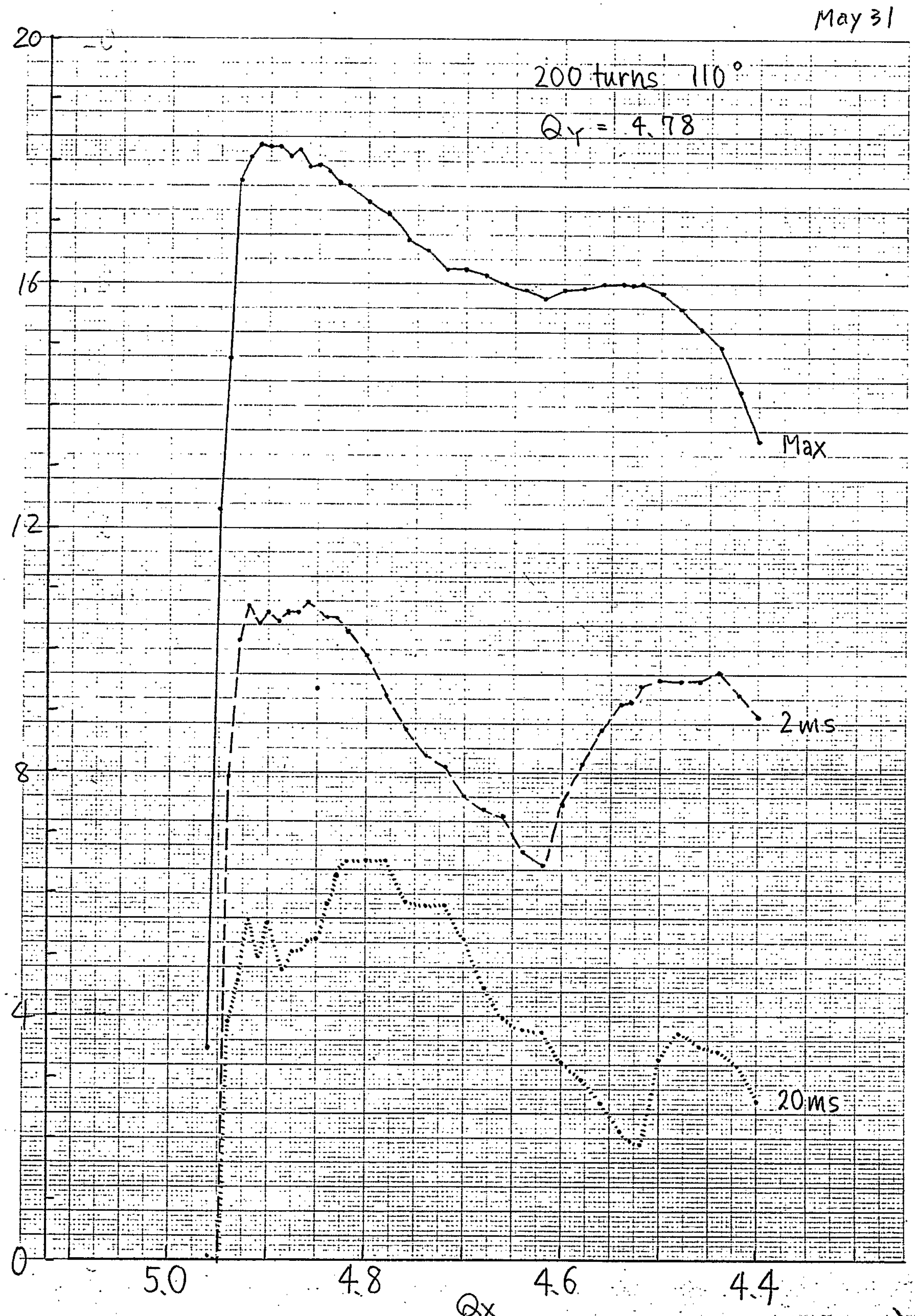
May 31
200 turns 110°
Qy = 4.78
20
16
12
8
4
0
Max
2ms
20ms
5.0
4.8
4.6
4.4
Qx

Fig. 5 (b)

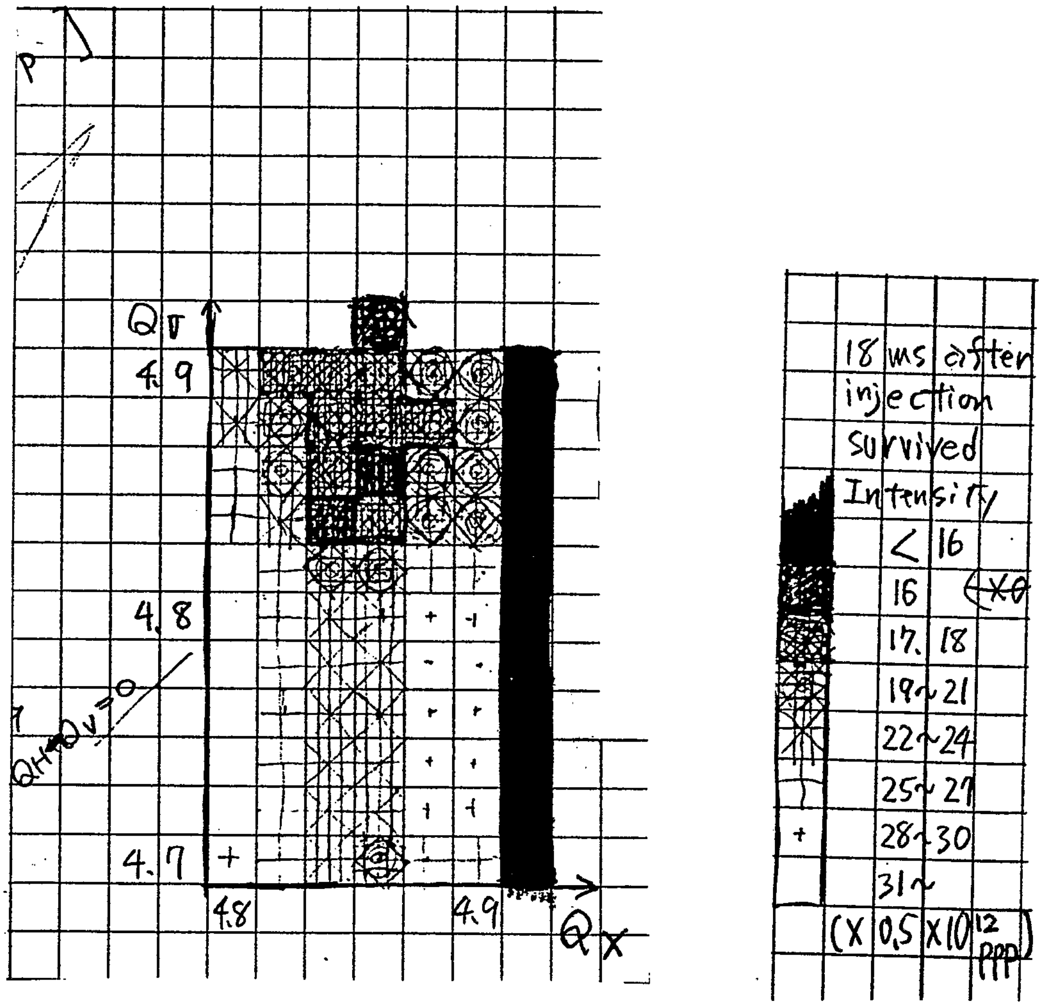
Qv
4.9
4.8
4.7
4.8
4.9
Qx
18 ms after injection survived Intensity
< 16
16
17, 18
19~21
22~24
25~27
28~30
31~
(X 0.5 X10^12 ppp)

Fig. 6

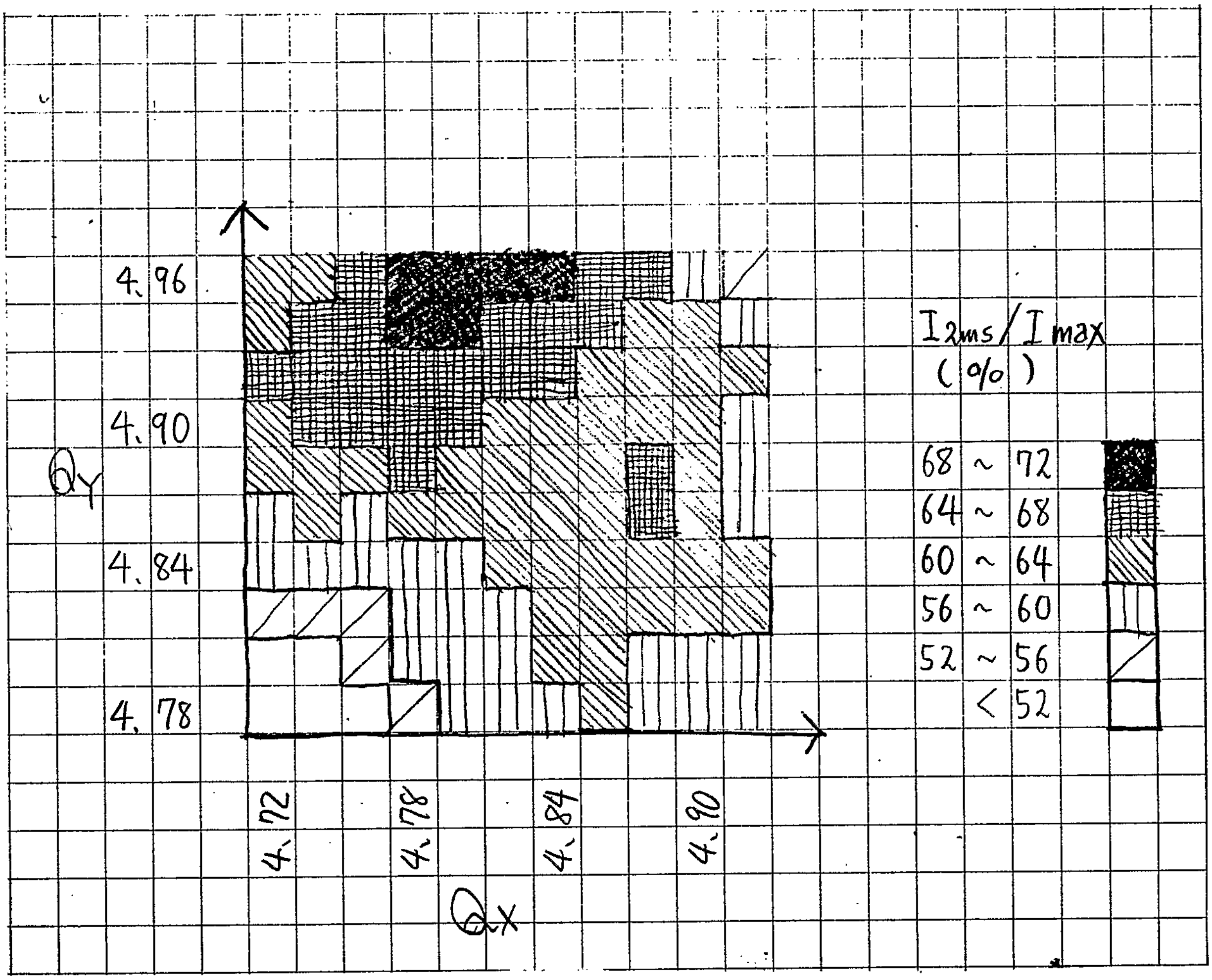
4.96
4.90
Qy
4.84
4.78
4.72
4.78
4.84
4.90
Qx
I2ms / I max
(%)
68 ~ 72
64 ~ 68
60 ~ 64
56 ~ 60
52 ~ 56
< 52

Fig. 7

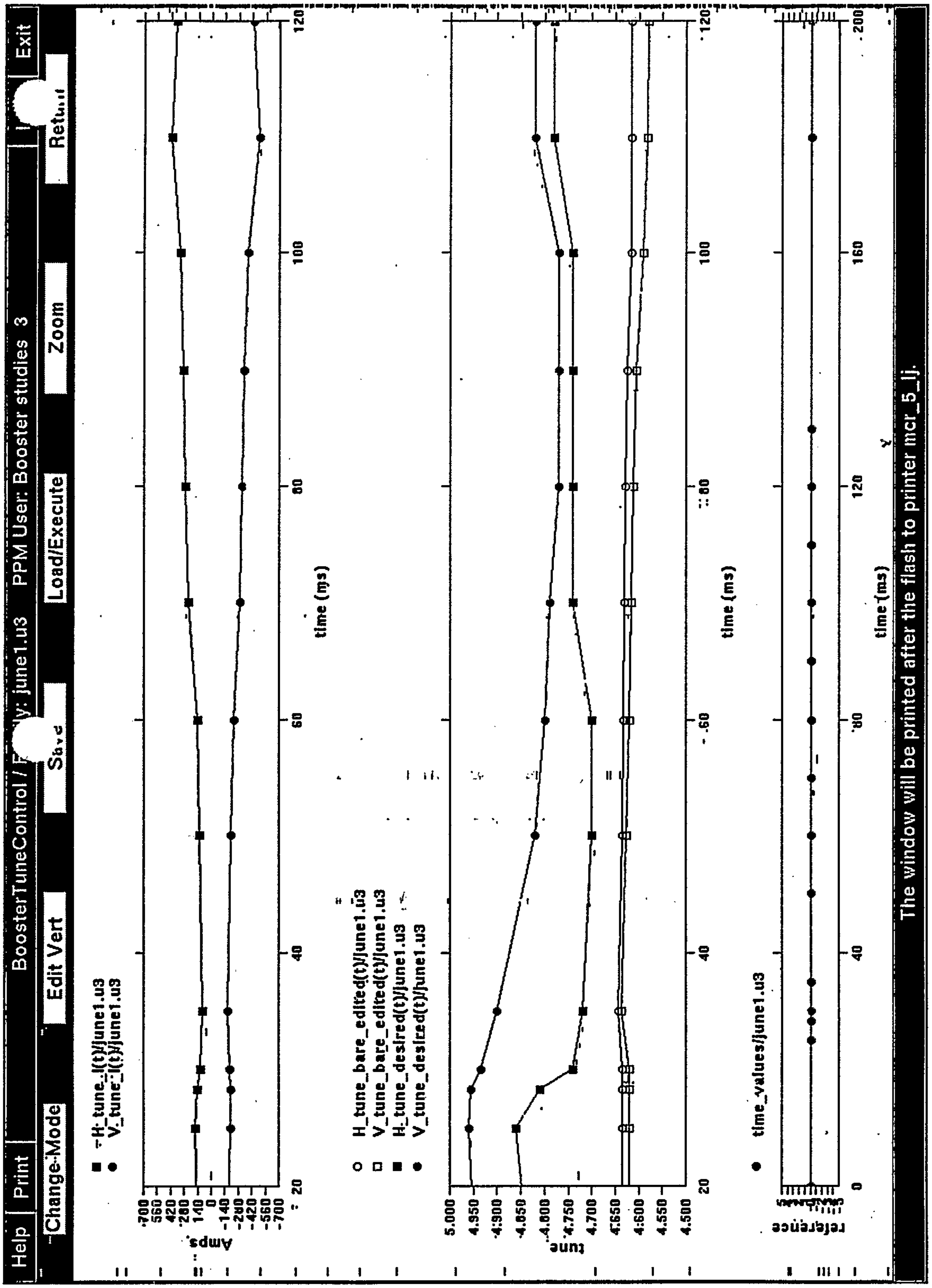
Help
Print
Change Mode
Edit Vert
Load/Execute
Zoom
Exit
PPM User: Booster studies 3
H_tune_I(t)/june1.u3
V_tune_I(t)/june1.u3
Amps
time (ms)
H_tune_bare_edited(t)/june1.u3
V_tune_bare_edited(t)/june1.u3
H_tune_desired(t)/june1.u3
V_tune_desired(t)/june1.u3
tune
time_values/june1.u3
reference
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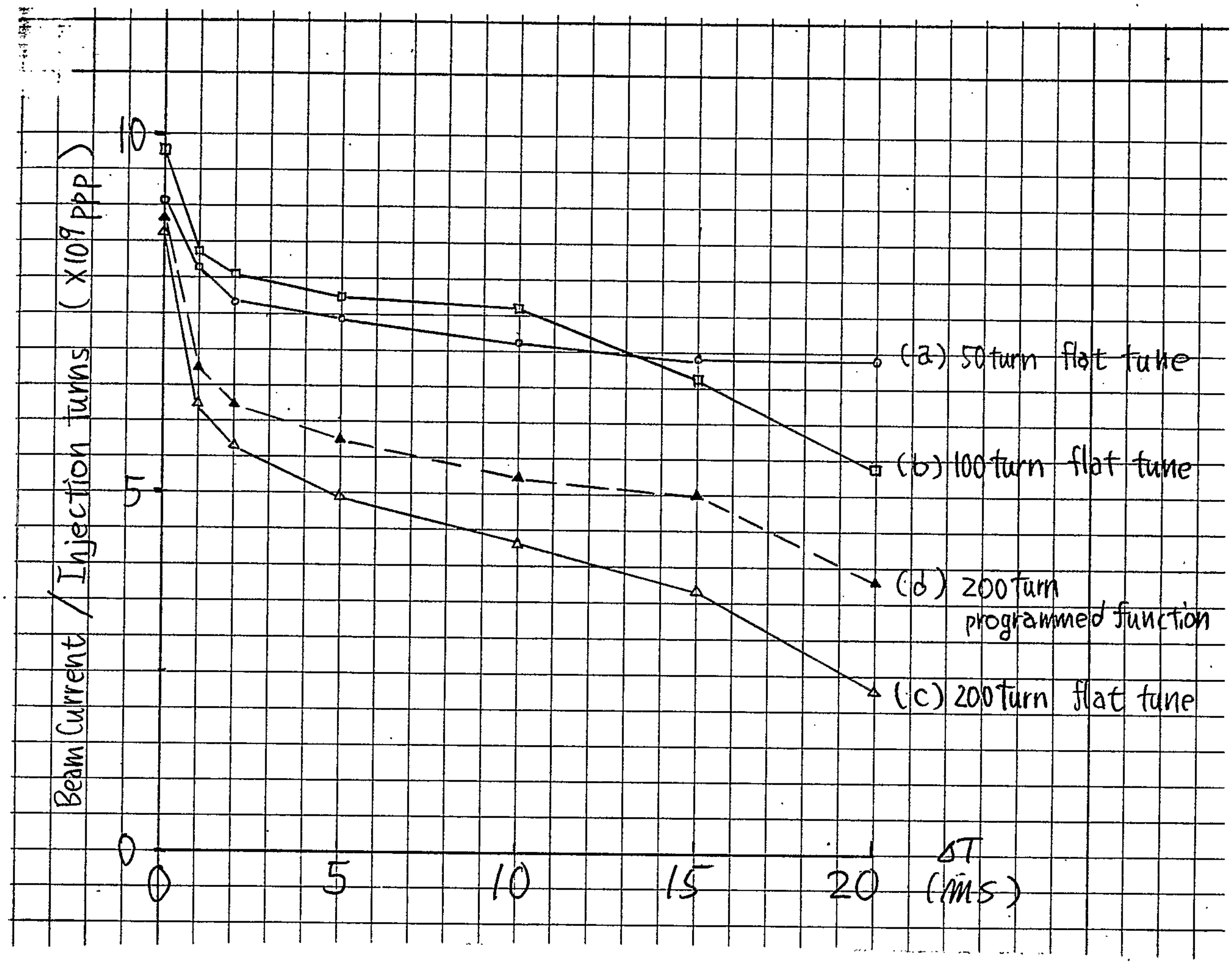
Fig. 8



Beam Current / Injection turns (X10⁹ ppp)
10
5
0
0
5
10
15
20
ΔT (ms)
(a) 50turn flat tune
(b) 100turn flat tune
(d) 200turn programmed function
(c) 200turn flat tune

Fig. 9

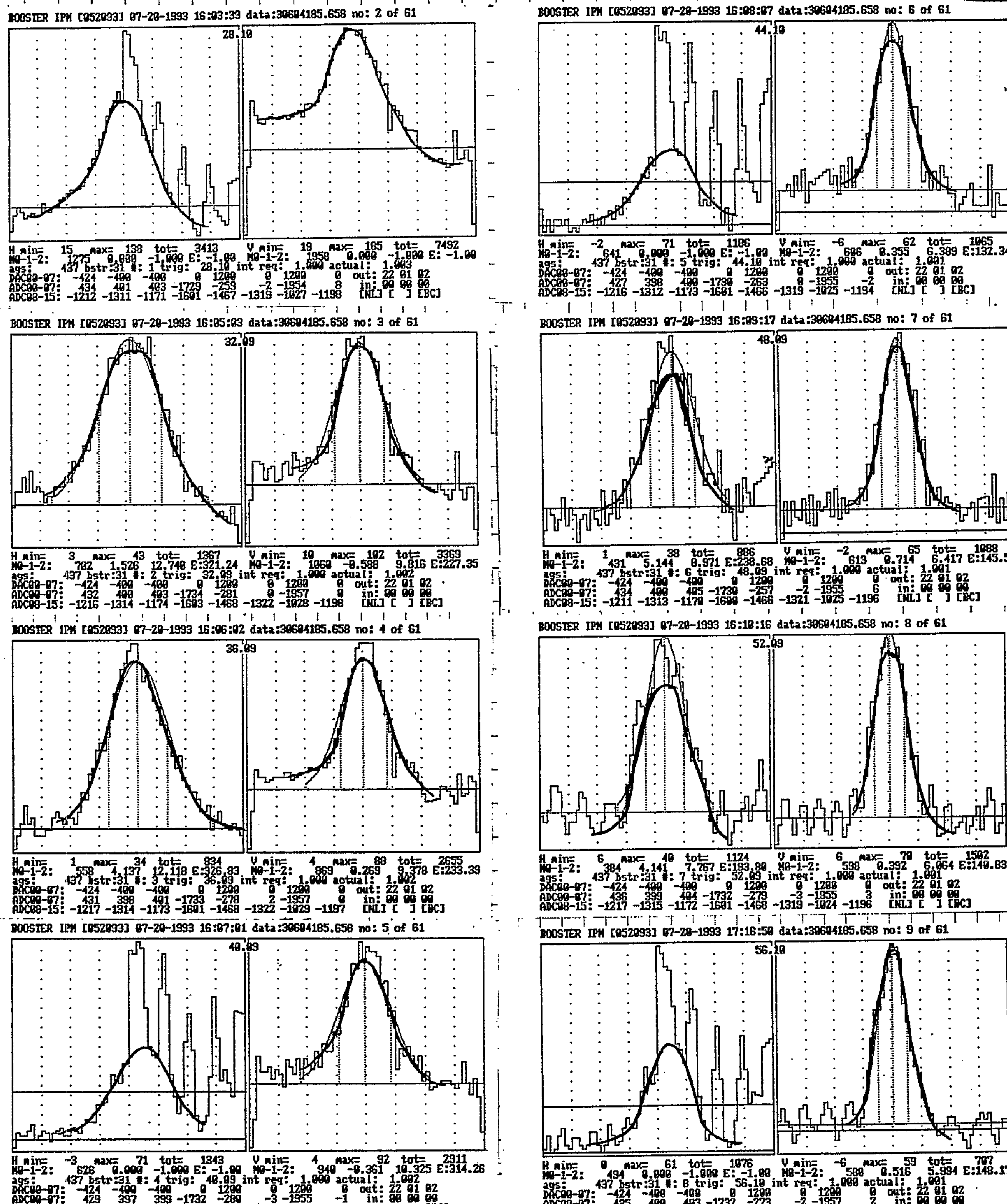

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Fig. 10(a)

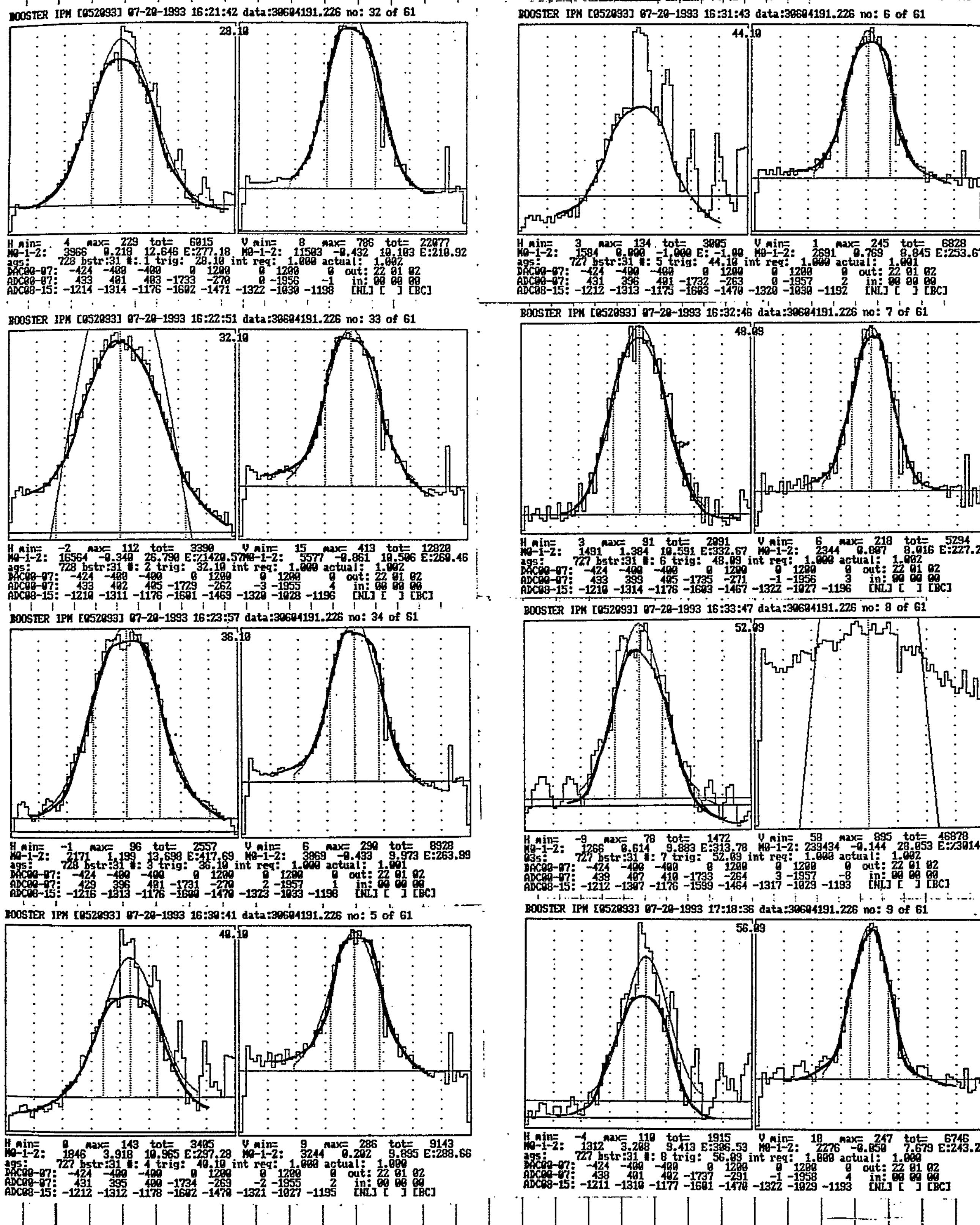
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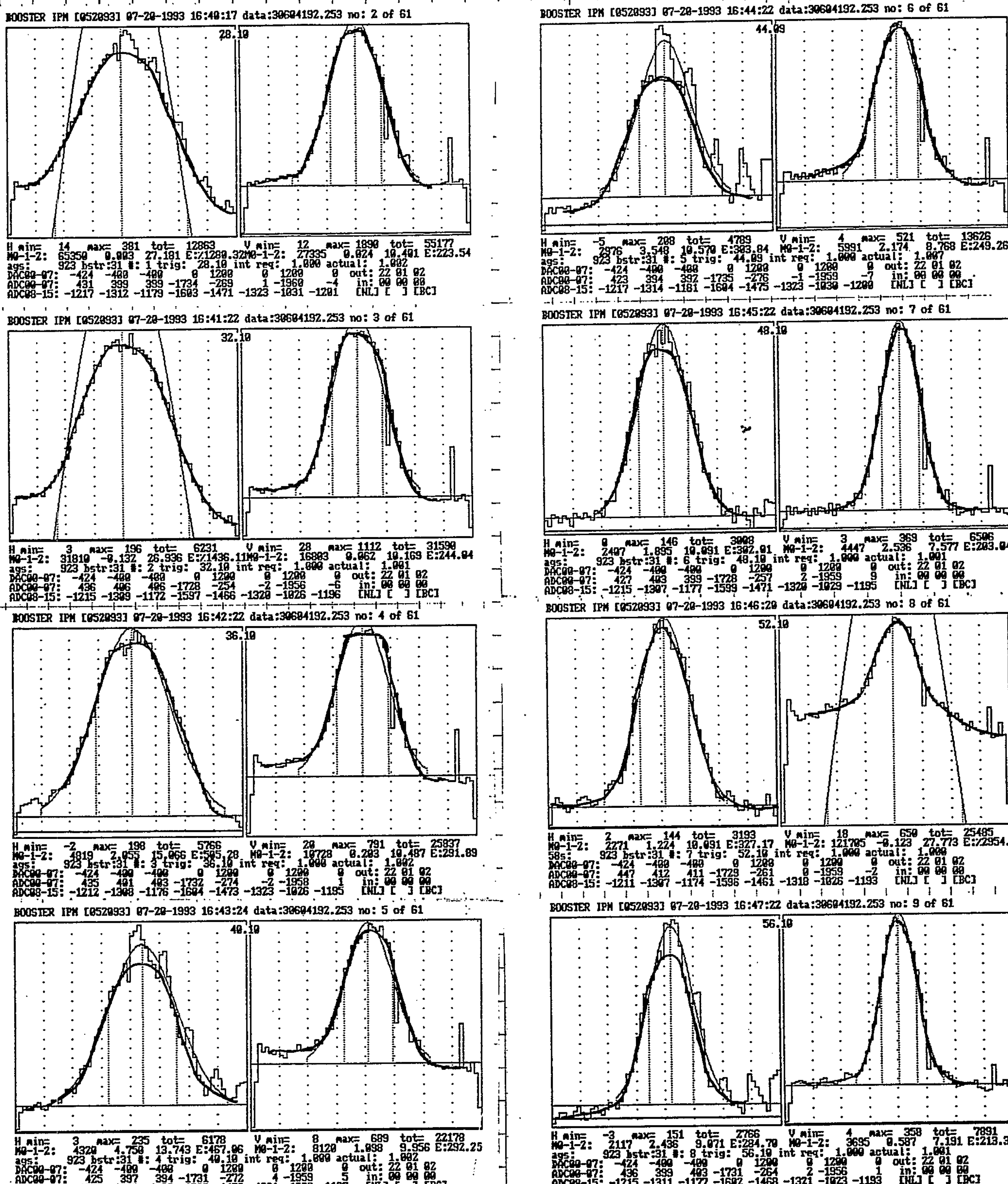
Fig. 10(b)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BOOSTER IPM [052093] 07-20-1993 16:45:22 data:30604192.253 no: 7 of 61
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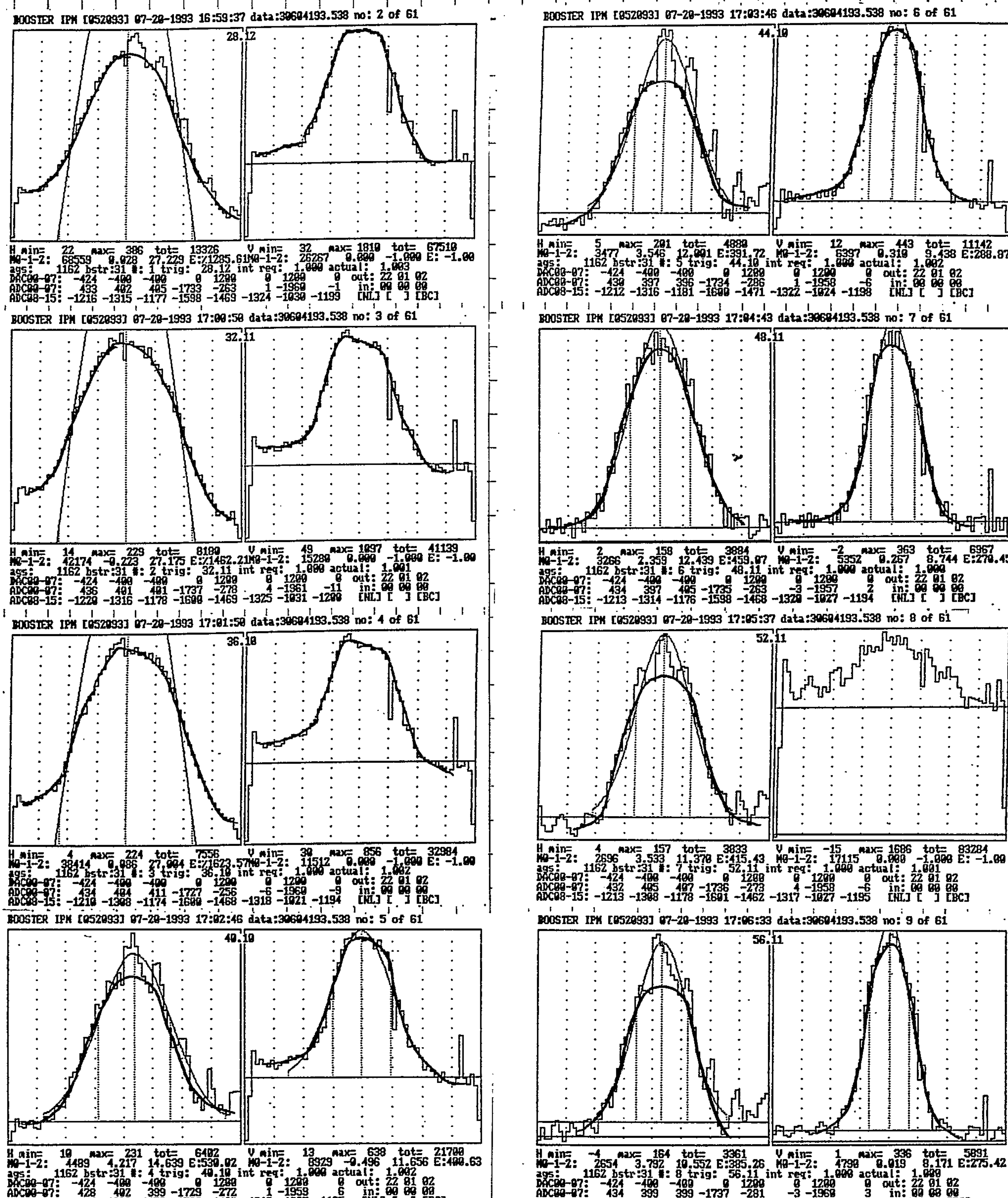
Fig. 10(c)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BOOSTER IPM [052093] 07-20-1993 17:00:50 data:30604193.538 no: 3 of 61
BOOSTER IPM [052093] 07-20-1993 17:04:43 data:30604193.538 no: 7 of 61
BOOSTER IPM [052093] 07-20-1993 17:01:50 data:30604193.538 no: 4 of 61
BOOSTER IPM [052093] 07-20-1993 17:05:37 data:30604193.538 no: 8 of 61
BOOSTER IPM [052093] 07-20-1993 17:02:46 data:30604193.538 no: 5 of 61
BOOSTER IPM [052093] 07-20-1993 17:06:33 data:30604193.538 no: 9 of 61

Fig. 10 (d)