national accelerator laboratory

TM-468
0400

OPERATING THE MAIN RING AT 500 GEV

L.C. Teng

February 5, 1974

Various factors involved in operating the main ring at 500 GeV are examined.

I. Bending Magnet Field

Values given here are averaged over the measurements of 270 B1 magnets and 110 B2 magnets. The data are processed by A. Ruggiero.

A. Saturation (Ampfactor)

The Ampfac at a given field intensity is defined as

$$\text{Ampfac} \equiv \frac{\text{Current required}}{\text{Current required if } \mu = \infty}$$

	18 kG	21 kG	22.5 kG
Ampfac B1	1.026	1.103	1.205
Ampfac B2	1.024	1.099	1.195
Difference	0.2%	0.4%	1.0%

The difference between the fields in B1 and B2 gives rise to closed-orbit distortions (caused mainly by the 18th harmonic of the field error). The closed-orbit distortions calculated by S. Ohnuma are for 1% field difference. (Distortion is proportional to the relative B1 - B2 difference. 1% is the value at 22.5 kG or ~500 GeV.)

	$\nu = 20\frac{1}{4}$	$\nu = 19\frac{1}{4}$	$\nu = 17\frac{1}{4}$
Max. excursion (mm)	±7.5	±8.5	±13.1

These distortions are excessively large and must be corrected by trim dipoles. Two different configurations of trim dipoles have been worked out by J. MacLachlan.

Configuration 1 - 6 dipoles at stations 47

	ν = 20.25	ν = 19.25	ν = 17.25
$(B\ell)_{47}$ (kGm)	2.66	2.50	2.43
Max. excursion (mm)	±2.5	±2.5	±3.0

Configuration 2 - 18 dipoles at stations 11, 17, and 49

	ν = 20.25	ν = 19.25	ν = 17.25
$(B\ell)_{11}$ (kGm)	-2.33	-2.39	-2.54
$(B\ell)_{17}$ (kGm)	-0.81	-0.83	-0.91
$(B\ell)_{49}$ (kGm)	2.66	2.69	2.77
Max. excursion (mm)	±0.8	±0.8	±1.0

Configuration 1 already gives an adequate correction. These trim dipoles must be pulsed, starting at ~450 GeV and reaching the strengths $(B\ell)$ given above at 500 GeV.

S. Ohnuma investigated also the possibility of reducing the closed-orbit distortion by exchanging some B1 magnets for B2 magnets and vice versa. The results are, for $\nu = 20\frac{1}{4}$

	Max. orbit distortion (mm)
No exchange	±7.5
17-4 to B1	±6.5
{11-2, 11-3 to B1; 48-4, 48-5 to B2}	±4.1
{11-2, 11-3, 17-4 to B1; 48-4, 48-5 to B2}	±2.7

Although the orbit distortion can be reduced substantially in this manner the resulting mismatch in aperture is rather undesirable.

B. Field shape

Percentage field errors at horizontal positions ±1", ±2" for B1 and at ±1" for B2 are given below.

B1	-2"	-1"	0	1"	2"
18 kG	-.0107%	-.0033%	0	-.0061%	-.0131%
21 kG	-.0092%	-.0018%	0	-.0034%	-.0125%
22.5 kG	.0575%	.0305%	0	.0355%	.0783%

B2	-1"	0	1"
18 kG	-.0007%	0	-.0022%
21 kG	-.0005%	0	-.0011%
22.5 kG	.0362%	0	.0486%

One can define the useful aperture as the region in which the tune shift $\delta\nu$ is within ±0.2 (this should be considered as an optimistic upper limit). If the tune shift is caused by the bending magnets alone this corresponds to $\frac{B'}{B}$ within $\pm 0.008\ m^{-1}$ or $\pm 0.02\%\ in^{-1}$. Rough eyeball interpolation of the values given in the tables above shows that this condition imposes no aperture limitation at 18 kG and 21 kG. But at 22.5 kG (~500 GeV) this condition gives

At 22.5 kG (~500 GeV) for $\delta\nu$ within ±0.2, $\frac{B'}{B}$ within $\pm 0.02\%\ in^{-1}$

$$\begin{cases} \text{B1 aperture} & \pm 0.3'' = \pm 7.6\ \text{mm} \\ \text{B2 aperture} & \pm 0.24'' = \pm 6.0\ \text{mm} \\ \text{Aperture acceptance} & \varepsilon = 0.5\pi\ \text{mm-mrad} \end{cases}$$

where the B1 and B2 apertures are roughly matched and where in calculating the acceptance we have taken out the momentum width corresponding to $\frac{\Delta p}{p} = \pm 10^{-4}$. This acceptance is adequate for the beam emittance of ~0.1π mm-mrad at 500 GeV but leaves very little room (~±5 mm) for moving the beam horizontally.

II. Quadrupole Magnet Field

Values given here are averaged over the measurements of 127 new-type 7-ft quadrupoles. The data are processed by A. Ruggiero.

A. Saturation (Ampfactor)

The field gradient and the ampfac are given for various quadrupole currents below

I_Q(A)	B'(kG/m)	Ampfac
100	6.93	1
1000	58.04	1
2000	114.02	1.018
3000	169.52	1.027
4000	222.43	1.044
5000	265.06	1.095
6000	296.93	1.173
6500	309.41	1.219

These are plotted in Fig. 1 for $I_Q \geq 4500$ A. Another curve we need is B' against ν for the main-ring lattice. This is calculated by S. Ohnuma for 300 GeV and equal QF and QD currents, and is given on the next page.

B' @ 300 GeV (kG/m)	ν_x	ν_y
162	17.143	17.186
164	17.379	17.422
166	17.618	17.661
168	17.867	17.921
170	18.034	18.097
172	18.314	18.355
174	18.557	18.598
176	18.800	18.840
178	19.043	19.082
180	19.286	19.326
182	19.531	19.570
184	19.777	19.816
186	20.024	20.063
188	20.273	20.311
190	20.523	20.561
192	20.775	20.813

This is plotted in Fig. 2. For other energies B' is proportional to the momentum of the particle. To extract a 500-GeV beam at the $\frac{41}{2}$ and $\frac{39}{2}$ resonances we must have

	$\nu_x = 20.5$	$\nu_x = 19.5$
B' @ 500 GeV (kG/m)	315.9	302.5
I_Q(A)	6850	6240

As estimated by R. Cassel the quadrupole power supply will be able to deliver a maximum current of I_Q = 6860 A after the series capacitors in the substation are installed. This is rather close to the required current at $\nu_x = 20.5$. For 500-GeV operation it is, therefore, desirable to operate the main ring at a tune of 19¼.

B. Field shape

Percentage field-gradient errors at horizontal positions ±1" and ±2" are given below

I_Q	-2"	-1"	0	1"	2"
4000 A	-0.29%	0.08%	0	0.10%	-0.23%
5000 A	-1.56%	0.02%	0	0.02%	-1.57%
6000 A	-3.83%	-0.10%	0	-0.11%	-3.98%
6500 A	-5.48%	-0.19%	0	-0.20%	-5.57%

In Fig. 3 these values are plotted as heavy crosses on the gradient curve of the quadrupole "7045". This particular quadrupole was measured in more detail by C. Schmidt in 1970. Comparing the crosses and the curves one gets an idea of the variations of individual quadrupoles.

Taking the criterion that the tune shift $\delta\nu$ due to the quadrupole alone must be within ±0.1 (It appears that the useable aperture of the quadrupoles is larger than that of the bending magnets even with this tighter $\delta\nu$ limits.) we get the condition that the gradient error must be within ±0.4%. Rough eyeball interpolation of the values given above gives the following useable apertures.

I_Q(A)	4000	5000	6000	6500
Aperture (in)	-	±1.7	±1.3	±1.2

Compared to the aperture limitations imposed by the bending magnets we see that quadrupole aperture limitations can be ignored.

III. Substation Capacity

With the addition of

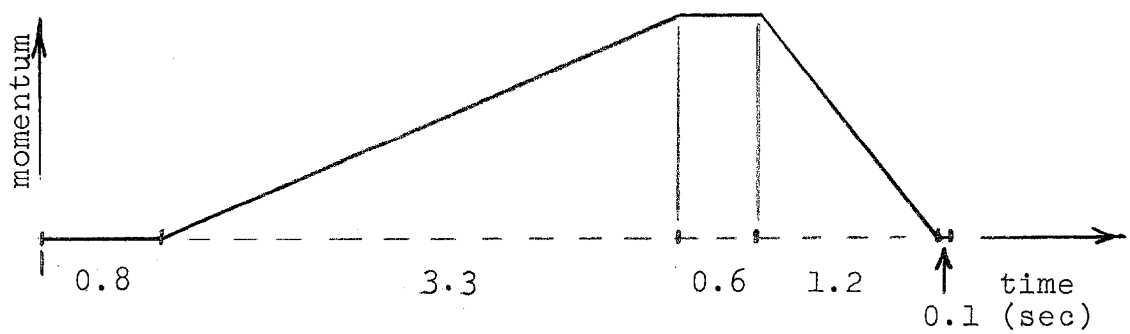
A. The third pulsed-power transformer,

B. The series capacitors to control the power factor, and

C. The increased capacity of the bus work, there will be no difficulty for the substation to handle the 500 GeV-operation. Whether the voltage droop is acceptable to the power company is, however, a separate question.

IV. RF and Acceleration Cycle

With the presently planned modifications of the cavities we may hopefully reach an acceleration rate of 150 GeV/sec. In that case we may contemplate a 6-sec machine cycle at 500 GeV shown below.



V. Extraction

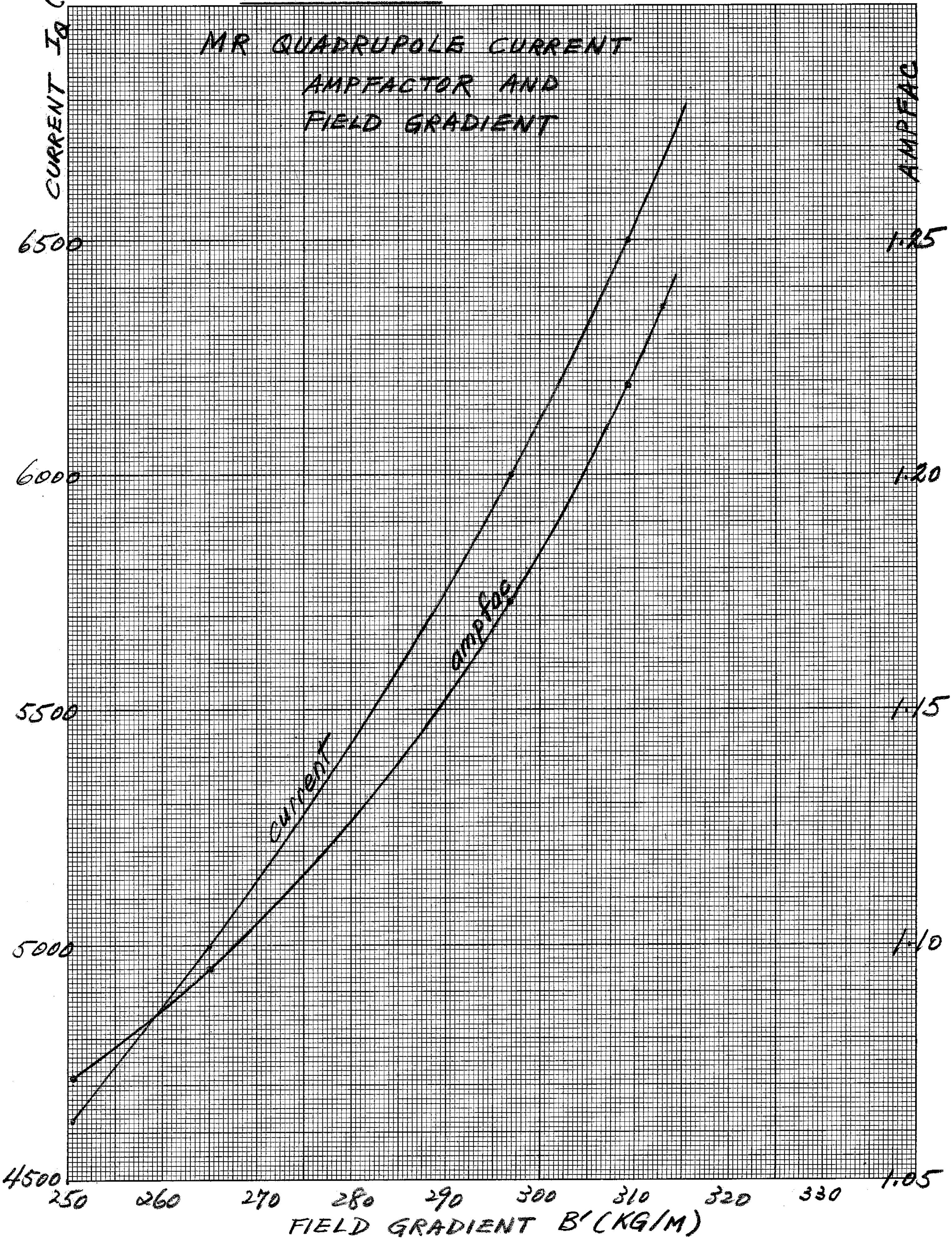
This is the most troublesome problem.

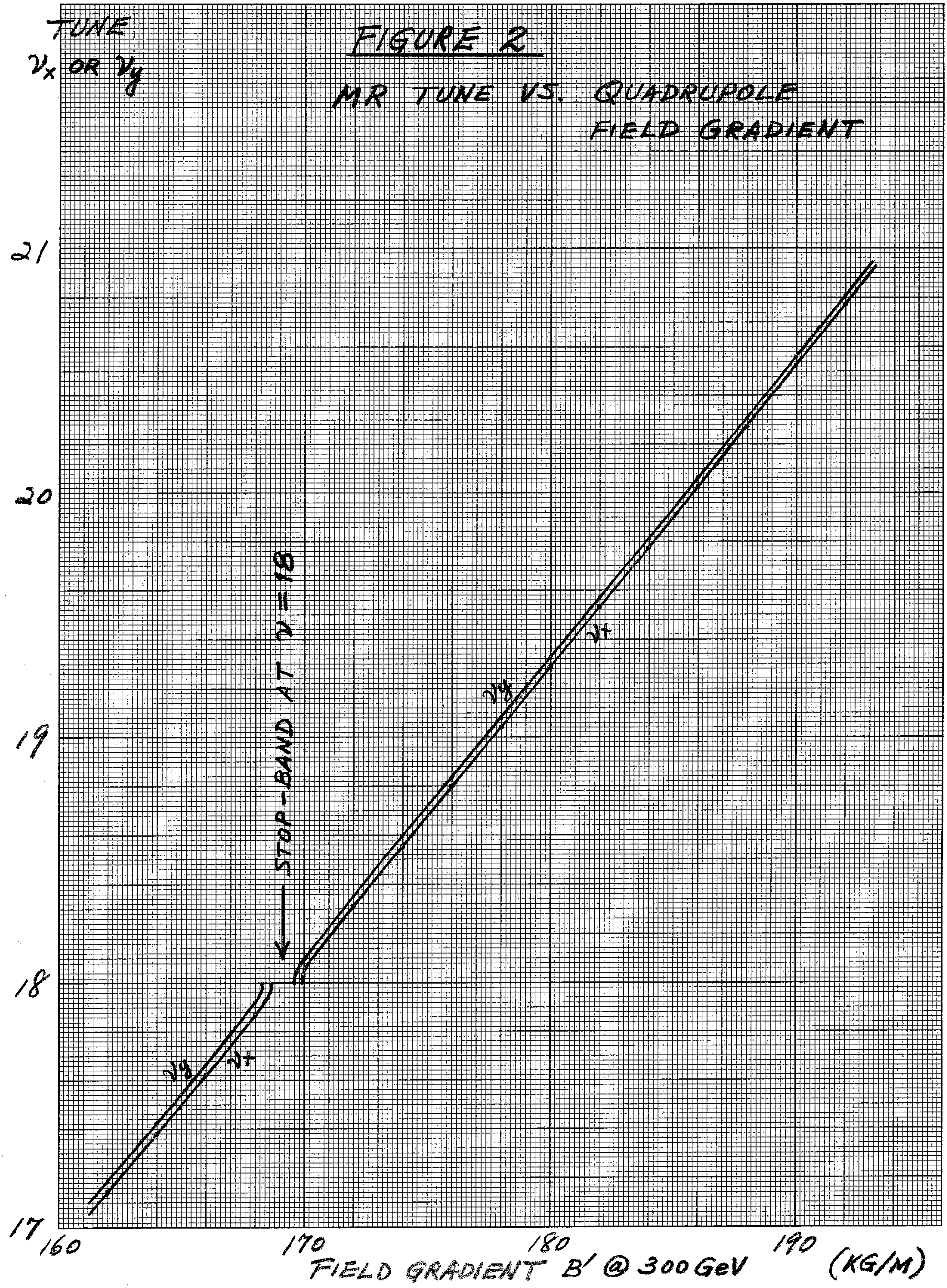
A. For fast extraction we have to move the beam locally next to the septum before kicking. This can presumably be done in the usual manner by a local (say, one wave length) beam bump, except because of the very small useful aperture (±7 mm) at 500 GeV one may have to trim slightly the horizontal position of the beam all around the ring when the local bump is pulsed on.

This is bothersome, but can be done. We conclude, therefore, that fast extraction is not a serious problem.

B. The very large sextupole field (primarily from the bending magnets) and the octupole field (primarily from the quadrupole magnets) must be compensated for the slow resonant extraction. The proper way to accomplish these corrections will be studied in detail. In any case the amount of effort and equipment will be substantial.

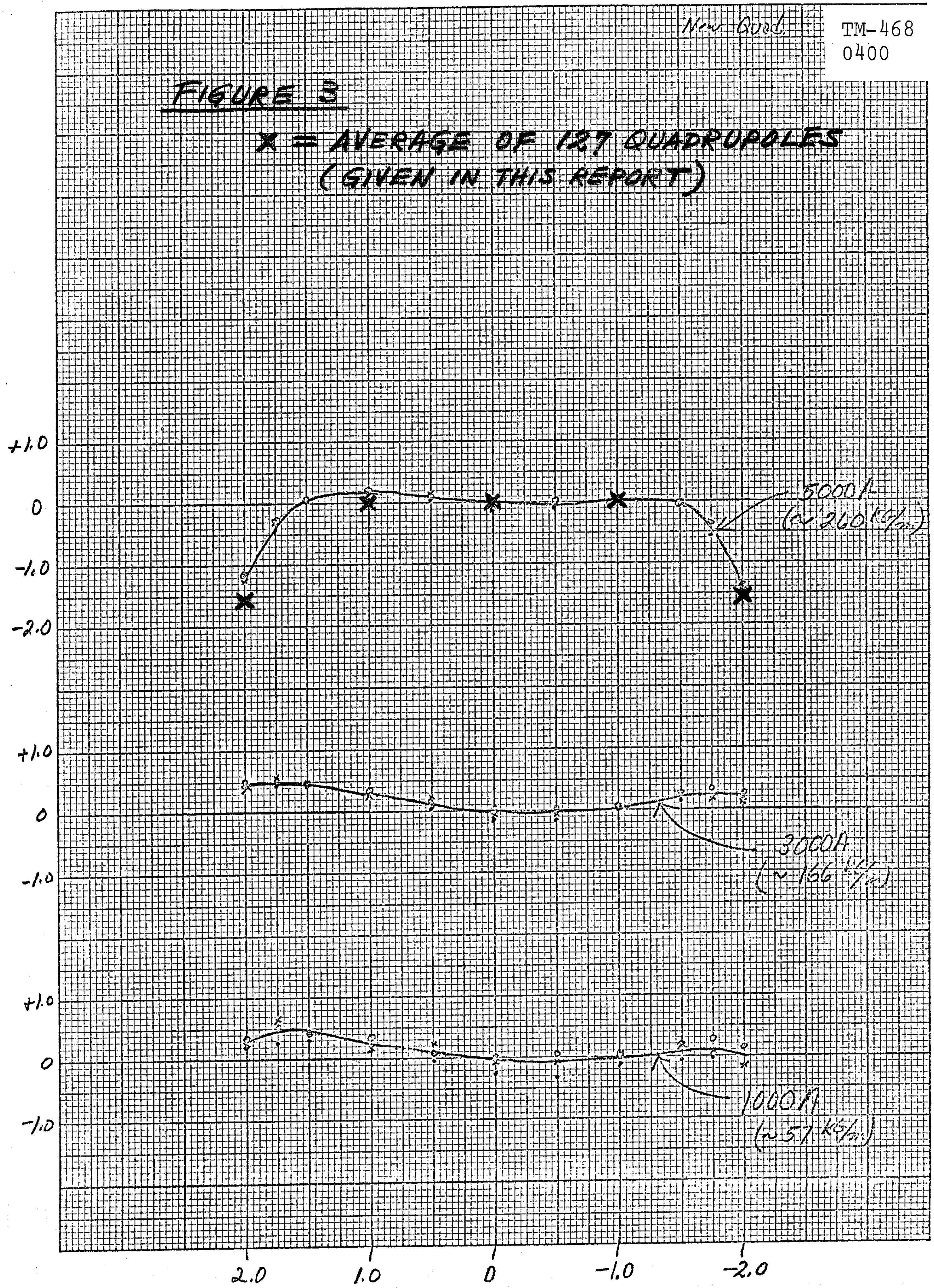
FIGURE 1


MR QUADRUPOLE CURRENT
AMPFACTOR AND
FIELD GRADIENT
CURRENT I_Q (A)
AMPFAC
6500
6000
5500
5000
4500
1.25
1.20
1.15
1.10
1.05
current
ampfac
250
260
270
280
290
300
310
320
330
FIELD GRADIENT B' (KG/M)


TUNE
ν_x OR ν_y
FIGURE 2
MR TUNE VS. QUADRUPOLE
FIELD GRADIENT
21
20
19
18
17
STOP-BAND AT ν = 18
ν_y
ν_x
160
170
180
190
FIELD GRADIENT B' @ 300 GeV (KG/M)

7045 12/29/70

TM-468
0400



TM-468
0400

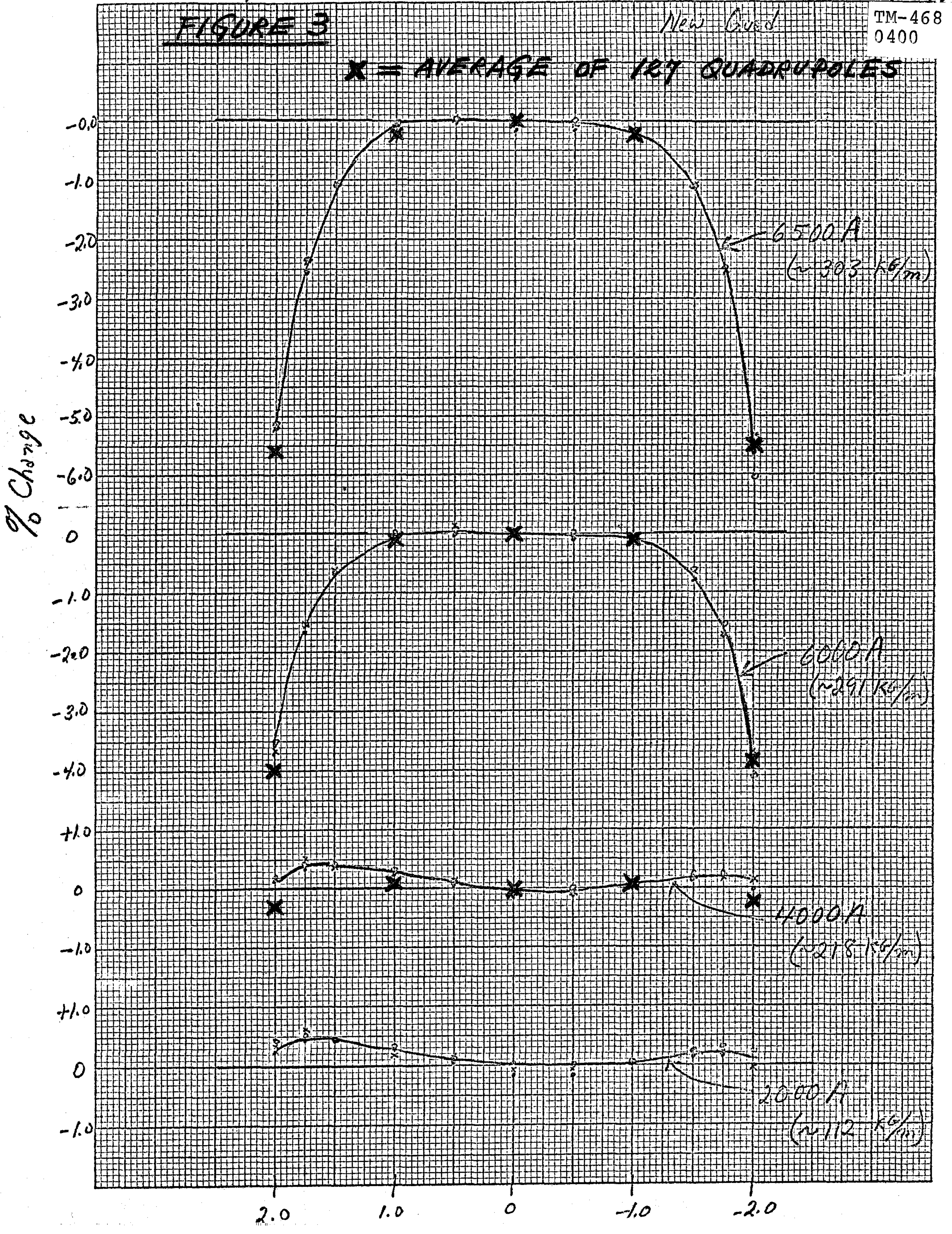


FIGURE 3
New Quad
X = AVERAGE OF 127 QUADRUPOLES
% Change
-0.0
-1.0
-2.0
-3.0
-4.0
-5.0
-6.0
0
-1.0
-2.0
-3.0
-4.0
+1.0
0
-1.0
+1.0
0
-1.0
6500 A
(~303 kG/m)
6000 A
(~291 kG/m)
4000 A
(~218 kG/m)
2000 A
(~112 kG/m)
2.0
1.0
0
-1.0
-2.0