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# COMMENTS ON THE: AGS CHROMATICITY: II

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Technical Note

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## I. Introduction

Recent measurements at the AGS have determined how the chromaticity of the AGS is affected by the ramp rate of the main magnet. This information, combined with the calculations of the chromaticity carried out by the program MAD, enable us to predict the chromaticity of the AGS over the whole cycle of the magnet. The predicted results agree well with the measured results, explaining the questions remaining unanswered in an earlier note.[1] The good agreement we now have between measurement and calculation gives us a basis for doing detailed models at injection on the one hand and for improving the calculations and measurements on the other.

## II. Measurements of Chromaticity at Injection

The chromaticity of the AGS at injection has been measured in 1985 (Gardner and Ahrens),[2] 1986 (Ahrens and van Asselt),[3] and 1987 (Gardner, Gill, and van Asselt).[4] Figure 1 follows a plot in the most recent of these papers which summarizes the results and shows the dependence of the chromaticity on the ramp rate. The fitted straight lines are given by:

$$\varepsilon_H = -2.37 + 0.24\,\dot{B} \tag{1}$$

$$\varepsilon_V = 0.1 + -0.27\,\dot{B} \tag{2}$$

where:

$\varepsilon$ is the chromaticity
$= (dQ/Q)/(dP/P)$

$\varepsilon_H$ is the horizontal chromaticity;
$\varepsilon_V$ is the vertical chromaticity;
$\dot{B}$ is the ramp rate in kilogauss per second.

The chromaticity depends on the ramp rate since eddy currents are induced in the magnets and vacuum chambers, resulting in, among other components, a sextupole field. The constant terms in the equations above come from sextupole components inherent in the magnets, a very small component in the body of the magnet, and a much larger effect from the end regions. These sextupole fields scale with the main field and therefore with the momentum, while the eddy current fields depend only on $\dot{B}$ and therefore the eddy current effect on the chromaticity goes inversely with the momentum. Thus we can project the effect of the eddy currents on the chromaticity over the whole momentum range of the AGS as:

$$\varepsilon_H = 0.24 * \dot{B} x P_{inj}/P \quad (3)$$

$$\varepsilon_V = - 0.27 * \dot{B} x P_{inj}/P \quad (4)$$

where:

$P_{inj}$ is the injection momentum;
$P$ is the momentum.

III. The Ramp Rate

The ramp rate, $\dot{B}$, has been measured by Ahrens and we show his data in Figure 2, where we have translated Gauss Clock Counts into momentum using Weisberg's calibration.[5] Above 20 GeV/c the magnets are saturating and $\dot{B}$ has not been tabulated so our data is just a linear projection. It should be noted that this plot is a typical $\dot{B}$ program, but that it can certainly change from time to time and to fully understand a set of chromaticity measurements, the $\dot{B}$ program in use must also be measured.

Using Equations 3 and 4 we can calculate the chromaticity changes due to the eddy currents over the whole AGS range. The results are given in Figure 3. Note that as we go into flat top there is a chromaticity shift, and more importantly note that at low field there are significant chromaticity swings due to the eddy currents.

## IV. The Calculated Chromaticity

As reported previously,[1] we have used the computer program MAD to calculate the chromaticity based on the DC magnetic field measurements of Thern.[6] Figure 4 shows the chromaticity calculated by MAD based on these field measurements. Three regions are distinguishable; the high field region where the magnets are saturating; the mid field region where the sextupole component is a constant fraction of the primary field, and the low field region where there is a residual field effect. In an individual magnet, the residual field is a relatively large effect, particularly at heavy ion injection, however, the sextupole components of the residual field in open and closed magnets have opposite signs and therefore largely cancel in their effects on the chromaticity.

It is useful to parameterize the curves in Figure 4, which we do in this preliminary and rather awkward way:

A. Mid-Field

$$\varepsilon_H = -2.335$$
$$\varepsilon_V = +0.125$$

B. High-Field

We have not generated a fit yet so the high field region is interpolated from the calculated points.

C. Low-Field

$$\varepsilon_H = -0.017 - 0.114/p$$
$$\varepsilon_V + -0.016 + 0.140/p$$

The procedure for finding the chromaticity predicted by MAD for DC magnets at any value of P is:

a. At 15 GeV/c, use the mid field value;
b. Above 15 GeV/c, interpolate from the calculations;
c. Below 15 GeV/c, add the low field formula to the 15 GeV/c value.

This parameterization gives, we believe a simple and quite accurate picture of what is going on. In particular it gives us an easy way to calculate the behavior of the chromaticity at heavy ion injection. (However there are indications that the detailed behavior of the calculated chromaticity at injection may be a little more complicated than indicated here.) In this formulation, ideally, there should be no constant terms in the low field expressions. Those that appear here should be viewed as small imperfections in the fitting process.

Note that the fitted constant terms in Equations 1 and 2 give good agreement with the mid-field values, as they should.

## V. The Predicted Chromaticity

The overall predicted chromaticity is just that calculated by MAD as shown in Figure 4 plus that resulting from the ramp rate induced eddy currents as shown in Figure 3. Figure 5 shows these sums as well as the measured results of Ahrens, et al.[7] We are very pleased with the agreement. It is certainly as good as we deserve. At high field there are enough subtleties in the MAD parameters to let us feel that we can plausibly improve the fit there. At low field, we just have to assume that the ramp rate was 20% higher at the time of the chromaticity measurements than shown in Figure 2 to explain the discrepancies.

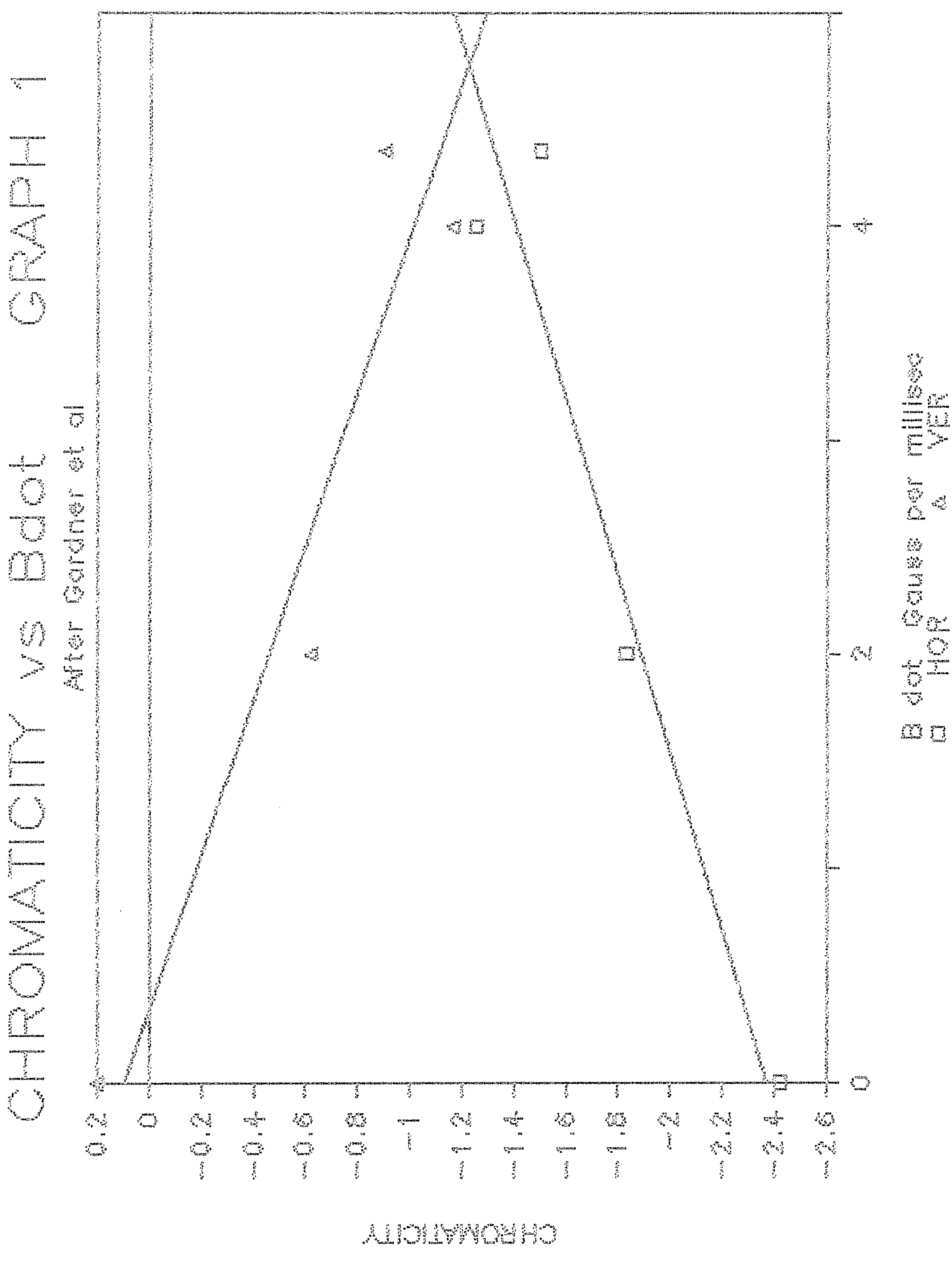
## VI. Conclusions

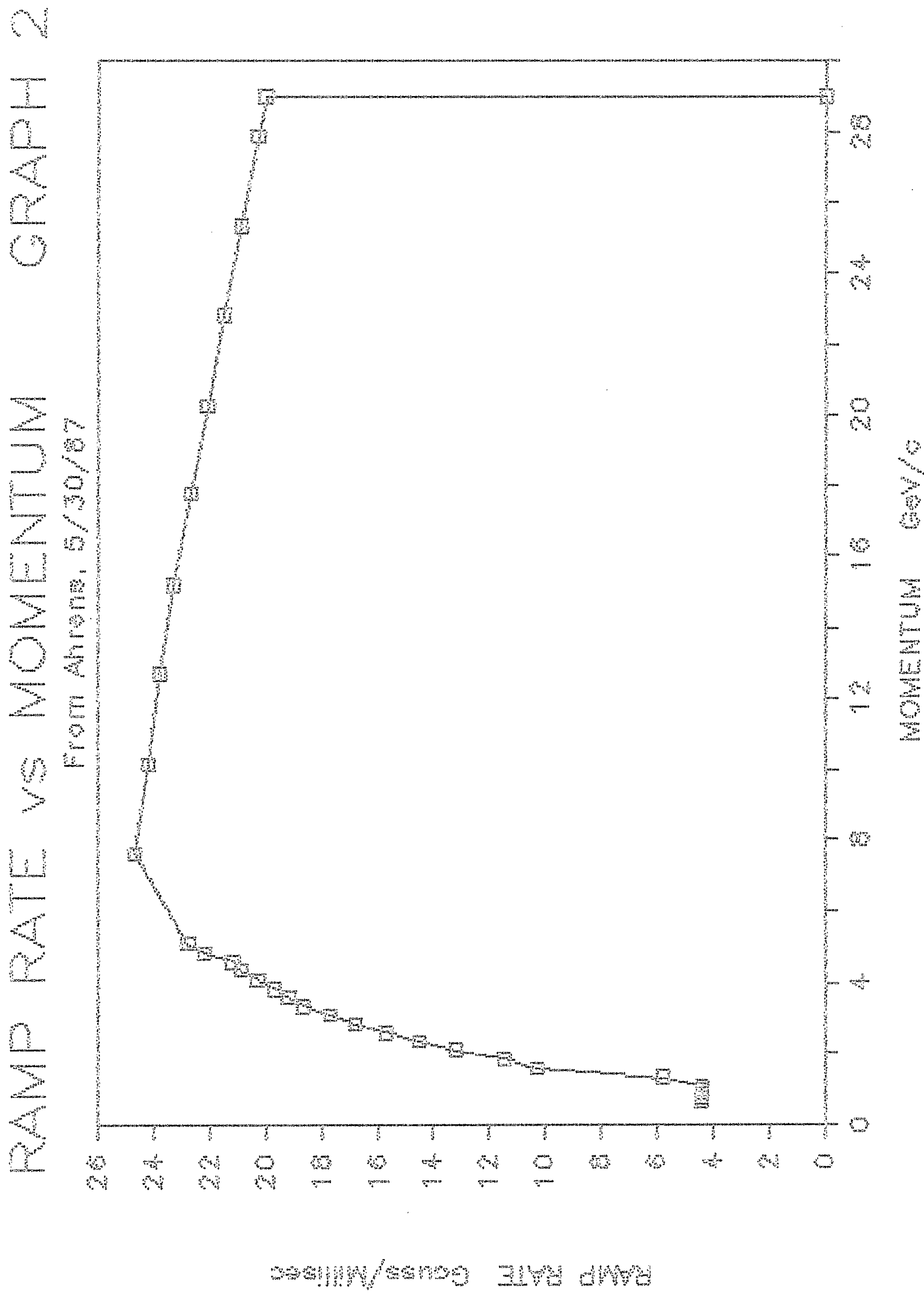
We have a good parameterization of the chromaticity as a function of momentum and ramp rate. MAD gives us a good model of the AGS. We can make detailed predictions of the complex behavior of the chromaticity at low field.

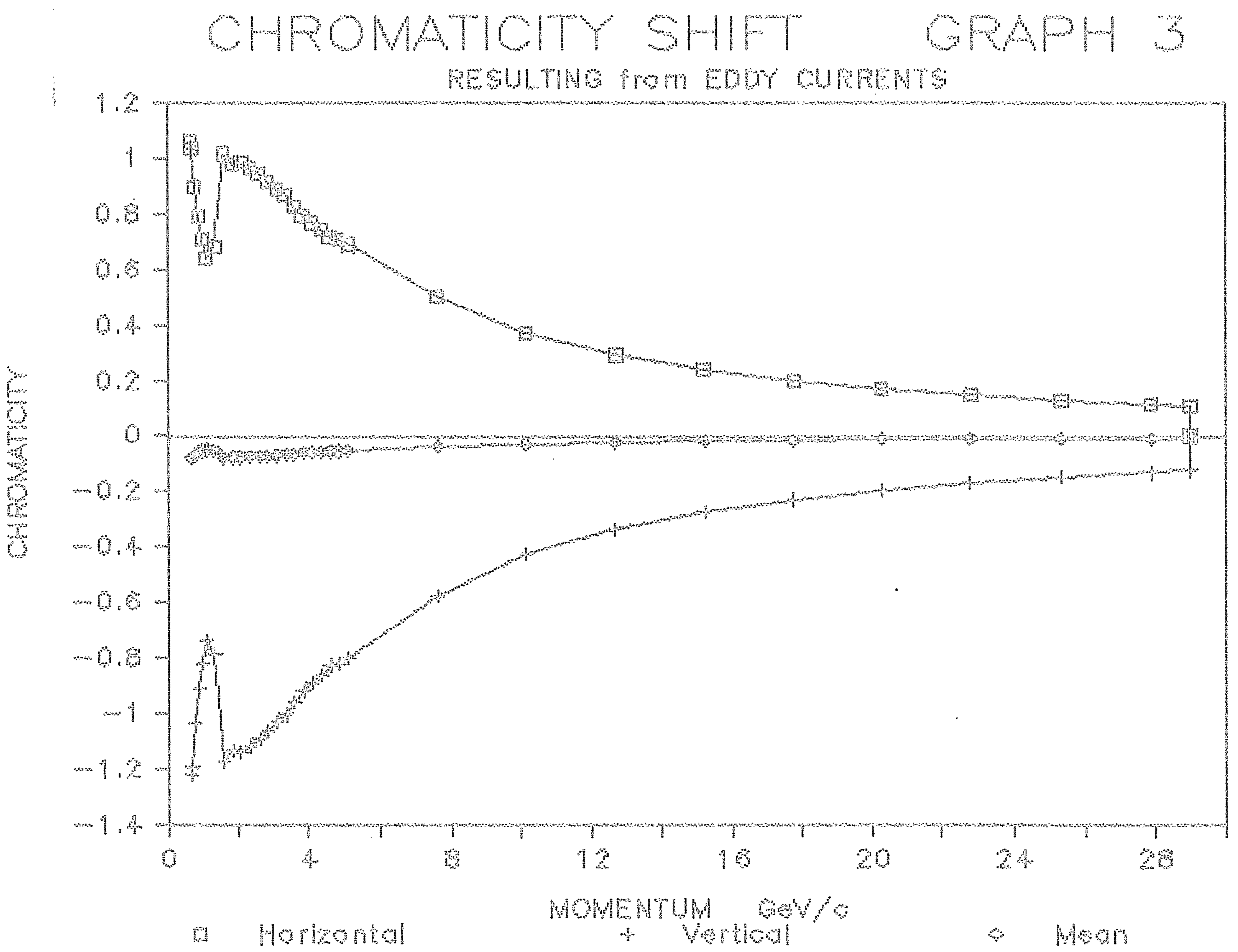
For the future, more and better measurements of the machine parameters, coupled with more careful calculations will enable us to develop our model to still better accuracy. In addition, it now seems appropriate to standardize the model in MAD and to undertake to make it more generally accessible.

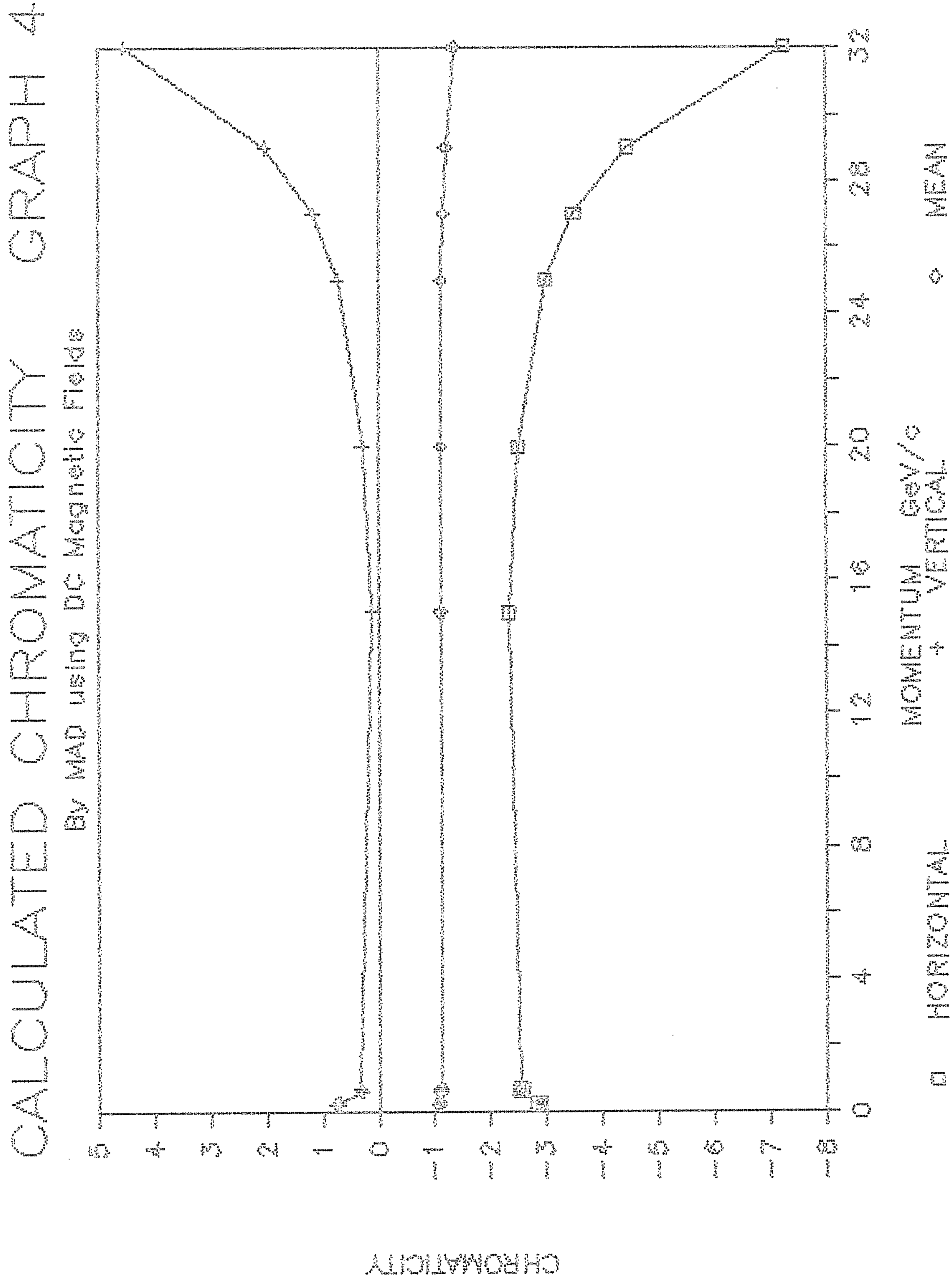
## VII. References

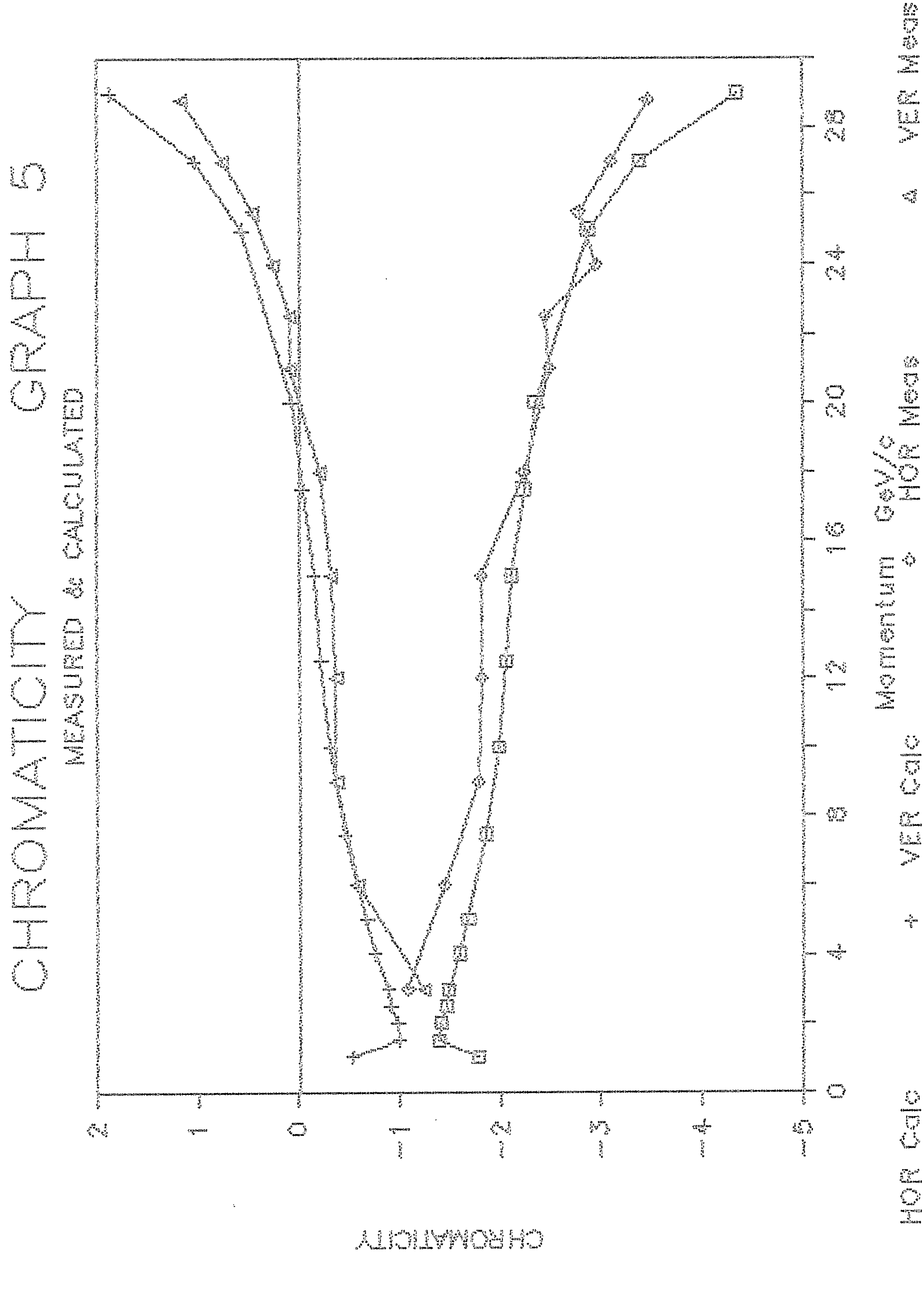
1. Auerbach, Bleser, Thern, AGS/AD/TN 275, 2/25/87.
2. Gardner & Ahrens, BNL 36490, 1985 Partical Accelerator Conference, 5/13/85.
3. Ahrens and van Asselt, AGS SR-206, 6/26/86.
4. Gardner, Gill, and van Asselt, AGS SR-226, 6/7/87.
5. Weisberg, AGS TN 145, 3/13/78.
6. Thern, to be published.
7. Ahrens, Potier and van Asselt, AGS SR-182, 6/6/85.


CHROMATICITY vs Bdot GRAPH 1
After Gardner et al
CHROMATICITY
0.2
0
-0.2
-0.4
-0.6
-0.8
-1
-1.2
-1.4
-1.6
-1.8
-2
-2.2
-2.4
-2.6
0
2
4
B dot Gauss per millisec
HOR
VER


RAMP RATE VS MOMENTUM GRAPH 2
From Ahrens, 5/30/87
MOMENTUM GeV/c
RAMP RATE Gauss/Millisec
0 4 8 12 16 20 24 28
0 2 4 6 8 10 12 14 16 18 20 22 24 26


CHROMATICITY SHIFT GRAPH 3
RESULTING from EDDY CURRENTS
CHROMATICITY
1.2
1
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8
-1
-1.2
-1.4
0
4
8
12
16
20
24
28
MOMENTUM GeV/c
Horizontal
Vertical
Mean


CALCULATED CHROMATICITY GRAPH 4
By MAD using DC Magnetic Fields
CHROMATICITY
5
4
3
2
1
0
-1
-2
-3
-4
-5
-6
-7
-8
0
4
8
12
16
20
24
28
32
MOMENTUM GeV/c
□ HORIZONTAL
+ VERTICAL
◇ MEAN


CHROMATICITY GRAPH 5
MEASURED & CALCULATED
CHROMATICITY
Momentum GeV/c
HOR Calc + VER Calc ◇ HOR Meas △ VER Meas
2
1
0
-1
-2
-3
-4
-5
0
4
8
12
16
20
24
28