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Measuring the Momentum of the AGS Beam

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Reported by E. Bleser

Subject Measuring the Momentum of the AGS Beam

Objectives

Our goal was to measure the momentum of the AGS beam using two different methods in order to compare them and to evaluate their precision. The two different methods were to use the Gauss clock and to use the frequency meter. These devices are nominally precise to nearly 10^{-5}, but in measuring the momentum they typically agree by no better than 10^{-3}. We expected that the problem was with eddy currents produced by the changing magnetic field and therefore were interested in taking data on the recently installed front porch. Also working at this low field value means that the radius of the orbit, which is unknown, is not very important.

Procedure

The experimental procedure was to record on successive pulses the frequency meter for various values of the Gauss clock. The window on the frequency meter was one millisecond wide. Also recorded using the IPM Program were the magnetic field and Bdot as functions of time.

RESULTS

A. The Magnetic Field

Figure 1 shows the general behavior of the magnetic field, B, as a function of time, and Figure 2 shows Bdot, the time derivative of this field. At about 52 milliseconds after To (T zero) the field starts to ramp up at a uniform rate. At 130 milliseconds the ramp rate starts to increase, but for this run we start to go into a front porch at 160 milliseconds, the ramp rate decreasing to a very low value by 170 milliseconds. Since the IPM takes this data on successive pulses and since Siemens is not synchronized to real time, the data show some jitter, which we can ignore.

Our question in general is how well do we know the field. Since the field is proportional to the beam, we choose to talk of momentum rather than field. The field, or, as we shall henceforth say, the momentum, is proportional to the Gauss clock. In fact the Gauss clock was calibrated so that the momentum in GeV/c is $5*10^{-4}$ times the Gauss clock counts. Therefore to first order we have simply:

$$P = 5*10^{-4}*GC$$

Previous work has indicated that for better accuracy we must add a constant term to allow for an offset in the Gauss clock, that we must allow the multiplicative term to vary slightly to allow for inaccuracies in the calibration, and that there is probably a dependence on Bdot since the beam is circulating in a vacuum chamber between the magnet poles while the Gauss clock is a winding around the backleg of the magnet. Therefore we have:

$$P = a + b*GC + m*dB/dT \qquad 1.$$

(See Appendix 1 for a discussion of the radial dependence.)

B. The Frequency Meter

We measured the frequency by opening a one millisecond wide window, triggering off the Gauss clock. We adjusted this number by subtracting from it 0.5 milliseconds times the slope in time of the frequency. The results, transferred to a real time scale are shown in Figure 3.

Since the RF frequency is:

$$f = 12*\beta*c/2*\pi*R$$

and we define:

$$f_o = 12*c/2*\pi*R$$

and we know:

$$P = \beta*m_o/\sqrt{1-\beta*\beta} \qquad 2.$$

we then have:

$$P = m_o/\sqrt{(f_o/f)^2 -1}$$

Where:

$\beta = v/c$
v = velocity of the proton
c = speed of light
R = radius of the AGS (see Appendix 1)
m_o = mass of the proton

Figure 4 shows the momentum calculated from the frequency measurements. This looks just like the magnetic field shown in Figure 1 since on this scale they are indistinguishable.

ANALYSIS

We have two measurements of the momentum. One is from the frequency, P(f). It depends on the radius, which we know very well for our purposes (Appendix 1). Therefore we can accept it as correct and absolute. The other measurement of the momentum, P(GC), is based on our hypothesized Equation 1. It involves 3 unknown constants and two sets of data, the Gauss clock and the Bdot measurements. If we make the assumption that:

$$P(f) = P(GC)$$

Then this gives:

$$P(f) - b*GC = a + m*dB/dT \qquad 3.$$

In Figure 5 we plot as data points the left hand side of this equation

$$P(f) - b*GC$$

Note that these data points look very much like the dB/dT curve in Figure 2. This was achieved solely by varying b. Recall that in units of 10^{-4} GeV/c//Gauss clock counts, b was intended to be 5. This note has a fitted value of 5.089. It is principally determined by the flat region from 70 to 130 milliseconds. Varying b by ±0.002 significantly disturbs the fit.

It is now easy to make an eyeball fit of the right hand side of Equation 3 to the data points to get a, the offset in the Gauss clock, and m, the dependence on Bdot. The results are:

$$a = 0.0515 \text{ GeV/c}$$

$$b = 5.089*10^{-4} \text{ GeV/c//GC}$$

$$m = 0.0027 \text{ GeV*sec/Gauss*c}$$

Figure 5 summarizes this paper by displaying as data points, P(f) - b*GC, and as a line the fitted curve a + m*dB/dT. The agreement is very striking except for the first three points for which we have no readily available explanation.

CONCLUSIONS

We have two different ways of calculating the momentum. Using just 4 fitted constants we get remarkably good agreement to a precision of a few MeV/c. Our hypothesis of a Bdot dependence seems to be strikingly confirmed. Before claiming success however we must carry out several further checks:

a. Do measurements of the full momentum range;
b. Confirm constancy of constants;
c. This analysis can predict R. See if the predictions agree with the measured results during the SEB running;
d. Understand the sign of the Bdot effect. (See Appendix 2)

APPENDIX 1

THE RADIUS

For this low intensity proton run the PUE's could not detect the beam so we could not measure the radius. Therefore we best not worry too much over what we can not see. Two PUE's were amplified enough so that they could send a signal to the radius shifter. We need simply assume that this device was working and that it held the beam as desired in the center of the PUE's. We then have two questions: 1.) What is the nominal radius? and 2.) What is the sensitivity of our momentum determination to this radius?

A. The Nominal Radius

In TN 217 we found that the sum of the chord lengths (divided by 2 pi) along the orbit that goes through the center of the PUE's is:

12845.471 centimeters

In each magnet the curved path of the orbit is a few mills longer than the chord length so we must add to this length 0.249 centimeters. Thus we have the theoretical radius of the AGS:

R(theoretical) = 12845.720 centimeters

(It is interesting to note that the radial survey [TN 289], while not claiming such absolute precision, agrees with this number to an eighth of a centimeter.)

The high momentum region is very sensitive to the value of the radius (as we shall see below), and in an experiment similar to this one, but as yet unpublished, we found a fitted value for R of:

R(fitted) = 12845.69 centimeters

This is gratifyingly close to the theoretical value and for the purposes of this paper is the number we shall use.

B. Error Analysis

There are four pertinent parameters in this analysis: B, R, P, and f. They are related by two equations, so only two can be chosen freely.

If we measure B and R, then the error in P is given by (Bouvet, CERN 70/4):

$$dP/P = (\gamma_{tr})^2 * dR/R + dB/B$$

For this work it is perhaps safe to say initially that R is stable to a centimeter and that we know it absolutely to a centimeter. A one centimeter error in R gives a 0.5% error in P, which might shift our fitted value of b, 5.09, by plus or minus 0.025. The displacement of the first three points in Figure 5 could be due to a one centimeter displacement of the injected beam. For the next 60 milliseconds the data are very smooth, suggesting the beam orbit is stable to the one millimeter level.

If we measure f and R, then the error is given by:

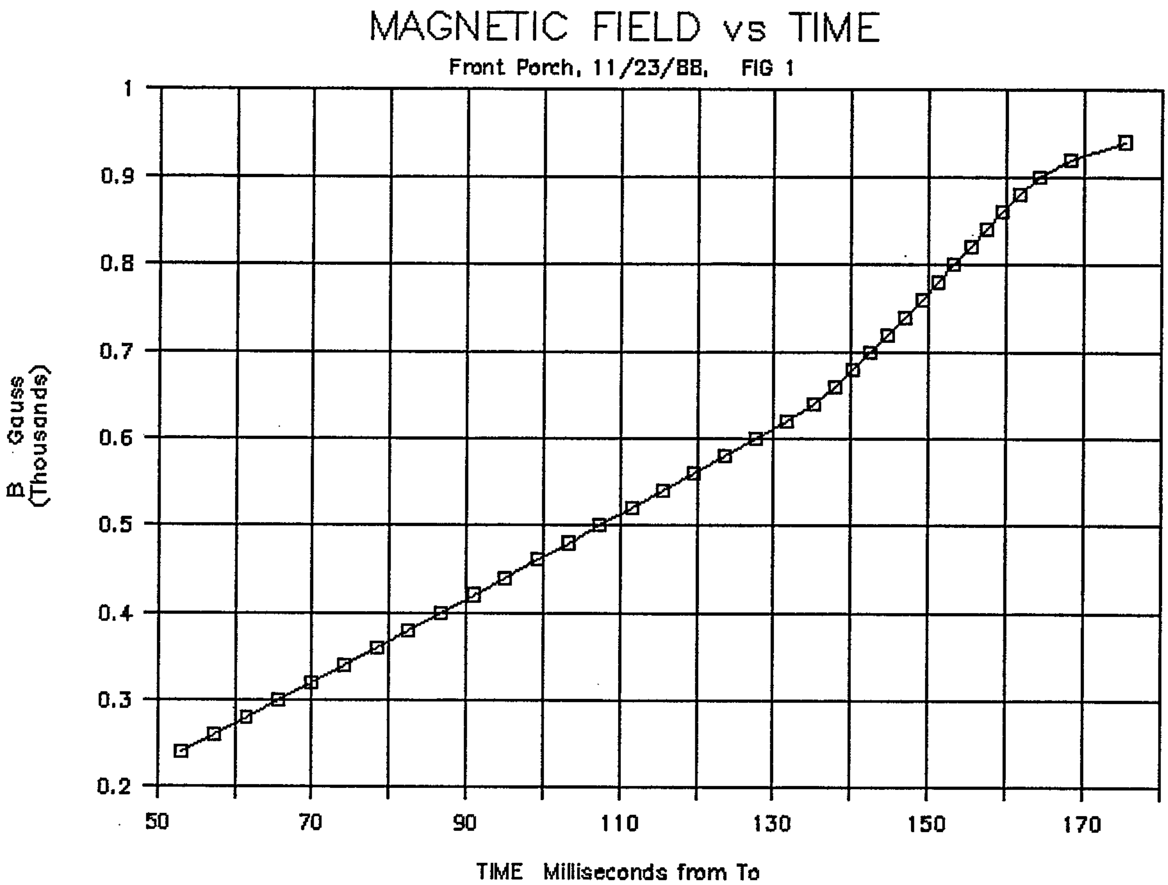
$$dP/P = \gamma^2 * df/f + \gamma^2 * dR/R$$

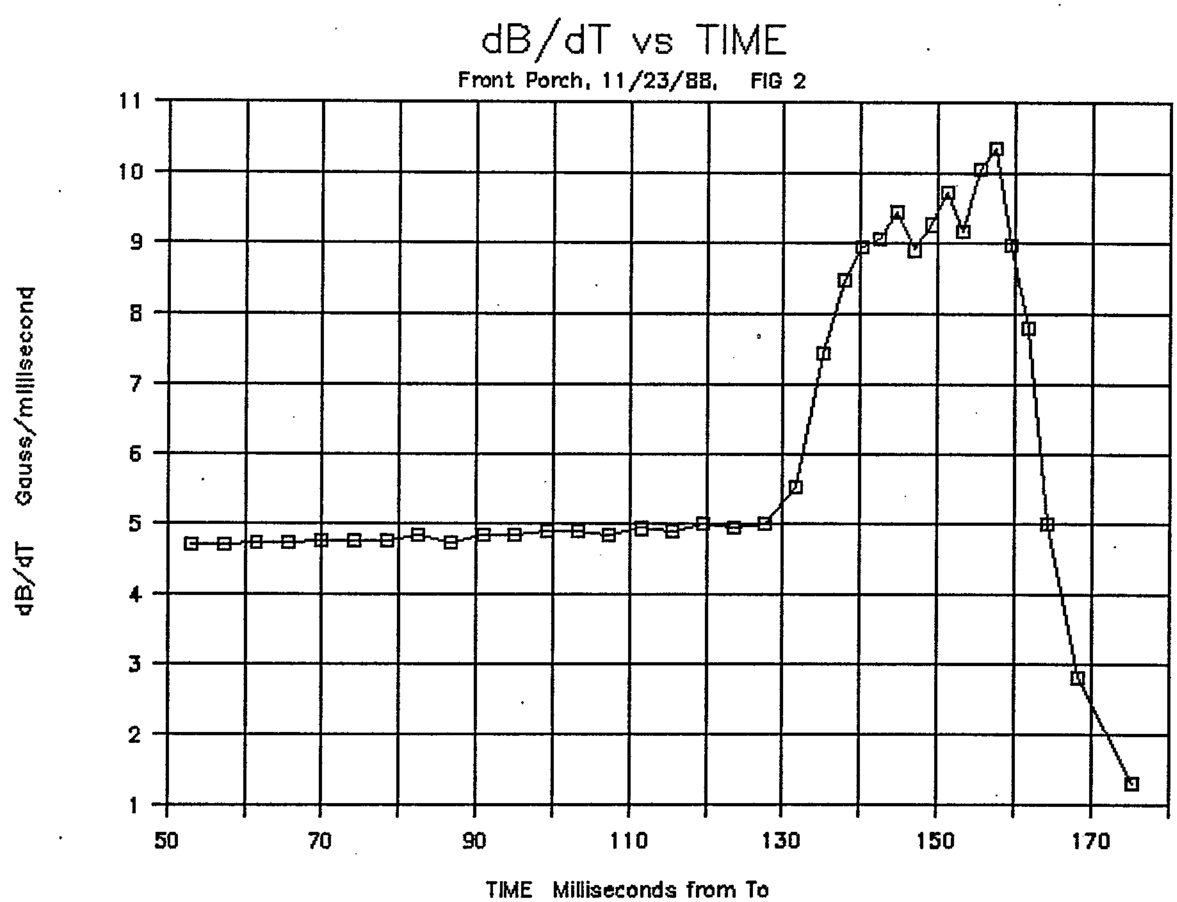
At injection gamma squared is 0.5, at extraction it is 1000. Therefore an experiment of this sort is very sensitive to the radius at high momentum but hardly at all at low momentum. P(f) in this experiment is determined almost entirely by the frequency measurement and not at all by our choice of R.

APPENDIX 2

This spring we carried out a an experiment similar to this one and reported it at a Friday seminar. It has not been written up since we assumed we were seeing an effect due to eddy currents in the vacuum chamber. However such an effect would have a sign opposite to what we observed, and thus the experiment was not understood. This second experiment confirms the first by finding again the same seemingly wrong sign. Therefore we propose a different eddy current model. This is a post hoc, ergo propter hoc argument and should be treated as such until there is further confirmation.

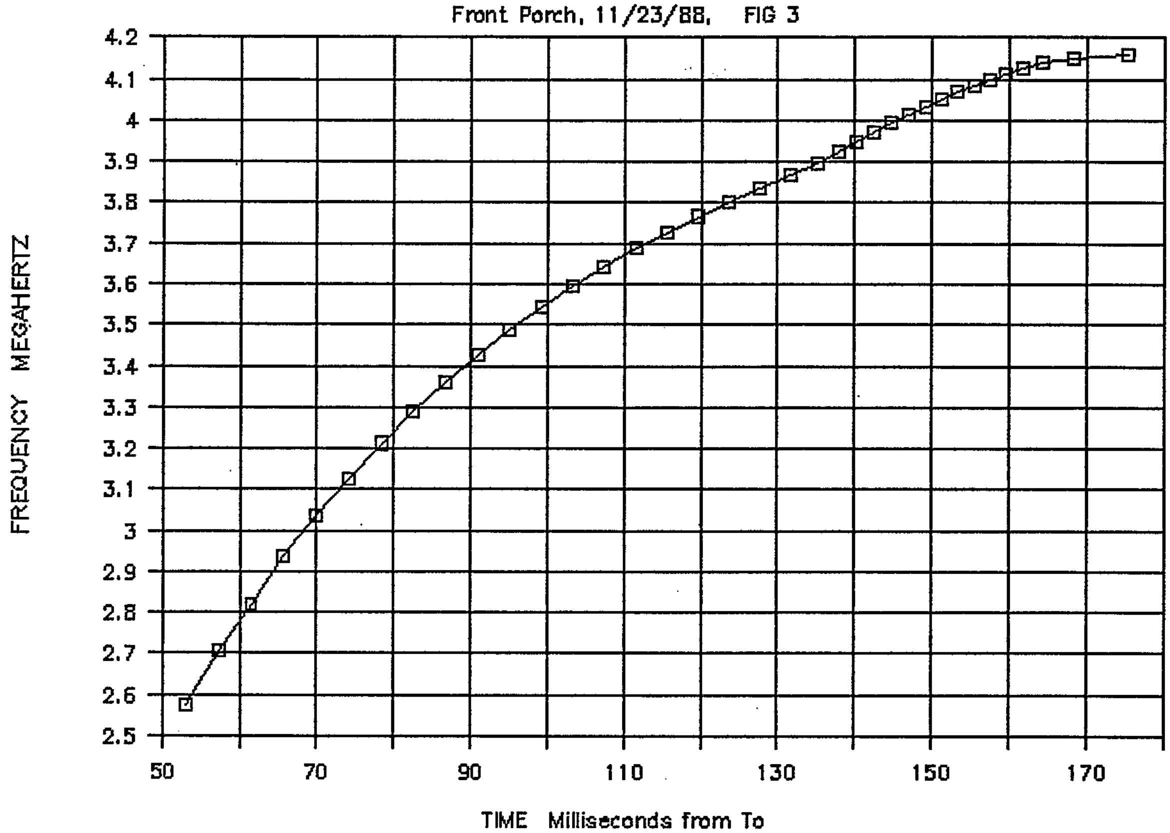
In the magnet the main coil is close to the pole tip and concentrates the flux lines through the pole tip. In contrast there can be significant flux leakage out of the backleg. During the ramp up, eddy currents are generated in the laminations. Even though they are small they are real. Imagine them as being collected all together as a current in a closed loop of conductor around the backleg of the magnet. The current in this loop depends on Bdot. It makes the field in the backleg lag behind the field in the gap. This is the effect that we see when we have to add a term proportional to Bdot to the field measured by the backleg winding in order to get agreement with the field measured by the proton beam circulating in the magnet gap. We have not made any quantitative evaluation of this effect but it has the right sign and it might explain what we see. It is perhaps reasonable that dipole eddy current effects are generated in the magnet as a whole, which does have a certain resemblance to a dipole, while sextupole eddy current effects are principally generated in the vacuum chamber, which is very small compared to the magnet, but which is the only ready source of sextupole terms, and thus has dominated our thinking about eddy currents.


MAGNETIC FIELD vs TIME
Front Porch, 11/23/88, FIG 1
B Gauss (Thousands)
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
50
70
90
110
130
150
170
TIME Milliseconds from To


dB/dT vs TIME
Front Porch, 11/23/88, FIG 2
dB/dT Gauss/millisecond
11
10
9
8
7
6
5
4
3
2
1
50
70
90
110
130
150
170
TIME Milliseconds from To

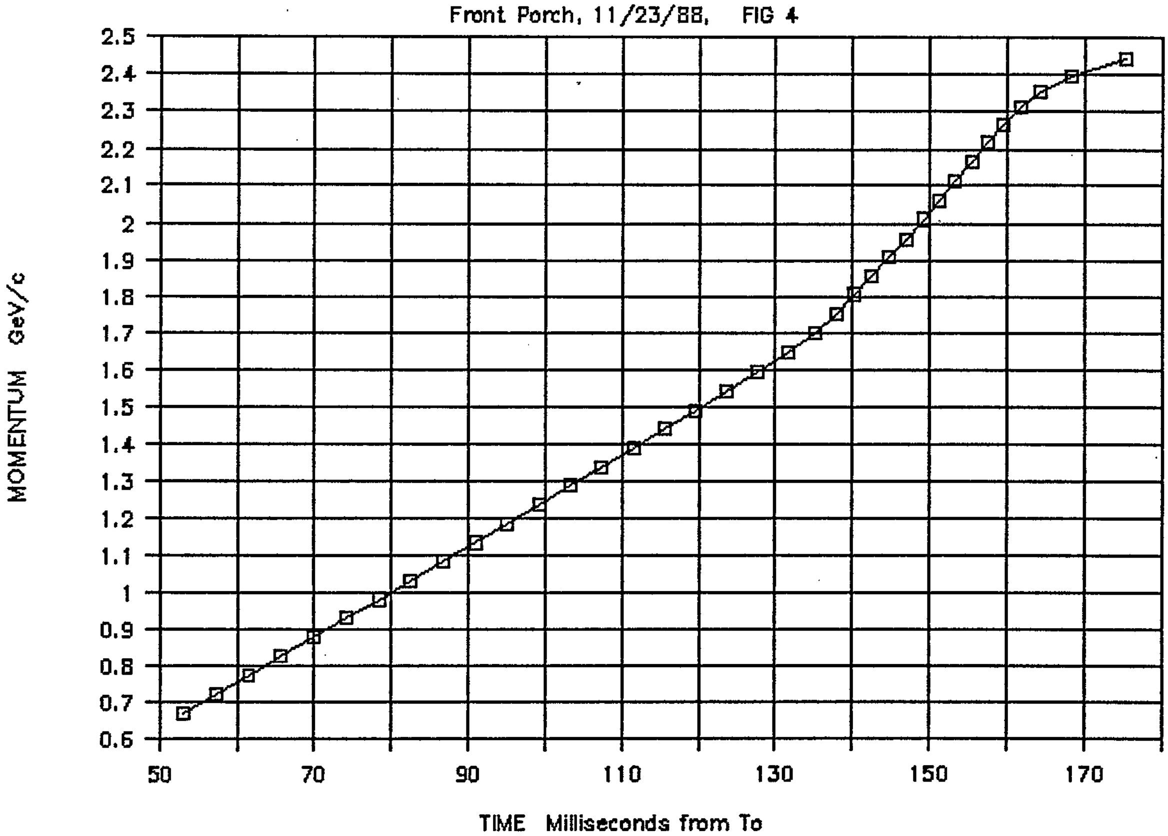
RF FREQUENCY vs TIME

Front Porch, 11/23/88, FIG 3



MOMENTUM vs TIME

Front Porch, 11/23/88, FIG 4



P(f)−b*GC vs TIME

a=0.0515, m=0.0027, b=0.0005089 FIG 5