SPS/DI/EJNW/ek

4 August, 1976

*SPS COMMISSIONING REPORT NO. 14 (REVISED)

Topic : A Measurement of Chromaticity and its Compensation during Acceleration

Date : 18th June, 1976

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1. Introduction

Figure 1 shows qualitatively how the three components of chromaticity of the SPS vary during a 300 GeV cycle. The three components appear on the right hand side of the equation:

$$\xi = \{dQ/Q\} / \{dp/p\} = a + b \{B_{inj}/B\} + c \{\dot{B}/B\}$$

The three terms originate from the momentum dependence of the focusing strength of the lattice quadrupoles, the sextupole component in the remanent field of the lattice dipoles and the sextupole field set up by eddy currents in the vacuum chamber walls as the dipoles are pulsed. There are two such equations each with different coefficients describing the momentum dependence of Q_H and Q_V.

The chromaticity correcting sextupoles LSF and LSD are designed to compensate both ξ's producing a time varying chromaticity equal and opposite to that of the machine. We aimed to thus reduce ξ by an order of magnitude so that, even in the early part of the cycle where $\Delta p/p$ can be as large as ± 0.4%, the Q spread is less than ± 0.02. One can then hope to adjust Q so that none of the protons hit neighbouring stopbands.

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The correction is specified as a set of six coefficients $(a, b, c)_{H,V}$. After a matrix multiplication, these six numbers are used to construct a digital table which specifies the waveform which the LSF and LSD power supplies are expected to follow (Fig. 2). The tables are loaded into the two function generators where they are stored and used each pulse to generate the reference voltage for the power supplies. Above 90 GeV, where compensation becomes less critical, the LSF and LSD currents are held constant so that they only partially compensate ξ .

One can calculate the constant a rather reliably from the lattice dynamics. An earlier experiment (1) established $\xi = a+b$. In addition, we were able to estimate(2)c, the eddy current coefficient from measurements on the complete set of dipoles and thus construct a semi-empirical set of coefficients which proved adequate for our immediate aim of reaching 400 GeV.

Table 1. - Chromaticity Correction Coefficients

(these have opposite sign to the chromaticity of the bare machine).

	H	V
a	1.29	1.29
b	0.61	- 0.61
c	- 0.337	0.252

This experiment was intended to check the efficacy of these coefficients and of the software which translated them into sextupole currents by measuring the residual chromaticity at three energies shown by a cross in Fig. 1. The highest enery, 200 GeV, was chosen to reveal any error in a, since bands have little effect there. The other two energies were chosen to be as close to the peak in $\dot{B}/B$ where one could check the effect of the coefficient c.

The measurements show that the semi-empirical coefficients were indeed sufficient to keep the error in ξ compensation below 0.2 throughout the cycle.

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2. Technique

We used a trapezoidal perturbation in the radial position program to displace the radial position and mean momentum of the beam for a time of 100 msec. During the first 10 msec of the bump we sampled the r.f. frequency with a Hewlett-Packard Computing Counter thus determining the momentum shift. Immediately afterwards, we measured ν (the Q value for the beam) in both planes and measured the mean radial position as an additional check on the displacement of the beam.

Three sets of measurements were made by lining the bump at the points indicated by a cross in Fig. 1. Octupoles were switched off before each measuring point.

3. Chromaticity at 200 GeV

Figure 3 shows the measured values of Q (which we call ν to distinguish them from theoretical values) as a function of $\Delta p/p$ at 201 GeV/c. At this energy, the influence of the remanent field and eddy current terms is small and can be subtracted as a small correction. The measurements were made with the LSF and LSD sextupoles on, partially correcting chromaticity at their 90 GeV plateau currents. Their effect too can be subtracted from the slope of the line ($dQ/dp/p$) so that one arrives at empirical values of $g_H = -1.15$ and $g_V = -1.41$.

The average g value agrees excellently with that assumed in Table 1. The small split, 0.26, was foreseen in the analysis of magnet measurements and is presumably due to the geometric design of the dipoles which is known to produce a small sextupole component. However, since it is within the tolerance we allow on ξ and is not much larger than the experimental error we prefer not to read too much significance into it at this stage.

4. Chromaticity at 50 GeV

The dashed curve in figure 3 shows ν measurements with the LSF LSD's following their nominal correction program (Table 1). The gradients suggest the residual chromaticities are only $\xi_H = +0.07$ $\xi_V = 0.18$ again within tolerance and experimental error. At this energy, the eddy current term is quite strong and one would expect any error in the predicted value of d to show itself.

We went on to run the LSF LSD sextupoles with d=0 as input data to their control program leaving the other terms untouched. The slopes of the ν curves (solid lines) immediately increase. The change in chromaticity corresponds to that which one would expect if the control programs were working properly to within $\pm$ 0.06 giving us confidence in the software and experimental techniques.

5. 13 GeV Measurements

At the peak of $\dot{B}/B$ one is so close to transition that accurate measurements of this kind extending over 10 or 20 msec are very difficult. We did however succeed in measuring ν versus $\Delta p/p$ at 13 GeV, high up on the $\dot{B}/B$ curve with full LSF LSD compensation (Fig. 5).The data is scattered but the lines which give $\xi_H = -0.13$ and $\xi_V = -0.16$ show that the compensation is good.

6. Conclusions on Chromaticity

Taken together with the previous injection measurements we conclude that the errors in compensation when one uses the coefficient in Table 1 are small. Theoretical predictions of eddy current effects and of the geometric term are good.At transition where $\Delta p/p$ is large one can expect the Q spread to be still within 0.02. This is confirmed by the observation that rarely does one see a significant loss at transition. Elsewhere in the cycle the Q spread is even smaller and indeed coherent ranging lines following a Q kick do seem to be long at all energies.

Later, should one wish to control ξ more precisely, perhaps to ensure it has the right sign to damp an instability, more detailed studies may be required using the same technique, but for the moment we feel we have the chromaticity well enough corrected to prevent resonant loss.

7. Some Other Interesting Observations

As a by-product of the measurements of r.f. frequency and mean radial position, we were able to establish the mean radius of the accelerator, expected to be 1100.0026 m when one takes into account the curved path of protons through the dipoles of the lattice. Table 2 gives our results which show the radius to be 6 mm larger than expected. The RF Group have independently seen and measured the same effect (3).

Table 2

Energy	$\bar{R}$ - 1100 m
300	9.2 mm
200	8.5 mm
50	7.1 mm

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An effect of the same sign and magnitude was seen at NAL. Can it be that we borrowed their laser device for establishing the external survey or is it merely the sort of statistical fluctuation one expects with a geometry of this size? The argument is academic since it does not affect the operation of the accelerator.

At the extreme edges of the 50 GeV measurements the beam survived well over a momentum range of more than 2% full width, and closed orbit measurments showed it almost touching the physical aperture of the machine. The acceptance of the SPS is potentially very large.

In the 200 GeV measurements the beam was taken across the half integer resonance during the rise time of the bump yet a reasonable proportion of the beam survived. The rate of change of Q is about 0.2 in 100 msec.

E.J.N. WILSON

REFERENCES

1. Commissioning Report no 5

2. M. Cornacchia - LAB II - DI - PA/Int. 75-8

3. Commissioning Report no 11

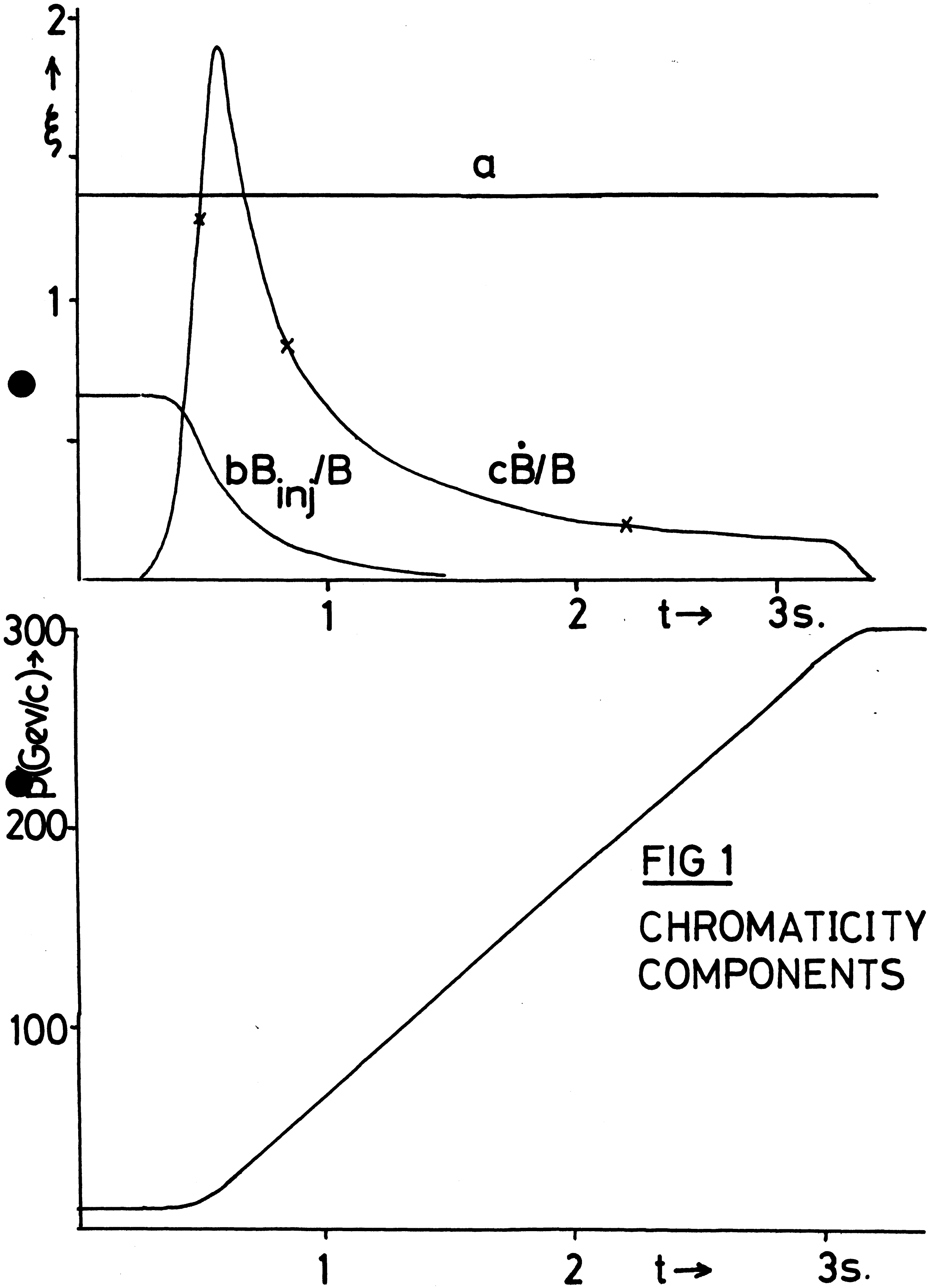

FIG 1

CHROMATICITY COMPONENTS

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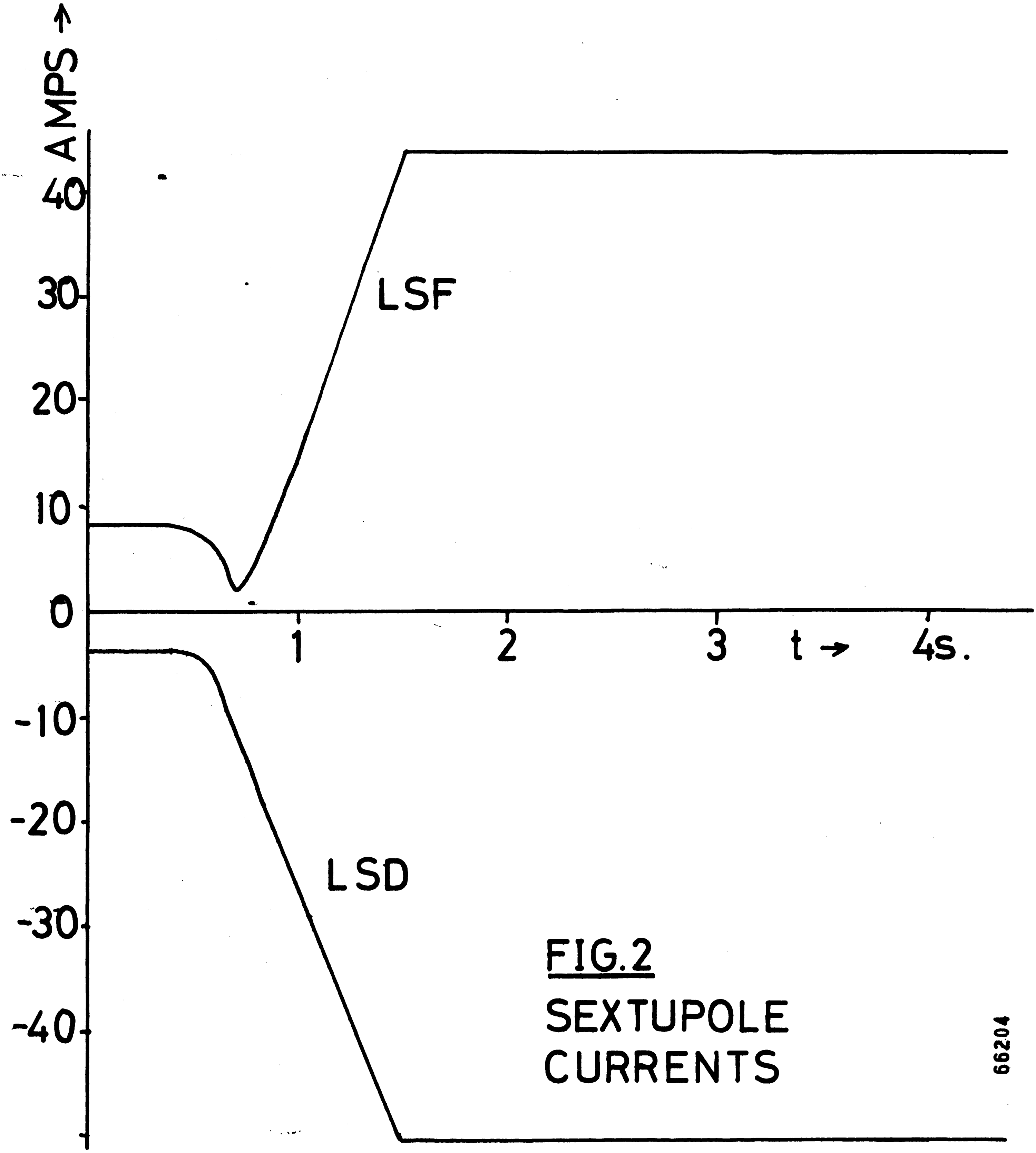

FIG. 2

SEXTUPOLE CURRENTS

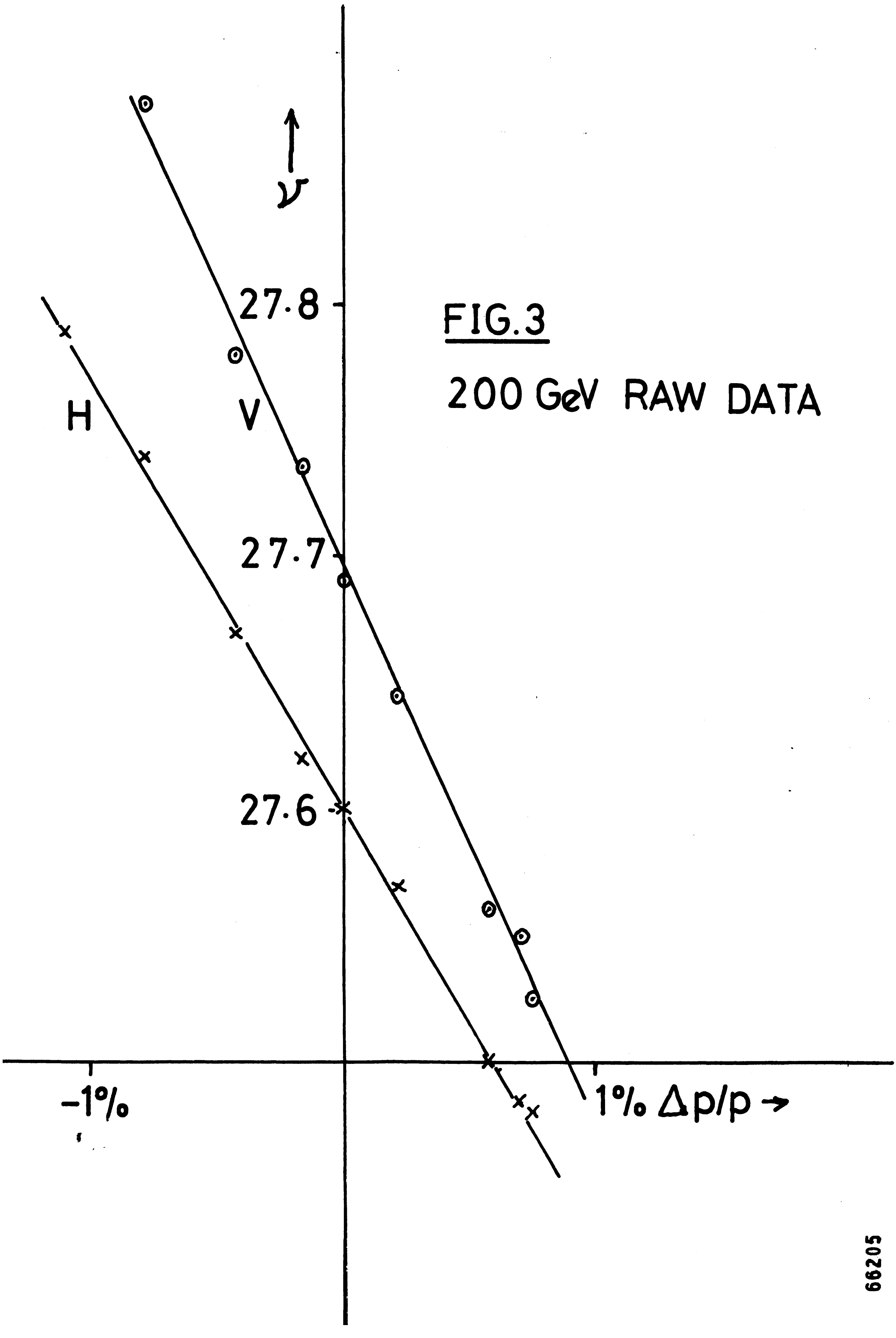

FIG.3

200 GeV RAW DATA

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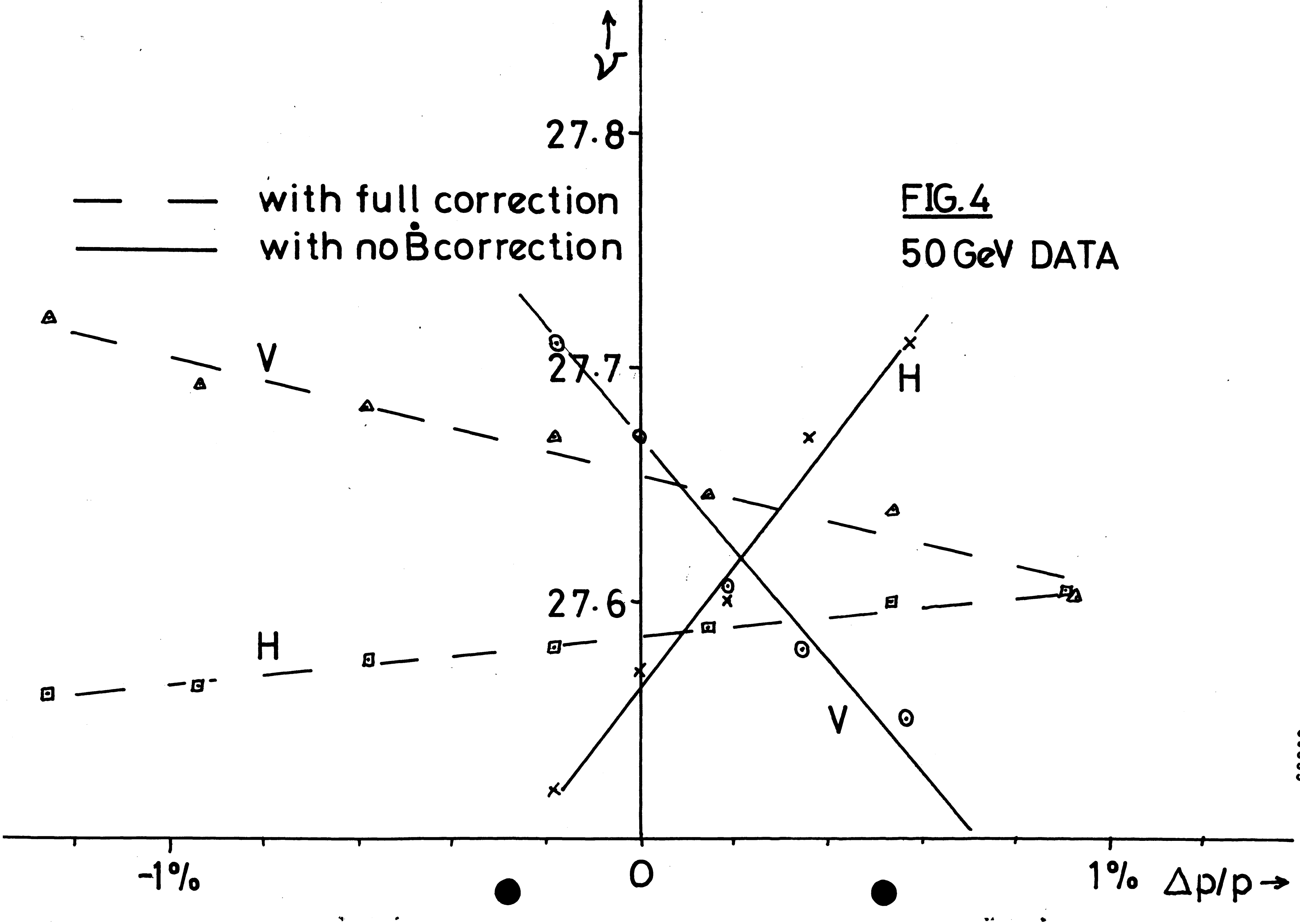

FIG. 4
50 GeV DATA