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Test of a Dispersion Sweep Correction System by using a Centroid in the DIRAC Beam Line

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Abstract

A new beam position detector named "centroid" is placed in the DIRAC target station and is aligned with respect to the beam. Behind it there is a set of various targets used for the DIRAC experiment. The ‘centroid’ itself collects the secondary electrons emitted by the target when hit by the proton beam. This provides an on-line verification of the beam position without obstructing the beam path by a screen and without perturbing the experiment. A computer application then calculates the corrections needed to center the beam in both planes as a function of time. This note will explain how this is done.

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INTRODUCTION

The DIRAC (DImeson Relativistic Atom Complex) experiment takes place in the south part of the PS East Hall (proton beam line ZT8). The beam, with an intensity of about 10^{11} protons, is slowly extracted from the PS machine over 400ms and has an average momentum of 24GeV/c. Due to the resonant extraction process the particles in the head of the extracted beam spill have a lower momentum than the particles in tail. Adding the dispersion of the transfer line to this makes the beam sweep horizontally over the target of the experiment.

In the requirements of the DIRAC experiment it was stated that the beam spot should be fixed on the target. Therefore two correction dipoles, one horizontal and one vertical, which are independently controlled by a function generator were installed prior to the commissioning of the DIRAC experiment.

Until now the horizontal and vertical beam position and dispersion sweep were manually verified and corrected by inserting a scintillator screen at the place of the target and programming a sweep compensation function in the function generators until the beam hit the fixed position.

The disadvantages of these manual adjustments are related to the insertion of the screen in the beam line. For each correction or verification of beam position on the target one needs to insert a screen. Before inserting the screen the experimenter needs to reduce the high voltage in order to prevent the equipment in the experiment breaking down due to an increased flux of muons.

A new beam position detector named "centroid" is placed in the DIRAC target station and is aligned with respect to the target centre. Behind it there is a set of various targets used for the DIRAC experiment. The “centroid” itself collects the secondary electrons emitted by the target when hit by the proton beam. This provides an on-line verification of the beam position without obstructing the beam path by a screen and perturbing the experiment. A computer application then calculates the corrections needed to center the beam in both planes as a function of time. This note will explain how this is done.

1. THE CENTROID

The centroid consists of a ceramic disc with a conductive silver layer. Its diameter is Φ80mm with a hole of Φ30mm in its center, as shown in Figure 1.The proton beam itself passes through this hole and therefore does not interact with the monitor.

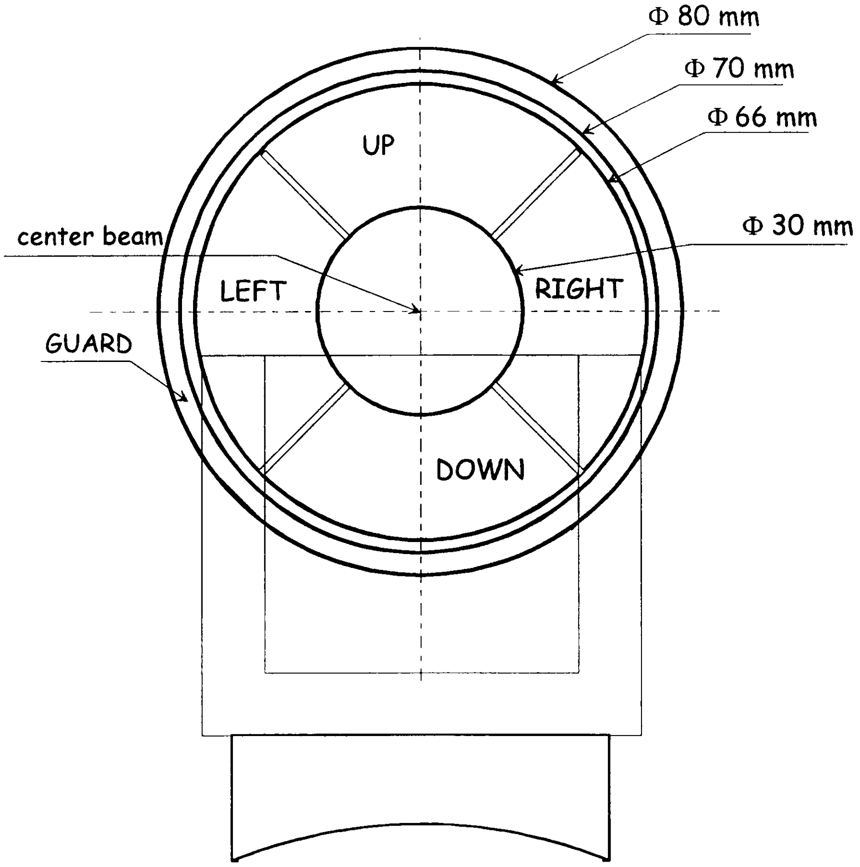

Fig. 1. Detector layout

The conductive layer is divided into four quadrants, each one isolated from the others. Each quadrant covers a given area (right, left, up, down) and two planes, vertical and horizontal, are defined. The vertical plane is composed by the up and down quadrants and right and left quadrants form the horizontal plane.

The centroid is polarized as illustrated on Figure 2. A bias voltage is applied on the targets while the electrodes are virtually grounded through the electronic input.

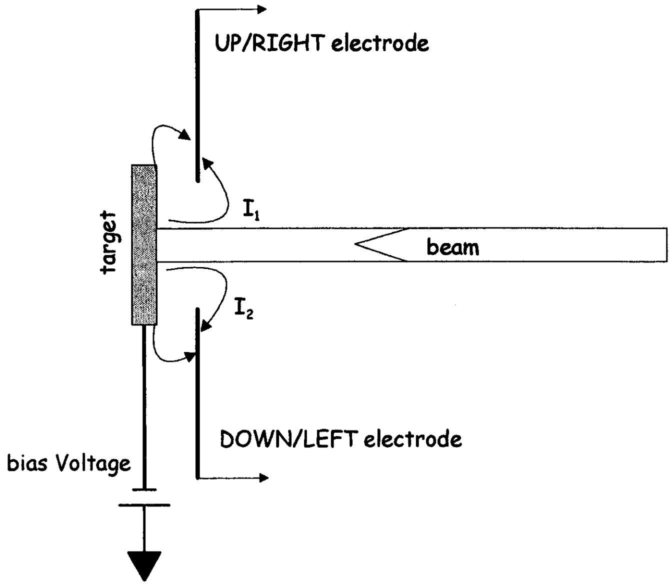

Fig. 2. Polarization diagram of the detector

When the beam hits the target, secondary electrons are generated. If the polarization is sufficient these electrons are captured by the electrodes, which results in a current. This current is directly proportional to the number of electrons collected on the electrode and the number of electrons per electrode depends on the position of the proton beam with respect to the target. If the proton beam is centered on the target all the four currents I_1, I_2... are equal. On the other hand, if the center of gravity of the beam is moved towards the right, the current on the right electrode will be larger than the current on the left electrode, and vice versa.

The principle, for determining the center of gravity, is explained by figure 3 for one plane.

Let us define by P the ratio of the difference Δ by the sum Σ of I_1 and I_2 from the electrodes (Figures 2 and 3)

$$P=\frac{V_1-V_2}{V_1+V_2}\rightarrow P=\frac{I_1-I_2}{I_1+I_2}=\frac{\Delta}{\Sigma} \qquad [1]$$

As we can see, this expression is independent of the proton beam intensity and it gives an indication of the instantaneous beam position in the horizontal or vertical plane [Ref. 1].

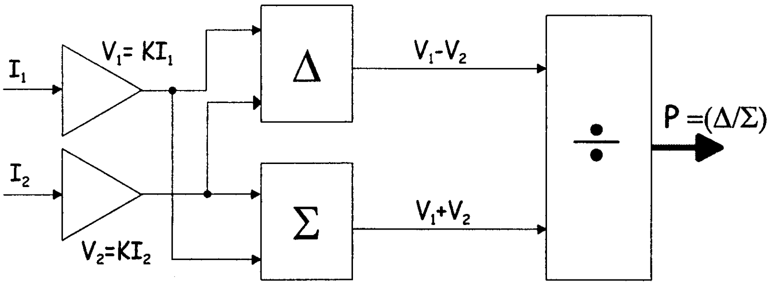

Fig. 3. Block diagram of the measurement system principle (K is a constant factor).

2. REAL TIME PROCESSING.

A fully electronic system, where the beam position is calculated instantaneously, can be used in a feedback loop to maintain the proton beam centred on the target in both the horizontal and the vertical plane. Figure 4 shows a block diagram of this system.

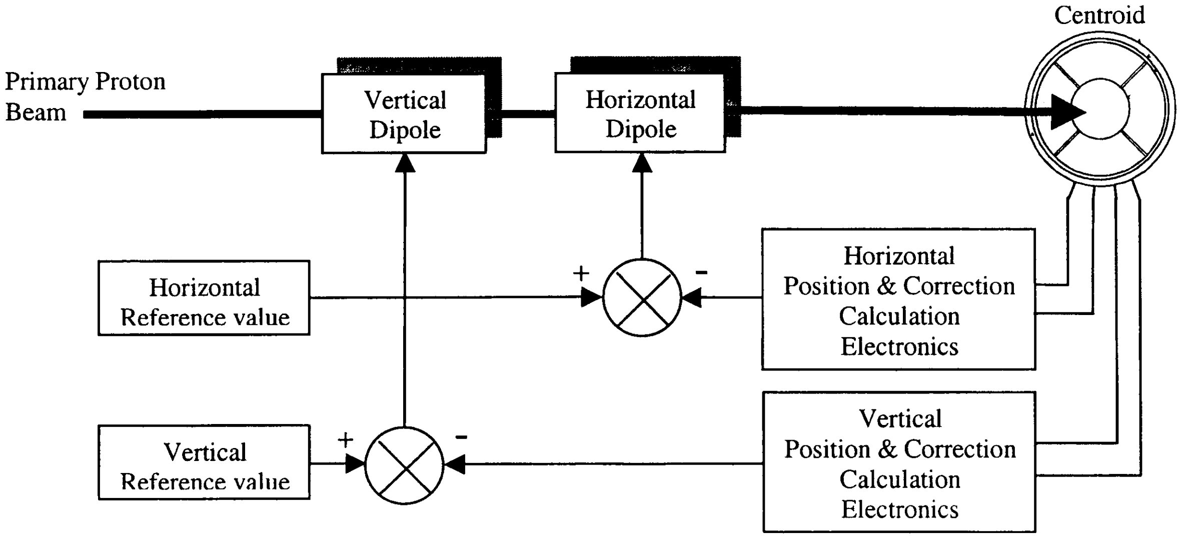

Fig. 4. Diagrams of the feedback system

The electronics connected to the left-right quadrant of the centroid calculate the horizontal beam position error and the current difference that needs to be applied to the horizontal dipole in order to center the beam in the horizontal plane. The same principle is applied to the vertical dipole.

The signals coming from the four plates are very small and therefore very sensitive to noise. This means that one needs to filter the signals and use electronics that introduce a very low noise level otherwise the error in the position calculation becomes too important and corrections can not be made.

This system is still under test and dedicated beam time is needed to validate the system.

3. TYPE OF ELECTRONICS ASSOCIATED TO EACH QUADRANT

In the above mentioned real time processing technique it is foreseen to convert the currents coming from each quadrant into voltages using classical operational amplifiers. The overall bandwidth (amplifier followed by Δ / Σ circuits) is expected to be at least 100Hz (i.e. above the dipole bandwidth). As said in paragraph 2 this is under investigation.

Originally (or historically) each quadrant was connected to an integrator. At the spill end it was easy, using an oscilloscope or voltmeters, to determine the average (averaged over the spill time) horizontal and vertical position. This is the reason why presently we still use integrators connected to each quadrant and process them as described in the next paragraphs.

It is however evident that the computer based dispersion sweep compensation system (paragraph 6) could also make use of current to voltage converters instead of integrators (this would avoid differentiating the signal as described in paragraph 6 of this report).

4. THE INTEGRATION ELECTRONICS.

The electronics used in the signal measurement and treatment is simple. The signal delivered by the electrodes is integrated and then acquired by a VME - Sampler in order to be digitally processed. (see paragraph 6).

Figure 5 depicts the schematic of the used circuit.

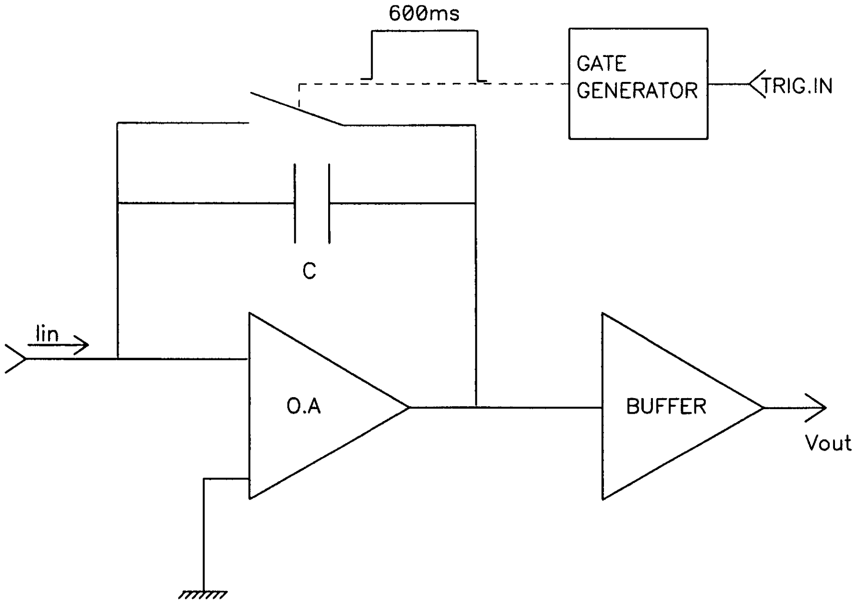

Fig. 5. Schematic of the electronics

4.1 The integrator.

The integrator itself is represented by O.A. + C in Figure 5.

After some investigations we opted for the IVC102 (Burr-Brown) O.A since its characteristics met the required specifications (low noise current, internal capacitors). The overall bandwidth is about 500kHz.

The integrator output voltage (V_{OUT}) is proportional to the entrance charge (I_{IN} on figure 5) from the electrode according to.

$$V=\frac{Q}{C}=\frac{I\times t}{C} \qquad [2]$$

Using a capacitor of 100pF (the maximum internal capacitor of the ICV102), we thus obtain a voltage of V=1V for 6.25×10^8 secondary electrons.

The integrator is controlled by an adjustable gate of about 600ms in the present case.

5. MEASUREMENTS AND RESULTS WITH INTEGRATION ELECTRONICS

We did two types of measurements on the detector in order to calibrate it and make it ready for operation.

First measurements were made in order to measure the offset and the sum signal from the centroid as a function of the polarisation voltage. With the second measurements we obtained the calibration curve of the centroid (P vs. mm) in the two planes.

For these measurements we used the integrating circuit in local mode connected to an oscilloscope.

5.1. Offset Measurement.

As mentioned before, a first type of measurement was made with the Centroid in order to check the offset of the system and to determine the polarisation point.

The Centroid was polarised by adjusting the bias voltage (Fig 2) from 0V to –350V with ΔV= 10V/steps. For each point we measured the offset, without beam, and the total current per plane (ΣmV) with beam. Results are shown in Figure 6.

As we can observe in figure 6, with the beam when the polarisation reaches -300V, there are some problems and the offset increases dramatically. This may come from the high vacuum pressure existing at the detector level (about 10^{-2} torr) and the detector physical arrangement itself, because the ceramic plate is very close to the polarised target. Therefore, we choose the polarisation voltage between –80/-100V, so to have a good ratio Σ/Offset and also a stable response.

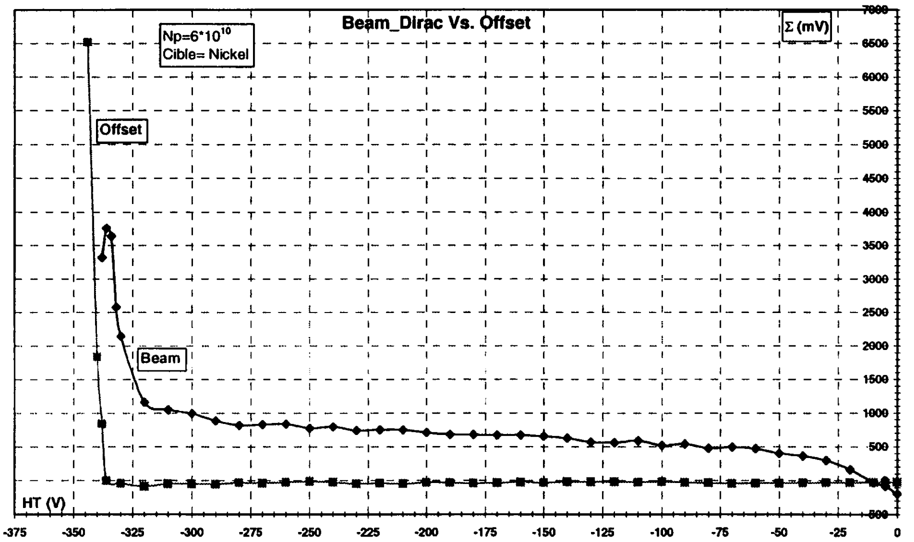

Fig. 6. Offset measurements

5.2. Position measurements.

The beam was moved in well-known steps [in mm] and at every point we measured Δ and Σ with the electronics. The measurements are represented graphically (Figure 7.1, 7.2) [*and the regression lines displayed*]. The linearity of our system is quite good. (since the correlation factor R= 0.986 for the vertical plane and R=0.996 for the horizontal plane).

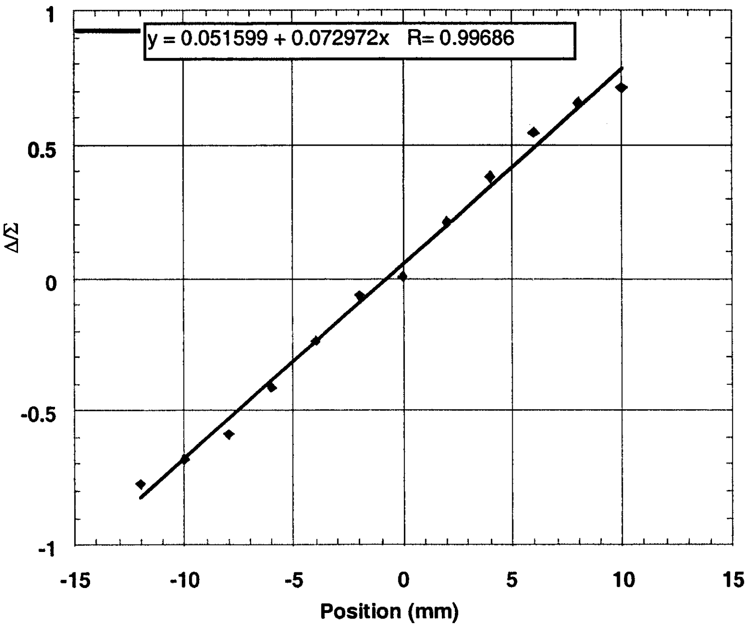

Fig. 7.1. Horizontal response

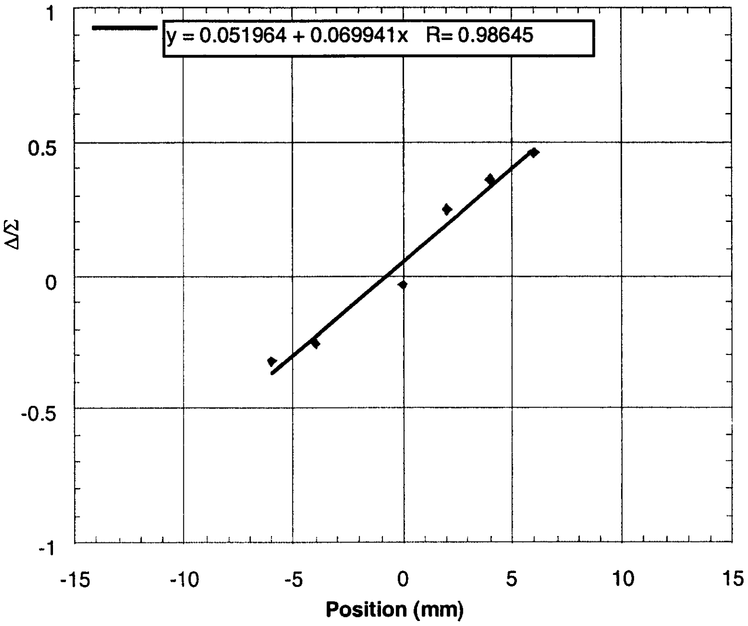

Fig. 7.2. Vertical response

If we calculate the relation between a given displacement Δx and the corresponding ΔP as measured by our system, we find that :
Δx=1mm corresponds to ΔPv= 0.12 (Aprox) in the vertical plane (15mm per unit)
Δx= 1mm corresponds to ΔPh= 0.12 (Aprox) in the horizontal plane. (15mm per unit)

We can say that the response is the same in the two planes and, therefore, use a single plot for the two planes . This curve is shown in figure 8.

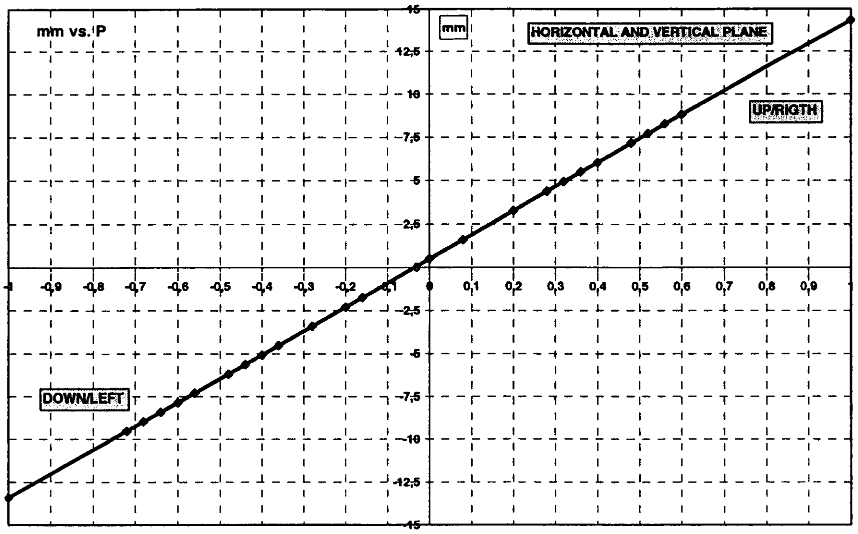

Fig.8. Position vs. P

5.3. Secondary electron emissions Yield.

We can also estimate the secondary electron emission yield under operating conditions.
The beam main parameters are:

- Proton Intensity: ≅ 10^{10} protons (Energy 12-24 GeV/c)
- Spill duration ≅ 500ms
- Target: Nickel.

The detector is biased at -80V and the integrator capacitance is 100pF.

Referring to figure 6, for one plane we see that the integrated sum signal is Σ = 500mV, which corresponds to $3.125\text{x}10^8$ secondary electrons. Considering the two planes we conclude that the secondary emission coefficient is about 6.25%, which is coherent.

6. DIspersion Sweep COmpensation system:

6.1. Theoretical principle

The system described in this chapter makes use of the integrated signals, which are discussed in paragraph 5. The idea is to use these signals to calculate a correction in order to reposition the beam on the center of the target. The example below is given for the horizontal plane, but the same principle applies for the vertical plane.

The electron current of the centroid left-right quadrant is integrated by the electronics providing a voltage as a function of time given by the formulae [3] and [4].

$$v_{left}(t) = \int_0^t I_{left}(t)dt \qquad [3]$$

$$v_{right}(t) = \int_0^t I_{right}(t)dt \qquad [4]$$

The ratio given in formula [5] is proportional to the horizontal beam position in the centroid as a function of time.

$$\frac{\Delta_h}{\Sigma_h} = \frac{\frac{d}{dt}(v_{left}(t) - v_{right}(t))}{\frac{d}{dt}(v_{left}(t) + v_{right}(t))} = \frac{I_{left} - I_{right}}{I_{left} + I_{right}} \propto x(t) \qquad [5]$$

In the dispersion sweep compensation system, hereinafter referred to as 'DISCO' system, the integrator voltages are sampled and stored in a memory. All the remaining treatments are then processed digitally and result is the beam position versus time in both planes from which one can calculate the necessary corrections to the magnet currents in order to center the beam during the whole spill.

6.2. System overview

The schematic overview of the complete DISCO system is illustrated in figure 9. The average horizontal beam position on the target is controlled by means of the two horizontal bending magnets 1 and 2. The dispersion sweep, which is then around the horizontal central position of the target and thus the Centroid, is then corrected by the horizontal dipole that is controlled by a function generator (GFAS). A vertical correction dipole also connected to a function generator compensates for any vertical movements as a function of time.

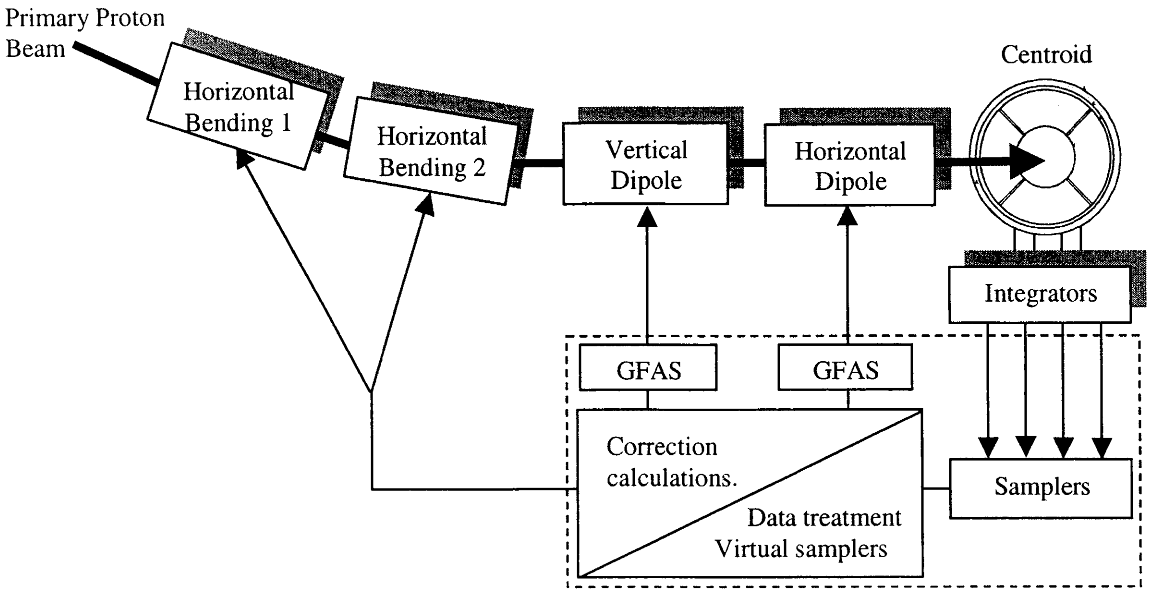

Fig.9. The equipment used for the beam positioning on the DIRAC target.

A VD10 sampler in a VME crate situated in the APRON building in the East Area samples and memorizes the integrated signals of Centroid, which represents the number of electrons collected by each of the four plates during the time the beam hits the target. From this point on the raw data is available in the control system for position and correction calculations.

6.3 Sampling

The signals from the four integrators are digitized and stored using a 16 bit (±15 bit) sampler at a clock rate of 1KHz. Two timings, a start and a stop, are associated with the sampling in order to control the window of data validity. The start timing also acts as the reset of the four hardware integrators directly connected to centroid. Figure 10 shows an acquisition of the four plates during one spill on the target.

As can be seen in figure 10, at the reset of the integrators the signal gets a negative offset, which is corrected during the treatment of the data. The corrected signal is then available by means of a virtual sampler within the control system.

The principle of virtual samplers is used throughout the whole position calculation, which gives the possibility to check each step within the calculation process up to the final result, which are the horizontal and vertical position as a function of time.

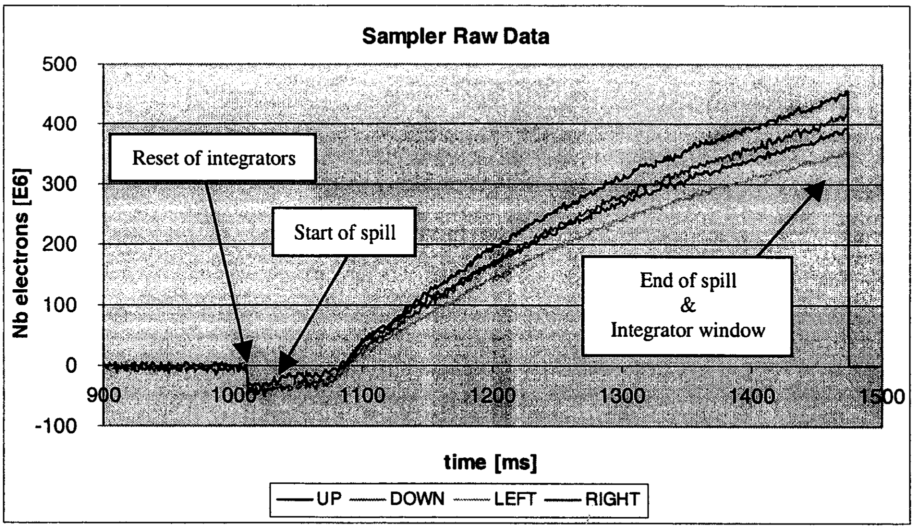

Fig.10. The sampled raw data integrator signals of the four individual plates.

6.4 Position calculations

As previously mentioned the horizontal position can be calculated from the centroid data by:

$$x = C_h \frac{\Delta_h}{\Sigma_h} + K_h = C_h \frac{\Delta S_{right} - \Delta S_{left}}{\Delta S_{right} + \Delta S_{left}} + K_h \qquad [6]$$

where:
ΔS_{right} = Differentiated sample of signal measured by the right plate
ΔS_{left} = Differentiated sample of signal measured by the left plate
C_h = Horizontal calibration factor
K_h = Offset of vertical position

For the vertical position this becomes:

$$y = C_v \frac{\Delta_v}{\Sigma_v} + K_v = C_v \frac{\Delta S_{up} - \Delta S_{down}}{\Delta S_{up} + \Delta S_{down}} + K_v \qquad [7]$$

where:
ΔS_{up} = Differentiated sample of signal measured by the upper plate
ΔS_{down} = Differentiated sample of signal measured by the lower plate
C_v = Horizontal calibration factor
K_v = Offset of vertical position
Now the physical link between the beam position on the target and centroid signals is established and can be used to perform correction calculations.

The position of the beam on the DIRAC target within the DISCO system is determined by three parameters:

1. Average horizontal beam position
2. Dispersion sweep due to dp/p distribution of the spill, horizontal beam position as a function of time.
3. The vertical beam position as a function of time

Virtual samplers, where one can re-sample the treated raw data, and a prototype application made it possible to perform semi-automatic corrections as explained below.
For the first correction, the average horizontal beam position, one can use the integrated signals of the left and right hand plates of the centroid at the time the spill has ended. These single samples of the integrated signals contain the history of the beam position during the spill.

The second and third are both corrections, which are related to a position as a function of time. This means that one needs to differentiate the signals coming from the four integrators.

The sampling is done at a rate of 1KHz and the signal is derived with a sliding derivation window of 20ms (20 samples) which slides with steps of 1ms (1 sample), as formulated below:

$$\frac{\Delta S(n+10)}{\Delta n}=\frac{S(n+20)-S(n)}{20} \qquad [8]$$

where:
S = Value of the sample
n = Sample number (1 ms sample interval)

Figure 11 shows an example of the result after applying formula [8] to the integrated signal of the left-hand plate, where one can recognize the spill shape.

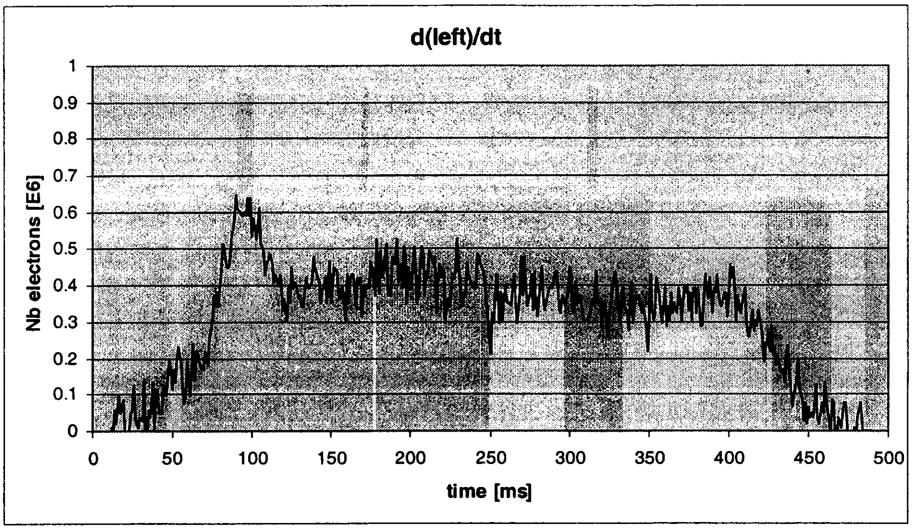

Fig.11. The differentiated signal of the left hand plate.

In order to calculate the horizontal and vertical position, as a function of time one needs to apply the differentiated data, as given in figure 11, to the formulae [6] and [7].

Figure 12 and 13 show examples of the calculated and re-sampled horizontal and vertical position as a function of time before any correction was applied. The horizontal position sweeps around the center of the target due to the dp/p distribution in the spill. The vertical position is just due to a bad steering in the beam line. The signals illustrated in the figures are filtered according the filter described in paragraph 6.5.

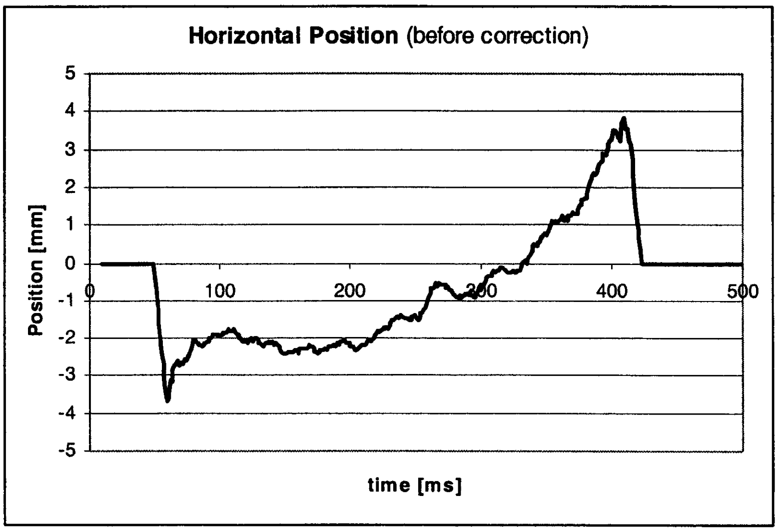

Fig.12. The calculated and filtered horizontal position as a function of time before correction.

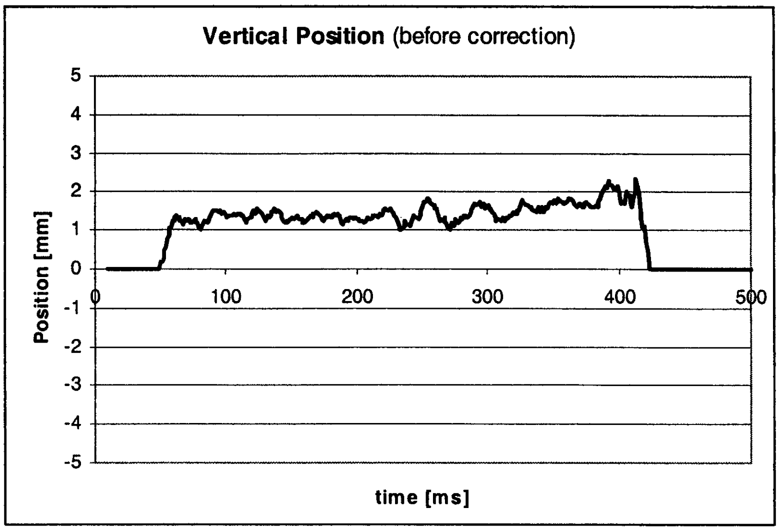

Fig.13. The calculated and filtered vertical position as a function of time before correction.

After a few iterations, the prototype application found a set of values for the two bending magnets and the function generators (GFAS) that control the horizontal and vertical dipoles. Figures 14 and 15 show the calculated horizontal and vertical position as a function of time after the corrections were applied.

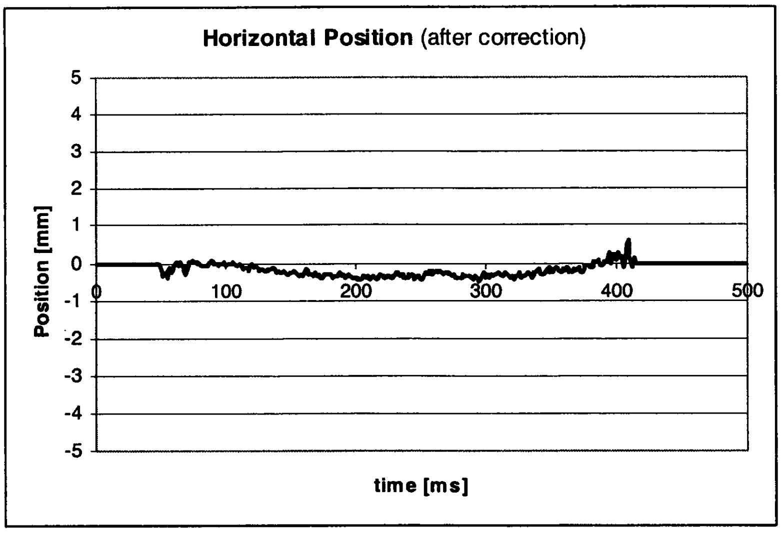

Fig. 14. The calculated and filtered horizontal position as a function of time after correction.

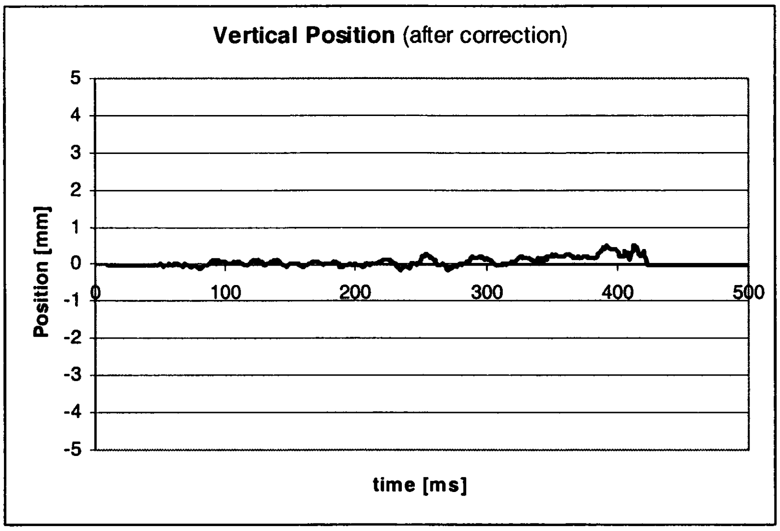

Fig. 15. The calculated and filtered vertical position as a function of time after correction.

6.5 Filtering the differentiated data

The actual position calculation is, as already mentioned, done according the two formulae [6] and [7]. However, since the spill intensity is not constant in time the integrated signal contains parts of which the derivative approaches zero. In the position calculation this results in very small values for both variables Δ and Σ and therefore becomes very sensitive to errors in the measured values, which then result in important errors in the position values. For this reason the differentiated signal should be filtered in order to smooth out the gaps and peaks. This filtering is done numerically by means of a so-called 'Savitzky-Golay' smoothing filter or DISPO (Digital Smoothing Polynomial filter) [Ref.2]. By filtering this way one replaces a data point by some weighted local average of the surrounding data points. Since the physical process of the slow extraction and the dispersion sweep is smooth, this can be done without biasing the final result too much.

The equation used to filter the data is given by:

$$g_i = \sum_{n=-nL}^{nR} D_n f_{i+n} \qquad [9]$$

where:

g_i = the filtered value of the data point
f_{i+n} = the value of the raw data point
n_R = the number of data points used on the right hand side of the data point of interest
n_L = the number of data points used on the left hand side of the data point of interest
D_n = filter coefficients

The filter coefficients are calculated by a polynomial of higher order. This means that each data point f_i is least square fit by a polynomial to all points in the moving window.
In the disco case the values for n_R and n_L are both ten which gives a total averaging window of twenty samples or milliseconds.

6.6 The Automatic DISCO Application.

As previously mentioned, the horizontal and vertical positions as a function of time are available on a workstation under the form of virtual samplers. These virtual samplers are in fact a re-sampling of the calculations made on the raw data and are updated every cycle concerned.
The second part of the system is the actual correction calculation, which until now has been done by a prototype application that makes use of MS Excel and an interface between the PS control system and MS Excel, the so called 'passerelle'.

During the shutdown 2001/2002 a final application will be written, which will be much more user friendly and automated than the prototype.

The general idea is to average the raw data over the number of cycles concerned in one super cycle. This will then give the best solution for the whole super cycle. The input of the application program is thus the re-sampled horizontal and vertical position as a function of time for each cycle in the super cycle. The application, in which the response matrices between the magnets and the target are known, will then decide which correction needs to be made and it will program the current modifications in the function generators connected to the power supplies.

The flow chart, illustrating the structure of the program is given in figure 16.

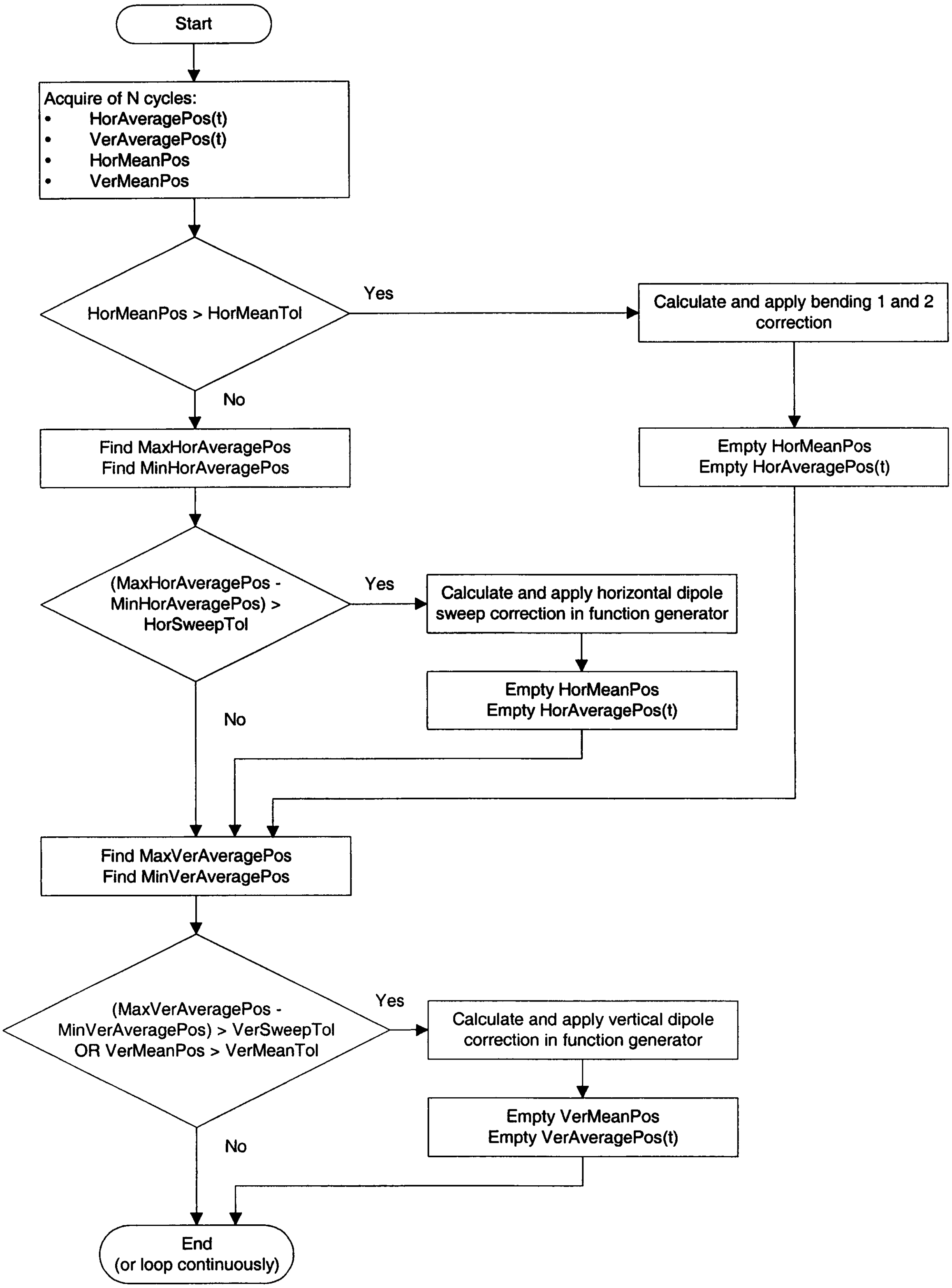

Fig.16. The DISCO calculation Flow Chart.

7. CONCLUSIONS

The centroid and its electronics based on integrators, have proven to work correctly and the measurements show that the device is at least linear within the ±10mm range, which is largely sufficient for the present use. Calibrations have been made and the exact relationship between the number of electrons counted by the different plates and beam position is established.

The two methods, 'real time' and 'integration' in combination with the DISCO system that are respectively described in chapter 2, 3 and 5 can both be used to keep the beam centered on the target. However, both methods have their advantages and disadvantages.

The real time method has the advantage of being a real feedback system that will correct the beam position instantaneously. The problem with this system, however, is that when there is a drift of the central beam position the power supply of the correction dipole to compensate the sweep will quickly reach it limits of ±10A so that the sweep can not be corrected anymore.

The integration method in combination with the DISCO system prevents the correction dipole from going to its limits by using the two bending magnets to center the beam. The only inconvenience is that the system is a feed forward that is based on the history of one super cycle. It will thus find the optimum sweep compensation function for a complete super cycle, which is not necessarily the best one for each cycle individually. Since this system is mainly software based it is easy to maintain and modify due to its flexibility.

If, in future, the feed forward does not seem to be sufficient, one can always superimpose the feed back system on the feed forward system. The latter will then perform the minor final correction to the individual cycles. This, however, means that some additional hardware needs to be developed and installed.

As mentioned a system based on current to voltage converters followed by the DISCO system could also be foreseen.

References:

[1] D.Pereira, O Sala, U Schitter. New method for controlling on target beam position. NIM A267 (1988) 41-42.

[2] Numerical recipes in C, the art of scientific computing, 2nd edition (1992).Cambridge University Press. Cambridge, UK

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