CNGS Muon Monitors

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The response of the muon detectors during the CNGS run 2007 and possible reasons for a non-linear behaviour with respect to the beam intensity are discussed. Results of the CNGS run 2008 are shown: The modifications done during the shutdown 2007/08 were successful and resulted in the expected linear behaviour of the muon detector response.
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Aurélien Marsili, Bernd Dehning, Gianfranco Ferioli, Edda Gschwendtner, Eva Barbara Holzer, Daniel Kramer

CERN, AB Department, CH-1211 Geneva 23

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1 Introduction

1.1 The CNGS Experiment

The aim of the CNGS experiment [1] is to provide the experiments in Gran Sasso, Italy, with muon neutrinos $\nu_\mu$, with an average momentum of 17 GeV/c. A primary proton beam (400 GeV), coming from the Super Proton Synchrotron (SPS), impinges on a graphite target. This creates a secondary beam containing kaons and pions. Two specific magnets, a ‘horn’ and a ‘reflector’, focus the secondary beam towards Gran Sasso and select its energy. This secondary beam travels through a decay tunnel, a 1-km-long vacuum tube; $\pi^+/K^+$ being not stable, they decay into $\mu^+ + \nu_\mu$. At the end of the decay tunnel is a hadron stop, consisting of 3 m of graphite and 15 m of iron, and designed to stop all remaining protons and $\pi/K$. Muons pass through the monitors and are absorbed later on, in the rock.

As both $\mu^+$ and $\nu_\mu$ come from the same decay and fly in the same direction, neutrinos can be easily tracked by monitoring muons. Thus, two stations of detectors are installed, one just after the hadron stop (TNM41), and another 67 m downstream of the first one (TNM42, cf. Fig. 1). Each one of these sets is cross-shaped: it is made of 42 BLM detectors, each ‘line’, called — vertical
Figure 1: Structure of the CNGS experiment. The muon monitors described here are on the very end of the experiment. The hatched grey corresponds to rocks.

Figure 2: Above: Time structure of a SPS supercycle in October 2007. Below: Time structure of the CNGS extractions in one cycle.
and horizontal — consisting of 10 monitors on each side, usually separated by 11.25 cm, and one central detector common to both lines (cf. Fig. 3). There is an additional detector, which can be remotely displaced.

The profile of the signal from the first cross is very sensitive to the alignment between target and focusing horn, whereas the second cross is more sensitive to the alignment between proton beam and target [2].

The SPS operates in supercycles: for the data considered here (2007), a supercycle lasts 39.5 s, and consists of a long fixed target cycle, 3 CNGS cycles, and one machine development cycle. Each CNGS cycle is 6 s long. It includes 2 extractions, lasting 10.5 μs each, and separated by 50 ms (cf. Fig. 2). Each detector reading is logged for every extraction.

1.2 Muons Detectors

The detectors used as muon monitors are the standard Beam Loss Monitors (BLM) used for the LHC. They are ionisation chambers: cylinders which have a length of 48 cm, and a diameter of 16 cm, containing 61 electrodes and filled with N₂ at 1.1 bar (cf. Fig. 4). The bias voltage applied between two electrodes is 1200 V, corresponding roughly to 2400 V.cm⁻¹.

1.3 Global Description of the Electronics

All components of the monitor system (cables, ionisation chamber) can be assimilated as a basic electronic component (cf. Fig. 5). The ionisation chamber itself is considered as a capacitance of \( C_2 = 312 \, \text{pF} \). It is connected to the high voltage supply with a resistor of 10 MΩ.

To make sure that the high voltage remains constant, and to provide the chamber with a current for short pulses, a capacitor of value \( C_1 = 470 \, \text{nF} \) is plugged in parallel configuration with the power supply; however, because of the very high resistance between chamber and power supply, we can consider that no current passes through this wire: it behaves like an open switch. Thus, capacitor \( C_1 \) is plugged in serial configuration with the ionisation chamber \( C_2 \). The equivalent capacitance is

\[
\frac{1}{C_1} + \frac{1}{C_2} = \frac{1}{C_1 + C_2} = \frac{C_1.C_2}{C_1 + C_2} \approx \frac{C_1.C_2}{C_1} = C_2
\]

A multiwire cable (NG 48) connects the chambers to the acquisition electronics. The capacity between wires ranges from 32 to 47 nF (cf. Chap. 3.7). The charges created in the ionisation chamber travel through the wires to the acquisition card.

The operational amplifier, together with the feedback capacitor C, integrates the current coming from the chambers, giving an output tension proportional to the amount of charges (negative) collected during integration time. The switch S is used to discharge C after an acquisition.

The operational amplifier is used here as an integrator. It is integrating current over time, giving an output voltage proportional to the quantity of charges stocked in the capacitor.
Figure 3: Picture of a muon detector station. The 41 muon monitors are arranged in a cross shape. The distance between two neighbouring ionisation chambers is 11.25 cm. The total height/width covered by the detectors is 2.70 m. There is additional detector which can be remotely controlled, and is used for cross-calibration.

Figure 4: Inner structure of a muon detector. The length is 48 cm, diameter is 16 cm, filled with $N_2$, and there are 61 electrodes.
Assuming that $\varepsilon = 0$ we have:

$$U_{\text{out}} = -U_C = -\frac{q_C}{C}$$

$$q_C = -C \cdot U_{\text{out}}$$

so:

$$U_{\text{in}} = U_R = R \cdot I = R \frac{dq_C}{dt}$$

$$U_{\text{in}} = -R \cdot C \frac{dU_{\text{out}}}{dt}$$

$$U_{\text{out}} = -\frac{1}{R \cdot C} \int U_{\text{in}} \, dt$$

As $U_{\text{in}} = R \cdot I$ then:

$$U_{\text{out}} = -\frac{1}{R \cdot C} \int R \cdot I \, dt$$

$$U_{\text{out}} = -\frac{1}{C} \int I \, dt$$

(1)

Hence $U_{\text{out}} = -\frac{Q_{\text{total}}}{C}$, $Q_{\text{total}}$ being the charge created in the chamber.

1.4 Time Structure of Measurements

The quantity of charges deposited in the chamber during one extraction is measured. This global charge is quantified by integrating the current coming from the chamber with an integrator. In order to get rid of the background noise — i.e. all charges already present in the chamber before extraction — the charge in the chamber is measured before and after extraction. Charges are accumulating in the chamber between both acquisitions (cf. Fig. 7). The result of the measurement for one extraction is $\text{Acq2} - \text{Acq1}$. 

Figure 5: Global electronic system, showing the charge integrator and the different components.
Figure 6: Behaviour of the charge integrator. $R = 5 \, \text{k}\Omega$ and $C = 220 \, \text{nF}$.

Figure 7: Time structure of measurements. The time between acquisitions is optimised to avoid 50 Hz noise.
Long cables make the system sensitive to 50 Hz signal induction, which is largely suppressed by synchronising the acquisition with the frequency. Consequently, measurements have to be separated by a multiple of the noise period: 20 ms. The noise level is then exactly the same at both measurement times.

The measurement steps are:

1. First acquisition: 20 ms before extraction,
2. At the same time, beginning of integration (charges accumulation in the chamber),
3. Extraction (10.5 $\mu$s),
4. Second acquisition, 20 ms after extraction; end of charge accumulation,
5. Discharging capacitors.

As both extractions are separated by 50 ms, all these steps start again 10 ms later — 20 ms before the second extraction.

1.5 CNGS Operation Mode and Data Structure

The data can be accessed with the TIMBER tool, the LHC logging system. Data are logged in arrays, depending on:

- two extractions,
- two crosses (called TNM41 and TNM42),
- two directions (vertical and horizontal) of each cross.

This means that 8 different combinations can be found. In TIMBER, one dataset corresponds to one combination.

Each array contains, in addition to the specific combination (extraction, cross, direction), per entry:

1. Time information of the extraction: year, month, day, hour, minute, second and millisecond; called timestamp;
2. The proton beam intensity for this specific extraction (number of protons hitting the target);
3. The detector signals for the considered profile, horizontal or vertical — that is $2 \times (10$ detectors) + the centre one. These values are already pre-processed, and give the normalised charge created in the chamber per proton impinging on the target.
2 Analysis of Muon Detectors Measurement

2.1 Beam Intensity

The first investigation concerns the beam intensity data, which are the numbers of ‘Protons On Target’ (called ‘p.o.t.’) per extraction, for every timestamp. During SPS normal operation, we observe an intensity variation around average of 15% (cf. Fig. 8). On average, the 2\textsuperscript{nd} extraction is higher than the 1\textsuperscript{st} (cf. Fig. 9).

2.2 Muon Monitors Signal versus Beam Intensity

The data pre-processing consists in converting the reading card output into charges collected in the chamber. Then, this number is normalised, by dividing it by the beam intensity (number of protons on target for this extraction). This gives the proportionality coefficient, which should be constant over intensity.

It is the case in the response from the detector in the second muon detector station (TNM42). These detectors lie behind 67 m of rock, so they receive less particles and produce less charges per proton on target. This signal is constant. The vertical profile of the first muon monitors station (TNM41) also gives a linear signal (cf. Fig. 10).

However, the detectors from the horizontal profile of cross TNM41 show a different pattern (cf. Fig. 11). The value changes: the monitors behaviour is not linear with respect to the beam intensity, the normalised signal starts decreasing after a certain intensity threshold; this threshold is not constant and depends on the detector. This non-linear behaviour starts at different values of beam intensity, even for detectors getting the same signal.
Figure 9: Closer view of beam intensity versus time (19th Oct. 2007). One can easily see that the two extractions are well separated.

The sub-patterns that can be seen in the plot when zooming in (points being aligned on almost vertical lines, cf. Fig. 15) come from the digital measurement, where 1 bit corresponds to $\approx 6.975 \cdot 10^9$ charges (cf. Chap. 1.3).

### 2.3 Profile: Detector Signal vs. Position

The horizontal and vertical muon profiles of the first cross (TNM41) are displayed in Fig. 12 and 13. Each data point gives the mean of the signal (cf. number of entries) for the corresponding detector, after suppression of out-of-range data (cf. Chap. 2.4) for a specific intensity range: from $14 \cdot 10^{12}$ to $20 \cdot 10^{12}$ p.o.t./extraction (maximum intensity for 2007). The error bars show the standard deviation of the detector signal distribution.

The differences between standard deviations confirm the first observations about the detector non-linear behaviour: they are much higher on the horizontal profile (Fig. 12) than on the vertical profile (Fig. 13), and their values are not constant. One has to remember that one detector’s standard deviation is sensible to intensity range, since the non-linear behaviour appears above a certain intensity threshold. This value is specific to each detector.

Depending on the chosen intensity range, the profile is distorted at certain detector positions. The intensity range has a strong influence on the detector behaviour: the slope is around $-5 \cdot 10^{-15}$ ch/pot$^2$. When the intensity range increases by $10^{12}$ p.o.t./extraction, the spread of the cloud increases by 0.005 charges, which represents 3% of the signal value.

This changes the shape of the profile. Above $18 \times 10^{12}$ p.o.t./extraction, all detectors present a non-linear behaviour. All standards deviations would have almost the same high value. Between $14 \times 10^{12}$ and $18 \times 10^{12}$ p.o.t./extraction, some detectors give a constant signal, some do not. Thus, standard deviations have different values.
Figure 10: Detector signals versus intensity of the vertical profile of first cross (TNM41), from 5\textsuperscript{th} Oct. 2007 to 20\textsuperscript{th} Oct. 2007. The centre detector, with the highest signal, was plotted in black; blue correspond to the left profile of the cross, red to the right part. The lower part of the graph, below $13\times10^{12}$, corresponds to the few extractions with lower intensity visible in Fig. 8. The detectors response is linear: the normalised signal is constant.
Figure 11: Detector signals versus intensity of the horizontal profile of the first muon monitor station (TNM41), from 5th Oct. 2007 to 20th Oct. 2007. Same conventions for colours as in Fig. 10.
Figure 12: Mean and standard deviation of the detector signal versus detector position of the horizontal profile of first muon monitors station (TNM41). Data from Oct. 5th, 2007 to Oct. 20th, for an intensity greater than $18 \times 10^{12}$ p.o.t./extraction.
Figure 13: Detector signals versus detector position, for the vertical profile of the first muon monitors station (TNM41). The vertical profile is not symmetric: signal from detector #12 (first detector right of the central one) is as high as centre detector signal. This is most likely due to a misalignment of the beam.
2.4 Data Sorting Algorithm

The first check of this algorithm is making sure that no value is zero. As soon as the intensity — or one of the 21 detector signal values — is zero, the whole dataset for this timestamp is dropped. This way, almost all out-of-range data are suppressed.

Sometimes, a few detectors present a null signal. Generally, in this case, the non-null signals are not correct: out of the correct range, or even negative. Their values differ from at least 1/3 of the mean, which corresponds to more than 10 times the standard deviation of the main cloud. Sometimes, the value is twice the mean; this may be due to problems while reading the output. This datasets are excluded by the first data check.

Hence, the sorting algorithm is used, to eliminate the remaining out-of-range data.

An easy way to measure the detector non-linear behaviour, and to quantify it, is to calculate mean and standard deviation \( \sigma \)\(^1\) for every signal. In order to have accurate values, null values are suppressed. As soon as either intensity or one detector signal is null, the entire timestamp is dropped.

However, some datasets are still not correct — not within \( 4 \sigma \), but non zero neither. Some specific cases are encountered more often, such as detector signal being close to zero, or twice the usual value. This is an important issue, especially when calculating mean and standard deviation automatically: the result is dominated by these out-of-range data. In order to avoid that, this calculation was made in several steps.

1. A histogram is drawn over the total range,
2. The mean and \( \sigma \) are automatically calculated,
3. The values range is replaced by \([\text{mean} - (3 \times \sigma) ; \text{mean} + (3 \times \sigma)]\),
4. Another histogram is plotted, and the same steps start again.

These steps can be reproduced several time, and out-of-range data are eliminated step after step. The result is a histogram centred on the mean of the main ‘cloud’. We avoid mistakes by checking the ratio of excluded data, comparing visually with the global plot, and checking that the given mean corresponds to the main ‘cloud’ on the graph. Signal mean and \( \sigma \) were calculated with data from both extractions, enabling to widen the intensity range.

In addition to that, \( \sigma \) is proportional to mean. Thus, in order to have relevent figures, one should consider normalised standard deviation; that is to say, \( \sigma \) divided by mean. The Table 1 shows these results, comparing the horizontal and vertical parts of cross 41, corresponding to Fig. 12 and Fig. 13.

To cross-check that the two extractions per CNGS cycle have no influence on the detectors behaviour, the same values have been calculated with separated extraction. The results are almost the same, but slightly lower, due to a smaller

\(^1\)Please note that the framework used for data analysis (ROOT) refers to standard deviation as Root Mean Square (RMS) even if this is not correct. RMS equals \( \sqrt{E(x^2)} \), whereas standard deviation is \( \sqrt{E((x-E(x))^2)} \). Note that RMS equals standard deviation only if \( E(x) = 0. \)
energy range. The difference between extractions has no influence on signal standard deviation.

### 2.5 Different CNGS Cycles

The influence of the different cycles is also checked. Timestamps have to be sorted out by comparing one with the next one, the time between two extraction giving the number of the cycle.

Some cycles are missing. This is tracked by comparing timestamps; as seen before, in 2007 cycles are separated by 6 seconds, and two supercycles by 39.6 s. One can easily notice when a timestamp is missing, and know exactly which one ($1^{st}$, $2^{nd}$ or $3^{rd}$).

The result of this sorting is shown in Fig. 15. Each cycle has a different colour. The separation between cycles is obvious on the plot, but it is a small effect, around 0.1%, beyond the total standard deviation. However, this could be explained by the way the SPS was filled.

The same result can be seen in Fig. 16, which displays detector signal versus time. The three cycles are well separated, but this is again a small effect, at the order of the standard deviation (0.3%).
Figure 14: Signal of central detector versus intensity, for vertical profile of first cross (TNM41). See Fig. 11. ‘+’ refers to first extraction, ‘×’ to the second one. Separated ‘clouds’ are visible.

Cross 41, V, Det #10, 19/10/2007

Figure 15: Signal of the central detector versus intensity, for the vertical profile of first cross (TNM41) (cf. Fig. 11). ‘+’ and light colours refer to first extraction, ‘×’ and darker colours to the second one. Separated ‘clouds’ are visible: values from 1st cycles are plotted in blue; 2nd in red; 3rd in green.
Figure 16: Signal from central detector versus time, for vertical profile of first cross (TNM41), the 19th of Oct. 2007. ‘+’ refers to first extraction, ‘×’ to the second one. The 3 cycles are well separated: values from 1st cycles are plotted in red; 2nd in green; 3rd in blue.

3 Possible Reasons for Non-Linearity Effects

In this chapter, we discuss the possible reasons for the non-linear behaviour in the horizontal profile of the first detector cross (TNM41).

3.1 Detectors Origin

One of the main differences between detectors is that some of them were produced in Protvino, Russia; the others come from CERN. However, Table 2 shows that there is no link between their origin and their behaviour. The third column corresponds to the production number of the ionisation chamber, the identification number engraved on the top of the detector.

3.2 Saturation — Space Charge Effect

The non-linear effects appear on an intensity range (14 to 16$\cdot 10^{12}$ p.o.t./ extraction) varying only by 10%, which is too low to consider the effect of saturation. This would be relevant over a larger range.

The correction factors and critical ionisation rate were calculated for space charge effect and recombination losses [3].

Recombination losses, at this ionisation rate, would induce a variation of the signal of 0.3%. This is far below the effect observed here, and is within the scale of the standard deviation.

The signal was also checked for space charge effect: it does not show such characteristics. Because of space charge effect, according to [3] the charge measured at the output of the detector $Q_m$ would differ from the charge actually created in the chamber $Q_c$ and follow the law:

$$Q_m = K_2 \cdot (Q_c)^{\frac{3}{4}} \quad \text{with} \quad K_2 = \frac{1}{d} [4 \cdot \epsilon_0 \cdot V_{S PS} \cdot tC \cdot \mu \cdot U^2]^{\frac{1}{4}}$$  \hspace{1cm} (2)
Table 2: Origin and production number of the monitors in the horizontal profile of TNM41.

<table>
<thead>
<tr>
<th>Det. number</th>
<th>Origin</th>
<th>IC Number</th>
</tr>
</thead>
<tbody>
<tr>
<td>Detector 1</td>
<td>Protvino</td>
<td>26</td>
</tr>
<tr>
<td>Detector 2</td>
<td>Protvino</td>
<td>49</td>
</tr>
<tr>
<td>Detector 3</td>
<td>CERN</td>
<td>21</td>
</tr>
<tr>
<td>Detector 4</td>
<td>Protvino</td>
<td>28</td>
</tr>
<tr>
<td>Detector 5</td>
<td>Protvino</td>
<td>29</td>
</tr>
<tr>
<td>Detector 6</td>
<td>CERN</td>
<td>22</td>
</tr>
<tr>
<td>Detector 7</td>
<td>Protvino</td>
<td>31</td>
</tr>
<tr>
<td>Detector 8</td>
<td>CERN</td>
<td>23</td>
</tr>
<tr>
<td>Detector 9</td>
<td>Protvino</td>
<td>32</td>
</tr>
<tr>
<td>Detector 10</td>
<td>CERN</td>
<td>24</td>
</tr>
<tr>
<td>Detector 11</td>
<td>CERN</td>
<td>41</td>
</tr>
<tr>
<td>Detector 12</td>
<td>CERN</td>
<td>25</td>
</tr>
<tr>
<td>Detector 13</td>
<td>Protvino</td>
<td>33</td>
</tr>
<tr>
<td>Detector 14</td>
<td>CERN</td>
<td>26</td>
</tr>
<tr>
<td>Detector 15</td>
<td>Protvino</td>
<td>34</td>
</tr>
<tr>
<td>Detector 16</td>
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<td>27</td>
</tr>
<tr>
<td>Detector 17</td>
<td>Protvino</td>
<td>35</td>
</tr>
<tr>
<td>Detector 18</td>
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</tr>
<tr>
<td>Detector 19</td>
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</tr>
<tr>
<td>Detector 20</td>
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<td>69</td>
</tr>
<tr>
<td>Detector 21</td>
<td>Protvino</td>
<td>40</td>
</tr>
</tbody>
</table>

$K_2$ is a constant described in [3], where $d = 0.575 \text{ cm}$ is the distance between two electrodes; $V_{SPS} = 1200 \text{ cm}^3$ is the active volume of the ionisation chamber; $t_C = 10.5 \mu s$ is the extraction time; $\mu = 2.13 \times 10^{-6} \text{ cm}^2.\text{V}^{-1}.\mu\text{s}^{-1}$ is the ion mobility; and $U = 1200 \text{ V}$ the drift voltage between electrodes. The unit of $K_2$ is $C^3$. Taking the logarithm of (2) gives:

$$\log Q_m = \log K_2 + \frac{3}{4} \log Q_c$$

$Q_c$ being proportional to intensity, plotting $f(\log Q_c)$ would give:

$$f(\log Q_c) = \log K_2 + \frac{3}{4} \log (\alpha I)$$

$$f(\log Q_c) = \log K_2 + \frac{3}{4} \log \alpha + \frac{3}{4} \log I$$

$$f(\log Q_c) = \frac{3}{4} \log I + C$$

So the curve, plotted logarithmically, should show a slope of $\frac{3}{4}$. But this is not the case: the curve has a slope 1.

If the effect presented here was saturation, it would set a certain threshold in Fig. 11: detectors would saturate above this threshold and show a non-linear behaviour; whereas detector under this threshold would not. It is not the case.
here: we can see that two detectors producing the same signal do not have the same behaviour. One is linear where the other is not.

Hence, saturation and space charge effect can not explain the non-linear behaviour.

3.3 Centroids

Centroids refer to the position of the muon profile ‘centre’. This value describes how centred the beam is horizontally and vertically, compared to the entire line of detectors, and is defined as:

\[ C = \frac{\sum_i x_i d_i}{\sum_i d_i} \]

where \( x_i \) is the distance between the muon monitor \( i \) and the middle of the cross (central detector), and \( d_i \) the detector signal.

There is of course a correlation between the signal from a specific detector and the values of the centroids. For instance, for the vertical profile of a cross, when the centroids increase — i.e. when the secondary beam moves up — the lower detectors get less particles, whereas the upper detectors get more. Thus, the upper detectors present a positive correlation with centroids, whereas the lower ones have a negative correlation.

This was of course expected, but still allows us to compare the behaviour of one detector to the others. However, the effects of the displacement of the beam are negligible compared to the non linear behaviour studied here. The position of the beam was stable for each date considered here.

3.4 Acquisition Cards

The detector outputs are connected to acquisition cards. Each acquisition card has 16 inputs. The ones connected to the first card are the detectors from the horizontal profile of the cross, number 1 to 10 (detector 11 being on another card), and 12 to 17. All “misbehaving” detectors seem to be connected to the same acquisition card, for an intensity up to \( 16 \times 10^{12} \) p.o.t./extraction. All the remaining detectors from the horizontal line — detectors 18 to 21 — are plugged on the second card, as well as first detectors from vertical line, up to 16 entries.

However, one has to remember that the non-linear behaviour strongly depends on the intensity range. In Fig. 12, taking only their standard deviation \( \sigma \) into account, detectors 18 and 19 (right part of the profile) seem to have a correct response. That is only because their non-linear behaviour appears above \( 18 \times 10^{12} \) p.o.t./extraction (cf. Fig. 11). Calculating the RMS of these detectors between 18 and 20 \( \times 10^{12} \) p.o.t./extraction would give a result of the same order as the others. It could be concluded that misbehaving detectors are all connected to the same card, the first one; but results for higher intensities prove that it is wrong.

On the other hand, considering an intensity range from 14 to \( 16 \times 10^{12} \) p.o.t./extraction leads to the conclusion that detectors 1 and 2, as well as 7 and 8, have a correct answer, since their signal starts decreasing above \( 16 \times 10^{12} \) p.o.t./extraction.
However, the entire intensity range shows that almost all detectors have a non-linear answer. Only the last one (detector #21) seems to have a correct behaviour over the total intensity range. Values for even higher intensities (up to $22 \times 10^{12}$ p.o.t./extraction) would be useful to conclude; unfortunately, these numbers were not reached in 2007.

Hence, there is no reason that the non-linear behaviour could be due to different cards.

### 3.5 Electron and Ion Drift

As seen before, a CNGS extraction lasts 10.5 $\mu$s. The electron drift speed being $v_e \simeq 2 \text{ cm/}\mu\text{s}$ [3], and the distance between two electrodes $\simeq 0.5 \text{ cm}$, electrons drift within:

\[
0.5 \div 2 \simeq 250 \text{ ns}
\]

This is negligible compared to the duration of an extraction, so we can assume that the charge due to electrons is deposited within 10.5 $\mu$s. Thus, the average current due to electrons, during this time, is:

\[
\frac{0.32 \mu C}{10.5 \mu s} \simeq 32 \text{ mA}
\] (3)

Ion mobility is $\mu = 2.13 \cdot 10^{-6} \text{ cm}^2.\text{V}^{-1}.\mu\text{s}^{-1}$ [3]. In a electric field of 2400 V.cm$^{-1}$, this gives a speed of:

\[
2.13 \cdot 10^{-6} \times 2400 = 5.1 \cdot 10^{-3} \text{ cm.}\mu\text{s}^{-1}
\]

The duration of this charge deposition is:

\[
\frac{0.5 \text{ cm}}{5.1 \cdot 10^{-3} \text{ cm.}\mu\text{s}^{-1}} \simeq 100 \text{ } \mu\text{s}
\]

which lasts much longer than one extraction. Since the charge is integrated during 20 ms after the extraction, there is no cutting of signal.

The average current due to ions would be:

\[
\frac{0.32 \mu C}{100 \mu s} = 3.2 \text{ mA}
\]

which is negligible compared to the current due to electrons.

Hence, the quantity of charges considered here can not make the electronics saturate.
### 3.6 Integrator Behaviour – Limitations

Saturation of acquisition cards could be a reason of the signal non-linear behaviour. Here, one of the limiting factors is the maximum output voltage of the amplifier, which is $\bar{U}_{\text{out}} = 10$ V (cf. Fig. 6). Assuming that the amplifier has an ideal behaviour, then $\varepsilon = 0$ and $U_C = U_{\text{out}}$ so $\bar{U}_C = \bar{U}_{\text{out}}$. As $U_C = q/C$ then we have:

$$Q_{\text{max}} = C \times \bar{U}_{\text{out}} = 220 \, \text{nF} \times 10 \, \text{V}$$

$$Q_{\text{max}} = 2.2 \, \mu\text{C}$$  \hspace{1cm} (4)

According to the maximum amount of charges created in the chamber, this limit is never reached (cf. eq. 5).

The other limiting factor would be the current $I$ in the circuit (cf. Fig. 6). As seen in Chap. 3.5 the average current is around 32 mA (cf. eq. 3). The amplifiers can deal with currents up to 100 mA, so this should not lead to saturation either.

The amount of charges deposited in the chamber during one extraction is calculated as follows: let us consider an average value of $4 \cdot 10^{12}$ charges. This corresponds to

$$4 \cdot 10^{12} \times 1.6 \cdot 10^{-19} \simeq 0.64 \, \mu\text{C}$$  \hspace{1cm} (5)

We can consider that half of this charge is due to electrons, the other half coming from the ions. Maximum would be $6 \cdot 10^{12}$ charges; that is roughly $1 \mu\text{C}$.

Hence, the quantity of charges created in the chamber would not make the electronics saturate.

### 3.7 Cabling Topology

The main dissimilarity between vertical and horizontal profile of the detector station (cross), which could explain this difference in behaviour, lies in the cabling structure. The detectors are connected to the acquisition cards by multwire cables. These cables are 750 m long, and go from TNM 41 and TNM 42 to UA 87, where the electronics is installed.

The cables are made of 48 wires, grouped by 2. These two wires are twisted, mapping a helix. The 24 pairs are divided into two groups. Half of them, forming the core of the cable, are also twisted all together. Then, the other half, forming the external layer, twists around the core as well (cf. Fig. 17).

The core and the external layer never mix.

The entire cable is shielded. Wires have their own built-in capacitance, and see also extra capacitances between two wires, as well as between a wire and the shielding. The capacitance between wire and ground, for wires from the core, is 32 to 35 nF; and the ones from the external layer is 47 nF. This capacitance is constant, as these wires always stay on the outer part of the cable, close to the shielding. On the other hand, the inner wires coupling capacitance depends on the position on the wire, and on the coupling with other wires. It is also lower than the shielding coupling capacity.

For instance, we could consider the two detectors located at the extremities of a profile: the lower lines in Fig. 11, detector #1 (blue) and #21 (red). We could think that the cable for detector #21, which shows a correct behaviour, is close to the shielding. It has then a quite high coupling capacity, allowing it to
carry charges properly. On the other hand, the cable for detector #1 would lay in the middle of the helix, implicating a non-linear signal, even if the number of charges is the same.

The detectors from the vertical profile of the cross are connected to the wires from the external layer of the cable, whereas the horizontal detectors are connected to the inner wires. The 6 remaining wires, which are not connected to any detector, are grounded.

Hence, as they see different capacitances, there lies a physical difference between horizontal and vertical monitors, which can explain the non-linear effect.

![Topology of wire pairs inside one cable.](image)

**Figure 17:** Topology of wire pairs inside one cable.

## 4 Modifications During Shutdown 2007 – 2008

To compensate these capacity coupling effects, and make sure all wires have the same behaviour, they must have the same capacitance. The simplest solution is to increase each wire capacitance. Then, the differences between wire capacitances is negligible compared to their total capacitance. Increasing capacitance also reduces the maximum voltage by a factor 10, as well as the discharge of the chamber into the wires, and therefore the effects of the different couplings.

This was achieved by adding a 220 nF capacitor between each wire and the shielding, on the cable end which is linked to the detectors.

The capacitance of cables is on average 257 nF, with an incertitude of ±7 nF, depending on what cable is considered. This incertitude is negligible compared to the total capacitance.
Figure 18: Results for 2008: high intensity, from 27\textsuperscript{th} Aug. to 29\textsuperscript{th} Aug. Detector signals versus intensity, for horizontal profile of first cross (TNM41), for both extractions of the first cycle. The normalised detector signal is now constant for high intensities, up to $24 \times 10^{12}$ p.o.t./extraction.
Figure 19: Results for 2008: Mean and standard deviation of detector signal versus detector position, for horizontal profile of the first cross (TNM41), for high intensity, for both extraction of the first cycle. One can see that normalised standard deviation is very low: around 0.3%.
5 Results for 2008

The first high-energy extractions in 2008 showed an immediate effect (cf. Fig. 18 and 19): the non-linear behaviour in the horizontal profile of TNM41 disappeared, for intensities up to $24 \times 10^{12} \text{ p.o.t./extraction}$.

The normalised standard deviation is less than 0.3% of the signal; moreover, it is now equal for all detectors.

All monitors now show a linear response. This proves that the cabling topology caused the non-linear behaviour and that setting all cables to a fixed capacitance corrected the detector response.

6 Conclusion

In order to understand the non-linear behaviour of the muon detectors appearing in 2007, many aspects of the monitors and data were checked. This non-linear behaviour does not show any link to the following characteristics: beam intensity, beam position, detector signals, extraction, cycle number; detector origins, timing of the electronic cards, and linearity of the electronic cards. The electronic cards do not saturate.

The only relevant aspect is the wires topology inside multiwire cables, and their different behaviour with respect to capacitance coupling. This aspect was corrected by increasing each wire capacitance to a fixed value.

Results from 2008 immediately showed that the problem was corrected by these modifications. All detector have now a linear behaviour; the standard deviation of the measurement is below 0.3%.

References

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