Verification of the CNGS Timing System using Ultra-Fast Diamond Detectors

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A new ultra-fast diagnostic tool was installed in the CNGS facility in 2011 following the neutrino time-of-flight results published by OPERA in September 2011. Several polycrystalline CVD diamond detectors were placed in the secondary beam line about 1200 m downstream of the CNGS target in order to measure the time structure of the muons which are produced together with the muon neutrinos. This allows an accurate measurement of the GPS timing of individual secondary particle bunches crossing these detectors, and provides an independent timing measurement at CERN, which has previously been based solely on the fast beam current transformers installed in the primary proton beam line upstream of the CNGS target. Both the position of the detectors, and the time between the detection of the particles at the beam current transformer and the diamond detectors have been measured very carefully and a sound analysis of the detector signals was done. This allows comparison of the measurements between the beam current transformer and the diamond detectors. The results reveal that the GPS timing measurements performed at CERN are consistent.

1 Introduction

The CNGS facility (CERN Neutrinos to Gran Sasso) \cite{2011} aims at the direct detection of muon-neutrino to tau-neutrino oscillation by measuring the appearance of the tau-neutrino. An intense muon-neutrino beam is generated at CERN and directed over 732 km towards the Gran Sasso National Laboratory (LNGS) in Italy, where four large and complex detectors (BOREXINO \cite{2012}, ICARUS \cite{2013}, LVD \cite{2014}, OPERA \cite{2015}) are located. In addition to the main goal of tau-neutrino measurements, the facility profits from accurate time and distance measurements between the source of the CNGS neutrino beam and the Gran Sasso experiments, allowing the determination of the neutrino velocity with high accuracy. Until 2011 the start time of the neutrinos racing towards Gran Sasso has been solely based on measurements of the fast beam current transformer that is installed in the primary proton beam line upstream the CNGS target; the time structure of the protons passing through the beam current transformer gives the Global Positioning System

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(GPS) time tag. After the publication from the OPERA collaboration in September 2011 on the neutrino velocity measurements [6], several polycrystalline chemical vapour deposition (pCVD) diamond detectors (DD) were placed in the secondary beam line about 1200 m downstream of the CNGS target in order to measure the time structure of the muon spills independently. This allows an accurate measurement of the GPS timing of the muon bunches crossing these detectors, and provides an independent timing measurement at CERN.

2 The CNGS Facility

The 400 GeV/c CNGS proton beam is fast extracted from the CERN SPS accelerator; during a 6 s long cycle there are two extractions separated by 50 ms, each lasting 10.5 µs and with up to $2.4 \times 10^{13}$ protons/extraction. The beam is sent down an 840 m long proton beam line onto a carbon target producing kaons and pions. The positively charged pions and kaons are energy-selected and guided with two focusing lenses, the so-called horn and reflector, in the direction of Gran Sasso. These particles decay in a 1000 m long, 2.5 m diameter vacuum tube into muon-neutrinos and muons. All the hadrons (i.e. protons that have not interacted in the target), and pions and kaons that have not decayed in flight, are absorbed in a hadron stopper. Only neutrinos and muons can traverse this 18 m long block of graphite and iron. The muons, which are ultimately absorbed downstream in around 500 m of rock, are measured in two muon detector stations, each consisting of 41 ionisation chambers. The stations reside in two caverns called pit 1 and pit 2 which are separated by 67 m of rock. The average energy of the muon-neutrinos which are sent to Gran Sasso, is $\sim 17$ GeV/c. A schematic overview of the CNGS neutrino beam facility at CERN is shown in Fig. 1.

![Schematic overview of the CNGS neutrino beam facility at CERN](image)

Figure 1: Schematic overview of the CNGS neutrino beam facility at CERN.

The time information at CNGS for the OPERA neutrino time-of-flight (ToF) analysis was derived from a fast beam current transformer (BCTF40) [7] that is installed in the CNGS extraction line upstream of the CNGS target. The time structure of the extracted protons is measured with this BCTF40 detector and the time information is tagged with a GPS time.

In order to independently verify the timing measurements of the BCTF40 signal, ultra-fast polycrystalline diamond (pCVD) detectors were installed in the muon pits in November 2011 and also equipped with GPS time tagging means.
3 Flux Simulation

Monte Carlo simulations were exploited to assess the feasibility of the measurement and the detector working environment. Calculations were performed with the FLUKA [8] code by slightly modifying the standard set-up already used for all CNGS related simulations [9]. The reliability of this simulation framework has been verified on many observables, in particular for what concerns the response of the ionisation chambers in the muon pits [10]. Diamond detectors were modelled as a uniform layer sandwiched between two Al supporting layers of 3 mm thickness. The detectors thickness has been indicatively set at 0.1 mm, with a density of 3.52 g/cm$^3$. In the simulation, two such sandwiches were inserted in each of the muon pits, one near to the entrance wall and one in front of the ionisation chambers, oriented perpendicularly to the beam and spanning the whole transverse dimension of the pit. The energy deposition in the detector layers were simulated as a function of the arrival time of particles and as a function of radial distance with respect to the beam axis. For both position in each pit, the distribution of deposited energy versus arrival time peaks at the time corresponding to the travel time of fully relativistic particles. The falling edge of the simulated signal drops two orders of magnitudes in about 2 ns. Very small secondary peaks are present, with amplitude five orders of magnitudes lower than the prompt peak. The time delay of these secondary peaks is consistent with particles reaching the detectors after being reflected by the pit walls. Convolution of this response with the time structure of the beam shows that the original beam time structure is only minimally affected.

Particle fluencies and deposited energy at the actual diamond detectors positions are reported in Tab. 1 for $1 \times 10^{13}$ protons on target (pot). The contribution from charged hadrons and neutrons is negligible. Energy deposition values have been rescaled to the finally used detector thickness.

![Table 1: Particle fluencies and deposited energy at the diamond detectors positions for $10^{13}$ pot.](image)

<table>
<thead>
<tr>
<th>Position</th>
<th>$\mu$ flux</th>
<th>$e^+e^-$ flux</th>
<th>$\gamma$ flux</th>
<th>Dep. energy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pit1, center</td>
<td>$2.4 \cdot 10^6$</td>
<td>$2.7 \cdot 10^6$</td>
<td>$1.5 \cdot 10^7$</td>
<td>7750</td>
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<tr>
<td>Pit1, lateral</td>
<td>$2.3 \cdot 10^6$</td>
<td>$8.6 \cdot 10^5$</td>
<td>$5.5 \cdot 10^6$</td>
<td>1250</td>
</tr>
</tbody>
</table>

4 Experimental Set-up

4.1 Diamond detectors

pCVD diamond is a suitable detector material for the measurement of the time structure of the CNGS muon beam. With a signal full width half maximum (FWHM) of 2 ns it is able to resolve the 5 ns bunch structure of the beam. Short signal time is realised by operating the detectors at 1 V/µm and making use of the high free charge carrier mobility in diamond. The signal is composed of a DC part of 10.5 µs length and is modulated by a 5 ns structure resulting from the SPS RF. The linearity of the signal delivered by the DDs allows a measurement in the high ionisation range as delivered by the CNGS facility.

Three pCVD diamond detectors were installed in pit 1, two at the centre and one at the left side of the measurement station. Two of them are depicted in Fig. 2. The detector material was produced by Diamond Detectors Ltd [11] with a specified thickness of 500 µm and a specified charge collection distance (CCD) of 200 µm. All main DD parameters are listed in Tab. 2. The detectors were provided by Cividec Instrumentation [12] in RF-tight PCB housings with 50 Ω readout lines. This minimizes the over-all detector capacitances and time constants for keeping the time response as fast as possible.

4.2 Electronics, Read-out and Calibration

The detectors were connected to the bias voltage via a loading resistor $R_1$ of 1 MΩ resistance and a charging capacitor $C_1$, see Fig. 3. The signals were read out at the low-voltage side of the detector, which was DC-terminated to ground by a 1 MΩ resistor. The charging capacitors were of 11 nF capacitance for CT and Left, and of 2 nF capacitance for CB. All detectors were operated at 500 V, i.e. 1 V/µm. This leads
Figure 2: Photo of the muon detector station (left) and of the a diamond detector station (right).

Table 2: Main parameters of the diamond detectors installed in muon pit 1.

<table>
<thead>
<tr>
<th>Detector name</th>
<th>Center Top (CT)</th>
<th>Center Bottom (CB)</th>
<th>Left</th>
</tr>
</thead>
<tbody>
<tr>
<td>Specified thickness [µm]</td>
<td>500</td>
<td>500</td>
<td>500</td>
</tr>
<tr>
<td>Electrode size</td>
<td>Ø=3 mm</td>
<td>8×8 mm²</td>
<td>8×8 mm²</td>
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<tr>
<td>Electrode area [mm²]</td>
<td>7.1</td>
<td>64</td>
<td>64</td>
</tr>
<tr>
<td>Ionisation volume [mm³]</td>
<td>3.53</td>
<td>32.0</td>
<td>32.0</td>
</tr>
<tr>
<td>Detector capacitance [pF]</td>
<td>3</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>Time constant [ps]</td>
<td>150</td>
<td>500</td>
<td>500</td>
</tr>
<tr>
<td>Charging capacitance [nF]</td>
<td>11</td>
<td>2</td>
<td>11</td>
</tr>
</tbody>
</table>

to an average electron-hole mobility of 750 cm²/Vs and a corresponding drift velocity of 0.7 × 10⁵ m/s. The detectors were directly read out without electronic amplification. The low detector capacitances of 10 pF and 3 pF in combination with the 50 Ω readout impedance provide fast time constants of 500 ps and 150 ps, respectively. This allows resolution of the 5 ns RF structure from the extracted SPS beam, which has already been proven [13].

Two LeCroy WaveRunner 104MXi-A oscilloscopes with an analogue bandwidth of 1 GHz and a sampling frequency of 5 GS/s were used for the data readout. The oscilloscopes sample the incoming analogue signals with 8 bits, providing an analogue to digital converter (ADC) range of 255. All detectors were connected to the readout oscilloscopes via CK50 cables [14] of 76 m length. The 50 Ω cables have a specified attenuation per 100 m of 9.1 dB at 1 GHz and 2.7 dB at 100 MHz and a velocity ratio of 78%. The transmission time of the three CK50 cables was measured using a reflectometer with a 500 ns pulser, and resulted in 328.1 ns, 328.3 ns and 328.1 ns for CT, CB, and Left, respectively. The trigger signals of the oscilloscopes were calibrated within a precision of 0.5 ns.

All detectors were individually calibrated with an ²⁴¹Am α-source after installation in the pit. The expected average ionisation charge was 5000 electrons per MIP. Additionally the current induced by the drifting charge carriers as measured with the muon beam was compared to the simulated current from the FLUKA simulation, cf. Sec. 3. The average of the simulated current over the three diamond detectors agrees to a 15% level with the average of the measured current.

5 Trigger and Timing

To confirm the accuracy of the CNGS timing system it is necessary to relate the timing signals from the DDs with those from the BCTF40 detector previously used. This is achieved by finding the ToF between
the two detector points using the measured timestamps and relative offsets, and ensuring that they agree
with the nominal ToF over the same distance. In order for the ToF to be known on the nanosecond scale it
is necessary to know precisely all the delays introduced between the detection of a particle and the signal
being registered by the system in addition to the distance travelled by the particle. The transmission times
of all data-carrying cables were measured using a variety of methods, including reflectometry and using a
transportable CS4000 caesium clock [16]. The distance travelled was measured by an independent survey
group.

5.1 Survey

Initially, the survey group has aligned all the components of the CNGS line, including the BCTF40, with
respect to a network of geodetic points which was determined by topographical methods linked to the SPS
geodetic network from where the protons are arriving. Neither GPS measurements at the surface level nor
link between surface to tunnel were realised. The relative accuracy of this underground network could be
estimated to be better than few millimetre. Then, measurements were carried out to localise the diamond
detector position with respect to the same network and these measurements yielded a distance $d_{BCTF-P1}$
between the BCTF40 and muon pit 1 of:

$$d_{BCTF-P1} = (1859.95 \pm 0.02) \text{ m}.$$  \hfill (1)

5.2 Setup at CERN

There are two timing measurements made on the CNGS beam line; one for the primary (proton) beam
as it leaves the SPS ring and passes BCTF40 and one for the secondary (muon and neutrino) beam from
the DDs located in pit 1, see Fig. 4. The delays examined here are those between the actual start time of
an event window as measured by the GPS located in the CERN control room (CCR) and the same time
measured at the detector stations. The time is not logged directly at the detectors but by an oscilloscope
located around 76 m away.

5.2.1 Primary Beam

There are four individual values which sum to create the total delay for the primary beam timestamp;
the time taken to traverse the hardware between the BCTF40 and the scope, between the scope and the
Central Timing Receiver (CTRI) in HCA442 near the tunnel entrance, between the CTRI in HCA442 and
the one in CCR, and a value of 99 216 subtracted from the GPS timestamp as a first correction in order to
bring it close to the time of arrival of the beam at the BCTF40. These values sum to give a total value:

$$\delta_{OFFSET}^{BCTF} = -580 \text{ ns} + 26.6 \text{ ns} + 10077.8 \text{ ns} - 99 216 \text{ ns} = (-89 601.6 \pm 5)\text{ns}. \hfill (2)$$
Figure 4: Overview of timing offsets at the CNGS facility. The distance between the BCTF40 and the DDs is about 1860 m.

All stated times include the delay added by hardware latency. The negative sign for the delay value between the detector and the scope is due to the fact that the timestamp being logged on the data system is triggered at the scope, but its value comes from the GPS receiver located in CCR. This has been visualised in Fig. 5. In order to measure the delay between the two CTRIs, the CS4000 was transported between them, connecting it to the External Clock Input at one end, and the External Start Input at the other. The accuracy of the CS4000 in the time between the two measurements is estimated at less than ±1 ns [17].

Figure 5: Time delays for primary beam timestamp.

5.2.2 Secondary Beam

A similar process applies to the timing of the secondary beam (Fig. 6). It is characterised by three separate delays; between the DDs and the scope, between the CCR and a Central Timing Receiver (CTRV), and between the CTRV and the scope. The delays sum to give the value:

$$\delta_{\text{OFFSET}}^{\text{DD}} = -328.2 \text{ ns} + 31.1 \text{ ns} + 29083 \text{ ns} = (28785.9 \pm 2) \text{ ns.}$$  \hspace{1cm} (3)

5.3 Calculation of $\delta_{\text{total-delay}}$

The GPS timestamps as logged on the TIMBER database [15] ($t_{\text{GPS,BCTF}}$ and $t_{\text{GPS,DD}}$ for the primary and secondary beams respectively) are adjusted by the above offsets to give:

$$t_{\text{BCTF}} = t_{\text{GPS,BCTF}} + \delta_{\text{OFFSET}}^{\text{BCTF}}$$

and

$$t_{\text{DD}} = t_{\text{GPS,DD}} + \delta_{\text{OFFSET}}^{\text{DD}} - 32\,500 \text{ ns}$$

for the start times of the measurement windows. The $-32\,500 \text{ ns}$ delay is an accumulation of software delays and the trigger pulse offset.

There is evidence for variations in the cabling delays according to the ambient temperature which can change from day to day [16]. These variations are monitored continuously for the delay between the CTRIs by a fibre running in parallel to the cable by comparison with the original calculated value of $10\,077.8 \text{ ns}$. The estimated yearly variation is less than 1 ns.

A constant difference is found when examining the data logged on the TIMBER database:

$$t_{\text{GPS,BCTF}} - t_{\text{GPS,DD}} = 79\,911 \text{ ns}.$$  

This therefore gives a time difference of:

$$\delta_{\text{total-delay}} = t_{\text{DD}} - t_{\text{BCTF}} = -79\,911 \text{ ns} + 28\,785.9 \text{ ns} - 32\,500 \text{ ns} + 89\,691.6 \text{ ns} = (6066.5 \pm 6.0) \text{ ns}$$

between the start of the sample window of the BCTF40 and the start of the sample window of the DDs. For each detector there is also an offset from the start of the window to the signal start within the window. This delay will be examined in the next chapter.

6 Data Analysis

The timeline offset $\delta_{\text{offset}}$ of the data within the read-out windows is derived. This is needed, since the windows from BCTF40 and the DDs might not be equally fitted around the signals. Using $\delta_{\text{offset}}$ and the read-out window offset $\delta_{\text{total-delay}}$ calculated in Sec. 5, it is possible to measure the ToF of the SPS protons from the BCTF40 to the DDs. At their arrival at the DDs the protons have been converted to muons as described in Sec. 2. This serves as a cross-check of the timing of the BCTF40 detector, which was used for the ToF$_{\nu}$ measurements [6].

The recorded data from the DDs and from the BCTF40 is analysed offline making use of the ROOT analysis framework [18]. As described in Sec. 2 the SPS delivers two extractions per cycle. Since the second extraction only holds redundant information concerning the timing analysis, this analysis focuses on the data from the first extraction. The sample rate of the presented data is 1 GS/s. Hence, only every fifth data point from the original data taking at 5 GS/s is used. In total 151 spills recorded on 15.11.2011 between 10 a.m. and 11 a.m. (UTC) are taken into account for the presented analysis, of which 119 resulted from non-empty extractions.

Firstly, we show the detector response from single extractions, then the data treatment is explained, followed by the discussion of the treated data from the three DDs and the BCTF40 individually. The DD and the BCTF40 data is then used to calculate $\delta_{\text{offset}}$. 

![Diagram of beam line](image_url)
6.1 Detector Response

The bare detector response as measured with the oscilloscope within a time window of 12 μs from a single extraction for the three DDs and the BCTF40 is shown in Fig. 8.

As these plots hold 12000 data points each, the signals appear as a broad band at the given plot resolution. A simple 5 ns average per point is added in red to guide the eye. The four detector responses in Fig. 8 originate from the same extraction, hence a similar topology is expected for all of them. A comparison by eye reveals, that certain features of the signal present in all four signals, e.g. the dip flanked by two peaks from 6600 ns to 8500 ns (see arrows). The accordance of the signals renders a timing analysis possible that utilises the topology of signals. Note that the BCTF40 is a beam current transformer and detects the SPS beam current, whereas the DDs detect muons originating from pions and kaons produced by SPS protons in the target. However, the DD signals are very similar to the BCTF40 signal. A zoom from 2100 ns to 2200 ns for CT is shown in Fig. 9. The 5 ns (200 MHz) SPS beam structure is evident.

It is worth mentioning that the signal does not return to its baseline at the end of a bunch; each bunch has a tail of the order of few nanoseconds. This leads to a certain pile-up of signal from neighbouring bunches. However, this pile-up does not spoil the timing analysis.

6.2 Signal to Noise Ratio

The baseline and the baseline noise of the $i$-th extraction, $b_i$ and $\sigma^n_{noise}$, measured in ADC counts, are calculated for every non-empty extraction in the first 400 ns of the read-out window for the DDs, and in the last 400 ns for the BCTF40. The mean $\hat{\sigma}_n^{noise}$ characterises the mean baseline noise, $\hat{b}$ the mean baseline. Then for each DD as well as for the BCTF40 the average signal amplitude $\langle y \rangle_i$ is calculated in the range from 5000 ns to 6000 ns where the signal reaches a maximum. Again, the mean $\langle y \rangle$ represents the mean signal amplitude in this region. The two values are used to quantify a signal-to-noise ratio (SNR) for every detector; all numbers are shown in Tab. 3.

<table>
<thead>
<tr>
<th></th>
<th>BCTF40</th>
<th>CT</th>
<th>CB</th>
<th>Left</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sigma^n_{noise}$/ADC counts</td>
<td>650</td>
<td>1.09</td>
<td>1.17</td>
<td>1.43</td>
</tr>
<tr>
<td>$\langle y \rangle$/ADC counts</td>
<td>-11570</td>
<td>-30.35</td>
<td>23.72</td>
<td>8.16</td>
</tr>
<tr>
<td>$b$/ADC counts</td>
<td>-18791</td>
<td>-100.45</td>
<td>-71.0</td>
<td>-104.90</td>
</tr>
<tr>
<td>SNR</td>
<td>11.1</td>
<td>64.3</td>
<td>81.0</td>
<td>79.1</td>
</tr>
</tbody>
</table>
The SNR values in Tab. 3 illustrate the difference in signal quality between the DDs and the BCTF40. The DDs deliver an SNR of above 64, in comparison to an SNR of 11 for the BCTF40. The signal quality of the BCTF40 also suffers from oscillations or pick-up noise in the regions from 0 ns to 2000 ns, and from 8000 ns to 12 000 ns. A frequency analysis of these parts revealed a major contribution at 25 MHz. This pick-up is common to all recorded extractions for the BCTF40. These parts of the signal are therefore disregarded in the timing analysis. CB and Left have better SNRs than the CB for two reasons: the electrode areas of CB and Left are larger than that of CT leading to a larger signal and the fact that the noise is not dominated by the detectors’ capacity but rather by least-significant-bit noise of the scope.

6.3 Time Resolution

The single pulse time resolution of DDs for MIPs in combination with fast electronics has often been proven to be < 1 ns [19]. This holds true as well for the DDs used in this analysis and has been tested in the laboratory before installation. The difficulty here is the complexity of the signal; the uncertainty of the point in time of the arrival of the first bunch at the DDs is not dominated by the time resolution of the DDs themselves but by the long rise time (1 µs) of the kicker magnet.

The time resolution of the diamond detectors is estimated by analysing the signal within the rising edge, from 800 ns to 1000 ns. The SPS beam structure can easily be found by comparing five different sums $\sum^{(n)}$, where each sum represents a sum over signal amplitude values $y_{DD}(t)$ separated by 5 ns with an offset of $n = 0, 1, 2, 3, 4$ ns: $\sum^{(n)} = \sum_{i} y_{DD}(5i + n)$. The largest sum finds the phase $\varphi_{\text{max}}$ of the maximum within the 5 ns SPS beam structure. In all 119 cases, the ratio of the difference between largest and smallest sum to the difference between second largest and smallest sum is > 1.2, hence $\varphi_{\text{max}}$ is found unambiguously (see Fig. 10 (left) as an example for CT) and the time resolution is $\leq 1$ ns. The remaining uncertainty is of the type $n \times 5$ ns due to the imprecise knowledge about the arrival of the very first bunch. To quantify this $n \times 5$ ns uncertainty, the point in time where the signal exceeds three times the RMS noise is found and corrected by $\varphi_{\text{max}}$. The resulting histogram of the arrival time is shown in Fig. 10 (right). The evident 5 ns structure of the time of arrival shows the aptitude of this approach. The rms is 16.23 ns, resulting in $n = 3.25$.
Figure 9: A zoom in the detector response for CT.

Figure 10: The ratio of the difference between largest and smallest sum to the difference between second largest and smallest sum is shown (left). The corrected arrival time for the 119 events non-empty extractions (right).

6.4 Data Treatment

6.4.1 Averaging

In order to make a statement about the CNGS timing at CERN, the 119 non-empty signals are combined to form an average signal. This averaging makes the analysis robust against fluctuations in the single extractions. In order to average the signals correctly, the phase $\varphi_{\text{max}}$ is used. The timeline of every single pulse is shifted by $-\varphi_{\text{max}}$ in order to ensure a match of the bunch structure. For simplicity the baseline was shifted to zero. The average pulse values $y_{\text{avg}}(t) = g(t) = \sum_i y_i(t)/119 - b$, with the baseline $b$ from Tab. 3. The average signal for CT is shown in Fig. 11.

The average shift $\varphi_{\text{max}}$ is determined for each detector: 1.8 ns for CT, 2.4 ns for CB, 1.8 ns for Left, and 1.9 ns for BCTF40. Hence for the final result, a delay $\delta_{\text{avg-shift}} = -0.1, 0.5, -0.1$ ns has to be taken into account for CT, CB, and Left, respectively.

6.4.2 Filtering and Normalisation

The averaged signal is now filtered in order to get rid of the SPS beam structure which facilitates the later timing analysis. The applied filter method is a raised-cosine filter of width $w$, which belongs to the class of Finite Impulse Response filters. The applied equation for filtering is:

$$y_{\text{avg,filtered}}(t; w) = \sum_{j=-w/2}^{w/2} y_{\text{avg}}(t + j) \times (1 + \cos(2\pi(j/w))),$$

(8)
and the averaged, filtered signal with \( w = 15 \) ns for CT, CB, Left, and BCTF40 are shown in Fig. 12. Each DD signal is normalised to its average amplitude between 6650 ns and 6750 ns, the section of highest signal amplitude. The same is done for the BCTF40, but with the average amplitude taken between 6510 ns and 6610 ns.

6.5 Calculation of \( \delta_{\text{offset}} \)

Fig. 7 explains the timeline offset \( \delta_{\text{offset}} \) between the signals within their read-out windows. The averaged and filtered pulses are used to determine \( \delta_{\text{offset}} \) in two different ways. The “fitting method” uses the topology of the signal at different positions applying a fit to the detector responses over a sample section of 80 ns width. The chosen sections feature a trough. This method is referred to as local. A method that uses a much wider section, is the cross-correlation method. This calculates the cross-correlations between two signals over a number of microseconds. Therefore, this method is referred to as global.

6.5.1 The Local Method

The fitting method exploits a rather simple approach of fitting second order polynomial to an apparent trough in the detector responses. We use

\[ y_{\text{fit}}(t) = a(t - t_0)^2 + b \]

within a section of 80 ns width. The \( t_0 \) defines the lowest point of the trough and is readily determined for all four detector signals. The method is applied in two regions; from 4550 ns to 4630 ns (Fit 1) and from...
6380 ns to 6460 ns (Fit 2) for the DDs, but 140 ns earlier for both fits for the BCTF40. Each fit yields a $t_0$. The values are collected in Tab. 4 (top). The difference between the $t_0$ for the DDs and the BCTF40 form $\delta_{\text{offset}}$, $\delta_{\text{offset}} = t_0^{\text{DD}} - t_0^{\text{BCTF}}$, see Tab. 4 (bottom).

![Figure 13: The averaged, filtered detector response around a trough and the corresponding parabolic fits (grey).](image)

*Table 4: Fit results for $t_0$ and the resulting $\delta_{\text{offset}}$.*

<table>
<thead>
<tr>
<th>Trough</th>
<th>$t_0$ [ns]</th>
<th>BCTF40</th>
<th>CT [a.u.]</th>
<th>CB [a.u.]</th>
<th>Left [a.u.]</th>
</tr>
</thead>
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<tr>
<td>1</td>
<td>4447.6</td>
<td>4586.1</td>
<td>4587.3</td>
<td>4583.7</td>
<td></td>
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<td>2</td>
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<td>6415.7</td>
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<table>
<thead>
<tr>
<th>Trough</th>
<th>$\delta_{\text{offset}}$ [ns]</th>
<th>CT-BCT</th>
<th>CB-BCT</th>
<th>Left-BCT</th>
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</thead>
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<td>139.7</td>
<td>136.1</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>139.4</td>
<td>141.9</td>
<td>146.2</td>
<td></td>
</tr>
</tbody>
</table>

As the result of this method, the mean and standard deviation of the six $\delta_{\text{offset}}$ values are quoted, taking into account $\delta_{\text{avg-shift}}$:

$$\delta_{\text{offset}} = (140.4 \pm 3.2) \text{ ns},$$

$$\delta_{\text{offset}} = (140.0 \pm 1.3) \text{ ns w/o Left}.$$

### 6.5.2 The Global Method

This method employs a one-parametric likelihood function (LF) between two signals to form a likelihood estimator $\Theta$, e.g. between CT and BCTF40: $\Theta(\tau) = \text{LF}(f_{\text{CT}}(t), f_{\text{BCTF40}}(t))$, in order to find a possible offset between them. If a signal coming from either a DD or from the BCTF40 is correlated with itself, it is called an auto-estimator ($\Theta_a$). A cross-estimator ($\Theta_x$) is the result of a correlation of two signals stemming from different detectors. In order to find the $\delta_{\text{offset}}$, the correlation is calculated as a function of a parameter $\tau$ which describes a time shift between the time arguments of the correlated functions, hence $\Theta_x(\tau) = \text{LF}(f_1(t), f_2(t + \tau))$, and $\Theta_a(\tau) = \text{LF}(f_1(t), f_1(t + \tau))$. The auto-estimator is used to check that the used method yields reasonable results in terms of topology and amplitude. The expected result for the $\Theta_a$s is a minimum at $\tau = 0$. Furthermore, the depth of the minimum for the $\Theta_a$ can be compared to that of the $\Theta_x$; the latter is expected to be smaller than the former. The absolute value at the minimum of $\Theta_a(\tau)$ should be zero for all auto-estimators.

The chosen likelihood function uses the absolute difference in first derivative at a given point in time for the two signals under test, hence $|f'_1(t) - f'_2(t + \tau)|$. This difference is calculated for every point in time $t$ in a specified range, i.e. from $t_{\text{start}}$ to $t_{\text{end}}$. The absolute values are being summed, the sum forming the cross-estimator value $\Theta_x(\tau)$ or auto-estimator value $\Theta_a(\tau)$. This procedure is then repeated for $\tau$ ranging from -500 to +500 ns. In order to find the offset within the recording windows, the minimum of the $\Theta_x(\tau)$ and $\Theta_a(\tau)$ is found. The full formula is:
\[ \hat{\Theta}_z(\tau) = \sum_{t=t_{\text{start}}}^{t_{\text{end}}} |f_1(t) - f'_2(t + \tau)|, \tau = -500 \text{ ns}, ..., 500 \text{ ns} \] (10)

and the respective formula for \( \hat{\Theta}_a(\tau) \). The local derivative for a progression — the recorded signal is a progression with 1 ns steps rather than a continuous function — is the difference of two neighbouring points: 
\[ f' = \frac{f(t) - f(t+1 \text{ ns})}{\Delta t = 1 \text{ ns}} \]

It is stressed that the “standard” cross-correlation function 
\[ (f \ast g)(\tau) = \sum f_1(t)f_2(t + \tau) \]

has not been chosen as LF. The cross-correlation is not independent of the absolute values of the tested correlated signals, hence global maxima might appear due to changes in amplitude values, and not due to a better match. Therefore, in the presented analysis the difference rather than the product of two functions is chosen for the LF in order to avoid this dependence. Then, as the correlated functions the first derivative is chosen. This has the advantage that the minimum of the likelihood estimator is more pronounced, as can easily be shown. Additionally, differentiation attenuates the low frequency spectrum where most of the spectral differences between detectors are located, e.g. possible skin effect on the cables, different detector capacitances, and possible offset on the signals.

Both auto- and cross-estimators have been calculated in the range from \( t_{\text{start}} = 4000 \text{ ns} \) to \( t_{\text{end}} = 8000 \text{ ns} \). The calculated auto-estimators are shown in Fig. 14 (top left) for a filter width of \( w = 15 \text{ ns} \). The minima of all \( \Theta_a \)s are at \( \tau = 0 \), independent of \( w \). Cross-estimators against \( \tau \) for three different filter widths are shown in Fig. 14. In order to avoid an overlay of the different cross-correlation graphs, arbitrary offsets have been added to the \( \hat{\Theta}_x \)s.

The minima of the \( \hat{\Theta}_a \)s are more pronounced then the minima of the \( \hat{\Theta}_x \)s, as expected. The position of the minima for \( \hat{\Theta}_a(\text{CT, BCTF40}), \hat{\Theta}_x(\text{CB, BCTF40}), \) and \( \hat{\Theta}_x(\text{Left, BCTF40}) \) are listed in Tab. 5. It is evident from the lower right picture of Fig. 14, that a filter width of 5 ns is not sufficient to filter out the SPS bunch structure from the detector response. Additionally, the \( \hat{\Theta}_x \)s between different DDs have been checked. The positions of the minima are also located at \( \tau = 0 \), which further proves the reliability of this method.

<table>
<thead>
<tr>
<th>pos. of minimum of ( \hat{\Theta} )</th>
<th>CT</th>
<th>CB</th>
<th>Left</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \delta_{\text{offset}}/\text{ns} ) for ( w = 15 \text{ ns} )</td>
<td>137</td>
<td>136</td>
<td>139</td>
</tr>
<tr>
<td>( \delta_{\text{offset}}/\text{ns} ) for ( w = 20 \text{ ns} )</td>
<td>138</td>
<td>137</td>
<td>138</td>
</tr>
<tr>
<td>( \delta_{\text{offset}}/\text{ns} ) for ( w = 30 \text{ ns} )</td>
<td>139</td>
<td>139</td>
<td>140</td>
</tr>
</tbody>
</table>

Figure 14: The likelihood auto-estimator \( \hat{\Theta}_a(\tau) \) is shown for \( w = 15 \) (top left) and the likelihood cross-estimator \( \hat{\Theta}_x(\tau) \) for \( w = 30, 15, 5 \text{ ns} \) (others).
As the result of the minimum likelihood method, the mean and standard deviation of the nine $\delta_{\text{offset}}$ values are quoted, taking into account $\delta_{\text{avg-shift}}$:

$$
\delta_{\text{offset}}^\Theta = (138.2 \pm 1.2) \text{ ns}.
$$

7 Results

In order to verify the CNGS timing at CERN, we measured the ToF for charged particles from the beam current transformer BCTF40 to the diamond detectors downstream of the CNGS target and compare it to their nominal value.

The measured ToF uses the total delay between the start of the read-out windows $\delta_{\text{total-delay}}$ and the offset $\delta_{\text{offset}}$ of the timelines within the recording windows, hence $\text{ToF} = \delta_{\text{total-delay}} + \delta_{\text{offset}}$. As presented in Sec. 5, the time difference between the start of the recording window of the BCTF40 and the recording window of the DDs, is $\delta_{\text{total-delay}} = (6066.5 \pm 6.0) \text{ ns}$. In Sec. 6, $\delta_{\text{offset}}$ was measured with two different methods to be $(140.4 \pm 3.2) \text{ ns}$ and $(138.2 \pm 1.2) \text{ ns}$, using the fitting method and the likelihood cross-estimator method, respectively. The measured ToF is hence

$$
\text{ToF}_{\text{fit}} = (6206.9 \pm 6.8) \text{ ns}
$$

for the fitting method, and

$$
\text{ToF}_{\hat{\Theta}} = (6204.7 \pm 6.1) \text{ ns}
$$

for the cross-correlation method. For both values, the largest contribution to the total uncertainty is the uncertainty of the cable connection between the BCTF40 and the oscilloscope in HCA442. This value will be remeasured in 2012.

The value for the nominal ToF combines the travelled distance of $(1859.95 \pm 0.02) \text{ m}$, as measured by the CERN GEO survey and the combined velocity $v$ of the original proton and its production/decay products. The SPS protons have a momentum of $400 \text{ GeV/c}$, the pions and kaons an average momentum of $35 \text{ GeV/c}$, and hence the muons have an average momentum of $17 \text{ GeV/c}$. We find

$$
\text{ToF}_{\text{nom}} = \frac{1859.95 \text{ m}}{v} = (6205.3 \pm 2.5) \text{ ns},
$$

where the uncertainty is dominated by decay position of the pions/kaons within the decay tube. $\text{ToF}_{\text{nom}}$ lies well within the errors of $\text{ToF}_{\text{fit}}$ and $\text{ToF}_{\hat{\Theta}}$.

8 Conclusion

As a result of the neutrino time-of-flight publication of OPERA in 2011, polycrystalline CVD diamond detectors were installed in the secondary beam line downstream from the CNGS target in order to measure the GPS time structure of the muon spill. This allows verifying in an independent way the CNGS timing at CERN, which was previously only based on the measurements of the protons passing through a fast beam current transformer (BCTF40) before they hit the CNGS target. The distance between the two detectors was carefully measured as well as all the time delays from the detection of the particles until the signal is being registered. Detailed analysis of the signal shape was performed. The theoretical time-of-flight of particles travelling with the speed of light between the BCTF40 and the diamond detectors was compared with the measured time-of-flight of the charged particles passing through these detectors. The results show that the timing measurements performed at CERN using the BCTF40 and the diamond detectors are consistent.

Acknowledgement

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