

The CNGS beam and Borexino in 2009 - 2011

Laura Perasso

Istituto Nazionale di Fisica Nucleare, Genova - Italy *

May 10, 2012

1 Introduction

The CERN to Gran Sasso (CNGS) neutrino beam (see [1] and [2] for more details) has been designed to study the $\nu_\mu \rightarrow \nu_\tau$ transitions via the evidence of ν_τ interactions in the OPERA and ICARUS detectors located at the Laboratori Nazionali del Gran Sasso, near l'Aquila, in Italy.

The ν_μ s of the CNGS beam produce muons in the Gran Sasso rock upstream of Borexino via charged current interactions; other charged and neutral current interactions are expected in the detector itself and some could mimic the Borexino events. All these CNGS induced events are a background for Borexino and, as such, they must be identified and removed from the analyzed data sample. At the same time they are a good sample of muons of known direction and we used them to determine Borexino muon tagging efficiency and tracking performance; besides, since Borexino is just in front of OPERA in Hall C, we also exploited these CNGS muon events common to the two experiments to test the Borexino tracking algorithms for horizontal tracks [3].

A subset of this muon sample has also been used to try to measure the neutrino velocity, after OPERA announcement in september 2011 [4]. This neutrino velocity analysis is limited by the poor Borexino GPS time resolution and other delay measurement uncertainties, as explained in the last Section, but it is important in itself to tune the analysis which will be used for the next "Bunched Beam" configuration data, expected in may 2012, to provide a more accurate neutrino velocity measurement, using the new Borexino CNGS event triggering scheme and a total brand new GPS design and hardware.

In this note, written to define some CNGS beam characteristics, and used terminology, and to summarize the Borexino CNGS event selection, we briefly describe the CNGS neutrino beam in its standard and in its "Bunched Beam" configuration (Section 2), the CNGS beam induced event selection in Borexino (Section 3), the Borexino CNGS data sample in the years 2007-2008-2009-2010 and 2011 (Section 4), the Borexino neutrino Time of Flight (ToF) definition (Section 5) and the proton extraction Wave Form data (Section 6) in the "Bunched Beam" period in 2011.

2 The CNGS beam

The ν_μ s of the CNGS beam come from the decays of the kaons and pions produced in the interaction between accelerated protons and a carbon target; all the other produced particles are stopped by a "hadron stop" wall and only the surviving neutrinos travel the $\approx 730Km$ from CERN to Gran Sasso.

The protons are accelerated at CERN in the Linear Accelerator LINAC2 at $50MeV/c$; they are then injected in the Proton Synchrotron Booster (PS Booster) where they are accelerated to $1.4GeV/c$

*perasso@ge.infn.it

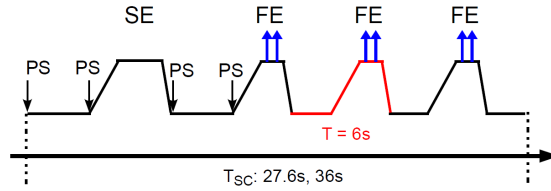


Figure 1: One SPS Super-Cycle and three CNGS cycles; *PS* indicates when the PS protons are injected into the SPS; *FE* indicates the timing of the two proton Fast Extractions to produce the CNGS beam.

and up to $14\text{GeV}/c$ in the Proton Synchrotron (PS).

At the end of one PS acceleration cycle (lasting 1.2 seconds), the protons are injected into the Super Proton Synchrotron (SPS) via a 5-turn extraction, each bunch of extracted protons having the same length of the PS circumference; since the SPS circumference is ≈ 11 times the PS circumference, two PS acceleration cycles are sufficient to fill the SPS circumference.

The protons stored in the SPS are then accelerated to $400\text{GeV}/c$ and are then extracted in two Fast Extractions at the maximum of the magnet ramping; each CNGS Fast Extractions produce one proton *spill* $10.5\ \mu\text{s}$ long and the two produced spills are $50\ \text{ms}$ apart.

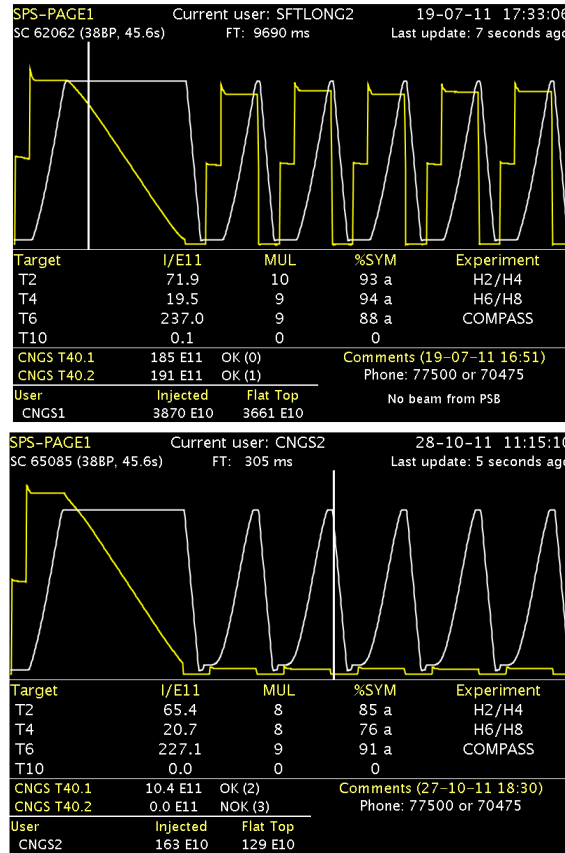


Figure 2: One SPS Super-Cycle with five CNGS cycles: in the normal "long extraction" configuration (top) and in the new, "Bunched Beam", configuration (bottom). See text for more details.

Inside a CERN SPS Super-Cycle of few tens of seconds (27.6 s, 36 s, or other, depending on the

SPS physics program) there are 2, 3 or more CNGS cycles, each having a 6 s period (see sketch in figure 1).

In the Bunched Beam (BB) configuration we had in the *October 21st – November 06th* 2011 period, dedicated to the neutrino velocity measurement, we had only one Fast Extraction per CNGS cycle, made of 4 bunches of protons, each few ($\approx 1 - 2$) nanoseconds wide: in this way we could have a very good timing for the protons hitting the target (see Section 6).

In figure 2 we show the CERN display ¹ of the SPS beam structure for five CNGS cycles in the normal "long extraction" configuration and in the new, "Bunched Beam", configuration: for each CNGS cycle we can see the two SPS proton fillings, corresponding to an increase in the total particle number in the SPS (the two steps in the the yellow line, proportional to the particle number) and the SPS magnet ramping (white line) on top of which there are the two (or one, for the BB) proton Fast Extractions.

The beam intensity is given in number of "protons on target" (*pot*) for each Extraction and this has been $\approx 2 \cdot 10^{13}$ *pot* in 2009, 2010 and 2011 and $\approx 1.1 \cdot 10^{12}$ *pot* in the Bunched Beam runs, as shown in figure 3.

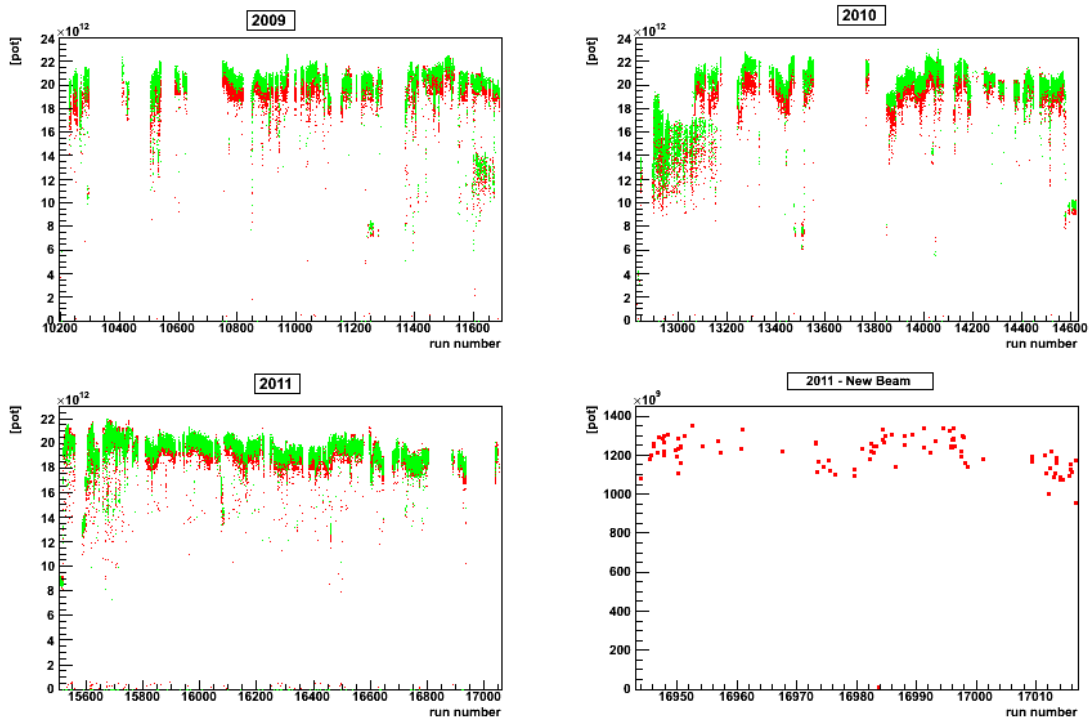


Figure 3: Extraction intensities versus Borexino run number in 2009, 2010, 2011 and during the Bunched Beam at the end of 2011.

The calculated [5] neutrino fluxes at LNGS, for a neutrino energy between 0 and 100 GeV, are summarized in table 1.

The ν_μ energy, plotted in figure 4 - top, has been optimized for the appearance of ν_τ , given the 730 km distance between CERN and the detectors at Gran Sasso; the mean energy is about 18 GeV [6].

What Borexino detects are the muons produced by the ν_μ s in the rock upstream of the Gran Sasso Hall where the detector is located and the ν_μ s interactions inside the detector itself. The expected number of muons per neutrino interaction in the rock is usually one (only 0.3 % of the

¹<http://op-webtools.web.cern.ch/op-webtools/vistar/vistars.php?usr=SPS1>

particle	fluxes
ν_μ	$\sim 7.4 \cdot 10^6$
$\bar{\nu}_\mu$	$\sim 2.9 \cdot 10^5$
ν_e	$\sim 4.7 \cdot 10^4$
$\bar{\nu}_e$	$\sim 6.0 \cdot 10^3$

Table 1: Expected neutrino fluxes from CNGS at LNGS, in $\nu/cm^2/10^{19}pot$ units (from [5]) .

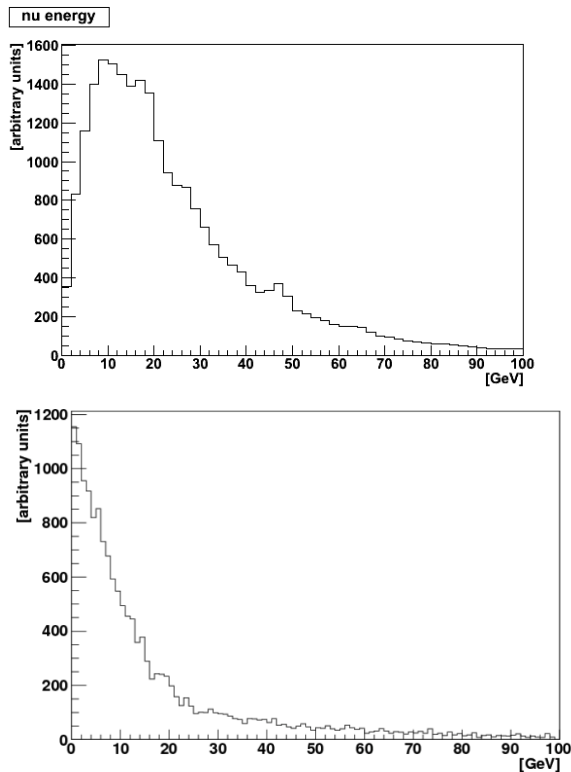


Figure 4: On top: energy distribution of the CNGS ν_μ . On bottom: energy of the muons from the Gran Sasso rock entering the LNGS Hall [6].

interactions produce more than one muon) and the muon energy distribution is plotted in figure 4 - bottom.

At LNGS the neutrino beam is coming up with a zenith angle of -3.2° ; the azimuth angle with respect to Hall B axis (parallel to Hall C, where Borexino is located) has been measured to be an amazing 0.18° [7] ; its width is more than one kilometer.

3 Borexino CNGS event selection

For the measurement of the neutrino Time of Flight a very good CERN - LNGS time synchronisation is mandatory and since the beginning a GPS-based solution has been adopted. Both CERN and LNGS have the same double unit UTC clock system with comparable performances (time resolution < 100 ns) and their single units are both based on a GPS system (Symmetricom Xli GPS receiver) and a Rb clock. The two GPS receivers, at CERN and LNGS, work in the so called "common - view mode" and both systems have been accurately intercalibrated [8].

At LNGS the same UTC time is sent from a master located outside the gallery to the slaves

located underground at the experiment sites via an optical fiber $\approx 8 \text{ Km}$ long; the time delays between the master and the slaves at OPERA, LVD and Borexino have also been accurately measured [9]. At CERN this UTC time is sent to the Central Control Room and is used to *time stamp* all the data logged in the long term CERN Data Base.

In 2006, the only requirement was being able to discriminate events between cosmic muons and muons coming from the neutrino beam interactions. When OPERA decided to undertake the neutrino speed measurement, they soon realized that the GPS receivers formerly installed at CERN and LNGS would feature an insufficient accuracy and, together with CERN, decided to add two identical systems, at CERN and LNGS, composed of a much better GPS receiver (Septentrio PolaRx2e), of the kind used for professional time-transfer applications, always operating in "*common – view mode*", and a Cs atomic clock (Symmetricom Cs4000). This new system (see [10] for more details) has been installed in 2008 and has been continuously monitored and accurately calibrated.

We define "*on – time events*" the Borexino events which trigger the detector in a time window around the expected neutrino, or muon from the neutrino interaction in the rock in front of Borexino, arrival time at the detector, considering its velocity, supposed c , and the CERN-Borexino distance, $\approx 732 \text{ Km}$; this window, optimized on data, is between 2.4000 and 2.416 milliseconds, taking into account the $\approx 10.5 \mu\text{s}$ spread in the proton beam extraction time.

To define the neutrino arrival time we must know when its parent proton goes across a specific detector - with very good time and space resolution - at CERN: this has been selected to be the Beam Current Transformer (BCT) detector, located $743.3991 \pm 0.002 \text{ m}$ upstream of the CNGS proton target; the proton beam time-structure at the BCT is digitized for $20 \mu\text{s}$ by a 1 *GSs* Wave Form (WF) digitizer (ACQUIRIS DP110) triggered by the kicker magnet signal and the full BCT WF data for each extraction is stored into the CERN long term Data Base ² with 1 nanosecond resolution; these data, GPS tagged, are then copied by the interested experiments into their local systems, the GPS timestamp being the key to connect the event time at LNGS with the relative spill from CERN.

In the same way, in Borexino, each triggered event is stamped with the GPS time read from the slave unit and, to correlate these events to the correct beam spill, we compare each GPS trigger time with the GPS BCT spill times (in UTC unit) recorded at CERN, and call "*time difference*" the measured quantity:

$$Time_{diff} = BX_{trigger \text{ GPS}} - CERN_{extraction \text{ BCT GPS}} \quad (1)$$

The time difference between each Borexino trigger GPS time and the closest previous CERN GPS time tag of the extraction kicker pulse are calculated and plotted (see figure 5 left): the clear peak at around 2.4 ms corresponds to the approximate *Time Of Flight* between CERN and LNGS.

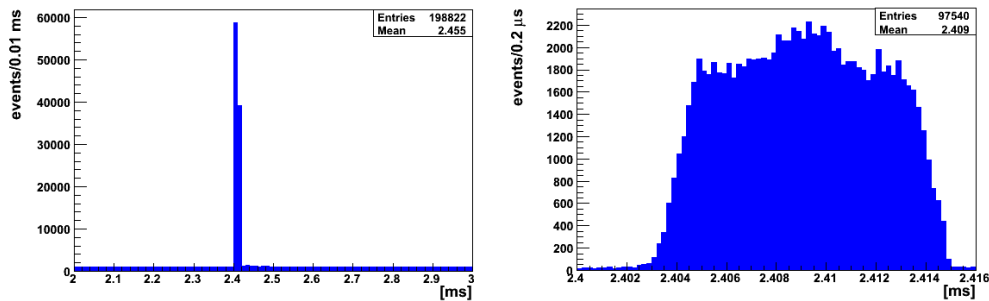


Figure 5: Recorded GPS time differences for the raw "*on - time*" events for the $10 \mu\text{s}$ wide proton spill. The plot on the right is a blow-up of the left one.

²variable TT40.BCTFI.400344

Plotting the time differences on a finer scale, we see (figure 5 right) that they actually have a $\approx 10\mu\text{s}$ spread, being such the parent proton extraction time duration and a consequent extraction time uncertainty.

In these plots we do not separate the events going across the Borexino Stainless Steel Sphere from those going only across the Water Tank (see [11] for a complete description of the Borexino detector), nor we split the events coming from to the first or the second extraction: this is done in the final analysis, which is in progress.

The events between the time window 2.40 - 2.416 milliseconds are listed in a file and are flagged in the Borexino DSTs as "CNGS *on time events*".

This sample includes all the events actually induced by the CNGS neutrino and accidental coincidences, mostly due to the ^{14}C decays inside Borexino. The fraction of accidental coincidences, measured by the application of an off-spill time window of the same duration, is $\sim 2\%$.

4 The CNGS Borexino data sample

Borexino detected the CNGS ν_{μ} s events since 2006 (see [12]), when it was still partly full of water and could act only as a Cherenkov detector. Since 2007, with liquid scintillator inside the Stainless Steel Sphere and water in the surrounding Water Tank, Borexino detected and flagged all the events *on - time* (as defined in previous section) with the arrival of the CNGS neutrinos. In table 2 we list all the analyzed runs.

year	BX DST week interval	run interval	total number of runs
2007	Sep_23 - Oct_14	5972 - 6132	26
2008	Jun_15 - Nov_02	8013- 9052	338
2009	May_24 - Nov_22	10201 - 11685	619
2010	Apr_18 - Nov_21	12833 - 14620	861
2011 all	Mar_13 - Nov_13	15509 - 17049	1007
2011OB	Mar_13 - Oct_16	15509 - 16938	954
	Nov_06 - Nov_13	17042 - 17055	
2011BB	Oct_16 - Nov_06	16944 - 17017	53

Table 2: Summary of the analyzed runs in the 2007-2011 period. In 2011, we had a long period with the old beam structure (OB) and a short period with the new Bunched Beam structure (BB); in the table the two periods are listed together and separately.

year	beam period	10^{19} p.o.t delivered	10^{19} p.o.t. in BX data	on-time events	^{14}C subtracted
2007	Sep 22 – Oct 20	0.08	0.07	873	
2008	Jun 18 – Nov 03	1.78	1.33	17687	
2009	May 27 - Nov 23	3.53	2.34	33739	32722
2010	Apr 20 - Nov 22	4.04	3.25	41752	40354
2011 OB	Mar 19 - Nov 14	4.78	4.41	61382	59520
2011 BB	Oct 21 - Nov 6	$7.43 \cdot 10^{-3}$	$6.87 \cdot 10^{-3}$	116	74
total 2009-11		12.36	10.01	136989	132670

Table 3: Summary of the CNGS beam periods in 2007-2011; we list the the periods the CNGS beam has been ON, the total number of *pot* delivered by CERN, the total number of *pot* in the Borexino data sample, the number of *on-time* triggers detected by Borexino in the same periods and the number of clean ^{14}C subtracted triggers.

In table 3 we summarize the periods the CNGS beam was ON, the total number of *pot* delivered by CERN, the total number of *pot* in the Borexino data sample, the number of *on - time* events

in Borexino and the number of *real* CNGS events, once the most important Borexino background (^{14}C) has been subtracted ³.

Of all the *on-time* events, roughly half go through only the Water Tank (the so called Outer Detector - OD), the other half going across both the WT and the Stainless Steel Sphere (Inner detector - ID).

Since some of the Borexino calibration campaigns took place during beam time, the values for *pot* in the Borexino data sample are sometimes lower than the corresponding values for *pot* delivered from CERN, as can be seen in figure 6, where we show the integrated beam intensity delivered from CERN and recorded by Borexino versus time.

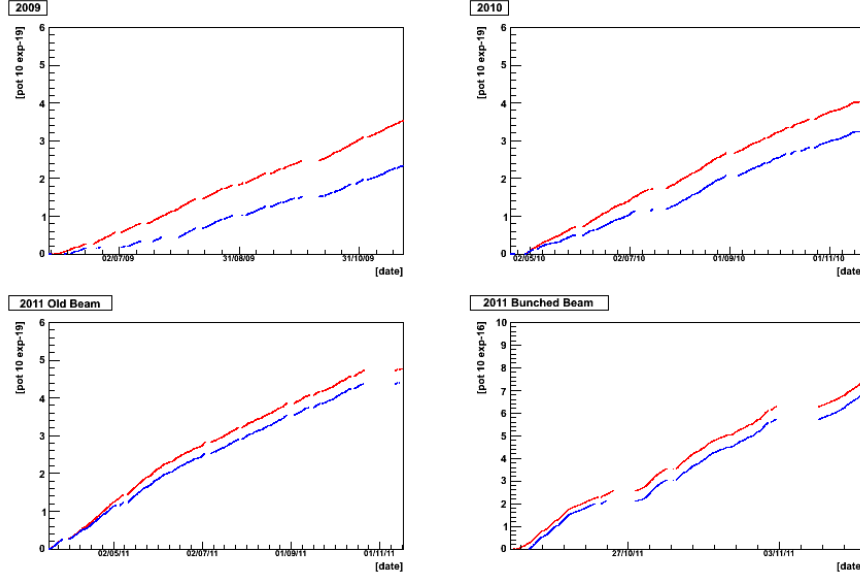


Figure 6: Integrated beam intensity - in (*pot*) - delivered from CERN (in red) and recorded by Borexino (in blue).

5 The Borexino neutrino ToF definition for the 2011 BB period data

The *Time of Flight* from CERN to Borexino is defined as the time difference between the Borexino event time, that is the time the neutrino (or muon) goes across the detector at LNGS and the time its parent proton goes across the BCT detector; we ignore here the fact that protons, pions, kaon and muons travel at a velocity slighter slower than light, since it is a totally irrelevant effect.

What we call *Time of Flight* is different from the $Time_{diff}$ in (1): the $Time_{diff}$ is the *mere* difference of the two UTC GPS values as written on tape - in the Underground Gran Sasso Laboratory - and on the Data Base - at CERN- , values which *must* be corrected by all the offsets and delays which affect the recorded values: in particular the proton-BCT-GPS-time at CERN becomes:

$$CERN_{real\ hit\ time} = CERN_{UTC\ value} + \delta_{CERN} + \delta_{WaveForm} \quad (2)$$

where:

³here we define ^{14}C events the events satisfying the condition: ($GetTrigger().GetTrgType() == 1$) AND ($bx_{event} \rightarrow GetLaben().GetNPmts() < 1000$) AND ($bx_{event} \rightarrow GetTrigger().GetBtbInputs() == 0$)

- δ_{CERN} is made of a fixed quantity, representing the delay induced by internal CERN cabling, and variable corrections to compensate for the short time noise in the GPS signal at the GPS receiver at CERN: all these quantities have been either measured or calculated from GPS data and provided to us by our CERN colleagues (see CERN note [13]);
- $\delta_{WaveForm}$ is the delay between the GPS time stamp and the actual time the proton goes across the BCT: these values are read, event by event, from the CERN Data Base.

In the same way the Borexino real event GPS time becomes:

$$BX_{real\ event\ GPS\ time} = BX_{trigger\ GPS\ value} + GPS_{BX\ offset} + \delta_{fiber} + \delta_{LNGS} - \delta_{BX} \quad (3)$$

where:

- $GPS_{BX\ offset}$ is a fixed Borexino analysis GPS offset (946681200 ns);
- δ_{fiber} is the GPS master-slave delay at LNGS, measured in july 2006 [9] and checked in may 2012;
- δ_{LNGS} are the calculated delays between the GPS satellite system and the receivers at the LNGS, to compensate for the short time variations at LNGS: these quantities have been calculated from GPS data and provided to us by our CERN colleagues (see [13]);
- δ_{BX} are the measured, and Monte Carlo checked, internal Borexino detector and DAQ time delays and offsets.

For the δ_{LNGS} and δ_{CERN} accurate hardware calibrations and data treatment see [15] for the full documentation.

Once all the involved delays are known, we can measure, event by event, the *Time of Flight*, that is ($BX_{real\ event\ time} - CERN_{real\ BCT\ time}$):

$$T_{tof} = Time_{diff} + \delta_{fiber} + \delta_{LNGS} - \delta_{BX} - \delta_{CERN} - \delta_{WaveForm} \quad (4)$$

To calculate the neutrino velocity, once the T_{tof} in (4) is calculated, we still have to know the BCT (CERN)- Borexino distance: before we get the dedicated surveyors measurement, we can use the known BCT (CERN)-OPERA distance, once we know the Borexino-OPERA distance and compare this final measured *Time of Flight* with the official one, 2439280.844 ns [4].

6 The extraction proton Wave Form in the 2011 BB period

As already mentioned, the poor knowledge of the transit time of the parent proton at CERN, due to the 10.5 μ s spread of the proton extraction time, forbids us to directly measure the neutrino T_{tof} ; this problem can be overcome, as done by OPERA (see [4]), with a statistical analysis of the proton wave forms compared to the "on - time events" time difference distribution.

To eliminate this uncertainty and to verify the used methodology had no intrinsic bias, soon after OPERA's claim in september 2011, CERN modified the SPS set up and provided a very short - one nanosecond - proton extraction; the price we pay for this very short spill is a reduced beam intensity, from $\approx 2.4 \cdot 10^{13}$ to $\approx 1.1 \cdot 10^{12}$ pot per extraction, as shown in figure 2 bottom-left.

This new Bunched Beam (BB) has a much lower proton starting time uncertainty: each extraction, only one per CNGS cycle, has 4 proton bunches, separated by 524 ns, each $\approx 1 - 2$ ns long; in this way there is no need of a proton BCT Wave Form statistical analysis but a direct, event by event, timing measurement is possible.

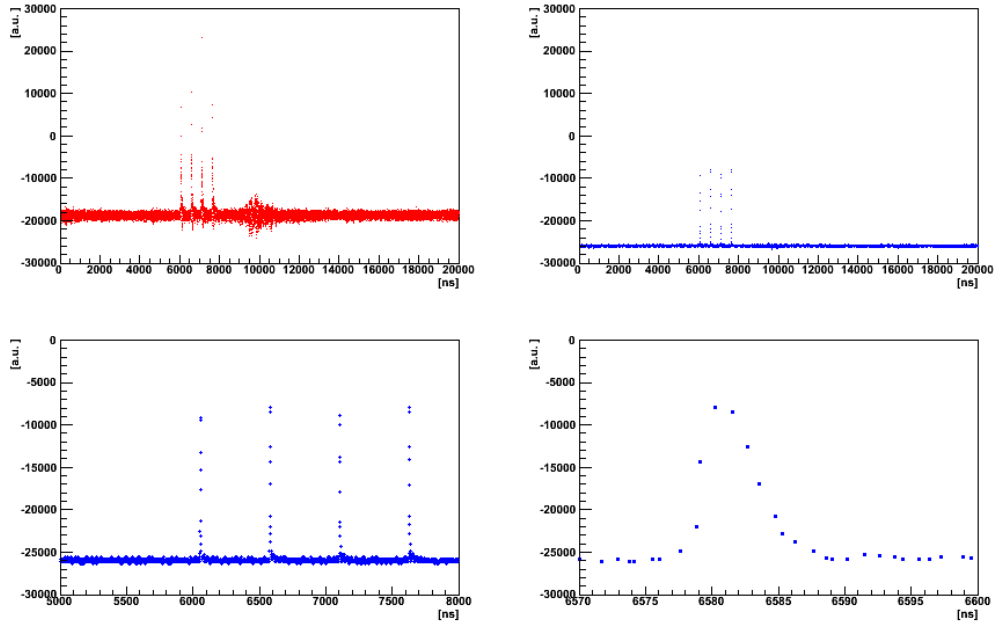


Figure 7: The Bunched Beam Wave Form time structure at the BCT: in the top left plot (red) one typical WF before run 16952; in the top right plot (blue) one typical WF after run 16952. The two bottom plots are blow ups of the top right plot. Note that the real Extraction length is much shorter, ≈ 1 nanosecond.

In figure 7 we show the Bunched Beam Wave Form at the BCT versus time: for runs before October 24 (run 16952) the Wave Form of the proton extraction shows (top left plot, in red) a different offset and a signal saturation; after this date the proton Wave Form shows a more clean structure (the three plots in blue, the last two ones being the blow up of the first one) even if the 4 bunch peaks can be easily defined also in the previous runs. In the bottom right plot we can see how the proton bunch width is really very narrow, even if widened by the detector: few nanoseconds, one in reality, providing a very good proton timing.

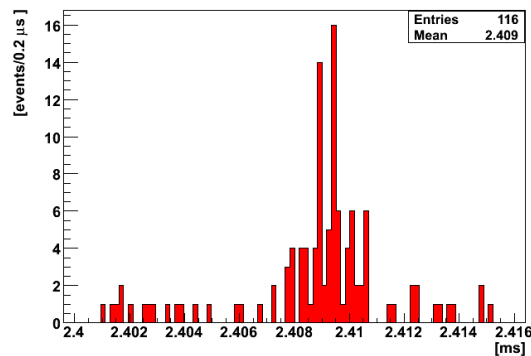


Figure 8: Recorded (Borexino - CERN) GPS time differences, as in eq. (1), for all 116 the row "on-time" events for the 2011 Bunched Beam.

As shown in table 3, in the 16 days of BB data taking, CERN delivered $7.43 \cdot 10^{-3}$ [pot], out of which $6.87 \cdot 10^{-3}$ were collected by Borexino, this small difference being almost entirely due to problems in the first night of beam, as can be seen in figure 6 bottom right.

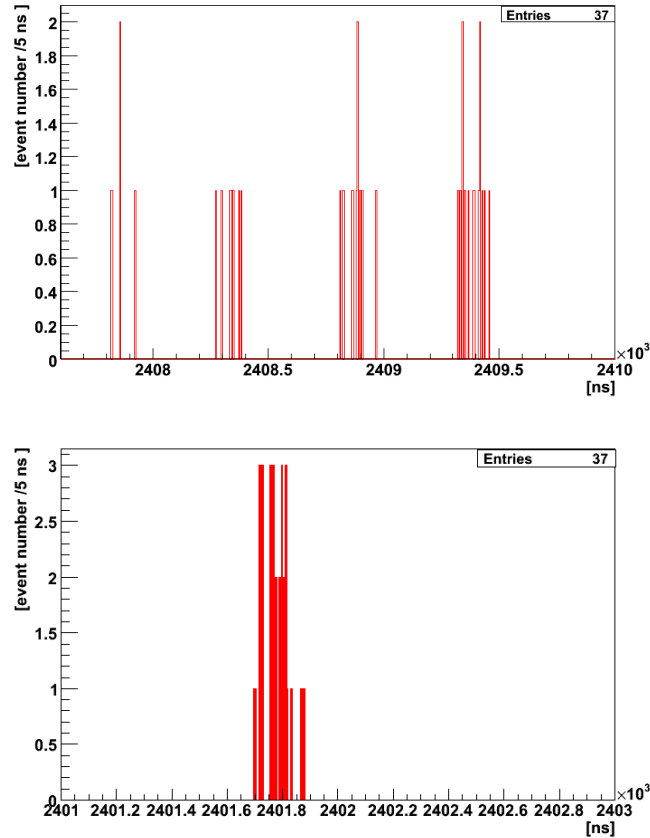


Figure 9: Recorded (Borexino - CERN) GPS time differences for the 37 selected (as explained in the text) "on - time" events, for the Bunched Beam. On top: the 4 proton bunch beam structure is clearly visible; on bottom: the same events as in the top plot but with the Wave Form timing subtracted.

Due to the lower beam intensity, a small number of events was expected, but thanks to the big Borexino volume (the total Water Tank surface perpendicular to the beam direction being $\approx 265.6 m^2$), we were able to collect a good sample of 116 "on-time events". In figure 8 we plot the $Time_{diff}$ values for these raw BB events as in figure 5 right we did for the Normal Beam events: the mean value is the same, while the new width is few tens of nanoseconds.

As stated before, to have a more clean "CNGS events" sample, we have to remove the ^{14}C events; besides we have to be sure that the Bunched Beam extraction info we have in the CERN Data Base (DB) refer to Extraction 1 (we remind here that we only have *ONE* Extraction per CNGS cycle in the Bunched Beam period) and that, for each event, we do have the relative proton extraction Wave Form information. Besides, we can separate the events going across the Water Tank *AND* the Stainless Steel Sphere ("trigger type 1" events) from those going only across the Water Tank ("trigger type 2" events). Since, in October 2011, we had a more accurate trigger timing for "trigger type 1" events, in this preliminary analysis we only consider these ones.

The $Time_{diff}$ for the 37 "surviving" "trigger type 1" "CNGS events" is plotted in figure 9 top, where the 4 bunch structure of the proton extraction is clearly visible.

If we subtract to each event the time delay of the relative proton bunch (524 ns apart from each other), we obtain the preliminary plot in figure 9 bottom. Note that to obtain the final T_{tof} value, we have to add all the needed corrections, as in equation (4): work is in progress and the final analysis will soon be published.

7 Conclusion and Acknowledgments

This note has been written to define some CNGS beam characteristics, and related terminology, and to summarize the Borexino CNGS event selection.

The Borexino neutrino velocity definition for the 2011 Bunched Beam is also provided; this measurement, simple and difficult at the same time, requires careful checks of all the needed numbers: work is in progress and the results will be published by the CNGS Working Group in the near future.

At the end of this adventure, the author would like to thank the CERN Data Base people, Chris Roderick, Daniel Dinis Teixeira and Dario Autiero, the beam expert Edda Gschwendtner and the "CERN timing experts", Pablo Alvarez Sanchez and Javier Serrano, for their very generous help in all these years.

References

- [1] <http://proj-cngs.web.cern.ch/proj-cngs/Publications/DescriptionGeneral.htm>
- [2] G. Acquistapace et al., CERN-98-02, INFN/AE-98/05; CERN-SI/99-034(DI), INFN/AE-99/05 Addendum (1998).
- [3] G. Bellini *et al.* [Borexino Collaboration], “*Muon and Cosmogenic Neutron Detection in Borexino*” JINST **6** (2011) P05005 [arXiv:1101.3101 [physics.ins-det]].
- [4] T. Adam *et al.* [OPERA Collaboration], “*Measurement of the neutrino velocity with the OPERA detector in the CNGS beam*” arXiv:1109.4897 [hep-ex].
- [5] A. Ferrari, A. Guglielmi and P.R. Sala, *CNGS neutrino beam: from CERN to Gran Sasso*, Nucl. Phys. **B 168** (2007) 169.
- [6] A. Ferrari, A. Guglielmi, M. Lorenzo-Sentis, S. Roesler, P.R. Sala and L. Sarchiapone, CERN-AB-Note-2006-038 (2006).
- [7] D. Autiero, *Update on the CNGS beam*, in Second CNGS-LNGS Meeting “Waiting for the beam”, 22 June 2006, (2006).
- [8] J. Serrano, P. Alvarez Sanchez, J. Lewis and D. Autiero, *Inter-laboratory synchronization for the CNGS project*, in 10th European Particle Accelerator Conference (EPAC 06), Edinburgh, Scotland, 26-30 June 2006, (2006).
- [9] P.Alvarez, D.Autiero, G. Di Carlo, C. Guerin, B.Ninet, L.Perasso, M. Selvi: *Measurements of the fibers delays for the GPS signal underground distribution LNGS* - July 20, 2006
- [10] P.Alvarez, J.Serrano: *Time transfer techniques for the synchronisation between CERN and LNGS* CERN BE-CO-HT Note, October 16, 2011
- [11] G. Alimonti et al., Borexino collaboration, *The Borexino detector at the Laboratori Nazionali del Gran Sasso*, Nucl. Inst. and Meth. **A 600** (2009) 568
- [12] L.Perasso: *Borexino, CTF and the CNGS neutrino beam* Borexino General Meeting - 7 july 2006
- [13] Pablo Alvarez: *CERN to LNGS time transfer calculations* CERN BE-CO-HT Note, february 22, 2012
- [14] Laura Perasso’s files with CERN DB CNGS event selected data
- [15] <http://www.ohwr.org/projects/cngs-time-transfer/wiki>