Neutrinos from CERN To Gran Sasso: The CNGS Project

Marcos Dracos
IPHC, Université de Strasbourg, CNRS/IN2P3, F-67037 Strasbourg, France
E-mail: marcos.dracos@ires.in2p3.fr

Abstract. The CNGS project (CERN Neutrinos to Gran Sasso) has been approved to make an unambiguous and direct observation of $\nu_{\mu} - \nu_{\tau}$ oscillations. An intense and relatively pure $\nu_{\mu}$ beam is generated at CERN and directed towards LNGS (Laboratori Nazionali del Gran Sasso) in Italy. Two experiments, OPERA already started in 2007 and ICARUS T600, will try to detect tau neutrinos using large and complex detectors. These “appearance” experiments will use the $\tau$ decay topology as signature of the presence of $\nu_{\tau}$ in the initial neutrino beam. An overview of the CNGS beam facility is given. Results from the first observed OPERA events and performances are presented. Few elements are given concerning the ICARUS T600 starting.

1. Introduction
Neutrino oscillations have proved that neutrinos have a non zero mass. Up to now, to prove that neutrinos oscillate, experiments have observed the disappearance of neutrinos from their production up to their detection. The CNGS project have been proposed to observe for the first time the appearance of $\nu_{\tau}$ in a $\nu_{\mu}$ beam and prove without ambiguity that the neutrino disappearance of one flavour eigenstate is due to the oscillation to another flavour eigenstate. This direct observation of neutrino oscillations will remove theoretical speculations about other possible mechanisms to explain the neutrino disappearance already observed by several experiments.

2. CNGS facility
For the CNGS facility [1, 2, 3], the neutrino beam is produced using a high intensity 400 GeV proton beam extracted from the CERN SPS accelerator. The protons collide with a graphite target producing mostly pions and kaons which decay through $\pi^{+(-)} \rightarrow \mu^{+(-)} + \nu_{\mu} (\bar{\nu}_{\mu})$ and $K^{+(-)} \rightarrow \mu^{+(-)} + \nu_{\mu} (\bar{\nu}_{\mu})$. The positively charged $\pi/K$ are guided using two focusing lenses (horn, reflector) in the direction towards Gran Sasso (Fig. 1). These mesons decay mainly into muon-neutrinos and muons in the 992 m long decay vacuum tube. The remaining particles are stopped by a hadron stop located at the end of the decay tunnel. Two muon detector stations are used to monitor the intensity and profile of the neutrino beam produced.

The graphite target has been designed to afford $7 \times 10^{13}$ 400 GeV protons per 6 s cycle. Two fast extractions of the beam are performed per cycle spaced by 50 ms and lasting 10.5 $\mu$s each. This pattern can be repeated several times in a super–cycle. Typically, 3 cycles are operated during a super–cycle of about 40 s.
The beam is strongly focused on the target ($\sigma = 0.5$ mm) and it is inclined by $3.4^\circ$ downwards in the direction of the LNGS. The target station contains a magazine equipped with 5 target units. Only one is used to produce the neutrino beam, the other four provide in-situ spares with the possibility to replace remotely the irradiated target in case of failure. Each target unit is made of 13 graphite rods (10 cm long, 5 mm diameter for the 2 first and 4 mm for the remaining 11).

Downstream of the target station, a hadron collection system has been installed to direct the extracted mesons from the target towards LNGS. This magnetic focusing system consists of 2 magnetic horns (the second horn is called reflector), pulsed during each proton beam extraction with a current of 150 kA for the fist horn and 180 kA for the second one.

Fig. 2 shows the obtained neutrino energy spectrum. On the same figure, the oscillation probability multiplied by the charged current $\nu_\tau$ cross section is also depicted. The two distributions have their maximum more or less at the same position showing the good beam optimization for $\nu_\tau$ appearance experiments. The mean neutrino energy is of the order of 17 GeV while the distance between CERN and LNGS is 732 km leading to an oscillation parameter $L/E$ of the order of 43. The produced $\nu_\mu$ beam contains a fraction of $\nu_e$’s and $\bar{\nu}_\mu$’s producing a charged current event contamination at the level of the experiment of the order of 0.8% and 2.0% respectively.

CNGS commissioning has been done in 2006 where $8.5 \times 10^{17}$ protons have been sent on the target (p.o.t.) before experiencing a water leak problem on the second horn and few other minor problems. Repairing has been performed during the 2006 winter shutdown. In 2007, after a 6 weeks run ($7.9 \times 10^{17}$ p.o.t.), a failure of ventilation system installed in the target area has been observed due to radiation effects in the control electronics of this system. Due to this problem, the beam has been stopped and extra radiation shielding has been installed in order to protect more efficiently the related electronics. This run has allowed OPERA experiment to observe the first neutrino interaction in lead/emulsion bricks in Gran Sasso.

In 2008, a full run has been performed with $1.78 \times 10^{19}$ p.o.t. to be compared to the optimal value of $4.5 \times 10^{19}$ p.o.t. The low integrated efficiency of the neutrino facility is mainly due to frequent failures of the relatively old CERN accelerator complex. During this run,
about $2 \times 10^{13}$ p.o.t. were routinely obtained per fast extraction close to the nominal one of $2.4 \times 10^{13}$ p.o.t.

3. OPERA experiment

The aim of OPERA experiment [4] is to observe $\nu_\tau$ appearance in the CNGS $\nu_\mu$ using nuclear emulsions providing the necessary granularity for this delicate detection. The detector, located in Hall C of the LNGS underground laboratory, is divided into two identical parts called super-modules (Fig. 3). Each super-module is composed by a target and a spectrometer. The target has 31 lead/emulsion brick walls, giving a total mass of 0.64 kton, interleaved with 31 electronic Target Tracker walls. The Target Tracker walls are made of horizontal and vertical scintillating strips and their main role is to find the right bricks to extract where the neutrino interactions occur. They also provide calorimetric information about the overall deposited energy in the OPERA detector.

Each super-module’s spectrometer consists of a dipolar magnet in which 22 RPC layers are installed. Inside and outside of the two magnet arms, 4 layers of drift tubes (HPT) are installed to measure precisely the charged tracks bending produced by the spectrometers magnetic field. One layer of crossed strip RPC’s, called XPC’s, is placed just after the last Target Tracker wall of each super-module. A VETO detector composed of two layers of glass RPC’s is installed in front of the OPERA detector to reject muons (and cosmic tracks) produced mainly in the rock in front of the experiment by CNGS neutrino interactions. A detailed description of the detector can be found in [5].

![Figure 3](https://example.com/figure3.png)

**Figure 3.** Schematic view of the OPERA detector.

![Figure 4](https://example.com/figure4.png)

**Figure 4.** OPERA detection technique using layers of lead (target) and nuclear emulsions (detector).

To reconstruct the $\nu_\tau$ interactions and especially the produced $\tau$ decay kink which is the signature of this kind of events (Fig. 4), a micro-metric accuracy is needed ($\tau$ path of the order of 1 mm). The solution chosen for this purpose, able to cover large surface and volume providing the needed accuracy in a cost effective way, is the utilization of nuclear emulsions. DONUT experiment [6] has already demonstrated that the concept of stacking emulsion films with interleaved metallic plates called Emulsion Cloud Chamber (ECC), is able to detect $\nu_\tau$ interactions by observing the resulting $\tau$ decays. The OPERA ECC consists of 57 emulsion sheets 300 microns thick each and 56 lead sheets of 1 mm thickness. The surface covered by each brick is $128 \times 102$ mm$^2$ with a total thickness of 79 mm and a weight of about 8 kg. The nuclear
emulsion sheets used in OPERA are made of a transparent plastic base film for mechanical support (200 µm thick) on which are deposited two 44 µm thick layers of photosensitive gel. The intrinsic emulsion coordinate resolution is 0.2 µm.

A similar topology to τ decays is produced by the decay of charmed mesons, having comparable lifetime. This background is mainly reduced by rejecting events containing “wrong” sign muons (muons coming directly from νµ interactions or τ− decays are negatively charged while those coming from charmed meson decays have a positive charge). Another way to remove this kind of events is to reject all events where a muon is found to belong to the primary vertex.

3.1. Brick processing

After the electronic detectors have indicated the candidate brick to contain a neutrino interaction, this brick is extracted from the detector by an automatic system. This system runs permanently during and after the data taking periods. The extracted bricks are not replaced leading to a total decrease of the target mass of about 15% after 5 years of data taking.

On each brick, a changeable sheet doublet (CSD) of emulsions, placed in a box attached to its downstream face, is scanned to confirm the electronic detectors prediction before opening the brick itself. If at least one track is found in the CSD, then the brick is disassembled and sent for further processing, otherwise it is equipped with a new CSD and returned back to the detector. Processing includes the deposition of fiducial marks on the emulsions by X-ray exposure, 12 hours exposure to cosmic muons (outside the underground laboratory) in order to improve the film to film alignment, development of the emulsions and scanning using optical high–magnification microscope systems.

The development of automated emulsion scanning systems during the last years allows now a scanning of about 20 cm²/hour of emulsion surface in fully automated mode. 25 scanning tables are devoted to this scanning in Europe while 5 other high speed tables scanning with a speed higher than 50 cm²/hour are used in Japan.

After a scan–back of tracks found in the CSD has been performed and a candidate primary vertex has been found, a volume scan around this position is performed in order to find all attached tracks and secondary vertices. After this stage, a particle identification, electromagnetic shower reconstruction and measurement of particle momentum using the Coulomb multiple scattering can be done. Combining the scanning and electronic detectors information, a decision about the nature of the observed interaction is then made.

Fig. 5 presents a charged current event detected during the short run of 2007. The left part shows a top view of the event recorded by the electronic detectors while the right part presents the region around the neutrino interaction point as reconstructed in the associated lead/emulsion brick. On this part of the figure, a decay kink is very well seen (red track) very probably produced by the decay of a charged charm meson (this particle left a visible short track in the emulsion layers before decaying). A muon attached to the primary vertex has been found proving well that this interaction has been produced by a νµ and thus excluding a ντ interaction and τ decay. A clear electromagnetic shower is also seen on this figure showing the ability of detecting this kind of topologies using the emulsion technique.

3.2. OPERA running

During the short 2007 CNGS run, OPERA collected 38 neutrino interactions while during the 2008 run 1700 interactions have been observed [7]. Up to July 2009, about 1000 bricks have been scanned from the 2008 run where no ντ candidates have been found, while the expected number of candidates for the whole collected events is 0.6. Already, 10 “charm” candidate events have been found showing well that the OPERA detector is able to detect this kind of topologies. Some delay observed concerning the brick scanning is mainly due to the earthquake which occurred last April in the L’Aquila region causing the LNGS closure for more than a month.
Figure 5. A candidate charm event as seen by the electronic detectors (left) and the nuclear emulsions (right). The red track is produced by a short lifetime particle supposed to be a charged charm meson.

For the 2009 run already started beginning of June, $3.2 \times 10^{19}$ p.o.t. are expected to be delivered to CNGS corresponding to about 3000 events observed by OPERA. This value is by 30% lower than the nominal one and will oblige the collaboration to run more than 5 years (duration initially expected) in order to accumulate the necessary statistics corresponding to $22.5\times 10^{19}$ p.o.t. that would allow to extract statistically significant results. For $22.5\times 10^{19}$ p.o.t. and $\Delta m_{13}^2 = 2.5 \times 10^{-3}$ eV$^2$, OPERA expects to observe 10.4 $\nu_\tau$ interactions ($2.9 \tau \rightarrow \mu$, $3.5 \tau \rightarrow e$ and $4 \tau \rightarrow \text{hadrons}$) with less than one background event.

4. ICARUS T600

ICARUS T600 [8] is a large cryostat divided in two identical, adjacent half-modules of internal dimensions $3.6 \times 3.9 \times 19.9$ m$^3$, each containing 300 t of liquid argon (LAr). It was initially designed to be the first part of a larger detector.

Each half–module is composed by two Time Projection Chambers (TPC), the field shaping system, monitors, probes and PMTs. They are externally surrounded by a set of thermal insulation layers (Fig. 6 and 7). Each TPC is formed by three parallel planes of wires, spaced by 3 mm, oriented at $0, \pm 60^\circ$ angles. The parallel wires pitch is 3 mm, and their role is to detect the ionization electrons produced inside the liquid argon volume. The cathode plane is parallel and equidistant to the wire planes in each TPC. A high voltage system produces a uniform electric field, perpendicular to the wire planes, forcing the drift of the ionization electrons (the maximum drift path is 1.5 m).

The installation of ICARUS T600 is now near to completion in the LNGS underground laboratory in Hall B. The detector, the cryogenic plant and the data acquisition are almost ready. The underground laboratory infrastructures, required for the detector filling, have been completed and the T600 start-up procedures, logistics and authorizations have been almost defined. It is expected that the filling of the detector with 600 tons of liquid Argon should be done before the end of the current CNGS run allowing the experiment to detect the first CNGS neutrinos.

With its fiducial mass of 480 t liquid argon, ICARUS T600 is expected to observe about 1200 $\nu_\mu$ and 7 $\nu_e$ charged current interactions per year for $4.5 \times 10^{19}$ p.o.t. For 5 years data taking, $7 \pm 2.6 \tau \rightarrow e$ events are expected to be observed out of the background in a statistical way.

This detector operation will be a significant achievement opening the way to the utilization
5. Conclusions

CNGS neutrino facility operates now in stable conditions providing in 2008 $1.8 \times 10^{19}$ p.o.t. while $3.2 \times 10^{19}$ p.o.t. are expected in 2009. It has to be recalled that the nominal number of protons on the target is $4.5 \times 10^{19}$/year, significantly higher than what was delivered up to now.

OPERA experiment runs now in optimal conditions and has recorded 1700 neutrino interactions during the 2008 run. The collaboration has already scanned 1000 lead/emulsion bricks allowing to observe 10 “charm” candidate events having a similar topology to the $\nu_\tau$ interactions. While no $\nu_\tau$ events have been yet detected, the charm events observation proves well that the chosen detection technique is able to detect this kind of event topologies. For 2009, 3000 neutrino interactions are expected to be observed.

ICARUS T600 detector is now almost ready to be filled with liquid argon that will allow to observe soon the first CNGS neutrinos.

References

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