ICARUS: a new challenge within the Fermilab Short Baseline Neutrino Program

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on behalf of the ICARUS collaboration

New Trends in High-Energy Physics

Odessa
May 12-18, 2019
• ICARUS-T600 at LNGS: *a very successful run*
• Sterile neutrinos and the SBN project
• ICARUS upgrade: *from underground up to the surface*
• Installation and commissioning at FNAL
The ICARUS collaboration

O(100) scientists

Catania (INFN and Univ.)
  GSSI
  LNGS
INFN Milano Bicocca
INFN Napoli
Padova (INFN and Univ.)
Pavia (INFN and Univ.)

Spokesman: C. Rubbia (GSSI)

Brookhaven (BNL)
Colorado State
FNAL
Houston
Pittsburgh
Rochester
SLAC
Texas (Arlington)
Southern Methodist Univ.

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Liquid Argon TPC: an “electronic bubble chamber”

- First proposed by C. Rubbia in 1977: long R&D at INFN and CERN culminated in first large-scale experiment: ICARUS-T600 at LNGS (2010)

- LAr TPCs are suitable detectors for neutrino physics:
  - 3D reconstruction with high (mm\(^3\)) spatial granularity
  - Homogeneous, full-sampling calorimetry for contained particles
  - Scintillation light $\rightarrow$ fast signals for timing/triggering
  - Electrons can drift for several meters $\rightarrow$ very large detectors (ktons)

- LAr physical parameters very similar to Freon of “classic” bubble chambers:

<table>
<thead>
<tr>
<th>FREON:</th>
<th>LIQUID ARGON:</th>
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<tbody>
<tr>
<td>Density</td>
<td>Density</td>
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<tr>
<td>1.5 g/cm(^3)</td>
<td>1.4 g/cm(^3)</td>
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<tr>
<td>Radiation length</td>
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<tr>
<td>11.0 cm</td>
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ICARUS-T600 at LNGS

- 2 identical modules: each is 19.6x3.6x3.9 m³, with total active mass of 760 t
- Drift distance 1.5 m and electric field 500 V/cm → drift time ~ 1 ms
- 3 signal wire planes with “non-destructive” readout for a total of ~ 54000 channels
- Pitch and inter-plane distance both 3 mm; 400 ns sampling time
- 74 (20+54) 8” PMTs with TPB wavelength-shifter coating

ICARUS was exposed to CNGS beam and cosmics for 3 years (2010-2013)
Run confirmed expected performance and obtained important physics results
It proved the maturity of the LAr-TPC technique for large-scale experiments

ICARUS paved the way to the next generation long-baseline project: DUNE
ICARUS reconstruction performances

- High electron lifetime: > 7 ms (impurity concentration < 40 ppt)
  Crucial step towards future larger detectors
  *2014 JINST 9 P12006*

- Excellent spatial/calorimetric reconstruction.
  Accurate dE/dx measurement with fine sampling (0.02X₀).
  Particle ID from dE/dx vs. range
  *AHEP (2013) 260820*

- Momentum of escaping muons can be measured by multiple Coulomb scattering. Average ~ 15% resolution on stopping muons (0.5 ÷ 5 GeV/c)
  *JINST 12P04010*
High-energy CNGS $\nu_e$ CC interaction:

- $\nu_e$ CC event (electron-initiated EM showers) separation from NC background with $\pi^0$ ($\gamma$-initiated showers) is crucial for oscillation physics.
- LAr-TPC provides 3 handles:
  - Visual identification of $\gamma$ conversion gap
  - Reconstruction of $\pi^0$ invariant mass
  - $dE/dx$ measuring on each wire allows calorimetric accuracy with fine sampling (2% $X_0$)
ICARUS search for sterile neutrinos

- ICARUS searched for sterile $\nu$ oscillations through $\nu_e$ appearance in the CNGS beam
- L/E $\sim$ 36 km/GeV, far from LSND value $\sim$ 1 km/GeV → “sterile-like” oscillation was averaged out, canceling energy dependence
- 7.9 $10^{19}$ pots analyzed ($\sim 2650 \nu$ interactions)
- Expected $\sim 8.5 \pm 1.1$ $\nu_e$ background events in absence of anomaly, mostly from intrinsic $\nu_e$ beam contamination
- Estimated $\nu_e$ identification efficiency $\sim 74\%$ with negligible background from misidentification
- 7 events observed → no evidence of oscillation
- Most of LSND allowed region is excluded - except for small area around $\sin^2 2\theta \sim 0.005$, $\Delta m^2 < 1 \text{ eV}^2$
- Similar result by OPERA with same CNGS beam and different detection technique

Perspectives for sterile neutrino physics

- The sterile neutrino scenario is far from understood and needs a definitive clarification.
- Some “anomalies” from accelerators (LSND), reactor, neutrino sources, point out to flavour transitions in the $\Delta m^2 \sim 1 \text{ eV}^2$ range.
- However, no evidence of oscillations in $\nu_\mu$ disappearance data (MINOS, IceCube).
- Tension between appearance and $\nu_\mu$ disappearance results. Measuring both channels with the same experiment will help disentangle the physics scenario.
- A comparison between far/near detector is crucial for any accelerator experiment, with a better control of backgrounds and systematics.

SBN satisfies these requirements: it could have a crucial role in solving the sterile neutrino puzzle!
The SBN project

$L/E_\nu \sim 600 \text{ m} / 700 \text{ MeV} \sim \theta(1 \text{ m/MeV})$

T600 also off-axis on NUMI beam: Asset for DUNE

NUMI beam (approximate)
The experiment will exploit 3 LAr-TPCs exposed to the FNAL Booster Neutrino Beam, (only ~ 0.5\% $\nu_e$ contamination) at different distances from target: SBND, MicroBooNE and ICARUS at 110, 470, and 600 meters respectively.

The experiment is expected to clarify the sterile anomaly by precisely/independently measuring both $\nu_e$ appearance and $\nu_\mu$ disappearance.

Using the same detector technology for all the 3 detectors will greatly reduce the systematic errors: SBND (near detector) will provide the “initial” beam composition and spectrum.

The great $\nu_e$ identification capability of LAr-TPC will help reduce the NC background.

During SBN operations, ICARUS will also collect ~ 2 GeV neutrinos from NuMI (Neutrino Main Injector) Off-Axis beam. This will be an asset for the future long-baseline project:

- $\nu$ interaction cross-section measurements and identification/reconstruction studies
- In particular, a large $\nu_e$ component with ~ 3 GeV energy (in the DUNE range)
$\nu_e$ appearance sensitivity for 3 yr (6.6 $10^{20}$ pot) at BNB

LSND 99%CL region will be covered at $\sim 5\sigma$ level

Exploiting high rates and detector correlations, $\nu_\mu$ disappearance sensitivity will be extended by one order of magnitude beyond present limit in 3 yr
The new experimental challenge: a LAr-TPC on surface

- ICARUS will take data at shallow depth (only 3 m concrete overburden)
- ~11 muon tracks will hit each ICARUS module in the ~1 ms drift window and be randomly overlapped to the beam neutrino interaction

**Cosmic rays from T600 surface test run + low energy CNGS beam events**

- Cosmic-related photons can mimic $\nu_e$ interactions (via Compton or asymmetric pair production) and result in significant background
- They can be mitigated by unambiguously identifying the timing of each (cosmic and beam) ionizing event occurring during the $O(1)$ ms TPC drift window
- This requires signals on a faster time scale than the TPC including:
  - improved LAr scintillation light detection system
  - Cosmic Ray Tagger (CRT) surrounding the detector
To face the new experimental conditions at FNAL (shallow depth, higher beam rate), T600 underwent intensive overhauling at CERN, before shipping to US.

Overhauling took place in the CERN Neutrino Platform framework (WA104) from 2015 to 2017.

Several technology developments were introduced while maintaining the already achieved performance:

- new cold vessels, with a purely passive insulation;
- renovated LAr cryogenics/purification equipment;
- improvement of the cathode planarity
- new faster, higher-performance read-out electronics;
- upgrade of the PMT system: higher granularity and ns time resolution
Upgrade of the light collection system

In shallow depth operation, the light collection system will allow to:

- Precisely identify the time of occurrence \( (t_0) \) of any ionizing event in the TPC
- Determine the event rough topology for selection purposes
- Generate a trigger signal for read-out

**ICARUS@SBN** uses 90 8" PMTs per TPC (5% coverage, 15 phe/MeV) that provides:

- Sensitivity to low energy events (~ 100 MeV)
- Good spatial resolution (≤ 50 cm)
- ≈ ns timing resolution
- Possible cosmics identification by PMT space/time pattern

![Graph showing gain vs. power supply voltage](graph.png)

The gain reduction in LAr w.r.t. room temperature (up to a factor 10) will be compensated by a ~ 100 V increase in power supply voltage.
Upgrade of the TPC read-out electronics

ICARUS electronics at LNGS was based on:

- “warm” low-noise front-end amplifier
- Multiplexed 10-bit ADC
- Digital VME module for local storage, data compression, trigger information

However, in view of the SBN program, some components were modernized and improved:

- Serial 12-bit ADC, fully synchronous in the whole detector → ~20% improvement in muon momentum resolution via MCS
- Serial bus architecture increases transmission rate to Gbit/s
- More compact layout: both analog+digital electronics hosted on a single flange

Volume 60 times smaller

New electronics extensively tested on a 50-liter TPC@CERN

JINST 13 (2018) P12007

Digital crate + analog crate (~600 liters)

10 liters mini-crate hosts 9 boards (576 channels)
ICARUS installation at FNAL

- T600 installed inside warm vessel in August 2018
- Installation of TPC/PMT feedthrough flanges and connectivity tests, completed by February 2019
- Leak tightness tests completed
- Top cold shields and top CRT support installed

Feed-throughs installed on top

- PMT electronics and trigger being tested at cryogenic temperatures at CERN
- Installation of proximity cryogenics started in February
- Side CRT installation also ongoing
- Director’s Review in December 2018 recognized the great progress of SBN
The successful readout test confirms the good performance of the full TPC electronics!
The Cosmic Ray Tagging system (CRT)

- Surrounds the cryostat with two layers of plastic scintillators: 1100 m²
- Tags incident cosmic or beam-induced muons with high efficiency (95%) giving spatial and timing coordinates of the track entry point
- Reconstructed CRT hits are matched to activity in the LAr volume
- Few ns time resolution allows measuring direction of incoming/outgoing particle propagation via time of flight

**TOP**
~ 400 m²: roof+angled parts
Will catch ~80% cosmic ms
SiPM readout

**SIDES**
~ 500 m² on four sides
SiPM readout

**BOTTOM**
~ 200 m², already installed
2 parallel layers
PMT readout
Reconstruction and analysis in SBN

- A detailed understanding of detector-related systematics and their correlation across near/far detectors will be crucial to SBN physics.

- Common reconstruction tools and oscillation analysis are therefore fundamental.

- ICARUS joined the LArSoft framework: mutual sharing of algorithms and tools and cross-check between different reconstruction approaches.

angle between sim/reco direction for EM showers

electron lifetime (reco vs. sim)

θ=2°, θ=6°

3D reco of stopping muon

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<tr>
<td>Integral</td>
<td>8275</td>
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</table>

raw (LNGS) hit-finding
deconvolution hit-finding
ICARUS transportation (from CERN to FNAL)

leaving from CERN, June 12\textsuperscript{th} 2017

arriving at SBN Far site building at FermiLab, July 26\textsuperscript{th} 2017

Antwerp: unloading from barge from Basel and loading into ship to Burns Harbor (Indiana)

SBN far site building at FermiLab
Chymney installation (October 2018)
Positioning the readout system (May 2019)

Readout electronics

Power supply
ICARUS at FNAL – plans and commissioning

- TPC/trigger electronics installation to be completed and tested by spring 2019
- PMT electronics installation also to be completed during the spring
- ICARUS expected to be ready to fill at the end of July 2019
- After cryogenics commissioning, cooldown and filling, ICARUS T600 should be operational during the last quarter of 2019
- Commissioning of CRT, DAQ, trigger and slow controls will follow
- Data-taking for physics is expected by the end of this year
Conclusions

- The ICARUS-T600 successful 3-year run at LNGS proved that LAr-TPC technology is mature and ready for large-scale neutrino physics experiments.

- ICARUS searched for LSND-like anomaly via $\nu_e$ appearance in the CNGS beam. The negative result constrained significantly the allowed parameter region.

- The SBN project at FNAL is expected to clarify the sterile neutrino puzzle, by looking at both appearance and disappearance channels with three LAr-TPCs.

- After an extensive refurbishing, ICARUS is being installed as the SBN far detector at FNAL. Data taking expected in 2019, near detector in 2021.

- ICARUS will see first neutrinos by the end of this year!
Спасибі
Backup slides
ICARUS at LNGS was also exposed to atmospheric neutrinos (exposure ~0.74 kt year)
first observation of atmospheric neutrinos with a LAr-TPC
14 events found (8 $\nu_e$ CC + 6 $\nu_\mu$ CC) vs. 18 expected (taking into account: triggering,
filtering and scanning efficiencies)
Very good benchmark for the forthcoming SBN experiment: similar energy/features. Useful
to develop filtering and reconstruction tools
$\nu_e$ spectra (oscillation signal + backgrounds) for 3 years ($6.6 \times 10^{20}$ pot)

In absence of oscillations, spectra should be $\sim$identical

Example for $\sin^2 2\theta = 0.013$
$\Delta m^2 = 0.43$ eV$^2$

$\nu_\mu$ spectra (oscillation modulation) for 3 years ($6.6 \times 10^{20}$ pot)

Example for $\sin^2 2\theta = 0.01$
$\Delta m^2 = 1.10$ eV$^2$

In absence of oscillations, spectra should be $\sim$ identical
Upgrade of the light collection system

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Timing/gain equalization will be performed with laser pulses
\( \lambda = 405 \text{ nm} \)
FWHM < 100 ps
peak power ~ 400 mW
PMT tests at CERN

- All PMTs tested at room temperature in a dedicated dark room at CERN
- A subset of 60 PMTs tested immersed in LAr to compare the PMT performance in cryogenic environment to room temperature
- All PMTs illuminated with laser light pulses

PMTs were characterized individually at 300K and 87K:
- Gain
- Dark count rate
- Peak/valley ratio
- Uniformity of photocathode response

The gain reduction in LAr w.r.t. room temperature (up to a factor 10) will be compensated by a ~ 100 V increase in power supply voltage

JINST 13 (2018) P10030
The analog front-end shaping was also modified:

- Lower noise ~ 1200 e- equivalent (~20% S/N improvement w.r.t. LNGS electronics)
- Shorter shaping time (~ 1.5 μs for all planes) matching electron transit time between planes
- Drastic reduction of undershoot after large signals: better description of crowded vertex region

*Tests on 50-liter TPC at CERN:

In particular, Induction 2 signal keeps bipolar shape (unlike in old front-end)

- Possible off-line integration with suitable LF filtering
- Allows calorimetric measurement in this plane too (with ~2 worse resolution than Collection)
- May improve $\nu_e$ identification efficiency by ~ 20%
ICARUS simulation and reconstruction

- LNGS experience will be fundamental for SBN analysis
- However, different experimental conditions:
  - Much larger event statistics
  - Overlap of cosmics on $\nu$ events
  - Rich information from light and CRT
- Full simulation performed with realistic geometry and signals from all subdetectors (TPC,PMT,CRT)
- Signal/noise modelization uses information from LNGS and small prototypes at CERN

PMT vs. TPC information

- $\nu_\mu$ CC interaction with $\sim 1.4$ GeV deposited energy
- 49 PMTs have visible signal (over 10 phe)
- Fired PMTs extend over $\sim 8m$
CERN Neutrino to Gran Sasso beam

L/E = 730/20 ~ 36 km/GeV
CNGS beam spectrum
Neutrino interactions

Neutral Current

Charged Current
Origin of Matter  Could neutrinos be the reason that the universe is made of matter rather than antimatter? By exploring the phenomenon of neutrino oscillations, DUNE seeks to revolutionize our understanding of neutrinos and their role in the universe.

Unification of Forces With the world’s largest cryogenic particle detector located deep underground, DUNE can search for signs of proton decay. This could reveal a relation between the stability of matter and the Grand Unification of forces, moving us closer to realizing Einstein’s dream.

Black Hole Formation  DUNE’s observation of thousands of neutrinos from a core-collapse supernova in the Milky Way would allow us to peer inside a newly-formed neutron star and potentially witness the birth of a black hole.
TPC = Time Projection Chamber
ICARUS-T600: LAr TPC working principle

- 3 wire planes with 0°, +60°, -60° orientation w.r.t. horizontal; both pitch between wires and distance between planes are 3 mm
- Wire biasing guarantees (almost complete) plane transparency, and non-destructive readout in both Induction wire planes
- Last plane collects charge, allowing measurement of deposited energy
- ~ 54000 total readout wires, with 400 ns sampling time

Typical signal in collection (last) plan