R&D on LAr single phase TPC at CERN

ICARUS-WA104 Collaboration

S. Centro

CERN 13.01.2015

The need for a continuing neutrino program

- The recent success of ICARUS-CNGS2 experiment has conclusively demonstrated that LAr-TPC is *the leading technology for future short/long baseline accelerator driven neutrino physics.*

- INFN has signed an MoU for WA104 activity in CERN and just concluded an important cooperation agreement for a SBN experiment in the framework of a US-LBNF collaboration, involving the long term realization of a truly large mass, LAr-TPC detector.

- *The direct and continued access to a neutrino beam (FNAL) is necessary* to maintain the appropriate levels in R&D and participation in physics developments *within a "learning" process based on real events and cross sections.*

Next neutrino activities

- ICARUS has been moved to CERN late 2014 for overhauling. Technology developments *while maintaining the already achieved basic features of T600* will introduce important new features.

- ICARUS will then be operated (*at SNB @ FNAL, provided the proposal submitted these days to PAC will be approved*) collecting a large event sample ($\geq 10^6$) on short baseline with appropriate energy for the future LBNF exp.

- In addition to a *definitive clarification of sterile neutrino*, the R&D program in LAr may pave the way to ultimate realization of the LNBF detector for instance with:
  - An accurate determination of cross sections in Argon;
  - The experimental study of all individual CC and NC channels;
  - The realization of sophisticated algorithms capable of the most effective identification of the events.

T600 run at LNGS: first publications

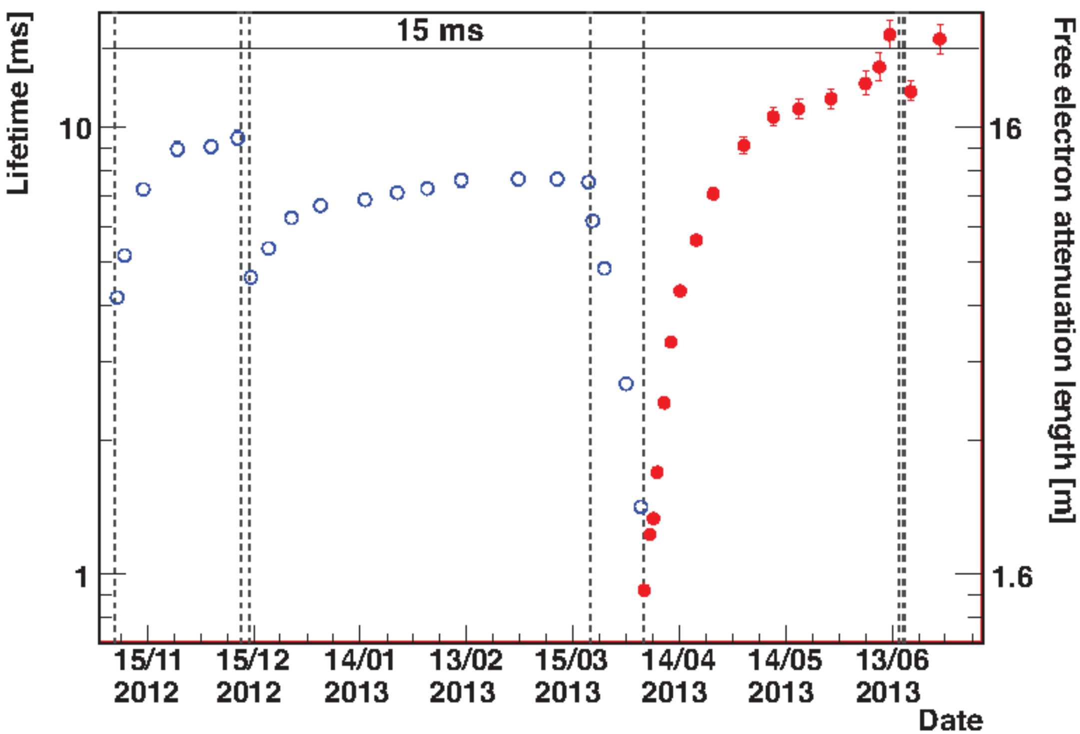
1. "Underground operation of the ICARUS T600 LAr-TPC: first results", JINST **6** (2011) P07011.
2. "A search for the analogue to Cherenkov radiation by high energy neutrinos at superluminal speeds in ICARUS", PLB 711 (2012) 270.
3. "Measurement of neutrino velocity with the ICARUS detector at the CNGS beam", PLB 713 (2012) 17.
4. "Precision measurement of the neutrino velocity with the ICARUS detector in the CNGS beam", JHEP 11 (2012) 049.
5. "Precise 3D Reconstruction Algorithm for the ICARUS T600 Liquid Argon Time Projection Chamber Detector", AHEP 2013 (2013) 260820.
6. "Experimental search for the LSND anomaly with the ICARUS detector in the CNGS neutrino beam", EPJ C73 (2013) 2345.
7. "Search for anomalies in ν_e appearance from ν_μ beam", EPJ C 73.2599 (2013).
8. "The trigger system of the ICARUS experiment for CNGS beam", JINST 9, P08003 (2014)
9. "Experimental observation of an extremely high electron lifetime with ICARUS-T600 Lae-TPC", JINST 9. P12006 (2014)8

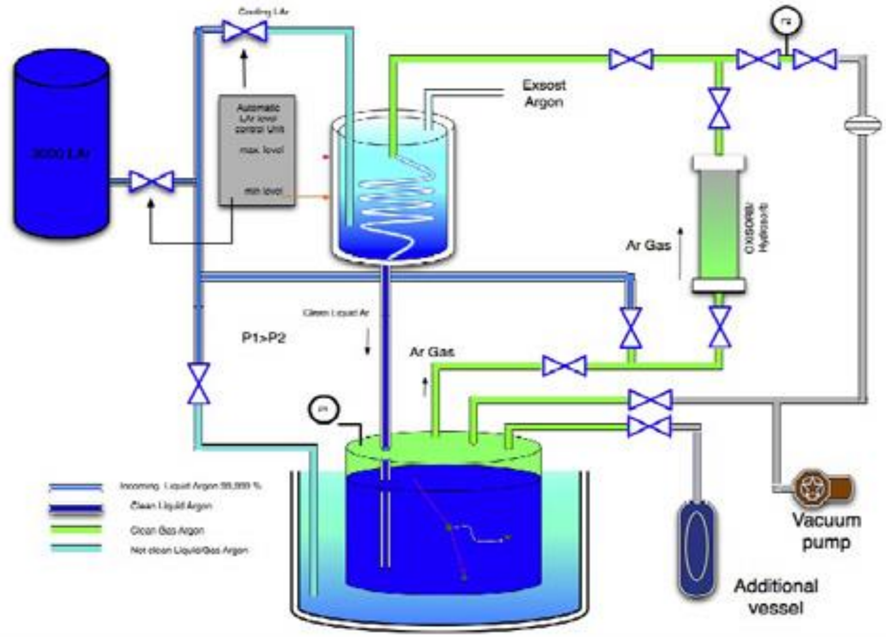
Analysis of the large amount of physics data becoming progressively the main activity of the CNGS2 collaboration

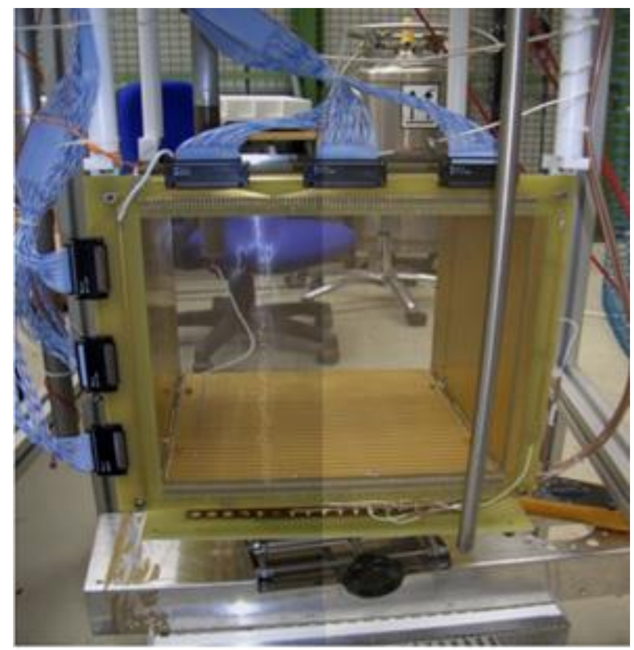
New purity achievements

- LBNF requires: τ_{ele}>12 ms and E_{drift} = 0.5kV/cm for 15% attenuation at 3.0 m,
- The result in Icarino is τ_{ele} ≈21 ms corresponding to ≈15 ppt, namely a ≈10^{-11} molecular Oxygen eq. impurity.

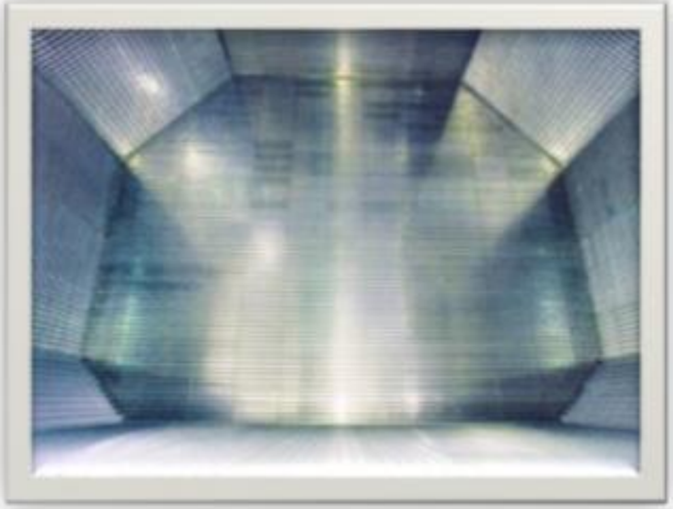
T600

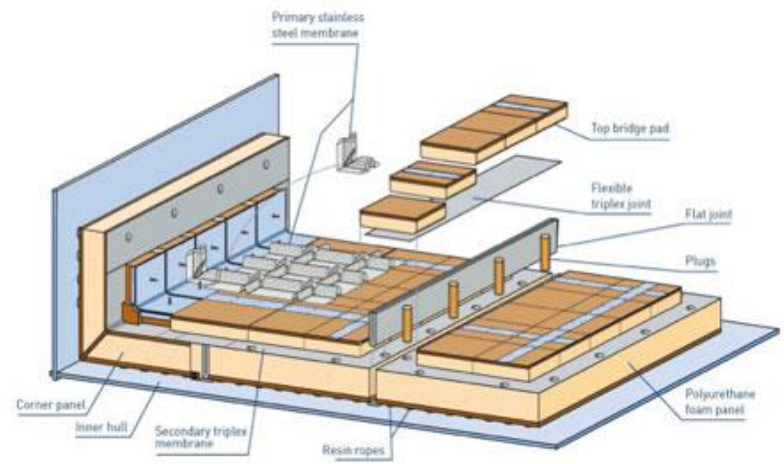






R&D-3: New Thermal Insulation





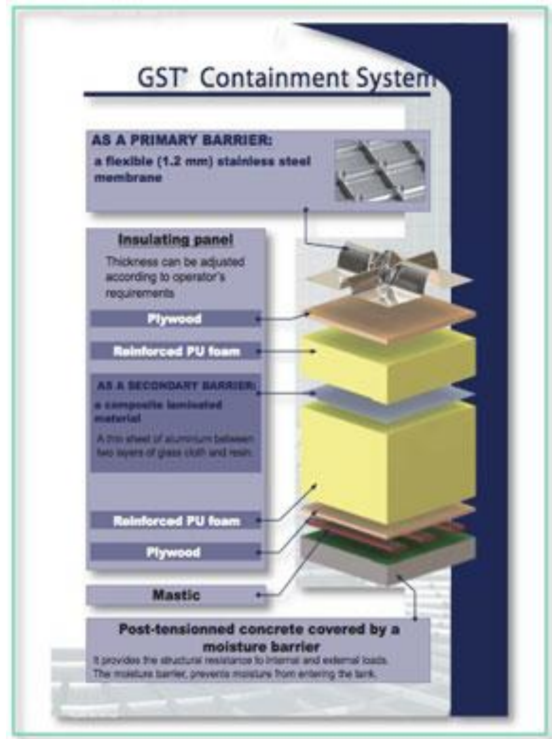
Purely passive insulation chosen for the installation at CERN, coupled to our standard cooling shield with boiling Nitrogen.

Technique developed for 50 years and widely used for large industrial storage vessels and ships for liquefied natural gas.

Expected heat loss through the insulation: T600 ≈ 6.6 kW

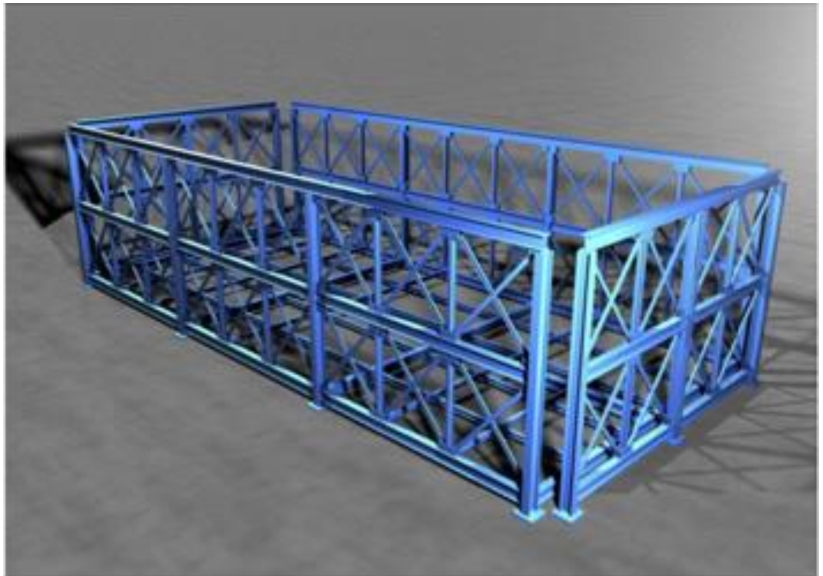
Preliminary design appointed to GTT in Jan 2013

No internal membrane is required for our case

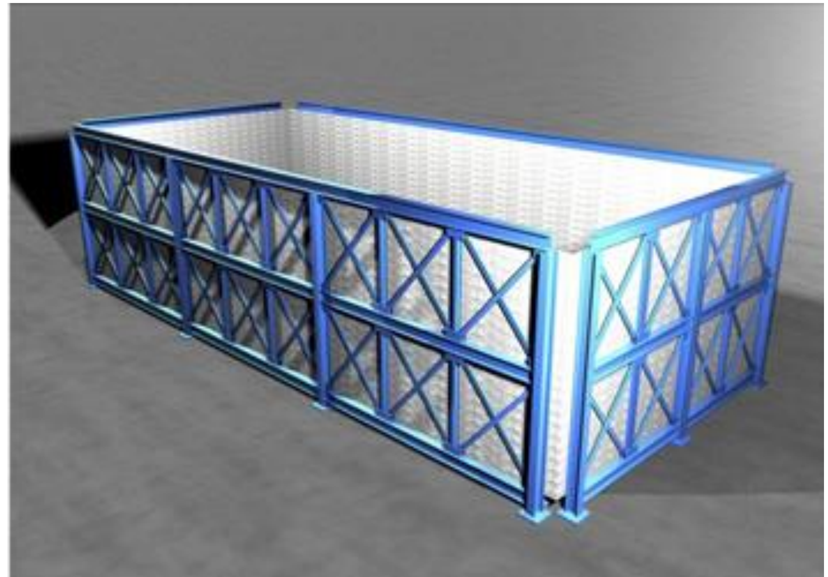


New T600 layout

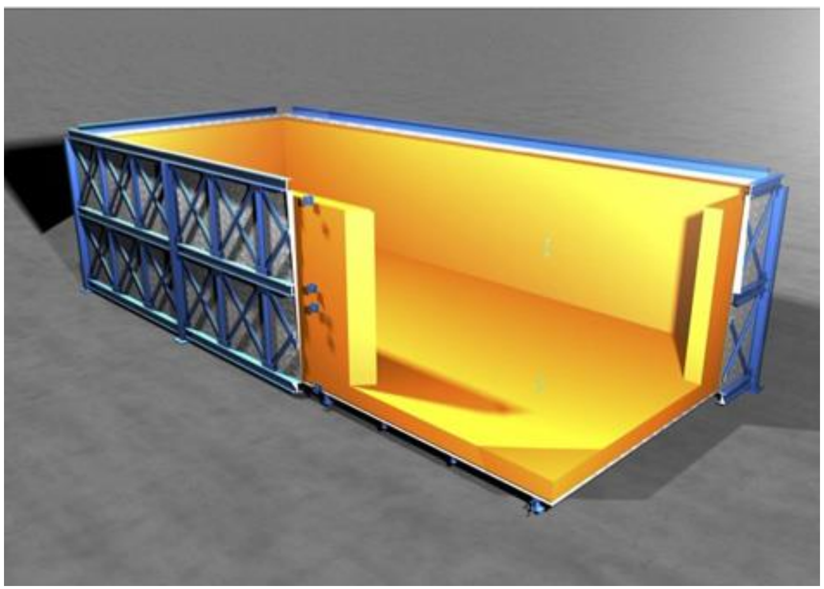
Warm vessel cage



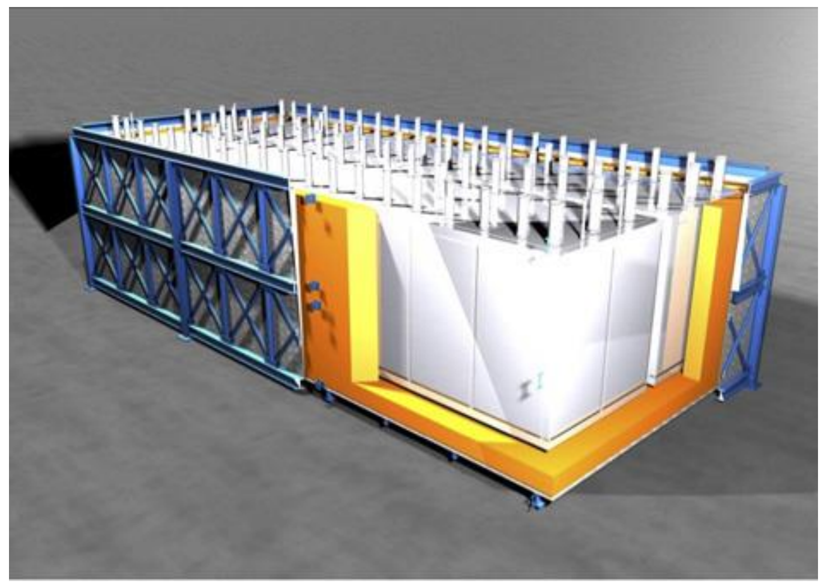
External skin



Insulation panels

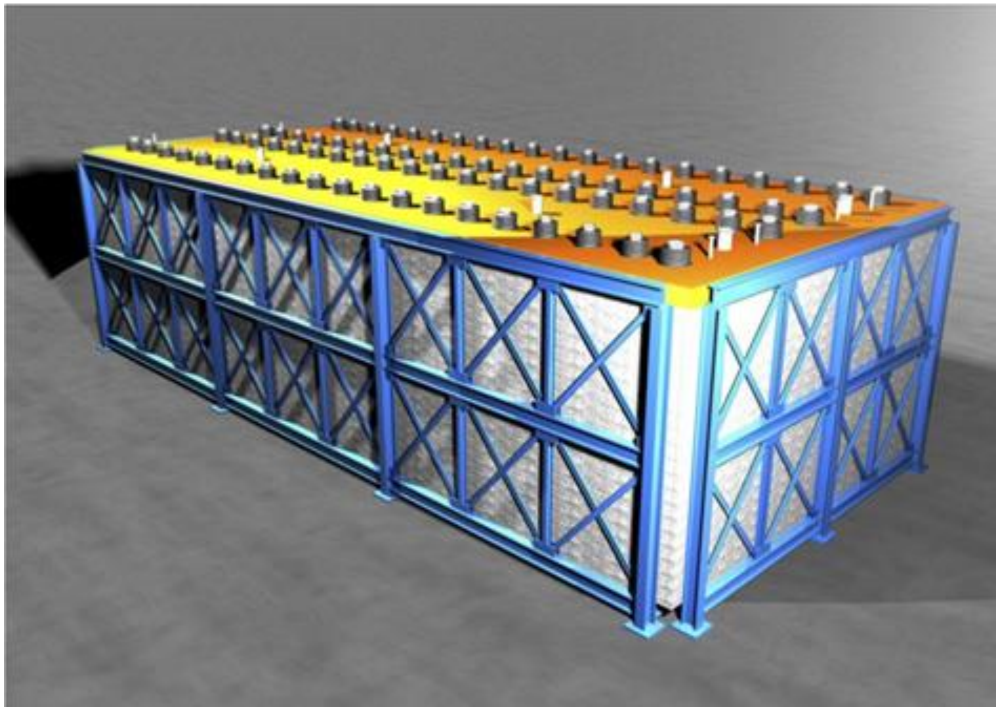


T600 modules

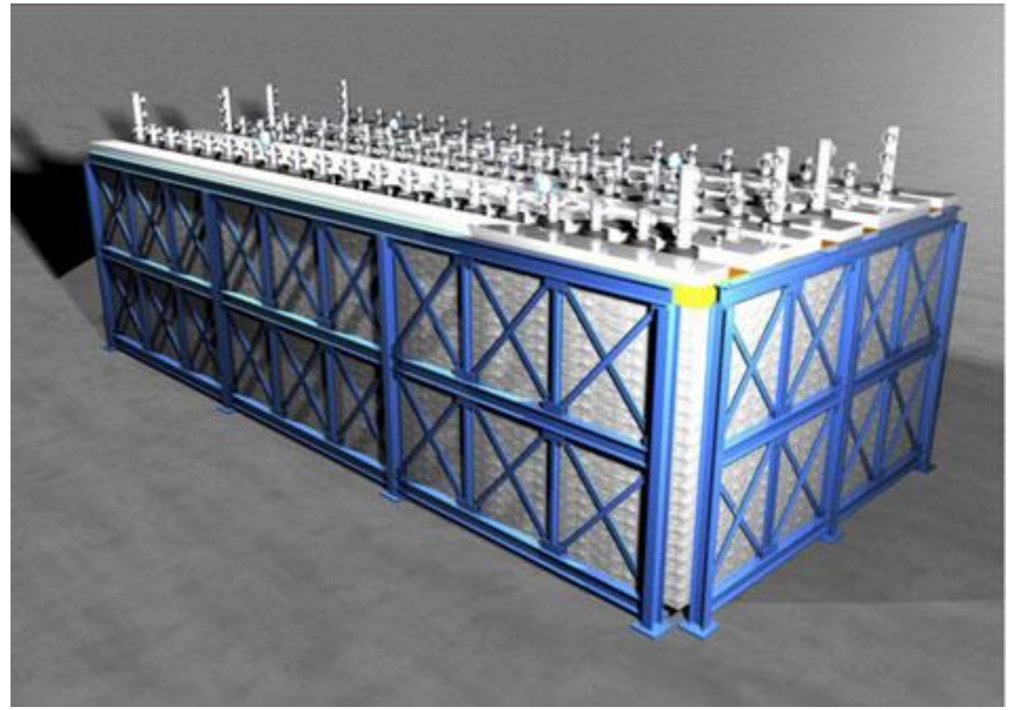


New T600 layout

Insulation top



Top flanges (final layout)



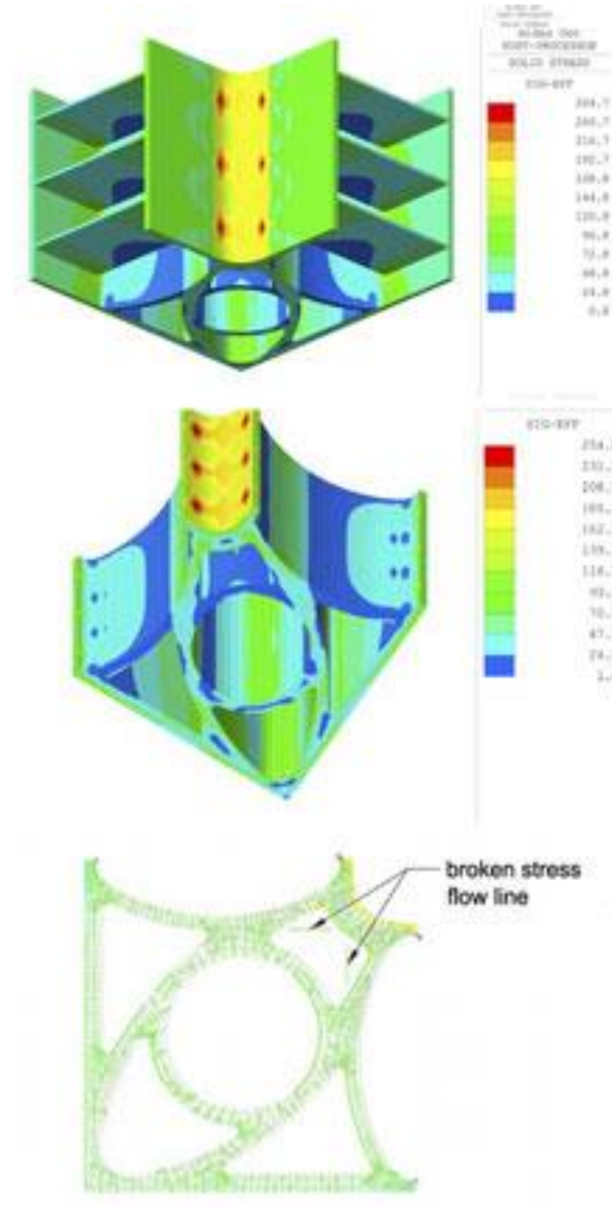
R&D-4: New cold bodies design

The new cold bodies design appointed to a mechanical engineering company connected to the Milano Politecnico (Finzi e Associati).

Work is progressing:

- Detailed modeling of the aluminum profiles (complete).
- Compute behavior under the several loading conditions (complete)
- Optimization of the aluminum profiles (done)
- Define assembly and welding procedures (in progress)
- Verify time scale and construction cost (in progress)

This solution could represent a valid alternative to membrane (as originally foreseen for MODULAr) for LAr containment.



Status of ICARUS Activities: transfer to CERN

- The second half-module, positioned in the transfer box since last November 24, has been loaded onto the transport truck last December 9 around 17:00 and finally left the Gran Sasso Laboratory at 21:40. The second box is positioned in Building 185 at the side of the clean room.

- The first half module has been completely transferred from the transport box into the clean room (December 10). The clean room has been disconnected from the transport box and closed.

- The operation required two days, including the opening of the transport box, the connection to the clean room and the preparation of tools and materials. CERN involvement has been essential.

- The first transport has been closed on December 15 and moved elsewhere.

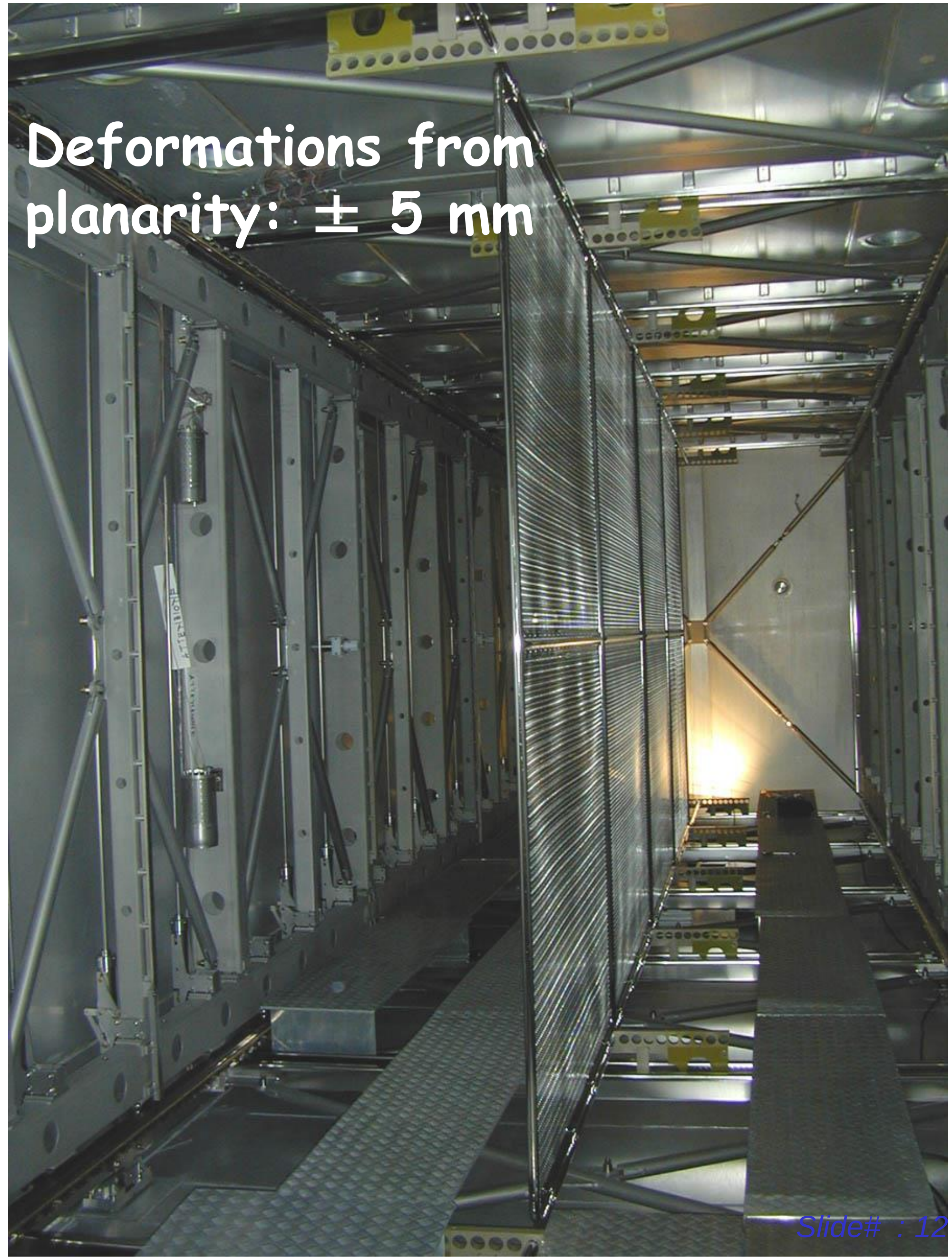
Overhauling activities at CERN (2015-2017)

- Second check on TPC conditions, after transportation (wires, PMTs, all material un-mounted and fastened to main structure, i.e. race-tracks).

- Activities on cathode:
  - Mapping of deformations.
  - Substitution of panels. A new design (presently under finalization) with better planarity will be implemented.

- Activities on photomultipliers:
  - Design of new support structure, to sustain the increased number of detectors per TPC (around 100).
  - Replacement of old devices with new 8" ones, with higher-QE (manufacturer to be chosen), and coated with wavelength shifter (TPB).

Present cathode



PMT replacement

- In the previous phase of the ICARUS program, the Collaboration has gained experience in detecting light signals in LAr with conventional PMTs with a wavelength shifter (TPB) deposited on the glass windows.
- The original (first series) ETL 9357FLA tubes, presently mounted behind the TPCs, are largely outdated.
- New devices are available on the market with better QE, such the Hamamatsu R5912 series or ETL 9357FKBL.
- Characterization of such devices, for employment in the overhauled T600, is in progress:
  - Gain and linearity as a function of temperature
  - Effective Quantum Efficiency (i.e.: with TPB on window)
  - Photocathode uniformity
  - Noise

PMT selection

- HAMAMATSU R5912 series are good candidates for the present PMT replacement.
- 10/14 dynodes models are available. Additional tests are ongoing to define the best option, in terms of linearity and gain attainable as a function of the HV biasing polarization and the voltage divider configuration.

Final decision is expected at the beginning of 2015.

- Further R&D activities are ongoing, related to:
  - Best voltage divider configuration and signal extraction;
  - PMT shielding, in order to avoid spurious signals on the wire planes in front of them (shadows in the 2D views).

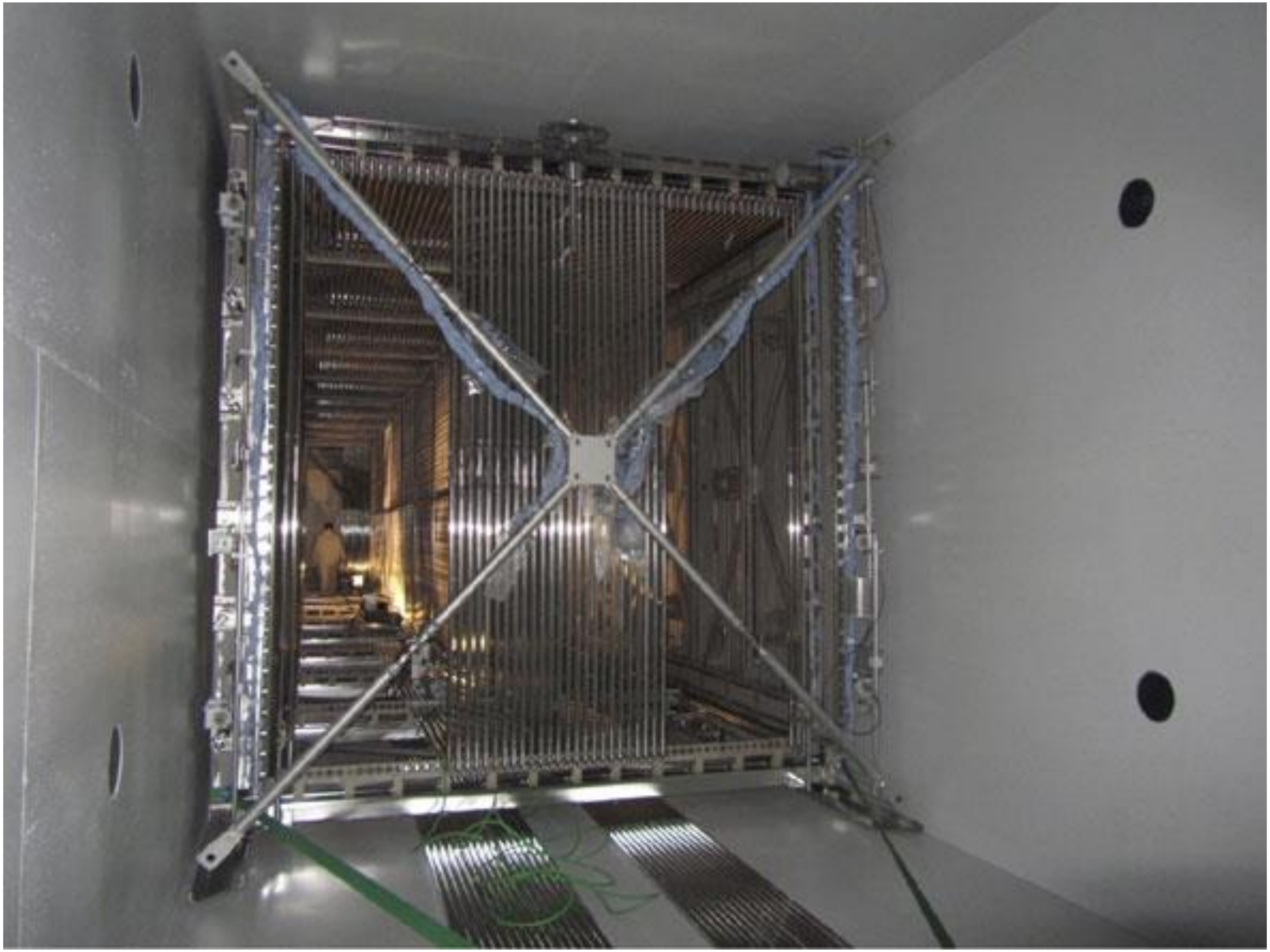
The first transport box entering hall B

Tight space

The first transport box in hall B

Opening of the first vessel

Sliding in of first detector



Ready for travelling

Ready to move inside white chamber at CERN

Sliding inside chamber at CERN

The detector in place as never seen before

Electronics upgrade for the ICARUS T600 LAr-TPC

as presented at FNAL, 15 November 2014

(Francesco Pietropaolo)

Critical considerations

- It is important to remember that DAQ architecture for T600 was conceived in 1997 and front-end dual channel BiCMOS circuits were designed in 1998. The full system was designed and built from 1999 to 2000 and operated first time in 2001.
- In this scenario it's very important to make a critical analysis at **system level** to spot areas where the necessary changes could led to a more efficient structure.
- Adopting a top down approach one **evident limitation** of T600 DAQ is due to the choice of VME standard (8-10 MB/s), perfectly legitimate at that time.

Outline

Improvements are conceivable based on more modern electronic components. Main upgrades concern:

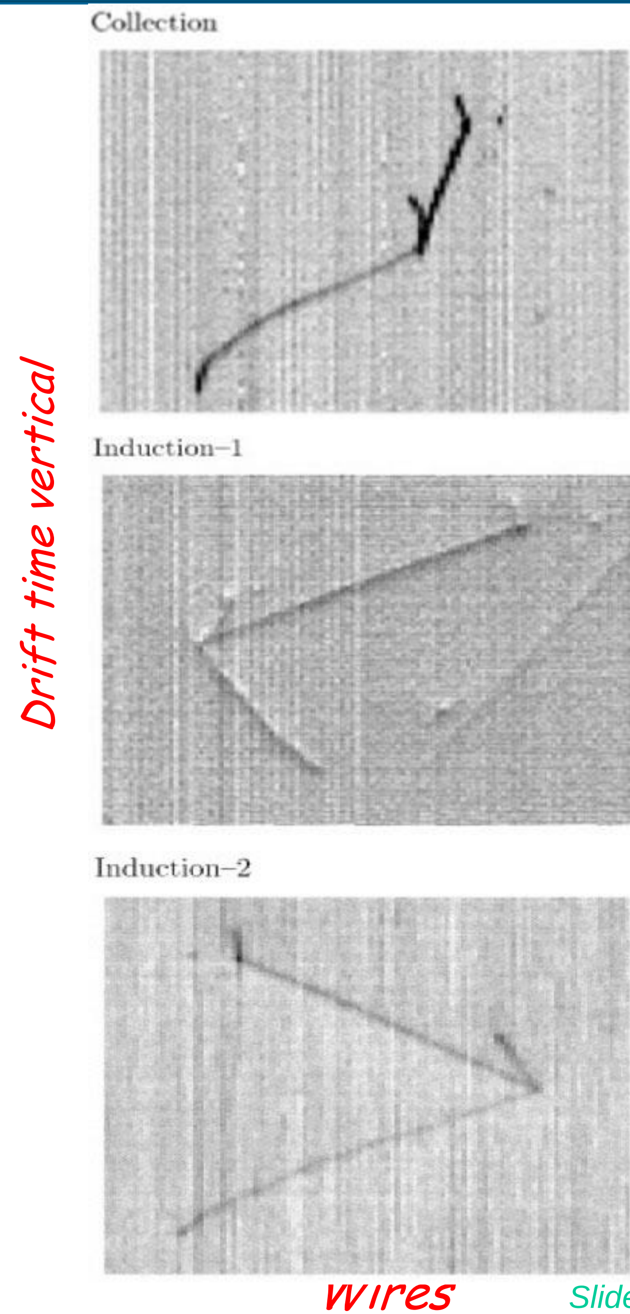
- More compact version of the front-end amplifier
- Adoption of high frequency serial ADCs
- Housing and integration of electronics onto detector and/or (possibly) "*cold*" electronics
- Adoption of a modern serial bus architecture
- Optical links for Gbit/s transmission rate

The present analog/digital front-end

- The analog chain consists of a front-end low noise charge sensitive pre-amplifier, based on a BiCMOS dual channel IC, custom designed, with external j-Fet input stage and followed by a baseline restorer stage.
  - Two different decay times: 3us ("current mode") for collection and induction1 wires, ~30 us ("charge mode") for induction2 wires.
  - Overall gain is 1*V*/164*fC*.
- The 10*bit* ADC input range is 1*V* with least count equivalent to 1000 electrons, matching the amplifier noise of ~1200 el. with a detector capacitance of 450*pF* (wires plus cables).
- The digitizing stage consists in a set of 32 channels connected (through 16:1 MUX) to a 10*bit* ADC sampling at 20*MHz*. The sampling time is then 400*ns* per channel, *revolving*.
- An S/N > 10 was obtained during the whole LNGS run.

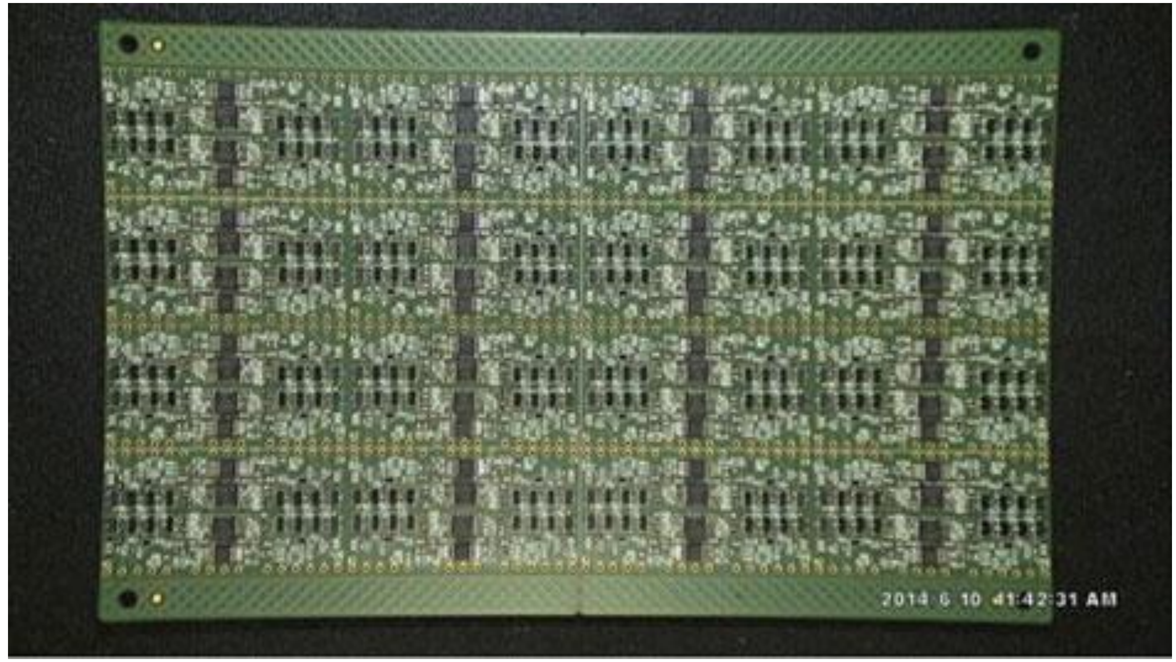
Induction vs collection signals

- Based on the T600 experience, the induction2 front end still require further optimization, addressing mainly:
  - The signal pulse height affected by the preamp rise-time (presently set at ~2us peaking time)
  - The residual undershoot of the electronic chain degrading in particular the reconstruction of complex event topologies in the induction2 view.
- Improvement of induction1 signals presently read in "current" mode are also being investigated.



New preamplifiers design

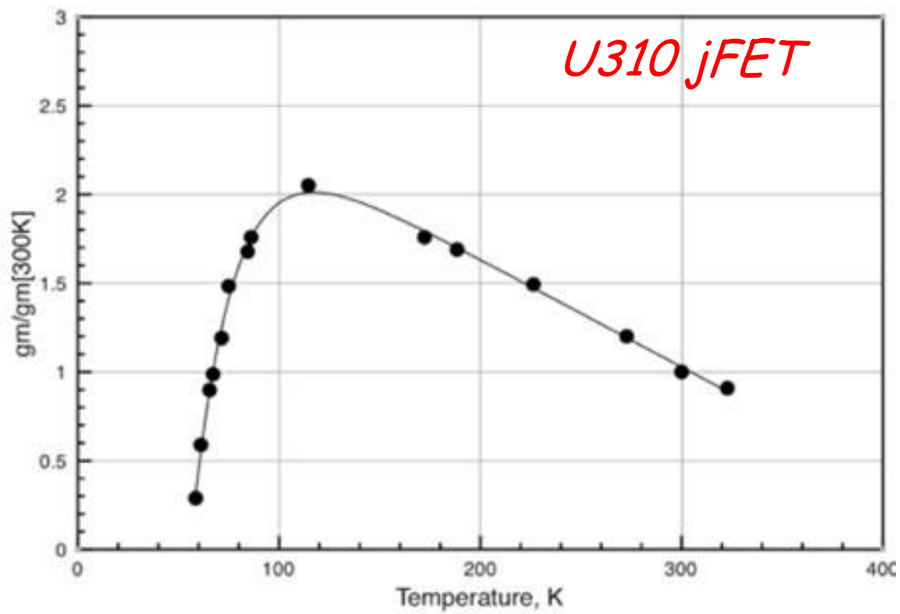
- Two jFet, IF4500 (Interfet) or BF861/2/3 (Philips), are connected in parallel to increase g_m (50-60 mS) at input.
- A custom IC in BiCMOS technology is used to miniaturize the amp: a two channel classical unfolded cascode integrator with external feedback network
- Independent optimization of the pre-amp response (rise/decay time, gain) is envisaged for collection and induction signals.



Production PC Board "scored" so that the IC circuits are "snapped" in eight sets of eight pre-amplifiers

The "Cold" option

- The possibility of front-end in liquid Argon has also been investigated. The amplifier serial input noise, $e^2 \propto C_d^2/g_m$, linearly increases with detector and cable capacitance, C_d, and decreases with input stage trans-conductance, g_m.

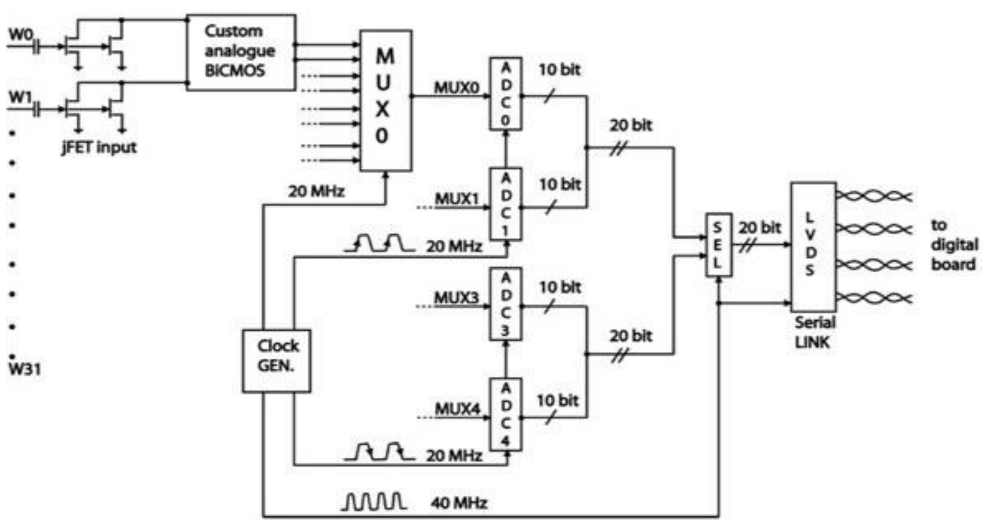


- *Shorter cable and 26% higher gm at LAr temp. would allow S/N improvement.*
- *However, due to the lack of accessibility inducing the risk of a sizable dead volume, a "warm" architecture with accessible/replaceable electronics has been preferred.*
- *This option would also allow implementation of major improvements on electronics due to its natural evolution and progress.*

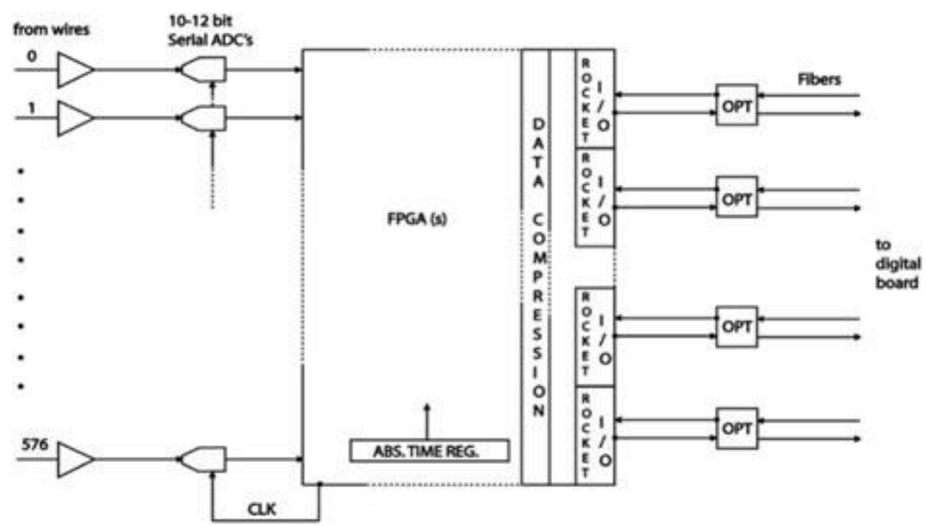
New simplified digital schematics

- A relevant change, in the new electronics design, concerns the adoption of serial ADCs (10-12 bits, one per channel) in place of the multiplexed ones used in T600 al LNGS.
- The main advantage is the *synchronous* sampling of all channels (at 400 ns sampling time) of the whole detector, not to mention compactness and price.

Present ICARUS front-end



Upgraded DAQ scheme



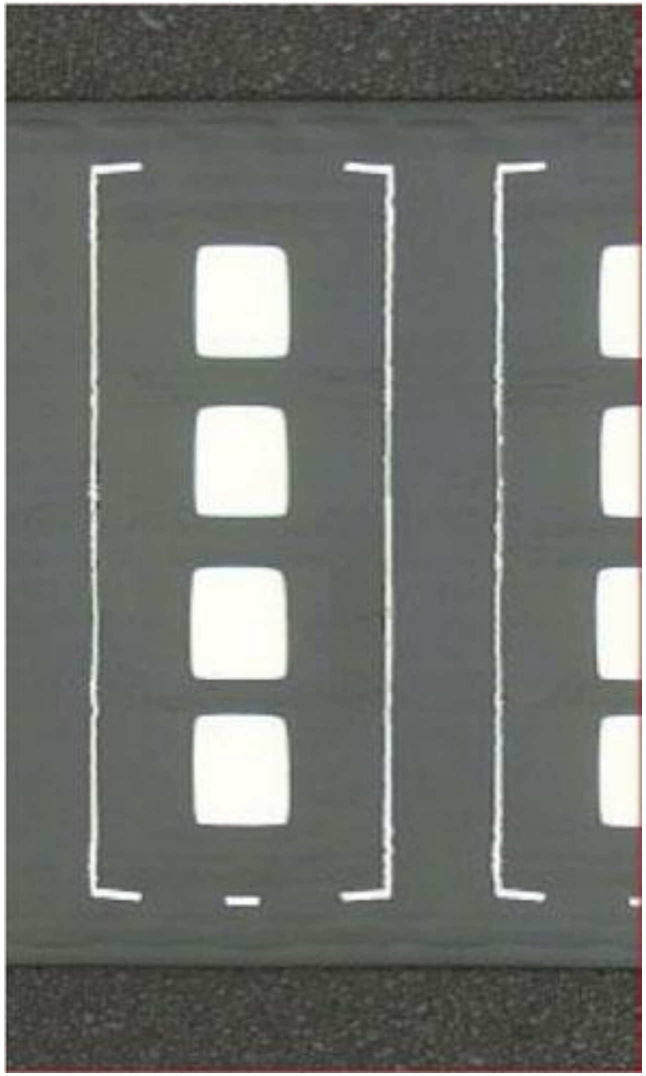
The flange of T600 is an opportunity

- For T600 a very reliable and cost effective flange has been developed.
- Presently it allows for the connections of 18 twisted pair flat cables, each conveying 32 signals from wire chamber to external electronics. (576 ch's per flange).
- **It is conceivable with a compact design to host the full electronics on the flanges,** using the external side of the flange as a sort of backplane that support both analogue and digital electronics.
- It requires a minor change of flange design. The overall cost will be drastically reduced.

The ICARUS signal flanges

- The external contacts, on both sides, are on a different plane respect to the internal vias, allowing for SMD connectors use and guaranteeing vacuum tightness.

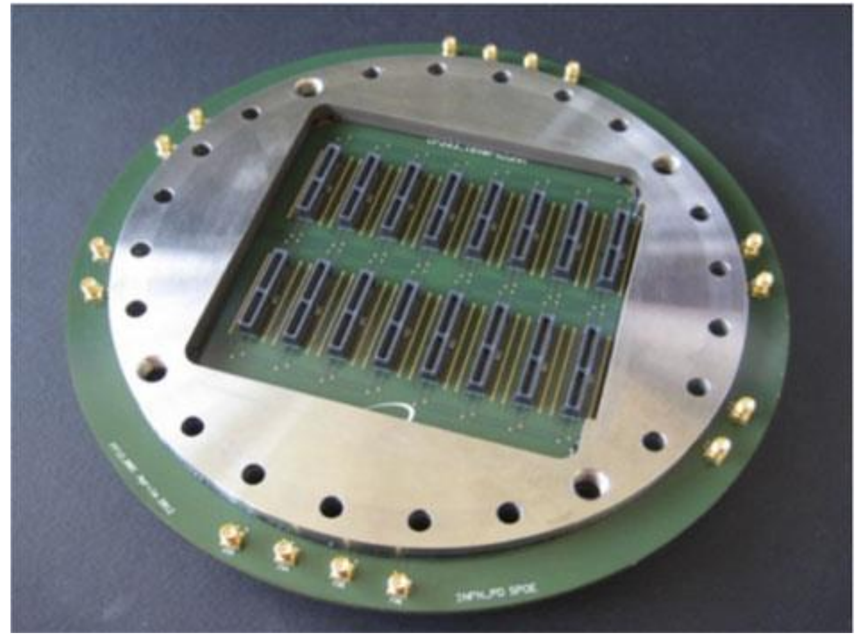
- Reinforcing brass disks are embedded to the flange structure making it able to stands atmospheric pressure without deformation in case of use on vacuum vessels.

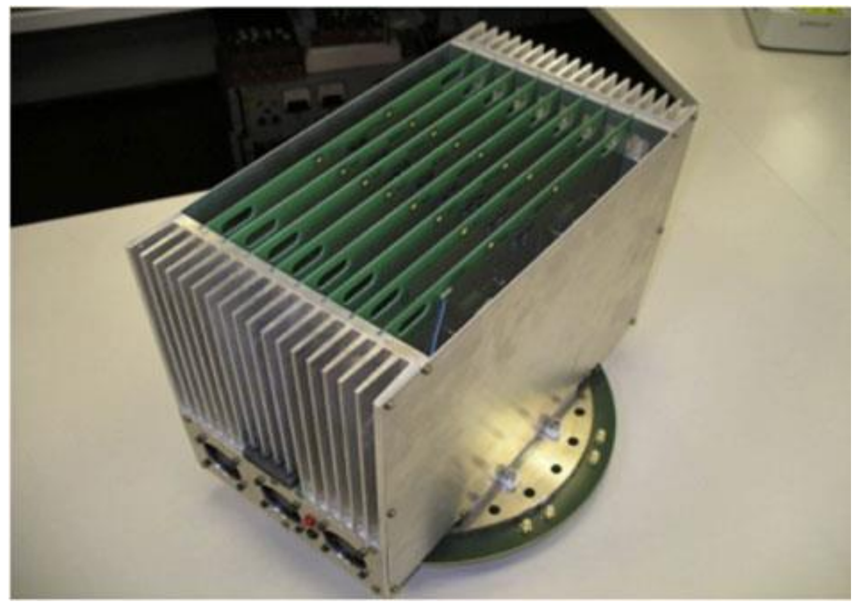


The flange as electronics backplane

- Multiplicity has been reduced to 16 cables (512 channels) to allow for more space among connector rows and permitting the use of the external side of the flange as electronic cards backplane in a special crate.

- The connectors on the external side allow for direct insertion of electronics boards where both analogue and digital electronics, with a compact design, are housed.





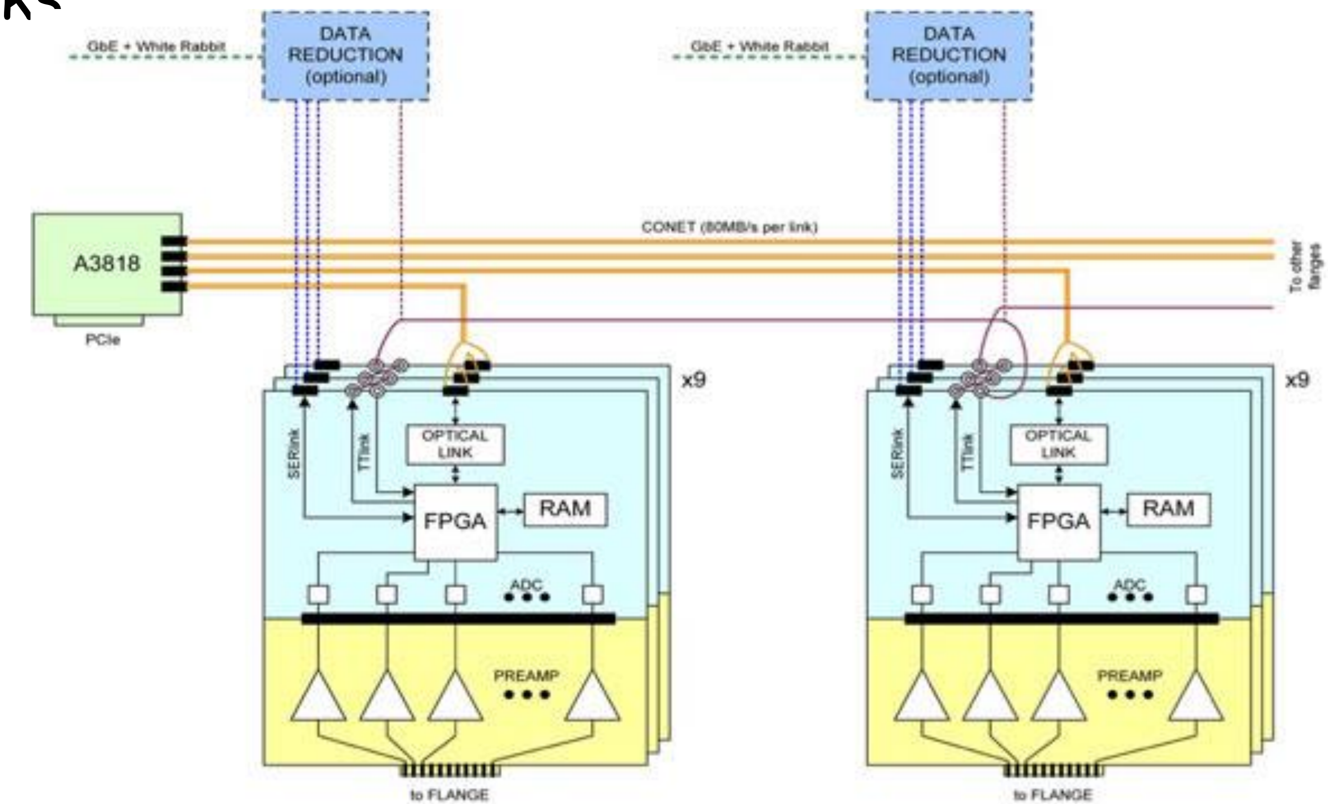
Prototype boards under test

- The first working prototype boards are presently under test at LNL (Padova). Each board serves 64 channels and uses serial optical links.
- The digital part is fully contained in a single high performance FPGA (Altera Cyclone V) per board, used to handle filter and organize the serial information provided by the serial ADC's, allowing also easy firmware upgrading.
- A single serial optical link (1.5 Gb/s) per flange is foreseen, amply sufficient to sustain data throughput without dead time

Improved data throughput

- Performance, in terms of throughput of the read-out system, will be improved replacing the VME (8 - 10 MB/s) and the sequential order single board access mode inherent to the shared bus architecture, with a modern switched I/O. Such I/O transaction can be carried over low cost optical Gigabit/s serial links

A prototype is under development, based on CONET (by CAEN) transfer protocol and one A3818 controller for up to 4768 channels



General layout comparison

- *Old electronics configuration*

- ~595 liters, 576 chs (modulo 32). Bandwidth: 10MB/s

- *New improved system*

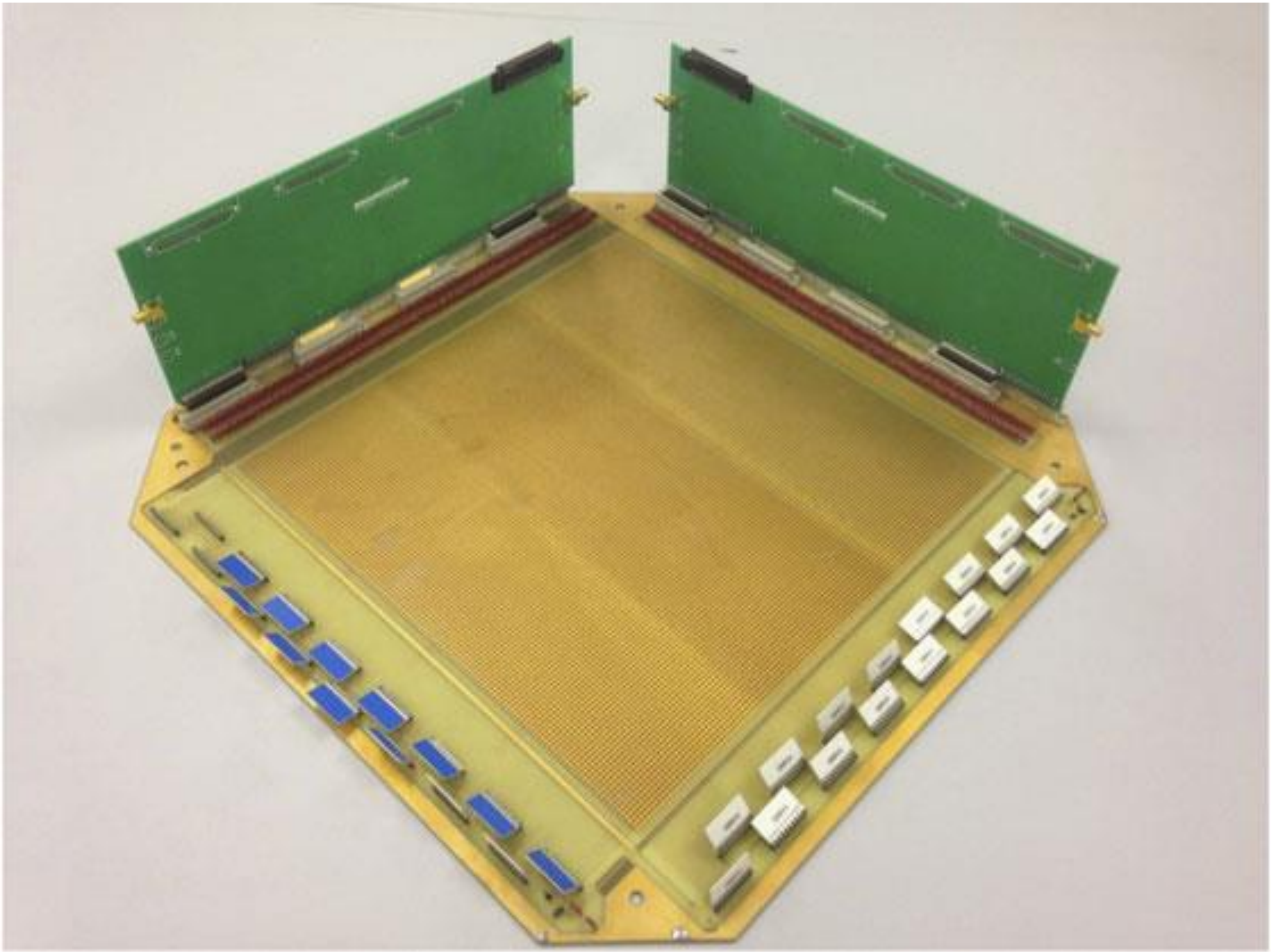
- *~10 liters, 512 chs (modulo 64). Bandwidth: >1GB/s*

Final considerations on DAQ

- The ICARUS DAQ basic architecture is well suited even for larger size LAr-TPC.
- Main upgrades concern:
  - More compact version of the front-end amplifier;
  - Adoption of high frequency serial ADC;
  - Adoption of a modern serial bus architecture;
  - Optical links for Gb/s transmission rate;

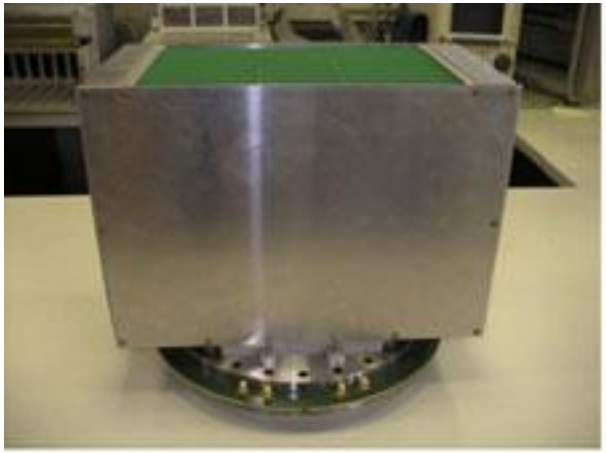
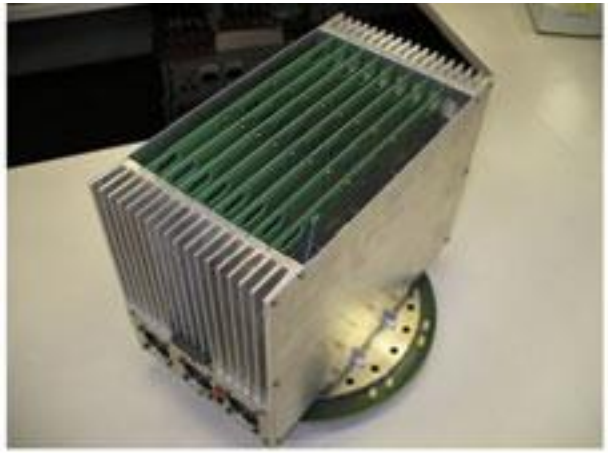
Housing and integration of electronics onto flanges or cold electronics? Or a mix: cold front-end and warm digital processing? In cooperation with BNL team, tests with cold front-end will be performed at CERN

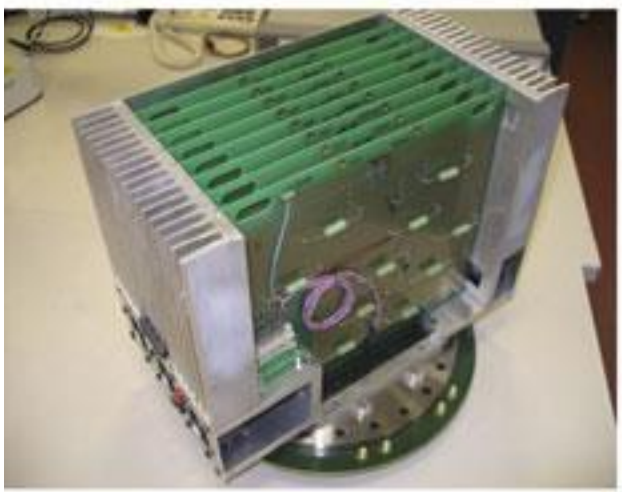
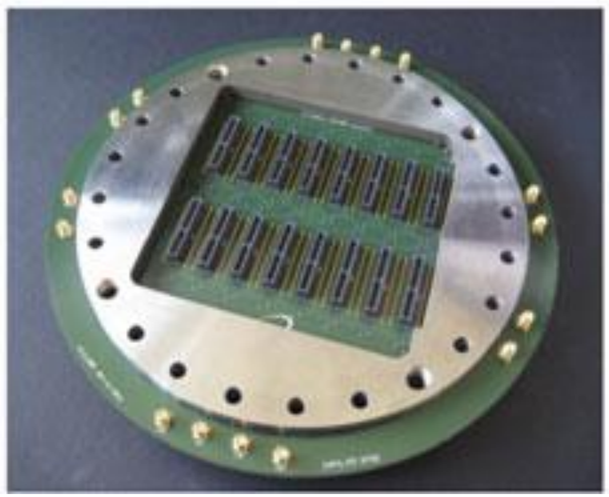
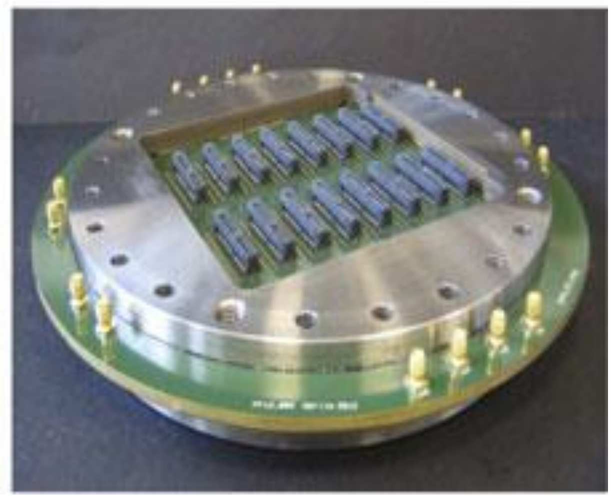
Prototype for cold electronics



Thank you !

Prototype of flange under test

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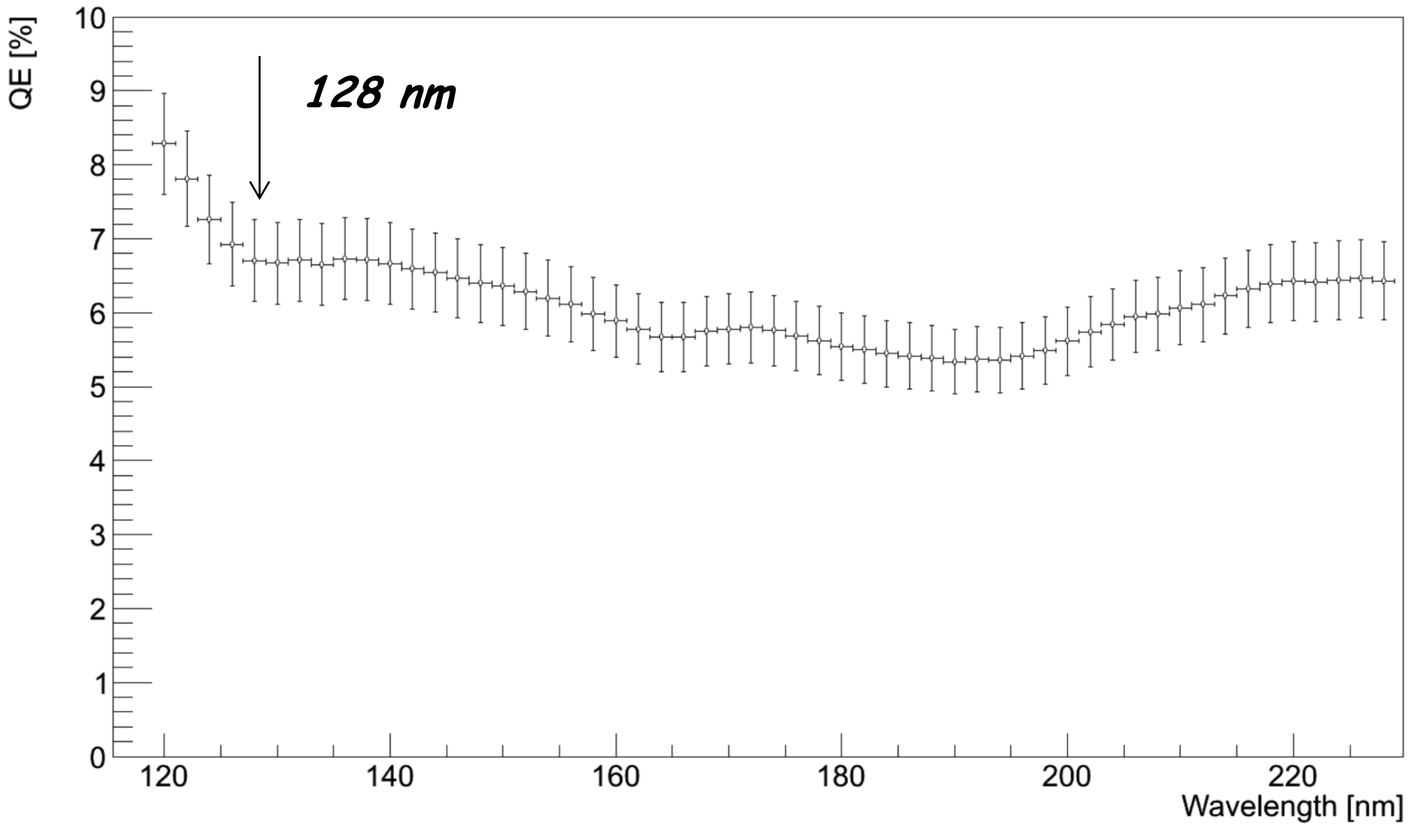
    - Gain and linearity as a function of temperature
    - Effective Quantum Efficiency (i.e.: with TPB on window)
    - Photocathode uniformity
    - Noise

Quantum efficiency

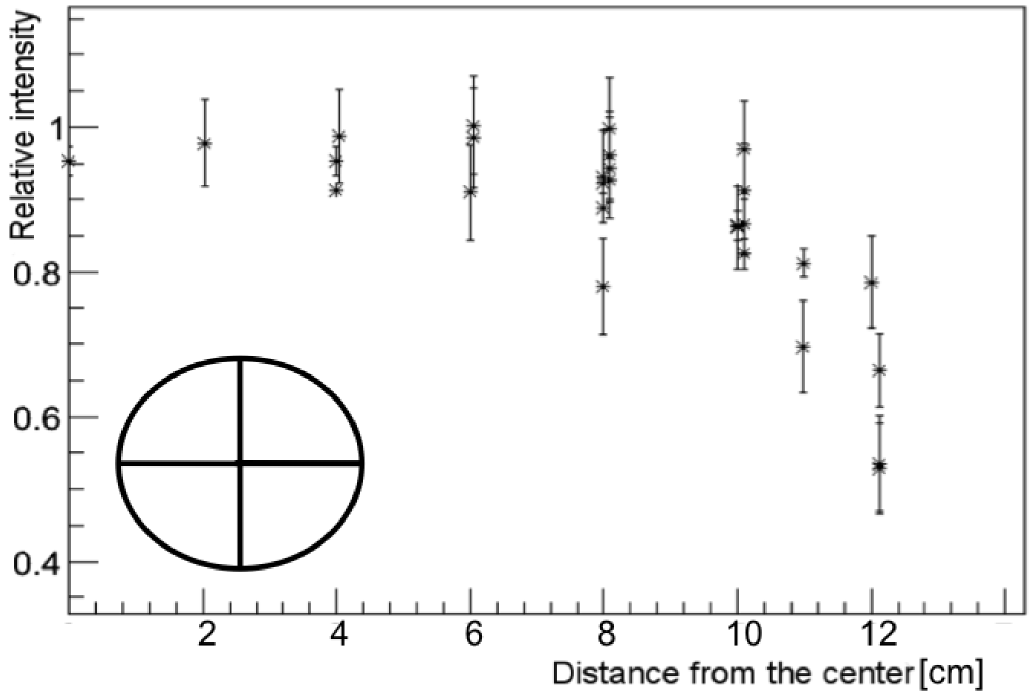
- Example of effective Quantum Efficiency of HAMAMATSU R5912 series as a function of the incident light wavelength.



- Measurements are carried out using a monochromator.
- The PMT glass window was coated with a TBP layer 200μg/cm^2 thick.

Response uniformity

- Example of response uniformity of HAMAMATSU R5912 series.



- Measurements are carried on by illuminating the PMT windows in different positions, with an optical fiber. Data in figure are normalized to the response in the central position.

MC simulation

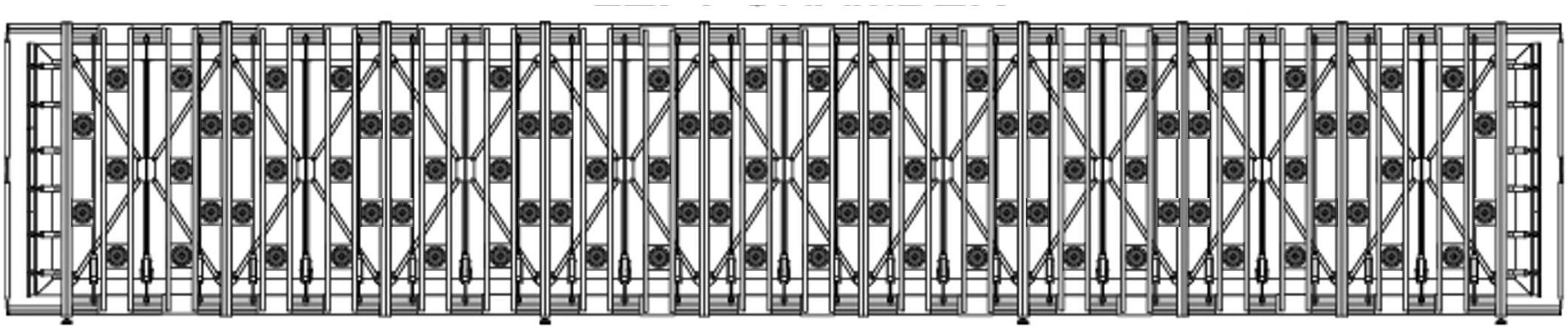
- Dedicated Monte Carlo calculations have been carried out in order to evaluate the localization capability (resolution) of the light collection system, with the following input parameters:
  - Cosmic muons distribution follows a $\cos^2(\theta)$ dependence on the azimuthal angle;
  - Interaction in LAr generates 42000 VUV γ/cm (m.i.p. at 500 V/cm);
  - 5% Quantum Efficiency is conservatively assumed for the PMTs (including TPB conversion and geometrical efficiency);
  - 200 MeV electromagnetic showers are simulated as clusters of points releasing 1 MeV each.
- For each simulated event, the original position coordinates (vertical, X and longitudinal, Z) are evaluated by averaging on the PMT coordinates, weighted on the related signal intensities.
- The space resolution is defined as the distance between the simulated and reconstructed positions, and it is evaluated as a function of the PMT geometrical layout (number of devices, positions in X,Z).

ICARUS overhauling

- The upgraded light collection system will have the following characteristics (in red, improvements w.r.t. old configuration):
  - High granularity (~100 devices per TPC);
  - Large surface, higher QE photomultipliers (8″);
  - Sensitivity to 128 nm photons from LAr scintillation, obtained by coating the (sand blasted) PMT windows with TPB;
  - PMTs located in the 300 mm space behind the wire planes, with dedicated support structures;
  - Implementation of electrostatic shields, to prevent inducted spurious signals on wire planes;
  - Read-out electronics based on 12-bit ADC waveform digitizers:
    - ~ 20 MHz sampling rate + ~ 100 ns shaper or
    - 1 GHz sampling rate + zero skipping + direct signal in order to exploit the available beam bunch-structure as suggested by Carlo Rubbia.

Proposed PMT deployment

- The present T600 light detection system can be extended/completed with additional 8" PMTs.
- Given the present TPC mechanical structure, a possible layout foresees a PMT deployment of 90 devices behind each chamber (a total of 360 PMT in the whole T600 detector).
- This design yields a 5% photocathode coverage.



The drawing above shows a 90-PMTs layout: PMTs are depicted as dark circles. A photo-editing of the deployment is also shown (top-right).

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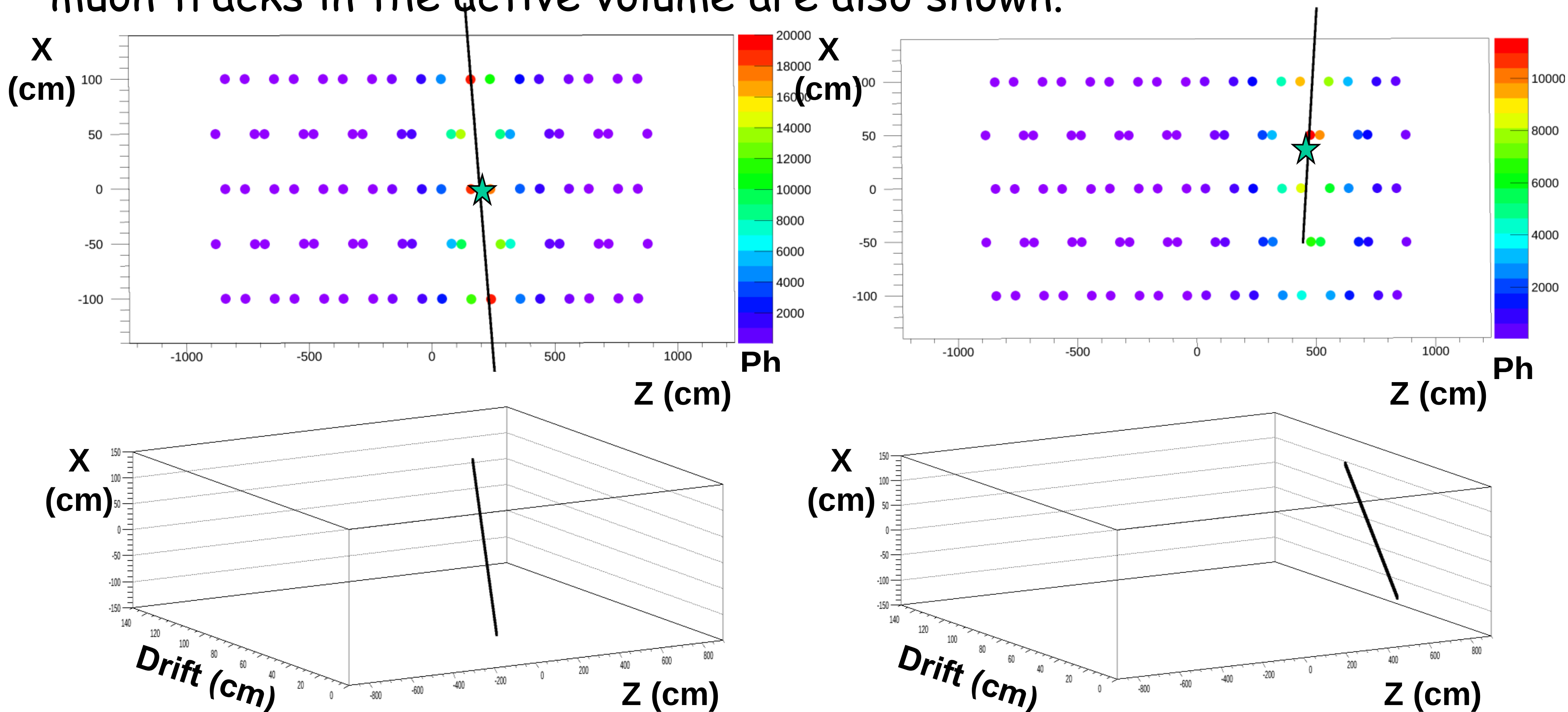
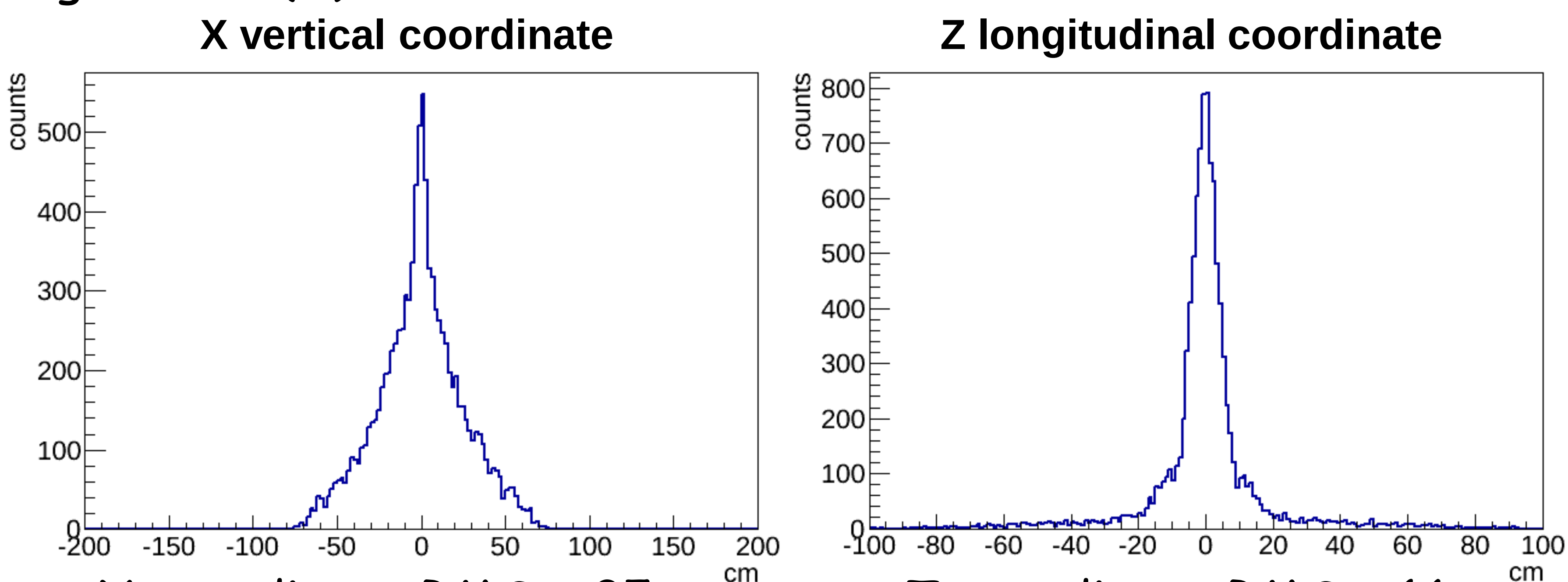
Event localization

- Examples of MC cosmic muon tracks in ICARUS T600 LAr-TPC with 90 devices behind each wire plane. The color code reflects the light intensity (photon number Ph.) seen by each PMT. The star indicates the reconstructed position coordinate on the PMT plane. 3D picture of the muon tracks in the active volume are also shown.



Space resolution

- For the considered PMT geometrical layout (90 devices for each chamber) the resolution is found to be better than 1m.
- In the plots the residual distance from the reconstructed and simulated track position is shown for the vertical (X) and longitudinal (Z) coordinate. 10000 simulated events are considered.



X coordinate RMS = 25 cm

Z coordinate RMS = 16 cm

- Reconstruction algorithms, although already quite satisfactory, can be still significantly improved, especially for boundary events.

Conclusions

- In the new experiment it will be necessary to correctly identify the events associated with the beam spill, therefore it is important to improve our ability to associate tracks in the TPCs with their own interaction times.
- An upgrade of the T600 light collection system, with an increasing the number (about 100 per wire chamber) of modern high performance PMTs is required. The association between tracks and light signals can be obtained with a resolution far lower than 1 m in space and 100 ns in time or even better to exploit the beam bunch structure.
- Dedicated R&D activities are ongoing in order to select the new model.
- This is one of the main goals of the CERN program WA104 for overhauling the T600 detector.

Final decision is expected at the beginning of 2015.