Complex systems and challenging mechanical structures for high energy physic experiments. Some examples from the Neutrino Platform.

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***Abstract*—High-energy physic experiments are complex systems. The particle detectors, the electronics for data selection and acquisition, the services, and the mechanical support structures are all integrated in a highly crowded and optimized space. The size and sophistication of these systems have been constantly growing during the last decades.**

This note summarizes some basic common characteristics of these apparatuses and describes how these concepts are implemented in several experiments under design or construction to study the behaviour of neutrinos.

Neutrinos are intriguing particles: they have no electrical charge, much smaller mass than the other particles and weakly interact with matter. The Standard Model of particle physics as it is today cannot explain some of their measured properties. Therefore, the neutrino studies are gaining importance in the field of high-energy physic.

One hundred and seventy-five research institutes all over the world have established a common important programme of experiments. It foresees the construction of a series of detectors from small prototypes to large elements operating in liquid argon cryogenic environment. The first prototypes have a size of a few cubic meters while the ultimate detector will be in four elements 22.4 m x 14 m x 45.6 m each. One of these elements will contain about 17’000 tonnes of liquid argon. They will be located in an old mine in South Dakota. The cavern is 1500 m below the ground level, a challenge for the transport and assembly of all the components.

As final example, I describe the design and construction of the ICARUS experiment aluminium cryostats. This experiment is one of the milestones of the neutrino programme and it makes use of the largest liquid argon Time Projector Chamber built and operated so far with a bath of approximately 760 tonnes of fluid.

Keywords*—*Detectors, Neutrinos, Mechanical structures

I. INTRODUCTION

A. *Complexity in experiments – general description.*

High-energy physic experiments are extremely complex systems as shown in Fig. 1. They are designed to study the interactions of particles with other particles or with the matter of a target. In both cases, the heart of the system is the detector. This latter is located around the region where particles collide and it is made of elements that react to the phenomena arising during the particle interactions (for example generation of photons or other particles). These ‘reactions’ produce signals that are collected, selected and memorised by the data acquisition system of the experiment. These data are then analysed and studied by the experimental physicists.

Specific machines, the colliders produce and accelerate the interacting particles. In other cases, the particles originate from natural sources like radioactive decays or cosmic rays.

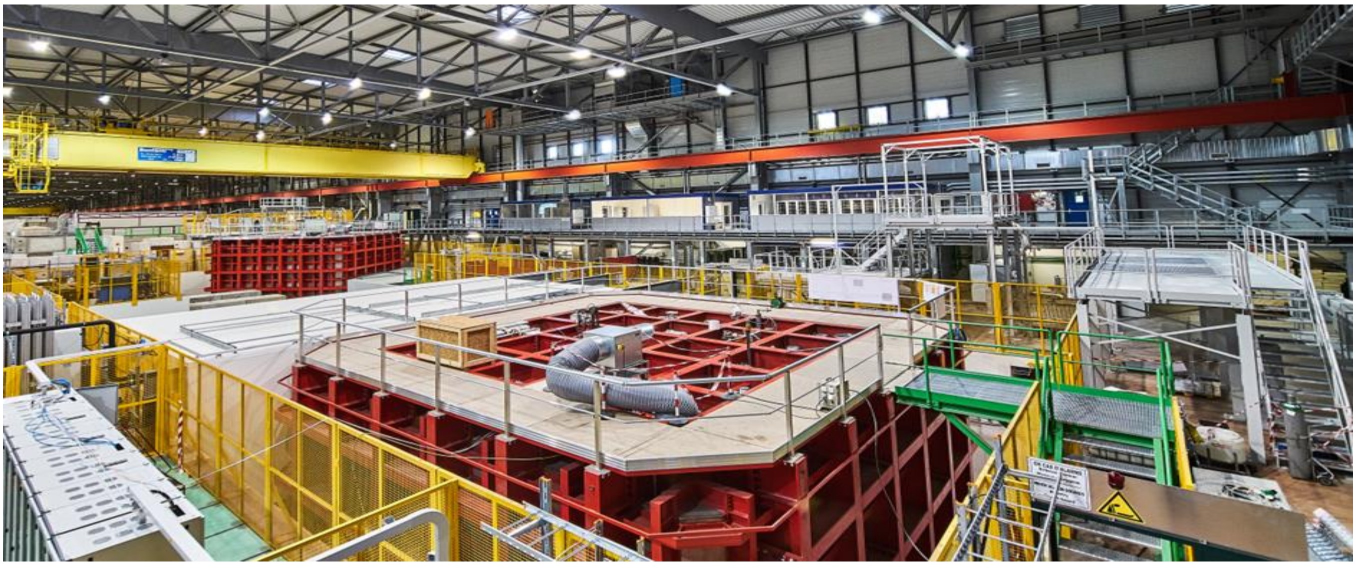

Fig. 1. An example of different systems integrated in a large experimental area. The CERN Neutrino Platform (in red the two containment structures of the ProtoDUNE detectors).

To work properly, a detector needs a performing data acquisition system. It needs as well services like power supply elements, cooling fluids, ventilation of the experimental area, control and regulation systems (pressure, temperature, etc.). All these services requires an impressing amount of cabling and piping: large quantities of these elements are space consuming and heavy. Finally, adequate mechanical support structures must position and align the detectors and all the services must be integrated on board.

Certain detectors are conceived to be sensitive to a given class of particles and are disturbed by others that generate noise in the data acquisition system. Often, these detectors are ‘shielded’ by filters allowing only the right particles to pass through. These filters can be made of less traditional materials than those used in normal constructions. Lead, tungsten, graphite, borated polyethylene, and cast iron are some example of materials for filters.

The detectors incorporate the sensitive elements into structures that can be made of very ‘exotic’ materials: dense elements for certain applications or at the contrary, as light as possible structures for other applications. Sampling calorimeters, the detectors recording the energy associated to a given event, are made of sensitive layers alternated with very dense layers (for example tungsten or lead). On the other hand, the inner tracking systems, the detectors closer to the interaction point in the colliders are made of silicon semiconductor elements positioned on extremely light carbon fibre supports.

In all cases, the ideal detector should be made of sensitive elements that cover all the solid angle around the particle interaction point. The support structures represent a discontinuity of the solid angle. It is a space filled by a passive mass that do not detect interesting phenomena and on the contrary could generate noise in the detector.

Another strong requirement for the detectors is a precise alignment and position of their different components. The reconstruction programs of the data analysis systems use the coordinates of the detected particle trajectories. Position errors impair the precision of these computations.

In any mechanical structure, some clearance between parts under assembly facilitates the manufacturing work. Clearance can allow an enlargement of the construction tolerances. It can as well absorb without extra stresses the deformations of the structures under their weight, thermal loads or other loads. In case of a detector, clearance is again a dead area, a place where there are no sensitive elements.

For all these reasons, the structures of a detector must be as little invasive as possible and require precise construction, small clearance, and little deformations under all load cases. To summarize:

- the design must maximize the rigidity of the structure and minimize its mass,
- the construction must be as precise as possible and cope with small clearance between parts.

All this with the basic requirement of keeping the industrial costs at affordable and reasonable level.

Several experiments are immersed in a magnetic field to bend and track charged particles. In this case, the material employed in the construction must have relative magnetic permeability as close as possible to one in order not to impair the quality of the field and consequently the precision of the particle tracking. Aluminium alloys, austenitic stainless steel or plastic materials satisfy this requirement.

Finally, in some cases, the materials of the detectors and services must be radiation resistant.

Detectors have grown in size and complexity during the last decades. For instance, the Large Hadron Collider (LHC) detectors are located in caverns approximately 50 m long, 30 m wide and 50 m high. The weight of one of these detectors is of the order of thousands of tonnes. Despite the large size, the manufacturing and assembly precision of the most important elements is of the order of a few millimetres. As an example, the muon filter of ALICE experiment is made of three conical and cylindrical elements weighting 40, 18 and 11 tonnes respectively [1]. Thank to adjusting supports, the axis of each element could be located at less than ± 2 mm respect to its theoretical position. ALICE central detectors are made in several 7-m-long elements with a total weight of more than 80 tonnes and are supported by a cylindrical frame structure 8.5 m in diameter, 7 m long and 10 tonnes heavy. The support and alignment structure has in this case a weight about eight times smaller than the supported detectors. The clearance between the structure and the detector elements is between 0 and 4 mm. The maximum deformation of the support frame under the load of the detectors is about 5 mm. To resume the order of magnitude of deformations and tolerances is a few millimetres while overall dimensions of the structures are several meters and loads represent hundreds of tonnes.

The cost of high-energy physic experiments has grown in parallel with complexity and size. Today it can be afforded only by collaborations of many different institutes worldwide. Often, to save in costs, experiments are built re-using components or facilities: experimental caverns and service buildings are re-adapted or detector elements are re-furbished. This fact imposes some extra boundary conditions to new projects and sometimes makes the technical and design choices more difficult than in an ideal ‘starting from zero’ configuration.

The coordination of a large team of specialists from different institutes requires a considerable project management effort during the design, construction, operation and dismounting. This aspect, together with the life cycle of the experiment and of its components will not be described in this note.

In the following pages, I will focus on the structures of an important programme of experiments, the neutrino baseline. I will show that many of the general aspects described above are typical of this programme as well.

B. Neutrino experiments.

Neutrinos typically pass through normal matter unimpeded and undetected since they interact weakly with other particles [2]. They are the most abundant matter particles in the universe, and they are all around us, but we know very little about them.

A Neutrino has no electric charge and the mass is much smaller than that of the other known elementary particles. For long time his mass was thought to be zero.

An important phenomenon involving neutrinos is the neutrino oscillation. A neutrino created in a weak interaction and having a specific lepton flavour can later be measured with a different flavour [2]. The Neutrino oscillation is of great interest, as it implies that the neutrino has a non-zero mass. This fact requires a modification to the Standard Modell of particle physics. The experimental discovery of neutrino oscillation, and thus neutrino mass, by the Super-Kamiokande Observatory and the Sudbury Neutrino Observatories deserved the 2015 Nobel Prize for Physics.

A way to measure the rate of flavour change is to generate a beam of neutrinos and then count how many neutrinos of a given flavour are present at the starting point, and how many at some distance away. Thus, neutrino oscillation experiments generally have more than one detector. The near detector is located a few hundred meters downstream of the neutrino source and it characterizes the neutrino beam in its initial state. The far detector is located at a distance that can be ‘short’ (less than one kilometre) or ‘long’ (several hundreds of kilometres).

II. LIQUID ARGON DETECTORS

Neutrinos can travel through dense matter without interacting with a single atom. To observe the rare interactions it is necessary to build and operate for years very special detectors. They are made of large masses of target materials and they record the track of the particles emerging from the rare interactions of neutrinos with the target atoms. Liquid-argon detectors represent one of the most promising technique to show what happens when a neutrino hits a nucleus of an atom. Tracks that the resultant particles leave behind are shown in high resolution, and it’s possible to distinguish the various particle types. They were first proposed in the seventies [3] and further developed in the last decades.

A liquid argon time projection chamber (LarTPC) is essentially a box of liquid argon as shown in Fig. 2. The Argon is both the neutrino interaction medium and the tracking medium for charged particles produced in the interactions. During one of these events, ionization charges are produced along the tracks of the charged particles. These ionization charges drift at constant speed toward one side of the detector under the influence of an electrical field ‘E’ applied uniformly in the argon volume. A grid of sensor wires positioned on a plane finally collects the charges. For each charge, the amplitude, wire position and arrival time are recorded and used in the data analysis software to reconstruct the event topology [4]. Photosensitive detectors record as well the argon scintillation light emitted during the event. This is used for event triggering and to determine the initial interaction time t_0.

One important parameter is the purity of liquid argon that should be as high as possible. Argon is a noble gas and do not intercept the drifting charges, while polluting elements absorb the charges and decreases the performance of the detector. For this reason, the surrounding structure must be designed to avoid both fluid leakage and contaminations of the argon bath.

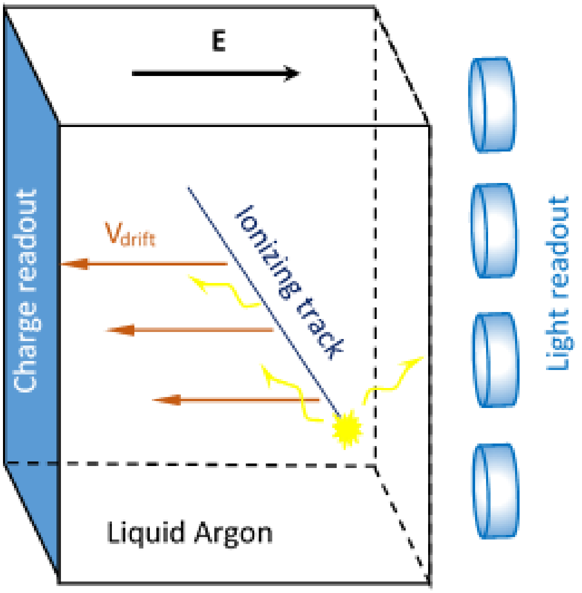

Fig. 2. The working principle of a liquid Argon neutrino detector.

The density of liquid argon is 1392.8 kg/m^3 (approximately 1.4 times that of water). For large detectors the hydrostatic pressure against the reservoir walls represents a considerable load. For this reason, the containment structures must be carefully designed to limit stresses and deformations.

Another important point is the operation temperature of liquid argon at atmospheric pressure, which is 78 K (-186 ^{o}C). The fluid must therefore be stored in a well-insulated structure and continuously cooled. For the large detectors under design the necessary cooling infrastructures will have dimensions and complexity comparable to industrial plants for chemical or petrochemical applications.

III. THE NEUTRINO PROGRAM

The unknown properties of neutrinos could give answers to several basic questions about the universe.

One hundred and seventy-five research institutes from all over the world have established an ambitious and long-term program to carry out experiments in the field of neutrino physics. According to the different properties that each experiment aims to measure, there are two possibilities.

- The far detector is located at a few hundred meters from the point in which the neutrino beam is generated (short baseline).
- The far detector is located at several hundred kilometres from the neutrino generation point (long baseline).

In both cases, the large detectors can be used as well to study neutrinos coming from space (such as rare processes like supernova neutrino detection).

The two baselines are complementary in terms of both physic studies and technology. The research and development for the two baselines is carried out in parallel and the improvements are transferred from one to the other whenever possible.

A. The short baseline at FNAL

The Short-Baseline neutrino program (SNB) at Fermi National Accelerator Laboratory (FNAL) will measure the neutrino oscillation using the Booster Neutrino Beam. Three detectors are under construction: SBND (the near detector), MicroBooNE (the intermediate detector) and ICARUS (the far detector).

These three detectors use a liquid-argon time projection chamber (LArTPC). Each of them contributes as well to the development of this particle detection technology for the long-baseline Deep Underground Neutrino Experiment (DUNE).

The SBN far Detector is the ICARUS T600, the largest LArTPC built to date. This detector operated for some years in Italy as a far detector in a long-baseline experiment. When that experiment completed, the ICARUS detector was taken to CERN and refurbished. The modifications include newly developed readout electronics and a new cryogenics system. ICARUS will operate at ground level and not in a deep cavern as it was during its first use. The need to separate the interesting neutrino events from the noise generated by cosmic events requires several modifications of the electronic and of the detecting elements [5].

The ICARUS-T600 detector consists of two large identical modules with internal dimensions 3.6 x 3.9 x 19.6 m^3 each of them filled with ~385 tons of ultra-pure liquid argon. These elements are surrounded by a common thermal insulation. Each module houses two TPCs separated by a common central cathode for an active volume of 3.2 x 2.96 x 18.0 m^3 (as shown in Fig. 3) [5].

One TPC is made of three parallel wire planes. Globally, there are 53’248 wires with length up to 9 m. A three-dimensional image of the ionizing event is reconstructed combining the wire coordinate on each plane at a given drift time with 1 mm^3 resolution over the whole active volume.

The TPCs are installed inside two new aluminium cryostats. The cryostats are self-supporting. In other words, they withstand the load given by the liquid argon. The insulation and the other structures around the cryostats do not give any contribution to their stiffness and resistance. These cryostats are complicate objects in terms of design and construction. They are made of welded aluminium elements, require a construction precision within a few millimetres, are heavily stressed and must be leak tight. Chapter IV describes in detail their design and construction.

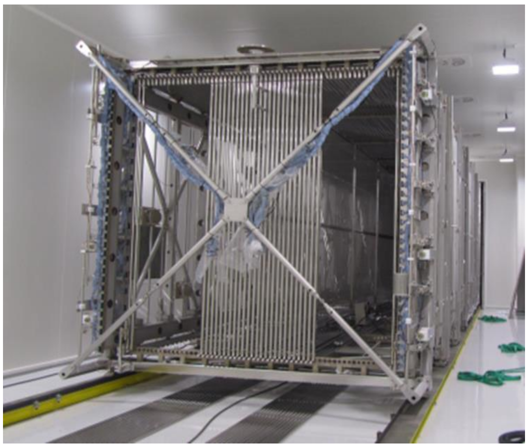

Fig. 3. One of the ICARUS detectors during the refurbishment at CERN.

B. The long baseline DUNE experiment

In the long baseline, DUNE experiment, the neutrino beam produced at FNAL in Illinois will be sent to a detector located at Sanford Underground Research Facility in South Dakota (see Fig. 4).

FNAL is upgrading its facilities in order to produce the intense neutrino beam required for this application. With this development, this will be the most particle-packed high-energy neutrino beam in the world.

DUNE consists of two detectors, a smaller near detector at FNAL and a much larger far detector in a cavern 1500 m beneath the surface in an old South Dakota mine. The second detector is 1300 km far away from the first.

The far detector will be by far the largest ever built using liquid argon technologies. The ground breaking for this project took place in July 2017 and the experiment is expected to be operational in 2026. The far detector will be made of four cryogenic modules, each of which will contain approximately 17’000 tons of liquid argon. A central service cavern will house the cryogenics system, electrical power equipment, air-handling units, and other support equipment. About 875’000 tonnes of rocks will be excavated in the next years to create the experimental and service caverns.

The DUNE collaboration is as well constructing two 800-ton prototype detectors, called ProtoDUNEs, at the CERN Neutrino Platform. They will use a low-intensity particle beam provided by the CERN accelerator complex. The two prototypes will assess the performances of two different configurations of detecting elements. The results of the tests will drive the final technological choices for the four far detector DUNE modules.

A smaller, 35-ton prototype for DUNE was tested at FNAL in early 2016.

All the prototypes have a similar support structure. It consists of a box assembled from frames made of construction steel beams welded together. The box support the inside thermal insulation material. An austenitic steel skin made of corrugated thin plates welded together in situ assures the tightness and contain the argon. The skin lays against the insulation panels. Therefore, the hydrostatic pressure of the liquid argon loads the external box frames. The large detectors in South Dakota will have a similar structure. The complication is given by the need to design modular components that are small enough to pass through the access shaft that is a few meters wide (~ 5 m x 4 m).

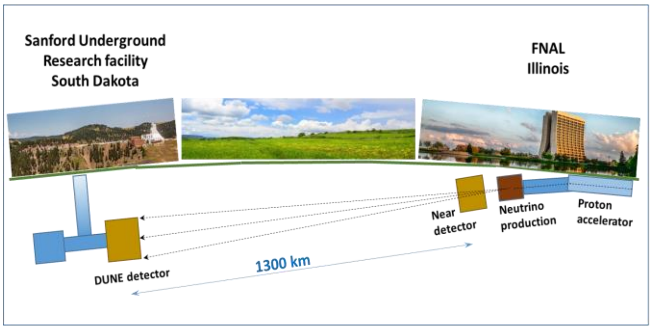

Fig. 4. The long baseline DUNE experiments. Neutrinos produced in Illinois are sent to the DUNE detector at 1300 km distance in South Dakota.

IV. THE ICARUS CRYOSTATS

Each ICARUS cryostat consists of an aluminium alloy structure with dimensions approximately 20 m x 4 m x 4 m. They were manufactured at CERN in the framework of this detector refurbishment programme. ICARUS will finally be used as far detector for the neutrino short baseline in FNAL as described in chapter III.

At the end of the construction, the cryostats were cleaned, then the TPCs were inserted and the doors were definitely closed. Finally, the assembly was transported and installed at FNAL.

At FNAL, the first phase of the operations will be the removal of the air from the cryostats. Then the system will be cooled and filled with liquid argon at 87 K.

During their lifecycle, two loading configurations are critical for the two cryostats:

- the phase with vacuum inside and atmospheric pressure outside,
- the nominal working conditions with liquid argon inside.

For the structural design, the Eurocode 9 [6] and related harmonized norms were used whenever possible despite the fact that no specific norms exist for this kind of aluminium construction.

The manufacturing of the structure foresees a modular assembly starting from extruded profiles (grade EN AW 6082 T6). The profiles were welded together by the extruding company to form sandwich panels. Then the panels were machined to the design size on a large milling machine. In this way, all the dimensional changes caused by the weld shrinkage were corrected. The panels are between 4 m and 6 m long and about 4 m wide. The thickness of the sandwich is 170 mm and the walls of the profiles are 8 mm thick. Once delivered to CERN the panels were pre-assembled to form the cryostat structure and then welded as shown in Fig. 5 and Fig. 6. A mixed team of CERN personnel and project associates from the Pakistan Agency for Atomic Energy (PAEC) carried out the work.

Fig. 5. Different phases of the pre-assembly of the aluminium panels. In red, the temporary support elements used to position the parts.

Fig. 6. First pass weld of one of the panels.

The final assembly and welding took approximately five months for the first cryostat and four for the second one.

Each cryostat required the execution of approximately 540 meters of welds. Each of these welds was in two passes; therefore, the total welding length was more than two kilometres for both the cryostats. The first pass was the one originating the majority of the contraction after solidification, approximately three quarters of the total.

The project had to adapt to the existing TPC dimensions and to the size of the building in BNAL. Consequently, the clearance between the TPC and the cryostat inner walls was extremely reduced (locally about 10 mm). Since each TPC had to be inserted in its cryostat from one side, the shape tolerance of the cross section was ± 5 mm and the straightness ± 10 mm on the total 20-m long structure.

The shrinkage of each weld due to the solidification of the melted aluminium was of the order of some millimetres; the same order of magnitude of the assembly tolerances. The challenge during the final assembly was to keep the shrinkage of the welds under control. This was the only way to assemble the different parts and obtain a result within tolerances.

The aluminium welds were computed, executed and controlled according to the European standards for vacuum and pressure vessels (class B for the level of defects) [7] [8]. Class B for the structural welds means very high quality and an extremely low rate of defects. This was necessary since this application requires leak tightness at cryogenic temperature. The required quality of the welds can be achieved only when the welds are executed in the optimal, flat position. A few tests were carried out with welds in different position (vertical) but the results were not correct. Therefore, it was mandatory to develop a technique and the appropriate tools to allow several rotations of the structure during its manufacturing. The tool was designed to rotate smoothly an object approximately 20-m long and 30 tonnes heavy.

The first rotation, shown in Fig. 7, was the most critical since only a few welds were already made. Hinges, tack welds, a provisional inside support structure, and friction in the locking joints of the panels kept the structure together.

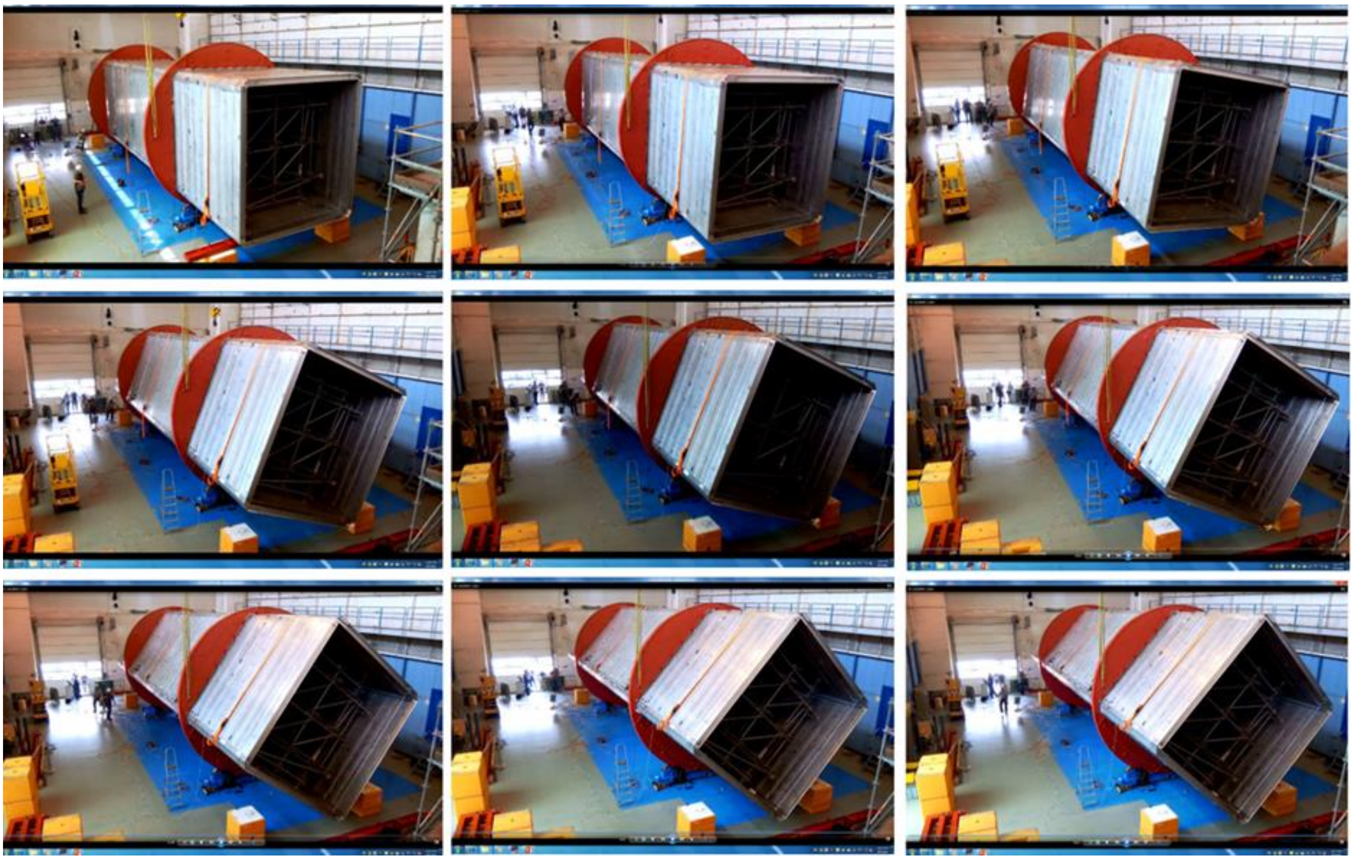

Fig. 7. The first part of the rotation of one of the cryostats. In red the two supporting wheels rolling on rotators.

The rotation of the structure was simulated by finite element computations to check the stress in the tack welds and the relative movements between adjacent panels.

The number of tack welds had to be as low as possible. Too many tack welds would have blocked the relative position of the panels during the welding. The weld shrinkage in this case would have been blocked originating unacceptable cracks in the welds.

The chosen welding sequence was to complete all the first passes of the whole structure and then make the second ones.

The number of necessary rotations was quite large, between 15 and 20 per cryostat. This because the welds had to be executed alternatively on both sides of the cryostat to compensate and limit the deformations. After one or two welds on a side, the cryostat had to be turned to make another one or two welds on the opposite side. Making all the welds on one side and then turning by 180 degrees and making the welds of the other side would have originated large out of tolerances in the straightness.

Transducers were located in strategic positions to control that during the rotations the adjacent panels were not moving one respect to the other. Fig. 8 shows the displacements recorded during the first rotation, the most critical one. They were extremely low and under control during all time. In other words the adjacent panels staid in position.

At the end of the manufacturing, the cryostat structural soundness and leak tightness were tested. The contained air was pumped away to have vacuum inside the cryostat and atmospheric pressure outside. Strain gages were glued in critical positions to compare the measured values of deformation with the computed ones. The agreement between the two values was within 20%, with measured numbers slightly below the computed ones. This level of precision is quite reasonable for this kind of measurements.

V. CONCLUSIONS

The neutrino baseline foresees the design, construction and operation of several experiments. This work is carried out by an international collaboration involving many institutes worldwide.

An experiment represents the integration of many high technology components in a highly optimized volume. Large structures constitute the structural backbone of these systems.

Accurate design and construction allow the possibility of combining high precision, rigidity and minimum space occupancy.

These structures are quite unusual, but they are designed and manufactured following the international norms and standards currently applied for all industrial applications.

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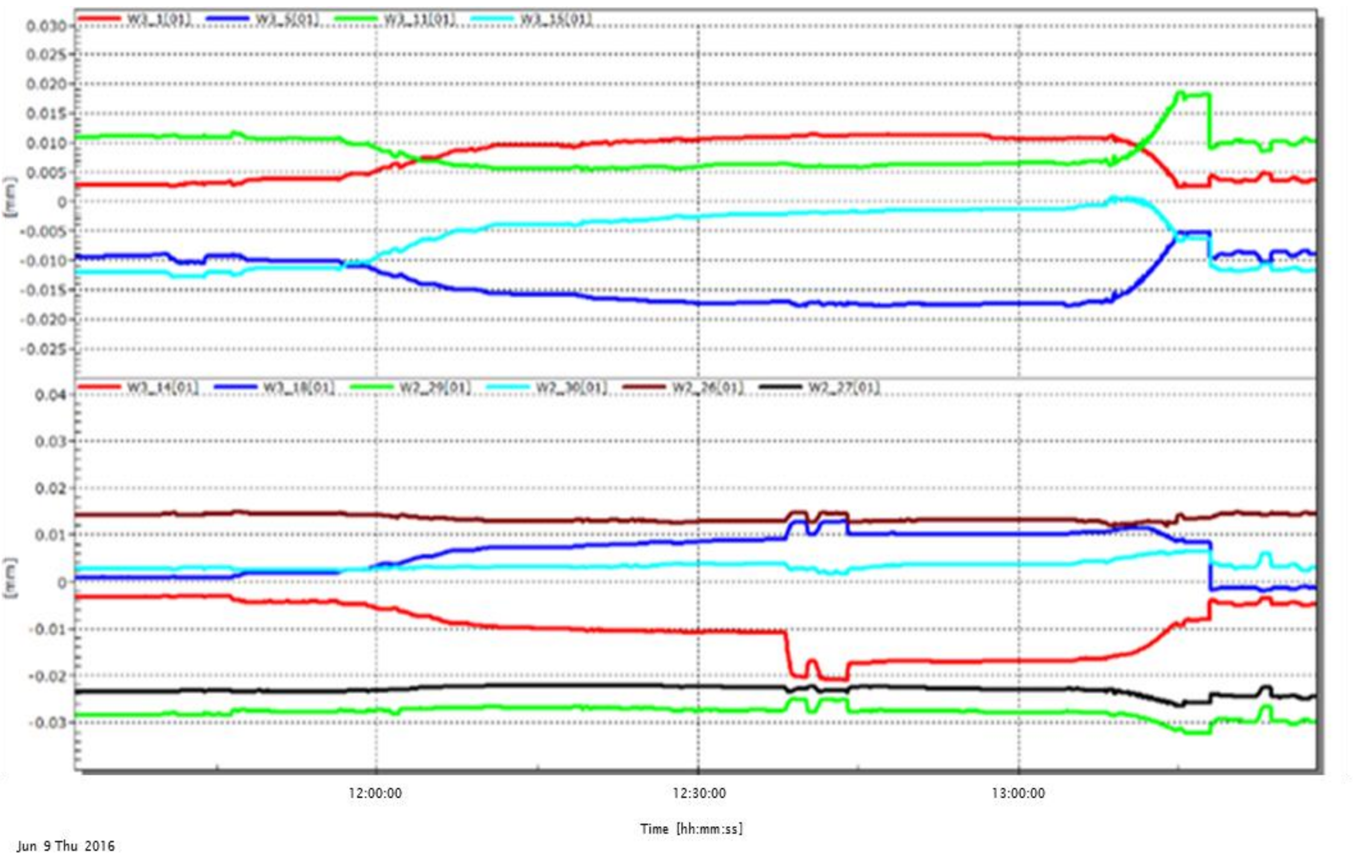

Fig. 8. Relative displacement of adjacent panels during the first rotation of the first cryostat. The horizontal axis reports the time. The vertical axis gives the relative displacement (in millimeters) of one panel respect to the adjacent one. Each colored line corresponds to the reading of one transducer. The values are practically constant during the whole operation. This means that the parts stay safely in place.

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