The NeMO Project
Technical aspects present and future operations

M. Sedita
Istituto Nazionale di Fisica Nucleare – Laboratori Nazionali del Sud (INFN-LNS), Catania, Italy

For the NeMO Collaboration

Abstract – The detection of High-Energy neutrinos coming from the deep Universe is considered by the Astrophysics and Particle-Physics communities one of the main scientific goals of the next years.
The INFN, (Istituto Nazionale Fisica Nucleare), has under way an advanced R&D program that includes long term exploration of a 3500 m Deep-Sea site close to the Sicilian coast, in Italy, for the installation of a High-Energy Neutrino detector and the realization of a technological demonstrator (the "NEMO Phase 1" project), to be installed at 2000 m depth close to Catania. This infrastructure is used also for others scientific applications and operates as a multidisciplinary underwater laboratory.
The "NEMO Phase 2" project will be presented too. It consists of a new facility, placed on the Sea floor at 3500 m depth, 40 nautical miles SE of the south coast of Sicily.
Technical aspects of the facility under realisation will be presented with particular attention to:
- Backbone Cable
- Deep Sea Power and Data Distribution Network
- Power and Data Transmission
- Connection system

I. INTRODUCTION

The realisation of a km^3 scale detector for astrophysical neutrinos is considered today one of the most important aims of the next decade. Indeed, due to their small interaction cross section, high energy neutrinos are expected to provide information on the most violent events occurring in our Universe and to extend our knowledge beyond the distances that can be explored with gamma rays and cosmic ray observations. Many possible sources of high energy neutrinos either galactic (SuperNova remnants, MicroQuasars, interaction of cosmic rays with interstellar medium,...) and extragalactic (Active Galactic Nuclei, Gamma ray Bursts,...) have to be investigated.

On the other hand, the observation of high energy neutrinos would contribute to solve the high energy cosmic ray origin puzzle.

The Mediterranean Sea offers optimal conditions to locate the telescope and, moreover, it has full complementarity, in terms of sky coverage, with the ICECUBE detector that is under construction at the South Pole [1]. Moreover, such an installation in the deep sea (at depth of more than 3.500 m) is of extreme interest for deep-sea sciences allowing a permanent monitoring of oceanographic parameters and many opportunities of multidisciplinary research (biology, seismology,...).

The NEMO collaboration was formed in 1998 with the aim to carry out the necessary R&D towards the km^3 neutrino detector [2]. In the beginning the activity has been mainly focused on the search and characterization of an optimal site for the km^3 installation (sec. II) and on the development of a feasibility study of the detector.

The realization of a small scale technological demonstrator, the so called NEMO Phase 1 project, is in progress (sec. III).

More recently the NEMO Phase 2 has been undertaken. This new facility will increase the R&D activity towards the optimal depth for the telescope location (sec. IV).

The NEMO collaboration recently, together with the ANTARES and NESTOR collaborations, take parts on the KM3NeT consortium to perform a technical Design Study for a single European neutrino telescope infrastructure, (sec. V).

II. SITE SELECTION AND CHARACTERIZATION

The installation of the km^3 detector needs a complete knowledge of the site physical and oceanographic characteristics over a long time period. More than 20 sea campaigns have been performed, aiming at studying the seasonal and long term behaviour of water optical characteristics and oceanographic properties (like currents, sedimentation and seabed geology).

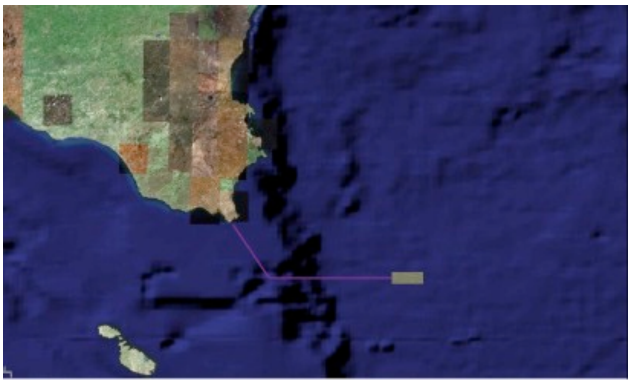

Fig. 1. The south Ionian Sea, showing the location of the site selected and characterized by the NEMO collaboration. Lat. 36°20' N and Long. 16°00'.

The location of Capo Passero site (fig. 1), at about 80 km from the southern coast of Sicily and about 50 km far from the shelf break, was chosen in order to ensure the best condition of stability in time of the water parameters and to avoid any perturbation arising from the presence of the shelf break. The nature and structure of the seabed was studied in detail in order to design the mooring structures of the neutrino detector.

A. LIGHT TRANSMISSION PROPERTIES

Water transparency can be parameterized in terms of light absorption (a), scattering (b) and attenuation (c), which is the combined effect of the first two. These quantities have to be measured *in situ*. We used a set-up based on a CTD probe (that measures water salinity and temperature as a function of depth) and on the AC9 transmissometer (that allows to measure light absorption and attenuation at nine different wavelengths, from 412 to 715 nm) [3].

A series of campaigns to study the seasonal and long term behaviour of oceanographic and optical properties has been carried out. In fig. 2 we show the absorption and attenuation lengths in the blue region (440 nm) measured at the depths of interest for the telescope (more than 2500 m) in different campaigns. The measured values of the absorption length are about 70 m, close to the one of optically pure sea salt water. Seasonal variations are negligible and compatible with the instrument experimental error.

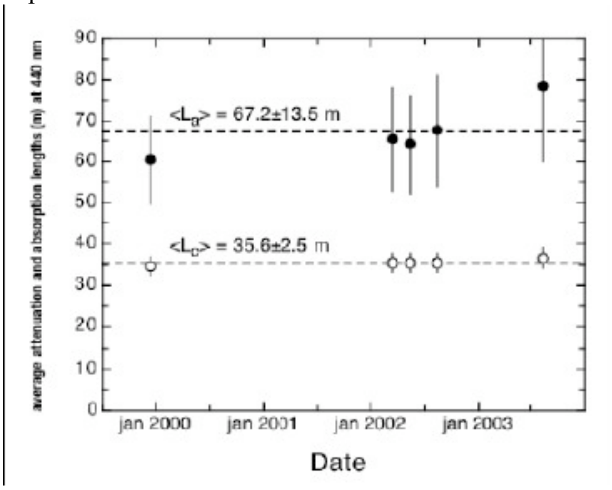

Fig. 2. Values of the absorption (full symbols) and attenuation (open symbols) lengths at 440 nm measured during five different campaigns. The reported values are the average in the depth region 2850-3250 m. Dashed lines are the average over the five campaigns.

B. OPTICAL BACKGROUND

Another characteristic of the deep-sea water that can have severe impact on the detector performance is the optical background. This background comes from two natural causes: the decay of ^{40}K, which is present in seawater, and the *bioluminescence* that is the light produced by biological organisms. Of these two effects the first one shows up as a constant rate background noise on the optical modules, while the second one, when present, may induce large fluctuations (both in the baseline and as presence of high rate spikes) in the noise rate.

In Capo Passero an average rate of about 20-30 kHz of optical noise, compatible with what expected from pure ^{40}K background, with rare high rate spikes due to bioluminescence has been measured at a depth of 3000 m in several sea campaigns. This result is in agreement with the vertical distribution of bioluminescent bacteria measured in Capo Passero that shows a very low concentration of these bacteria at depths greater than 2500 m.

C. OCEANOGRAPHYC PARAMETERS

Deep sea currents have been continuously monitored in Capo Passero since 1998. The analysis shows that the behaviour in the area is almost homogeneous along the part of the water column that has been monitored (at depths between roughly 2800 and 3400 m) with very low average values (around 3 cm/s) and peaks never exceeding 12 cm/s. The presence of rather low currents implies reduced mechanical stresses on the detector structures. The downward flux of sediments has also been analysed. The annual average value of material sedimenting at large depth in Capo Passero is about 60 mg m^{-2} day^{-1}, a rather small value as expected for an oligotrophic environment such as the Ionian Plateau [4].

III. THE NEMO PHASE 1 PROJECT

As an intermediate step towards the underwater km^3 detector and to ensure an adequate process of validation we have decided to realize a technological demonstrator including most of the critical elements of the proposed km^3 detector. This project is called NEMO Phase 1 [2].

The project is under realization at the Underwater Test Site of the Laboratori Nazionali del Sud in Catania, where a 28 km electro optical cable, reaching the depth of 2000 m, allows the connection of deep-sea instrumentation to a shore station. The NEMO Phase 1 system, see fig. 3, is composed by Junction Boxes a tower. This will allow to test the mechanical characteristics of both as well as the data transmission and power distribution system of the whole apparatus. The completion of the project is foreseen by the end of 2006.

A. THE LNS TEST SITE

The Test Site of the Laboratori Nazionali del Sud consists of an electro-optical submarine cable, to connect the underwater installation at 2000 m depth to the shore, and a shore station.

The cable system is composed by a 23 km main electro-optical cable, split at the end in two branches, each one 5 km long. One branch is dedicated to the NEMO Phase 1 experiment, while the other one host the first cabled multidisciplinary sea floor observatory, called SN-1, realized by the Istituto Nazionale di Geofisica e Vulcanologia (INGV) [5].

The cable, realised by Nexans, carries 6 electrical wires and 10 single mode ITU-T G652 optical fibres. A shore station, located inside the port of Catania, will host the energy power system of the laboratory, the instrumentation control system, the landing station of the data transmission system and the data acquisition, as well as mechanics and electronics workshops for the assembly of the components. The submarine cable has been deployed in 2001. In January 2005 the terminations of the two branches were recovered and on each one a titanium frame was installed. The frame supports with the wet mateable receptacles on which the underwater structures will be connected.

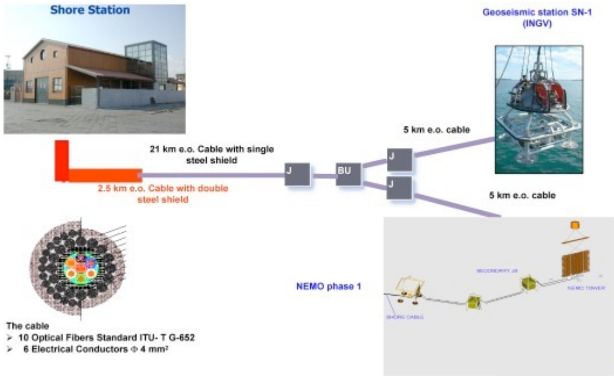

Fig. 3. Schematic layout of the NEMO Phase - 1 project.

B. JUNCTION BOX

An alternative design to the standard Titanium pressure vessels used for junction boxes operating in seawater for a long lifetime has been developed.

The approach is to decouple the pressure and the corrosion problems. Therefore, the proposed JB is made of a pressure resistant steel vessel hosted in a fibreglass container to avoid direct contact between steel and seawater. The fibreglass container is filled with oil to compensate the external pressure. This solution improves the reliability and also reduces costs by avoiding the use of expensive alloys.

Fig. 4. The Junction Box, internal and external structure

C. MECHANICAL STRUCTURES

The tower that will host the optical modules and the instrumentation is a three dimensional flexible structure composed by a sequence of storeys (that host the instrumentation) interlinked by a system of cables and anchored on the seabed. The structure is kept vertical by appropriate buoyancy on the top.

The final features of the tower, (number and length of storeys, number of optical modules per storey, distance between the storeys), has to be optimized for the physics requirements of the detector, following the results of numerical simulations.

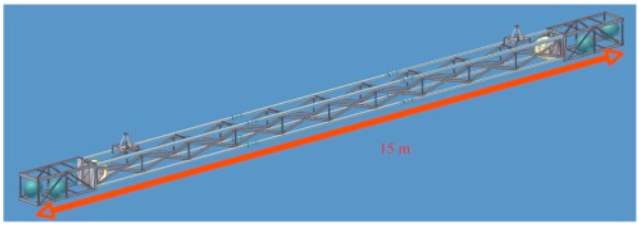

Fig. 5. A NEMO "tower" storey.

However, the modular structure of the tower will permit to adjust these parameters to the experimental needs. For the Phase-1 project we have realised a prototypal 4 storey tower where each storey (fig. 5) is made with a 20 m long structure hosting two optical modules (one down-looking and one looking horizontally) at each end (4 OM per storey). An additional spacing of 150 m is added at the base of the tower, between the anchor and the lowermost storey to allow for a sufficient water volume below the detector. In its working position each storey will be rotated by 90^o, with respect to the up and down adjacent ones, around the vertical axis of the tower.

The tower will also be equipped with an acoustic triangulation system for position purposes and with environmental sensors.

D. OPTICAL MODULE ELECTRONICS

An electronic board, built with discrete components, has been designed, realized and tested as the front-end electronics for the Optical Modules. Sampling at 200 MHz is accomplished by Flash ADCs, whose outputs are captured by an FPGA which classifies the signal as valid or not, stores it with an event time stamp in an internal 12 kbit FIFO, packs OM data and local slow control information, and codes everything into a bitstream ready to be transmitted on a differential pair. The main features of this solution are a moderate power consumption, the high resolution and the huge input dynamics obtained by a quasilogarithmic analog compression circuit, and the fine time resolution. Through an incoming slow control channel, managed by a DSP, all the acquisition parameters can be changed, and there is the possibility to remotely re-program the FPGA downloading new codes. Moreover, the board has embedded electronics, analog and digital, in order to control the Optical Module power supply.

This board will be used in the NEMO Phase 1 project, but as a further improvement towards the km^3 a full custom VLSI ASIC to be used as the front-end electronics for the Optical Modules, designed in AMS 0.35μm CMOS technology, is under development. The trigger, photomultiplier signal classification, fast analog sampling and slow digital conversion, event time stamp, data packing and transfer functions are performed by this chip. The main features of this solution are represented by its low power dissipation, the high resolution, the high input dynamics, the high time resolution and the possibility to remotely change all the acquisition parameters by slow control.

E. DATA TRANSMISSION SYSTEM

For a 5000-6000 Photo-multipliers neutrino telescope the expected overall rate, assumed to be about 30 kHz for each PMT essentially due to background, is on the order of 20-30 Gbps, while the distance over which the data have to be transmitted can be of the order of 100 km. These considerations recommend the use of fibre optics transmission system and power consumption as low as possible.

For synchronization purposes, a common timing must be known in the whole apparatus at the level of detection device to allow correlation in time of events. We have chosen the Synchronous Digital Hierarchy (SDH) protocol, which embeds data, synchronism and clock timing in the same serial bit stream, and allows an easy distribution of the clock signal to the whole apparatus. In situ time calibrations will be performed with a dedicated system for a correct interpretation of the PMT measurements.

The technology adopted relies on Wavelength Division Multiplex (WDM) techniques, using totally passive components with the only exception of the line termination devices, i.e. electro-optical transceivers. The great advantages in terms of power consumption, reliability, and simplicity recommend this technique as a perfect candidate for final km^3 detector.

Considering NEMO Phase 1 as a feasibility test toward the km^3 detector, its data transport system has been designed based on technical choices that allow scalability to a much bigger apparatus.

At the center of each floor of the tower an electronics circuit, called Floor Control Module (FCM), is placed. The FCM collects data from the floor PMTs and the floor control and auxiliary signals, creates an STM-1/SDH data stream at about 155 Mbps, and send data toward the landside laboratory. From the opposite direction, the FCM receives slow control data, commands and auxiliary information, and the clock and synchronizations signals needed for apparatus timing.

Bidirectional data transport is realized by means of a backbone optical fibre connected to each FCM module on an Add & Drop basis at different wavelength for both directions. Such backbone links each tower directly to the on shore side. Actually, in order to provide redundancy, data streams are doubled and re-directed onto two fibres using a “power splitter”. The one fibre of the two used to carry the meaningful information is chosen on the on-shore station.

The underwater structure has a mirrored onshore counterpart, where all optical signals are reconverted into electrical signals. In the on-shore laboratory the Primary Reference Clock (PRC), which is used to give the same timing to all the towers of the apparatus, is also located.

Assuming that the two fibres per tower maintain their integrity, the designed system provides other experiments with a further bidirectional channel.

F. ELECTRICAL POWER SYSTEM

An evaluation of the total power budget needed for the km^3 detector can be made considering an approximate load of 20 W at the level of each storey (four OMs plus some instrumentation with related electronics) plus some extra load at the Junction Boxes (~ 200 W). This leads to a total amount of power required of about 40 kW.

Several solutions for the energy distribution system have been analyzed: in direct current, in alternate current mono phase and alternate current three phase. These solutions have been compared in terms of voltage drops and Joule losses.

For the Phase 1 project a three phase AC system has been chosen since it presents some advantages in terms of voltage drops and reliability. This system is used for the energy distribution up to the level of the local electronics module in each storey where a conversion to DC is made.

A design of the power control system was also made. This is able to acquire currents and voltages plus some environmental parameters, such as temperature, humidity, etc., inside the boxes, switch the power on and off to each feeding line, both under ordinary and fault conditions, detect failures and remotely control the breakers in order to continue feeding the JB interested by the fault.

G. ELECTRO-OPTICAL CONNECTION SYSTEM

The electro-optical connection system on the NEMO Tower is composed by a backbone cable system that ensures the power delivery and data transmission between the Tower Base Module (TBM) and the tower floors and between the floors themselves.

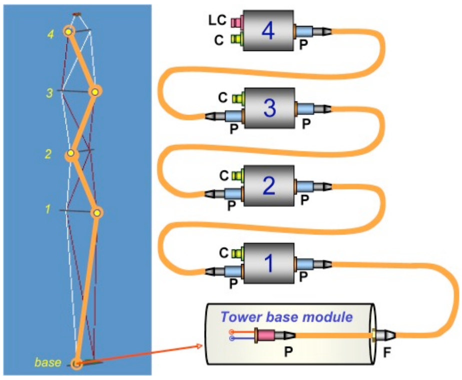

Fig. 6. Cables connection system

The backbone is equipped with one breakout module (fig. 7) for each floor that hosts an Add and Drop optical module, an electro-optical dry mateable connector and two penetrators.

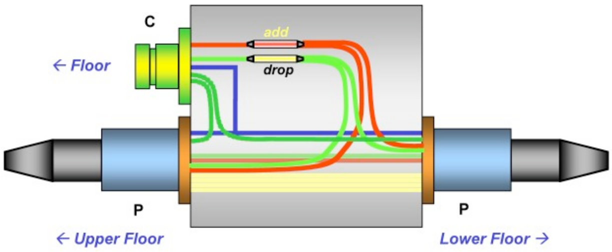

Fig. 7. Backbone Breakout Module

Each floor is connected by a FCM (Floor Control Module) that switch power and signal to the photomultipliers and to the floor instrumentation.

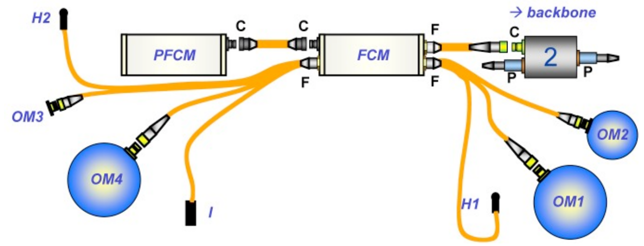

Fig. 8. FCM Connection System

IV. THE NEMO PHASE 2 PROJECT

The main goals of the NEMO Phase 2 are the realization of an underwater infrastructre at 3500 m depth on the Capo Passero Site, the Test of the detector structure installation procedures at 3500 m depth, the installation of a 16 storey tower and a long term monitoring of the site. The system will be upgradable with the expansion of the system.

The infrastructures under costruction are:

- The shore station in Portopalo di Capo Passero to host the power feeding and data acquisition systems
- The backbone cable
- The Shore Power System
- The Submarine Power System
- The Monitoring and Control System
- Underwater infrastructures

Status:

- Competiton for the backbone cable and power system completed
- A building (1.000 m^2) located inside the harbour area of Portopalo has been acquired. It will be renovated to host the shore station.

The lay out of the NEMO Phase 2, wich completion is planned in 2007, is shown in the fig. 9.

Along the backbone cable other two electro-optical output are foreseen for multidisciplinary research activities performed from other institutions (INGV, NATO Undersea Research Centre…).

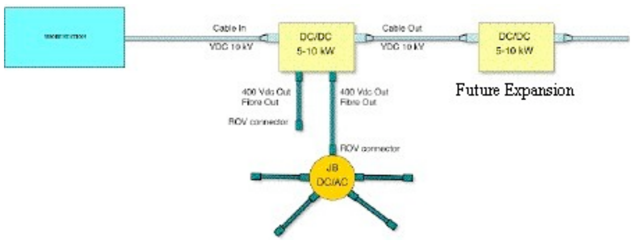

Fig. 9. Lay-Out of the NEMO phase 2

A. THE BACKBONE CABLE

Due to the larger distance, in comparison of the NEMO Phase 1, the backbone cable chosen for the Phase 2 is a DC cable as shown in the fig. 11.

Along the backbone, at different depth, -100 m and -1000 m, two passive Branching Unit for multidisciplinary activities are placed. The lay out of the system is shown in the fig. 10.

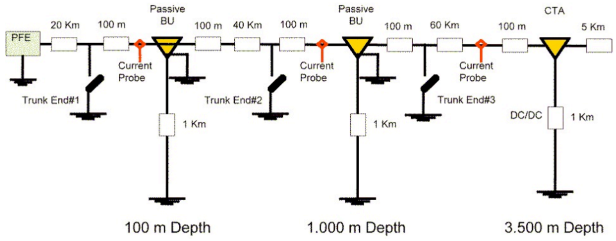

Fig. 10. The Backbone Cable and BU.

The cable, realised by Alcatel, carries 1 electrical conductor at 10 kVDC allowing a power transport not less 50 kW and 20 single mode ITU-T G652 optical fibres. The cable total length is around 100 km.

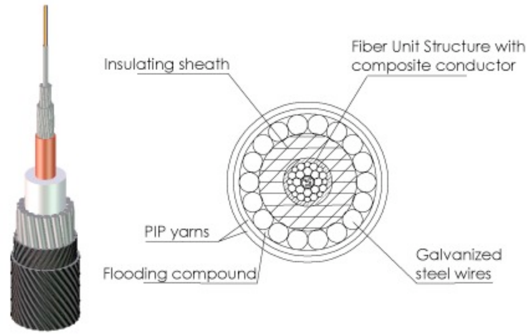

Fig. 11. Electro-optical Cable

B. SHORE POWER FEED EQUIPMENT

The power system is composed by a Shore Power Feeding Equipment. The lay out is shown in fig. 12.

The Shore PFE it's composed mainly by a DC converter and a controller. The PFE provides 50 kW at 10 kVDC with sea current return.

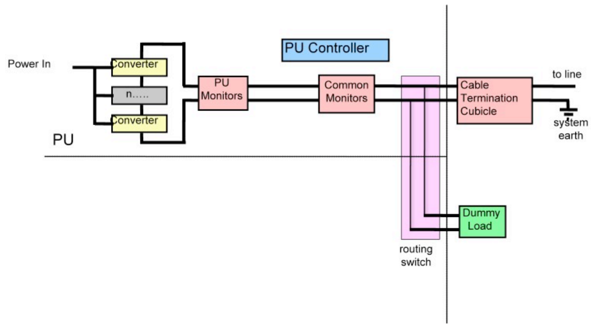

Fig. 12. Shore Power Feed Equipment

A monitoring control system of the Shore PFE is provided too

A Supervisory Unit to control the submerged Active Branching Unit, allowing power switch command, is provided. It consist of Dark Fiber Monitoring Equipment.

The supervisory messages sent from the DFME to the submerged BU are transmitted by an over-modulation of the optical line output signal with a subcarrier tone, see fig. 13.

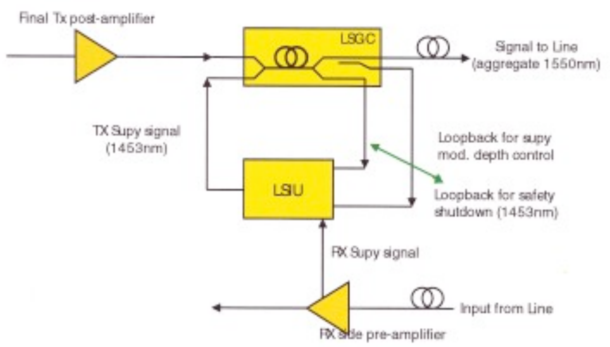

Fig. 13. Dark Fiber Monitoring Equipment

C. *Active BU and DC/DC Converter*

The submerged plant as shown in fig. 14 is composed by an Active BU and a DC/DC Converter.

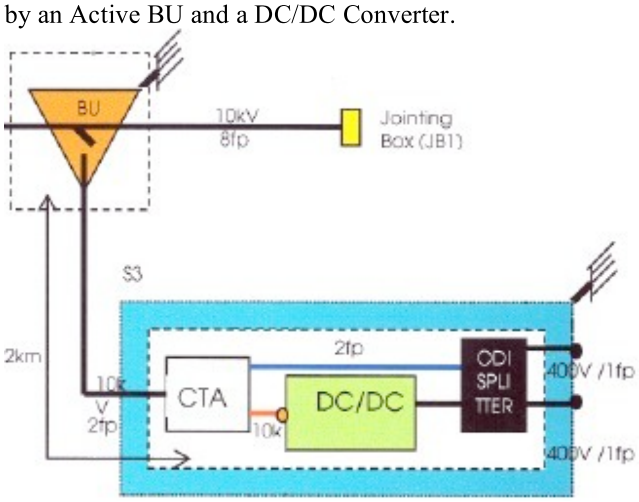

Fig. 14. Active BU and DC/DC Converter

The Active BU is controlled, by the DFME, from the Shore. Circuit internal to the BU allow to power the two output, one for the science and the other one for future extensions.

The DC/DC Converter is based on a design developed by JPL NASA for the NEPTUNE Project [6]. It is constructed from a number of low power sub-converters blocks. These blocks are arranged in a series-parallel configuration, see fig. 15, to share the load and provide redundancy. The entire power converter is housed in a separate pressure vessel Fluorinert filled.

The converter has an input of up to 10 kV and output of 400 V/25 A, the estimated efficiency is > 90% at full load.

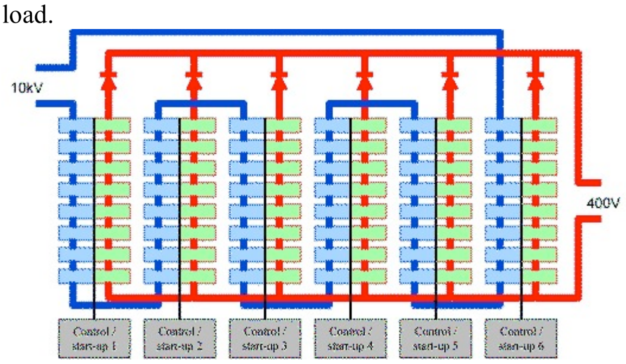

Fig . 15. DC/DC Converter

V. EUROPEAN DESIGN STUDY FOR THE KM^3 DETECTOR

The technology of deep-sea neutrino telescopy, already demonstrated in small-scale pilot projects, has matured to the point where the technical preparatory work for a single European infrastructure can begin.

The KM3NeT Design Study consortium has been formed from the ANTARES [7], NEMO and NESTOR [8] collaborations. The world expertise in the development and construction of deep-sea neutrino detectors, 25 European Institution, is presently concentrated within these collaborations.

Together with the knowledge and experience of the groups for associated sciences in the KM3NeT consortium a sound basis is formed to ensure an effective and realistic planning and implementation of the various tasks needed to successfully design the future KM3NeT infrastructure [9].

This Design Study is a joint effort of all member institutes of the European deep-sea neutrino telescope community to this effect.

The primary objectives of this Design Study are the development of a cost-effective design for a large neutrino telescope, the evaluation of procedures for the assembly and construction of the telescope and the preparation of models for the operation and maintenance of the infrastructure.

The EU in the FP6 program approved the funding request for 3 years and the final results will be ready in 2009.

CONCLUSION

The realization of a *km*3 telescope for high-energy astrophysical neutrinos is a challenging task and several collaborations in Europe are already working on the realization of first generation demonstrators. More efforts are needed to develop a project for the *km*3 detector.

In its five years of activity, the NEMO collaboration has contributed in this direction by performing an intense R&D activity.

An extensive study on a site close to the coast of Sicily has demonstrated that it has optimal characteristics for the telescope installation. A complete study has been performed to analyse all the detector components both in term of their technical feasibility and installation, showing that a detector with effective area over 1 km^3, is realizable at an affordable cost.

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