MEMPHYS:
A large scale water Čerenkov detector at Fréjus

1 MEMPHYS detector

1.1 General considerations

The 20 year long successful operation of the Super-Kamiokande detector has clearly demonstrated the capabilities and limitations of large water Čerenkov detectors:

- This technique is by far the cheapest and the most stable to instrument a very large detector mass, as price is dominated by the photodetectors and their associated electronics (this price growing like the outer surface of the detector), while the active mass, made of water, is essentially free except for the purification system
- These detectors are mainly limited in size by the finite attenuation length of Čerenkov light, found to be 80 meters at $\lambda = 400$ nm in Super-Kamiokande, and by the pressure of water on the photomultipliers at the bottom of the tank, which gives a practical limit of 80 m in height. At large depths, the maximal size of underground cavities actually limits relevant dimensions to about 70 m.
- The detection principle consists in measuring Čerenkov rings produced by charged particles going faster than light in water. This has several consequences:
  1. neutral particles and charged particles below Čerenkov threshold are undetectable, so that some energy may be missing
  2. complicated topologies are difficult to handle, and in practice only events with less than 3 to 5 rings are efficiently reconstructed
  3. ring topology, based on their degree of fuzziness, allows to separate between electromagnetic (e, γ) rings and (μ, π) rings
  4. the threshold in particle energy depends mainly on photocathode coverage and also on water purity (due to radioactive backgrounds, such as radon). Super-Kamiokande has achieved an energy threshold of 5 MeV with 40% cathode coverage
  5. due to points 1 and 2, water Čerenkov detectors are not suited to measure high energy neutrino interactions, as more rings and more undetectable particles are produced. A further limitation comes from the confusion between single electron or gamma rings and high energy π^0's giving 2 overlapping rings. In practice water Čerenkov's stay excellent neutrino detectors for energies below 1 (may be 2) GeV, when interactions are mostly quasi-elastic and the 2 rings from π^0 well separated.

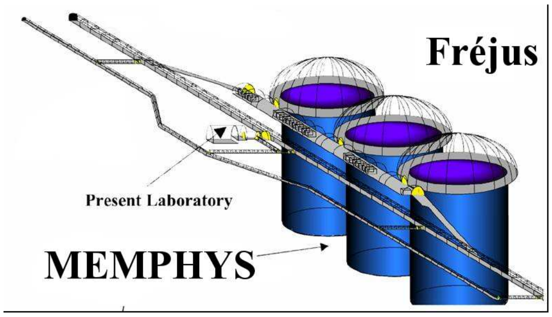

Figure 1: Sketch of the MEMPHYS detector under the Fréjus mountain (Europe).

1.2 Detector design

Three detector designs are being carried out worldwide, namely Hyper-Kamiokande [1] in Japan, UNO [2] in the USA and the present project MEMPHYS in Europe (Fig. 1) [3]. All of them are rather mild extrapolations of Super-Kamiokande, and rely on the expertise acquired after 20 years of operation of this detector. Their main characteristics are summarized in table 1.

These 3 projects aim at a fiducial mass around half a megaton, taking into account the necessity to have a veto volume on the edge of the detector, 1 to 2 meters thick, plus a minimal distance of about 2 meters between photodetectors and interaction vertices, leaving some space for ring development. The main differences between the 3 projects lie in the geometry of the cavities (tunnel shape for Hyper-Kamiokande, shafts for MEMPHYS, intermediate with 3 cubic modules for UNO), and the photocathode coverage, similar to Super-Kamiokande for Hyper-Kamiokande and MEMPHYS, while UNO keeps this coverage on only 1 cubic detector, while the 2 others have only 10% coverage for cost reasons. Another important parameter is the rock overburden, similar for UNO and MEMPHYS (4800 mwe), but smaller for Hyper-Kamiokande (1500 mwe), which might be a limiting factor for low energy physics, due to spallation products and fast neutrons produced by cosmic muons, more abundant by 2 orders of magnitude (see figure 2).

The basic unit for MEMPHYS consists of a cylindrical detector module 65 meters in diameter and 65 meters high, which can be housed in a cylindrical cavity with 70 meter diameter and 80 meter height, as proven by the prestudy. This corresponds to a water mass of 215 kilotons, that is only 4 times the Super-Kamiokande detector. Conservatively substracting 2 m for the outer veto plus 2 m for the fiducial volume, this leaves us with a fiducial mass of 146 kilotons per module. The baseline design uses 3 modules, giving a total fiducial mass of 440 kilotons, like UNO, corresponding to factor 20 increase over Super-Kamiokande (4 modules would give 580 kiloton fiducial mass). The modular aspect is actually mandatory for maintenance reasons, so that at least 2 of the 3 modules would be active at any time, giving 100% duty cycle for supernova explosions. Furthermore, it would offer the possibility to add Gadolinium in one of the modules, which has been advocated to improve diffuse supernova neutrino detection. We estimate an overall construction time of less than 10 years, and of course the first module could start physics during the completion of the two other modules.

Parameters	**UNO** (USA)	**HyperK** (Japan)	**MEMPHYS** (Europe)
Underground laboratory			
location	Henderson / Homestake	Tochibora	Fréjus
depth (m.e.w.)	4500/4800	1500	4800
Long Base Line (km)	$1480 \div 2760$ / $1280 \div 2530$	290	130
	FermiLab÷BNL	JAERI	CERN
Detector dimensions			
type	3 cubic compartments	2 twin tunnels	$3 \div 5$ shafts
		5 compartments	
dimensions	$3 \times (60 \times 60 \times 60)\mathrm{m}^3$	$2 \times 5 \times (\phi = 43\mathrm{m} \times L = 50\mathrm{m})$	$(3 \div 5) \times (\phi = 65\mathrm{m} \times H = 65\mathrm{m})$
fiducial mass (kt)	440	550	$440 \div 730$
Photodetectors			
type	20" PMT	13" H(A)PD	12" PMT
number (internal detector)	57,000	20,000 per compartment	81,000 per shaft (Inner Vol.)
surface coverage	40% (1/3) & 10% (2/3)	40%	30%

Table 1: *Some basic parameters of the three Water Čerenkov detector baseline designs. An option is to fill one tank of MEMPHYS with Gadolinium (0.2% Gd Cl_3).*

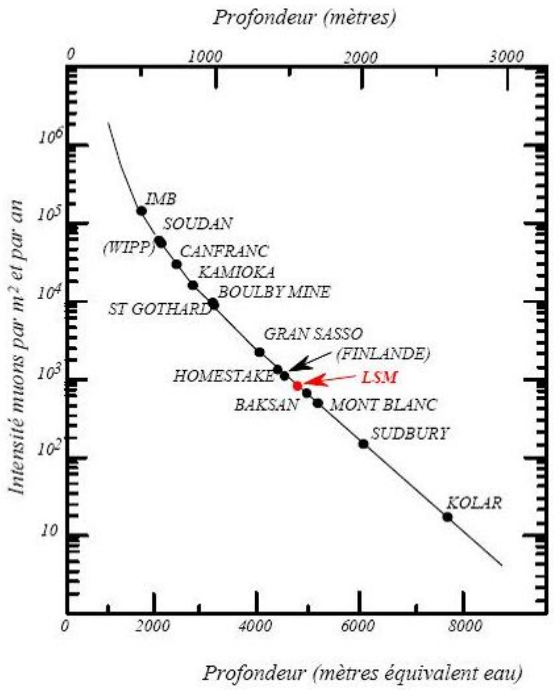

Figure 2: *Muon flux as a function of overburden. The Frejus site is indicated by "LSM".*

1.3 Photodetection

The baseline photodetector choice is photomultipliers (PMT) as they have successfuly equipped the previous generation of large water Čerenkov detectors and many other types of presently running detectors in HEP. The PMT density should be chosen to allow excellent sensitivity to a broad range of nucleon decays and neutrino physics while keeping the instrumentation costs under control.

Our goal for MEMPHYS is to reach in the whole detector the same energy threshold as Super-Kamiokande, that is 5 MeV, important for solar neutrino studies, for the proton decay into $K^+\nu$ using the 6 MeV tag from ^{15}N desexcitation, and also very useful for SN explosions, since the measurement of the ν_μ and ν_τ fluxes could be achieved using the neutral current excitation of Oxygen.

Our first approach was to consider 20" Hamamatsu tubes as used by Super-Kamiokande, but the cost for 40% coverage becomes prohibitive, as these tubes are manually blown by specially trained people, which makes them very expensive. Following a suggestion presented at the NNN05 conference by Photonis company, we have considered the possibility of using instead 12" PMT's, which can be automatically manufactured and have better characteristics compared to 20" tubes: quantum efficiency (24% vs 20%), collection efficiency (70% vs 60%), risetime (5 ns vs 10 ns), jitter (2.4 ns vs 5.5 ns). Based on these numbers, 30% coverage with 12" PMT's would give the same number of photoelectrons per MeV as a 40% coverage with 20" tubes. Taking into account the ratio of photocathodes (615 cm^2 vs 1660 cm^2), this implies that going from 20" tubes to twice as many 12" tubes will give the same detected light, with a bonus on time resolution and on pixel locations. If the dark current of better photocathodes does not increase dramatically the trigger rate, we can expect MEMPHYS performances be at least as good as Super-Kamiokande. A GEANT4 based Monte Carlo is under development to quantify the effective gain. Pricewise, each 20" PMT costing 2500 Euros is replaced by 2 12" PMT's costing 800 Euros each. The only caveat is to make sure that the savings on PMT's are not cancelled by the doubling of electronic channels. An R&D on electronics integration is presently underway (see Sec. 1.5).

1.4 Photomultiplier tests

A joint R&D program between Photonis company and French laboratories has been launched to test the quality of the 12" PMTs in the foreseen conditions of deep water depth, and to make a realistic market model for the production of about 250,000 PMTs that would be necessary to get the 30% geometrical coverage.

In parallel, studies on new photo-sensors have been launched. The aim is to reduce cost, while improving production rate and performance, as it is essential to achieve the long term stability and reliability which is proven for PMTs. Hybrid photosensors (HPD) could be a solution: the principle has been proven by ICRR and Hamamatsu with a 5" HPD prototype. Successful results from tests of an 13" prototype operated with 12 kV are now available, showing a $3 \cdot 10^4$ gain, good single photon sensitivity, 0.8 ns time resolution and a satisfactory gain and timing uniformity over the photo-cathode area. The development of HPD has also been initiated in Europe, in collaboration with Photonis.

1.5 Smart-photodetector electronics

The coverage of large areas (around 17,500 m^2 for MEMPHYS) with photodetectors at lowest cost implies a readout integrated electronics circuit (called ASIC). This makes it possible to integrate: high-speed discriminator on the single photoelectron (pe), the digitisation of the charge on 12 bits ADC to provide numerical signals on a large dynamical range (200 pe), the digitisation of time on 12 bits TDC to provide time information with a precision of 1 ns, and channel-to-channel gain adjustment to homogenize the response of the photomultipliers and to thus use a common high voltage. Such an ASIC for readout electronics allows moreover a strong reduction of the costs, as well as external components (high-voltage units, cables of great quality...) since the electronics and the High Voltage may be put as close as possible to the PMTs and the generated numerical signals are directly usable by trigger logical units and the data acquisition computers (Fig. 3).

The main difficulty in associating very fast analog electronics and digitization on a broad dynamic range does not make it possible yet to integrate all these functions in only one integrated circuit, but certain parts were already developed separately as for example in the OPERA Read Out Channel [4] (Fig. 4). The evolution of integrated technologies, in particular BiCMOS SiGe 0.35μm, now make it possible to consider such circuits and has triggered a new campaign of research and development.

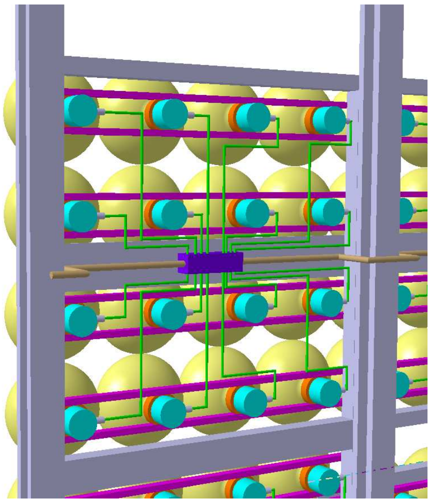

Figure 3: *Sketch of a possible photosensor basic module composed of a matrix of 4×4 12″ PMTs with the electronic box containing the High Voltage unit and the Readout chip.*

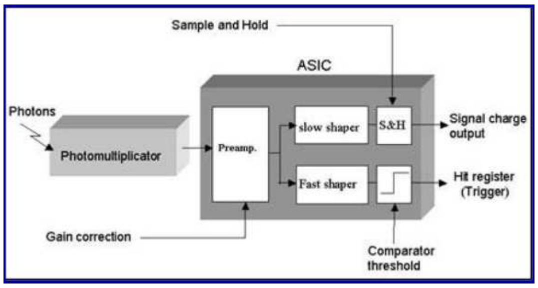

Figure 4: *Sketch of the existing Read Out electronics developed for the OPERA Target Tracker and that is intented to be extended for MEMPHYS by integrating the ADC and TDC.*

References

[1] *UNO proposal*, `Preprint SBHEP01-3, June 2001`.

[2] `http://jkt.tokai.jaeri.go.jp/`, .

[3] A. de Bellefon *et. al.*, *Memphys:a large scale water cerenkov detector at fr'ejus*, `hep-ex/0607026`.

[4] A. Lucotte *et. al.*, *A front-end read out chip for the OPERA scintillator tracker*, *Nucl. Instrum. Meth.* **A521** (2004) 378–392.