SoLid - Progress Report

Search for short baseline antineutrino disappearance with composite ^{6}Li detectors

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The Solid collaboration is currently carrying out a new generation of neutrino experiment, which addresses the key challenges for high precision $\bar{\nu}_e$ measurements at very short distance from nuclear reactors. The primary goal is to test the sterile neutrino hypothesis by searching for very-Short-Baseline neutrino oscillation. This physics case has implications in particle physics and cosmology, as well as reactor and nuclear physics. Furthermore, the detector concept opens very attractive options for future applications in reactor monitoring. In the first part, this document describes the objectives of the experiment, in relation to the international context and the state of the art in the field. Afterwards, it presents the reactor neutrino source, the detector setup, its performance and the physics program. Finally, it highlights the leading role of the French community within this international collaboration and conclude by presenting its perspectives in the medium-to-long term.

Contents

1 Physics motivation

1.1 Objectives

1.1.1 Sterile Neutrino and Reactor Antineutrino Anomaly

Sterile neutrinos, originally introduced by Bruno Pontecorvo in 1967, are well-motivated in many extensions of the Standard Model as they appear in most of the possible mechanisms to explain neutrino masses. Apart from these theoretical considerations, the first hints appear from both SAGE and GALLEX solar neutrino experiments which measured a significant deficit of the neutrino flux, when using high-activity ν_e sources during calibration runs [1]. Then, two accelerator-based neutrino experiments, LSND and MiniBoone have observed persistent anomalies, in electron neutrino appearance and muon neutrino disappearance [2]. The third signal, in the early 2010, came from the re-evaluation of the $\bar{\nu}_e$ reactor flux obtained with state-of-the-art prediction model. It exhibits a 6% average deficit on the measured antineutrino flux [3]. This deficit, known as the Reactor Antineutrino Anomaly (RAA), is significant at 2.5 σ level. Though some tensions persisted when combining both LSND and MiniBoone results, no phenomenological models are known to better fit all the data than adding sterile neutrinos at eV-scale. The direct search for such a sterile neutrino at very short baseline owns a clear-cut physics case. Several projects are thus carried out in the context of an international competition. In this framework, SoLid was specifically designed to address the Reactor Antineutrino Anomaly by performing new measurements at very short-baseline from the BR2 research reactor core. The energy resolution and the high segmentation of the detector will allow to perform rate/shape oscillation analyses, independently from the reactor flux model. The objective is to cover, in three years of data taking, the best fit values to test in fine the existence of light sterile neutrino(s) with $\Delta m^2_{14} \sim 1\ eV^2$.

1.1.2 Reactor Shape Anomaly

Recent θ_{13} precision measurements are all indicating a deviation in the $\bar{\nu}_e$ energy spectrum shape, from 5 and 6 MeV [4], also known as the 'Reactor Shape Anomaly'. It is likely related to nuclear and reactor physics and thus put the $\bar{\nu}_e$ flux prediction and its uncertainties estimation into question. Models are scrutinized and many dependencies are currently investigated: fission yields and their dependences with neutron energy spectrum, beta spectrum shape and weak magnetism correction, time-dependent relative contribution of fissile isotopes (^{235}U, ^{239}Pu, ...) or the energy response linearity of detectors (Gd-LS). SoLid experiment will address this shape anomaly by providing new measurements, which are unique in several respects. First, the SoLid apparatus is using a new detection principle with slightly different systematics than usual liquid scintillator. It could give insights about whether the shape anomaly comes from an energy reconstruction artefact. Secondly, the BR2 reactor core is a HEU research reactor core which is unique in its design and operating mode (Highly Enriched Uranium: 93 % of ^{235}U). By combining several experiments, with different fuels and operations, the reactor community might be able to identify the origin of the shape anomaly. Besides, French groups are currently performing state-of-the-art prediction of the $\bar{\nu}_e$ energy spectrum by using 'ab initio' summation method instead on relying on integral beta conversion measurements. These summation approach is thought to be the best way to address the problem. It should be noted that the understanding and the precise prediction of reactor antineutrino spectrum is an essential ingredient for next Medium-Baseline Reactor experiment JUNO.

1.2 State of the art and challenges

The way to detect $\bar{\nu}_e$ coming from nuclear reactors is the inverse beta decay interaction (IBD):

$$\bar{\nu}_e \ + \ p \ \rightarrow \ n \ + \ e^+ \qquad\qquad (E_{\bar{\nu}_e} > 1.805 \text{ MeV})$$

This process owns the advantages of having the highest cross-section at typical reactor energy and of being known with uncertainties at % level [5]. Experimental approaches are generally using the coincidence technique, which consists of detecting both the positron and the neutron, within a short time window, typically up to hundreds of microseconds [6]. This provides a robust selection of IBD interaction, with a good control of accidental backgrounds. A variety of segmented detectors has been operated by former reactor neutrino experiments. Most of them have used a large mass of $\bar{\nu}_e$ target together with neutron detectors, typically layers of ^{3}He counter. The different $\bar{\nu}_e$ target used were, either liquid scintillator (LS) read out by photomultiplier tubes (PMT) allowing only the measurement of IBD coincidences, or inert volumes (water or polyethylene) allowing the measurement of neutron capture rates. This last technique enables the neutrino flux determination at 2% level near Krasnoyarsk, Rovno and Bugey reactors [7]. More recently, oscillation experiments near reactor had to scale the fiducial volume to several tonnes while improving the energy resolution. They hence used homogeneous volumes of liquid scintillators. It results on a very good visible energy containment and a reliable neutron capture efficiency, which made possible the high precision θ_{13} measurements [4].

Nevertheless, there are several challenges to be overcome by new very short baseline experiments, which are aiming to operate at ground level and at closer distances from reactor core than ever before (~ 10 m):

- Cosmic-ray background, in particular neutron and muon, can induce secondary reactions such as spallation and activation in the fiducial volume of the detector. It results in a time-correlated background which occurs orders of magnitude more frequently than the expected $\bar{\nu}_e$ rate. In order to minimise these backgrounds, current neutrino experiments operate underground with an overburden of at least 50 m water equivalent. However, the closer we get to the reactor core, the more difficult it becomes to benefit from 'natural' cosmic shielding.
- Reactor cores are intense source of neutron and γ-ray. These backgrounds, which could be very high close to the reactor core, roughly scale with the power and thus with the antineutrino signal. In addition, high density passive shielding, necessary to substantially reduce gamma-rays, increases other background radiations, especially spallation, that are also difficult to predict or shield. Reactor background might be therefore difficult to mitigate.
- Last but not least, the high level of safety and security inside the reactor containment building impacts the choice of the detector components, the nature of the installation and the operational regime of the experiment. In particular, the use of large amount of hazardous component (like flammable liquid scintillator) is often prohibited. Besides, there is very little space available.

1.3 Very Short Base-Line experiments

The so-called 'Reactor Antineutrino Anomaly' triggered several projects world-wide (see Table 1). All these reactor neutrino experiments started to record physics data, or are in commissioning phase. First results have already been published by NEOS [9] and DANSS [15] but systematics are still to high to conclude. Notwithstanding, the last combined and model-independent analyses are still in favor of sterile neutrino with mixing parameters $\Delta m^2_{14} = 1.3$ eV^2 and $sin^2\theta_{ee} = 0.049 \pm 0.023$ (2σ) [8]. The SoLid experiment, which has started its Physics Run in February 2018, enters in a timely manner in this international competition.

Project	Tech.	Seg.	Mass [t]	P_{th} [MW]	Fuel	L [m]	Overb.[m.w.e]	S/B
SoLid [12,13]	**PS**-^{6}Li	3D (5 cm)	1.6	60-80	HEU	6 - 9	~ 15	3
Stereo [14]	**LS**-Gd	1D (25 cm)	1.8	55	HEU	9 - 11	~ 15	≥ 1
Prospect [11]	**LS**-^{6}Li	2D (15 cm)	3	85	HEU	7 - 12	few	~ 3
DANSS [15]	**PS**-Gd	2D (5 mm)	0.9	3000	LEU	10.7 - 12.7	~ 50	20
NEOS [9]	**LS**-Gd	none	1	2800	LEU	24	~ 20	22
Neutrino-4 [10]	**LS**-Gd	2D (10 cm)	1.4	90	HEU	6 - 12	~ 10	≥ 1

Table 1: Comparison of sterile neutrino experiments near reactor, listing the detection technique (Tech.), the segmentation (Seg.), the target mass (Mass), the thermal power (Pth) and fuel of the reactor, the baseline (L), the overburden (Overb.) and the expected signal to background ratio (S/B).

In order to obtain a convincing sterile neutrino signature, all these very short-baseline reactor experiments must use segmented (and/or movable) detector while responding as efficiently as possible to the difficulties raised in section 1.2. Most of them are still using cells of usual homogenous liquid scintillator, coupled with PMT for the optical readout. It enables a good energy resolution but it is not efficient for background identification/rejection. Conversely, two innovative experiments, SoLid and DANSS, have made the choice of developing segmented plastic scintillator, with slightly different geometries and optical readouts. SoLid presents the advantage of combining both 3D topology reconstruction and pulse shape discrimination.

In this international competition, the SoLid detector and its physics program has the following features:

- The detector concept is a change of paradigm (see section 2.2). Instead of increasing the passive shielding, we use the detector itself to actively identify and reject all categories of backgrounds limiting the need for dense materials around the detector. The SoLid approach enables a less complex detector design and increases the ability to understand and reject unforeseen backgrounds. Moreover, this innovative concept exhibits linear energy reconstruction with slightly different systematics.

- The (HEU) BR2 reactor core is unique in its core geometry and operating mode. Reactor background has been measured to be low, predictable and stable over years. Furthermore, we benefit from a very strong partnership with the BR2 management. Since 2012, it provides all the technical support to operate the non-hazardous detector, in a spacious and quiet area, with no time limitation.

- Last, the probed oscillation-length, between 6 and 9 meters, is the shortest amongst all the experiments. It will allow to probe higher Δm^2, than most of the others projects, roughly centered around 10 meters.

All in all, the SoLid project, while being complementary to other searches, has a unique position in this landscape. It will allow to perform world-class search for sterile neutrino and precise measurements of the antineutrino flux and energy spectrum coming from the ^{235}U fissile isotope.

Besides reactor experiments, an active sterile search is also performed by using accelerator decay-in-flight (DIF) neutrino beams. At the present time, the results obtained with LSND and MiniBoone indicate similar mass-squared splittings at eV-scale. However, it is presently not clear whether the appearance and disappearance experiments can be simultaneously explained by sterile neutrinos. The US is currently running the Booster Neutrino Beam (BNB) which enables the deployment of multiple detectors at different baselines: SBND, MicroBooNE and ICARUS. However, these approaches are very expensive and suffer from large cross-sections uncertainties. A competitive reactor experiment like SoLid has the advantage of using a very well known probe (IBD) combined with an intense man-made source of antineutrinos. Besides, it covers the electron neutrino to sterile neutrino oscillation phase-space that is not easily reachable with accelerators. SoLid is then also fully complementary to this accelerator-based program.

2 SoLid experiment

2.1 The BR2 reactor at SCK-CEN

The SoLid experiment is operated at the BR2 reactor of the Belgian Nuclear Research Centre, SCK-CEN, in Mol. This 'tank-in-pool' reactor is among the most powerful research reactor in the world, with thermal and fast neutron flux up to 10^{15} n.cm^{-2}.s^{-1}. It is mainly used for nuclear fuel R&D, for production of medical isotopes (^{99m}Tc) and doped silicon semi-conductor (NTD) [17]. Its fuel matrix, which is highly enriched (93.5 % ^{235}U), has a unique twisted design which enables high thermal power in the range of 60-80 MW$_{th}$ in combination with a effective core volume smaller than one cubic meter ($\phi \sim 50$ cm; h ~ 90 cm). It should be noted that the SoLid technological development for future application of reactor monitoring is of particular interest to SCK-CEN, as safeguards is one of its statutory tasks.

The detector is installed in direct line of sight with the nominal center of the reactor core at a distance of 6 meters (see Figure 1). This is the third detector installed at this location by the collaboration, after NEMENIX in 2013, and SM1 in 2015. It is arranged normal to detector-reactor axis, facing the concrete reactor pool wall. The experimental setup is bio-shielded with 20 cm lead between the detector and the reactor pool. No other experiments or beam lines surround the experiment at this floor of the containment building. Unlike other neutron source facilities (ILL, Oak Ridge HFIR), the reactor background conditions are low and stable over years. Nevertheless, the overburden of the experiment is small ($\sim$ 30 m.w.e.) and not effective enough to protect from external cosmic background. This last point has been determined experimentally with NEMENIX and SM1 prototype and compared with a full-chain Geant4-based Monte-Carlo simulation [16].

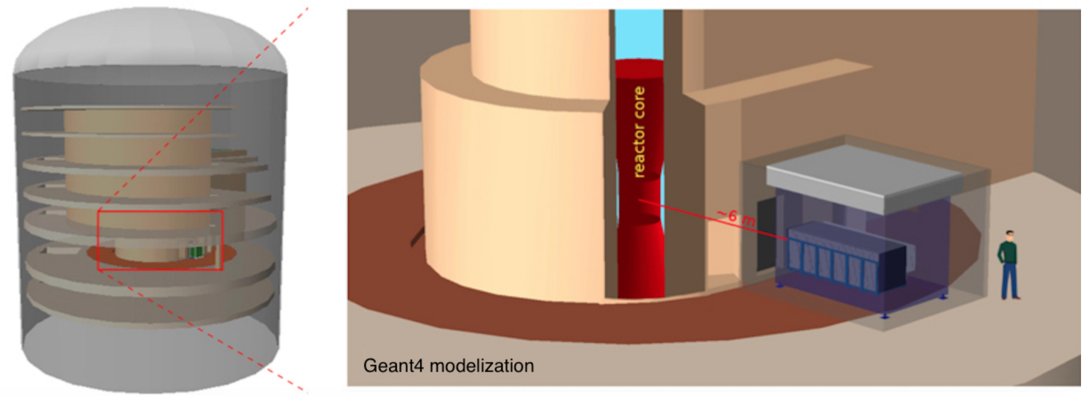

Figure 1: Sketch of the BR2 containment building and positioning of the SoLid detector (Geant4).

At the end of February 2015, the reactor was shut down for a 1.5 year-long overhaul of its Beryllium fuel core matrix. The installation was restarted, as planned, in July 2016. In practice, the reactor operates at nominal power ($\sim$ 65 MW_{th}) during cycles of about 30 days each. It alternates with shutdown periods of the same duration. There is on average 6 cycles of reactor ON per year, resulting in a duty cycle of about 150 days/year.

2.2 From SM1 prototype to full scale detector

2.2.1 Detection principle

The basic detector cell consists of a cube of Polyvinyltoluene (PVT) of $(5 \times 5 \times 5)\ cm^3$, of which two faces are covered with thin micro-composite screens made of ^{6}LiF:ZnS(Ag) scintillator. The PVT, which provides the proton-rich $\bar{\nu}_e$ target, is a mouldable plastic scintillator with high light-yield and excellent optical transparency. Following positron interaction it produces a prompt and rapidly decaying scintillation signal (ES). The PVT acts also as a neutron moderator. After thermalization process, over a period of up to hundreds of microseconds, neutrons are captured in the ^{6}LiF:ZnS(Ag) screens, through a break-up reaction on ^{6}Li:

$$n \ + \ ^6Li \ \longrightarrow \ ^3H \ + \ \alpha \ + \ 4.78MeV$$

The high density of ionisation energy following neutron capture leads to a large population of excited states, with a wide range of recombination transitions to the ground state. The resulting neutron signal (NS) exhibits a relatively long tail lasting several microseconds, which is significantly longer in duration than the prompt positron signal of PVT. IBD reaction products can thus be distinguished using pulse-shape information (see Figure 3).

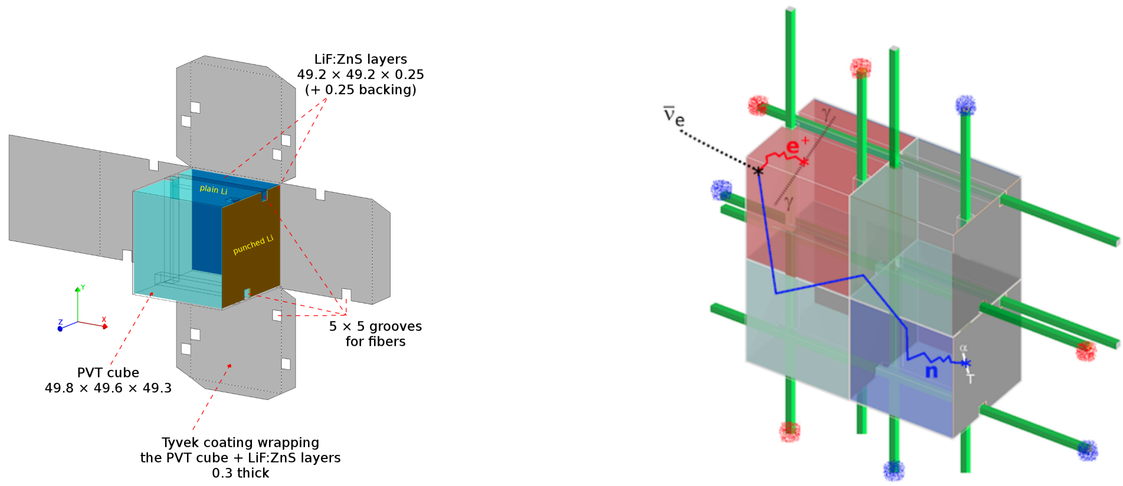

Figure 2: (Left) PVT cube covered with a layer of ^{6}LiF:ZnS(Ag) and wrapped in a reflective material. (Right) Principle of $\bar{\nu}_e$ detection in separated voxels: wavelength shifting fibres placed in perpendicular orientations allow to collect the scintillation light from each cells of the array.

All cubes, along with their ^{6}LiF:ZnS(Ag) screens, are wrapped within a reflective Tyvek sheet, which enhances light capture and minimises light leakage to neighbouring cells. Scintillation light, produced by both ^{6}LiF:ZnS(Ag) and PVT, are then partly trapped in four wavelength shifting fibres (St Gobain - BCF-91A), which cross each cube in four opposite faces. The wavelength-shifted light is then collected by a silicon photomultiplier (Hamamatsu - S12572-050P) optically coupled to one of the end of the fibre. The SiPM pulse amplitude spectrum is related the number of single pixel avalanches (PA) triggered by the incoming photons. In order to improve the light collection, a mirror is attached to the other end of the fibre. The fine segmentation and the orthogonal readout enables the localisation of the scintillation signal via an hodoscope technique. Taking into account that IBD events are spatially very well contained (positron and neutron is are likely to be detected in a neighbouring cell), the topology reconstruction is exploited to reduce drastically the remaining time-correlated backgrounds (see section 2.2.2).

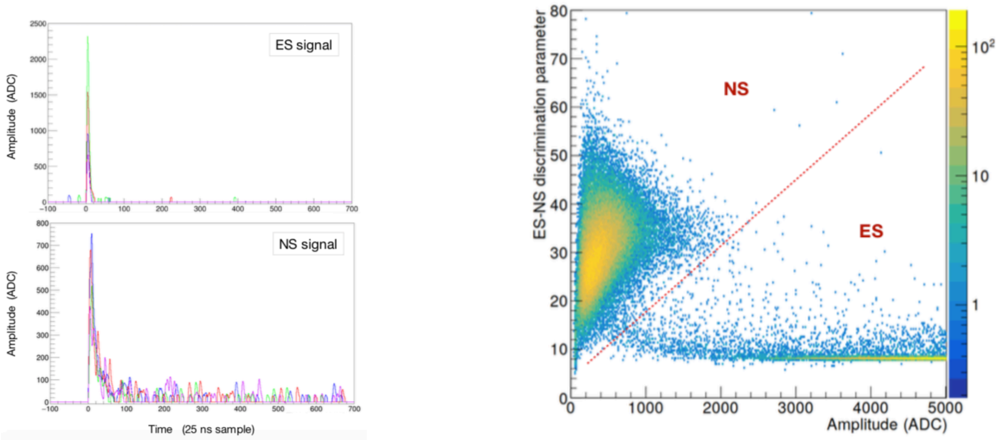

Figure 3: (Left) Typical examples of scintillation response to ES signal in PVT (top) and NS signal in ^{6}LiF:ZnS(Ag) screens (bottom). (Right) Example of pulse shape discrimination based on integral over amplitude ratio.

2.2.2 SM1 Prototype highlights

A 288 kg prototype detector, designed by SUBATECH, was deployed at BR2 in 2015 and collected data during both periods ON/OFF. This campaign was impacted by the poor performance of the analog electronics, which has required to raise the trigger threshold, then decreasing drastically the efficiency for triggering on neutron signals. Despite this limitation, its operation demonstrated all the expected performances and capabilities of the detection principle (see references [12, 13]). Some features are highlighted in this section. First, Muons have been efficiently tagged and tracked. This capability was first exploited to equalize the light response of all channels to a precision of 3% which demonstrated the stability of the energy scale over time. Cosmic muons can produce several secondary events in the detector. Two classes of those, spallation neutrons and Michel electrons, have been carefully studied. Both reconstruction, combined with our knowledge on the decay properties of muons and the neutron moderation in PVT, validated the time delay coincidence techniques as well as the particle identification based on PSD (see Figure 4 for spallation neutron reconstruction). These studies allowed to investigate the IBD like signatures and demonstrated unprecedented background rejection capabilities [13]. Combining the event topology and hit multiplicity with the prompt ES signal to NS signal time difference, the background event rate was reduced by orders of magnitude (see Figure 5).

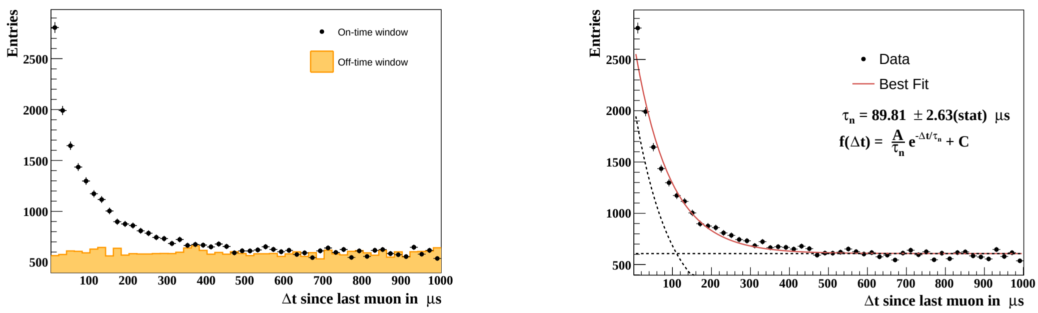

Figure 4: Δt distributions between a tagged muon and a neutron-like signal (Left). A combined fit with an exponential function and a flat background yields the value of $\tau_n = 89.81 \pm 2.63$ (stat) μs for the neutron capture time (Right).

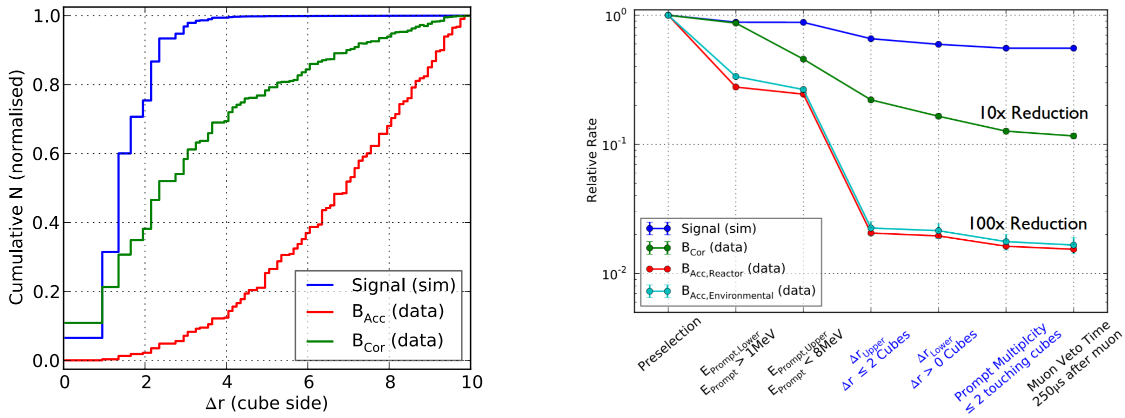

Figure 5: (Left) Cumulative distribution of radial separation between positron and neutron candidates (ΔR), prior to other IBD selections. (Right) Signal and background relative rates for selection cut applied sequentially. The relative rates are obtained by normalising to the number of prompt-delayed coincidences reconstructed (Δt cut only).

2.2.3 Full scale design

The full-scale design builds on the successes of the construction and operation of the SM1 prototype, Monte-Carlo Geant-4 simulation and a dedicated test bench operated at LAL (see section 4.2.5). The cells are stacked in planar frames of 16x16 cubes, designed bu SUBATECH, with a typical surface area of about 1 meter square. 10 planes are then grouped to form one module (see Figure 6). Overall, the SoLid Phase-I is composed of 5 modules, containing 12800 detection cells and corresponding to a fiducial mass of 1.6 tons. The 3200 MPPC channels are readout with a new customized electronics, with far superior noise-tolerance, capable of continuously processing around 3Tb/s of ADC data. The system employs an FPGA-level waveform characterization which triggers in real time on complex signatures of IBD neutron events [18]. Following a neutron trigger, data from a space-time region of interest are read out.

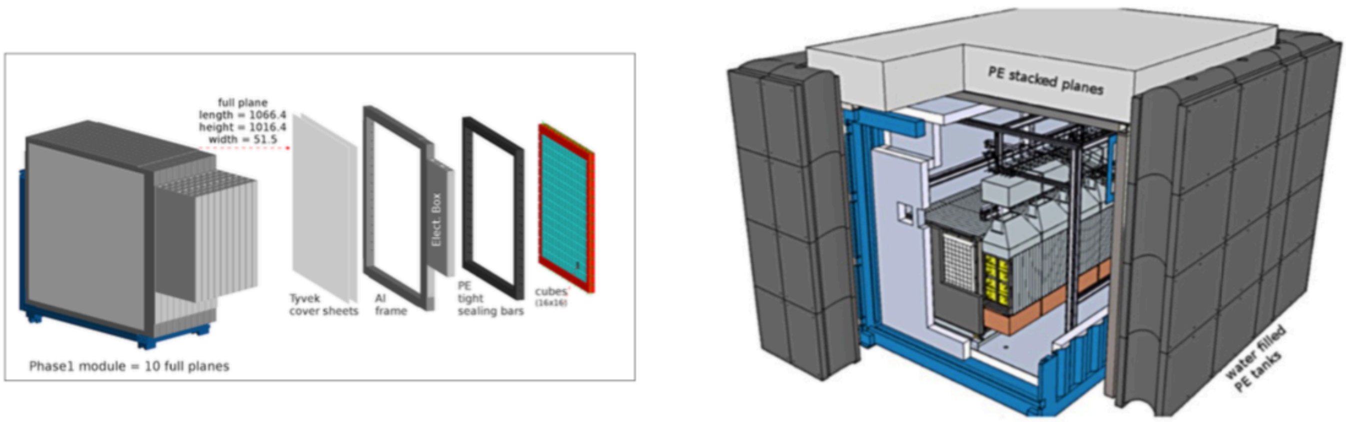

Figure 6: (Left) Mechanical designs of a SoLid module with its electronic boxes. (Right) Sketch of the full scale detector inside its container surrounded by 50 cm thick passive shielding (Water brick and Polyethylene plate).

The detector and its electronics are installed within a container ($2.4\times2.6\times3.8$ m^3), which acts as a Faraday cage. It is cooled to an ambient temperature of $\sim 5°$C, enabling to reduce by one order of magnitude the MPPC dark count rate. In order to control the detector/electronics environement during data-taking, several sensors (Temperature, Humidity, Pression, Luminosity), have been instrumented by LPC-Clermont (see section 4.1.1). Gamma background is monitored by using NaI scintillator (PMT coupled) and a new Radon detector also proposed by LPC-Clermont is currently being implemented (see section 4.2.6). A passive shielding, designed by SUBATECH (see section 4.1.1), surrounds entirely the container to reduce cosmic and reactor-induced backgrounds. It consists of water-shielding bricks on the sides (50 cm thick, 3.4 m high) and Polyethylene plates on top (50 cm thick,). In order to capture remaining thermalized neutron, thin cadmium sheets (2 mm thick) are sandwiched between the passive shielding and the container. Last, an automated calibration system, CROSS, has been designed by LPC-Caen (see section 4.1.1) to make the survey and the precise calibration at % level (energy reconstruction, neutron efficiency) on site and during the data-taking.

2.2.4 Construction & Quality Assurance

The construction of the full-scale SoLid detector started in summer 2016 at Ghent University, and took almost one year. It required a very important effort in terms of human resources. French community participated at the level of $\sim$ 50 person-weeks. In order to guarantee a good response and homogeneity of all detection cells, a quality assurance process, driven by French collaborators (see section 4.2.3), was implemented. All the components information (batch, weight) has been carefully tracked and stored in a dedicated database. It allowed to control at per-mil level the proton content. Meanwhile, an automated calibration system, CALIPSO, designed by LPC-Caen (see section 4.1.1), allowed a first calibration and the identification of defective components during the construction. It reveals a very good uniformity over all the cells, a neutron capture efficiency above 60 % and a light yield higher than 60 PA/MeV.

2.2.5 Detector operation

The installation of the detector on site at BR2 started late September 2017. The detector was operational at the beginning of 2018 after a successful commissioning. Figure 7 shows online trending plots obtained during the last reactor ON cycle. It can be seen that the trigger rates, as well as SiPM response, are stable over this period. Data-taking dead-time was monitored continuously and was found to be negligible. Analysis is on-going and preliminary results will be presented at the upcoming 2018 summer conferences.

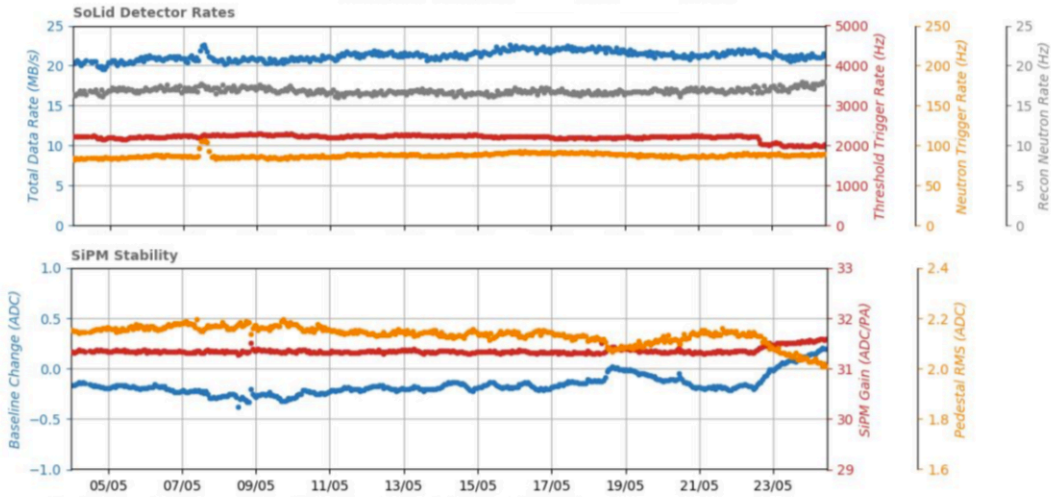

Figure 7: (Top) Data rates of last Reactor ON cycle: total, threshold trigger (x-y time coincidence above 2 MeV) and neutron trigger (PSD peak-counting algorithm). (Bottom) Mean stability of all SiPMs ; small variations are due to neutron trigger tests and temperature changes caused by some interventions.

2.3 Physics program & discovery potential

The physics campaign started, after three months of installation and commissioning, on 6th of February 2018 (BR2 cycle I01/2018a). The data taking is planned to last at least 3-years in order to accumulate enough statistics and achieve a relative measurement almost solely limited by the systematics of the detector. Several major physics results and publications can be expected all along the physics run.

First, the Phase-I, after only one year of data taking (5/6 cycles), will enable to collect an accumulated statistics above 5.10^4 $\bar{\nu}_e$ reconstructed events, sufficient to obtain two new important measurements:

- At research reactor, the thermal power uncertainty is of the order of 3-5%. An absolute neutron efficiency of a few percent or less would provide sufficient accuracy for an absolute measurement of the $\bar{\nu}_e$ flux to be made. It will allow to confirm/infirm RAA deficit observed at longer distances (> 10 m) and perform the first 'rate-only' oscillation analysis below 10 m with 2 to 5 points.

- We will also perform a first direct ^{235}U energy spectrum measurement, complementary to the Stereo measurement @ ILL, but using a different reactor and a new detector, with different systematics. Precision of the measurement will be limited by statistics, background and energy reconstruction uncertainties.

As long as the statistics will be accumulated and the systematics reduced, we would be able to pursue in more details the study of the ^{235}U energy spectrum deviation. The inter-comparison of the results coming from different experimental setups (HEU/LEU, LS-Gd/Plastic), combined with an improved 'ab-initio' prediction model, would be of major interest to understand the Reactor Shape Anomaly.

After 3 years of data taking, the recorded statistics will allow to complete a relative 'rate/shape' oscillation analysis for distances withins 6 and 9 m. A self-normalised analysis, independent of the reactor flux model, will enable to test the sterile neutrino hypothesis with mass $\Delta^2_{m14} \sim 1eV^2$ and constrain the active-to-sterile oscillation parameters space (see Figure 8).

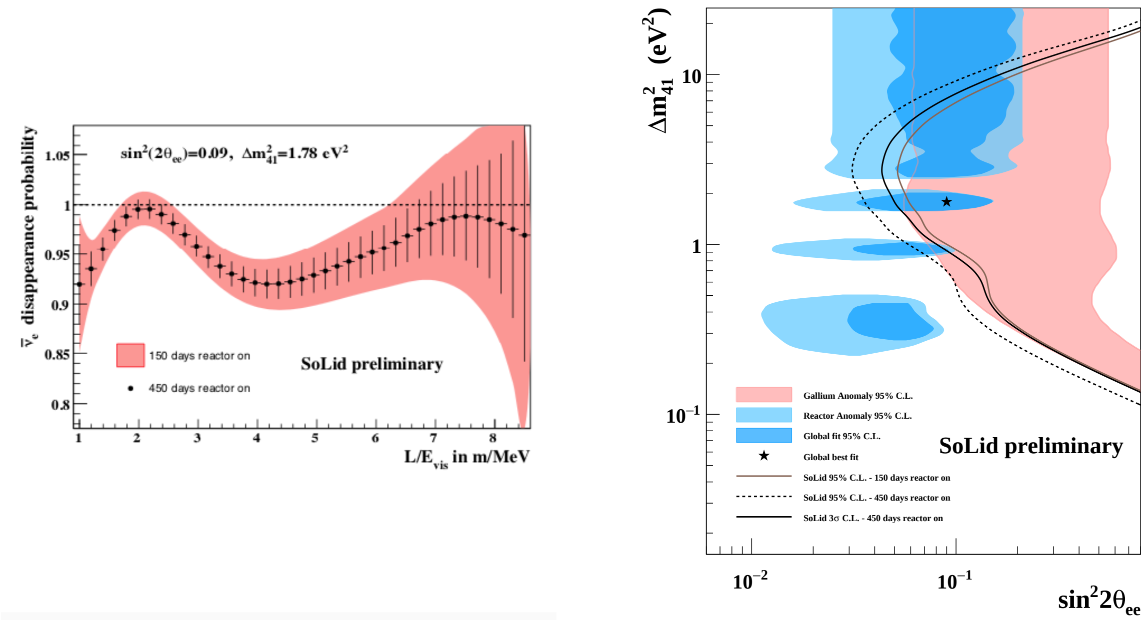

Figure 8: (Left) SoLid projected disappearance probability as a function of the L/E ratio, for best fit values: $\sin^2(\theta_{ee})$ = 0.09 and Δm^2_{14} = 1.78 eV^2. (Right) Reactor and Gallium anomalies allowed region and SoLid non-oscillation sensitivity contours in the hypothesis of one additional sterile neutrino (3+1 model).

3 International Collaboration

The SoLid collaboration is now driven by 12 laboratories gathering more than 40 physicists in France, UK, Belgium and USA (see Table 2). The necessary manpower and fundings have thus been gathered to handle the construction and the operation of the full-scale detector. Without including manpower, the overall budget of the entire SoLid detector is estimated to be about 1.2 M€. Several funding agencies contributed and the total budget of the eexperiment has been secured (see sections 3.1 and 3.2.2). All three parties have contributed about 1/3 of the total cost. Foreign partners contributions are gathered in section 3.1. The French consortium gather four laboratories: LAL, LPC-Caen, LPC-Clermont and SUBATECH. Its central role and impacts in the project are described in detail in sections 3.2 and 4.

The organisation of the collaboration is formalised by a constitution document, with an International Board (all laboratory representatives), a spokesperson (Antonin Vacheret, Oxford, UK), a technical coordinator (Nick Van Remortel, Antwerp, B) and an analysis coordinator (Frederic Yermia, SUBATECH, Fr). As long as the detector commissioning ended, human ressources have been redeployed to focus on data analysis. Several Working-Groups (WG) have been created: Calibration, Energy reconstruction, Backgrounds, DAQ/Software, Simulations, Proto-Analysis. The management team coordinate the different tasks. General meetings are organised at least 3 times year. Weekly meetings are held for each of the WG.

3.1 Foreign Partners

The project was initiated in UK by Oxford and Imperial College with the development of a neutrino detector prototype, NEMENIX, based on composite ^{6}LiF:ZnS(Ag). The overall UK effort, reinforced by Bristol University, was focused on upgrading the read-out electronics, the trigger scheme and the DAQ required for the full size detector. They handle the official software, from low level to data analysis, and took on the management of the large size Monte Carlo simulation on gridPP-Tier2. Their main technical contributions (design/construction) are: module structure, electronics box and container instrumentation. Regarding fundings, they got early support of the Science & Technology Facilities Council (STFC), and sub-department of Particle Physics at Oxford (Merton College) and Imperial College. In 2016, A. Vacheret was awarded at an ERC Consolidator Grant, at the level of 1.8 M€ (proposal 682474 - PEA fondamental matter 2015). UK teams are thus currently providing the experiment spokesperson, significant funding, Postdocs and Ph.D. effort to the collaboration (see Table 2).

Foreign Partners	Names (position)	Main contributions
Imperial College London (UK)	**A. Vacheret** (Ass. Prof.), D. Saunders (Postdoc), B. Hosseini (Postdoc), K. Graves (Phd)	DAQ/Electronics, Mechanics Software, Analysis
University of Oxford (UK)	**A. Weber** (Prof.), N. Ryder (Postdoc), B.C. Castle (Phd)	DAQ/Electronics
University of Bristol (UK)	**D. Newbold** (Prof.), D. Cussans (Res. Fell.), J. Rademacker (Reader), L. Arnold (Phd), S. Manley (Phd)	DAQ/Electronics, Software, Mechanics
Antwerp University (B)	**N. Van Remortel** (Prof.), A. De Roeck (Prof.), Y. Abreu (Postdoc), M. Verstraeten (Phd)	DAQ/Electronics, Simulation, Analysis
Universiteit Gent (B)	**D. Ryckbosch** (Prof.), I. Michiels (Phd), C. Moortgat (Phd), G. Vandierendonck (Phd)	Mechanics, Construction Software, Analysis
Vrije Universiteit Brussel (B)	**J. D'Hondt** (Prof.), P. Van Mulders (Postdoc), L. N. Kalousis (Postdoc), S. Vercaemer (Phd)	Simulation, Analysis, Oscillation Fit
SCK-CEN (B)	**S. Van Dyck** (BR2 reactor manager), B. Coupé (Staff), S. Kalcheva (Staff), L. Ghys (Postdoc), J. Mermans (Staff)	Detector integration/operation Reactor simulation
Virginia Tech (USA)	**J. Link** (Prof.), P. Huber (Prof.), C. Mariani (Ass. Prof.)	Chandler dvpt.

Table 2: Foreign partners: collaborators (physicists only) and their main contributions to the project.

The project began in Belgium in 2012, with the installation of NEMENIX experiment at SCK-CEN which paved the way for the deployment of the full-scale detector. It then expanded with three Belgian Universities: University of Gent, University of Antwerp and the Free University of Brussels (see Table 2). Over the years, SCK-CEN provided valuable supports, on the financial, human resources and technical aspects, for operating the detector on site. They fund logistics expenses as well as shielding materials. Besides, Belgian universities concentrated their efforts on the detector construction and its installation on site. They are now strongly involved in Monte-Carlo simulation, data processing and analysis. The Belgian partners, received funds for SoLid in a joint application to the Flemish Hercules foundation. This was supplemented by a research project of the Flemish Research Foundation (FWO) and the Belgian Federal Science Policy Office (BelSpo), to cover costs for PhD and postdoctoral researchers for a period of four years. The overall funding currently obtained in Flanders is therefore 1.2 M€, of which 35% was dedicated to the construction.

Regarding the American contribution (see Table 2), they provided in 2015 a one-year Post-Doc to work on analysis and read-out simulation. Currently, they pursue R&D efforts on the HiRES Chandler technology [19], as a future upgrade of the SoLid detector. They continue to seek for funding, at the order of 2 M$ (DOE or NSF) for a possible deployment at BR2 in 2020.

3.2 French Consortium

3.2.1 Human ressources

The SoLid Project clusters four IN2P3 laboratories with strong interplay (see Table 3). The collaboration between SUBATECH and Oxford began in September 2012, on applying for antineutrino detection for reactor monitoring in the context of nuclear safeguards (Oxford John Fell Travel Fund). They benefit from strong expertise in neutrino oscillation analysis and reactor physics. LPC-Caen, already involved since 2012 through students partnership in NEMENIX construction, joined the collaboration in 2013. They worked initially on reactor simulation, then took care of the neutron calibration. The French part has next increased in January 2015, with the entry of physicists from LAL, which have expertise in plastic scintillators and ultra low natural radioactivity (BiPo). Finally, in September 2016, a new group from LPC-Clermont laboratory, which comprises five part-time permanent members, joined the collaboration, thereby reinforcing our working capacity for running the project and analysing the data.

Laboratory	Names (position)	Main contributions
LAL	**M. Bongrand** (CR), L. Simard (PR), Y. Amhis (CR), M.H. Schune (DR), L. Manzanilas (Post-doc), D. Boursette (PhD) / S. Jenzer (IE), A. Blot (TCN), A. Migayron (AI)	Mechanics, Analysis, Calibration, BiPo
LPC-Caen	**B. Guillon** (MCF), G. Lehaut (CR), D. Durand (DR) G. Ban (PR), V. Pestel (Phd) / B. Carniol (IE), D. Goupilliere (AI), B. Bougard (TCN), C. Vandamme (TCN), J. Perronel (AI)	Reactor modelization, Mechanics, Analysis, Calibration
LPC-Clermont	**S. Monteil** (PR), H. Chanal (MCF), P. Crochet (DR) D. Boumediene (CR) / S. Binet (IR)	Instrumentation, Analysis
SUBATECH	**F. Yermia** (MCF), B. Viaud (CR), M. Settimo (CR), M. Fallot (MCF,), L. Giot (MCF), D. Henaff (PhD) / H. Carduner (IE), J. M. Buhour (IE), T. Milletto (TCN) Y. Bortoli (TCN), S. Fresneau (TCN)	Analysis, Calibration, Mechanics, Reactor modelization

Table 3: French Human ressources (physicists / engineers and technicians).

At present, the French collaboration gather fifteen permanent physicists, corresponding to roughly 11 Full-time equivalents (cf. Figure 9). During the construction phase, we also benefited from sizeable technical support from mechanical design offices and workshops (see section 4.1.1). It has reached its maximum in 2017, with four FTE working on the project (design, construction). As soon as the detector building ended, these efforts decreased significantly. For the next coming year, it stabilises around 0.4 FTE for the logistics of the CROSS robot and the instrumentation of the container. Physicist human ressources are currently consolidated by three PhD students and a Post-doctoral fellow (see Table 3). It will expand in 2018 by the recruitment of a new PhD student at LAL and two Post-Docs (ANR-funded) at SUBATECH and LPC-Caen. It will then allow to keep roughly constant human ressources ($\sim$ 11 FTE) for the next three coming years which will be focused on data analysis (see Figure 9).

		2014	2015	2016	2017	2018	2019	2020
LPC-CAEN	Physicist	0,7	0,7	0,9	2,4	3,7	3,7	3,7
	Ingeneers / Technicians	-	-	0,4	1,5	0,2	0,1	0,1
Subatech	Physicist	0,9	0,9	1,1	3	4	4	4
	Ingeneers / Technicians	1,25	0,25	1	2	-	-	-
LAL	Physicist	-	1,5	1,7	2,7	2,6	2,6	1,6
	Ingeneers / Technicians	-	-	0,2	0,6	-	-	-
LPC-CF	Physicist	-	-	-	0,6	0,6	0,6	0,6
	Ingeneers / Technicians	-	-	-	-	0,2	0,2	0,2

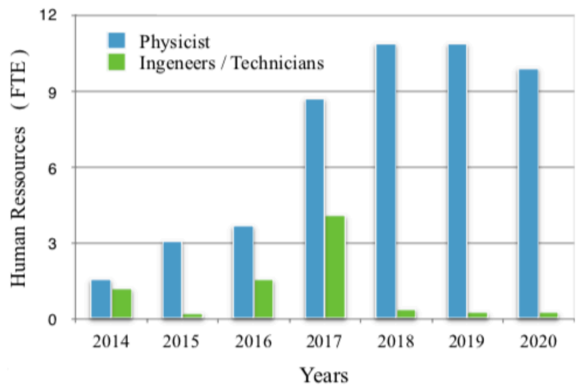

Figure 9: Evolution with time of the overall French human ressources (physicists / ingeneers and technicians) expressed in FTE (Full-time equivalent).

3.2.2 Funding sources

Since its beginning, the SoLid project got early support, full endorsement, and significant funding from each laboratory. For instance, a one module target mass was solely funded by the french laboratories (2015). The funding of the full-scale detector required additional ressources. Therefore, the search for funding has been carried out repeatedly and consistently. We are only discussing in the following the successful applications. First, SUBATECH laboratory got funded by Ressourcement Carnot-Mines 2013 for non-proliferation purpose at the level of 100 k€. After four calls for proposal to the ANR agency, French groups (SUBATECH/LPC-Caen/LAL) got funded in July 2016 with the ANR-16-CE31-0018-03 at the level of 600 k€, coordinated by F. Yermia (Subatech). It enables to consolidate the instrument construction, by financing 10 more detection planes (320 kg fiducial mass, 175 k€), and to increase the French manpower with three 2-years Post-Doctoral positions in each laboratories (SUBATECH, LAL and LPC-Caen). More recently, the LPC-Clermont group was elected in 2017 to an UCA funding for 20 k€. This allowed in particular to buy a Radon activity detector aimed at monitoring the BiPo background and served to welcome an Ukrainian student for a Master internship.

After two positive statements of the Scientific Council of IN2P3, the directorate provided an initial endowment at the level of 55 k€ in 2016, which was renewed downward in 2017 and 2018 at the level of 25 and 15 k€ respectively. During these periods, it covered most of the travel expenses of the French groups, as well as the CROSS calibration system built at LPC-Caen. Besides, IN2P3 provided human ressources by co-funding two PhDs, at LPC-Caen in 2016 (V. Pestel, Region Normandie) and SUBATECH in 2017 (D. Hennaff, Region Pays de Loire).

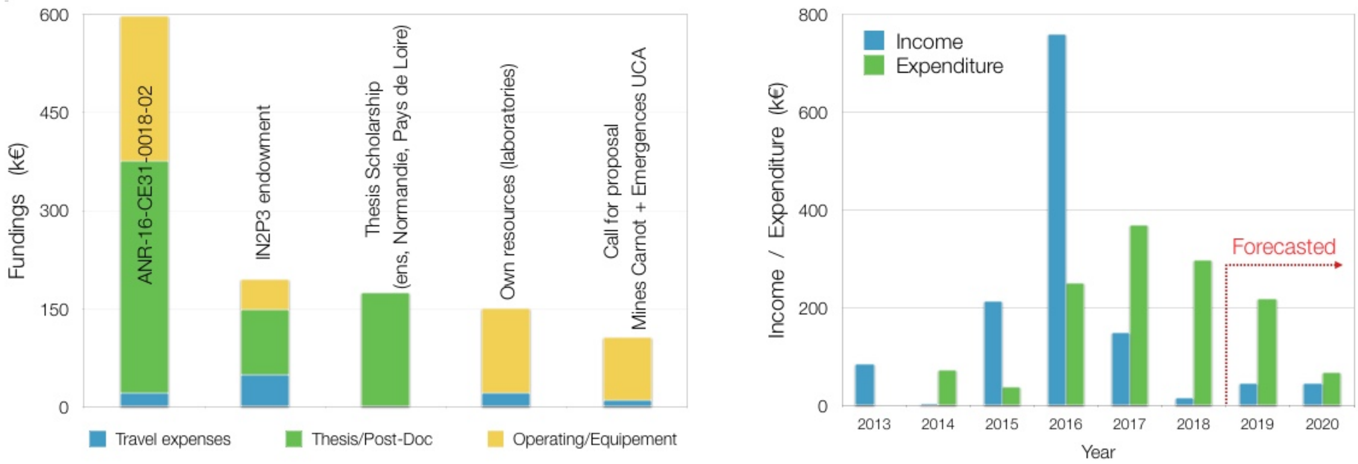

Figure 10: (Left) Overall budget categorized by source of funding and expenditure item (Detector Construction, Manpower and Travel expenses). (Right) Time evolution of the overall budget: income and expenditure.

The overall funding currently obtained in France is therefore 1.3 M€, of which 500 k€ were dedicated to the construction of the prototype and the full-scale detector, 630 k€ are currently devolved to human ressources. The rest, around 100 k€, has been used to cover the travel expenses (see Figure 10). For next coming years, the bulk of the expenditure item relates mostly to the incompressible non-permanent staff salary (PhD and Post-doctoral fellow). The fundings for the baseline operation of the experiment are secured. In contrast, the collaboration meetings, the contribution to shifts and the meetings dedicated to the Physics analysis (crucial in the first data-taking periods we currently have) are mostly relying on the laboratories budgets. The IN2P3 subventions were continuously decreased in the past years. The request for the year 2018 was 45 k€ for the four labs involved. The allocated budget was 15k€. This is in contrast to the situation experienced by some of the collaborators in the framework of the other experiments they take or took part in.

4 French Impacts

The French teams are complementary and share common expertise in reactor physics, neutron calibration, energy resolution or precision neutrino analysis. The competitive SoLid experiment allowed the French community, particularly young scientists, to consolidate their skills and their positions in the international neutrino physics field. They play a central role in the project and thus took on important responsibilities:

- Frederic Yermia (SUBATECH): Analysis Coordinator
- Luis Manzanillas (LAL): Run Coordinator, QA co-Coordinator, Calibration Coordinator
- Mathieu Bongrand (LAL): Publication/Communication Board
- Benoît Viaud (SUBATECH) / Mathieu Bongrand (LAL): Electromagnetic WG co-Coordinators
- Valentin Pestel (LPC-Caen): Neutron Calibration WG Coordinator, QA co-Coordinator
- Muriel Fallot (SUBATECH): Reactor WG Coordinator

Benefiting from a strong interplay, French groups actively contributed to the design and the construction of the detector. They are now taking care of the data analysis. Next sections highlight their main contributions.

4.1 Technical/Instrumental contributions

4.1.1 Mechanical designs [SUBATECH]

The mechanical design was the responsability of SUBATECH, taken care of by its mechanical department. F. Yermia was co-convener of the working group 'mechanics and construction' for the SM1 prototype, the design of the modules, the water shielding and the implementation of the whole experimental set-up at BR2 (see Figure 6). The final design of the full-scale detector builds on the sucessful SM1 achievements. A very close collaboration with the UK engineers has been necessary to deliver the design in time. The BR2 reactor being a nuclear safety area, all the inherent requirements have been fulfilled for the installation of the detector and the shielding. Due to oversized length of these frames, the machining for the Sub-modules plane has been subcontracted to a mechanical company. As a consequence, the French mechanical departments have been involved in the design, the assembly and the mounting of the detector components, prototype and plane design.

4.1.2 CALIPSO & CROSS [LPC-Caen, LAL]

The Quality-Assurance (QA) process has been realised thanks to a dedicated automated system, CALIPSO, proposed, designed and built by LPC-Caen (see Figure 11). This robot can position any well-known calibration sources (AmBe, ^{252}Cf, ^{22}Na, ^{60}Co) in front of a SoLid plane with a millimeter accuracy. A PE neutron collimator is added for performing NS calibration. Besides, a dedicated ^{22}Na self-triggering calibration head was designed at LAL, for the ES calibration. These systems were installed in Ghent laboratory in December 2016. It allowed to successfully measure the homogeneity of all the 12 800 detection cells during the construction phase (see section 4.2.3).

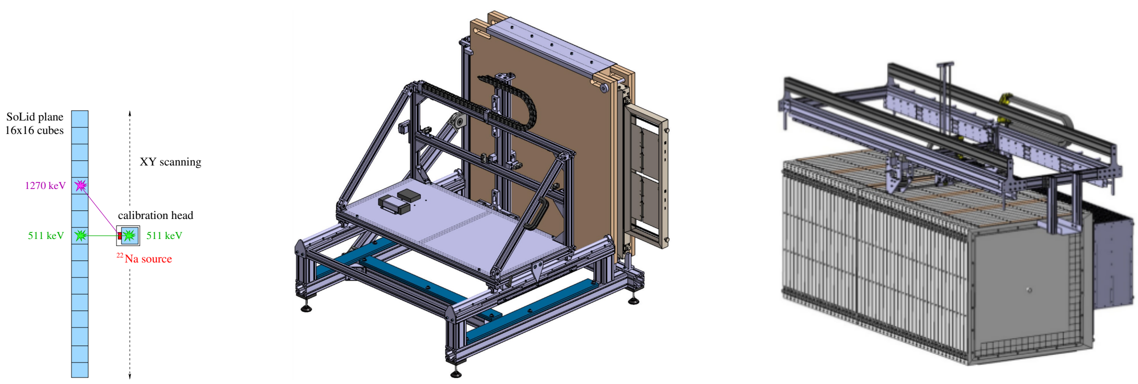

Figure 11: (Left) Sketch of the ^{22}Na source head. Mechanical design sketch of the two automated calibration systems: CALIPSO (center) and CROSS (right).

In order to survey the detector response on-site and all along the data taking, another 3D automated calibration system, CROSS, was also proposed, designed and built by LPC-Caen (see Figure 11). Each SoLid module (500 kg) were installed on a tray equiped with actuators, allowing to open few centimeters gaps between modules. Then, the automated system, installed within the container, can position any calibration sources between each modules, covering more than 52% of the plane surface. A dedicated window allows to insert the radioactive source within the container from the outside of the shielding. These systems allows to cover the large volume of the full-scale detector, while keeping the homogeneity/integrity of the overall fiducial target. The automatism and control-command, also developed by LPC-Caen, allow to drive calibration runs remotely, avoiding time-consuming manutention. CROSS makes then possible the successful survey and calibration of the detector response on-site (see sections 4.2.4 and 4.2.5).

4.1.3 Test bench @ LAL [LAL]

Performing a precise active to sterile neutrino oscillations search requires high light yield of the scintillating elements and uniformity of the response in the detector volume. The LAL group performed an optimisation study to maximise the light collection efficiency of PVT scintillating cubes. A precision test bench based on a ^{207}Bi calibration source has been developed to study improvements on the energy resolution and uniformity of the prompt scintillation signal of antineutrino interactions (see figure 12). A trigger system selecting the 1 MeV conversion electrons provides a Gaussian energy peak and allows for precise comparisons of the different detector configurations that were considered to improve the SoLid detector light collection. It is influenced by the choice of wrapping material, the position of the ^{6}LiF:ZnS(Ag) screen, the type of fibre, the number of optical fibres and the type of mirror at the end of the fibre. These test bench allowed to select the best possible materials and elements configuration. The overall gain results in an expected light yield of 52±2 PA/MeV for the SoLid Phase 1 detector while 18.6 PA/MeV has been measured for the SM1 configuration. This is an improvement of almost a factor 2.8 in the light yield. With this light yield the energy resolution target of $\sigma_E/E = 14$ % at 1 MeV has been achieved. The Phase-I detector plane light yield uniformity has also been improved to only 6 % difference between the most extreme cube positions thanks to the increase of number of fibres and optimal configuration (see Figure 12 right).

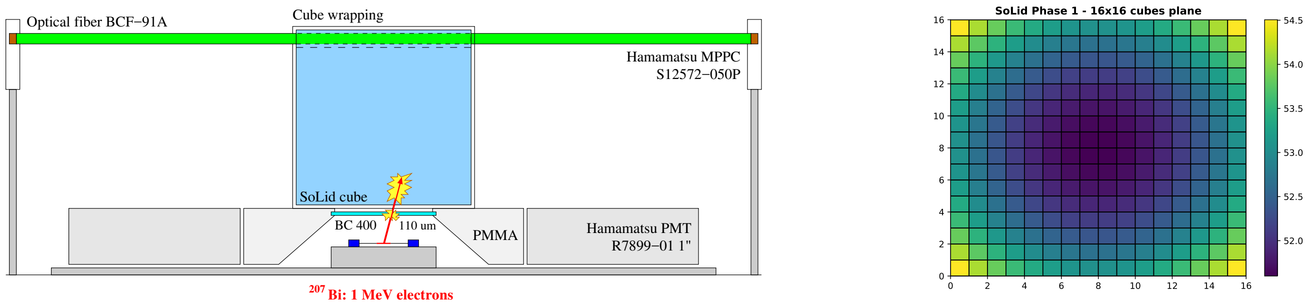

Figure 12: (Left) Schematic view of the LAL test bench: calibration source, PMTs and cube are mounted on a rail in order to move the system along the fibre. (Right) Resulting LY and homogeneity of a Phase-I detector plane.

4.1.4 Instrumentation / Environmental sensors [LPC-Clermont]

LPC-Clermont group took on the responsibility of the container instrumentation. Environmental observables such as pressure, temperature and humidity in the detector container are constantly monitored by means of a home-made system of sensors: a customised electronics board is hosting the sensors, which are controlled and read-out with a Raspberry-Pi device. This specific read-out is interfaced with the Data Acquisition and Run Control of the experiment.

4.2 Physics contributions

4.2.1 Analysis coordination and french involvment in the SoLid analysis [All]

The French activities related to the preparation of the Physics studies and the Physics analyses themselves are described in this section. They cover the full range of the sterile to active search as well as the antineutrino energy spectrum measurements. To a large extent, they build on the successes of the SM1 prototype, mostly promoted by the french laboratories. These prominent contributions are acknowledged by the charge of the Physics coordination of the SoLid Phase-I experiment led by F. Yermia, which was already the analysis coordinator for the SM1 analysis. The experience gained in Double-Chooz concerning the correlated backgrounds were primordial to understand the background at BR2. Furthermore we exploited the granularity to optimally select signal events based on the spatial topology. It allowed to validate successfully the SoLid technology [12] demonstrating that simple cut-based analysis significantly reduce the backgrounds, which led to the ERC and ANR fundings for the experiment.

Some specific analysis that French teams can lead, are already thought, to reduce background and the associated systematics as, for example, seeking to use the external SoLid layers as an active veto for fast neutron rejections and gamma coming from outside. This technique can be very powerful to reject directly fast neutrons but required some studies performed in France. Another study should be the use of annihilation gammas to determine a specific topology for the positron coming from IBD to improve the S/B ratio. Indeed the annihilations gammas escaping from the positron cube will produce some Compton scattering in others cubes around the IBD cube. This should provide a relevant topological feature for IBD interactions allowing to be treated by machine learning algorithms.

U235 Antineutrino spectrum measurements: French teams are currently working on the neutrino energy estimator (ES Working Group). The two cases where one or two annihilation photons are seen in the detector can be studied. In large scintillator detector the whole visible energy is used to estimate the positron energy. For a 3D segmented detector as the Solid one, alternative methods to estimate the positron energy can be designed excluding spatially the two 511 keV annihilation photons and correcting the measured kinetic energy by the positron mass to estimate the neutrino energy. SoLid can also probe deviations from prediction in other portions of the ^{235}U only spectrum comparing HEU and LEU core spectra from SoLid and Double Chooz [20]. SUBATECH being member of the Double-Chooz collaboration, the comparison of the measured spectrum would be facilitated. The main challenge will be to control the precision of the energy scale in the neutrino detectors to the few per mil level in both experiments.

Oscillation analysis and sterile neutrino hypothesis: The granularity of the detector and the properties of the PSD allows to envision the use of multivariate approaches in order to discriminate the signal from the background, in contrast with what is possible in the liquid scintillator techniques. Among them, the comparison of observed and simulated events will be quantified by building a likelihood comparing the event at the energy and position scale. We will develop an oscillation analysis using the most sensitive statistical methods. For this purpose a full software framework is under development. For the first result, a so called “blind analysis” strategy will be followed. This will be achieved by at least preventing that information from the reactor working group concerning the antineutrino spectrum is communicated to the people involved in the analysis. With a blind analysis, a bias of the results can be prevented, which is mandatory to test the reactor anomaly. In addition to this first analysis, measurements will also be performed for the separate modules of the detector located at a different distance.

4.2.2 Reactor & $\bar{\nu}_e$ flux prediction [SUBATECH, LPC-Caen]

The strategy of the SoLid collaboration is to combine the work already performed on the BR2 reactor simulation by the SCK-CEN team with the developments made and expertise gained over the last ten years by the Structure and Nuclear Energy group (SEN) at SUBATECH to calculate antineutrino spectra. The Subatech/SEN group has gained the required skills in the frame of the Double Chooz Reactor Working Group (that we have led for more than 10 years) [21] and in the frame of the nuclear physics measurements performed by the group on fission products of interest for reactor antineutrinos (TAGS experiments) [22]. In this context, the SEN group has become a leader in the prediction of reactor antineutrino spectra using the summation method relying on nuclear data. Since 2014, the team is co-responsible of the Working Group Reactor and Antineutrino Spectrum with the SCK-CEN, of the analysis of the outputs of the BR2 simulation run by the SCK-CEN for each cycle, of the subsequent calculation of the antineutrino spectrum. Since January 2018, the prediction of the antineutrino spectrum is delivered for each cycle (21 days) to the collaboration. The current work of the team is focussed on sensivity studies to estimate the systematic errors associated to the fission rates. In parallel, a BR2 simulation is developed at SUBATECH using the MURE reactor code, being able to estimate the off-equilibrium effects needed for the summation method.

LPC-CAEN has strong expertises in neutronic, nuclear and reactor physics. They contribute actively to another SCK-CEN project dedicated to accelerator driven sub-critical reactors (GUINEVERE/FREYA). LPC-CAEN is currently taking care of the spatial distribution of fission within the core. It is performed thanks to Monte-Carlo MCNPX simulation of the BR2 core, which is interfaced with the progiciel ROOT. Combined with Geant4 model of the detector, LPC-Caen is able to provide the precise acceptance of each SoLid module for each cycle. By combining both studies, French groups procure the number of antineutrino interaction within in the SoLid detector all along the data taking. At short-term and in collaboration with Imperial College of London and SCK-CEN, LPC-Caen will take care of building a protected Reactor databases, regrouping all relevant informations of the reactor operation, the emitted neutrino flux and its evolution with time.

4.2.3 QA & Calibration [LAL, LPC-Caen, SUBATECH]

The fine granularity (12 800 cubes) provides powerful tools to distinguish signal from background, but presents a challenge in ensuring homogeneous detector response: energy scale and neutron detection efficiency. For this purpose, a dedicated QA process was implemented during the detector construction.This task was carried out and coordinated by the French groups in collaboration with Ghent laboratory. The ^{22}Na source, placed in front of each one of the 256 cubes of each frame, was used to estimate the LY per cube for the ES calibration. An ^{252}Cf source inserted in a dedicated neutron collimator has been used for the neutron reconstruction efficiency optimisation and survey.

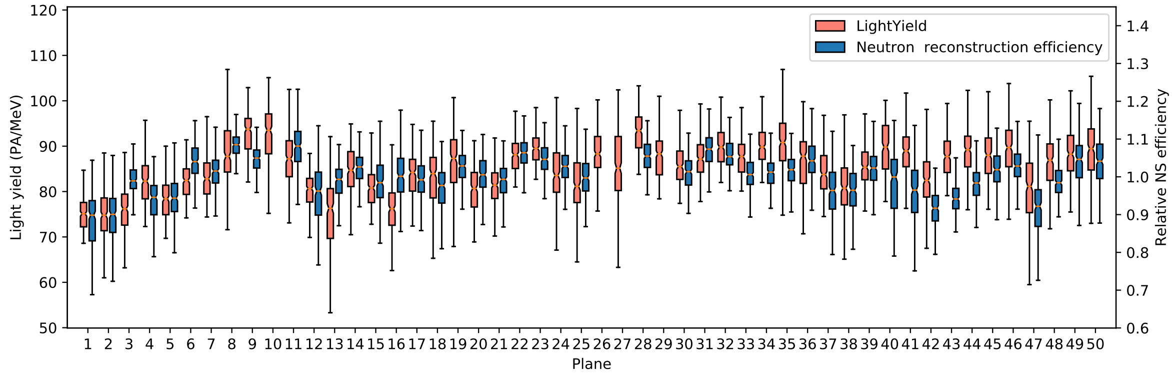

Figure 13: Candle plots of light-yield and relative neutron efficiency of all the detection cells, grouped per plane.

Most of the procedures were optimized and automated, which allowed to perform the quality assurance at a rate of 1 plane per 24h. These QA process allowed to identify defective components during the construction. We thus identify a bad ^{6}LiF:ZnS(Ag) batch (neutron efficiency divided by 3 for more than 200 cubes). The manufacturer, which confirmed a problem, thus provided a new one. Also, we intervened for frames in which one or more rows/columns presented light yields lower than 10% compared with neighboring rows/columns. In most of the cases it was found that one of the SiPMs or mirror connector were loose. These minor problems were fixed. The QA campaign was successfully completed and allowed to have a preliminary calibration of all the 12 800 SoLid cubes. It reveals a very good uniformity, a neutron capture efficiency above 60 % and a light yield larger than 60 PA/MeV (see Figure 13).

4.2.4 Neutron calibration [LPC-Caen]

Neutron reconstruction efficiency is the parameter that directly drives the IBD detection efficiency. LPC-Caen, which benefit from its former expertise in neutron detection (DEMON, nEDM), took on the responsibility of the neutron reconstruction and calibration. This is conducted in close collaboration with ICL and Bristol teams, which provide the neutron algorithm trigger. The quite challenging objective was to determine at % level the relative and absolute neutron efficiency of each of the 12800 detection cells.

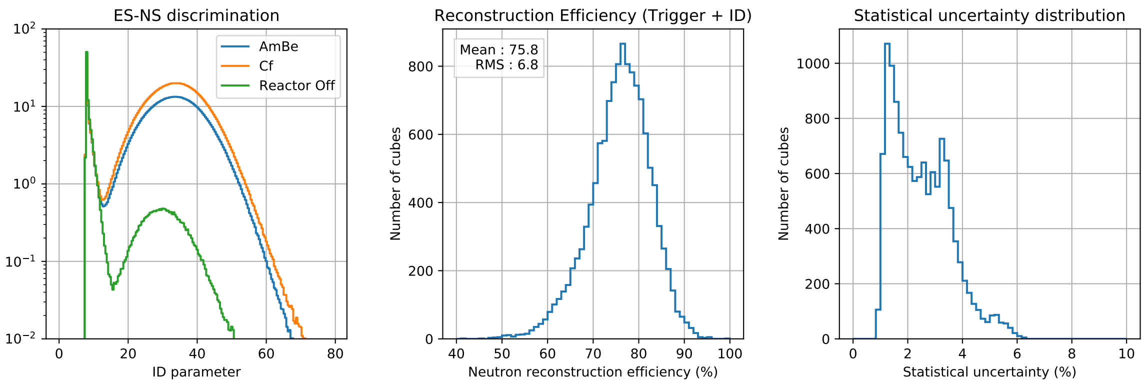

Figure 14: (Left) Pulse shape discrimination based on integral over amplitude ratio: first structure around 10 is the ES contribution, the second one is NS. (Center) Neutron reconstruction efficiency for the 12800 cells. (Right) Stastistical error on the neutron efficiency measurement for the 12800 cells.

To reach a high efficiency, the neutron identification is split in two steps. First, a dedicated neutron trigger, consisting on a peak counting algorithm along a 6.4 μs sliding window, was implemented to ensure the largest neutron trigger efficiency, while keeping the data rate sustainable. In order to reject impurities (mostly muons), a second offline identification consists of a pulse shape discrimination based on integral over amplitude ratio. The results are displayed on figure 14. The ES signals, which remain stables, irrespective of the reactor operation, can be well separated from the tagged NS events. In order to determine precisely the neutron reconstruction efficiency, a calibration campaign was realized on the full detector in its physic mode implementation. Two radioactive neutron sources are used: AmBe and ^{252}Cf for which activities have been calibrated below 2 % level at the National Physical Laboratory (UK). Besides, dedicated Monte-Carlo simulation (Geant4/MCNP) are used to estimate the neutron capture rate. In turn, this efficiency is evaluated cube per cube, with a mean statistical uncertainty of 2.5 % (see Figure 14). SoLid detector can reach a average neutron reconstruction efficiency of 75.8 ± 0.2 (stat). The systematic uncertainties, which are expected to be below 5 %, are currently under study.

4.2.5 Energy reconstruction, E-scale and resolution [SUBATECH, LAL, LPC-Clermont]

To be sensitive to a $\bar{\nu}_e$ oscillation, a precise knowledge of the Energy (E) reconstruction performance is vital. In particular, the E-scale should be known at the 2% level. Its dependence upon the actual deposited E must be determined. To that end, SoLid's cubes response is calibrated using γ sources at various energies, including ^{22}Na (0.511 and 1.27 MeV), ^{137}Cs (0.677 MeV) and AmBe (2.2 and 4.4 MeV). The detector's high segmentation is an hard challenge. Indeed, not less than 12800 cubes must be calibrated, using γs which don't deposit their whole energy within a cube: rather than a narrow peak, a broad distribution of deposits due to Compton scatterings must be analysed. We developped two methods (a and b) to tackle the latter issue. They fit to the data (a) MC spectra produced with various E-scales and resolutions or (b) the Klein-Nishina energy dependent differential cross-section convoluted with the resolution, which is fitted along side with the Compton edge position. Both rely on different assumptions: they obtain results equal within 2%, allowing the calibration to meet the required E-scale precision (see Figure 15).

Sources are placed at the back and front of each SoLid's module thanks to the CROSS system to perform regular in-situ calibrations. During the QA campaign, the E-scale in each cube was measured shortly after plane assembly. This proved a light yield of $\sim$ 80 PAs/MeV/Cube, above expectations. The PVT response energy dependence was also investigated (see Figure 15). At the same time: it allowed to develop the method that compares the first PA peaks to determine the gain of each SiPM and its cross-talk rate, and those determining the fibers attenuation lengths. For Both CALIPSO and CROSS, we adapted Solid's trigger system. We wrote a part of the G4 simulation of CROSS. These vital activities are entirely carried out by French groups. Together with the LPC-Clermont group, they constitute the greatest part of SoLid's Electron Signal (ES) reconstruction group, also in charge of the design of the reconstruction of ES objects (ex: positron) and of the characterisation of the associated resolution and efficiency across the Energy vs. Baseline plane, crucial inputs to the final oscillation fit.

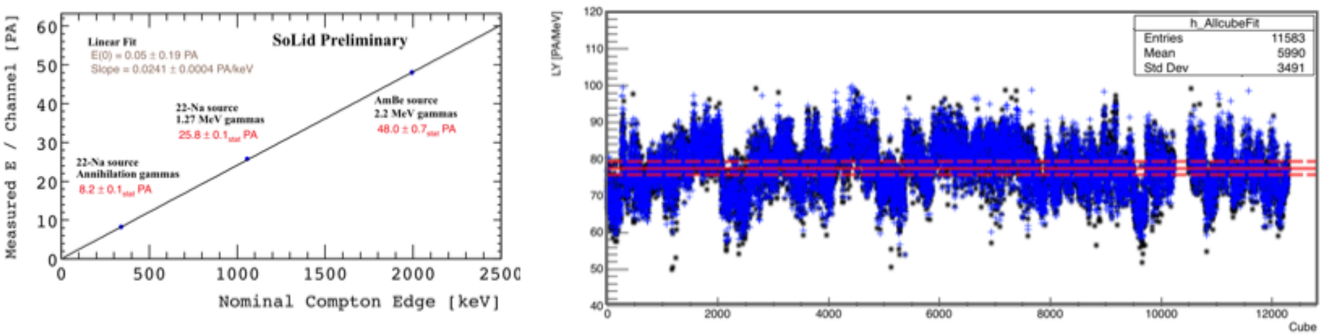

Figure 15: (Left) Energy response of a PVT cube exposed to 3 γ sources of varying energies, measured during the CALIPSO campaign. (Right) Energy scale measured in each cube by fitting to ^{22}Na data MC based distributions (black) or a PDF based on the Klein-Nishina cross section (red). The blue plain line shows the overall average.

4.2.6 BiPo background [LAL, LPC-Caen]

The ^{214}Bi-^{214}Po radioactive decay cascade has been identified by French groups as a very important background in the search for a IBD signal. The BiPo contamination can have two main sources: ^{6}Li-screens contamination and/or a Radon contamination of the air gap between the ^{6}Li-screens and PVT cubes. The electron or gamma emitted by the ^{214}Bi decay, interacting in the PVT, can simulate the prompt signal. The decay emission alpha of ^{214}Po, if it interacts in ^{6}LiF:ZnS(Ag), can simulate the delayed signal. It therefore acts as time-correlated background which can mimic IBD interaction. First, a dedicated cut-based analysis has been developed to survey of the BiPo contamination for each data course, with an excellent purity greater than 90%. The optimal rejection of this background has been defined, using different observables: minimum prompt energy, time and distance between the prompt and the delayed signals, energy deposited in neighboring cubes and pulse shape information. The Radon contamination of the air gap is sensitive to the conditions of ventilation or pressure in the containment building and therefore evolve with time inside the detector container. LPC-Clermont thus proposed and take on the responsability of instrumenting a dedicated Radon detector (developed by a CERN spin-off group) and aiming at monitoring the air borne Radon concentration all along the data taking. The installation of this apparatus is foreseen in June 2018.

4.2.7 Simulations [SUBATECH]

The SUBATECH group participate to the development of the Geant4 software, with contributions on the improvement of the physics and geometry of the detector and the optimisation of the simulations of cosmogenic backgrounds, mostly induced by muons. This activity is done coherently with the analysis studies mentioned in section 4.2.1.

4.3 Communications

The physics case is particularly rich and has the potential for very important scientific impacts. We thus maintain high level of communication towards specialised and wider audience. M. Bongrand is an active member of the conference and publication board which contributes to ensure the visibility of SoLid at the major conferences, bless the results and plots but also organizing the publication strategy and coordinating their production and reviews. The two first articles, describing the technology and its potentiality for neutrino precision oscillation measurements, were published in 2017 and 2018 in Journal of Instrumentation (JINST) [12,13]. Three new articles, which are currently being drafted, should be submitted to publication before the end of this year. We emphasize the leading role of the French teams in these editorial work:

- *'Light-yield optimisation for Solid phase 1'* (D. Boursette, M. Bongrand)
- *'Quality assurance of the SoLid Phase-I detector construction'* (L. Manzanillas, V. Pestel)
- *'Solid phase1 detector design'* (B. Guillon, N. Van Remortel)

The collaboration also widely communicate in the framework of seminar, workshop or international conference. There was more than fifteen proceedings in 2016-17 (see http://solid-experiment.org/talks), one third of which have been presented by French collaborators. In the following are listed the French communication actions in 2017:

F. Yermia, 'The Solid Experiment', EPS-HEP, Venezia (07/2017) / V. Pestel, 'The Solid Detector', EPS-HEP, Venezia (07/2017) / L. Manzanillas, 'The Solid experiment', Taup, Sudbury (07/2017) / M. Bongrand, 'The Solid experiment', CNNP, Catania (10/2017) / V. Pestel, 'Neutron calibration strategy', EPS-HEP (Poster Session), Venezia (07/2017) / D. Boursette, 'Light yield and energy resolution studies for SoLid phase 1', CNNP, Catania, (10/2017) / V. Pestel, Finale MT180 (06/2017) / B. Guillon, Faits-Marquants ENSICAEN, (06/2017)

A dedicated website, http://solid-experiment.org, is designed, hosted and operated by the LPC-Clermont laboratory. It provides general and up-to-date informations about the project (description, collaboration, publications, photos, press release...). Last but not least, French community share strong links with Universities (Nantes, Caen Orsay and Clermont-Ferrand) as well as high-level engineering schools (ENSICAEN, IMT Atlantique). We then use the project for educational purposes and will continue to supervise four to five students per year, through Master 1-2 internships.

4.4 CCIN2P3 ressources

The SoLid collaboration strongly benefits from the resources of the CCIN2P3. Firstly for the data transfer and storage which are crucial since SoLid experiment is taking 1.5 TB per day. They are stored on HPSS tapes with already 150 TB and the yearly attributed resources should allow to cover the needs. The storage on disks of processed files might require a significant amount of space too. The computing tools are under preparation on grid side for UK and Belgium while this system is not favoured at CCIN2P3. Significant CPU resources for data processing are nevertheless used by French groups and some foreign partners at CC. For simulation the CPU needs are much higher and the massive production will have to be shared among all the collaboration resources. This might require more resources at CCIN2P3 than what is currently used.

5 Evolutions & Perspectives

The SoLid experiment is built on a clear-cut Physics case related the two-fold measurements of the antineutrino flux and the antineutrino energy spectrum. At the present time, several projects have started world-wide and coming years are expected to be very fruitful. The fist campaign of data-taking with a complete five-modules SoLid detector has started in December 2017 with a successful commissioning phase which preceded the first Physics Run in February 2018. It allows the SoLid collaboration to enter in a timely manner in these international competition. The Physics exploitation of the apparatus is about three years in order to gather the statistics which must satisfy the ultimate physics objectives. It is therefore a well-defined, time-contained operation. Should hints of a sterile neutrino signal be unraveled, it must be noted that the versatility of the BR2 operation together with the privileged collaboration that we have with BR2 teams can allow to adjust the operation of the detector to the Physics needs. All in all, the next four years will be crucial to produce world-class measurements of the antineutrino flux and energy spectrum and perform the test of the sterile neutrino hypothesis at eV-scale. In short term perspective, the French group will keep their central role in the physics analyses and the sterile search. As far as medium to long-term plans of the four French groups are concerned, a large (or some) diversity of approaches must be acknowledged.

The **LPC Clermont group**, for time being, considers the SoLid activity as a self-contained program and do not plan, on a collective basis and given the structure of the group, to join another neutrino Physics program in the course nor at the end of the SoLid operation.

The **SUBATECH neutrino group** is currently involved in four neutrino experiments (Double Chooz, SoLid, JUNO, ORCA). Currently the manpower involved is split onto these experiments with the Double Chooz experiment ending within the next year, SoLid is a short time scale experiment (3-5 years) and, JUNO and ORCA, on a longer time-scale. For SoLid, during the last years, the SUBATECH group was responsible for the analysis coordination, the mechanical design and participated to the detector construction and commissioning. Since 2016 two CR have joint the group and a PhD student started in October 2017. Our activities are now mostly focused on the ES calibration of the detector, on the data analysis and on simulations, for most of which we have responsibilities within the collaboration. An ANR post-doc will also be opened soon reinforcing the activities on data analysis and increasing the impact of the group within the collaboration. For the future, a part of the group will be still involved in ORCA and JUNO will naturally involve more and more permanent people coming from reactor neutrino physics. JUNO is now under design and construction, and data taking will start in 2021, thus with a good timing with respect to the end of SoLid. Moreover, the group has shown interest in continuing the R&D on future neutrino detector with others IN2P3 laboratories in the next years.

The **LAL group** was involved in the preparation and construction of the Phase 1 detector and on its commissioning, running and calibration. The PhD thesis, which is ending this summer, also contributed significantly to the data analysis from the SM1 prototype to Phase 1. The group will now focus on the SoLid data analysis till the end of the experiment by working on reconstruction, background measurements and rejection, anti-neutrinos energy spectrum and final oscillation fit. A new PhD student, which is currently in internship, will start this October in perfect timing with the running of the experiment. On the contrary the ANR postdoc will end by summer 2019 with still 1.5 year of data to take. This will have a strong impact on the implication and visibility of the group to SoLid data analysis. The permanent people of LAL group are also strongly involved in the SuperNEMO double beta decay experiment which will start data taking by the end of the year. In the context of refoundation of Orsay IN2P3 laboratories, several workshops have been organised to discus the future of neutrino physics in these laboratories. For double beta decay, the will to build a common vision with CUPID-Mo group for the preparation of the next generation experiment has raised and some tools and skills are already shared. For the future of SoLid group or neutrino oscillations in general, several IN2P3 experiments were considered: T2K, JUNO, DUNE. An interest of several LAL people for DUNE experiment emerged. There is already some attempts to organise few technical contributions to the prototypes in order to gain experience for the future involvement to the DUNE far detector construction. Interest for T2K experiment was also expressed but this was not the favoured direction. We can note that a technology similar to SoLid scintillator segmented cubes is under test for T2K-II and maybe for DUNE near detectors. Also a natural transition from SoLid would have been to join JUNO experiment but less people have expressed interest at LAL. The SoLid/SuperNEMO people also show interest in future neutrino detector R&D that might also begin at IN2P3.

The **LPC-Caen group** gather four permanent physicist and a PhD student. Though discussions are ongoing about the DUNE project, and given the structure of the group, it will maintain its SoLid activities and currently do no plan to join another neutrino Physics program. Since the beginning, LPC-Caen was strongly involved in all aspects of the project. Currently, it focuses on neutron calibration, event reconstruction and reactor physics. At short-term, it will be reinforced by a two-years Post-Doctoral fellowship, which will support the transition of our activities to the precise measurement of ^{235}U neutrino energy spectrum, as well as the development of states-of-the-art neutrino oscillation fit. At mid-term, LPC-Caen is very interested on enhancing the technology development, that has been made. The design of the detector revisits the concept of neutrino segmented target and has several advantages compared to current $\bar{\nu}_e$ detectors: background rejection capabilities, compactness, simplicity, cost-effective and non-hazardous. Similar technology has thus under study for T2K-II and DUNE near detectors. Some opportunities are actually on discussion with the proximity of the local group and GRACE (Groupe Aval du Cycle Electro-nucleaire) about as small scale neutron detector for nuclear energy applications. Currently, the group also study the opportunities of deploying the SoLid technology in other nuclear research reactor with different enrichment or different neutron spectrum (fast or thermic) to give extensive measurements of different neutrino flux coming from fission, but with the same systematics. It could give precious informations about the reactor shape anomaly and could paved the way for long-term non-proliferation applications.

The unique features of the SoLid experiment to perform a very sensitive search for active to sterile neutrino oscillations as a solution to the reactor antineutrino anomaly have been presented. Combined with the BR2 reactor specifications, it will also allow a precise study of the reactor shape anomaly. The SM1 prototype has demonstrated the power of the segmentation and of the PSD to study coincidence signals and reject the backgrounds. The full scale SoLid detector is now taking data and will reach its maximal sensitivity in three years. The French collaborators from IN2P3 play a leading role in the SoLid experiment at several levels: detector design and construction, commissioning, quality assurance and calibrations, data analysis, reactor prediction and oscillation search. Substantial funding has been obtained from several agencies to ensure the detector construction and its running, with a decisive contribution from France. The ANR and laboratories funding have come to an end and support for the exploitation and production of scientific results is now critical for the French consortium.

References

[1] M. A. Acero, C. Giunti, and M. Laveder, *Limits on ν_e and $\bar{\nu}_e$ disappearance from Gallium and reactor experiments*, *Phys. Rev. D* **78** (2008) 073009. ; C. Giunti and M. Laveder, *Statistical Significance of the Gallium Anomaly*, *Phys.Rev. C* **83** (2011) 065504.

[2] LSND Collaboration, A. Aguilar et al., *Evidence for neutrino oscillations from the observation of $\bar{\nu}_e$ appearance in a $\bar{\nu}_\mu$ beam*, *Phys. Rev. D* **64** (2001) 112007 ; MiniBooNE Collaboration, A. Aguilar-Arevalo et al., *Improved Search for $\bar{\nu}_\mu \to \bar{\nu}_e$ Oscillations in the MiniBooNE Experiment*, *Phys. Rev. Lett.* **110** (2013) 161801.

[3] T.A. Mueller et al., *Improved predictions of reactor antineutrino spectra*, *Phys. Rev. C* **83** (2011) 054615 ; G. Mention et al., *The reactor antineutrino anomaly,*, *Phys. Rev. D* **83** (2011) 073006. ; P. Huber, *On the determination of anti-neutrino spectra from nuclear reactors*, *Phys. Rev. C* **84** (2011) 024617 [Erratum ibid. *Phys. Rev. C* **85** (2012) 029901].

[4] Double CHOOZ collaboration, Y. Abe et al., *Improved measurements of the neutrino mixing angle θ_{13} with the Double CHOOZ detector*, *JHEP* **10** (2014) 086. ; Daya Bay collaboration, F.P. An et al., *Measurement of the reactor antineutrino flux and spectrum at Daya Bay*, *Phys. Rev. Lett.* **116** (2016) 061801. ; RENO collaboration, J.H. Choi et al., *Observation of energy and baseline dependent reactor antineutrino disappearance in the RENO experiment*, *Phys. Rev. Lett.* **116** (2016).

[5] P. Vogel and J. F. Beacom, *Phys. Rev. D* **60** (1999) 053003. ; Alessandro Strumia et al., *Precise quasielastic neutrino/nucleon cross section*, *Phys. Lett. B* **564** (2003) 42.

[6] C. L. Cowan et al., *Detection of the Free Neutrino: A Confirmation*, *Science* **124** (1956).

[7] G.S. Vidyakin et al., *Limitations on the characteristics of neutrino oscillations*, *JETP Lett.* **59** (1994) 390. ; Y. Declais et al., *Search for neutrino oscillations at 15-meters, 40-meters and 95-meters from a nuclear power reactor at Bugey*, *Nucl. Phys. B* **434** (1995) 503.

[8] S. Gariazzo et al., *Model-Independent $\bar{\nu}_e$ Short-Baseline Oscillations from Reactor Spectral Ratios*, arXiv:1801.06467 (2018).

[9] NEOS collaboration, Y. J. Ko et al., *Sterile neutrino search at NEOS Experiment*, *Phys. Rev. Lett.* **118**, no. 12, (2017) 121802.

[10] A. P. Serebrov et al., *Status of Experiment NEUTRINO-4 Search for Sterile Neutrino*, arXiv:1611.05245 (2016).

[11] J. Ashenfelter et al., *The PROSPECT Physics Program*, arXiv:1512.02202 (2015).

[12] SoLid collaboration, Y. Abreu et al., *A novel segmented-scintillator antineutrino detector*, *JINST* **12** (2017) P04024.

[13] SoLid collaboration, Y Abreu et al., *Performance of a full scale prototype detector at the BR2 reactor for the SoLid experiment*, *JINST* **13** (2018) P05005.

[14] Stereo collaboration, N. Allemandou et al., *The STEREO Experiment*, arXiv:11804.09052 (2018).

[15] DANSS collaboration, I. Alekseev et al., *Search for sterile neutrinos at the DANSS experiment*, arXiv:1804.04046 (2018).

[16] Ibrahin Pinera-Hernandez (on behalf of the SoLid collaboration), *Identification of background components with the solid anti-neutrino detector*, *IEEE Nuclear Science Symposium* DOI: 10.1109/NSSMIC.2016.8069849 (2016).

[17] https://www.sckcen.be/en/Research/Infrastructure/BR2.

[18] SoLid collaboration, L. Arnold et al., *The SoLid anti-neutrino detector's readout system*, *JINST* **12** (2017) C02012

[19] http://cnp.phys.vt.edu/chandler/

[20] C.Buck et al. *Investigating the spectral anomaly with different reactor antineutrino experiments*, Phys. Lett. **B** 765 (2017). ; Y. Gebre et al., *Prospects for improved understanding of isotopic reactor antineutrino fluxes Phys. Rev.* **D97** (2018) 013003.

[21] A. Onillon, *Prediction of the Reactor Fission Rates and the Estimation of the Associated Uncertainties in the Frame of the Double Chooz Experiment*, PhD Thesis, Ecole des Mines de Nantes (2014) ; V.M. Bui, *Beta decay of fission products for the non-proliferation and decay heat of nuclear reactors*, PhD Thesis Ecole des Mines de Nantes (2012) ; V.M. Bui et al., *Antineutrino emission and gamma background characteristics from a thermal research reactor*, arXiv:602.07522 (2016) ; M. Fallot, *Conseil Scientifique de l'IN2P3, la structure nucleaire pour la physique des reacteurs et des neutrinos, October 2017.*

[22] M. Fallot et al., Phys. Rev. Lett. 109, 202504 (2012) ; A.-A. Zakari-Issoufou et al. Phys. Rev. Lett. 115, 102503 (2015).