JUNO: Jiangmen Underground Neutrino Observatory

The JUNO France collaboration

1 Introduction

In the last decades, neutrino experiments have achieved important results allowing for precision measurements of the neutrino oscillation parameters, at the level of a few percent. Nevertheless, two open questions remain concerning neutrino oscillations: "is there CP violation in the neutrino sector?" and "which neutrino is the lightest?". The second question is analogous to the determination of the Neutrino Mass Ordering (NMO), which presents currently two possibilities: the normal ordering (NO) or the inverted ordering (IO)[1]. The Jiangmen Underground Neutrino Observatory (JUNO) has been conceived to answer precisely this second question. JUNO is the largest liquid scintillator based experiment and it will be the first measuring simultaneously two oscillations modes. Though the detection technology is inherited from previous reactor neutrino experiments (e.g., Daya Bay, Double Chooz, ...), JUNO makes a leap forward achieving an unprecedented size and resolution. With its design, JUNO is expected to measure the NMO with a significance of 3 σ after six years of data taking (or 100,000 events) [1]. JUNO's determination of the NMO is very complementary to other ongoing efforts thanks to the fact that JUNO is the only experiment measuring it using reactor $\bar{\nu}_e$ oscillations, where the NMO signature does not come from matter effects (i.e. oscillations in vacuum).

In JUNO, the NMO measurement relies on the capacity of resolving the fine modulations expected in the oscillated electron anti-neutrino ($\bar{\nu}_e$) spectrum, as shown in Fig. 1. In the figure, $\bar{\nu}_e$s (black) are strongly suppressed due to the $\bar{\nu}_e$ oscillation term (Δm^2_{12}, θ_{12}). The fast oscillations (red and blue) are driven by the terms[2] Δm^2_{31} and Δm^2_{32} and their phase depends on the assumed mass ordering. Given the small difference between these curves, this measurement imposes strict experimental requirements: large statistics, an outstanding energy resolution of $3\%/\sqrt{E/\mathrm{MeV}}$ and a precision on the absolute energy scale better than 1% [1].

By measuring the oscillated spectrum, JUNO can perform high precision (sub-percent) measurements of the neutrino oscillation parameters Δm^2_{21}, θ_{12} and Δm^2_{31}. A determination of θ_{13} with a precision of $\sim$10% is also possible.

While the initial goal of JUNO was to measure reactor neutrino oscillations, JUNO is not limited to this single topic. Given the JUNO performance, it will be a competitive experiment for astro-particle physics (e.g., the detection of astrophysical neutrinos from core-collapse supernovae and diffuse supernova neutrino background), it has the sensitivity for solar and atmospheric neutrino detection, the detection of rare events as geo-neutrinos, proton decay, dark matter and, in the future, neutrino-less double beta decay. The number of events expected for the main physics channels in JUNO are summarized in Table 1 adapted from [F-1]. Some of these topics will be detailed in the next sections as part of the IN2P3 activities. The main contributions of the IN2P3 teams have been evaluated during the CS IN2P3 in 2018. Since then, significant progress has been done on the technical developments and analysis tools, and sensitivity studies have been prepared.

With its capabilities, JUNO is expected to have a key role in neutrino physics in the following decades. The IN2P3 teams, with their previous expertise, are in strategic positions to contribute to the JUNO success. As already mentioned, the collaboration with other IN2P3 neutrino experiments can further extend these opportunities in the future. In the past years, the regular participation to the GDR "Neutrino" (currently IRN) has facilitated exchanges with other experiments, as will be discussed in the next section, and it also gives visibility to the young members. The recent GDR DUPhy (Deep Underground Physics) includes topics of interest for JUNO, especially related to low background techniques.

[1] In the NO case, the order of the neutrino masses is $m_1 < m_2 < m_3$, where m_i is the mass of the neutrino ν_i. In the IO case this order is $m_3 < m_1 < m_2$.

[2] Note that $\Delta m^2_{31} = \Delta m^2_{32} + \Delta m^2_{21}$, so these are not independent terms, but their relation will depend on the NMO.

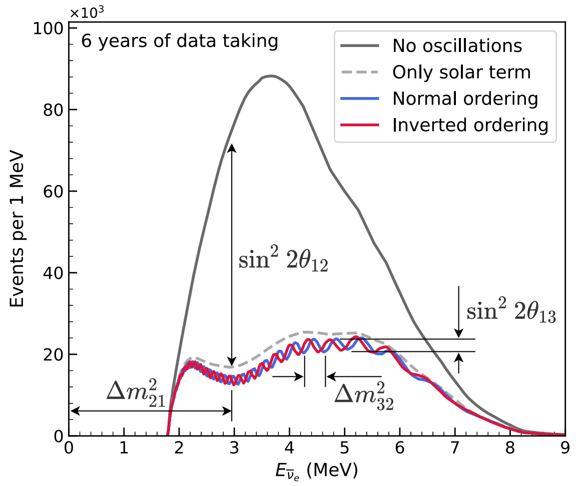


Figure 1: Relative shape difference of the reactor $\bar{\nu}_e$ flux for NO (blue) and IO (red), at the JUNO site.

Table 1: Summary of detectable neutrino signals and corresponding expected rates. From [F-1].

Research	Event rate
Reactor ν (0–12) MeV	60 IBD/day
Supernova burst (10kpc) (0–80) MeV	5000 IBD (in <10 s) + 2000 elastic scattering
DSNB (10–40) MeV	2–4 IBD/yr
Solar ν (0–16) MeV	O(100)/yr (^{8}B)
Atmospheric ν (0.1–100) GeV	O(100)/yr
Geo-neutrinos (0–3) MeV	∼400/yr

2 The JUNO project

JUNO [1] is a multi-purpose liquid scintillator neutrino experiment under construction in Southern China (Jiangmen), at 53 km from two nuclear power plants.

The design of the JUNO detector is shown in Fig. 2. The experiment will consist of an acrylic sphere with a ∼35.4 m diameter (Central Detector, CD) filled with 20,000 tons of liquid scintillator (LS). Reactor $\bar{\nu}_e$ are detected in the JUNO CD via the Inverse Beta Decay (IBD) reaction: $\bar{\nu}_e + \mathrm{p} \rightarrow \mathrm{e}^+ + \mathrm{n}$. In this reaction two signals are produced: a prompt signal from the positron scintillation and annihilation, and a delayed signal (average delay time of ∼200 μs), from the neutron capture by a hydrogen atom and subsequent de-excitation of the produced nuclei. The LS light emission is detected by ∼17,600 20-inch photo-multipliers (Large PMTs or LPMTs) and 25,600 3-inch PMTs (Small PMTs or SPMTs). The SPMT system was proposed by APC[3] and Subatech groups (end of 2014) that formed a sub-collaboration (mainly by APC, IHEP, INFN-Padova, and Subatech, led by APC) that realised the scientific studies and full conceptual design of the system for JUNO collaboration approval by mid-2016. It was introduced to mitigate the non-linearity effects and control the systematic uncertainties below 1% through the so-called dual calorimetry (see section 4.2). However, the SPMT design also enable to physics in its own for physics channels beyond IBD reactor, such as supernova, muon reconstruction, proton-decay, ... A complex multi-source calibration system will be deployed in multiple-positions to ensure the 1% energy precision and $3\%/\sqrt{E/\mathrm{MeV}}$ effective energy resolution [F-2]. The IN2P3 has a leading role in the SPMT system with major technical contributions and primary involvements in many related physics analyses.

The CD will be immersed in a Water Pool (WP) with a diameter of 43.5 m and a height of 44 m instrumented with 2,400 LPMTs and filled with 35 kilotons of ultra-pure water. The WP acts as a shield to the CD against external background and as an active veto for atmospheric muons. The muon veto is completed by a three-layer muon tracker called Top Tracker (TT), consisting of plastic scintillator strips recuperated from the Target Tracker of the OPERA experiment [2]. The TT covers about 60% of the surface above the WP. The TT was the first contribution proposed by the IN2P3 members to the JUNO collaboration and the OPERA Target Tracker was valued as a 3.2 M€ (in-kind) contribution. It is therefore, financially, France's biggest technical contribution to the project.

Finally, a high-resolution anti-neutrino detector, TAO (Taishan Antineutrino Observatory) [J-1] will be constructed at about 30 meters from one of the Taishan reactor cores. TAO will provide a reference spectrum for JUNO to reduce the model dependence on the reactor anti-neutrino spectrum due to the fine structures in the reactor anti-neutrino spectrum, and to provide a benchmark to test nuclear databases by comparing data with the measurement with the predictions of the summation method. The TAO detector consists of 2.6 tons of gadolinium-doped liquid scintillator contained in a spherical acrylic vessel and 10 m^2 SiPM (silicon photomultiplier). A resolution of 1.5% at 1 MeV is required and a statistics of around 2000 events per day is expected. So far, the IN2P3 teams have no commitments in TAO construction, but

[3]Since then the APC group moved to IJCLab.

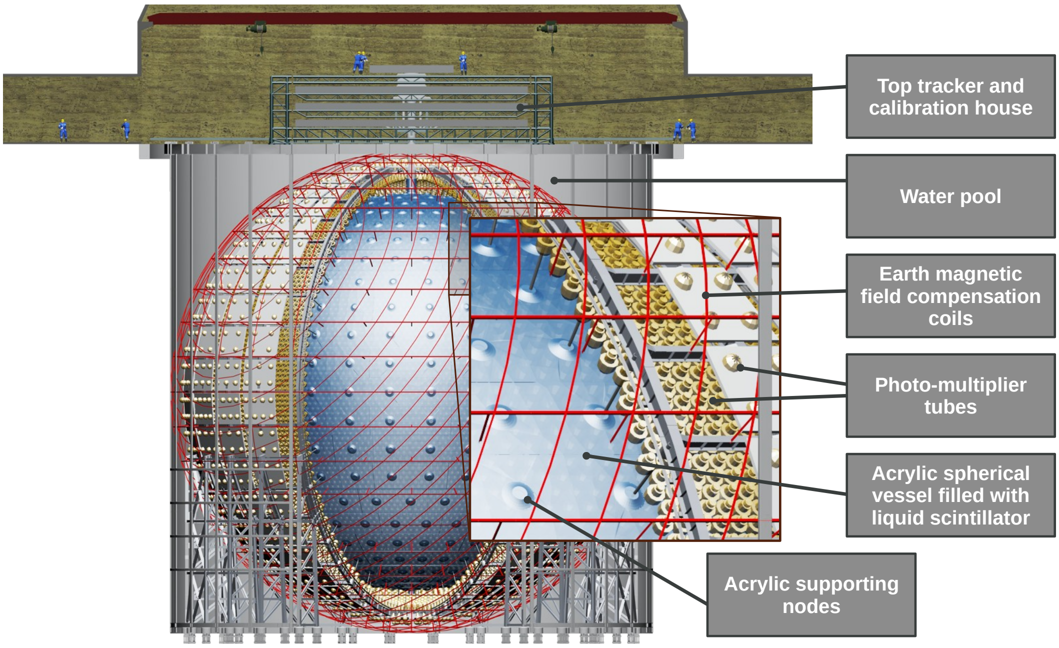


Figure 2: Overview of the JUNO detector with the main sub-systems.

a possible contribution to the TAO detector veto electronics is envisaged, using the electronics already developed for the SPMT.

2.1 The international collaboration

The JUNO collaboration consists of 77 institutes and more than 650 members. The French collaboration participates with a total of 18 scientists and 30 engineers. Despite the limited number of members, the French groups have major responsibilities for both the SPMT and the TT systems. The SPMT and TT contributions, as well as the participation to radioactivity measurements and software and simulation developments, ensure a very good visibility in the international context.

As shown in the organization chart of the collaboration (Fig. 3) the French collaboration is well represented in the management of the collaboration. To these management roles, additional responsibilities are assigned to IN2P3 members.

A number of papers describing the technical achievements and sensitivity to some physics reaches are published and more are expected in the coming years, especially with the finalisation of the detector construction and the start of the data taking. A complete list of published papers is given at the end of this document. The publications resulting from the IN2P3 contributions are explicitly indicated.

3 Status and Calendar

The JUNO project was approved in 2014 and since then one of the biggest challenges has been the construction of the underground laboratory, 700 m overburden, and related infrastructure. Some difficulties have been encountered, notably an unexpected water flow while digging the tunnels and the experimental hall. Because of this problem and the COVID-19 pandemic, a delay of about 2 years has been accumulated. The civil construction is now very well advanced and it is expected to be concluded by the end of 2021. In the meantime most of the system components are ready or under production. Just to mention some of them, the 20,000 LPMT have been produced, potted and tested, the 25,600 SPMTs have been produced, and are currently being potted and tested (see section 5.1); the liquid scintillator recipe is finalized and a complex purification system and background monitoring are almost ready. The electronics development (in which France is primarily involved for the SPMT and TT) are at the stage of production or pre-production. More details will be provided in Section 5 for the French deliverables. The final phases with the integration and detector installation are currently scheduled in 2022.

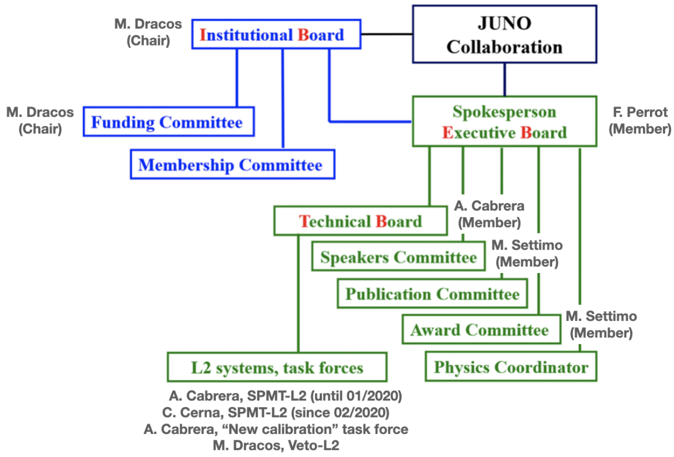


Figure 3: JUNO management organisational chart. The French participation is indicated.

4 The IN2P3 analysis contributions

At this early stage of the experiment, the physics topics contributions of the IN2P3 teams are strongly related to the detector hardware contributions. An extensive list of physics potentials of JUNO can be found in [1, F-1]. In this document, we only focus on the main activities currently ongoing and where contributions have been provided by IN2P3 members in the last years. The expertise of the IN2P3 members naturally opens to further contributions in the next years and an interest in other topics (as proton decay, geo-neutrinos, . . .) has been already presented for the perspectives 2020 [3]. The discussion on these topics is however too premature here.

The main role played in the proposal of the project as well as the hardware responsibilities are the foundations for a stable major role of IN2P3 on the SPMT and TT analyses.

4.1 Neutrino Oscillations

One of the principal JUNO physics goals are related to the precise measurement of neutrino oscillations using reactor anti-neutrinos produced in the Yangjiang and Taishan Nuclear Power Plants. More precisely, JUNO is expected to, by 2030, determine by itself the NMO with a 3 σ precision and measure three neutrino mixing parameters (θ_{12}, Δm^2_{21}, $|\Delta m^2_{31}|$) with a precision much better than 1%, as shown in Fig. 4, left. The success of this program will rely on JUNO achieving the required energy resolution, and being able to successfully reject accidental background as well as background induced by atmospheric muons (see Fig. 5). The French groups work on the SPMT, TT and low background control will have a direct influence in these topics, complementing each other.

JUNO will lead the global experiments in measuring the precision at sub-percent level within few years of the data taking (Fig. 4, left). IJCLab and Subatech have taken part in the creation of a JUNO analysis group leading the preparation of neutrino oscillations studies. Two independent oscillation fit framework analyses (using LPMT and SPMT) were developed by these laboratories in order to determine the precision on the oscillation parameters. These results update the previously published oscillation parameter sensitivity by carefully considering each source of systematic uncertainty. They are part of the upcoming JUNO collaboration paper [F-3] on sub-percent sensitivity measurement of oscillation parameters. IJCLab participates to the edition.

Another previous study, led by the same french groups, showed already that the SPMT system alone has the sensitivity to two of the oscillation parameters (θ_{12}, Δm^2_{21}) with a precision similar to that of the LPMT system. This possibility provides JUNO an interesting capability to do a self-verification of its results with a different impact from various systematic errors.

Among the existing or under construction experiments aiming to determine the NMO, JUNO is the only one aiming at doing it via the precise measurement of the interplay between the neutrino oscillations driven by Δm^2_{31} and Δm^2_{32} in the $\bar{\nu}_e$ disappearance channel. This puts JUNO in a position where its results are very complementary to those of all other experiments relying on matter effects to distinguish the NMO. In fact, while this complementarity has already been highlighted in the literature [4–7], we have

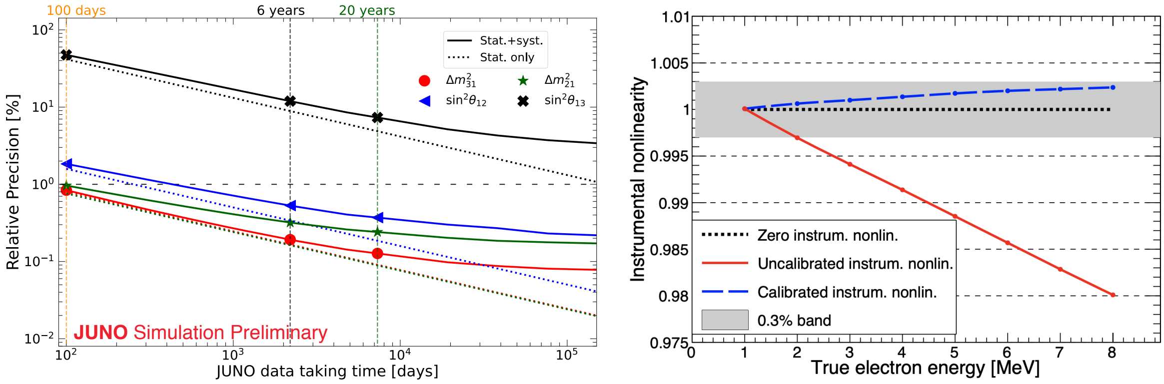


Figure 4: Left: Expected JUNO precision to measure various oscillation parameters as a function of data taking time. Right: Impact of the LPMT instrumental non-linearity and correction using the dual calorimetry calibration [F-2].

shown the potential to reach a 5 σ determination of the NMO before the end of the decade by combining JUNO data with data from neutrino accelerator experiments [F-4] (study led by IJCLab and Subatech), with atmospheric neutrino data from KM3NeT/ORCA [F-5] (study led by IPHC on the JUNO side and APC on the KM3NeT/ORCA side) and with IceCube/PINGU [F-6].

In addition to measure neutrino oscillations with reactor anti-neutrinos, JUNO has also the potential to study neutrino oscillations using atmospheric and solar neutrinos [J-3]. For the detection of solar neutrinos, it will be essential to carefully control the radiopurity of all materials going into the detector, especially the liquid scintillator at the level of 10^{-17}g/g in U/Th [F-7]. CENBG and CPPM teams participate in this control as it will be described in sub-section 4.3.

4.2 Dual calorimetry calibration for NMO determination

The Dual Calorimetry design was adopted by JUNO in 2016 with the introduction of the SPMT system. The main goal was to enable unprecedented precise control of the systematic uncertainties, namely the non-linearity which is the most dangerous bias for the NMO measurement, as well as a leading non-stochastic term in the energy resolution. Indeed, with a yield of about 1350 photo-electrons per MeV of deposited energy (PEs/MeV) expected for the LPMTs (stochastic uncertainty term in the energy resolution $< 3\%$), the non-stochastic term should be controlled to less than 1% in order to achieve the 3% energy resolution requirement. Due to their small size, the SPMTs will detect only a small fraction of the total light, with about 40 PE/MeV. They will thus be working in photon-counting regime in the energy region of interest for most of the physics goals of JUNO (up to tens of MeV). As part of the dual calorimetry design conceived by the APC/IJCLab, it is possible to design a so-called dual calorimetry calibration. This calibration will correct the instrumental non-linearity of LPMT, that is a nonlinear response between the created photons in the LS and the measured charge from the electronics. This effect is particularly delicate, since at a given energy the charge response of single LPMT may vary by more than two orders of magnitude. In the dual calorimetry calibration technique the LPMT and the SPMT systems response are compared when illuminated by a tunable light source (laser) placed in the center of the detector and having a large dynamic range. Since the SPMTs operates in photon-counting, they can serve as an approximate linear reference for the LPMT charge measurement [F-2]. The impact of such type of correction is illustrated in Fig. 4 (right) in an extreme hypothetical scenario of 50% non-linearity over 100 PEs for the LPMTs. The IN2P3 teams are primarily involved in the SPMT realisations (APC/IJCLab, CPPM, CENBG, Subatech) and contribute to the dual calorimetry calibration (APC/IJClab, Subatech). The members of IJCLab (and previously APC) are leading much of the aforementioned dual calorimetry method which has been described in a collaboration paper on the calibration strategy [F-2]. IJCLab led the writeup of the dual calorimetry contribution and participated in the edition team. This study has also been the subject of the PhD thesis of Yang Han (APC, 2017–2020 [T-2]). In this context, a verification test system (JINO), beyond the JUNO project, is under development at IJCLab, in collaboration with some members of Subatech.

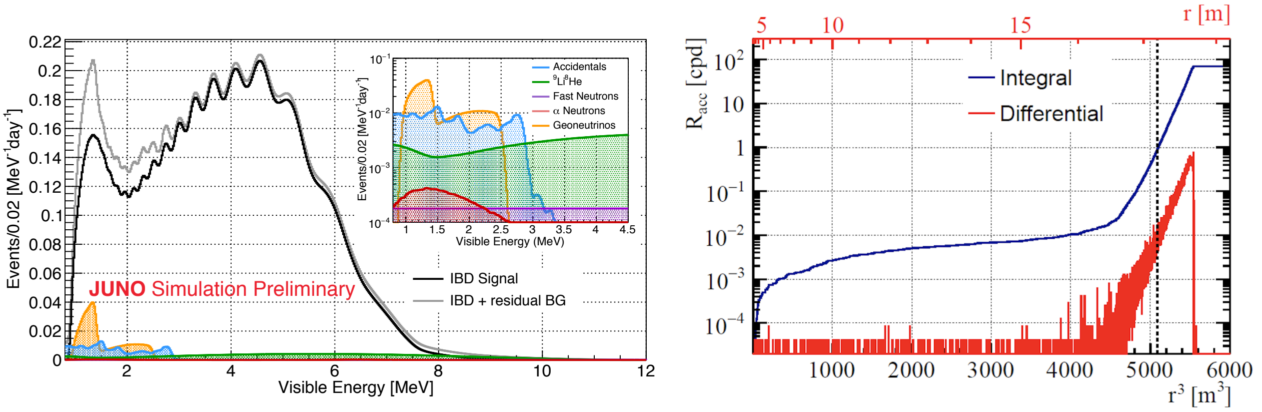


Figure 5: Left: Impact of the radiogenic background on the expected energy spectrum. Right: The differential (red) and integral (blue) distributions of the accidental rate as a function of the CD radius with the default selection cuts. The fiducial volume radius cut at 17.2 m is indicated as the dashed line.

4.3 Main backgrounds to NMO determination

The expected IBD rate[4] in JUNO is about 60 counts per day (cpd), therefore a careful control of the background sources is critical. There are three main types of backgrounds: cosmogenic background (related to atmospheric muons with ∼1.6 cpd), radiogenic background (related to radioactivity with ∼0.9 cpd) and geo-neutrinos (irreducible with ∼1.1 cpd). The CENBG, CPPM and IPHC laboratories are deeply involved in the reduction of the first two backgrounds which will have a key impact to the detection systematics for the different IBD analyses of JUNO.

Radiogenic background Radiogenic background (RB) is coming from natural radioactivity (mainly from the ^{238}U and ^{232}Th chains, the ^{40}K and the ^{222}Rn) present in all JUNO materials and in the environment. They can produce accidental coincidences mimicking the IBD signature, i.e., prompt signal with E>0.7 MeV and delayed signal with E≈2.2 MeV. The JUNO requirement is to have less than 10 events/s in the fiducial detector volume (R<17.2 m) coming from the RB. The impact of natural radioactivity on the spectrum is illustrated in Fig. 5 (left). To minimize the impact of natural radioactivity on the $\bar{\nu}_e$ spectrum, all the materials (especially those in the Central Detector) are carefully selected based on the radioactivity measurements and the detector design is optimized using simulations. This radioactivity control is required not only for the liquid scintillator (internal contamination at the level of 10^{-15} g/g at most) but also to all the other materials surrounding the detector.

The CENBG and CPPM groups are strongly contributing to this task for 5 years using Monte-Carlo simulation and low background techniques. Firstly, the acrylic vessel in contact with the liquid scintillator must be very radiopure in U/Th/K at a level of 10^{-12} g/g. To control the surface contamination of the acrylic panels down to this level for U/Th, a powerful and quantitative method using a Laser Ablation ICPMS technique has been developed in collaboration with experts at IPREM Pau. This technique is one of the three techniques blessed by the JUNO collaboration (with Neutron Activation Analysis and ICPMS) and is currently used to validate or reject the acrylic panels before their installation in the underground laboratory. Many critical surrounding materials (glass of 3" and 20" PMTs, stainless steel truss, rock, electronic boards, . . .) have been validated at the level of 1–10 mBq/kg by ultra low background gamma spectrometry detectors in the two platforms available in France (PRISNA at CENBG Bordeaux and LSM at Modane). For example, most of the materials of the SPMT system including bare PMTs, HV divider and potting as well as electronics boards have been screened in France allowing a total SPMT count rate within 0.2 Hz in the JUNO fiducial volume. Several critical Radon emanation and diffusion studies have been conducted in order to fulfill the requirement to have less than 10 mBq/m^3 of Radon activity in the WP. A publication summarising the radioactivity control strategy in JUNO [F-2] has been recently submitted with major participation of CENBG. Fig. 5 (right) illustrates the distribution of the accidental rate as a function of the CD radius with the default selection cuts: a promising count rate below 1.0 count per day seems achievable.

[4]Rates are provided after all IBD event selection cuts are applied. For more information see [1].

Cosmogenic background Being underground, the detector is naturally shielded against particles produced in cosmic-ray showers by the rock above. Cosmogenic isotopes will appear naturally in the JUNO liquid scintillator from the interaction of the remaining atmospheric muons (rate of about 3 Hz) crossing the detector. This particular background is difficult to reject due to the fact that some of these isotope decays (mainly ^{9}Li and ^{8}He) include also $\beta - $n decays that mimic the "prompt-delayed" signature from the IBD interactions. Due to the similarity between a $\beta - $n decay and an IBD interaction, the criteria requiring events to be IBD-like and inside the fiducial volume (which are essential to reject the remaining accidental background) are not efficient to reject this cosmogenic background. In [1] it was estimated that a similar number of cosmogenic events and IBD events from the surrounding nuclear power plants are expected if no muon veto is applied.

The JUNO strategy to reject these cosmogenic backgrounds relies on tracking the atmospheric muon producing them and then veto a cylindrical (radius 3 m) volume around the reconstructed muon track for 1.2 s. This strategy relies on being able to track well almost all the muons crossing the detector. Both the TT and the SPMT system, which are the two main IN2P3 contributions, will play important roles in this tracking. While the TT is only able to detect about 1/3 of the muons passing the CD, it will provide very well reconstructed events for calibration and testing of event reconstruction in other sub-detectors. Additionally the TT will help on the experimental determination of the cosmogenic isotopes lateral distribution. Some work on this identification using the TT has been started at IPHC and was discussed in Qinhua Huang's PhD thesis (LLR, 2016–2019 [T-1]). Given that the SPMTs have shorter transient time spread than most LPMT they provide additional timing information for the muon reconstruction. A muon passing through the CD will produce a large amount of photons saturating a large fraction of the LPMTs near the enter/exit point. The SPMTs however, by receiving a smaller fraction of those photons, will not saturate as easily providing an extension to the CD dynamic range which will help tracking muons through its volume.

4.4 Core Collapse Supernova (CCS)

With its huge target mass, the low-energy threshold, the unprecedented energy resolution and the energy scale precision, JUNO is a competitive experiment for astrophysical programs, such as galactic core-collapse supernova neutrinos (CCSN), diffuse supernova neutrino background (DSNB) and solar neutrinos.

The CCSN studies have direct impact on the design of the SPMT electronics (under French responsibility) and can provide additional valuable information to LPMT. In the CCSN, a massive star (above eight solar masses) is expected to collapse under its own gravity and then to explode emitting 99% of its binding energy in the form of a neutrino burst. Astrophysical models predict a rate of CCSN of about three per century in our galaxy. The detection of a CCSN burst is thus a once-in-a life event that we don't want to miss. The last observed CCS was in 1987 from Magellanic Cloud, so at least one galactic CCS is expected during the operation time of JUNO. The precise determination of the energy spectrum and its flavour and time evolution would allow us to infer parameters of interests for astrophysics, nuclear physics and particle physics (mass ordering, constraints on absolute neutrino masses or possible new physics). The duration of the burst is of only a few seconds, with most of the events arriving in the first $\sim$500 ms. The rate of expected events increases dramatically with the proximity of the SN (from 6000 IBD at a reference distance of 10 kpc, up to millions for the closest candidate for undergoing CCS, Betelgeuse, at $\sim$0.2 kpc).

The Subatech group is a main actor in the preparation of the analyses for CCSN with the SPMT system. The work includes the estimation of the hit rates for electronics requirements (e.g. the size of the DDR memory on the ABC board) and the impact of the SPMT readout on the event detection (Fig. 6). Though the number of lost hits can go up to 25% (5%) at the maximum peak rate for a CCS at 3 kpc (10 kpc), part of the charge of the missing hits will still be measured because of the charge pile-up [F-8]. Moreover, vertex and energy reconstruction algorithms for the SPMT have been developed or optimized at the energy of CCSN (15 MeV on average and end point of $\sim$50 MeV). The on-going analysis will make it possible to obtain the unfolded antineutrino energy spectrum. Given the large rate of events in a short period, external backgrounds are negligible while possible mixing and pile-up of events for very close SN are under study. This work is part of the PhD thesis of Victor Lebrin (Subatech, 2019–2022).

A multi-messenger trigger has been recently included by the collaboration to the global system, increasing also possibilities for solar neutrinos and faint transient source detection.

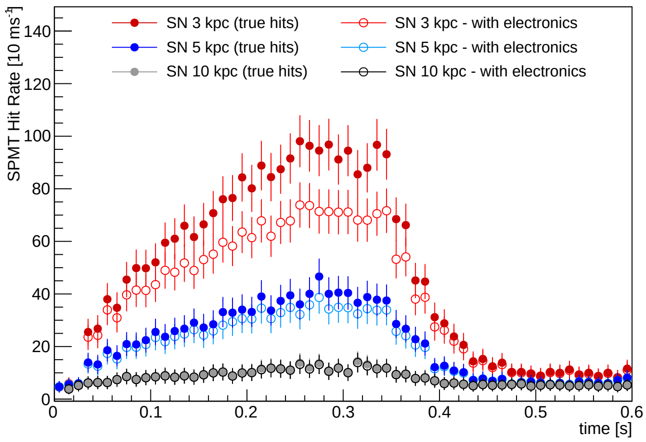


Figure 6: Impact of the SPMT electronics on the number of hits per PMT in 10 ms for different distances of the supernova (i.e., different event rates).

5 Technical developments

The IN2P3 teams have two main hardware contributions: one linked to the neutrino detector through the SPMT system and another linked to the Top Tracker detector. Since the CS 2018, most of the technical commitments have been successfully carried through despite the complicated COVID-19 situation of the last two years. These activities, further described in the next subsections, will be continued for at least the next year, with the detector installation and commissioning.

In addition to these hardware technical contributions, French teams also have significant contributions to the development of the official software pertaining to the corresponding hardware. Recent developments on the software will be highlighted in sub-section 5.3.

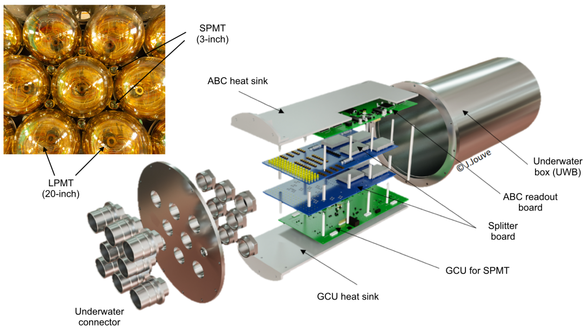
Finally, in order to manage and use the data collected by JUNO, it was necessary to develop a computing model for JUNO. The IPHC and CC-IN2P3 teams have been implicated in the development of this computer model, as described in sub-section 5.4, and the IN2P3 computing center is expected to both store some of the JUNO data as well as participate in official simulation and reconstruction campaigns.

5.1 SPMT system: Readout board and test benches

The major technical contribution ensured by the IN2P3 is the development and characterisation of the readout front-end electronics board, a work done by APC/IJCLab, CENBG and Subatech with the support of OMEGA. A sketch of the SPMT electronics system is shown in Fig. 7 in the underwater box (UWB). The SPMTs are grouped by 16 per UWB through an underwater cabling, with connectors and cables specifically designed for JUNO by the Axon company, in France. Each stainless steel UWB contains the stack of electronics boards that distribute the power (High voltage Units by Dubna, Russia) and separate the signal from the high voltage (HV splitter, by PUC Chile and UC Irvine, USA), readout the signal charge and time from SPMTs (**Asic Battery Card, ABC**, by IN2P3[5], as detailed below) and handle the data transfer to the Data Acquisition (DAQ) system and the time synchronisation (Global Control Unit, GCU, board, designed by IHEP, China, with a firmware developed in INFN, Italy[6]). The APC and CENBG members have also contributed to the conception of the UWB, benefiting from the ANTARES/KM3NeT underwater expertise available at CPPM. Further design developments and mechanical tests have been performed at CENBG. This preliminary design has then been transferred to PUC Chile. In addition, the R&D of the underwater cabling have been conducted and tested at CENBG with the Axon company and then transferred for production in China (IHEP and Axon China).

For each UWB, the 128 PMT signals are read out, after decoupling by the HVS board, with the ABC, whose PCB measures 35×17 cm and is composed of 12 layers. Eight 16-channel CATIROC (Charge And Time Integrated Read Out Chip) provide a trigger-less, digitised time and charge output. The other key component of the ABC is a high-performance Kintex-7 Field Programmable Gate Array (FPGA),

[5]APC/IJCLab, CENBG, Subatech with the support of OMEGA.
[6]Designed for the LPMT, it has then been adapted to the SPMT.



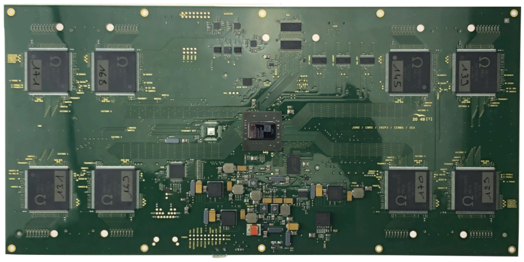


Figure 7: Left: Exploded view of the SPMT underwater box with the housed front-end electronics, high voltage and global control unit boards. Each connector is linked to 16 SPMTs for a total of 128 SPMTs per box. On the top left side, a picture from one of the test-bench shows the SPMT position in the space between LPMT. Right: A picture of the ABC (v1.2).

responsible for the communication of the CATIROC slow control parameters, as well as the data capture, processing and further packaging of the CATIROC output. The FPGA provides also the clocks and guarantee the synchronization of the ASICs. A 1-GB dual data rate (DDR3) high-bandwidth memory provides additional buffering resources, especially in case of a CCSN burst, to hold data until they are transferred to the GCU. The ABC allows for the readout of 128 PMT channels simultaneously.

The core of the ABC is the **CATIROC** (Charge And Time Integrated Read Out Chip), an ASIC initially developed by the OMEGA laboratory for large water Cherenkov detectors. The CATIROC has been extensively tested and validated for its usage in JUNO (especially by OMEGA and Subatech groups which also led the corresponding publication [F-8]). 2,000 CATIROCs have been produced and tested in 2019–2020, 1,760 have been selected to instrument the 220 ABC required by the project. Several key features have been identified which are particularly delicate in case of high rate of signals (as muons or a CCSN burst discussed in the previous section).

The initial design of the ABC was done by APC. Afterwards, the design of the ABC has undergone several improvements led by CENBG, with the support of APC/IJCLab and OMEGA, through different versions, mostly to improve the reliability, adapt the interfaces and correct some features. Three generations of boards have been produced for testing and the expected performances have been validated, including pedestal noise, Single Photoelectron Spectrum (SPE), trigger threshold definition and calibrations. These studies are part of the PhD thesis of Clément Bordereau (CENBG, 2017–2021 [T-3]) and the aforementioned thesis of Y. Han. Thermal studies have been conducted to ensure the heat dissipation and power budget in the UWB, particularly critical for an underwater system. The current version of the ABC has passed the Production Readiness Review within the collaboration and the mass production (200 + 20 spares boards) started in summer 2021.

The **firmware** for the ABC is a complex system which needs to collect the asynchronous signals coming from the 128 channels (8 independent CATIROCs). A first version of the firmware was developed by APC for the CATIROC validation board and a preliminary version adapted for the ABC board. The latter has been rewritten by the CENBG group which is currently responsible for the full **firmware** of the ABC and specific firmware functions in the GCU. Indeed, the use of 8 CATIROC in parallel has required major modifications in the data frame handling compared to the firmware strategy previously adopted. The completely new firmware properly treats the data frame arriving from each CATIROC, ensuring no data corruption. This first 'test' version of the firmware has been successfully used in the acceptance test-bench in China and most of the performance tests done in France. The JUNO operational firmware is under development, in particular to reduce part of the dead time due to the data treatment. It also includes the improvement in the data format, the communication part with the GCU (mostly for data and slow control transfer) and the digitisation of the discriminator signal directly at the FPGA level[7] to overcome an intrinsic dead time in CATIROC (critical for high-rate events, above 100 kHz, as can be expected for a CCSN burst or from muons). The integration between the ABC and the GCU is done in strict collaboration with colleagues from Italy and China.

Finally, to test the complete electronics chain a **combined test** has been built at CENBG to reproduce

[7]This functionality was developed and tested at APC on the firmware for the CATIROC validation board and the v0 version of the ABC board.

Figure 8: Combined test installed at CENBG, with the ABC, HV splitter and GCU boards (left) and the connected 128 SPMTs in the dark room (right).

the full underwater box (see Fig. 8), with the latest versions of the HV splitter, ABC and GCU, and 128 PMTs connected through the 100 m JUNO cables via the Axon connectors. This setup will serve for the tests of the 220 ABCs and for the extensive validation of the final version of the firmware. The current schedule, foresees a delivery of all the ABCs (tested and calibrated) to China in November 2021. Firmware development and testing will continue in France for the next year. The integration of the boards in the UWBs will be performed in China (beginning 2022). Given the COVID-19 situation this responsibility has been transferred to the IHEP group, with remote support from CENBG.

The SPMT electronics chain can be easily adapted for the purposes of TAO Veto detector readout (compact system with many readout channel and digitised charge and time). Given that the foreseen electronics chain in the TAO veto detector is the same as for the SPMT system, no specific development is required for those cards. The possibility of a French contribution to TAO in the form of 4 ABCs is under evaluation. The time schedule is similar to the JUNO one, with installation foreseen in 2022.

A total of 26,000 PMTs have been produced and tested by the HZC company. The SPMT specifications, testing, final bidding and company selection have been assured by APC, CENBG, IHEP. Thought already tested and validated by the HZC company and independently by IHEP [F-9], all SPMTs will undergo an **acceptance test** against failures after potting and cabling. For this purpose, the IN2P3 teams have provided three test-benches which reproduce most of the SPMT system electronics (HV splitter board and ABC). A dedicated firmware and DAQ software have been developed by CENBG and Subatech for these systems. The test-benches have been delivered to China (GuanXi University, Nanning) in December 2019 and commissioned in January 2020 with the on-site participation of the French teams. Currently, more than 8,000 SPMTs have been successfully tested. The SPMT tests will be finalized in the next months.

5.2 Top Tracker

As discussed previously the TT is one of the major contributions from IN2P3 to JUNO. As it was also mentioned previously, the JUNO TT will use existing modules from OPERA's Target Tracker [2]. The scintillator strips, measuring 6.8 m × 2.6 cm × 1.1 cm, are joined side by side in groups of 64 to create a TT module (shown in Figure 9 left) measuring 6.8 m × 1.7 m × 1.1 cm. The scintillation light produced in the plastic scintillator is then guided, using an optical fiber, to 64-channel multi-anode PMTs located at each end of the module. 4 modules are then placed side by side to form a detection plane, and two planes are used, where one plane is placed on top of the other with a perpendicular alignment, to form a TT wall, as shown in Figure 10 left. To form the TT, these TT walls are then distributed in a 7×3 grid in 3 vertical layers, with the central modules being moved up in relation to the other layers to make place for the calibration house, as shown in Figure 9 right. While the TT modules were already available by refurbishing the OPERA Target Tracker, a new electronics chain and supporting structure were required for JUNO.

The new electronics chain is composed, as depicted in Figure 10 right, of 4 different electronics cards: the Front-End Board (FEB), the Read-Out Board (ROB), the Concentrator Board (CB), and the Global Trigger Board (GTB). These cards, some of which are shown in Figure 11, are briefly described below:

FEB: responsible for the PMT interface and part of the PMT readout. This board houses a MAROC 3 (Multi Anode ReadOut Chip) ASIC, developed by OMEGA. In total, 992 boards are required for

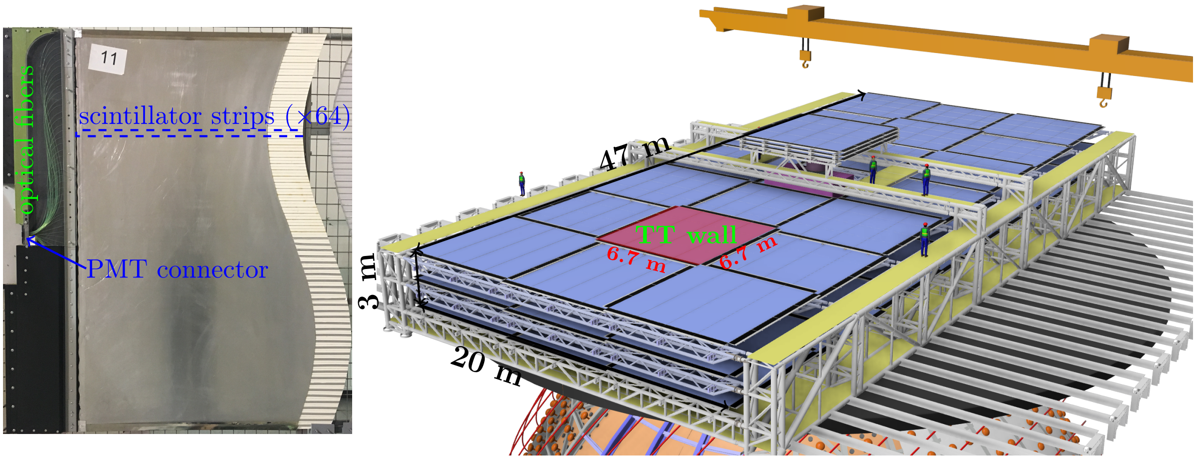


Figure 9: Left: Cut TT module. Right: The JUNO Top Tracker with a TT wall highlighted. From [F-1].

JUNO.

ROB: responsible for finishing the PMT readout and sending it to the CB. This board also provides the PMT HV and is responsible for the slow control. In total, 992 boards are required for JUNO.

CB: responsible for gathering all information related to one wall. Using this information the CB decides on the L1 trigger, and in its absence requires that the FEB resets the MAROC 3 chip to prepare it for a new event. Valid events are sent by this board to the DAQ. This board also is responsible for time-stamping all events with a nanosecond precision. In total, 63 boards are required for JUNO.

GTB: responsible for combining all information about L1 triggers on the TT to decide on an L2 trigger. This decision is then returned to the relevant CBs to inform if the event is valid, and if not to send a reset signal to MAROC 3 chip if need be. A single board is required for JUNO.

The L1 and L2 triggers mentioned above are required for the TT to be able to cope with the high environmental background from radioactive decays from the rock, which is estimated to be of about 50 kHz/PMT (to be compared with about 3 Hz of atmospheric muons in the whole detector). The L1 trigger requires that there are hits in at least 2 perpendicular planes of the wall in a given time window. This condition is necessary to determine precisely the position where the muon is crossing through the TT wall. Additional validation hits, or time ordering of the hits, can be required to further reject radioactive background events. Some of the evaluation of this trigger was done in the context of the PhD thesis of Q. Huang. The L2 trigger requires that 3 TT walls that are aligned and on different layers produce a L1 trigger. Both of these triggers are needed to reduce the TT rate by about 3 orders of magnitude to roughly 2 kHz of radioactive events. While this event rate is still significantly higher than the expected atmospheric muon rate, the Data Acquisition (DAQ) server is expected to be able to handle it. Additional offline reconstructions, in which alignment at the scintillator strip level is required rather than at the wall level, are needed to reject the remaining radioactivity induced background in the TT.

The CB and GTB are also connected to a White Rabbit Switch (WRS) to guarantee nanosecond precision time-stamping of all TT signals and provide the real detection times that are used to look for

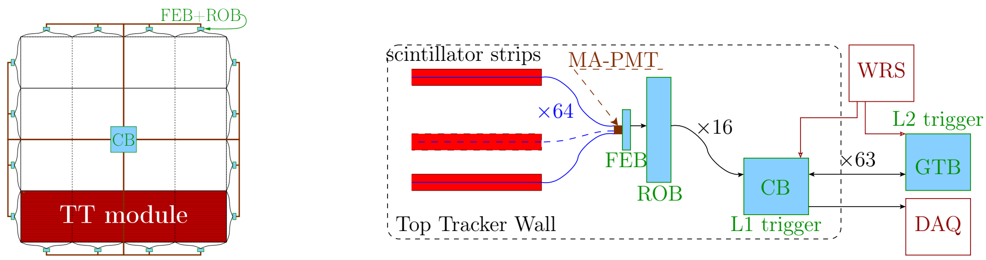


Figure 10: Left: Drawing of a TT wall, with one of the 8 TT modules highlighted. Right: Schematics of the TT electronics chain.

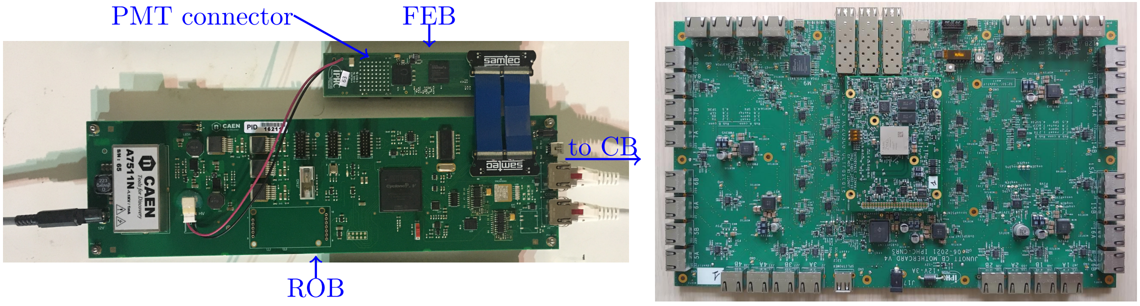


Figure 11: Final version of the FEB (left top), the ROB (left bottom), and of the CB (right).

the L2 trigger in the GTB. This time-stamping is also used in the CB and GTB to ensure which signals are validated or rejected by the L2 trigger.

All TT refurbishment tasks discussed previously were divided between 3 laboratories. The JINR (Russia) group is responsible for the mechanical structure (which is needed because the TT modules are flexible), while the INFN-Frascatti (Italy) and IPHC (France) have divided the responsibilities regarding the electronics update. The development and production of the ROB, as well as the production of the CB, are in charge of INFN. The IPHC is responsible for the development and production of all other cards and for the development of the CB.

At this point, all FEB have been produced [8] and have been sent to China. A test bench was developed at IPHC to individually characterize each of these boards and validate their production in 2020, despite constraints from the COVID-19 pandemics. Both the ROB and the CB have passed a final design review by the collaboration and pre-production tests (see Figure 12) are being finalized. The GTB is expected to pass a final design review in the beginning of 2022. The mechanics structure design has also already been finalized and is ready for production. Overall the TT is on time with respect to the current JUNO installation schedule.

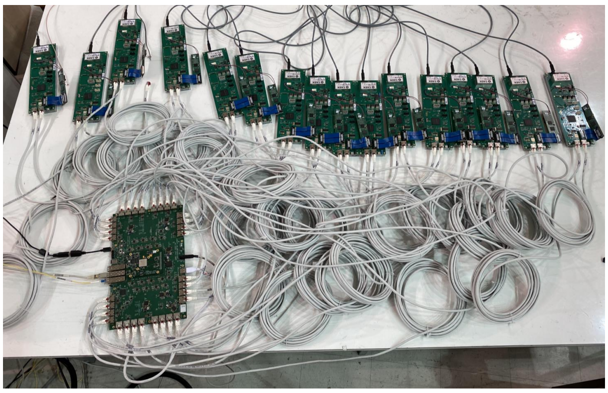


Figure 12: TT Electronics validation test of one CB connected to 16 ROB + FEB pairs.

5.3 Software

Related to the leading role of IN2P3 in the SPMT and TT systems, part of the IN2P3 activities also includes simulation and reconstruction algorithms developments. The simulation code for the SPMT electronics has been developed by the CENBG and Subatech groups and is implemented in the official software of the JUNO collaboration. The modeling of the JUNO-SPMT response and the impact of some electronics features on the SPMT reconstruction is part of the aforementioned thesis by C. Bordereau. The development of the vertex and energy reconstruction, optimized for the energy range of CCSN, have been developed within the PhD work of V. Lebrin. Further developments, using Machine Learning (ML) techniques are planned as part of a new PhD thesis (Leonard Imbert, Subatech, 2021–2023) and application of ML to atmospheric neutrino reconstruction has also been started at Subatech.

Similarly to what was described above for the SPMT, the TT software also needs to be prepared prior to the start of data taking. The TT simulation is currently being upgraded to provide a better description for the real response of the newly developed electronics chain at IPHC, using the prototype detector built in France. The IPHC group is in charge of the official software related to the TT. Measurements using this prototype have been, and will continue to be, taken in the context of 2 PhD thesis at IPHC (Luis Felipe Piñeres Rico, 2018–2022; Deshan Sandanayake, 2021–2024). In addition to the simulation, in the context of the PhD thesis of L. F. Piñeres Rico an effort is on-going to improve the TT reconstruction.

The IN2P3 groups are the main actors for the aforementioned (SPMT and TT) software integration in the official framework of the collaboration. These activities also includes the support for validation and a common simulation production, available for the full JUNO collaboration.

5.4 Computing

As is the case in several modern experiments, it is essential to prepare for the large amounts of data that will be collected and foresee the required computing power to process it. Likewise, large simulation samples (which also require significant computing power to be produced) are required to be able to properly analyse and interpret the collected data. With the goal of preparing the JUNO computing, a working group has been created within the collaboration with a strong presence from France, including contributions of engineers from the IN2P3 computing center. The IPHC group has also a leading role in this effort.

In the JUNO computing model [9] it is planned that the data collected at the JUNO detector will first be transferred to IHEP, and then distributed to 4 European computing centers: CC-IN2P3 (France), CNAF (Italy), JINR (Russia), and MSU (Russia). It is currently estimated that JUNO will produce about 3 PB of data per year, and will need about 12,000 cores for reconstruction, simulation and analysis tasks.

The data hosted at the European centers will serve both as a backup for the all the JUNO data, and to make it easier for them to participate in additional reconstruction campaigns. It is also foreseen that the European computing centers mentioned above will provide computing power similar to that provided by the Chinese computing center. This will make it possible to share the heavy load for simulation and reconstruction within the globe and optimize the access to JUNO data and simulation which will be essential to develop analyses.

The infrastructure elaborated for this distributed computing follows the one used by the WLCG (Worldwide LHC Computing Grid). This allows us to profit from the quality of the software already available, while at the same time guaranteeing the compatibility of our solutions with the workflow of all computing centers involved.

A Memorandum of Understanding is currently in preparation to organize the distributed computing, and distribute the expected workload among the 5 signatories.

6 Human and financial resources

The human resources at IN2P3 in JUNO are listed in Table 2, based on the data declared on NSIP during the first semester of 2021. Some JUNO members, who have no declared FTE, have been kept in the list if they are still in the JUNO lists, but have just not contributed in the past semester. In addition to the 5 laboratories participating directly in the JUNO collaboration (CENBG, CPPM, IJCLab, IPHC, Subatech), the OMEGA Microelectronics design center and the IN2P3 Computing Center are also directly involved in the project. In total 18 scientists (12 permanent researchers, 3 postdoctoral researchers and 3 PhD students) and 30 ITA are currently participating to the project. At least 2 new PhD students will also join the JUNO collaboration in the coming month, and some additional post-doctoral research positions are expected.

The French groups are organized by a national coordinator (M. Dracos, IPHC) helped by a national technical coordinator (currently J. Wurtz, IPHC). To further organize the French contributions, five task groups were created, each with a L2 coordinator at the national level, to separate several tasks: the "Science Analysis" (F. Yermia, Subatech), the "Data Center & pipelines" (J. P. A. M. de André, IPHC), the SPMT (C. Cerna, CENBG), the TT (J. Wurtz, IPHC) and the Radiopurity (F. Perrot, CENBG).

The JUNO project is financed mainly by the IN2P3. There is also a punctual participation from the Universities and Regions on which are located the JUNO laboratories through specific call for projects. Among them, the external contributions for PhD grants and post-doctoral positions are:

- APC: PhD grant, 2017–2020, (Y. Han) by Chinese Scholarship Council (CSC);
- CENGB: PhD grant, 2017–2021 (C. Bordereau) financed by IdEx, Université de Bordeaux;

Table 2: Human resources for JUNO. Fraction of FTE based on NSIP database for the first semester of 2021. The group leaders are noted with a 'PI' in their position and are the first name on the list. PhD equivalent authors, who have to contribute to the JUNO common funds, have a • mark before their name.

Laboratory	Name	Position	Fraction FTE
CENBG (15)	• Frédéric PERROT	MC, PI	50%
	• Cécile JOLLET	MC	69%
	• Anselmo MEREGAGLIA	CR	15%
	• Cédric CERNA	IR	62%
	Abdelkader REBII	IR	62%
	Frédéric DRUILLOLE	IR	50%
	Amelie FOURNIER	IR	4%
	Gérard CLAVERIE	IR	
	Patrick HELLMUTH	IR	
	Raphael BOUET	IE	8%
	Mathieu ROCHE	IE	
	Cédric HUSS	AI	8%
	Sébastien LEBLANC	AI	
	• Reem RASHEED	PostDoc	100%
	Clément BORDEREAU	PhD student (2018 – 2021)	100%
CPPM (1)	• José BUSTO	PU, PI	4%
IJCLab (6)	• Anatael CABRERA	CR, PI	31%
	Dominique BRETON	IP	4%
	Jihane MAALMI	IR	
	Didier AUGUSTE	AI	8%
	Rémy DORKEL	TCE	4%
	• Diana NAVAS-NICOLAS	PostDoc	88%
IPHC (11)	• Marcos DRACOS	DR, PI	50%
	• João Pedro A. M. DE ANDRÉ	CR	100%
	• Eric BAUSSAN	MC	50%
	Michal SZELEZNIAK	IR	100%
	Andrea TRIOSSI‡	IR	100%
	Jacques WURTZ	IR	88%
	Pascal POUSSOT	IE	81%
	Thomas ADAM	IE	8%
	Christophe WABNITZ	AI	15%
	Cédric SCHWAB	AI	5%
	Luis Felipe PIÑERES RICO	PhD student (2018 – 2022)	100%
Subatech (7)	• Frédéric YERMIA	MC, PI	50%
	• Mariangela SETTIMO	CR	54%
	• Benoît VIAUD	CR	35%
	• Mathieu BONGRAND	CR	15%
	Frédéric LEFEVRE	IR	
	• Rebin KARAPARAMBIL RAJAN	PostDoc	100%
	Victor LEBRIN	PhD student (2019 – 2022)	100%
OMEGA (5)	Selma CONFORTI DI LORENZO	IR	23%
	Stéphane CALLIER	IR	15%
	Gisele MARTIN CHASSARD	IR	5%
	Christophe DE LA TAILLE	IR	5%
	Sylvie BLIN*	IR	
CC-IN2P3 (3)	Rachid LEMRANI	IR	8%
	Sébastien GADRAT	IR	4%
	Quentin LE BOULC'H	IR	4%

‡ Departure in October 2021.

* Now at APC.

- IJCLab: Post-doc (D. Navas) financed by P2IO Labex via Neutrino Project NuBSM (2019–2024);
- IPHC: PhD grant, 2019–2022 (P. Piñeres Rico) financed by QMat; PhD grant, 2021–2024 (D. Sandanayake) by Unistra;
- Subatech: two PhD grants, 2019–2022 (V. Lebrin) and 2021-2024 (L. Imbert) co-financed by "Region Pays de La Loire"; post-doc Rebin Karaparambil Rajan, 2020–2022, financed by "Region Pays de La Loire".

The JUNO yearly budget from IN2P3 has been fairly stable with possible additions related to specific installation needs. For reference, in 2021 the global JUNO budget allocated from IN2P3 was of 220 k€.

Starting from 2022, with the start of data taking, collaborating countries will start contributing to the common fund based on their number of PhD equivalent authors[8] participating in the experiment. For clarity, the French collaborators that are listed as PhD equivalent authors for JUNO have a • mark before their name in Table 2. It has been currently defined a contribution of ∼5.7 k€/PhD author to the common funds for a normal year[9]. It is worth noting however that, for now, the computing contributions and costs have not yet been added to the common funds' calculation, pending signature of the computing MoU and the associated discussion.

7 SWOT auto-analysis

Strengths The JUNO-France members have strong experience in neutrino physics (Double Chooz, IceCube, OPERA, Solid, . . .), low background experiments (for neutrinoless double beta decay and dark matter) and high energy physics. This experience is well recognized within the collaboration with L2 and L3 responsibility roles, leading working groups and review committees (not all of them being mentioned in this document). We already have a significant representation in the JUNO management, that we should try to maintain and reinforce in the future. In the IN2P3 context, collaborations with other experiments within France have been initiated in a number of occasions, as it was the case of the mentioned combined analyses and aids in the detector design.

Threats The project has made significant progress in these years and the phases of integration and installation of the detectors will start soon. A really active time is expected soon. In this context, the sanitary situation, if aggravated, can be a potential threats for the future, though the collaboration is taking action to reduce any impact on the time schedule. For this reason, the original installation plans had to be modified. It was initially foreseen a strong participation from IN2P3 on site, however this participation is difficult for the moment. The possibility to perform a fully remote installation of the detector is under discussion within the collaboration. In parallel to this discussion, the possibility of sending a few people to follow the installation in China is also under investigation, however this will likely only be feasible if situation changes. Due to this unprecedented situation, there is a larger risk associated with the installation than would have been the case normally.

Weakness Concerning the physics analyses, the numerical dominance of Chinese colleagues may be a problem for having visibility and key positions in the future. So far no critical problems have been identified, nevertheless an organisation of coordination at European level is started.

Opportunities Within the French groups the improved synergies for some analyses (e.g., muons, impact of electronics and detector response) and the exchanges between engineers (e.g. between electronics groups, or for MAROC/CATIROC) can help create a major cohesion in the collaboration. As highlighted in the publications [F-4–F-6] the interplay between the high precision measurements by JUNO and other current and future experiments (with the participation of other IN2P3 teams) enable major physics opportunities, including also the use of NMO to explore Physics Beyond the Standard Model.

[8] JUNO defines PhD equivalent authors as collaborators holding a PhD degree that want to participate in physics publications.

[9] 2022 will have a reduced contribution as construction is still ongoing.

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