OSIRIS - The Online Scintillator Internal Radioactivity Investigation System of JUNO

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Abstract. The 20 kton liquid scintillator detector of the Jiangmen Neutrino Underground Observatory (JUNO), which is currently under construction in Southern China, has a vast potential for new insights into various fields of (astro-)particle physics. Stringent limits on the liquid scintillator radiopurity are required for several physics goals of JUNO. For both ^{232}Th and ^{238}U, a radiopurity of 10^{-15} g/g is required for reactor antineutrino measurements, 10^{-16} g/g for solar neutrino measurements. An independent detector, the Online Scintillator Internal Radioactivity Investigation System (OSIRIS), will be used to ensure these limits are kept. This report will present OSIRIS and its sensitivity to ^{232}Th and ^{238}U in detail.

OSIRIS allows an online radiopurity evaluation of the scintillator during the months-long filling of JUNO. The design of OSIRIS is optimized for tagging fast ^{214}Bi-^{214}Po and ^{212}Bi-^{212}Po coincidence decays in the decay chains of ^{238}U and ^{232}Th, respectively. The coincident decay signatures and their rates offer a potent background rejection as well as a direct translation into ^{238}U-/^{232}Th-abundances in the scintillator. OSIRIS will also be able to measure the levels of ^{14}C in the scintillator, down to a ^{14}C/^{12}C ratio of 10^{-17} at 90% confidence level. Furthermore, the level of ^{210}Po and a possible contamination by ^{85}Kr can be determined. To achieve its goals, OSIRIS features a water-submerged 20 ton liquid scintillator target monitored by 76 intelligent photomultiplier tubes (iPMTs). The novel design of the iPMTs allows a triggerless readout scheme with high signal quality. A single computer is sufficient to process the data stream into events for further analysis. The timing and charge calibration of the iPMTs will be performed with Laser- and LED-based systems. The energy and vertex reconstructions will utilise height-adjustable radioactive sources within the liquid scintillator.

JIANGMEN UNDERGROUND NEUTRINO OBSERVATORY

The Jiangmen Underground Neutrino Observatory (JUNO) is a liquid scintillator (LS) detector currently under construction in Southern China. Its central detector features a 20 kton liquid scintillator target, monitored by 17612 20"- and 25600 3"-PMTs [1]. With its excellent effective energy resolution of $3\%/\sqrt{E[MeV]}$ [1], it has a vast potential for various fields in (astro-)particle physics. The main goal of JUNO, which is to determine the neutrino mass hierarchy, is performed by measuring reactor anti-neutrinos with a baseline of 53 km. Besides this main goal, JUNO is expected to shed light on many other different open questions, for example supernova mechanisms.

In order to achieve these goals, the liquid scintillator used in JUNO has to fulfill stringent radiopurity limits. For both ^{232}Th and ^{238}U, a radiopurity of 10^{-15} g/g is required for reactor antineutrino measurements, 10^{-16} g/g for solar neutrino measurements [1]. Starting in 2023, the filling of the JUNO central detector will take several months. It is of utmost importance to ensure a liquid scintillator radiopurity meeting the JUNO requirements during the whole filling duration is achieved in order to reach the physics goals of JUNO. In order to reach these radiopurity levels, several purification steps are foreseen in the JUNO filling chain before the scintillator enters the central detector. The last step in this filling chain is the Online Internal Radioactivity Investigation System (OSIRIS). Placed directly before the JUNO central detector filling system, OSIRIS detector performs on-line radiopurity assessments of the liquid scintillator. In case contamination and air leaks occur, alarms will be raised and sent to the JUNO filling team. In the following sections, the OSIRIS detector will be presented in more detail.

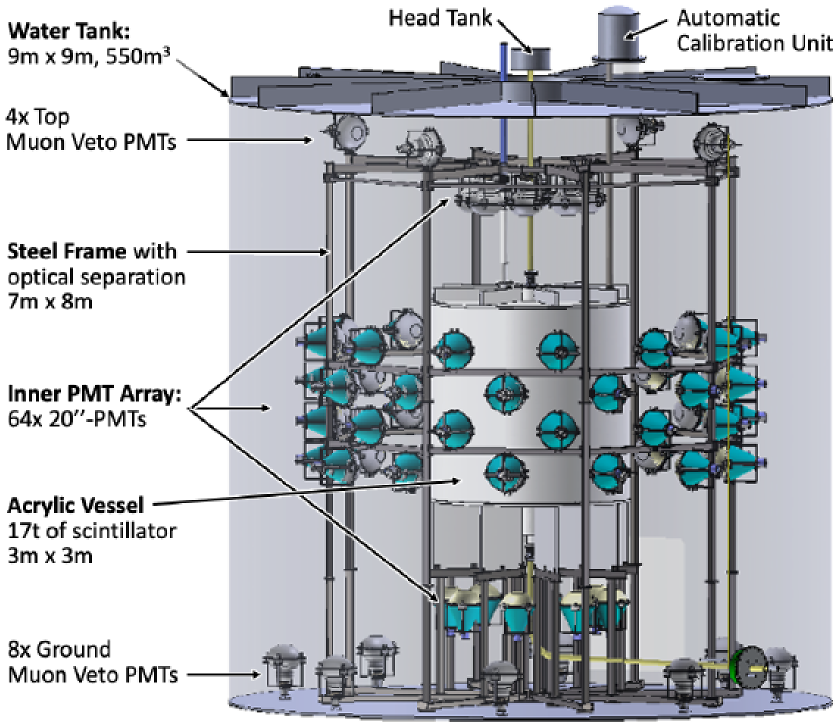

FIGURE 1: Overview schematic of OSIRIS [2].

Steel tank As shown in Fig. 1, OSIRIS features a 9×9 m cylindrical carbon steel tank filled with ultra-pure water. The water serves as a background shield and is also utilized as a muon veto. To avoid corrosion of the steel by the ultra-pure water, the insides of the tank are covered with a liquid- and gas-tight High Density Polyethylene (HDPE)-liner. Three steel plates in the foundation of the tank reduce backgrounds stemming from the rock underneath by two orders of magnitude [2].

Acrylic vessel The acrylic vessel (AV) in OSIRIS, a cylinder with 3-m width and 3-m height, can hold up to 18 tons (21 m^3) of liquid scintillator. Its wall thickness of 3 cm and external stiffeners provide the sturdiness needed for the LS filling and exchange programme. The vessel features diffusors for the LS on the inlet (top) and outlet (bottom). The inlet diffusor converts the vertical inflow of LS into a horizontal one to achieve laminar LS flow speeds in the vessel. As the acrylic vessel is in direct contact with the LS, its radiopurity is of the uttermost importance for OSIRIS. The radiopurity requirements of < 1 ppt for ^{238}U, ^{232}Th and ^{40}K have been closely monitored during production, storage and installation of the acrylic vessel [2].

Steel frame The octagonal stainless steel frame (SF), made from ultra-pure water compatible, low radioactivity 1.4404 stainless steel, serves two main purposes. The inner part supports the AV when both water tank and AV are empty. On the outer part, measurement devices such as the intelligent PMTs, the laser calibration system and other sensors are placed. The SF is furthermore utilized to mount the optical separation of the muon veto system of the detector. Radiopurity requirements specify the U/Th content of the stainless steel to be below 10 ppb.

Liquid Handling System The Liquid Handling System (LHS) fulfills multiple purposes. It handles the filling and exchange of liquids in the AV and water tank. While doing so, it maintains appropriate liquid and gas pressures in the detector subvolumes to prevent detector damages and the ingress of radon into the LS. Heaters and cooler units in the LHS enable creating opposing temperature gradients in the water tank and AV to enhance LS stratification.

Furthermore, the LHS distributes the high-purity nitrogen needed for the detector operation. Lastly, the LHS offers the possibility to operate OSIRIS in different modes described below.

In the so-called *Batch-Mode*, the LS present in the AV will be replaced by a new batch of LS which is then monitored for a period of several days up to weeks. This allows OSIRIS to reach its design sensitivity. See also page 6 for more details. This mode will be used heavily during the commissioning and calibration phase of OSIRIS, where in-depth studies are expected to reveal as much understanding as possible concerning the detector performance.

As the filling of the JUNO central detector will take several months, batch-mode operation does not provide sufficient exchange rates of LS to monitor the radiopurity of all product LS. Additionally, dead periods created by stops of the filling process might lead to undiscovered increases in LS radioactivity. For these reasons, the so-called *Continuous mode* will be used. In this scenario, warmer LS will be continuously filled into the acrylic vessel at the top and drained at the bottom. The whole LS volume will be replaced in approximately one day. With this exchange rate of about 1 ton per hour, OSIRIS will monitor a constant fraction of $\sim 15\%$ of the total LS flux in the filling chain [2]. As described in page 6, the sensitivity of OSIRIS in this operation mode heavily relies on the initial background levels of radon in the JUNO filling system.

Intelligent PMTs The novel intelligent PMT (iPMT) design combines a 20" Hamamatsu-PMT with readout electronics mounted directly on its back. This approach avoids long analog cables in the PMT readout scheme, leading to reduced noise and thus higher signal quality. A single Cat5e cable is sufficient for power and data transfer. The PMT signal digitisation is taking place on the iPMT itself; the iPMTs are self-triggered under normal operation.

A schematic drawing of the full iPMT assembly is shown in Fig. 2. Each iPMT consists of the aforementioned Hamamatsu-PMT, which is glued to a Polymethylmethacrylate (PMMA)-ring. The PMMA-ring serves as the central support structure of the iPMT and is used to mount the iPMT in a holder. A stainless steel housing, containing the iPMT readout electronics, is glued to the PMMA ring as well. The housing is filled with mineral oil to transfer heat away from the electronics via convection. Each electronics stack of the iPMT consists of five different boards:

The *Base* connects to the PMT pins and hosts voltage dividers for the PMT high voltage (HV). The voltage dividers which were laid out following the recommendations of Hamamatsu (positive HV towards anode, photo cathode at ground).

The *High Voltage Board* hosts a custom-made high-voltage module converting a 24 V DC supply voltage to a HV DC output for the PMT [3].

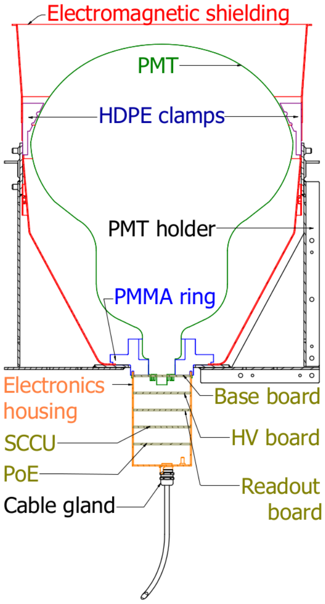

FIGURE 2: Overview schematic of the intelligent PMT assembly.

The *Read-Out Board (ROB)*, is the central board of the stack and used for signal digitisation and processing. The digitisation is performed by the VULCAN ASIC developed at ZEA-2, FZ Jülich. It records 240 ns-waveforms with a sampling rate of 500 MSps. By utilising three different gain settings, it offers a large dynamic range with high resolution between 0 up to 2048 photoelectrons. The digitised data is processed by an FPGA-ARM-combination (Xilinx ZYNQ 0720) and sent out via Ethernet. The FPGA offers the possibility to perform data analysis directly on the hardware, thus coining the term "intelligent" in intelligent PMT. For synchronisation purposes, the ROB also hosts a Clock-Data-Recovery (CDR) circuit. It is used to generate the reference clock for VULCAN as well as to receive information and the synchronisation of all iPMTs in form of a global timestamp. The data stream for this CDR-circuit is sent by *Surface Boards* which are placed outside of the detector volume.

The *Slow Control and Configuration Unit (SCCU)* hosts multiple communication interfaces to the different boards. It allows the highly configurable iPMT electronics to be reconfigured, even after the iPMT has been fully assembled and installed in the detector. The SCCU hosts the network interface which sends out the recorded data via Ethernet.

The last board in the stack is the *Power Over Ethernet board (PoE-board)*. Hosting a class 4 powered device controller, this board handles the power negotiation with PoE-switches and creates the supply voltages needed for the iPMT boards (24 V for the HV board, 5 V for the other boards). In total, the stack consumes about 10 W at the PoE side.

In order to mount the iPMTs in the detector, a stainless steel holder is used. The holder features a modular design to keep design tolerances and offers the possibility to mount additional equipment on the holder itself. An electromagnetic shielding is included in the assembly to reduce electrical noise and the influence of the earth magnetic field on the iPMT performance.

Muon veto The muon veto comprises the water tank, the optical separation and in total 12 iPMTs. The optical separation consists of HDPE-foils fixed to the steel frame. These foils divide the detector into an inner detector and the outer detector, where muons are being detected in the water shield by Cherenkov light. The light is measured by 4 iPMTs in a horizontal configuration on the top of the detector, and 8 iPMTs on the bottom facing upward. The expected muon rate in the detector is 0.39 Hz (0.04 Hz in the LS volume). Studies on the robustness of the system in terms of iPMT failure and different trigger scenarios have been performed utilising the GEANT4 simulation of OSIRIS [2].

Calibration systems The *Laser Calibration System* is used for the iPMT timing and charge calibrations. The laser creates pulses with a wavelength of 420 nm, 80 ps width (1 σ), tunable intensities and a maximum repetition rate of 20 MHz. The light is distributed within OSIRIS by optical fibres terminating in PTFE diffusor capsules held by stainless steel housings. Optical switches allow simultaneous calibrations of the inner and outer detector at the same time. In total, 24 light injection positions are foreseen in OSIRIS. These positions have been optimized by studies using the GEANT4 simulation of OSIRIS, ensuring a uniform illumination with light intensities between different PMTs of a factor 2 maximum. For the calibration of OSIRIS with the Laser Calibration System, daily calibration runs with durations of about 10 minutes are planned.

The *Source Injection System* utilises a refurbished Daya Bay ACU (Automatic Calibration Unit) placed at an off-center axis in OSIRIS. The ACU, shown in Fig. 3, will be used to perform iPMT timing and charge calibrations as well as energy and vertex reconstruction calibrations. For these tasks, the ACU features three different sources on three independent wheels in order to lower the sources directly into the LS volume. The first source is a 435 nm-LED placed in a diffusor capsule for timing and charge calibrations. Energy and vertex reconstructions will be performed with a high-activity multi-gamma source containing ^{137}Cs, ^{65}Zn and ^{60}Co (combined activity of ~ 3 kBq). These isotopes cover the crucial energy range for detecting Bi-Po-coincidences of 0.66 up to 2.5 MeV. For both LED and multi-gamma sources, weekly calibrations with durations between 60 (multi-gamma source) and 90 (LED) minutes at 25 different positions are foreseen. The ACU will also be used to introduce a "standard candle" in the detector to permanently monitor the liquid scintillator light yield during normal operation. To achieve this, the third ACU wheel carries a low-activity ^{40}K-source with an activity of below 1 Bq.

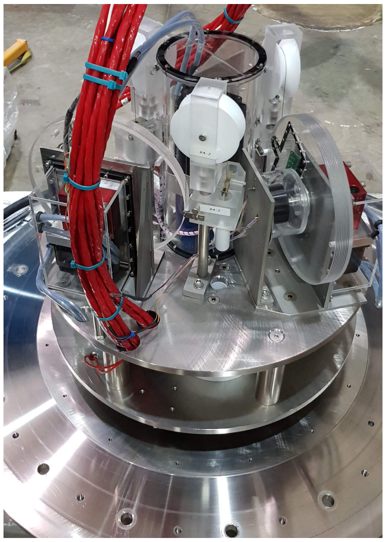

FIGURE 3: View of the turntable and the three wheels of the Automatic Calibration Unit.

Data acquisition and online monitoring As the iPMTs in OSIRIS are self-triggered devices, using a global analog trigger is not possible. The data stream from the iPMTs over Ethernet is processed by a single consumer-grade computer, the EventBuilder. This computer performs a software trigger and combines the recorded waveforms into events for further analysis. The expected physics data rates are $\approx$ 168 kB/s for science runs and up to 20 MB/s during calibration runs. As it is of utmost importance to monitor the BiPo-rates in the detector live, a separate computer is directly connected to the EventBuilder. It will perform an online monitoring of the BiPo-rates, as sudden spikes would indicate contamination or air leaks in the LS purification chain. The analysis of the data will be performed by using the flexible RootSorter software framework developed at Foschungszentrum Jülich. An overview of the analysis chain is shown in Fig. 4.

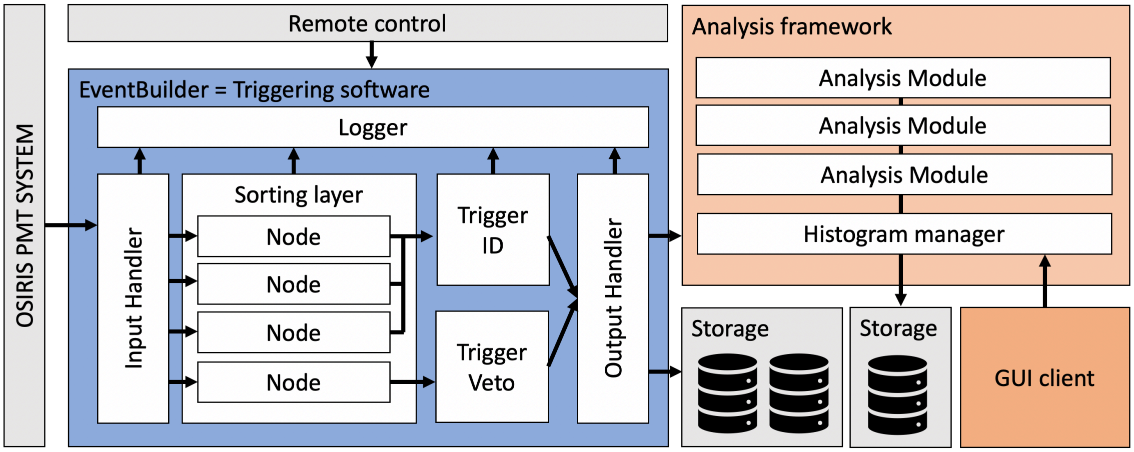

FIGURE 4: Overview of the DAQ data processing scheme [2].

Sensitivity of OSIRIS

OSIRIS will measure the radiopurity of the LS by detecting fast coincidence decays of ^{214}Bi-^{214}Po / ^{212}Bi-^{212}Po present in the decay chains of ^{238}U and ^{232}Th. Both bismuth isotopes decay predominantly via β^- decay, the polonium isotopes via α-decay, but with a much shorter half-life time (minutes vs microseconds). The resulting signal cascade is very characteristic and can be used to directly assess the abundance of ^{238}U and ^{232}Th in the LS. However, this method is susceptible to single-event backgrounds, as those can lead to accidental coincidences and thus misidentifications during reconstruction [2]. Studies performed with the GEANT4 simulation of OSIRIS identified the largest contributors to the single-event background in the liquid scintillator target as follows: γ-emitters in the surrounding rock of the experimental hall lead to a dominant background rate of 6.5 Hz. The second largest contributor is the glass of the intelligent PMTs with around 1.5 Hz [2].

Besides the two main sources of background described above, the sensitivity of OSIRIS also strongly depends on the radon contamination present in the liquid scintillator. Radon is emanated by the steel in contact with liquid scintillator, such as the pipes and the storage tanks of the LS purification chain. Also, radon is introduced by the gaseous nitrogen (N2) used to compensate liquid scintillator volumes that were removed for the filling process. The Radon levels present in the N2 are expected to be below 10^{-17}g/g [4]. In order to reduce radon contamination further during the filling phase, the filling scheme of the central detector itself and the purification of the N2 have been improved. A dedicated Radon counter is also included in the N2 system of OSIRIS to monitor the N2 levels on-line during filling. The dependence on the radon content in the LS is also shown in Fig. 5 for measurements in batch mode operation and different initial radon contamination. As can be seen, the LS radiopurity requirements for inverse beta decay (IBD) measurements can be confirmed within approximately one day, solar measurement radiopurities can be confirmed after around three weeks. For measurements in continuous mode during the filling of the JUNO central detector, batch-mode results from the commissioning phase and a height dependent BiPo-rate analysis allow confirming IBD limits also within roughly 2.5 days. In case of contamination, alarms will be raised within hours, which is enough time to divert the contaminated LS flow before it enters the central detector.

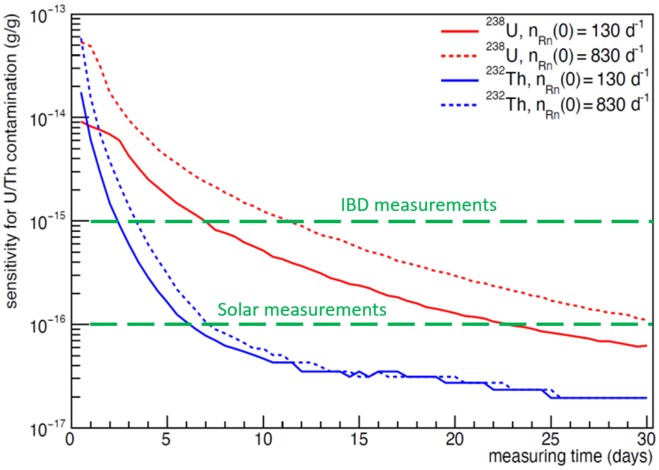

FIGURE 5: Contamination sensitivities against measuring time for ^{238}U (two upper curves) and ^{232}Th (two lower curves) in batch mode operation. The influence of different initial Radon levels in the LS is indicated by a solid and dashed line for each isotope. Graphic taken from [2] and modified.

OUTLOOK

The construction of OSIRIS started at the beginning of 2021. The tank, the acrylic vessel and the stainless steel frame have been successfully installed. Further, currently running installations include the clean rooms needed in OSIRIS and first parts of the LHS. Also, tests of the individual iPMTs before their installation in the OSIRIS have been started. In the middle of September 2022, German experts will arrive on-site to supervise and perform the commissioning of the different subsystems of OSIRIS. Several calibration runs with and without LS are foreseen to understand as much as possible about the detector response before the JUNO central detector filling begins in 2023. Figures 6, 7 and 8 show recent activities for the commissioning of OSIRIS, such as the installation of the acrylic vessel and steel frame as well as iPMT testing.

FIGURE 6: The acrylic vessel of OSIRIS being lifted into the steel tank.

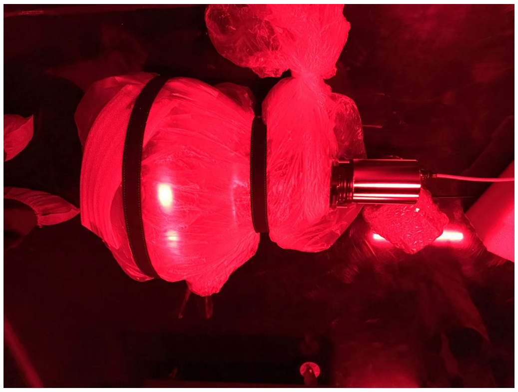

FIGURE 7: Test of an iPMT in a dark room prior to installation.

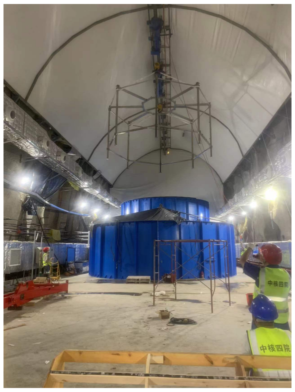

FIGURE 8: Lifting of the upper half of the OSIRIS SS frame into the tank.

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