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VIDARR: Aboveground Reactor Monitoring

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Abstract. Technology developed for the T2K electromagnetic calorimeter has been adapted to make a small footprint, reliable, segmented detector to characterise anti-neutrinos emitted by nuclear reactors. Based on the design of the T2K Near Detector ECal, the device detects anti-neutrinos through the distinctive delayed coincidence signal of inverse β -decay interactions using plastic scintillator and Hamamatsu Multi-Pixel Photon Counters. The device has been developed and constructed at the University of Liverpool and is situated in a 20 ft ISO container unit, capable of operating aboveground. The device finished a successful field trial at the Wylfa Magnox Reactor on Anglesey, UK where it was located roughly 60 m from the 1.5 GW_{th} reactor core and is now undergoing an upgrade with 50% more mass and channels as well as new electronics and sensors.

1. Introduction

New monitoring methods for nuclear reactors and the core activity and content are highly desirable, due to the expected growth of civilian nuclear power plants in the next years. Fission fragments produced during reactor operations release a large number of anti-neutrinos via beta decay. The anti-neutrinos flux and energy are dependent on the originating fission isotope, hence a measurement of the flux and energy spectrum can reveal information about the core status [1]. Hence, anti-neutrino detectors offer the potential for non-intrusive monitoring at short to medium stand-off distances. The potential of this technique was first recognised in the late seventies [2] and seen a recent revived interest with after the SONGS1 measurement [3, 4, 5].

The main detection mechanism is inverse beta decay, where the capture of an anti-neutrino on a proton results in the release of a positron and a neutron [6, 7], with the positron carrying energy information about the incident anti-neutrino. Scintillators can detect the positron and the γ -ray cascade released by the neutron upon capture. This distinct signal provides powerful background rejection. However, past anti-neutrino detectors faced technical challenges for widespread use near a power plant: the use of liquid scintillators, high-voltage photomultiplier tubes (PMTs) and the need for underground deployment, all increasing cost and complexity. The development of extruded plastic scintillator and MPCCs, as used in the T2K experiment, has opened a pathway for economically viable anti-neutrino detectors with a compact footprint and safeguards-friendly implementation [8].



2. The Liverpool Detector

The Liverpool detector developed as part of the VIDARR (Verification Instrument for Direct Assay of Reactors at Range) project is derived from the electromagnetic calorimeter of the T2K experiment [9], designed to measure the energy of electrons and positions. The sensitive volume consists of extruded plastic scintillator bars read out by Hamamatsu Multi Pixel Photon Counters (MPPCs). The plastic scintillator is robust, non-toxic and cost-effective. A wavelength shifting optical fibre guides light out of the bar to an MPPC. The MPPCs operate on low voltage and are compact and resilient, allowing for a compact, robust and transportable system. The active detector region includes gadolinium layers for detection of thermal neutrons, exploiting its high thermal neutron capture cross-section. The electronics readout system is based on the same Field Programmable Gate Array (FPGA) boards used in the T2K experiment with significant firmware adjustments for the detection of inverse β -decay interactions. An internal veto system provides rejection of cosmic ray tracks to enable aboveground operation.

The detector contains roughly 1 ton of plastic scintillator as the anti-neutrino interaction target and occupies a $1.7\text{ m} \times 1.7\text{ m}$ footprint. The plastic scintillator bars measure $40\text{ mm} \times 40\text{ mm} \times 1520\text{ mm}$, arranged in a hodoscope layout with alternating scintillator bar direction in the x - y plane for a total of 1720 individual channels. The scintillator planes are interleaved with gadolinium sheets as capture dopant. Each bar uses a wavelength shifting fibres coupled to a MPPC. The mechanical support structure assures correct alignment, allowing assembly off-site and transport of the full system. The detector is surrounded by 75 mm of high density polyethylene neutron shielding to reduce background from the reactor, with 25 mm of the shielding being boron-loaded to capture thermalised neutrons.

The readout electronics are derived from the T2K readout system and have been converted to operate on an internal trigger, rather than the external beam-synchronised trigger used in T2K. Trip-T Front-end Boards (TFB) read out up to 64 MPPCs and convert the analog charge signal from the MPPCs to a digital count. The Readout Merger Module (RMM) [10] gathers the signals of all 31 TFBs and sends the data of $30\text{ }\mu\text{s}$ preceding the trigger, temporarily stored in a FIFO buffer, to an IBM-compatible PC for data recording.

The detector was installed in a 20 ft ISO refrigerated shipping container, as shown in figure 1. The container acts as mobile laboratory with all required services for operation included within, including climate control and power supply. The self-contained unit allows simple deployment with minimal overheads for the power station staff and only requires a 3-phase 420 V power socket for operation.

3. Event Signature & Analysis

The plastic of the scintillator bars is the active target for anti-neutrino inverse β -decay interactions. These interactions produce a positron and an epithermal neutron. The positron is detected immediately through its scintillation track until it annihilates, releasing two back-to-back 511 keV γ -rays. The majority of the γ -rays will Compton scatter inside the detector and leave energy deposits close to the current noise threshold and are hence not used at the moment.

The neutron will be detected later when it captures on a nucleus following multiple scatters in the bulk of the detector. Gadolinium is used as a neutron capture agent thanks to its high thermal neutron capture cross-section and the release of an 8 MeV γ -ray cascade on capture. The neutron capture is then observed through the Compton scattering of the emitted γ -rays, creating a spatially diffuse energy deposit that is strongly correlated in time. The distinct signature of the neutron is used to trigger on events of interest and save them for the data analysis.

The raw data from the detector is processed in the offline data analysis using the ROOT analysis framework [11]. In order to facilitate high-level candidate event selection, the low-level data has to be translated into high-level physics properties. Periodic calibration runs with a clock-based trigger are used establish the baseline “pedestal” or zero pixel shape and signal



Figure 1. The detector inside the refrigerated 20 ft. ISO shipping container, showing the size and footprint of the detector itself. The rack in the foreground contains services and DAQ systems for readout.

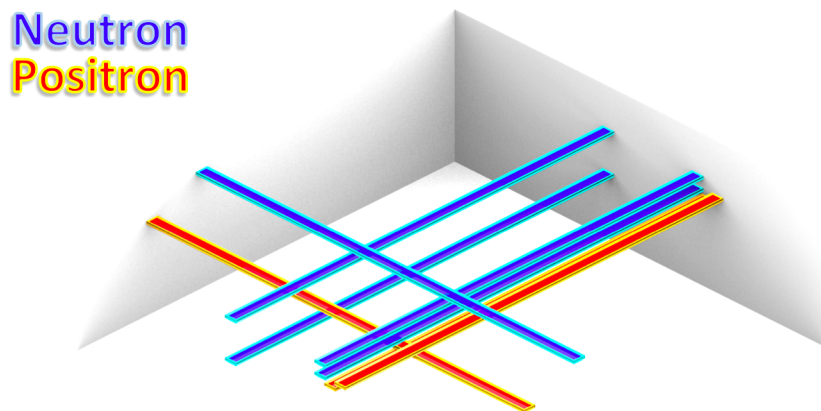


Figure 2. Typical event display of an inverse beta-decay candidate event. Red bars indicate hits in prompt time window, associated with a positron-like hit identified by the compact cluster of adjacent bars. Blue bars indicate hits in the trigger window, associated with a neutron-like hit, showing the diffuse deposition of energy throughout the detector.

and are used in conjunction with dark noise measurements to calculate the MPPC gain. These values are then used to convert signals from ADC units to pixels fired equivalent units.

Nearest neighbour-based reconstruction algorithms are used to identify high-level features of events that can be mapped to physics-related processes. The main features of interest are hit clusters (for positrons and neutrons) and tracks (for cosmic rays). These high-level objects are then used for a cut-based selection procedure based on source data to identify positron- and



Figure 3. *Left:* Photo of the 20 ft. ISO shipping container housing the detector lifted up by a HIAB truck for transport to the Wylfa Magnox power station. *Right:* The Liverpool team and Wylfa staff after the installation of the detector at the Wylfa site at 60 m distance to Reactor 1.

neutron-like signals. Anti-neutrino candidates are selected by looking for the distinctive delayed co-incidence signal of a positron preceding the neutron trigger within the $30 \mu\text{s}$ readout window. The topology of events of interest can be seen in figure 2.

4. Field Trial & Results

The Wylfa site is located on the Isle of Anglesey, North Wales in the U.K. and houses two 1.6 GW_{th} Magnox reactors. Reactor 2 was shut-down permanently in 2012. Reactor 1 continues operation under the novel inter-reactor transfer (IRX) programme whereby partially irradiated fuel is transferred from reactor 2. Reactor 1 was shut-down permanently at the end of 2015.

The University of Liverpool detector has been deployed at Wylfa power station for testing April 2014, shortly before the start of the final power generating cycle of the Wylfa Magnox power station. The container was transported via road from the University of Liverpool to the Wylfa site. The flat-bed truck used for delivery was an industry standard for transportation of cargo containers. It came with its own HIAB (lifting crane), minimising the burden on the power station for installation. Figure 3 shows the container being loaded on to the transport vehicle at the University of Liverpool. The detector was placed outside, between the reactor building and turbine halls at a distance of roughly 60 m from the centre of the reactor core. The detector is outside of internal security barriers, minimising the issues with site access and security clearance at the cost of being further from the reactor core.

In July 2014, reactor 1 at the Wylfa Magnox plant was taken offline and then restarted mid-month. This gradual ramp-up began with operation at ca. 0.9 GW_{th} , followed by an increase to ca. 1.6 GW_{th} towards the end of the month. The data taken by the detector in this period is shown in figure 4 with the daily candidate counts averaged in 5-day intervals versus the reactor thermal power reported by the site operators. The plot shows the clear increase in candidate events with the active reactor, even during the half-power period. Subsequent to the observation of the reactor turn on, the detector was taken down to investigate alternative running conditions.

5. Summary & Outlook

The field trial has successfully established the functionality of the detector design and its capability to operate autonomously in realistic conditions.

The next phase of the project is an upgrade to an enhanced detector design, using space volume in the existing mechanical support structure of the detector. This upgrade will see an addition of further 21 layers of scintillator bars, resulting in an increase of c. 50% target mass and c. 2700 total readout channels.

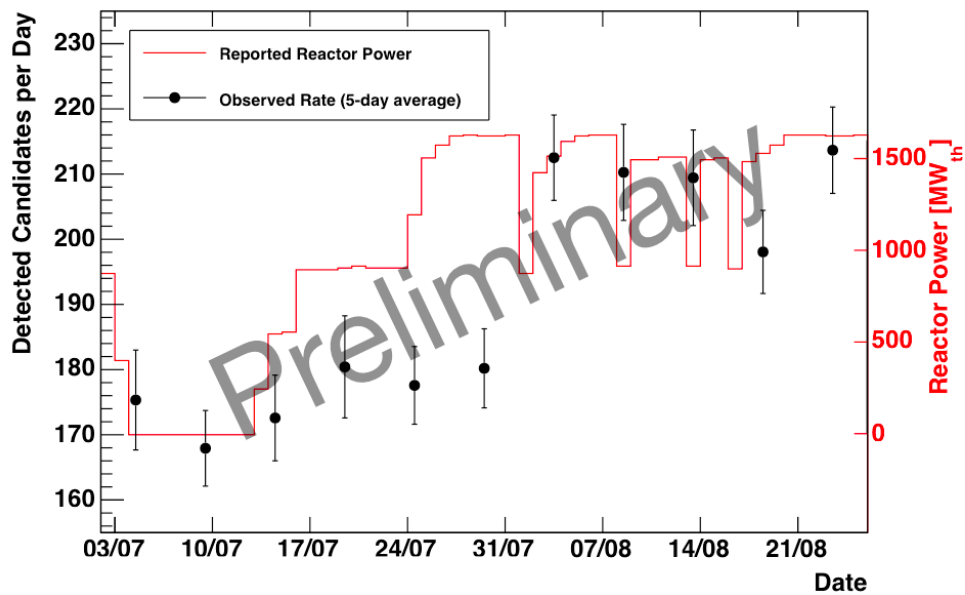


Figure 4. Event candidate count rate observed in the detector at 60 m stand-off distance compared to the thermal power output of the Wylfa Magnox Reactor 1 as recorded and reported by the plant operators. The daily event candidate rate is averaged in 5-day intervals.

As this process involves opening up and disconnecting the entire scintillator and MPPC assembly from the DAQ system, this opportunity will be used to replace the existing MPPCs with the latest generation Hamamatsu MPPC. Tests of the new models have shown an expected order of magnitude increase in gain and decrease in dark noise while providing c. 50% additional photodiode efficiency for running conditions similar to the detector.

Furthermore, the readout stack will be replaced with a custom-designed electronics and DAQ system. The new readout stack is being design with the new MPPCs in mind and is capable of continuous recording without no need for integration cycles and dead time from the readout process. Due to the lack of integration cycles and the improved dark noise performance of the MPPCs, the overall noise level for each signal part will drop and result in c. 10 ns-scale timing resolution for individual hits. This timing precision will be further augmented by an increase of coincidence window from 30 μ s to 100 μ s.

The combined improvements in rate and lowered thresholds and noise floors are expected to enable further increase the signal rate, better background rejection and make energy spectrum measurements possible.

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