

Readout System for the SoLid Neutrino Detector

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Abstract—The SoLid experiment aims to measure neutrino oscillation at a baseline of 6.4 m from the BR2 nuclear reactor in Belgium. Anti-neutrinos interact via inverse beta decay (IBD), resulting in a positron and neutron signal that are correlated in time and space. The detector operates in a surface building, with modest shielding, and relies on extremely efficient online rejection of backgrounds in order to identify these interactions. A novel detector design has been developed using 12800 5 cm cubes for high segmentation. Each cube is formed of a sandwich of two scintillators, PVT and $^{6}\text{LiF:ZnS(Ag)}$, allowing the detection and identification of positrons and neutrons respectively. The active volume of the detector is an array of cubes measuring 80x80x250 cm (corresponding to a fiducial mass of 1.6 T), which is read out in layers using two dimensional arrays of wavelength shifting fibres and silicon photomultipliers, for a total of 3200 readout channels. Signals are recorded with 14 bit resolution, and at 40 MHz sampling frequency, for a total raw data rate of over 2 Tbit/s. In this paper, we describe a novel readout and trigger system built for the experiment, that satis-

fies requirements on: compactness, low power, high performance, and very low cost per channel. The system uses a combination of high price-performance FPGAs with a gigabit Ethernet based readout system, and its total power consumption is under 1 kW. The use of zero suppression techniques, combined with pulse shape discrimination trigger algorithms to detect neutrons, results in an online data reduction factor of around 10000. The neutron trigger is combined with a large per-channel history time buffer, allowing for unbiased positron detection. The system was commissioned in late 2017, with successful physics data taking established in early 2018.

1 INTRODUCTION

1.1 The SoLid Experiment

SoLid is designed to measure neutrino oscillations at very short baselines, $\mathcal{O}(10)$ m, from a nuclear reactor

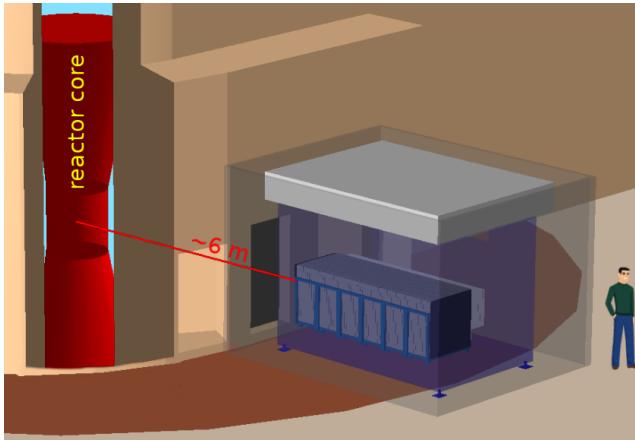


Fig. 1. Schematic showing the placement of the SoLid detector in the BR2 reactor containment building. The detector itself is placed in a customised shipping container, and surrounded by a 50 cm wall of passive water shielding. A roof structure supports 50 cm of High-density polyethylene (HDPE) passive shielding.

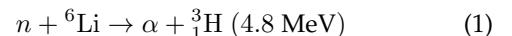
core. Hints of reactor neutrino oscillations at this energy and distance scale arise from both the reactor and gallium anomalies [1]. Measurements of the rate of $\bar{\nu}_e$ emitted by reactor cores show a deficit at $\sim 3\sigma$ significance when compared with expectations. Deficits of a similar significance are also observed in measurements of the ν_e rate emitted by radioactive sources. One proposed explanation is the existence of an additional non-interacting ‘sterile’ neutrino state, and a corresponding mass eigenstate; this fourth neutrino could influence the neutrino flavour transitions (oscillations) at very short distances. The existence of such oscillations can be tested using measurements of the $\bar{\nu}_e$ energy spectrum as a function of distance from a neutrino source.

The BR2 reactor core is especially suitable given its small core diameter of 0.5 m (see figure 1). The fuel composition is predominantly ($> 90\%$) ^{235}U , which is of particular interest to the nuclear physics community, who await updated $\bar{\nu}_e$ energy spectrum measurements from highly enriched fuels to resolve the 5 MeV distortion observed by previous reactor experiments [2]. The reactor is powered to around 60 MW for typically half the year in evenly spread 1 month cycles. The space in the reactor hall is sufficient for a relatively compact detector to be placed with modest passive shielding.

Compared to previous neutrino oscillation experiments that operate at longer baselines, this environment is particularly challenging. The detector has to be placed on the surface, with negligible overburden to shield from cosmic-ray backgrounds. Additionally, the reactor itself produces a large rate of gamma rays during operation that can further contribute to backgrounds. Previous experience of running a 288 kg (20% scale) prototype of the detector in spring 2015 [3], demonstrated the need for a controlled temperature environment to reduce and stabilise the SiPM dark count rate, as well as a need for electromagnetic shielding to prevent pickup of electronic noise. The detector is scheduled to run for around three years. Efficient online signal tagging is required in order to reach the experiment’s physics aims in this time period.

1.2 Detector Design

Anti-neutrinos are detected in SoLid via inverse beta decay (IBD), resulting in a positron and neutron signal that are correlated in space and time. To take advantage of this spatial correlation, the SoLid detector is highly segmented, with its detection volume formed of 12800 5 cm cubes. This corresponds to the scale of the mean separation between the positron and neutron interaction. The bulk of each cube is polyvinyltoluene (PVT) based scintillator that offers high light output and a linear energy response. Sheets of $^6\text{LiF:ZnS(Ag)}$ are placed on two faces of each cube to facilitate neutron detection. In order for each cube to be optically isolated, it is wrapped in white Tyvek®. Neutrons may be captured on the lithium via the interaction:



The alpha and tritium particles deposit energy in the ZnS(Ag) causing scintillation. These heavy nuclei scintillations are referred to as *nuclear signals* (NS). Crucially, the scintillation timescale of nuclear signals is considerably slower at $\mathcal{O}(1) \mu\text{s}$, than the PVT scintillation at $\mathcal{O}(1) \text{ ns}$. Nuclear signals are characterised by a set of sporadic pulses emitted over several microseconds. Pulse shape discrimination (PSD) techniques can be used to identify the nuclear signals with high efficiency and purity. These are used both in offline data analysis and, in simplified form, in the trigger. The full signal waveforms are therefore required for offline analysis. A sampling speed of around 40 MHz is sufficiently fast in order to perform effective PSD, whilst providing adequate time resolution. This has been demonstrated with smaller scale lab setups and by a large scale prototype of the full detector [3].

In IBD interactions, the positron is detected immediately via scintillation in PVT, and the neutron is detected after thermalisation and capture. The separation of the positron and neutron is 2 cubes or less in 90% of IBD interactions. The gamma rays resulting from the annihilation of the positron travel up to 30 cm, and can deposit energy in other neighbouring cubes. The mean time interval between the positron and neutron scintillation signals is around 60 μs , and the neutron capture efficiency of this configuration is around 66%. For a reactor power of 60 MW, the expected rate of neutrino captures in the detector is approximately 1200 per day (around 1 per 100 seconds).

The cubes are arranged in 50 planes of 16×16 cubes. Light from each detector plane is read out via a 2D array of vertical and horizontal wavelength shifting fibres that sit in grooves machined in the PVT. Two fibres sit along each row and column of cubes, giving 64 fibres per plane. The use of two fibres per vertical/horizontal direction enhances the overall light collection efficiency, as well as providing channel redundancy. One end of each fibre is coupled to a second-generation Hamamatsu silicon photo-multiplier (SiPM), whilst on the other end there is a mirror. The light yield has been measured to be 15 pixel avalanches (PA) per fibre per MeV of deposited energy, for a typical operational SiPM over-voltage of 1.5 V. At this over-voltage, in order to avoid saturated signals in the digitised waveforms for