Performance of the 
SoLid Reactor Neutrino Detector

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On behalf of the SoLid collaboration
Outlook

• Physics motivations
• The SoLid experiment
• Construction – QA - Commissioning
• Calibration - Operation and performance
• Summary
Physics motivation
Physics Motivations

- **Anomalies**: The **reactor antineutrino anomaly (RAA)** and **gallium anomaly** both show discrepancies wrt expectations at ~3σ level

- Oscillations into a **light sterile neutrino state** ($\Delta m^2 \approx 1 \text{ eV}^2$) could account for such deficits

![Graph showing reactor antineutrino anomaly](image1)

- **Distortion** observed around **5 MeV** (“bump”) in the reactor antineutrino energy spectrum
  - Hints point to $^{235}\text{U}$ (arXiv: 1609.03910, 1608.04096, 1512.06656)
  - **Energy scale non-linearity** of LS (arXiv: 1705.09434) ?

- New experiments at SBL needed
  - $\rightarrow$ **SoLid experiment with new technology**
The SoLid experiment
SolLid goals

SolLid goals:

- Using a **different detection technology**
  
  - RAA: Search for an **energy and space oscillation** pattern at short baselines ([6-9] m)
  
  - 5 MeV “bump”: Provide a **new** measurement of $^{235}\text{U}$ fuel antineutrino energy spectrum
The BR2 site and reactor

Best fit RAA → Oscillation length of 3-4 m for 3 MeV $\nu$'s ⇒ Compact source

- **Compact** reactor core $\Phi < 50$ cm, $h = 90$ cm
  - Baselines: 6.5 → 9 m
- Thermal power: 45-80 MW
- Highly $^{235}$U enriched (up to 93.5 %)
- 150 days per year duty cycle
  - Reactor off data for background estimation and subtraction
- **No nearby experiments**
- Overburden of ~10 mwe
- **Low background** (neutron, $\gamma$)
- **Excellent** collaboration with SCK•CEN

Dedicated Geant4 simulation
The SoLid technology

- Inverse beta decay: $\bar{\nu}_e + p \rightarrow e^+ + n$

- 3D highly **segmented composite detector**
  - 5 cm x 5 cm x 5 cm PVT scintillator cubes
    - $\bar{\nu}_e$ interaction
  - 2 layers / cube of LiF:ZnS(Ag) scintillator for neutron detection
    - Neutron capture on Li in ZnS layer:
      - $n + ^6\text{Li} \rightarrow ^3\text{H} + \alpha$
  - Nuclear signals (NS) and electronic signals (ES) very different
    - Waveform shape discrimination (“~PSD”) + neutron trigger

- Cubes optically separated (Tyvek)
- WLS fibers + SiPM to read out signals

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The SoLid (1600 kg) detector

- **5 Modules** of 10 planes
  - Planes of 16x16 cubes
- 4 x (fiber + SiPM + Mirror) per cube
- Automated calibration system (CROSS)
- Container (2.4×2.6×3.8 m) for **cooling at 10 °C**
  - Reduction of SiPM dark count rate

**Shielding:**
- Water wall: 50 cm thick, 3.4 m high, 28000 kg
- Polyethylene ceiling: 50 cm thick, 6000 kg
From Construction and QA to commissioning
From QA to commissioning

- ~13,000 cubes manually washed, weighted, wrapped, stacked, ...
- All cube components information stored in database

Planes, electronics and software qualified before installation with automated calibration robot CALIPSO
QA with CALIPSO

- Preliminary estimation of **LY and n eff** in all 12800 cubes

- **Exceeded** SoLid requirements
  - LY > 60 PA/MeV and n eff > 60%

- **Homogeneous** response

- Minor construction problems **identified and fixed**

One **bad** $^6$LiF:ZnS batch identified and replaced

**LY and relative neutron reconstruction efficiency** in all 50 planes

Response all 50 planes (12800 cells) validated!
Commissioning at BR2

- **First modules deployed** at BR2 on November 2017
- **Commissioning** of the full detector **completed** beginning of February 2018
- Taking data in **stable conditions** since May 2018
Operation, calibration and performance
**DAQ and triggers**

- **Random**: Full detector readout at 1 Hz
  - Non zero-suppressed waveforms for SiPMs monitoring
- **Threshold**: XY fibers coincidence > 2 MeV
  - Muon and high electromagnetic event tagger
- **Neutrino**: Algorithm for neutron trigger
  - **Neutron trigger** algorithm implemented in FPGA
    - Based on **peak counting**
    - Read out long time buffer around NS: [-500 μs, +200μs]
    - Multiplane readout (+/- 3 planes)
  - → **Unbiased prompt detection**
- **Triggers for data taking in physics mode** optimized at OV of 1.8 V

ArXiv:1812.05425 Submitted to JINST
Calibration

- Automated robot (CROSS) for **full detector calibration**
- **Periodic calibration** campaigns with $^{22}$Na and AmBe sources every reactor OFF period
  - Full $^{22}$Na scan in ~22 hours
  - Full AmBe scan in ~72 hours
- Dedicated calibration campaigns with $^{137}$Cs, $^{207}$Bi, $^{252}$Cf
- **100% of cubes** have been calibrated
- SiPMs equalization at the ~1% level

Clean $\mu$ tracks used for calibration at high energy
**Energy scale calibration**

- LY of about 96 PA/MeV (w/o x-talk subtraction) with good homogeneity

- Excellent agreement between $^{22}$Na (1.27 MeV) and AmBe (4.4 MeV) / $^{207}$Bi (1.7 MeV)

- Confirms PVT energy linearity

\[ \nu_e + p \rightarrow e^+ + n \]

- Muons used at high energy and for daily monitoring of energy scale
  - Very stable energy scale
  - Confirms linearity at high energy

See poster 374 from Giel Vanderendonck for more details about muon studies

11/07/2019

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Neutron calibration

- Calibration with AmBe (~4 MeV) and $^{252}$Cf (~2 MeV)
- Able to calibrate **n efficiency per cube** with both sources!
- Agreement at the ~3% level
- Neutron reconstruction efficiency > 75%!
- Statistical error ~2.5%
  - Dominated by cubes far from the source
  - Will decrease using data from other calibration campaigns (ongoing)
- Time of neutron capture for AmBe n’s ~ $71.8 \pm 2.4$ μs
Data taking and stability

- **Stable** data taking since May 2018 → Stable for both reactor on and off

- **Online**, live, remote **detector monitoring**

- Online event reconstruction for subsample of data

- **Physics variables available online**
Summary

- **New detector concept for $\bar{\nu}_e$ detection**
  - ArXiv:1703.01683 1802.02884 1806.02461 1811.05244 1812.05425
- **Construction of full detector (1600 kg) completed**
- **Commissioning** at BR2 research reactor **finished in February 2018**
- **Data taking** in physics mode **in stable conditions** since May 2018
- Calibration results indicate **excellent detector performance**
  - $LY > 70 \text{ PA/MeV} \rightarrow$ stochastic energy resolution of $\sim 12\%$
  - Neutron trigger efficiency $> 70\%$
  - **Linear energy response**
- Analysis of unblinded data sample for first **physics results ongoing**
  - See dedicated talk by Ianthe Michiels (Sat. on Neutrino session)
Thanks for your attention

The SoLid Collaboration
4 countries 12 institutes ~50 people

Stay tuned!

May 2017
Gent-Belgium
BACK UP
Expected physics results

- Baselines: 6 – 9 m
- Energy resolution: 14% / \sqrt{E}
- IBD eff: 30%
- Thermal power: 60 MW
- S:B of 3:1 5 Modules
- 450 days of reactor ON

New measurement of \( \nu \) spectrum of \(^{235}\text{U}\)

On track for first physics result around the end of the year, beginning of next year
Backgrounds

**Muon induced**
- Fast neutrons from spallation
- Stopping $\mu$’s (with Michel e$^-$)
- Cosmogenic isotopes (e.g. $^9$Li, $^8$He)

**Countermeasures:**
- Shielding/underground lab
- Active veto
- Pulse Shape Discrimination (PSD)

**Reactor induced**
- Neutrons (fast & slow)
- $\gamma$’s from n captures

**Countermeasures:**
- Shielding
- PSD
- Topology

**Radioactivity**
- Thorium/Uranium
- Radon/Argon
- Potassium

**Countermeasures:**
- Material radiopurity
- Topology
SoLid Calibration systems

Double calibration: during construction and in-situ

CALIPSO system

➢ Individual plane calibration
➢ Automated robot to place radioactive sources in front of each cube
➢ Calibration during detector construction
➢ Preliminary detector performance
➢ Used for quality assurance

CROSS system

➢ Global detector calibration
➢ Automated robot to place radioactive source between modules
➢ Calibration during reactor OFF periods
➢ Detailed detector performance
➢ Energy scale + n capture efficiency per cube

+ Muon calibration
Energy scale with $^{22}$Na source

- SiPMs are equalized (gains) at the 1% level!

- Crosscheck with data: ADC $\rightarrow$ PA

Individual PA arrivals can be identified

**SiPM response is very linear!**

- The total amplitude per cube ($A_{ij}$) is found summing the amplitudes of the 4 SiPMs associated to each cube

$$A_{ij} = \frac{A_{i}^{t}}{g_{i}^{t}} + \frac{A_{i}^{b}}{g_{i}^{b}} + \frac{A_{j}^{l}}{g_{j}^{l}} + \frac{A_{j}^{r}}{g_{j}^{r}}$$

t,b,l,r for the position of the SiPM in the frame
g the gain of each SiPM
Energy scale with $^{22}$Na source

- No photo-peak in PVT cubes $\rightarrow$ using Compton edge
- Two independent approaches to assess the energy scale

**Kolmogorov S test (KS)**
Compare measured sample to a Geant4 MC sample

**Analytical fit**
Use pdf based on Klein-Nishina cross-section

Agreement between both methods at the 1% level!
Calibrating with CROSS system

- **In situ** calibration
- Sits above detector planes
- Mechanically open gap between sets of ten planes (Module)
  - Source free to move in gap
  - 9 positions per gap used
  - 6 gaps in total → modules irradiated from two sides

Rails to move modules
**Resources for calibration**

- Neutron sources: AmBe (~4 MeV) + $^{252}$Cf (~2MeV)

- Neutron rate *calibrated at the 1% level* at the National Physical Laboratory (UK)

- Gamma sources:

<table>
<thead>
<tr>
<th>Source</th>
<th>$^{22}$Na</th>
<th>$^{137}$Cs</th>
<th>$^{207}$Bi</th>
<th>$^{60}$Co</th>
<th>n-H (AmBe/Cf)</th>
<th>AmBe</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy [MeV]</td>
<td>2x0.511 1.27</td>
<td>0.667</td>
<td>0.57 1.064 1.77</td>
<td>1.17 1.33</td>
<td>2.2</td>
<td>4.44</td>
</tr>
</tbody>
</table>

- Muons at high energy
Muon calibration

- Reconstruct muon tracks
  - → Edep / cube using well known dE/dx
- Monitoring detector stability
- Linearity at high energy
QA II

- **Automated** system to place radioactive sources in front of each cube
  - Gamma and neutron mode
  - Check **quality** and **uniformity** of the SolId planes
  - → Early identification of defective components
  - Gave a good **knowledge** of the detector response **before installation** at BR2
  - Allowed calibration of 1 plane / day

**Gamma mode**

\(^{22}\text{Na}\) source with **external trigger**

**Neutron mode**

\(^{252}\text{Cf}\) source with **polyethylene collimator**