Performance of the SoLid reactor neutrino detector

Noe Roy, on behalf of the SoLid collaboration

roy@lal.in2p3.fr

IJCLab SoLid ICHEP 2020 | PRAGUE

Outline

I. Physics motivation

II. Solid Detector

IV. Calibration of the detector

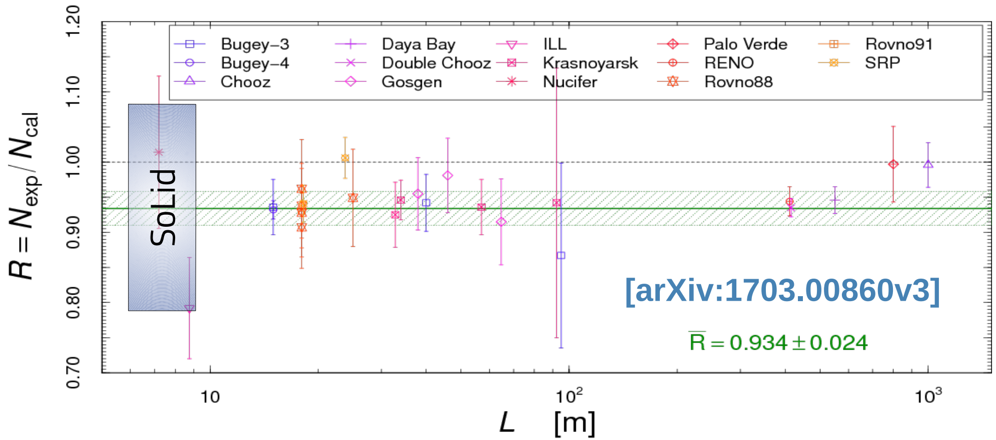
VI. Future prospects

Physics motivation

The **Reactor antineutrino anomaly** and the **Gallium anomaly** both show a ~ 3σ deficit at short baseline.

Oscillations into a light **sterile neutrino state** (Δm^2 ~1 eV^2) could account for those observations.

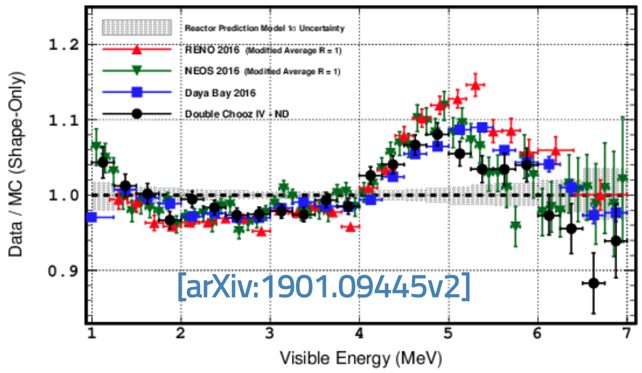
Among several isotopes (^{235}U, ^{238}U, ^{239}Pu, ^{241}Pu), ^{235}U might be the primary contributor to the Reactor anomaly. [arXiv:1704.01082]



Distortion of reactor antineutrino energy spectrum also called the “5 MeV Bump”.

- Possibly linked to non linearity energy response.

[arXiv:1705.09434]



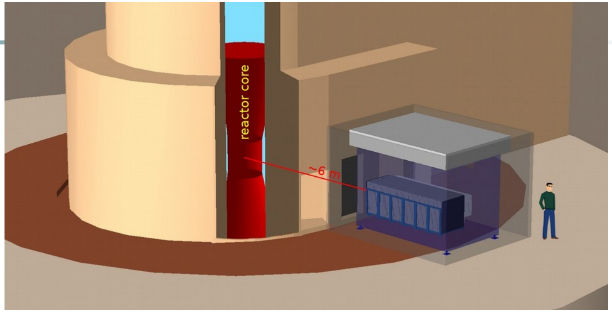
→ SoLid Experiment : Very short baseline (6m – 9m) reactor antineutrino experiment with a highly enriched ^{235}U fuel reactor core at BR2 reactor and with a linear energy response.

Specificity and challenges

- Interaction of interest → Inverse Beta decay (IBD) : $\bar{\nu}_e + p \rightarrow e^+ + n$

    - Spacial & time coincidence of e^+ and n.

    - Energy measurement of e^+.

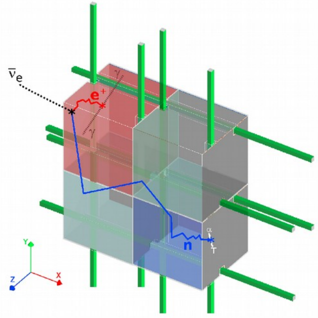


- **Reactor core proximity & low overburden → Atmospheric and reactor induced backgrounds.**

- **Highly segmented PVT (plastic scintillator) detector.**

    - Selection of IBD → **Exploitation of the signal topologies to reduce the background that can mimic the (e^+,n) correlation.**

    - Linear energy response.



Challenges to overcome:

- **Novel technology to understand and qualify.**
- **12 800 detection cells with several parameters to measure per cube.**
- Extensive calibration needed.
- Detector uniformity to achieve for a large number of detection cells.
- **Tag the gamma emission from e^+ annihilation.**

Detection cell

$\bar{\nu}_e + p \rightarrow e^+ + n$

- **Organic PVT scintillator** cube of 5x5x5 cm³ as neutrino target for **e⁺** detection: solid scintillator allows segmentation.

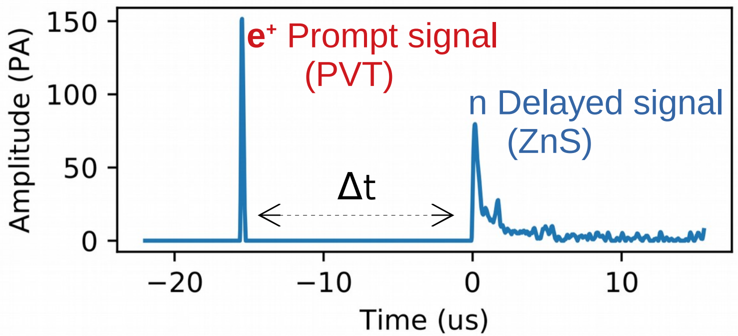
- **2 inorganic ⁶LiF:ZnS(Ag) scintillating screens** per cube for n detection after thermalisation :

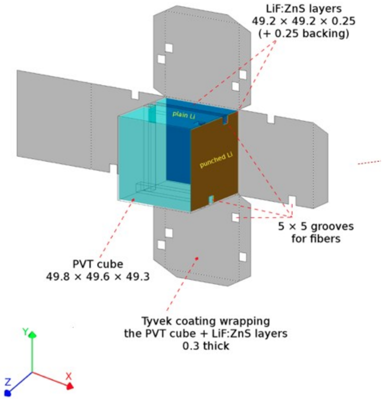
$n + {}^6Li \rightarrow \alpha + {}^3H$ coupled with ZnS scintillation.

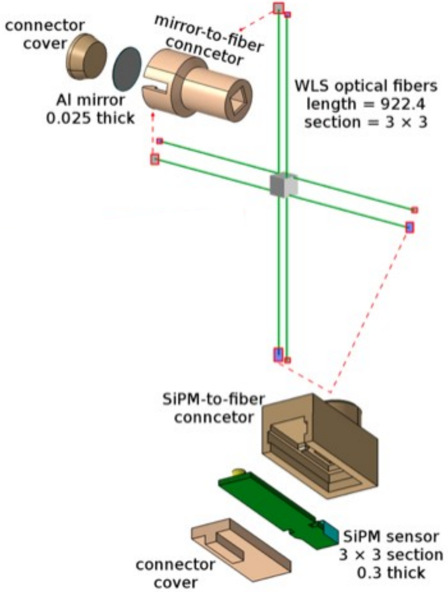
- Each cube is optically isolated with Tyvek layers.

- Signal readout by 4 Wavelength shifting fibers connected to a MPPC and a mirror at each end.

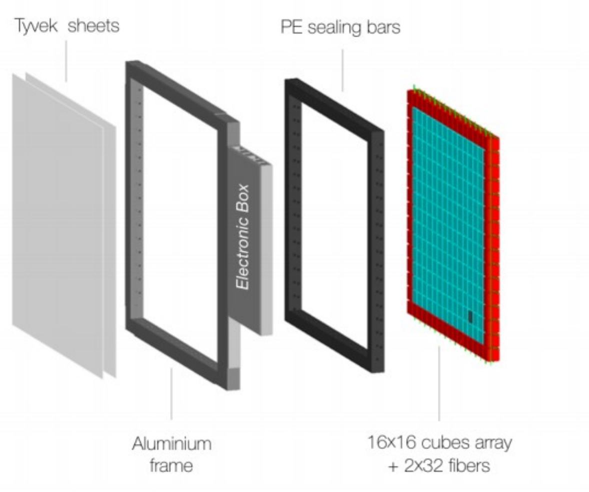
- **Look for a time coincidence between the 2 different types of signal.**



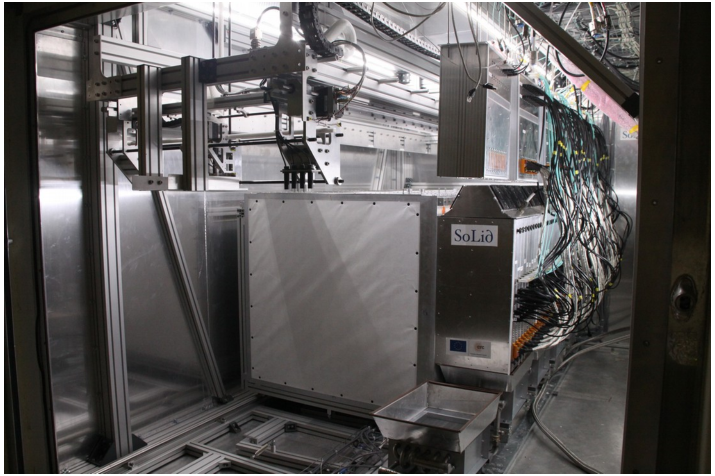




Detector design [arXiv:2002.05914]



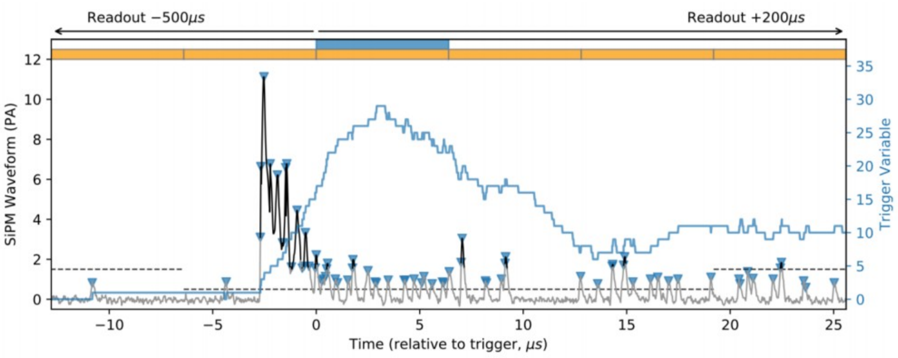
- **Modular detector with individual detection planes:**
  - 5 Modules of 10 detection planes each.
  - 16x16 detection cells per plane.
- Detector integrated in a cooled container at 11°C for MPPC dark count rate reduction.
- **Shielding** :
  - Water wall: 50 cm thick, 3.4 m high, 28000 kg
  - Polyethylene ceiling: 50 cm thick, 6000 kg
- **All environmental parameters monitored constantly.**
- Construction finished in 2017
  → All cells weights stored in a database.
- Integration & commissioning early 2018 @ BR2
- **Physics Data taking started in May 2018. → See talk from David Henaff**



Data acquisition system [JINST 14 (2019) no.11, P11003]

MPPC waveform sampling frequency of 40Mhz + 12800 detection cells → High data rate.

Trigger strategies and the Zero Suppression threshold are crucial to reduce the data quantity (2 Tb/s → ~200 Mb/s)



Neutron trigger based on peak counting.

- Read out long time buffer around ZnS signal : [-500μs, +200μs]
- Multiple planes readout (+/- 3 planes)

→ Unbiased and low threshold prompt signal detection

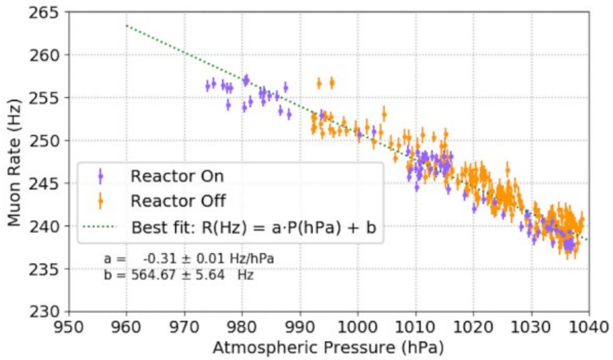
3 types of triggers :

Trigger Type	ZS Threshold	Condition	Readout Region: Space	Readout Region: Time (μs)	Trigger Rate (HZ)	Data rate (MB/s)
Random	Disabled	Periodic 1 Hz	Whole Detector	12.8	1.2	3.9 (19%)
High Energy	1.5 PA	Waveform Sample >50 PA	Triggered plane	6.4	2.1k	2 (10%)
Neutron	0.5 PA	N_{peaks} >17 peaks (W_{width} = 6.4 μs, T_{peak} >0.5 PA)	Triggered plane ± 3 planes	−500, +200	40	15 (71%)

Data quality monitoring

- Correlation between muon rate and atmospheric pressure.

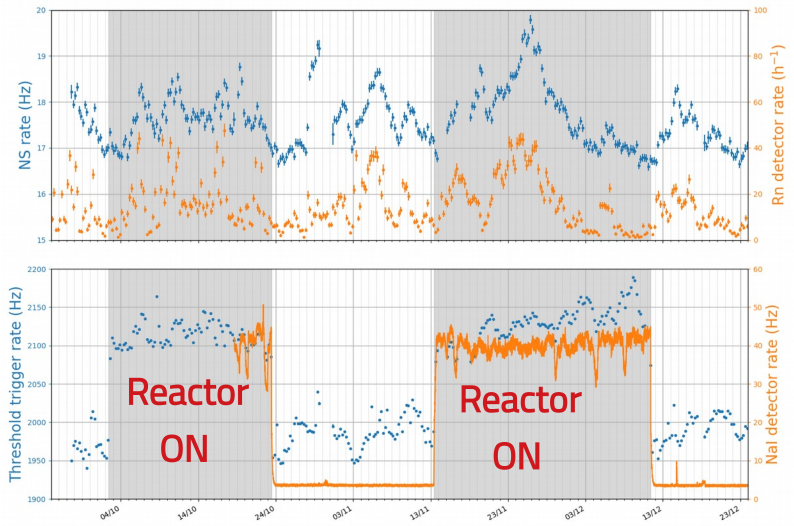
  → Background depends on the environmental conditions.

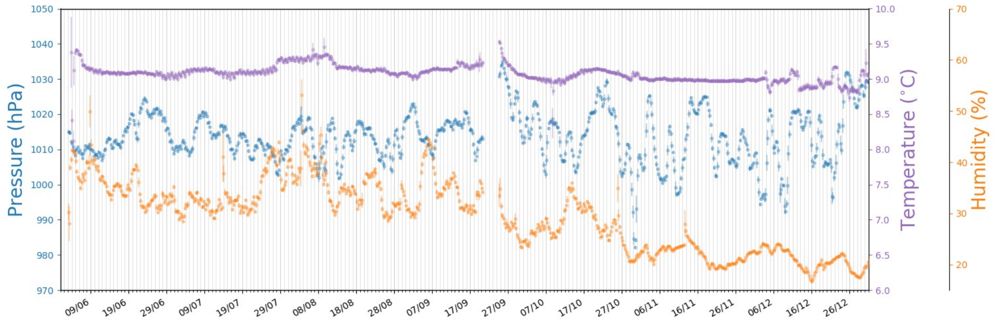


- Environmental parameters monitored continuously.

  → Temperature variation of 5 % day-night → **MPPC response stability.**

- ZnS signal, Threshold trigger and muon rates monitored over time.





ZnS signal rate stable irrespective to the reactor operation and strongly correlated to the airborne radon concentration. **→ Need to monitor it carefully over time.**

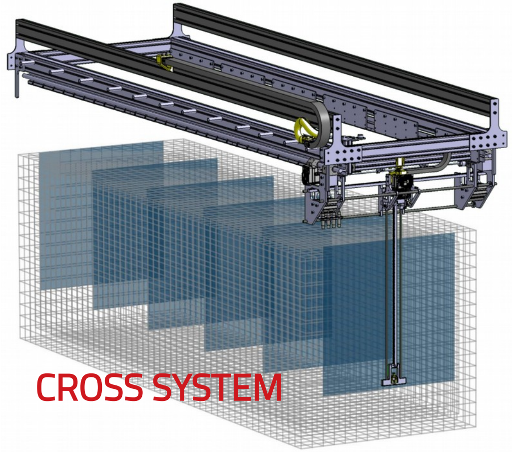
Calibration

- Automated calibration system (CROSS).

- 9 radioactive sources positions in 6 gaps in the detector (1 every 10 planes).

- Each gap is used to calibrate the +/- 5 planes around (~25 cm) ➞ need for penetrating sources.

- Available calibration sources :
  - Gamma sources : ^{137}Cs, ^{207}Bi, ^{22}Na and AmBe.
  - Neutron sources : ^{252}Cf, and AmBe.

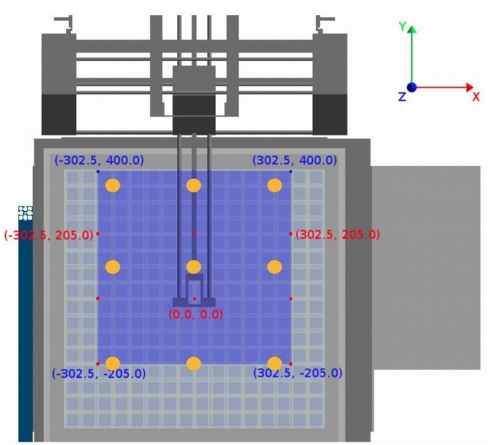


Big challenges:

- Calibrate 12 800 detection cells and 3 200 channels with several calibration parameters:
  - → **More than 20 000 parameters to measure and correct.**

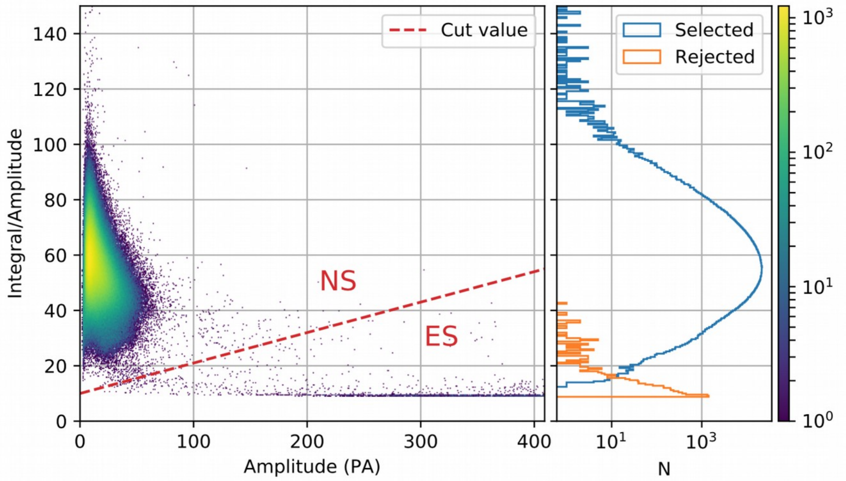
- Cube signal that combines signals of 4 fibers :

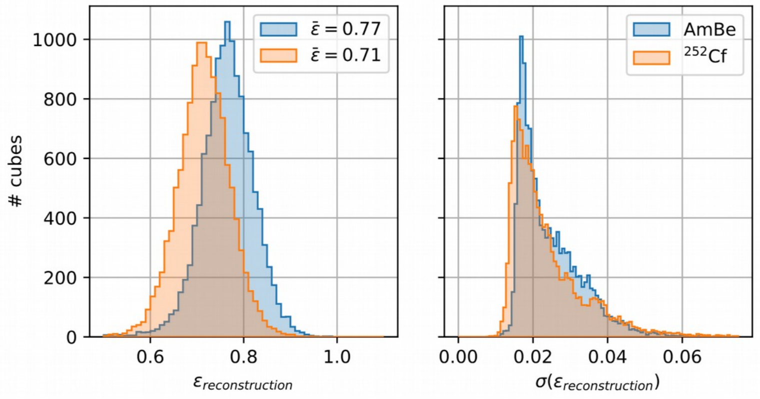
  - → Difficult to separate cube effect from fiber effect.
  - → Each fiber is shared by 16 cubes inducing correlations between cubes.

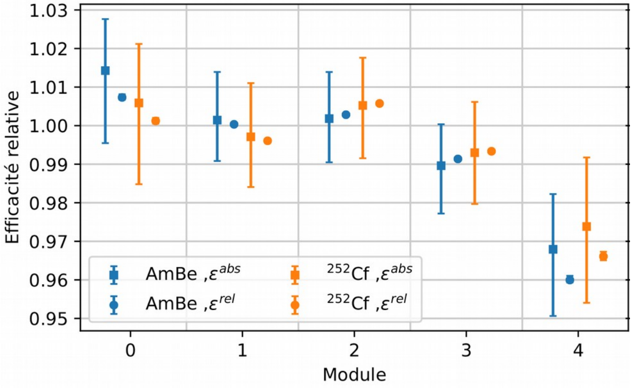


Neutron calibration [arXiv:2002.05914]

- AmBe and ^{252}Cf neutron sources.
- Good NS/ES discrimination.
- Neutron efficiency of **73.9 [+4.0 −3.3] %** measured for each cube.
- Good agreement between the 2 sources
- Relative **module detection efficiency within 3% (<1% for 4 modules).**







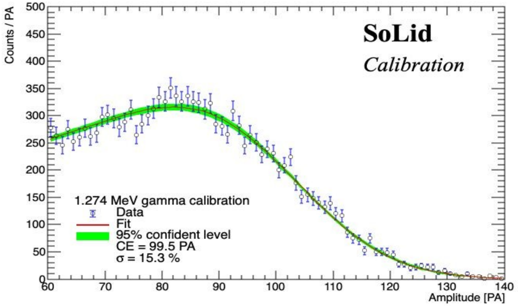
Energy calibration: parameters measurement

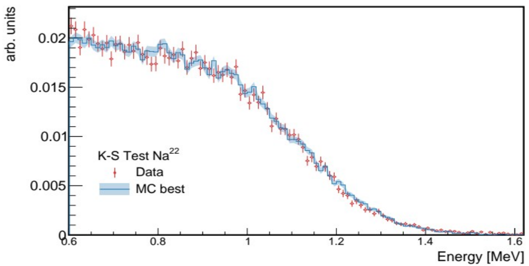
- Difficulty: we don't have access to the photoelectric peak ➞ Compton edge fit.

- Two methods developed to determine the Light Yield (#PA/MeV deposit) & the energy resolution :

- Analytical fit based on Klein-Nishina cross section.

- Kolmogorov-Smirnov test comparing Data and true G4 energy distribution numerically convoluted.



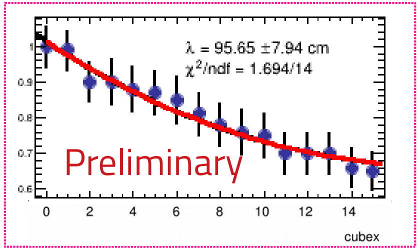


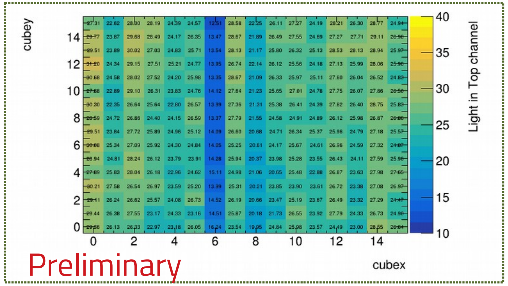
- Channel parameters measured/quantified :

- MPPCs equalized at 1% level.

- Individual Fiber attenuation.

- Fiber – MPPC optical coupling.





All cube light yield calibrated with a 3% precision.

Energy calibration: performances

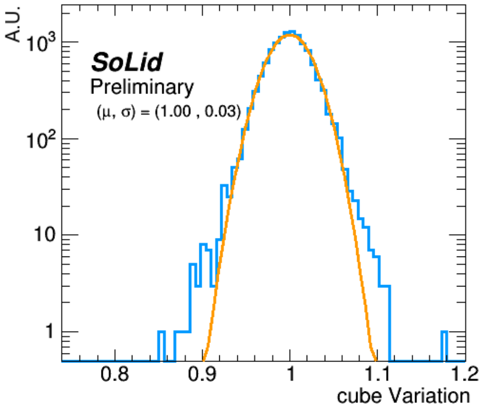
- 3% Light Yield variations within a plane after corrections.

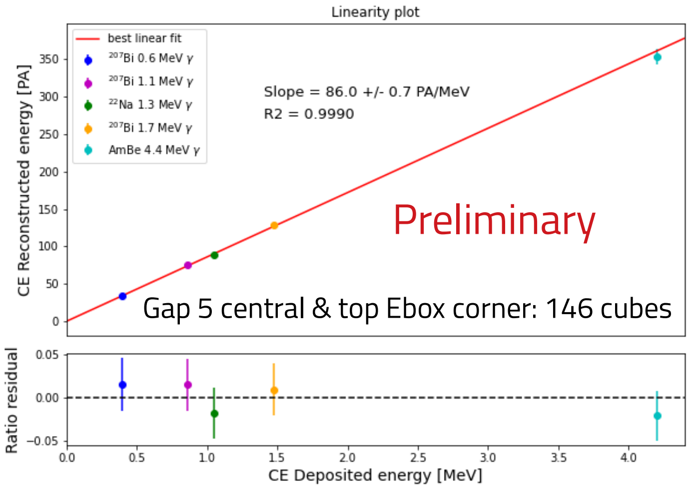
- Bellow 5% Light Yield variations module to module.

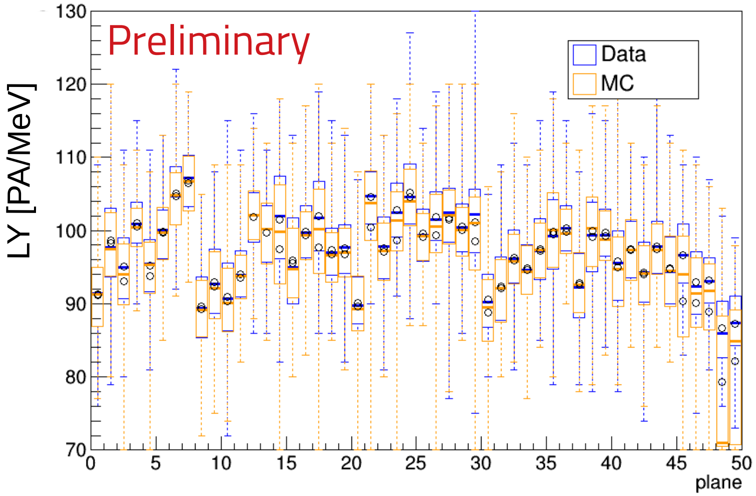
- Linearity at a couple of percent in the [.5 – 4] MeV region.

- Mean Light Yield of **96 PA/MeV (without MMPC cross talk subtraction).**

- Eres = 12% (stochastic) at 1 MeV.





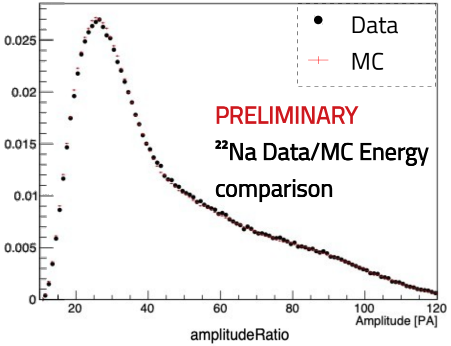


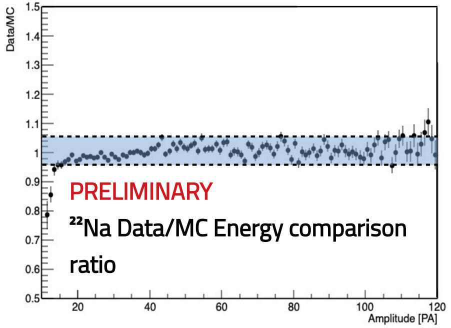
Energy calibration: qualification

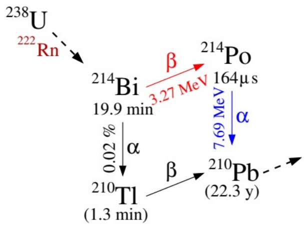
An important work has been needed to achieve a Good Data/Monte Carlo agreement on energy and topological variables

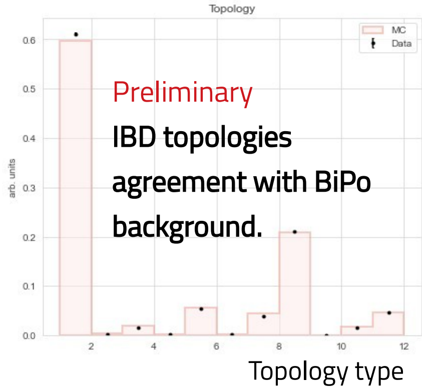
- With ^{22}Na calibration source → Data/MC at low energy for cubes and fibers. **Within 5% in [.2,1.2] MeV region.**

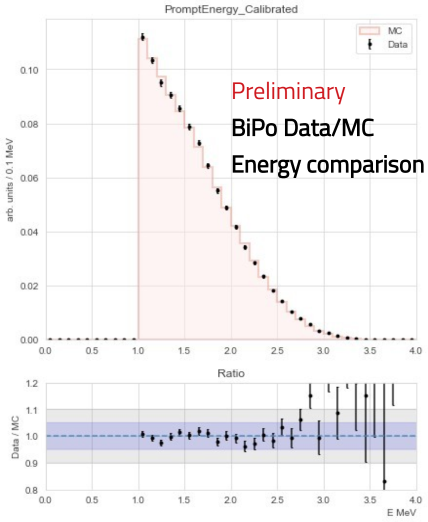
- With ^{214}Bi induced internal background as a proxy for IBD signal:

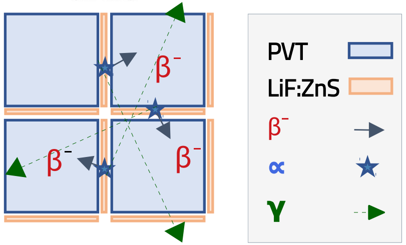












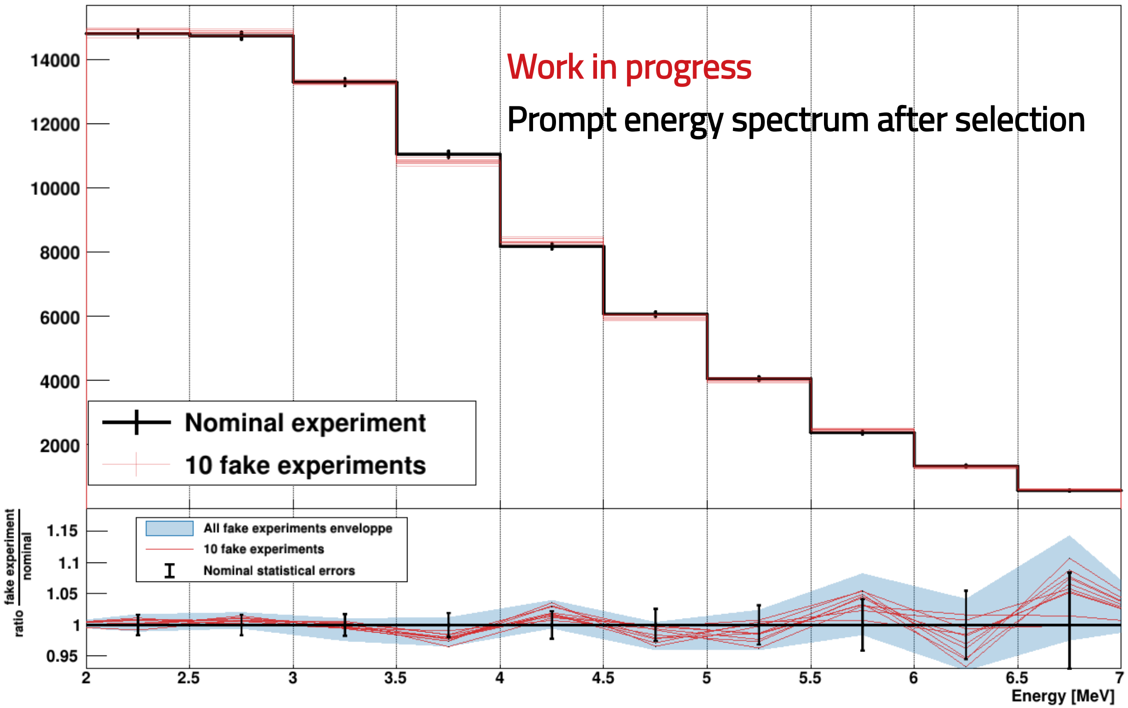
IBD Topologies: various space distribution for the annihilation gamma signal.

Energy calibration: systematic study

- **Work in progress for the LY systematic assessment.**

- Fake IBD simulations varying the cube individual Light Yield within 3%.

- Comparison done between the nominal and the fake experiments → **We compute all the ratios between the fake experiment and the nominal one.**

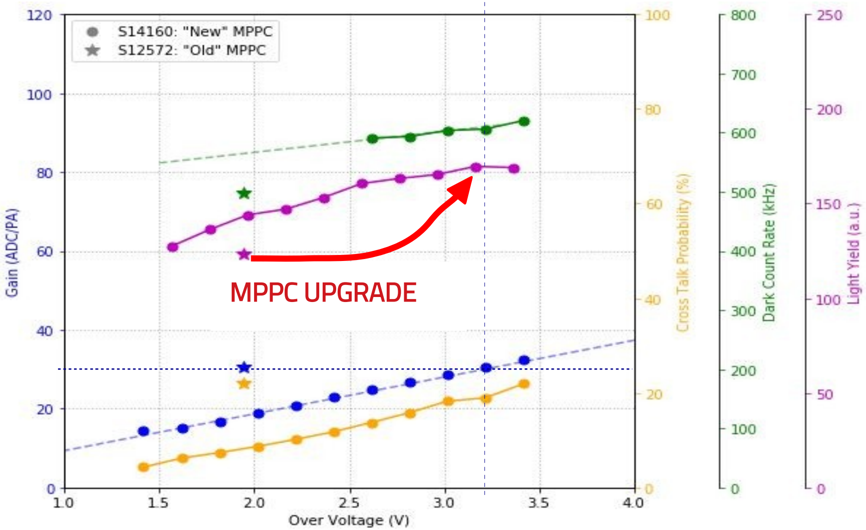


With the assumption of a S/B ~ 1, we already expect the LY uncertainties to fall into statistical uncertainty.

Detector upgrade

- Detector upgrade planned during summer 2020.

- New generation of MPPC → Higher light detection (~40%) in the same operation conditions.



July 2020

August 2020

September 2020

Detector extraction @ BR2

MPPC upgrade @ Antwerp

Recommissioning + 1 year of data taking

Conclusion

- Novel detector technology to answer to the antineutrinos anomalies.

- **Highly segmented plastic scintillator detector** (16x16x50 detection cells)

- Large amount of work necessary for the detector calibration, understanding and modelisation.

  → **Homogeneity & linearity of the detector at a few percent level.**

  ➞ **Data/Monte-Carlo agreement at a few percent.**

- Upgrade of the detector in progress.

Backup

BR2 reactor at SCK CEN

Compact reactor core Φ < 50 cm, h = 90 cm → Ideal for very short baseline experiment.

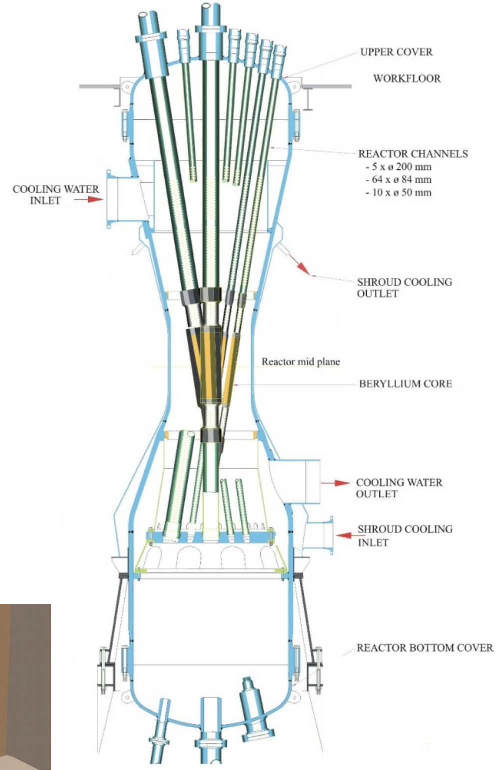
Thermal power: 40-100 MW.

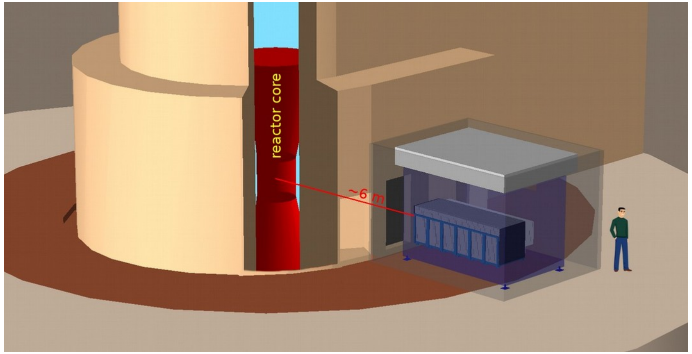
Highly ^{235}U enriched (up to 93.5 %).

150 days per year duty cycle.

Reactor off data for background estimation and subtraction.

No nearby experiments.





IBD Topologies

We defined 11 mutually exclusive topologies.

They are :1. Clean 15x15x15 volume around AC ;

2. Clean 3x3x3 volume around AC + AC not on boundary + 2reconstructedγ;

3. Clean 3x3x3 volume around AC + AC in (1,14),≥1 Rγ;

4. Clean 3x3x3 volume around AC + AC in (0,15),≥1 Rγ;

5. Clean 3x3x3 volume around AC + AC not on boundary + 1 Rγ;

6. 1 additional signals in 3x3x3 volume around AC + 2 Rγ;

7. 1 additional signals in 3x3x3 volume around AC + 1 Rγ;

8. 1 additional signals in 3x3x3 volume around AC + 0 Rγ;

9. >1 additional signals in 3x3x3 volume around AC + 2 Rγ;

10. >1 additional signals in 3x3x3 volume around AC + 1 Rγ;

11. >1 additional signals in 3x3x3 volume around AC + 0 Rγ.(

AC = cube with the most reconstructed energy in the event,Rγ= Reconstructedγ)

PRELIMINARY

Reminder :

	$0\ \gamma$	$1\ \gamma$	$2\ \gamma$
clean around AC	Topo1	Topo5	Topo2
1 cube around AC	Topo8	Topo7	Topo6
$>$ 1 cube around AC	Topo11	Topo10	Topo9

Topo3 and 4 are clean events, located on the boundaries.

IBD :

Topo1	Topo2	Topo3	Topo4	Topo5	Topo6
87084	68031	55927	73719	79269	94692
8.7%	6.8%	5.6%	7.4%	7.9%	9.5%

Topo7	Topo8	Topo9	Topo10	Topo11
205973	67245	60195	157527	52180
21%	6.7%	6%	16%	5.2%

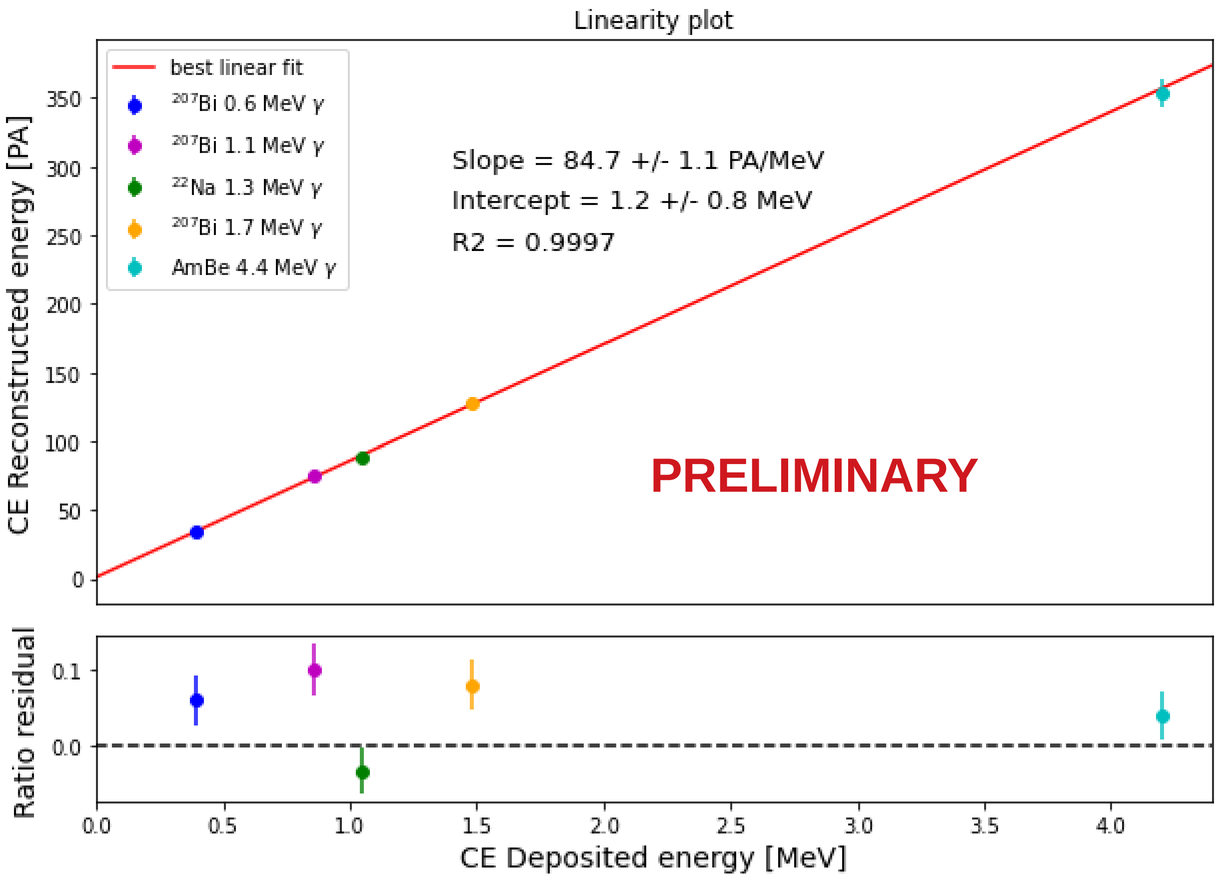
Ccube Algorithm

Method extensively used on medical physics [J. Opt. Soc.551Am.62(1972) 55.]

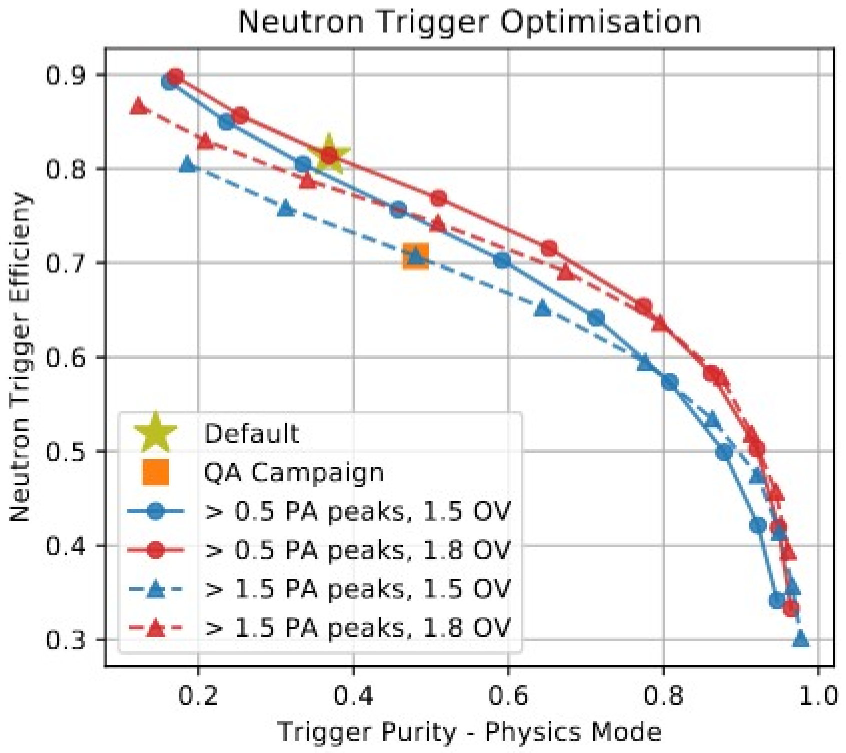
The CCubes algorithm (for Clermont-Cubes) is using a Maximum Likelihood-Expectation Maximization Bayesian approach with a physics-driven prior [data] for the light distribution seen by SiPM given by the Poisson statistics.

→ Convenient to reduce the fake cube reconstructions, the pile ups, the ambiguities…

Linearity for singular cubes & not 0 fit



Neutron trigger efficiency



Trigger efficiency vs Trigger purity (with an offline neutron ID) → Working point at 17 peaks.

More on Data/MC

Anihilation gamma cube agreement : 20% efficiency/cube less → Agreement @ 5% per fibers.