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Improved Technology for Unattended Remote Reactor Monitoring Under the NPT

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Future of NPT

- **Future Challenges for the NPT**
 - Expansion of number and complexity of facilities
 - Shrinking budgets
- **Changing Emphasis for verification under the NPT**
 - Risk based allocation of resources
 - State Level Approach could reduce need for inspections by relying on publicly available information and remote unattended monitoring
 - Nuclear reactors provide a minimal threat to diversion and could allow cost savings through reduction in inspections
- **Independent reactor operational history has value to safeguards**
 - Current regime relies on operator declarations
 - DPRK demonstrates safeguards concerns over “breakout”
 - Continuous remote unattended monitoring of reactors could provide a trusted operational history while reducing the need for costly inspections

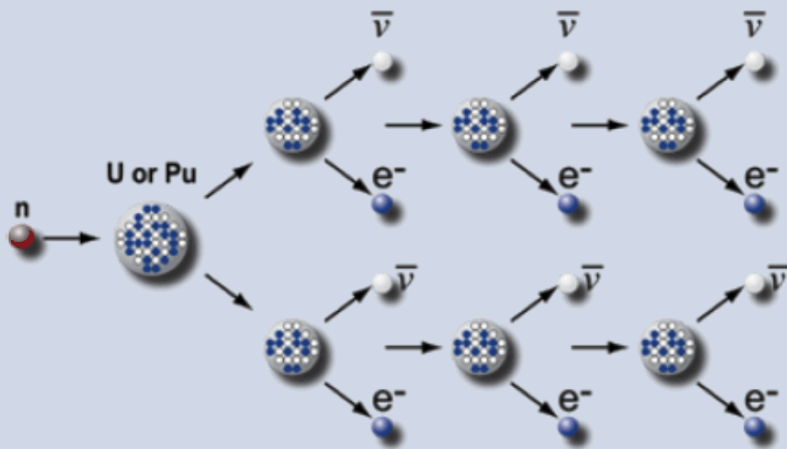
A Novel Technology for Reactor Safeguards

- Development of Antineutrino Detection for reactor monitoring
 - Supported by DOE/NA-22 for more than a decade, multiple technologies have been developed and deployed
- Antineutrino Monitoring of Reactors provides independent measurements of **Thermal Power** and **Fissile Inventory**
 - Non-intrusive with **NO** connection to plant systems
 - Continuous Remote Monitoring
 - Highly tamper resistant
- Potential Applications to Present and Future Safeguards
 - Independent **Confirmation** of Operator Declarations
 - **Reduction** in needed Inspector visits
 - Provide fissile content information for **Next-Generation** fuel cycles (MOX, Th, bulk process)

Reactors Produce Antineutrinos

Reactors emit huge numbers of antineutrinos

- 6 antineutrinos per fission from beta decay of daughters
- 10^{21} fissions per second in a 3,000-MWt reactor



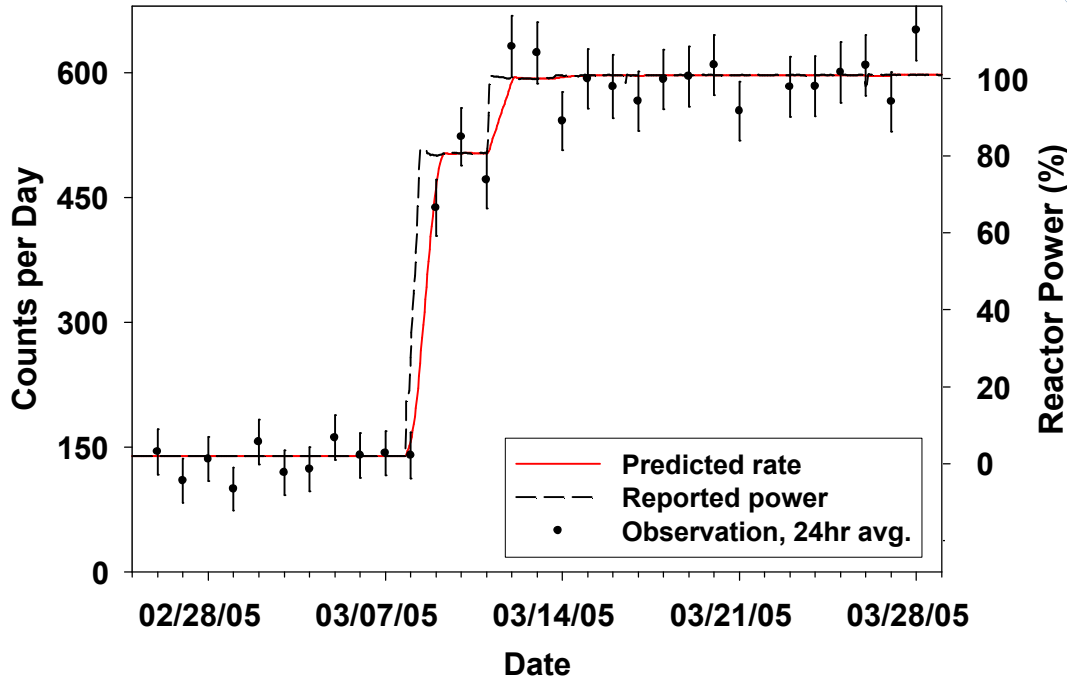
About 10^{22} antineutrinos are emitted per second from a typical PWR unattenuated and in all directions

Detected rates are quite reasonable

- 10^{17} antineutrinos per square meter per second at 25-m standoff
- 6,000 events per ton per day with a perfect detector
- 600 events per ton per day with a simple detector (e.g., SONGS1)

Example: detector total footprint with shielding is 2.5 meter on a side at 25-m standoff from a 3-GWt reactor

Reactor Power Monitoring using only \bar{v}



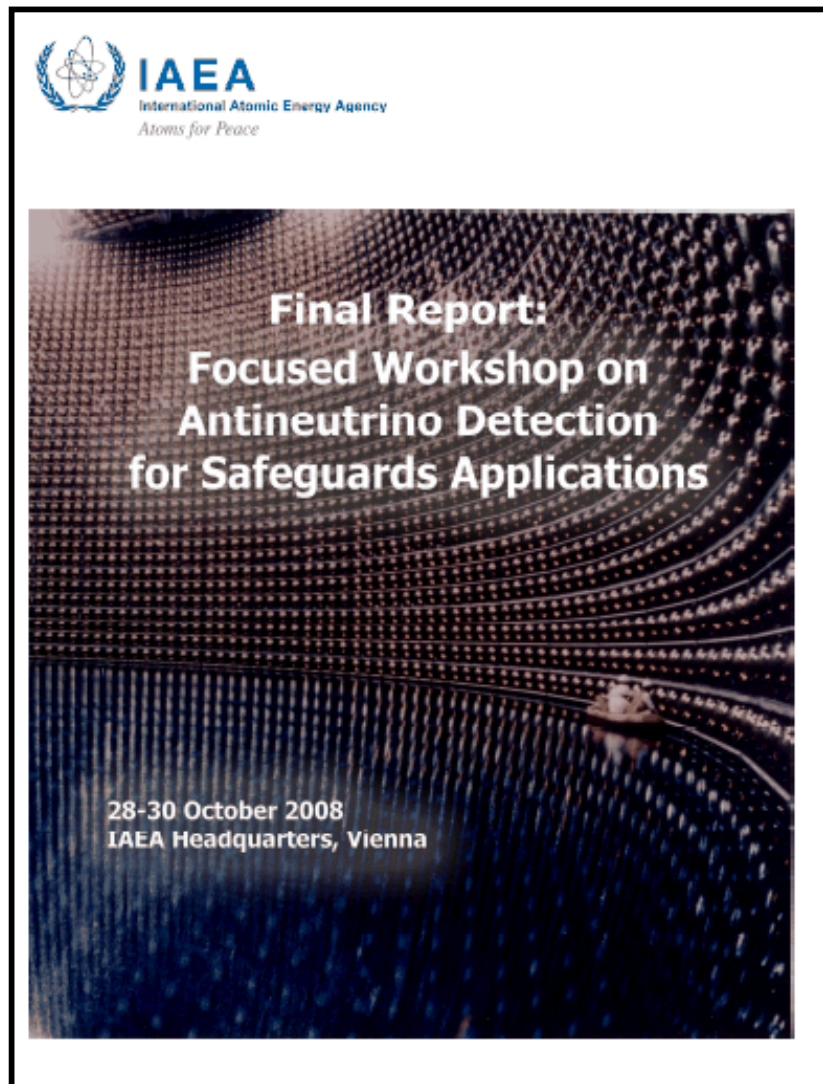
🕒 Timescale

1 – 3 Hours:
Sudden changes in
operational status (on/off)

1 Day:
Large power changes

7 Days:
Relative thermal power
measurement (2 – 3%)

Large power changes are readily observed with no physical connection to the plant

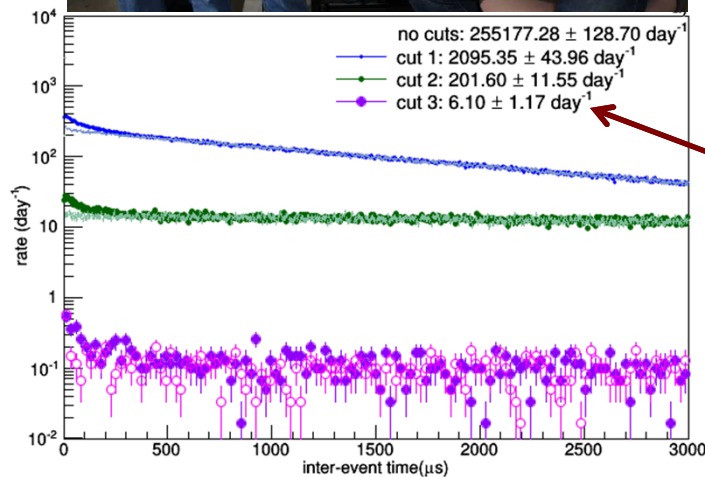


- Introduction of technology – 2003
 - Called for further development

- Focused Workshop – 2008
 - Suggested Application against
 - ◆ Research Reactors
 - ◆ Bulk Process Reactors

 - Requested Improvements in
 - ◆ Robust Deployability
 - ◆ Fully Independent measurement of fissile content

Promising Prototype Deployment

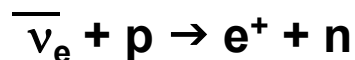


- As part of a joint SNL/LLNL project to develop aboveground detector technology, we deployed a 4-cell prototype segmented scintillator system
 - Based on novel combination of organic and inorganic scintillators, this system provides unambiguous particle identification
 - Deployed aboveground at SONGS in both shielded and unshielded configurations
- Very encouraged by performance of Segmented Scintillator prototype
 - This technology is focused on reducing the overall footprint and enabling a transportable detector that can be deployed in **high-background or unshielded locations**
 - Demonstrated **rejection of backgrounds** of 5 orders of magnitude even without an external shield
 - Data from unshielded deployment at SONGS showing rejection of backgrounds as successive selections are applied
- V-Fund project improves on this technology development and solves remaining challenge

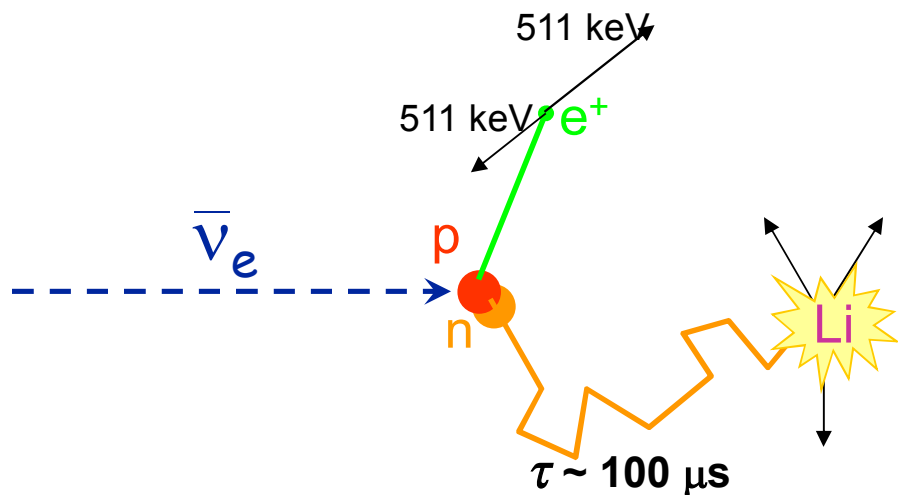
Antineutrino Detection



- We use the same antineutrino detection technique used to first detect (anti)neutrinos:



- Standard radiation detectors are sufficient to find this correlated signature



prompt signal + n capture on Li

- **Positron**

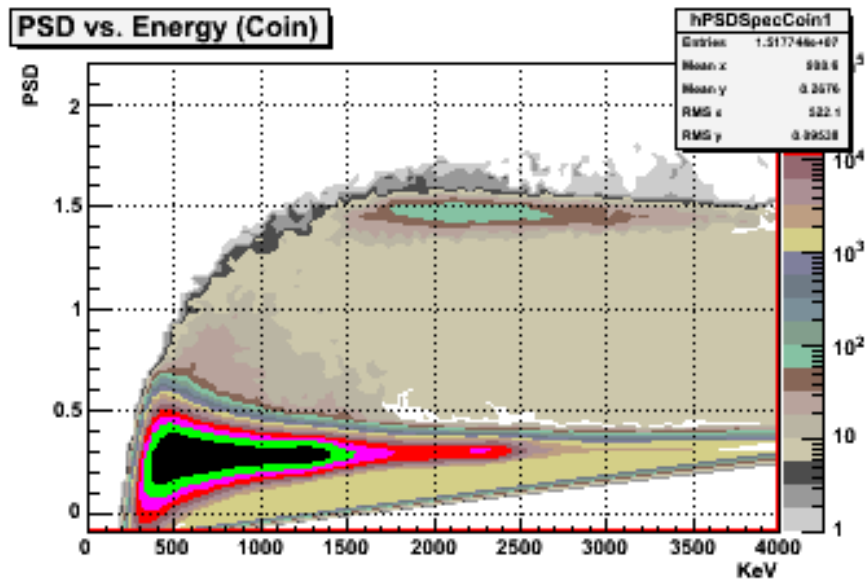
- Immediate
- 1- 8 MeV (incl 511 keV γ s)

- **Neutron**

- Delayed ($\tau = 100\mu\text{s}$)
- Capture detected in ZnS:Ag/ ^6LiF (typically used in neutron radiography)

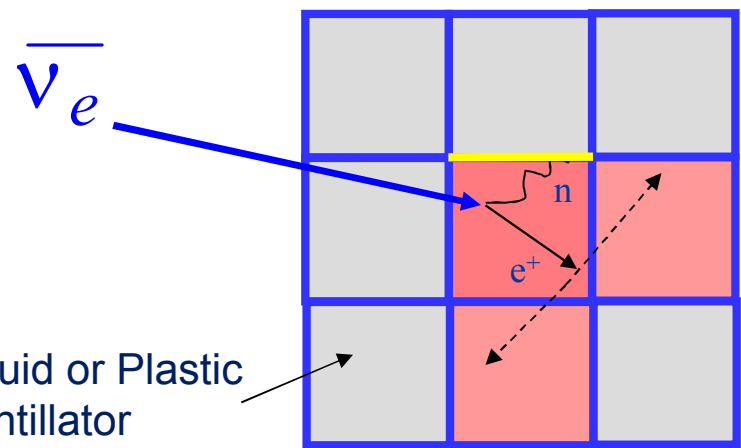
Particle Identification (PID)

Neutron identification through Pulse Shape Discrimination (PSD)



Positron Identification through Topology

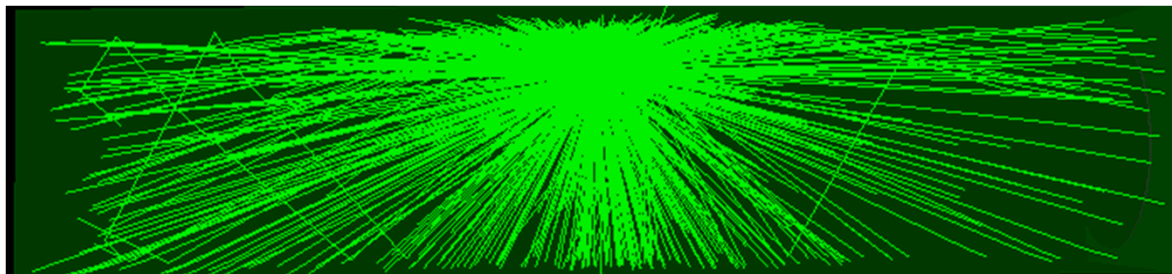
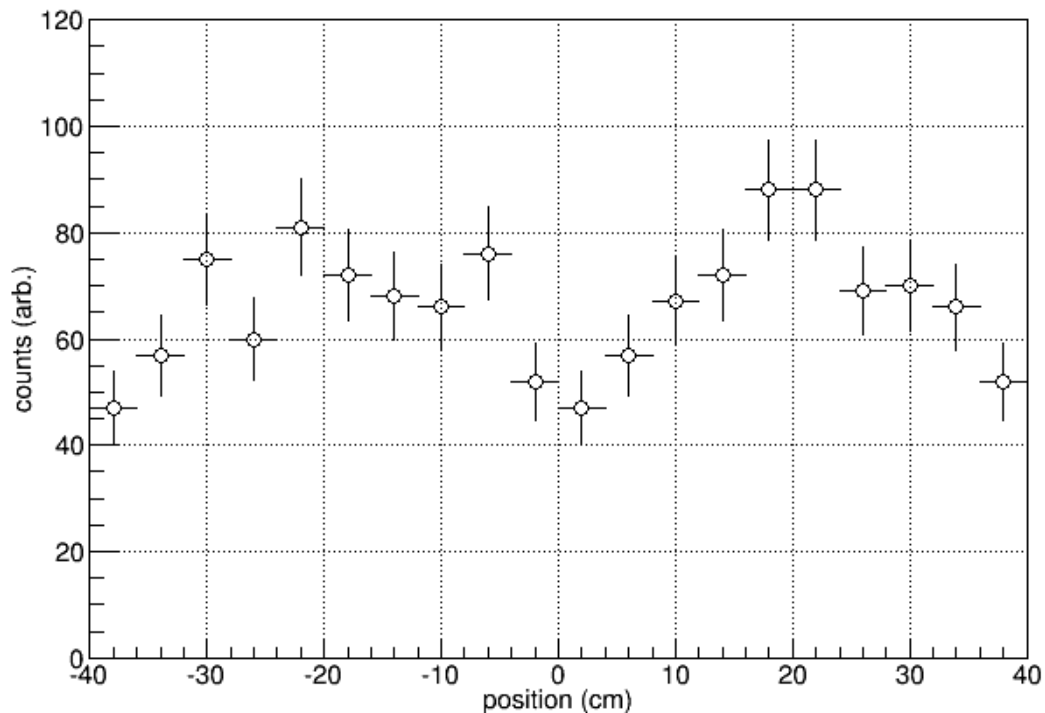
- Positrons are rare in nature
 - Deposit most of their kinetic energy very quickly through standard ionization losses
- Positrons will annihilate into two back-to-back 511 keV gammas
 - Very distinctive signature
 - Gammas will travel ~2-5" through most scintillators



This Work: Solve Optical Issues



Detected Neutron Events Along a Segment

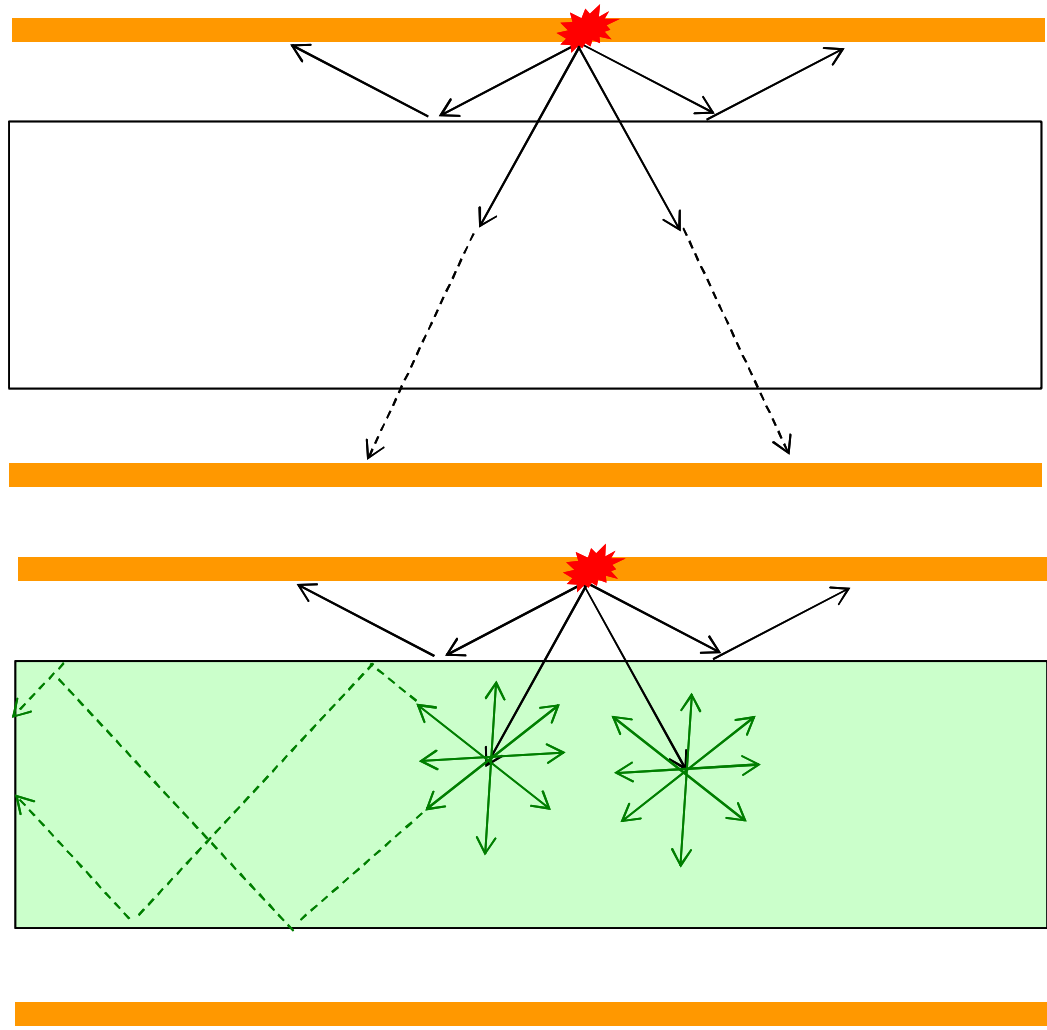


Optical grease coupled ZnS does not transmit light

Addition of WLS Helps Preserve Total Internal Reflection



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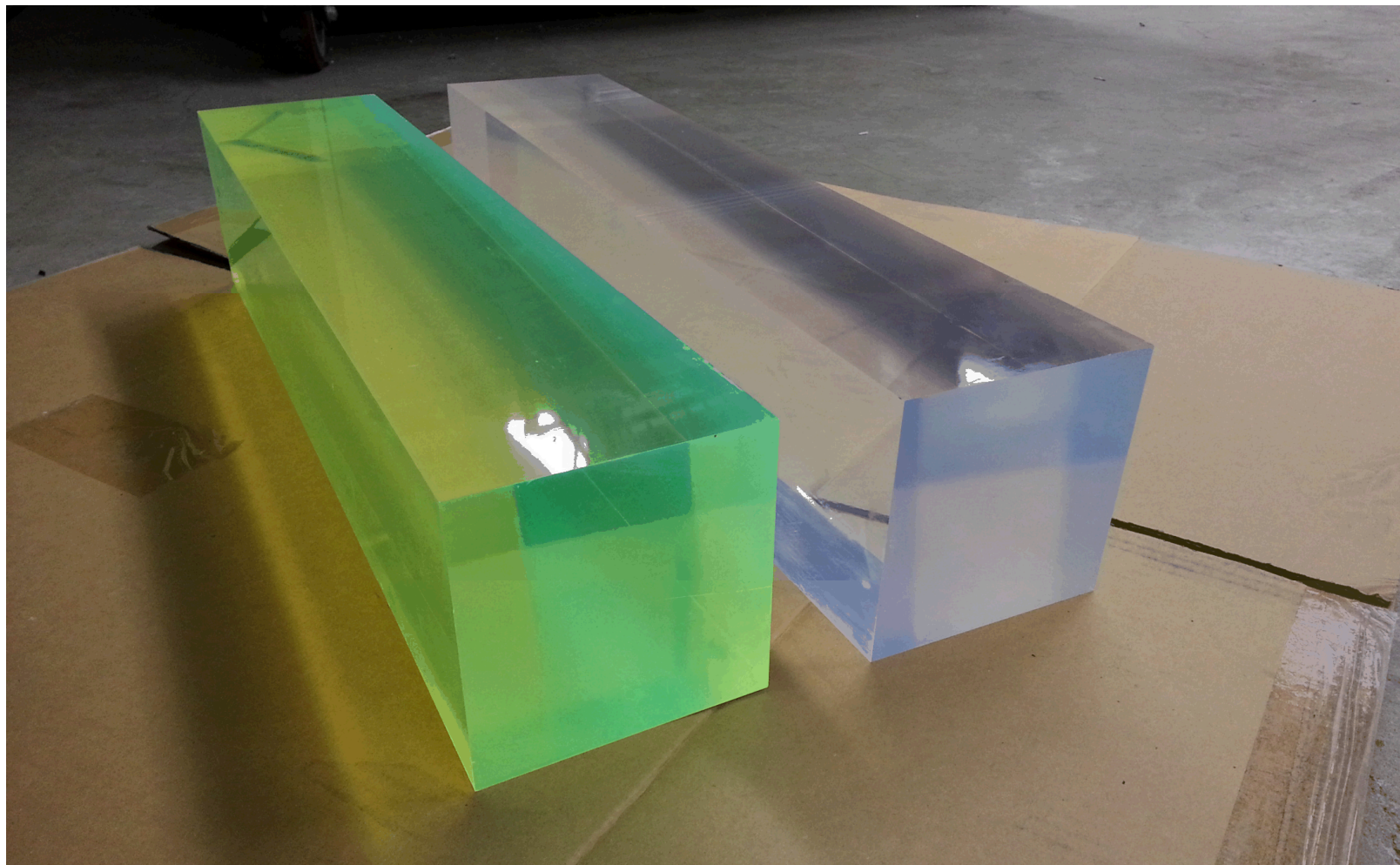
■ Standard Plastic Scintillator

- Light from ZnS is reflected at boundary
- Optical Grease coupling increased overall transmission into the plastic scintillator, but
- Light that is transmitted, tends to be absorbed in the opposing ZnS sheet.

■ Plastic + WLS

- Light that is transmitted is now absorbed and re-emitted isotropically
- Preserves internal TIR at the cost of inefficiency in the absorption/conversion process
- WLS wavelength also has reduced quantum efficiency in PMT photocathodes

Eljen 280 WLS Scintillator



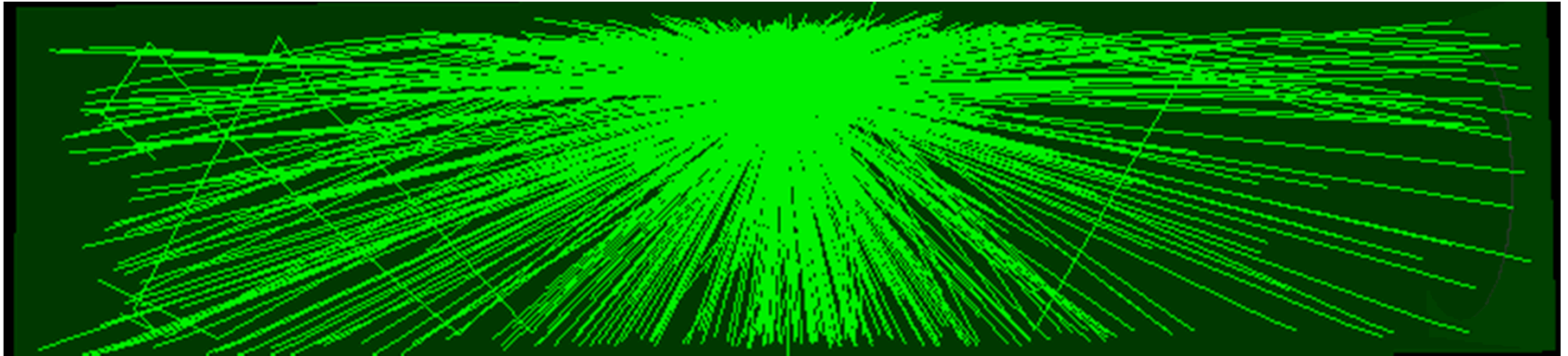
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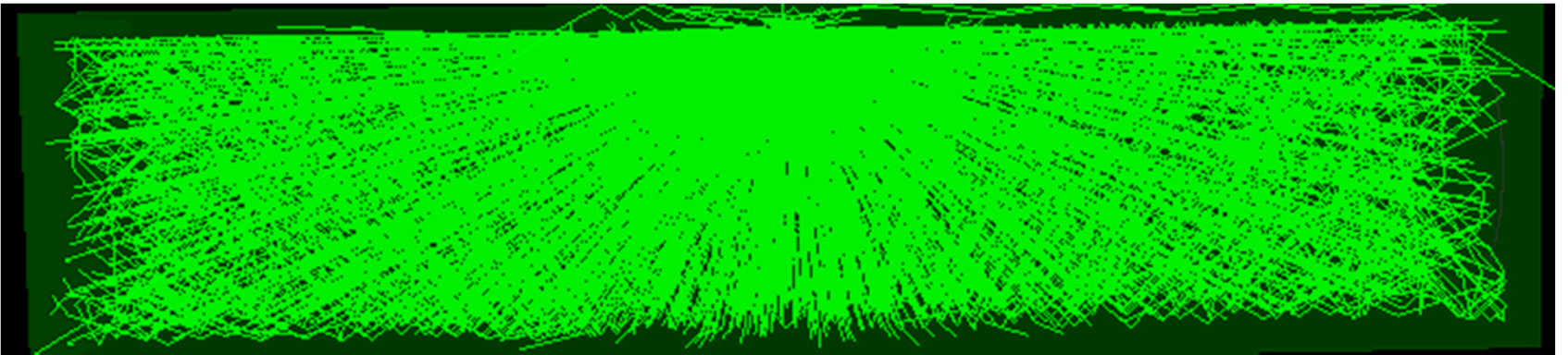
Montecarlo Comparison



Grease Coupled Normal Plastic Scintillator

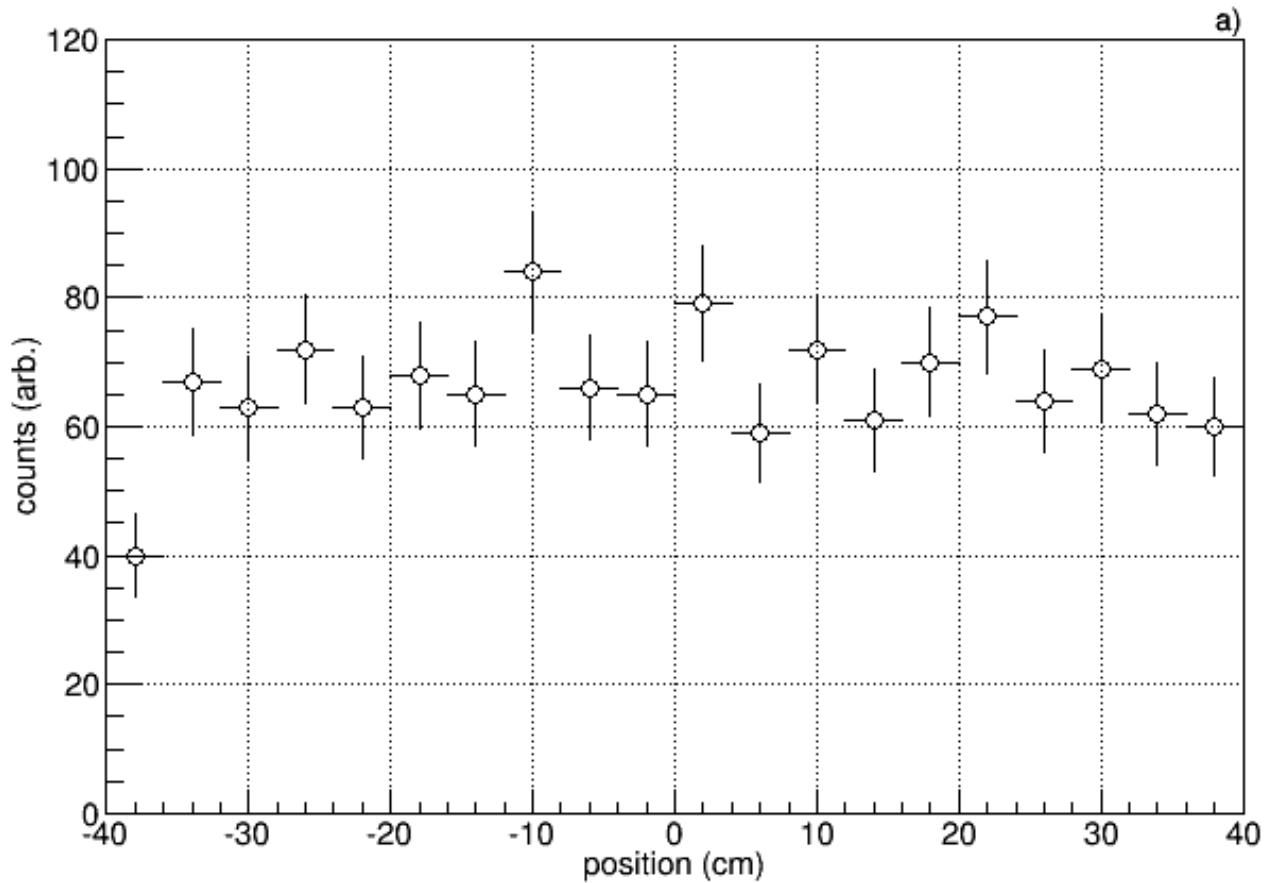


Air Gap with Wavelength Shifting Plastic Scintillator





Detected Neutron Events Along a Segment using WLS



WLS Also Allows Extended Length

Test Bar	Attenuation length	Normalized neutron efficiency §
Original grease coupled 60cm	35.6 +- 1.2 cm	10.1 +- 0.9 %
WLS, air gap, 60 cm	118 +- 7 cm	10.8 +- 0.9 %
WLS, air gap, 120 cm	154 +- 11 cm	12.6 +- 1.2 %
WLS, air gap, 180 cm	200 +- 20 cm	10.9 +- 1.1 %

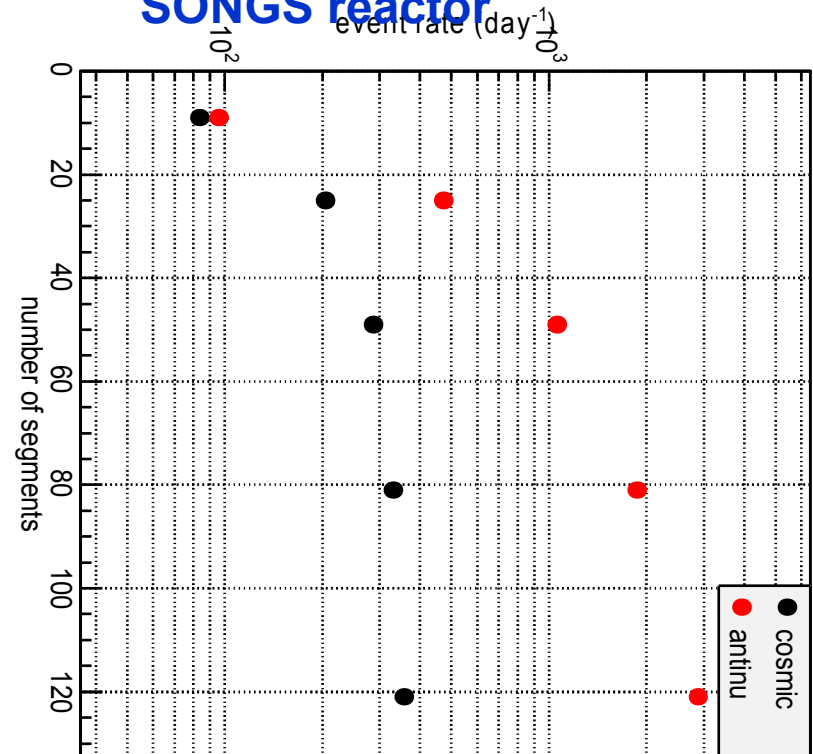
§ Efficiency calculated relative to a calibrated ^3He detector and normalized to detector area

Next Steps



- Need to test how performance scales with detector size (number of segments)
- Current simulations suggest major improvements
 - Expect efficiency for antineutrino detection to improve as more segments are used
 - Expect background rejection to improve as more segments are used

Simulation of aboveground performance 25m from SONGS reactor



Conclusions



- **WLS based segments show good uniform detector response even at 1.8m length**
 - Overall efficiency is improved compared to previously deployed prototype
 - Probably could go to 3m
- **Antineutrino efficiency expected to improve as more segments are added**
 - Single electronics rack could house $\frac{1}{2}$ ton active volume (16 cells)
 - Future work will investigate how backgrounds scale with additional segments
- **The technology could provide options to future NPT negotiations**
 - Robust solid state materials that are easily deployed
 - Simple analysis can be easily automated
 - **Continuous trusted operational history**

More details can be found in *Sweany et al, NIM A Volume 769, 1 January 2015, 37–43*