A Safeguards Friendly Device for Monitoring Reactor Anti-Neutrinos

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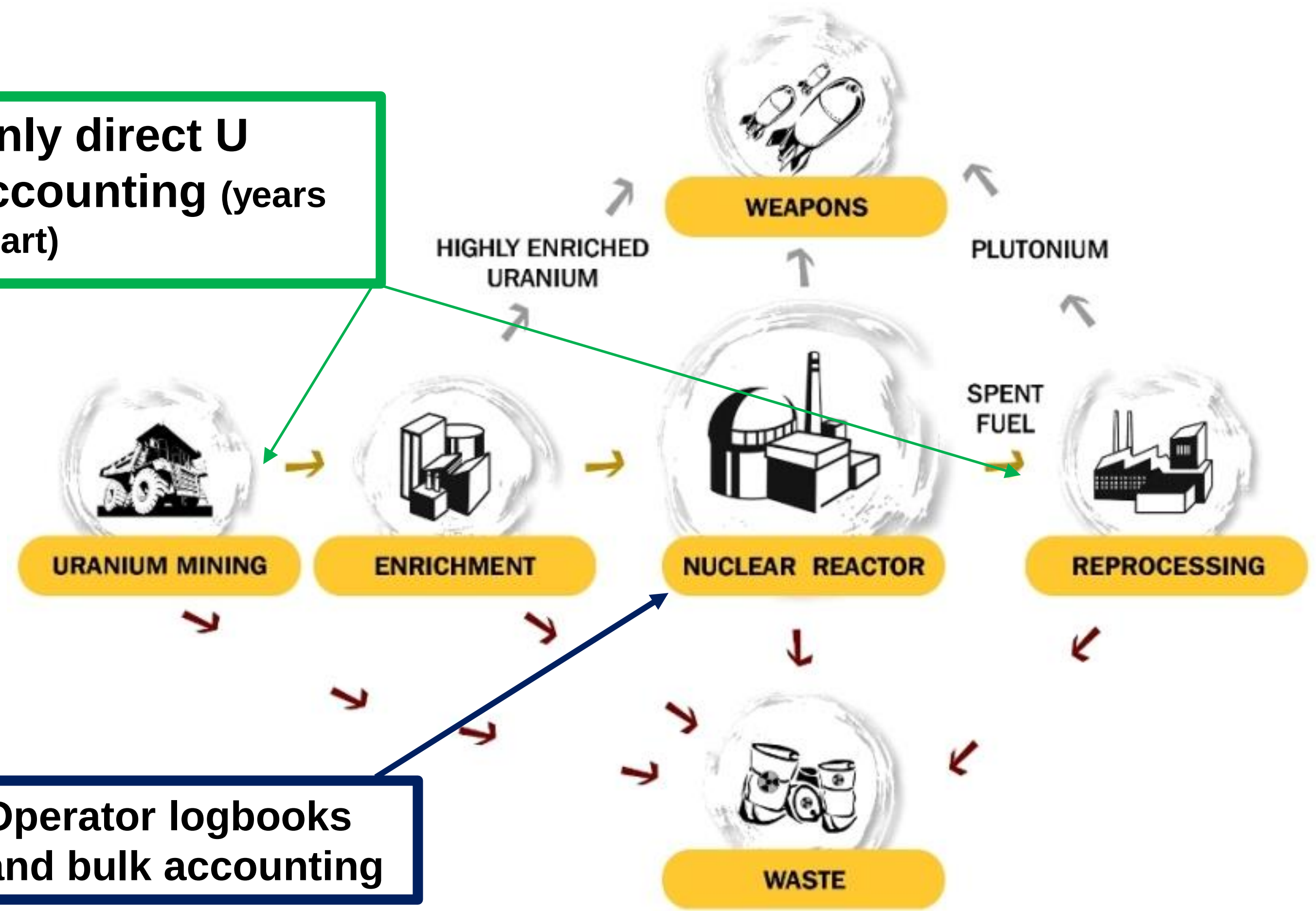
Wylfa Power Station

Anti-neutrinos and Nuclear Non-Proliferation

Only direct U accounting (years apart)



Operator logbooks and bulk accounting

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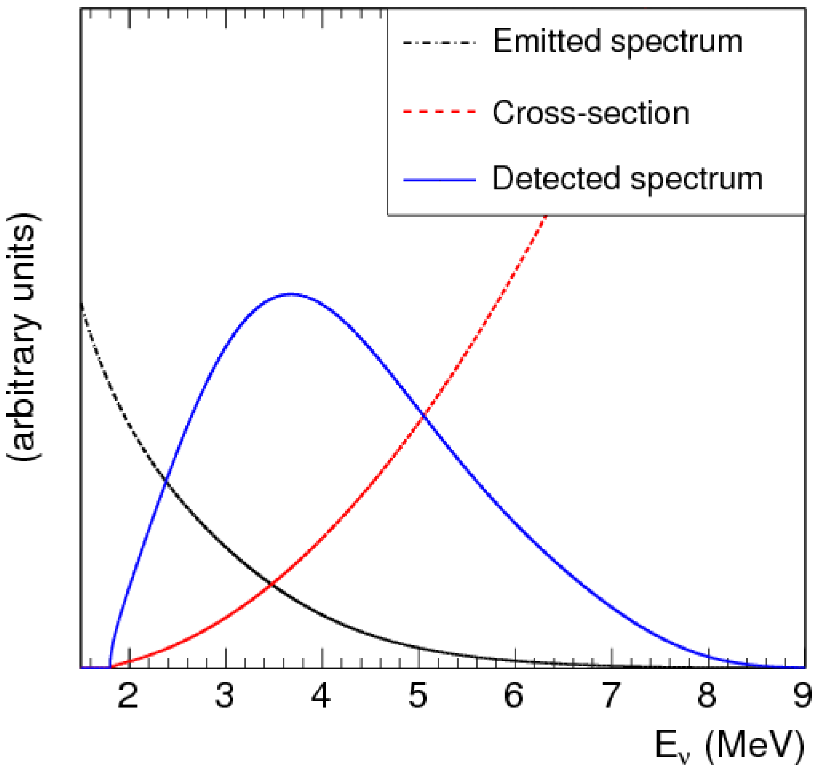
Reactor Anti-Neutrinos

- From fission fragment β-decay
- 10^{21} ν /s
- Isotropic emission
- Accounting at production
- Non-intrusive
- Neutrinos cannot be Shieldec
- Real-time fissile material measurement

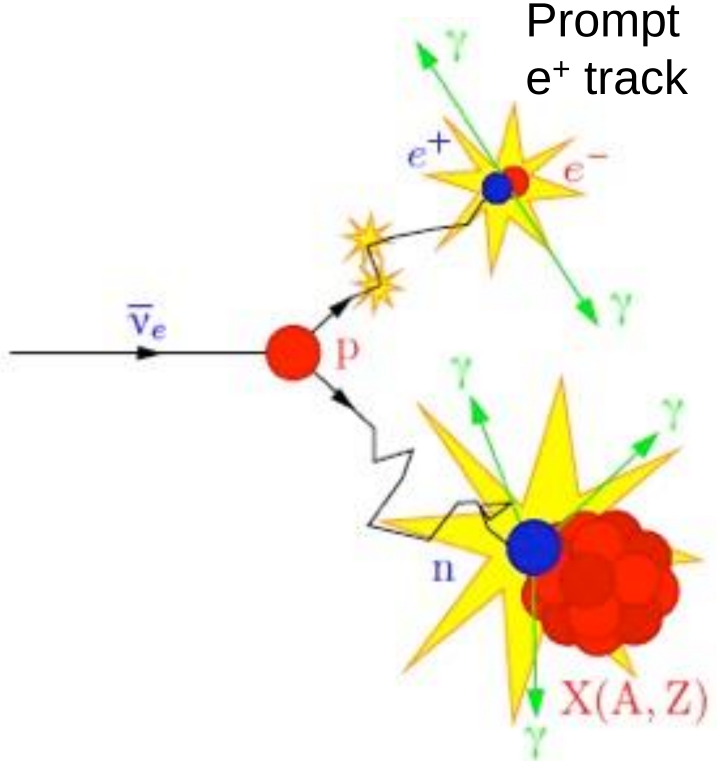
Energy spectrum plot



Detecting Anti-Neutrinos

- Via Inverse Beta-Decay
- Rely on delayed coincidence between fast component from positron
- And a slow component from a delayed Neutron Capture

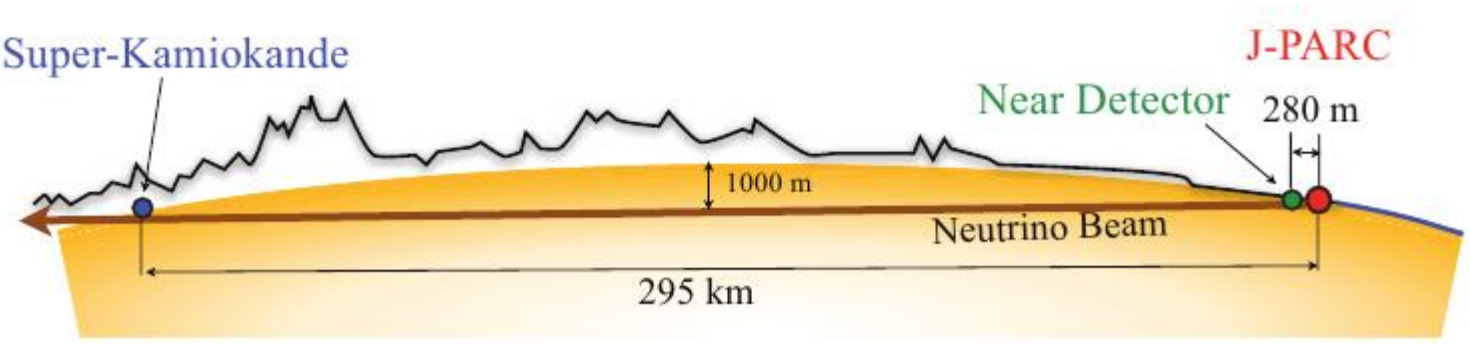
Prompt
e^+ track

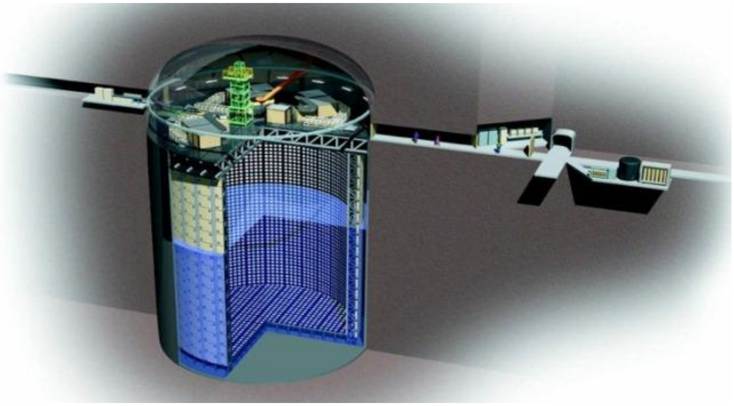


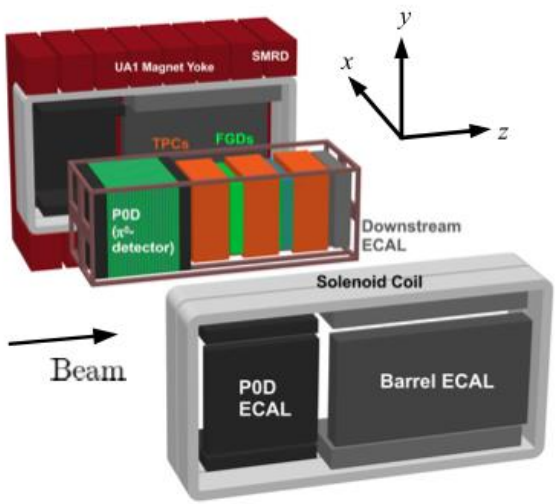
Delayed
8 MeV gamma ray cascade

Technology Motivation

The T2K Experiment







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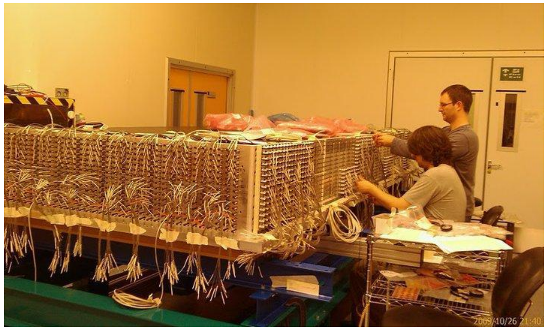
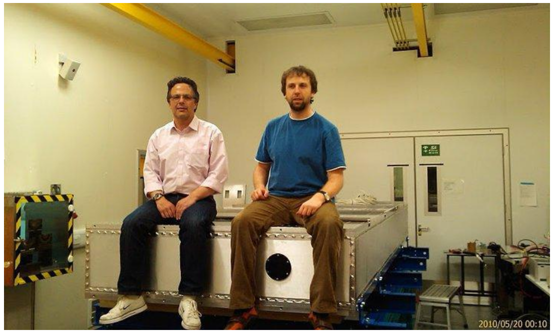
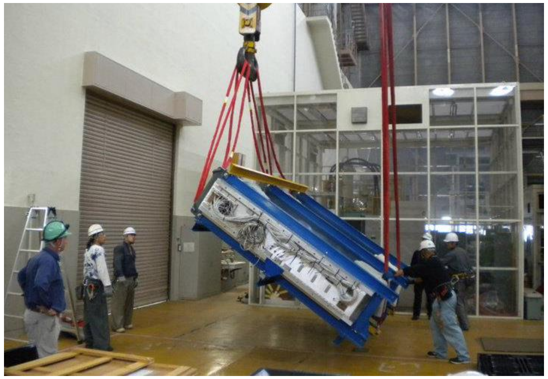
T2K

Barrel ECal Build at Liverpool







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FUNDAMENTAL PHYSICS BREAKTHROUGH PRIZE

Awarded 9th November 2015

All collaborators named & cited as laureates

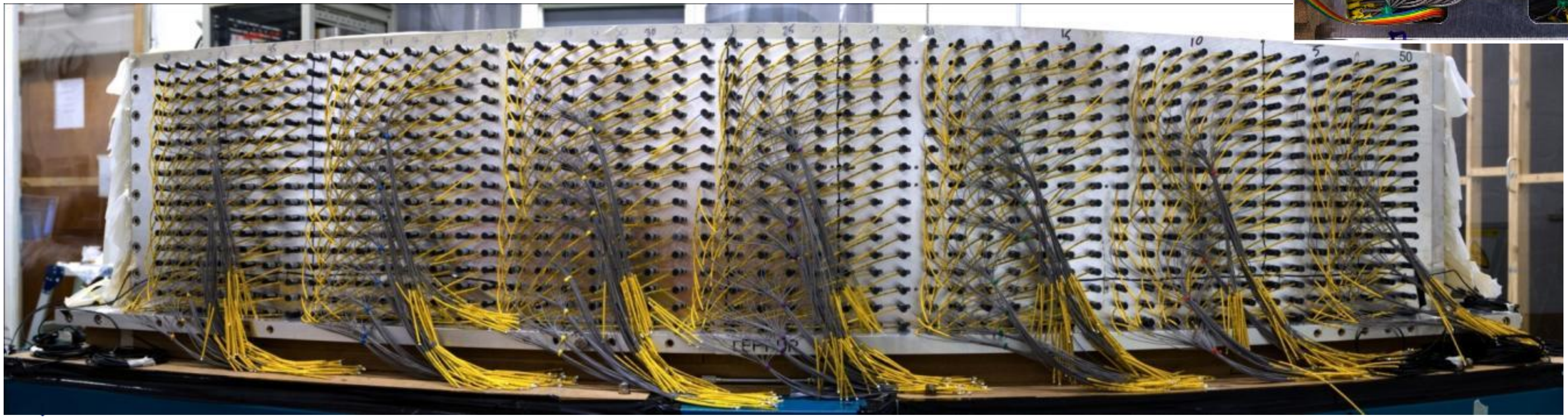
The T2K Near Detector Barrel ECal

- Designed and built at Liverpool University and Daresbury Laboratory – Shipped whole to Japan!

- State of the art neutrino detection technology

- Plastic Scintillator
- WLS Fibre
- MPPC Si-PMs – First Large Scale Use

- Earthquake proof!



An assembled ECal Module

The Detector

Applying ND280-ECal Technology

- Spin off from T2K
  - Exploit man years of development
  - Robust transportable design
  - Earthquake resistant technology

- System constructed and tested at Liverpool
  - Modified ECal design
  - T2K electronics
  - Cosmic ray veto system
  - Structural and cooling improvements

- Detector Vital Statistics
  - 2000 channels
  - 1 ton active mass

- The necessary introductions for site access were facilitated by DECC and ONR in response to an approach from the UK Support Programme to the IAEA*.

*The UK Support Programme is funded by the Department of Energy and Climate Change, to provide technical support to the IAEA Department of Safeguards. The Programme is administered by NNL under contract to DECC.

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From ND280-ECal to Anti-Neutrino Detector

Neutron Capture Doping

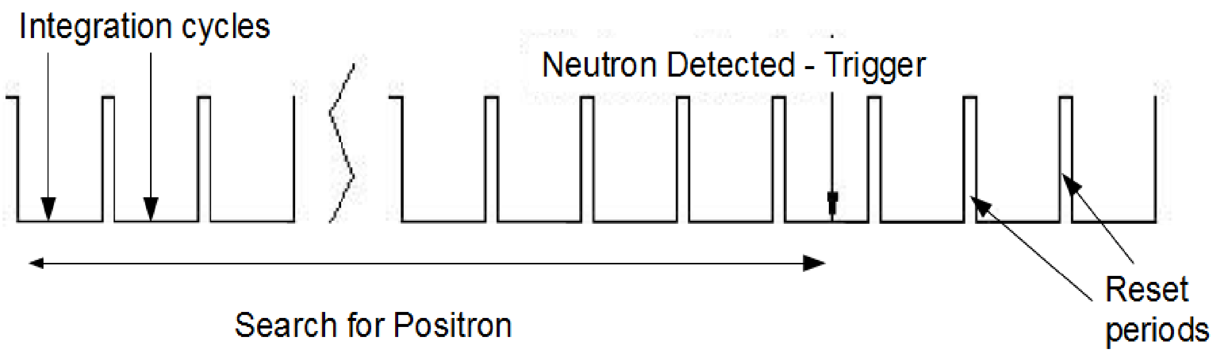
Lead

Gadolinium

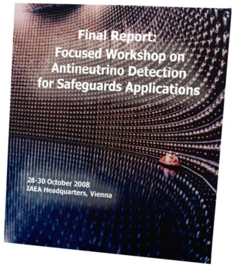
n $\rightarrow$ 8 MeV
γ cascade

Neutron capture
$\sigma \sim 250{,}000$ barns

Electronics Adaptation



A Safeguards Friendly Detector



Non-volatile/toxic/corrosive	Plastic Scintillator	✓
Non-liquid	Plastic Scintillator	✓
Easy operation	Low voltage MPPCs, simple interface	✓
Cheap	Extruded Plastic, MPPCs	✓
Transportable	Liverpool -> Wylfa in ISO container	✓
Robust	T2K ECal design, MPPCs	✓
Above ground operation	In-built cosmic ray veto	✓
Deployable in ISO container	Deployed in container for field-test	✓

“Final Report: Focused Workshop on Antineutrino Detection for Safeguards Applications”, IAEA Headquarters, Vienna Austria, 2008.

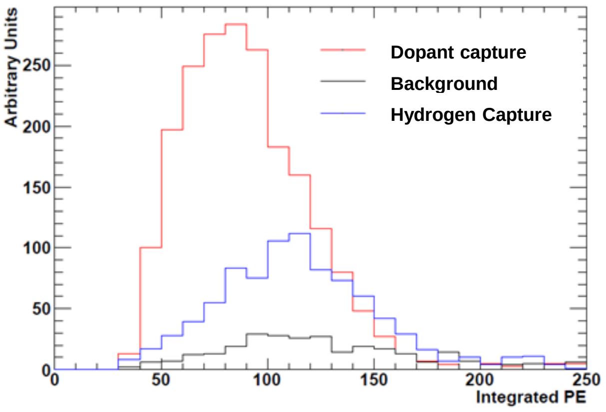
Detector Prototyping

- Test in lab using radioactive sources
  - Californium-252 (neutrons)
  - Cobalt-60 (~1MeV gammas)

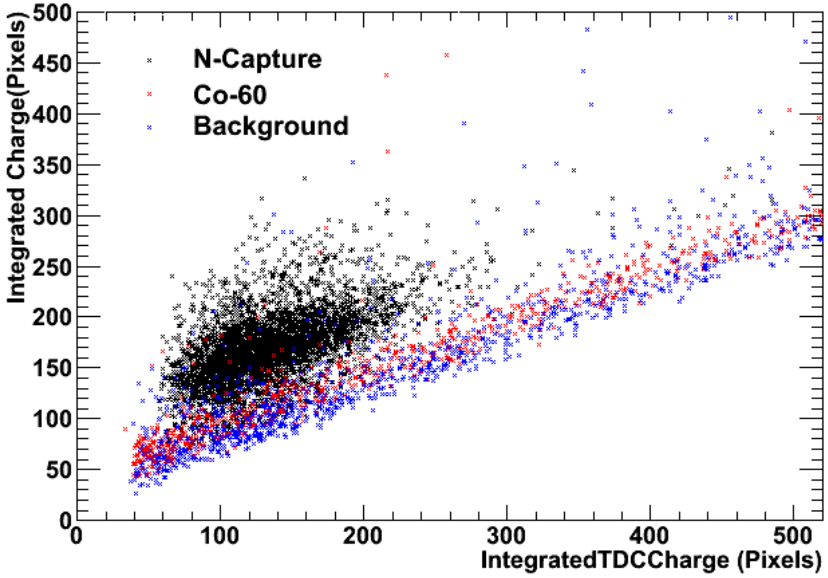
- Large increase in neutron events with capture agent

- 25 layer prototype to test neutron response

Neutron Capture Tests

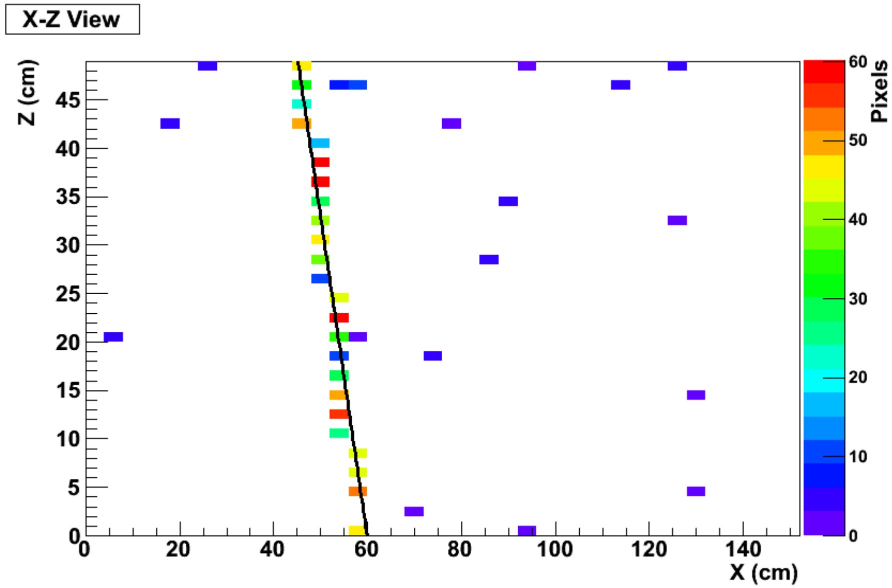


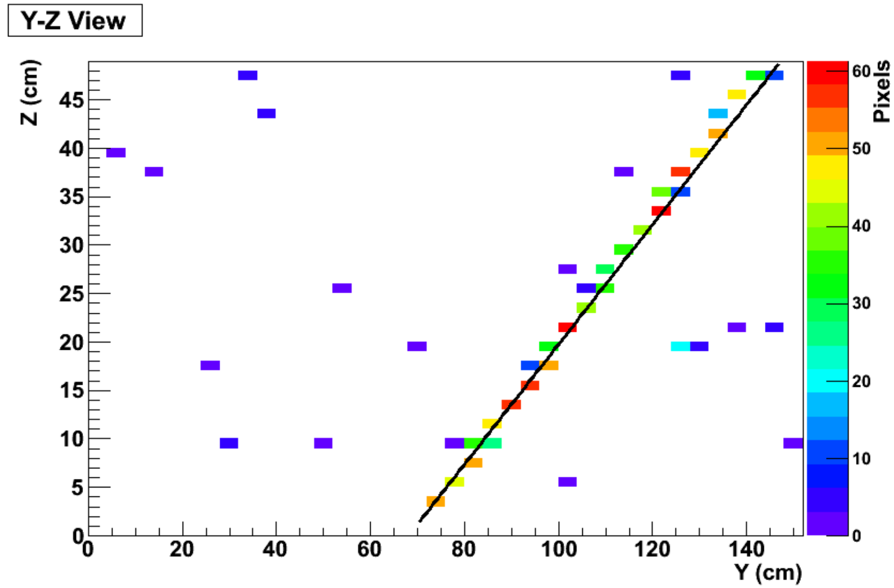
n/ γ discrimination



*IntegratedTDCCharge = sum of all energy deposits above a given threshold

Cosmic Rays

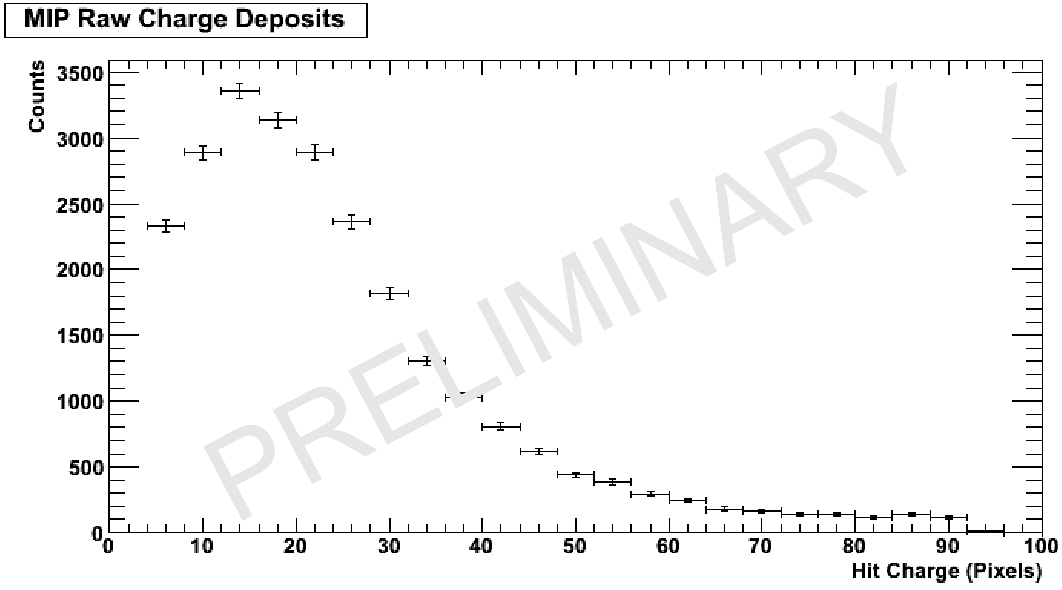




- Track reconstruction algorithm written and working
  - Fitted cosmic ray track shown
  - Hardware and software veto tested and working

Prototype Light Yield Calibration

- Fully configurable trigger and veto
  - Can select or reject cosmic rays easily
- Adapt calibrations from T2K ECal
  - MIP dE/dX
    - ~2.2 MeV/cm deposit
  - Attenuation, drift, etc.



Deployment

Field Test Deployment – Wylfa Power Station

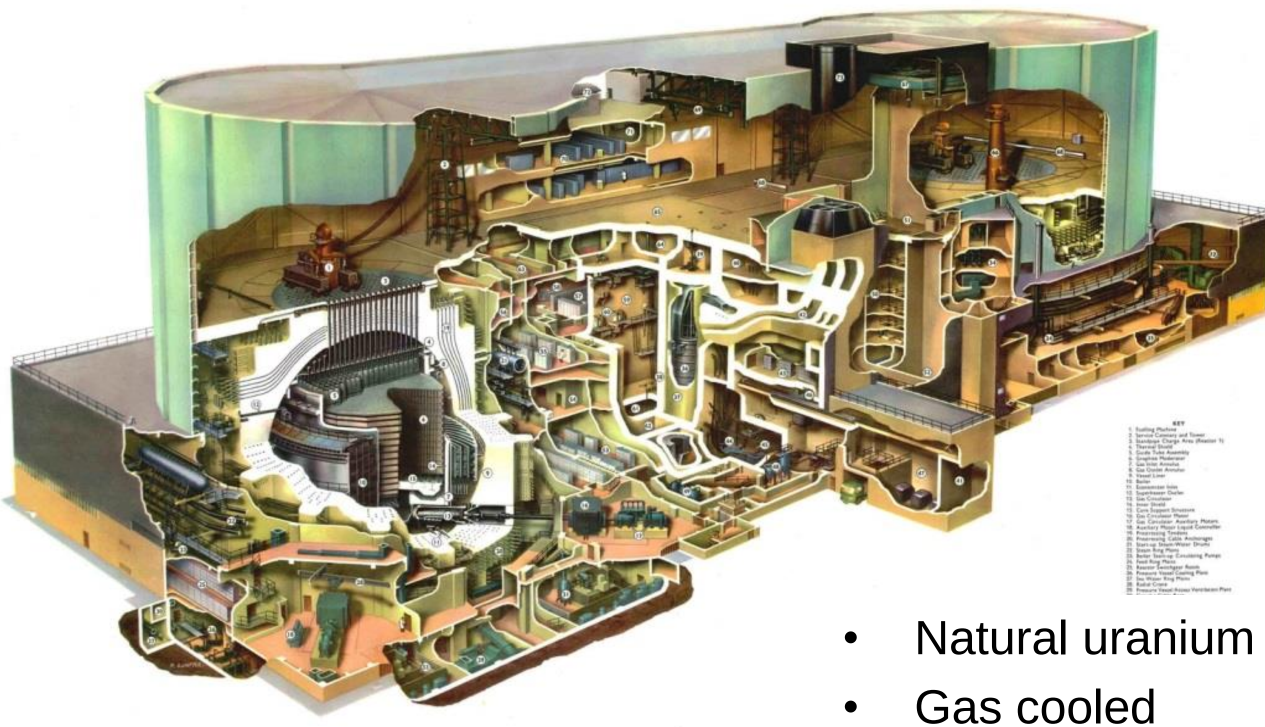
Containerisation

- Convert ISO 20ft shipping container into mobile lab
  - Power supply
  - Lighting
  - Power conditioning
  - Humidity/Temperature control
- Load detector, electronics & shielding
- Assembled & comissioned before dispatch
- Drive and Drop
  - Plug it in at power station
  - Ready for operations
- Whole transportable, ready to operate package!

Wylfa Power Station – Last of the Magnox

Reactor 2 – Shutdown 2012

Reactor 1 – Operating until 12/2015



- Natural uranium fuel
- Gas cooled
- Graphite moderation
- On-load refuelling!

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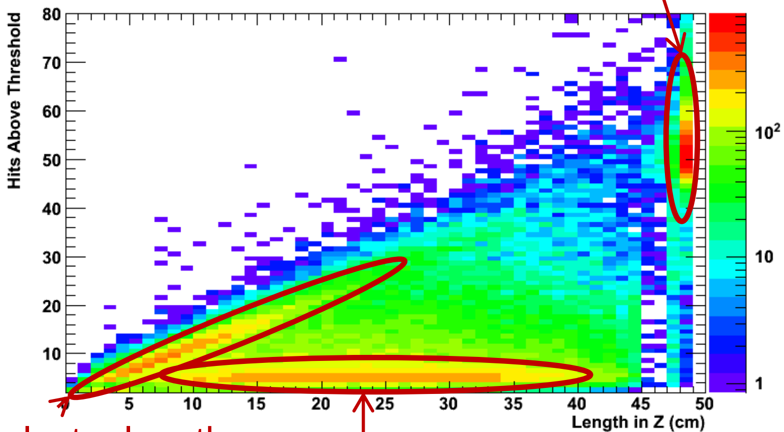
Image from :http://econtent.unm.edu/cdm/singleitem/collection/nuceng/id/41/rec/48

Particle Signature - Neutrons

Data at Wylfa (reactor off + cosmic rays)

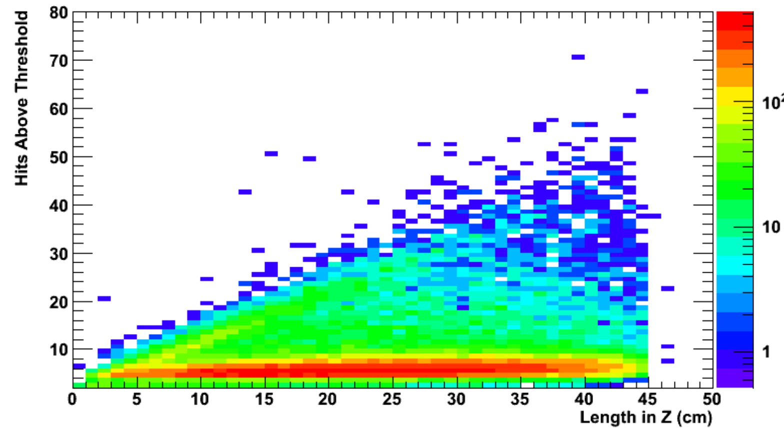
Track spanning detector



nHits ~ cluster length i.e. short track

No correlation i.e. neutron

Neutron Source Data



- Neutron selection developed using Cf-252 data
  - ~3 – 8 MeV energy deposit from neutron
  - Distinctive gamma cascade shape
- ~1Hz neutron captures selected

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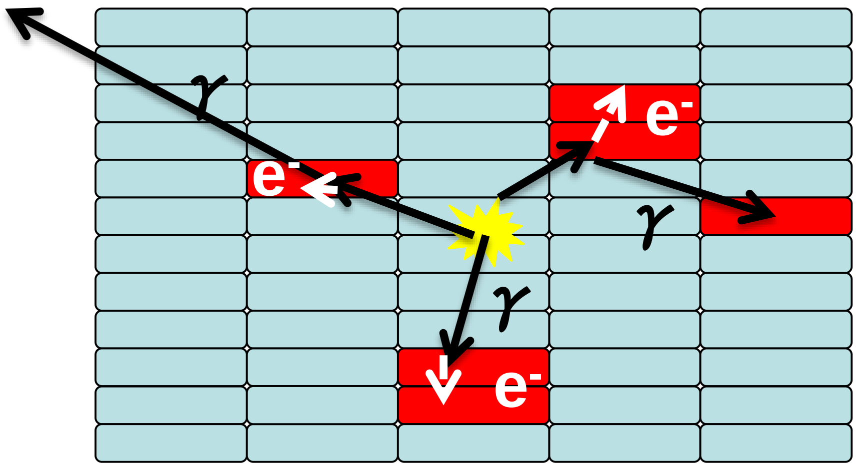
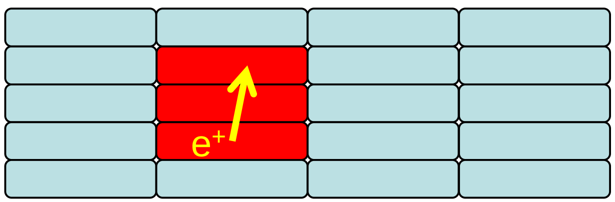
Particle Signature – Neutron

- 8 MeV gamma cascade on capture
- Multiple Compton scatters in detector
- Spatially separated hits coincident in time



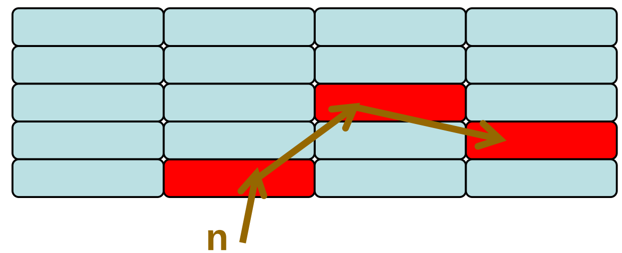
Particle Signature - Positrons

Positron



- Spatially adjacent hits
- Concurrent in time
- de/dx ~ 1.8 Mev/cm
- 2 - 8 MeV

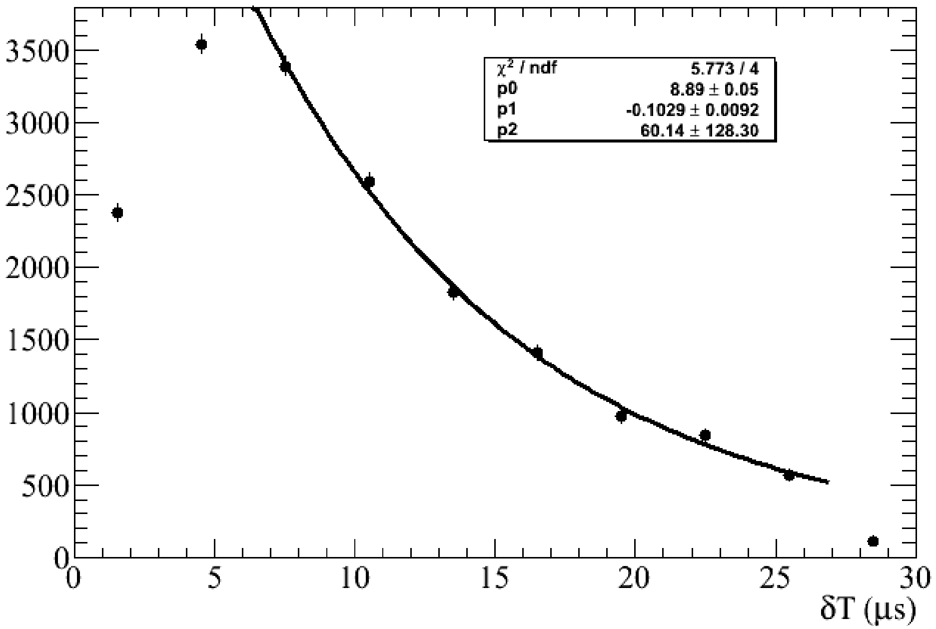
Fast Neutron



- Spatially separated hits
- Concurrent in time
- High de/dx recoils
- Concentrated around detector edges

Uncorrelated Background Subtraction

- Random coincidence n & e^+/γ events
- Flat δt distribution
- Calculate probability of random positron signal and subtract



Fit with exponential plus constant. Constant is consistent with 0 after subtraction

Reactor Start-up July 2014

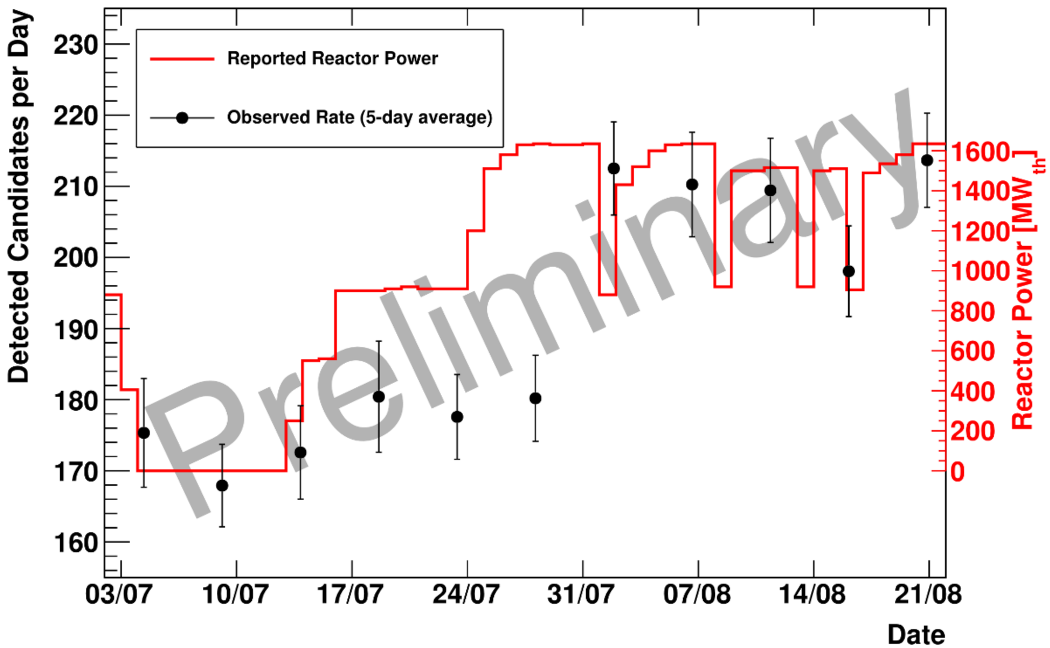
- Plastic Scintillator detector

- Deployed ~60 m from the core

- deployed aboveground in iso-container

- 1.6 GW_{th} power

- Even better if closer
  - c.f. $1/r^2$ dependence on flux



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Future Work

- Fully Funded upgrade of electronics
  - Replace DAQ developed and adapted from T2K – ND280
  - Design & build underway of custom readout specifically for Reactors
  - Working with John Caunt Scientific Ltd, funded via Innovate-UK
- New deployment
  - Wylfa shutdown imminent
    - location under-discussion
- Collaboration with National Nuclear Lab Ltd (NNL)

NATIONAL NUCLEAR LABORATORY

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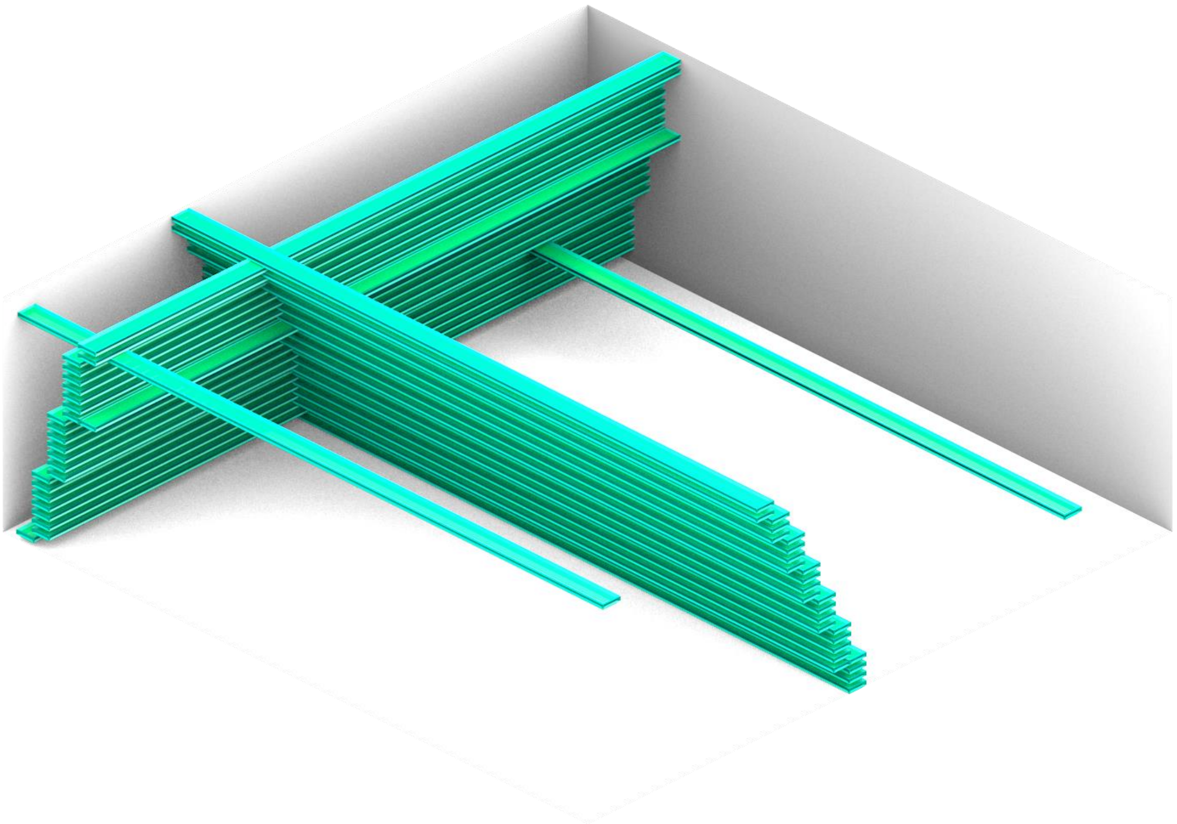
Summary

- A safeguards friendly anti-neutrino detector has been constructed at University of Liverpool
  - Direct Technology from fundamental research!
- Shipped in a ISO shipping container to Wylfa power station, UK for field test
  - Drop and plug in design – highly transportable
  - Only requires power connection
- Support from UK support program for deployment and grant submission to research council and Innovate-UK
- Currently taking data
- Observation of excess events after reactor turn on
- Working on spectral analysis

BACKUP

Cosmic Ray Event



Neutron Background Estimates

- Work in progress
- He-3 measurements of ambient neutron flux
- Relative fast neutron detection efficiency from Cf-252
- Increase in neutron capture with reactor on
- Estimate ~ 15 counts per day contamination

Proof-of-concept demonstrated

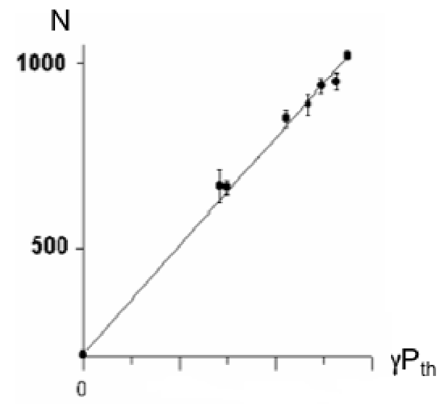
- Pioneered in Russia in the 80's
- LLNL / Sandia (US)

Remarkable monitoring of reactor operation.

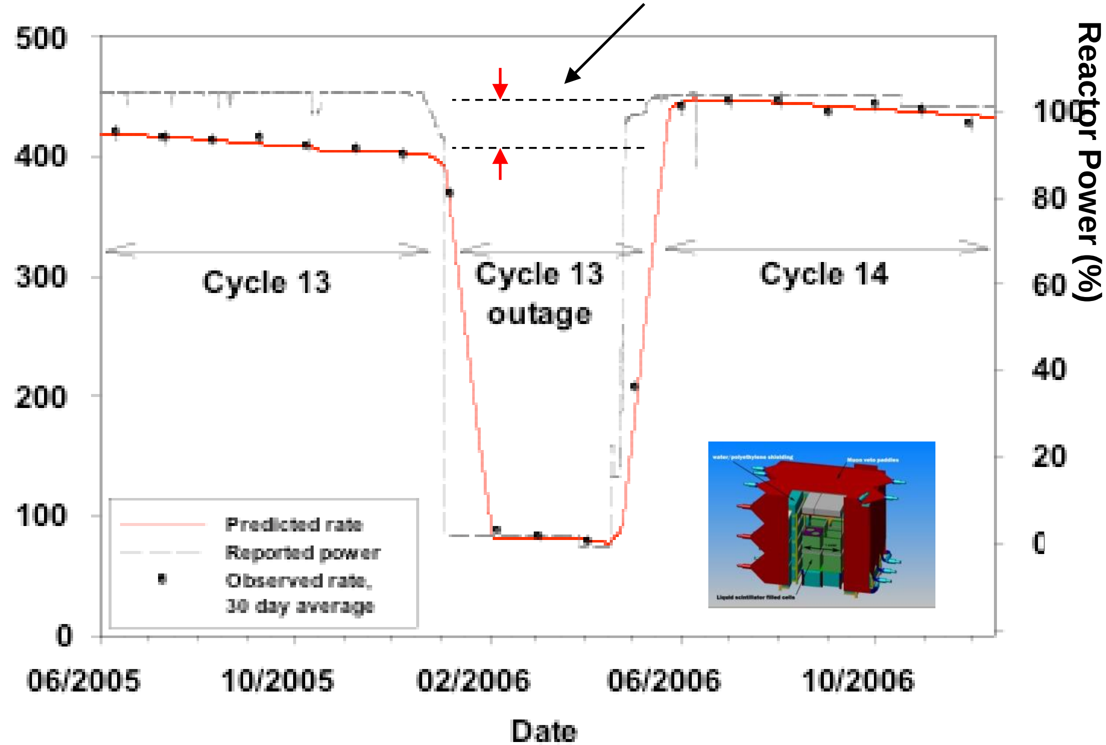
~450 evts/day after cuts

• Deployed 24m from the core
• 20 mwe overburden
• 3 GW_{th} power

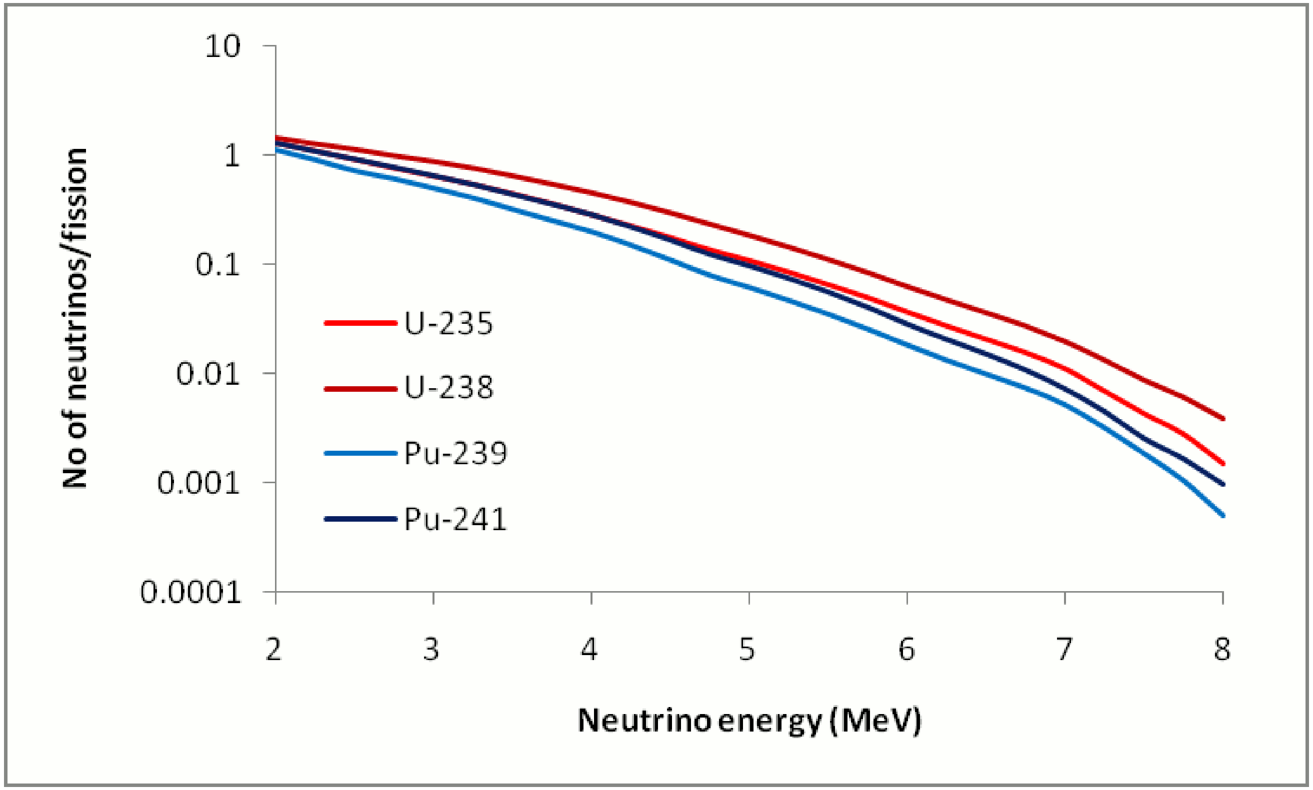
Need to improve in choice of technology



Removal of 250 kg ^{239}Pu, replacement with 1.5 tons of fresh ^{235}U fuel



Spectrum by fission nuclei



[T.A. Mueller et al., arXiv hep-ex/1101.2663v3]

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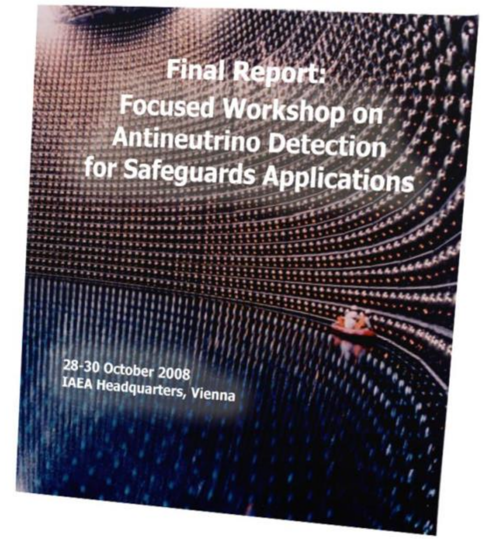
IAEA Recommendations

Next Generation Designs focus:

- Shipper-receiver differences,
- Bulk Process/ Online Refuel Reactor Verification
- Research reactor power
- Safeguards by Design, Integrated Safeguards
- Aboveground Detection
- Cheaper
- Manufactured from Safeguards friendly material

IAEA
International Atomic Energy Agency



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“Final Report: Focused Workshop on Antineutrino Detection for Safeguards Applications”, IAEA Headquarters, Vienna Austria, 2008.