The Neutrinos-Angra Experiment and Its Contribution to IAEA Nonproliferation Safeguards

3rd IAEA Technical Meeting on Nuclear data for antineutrino spectra applications

08/april/2025

Seoul National University - Korea

Ernesto Kemp (kemp@unicamp.br)
on behalf of the Neutrinos Angra Collaboration.

Outline

- Historical Background
- Reactor Neutrinos as Safeguards Tool
- The ν-ANGRA experiment
- The ON-OFF analysis
- Upgrades
- ν-ANGRA 2.0 (?)
    - A cryogenic detector
- Conclusions

Historical Background

How it all started…

WHITE PAPER REPORT on
Using Nuclear Reactors to Search for a
value of θ_{13}
January 2004

arXiv:hep-ex/0402041v1 26 Feb 2004

tories and beta beams. However, the possibility of measuring CP violation can be fulfilled only if the value of the neutrino mixing parameter θ_{13} is such that $\sin^2(2\theta_{13})$ greater than or equal to on the order of 0.01. The authors of this white paper are an International Working Group of physicists who believe that a timely new experiment at a nuclear reactor sensitive to the neutrino mixing parameter θ_{13} in this range has a great opportunity for an exciting discovery, a non-zero value to θ_{13}. This would be a compelling next step of this program. We are studying possible new reactor experiments at a variety of sites around the world, and we have collaborated to prepare this document to advocate this idea and describe some of the issues that are involved.

How it all started…

arXiv:hep-ex/0402041v1 26 Feb 2004

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How it all started…
2005 meeting at Angra dos Reis

Invitation to attend IV Workshop on Future Low Energy Neutrino Experiments

This message: [Message body] [More options]
Related messages: [Next message] [Previous message] [Next in thread] [Replies]

From: Jo�o dos Anjos <janjos@cbpf.br>
Date: Tue Jan 04 2005 - 09:07:12 CST

Dear Colleague,

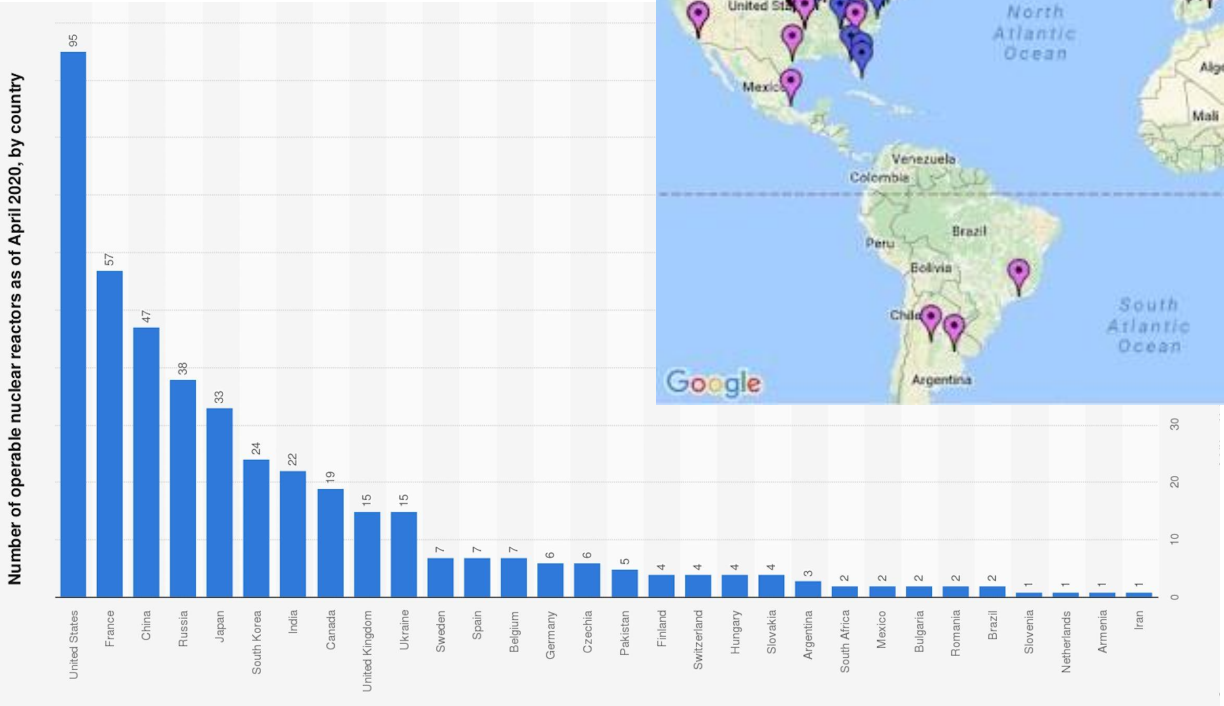
We would like to invite you to attend the IV Workshop on Low Energy Neutrino Experiments that will take place in the period February 23-25, 2005, at Angra dos Reis, Brazil. The workshop will be devoted to discuss the perspectives for next generation nuclear reactor experiments to study neutrino oscillations, as in the previous editions of this meeting. The detailed information regarding the scientific program and instructions for the registration can be found at:

http://www.ifi.unicamp.br/~lenews05

During the meeting, thanks to some very fruitful input from T. Lasserre and D. Reyna, we ended up deciding to build a small 'very near detector' anyway.

Reactor Neutrinos as Safeguards Tool

440 nuclear reactors in operation in ~ 30 countries around the world.



A 1000 MWe light water reactor gives rise to about 25 tonnes of used fuel a year, containing up to 290 kilograms of plutonium.

It takes about 10 kilograms of nearly pure Pu-239 to make a bomb

Reactor Neutrinos as Safeguards Tool

Why the interest in antineutrino detectors?

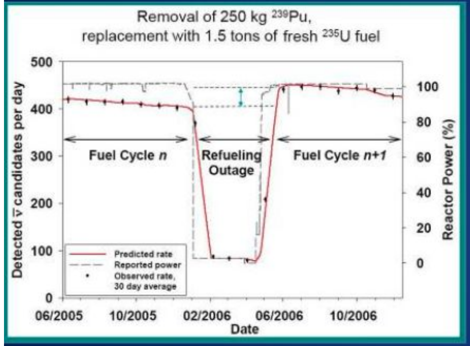
- Antineutrinos can not be shielded and are produced in very large amounts in nuclear reactors
(~ 10^{20} antineutrinos/s)

- Antineutrinos produced in reactors can reveal fissile composition of nuclear fuel

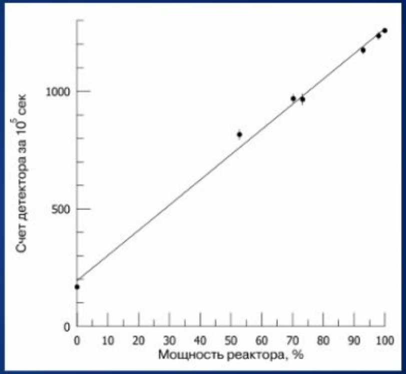
- Non-intrusive monitoring in real-time the reactor state:
    - thermal power & fissile material

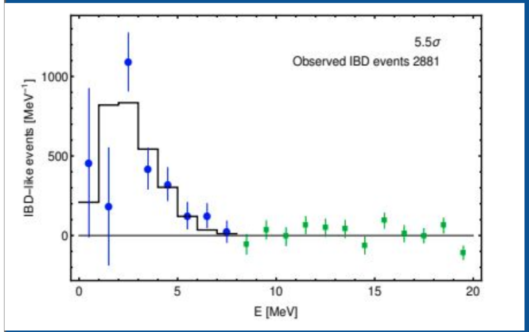
- Search for new methods on safeguards verification

San Onofre (USA)



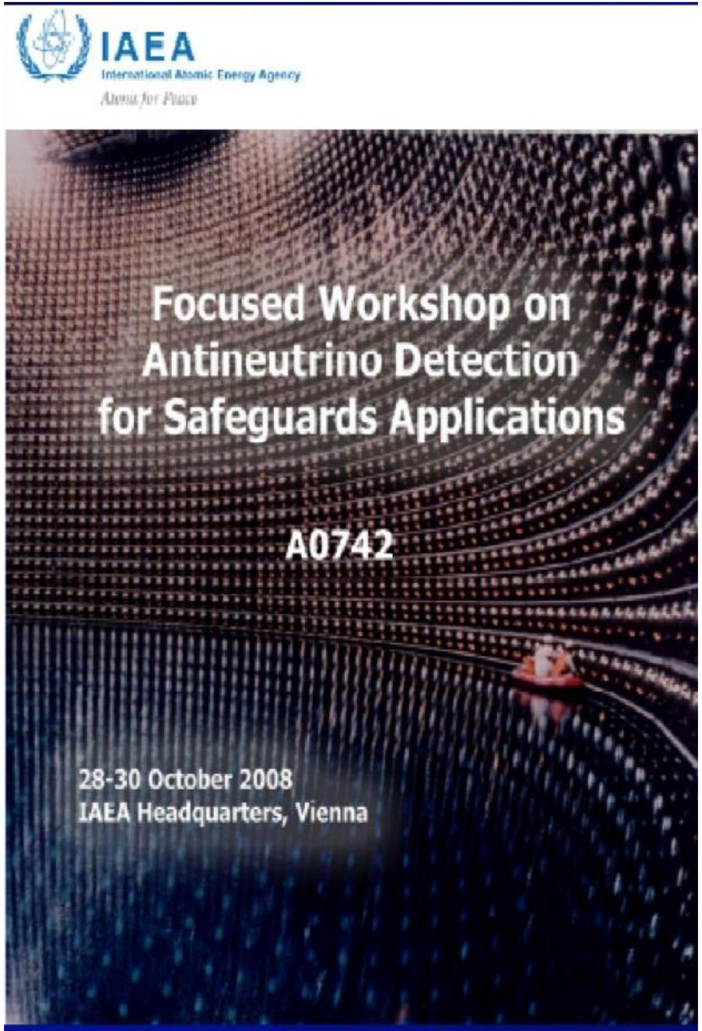
Rovno/Ucraine





CHANDLER

North Anna Nuclear Power Plant



DESIGN GUIDELINES:

Focused Workshop on Antinu-e

Detection for SG Applications (2008)

IAEA.org International Atomic Energy Agency

7.2 Medium Term:

If the above near-term goals are met, it is the opinion of the workshop conferees that antineutrino detectors will have demonstrated utility in response to the stated inspector needs in some specific areas of reactor safeguards. To further expand the utility of antineutrino detectors, several useful medium term (5-8 year timeframe) R&D and safeguards analysis goals are proposed.

1. Above ground deployment. Above ground deployment will enable a wider set of operational concepts for IAEA and reactor operators, and will likely expand the base of reactors to which this technology can be applied;
2. Provide fully independent measurements of fissile content, through the use of spectral information. This will allow the IAEA to fully confirm declarations with little or no input from reactor operators, purely by analysis of the antineutrino signal;
3. Develop improved shielding and reduced detector footprint designs, to allow for more convenient deployment. Current footprints are of order 2-3 meters on each side; modest reductions in footprint would expand the general utility of antineutrino detectors. .In this regard, a possible deployment scenario is envisaged where the component parts of the detector, shielding and all associated electronics are contained within a standard 12 metre ISO container, facilitating ease of movement and providing physical protection to the instrument. It should be noted that due to size and weight restrictions of ISO containers (approximately 25,000 kg net load) the

The Neutrinos Angra Experiment

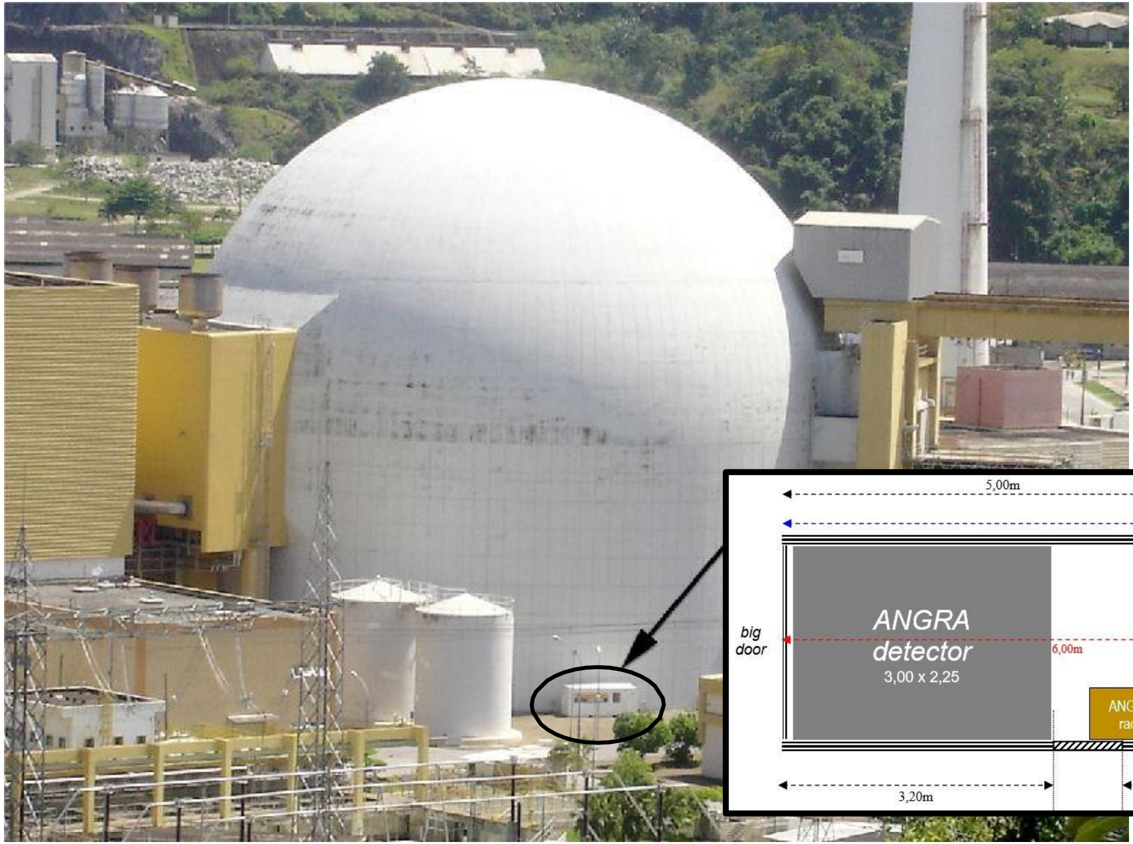
The Angra Collaboration

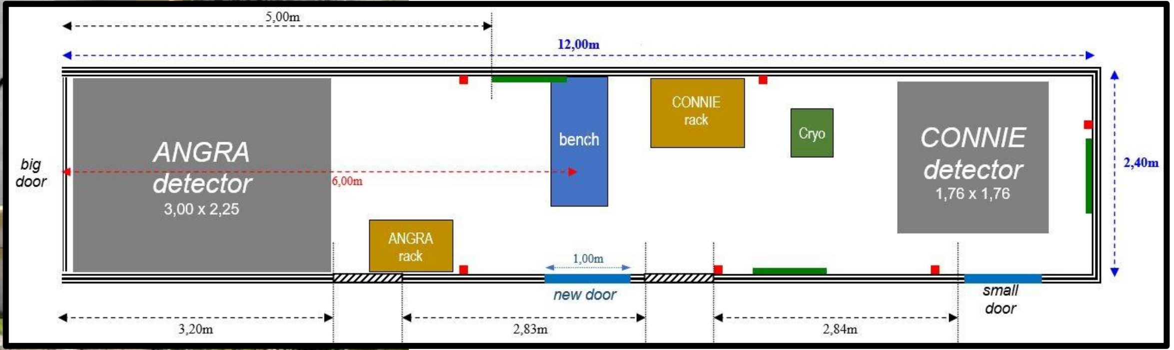
6 Brazilian Institutes:

- CBPF (Rio de Janeiro - RJ)
- UEFS (Feira de Santana - BA)
- UEL (Londrina - PR)
- UFBA (Salvador - BA)
- UFJF (Juiz de Fora - MG)
- Unicamp (Campinas - SP)

8 Researchers
3 Students

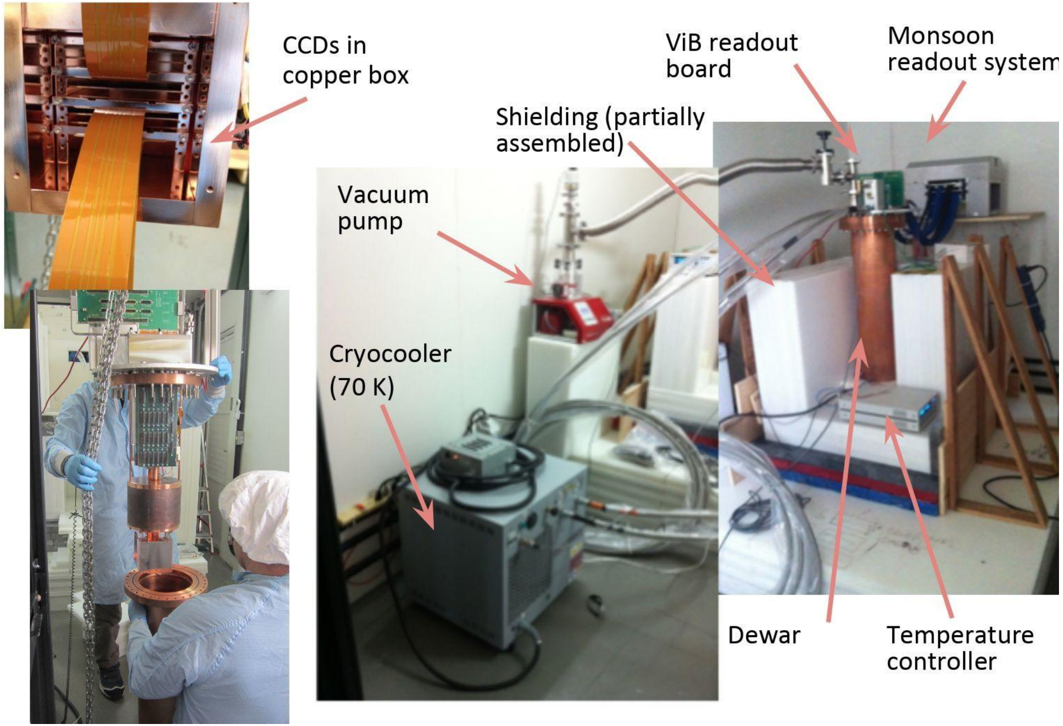
The experimental Lab





The experimental Lab

CONNIE detector installed in 2014



The ν-ANGRA Experiment

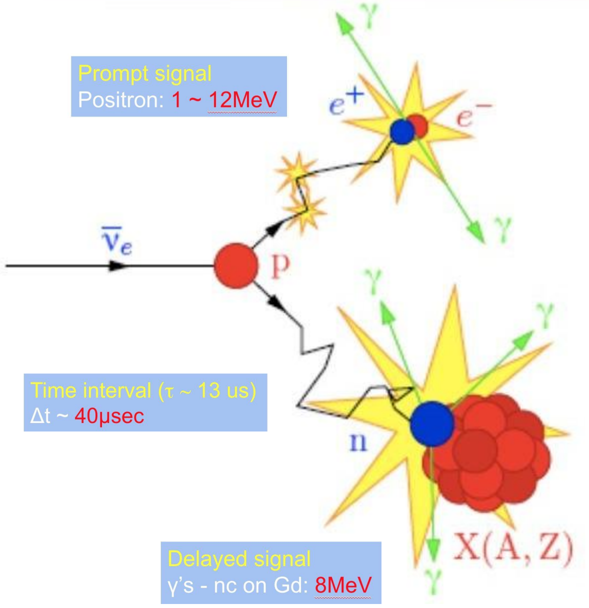
Major objective:

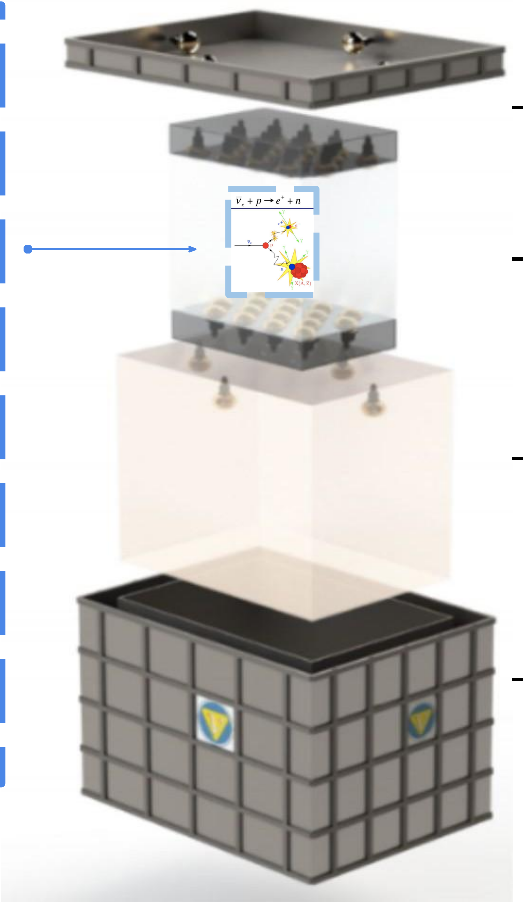
- Non-invasive monitoring of reactor activity:
    - Contribution to the International Atomic Energy Agency (IAEA) safeguards and non-proliferation efforts through the development of novel approaches to antineutrino detection

ν-ANGRA: a Water Cherenkov Detector

MADE IN BRAZIL

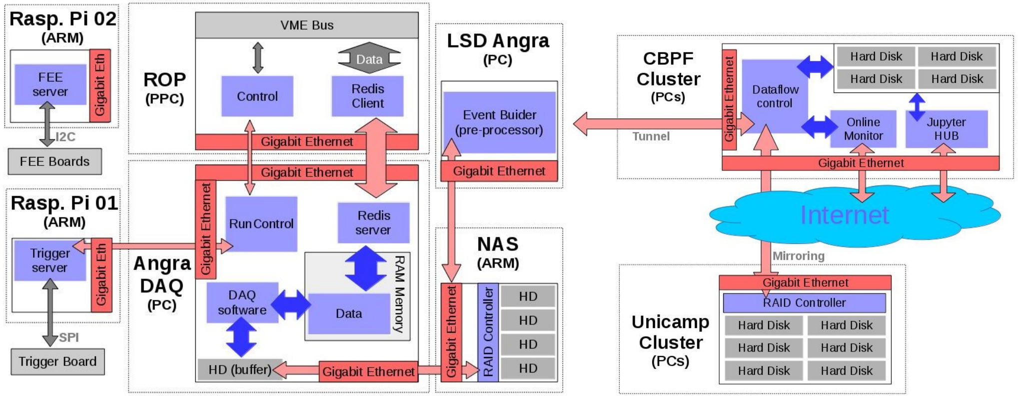
$$\bar{\nu}_e + p \rightarrow e^+ + n$$

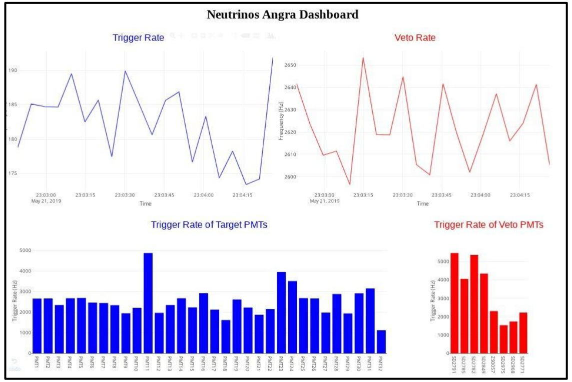


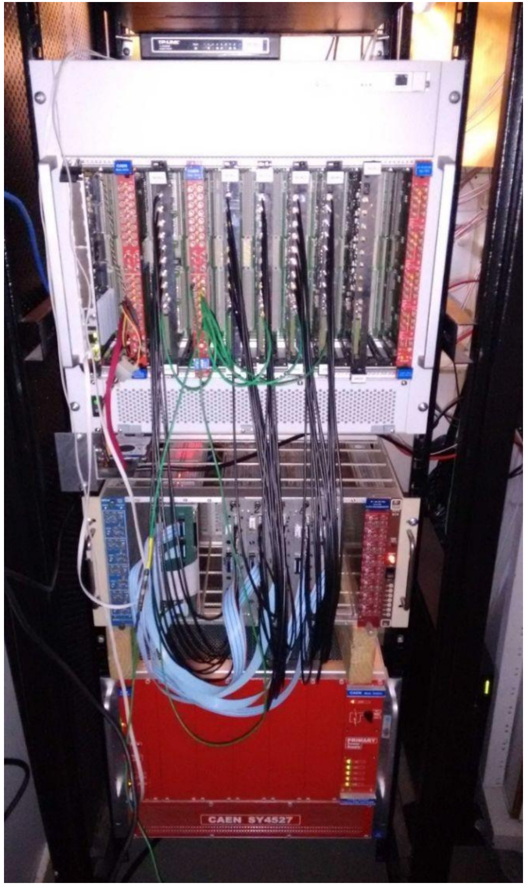


- Top veto (active): 4 PMTs
  25 cm height - pure water
- Neutrino Target (active): 32 PMTS
  ~ 1 ton GdCl3 doped water (0,2%)
- Inner Veto (active): 4 PMTs
  25 cm thick - pure water
- Shield (passive):
  25 cm thick- pure water

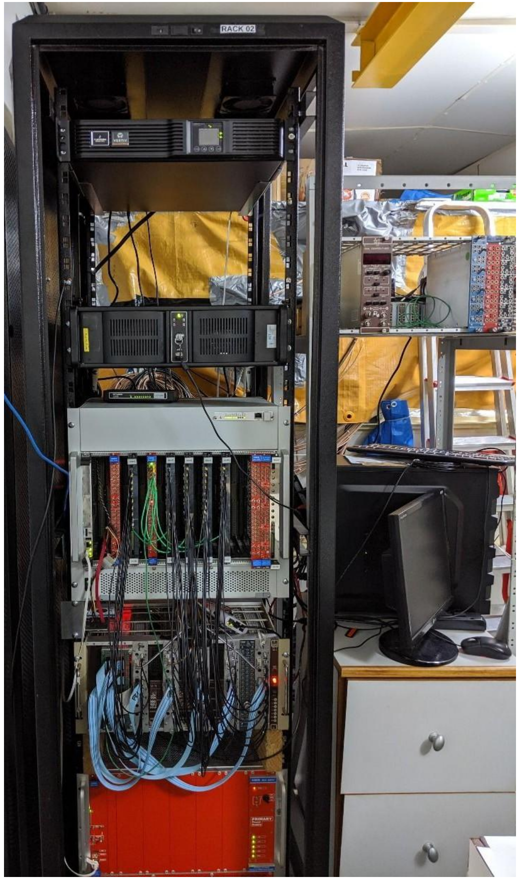
The Data Acquisition System (DAQ)



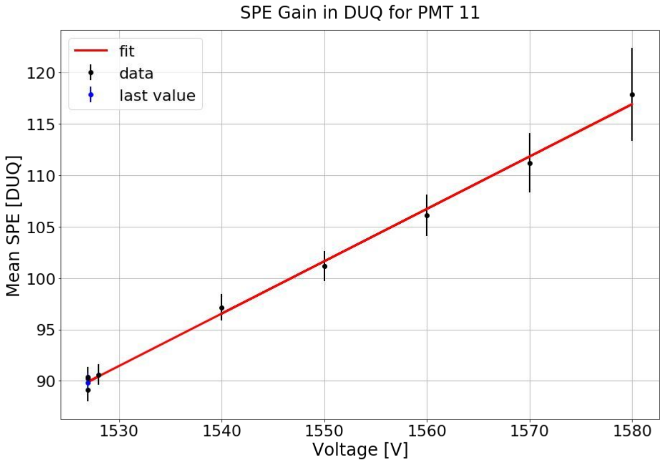


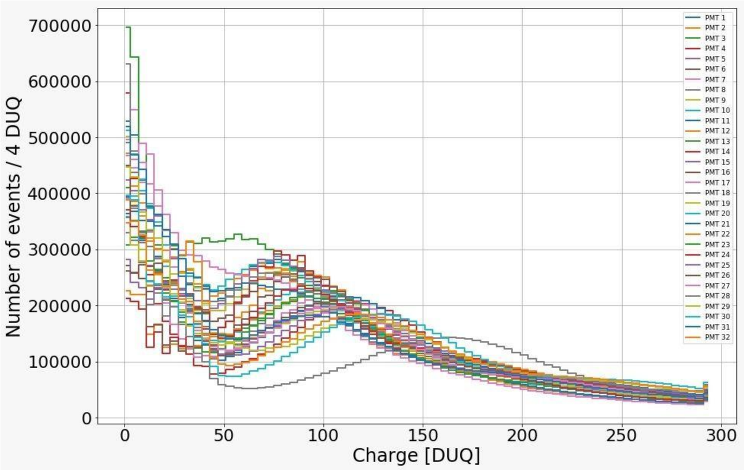


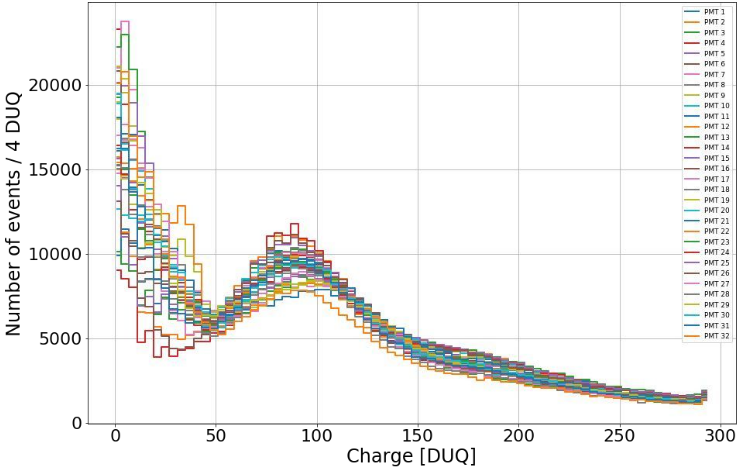
Commissioning



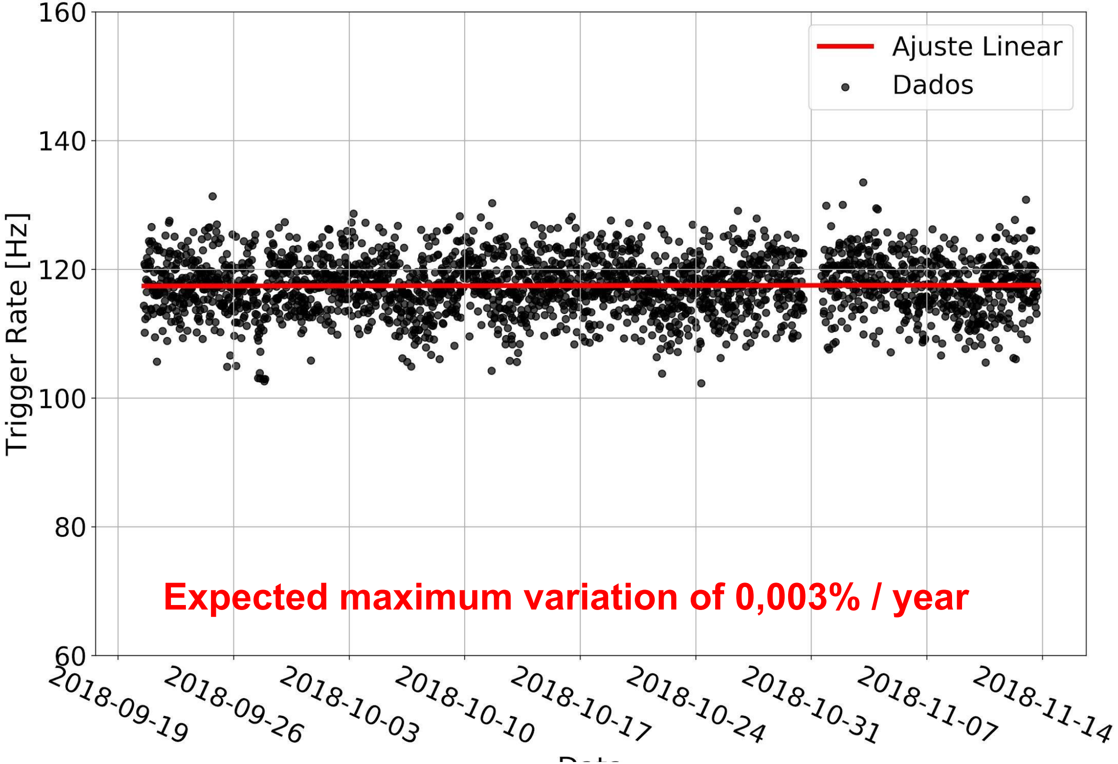
Full DAQ Control: Down to photoelectron level





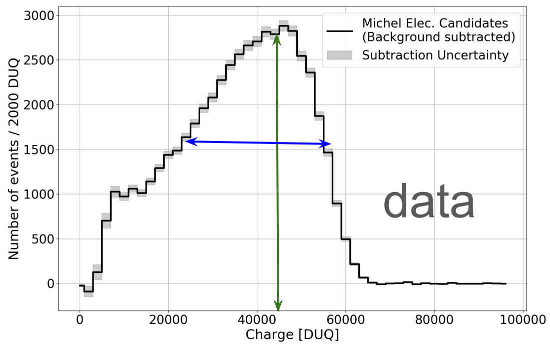


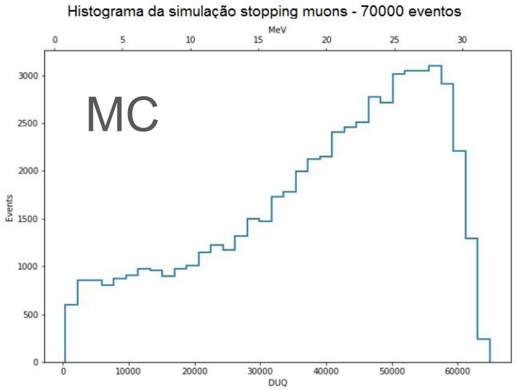
Stability



160
140
120
100
80
60
Trigger Rate [Hz]
Ajuste Linear
Dados
Expected maximum variation of 0,003% / year
2018-09-19
2018-09-26
2018-10-03
2018-10-10
2018-10-17
2018-10-24
2018-10-31
2018-11-07
2018-11-14

Stability check: Michel Electrons





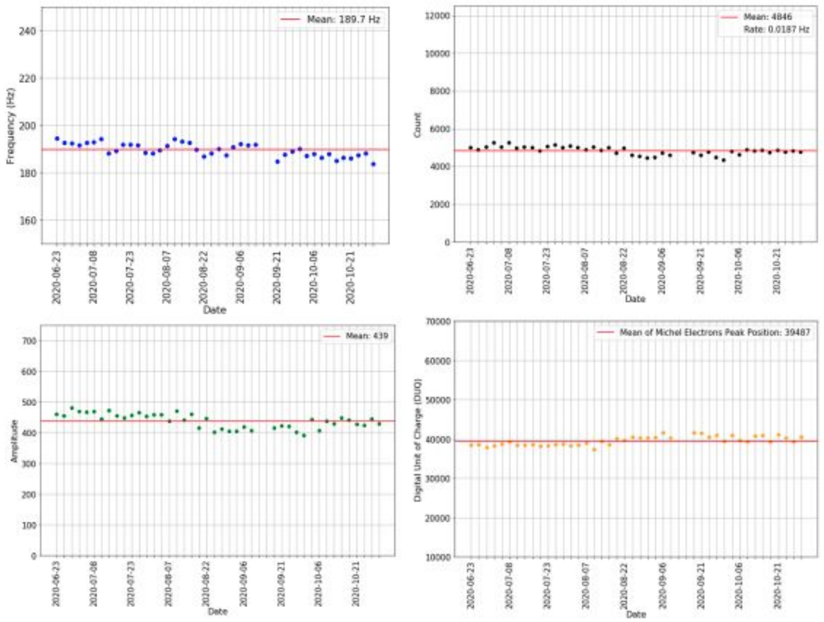


Figure 9: Upper left: Trigger rate of the ν-Angra detector for the analyzed dataset; Upper right: Time evolution of Michel electrons (ME) counting; Lower left: Time evolution of ME spectrum amplitude; Lower right: Time evolution of ME spectrum peak position.

Data analysis
&
Results

Data analysis
&
Results

Results from ON-OFF analysis of the Neutrinos-Angra detector

E. Kemp[1,*], W. V. Santos [1], J. C. Anjos[2], P. Chimenti[3], L. F. G. Gonzalez[4], G. P. Guedes[5], H. P. Lima Jr.[2,6], R. A. Nóbrega[7], I. M. Pepe[8], and D. B. S. Ribeiro[8]

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June 26, 2024

arXiv:2407.20397v2 [hep-ex] 7 Aug 2024

Abstract

The Neutrinos Angra Experiment, a water-based Cherenkov detector, is located at the Angra dos Reis nuclear power plant in Brazil. Designed to detect electron antineutrinos produced in the nuclear reactor, the primary objective of the experiment is to demonstrate the feasibility of monitoring reactor activity using an antineutrino detector. This effort aligns with the International Atomic Energy Agency (IAEA) program to identify potential and novel technologies applicable to nonproliferation safeguards.

Operating on the surface presents challenges such as high noise rates, necessitating the development of very sensitive, yet small-scale detectors. These conditions make the Angra experiment an excellent platform for both developing the application and gaining expertise in new technologies and analysis methods. The detector employs a water-based target doped with gadolinium to enhance its sensitivity to antineutrinos.

In this work, we describe the main features of the detector and the electronics chain, including front-end and data acquisition components. We detail the data acquisition strategies and the methodologies applied for signal processing and event selection. Preliminary physics results suggest that the detector can reliably monitor reactor operations by detecting the inverse beta decay induced by electron antineutrinos from the reactor.

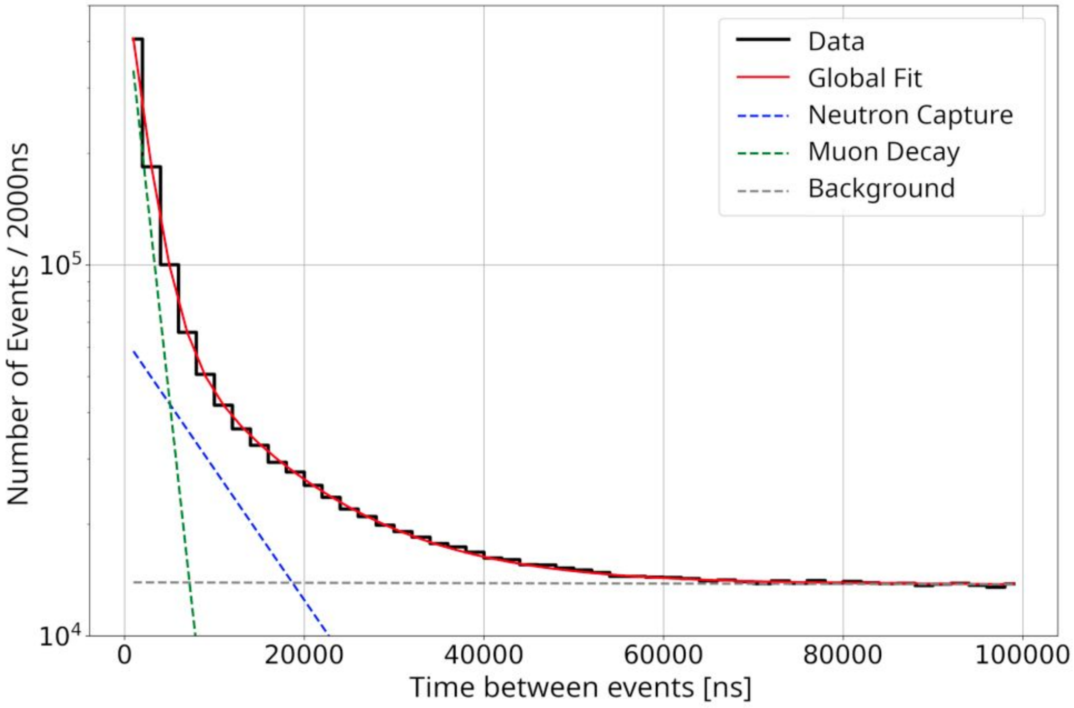
Event Selection:

Strategy: searching for pairs (e^+,n) from IBD

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

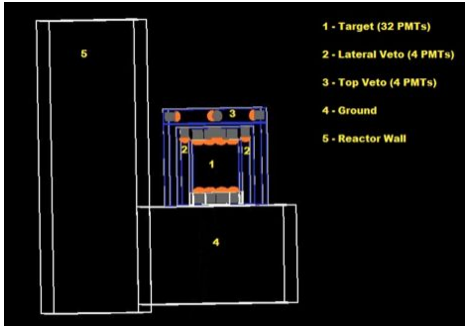
- Time between 2 consecutive events: from n-capture data
- e^+ (prompt): known and well-defined energy
- n (delay): known and well-defined energy (Gd de-excitation line)

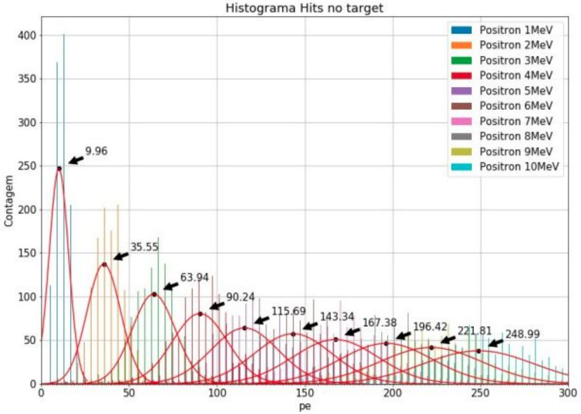
Time analysis

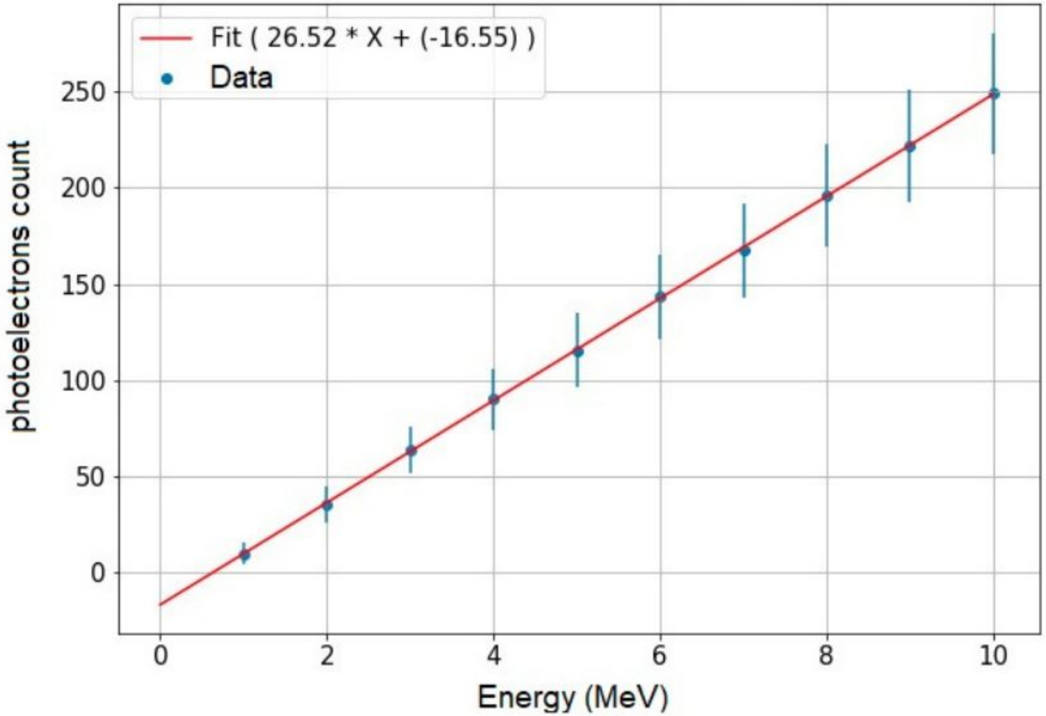


Component	λ
Muon Decay	$(1.9 \pm 3)\ \mu s$
Neutron Capture	$(12.32 \pm 0.05)\ \mu s$
Background Noise	(7.92 ± 0.01) ms

e^+ (prompt) cuts: energy scale from GEANT4 simulations

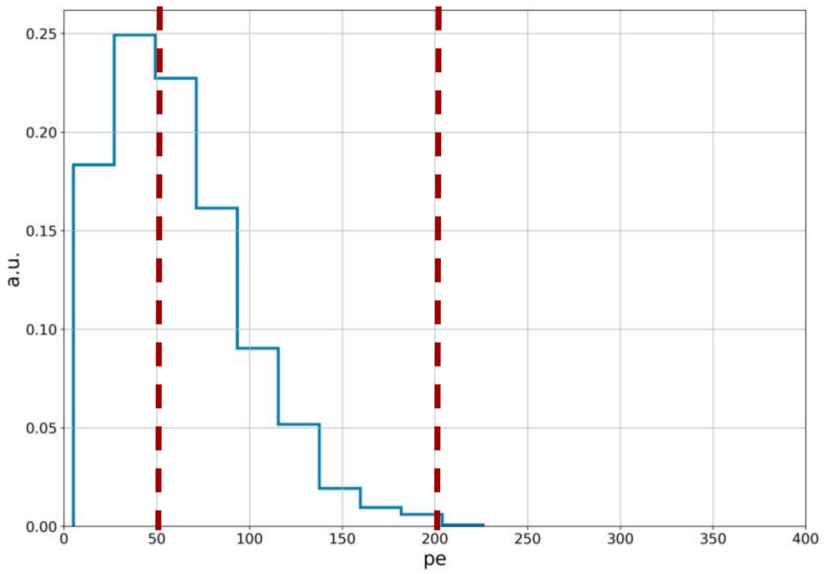






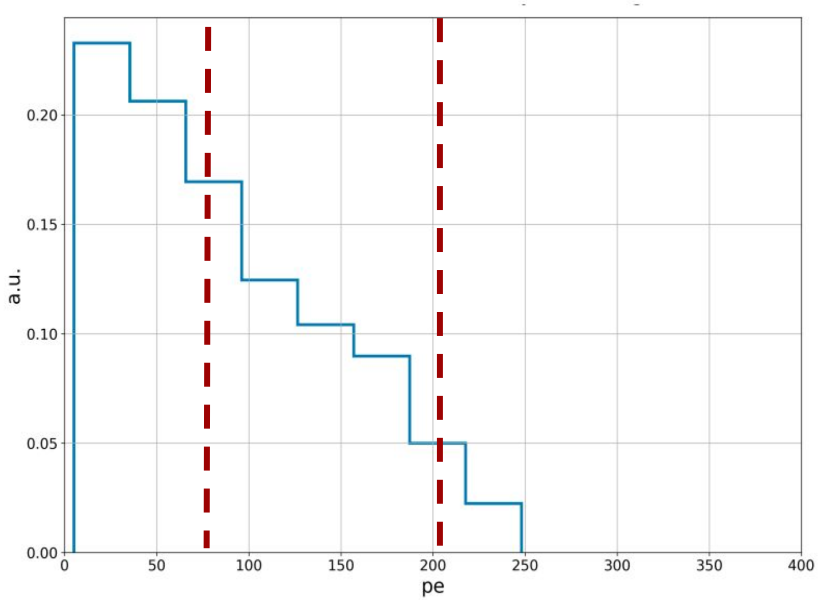
e^+ (prompt) cuts: energy scale from GEANT4 simulations

Expected PDF for IBD positrons in the target.
Neutrinos energy drawn from reactor's fuel spectra



n (delay) cuts: GEANT4 simulations (Gd de-excitation line)

Expected PDF for neutron capture signals



PMTs multiplicity in delay events

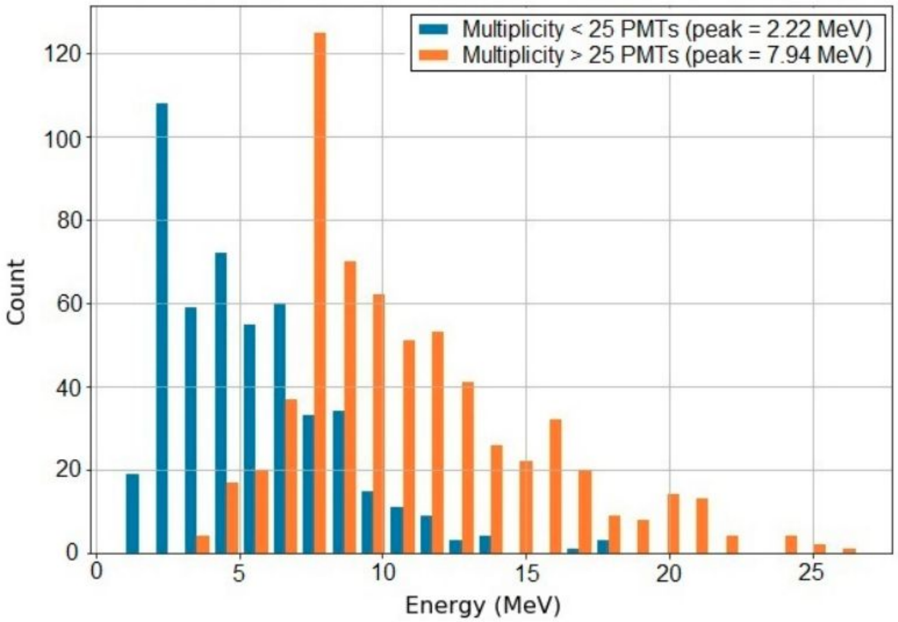


Figure 17: Simulated spectra of gammas from neutron capture filtered by the multiplicity M of PMTs activated in the events. $M \geq 25$ selects efficiently gammas Gd de-excitation from those of deuteron formation.

ON-OFF analysis: Results

ON-OFF: reactor neutrino IBD events are identified by comparing 2 datasets

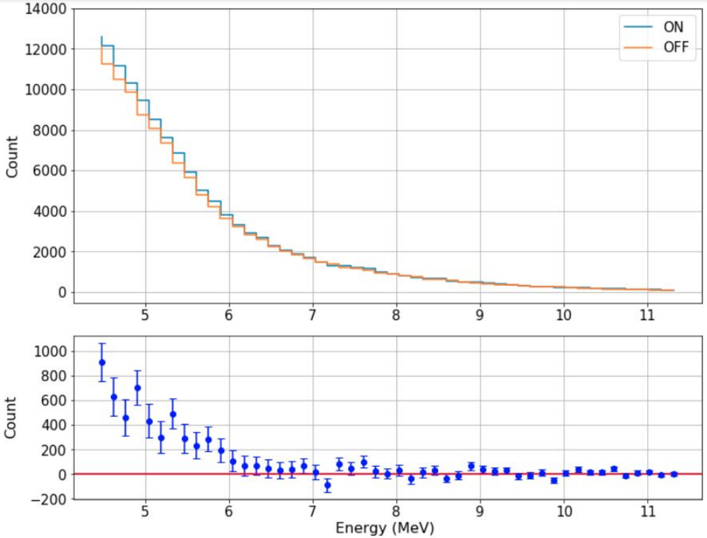
ON: reactor is fully operational

OFF: reactor shutdown for maintenance and refueling.

ON-OFF analysis: Results

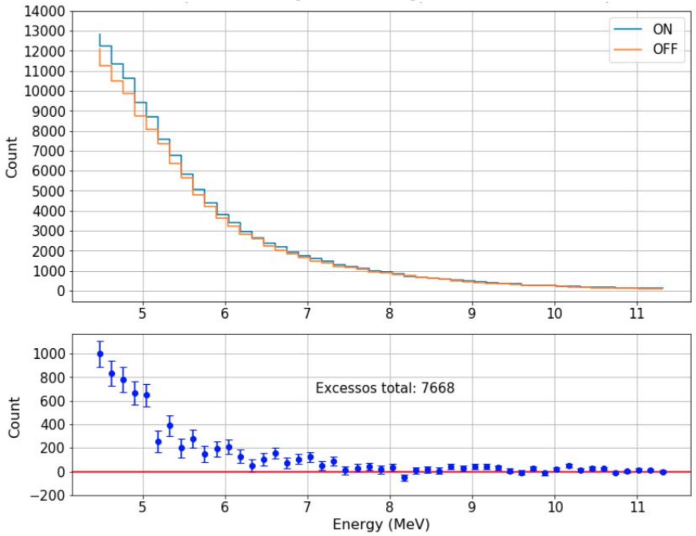
OFF: jul/2020;
ON1: aug-sep/2020;
ON2: sep-oct/2020.

ON1-OFF



$$\chi^2/dof \sim 13.4$$

ON2-OFF



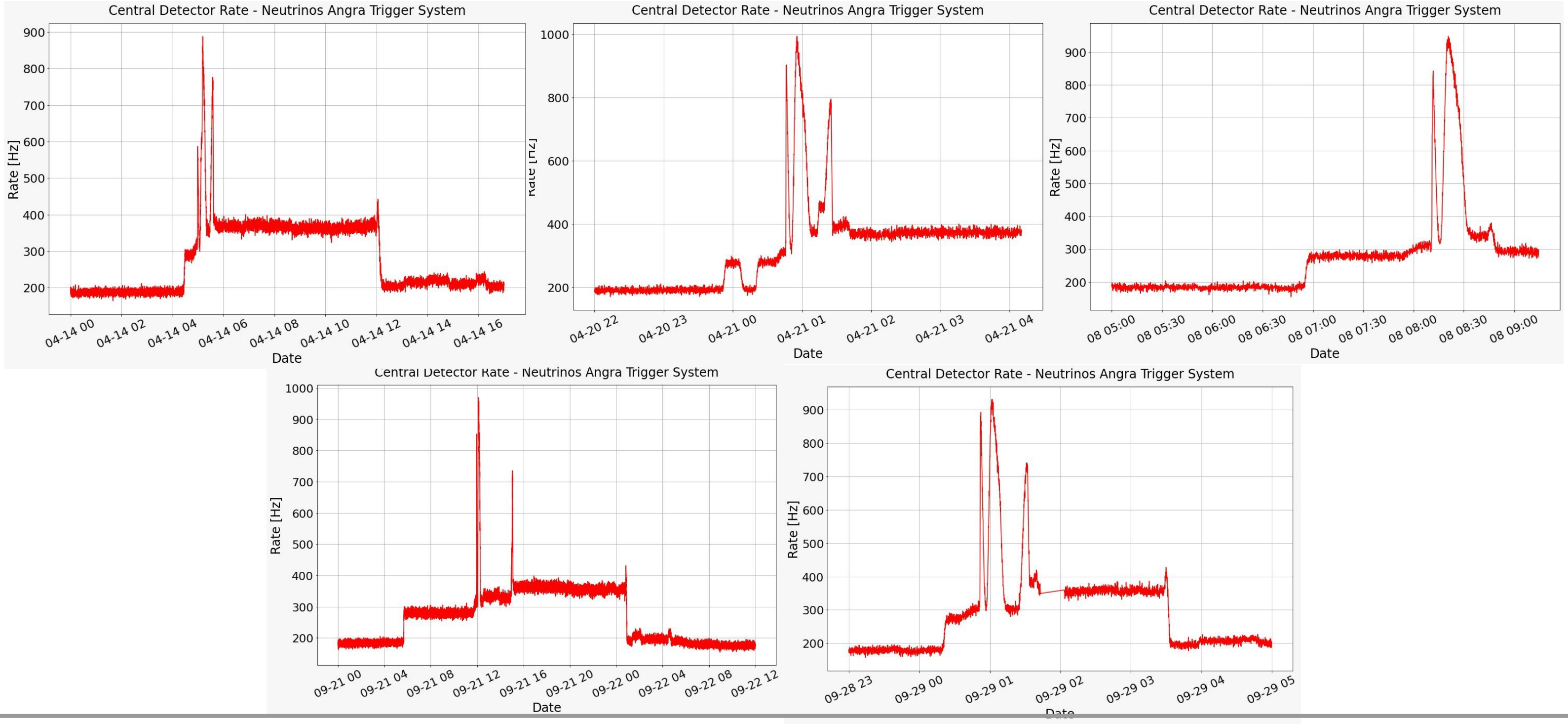
$$\chi^2/dof \sim 17.3$$

H_0: Excess are bkg fluctuations → ***Rejected*** (p-value < 10^{-9})

Detection of nuclear fuel transportation

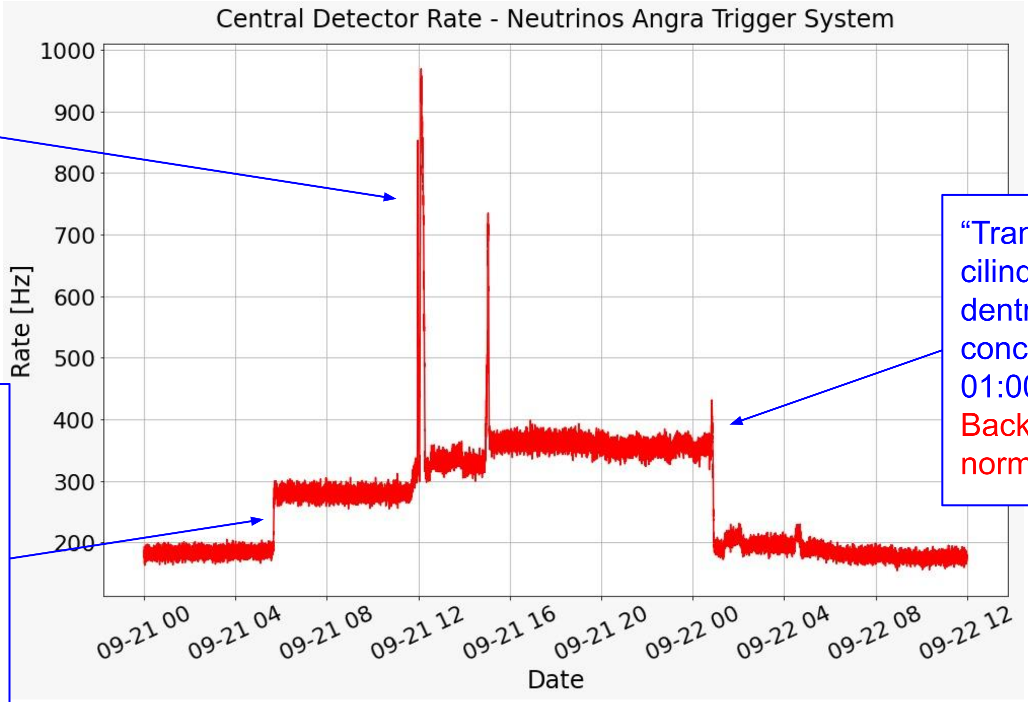
Transport of the fuel element from Angra 2

Each fuel element transport from Angra 2 resulted in an increase in the background rate observed in the experiment. This increase exhibits a pattern that can be explained by the transport logistics.



Transport of the fuel element from Angra 2

"Possible interventions carried out on the casks, as well as changes in the direction of their movement."
Abrupt increase in the measured rate, beyond the range where we can ensure linearity.



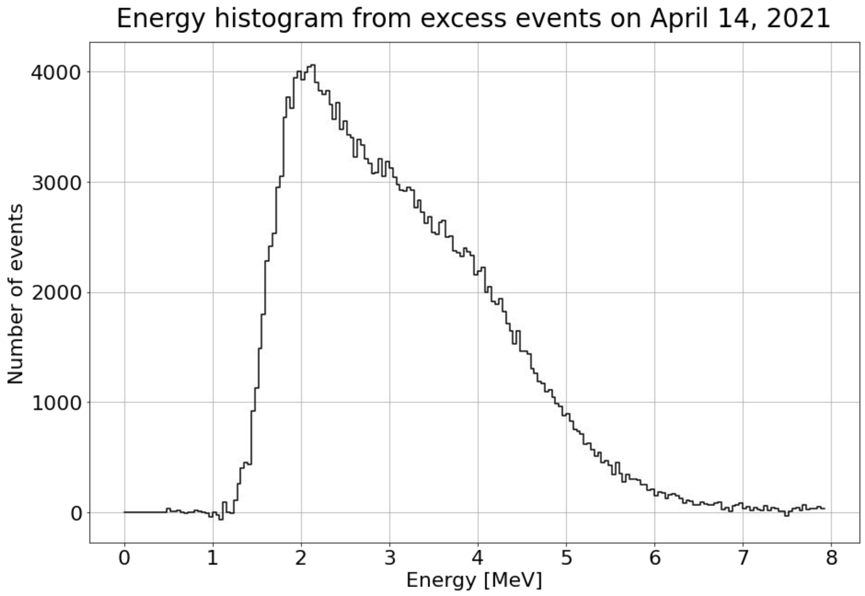
"Transferência de dentro do cilindro de chumbo para dentro do cilindro de concreto no dia 22/09 às 01:00h":
Background rate returned to normal levels

"The cask containing the fuel elements, inside the lead cylinder, left the plant on September 21st at 5:30 a.m."
Increase of between 50% and 90% in the measured background rate.

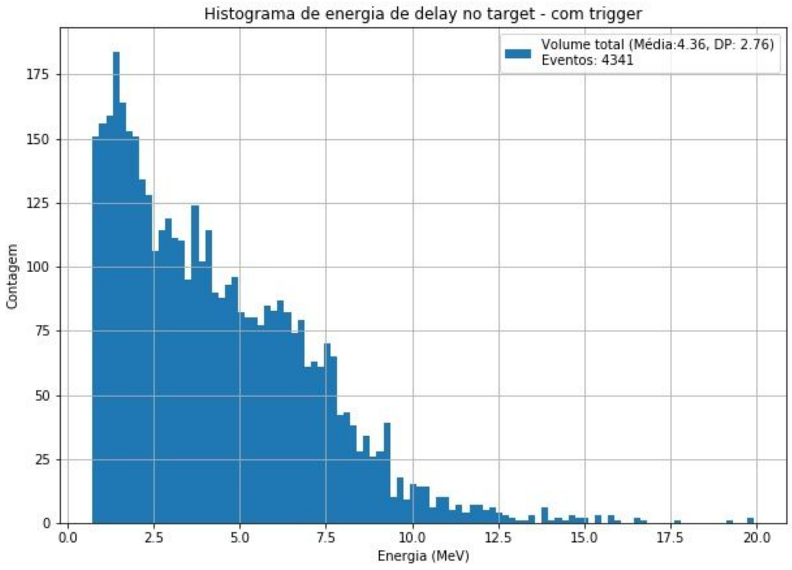
Transporte do elemento combustível de Angra 2

Do ponto de vista de energia da radiação, a hipótese é que estamos medindo os nêutrons gerados pelo decaimento do Urânio e Plutônio no EC.

Medida obtida no detector central



Simulação Computacional de nêutrons



Upgrades

Possible upgrades:

- Segmented scintillators on top and bottom of the tank
  - Better background rejection (PID)
  - Another calibration tool (muon tracks)

- Enhanced calibration methods
  - More sophisticated simulation models
  - Portable calibration sources (in compliance with safety regulations)
  - In-situ calibration techniques:
    - remote-controlled LEDs with different wavelengths → enhancements in the accuracy of the energy scale calibration.

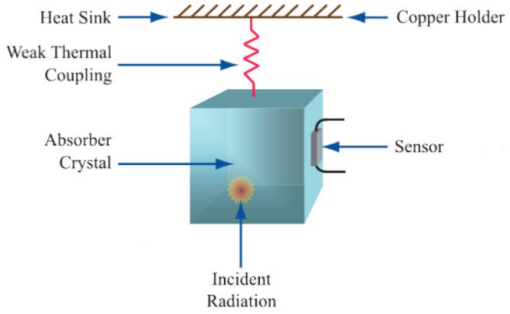
- Improved DAQ: hardware trigger based on AI (FPGAs)
  - Trigger does not depend on fixed thresholds (more efficient data handling)

- Water replacement with WBLS
  - better energy resolution → possible fuel content evolution measurements

ν-Angra 2.0: The cryogenic detector

Low-temperature Calorimeters

- Low-temperature detectors operated at mK temperature is a proven technology for rare event searches.
- Principle of operation:
  - When a particle interacts with a crystal at mK temperature, the majority of the energy deposition goes through the phonon production channel (thermal, acoustic, ballistic)
- By operating at 15 mK, the thermal noise is reduced significantly.
- High precision and efficient detectors



  - Release energy converted into increase of temperature: $\Delta T \propto \Delta E / C$
  - Low detector working temperature: $C \propto T^3$

At 15mK a particle of keV produces an increase of temperature of ueV!

(Much..) More details on such detectors:

2. First observation of reactor antineutrinos by coherent scattering with CONUS+

Edgar Sanchez Garcia (MPIK)

08/04/2025 14:00

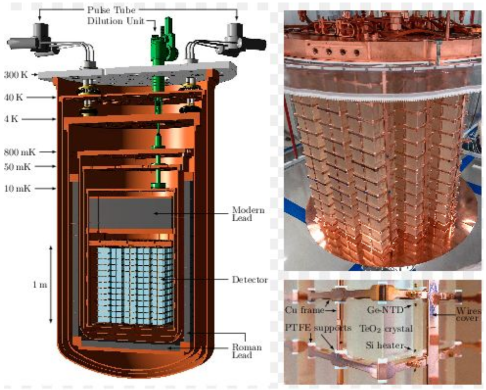
Experiments/Methods/...

Low-temperature Calorimeters

Main experiments with calorimeters for neutrinos and dark matter physics:

- neutrinoless double beta decay: CUORE/CUPID
- dark matter: CRESST, superCDMS, Tesseract
- CEvNS: RICOCHET, NU-CLEUS, CONUS+

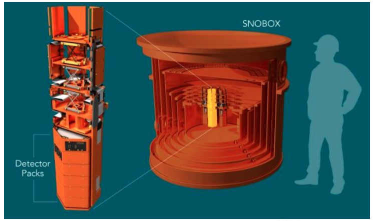
CUORE



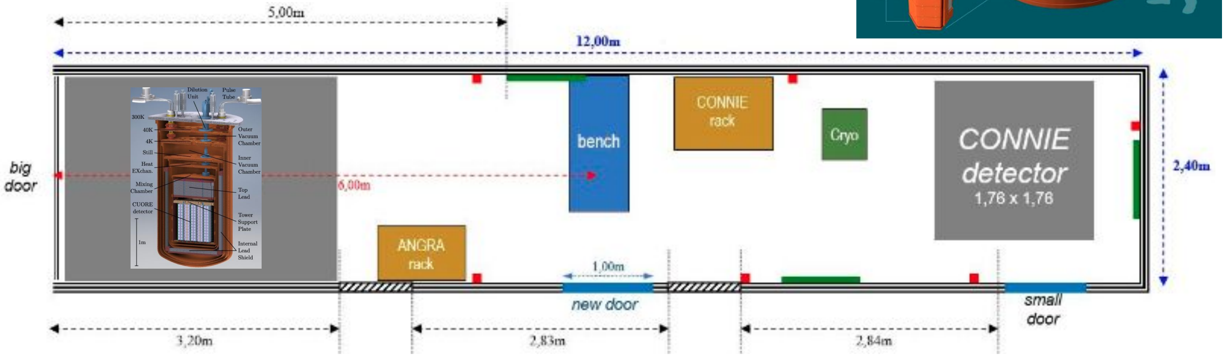
Current typical dimensions

- In order to have a 100 kg detector, you just need a small cryostat:
  - The cryostat, electronics etc can be put inside a room of 5x5x3 m^3

SuperCDMS



Challenging but feasible:
Fit the detector inside
the container lab



Low-temperature Calorimeters

v-ANGRA 2.0 : Cherenkov → CEvNS

- Different technique from CONNIE: explore complementarity

- To measure CEvNS you need sensors with high resolution in the biggest crystal possible
  - Transition Edge Sensors have already been proved to have threshold of a few eV
  - Kinect Inductance Sensors could in principle achieve similar sensitive

Most common

Our primary choice: Possible threshold reduction

Quantum sensors

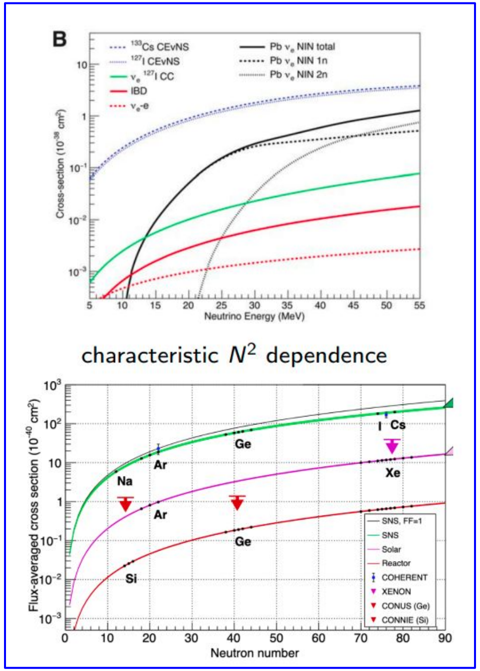
Low-temperature Calorimeters

ν-ANGRA 2.0 : Cherenkov → CEνNS

- Antineutrino Applied Physics:
  we should keep looking at the reactor activity,

  AND

- Fundamental physics:
  CEνNS phenomenology and characterization
  - X-section depends on TARGET MATERIAL
  - Calorimetry with different crystals in the detector



Conclusions

Final Remarks

- The Neutrinos Angra Experiment was totally made by Brazilian scientists and engineers.
  - We have designed, prototyped, built, tested, and commissioned the detector, the FE electronics, and the DAQ boards (BR
  - The entire R&D was carried out in Brazilian labs, also in cooperation with local commercial partners, demonstrating the feasibility of conducting neutrino science research with autonomy.

- We have results showing that the data has been taken with high quality,
  - We demonstrated the ability of the detector to count antineutrino events in correlation with the reactor operation.
  - The future physics program might include measurements of the fractions of nuclear isotopes in the nuclear fuel.

Final Remarks

- Different technologies can be explored in a second run.
  - water based liquid scintillator (WBLS).

→ total compliance with the safety rules + enhanced energy resolution

→ additional physics topics ?

- Towards new technologies
  - Cryogenic calorimeters

- New technologies require knowledge and expertise of local research groups
  - Partnership with USP - Prof. Pedro Guillaumon (Cuore collaboration member)

Take-away message

- The future of the scientific facility (the neutrino lab) at the Angra dos Reis power plant is very promising.

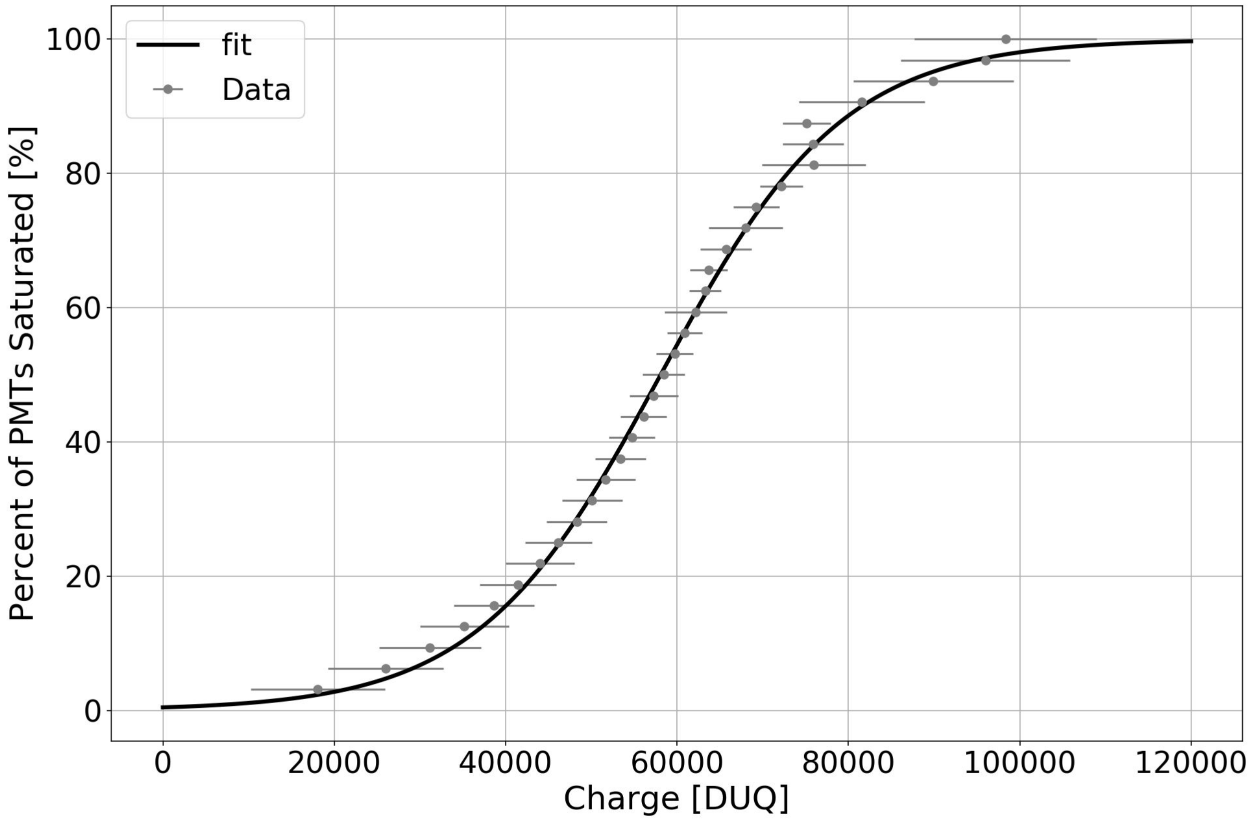
- The two collaborations running neutrinos experiments, ν-Angra and CONNIE, have successfully demonstrated the feasibility to conduct high-level and rather complex experiments in cooperation with the power plant operator.

We DO hope that
the neutrino lab in Angra dos Reis can establish itself as an international facility, open to research groups worldwide and contributing to the global neutrino program.

Thanks!

Backup

Saturation vs Charge



Transporte do elemento combustível de Angra 2 (2024)

Evolução temporal do espectro de carga