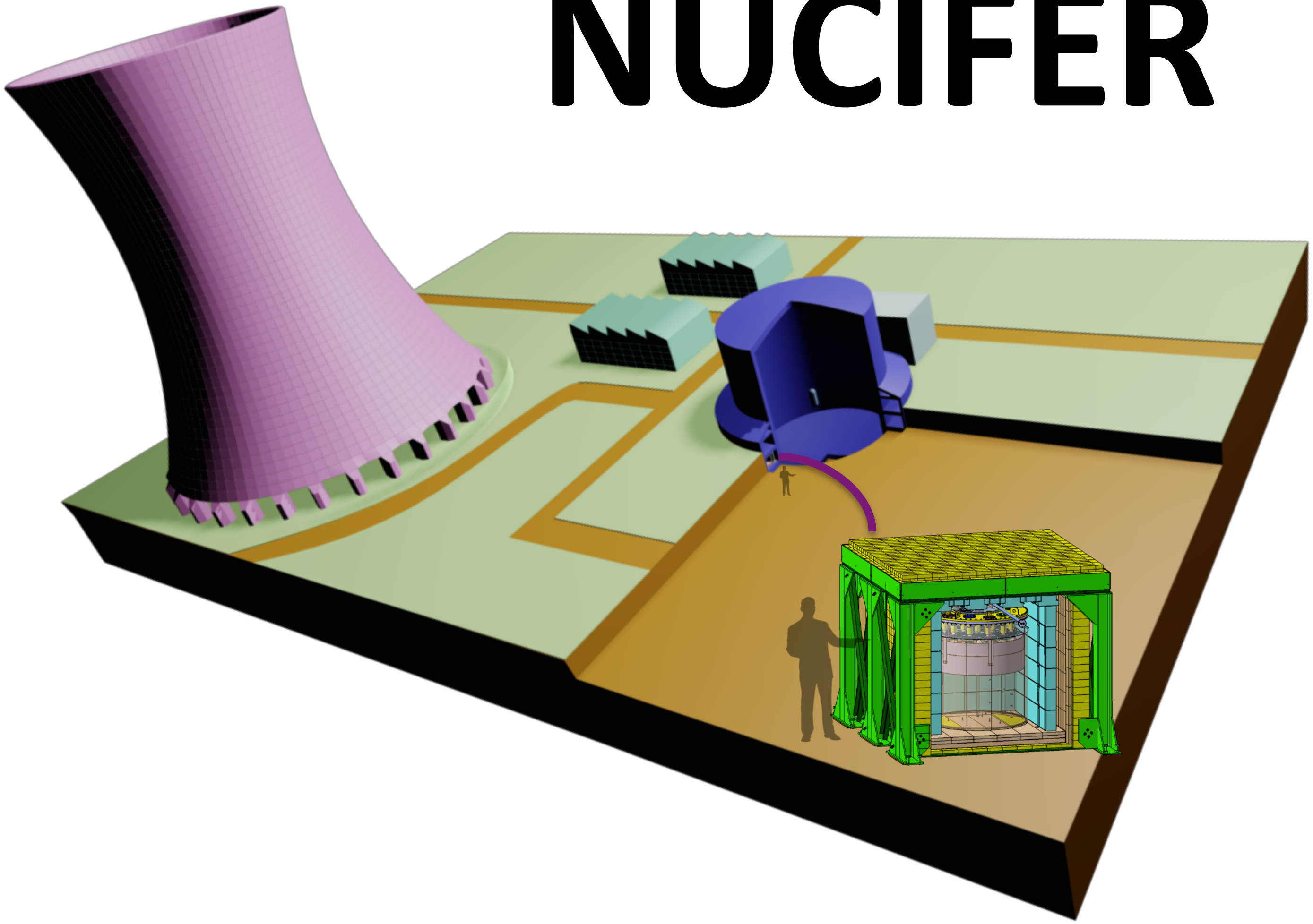
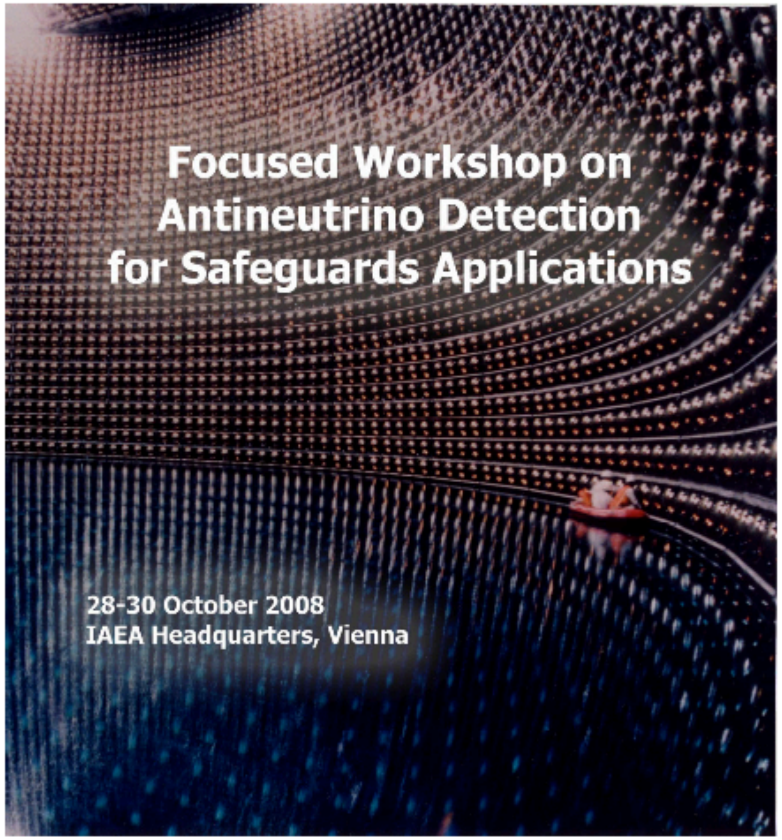
NUCIFER



Th. Lasserre, on behalf the Nucifer collaboration
CEA-Saclay ; IN2P3-Subatech

STR-361: Focused Workshop on Antineutrino Detection for Safeguards Applications, IAEA, Vienna, Austria, February 2009



Recommendation 1
Because antineutrino detectors uniquely offer the prospect of monitoring bulk process reactor systems that can't be handled by current item accountancy SG regimes, we recommend that the IAEA to consider this approach in the current R&D program for safeguarding bulk-process reactors.

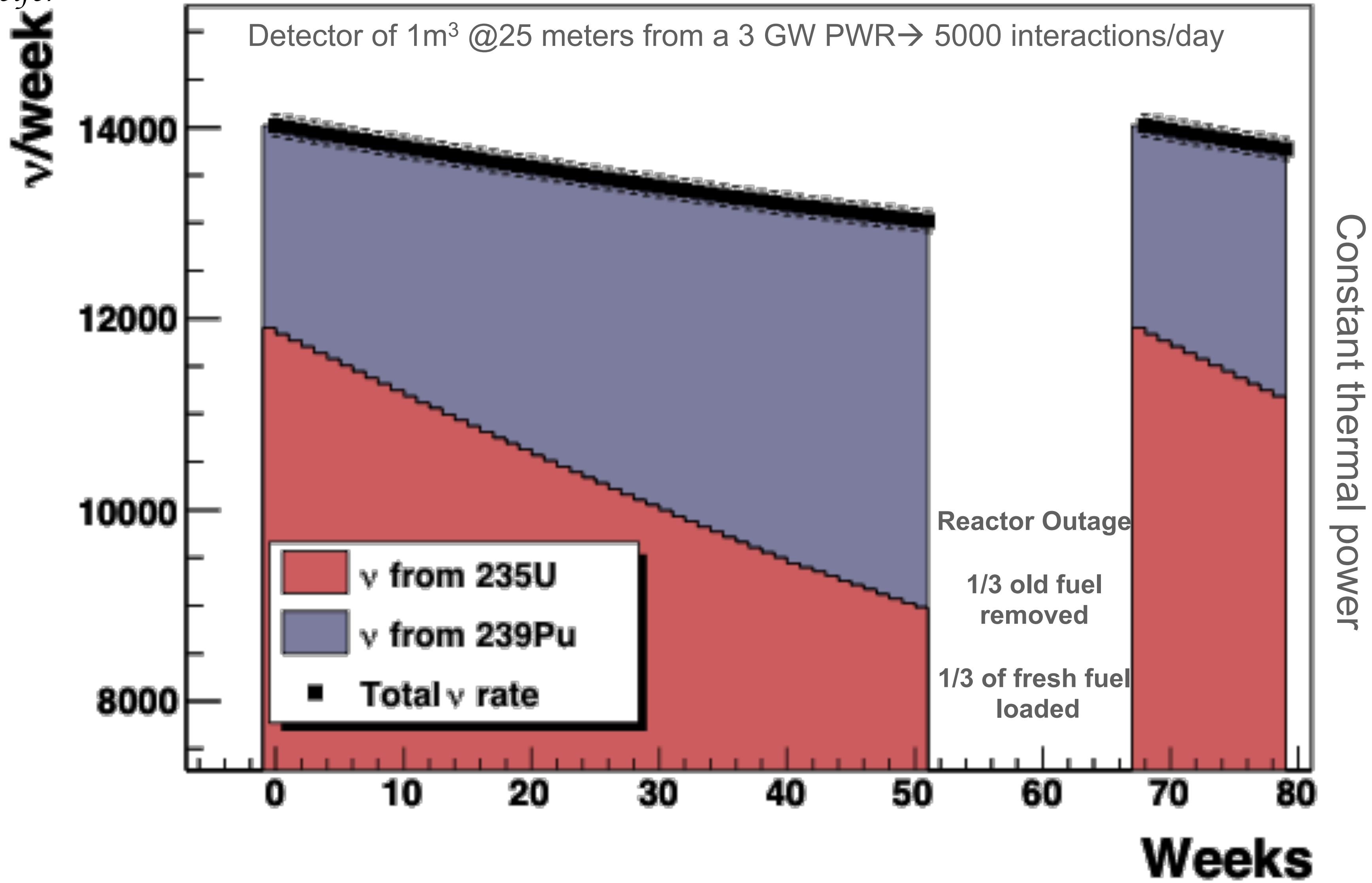
Recommendation 2
The IAEA should also consider antineutrino monitoring in Safeguards by Design approaches for power and fissile inventory monitoring of new and next generation reactors.

Recommendation 3
Working through the member state support programs, there should be further interaction between IAEA and the research community, including regular participation of IAEA safeguards departmental staff into international meetings such as the AAP.

Recommendation 4
The Expert group invites the IAEA safeguards departmental staff to visit our currently deployed and planned neutrino detection installations for SG. Such visits will provide insight to the IAEA on the practical aspects of deployment, and will give the community much needed feedback on safeguards relevance and future directions.

Recommendation 5
We recommend that IAEA work with experts to consider future reactor designs using simulation codes for reactor evolution and detector response that already exist.

Neutrinos & nuclear non-proliferation



Nucifer & IAEA specifications

- **IAEA Detector Design Guidelines:**
  - "Small" → 3 m x 3 m x 2,5 m maximum
  - Do not induce additional safety risk to the power plant
  - Remote & Easy Operation by Inspectors not trained as neutrino physicists
  - Reliable for remote operations
  - Not portable but 'Movable' to a certain extent

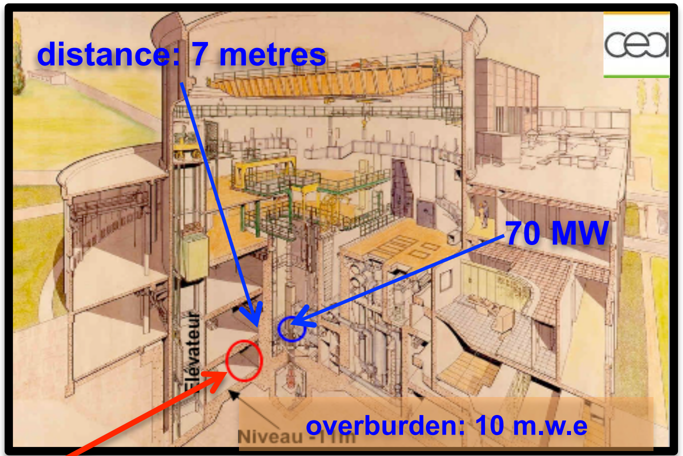
- **Main Challenges of Nucifer for integration into safeguard regime:**
  - Effort to simplify the state-of-the-art design and run close to surface while keeping detector performances

    Attempt: **50% detection efficiency** (5 times improvement w/r SANDS)
  - Proceed to the 'industrialization' of neutrino science

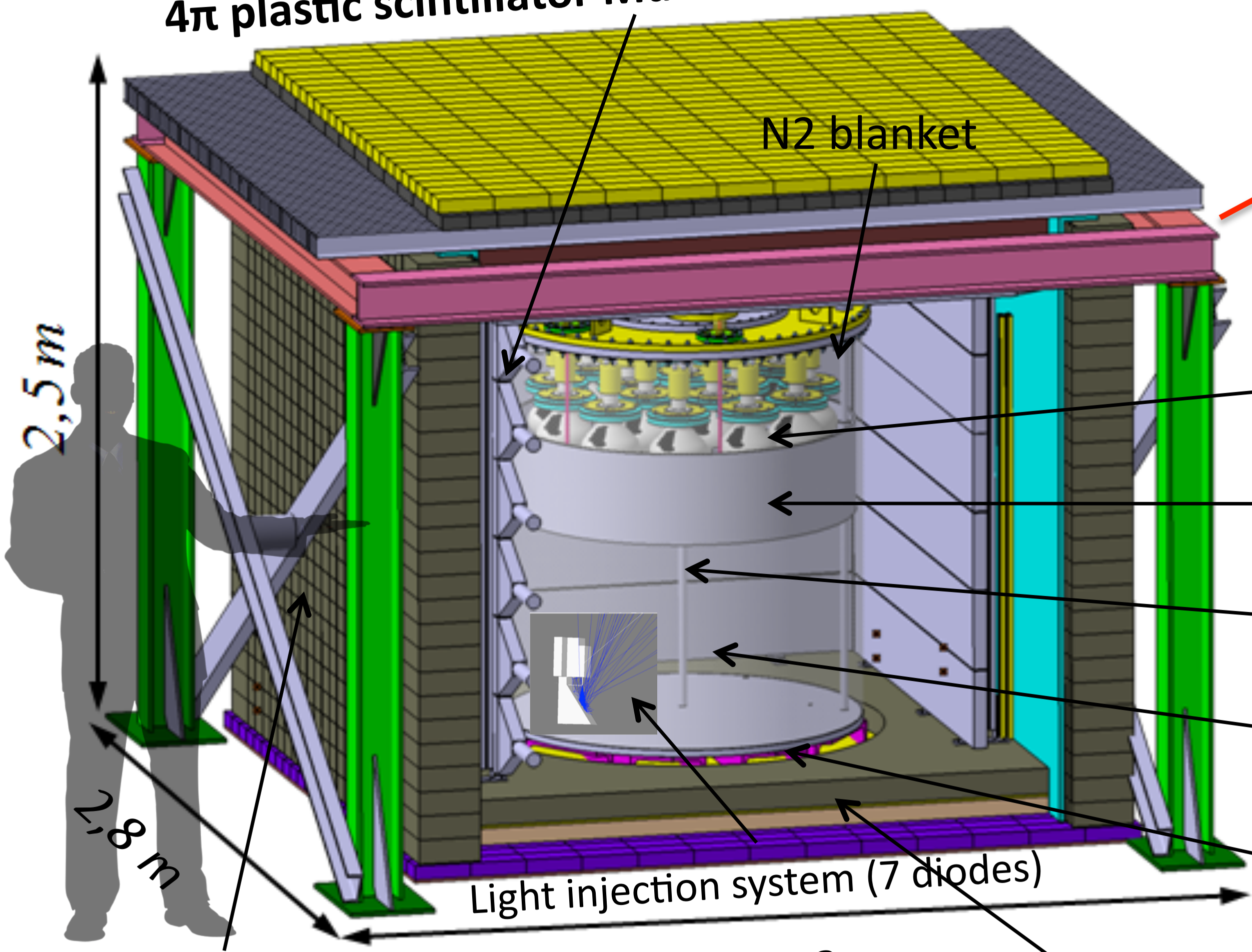
    Using the state-of-the art known technology (Double Chooz synergy)

Nucifer Overview

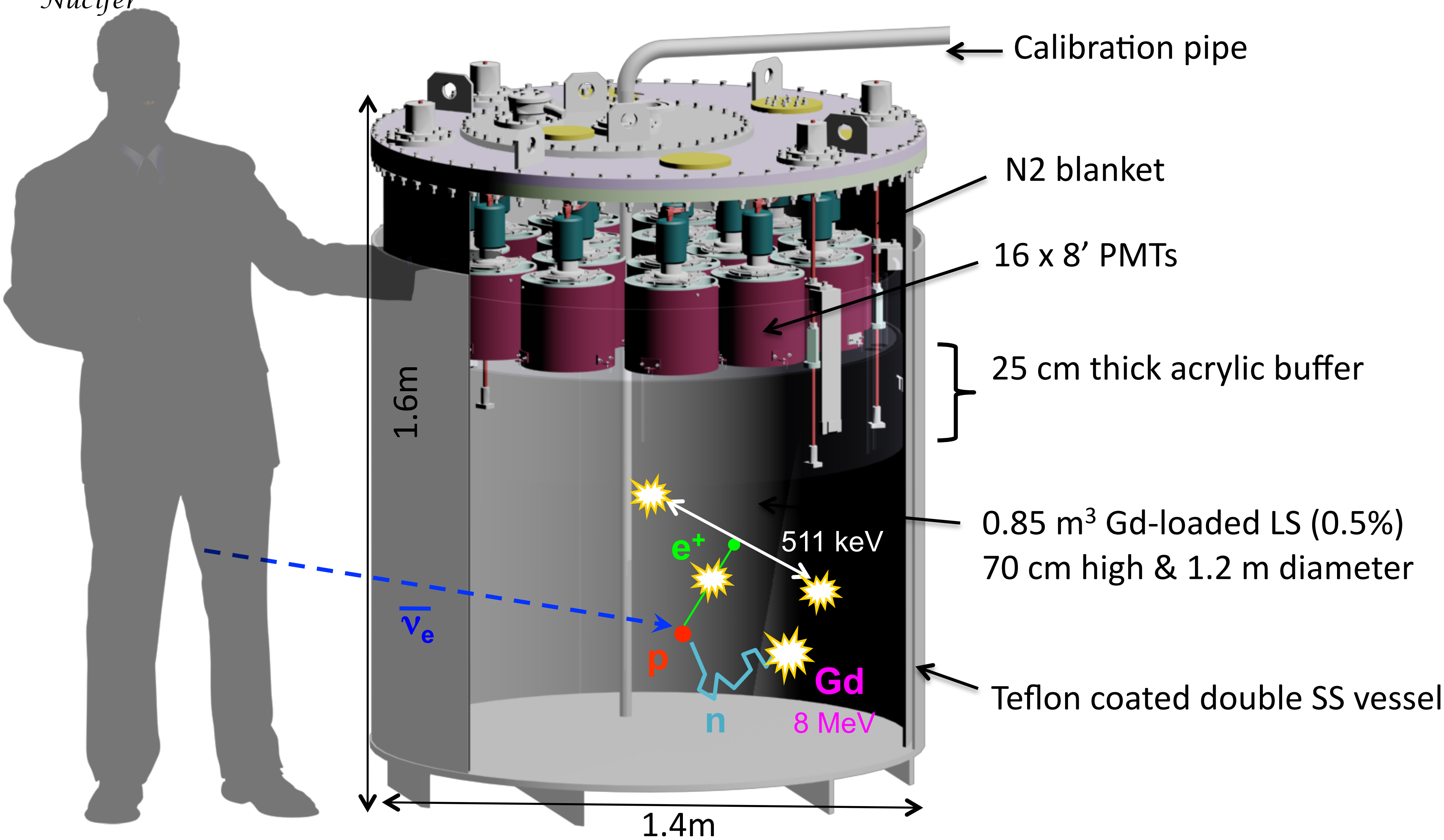
Thermal Power Measurement
Fuel Composition Measurement U/Pu



Osiris research reactor
CEA-Saclay (1000 ν/d)

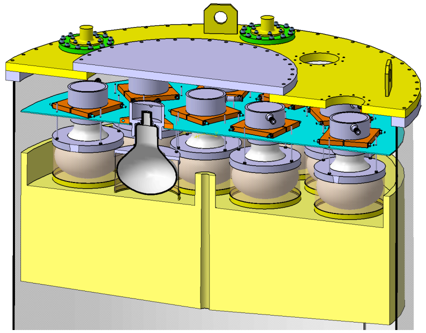


Nucifer Detector Module



Nucifer

Photodetection system



Integration in an ISO 7 clean room

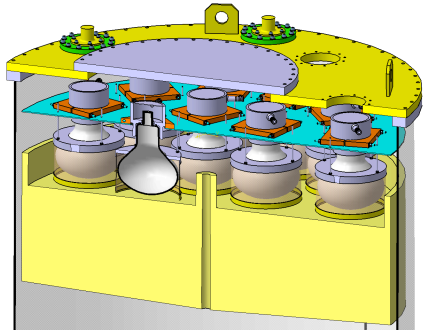
Central pipe hole for calibration

8” PMTs & magnetic shield (mu-metal)

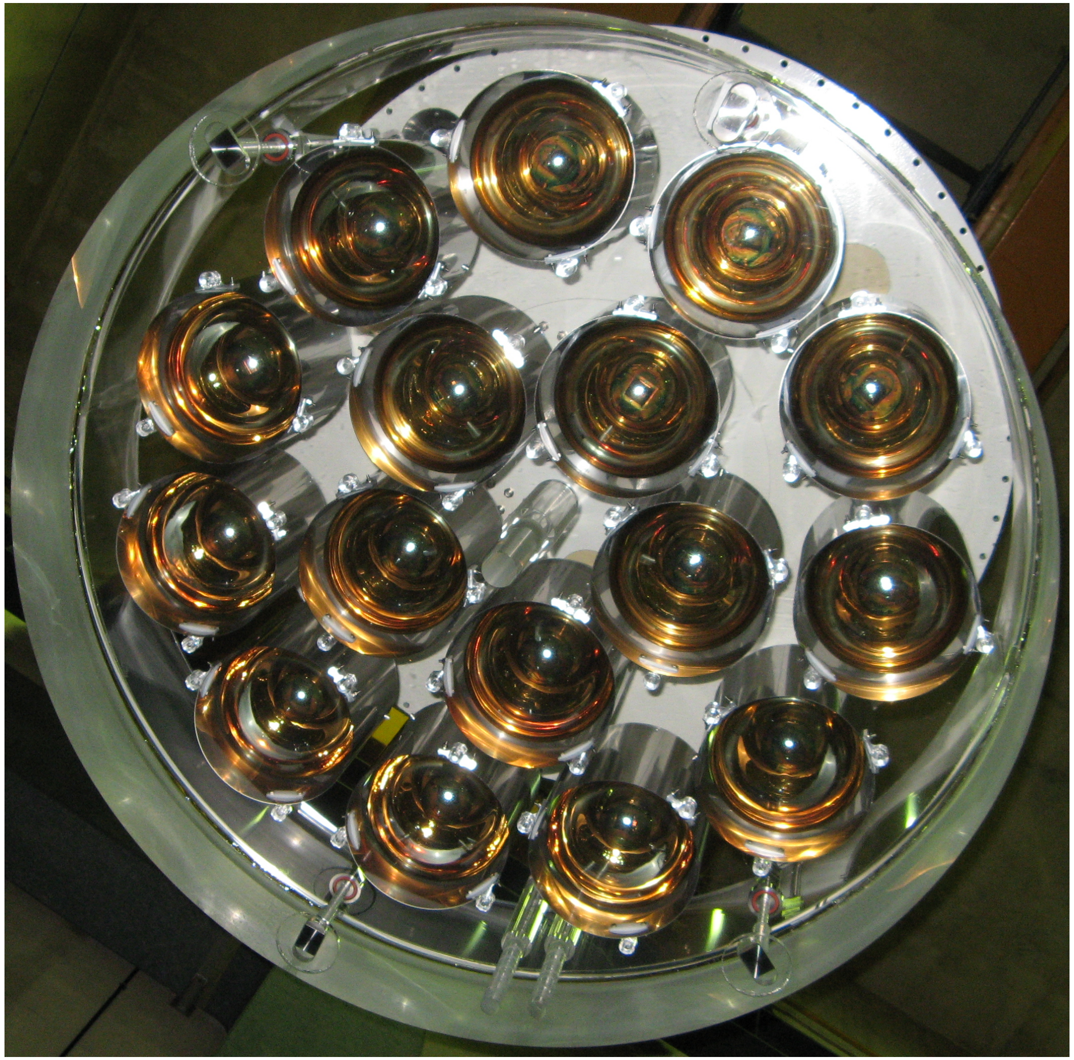
80l mineral oil pool (optical coupling & shielding)

250 mm thick acrylics vessel (radiopure, clean, highly transparent, non fluorescent)

Photodetection system

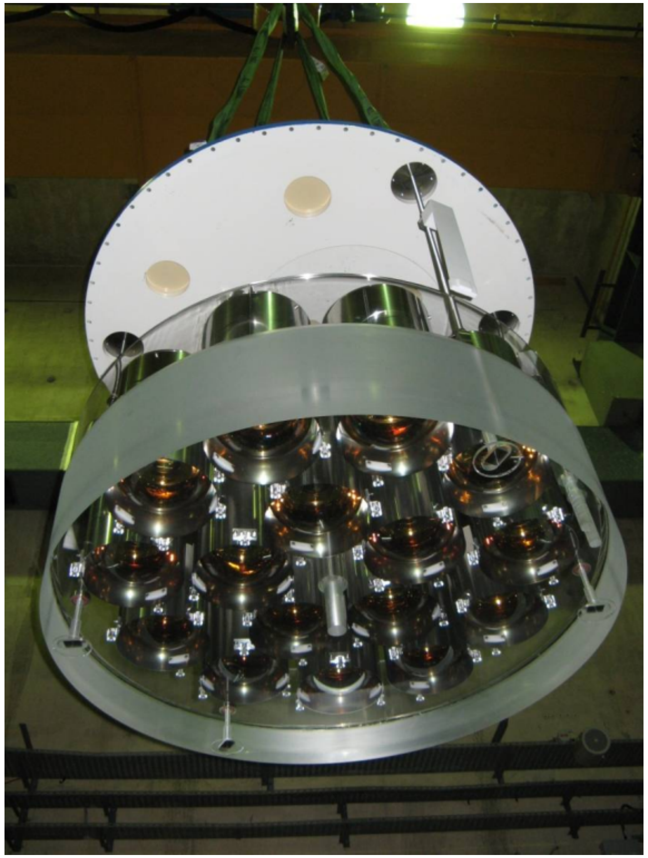


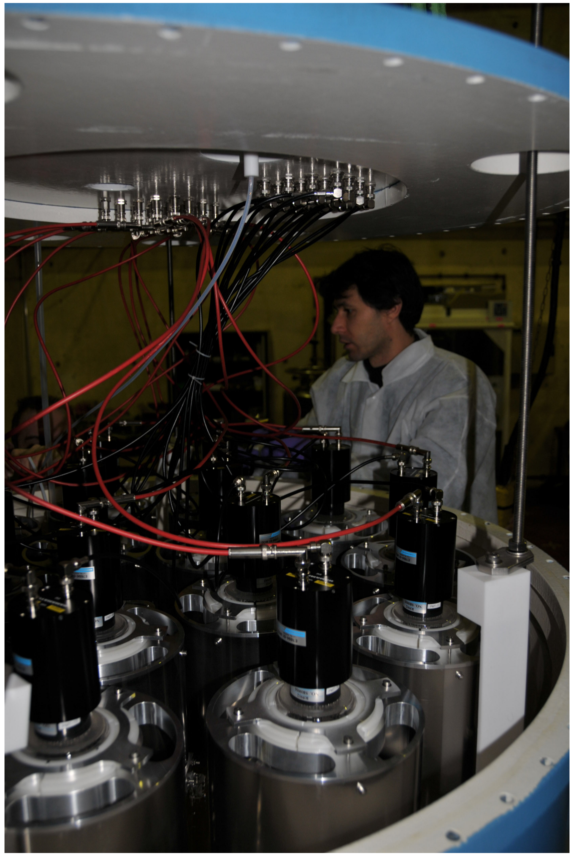
Bottom view



Test assembly in Saclay (2010)

Rehabilitated underground lab from dismantled accelerator.
Prototype vessel and non Gd-loaded LAB based scintillator for test.





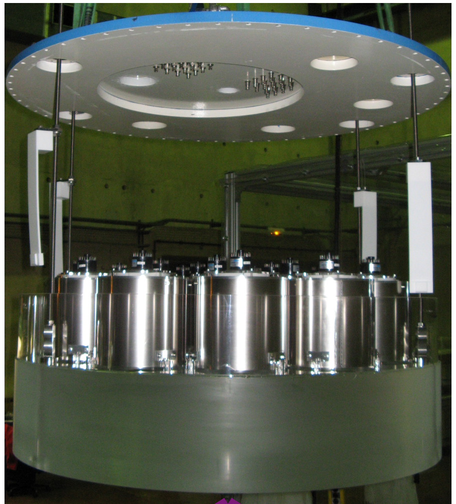
Target vessels

Nucifer

Concept: photodetection system hanged on the detector top lid

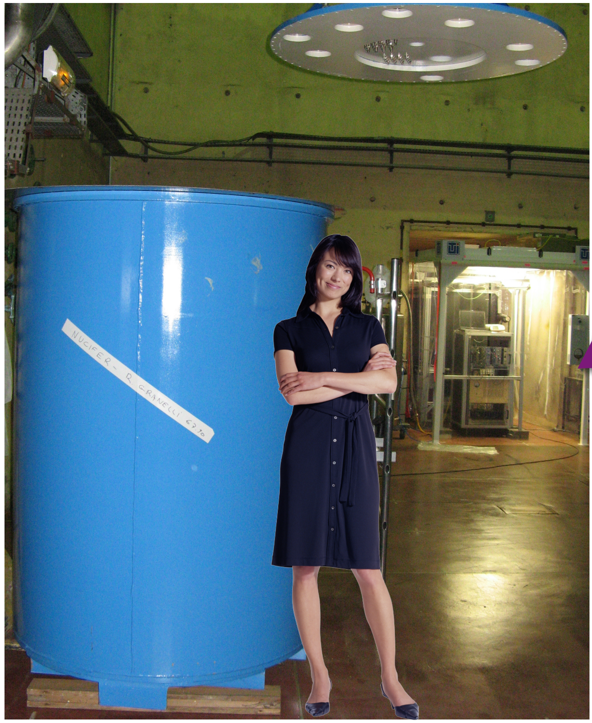
→ Prototype vessel

-Double Chooz mockup re-used
-1 cm thick steep
-No radiopurity constraints
-Reflective Paint inside



→Final Vessel

-New stainless steel vessel
-Double containment vessel with active leak detection
-Radiopurity screening (welds)
-Material compatibility: Teflon coating



lid & photo-detection system fit both vessels.

Detector is tight and kept under nitrogen atmosphere (10 mbar overpressure)

Target Scintillator

Specfications:

- Gd content = 0.5 ±0.05 % (mass)
- Material compatibility → Always kept under nitrogen atmosphere
- Light output > 40% of Anthracene (Pulse shape discrimination capability)
- Max. emission: 400<λ<500 nm
- Attenuation length>4 m
- Refractive Index = 1.49 ± 0.2
- Stability in time > 1 year

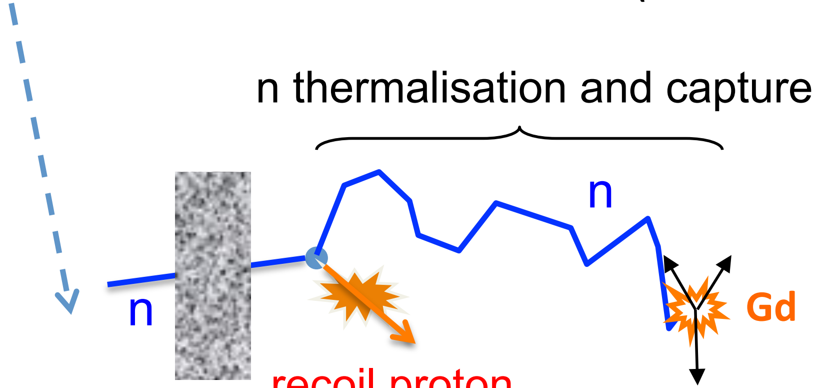
→ Our choice:

Eljen EJ335
0.5% Gd
1000l delivered in Salcay

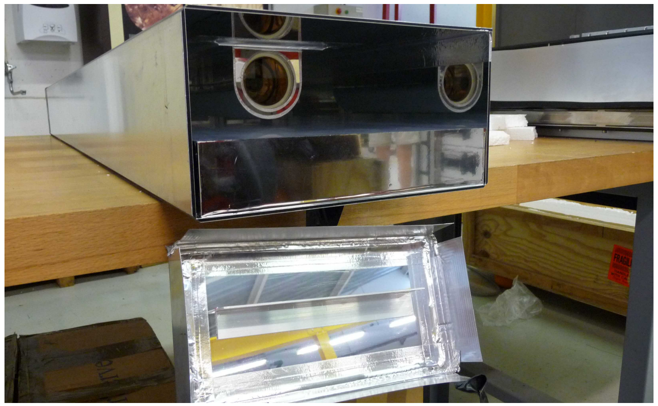
PROPERTIES	EJ-331	EJ-335
Gadolinium content:	0.5% w/w	0.25% w/w
Specific Gravity:	0.90	0.89
Light Output (% of Anthracene)	68%	55%
Wavelength of Maximum Emission	424 nm	424 nm
Bulk Light Attenuation Length:	>4 meters	>4.5 meters
Refractive Index	1.50	1.49
Flash Point	44°C (111°F)	64°C (147°F)
ATOMIC COMPOSITION		
No. of H Atoms per cm^3	5.27×10^{22}	6.16×10^{22}
No. of C Atoms per cm^3	4.00×10^{22}	3.93×10^{22}
H:C. Ratio	1.32	1.57
No. of Electrons per cm^3	29.8×10^{22}	30.6×10^{22}

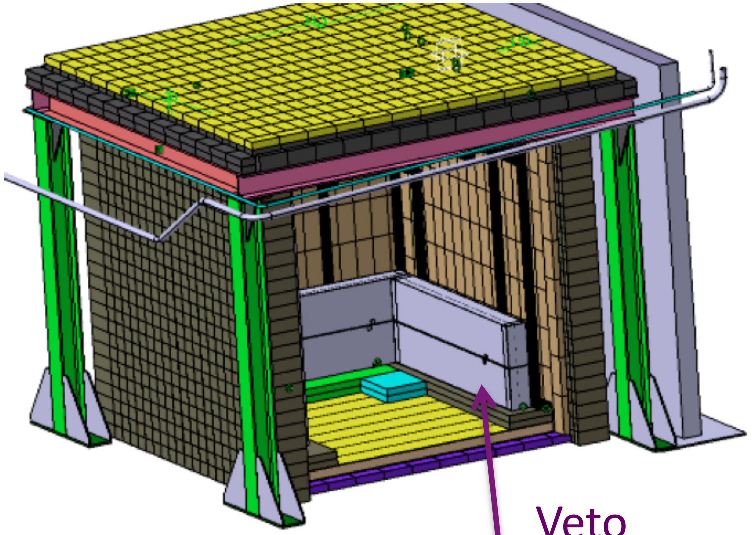
Muon Veto

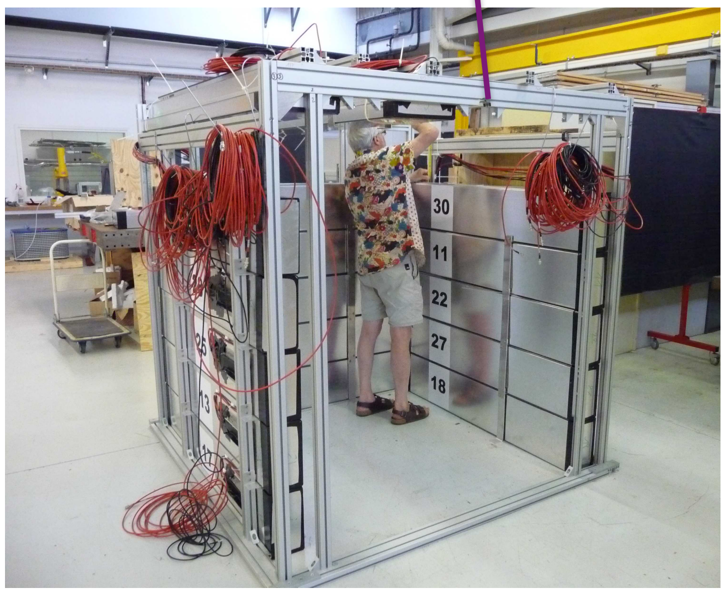
- Interaction of cosmic rays with surrounding material induce fast neutrons (dominant bkg)



- 30 boxes made of a 4 cm thick plastic scintillator + reflective coating + PMT



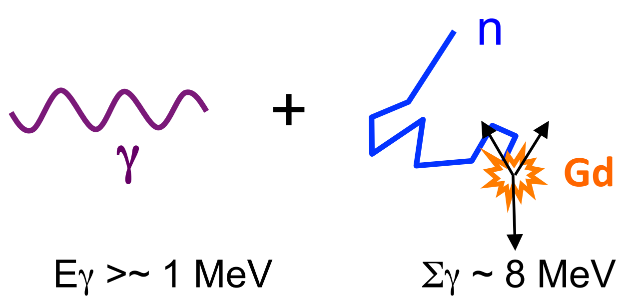




Aluminium structure

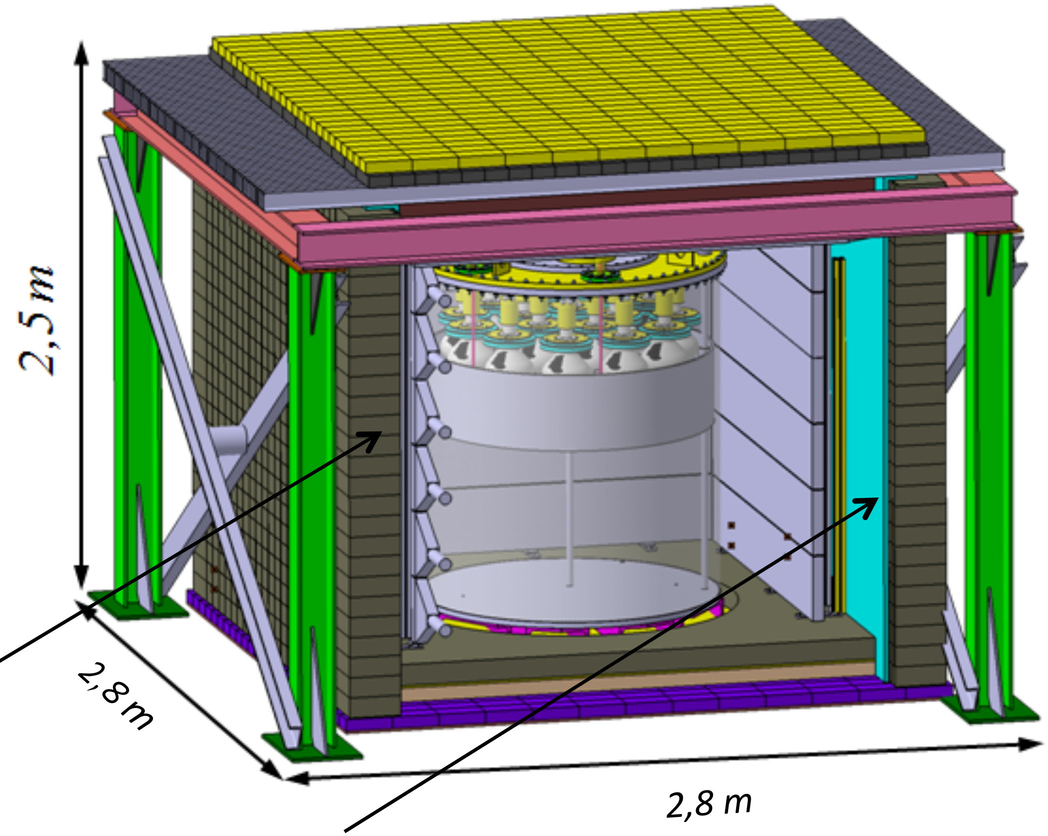
Passive Shielding
optimized for the Osiris/ILL run

Neutrino signal can be faked by an accidental γ-n coincidence:



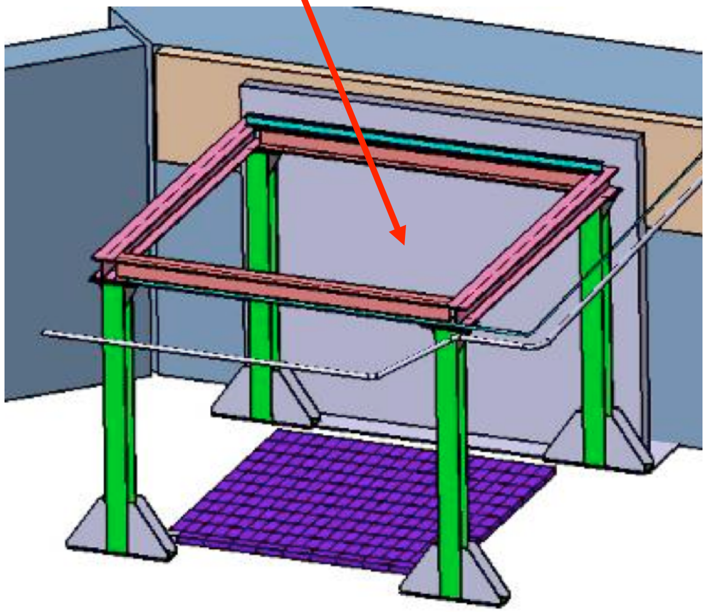
A mechanical structure supports shielding all around the detector:

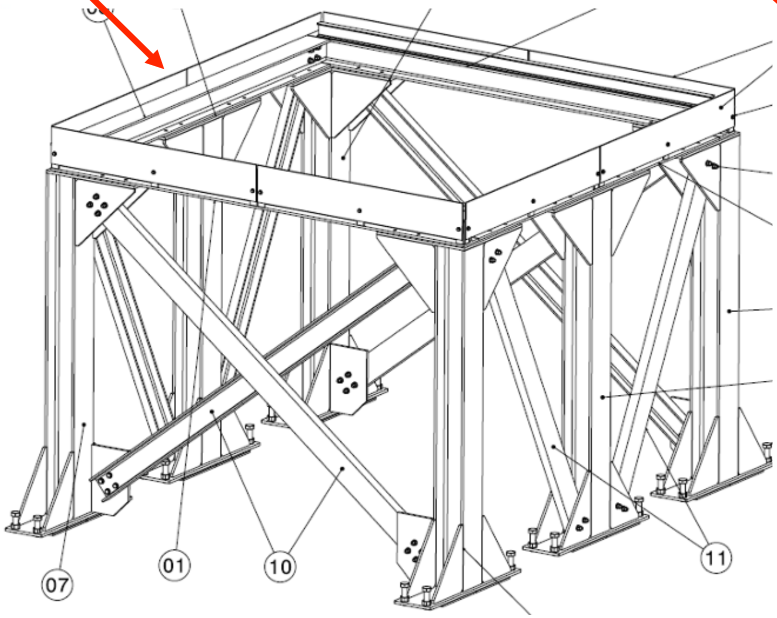
- 10 cm of lead to stop γ
- 15 cm of polyethylene to stop low E neutrons

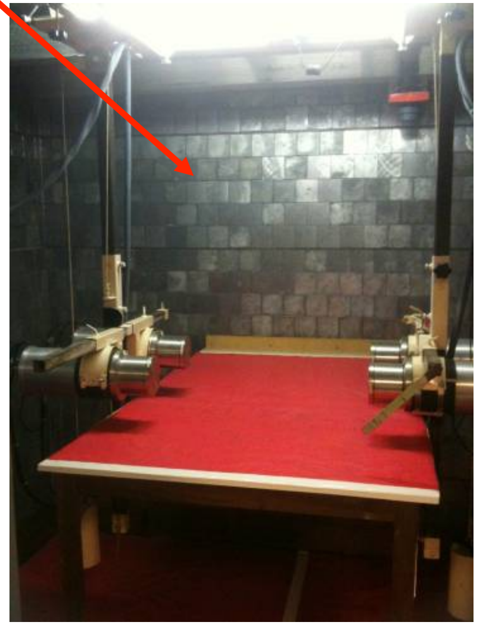


Gamma Shieldings

- 10 cm thick lead wall (earthquake's proofed)
- Lead & polyethylene supporting structure (earthquake's proofed)
- 4π 10 cm thick lead shielding – 3400 bricks –



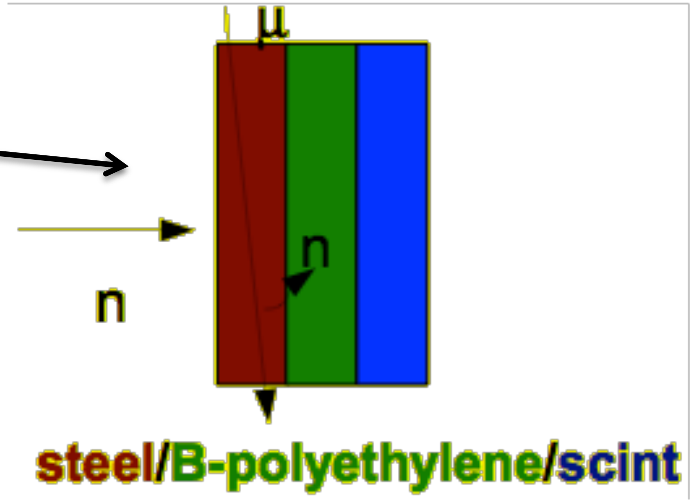




Neutron Shielding

4π Low-Z Shielding (Internal Layer)

- Thermal & fast neutrons shielding
- Best configuration @shallow depth
- 150 mm of Polyethylene
  20-60 mm boron doped (reducing the 2.2. MeV gamma line through
  $n_{th} + {}^{10}B \rightarrow {}^{7}Li + \alpha/\gamma$ (477 keV)
- Walls pre-assembled (C, H, T shapes)

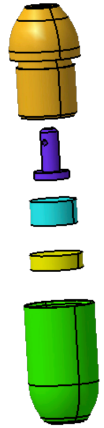


Calibration and Monitoring

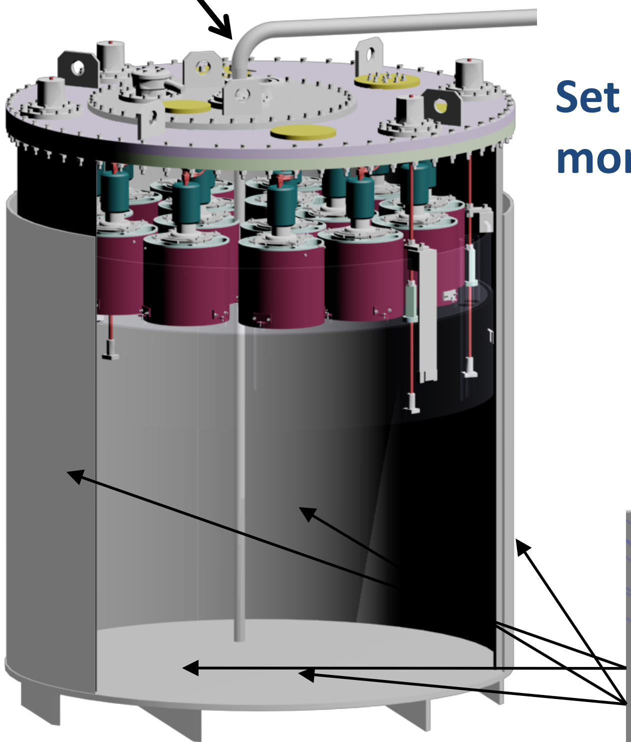
Calibration pipe allowing insertion of radioactive sources along axial axis:

- ^{137}Cs, ^{22}Na, ^{60}Co, Am-Be: response to γ rays in the 0 .7 - 4.4 MeV range
- Am-Be: neutrons tagged by 4 MeV γ
- set neutron energy cut in analysis and determine ε_{det}

source holder



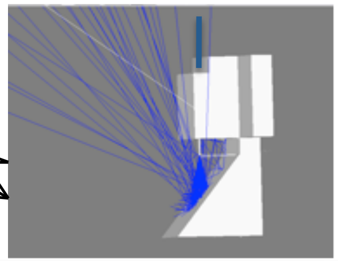
SS pipe



Set of 7 diodes injecting light inside the detector for independent monitoring of PMT gain and optical properties of the liquid:

- 2 diodes at the single photon level for monitoring G_{PMT}
- 5 larger intensity diodes for liquid stability and linearity
- Running continuously at low freq while data taking

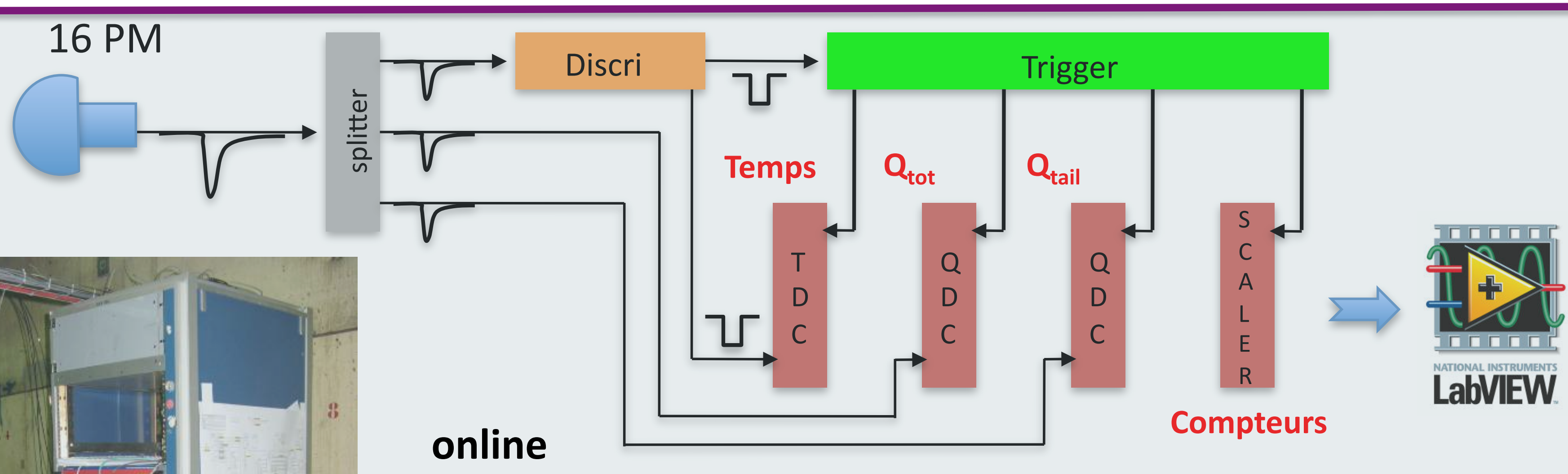
→ Allow for a clean background subtraction



Light injection system and diffuser

DAQ: data flow

4 types de triggers: physics, LEDs, random, Muon Veto



offline (but on site)

Binary → Data reduction & calibration → ROOT files

data & MC: same structure

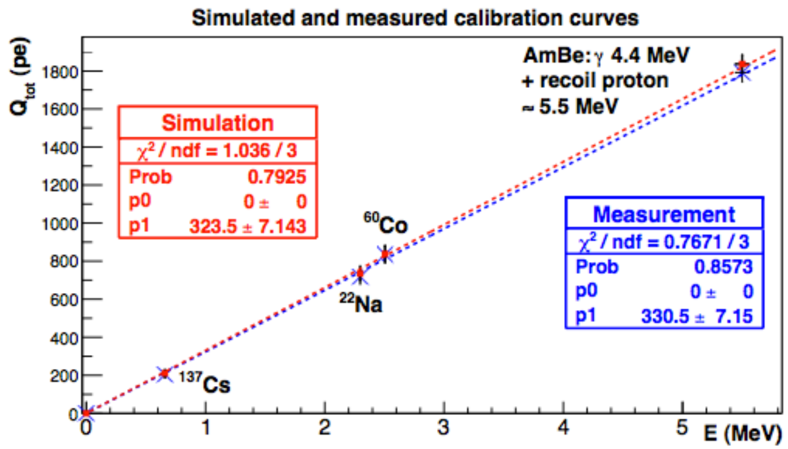
- Raw data
- Absolute time for each event
- Q/t calibration
- https://www. quality control.raa

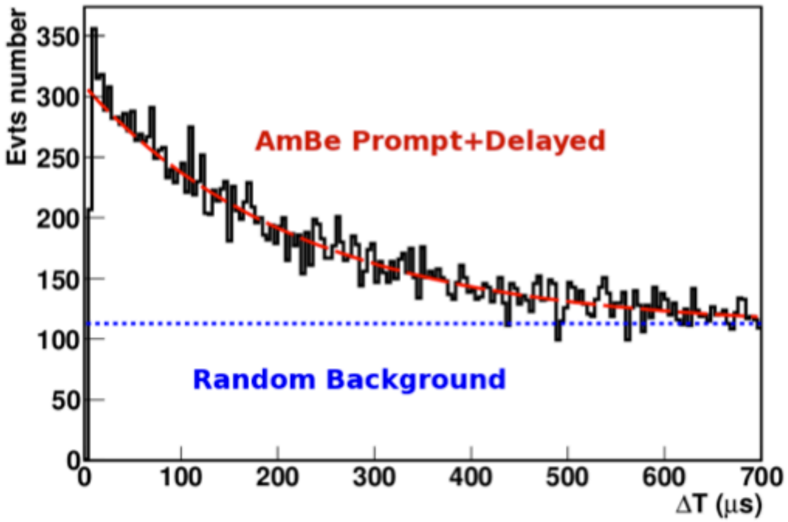
Utilisation de 4 sources radioactives : Porte source vue éclaté insérée dans le tube de calibration centrale.

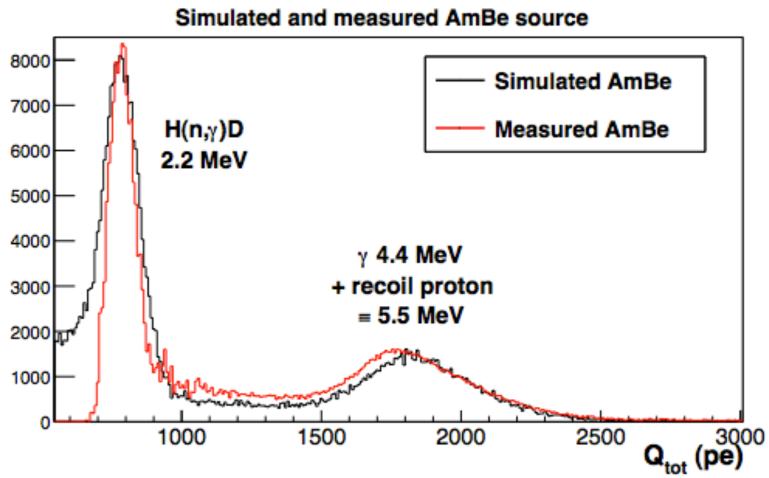
Prototype detector: linearity

(Test Run with DC mockup vessel)

- Calibration pipe → axial axis access
- γ range: 0.7 - 4.4 MeV
- tagged neutrons with AmBe → neutron energy cut for analysis and efficiency determination







Deployment Plan

- **Phase 1: OSIRIS – 2011/12**
  - Goal: Validation & full characterization of the Nucifer detector
  - Challenge: Experiment 7 m away from a nuclear core (utltra high backgrounds)
  - IAEA interest: Deployment very close to a core, inside a research reactor hall

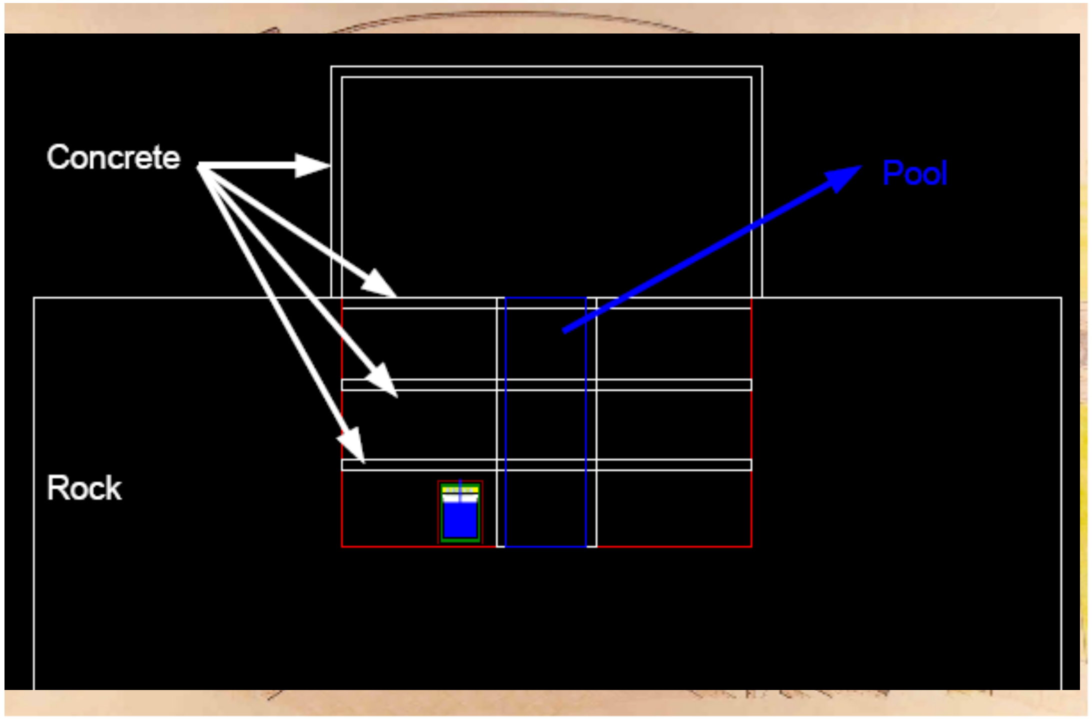
- **Phase 2: ILL -2012/13 ?**
  - Goal: Measurement of a pure ^{235}U fuel spectrum + Absolute detector calibration
  - Challenge: weaker nuclear power, farther location, high neutron background
  - IAEA interest: demonstration of our ability to change the detection site

- **Phase 3: Nuclear power station – 2013/14**
  - But : Precise measurement of thermal power and fuel evolution, in real conditions
  - Challenge: Find a site! IAIA 'political support' could be a breakthrough
  - IAEA interest: deployment at a private operator site.

Fundamental research interest: testing the Reactor Antineutrino Anomaly (especially to shape distortion close to Osiris/ILL compact cores)

Nucifer @ Saclay-Osiris

- **Site available at 7 m from the core**
  - Project supported by OSIRIS/DEN & CEA-Saclay
  - 15 mwe overburden
  - reactor induced γ rays implies
  - →**additional 10 cm lead shielding wall**



P.Durande-Ayme @ TRTR-IGORR joint meeting 2005

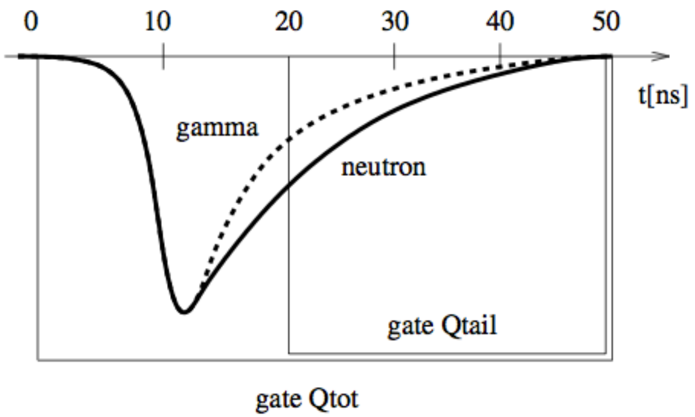
P_{th} (MW)	**70**
Fresh fuel	U_3Si_2Al plates
Enrichment (% of ^{235}U)	20
Fuel replacement	1/7th every 20d
Core dimensions (cm)	57 x 57 x 60
Distance from core center (m)	7
ν_e flux at det. center ($cm^{-2}.s^{-1}$)	2.3 10^{12}
ν_e int/day in Nucifer (0.856 m^3)	**1380**
muon flux attenuation	2.7

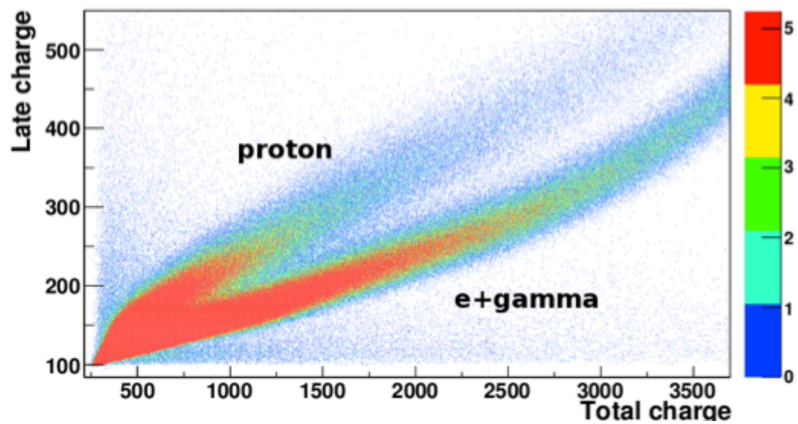
Nucifer@Osiris: Signal & Backgrounds

- **Signal:**
  - 850 liters of EJ335 LS. Challenge : 40% detection efficiency
  - Expected #events per day ≈ 730 × 70 MW × 0.85 m^3 × 0.4 eff. / $(1/7)^2$ = 700/day

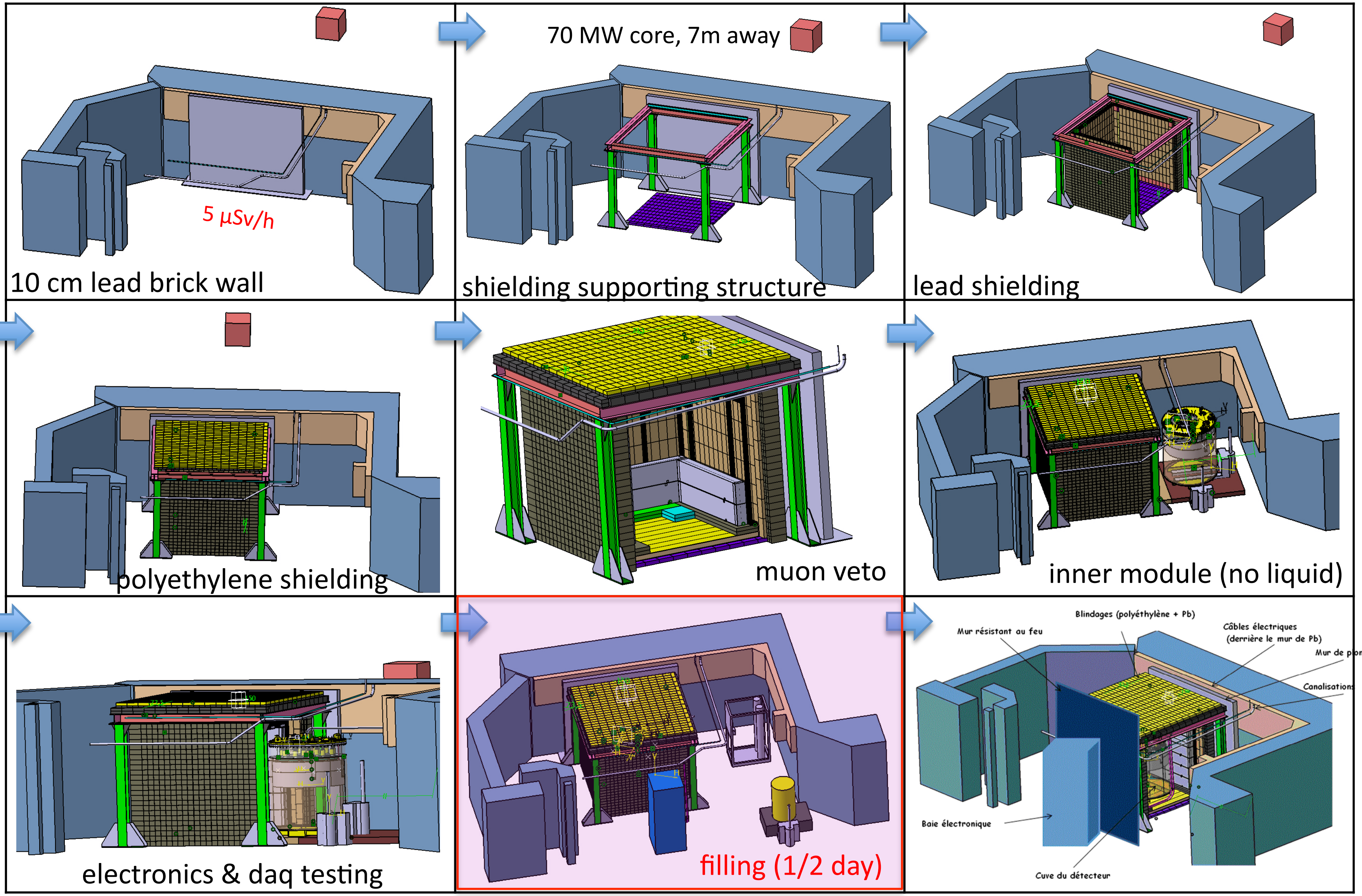
- **Accidental backgrounds**
  - Campaign of measurements → high gamma flux (MHz…)
    Also at high energy (> 3MeV) through neutron capture on reactor metallic structure
  - Expected signal to noise ratio : about 1 (add a 10 cm lead shield wall at Osiris)

- **Fast neutrons (overburden: 10 mwe only)**
  - Expected signal to noise ratio estimate : about 0.25 (before any PSD rejection)

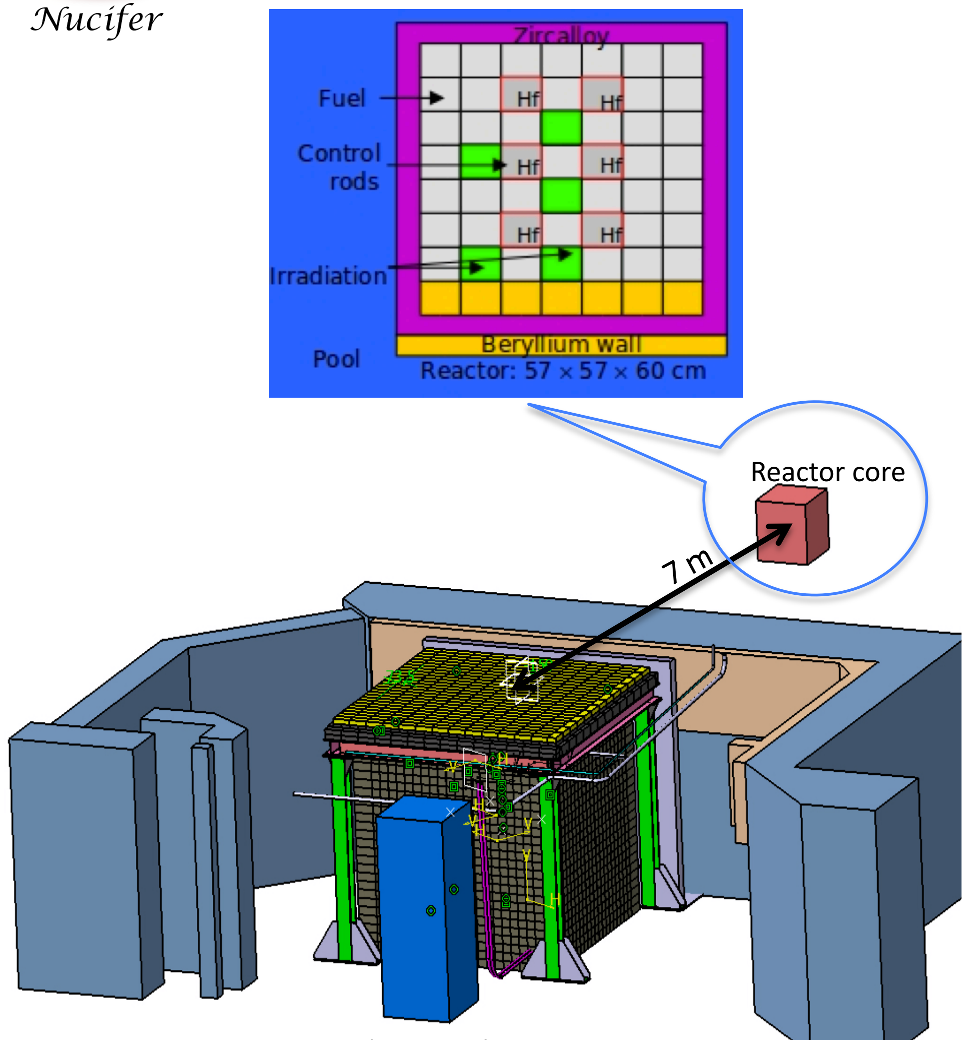




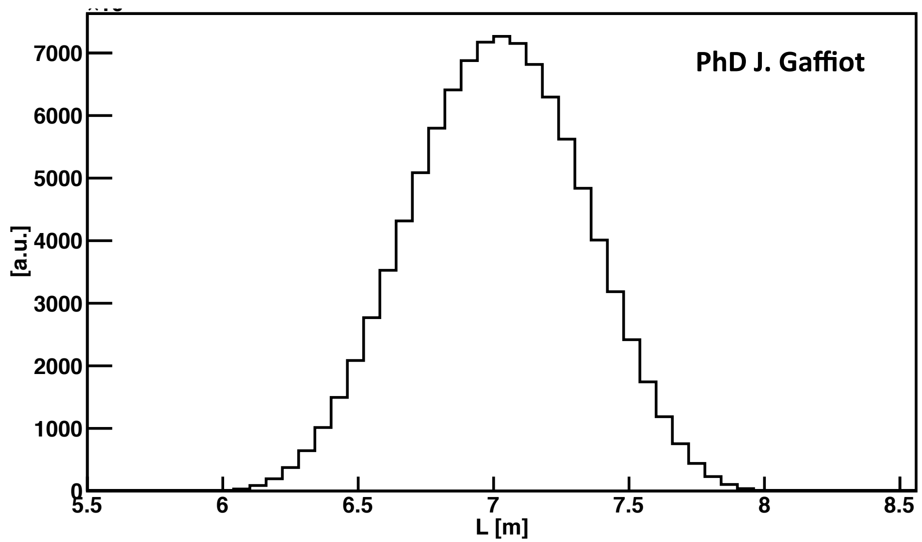
Nucifer @Osiris: Integration



The nuclear core compactness

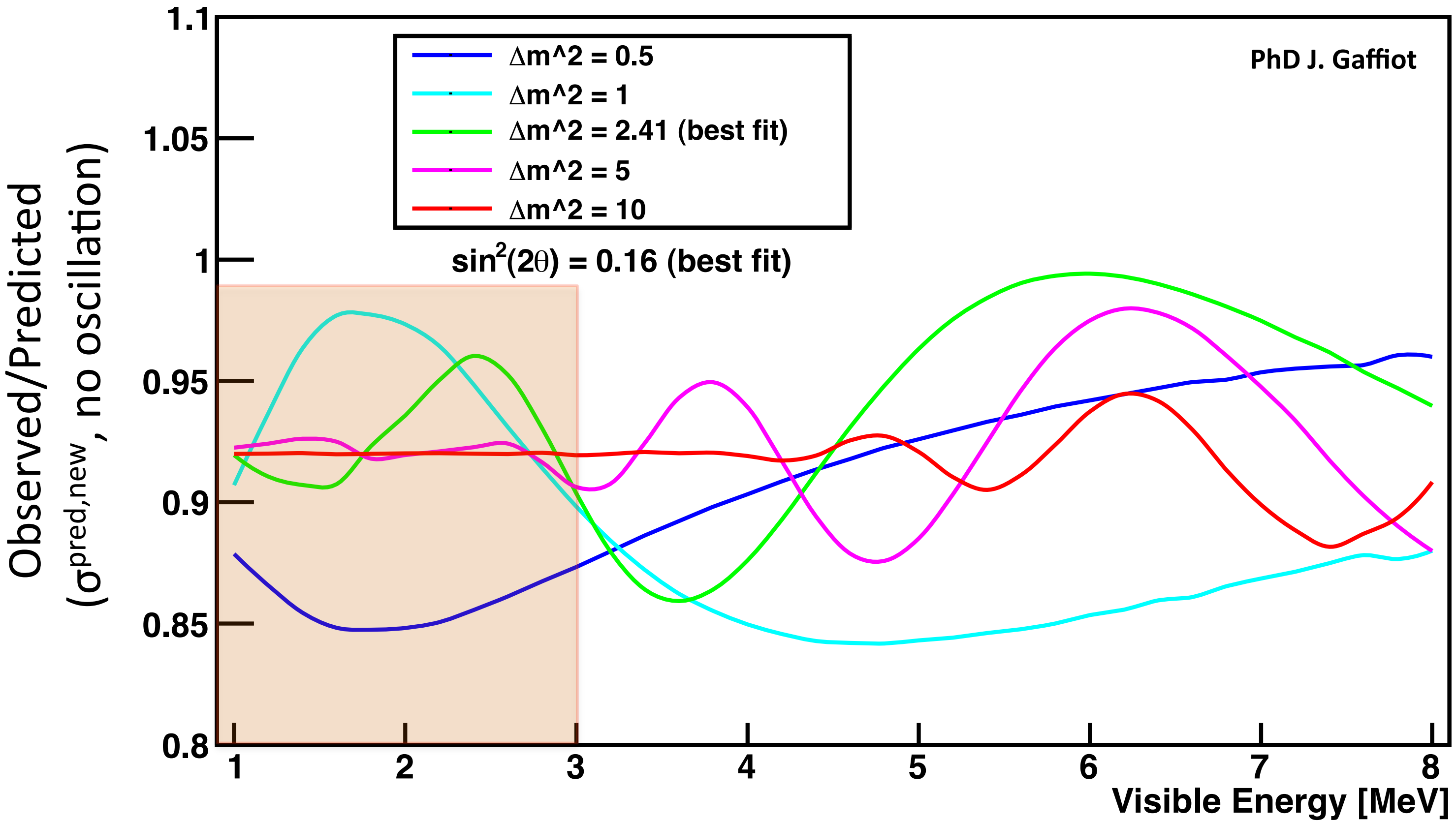


- **Core Size: 57x57x60 cm**
- **Detector Size : 1.2x0.7m (850l)**
- **baseline distribution**
  - <L>=7.0 m
  - variance : 0.3 m
  - oscillations are not wahsed out



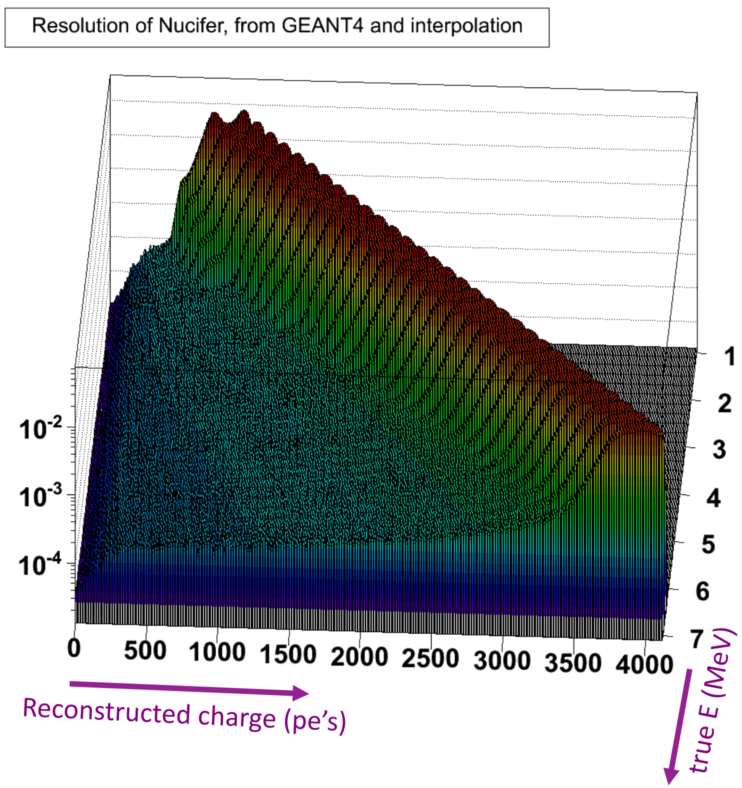
Nucifer hunt for sterile neutrinos

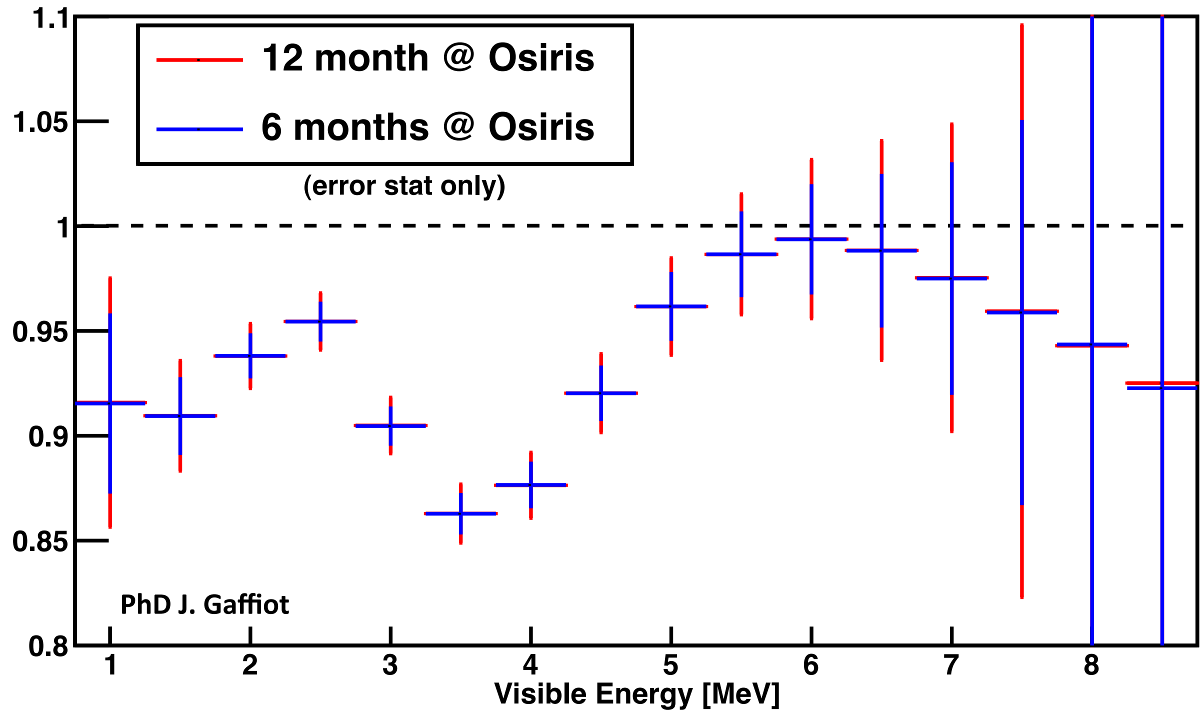
- **Testing the reactor antineutrino anomaly:**
  - Rate analysis → an additional results at very short distance, with a few % precision
  - Shape analysis → appealing test of the sterile neutrino hypothesis



Nucifer hunt for sterile neutrinos

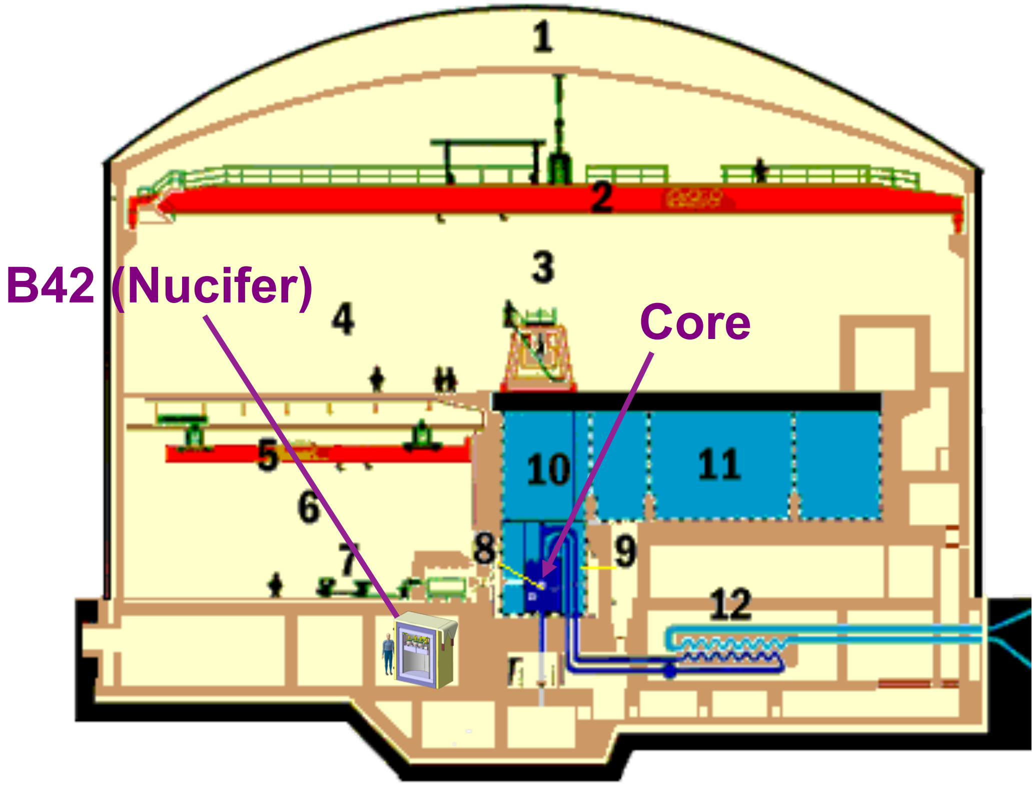
- Folding the Nucifer Geant 4 Monte Carlo detector response
  - Energy resolution from Geant4 simulation (not fully tuned yet)
  - Statistical errorfor 6 & 12 months of data at Osiris





Nucifer @ Grenoble-ILL

- **Site available at 9-11 m from the core** @ Room B42, old ILL exp.
  - First positive meeting with the directors in 2009
- **More favourable background** (20 times smaller γ flux than the one measured at Osiris. Neutron hot spot localized around aperture in the wall should be easy to shield.

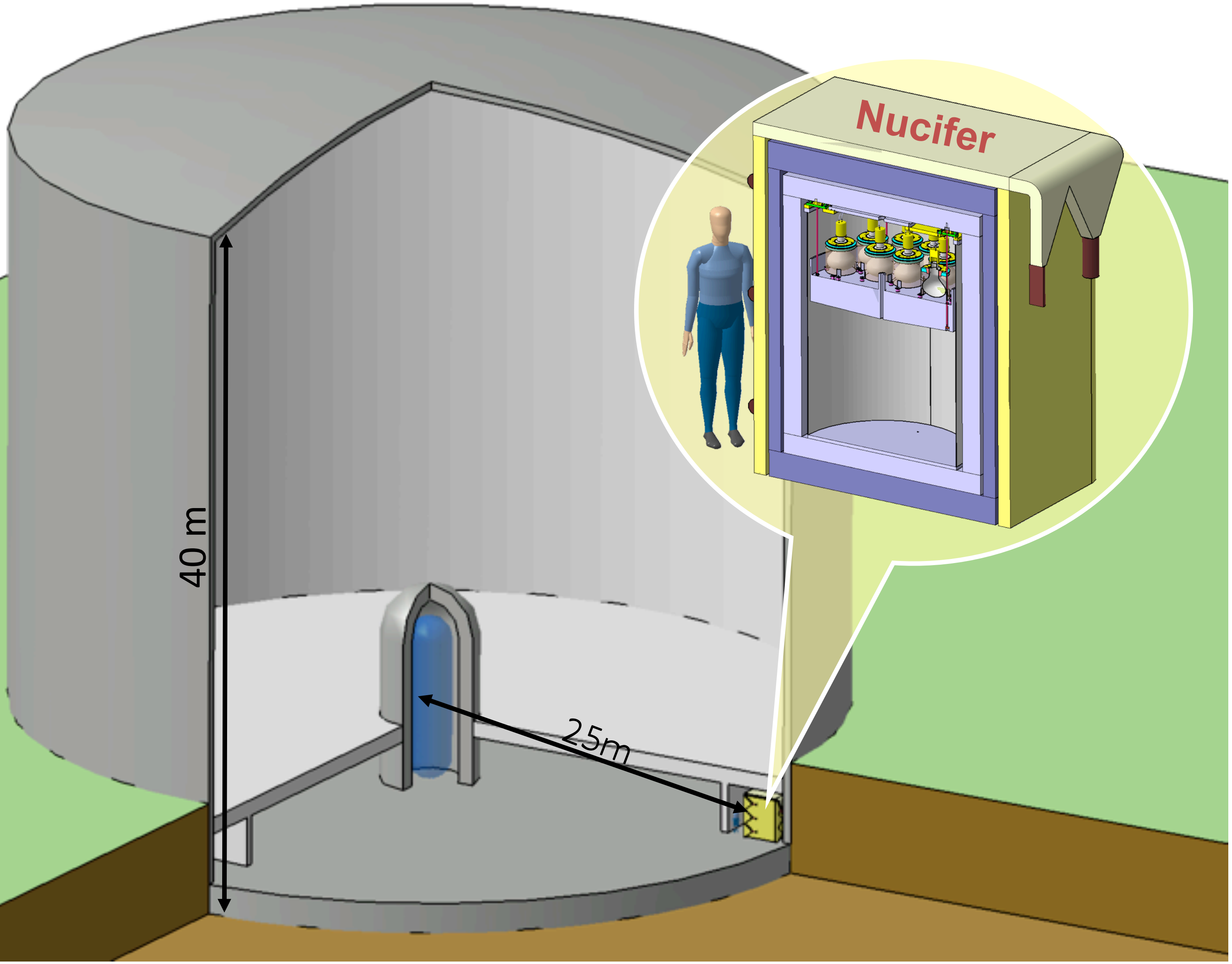


P_{th} (MW)	**57**
Fresh fuel	UAl plates
Enrichment (% of ^{235}U)	**93**
Fuel replacement	Total after 50 days
Core dimensions (cm)	80 (f) x 28 (H)
Distance from core center (m)	9
ν_e flux at det. center ($cm^{-2}.s^{-1}$)	8.4 10^{11}
ν_e int/day	>500
muon flux attenuation	2-3

Operation at a nuclear plant

Typical scenario:

- REP900 reactor
- P_{th} = 3.5 GW_{th}
- 850l scintillator
- Nucifer at 25 m from the core
- 2000/ day (50% eff)
- need >10 mwe overburden



Nucifer

Conclusion

- **NUCIFER could provide unattended monitoring and add quantitative measurements to the reactor safeguards toolbox:**
  - P_{th} monitoring & inter-calibration of reactors
  - Sensitivity to ^{239}Pu removal ≤ 100 kg @ 25m from REP900

- **A new perspective: sterile neutrino search**
  - Test the reactor antineutrino anomaly
  - Shape distortion expected for $\Delta m^2 \approx$ few eV^2

- **First Nucifer module tested in spring 2010**
- **Data Taking at Osiris by June 2011**
- **Deployment plan**
  - Osiris (2011-12), ILL ? (2012-13), Nuclear station (2013), …

Expected Sensitivity

Statistical tests of differentiation of two different isotopic compositions

Assume constant power and x-days measurements before and after a Pu removal:

4 days: detect the removal 105 kg of Pu with 75% confidence level, 4% probability of false alert.

16 days: see 55 kg of Pu with 75% confidence level, 4% probability of false alert. High CL for 80 kg.