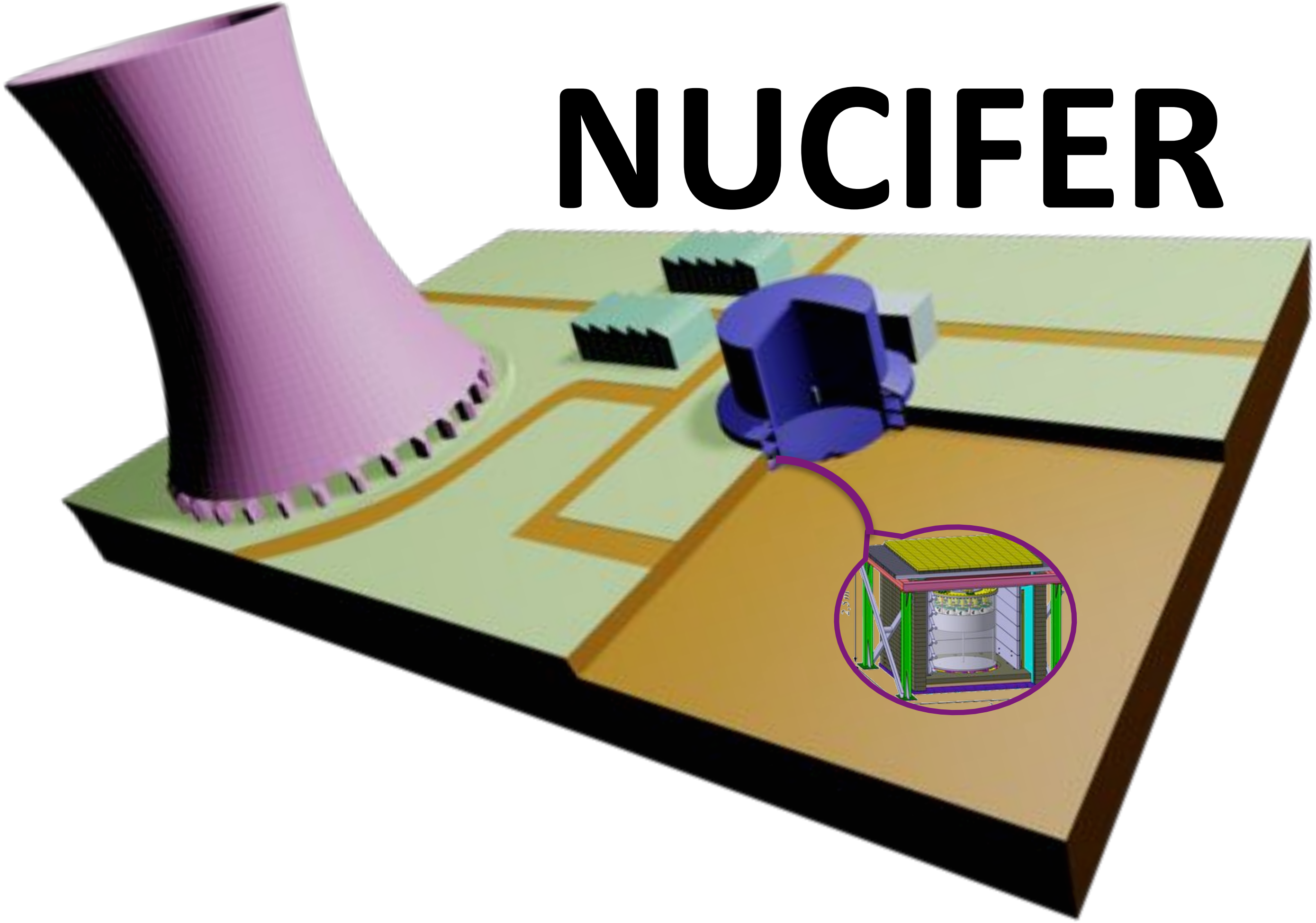
# NUCIFER



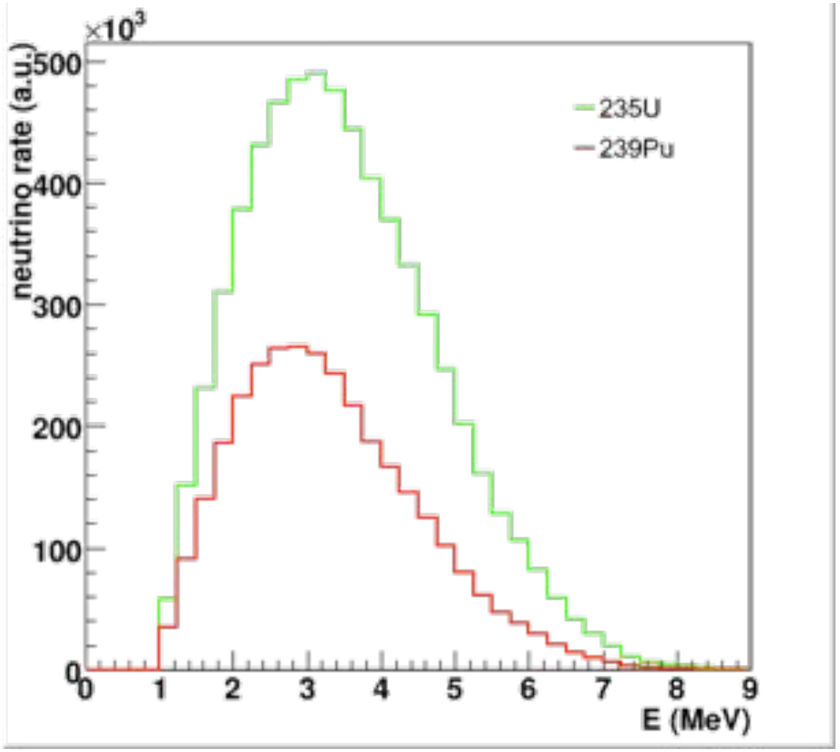
Th. Lasserre, on behalf the Nucifer collaboration
CEA-Saclay ; IN2P3-Subatech

# Applied Antineutrinos Physics

Nucifer

$$N_{\bar{\nu}} = \gamma\, P_{th} \times \left[1 + k(t)\right]$$

γ: proportionality factor
k(t): burnup sensitivity

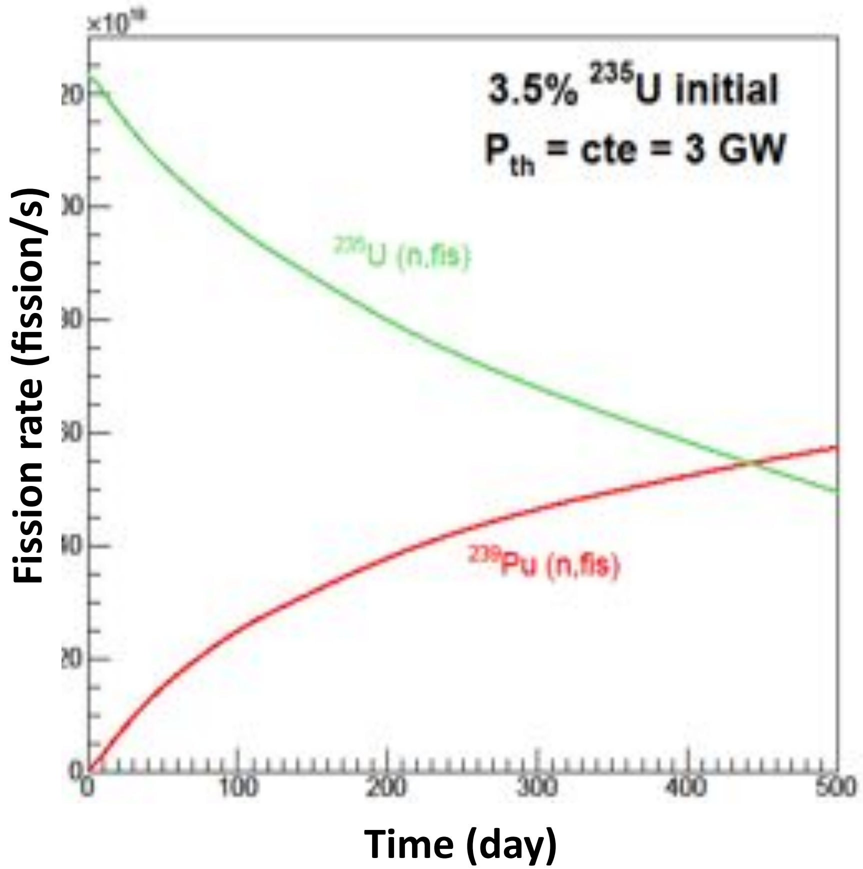



**Unique features in the "safeguards toolbox":**

- Directly related to the fission process.
- Very strong tamper resistance.
- Real-time information on isotopic fission rates.
- Can be operated remotely.
- Non-intrusive and continuous (demonstrated over year scale).

**→Complementary to existing methods**
**Compliant surveillance, few 10m from reactor but non-intrusive.**

# Applied Antineutrinos Physics




| Fission parameters | $^{235}U$ | $^{239}Pu$ |
|---|---|---|
| E/fission (MeV) | 193.5 | 198.9 |
| $<E_\nu>$ above threshold (MeV) | 2.94 | 2.84 |
| $N_\nu$/fission above threshold | 1.92 | 1.45 |
| $<\sigma_{int}>$ ($10^{-43}$ $cm^2$) | 3.20 | 2.76 |

→ For the same released thermal power, one expects to detect **60% less neutrinos from pure $^{239}Pu$ fissions than from pure $^{235}U$**

# Other worldwilde efforts

| done| data taking| being built|

| | Site | Techno | Data | Comment |
|---|---|---|---|---|
| US-LS | San Onofre | 3 GW, 25m, 0.5 t LS-Gd, 20mwe | | LLNL & SANDIA |
| US-LS | Canada | 75 m, 2t LS-Gd | 2010 | Réacteur CANDU |
| US-WC | San Onofre | $H_20$-Gd, 45 m | 2010 | Surface |
| US-CS | San Onofre | 25m, HP-Ge, 20 mwe | - | Electronics noise issues |
| ANGRA | Angra, Brazil | Gd-$H_20$, 25 m, surface | 2011 | Surface |
| ROVNO | ROVNO, Russia | LS @20mwe | ? | Segmented |
| DC-Near | Chooz, France | 9 GW, 8t LS, 400m, 120 mwe | 2012 | Spectrum measurement |
| KASKA | Joyo, Japan | 140 MW, 0.1 t LS-Gd | ? | RNR, PSD |
| **NUCIFER** | **Saclay & ILL** | **70 MW, 1t LS-Gd, 6m, 15 mwe** | **2010** | **pre-industrializable** |

# Synergy with Double Chooz


**Expertise for best cost-performance compromise**
**Simulation software and various bench tests**

# 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

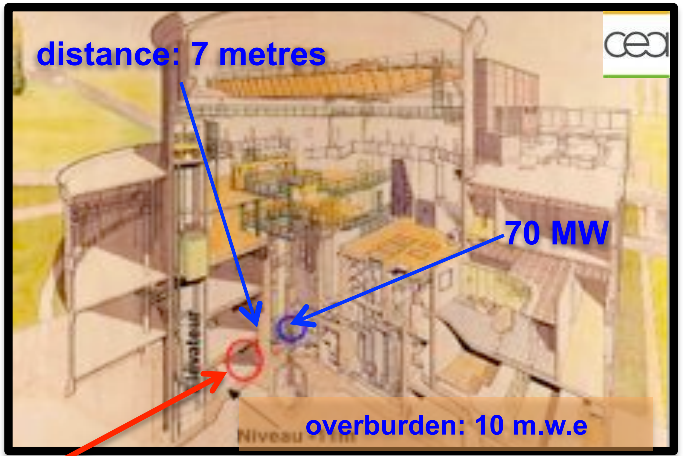
- **Main Challenges of Nucifer for integration into safeguard regime:**
  - Effort to simplify the state-of-the-art design and run close to surface while keeping detector performances

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

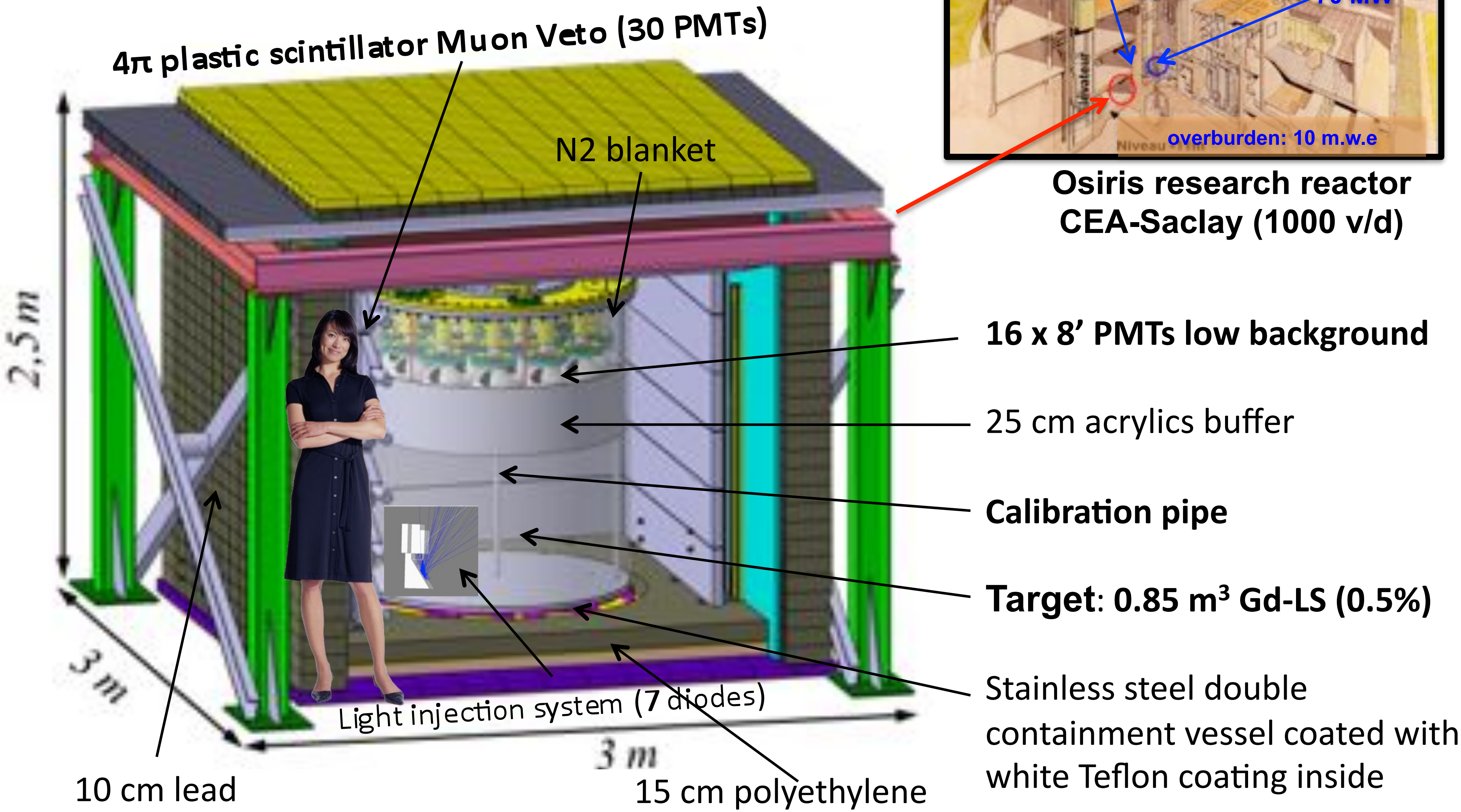
    Using the state-of-the art known technology (Double Chooz synergy)

# Nucifer Overview

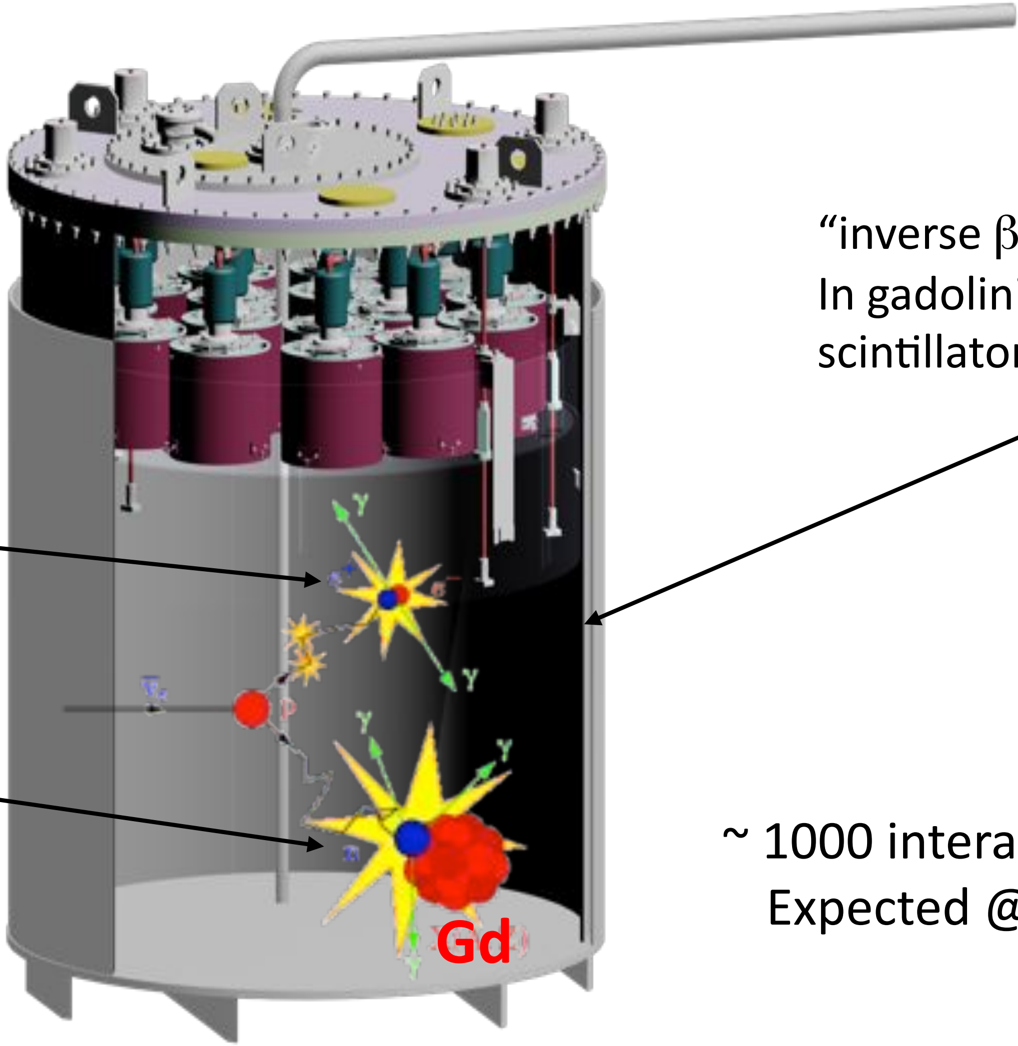
**Thermal Power Measurement**
**Fuel Composition Measurement $^{239/241}Pu$**




**Osiris research reactor**
**CEA-Saclay (1000 v/d)**



# Detection principle

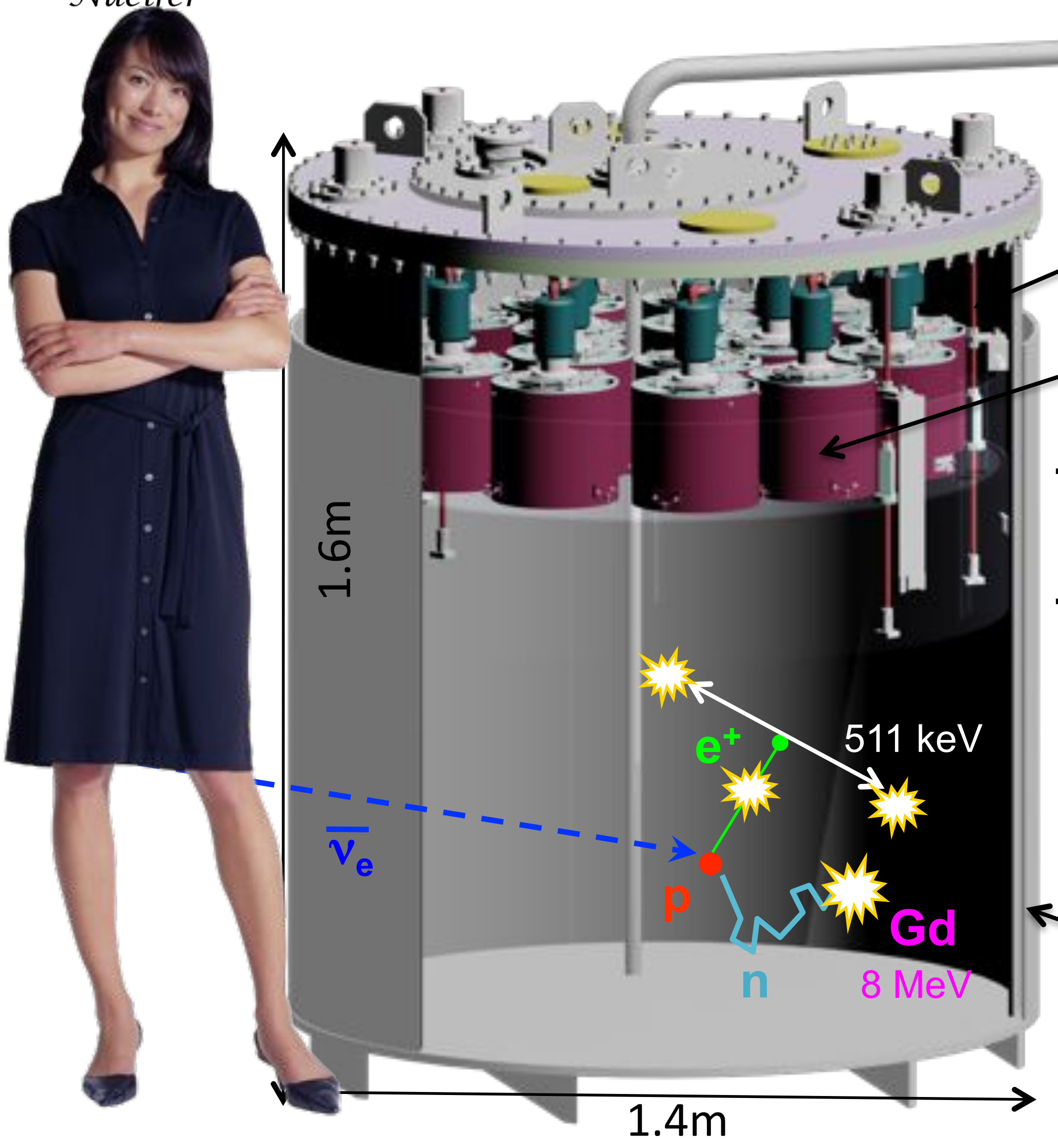



prompt positron signal
+
Delayed neutron signal ($\Delta t$~30 $\mu$s)

"inverse $\beta$-decay" process
In gadolinium doped liquid scintillator: $\bar{\nu}_e + p \rightarrow e^+ + n$

~ 1000 interactions $\nu$/jour
Expected @CEA-Osiris

# Nucifer Detector Module




Calibration pipe

N2 blanket (no fire ignition)

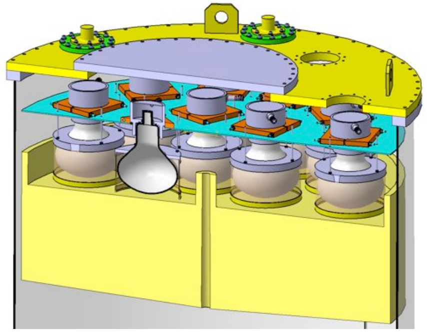
16 x 8' Photomultipliers to collect light

25 cm transparent acrylic buffer for better response uniformity and shielding against PMT radioactivity.

Target: ~0.85 $m^3$ Gd loaded liquid scintillator 70 cm high –diameter.

Double wall steel vessel for tightness. Internal white diffusive coating to wash out volume effects.

# Photodetection system



Integration in an ISO 7 clean room

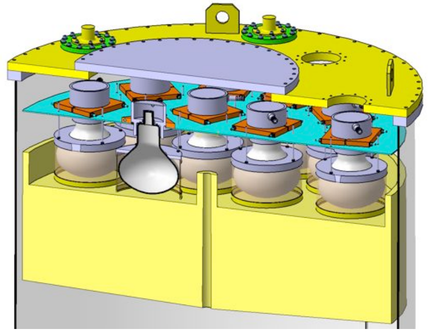
Central pipe hole for calibration

8” PMTs & magnetic shield (mu-metal)

80l mineral oil pool (optical coupling & shielding

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

# Photodetection system



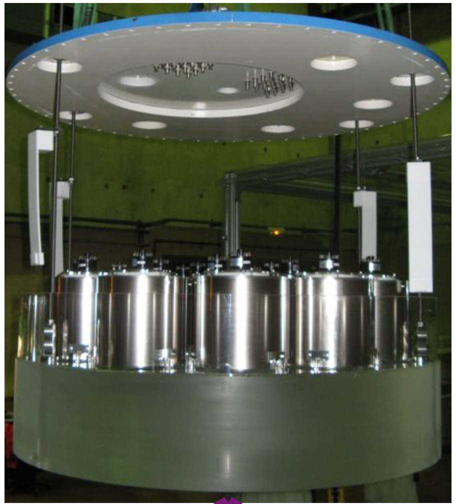
**Bottom view**

# Target vessels

**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
(See J. Gaffiots's results)



### →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.

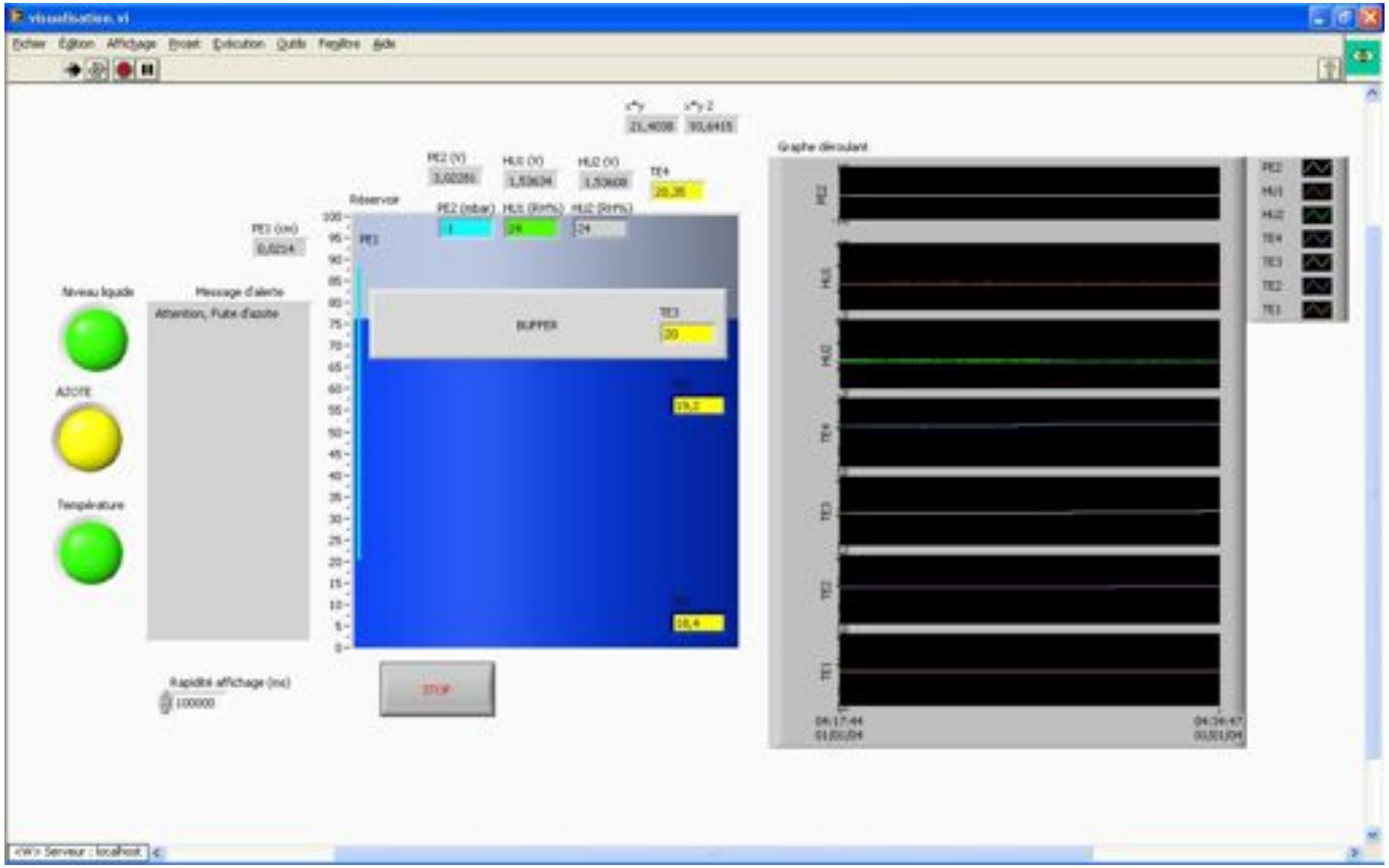
Detector is tight and kept under nitrogen atmosphere (10 mbar overpressure)

# Slow Control Systems (see R. Granelli's Talk)

Nucifer

Set of sensors inside and outside the detector:

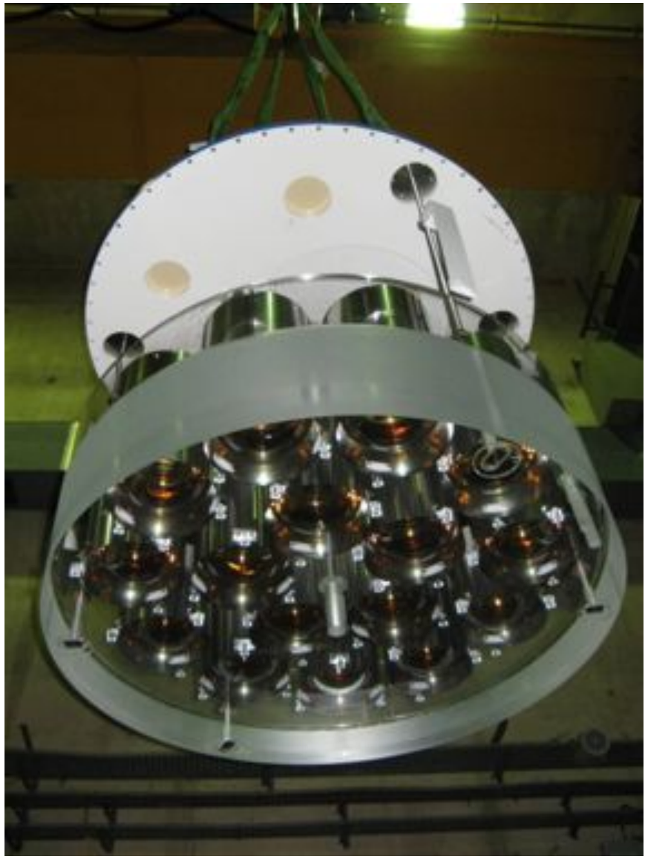
- $N_2$ blanket pressure
- $O_2$ partial pressure
- Temperatures
  - scintillator (2)
  - oil (1)
  - $N_2$ blanket (1)
- Liquid level (2 sensors)
- Liquid leak detection



- LabView based Software system
- Simplified software panel available in the reactor control room
- Alarms triggered by out of range values
- Low frequency sensors data included in detector data structure for stability studies

# Test assembly in Saclay

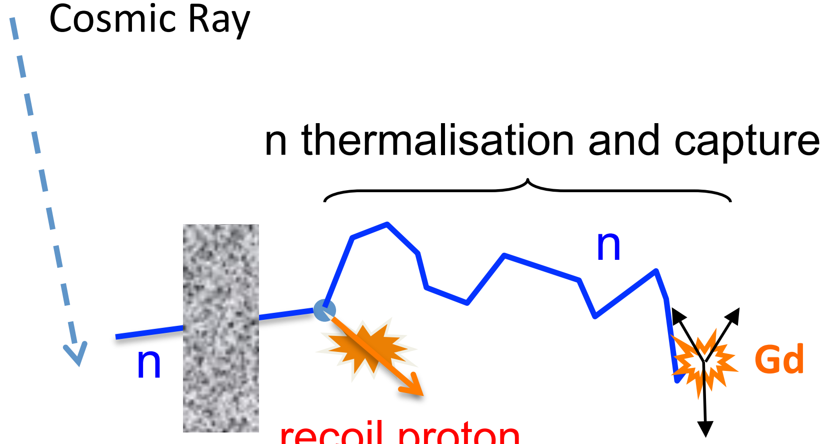
Rehabilitated underground lab from dismantled accelerator.
Prototype vessel and non Gd-loaded LAB based scintillator for test.



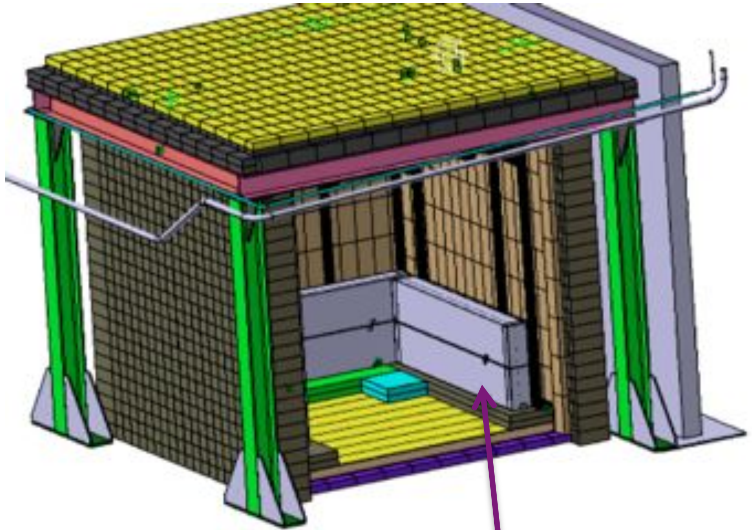
**(see talk from J. Gaffiot for the prototype characterization)**

# Muon Veto

• Interaction of cosmic rays with surrounding material can induce fast neutrons able to punch through shielding. A recoil proton fakes the prompt signal then the neutron is captured.
•Dominant surface background



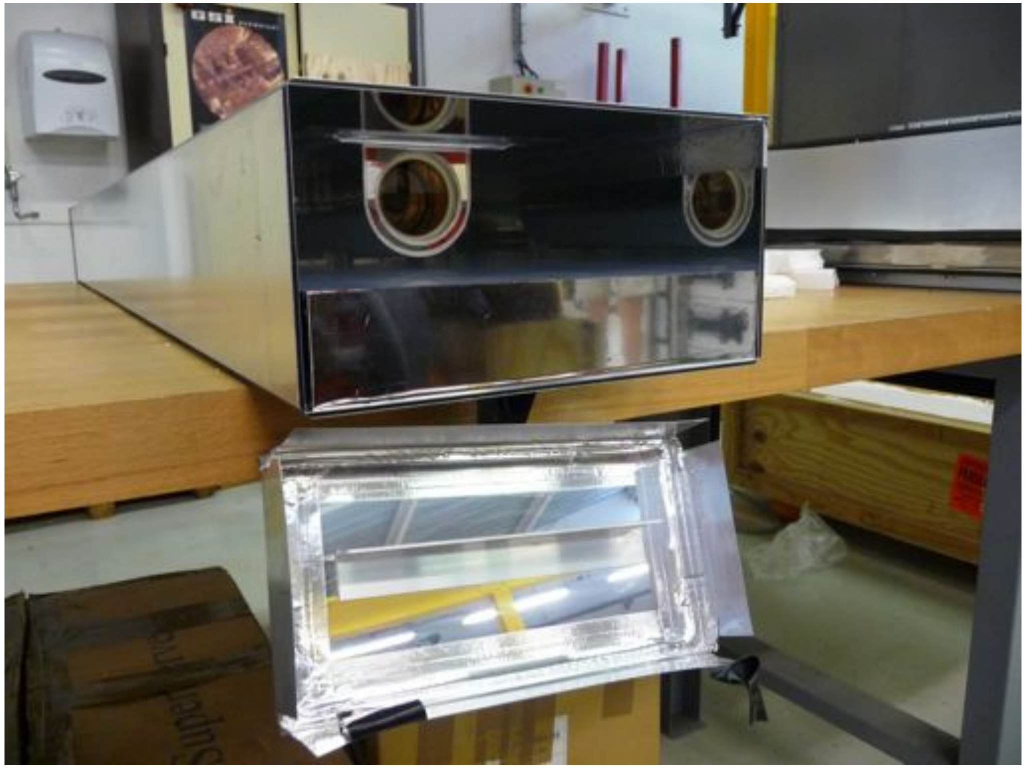

•Veto = An active shielding layer of plastic scintillator tags the nearby muons and veto the acquisition.



Aluminium structure

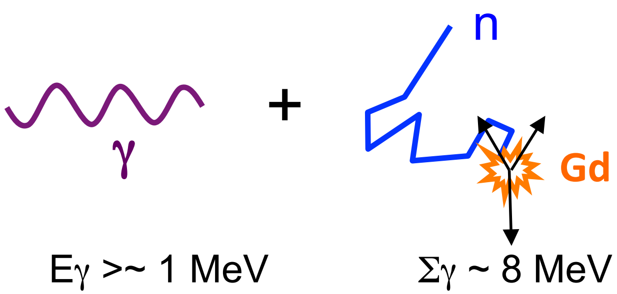
# Veto Muons Technology

- 30 boxes (side & ceiling are different) readout by 30 PMTs.
- Each box made of a 4 cm thick plastic scintillator + reflective coating + PMT
- Integration completed – assembly on site in October.
- Box tested under (MBq) high gamma activity inside the Nucifer Osiris room



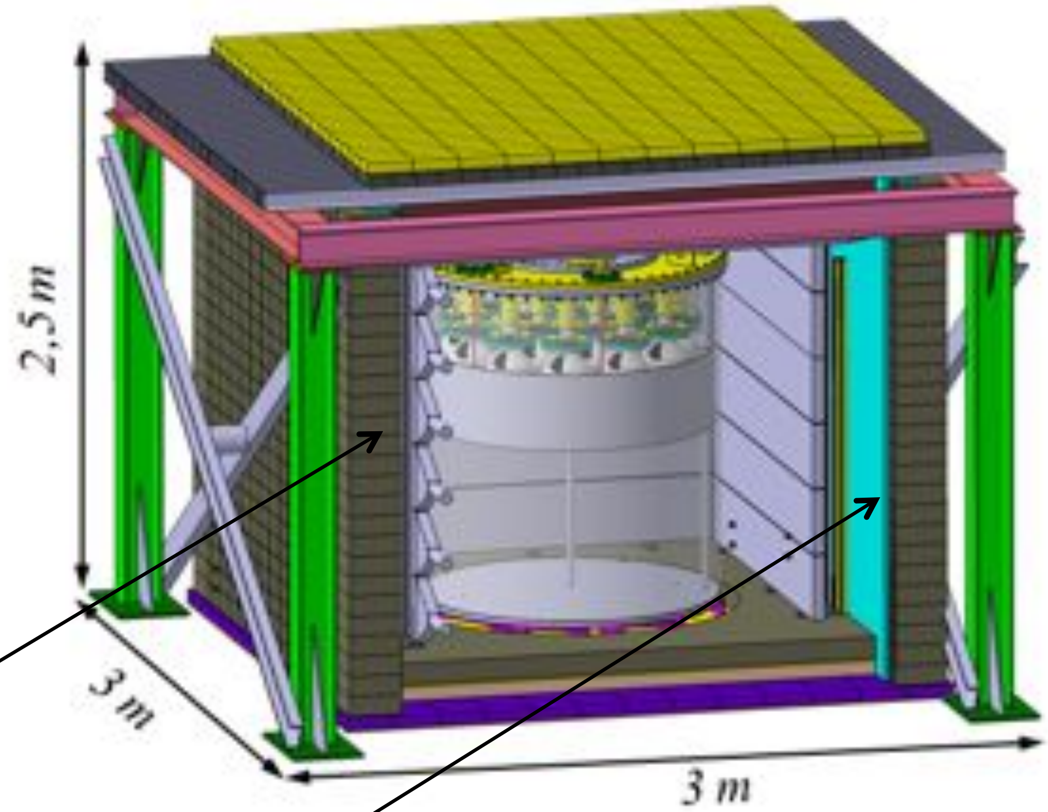
# Passive Shielding
## optimized for the Osiris/ILL run

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



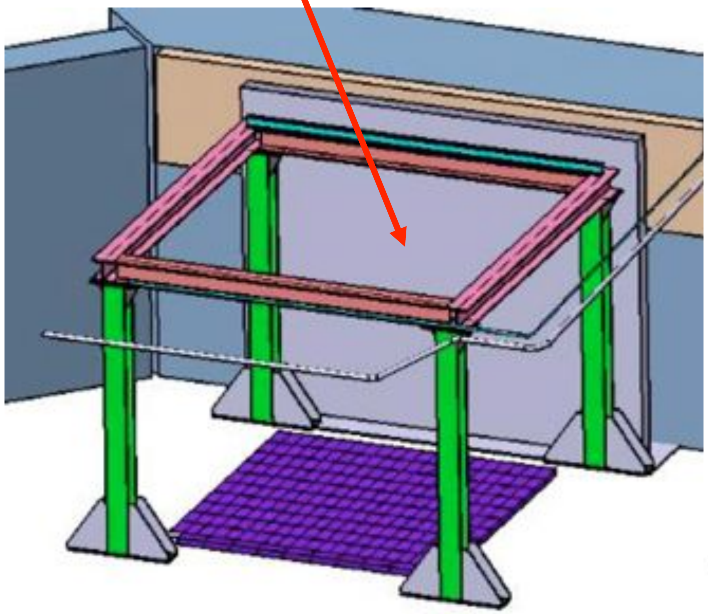

A mechanical structure supports shielding all around the detector:

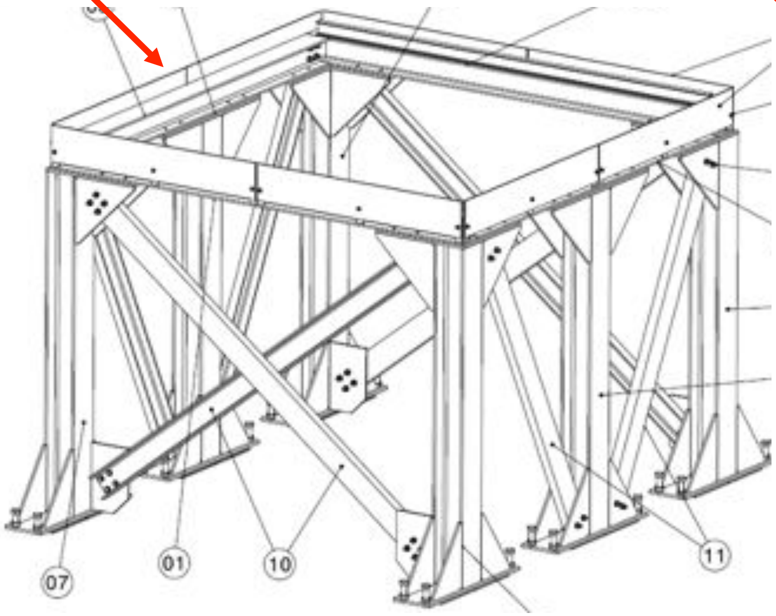
- 10 cm of lead to stop γ
- 15 cm of polyethylene to stop low E neutrons

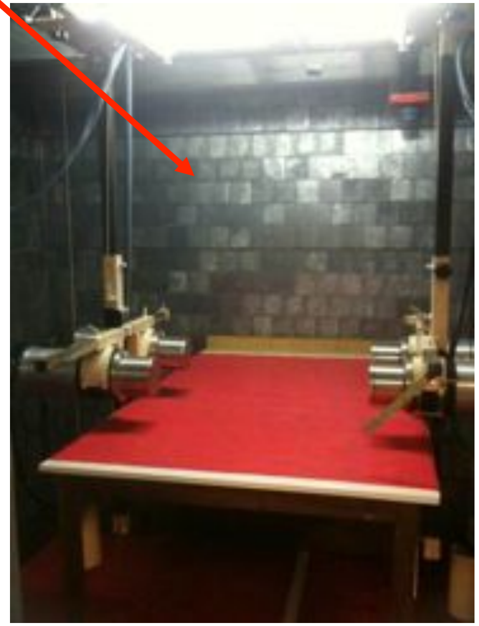


# Gamma Shieldings

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



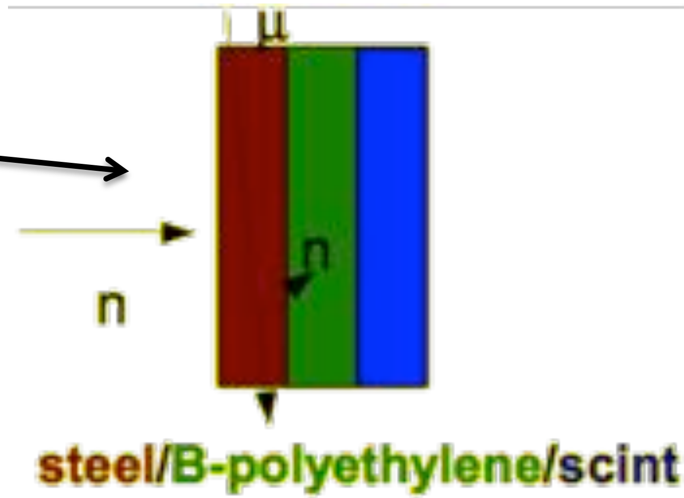


# Neutron Shielding

**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)
- All bricks procured (C, H, T shapes)
- Walls pre-assembled




# Calibration and Monitoring

Nucifer

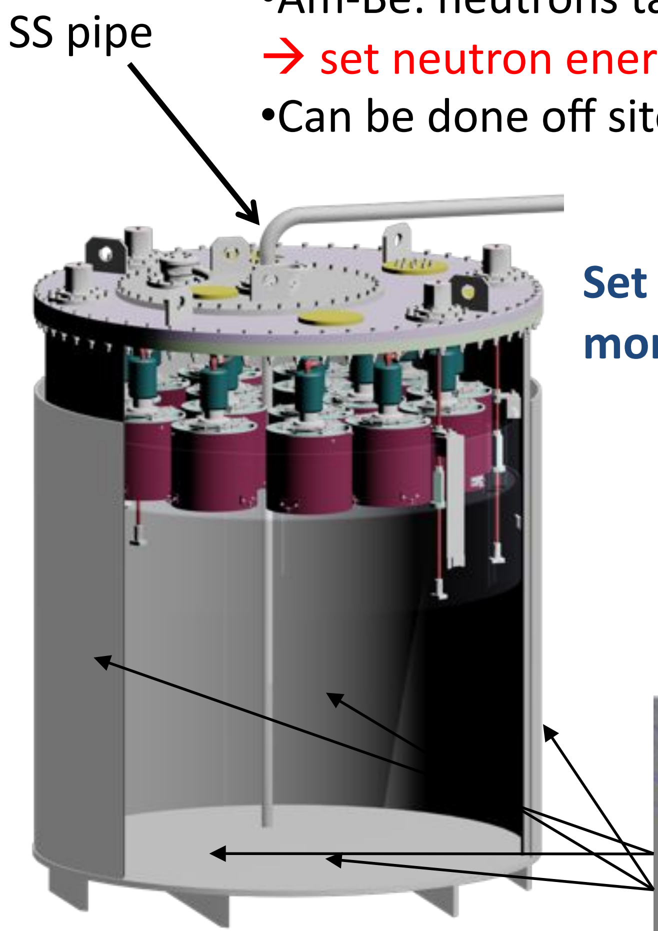
**Calibration pipe allowing insertion of radioactive sources along axial axis:**

- $^{137}$Cs, $^{22}$Na, $^{60}$Co, Am-Be: response to $\gamma$ rays in the 0 .7 - 4.4 MeV range
- Am-Be: neutrons tagged by 4 MeV $\gamma$

→ set neutron energy cut in analysis and determine $\varepsilon_{det}$

- Can be done off site before installation

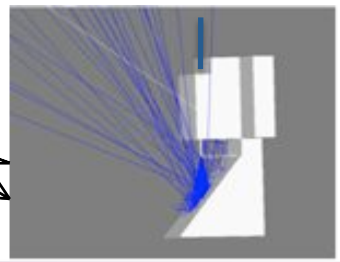
source holder




**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

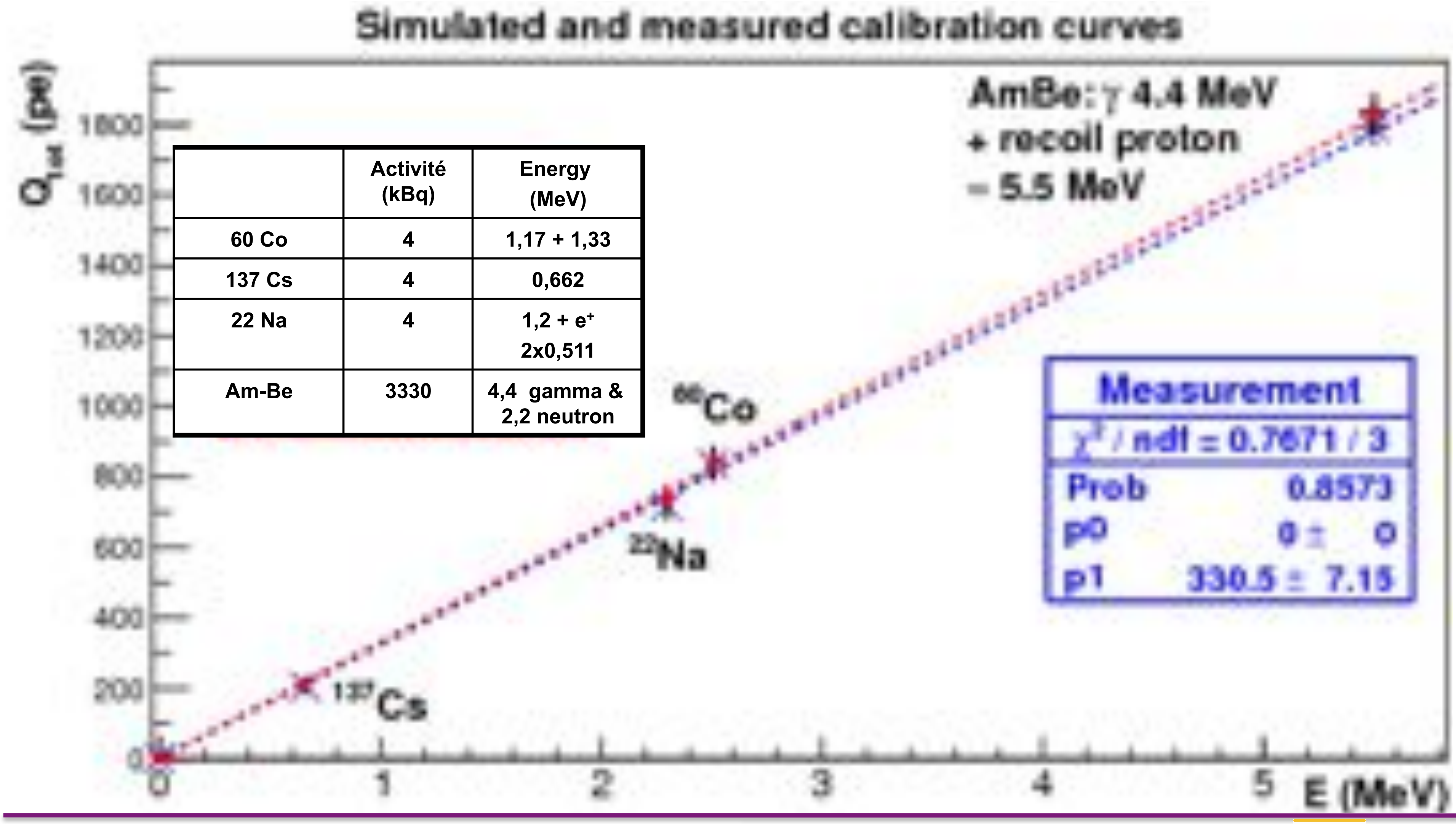


Light injection system and diffuser

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

# Prototype detector: linearity

## (see Jonathan Gaffiot's talk)



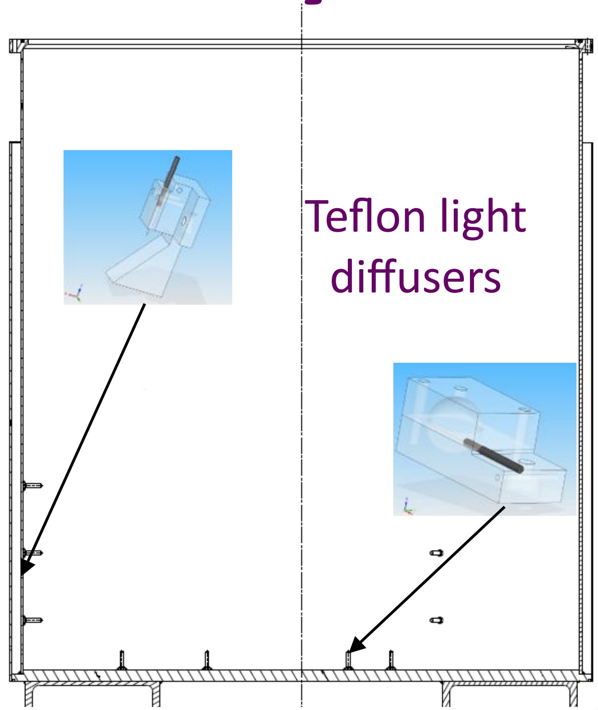

| | Activité (kBq) | Energy (MeV) |
|---|---|---|
| 60 Co | 4 | 1,17 + 1,33 |
| 137 Cs | 4 | 0,662 |
| 22 Na | 4 | 1,2 + $e^+$ 2x0,511 |
| Am-Be | 3330 | 4,4 gamma & 2,2 neutron |

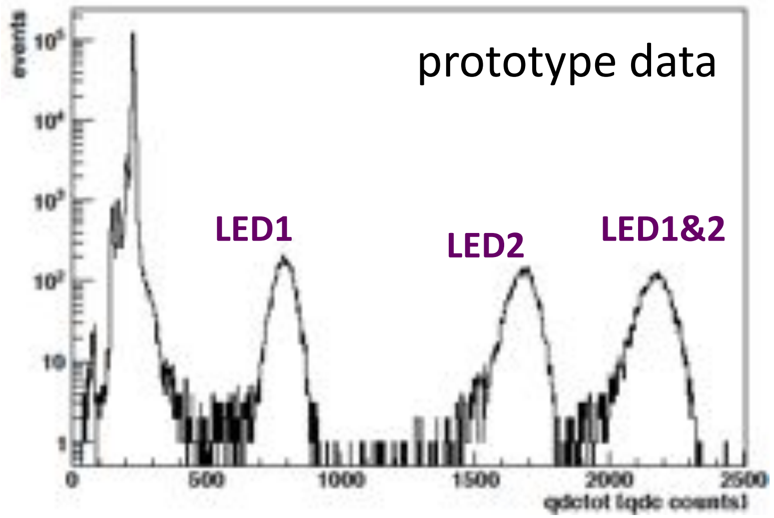
# Light Injection Calibration System

- **In-situ LED system to REMOTELY calibrate & monitor the detector stability.**

- **Final goal (beyond Nucifer): calibration at reactor site & using LED only (no radioactive sources)**

- **LED system developed for the Babar experiment (Saclay)**
    - LED pulser module ($\lambda$=450 nm)
    - 1st LED set: single photoelectron (gain) calibration/ monitoring
    - 2nd LED set: large dynamics injection for linearity calibration/monitoring
    - 3 types of PTFE diffusers
    - Possibility to calibrate/monitor over the whole experimental dynamics

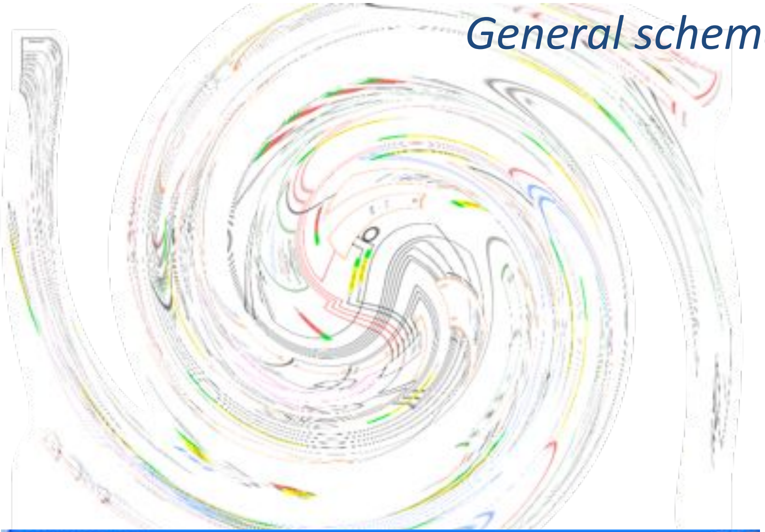


# Electronics and DAQ

Nucifer

*General scheme*



**Commercial electronic modules** (CAEN, WIENER)

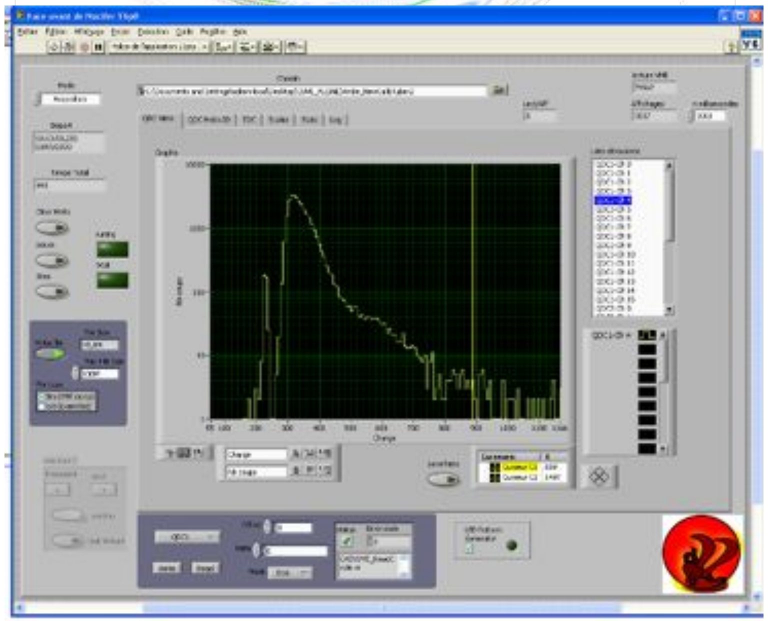
- Digitization:
  - High precision absolute time recording, with software reconstruction of delayed coincidences
  - Total charge for energy reconstruction
  - Late charge for PSD

- Trigger based on signal threshold & multiplicity

**Commercial acquisition software** (LabView)

- Dead time < 1% at 1.5 kHz trigger rate, allowing fast calibration and low E background studies. Synchronous modules

- Designed for remote running from control room To be tested during the OSIRIS run

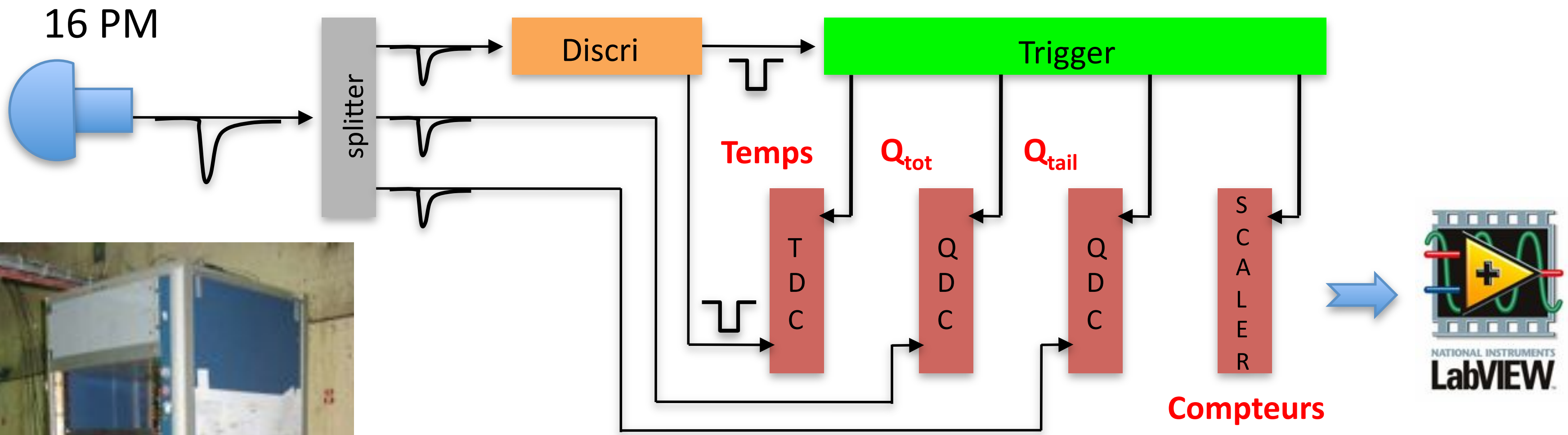


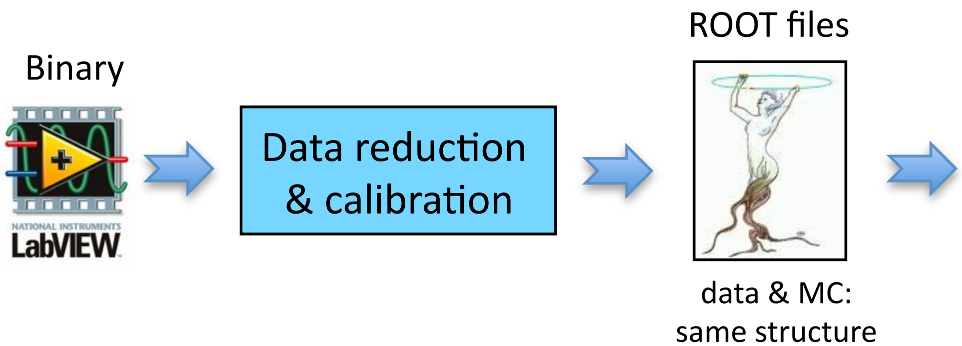
*Example of online display*

Nucifer

# DAQ: data flow

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




- Raw data
- Absolute time for each event
- Calibrated
- WWW quality control (single pe, LEDs, pedestal, …)

# Deployment Plan

- **Phase 1: OSIRIS** - 09/2010 → 12/2011 -
  - Goal: Validation & full characterization of the Nucifer detector
  - Challenge: First experiment 7 m away from a nuclear core (an extreme background environment → thick shielding)
  - IAEA interest: 1er deployment 7 meter away from a core, inside a research reactor hall

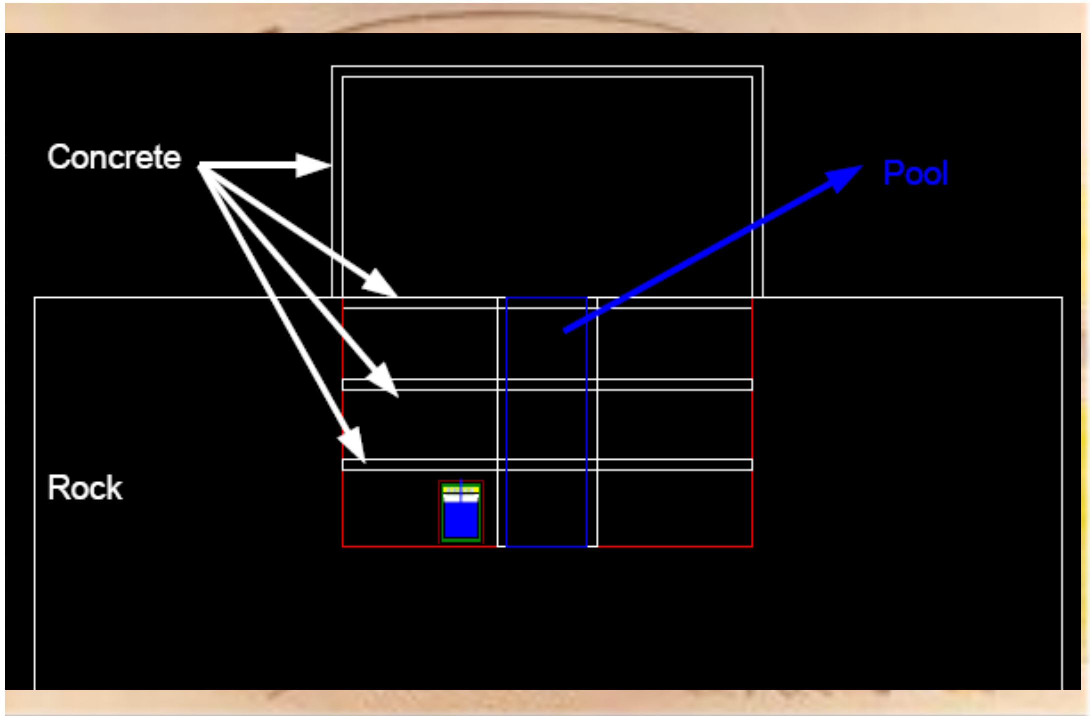
- **Phase 2: ILL** - 01/2012 → 12/2012 -
  - Goal: Measurement of a pure $^{235}U$ fuel spectrum + Absolute detector calibration
  - Challenge: weaker nuclear power, farther location, high neutron background
  - IAEA interest: demonstration of our ability to change the detection site

- **Phase 3: Nuclear power station** – 2013
  - 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.

- **Phase 4: Nuclear power station under safeguards (need IAEA)** >2014

# Nucifer @ Saclay-Osiris

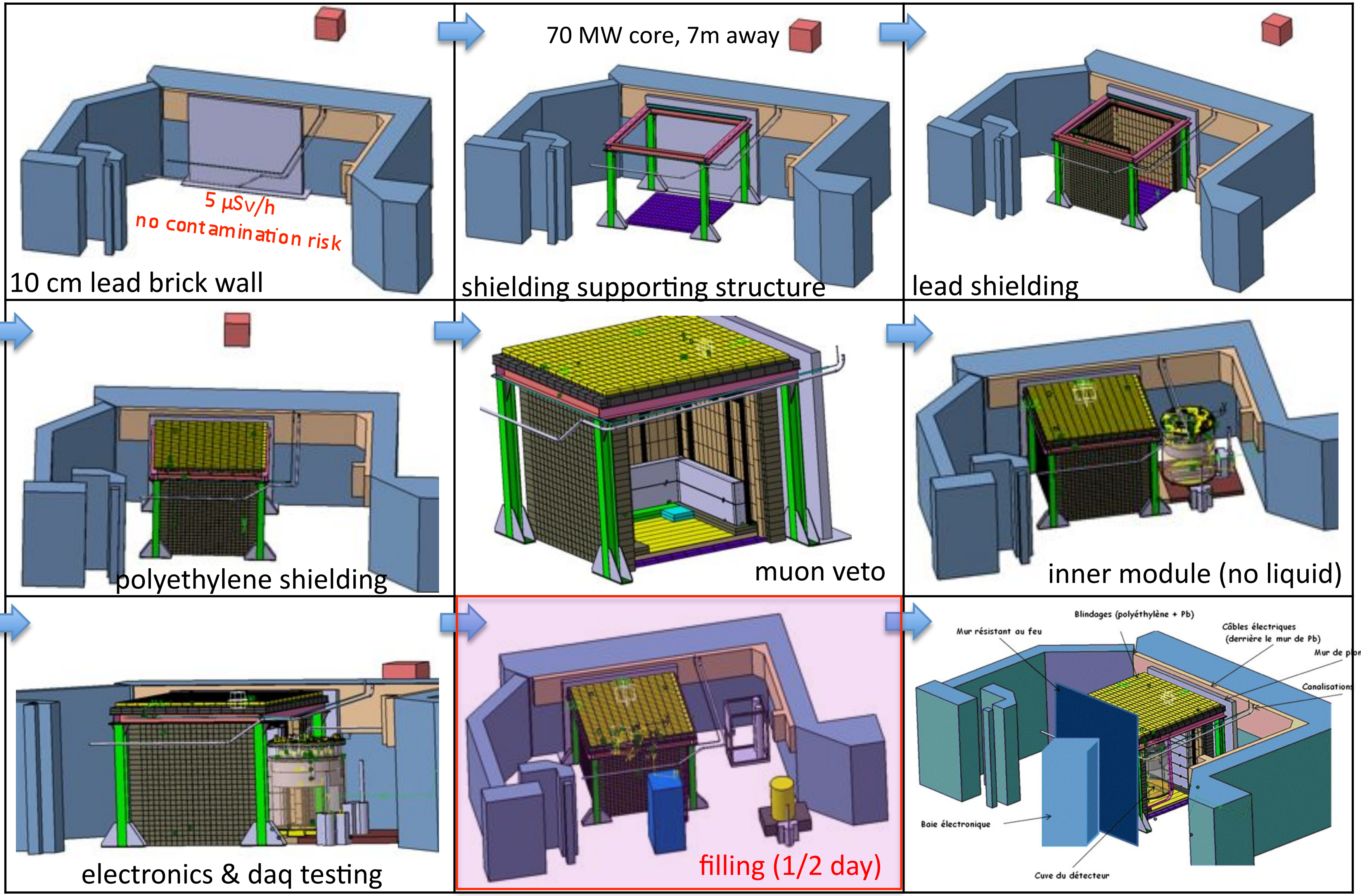
- **Site available at 7 m from the core**
  - Project supported by OSIRIS/DEN & CEA-Saclay
  - 15 mwe overburden
  - reactor induced $\gamma$ rays implies **an additional 10 cm lead shielding needed**




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** | 1/7$^{th}$ every 20d |
| **Core dimensions (cm)** | 57 x 57 x 60 |
| **Distance from core center (m)** | 7 |
| **$\nu_e$ flux at det. center ($cm^{-2}.s^{-1}$)** | 2.3 $10^{12}$ |
| **$\nu_e$ int/day in Nucifer ($1m^3$)** | **~1000** |
| **muon flux attenuation** | 2.7 |

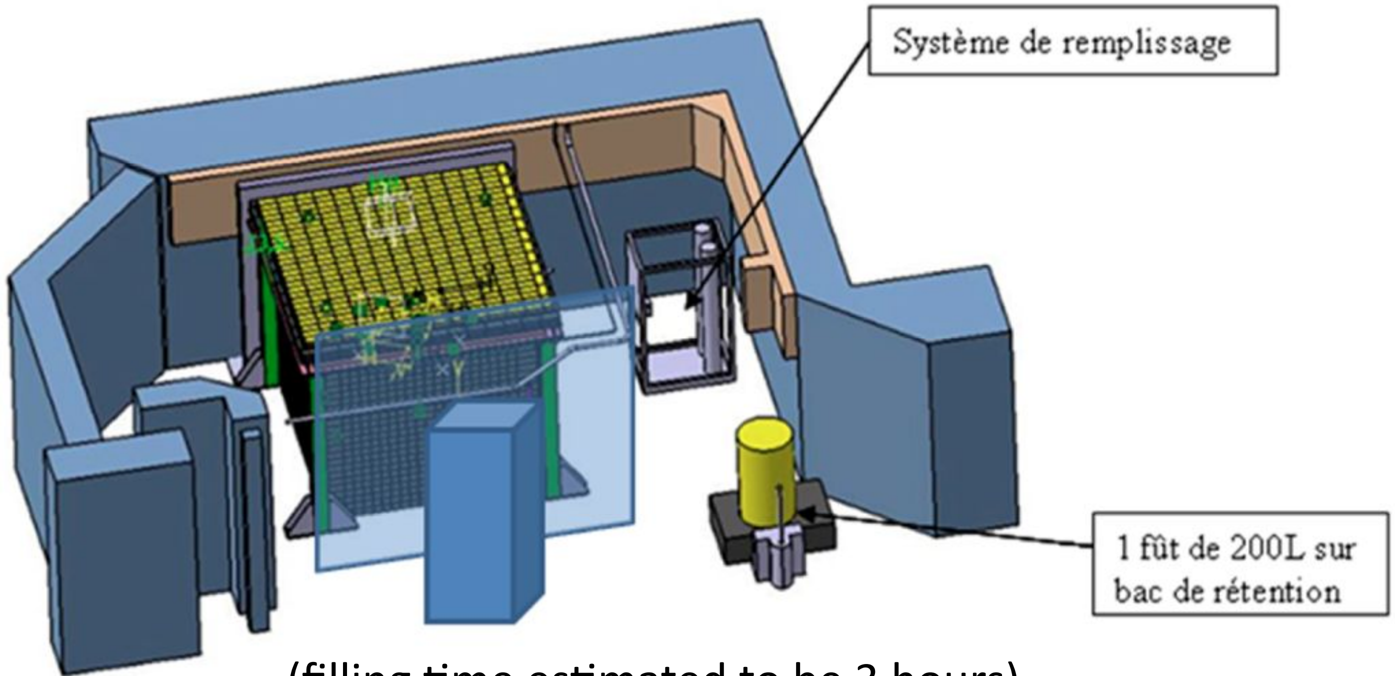
# Nucifer @Osiris: Integration



# Nucifer @Osiris: Filling

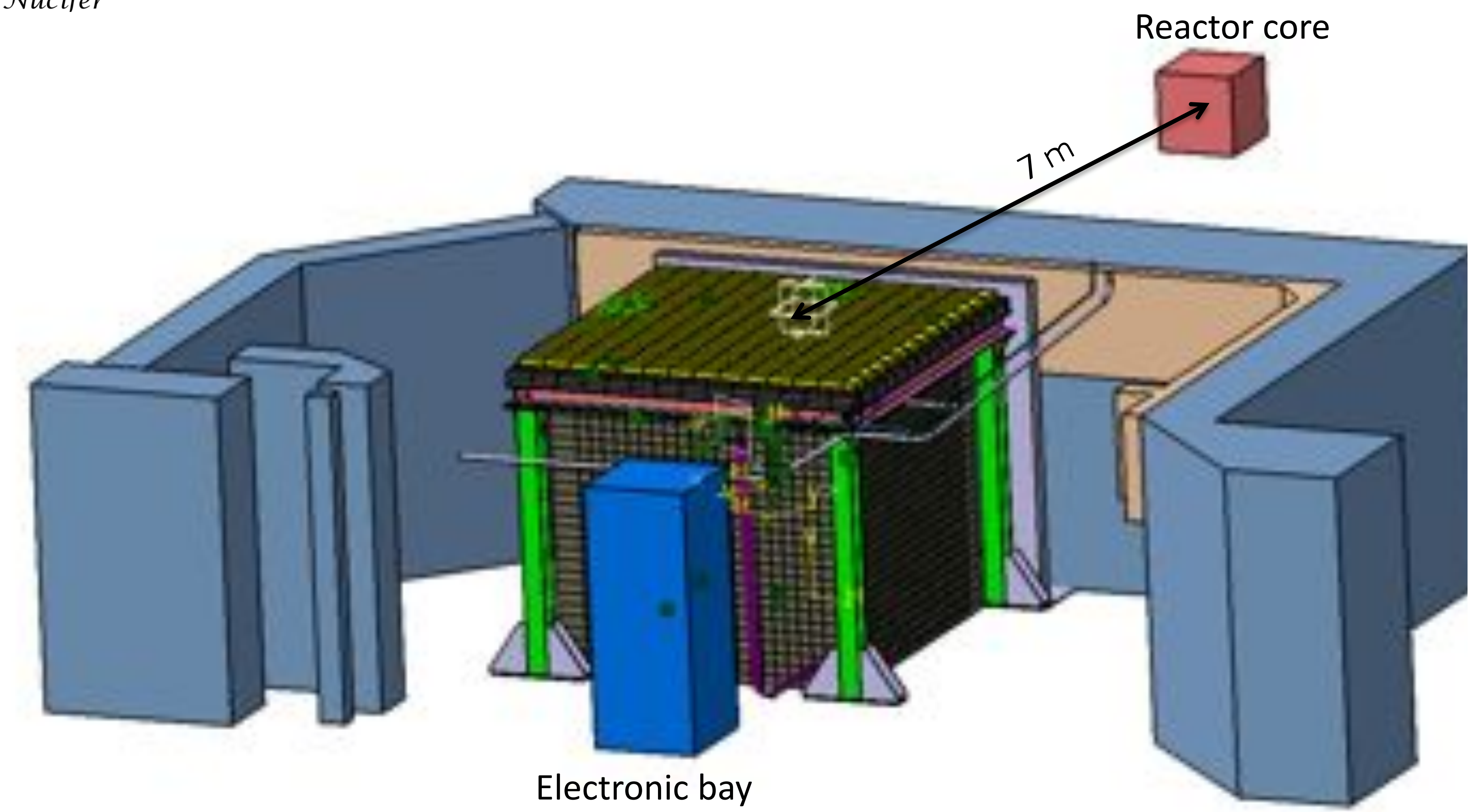
- **Integrate the Target vessel empty of liquid but full of $N_2$ gas at atm. pressure + 10 mbar**
- **Install spill tray & filling module (work with compressed air only)**
- **Temporarily close the Nucifer room and exhaust towards the power plant ventilation**
- **Bring the 5 x 200l gadolinium doped barrels (5 tons lift)**
- **No electrical system running – Fill the detector, 1% precision on the target H content**

portable filling module




(filling time estimated to be 3 hours)

# Nucifer @ Saclay-Osiris



# Nucifer@Osiris: Signal & Backgrounds

Nucifer

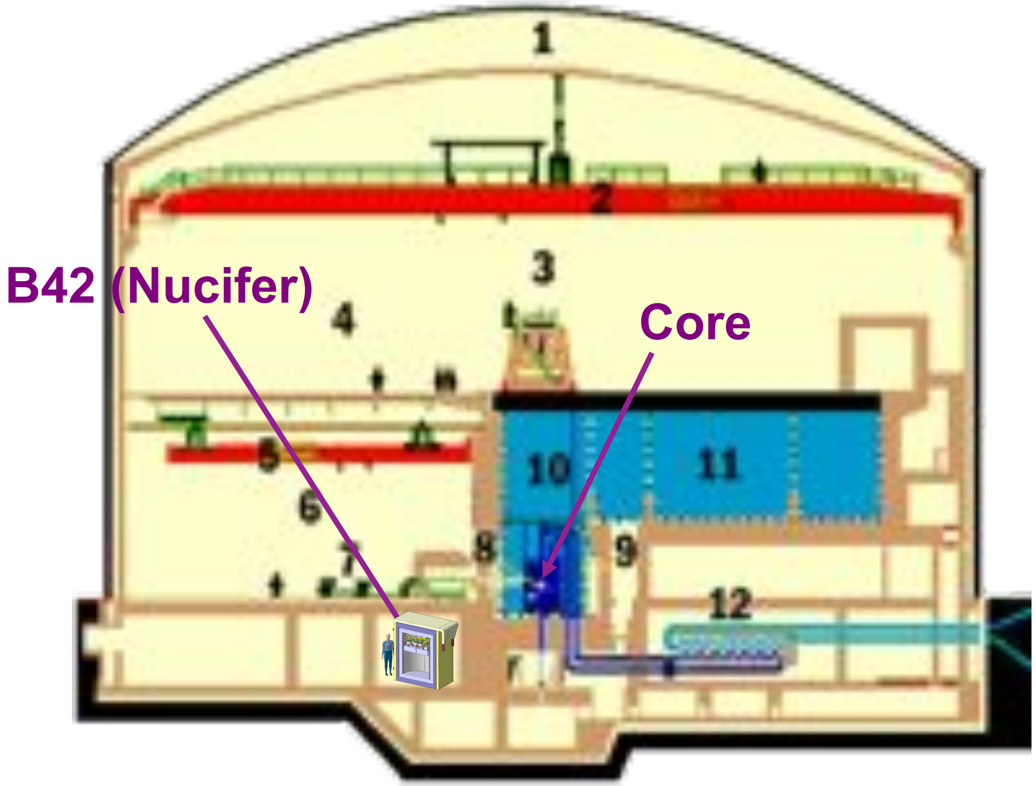
- **Signal:**
  - 850 liters of EJ335 scintillator → 4.48e28 free H
  - Challenge → towards a 50% detection efficiency
  - Expected #events per day ≈ 730 × 70 MW × 0.85 $m^3$ × 0.5 eff. / $(1/7)^2$ = 500/day

- **Accidental backgrounds**
  - positron like randomly correlated to neutrino like delayed event
  - Campaign of measurements → high gamma flux (MBq …)
  - Also at high energy (> 3MeV) through neutron capture on reactor metallic structure
  - Expected signal to noise ration of about 1
  - Necessity to add a 10 cm lead shield wall at Osiris (only)

- **Fast neutrons**
  - Overburden: 15 mwe only
  - Expected signal to noise ration of about 0.25 (before any PSD cut)
  - Focus on Pulse Shape Discrimination (PSD) cut to extract clearly the neutrino signal (discriminate $e^+$ signals from highly ionizing proton recoil induced by fast neutrons) PSD rejection under study?

# Nucifer @ Grenoble-ILL

- **Site available at 9-11 m from the core** @ Room B42, old ILL exp.
    - First positive meeting with the Power Reactor Directors → Proposal being prepared
- **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.

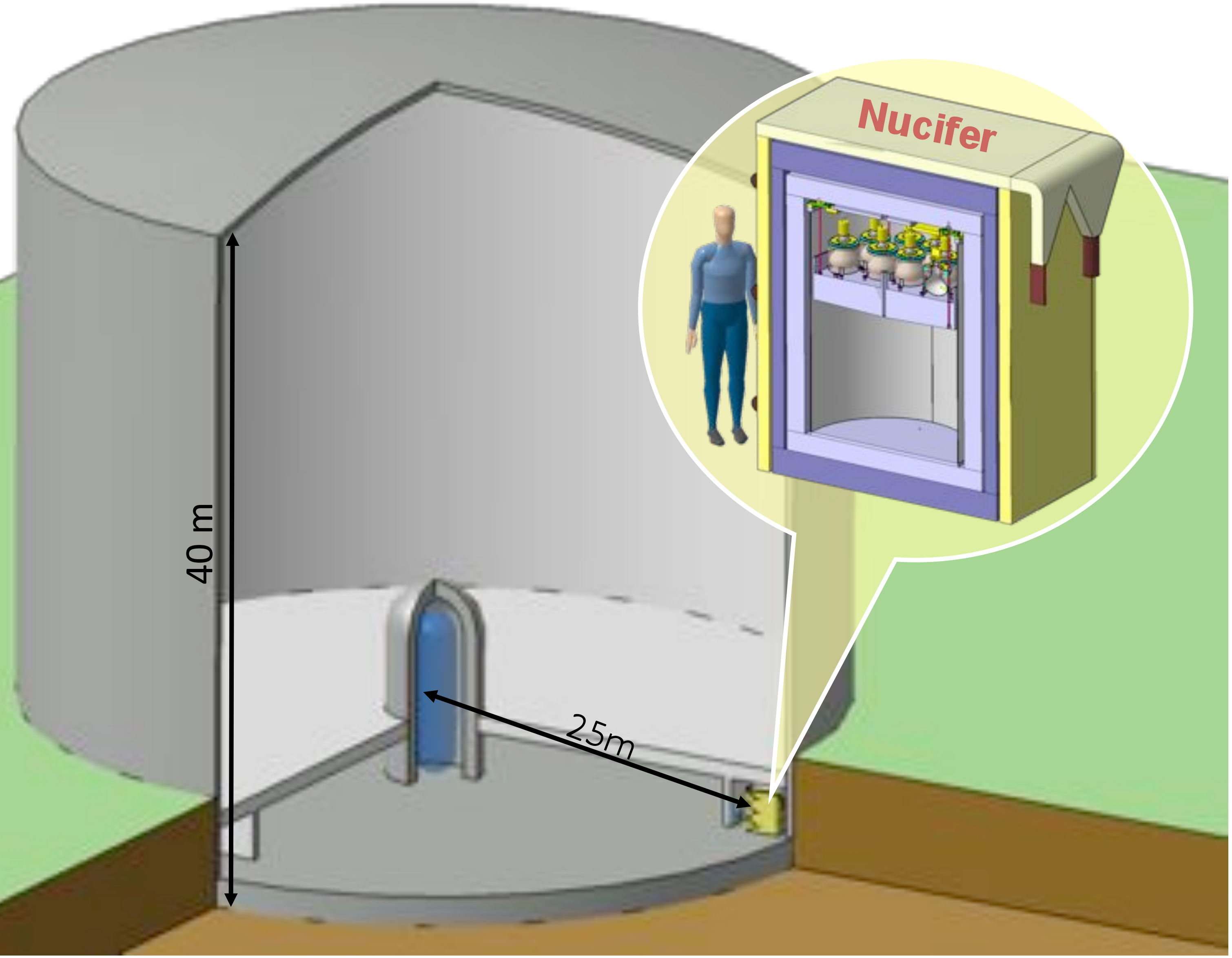



| | |
|---|---|
| $P_{th}$ (MW) | 57 |
| Fresh fuel | UAl plates |
| Enrichment (% of $^{235}$U) | 93 |
| Fuel replacement | Total after 50 days |
| Core dimensions (cm) | 80 (f) x 28 (H) |
| Distance from core center (m) | 9 |
| $\nu_e$ flux at det. center ($cm^{-2}.s^{-1}$) | 8.4 $10^{11}$ |
| $\nu_e$ int/day in Nucifer) | ~250 |
| 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



# Conclusion

- **NUCIFER could provide soon unattended monitoring and add quantitative measurements to the reactor safeguards toolbox:**
  - Tamper-proof ν signal
  - Weak impact on reactor safety **(see R. Granelli's Talk)**
  - $P_{th}$ monitoring, inter-calibration of reactors (new)
  - Sensitivity to $^{239}Pu$ removal ≤ 100 kg @ 25m from REP900

- **First Nucifer module tested in spring 2010 (see J. Gaffiot's Talk)**
- **Integration @CEA-Osiris site (Saclay) from October 2010**
- **Filling and first neutrino data by November 2010**

- **Deployment plan**
  - Osiris (2010-11), ILL (2012), Nuclear station (2013), …
  - Need IAEA feedback and hopefully support to boost phase 3?

- **Complete simulation package to test diversion scénarios**
  - **See J. Gaffiot's Talk**

# Backups

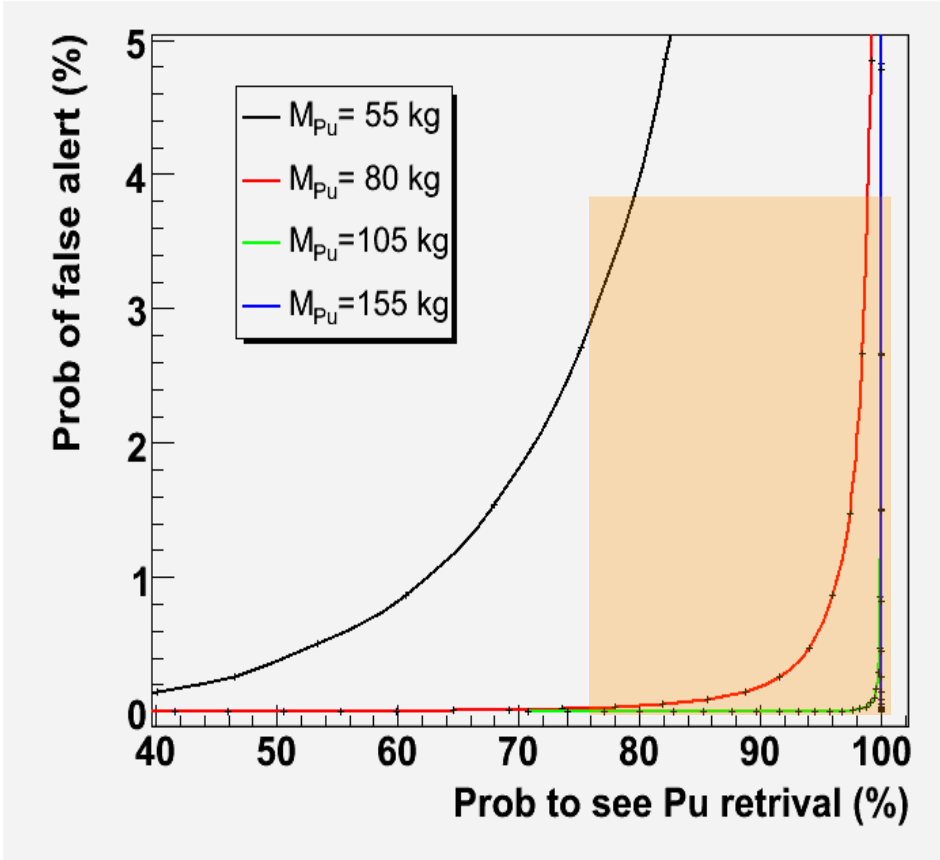
# Expected Sensitivity

**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.



# 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.