Detector R&D activities of the Nuclear Innovation Unit - CIEMAT

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Motivation of our detector R&D activities

Perform **nuclear physics experiments** in the best possible conditions and at the **adequate facilities (movable detectors)**:

1. **Neutron** induced reaction **cross sections** at n_TOF@CERN. (FPN and EC)
2. **β-decay experiments** at multiple accelerator driven facilities. (FPN and EC)
   - Neutron detectors for beta-delayed neutron studies
   - **γ**-ray detectors for high-ray spectroscopy.
   - High resolution Ge detectors.
   - Lower resolution inorganic scintillators for higher efficiencies.
3. **(α,n) reaction studies** at CMAM/Madrid and CNA/Sevilla (FPN)
4. **Medical applications** / proton therapy (CAM project)
5. Characterization of **radioactive waste** (MCIN, industry)

Very much related to this:

- Development of data acquisition systems (hardware and software).
- Monte Carlo simulation tools (we are members of GEANT4).

The n_TOF facility

Spallation source

CERN PS @ 0.8 Hz

p 20 GeV/c, 7ns RMS

$7 \cdot 10^{12}$ p/pulse

$2 \cdot 10^{15}$ n/pulse

EAR2

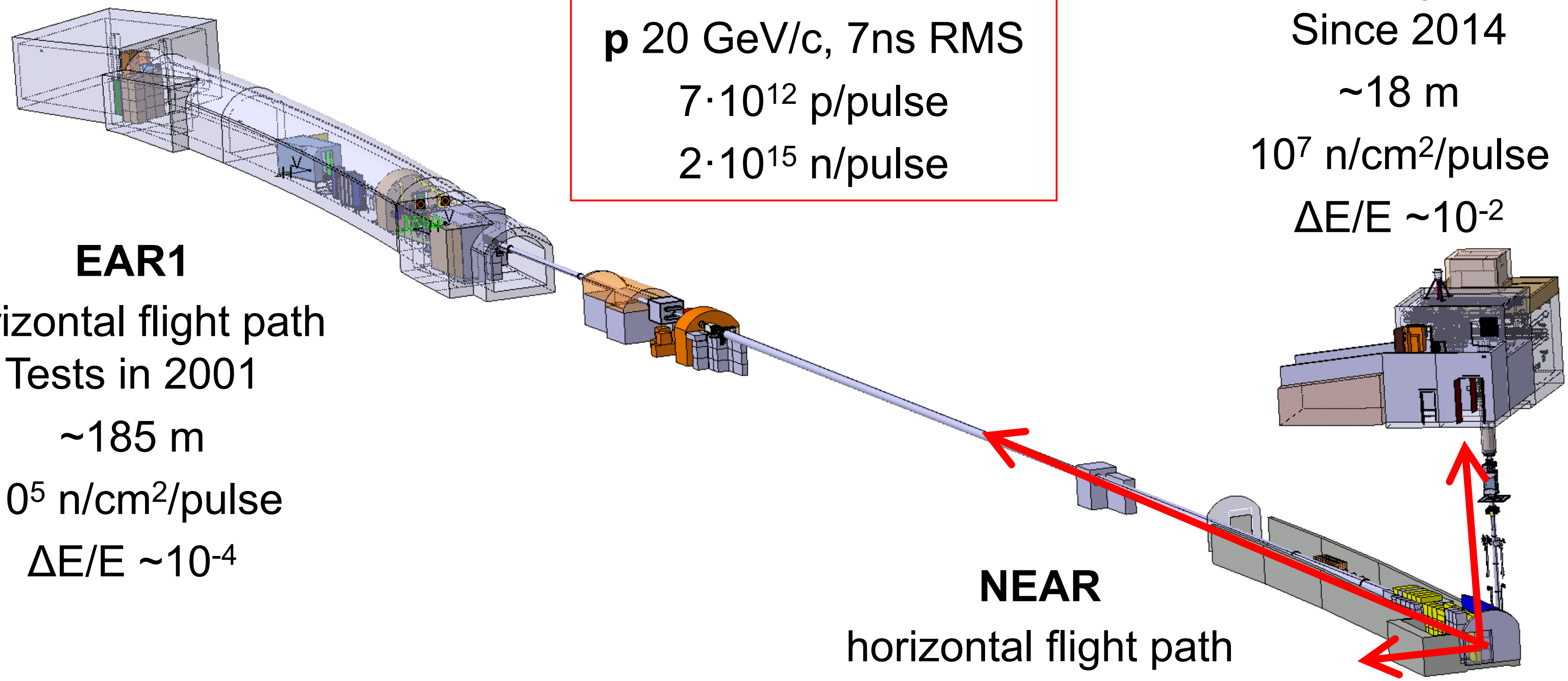
Vertical flight path

Since 2014

~18 m

10^7 n/cm^2/pulse

$\Delta E/E \sim 10^{-2}$



EAR1

horizontal flight path

Tests in 2001

~185 m

10^5 n/cm^2/pulse

$\Delta E/E \sim 10^{-4}$

NEAR

horizontal flight path

Tests in 2021

~3 m

10^8 n/cm^2/pulse

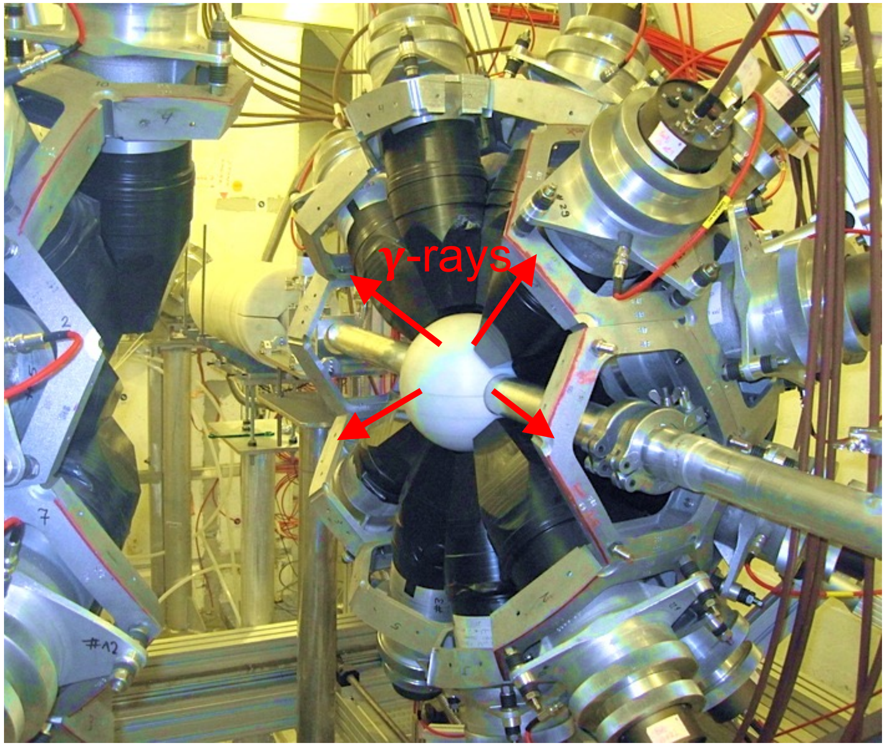
Detectors for (n,γ) cross section measurements

Measuring a (n,γ) cross section relies on counting the γ-ray cascades emitted in the neutron capture. Need to detect γ-ray cascades with an efficiency which is independent of the **unknown nuclear EM de-excitation** scheme.

- 100% efficiency **calorimeters**. Large scintillator arrays (10 MeV)
- **Total energy detectors** (TED) for which $\epsilon = k \cdot \sum E_\gamma$

The n_TOF Total Absorption Calorimeter (TAC) with 40 BaF_2 crystals. CIEMAT is leading the experiments with the TAC.

C. Guerrero et al., NIMA 608 (2009)
https://doi.org/10.1016/j.nima.2009.07.025
C. Guerrero et al., NIMA 671 (2012)
https://doi.org/10.1016/j.nima.2011.12.046

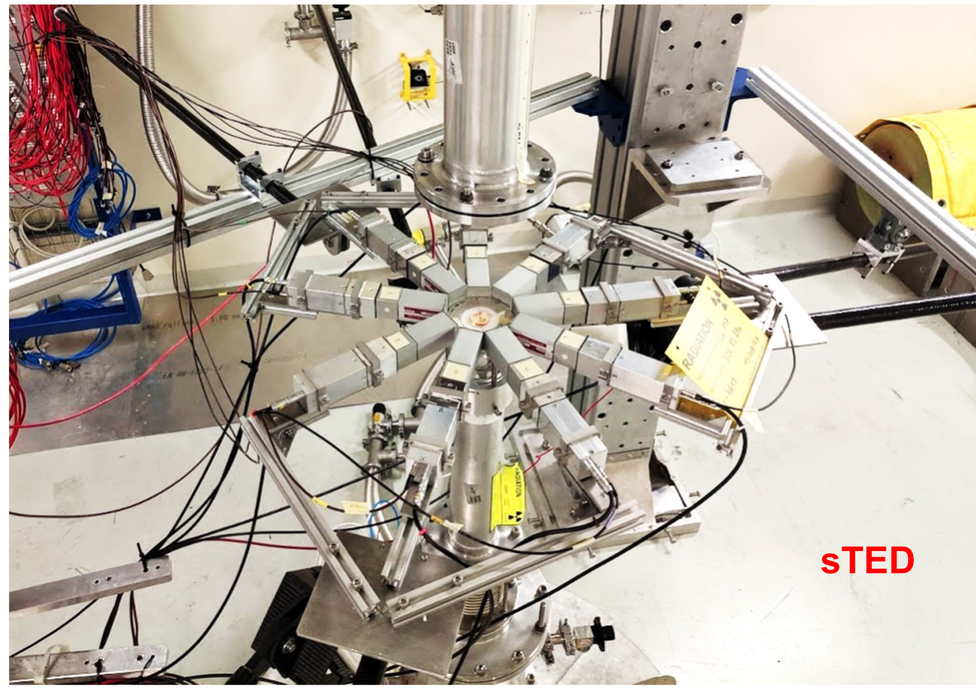


Total Energy detectors for high counting rate measurements

For low efficiency liquid scintillators,

$$\epsilon \simeq k \cdot \sum E_\gamma$$

Use of the pulse height weighting technique (PHWT).



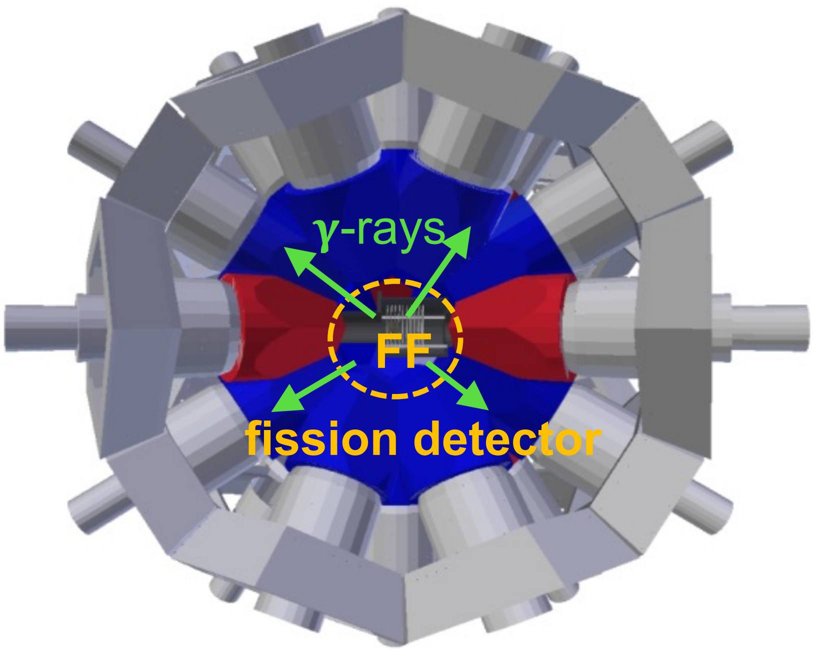
Deuterated liquid scintillator array sTED for very high counting rates (3 MBq) and suppression of the spallation flash (conditions at EAR2).

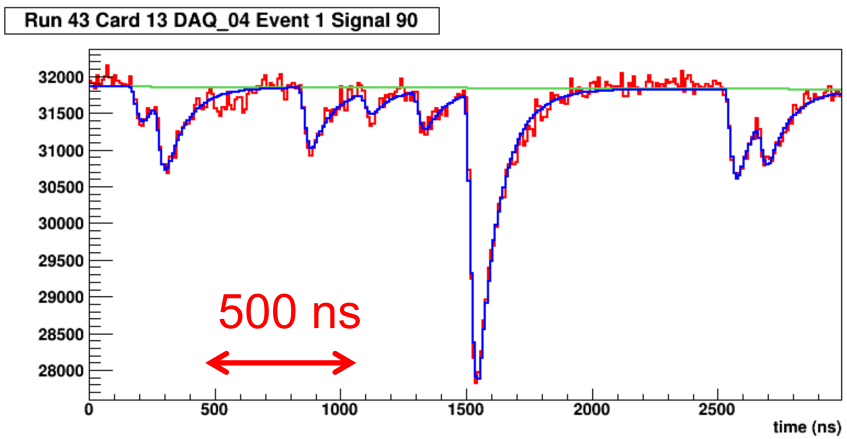
CIEMAT - V. Alcayne et al. Paper in preparation

Simultaneous ^{239}Pu(n,γ) and (n,f) measurement

Combined fission and capture detection. Collaboration between CIEMAT, JRC-Geel and U. Lodz. (*A. Sánchez PhD thesis*).

Experiment with 30 mg of ^{239}Pu (2 MBq / mg)



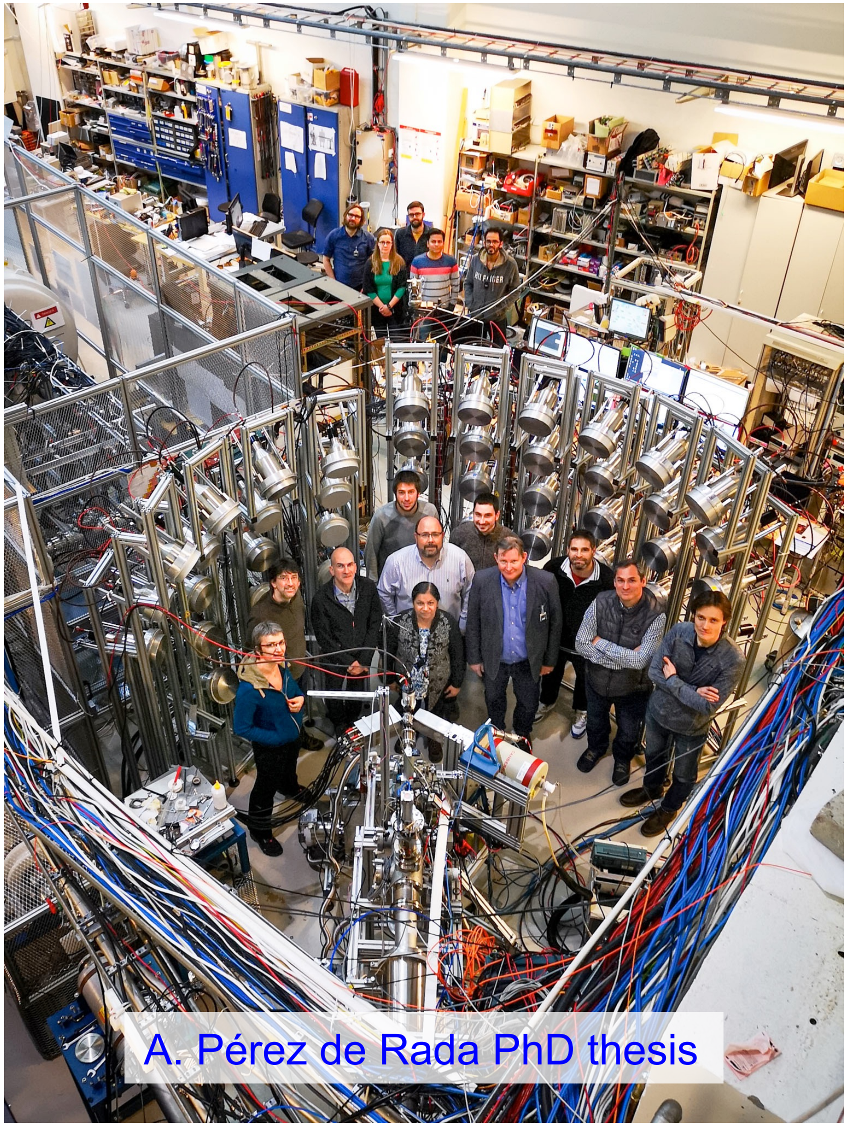


Ciemat
Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas

UNIVERSITY OF LODZ

Joint Research Centre
JRC

The MOdular Neutron SpectromeTER (MONSTER)



MONSTER is world's largest array for **β-decay measurements**, formed by 53 EJ301/BC501A liquid scintillator cells.

Designed by CIEMAT and built in collaboration with the Spanish company Scientifca Internacional S.L (one patent).

Driven by an international collaboration CIEMAT – IFIC – VECC Calcatta – University of Jyväskylä – Universitat Politècnica de Catalunya.

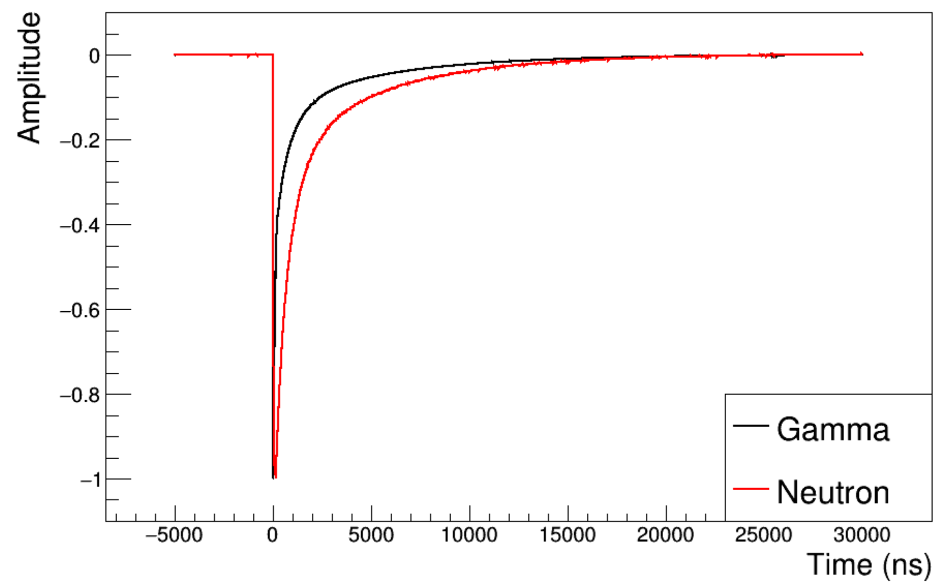
Experiments at GSI/FAIR (GE), Neutrons for Science – SPIRAL2 (FR), CERN-ISOLDE (CH), CMAM and CNA (ES)

Detectors for fundamental science and applications

Cs_2LiYCl_6:Ce (CLYC) inorganic scintillator that offers **combined neutron** and **γ-ray detection**:

- Typical **γ**-ray resolution ~5% @ 662 KeV.
- **Thermal neutron** detection via $^{6}Li(n,\alpha)^{3}H$ reaction.
- **Fast neutron** detection possible with ^{7}Li and ^{35}Cl.
- 10-100 times faster than ^{3}He.

Successful neutron background measurements at the **Laboratorio Subterráneo de Canfranc** with two 2”x2” CLYC detectors (*J. Plaza et al., in preparation*)



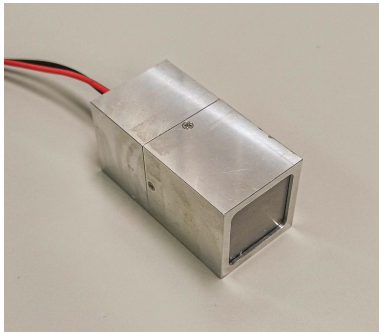
CLYC as combined neutron/γ spectrometer & dosimeter

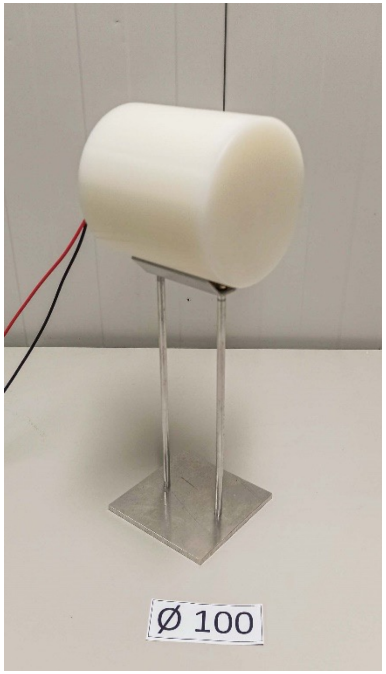
The **CLYC Neutron Gamma ONion** detector:

- Small CLYC inserted in polyethylene cylinders (Bonner– like system).
- Monte Carlo simulation of response for each cylinder.
- Deconvolution process to obtain the dose.

Capable of measuring neutron / **γ** fields relevant to:

- Nuclear waste & nuclear facilities
- Neutrons produced in proton therapy





The fully digital data acquisition system DAISY

Based on commercial AD14 Teledyne SP Devices digitisers.

- 14 bits vertical resolution
- 1 Gsample/s
- Various types of firmwares for triggered/trigger-less operation

We have developed on-line pulse shape analysis routines adequate for all types of detectors:

- Germanium (high energy resolution)
- Scintillators (good energy resolution, fast timing, particle type discrimination)
- ^{3}He Proportional counters with pulse shape analysis)

...

D. Villamarin et al, submitted to NIMA

Future challenges

I. Detectors for (n,γ) cross section measurements

1. New generation of total absorption calorimeters (TAC).

- Improve the **signal to background** ratio (induced by neutrons) and **reduce the energy deposition** per crystal. Go for **better resolution scintillators** ($LaCl_3$…), **larger segmentation** (various layers), use of **SiPMT** (less mass between layers). Preliminary studies done in EC projects (CHANDA) and FPN projects.

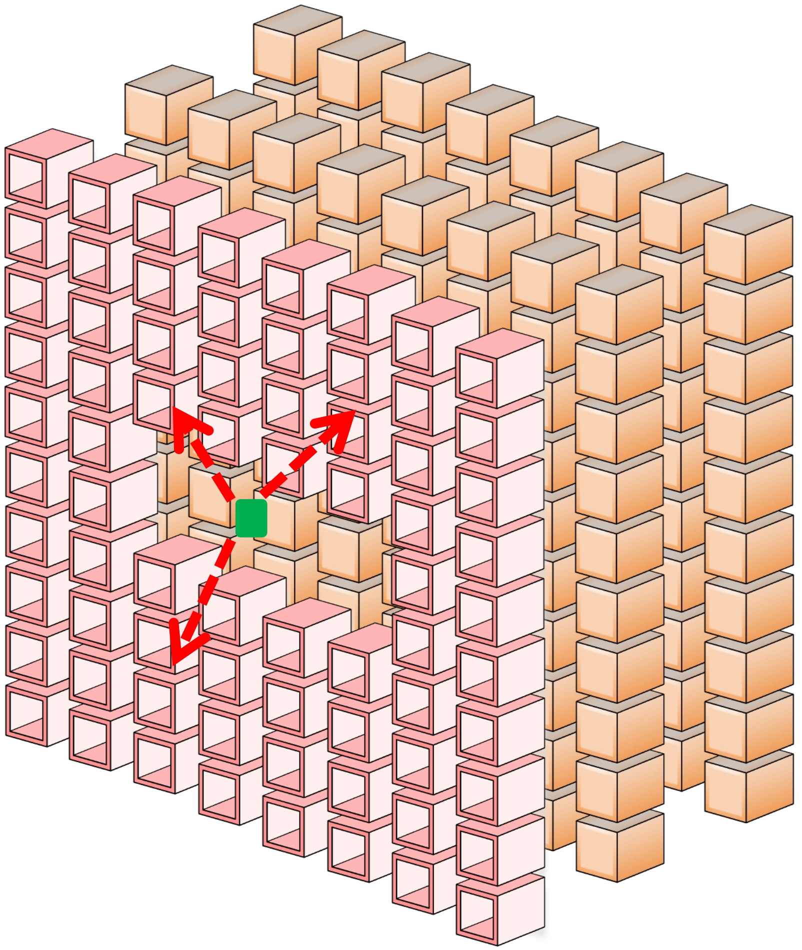
2. New generation of total energy detectors (TED)

- **Higher efficiency total energy** detectors. Proven recently that they are possible (E. Mendoza et al.). Concept of a slice-TED.
- **Solid deuterated organic scintillators**: d-stilbene (IFIC) and plastic scintillators (CIEMAT). Better handling, less toxic than liquids, less dead material, easier coupling to photosensors.

Highly segmented calorimeter

- Several layers of detectors.
- Small scintillator crystal volume.
- Readout with low mass photosensors.
- Fast timing (ns) and low electronic noise.
- Imaging capabilities.
- Background discrimination:
  - Events coming from outside.
  - Events not originating at the centre.
  - Multiplicity vs energy.

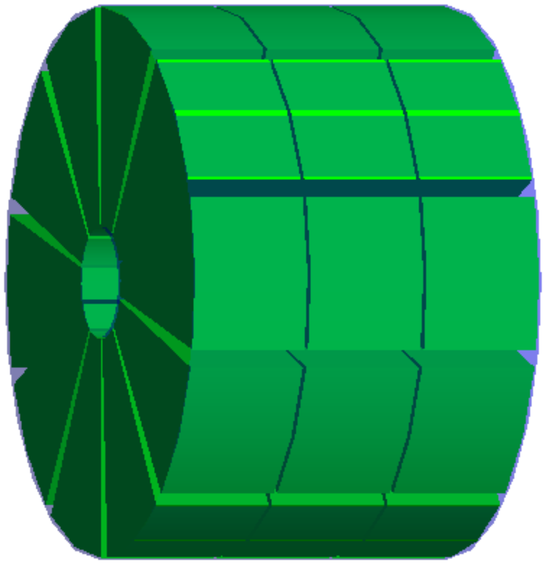
Time frame: after the long accelerator shutdown LS2 (2028 ->)



The slice-TED concept

In a recent paper, we have demonstrated that it is possible to have a high efficiency Total Energy Detector.

E. Mendoza et al., "Neutron capture measurements with high efficiency detectors and the Pulse Height Weighting Technique", NIMA 1043 (2023).
https://doi.org/10.1016/j.nima.2022.167894



Array of deuterated organic scintillators (liquid or plastic):

- 4 times higher efficiency than standard TED setups / 4 times less beam time (months to weeks).
- Lower sensitivity to the anisotropic emission or to angular correlations of the measured **γ**-rays.
- Low sensitivity to scattered neutrons.
- If possible, with low mass photosensors.

To be built and commissioned at n_TOF in 2024/2025.

Future challenges (ii)

II. Detectors for β-decay and (α,n) reaction studies

1. Neutron detectors

- **Solid/liquid scintillators**. Test of new materials (d-stilbene) for lowering the detection threshold / extending the range to low energies.
- Neutron transparent detector housing and direct optical coupling (no windows)
- Development of commercial **solid detectors** with good **pulse shape discrimination** capabilities (not yet there).
- Use of **highly segmented 4π arrays** for increasing the total detection efficiency without spoiling the time resolution.

2. γ-ray detectors

- **Inorganic scintillators**. Combined **γ**-ray and neutron detection with large volume Total Absorption Spectrometers based on CLYC. Simultaneous Total Absorption **γ**-ray spectroscopy and beta-delayed neutron emission probabilities with one single detector.
- Incorporation of **low mass photosensors and low noise electronics**, for reducing the thresholds down to 10 – 100 keV.

Future challenges (iii)

III. Applications

1. **Medical applications and nuclear waste characterisation**.

- Combined neutron and gamma-ray dosimetry and (low resolution) spectroscopy. CLYC detectors + unfolding techniques.

2. **Particle imaging.** Add imaging capabilities without efficiency loss -> analysis based on neural networks.

3. **Fusion / IFMIF DONES**. Monitors and detectors capable of standing very high neutron fluxes and perform experiments in high background conditions.

Summary and conclusions

We require a large variety of detectors for our experiments: neutrons (scintillators, ^{3}He…), **γ**-rays (inorganic and organic scintillators), charged particles (fission detectors).

Our scientific program requires access to several facilities -> movable detectors.

At CIEMAT we have a large experience with detector R&D for liquid scintillators, digital data acquisition systems + analysis algorithms and Monte Carlo simulation (coupled neutron and **γ**-ray problems).

The new detectors to be developed would benefit from electronics and photosensor developments which would allow us to move from photomultipliers to very compact photosensors (SiPMs). The main problem is the light output vs electronic noise for reaching low thresholds. **DRD2 or DRD6?**

From the point of view of DAQ, we would benefit from fast digitisers (>14 bits & Gs/s) with on board pulse shape analysis capabilities. The processors/FGA should be programmable in high level languages. **DRD7?**

Summary and conclusions (ii)

We have R&D projects with the nuclear industry and are involved in medical applications.

We are open to collaborations, as it is already the case with our CIEMAT colleagues from DM and, very recently, from DUNE.

Members of the team (not only dedicated to detector R&D)

People (6 +1 staff, 2 postdocs, 2+2 PhD students)	**Detetector R&D activities**
Daniel Cano Ott (Prof. de Investigación)	Fundamental science / applications
Vicente Bécares Palacios (Científico Titular)	Applications / Reactors
Jorge García (Técnico de grado medio)	Applications / electronics
Trino Martínez Pérez (Científico Titular)	Fundamental science / applications
Emilio Mendoza Cembranos (Científico Titular)	Fundamental science / applications
Víctor Alcayne Aicua (postdoc)	Fundamental science
Alberto Pérez de Rada Fiol (postdoc)	Fundamental science
Julio Plaza del Olmo (Científico de la Defensa)	Fundamental science / applications
David Villamarín (Científico Titular)	DAQ / applications / Fund. science
Adrián Sanchez Caballero (doctorando - FPN)	Fundamental science
Carlos Ballesteros Bejerano (doctorando - CIEMAT)	Applications / fundamental science
Francisco Álvarez Velarde (Científico Titular)	Simulations
Pedro Martínez (doctorando – CIEMAT)	Simulations
Sonia Panizo (doctorando – CIEMAT)	Simulations