A Compton-TDCR experiment for low energy non-linearity measurement of scintillators

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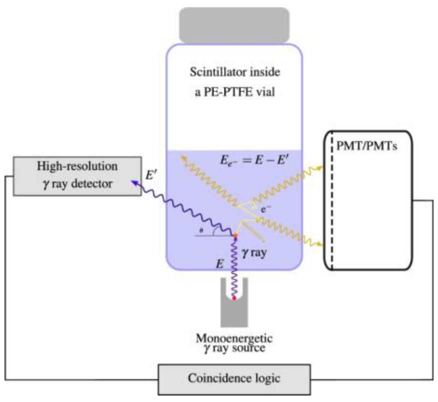
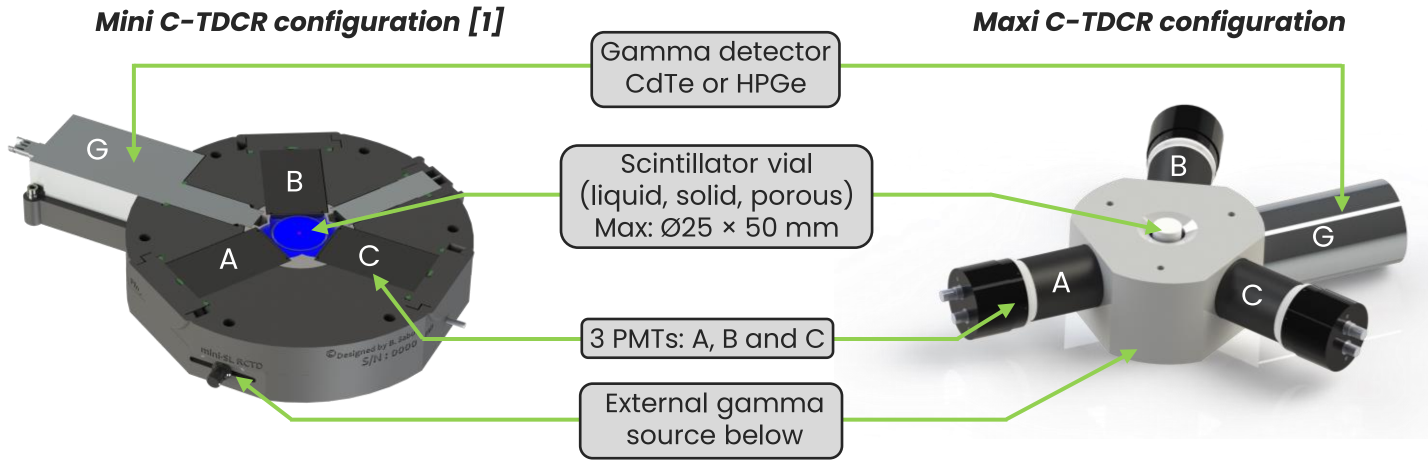
Context

Non-linearity of a scintillator refers to the **non-proportional relationship** between the **energy deposited in the material** and the **number of scintillation photons produced**. At low energies, recombination and saturation processes lead to a reduction in light yield. To characterize this non-linearity, the Laboratoire National Henri Becquerel (LNHB) has developed **two Compton-TDCR** (Triple-to-Double Coincidence Ratio) systems [1], referred to as **Mini** and **Maxi C-TDCR**. In these setups, three photomultiplier tubes (PMTs) detect the scintillation photons, while an external gamma-ray source provides a well-defined deposited energy through Compton scattering. By measuring coincidences between PMTs and scattered Compton photons, the method enables the determination of the **scintillator non-linearity curve**, particularly in the **low-energy region** (**below 30 keV**).

Diagram of the Compton-TDCR method [1]



Mini C-TDCR configuration [1] *Maxi C-TDCR configuration*



Experimental setups & Data analysis

Mini C-TDCR was designed to be a **prototype device**, whereas **Maxi C-TDCR** aims to be the **final version**.

	Mini C-TDCR	Maxi C-TDCR
Photomultipliers	Hamamatsu compact, 32 mm square	Hamamatsu custom, 51 mm
γ detector	CdTe, Amptek	HPGe, ORTEC
Incident beam	^{241}Am 74 MBq source $E_i = 59.54$ keV	
Digitizer	CAEN DT5751, 4 channels, 10 bits @ 1 GS/s	CAEN DT2751, 16 channels, 14 bits @ 1 GS/s

Post-processing data code in RUST and Python:
- → Apply dead time and coincidence window on 4 channels;
- → Calculate single (A, B, C, G) and coincidence (AB,… , AG,… , ABC=T ,ABG,… , ABCG) counting rates;
- → Apply analytical random coincidences correction [2].

Post-processing feasible on a wide range of coincidence windows to fit **scintillator decays**.

Non-linearity curve (with γ channel)

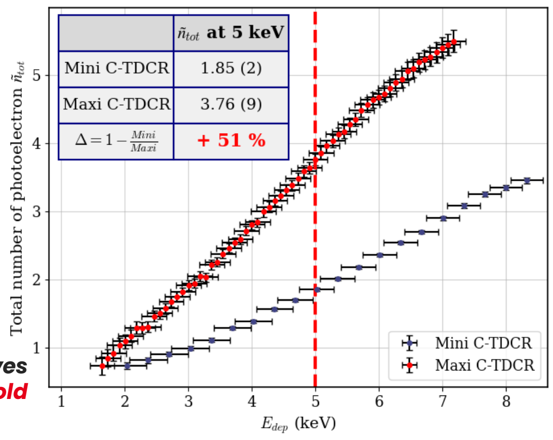
For **non identical PMTs** (X = A or B or C) in coincidence with γ channel G, relation between detection efficiency ε_{XG} and mean number of photo-electrons $\tilde{n}_{XG}$ in PMT X is : $\varepsilon_{XG}(E_{dep}) = 1 - e^{-\tilde{n}_{XG}(E_{dep})}$

Due to the **relationship** between counting rates and detection efficiency and the **independency** between PMTs (X ≠ Y):

$$\frac{TG}{XYG}(E_{dep}) \approx \frac{\varepsilon_{TG}}{\varepsilon_{XYG}} = \frac{\varepsilon_{XG}\,\varepsilon_{YG}\,\varepsilon_{ZG}}{\varepsilon_{XG}\,\varepsilon_{YG}} = \varepsilon_{ZG}(E_{dep})$$

➔ The **total mean number of photoelectrons** is : $\tilde{n}_{tot}(E_{dep}) = \tilde{n}_{XG} + \tilde{n}_{YG} + \tilde{n}_{ZG}$

- ❑ **Mini C-TDCR**: The e⁻ energy range covers from 2 to 8.5 keV with a 260 eV resolution.
- ❑ **Maxi C-TDCR**: The e⁻ energy range covers from 1.6 to 7.2 keV with a 140 eV resolution.



Non-linearity curves
Scintillator : 10 mL UltimaGold

Triple-to-Double Coincidence Ratio results (without γ channel)

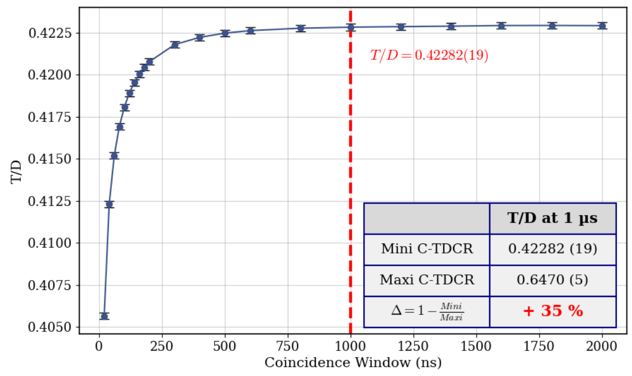
T/D is an indicator of the **detection efficiency of the scintillator.**

$$\frac{T}{D} = \frac{\textit{Triple coincidences}}{\textit{Double coincidences}}$$

PMTs collecting more light, T/D increases (between 0 and 1)

- ❑ Test with Tritium: For every coincidence window, Maxi C-TDCR has a much **more detection efficiency** than Mini C-TDCR and Micro TDCR [3].

T/D ratio as a function of coincidence window
Scintillator : 10 mL UltimaGold + ^{3}H



Comparison of global T/D ratio
Scintillator : 10 mL Toluene PPO + ^{3}H

	T/D at 40 ns
Micro TDCR [3]	0.766 (1)
Mini C-TDCR	0.660 (1)
Maxi C-TDCR	0.810 (1)
$\Delta_{Micro} = 1 - \frac{Micro}{Maxi}$	**+ 5 %**
$\Delta_{Mini} = 1 - \frac{Mini}{Maxi}$	**+ 18 %**

Maxi C-TDCR perspectives

Electron deposited energy E_e depends on **incident energy** beam and **angular position** of the γ detector: $E_e = E_i - E_f$ $\quad E_f = \frac{E_i}{1 + \frac{E_i}{511\ \text{keV}}(1 - \cos\theta)}$

Due to **geometrical consideration** and Compton edge: **One** incident energy and **one** γ detector position = **energy range of** E_e

❑ **Currently**, **Mini** and **Maxi C-TDCR** have:

→ 1 energy beam: $E_i = 59.54$ keV

→ 1 γ detector position: $\theta_\gamma = 90°$

$$E_e \in [2.91\,, 9.15]\ \text{keV}$$

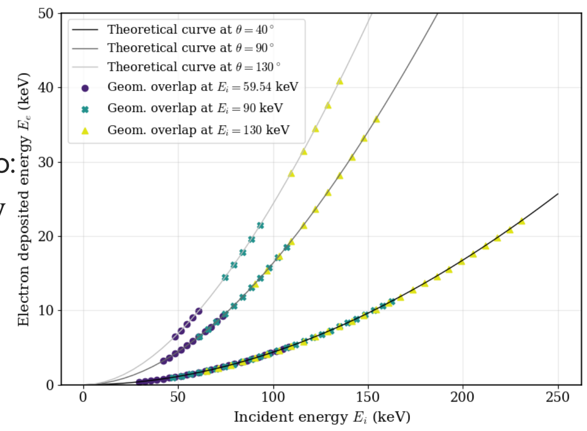
❑ **In the future**, **Maxi C-TDCR** aims to:

→ 3 energy beams: $E_i = 60; 90; 130$ keV

→ 3 γ detectors at : $\theta_\gamma = 40°;\ 90°;\ 130°$

$$E_e \in [0.44\,, 42.15]\ \text{keV}$$

Energy range of the deposited electron for 3 incident energy beams and 3 γ detector positions



Final results

In this work, **two Compton-TDCR configurations** were presented: the **Mini** and **Maxi C-TDCR** systems. In **conventional TDCR** measurements, the results obtained with the **Maxi configuration** show a **significantly higher detection efficiency**. In **Compton-TDCR mode**, both setups allow the determination of the scintillator **non-linearity curve** in the **2 to 7 keV energy range**, with a **higher sensitivity and improved energy resolution** for Maxi. This device can be used to characterize a wide variety of scintillators, including **liquid, plastic, porous, inorganic crystals and glasses scintillators**. Future developments of the Maxi C-TDCR will include the implementation of **three gamma detectors** positioned at different scattering angles, as well as the use of **three incident beam energies** to extend and refine the non-linearity measurements.

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