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Enhancing 4πβ–γ Coincidence Detection with Machine Learning for Optimized Absolute Radionuclide Activity Measurement

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Introduction

- **Accurate measurement of radionuclide activity (in Becquerels) is critically important** for safety, establishing consistent standards, and for the International Monitoring System (IMS) to detect nuclear testing as part of the CTBT.
- The **4πβ-γ coincidence counting method is a foundational, absolute technique** that has been used for decades to measure radioactivity accurately.

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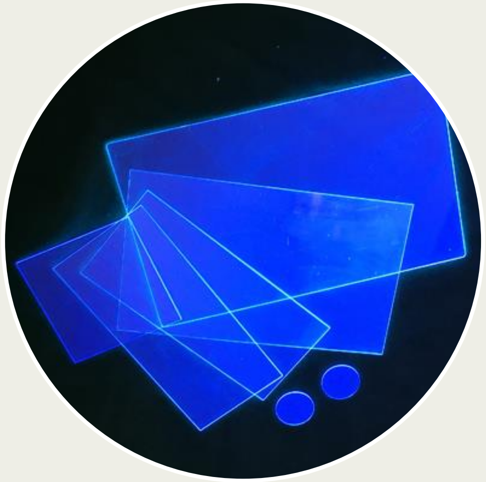
Introduction

- **Plastic scintillators are highlighted as a cost-effective technology** that is commonly used for the beta-detection channel in these 4πβ-γ coincidence counting systems.

- **Advanced electronic digitizers, an Offline Analysis Method (OAM) and Machine Learning (ML)** are identified as key technological advancements that could improve data acquisition, precision, and can save both time and cost in processing.



Objectives

- To improve **the effectiveness of the plastic scintillator** as a β counter in the 4πβ-γ system.
- To develop **an improved offline analysis technique incorporating machine learning** for digital pulse processing systems.
- To **improve the accuracy and efficiency of absolute radionuclide activity measurements** with the developed 4πβ-γ detection system by employing only one data acquisition experiment, reducing both time and cost.

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Methods

- In beta decay immediately followed by gamma emission, **the coincidence counts are based on the disintegration of the same atom**.

- **In simple terms,**

$$\rho_\beta = \varepsilon_\beta A \quad ,$$

$$\rho_\gamma = \varepsilon_\gamma A \quad , \text{ and}$$

$$\rho_{\beta\gamma} = \varepsilon_\beta \varepsilon_\gamma A \quad .$$

→

$$A = \frac{\rho_\beta \rho_\gamma}{\rho_{\beta\gamma}}$$

$$\varepsilon_\beta = \frac{\rho_{\beta\gamma}}{\rho_\gamma}$$

$$\varepsilon_\gamma = \frac{\rho_{\beta\gamma}}{\rho_\beta}$$

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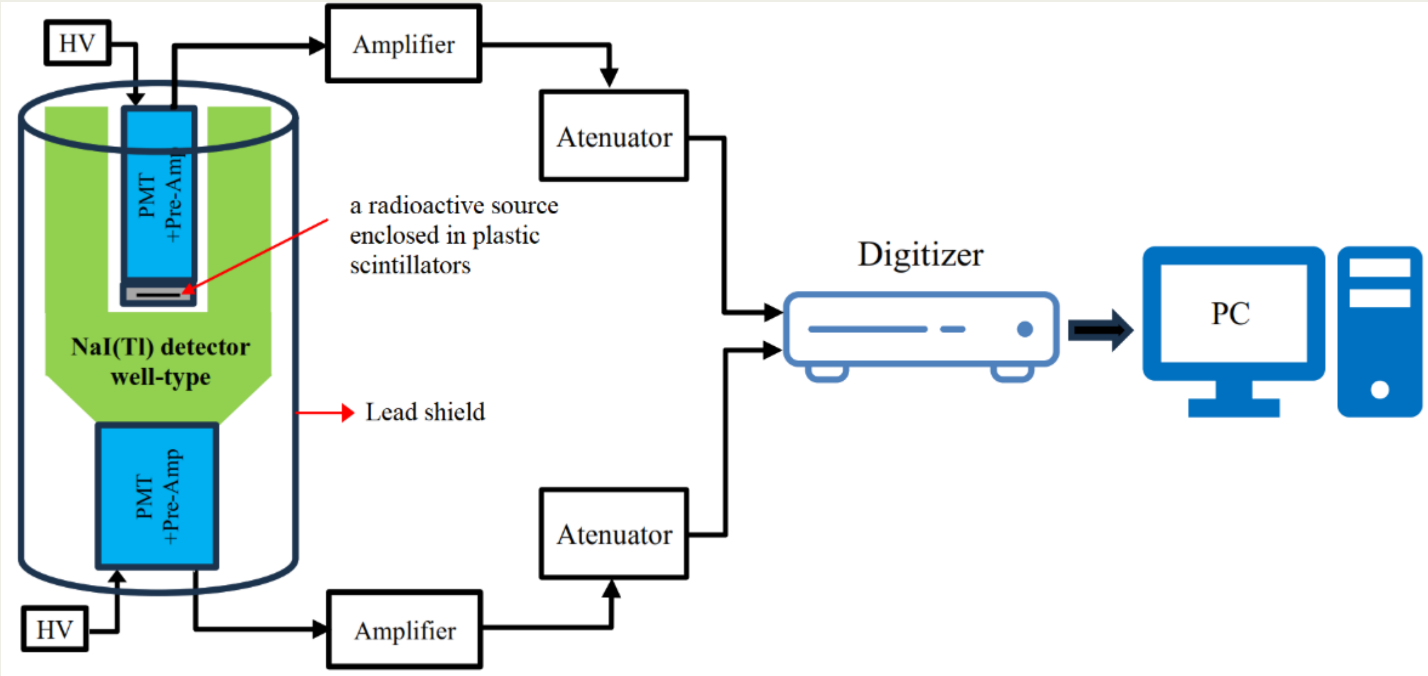
Methods

- To apply 4πβ-γ counting, at least **two independent detectors** are required, each sensitive to one type of radiation. Additionally, at least **one detector must have a 4π view** of the source to meet the requirements of the method.



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Methods

- to **correct** coincidence counting data for **the effects of non-extendable deadtime and accidental coincidences**.

$$\rho_{\beta\gamma} = \frac{R_c - (r_\beta + r_\gamma)R_\beta R_\gamma}{(1 - R_\beta\tau_\beta)(1 - R_\gamma\tau_\gamma)\mathrm{X}(r_\beta, r_\gamma) + R_c\tau_m \mathrm{Y}}$$

- Utilizing a 4πβ detector, **varying β efficiency and extrapolating it** to unit value can **derive an accurate value of the activity**, without needing to know the precise values of the nuclear decay scheme parameters.

$$\rho_\beta = A\left[1 - f_1\left[1 - \frac{\rho_{\beta\gamma}}{\rho_\gamma}\right]\right] \to A, \qquad as \ \frac{\rho_{\beta\gamma}}{\rho_\gamma} \to 1,$$

or equivalently

$$\frac{\rho_\beta\rho_\gamma}{\rho_{\beta\gamma}} = A\left[1 - f_2\left[\frac{1 - \frac{\rho_{\beta\gamma}}{\rho_\gamma}}{\frac{\rho_{\beta\gamma}}{\rho_\gamma}}\right]\right] \to A, \qquad as \ \frac{\rho_{\beta\gamma}}{\rho_\gamma} \to 1.$$

Practically, the functions of f_1 and f_2 are supposed to be polynomials in

$$\left[1 - \frac{\rho_{\beta\gamma}}{\rho_\gamma}\right] \text{ or } \left[\frac{1 - \frac{\rho_{\beta\gamma}}{\rho_\gamma}}{\frac{\rho_{\beta\gamma}}{\rho_\gamma}}\right].$$

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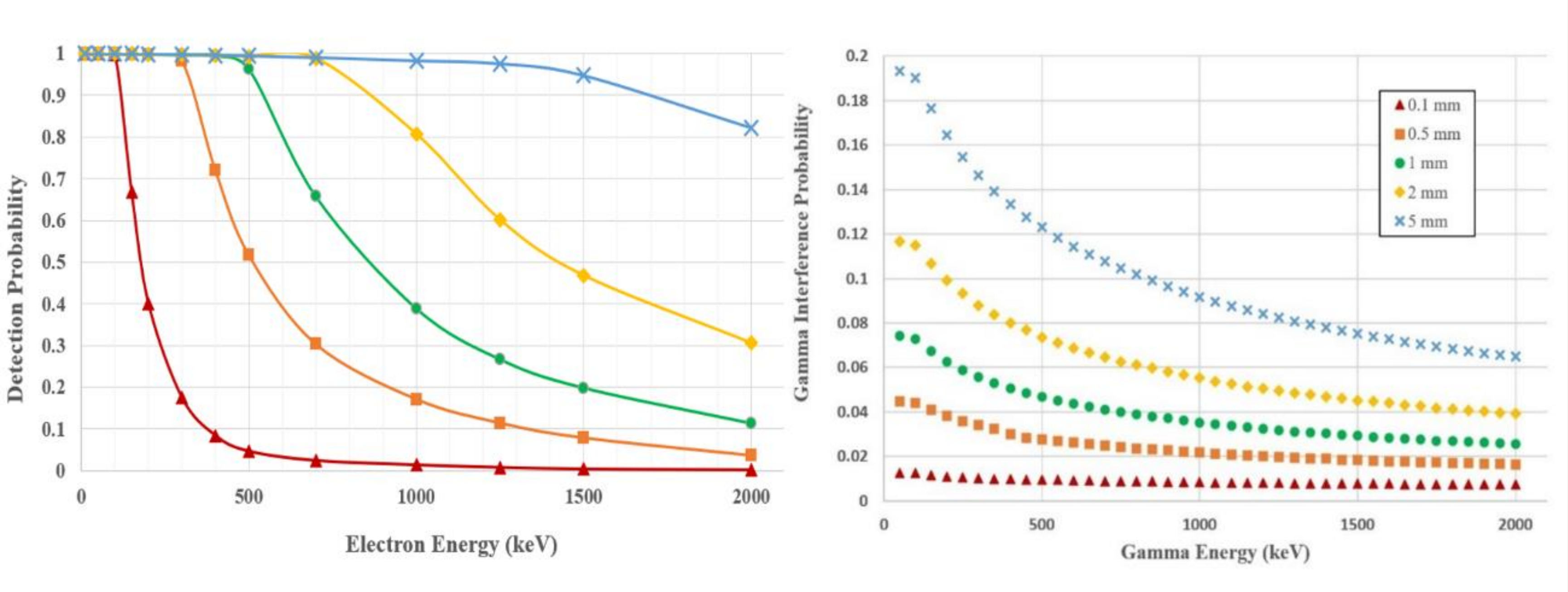
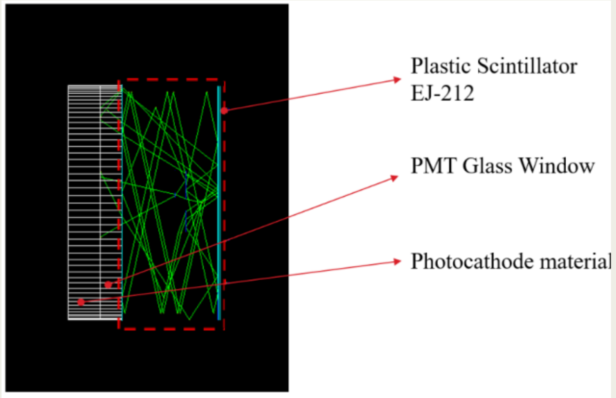
Methods

- The **GEANT4** simulation was used **to investigate the optimal thickness of the plastic scintillator** as the β detector, that absorbs incoming electrons while minimizing photon interference.





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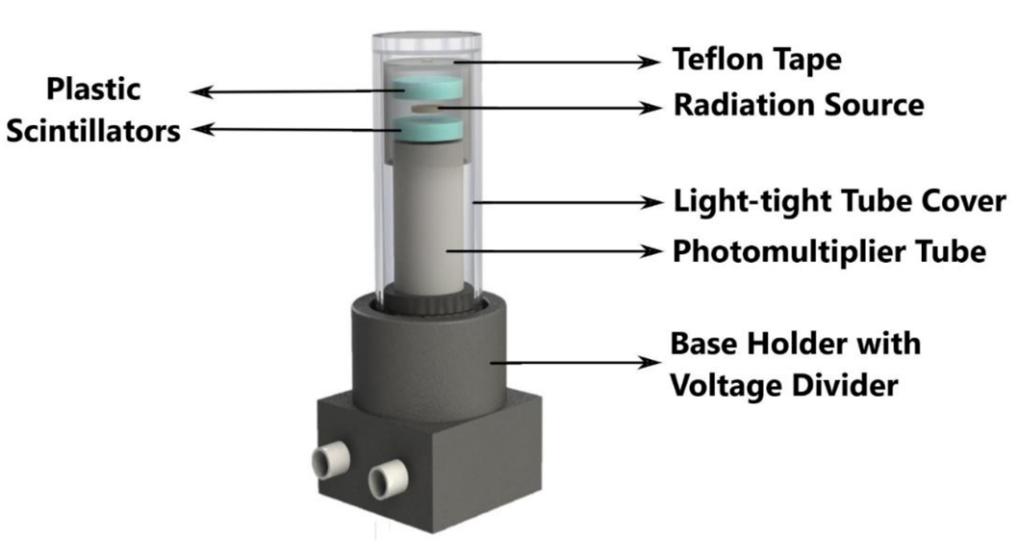
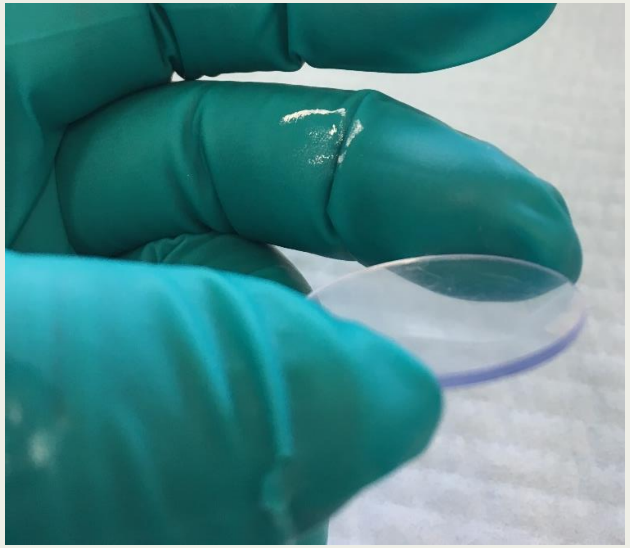
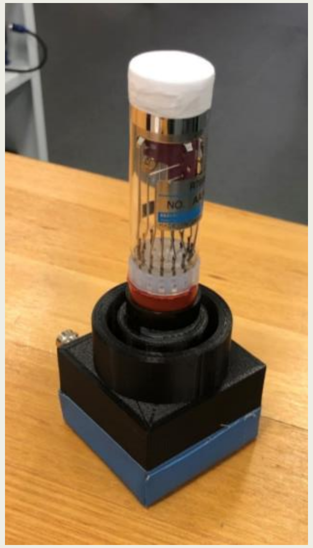
Methods

- For **Cobalt-60**, the beta detector setup consisted of **two 1 mm round plastic scintillators** wrapped in Teflon, with optical grease applied to eliminate air gaps, and without any cavity included.
- The ^{60}Co solution was dispensed on a plastic scintillator. Once dried, the scintillator was bonded to another one using BC-600 optical cement.

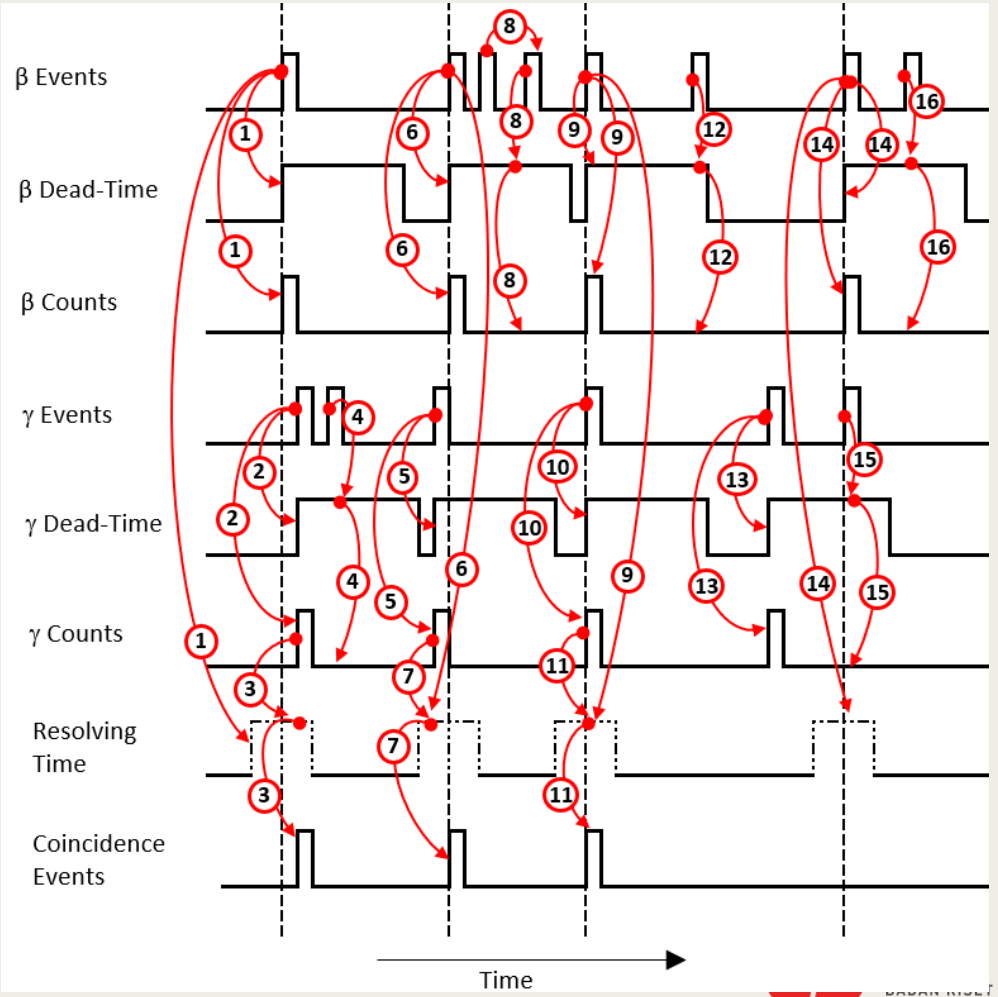






Methods

- The CAEN digitizer generates compact **binary list-mode data**, which we decoded **using Python for offline analysis**.
- **Valid β–γ coincidences** were identified within an **adaptive resolving time triggered by β events**.



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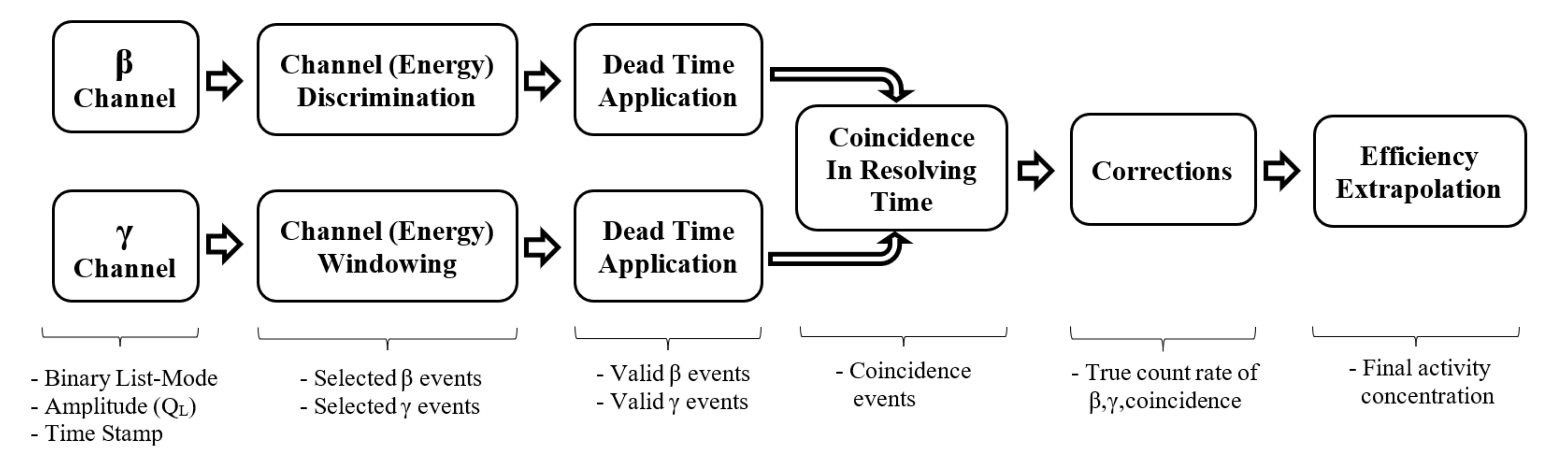
Methods

- Unlike conventional methods that require pre-defined parameters (dead time, threshold, resolving time, etc.) and repeated experiments, our **offline approach** allows **all parameters to be flexibly adjusted during analysis**.
- This **ensures reliable results** while avoiding hardware limitations and environmental fluctuations.



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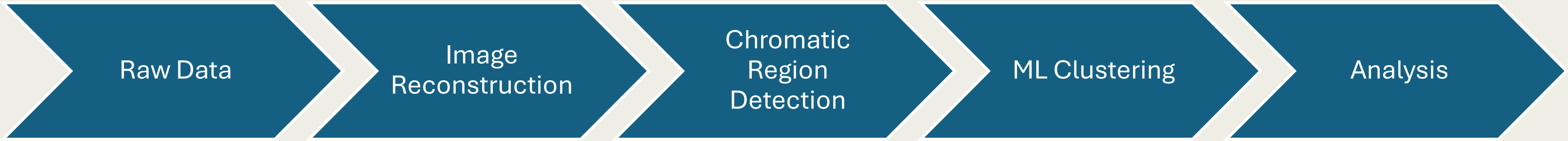
Methods

- A **machine learning (ML)** algorithm was implemented, especially to discriminate true β signals from noise**, enhancing the reliability of the coincidence counting process.**
- The ML: automatically **identify the high-density "chromatic"** region in PSD data and **determine the optimal PSD threshold** to separate particle types.



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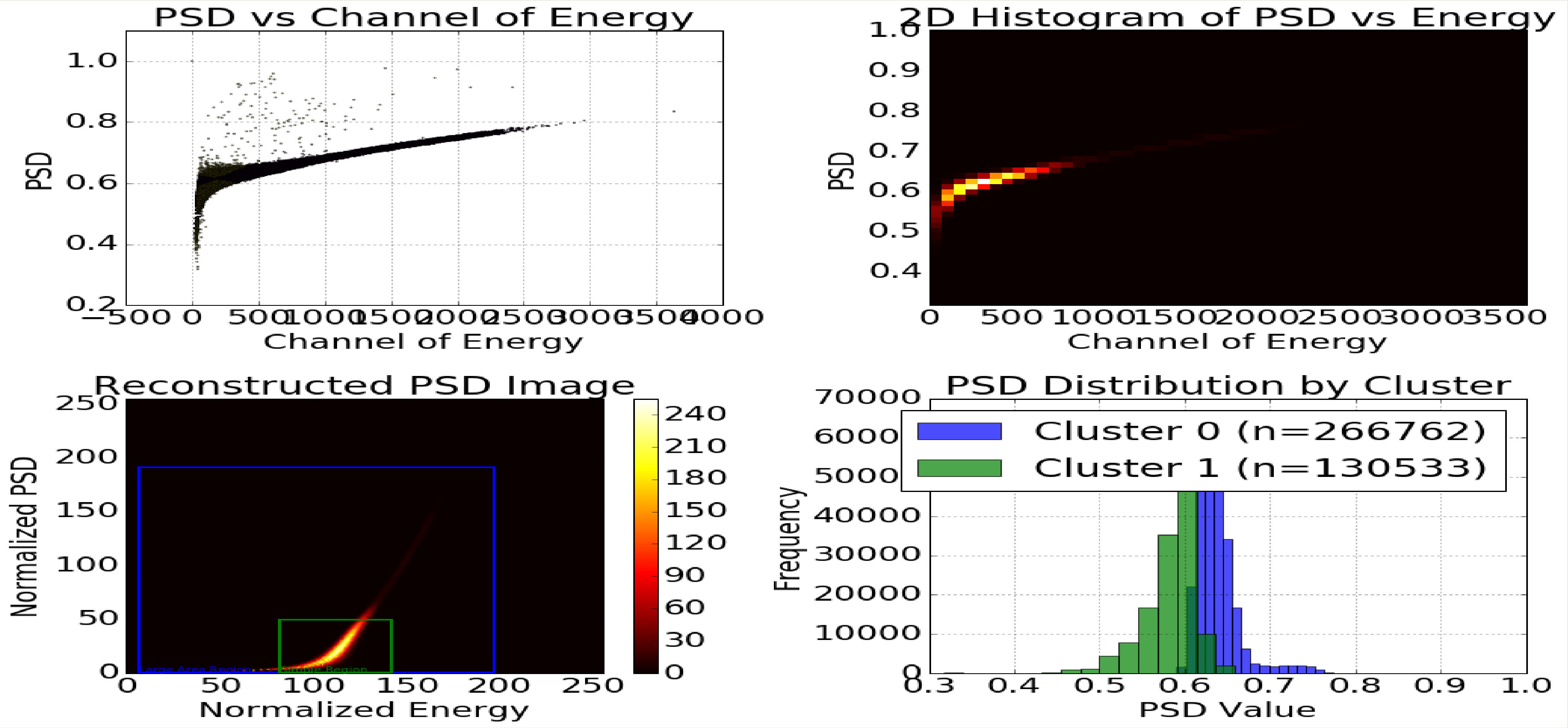
Methods



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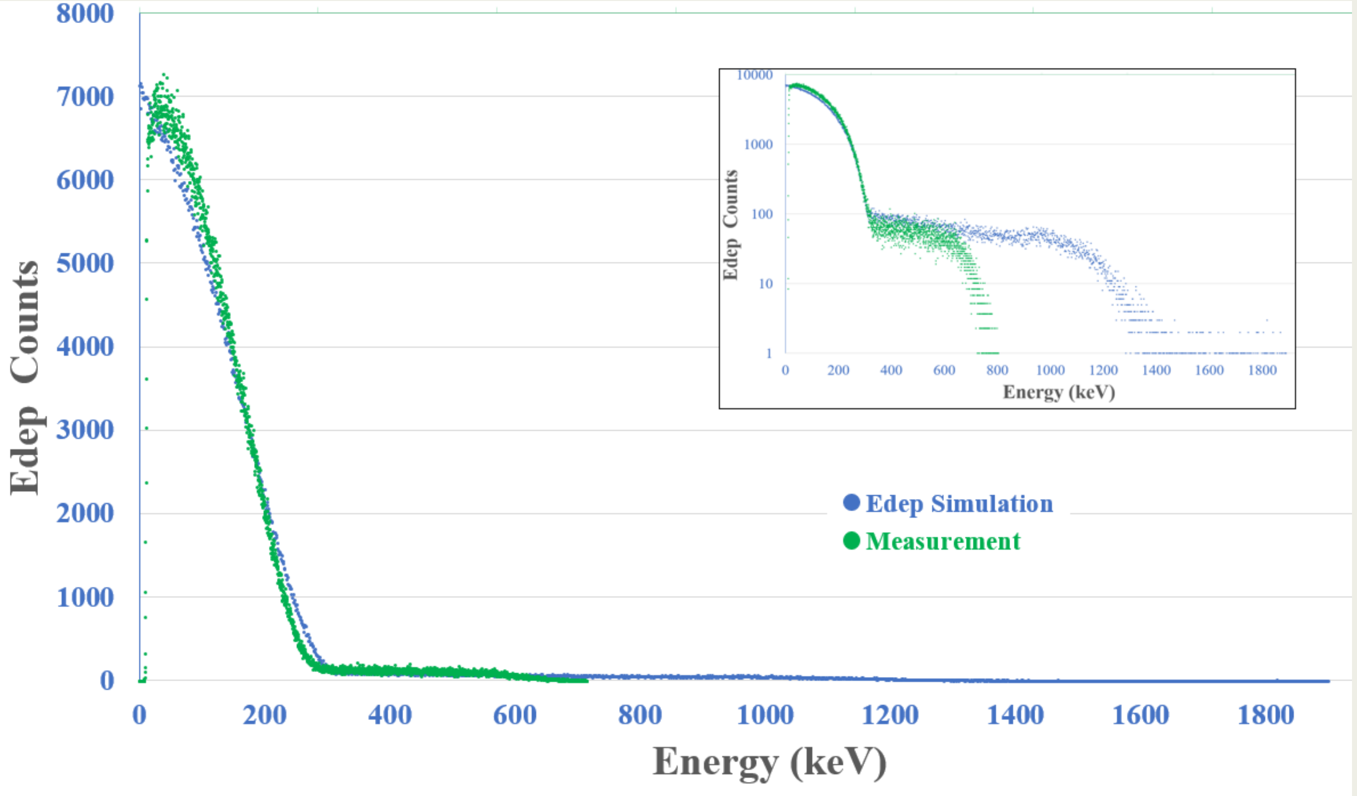
Results

- For the β detector, **the simulated spectrum** for the EJ-212 plastic scintillator **corresponds closely with the measured spectrum** of Cobalt-60



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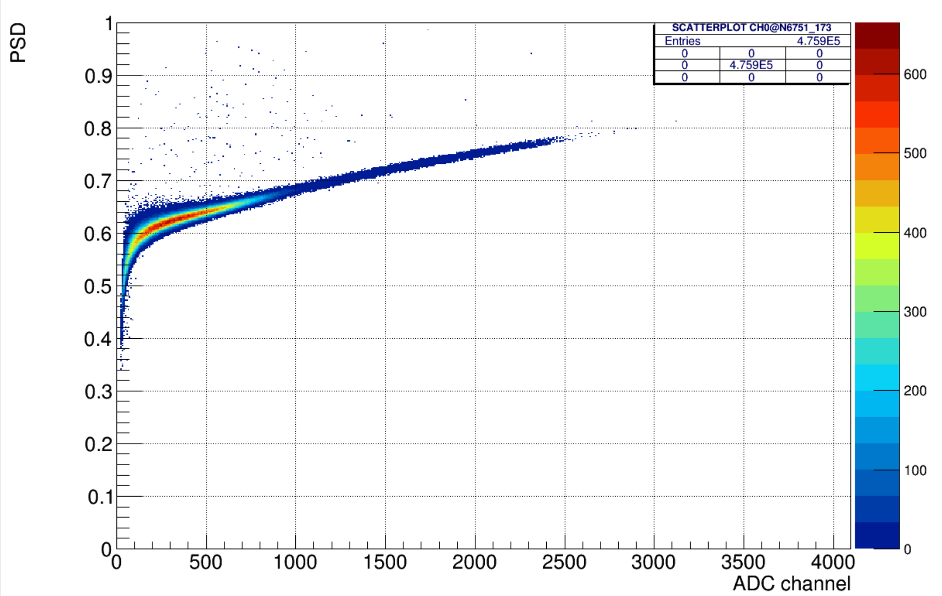
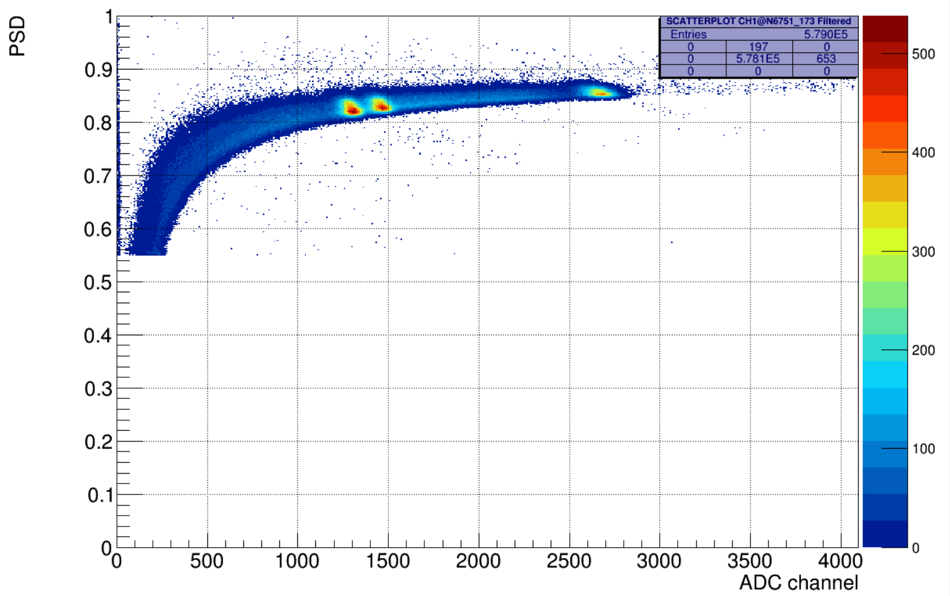
Results

- Two-dimensional **histograms of the β-channel and the γ-channel** generated from the CoMPASS software while measuring a 60Co source.





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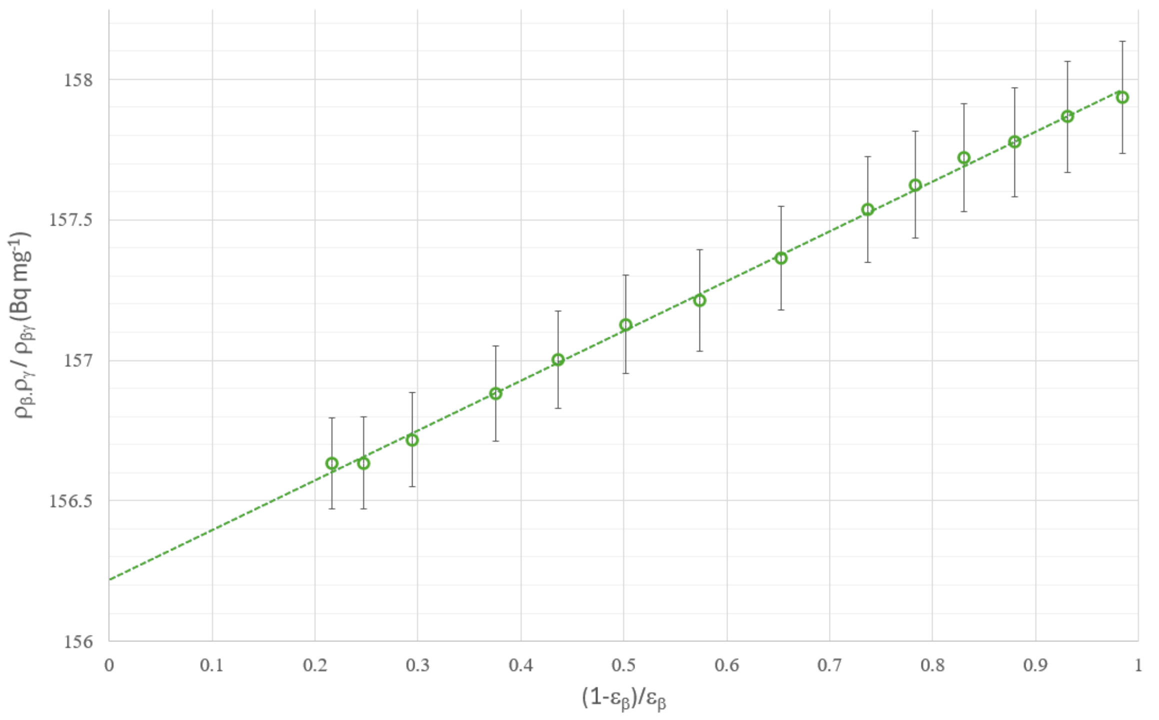
Results

- Setting **variation of beta efficiency and machine learning implementation** were addressed by **the offline analysis.**
- **Efficiency extrapolation** was performed **to obtain the final value of activity concentration** using only one set of experimental measurement data



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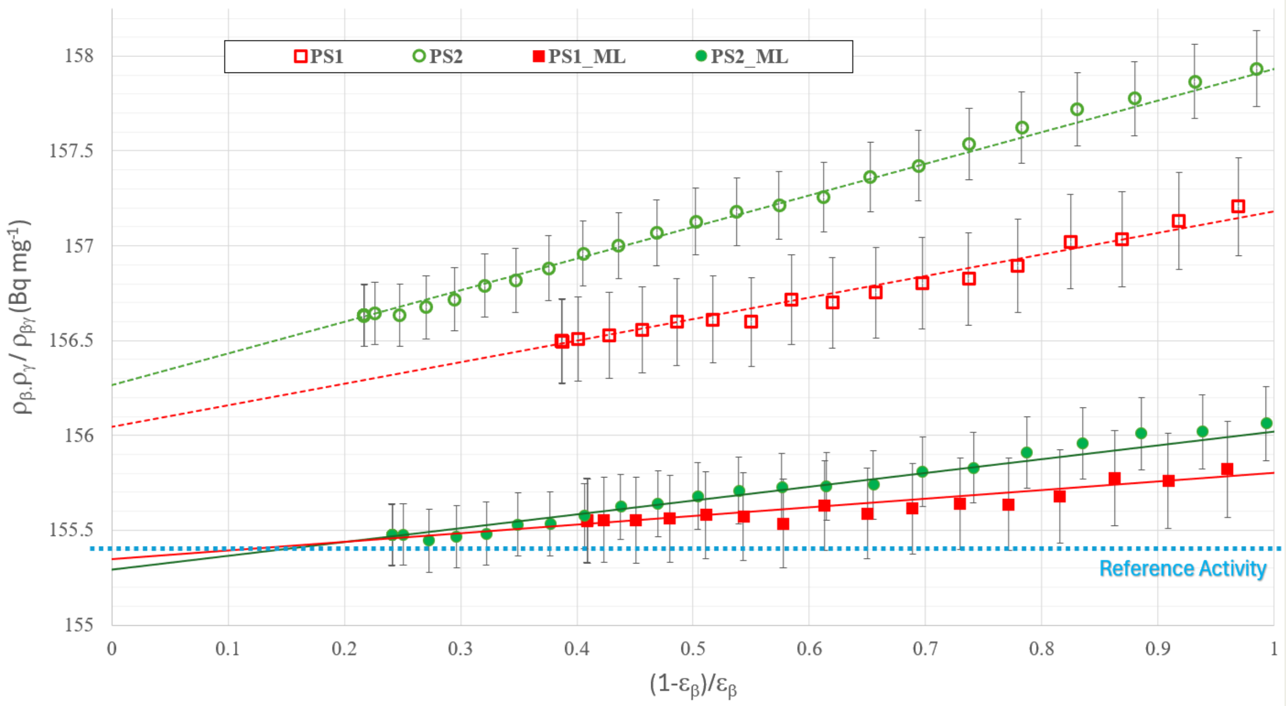
Results

- With **the reference value of 155.46 ± 0.4 Bq/mg**, the **application of machine learning improved the accuracy of the measurements** for both samples.
- For sample PS1, the result improved from 156.04 ± 0.16 Bq/mg **to 155.35 ± 0.16 Bq/mg**
- For sample PS2, the result improved from 156.3 ± 0.22 Bq/mg **to 155.29 ± 0.22 Bq/mg**.



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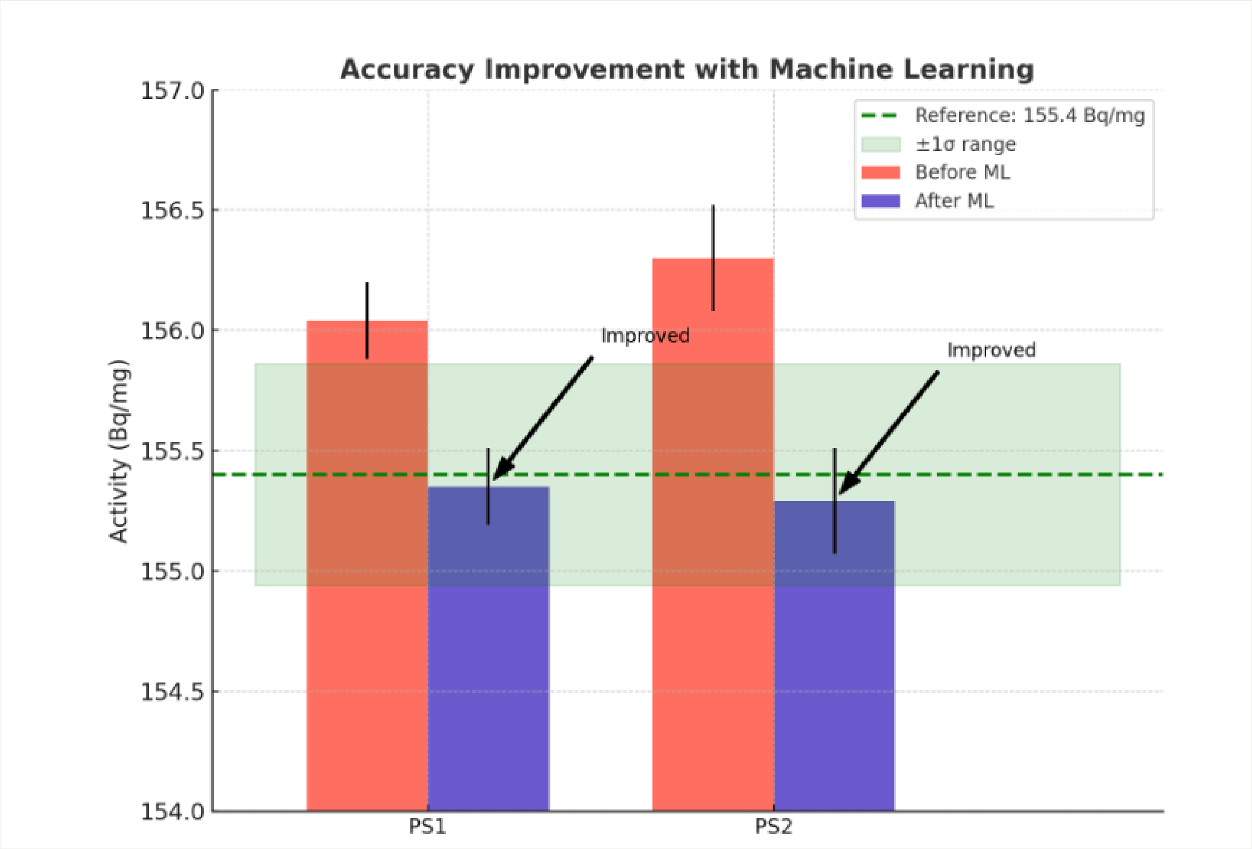
Results

- **Closer to Reference Value** – After applying machine learning, results for both samples (PS1 & PS2) aligned more closely with the reference.
- **Error Bars Within Uncertainty** – Post-ML measurements fall entirely within the reference uncertainty range (blue area).
- **Improved Accuracy** – Machine learning significantly enhanced the accuracy of radionuclide activity measurements.



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Conclusion

- **The offline analysis method integrated with machine learning** for coincidence counting using a 4πβ (Plastic Scintillator)–γ system was successfully implemented, **significantly enhancing the accuracy of absolute radionuclide measurements.**

- **In contrast to conventional techniques** that may require multiple experimental runs, **this approach enables accurate absolute radioactivity calculations from a single data acquisition**, thereby reducing measurement time and minimizing unwanted signal fluctuations.

- The system demonstrated **high accuracy** in determining the activity of ^{60}Co, with a deviation of only **0.09% from the reference activity**.

Thank You