Development of a Portable Low Background α and β Detection Module based on Micromegas and Waveform Digitizing Electronics

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Introduction

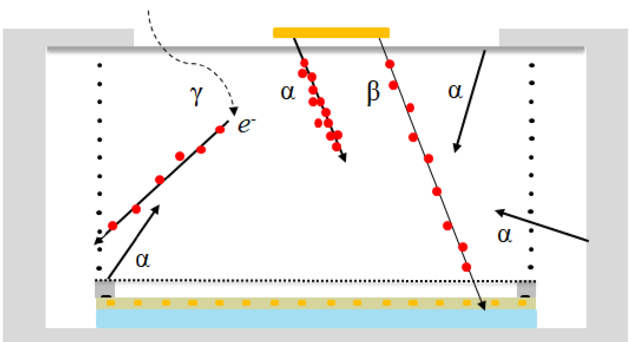
- **Applications of Alpha and Beta Radiation Detection:** Alpha (α) and beta (β) detection are widely used in nuclear physics, environmental monitoring, and nuclear safety. For instance, tritium (^{3}H) and 14-Carbon (^{14}C) isotope labeling are commonly used for labeling active pharmaceutical ingredients (APIs) in drug discovery. Additionally, α particles emitted by radioactive radon, released into the atmosphere, represent a considerable health hazard to humans.
- **Measurement Challenges:** Due to their specialized applications, the samples often exhibit weak levels of radioactivity, making high-sensitivity measurements particularly important. However, because of their limited penetration capabilities and significantly different energy characteristics, accurate measurement of α and β particles requires leveraging their distinct properties. In gaseous media, α and β particles' track lengths are longer than those in solid or liquid media, making their track features more prominent.
- **Detection System:** Consequently, a TPC (Time Projection Chamber) detector equipped with a micromegas anode plane is suitable for the detection and discrimination of α and β particles. Meanwhile, a waveform digitization electronics system has also been developed to support these measurements.

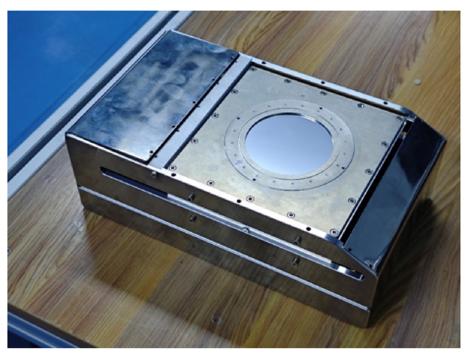
Prototype System

Detector Structure

The detector comprises a TPC with dimensions of $100\,\text{mm} \times 100\,\text{mm}$, featuring 60×60 anode strips in conjunction with a Micromegas detector consisting of 8 anti-coincidence pads. The TPC has a drift region of 53 mm and an avalanche amplification region of 0.1 mm.

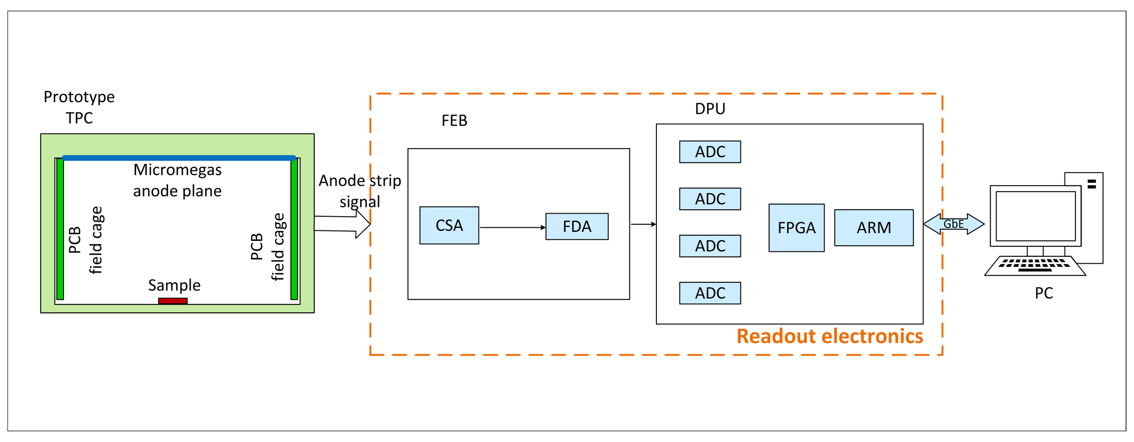
This configuration offers a compact and efficient design for tracking α, β, and background radiation particles, ensuring that their track features are accurately recorded and distinguished by track length, incident position, energy deposition, etc. The incorporation of anti-coincidence pads significantly enhances background rejection, particularly for cosmic μ particles, thereby improving the reliability of the measurements.



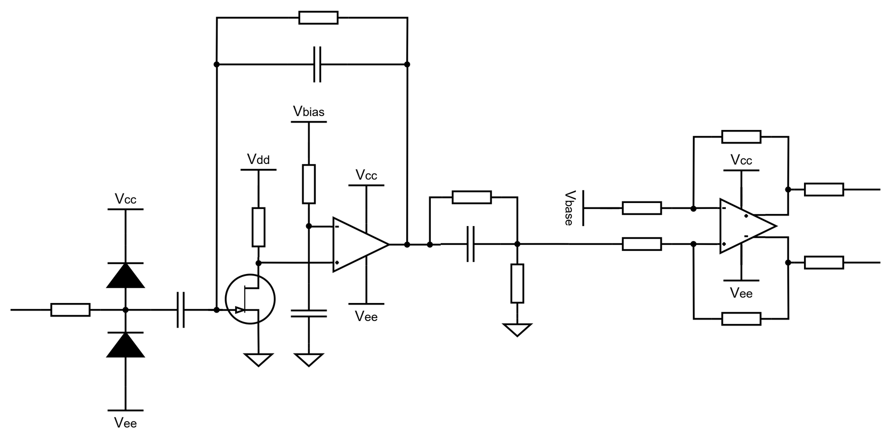


Readout Electronics

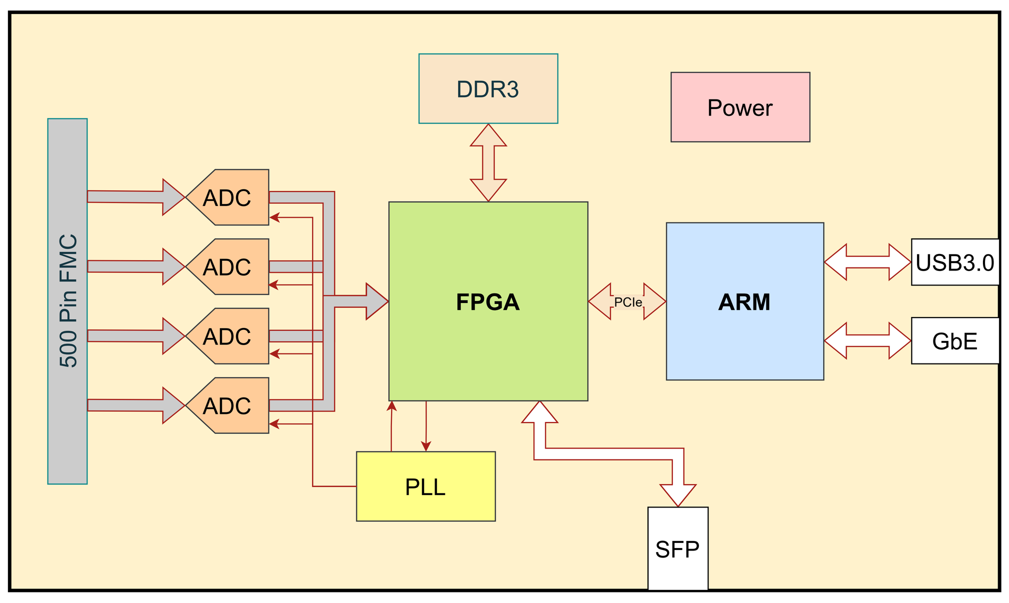
The readout electronics ensure accurate signal detection and processing, enabling effective data acquisition. The main components are outlined below.



- **ARB (Anode Readout Board):** The ARB includes induction pads to detect ionization signals and resistors for charge dissipation on anode pads. A mesh amplification and shaping circuit verifies detector performance and measures energy spectra.
- **FEB (Front-End Board):** The FEB has 128 charge-sensitive preamplifiers to amplify anode signals, improving the signal-to-noise ratio and overall sensitivity.



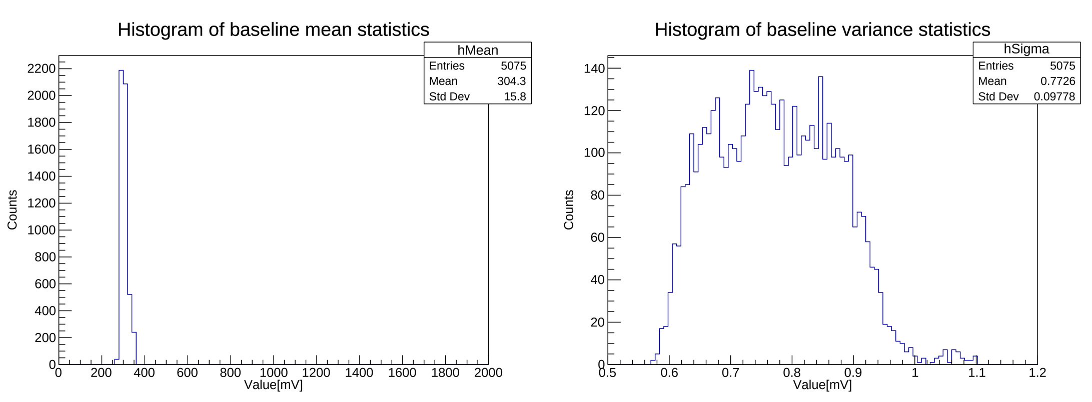
- **DPU (Data Processing Unit):** The DPU includes an ADC for digitizing preamplified signals and an FPGA for signal filtering, shaping, trigger selection, data compression, waveform extraction, and data transfer, ensuring efficient data handling.



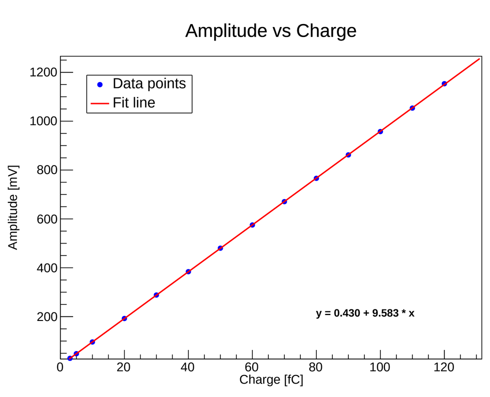
Performance Evaluation

Electronics Performance Testing

- **Electronics Noise Testing:** The ENC (Equivalent Noise Charge) of the readout electronics is below 0.12 fC.

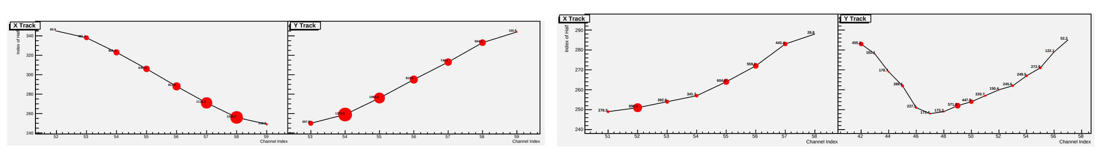


- **Electronics Linearity Testing:** The results demonstrate excellent linearity with an R^2 (Coefficient of Determination) value of 0.99999, a p-value of 0.282, and a system integral non-linearity (INL) of less than 0.003 mV.

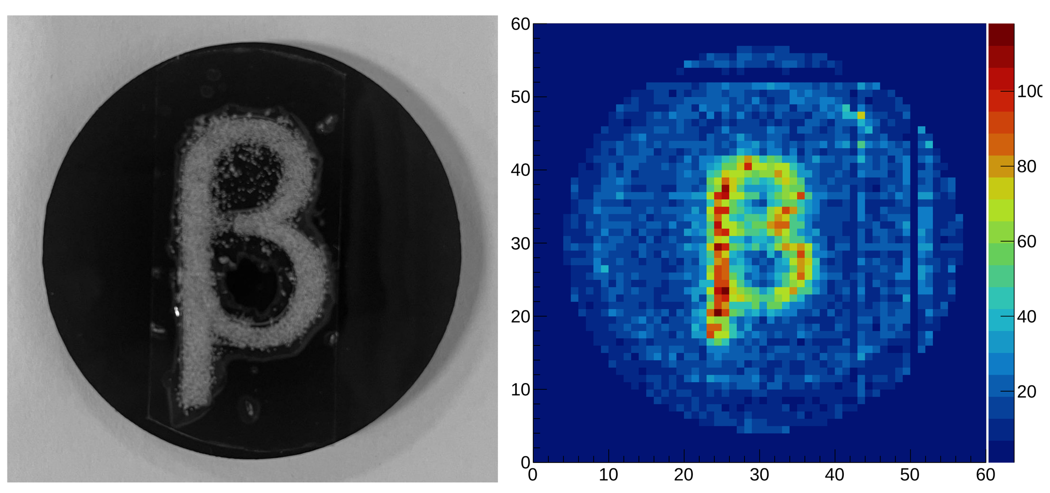


System Performance Evaluation

- **Typical Track Visualization:** The detector is capable of tracking α and β particles.



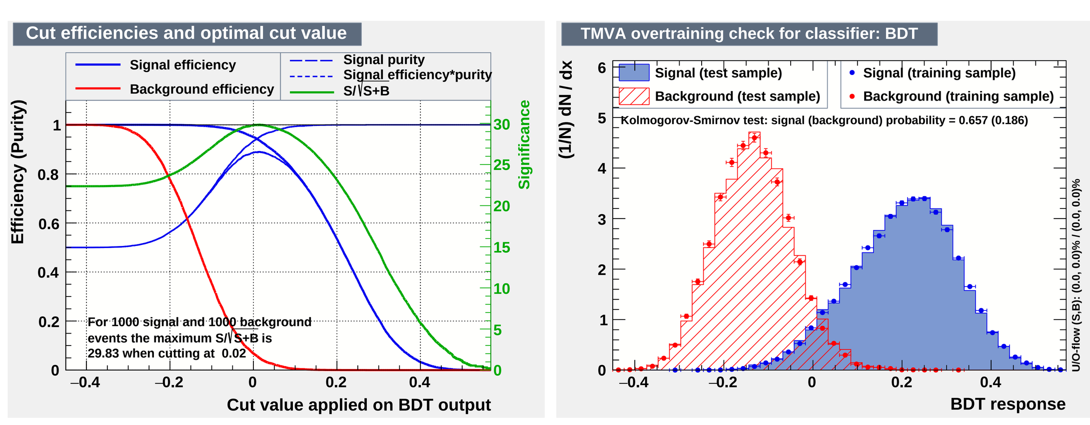
- **Imaging Evaluation:** Imaging was conducted using a 0.2 g powder containing ^{40}K (CAS NO. 7447-40-7), which was arranged in the shape of the letter 'β' for visualization purposes.



- **Detection Efficiency:** Detection efficiency testing using a standard ^{90}Sr source showed an efficiency greater than 90% after background subtraction.

Particle Identification Capability

The particle identification capabilities of the system are assessed using the TMVA (Toolkit for Multivariate Data Analysis) method, specifically the BDT (Boosted Decision Trees) approach. This approach involves training the system to distinguish between different types of radiation based on various input features, enhancing its ability to accurately identify alpha, beta, and background radiation.



According to the BDT training results, when a source count retention rate of 55% is maintained under unshielded conditions with a membrane window of 5 cm in diameter, the background count rate is approximately 6 cpm (counts per minute).

Conclusion

- The TPC detector, equipped with a Micromegas anode plane, demonstrates high sensitivity and detection efficiency for both α and β particles.
- The system shows strong discrimination between beta particles and background, with a background level of about 0.3 cpm/cm^2 after background suppression.
- Simulations suggest that the use of low-background materials and enhanced shielding can significantly improve performance. Future efforts will focus on algorithm optimization and additional shielding to further reduce background levels in measurements.