

OVERVIEW OF RADIATION DETECTORS AND METHODS FOR OPTIMIZING MEASUREMENTS ACCURACY

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Abstract

Radiation detectors are essential instruments in nuclear science, medical imaging, environmental monitoring, industry, and radiation protection. Their performance directly impacts data quality, safety assessments, and system reliability. This paper provides a comprehensive overview of the major classes of detectors, including gas-filled, scintillation, semiconductor, and neutron-sensitive systems, highlighting their operating principles, interaction mechanisms, and key performance characteristics. Particular emphasis is placed on the fundamental physical processes, including ionization, scintillation, charge transport, and secondary electron production, that determine the detector response and sensitivity. It also reviews common sources of measurement uncertainty and describes contemporary strategies for optimizing performance, such as improved signal processing, improved gas quenching techniques, optimized material selection, temperature stabilization, and robust calibration procedures. The findings show that appropriate detector selection combined with well-controlled operating conditions can significantly improve energy resolution, detection efficiency, and measurement reliability. This review provides a practical basis for researchers and practitioners seeking to improve measurement accuracy and select the most appropriate detection technologies for specific radiation environments.

Key words: Radiation detectors, radiation protection, measurement accuracy, detection technology.

Përmbledhje:

Detektorët e rrezatimit janë instrumente thelbësore në shkencën bërthamore, imazherinë mjekësore, monitorimin mjedisor, industrinë dhe mbrojtjen nga rrezatimi. Performanca e tyre ndikon drejtpërdrejt në cilësinë e të dhënave, vlerësimet e sigurisë dhe besueshmërinë e sistemit. Ky punim ofron një përmbledhje koncize por gjithëpërfshirëse të klasave kryesore të detektorëve, duke përfshirë sistemet e mbushura me gaz, shintilacionin, gjysmëpërçuesit dhe sistemet e ndjeshme ndaj neutroneve, duke theksuar parimet e tyre të funksionimit, mekanizmat e ndërveprimit dhe karakteristikat kryesore të performancës. Theks i veçantë i vihet proceseve themelore fizike, duke përfshirë jonizimin, shintilimin, transportin e ngarkesës dhe prodhimin sekondar të elektroneve, të cilat përcaktojnë përgjigjen dhe ndjeshmërinë e detektorit. Gjithashtu shqyrtohen burimet e zakonshme të pasigurisë së matjes dhe përshkruhen strategjitë bashkëkohore për optimizimin e performancës, të tilla si përpunimi i përmirësuar i sinjalit, teknikat e përmirësuar të shuarjes së gazit, përzgjedhja e optimizuar e materialit, stabilizimi i temperaturës dhe procedurat e forta të kalibrimit. Gjetjet tregojnë se përzgjedhja e duhur e detektorëve e kombinuar me kushtet e funksionimit të kontrolluara mirë mund të përmirësojë ndjeshëm rezolucionin e energjisë, efikasitetin e zbulimit dhe besueshmërinë e matjes. Kjo përmbledhje ofron një bazë praktike për studiuesit dhe praktikuesit që synojnë të përmirësojnë saktësinë e matjes dhe të zgjedhin teknologjitë më të përshtatshme të zbulimit për mjedise specifike të rrezatimit.

Fjalë kyçe: *Detektorë rrezatimi, mbrojtje nga rrezatimi, saktësi matjeje, teknologji detektimi.*

Introduction

Ionizing radiation is an important part of the technology development, medical diagnostics, materials analysis, energy production, etc. These radiations have ionizing effects on molecules and atoms, leading to cell and DNA destruction which can lead to irreversible damage to the organism up to death. Consequently, it is necessary to protect ourselves from it by applying the ALARA principle to optimize time, distance and use of protective equipment. Ionizing radiations are part of the electromagnetic spectrum that is not visible to the human eye, therefore it is necessary to use radiation detection techniques with special equipment.

Radiation detection technology plays a fundamental role across nuclear physics, medical imaging, radiation protection, industrial quality control, and environmental dosimetry. Over the last decades, technological advancements in materials science, microelectronics, and signal processing have significantly improved detector performance, reliability, and measurement precision. With the growing demand for real-time, high-resolution, and low-noise detectors, the field has seen substantial innovation in semiconductor detectors, scintillation materials, gas-filled detectors, and hybrid systems (Knoll, 2010).

At the same time, measurement optimization has become equally important, especially in environments where accuracy, environmental stability, and long-term operation are required. The scientific literature highlights various optimization strategies, including material engineering, detector geometry refinement, advanced signal processing, and simulation-based calibration. Understanding these developments is essential for selecting the most suitable detector type for a given application and for improving measurement quality (Arpit Patel & Himanshu Mazumdar, 2023).

2. Types of radiation detectors

2.1 Semiconductor detectors

Semiconductor detectors have become a leading solution for high-resolution radiation detection due to their direct conversion mechanism, compactness, and excellent energy resolution. Materials such as silicon (Si), germanium (Ge), and wide-bandgap semiconductors (SiC, GaN, and Ga₂O₃) are extensively used in harsh environments, including high-radiation fields and elevated temperatures. The operation is based on semiconductor elements doped with impurities in the crystal lattice, thus forming the pn junction and combinations of these junctions. Ionizing radiation will create electrons in the impurity-rich area which, due to the potential difference, will flow to the detector poles as in Figure 1. These detectors offer high charge collection efficiency and fast response, making them suitable for spectroscopy, particle tracking, and medical imaging (Karmakar et al., 2021).

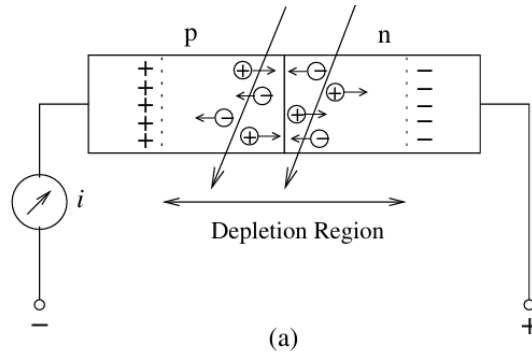


Figure 1. Semiconductor detector scheme

Recent studies emphasize the advantages of wide-bandgap materials, which exhibit strong radiation hardness and low leakage currents, enabling stable operation even after high-dose exposure. Research on 4H-SiC, GaN, and β -Ga₂O₃ shows their potential for neutron, gamma, and charged-particle detection in next-generation monitoring systems. These materials also support thin-film designs, low-power operation, and micro-detector architectures (Capan, 2024).

Thin-film semiconductor neutron detectors with conversion layers of boron carbide (B₄C) or lithium fluoride (LiF) have also been investigated as replacements for helium-3 detectors. Monte Carlo simulations and experimental results show that performance strongly depends on converter thickness and geometry optimization (Zhongming Zhan & Michael D. Aspinall, 2021).

2.2 Scintillation detectors

A scintillation detector relies on the properties of scintillating materials to convert photons of ionizing radiation into visible light pulses. When the radiation interacts with the scintillating crystal, it excites the atoms of the material, which, upon returning to their ground state, emit photons of light, with an intensity proportional to the energy absorbed (Figure 2). These photons are collected by a photomultiplier, where they are converted into an amplified electrical signal (Figure 3). The output signal is processed electronically to determine the intensity and, in many cases, the energy of the incident radiation. Due to their high sensitivity and fast response time, scintillation detectors are widely used in nuclear dosimetry and spectrometry. Scintillation detectors remain widely used due to their high detection efficiency, mechanical durability, and suitability for large-volume detection

systems. Traditional scintillators such as NaI(Tl), CsI(Tl), and BGO offer strong gamma-ray sensitivity, while new generations of scintillators focus on enhanced light yield, faster decay times, and improved linearity (M. Moszyński et al., 2016).

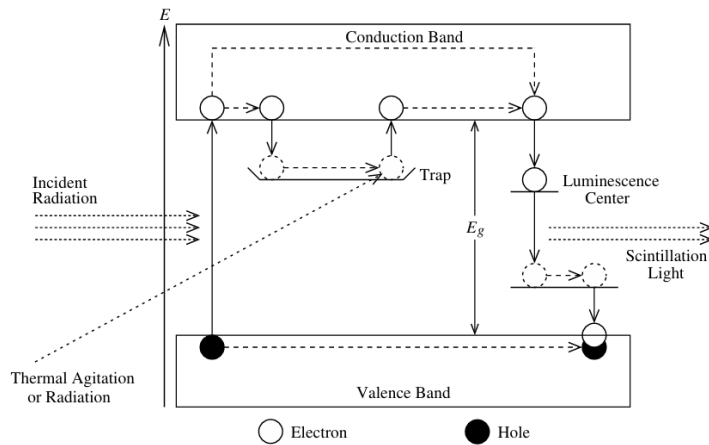


Figure 2. Scintillator detector scheme

Recent advances highlight engineered scintillators, including perovskite-based materials and nanocomposite scintillators. These exhibit improved radioluminescence, tunable optical properties, and potential for low-cost mass production. Such materials are emerging as strong candidates for medical imaging, homeland security, and environmental monitoring (George Kakavelakis et al., 2020).

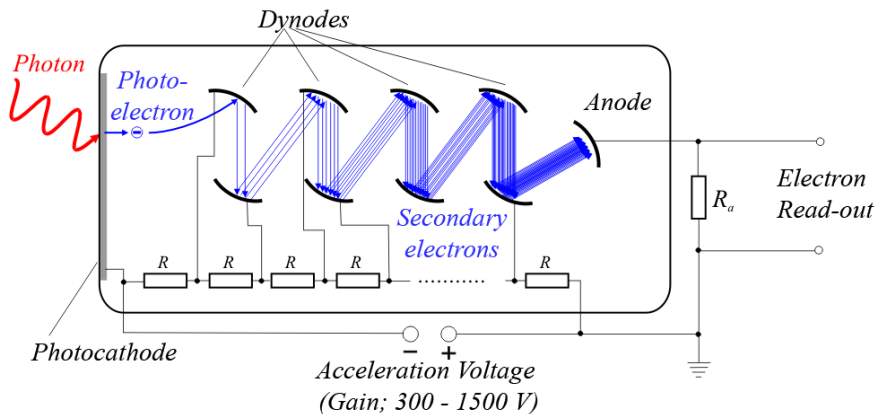


Figure 3. Scintillator detector working principle

Modern scintillator designs integrate photonic structures or metamaterials to boost light extraction efficiency and reduce internal optical losses. These enhancements lead to faster and more efficient detectors capable of high-precision timing measurements, suitable for time-of-flight PET and fast neutron detection (Singh, 2024).

2.3 Gas-Filled Detectors – Ionization Chamber

Gas-filled detectors form a capacitor that creates an electric field. Gas is introduced into the electrode and cathode of the detector and ionizes during interaction with the material as shown in Figure 4. The interaction with radiation forms avalanche effects (Figure 5), i.e. a collection of charges oriented towards the cathode and anode which are further processed in electronic circuits.

Gas-filled detectors such as ionization chambers, proportional counters, and Geiger-Müller tubes have historically served as robust and cost-effective detection systems. They are widely used in radiation protection, environmental monitoring, and laboratory measurements due to their simple design, stability, and scalability (Nicholas Tsoulfanidis & Sheldon Landsberger, 2021). Such ionization chamber-type models are used in calibration laboratories to reference the dose given by a radiation source directly connected to an electrometer, as is the case of the Secondary Standard Dosimetric Laboratory at the Institute of Applied Nuclear Physics.

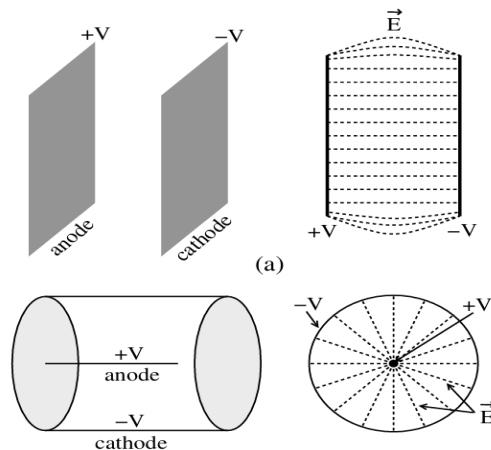


Figure 4. Ionising chamber working principle as one capacitor and building of electric field

Advanced proportional counters with micro-pattern structures such as Gas Electron Multipliers (GEM) and Micromegas provide high spatial resolution and are used in particle physics experiments. These detectors leverage micro-fabricated electrodes to achieve strong electric-field gradients and rapid signal amplification (Sauli, 2016).

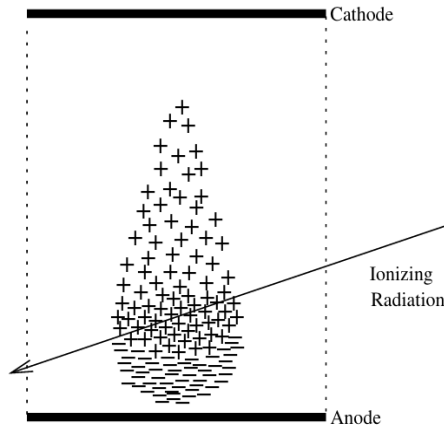


Figure 5. Creating the avalanche effect in the ionization chamber

Gas-filled neutron detectors using boron-lined proportional tubes have become a practical alternative to Helium-3 based systems, especially following the global He-3 shortage. Optimized boron coating thickness and cylindrical geometry significantly improve neutron absorption and minimize gamma-ray interference.

3. Optimization techniques for radiation measurement

3.1 Material engineering

One of the main optimization strategies involves engineering detector materials to improve charge transport, radiation hardness, and optical output. Studies on wide-bandgap semiconductors show that material purity, defect density reduction, and interface engineering produce significant performance gains. These enhancements reduce noise, increase sensitivity, and prolong detector lifespan in harsh environments (Karmakar et al., 2021).

For scintillators, doping concentration and crystal growth techniques strongly influence light yield and decay time. Optimizing dopant levels (e.g., Ce^{3+} ,

Eu²⁺) and using co-doping strategies has proven effective in balancing high brightness with fast timing response (Ahmed, S. N, 2007).

At the Institute of Applied Nuclear Physics (IANP), many measurements and radiation detections are performed for various activities such as radioactive waste management, radiation source monitoring, transport of radioactive materials, response to radiological emergencies, etc. Mostly are used HpGe semiconductor detectors, Geiger-Müller type detectors such is RadEye ionization chambers, scintillation detectors such as the Harshaw6600 system, etc (Dritan Prifti & Kozeta Tushe, 2025). Some devices used at IANP like Identifinder Flir and RadEye PRDs are shown in Figure 6.



(a) (b)

Figure 6. Radiation detectors used at Institute of Applied Nuclear Physics a) Identifinder Flir with semiconductor detectors, b) RadEye personal radiation detector with Ionizing chamber working as Geiger-Müller detectors.

Also, the use of materials properties for radiation detection, storage and release of signals such as thermoluminescence has enabled the development of advanced methods for radiation dose assessment. Advances in materials processing, such as the introduction of impurities in LiF dosimeters and the development of strict protocols for their use have improved the conditions of protection from ionizing radiation (E. Gega et al., 2025).

3.2 Detector geometry optimization

Detector geometry, including thickness, surface finish, electrode configuration, and converter layer design, plays a fundamental role in optimizing detection efficiency and overall detector response. Monte Carlo

simulation frameworks such as GEANT4 (Agostinelli et al., 2003; Allison et al., 2016) and MCNP (Goorley et al., 2017) are widely employed to model particle transport and energy deposition in complex detector geometries. These tools enable a detailed stochastic description of particle–matter interactions, including scattering, absorption, and secondary particle production, allowing accurate prediction of detector response functions under various irradiation conditions.

In scintillator–photodetector systems, photon transport is strongly influenced by optical coupling efficiency, refractive index mismatch, reflector properties, and surface roughness, which govern the balance between photon trapping and extraction. Monte Carlo optical simulations have shown that optimized reflector geometries and surface treatments can significantly enhance light collection efficiency, in some configurations by tens of percent, while simultaneously affecting timing performance due to multiple reflection paths.

3.3 Advanced signal processing

Optimized digital signal processing including pulse shaping, noise filtering, and rise-time discrimination greatly enhances detector performance, particularly in high-rate environments. Modern FPGA-based and ASIC-based readout systems enable real-time data acquisition with improved energy resolution and lower dead time.

Machine-learning based techniques have recently been used to improve background suppression, predict detector degradation, and reconstruct energy spectra, demonstrating promising results in high-precision experiments (Abbas J. Jinia, 2024).

Discussion

The reviewed literature highlights a common theme: material innovation combined with optimized detector design leads to substantial performance improvements. Semiconductor detectors are advancing through wide-bandgap materials and improved fabrication methods, offering excellent spectral performance even in extreme conditions. Meanwhile, scintillators benefit from engineered photonic structures and novel materials such as perovskites, making them increasingly competitive in both resolution and cost (Karmakar et al., 2021; Abdellah et al., 2021; Singh et al., 2024).

Simulations based on Monte Carlo transport methods have become essential tools for the performance prediction and optimization of radiation detectors, particularly in neutron detection systems, hybrid detector architectures, and

complex multilayer geometries. Codes such as GEANT4 and MCNP enable detailed modelling of particle interactions, detector response functions, and energy deposition profiles, providing insights that are often inaccessible through experimental measurements alone.

Finally, advances in signal processing and electronics particularly digital readout systems and machine-learning algorithms expand detector capabilities, enabling improved resolution, noise reduction, and dynamic range.

Conclusion

Radiation detection technologies have undergone significant advancements driven by progress in material science, detector design, and digital signal processing. This review highlights that no single detector type is universally optimal; instead, performance strongly depends on the specific application and operating conditions.

Semiconductor detectors offer superior energy resolution and are best suited for high-precision spectroscopy, while scintillation detectors provide high detection efficiency and flexibility for large-scale systems. Gas-filled detectors remain reliable and cost-effective solutions, particularly in radiation protection and environmental monitoring.

A key finding of this study is that measurement accuracy is not determined solely by detector type, but by the combined optimization of material properties, detector geometry, and signal processing techniques. Monte Carlo simulations and modern computational tools play a crucial role in this optimization process, enabling detailed prediction and improvement of detector response.

Furthermore, emerging technologies such as wide-bandgap semiconductors, engineered scintillators, and machine-learning-based signal processing are expected to significantly enhance detector performance soon.

In conclusion, the integration of advanced materials, optimized design, and intelligent data processing represents the main direction for the development of next-generation radiation detection systems, with improved sensitivity, reliability, and measurement accuracy.

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