

A micro-dose detector system for particle identification using a double-stacked pixel array based on dE/dx

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Abstract

In the measurement of low-dose spatial radiation, the precise identification of particle types is crucial for investigating the molecular mechanisms underlying the effects of radiation on neural cell function. To address the challenge faced by conventional detection techniques in balancing high spatial resolution with multi-particle discrimination capability, this study proposes a particle identification scheme based on the ionisation loss dE/dx using a dual-stacked pixel array. This scheme employs a CMOS pixel array as the core detection unit. Through a dual-stacked structure design, it achieves precise capture of particle energy deposition. By utilising the Bethe-Bloch formula to establish a correlation model between dE/dx and the particle's charge and momentum, and combining this with the energy deposition ratio method, it enables efficient discrimination between protons and heavy ions. Simulation and experimental results demonstrate that this technology achieves a particle discrimination resolution of over 97%, with clear boundaries in the energy deposition ratio distributions of protons and carbon ions; the detector grey values exhibit an excellent linear correlation with particle energy ($R^2 > 0.99$), and the identification accuracy for vertically incident particles is 98.8%. This technology meets the core requirements for detecting the spatiotemporal distribution characteristics of particle types in neural cell sandwich detection scenarios, providing reliable technical support for research into low-dose spatial radiation.

Full Text

Preamble

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Abstract

—In the measurement of low-dose spatial radiation, the precise identification of particle types is crucial for investigating the molecular mechanisms underlying the effects of radiation on neural cell function. To address the challenge faced by conventional detection techniques in balancing high spatial resolution with multi-particle discrimination capability, this study proposes a particle identification scheme based on the ionisation loss dE/dx using a dual-stacked pixel array. This scheme employs a CMOS pixel array as the core detection unit. Through a dual-stacked structure design, it achieves precise capture of particle energy deposition.

By utilising the Bethe–Bloch formula to establish a correlation model between dE/dx and the particle's charge and momentum, and combining this with the energy deposition ratio method, it enables efficient discrimination between protons and heavy ions. Simulation and experimental results demonstrate that this technology achieves a particle discrimination resolution of over 97%, with clear boundaries in the energy deposition ratio distributions of protons and carbon ions; the detector grey values exhibit an excellent linear correlation with particle energy ($R^2 > 0.99$), and the identification accuracy for vertically incident particles is 98.8%. This technology meets the core requirements for detecting the spatiotemporal distribution characteristics of particle types in neural cell sandwich detection scenarios, providing reliable technical support for research into low-dose spatial radiation.

Index Terms —spatial radiation; particle identification; dE/dx ; double-layer pixel array; CMOS detector

. Introduction With the advancement of human spaceflight, increasing attention is being paid to the damaging effects of space radiation on astronauts' central nervous systems [1].

Space radiation primarily consists of protons, alpha particles and heavy ions [2]; the energy deposition characteristics of these different particle types vary significantly [3], and the mechanisms by which they damage nerve cells also differ fundamentally [4].

Therefore, the precise identification of particle types and the acquisition of key parameters such as particle incidence flux, deposited energy and type distribution are prerequisites for conducting research into the molecular mechanisms of radiation damage.

Current particle identification techniques primarily include magnetometer methods [5], scintillation detection [6] and semiconductor detector methods

[7]. Although magnetometer methods offer high identification accuracy, they are bulky and difficult to adapt to μm -scale detection scenarios in neural cells [8]; scintillation detection offers high detection efficiency but has limited spatial resolution [9]; while traditional semiconductor detectors, although offering the advantage of miniaturisation, struggle to simultaneously achieve high spatial resolution and multi-particle identification capabilities [10]. Identification methods based on the ionisation loss dE/dx utilise the inherent differences in energy loss per unit distance in a medium between different particles [11]; characterised by simple principles, rapid response and high integration, they have become the preferred technical approach for spatial radiation detection [12].

In this paper, based on CMOS pixel array technology, a dual-stacked detection architecture is designed and a dE/dx particle discrimination model is constructed. By employing the energy deposition ratio method to enhance particle characteristic differences, precise discrimination between protons and heavy ions is achieved. This solution combines high spatial resolution ($6.5 \mu\text{m}$ pixel pitch) with real-time discrimination capability, meeting the spatial requirements of neural cell interlayer detection and providing an integrated solution for micro-dose radiation measurement.

II. Principles of Particle Identification The core principle of dE/dx differentiation When charged particles move through a silicon medium, their energy loss is primarily due to Coulombic interactions with the valence electrons of the medium's atoms; the energy loss per unit distance (dE/dx) is given by the Bethe-Bloch equation [13]: (2-1)

$$dE/dx = \frac{4\pi N_A Z^2 A M u}{\epsilon_0} \frac{z^2}{\beta^2} \left[\ln \left(\frac{2m_e c^2 \beta^2}{I} \right) - \beta^2 \right]$$

(2-2)

Here, dE is the energy deposited by a particle over a unit distance dx , m is the rest mass of the electron, c is the speed of light, z is the charge of the incident particle, and β is the ratio of the particle's velocity to the speed of light ($\beta = v/c$), I is the average excitation energy of the medium's atoms, where for silicon material $I = 173 \text{ eV}$; ϵ_0 is the permittivity of free space; n is the electron density of the material; Avogadro's number is N_A ; Z is the atomic number of the constituent element of the material; ρ is the density of the material; A is the relative atomic mass of the constituent element of the material; and $M u$ is the molar mass constant.

In actual detection, there are statistical fluctuations in particle energy loss [15], necessitating the introduction of the Fano factor F to describe the sub-Poissonian fluctuation characteristics. The variance in the number of electron-hole pairs generated is:

$$\sigma^2 = FN F$$

(2-3) In particular, $\epsilon = 3.61$ eV represents the average ionisation energy of silicon, and $F = 0.11$ for silicon; this correction term ensures the accuracy of the energy loss measurements [16].

Principles of dE/dx measurement enhancement in high dynamic range imaging
Accurate measurement of dE/dx requires the distortion-free capture of particle energy deposition signals. Conventional imaging modes are prone to issues where low-energy particle signals are overwhelmed by noise and high-energy particle signals become saturated, leading directly to errors in dE/dx calculations [17]. This system employs a dual-gain readout high dynamic range (HDR) imaging mechanism [18], which ensures reliable signal acquisition for the precise measurement of dE/dx.

Its core principle involves the simultaneous acquisition of low-gain (LG) and high-gain (HG) image data to achieve the complete capture of particle deposition signals across a wide energy range [19].

The low-gain mode optimises the pixel well capacity [20], preventing signal overflow and saturation for particles with high deposition energy, such as high-energy heavy ions, thereby ensuring the accurate quantification of high-energy particle deposition values [21]; The high-gain mode optimises readout noise, amplifying the deposition signals of weak-signal particles such as low-energy protons, thereby effectively improving the signal-to-noise ratio of weak signals and resolving the issue of low-energy particle signals being difficult to identify [22]. The two types of image data are output synchronously from the readout chains at the top and bottom of the detector, respectively, and data integration is performed on the host computer using a linear weighted fusion algorithm, with the fusion formula given by [23]:

(2-4)

Here, I represents the pixel value of the fused high dynamic range image, and I_L and I_H represent the pixel values of the low-gain and high-gain images, respectively, whilst α and β are weighting coefficients that can be dynamically adjusted according to the particle energy range [24].

Following optimisation for HDR imaging, the detector's charge detection range has been significantly expanded, with the linear response range of the energy deposition signal covering 10 keV to 500 keV. This fully accommodates the energy deposition characteristics of protons and heavy ions in space radiation, effectively eliminating interference from signal saturation and the masking of weak signals in the calculation of dE/dx, thereby enabling precise measurement of dE/dx values for particles of different energies and types [25].

Particle classification algorithm workflow
The dE/dx-based particle identification workflow comprises four main stages: data pre-processing, dE/dx calculation, feature extraction and species identification, as detailed below:

The raw data acquired by the dual detectors undergoes noise filtering and the removal of invalid frames; dark current noise is subtracted; valid signal pixel

clusters

generated by particle impacts are retained; and the raw hardware format is converted into NumPy arrays for subsequent calculations.

The dE/dx calculation utilises the calibrated relationship between pixel grey-scale values and energy deposition to convert the grey-scale matrices of D1 (front detector) and D2 (rear detector) into energy deposition matrices E1 and E2. The particle's travel distance L1 and L2 are estimated based on the distribution range of the hit pixels, and the ionisation loss values in the two detector layers are calculated accordingly.

The E1/E2 energy deposition ratio is extracted as the core discriminating feature; this ratio effectively reflects the energy loss attenuation characteristics of particles in different detector layers, thereby enhancing the distinguishing features between protons and heavy ions.

Energy deposition ratio characteristic intervals for protons and heavy ions are established based on Monte Carlo simulations, and particle type classification is performed by combining these with the dE/dx values. If both the ratio and the dE/dx value match the characteristics of a proton, the particle is classified as a proton; if both match the characteristics of a heavy ion, the particle is classified as a heavy ion. As shown in Figure 2 [Figure 2: see original paper]-1.

III. Design of a dual-layer detection system Design of a dual-layer detection system To achieve precise measurements of dE/dx , a dual-stacked pixel array detection system was designed, as shown in Figure 3 [Figure 3: see original paper]-1. The system comprises two layers of 2048×2048 pixel arrays, with a pixel pitch of $6.5 \mu\text{m}$ and a detector spacing of 25 mm. Signal transmission and thermal isolation are achieved via flexible flat cables, thereby preventing the heat generated by the mainboard circuitry from affecting the

detection performance of the silicon medium. The hardware layer handles the capture, conversion and transmission of particle signals, whilst the software layer performs data processing, dE/dx calculation and particle identification.

Modular design of hardware systems The hardware system utilises an XC7K325T FPGA as its core control unit and employs a modular design approach, integrating six core modules: power management, analogue-to-digital conversion (ADC), image sensor driving, USB 3.0 high-speed communication, temperature sensing and clock driving. Each module operates independently and features standardised interfaces, ensuring the system's stability and scalability.

The power management module employs a combined architecture comprising the LTM4613 DC/DC converter and the LT1764 LDO regulator. An external 12V power supply is converted by the DC/DC converter into an intermediate 5V voltage, which is then precisely regulated by the LDO regulator to produce

multiple voltage levels, including 3.3V, 1.2V and 1.3V, to supply power to components such as the FPGA, image sensors and the USB 3.0 controller; The module incorporates a multi-stage filtering network that effectively suppresses power supply ripple, with a voltage regulation accuracy of $\pm 1\%$, providing a stable power supply environment for the acquisition of weak signals. As shown in Figure 3-2.

The image sensor driver module utilises a 600 MHz differential clock as its core driver, generating a stable clock signal via SiTime's SWPQ201 active crystal oscillator. Combined with LVDS equalisation technology, this ensures synchronisation of the row and column drive timing for the pixel array. The module supports HDR dual-gain readout mode configuration, allowing gain parameters to be dynamically adjusted via FPGA registers to accommodate the detection requirements of particles with different energy levels. As shown in Figure 3-3.

The USB 3.0 high-speed communication module is designed around the Cypress CYUSB3014 chip and configured in Slave FIFO mode, offering a data transfer rate of up to 1600 Mb/s to ensure high-speed, lossless transmission of sensor data. The

module is compatible with USB 2.0, enhancing the system's hardware compatibility, whilst also incorporating data error checking and retransmission mechanisms to ensure reliable data transmission. As shown in Figure 3-4.

The clock driver module provides precise clock signals to all system modules. In addition to the 600 MHz sensor drive clock, it generates a 200 MHz FPGA system clock, a 50 MHz USB communication clock, and a 20 MHz temperature sensor clock, amongst others. All clock signals undergo filtering and impedance matching to reduce clock jitter and ensure timing synchronisation across all modules. As shown in Figure

Measure the corresponding differential clock using an oscilloscope, as shown in 600 MHz differential clock signal.

Software system design The software system adheres to a layered design principle, comprising low-level driver software on the FPGA side and data processing software on the host computer side. Data exchange and instruction transmission between these two layers are facilitated via a USB 3.0 interface, ensuring both the system's real-time performance and interactivity.

The low-level driver software on the FPGA side is developed using the Verilog HDL language, implementing core functions such as clock and reset management, protocol parsing and configuration, sequence generation, training and calibration, DDR3 data caching, and multi-module coordinated control. Among these, the clock management module utilises an MMCM IP core to perform clock division, multiplication and phase adjustment; the training and calibration module resolves bit-width misalignment and channel delay issues in multi-channel data transmission, ensuring data acquisition accuracy; The DDR3 buffer module provides temporary storage for vast amounts of probe data, preventing

data loss and meeting high-speed acquisition requirements; each module utilises asynchronous FIFOs to resolve data transmission issues across clock domains, ensuring timing control accuracy and data processing efficiency.

The host-side data processing software is developed using the PyQt framework and features a visual human-machine interface. It integrates five core modules: data input and pre-processing, dE/dx calculation, particle type identification, particle track reconstruction, and result output and visualisation. The software supports both single-shot and continuous data acquisition modes, displaying in real time the raw greyscale images from both detectors, particle impact positions, energy deposition values and identification results. It features a built-in data export function, allowing detection data and identification results to be saved in formats such as Excel and TXT for subsequent data analysis. It also supports the visual configuration of detection parameters, enabling dynamic adjustment of gain, exposure time, identification

thresholds and other parameters to suit different detection scenarios. As shown in

Dual-layer physical structure design The system employs a dual-stacked sandwich-layer physical architecture, which is a key design feature for achieving precise dE/dx measurements and adapting to the sandwich-layer environment of neural cells. This architecture spatially decouples the detection unit from the main control board. The upper layer comprises a dual-stacked pixel array detection sub-board, whilst the lower layer houses the main control and signal processing board. The two layers are secured by metal support columns, the height of which is adjustable, enabling a detector spacing of 0–50 mm to precisely meet the spatial requirements for μm -scale detection of neural cells.

Signal transmission between the detection sub-board and the main board is achieved via a polyimide flexible flat cable (FFC). The flexible flat cable not only accommodates connection requirements for varying spacings, but also has a thermal conductivity of just $0.12 \text{ W}/(\text{m} \cdot \text{K})$, which is far lower than that of rigid metal connectors. This effectively blocks the transfer of heat generated by the main board's circuitry to the detection sub-board, thereby preventing issues such as changes in carrier lifetime and a decline in electric field uniformity caused by temperature fluctuations in the silicon medium, thereby ensuring the stability of particle charge capture and collection and providing a stable physical environment for dE/dx measurements. Furthermore, ultra-thin heat sinks have been added to the surface of the detection sub-board to further reduce temperature drift in the detection unit,

ensuring the system's performance operation. As shown in Figure 3-8.

stability

during

prolonged

continuous

IV. Experiments and Analysis of Results Simulation verification The simulation results show that the distribution of the energy deposition ratio $E1/E2$ between protons and heavy ions forms two distinct bands with clear boundaries and no significant overlap, as shown in Figure 4 [Figure 4: see original paper]-1. The resolution formula is:

$$\frac{1}{\sigma} = \frac{2}{\mu} \sqrt{\frac{12}{22}} \quad (4-1)$$

Where μ represents the mean and σ the standard deviation, the calculation yielded a resolution of over 97%, thereby validating the feasibility of the particle discrimination scheme based on dE/dx .

Simulation results of particle energy deposition ratio distribution.

Setting up the experimental system The experiment comprises two parts: simulation verification and physical testing.

The simulation utilised the Geant4 Monte Carlo code to construct a model of a double-stacked detector, with particle sources set to protons (110 -221 MeV) and carbon ions (111 -430 MeV/u), simulating a perpendicular incidence scenario; The physical tests were conducted at the accelerator platform of the Shanghai Proton and Heavy Ion Hospital, as shown in Figure 4-2. The distance between the two detectors

was fixed at 25 mm, and coaxiality was calibrated using a laser alignment system with a deviation of ≤ 0.1 mm. Detection data for particles of different energies were collected.

Background data was acquired using black tape for light shielding, with continuous acquisition at a rate of 1000 ms per frame for 300 s; during beam detection, the detectors operated in HDR mode, with real-time monitoring of operating temperature to prevent temperature drift from affecting measurement accuracy.

Shanghai Proton Heavy Ion Hospital Carbon Ion Proton Accelerator Experimental Environment.

Thermal stability testing The thermal stability test focuses on verifying the thermal isolation effectiveness of the dual-stacked structure connected via flexible printed circuits, ensuring the detector's performance stability under complex temperature conditions.

The experiment was conducted at a room temperature of 25°C. At the outset, the initial temperatures of the core board and the detector were recorded, whilst the detector's background noise level was simultaneously tested and recorded to complete the initial state calibration. The system was then activated, placing the mainboard circuitry into a prolonged full-load operating state. The system's actual power consumption was recorded in real time, whilst the core board temperature, detector temperature and detector background noise parameters

were recorded hourly. This process continued for 12 hours to fully observe the cumulative temperature changes and fluctuations in background noise; the results are shown in Figure 4-3.

To evaluate the system's performance in thermal stability experiments, this paper conducted a Region of Interest (ROI) difference analysis on two raw images captured before and after the experiment. A 200×200 -pixel region at the same location in the images was selected as the Region of Interest, and the corresponding regions were extracted from the baseline image (Image 1) and the image taken after a period of operation (Image 2) for comparison. The ROI heatmap reveals that the difference signals in both images are generally sparsely distributed, with only a few discrete high-value bright spots appearing in localised areas; difference values in most regions remain at a low level. The difference distribution histogram further quantifies this phenomenon, showing that the mean difference value is 0.21, the median is 0.00, and the vast majority of pixels have difference values concentrated around 0, with only a very small number of pixels exhibiting significant differences. The test results indicate that, owing to the low thermal conductivity of the flexible interconnects on the polyimide substrate and the physical isolation provided by the dual-layer design, the difference in the ROI regions between the baseline image and the post-operation image remained generally small during prolonged full-load operation of the core board. No large-scale, systematic signal shifts or noise accumulation occurred, demonstrating that the system maintained good thermal stability and high signal output consistency throughout the experiment.

Furthermore, when comparing the detector background noise data from the initial stage of the experiment with that after prolonged operation, the mean and variance of the noise levels were calculated in accordance with Equations (4-2) and (4-3) respectively:

$$n_i = \frac{1}{N} \sum_{j=1}^N (G_{ij} - \bar{G}_i)^2$$

$$(4-2)$$

$$n_i = \frac{1}{N} \sum_{j=1}^N (G_{ij} - \bar{G}_i)^2$$

$$(4-3)$$

Here, G_{ij} represents the grayscale values for each pixel position across all frames i , \bar{G}_i represents the mean grayscale value, and n_i represents the noise level.

The temperature data and noise level data are plotted together as shown in Figure

The figure illustrates the performance trends of the detector over a 12-hour period, showing the dynamic changes in the temperature of the FPGA core board and the detector's noise level from top to bottom. Throughout the entire test cycle, the temperature of the FPGA core board remained stable between 60.0°C and 60.4°C .

Although the noise level showed a gradual upward trend as the test progressed, no significant performance degradation was observed. This indicates that the impact on the detector's signal acquisition and energy measurement accuracy is limited, thereby validating the temperature control capability and stability of the dual-stacked thermal isolation structure when connected to a heat source for extended periods.

Functional testing chirp To comprehensively verify the integrity of the system's imaging capabilities and the reliability of data acquisition under different illumination scenarios, imaging tests were designed for three typical lighting conditions: total darkness, low light transmission, and strong illumination. As shown in Figure 4-5, in a dark environment, the pixel array received only dark current noise, and the output image exhibited a low-noise background, verifying the system's dark-field acquisition capability and noise suppression performance in the absence of light input.

Output of full blackout environment detector.

Energy-Gray scale calibration results A calibration model relating the detector grey scale values to particle energy was established through detection experiments using particles of different energies. For carbon ions, a 155 mm solid water shield was used. The calibration results demonstrate an excellent linear correlation between the detector grey scale values and particle energy, ensuring the accuracy of the dE/dx calculation. The detailed findings are presented in TABLE 5 -1. The resulting image is shown in Figure 4-6.

Summary of energy gray scale calibration parameters and imaging performance of heavy ion beams with different energies

Beam energy/MeV/u

D1 average gray value

D2 average gray value

value for the D1 and D2 dual-detector system under a fixed 100 mm solid water shield. Tests were conducted using carbon ion beams at three energy levels: 111 MeV/u, 285 MeV/u and 430 MeV/u. The results show that the average grey values of both detectors exhibit a significant linear increase with rising beam energy, and the data points align closely with the linear fit, indicating that, under conditions of a fixed 100 mm water shield, the detector grey values and beam energy demonstrate an excellent linear correlation. The detailed findings are presented in TABLE 5-2.

Summary of Energy Gray Scale Calibration Parameters and Imaging Performance for Proton Beams of Different Energies

Beam energy/MeV/u

D1 average gray value

D2 average gray value

Experiment on the identification of particle types The particle identification experiment focuses on carbon ions and protons in space radiation. Utilising the accelerator platform at the Shanghai Proton and Heavy Ion Hospital, the experiment verifies the effectiveness of the dual-layer pixel array imaging method by separately testing the energy deposition characteristics of the two particle beams, thereby providing a basis for distinguishing particle types in practical radiation detection. Carbon ion and proton beams were selected as the sole particle sources to avoid signal interference from mixed beams. The proton flux was set at 2,000 particles per spot to ensure that the detection signal intensities of the two particle types were matched. The distance between the two detectors was fixed at 25 mm. Prior to the experiment, the coaxiality between the detectors and the beam centre was calibrated using a laser positioning system, with the deviation controlled within 0.1 mm. Background data was simultaneously recorded for subsequent noise subtraction. The scatter plot data obtained from the calculations is shown in Figure

Scatter diagram of particle energy deposition ratio under different energies.

V. Conclusion This paper proposes a particle identification technique based on dE/dx using a dual-stacked pixel array. By designing a dual-stacked CMOS pixel array, the technique enables the precise capture of particle energy deposition. A dE/dx identification model is established using the Bethe-Bloch formula, and combined with the energy deposition ratio method, it achieves efficient discrimination between protons and heavy ions. The core advantages of this technique lie in the dual-stacked structure, which balances high spatial resolution (6.5 μm) with thermal stability; the dE/dx model, which fully accounts for the statistical characteristics of particle energy loss; and the energy deposition ratio method, which enhances the distinctive features of different particles. Experimental results demonstrate that this technology achieves a particle discrimination resolution of over 97%, with a discrimination accuracy of $\geq 98.8\%$; the grayscale values exhibit excellent linear correlation with particle energy, thereby meeting the core requirements for particle type detection in the measurement of low-dose space radiation.

Future research directions include: optimising radiation-resistant design to enhance the long-term operational stability of the detector in high-radiation space environments; expanding multi-particle discrimination capabilities by enriching the energy deposition characteristic database to achieve precise differentiation of various space radiation particles, such as electrons and alpha particles; and advancing the integrated integration with microfluidic neural cell culture chips to establish a direct correlation between radiation physical parameters and changes in neural cell function, thereby providing more direct experimental methods for research into radiation damage mechanisms.

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