MSc Thesis Defense

COSMIC RAY CAMERA DISCOSAT-1
CMOS CHARACTERIZATION USING A PROTON BEAM

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MSc Software Design

In collaboration with Aarhus University and Danish Centre for Particle Therapy, as part of DISCOSAT project

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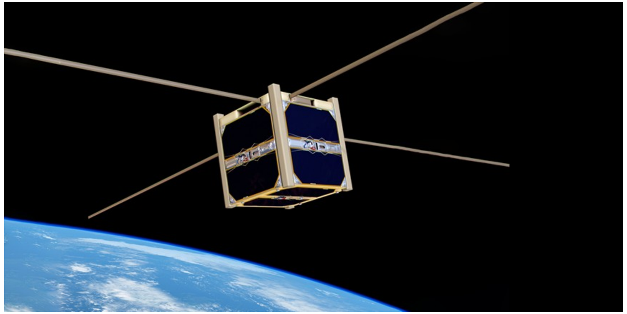
Agenda

1. Background & Previous Work
   - DISCOSAT-1 & Cosmic Rays
   - Cosmic Ray Experiment
2. Thesis Project Objectives
3. Cosmic Radiation & Radiation in LEO
4. Complementary Metal-Oxide-Semiconductor (CMOS) & Particle Detection
5. Irradiation Experiments
6. Proton Beam Experiment
   - Data Acquisition & Data Processing
   - Dose Measurement & Energy Dependency
7. Limitations & Future work

Background: DISCOSAT-1



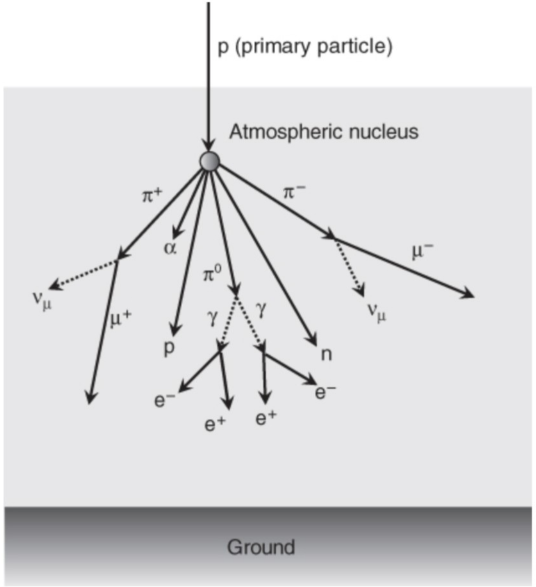
- Danish Student CubeSat Program (DISCO)
- 1U CubeSat in Low Earth Orbit (LEO) launched in April 2023

Goals:

- ➢ Demonstrate the viability of certain technologies for DISCOSAT-2 (3U CubeSat Earth-imaging satellite).
- ➢ Validate the image pipeline through a model system (IPU), which consists of a Tensor Processing Unit (TPU) chip within a Coral Board mini, and a Coral camera (CMOS sensor).
- ➢ Cosmic Ray Experiment: exploring the effects of cosmic rays on hardware components by counting high energetic particles that pass through the satellite.

Background: Cosmic Rays

- Cosmic Rays:
  - High-energy particles originating from outer space.
  - Primarily composed of protons, traveling close to the speed of light
- Primary Cosmic Rays (PCRs):
  - Cosmic Rays that directly reach the Earth's atmosphere.
  - Composed mainly of protons and some heavier nuclei.
- Secondary Cosmic Rays (SCRs):
  - Produced when PCRs interact with particles in the Earth's atmosphere.
  - Include neutrons, muons and other particle fragments.



Source: Eishi H. Ibe. (2015)

Previous work: Cosmic Ray Experiment

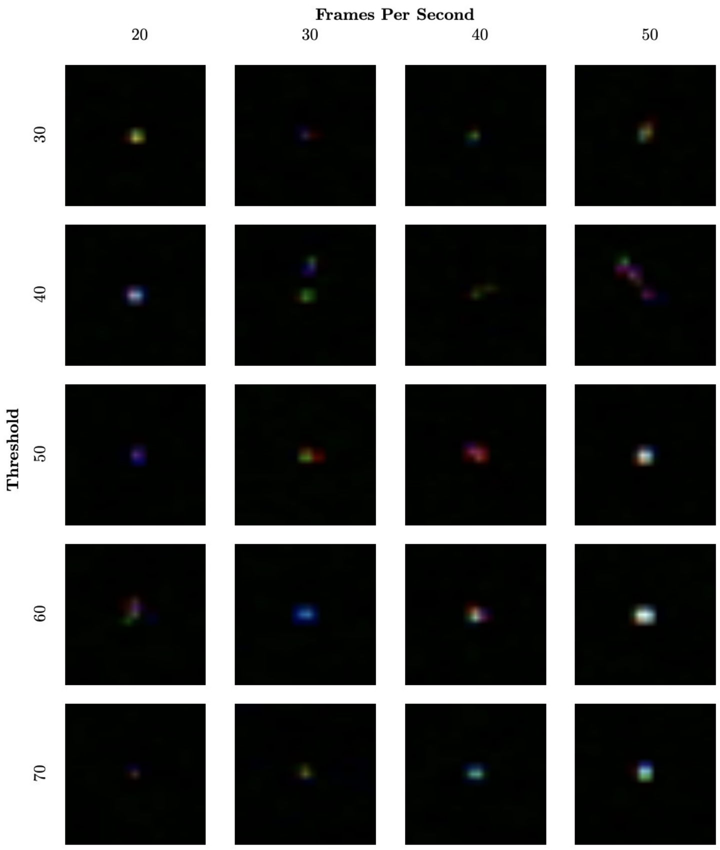
- Development of CubeSat Camera Control software for DISCOSAT-1 particle detection.

- Cosmic Ray flux measurements at ground level (SCRs).

$$\phi = N/(A * T)$$

Flux (muons/cm^2/min)	Duration (minutes)	Duration (hours)	Detections (N)
0.03060	324.68	5.41	1
0.04366	227.60	3.79	1
0.18238	54.48	0.91	1
0.02200	451.60	7.53	1
0.23211	85.62	1.43	2
0.08791	565.12	9.42	5
0.09660	1440.00	24.00	14
0.06900	1440.00	24.00	10

SCRs flux measurements



Thesis Project Objectives

- Investigation of camera’s response and performance under irradiation.
- Evaluation of camera sensitivity, durability and performance.
- Gaining insights into dose measurement and energy dependency.
- Identification of potential vulnerabilities and performance limitations.

Methodology:

- Camera irradiation experiments
- Data collection and analysis

Cosmic Radiation

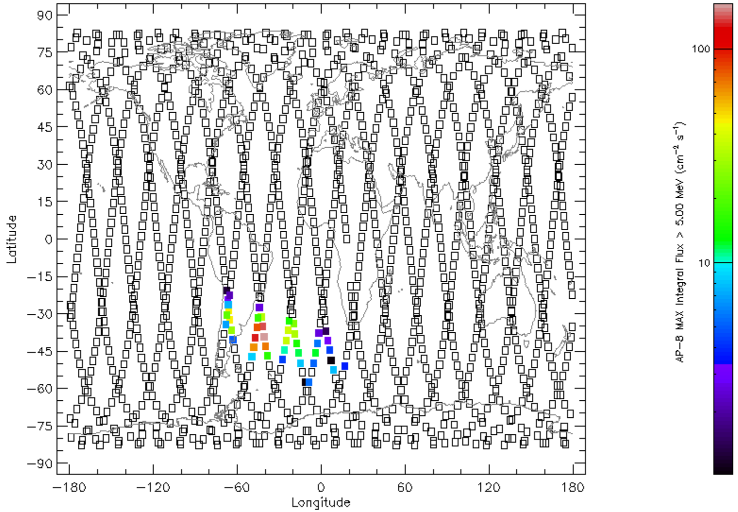
- Critical factor in the design and operation of spacecraft and electronics.
- Affects mission reliability and astronaut safety in space.

Effects on electronic components:

- **Single-Event Upsets (SEUs):** Disruption of circuits by a single particle leading to data corruption or system failures.
- **Latch-Ups**: Persistent malfunctions triggered by cosmic particles.
- **Total Ionizing Dose (TID)**: Long-term radiation exposure degrades materials causing permanent damage.

Radiation in LEO : DISCOSAT-1

- The radiation environment for DISCOSAT-1 in Low Earth Orbit (LEO) using the Space Environment Information System (SPENVIS).



Trapped proton flux > 5 MeV world view

➢ **Trapped Proton Radiation:**

Significant flux in regions like the South Atlantic Anomaly (SAA).

➢ **Solar Proton Events (SPE) :**

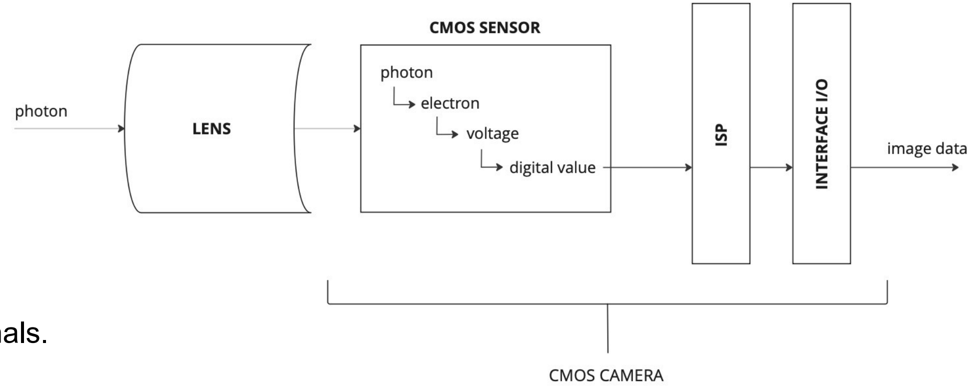
Higher exposure expected during the Solar Cycle 25 peak (2024-2026).

➢ **Galactic Cosmic Rays (GCR):**

Frequent encounters with 5-250 MeV protons, with lower occurrence of higher-energy protons.

Complementary Metal-Oxide-Semiconductor (CMOS)

- Low power consumption COTS sensors with high spatial resolution and real-time data processing.
- Widely used in scientific applications due to better sensitivity and lower cost than CCD sensors.



Schematic diagram of a CMOS camera's components.

Light to Digital Conversion:

- Photodiodes in the sensor convert light into electrical signals.
- Nearby amplifiers convert these signals into voltages.
- On-chip Analog-to-Digital Conversion (ADC) transforms voltages into digital values.
- Image Signal Processor (ISP) enhances the image (noise reduction, colour correction).
- Interface transmits data to external devices.

CMOS sensors as Particle Detectors

- Widely used in consumer electronics; repurposed for radiation detection.
- Cost-effective alternative to specialized radiation detectors.

Types of radiation detected**:**

Alpha (α) particles: Heavy, double positive charge, low penetration (stopped by paper/skin).

Beta (β) particles: Electrons (β−) or positrons (β+), moderate penetration (stopped by aluminum foil).

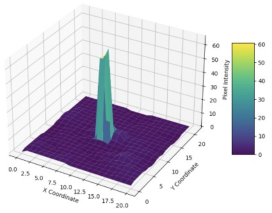
X-rays: High-energy photons, deep penetration, widely used in medical imaging.

Gamma (γ) rays: High-energy photons, extremely penetrating (passes through lead), ionizing.

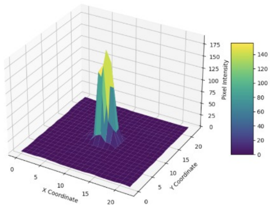
- Ionizing particles create charge in CMOS pixels.
- Charge collected is proportional to particle energy.
- Sensor can be calibrated to distinguish different particles and measure dose rate.

Irradiation Experiments

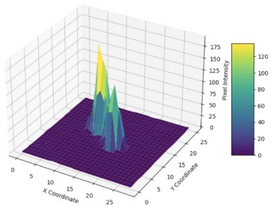
- Camera irradiation experiments with DISCOSAT-1 prototype.
- In collaboration with the Physics Department of Aarhus University.



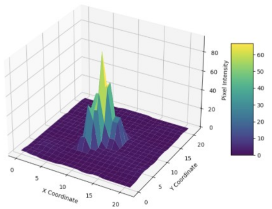
(a) ^{238}U alpha



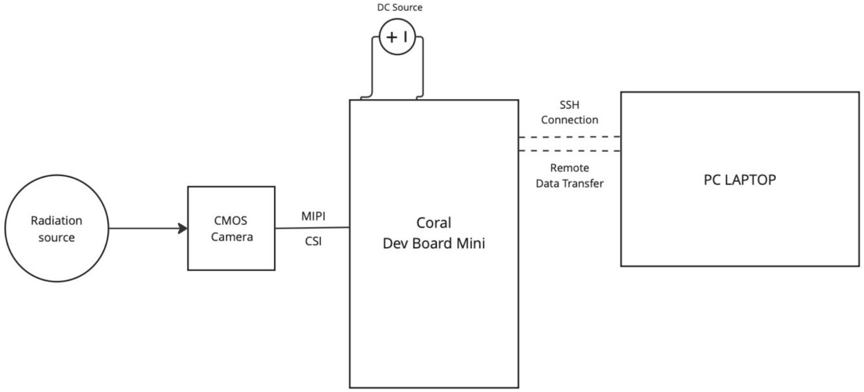
(b) ^{207}Bi beta



(c) ^{60}Co gamma



(d) ^{22}Na gamma



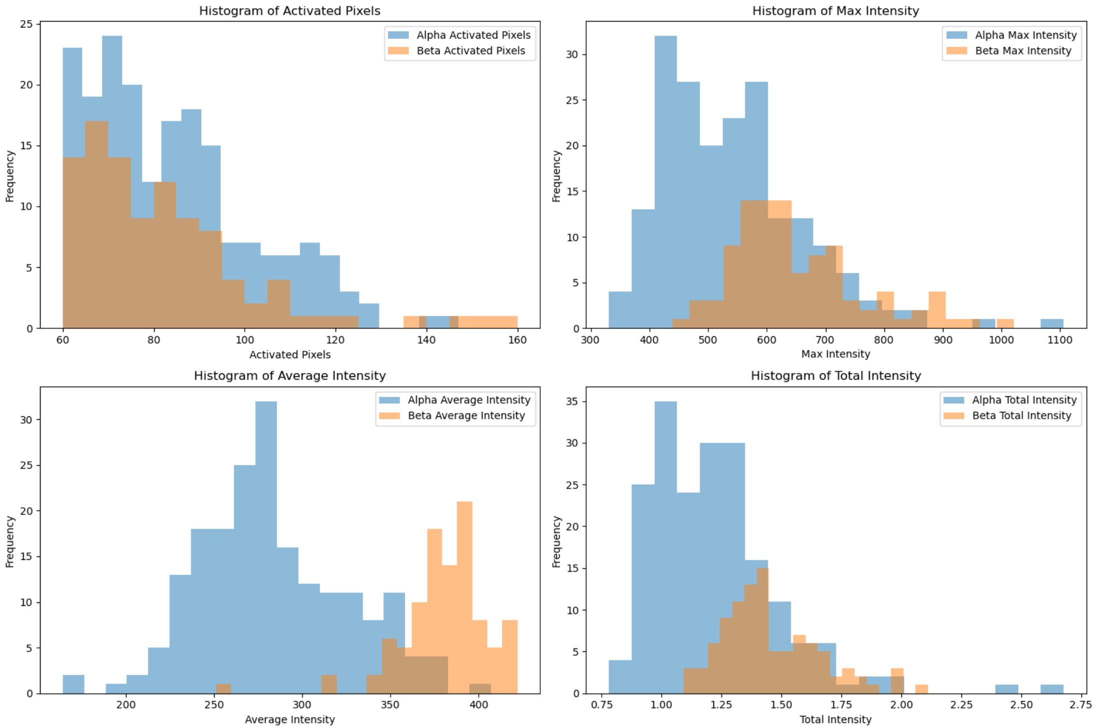
Block diagram of the experimental set up.

Source	Particle	Detections
Uranium-238	α	227
Bismuth-207	β	282
Cobalt-60	γ	42
Sodium022	γ	140

Table of acquired experimental data.

Irradiation Experiments: Results

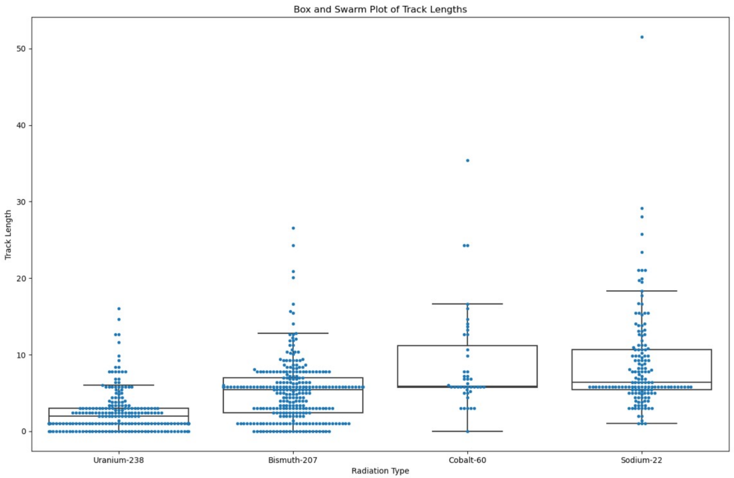
- Initial feature extraction exploration
- Histograms for activated pixels, average, maximum and total pixel intensity for Uranium-238 (α) and Bismuth-207 (β) radiation sources



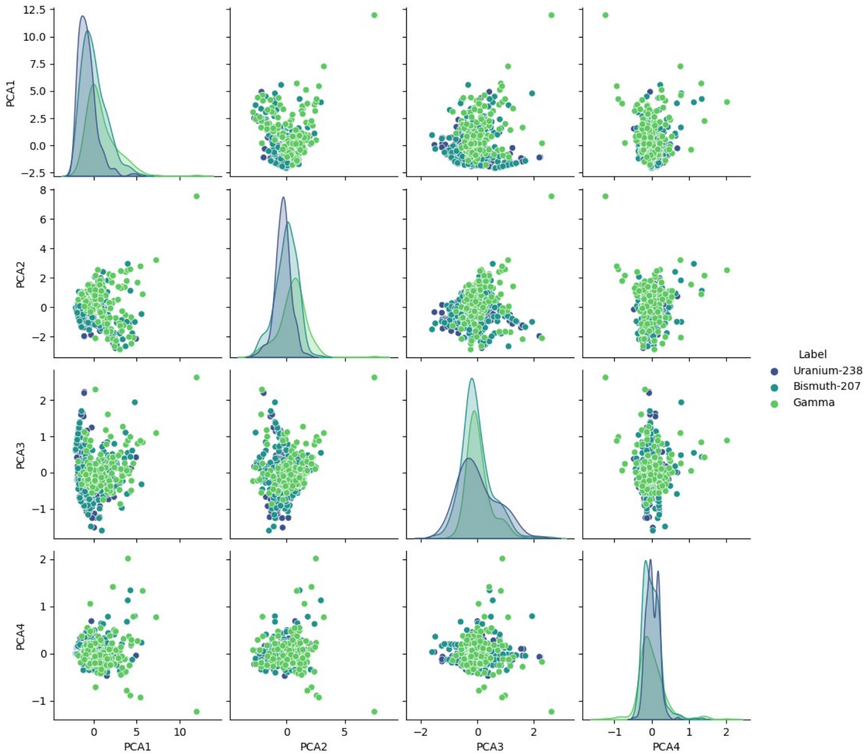
- ✓ Successful particle detection
- ✓ Extract important features for deposited energy
- ✓ Particle classification potentiality
- ✓ No saturation or degradation
- ✓ Insignificant noise

Irradiation Experiments: Results

- Multiple particle emissions per source (e.g. secondary radiation)
- High likelihood of mislabelled data
- Overlapping clustering
- Limited data



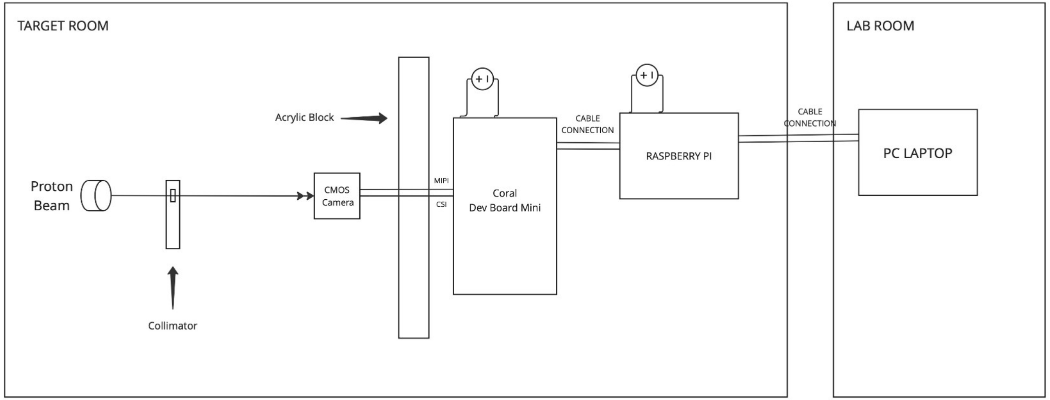
Box and Swarm Plot of Track Lengths for all sources.



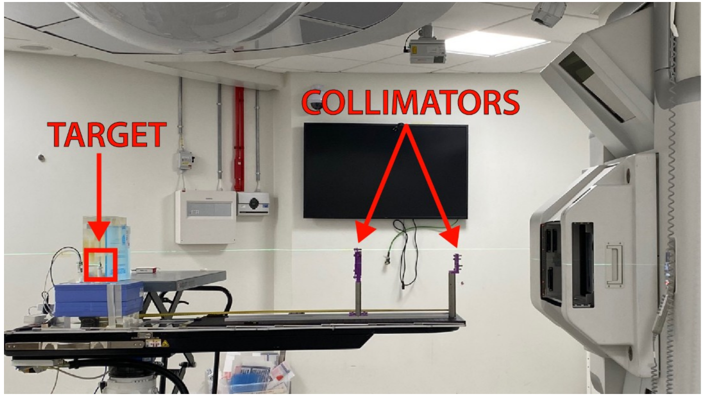
Principal Component Analysis on the whole dataset.

Proton Beam Experiment

- Testing the camera's durability under high energetic protons, its performance as a dosimeter and extracting information regarding the particles Linear Transfer Energy (LET) levels.
- Horizontal proton pencil beam scanning (PBS) in the Danish Centre for Particle Therapy at Aarhus University Hospital.



Simplified diagram of the proton beam experiment set up.



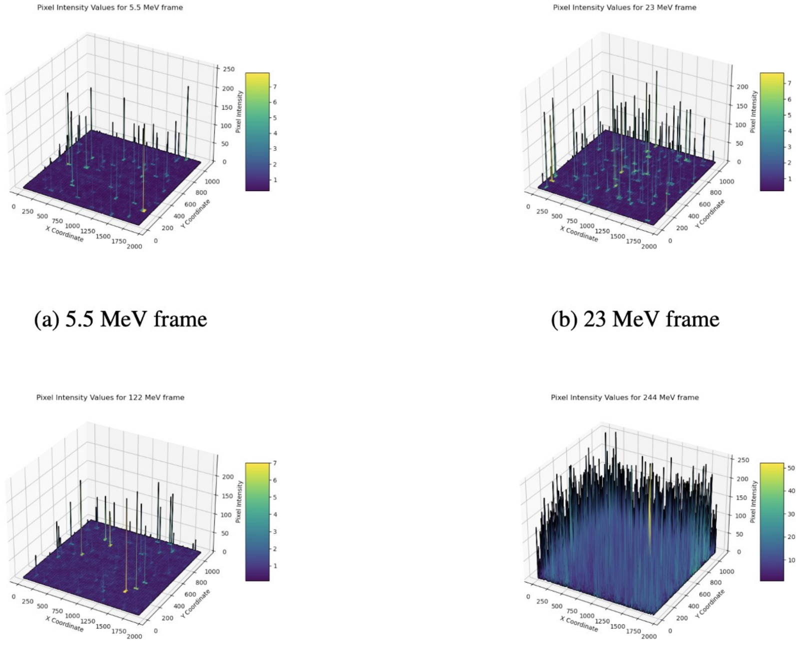
Side view of the camera irradiation experimental set up.

Proton Beam Experiment: Data Acquisition

Parameters:

- **Monitor Units (MU)** : 1, 10, 100, 1.000, 10,000, 50.000
- **Energy (LET)** : 5.5, 23, 33, 122, 244 MeV
- **Current** : 50 nA
- **Frames per second (FPS)** : 40
- **Image resolution** : 1920 x 1080 pixels
- **Pixel Value Threshold** : 30

- ➢ High-energetic particle detection
- ➢ No damage or degradation shows durability
- ➢ Insignificant noise (pixel value smaller than 10)
- ➢ Saturation between 122 – 244 MeV energy level



(a) 5.5 MeV frame (b) 23 MeV frame

(c) 122 MeV frame (d) 244 MeV frame

Proton Beam Experiment: Data Processing

K-means Colour Quantization key steps:

- Euclidean Distance Calculation:

$$d(x,c) = \sqrt{(R_x - R_c)^2 + (G_x - G_c)^2 + (B_x - B_c)^2}$$

- Cluster assignment: $\text{label}(x) = \arg\min_k \; d(x, c_k)$
- Centroid Update: $c_k = \frac{1}{N_k} \sum_{x \in C_k} x$
- Convergence Criteria: $\text{converged if } \|c_k^{(t)} - c_k^{(t-1)}\| < \epsilon \quad \forall k$
- Convert to grayscale
- Binarization with Otsu's thresholding
- ✓ Particle counting for each frame

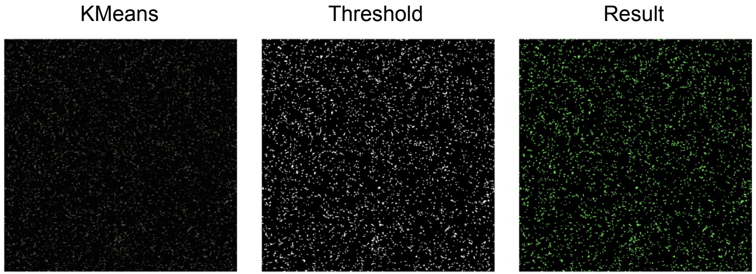


Image segmentation steps for Class 244 MeV frame.

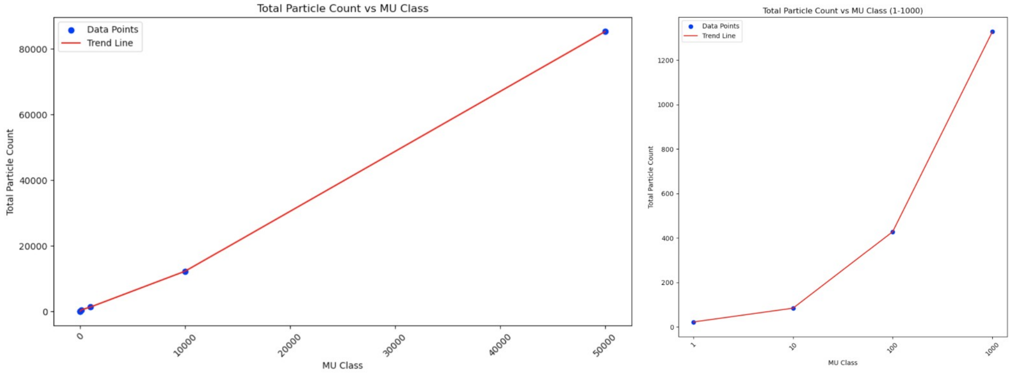
MU Class	Number of Frames	Total Particle Count	Avg Particle Size
1	1	22	2.227
10	2	84	3.194
100	4	428	3.784
1000	15	1327	3.723
10000	108	12237	3.702
50000	449	85304	3.716

Particle Count, Size, and Number of Frames by MU Class.

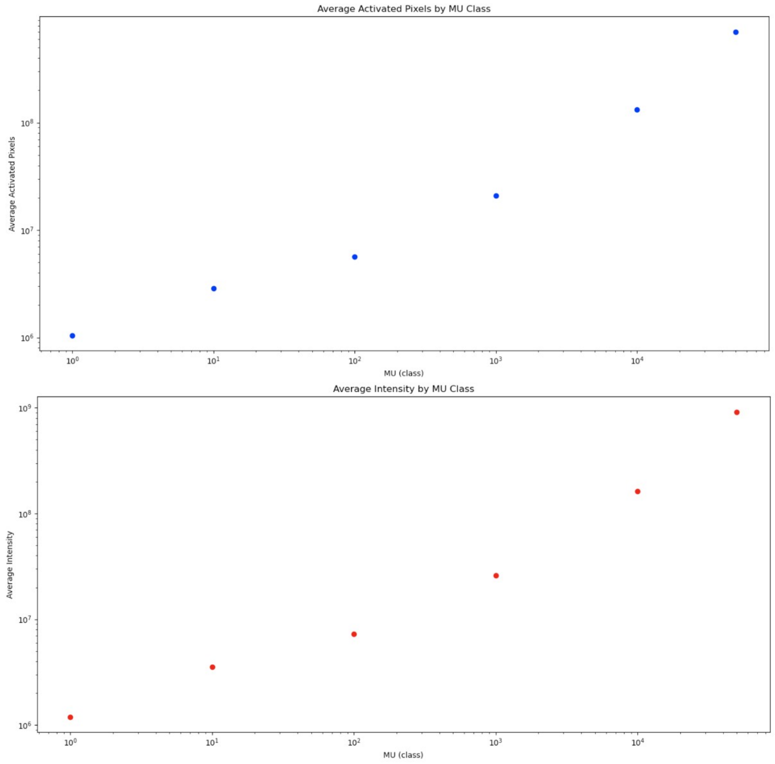
Proton Beam Experiment: Dose measurement

- Determine camera’s dosimeter capabilities
- Constant energy level at 122 MeV
- Monitor Units values : 1, 10, 1.000, 10.000, 50.000 MU
- Features extraction: Activated Pixels and Pixel Intensity
- Particle counts

✓ Proportionality is observed



Total Particle counts for each MU Class (1 - 50000) and (1-1000) MU respectively.



Average activated pixels and average intensity (log) by MU.

Proton Beam Experiment: Dose Measurement

- Linear Regression Line for particle counts versus MU
- High Mean Squared Error (MSE)
- Very few data points

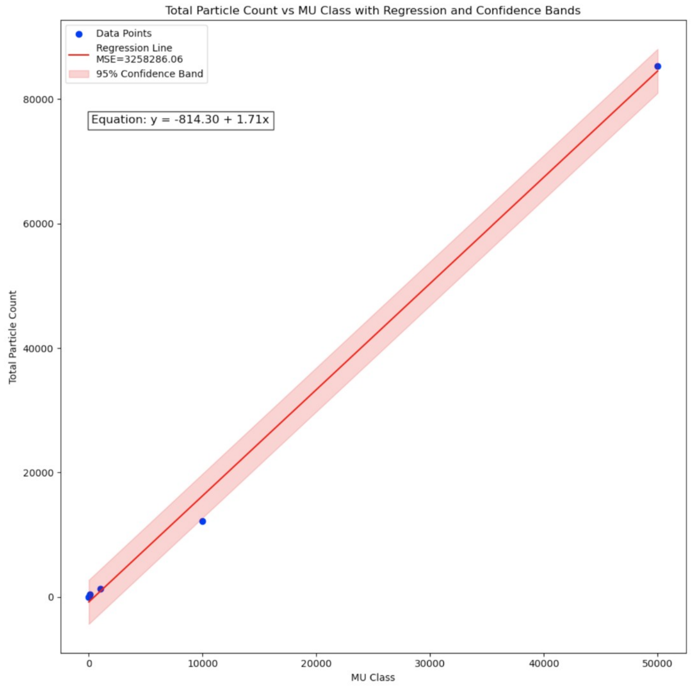
$$\boxed{\text{Total Particle Count} = -814.30 + 1.71 \times \text{MU Class}}$$

- Expected number of protons vs Number of protons detected
- Estimated proton flux: $5000\,\text{protons}/\text{cm}^2/\text{s for 1 MU}$

$$\text{Total expected protons} = \text{Flux} \times \text{Exposure Time per Frame}$$

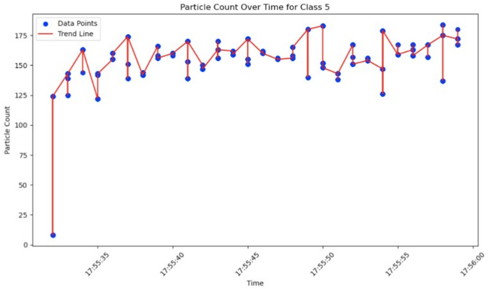
$$\begin{aligned}\text{Total Expected Protons} &= 5000\,\text{protons/cm}^2/\text{sec} \times 0.1006\,\text{cm}^2 \times 0.025\,\text{sec} \\ &= 5000 \times 0.1006 \times 0.025 \\ &= 12.575\,\text{protons}\end{aligned}$$

- The detection algorithm detected 22 particles for 1 MU

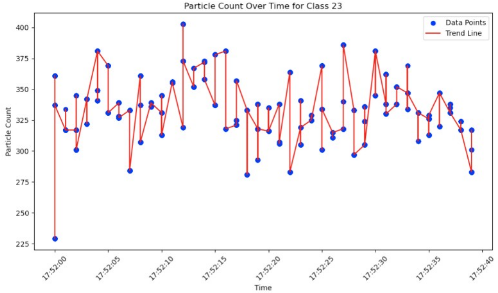


Total particle counts vs MU with Regression and Confidence Bands.

Proton Beam Experiment: Energy Dependency

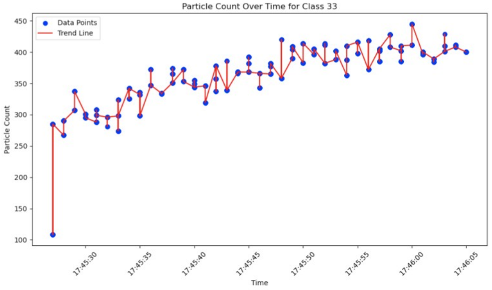


Class 5.5 MeV

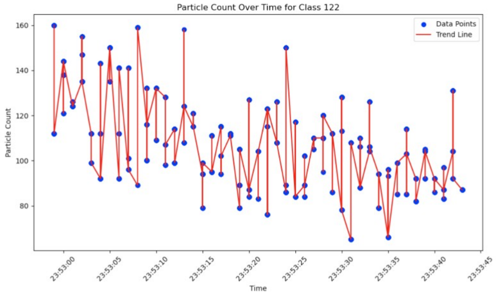


Class 23 MeV

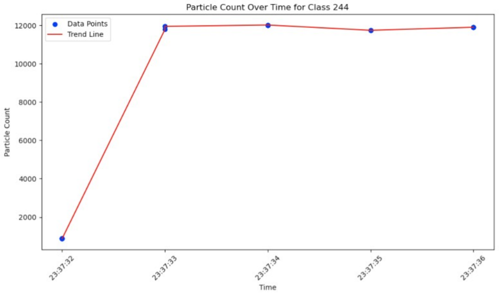
- Time-series plots show particle counts for each class.
- Fluctuations are observed, except for Class 244 MeV.
- Overall lack of proportionality between energy levels and pixel activations is noticed.



Class 33 MeV



Class 122 MeV



Class 244 MeV

Limitations & Future Work

- Limited amount of data across all experiments.
- Complexity of the real-world radiation detection and irradiation studies for spacecraft cameras.
- Repeating experiments under a well-considered and controlled set up to improve reliability and performance.
- Future camera characterization efforts within the DISCOSAT project.

Dose measurement:

- Not precise measurements.
- Thorough camera irradiation calibration is essential.

Energy dependency:

- Collect data across a wider spectrum of proton energies.
- Discover energy level of sensor saturation and degradation.

Thank you for listening