Development of Particle Classification Processing by Onboard Edge-AI System

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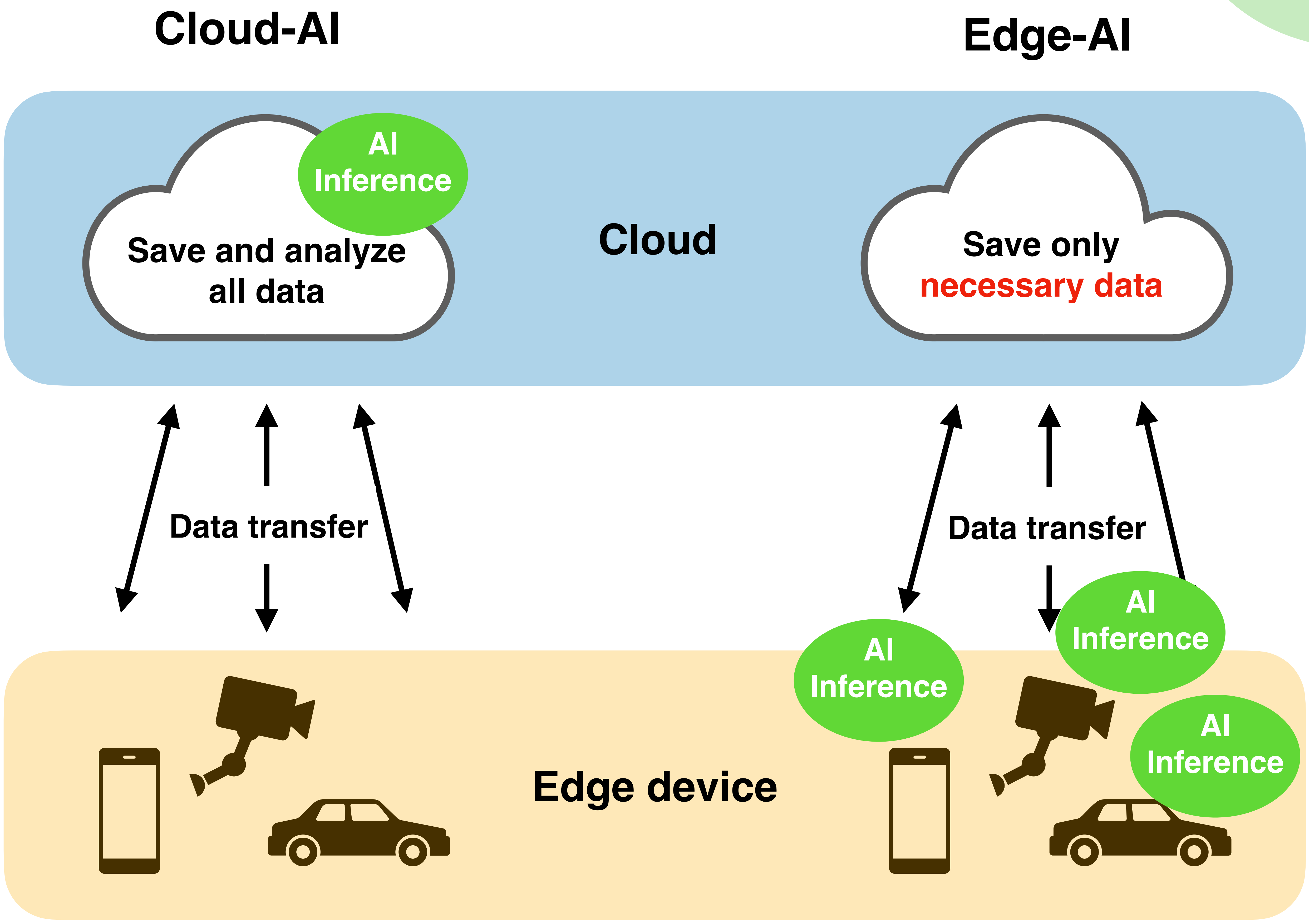
2025/12/2 @ Shiinoki Cultural Complex, Ishikawa Prefecture

Background and purpose

Edge-AI

Edge AI technology, which implements machine-learning capabilities directly on hardware, has been rapidly advancing.

- Applications in imaging systems are receiving increasing attention, particularly for:
  - Real-time processing
  - Data reduction

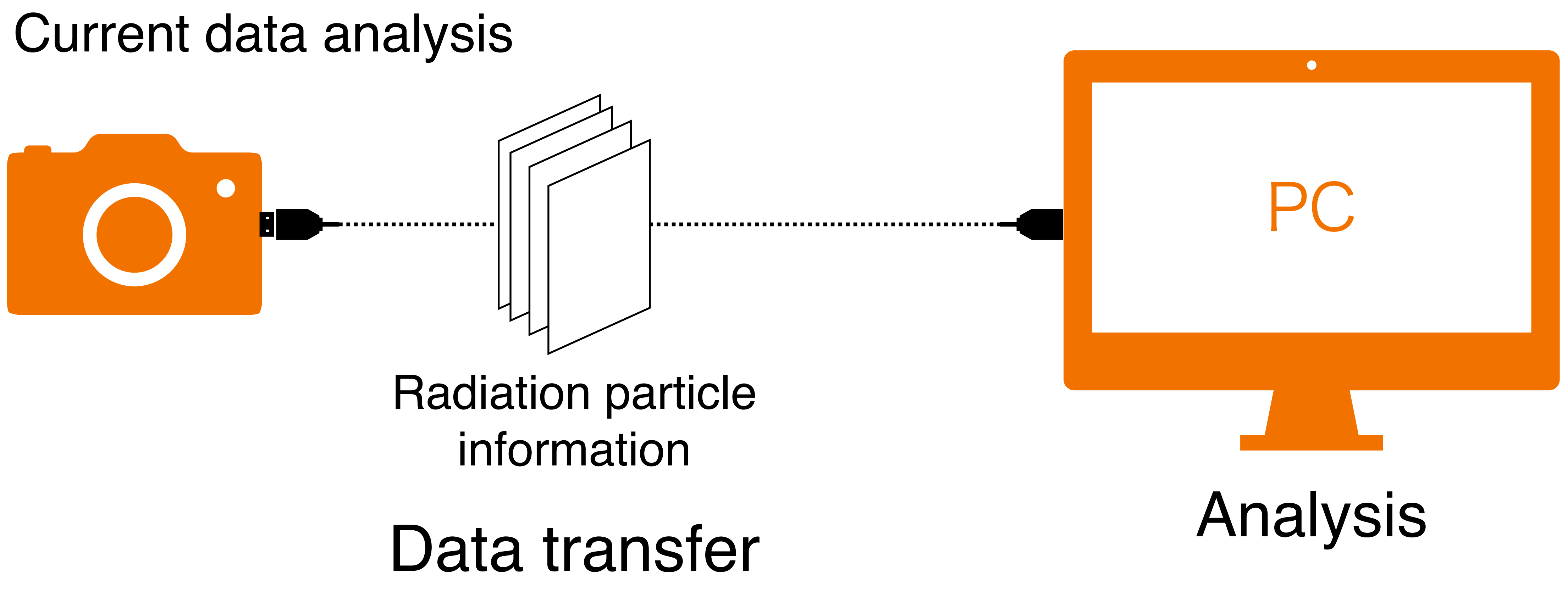


Background and purpose

We have been developing a quantum imaging camera to visualize radiation particles.

Current data analysis

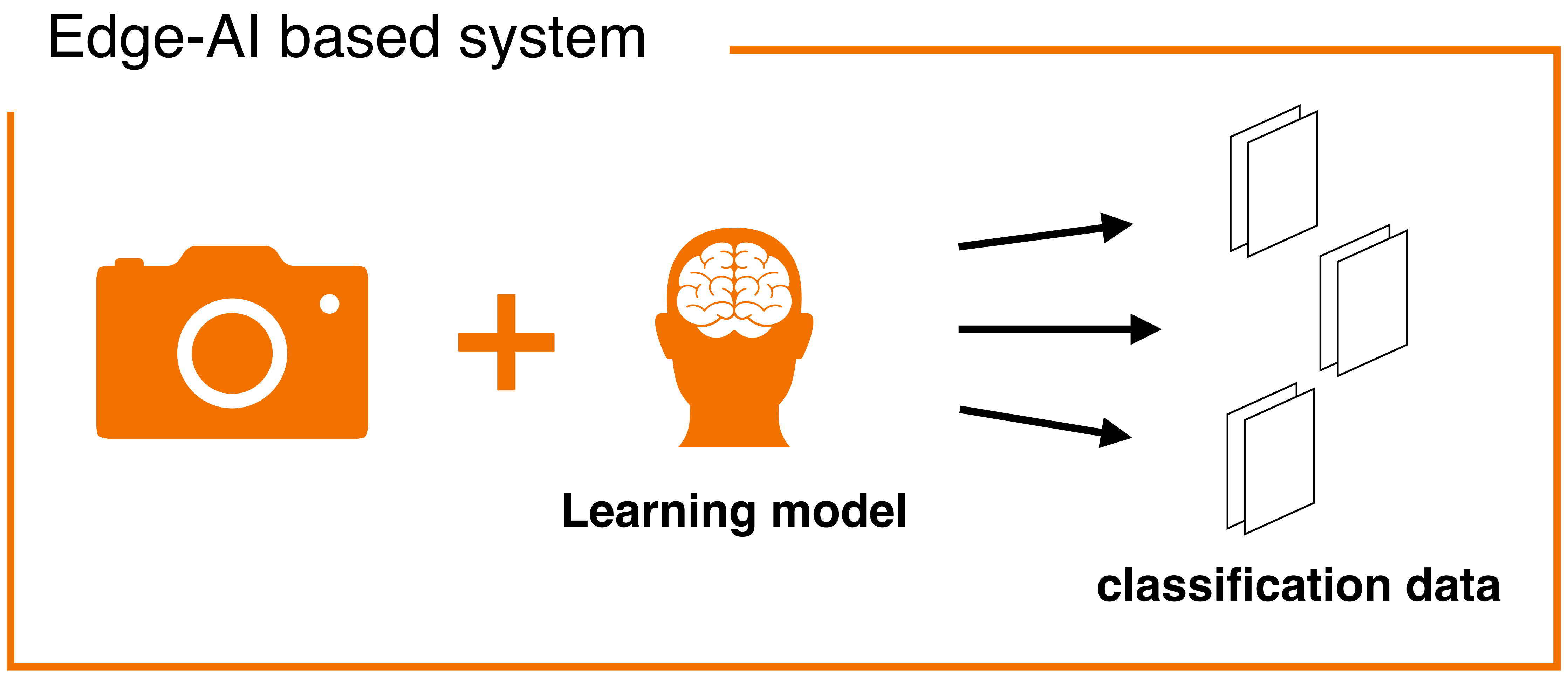
- Data transfer to an external computer is required for analysis.
- Software analysis processing



<u>To realize high-performance imaging cameras</u>

Edge-AI based system

- Data readout via FPGA + CPU-equipped board
- Data analysis by machine learning models
  - Analysis at the detector (edge device)
  - Classification of radiation particles



Background and purpose

Purpose

Establishment of a development methodology for detector systems with evaluation boards equipped with Zynq MPSoC and evaluation of the feasibility of particle classification capabilities.

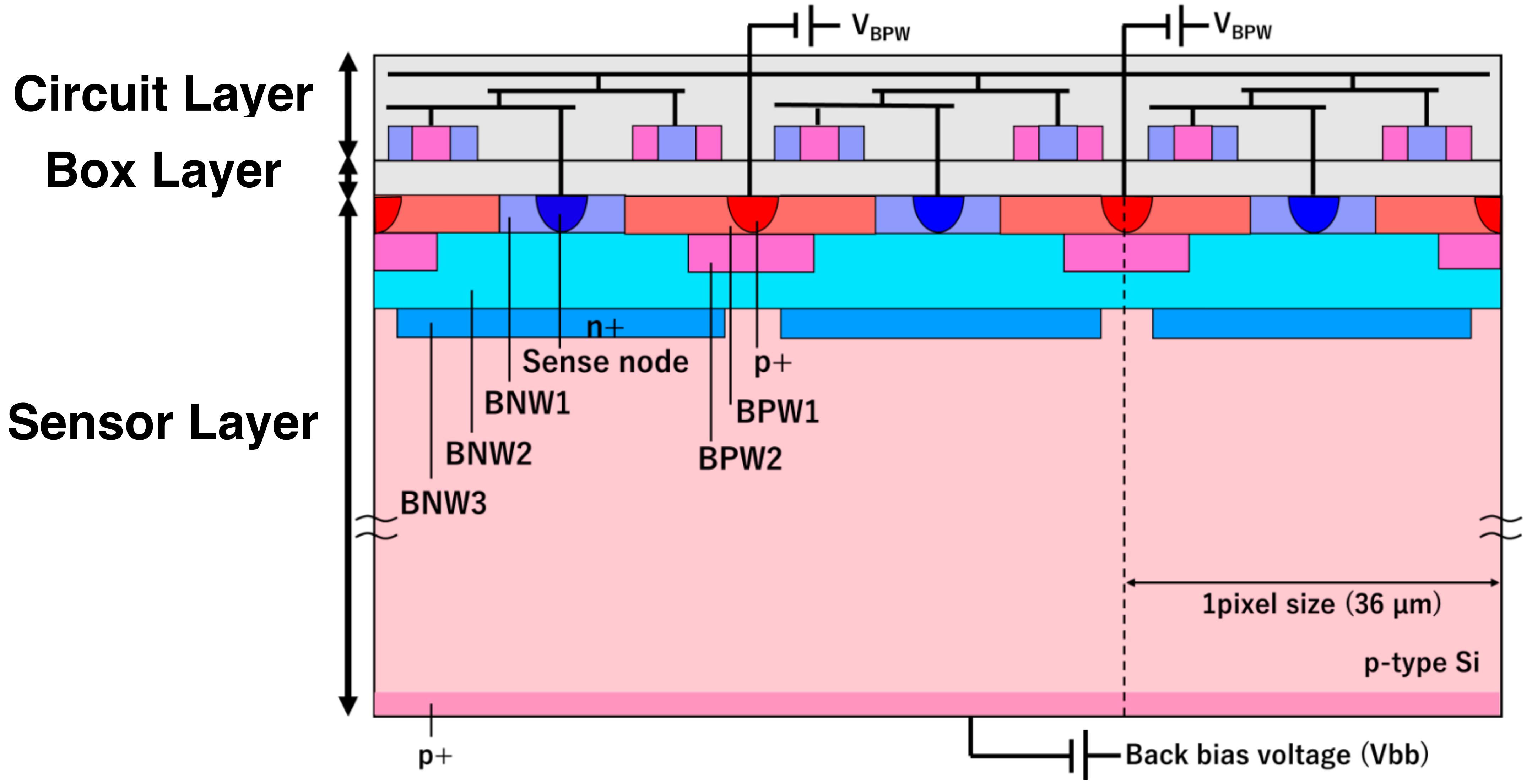
Development process

1. Particle classification model development and performance evaluation
2. Study of implementation methods for detectors and creation of an optimized model
3. Embedded system development (firmware and software development)
4. Demonstration of particle classification processing

SOI-CMOS pixel detector “XRPIX”

SOI-CMOS pixel detector

Radiation detectors with integrated readout circuit and sensor layer using Silicon-on-Insulator (SOI) technology

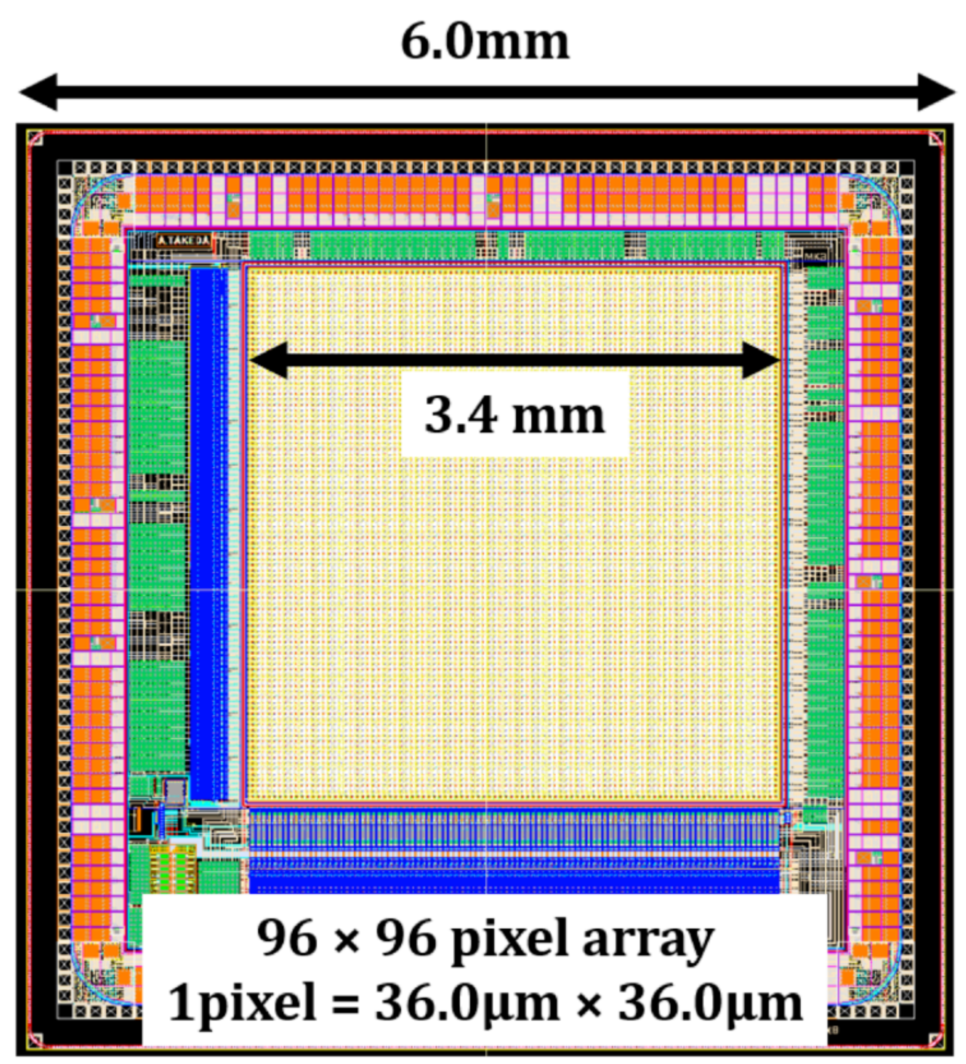


Cross-sectional view of SOI-CMOS pixel detector

XRPIX8.3

Pixel size : 36 μm sq.

Number of pixels : 9216 (= 96 × 96)



XRPIX8 Chip layout

Zynq UltraScale+™ MPSoC　ZCU102 Evaluation Board

ZCU102 Evaluation Board

The ZCU102 equipped with an MPSoC (MultiProcessor System on a Chip) enables the development of various applications.

- Processing System（**PS**）
  - Arm Cortex-A53, Arm Mali-400 MP2 (GPU), etc
- Programable Logic（**PL**）
  - FPGA、Block RAM
  - Deeplearning Processing Unit（DPU）

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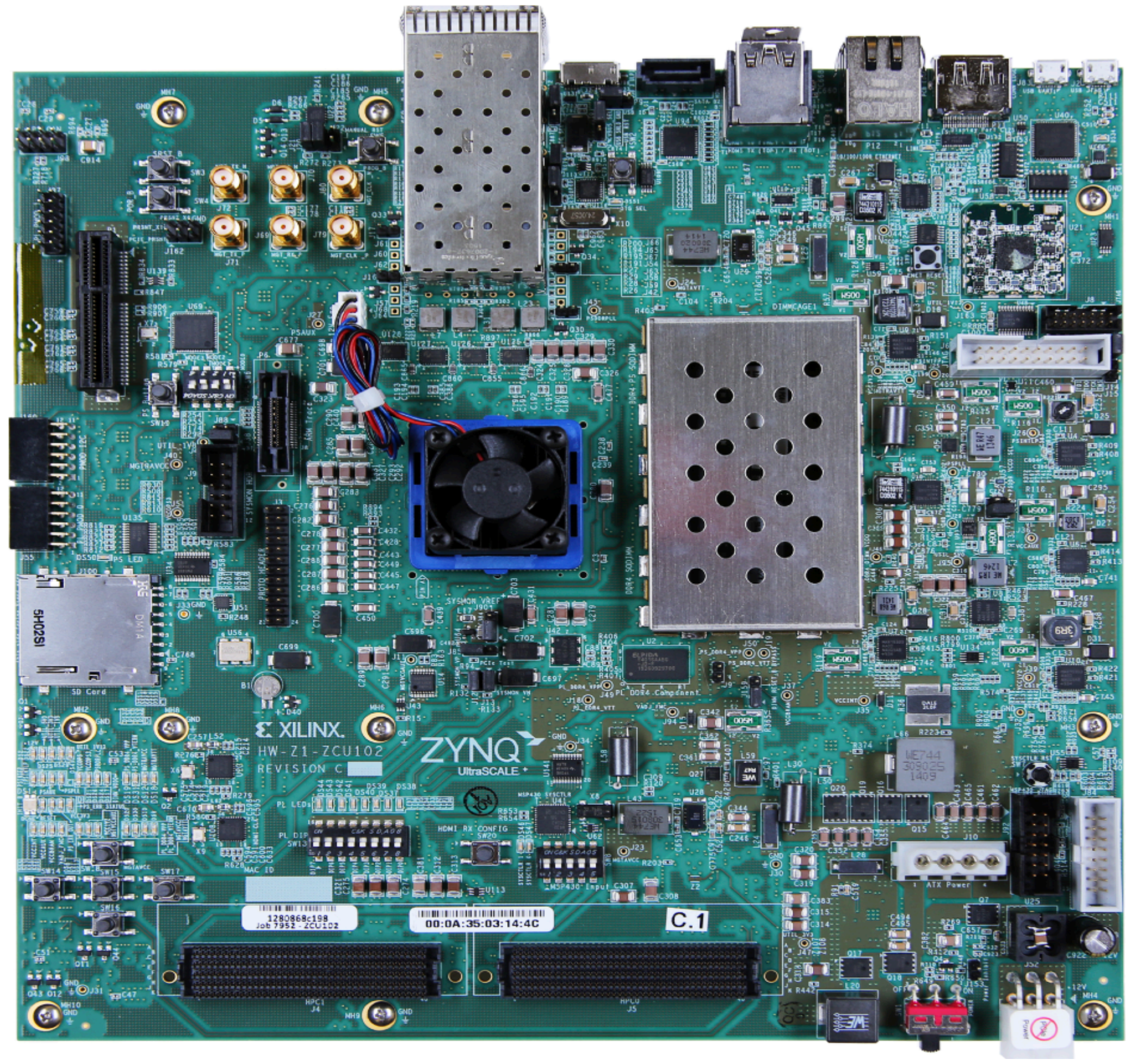
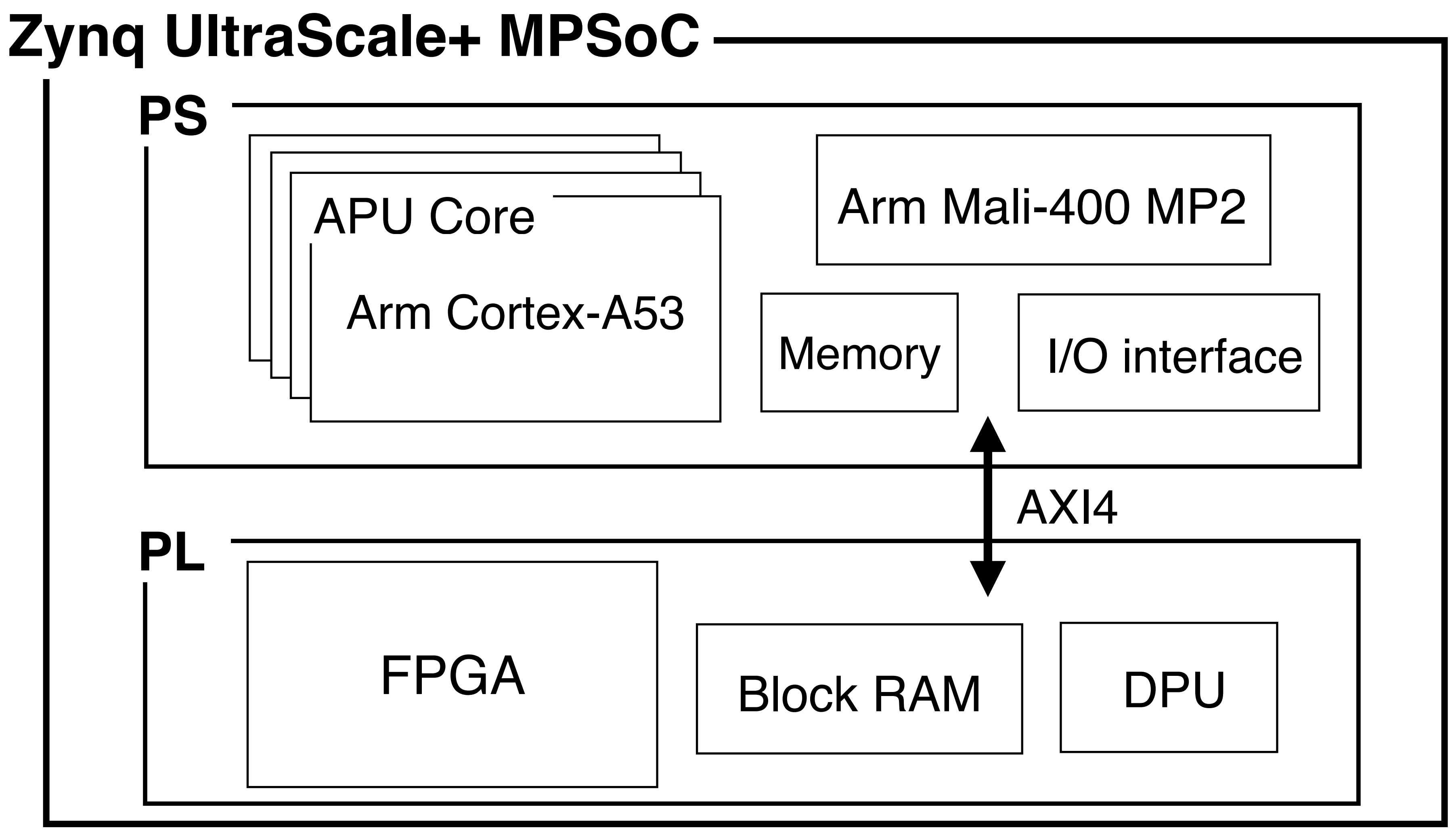
AI model accelerator IP
Implement and run the optimized model



Zynq UltraScale+™ MPSoC ZCU102 Evaluation Board



Zynq UltraScale+™ MPSoC PS,PL

Radiation particle data

Particle data output from the detector

- Outputs energy values for 16x16 (=256) pixels
- Three types of particle data used： β-ray, X-ray, α-particle

Energy distribution pattern
- β-ray：line
- X-ray：point
- α-particle：circle

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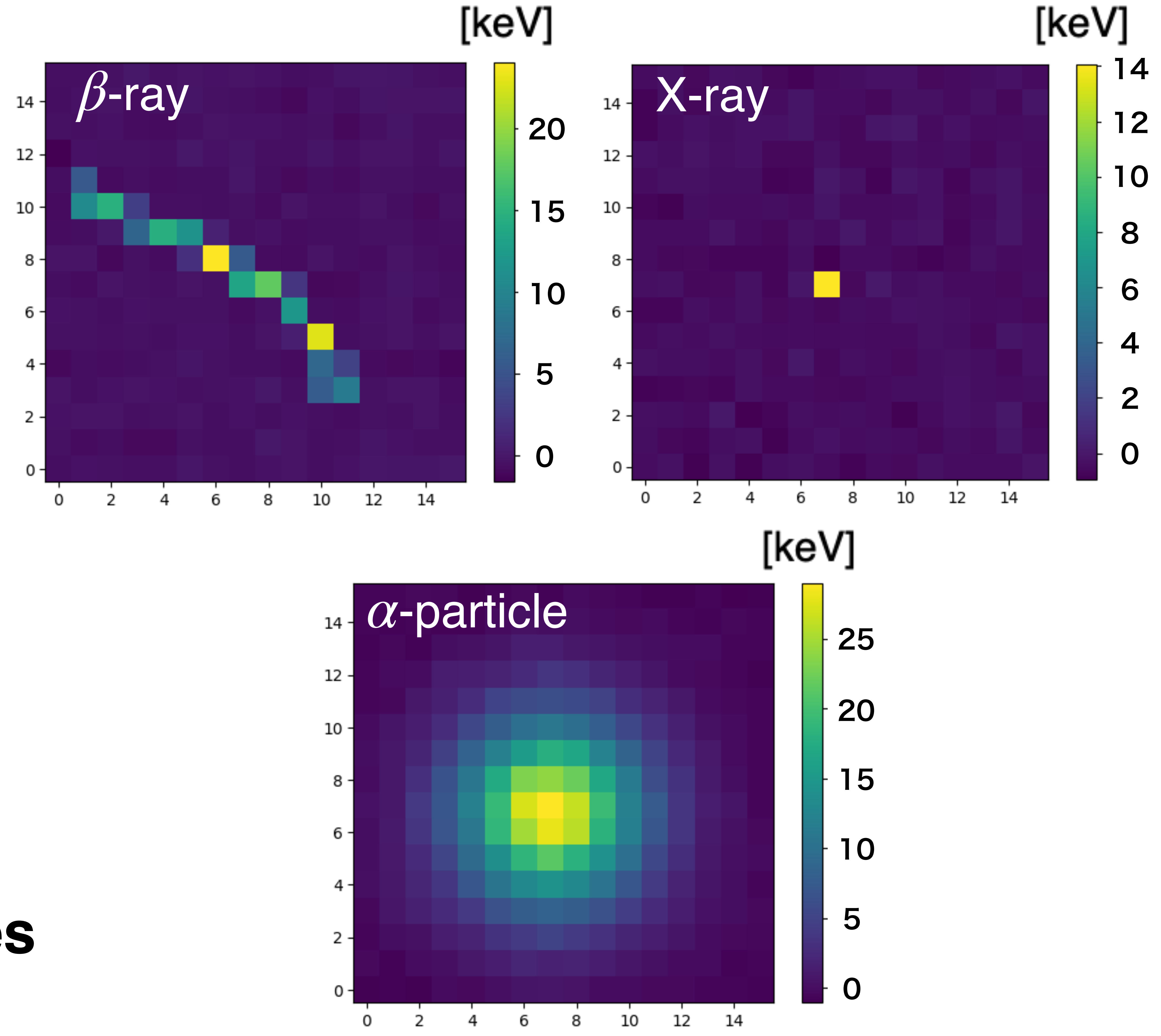
classification of particles based on differences in energy distribution patterns



Energy distribution of β-ray, X-ray, and α-particle

Particle classification model development

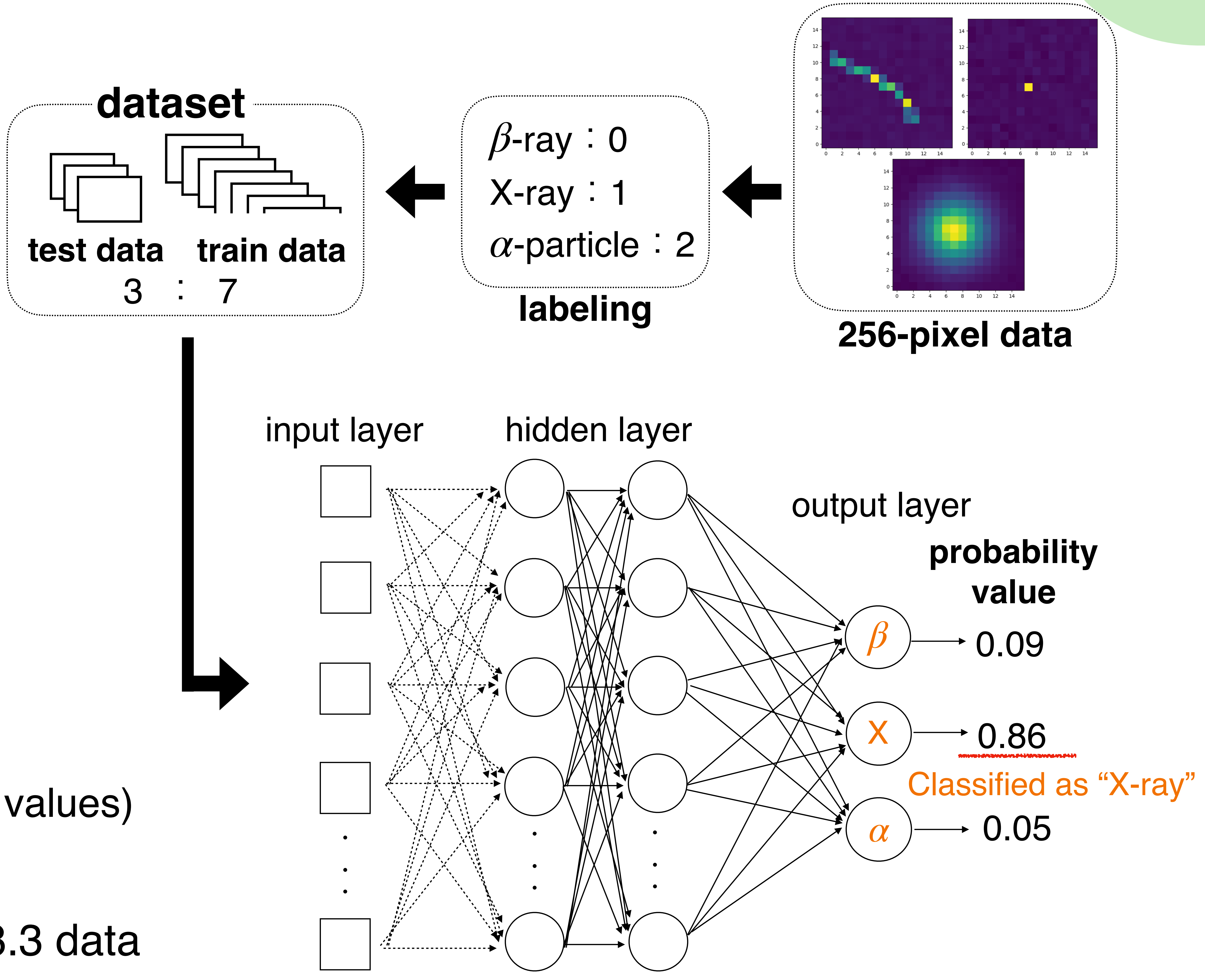
Dataset

- Labeling for three types of particle data
- Create test data and train data at a ratio of 3:7

Classification model development

Create a learning model with neural networks.
Using the TensorFlow framework.

- Composed of three types of layers
  - input layer : Input as a one-dimensional array
  - hidden layer : Model parameter-based calculation
  - output layer : Output of inference results (probability values)



Structure of particle classification model

Software-based evaluation using XRPIX8.3 data

⇨ **Achieved over 99% accuracy**

Particle classification model optimization

Implementing a classification model into a detector requires techniques such as model parameter compression.

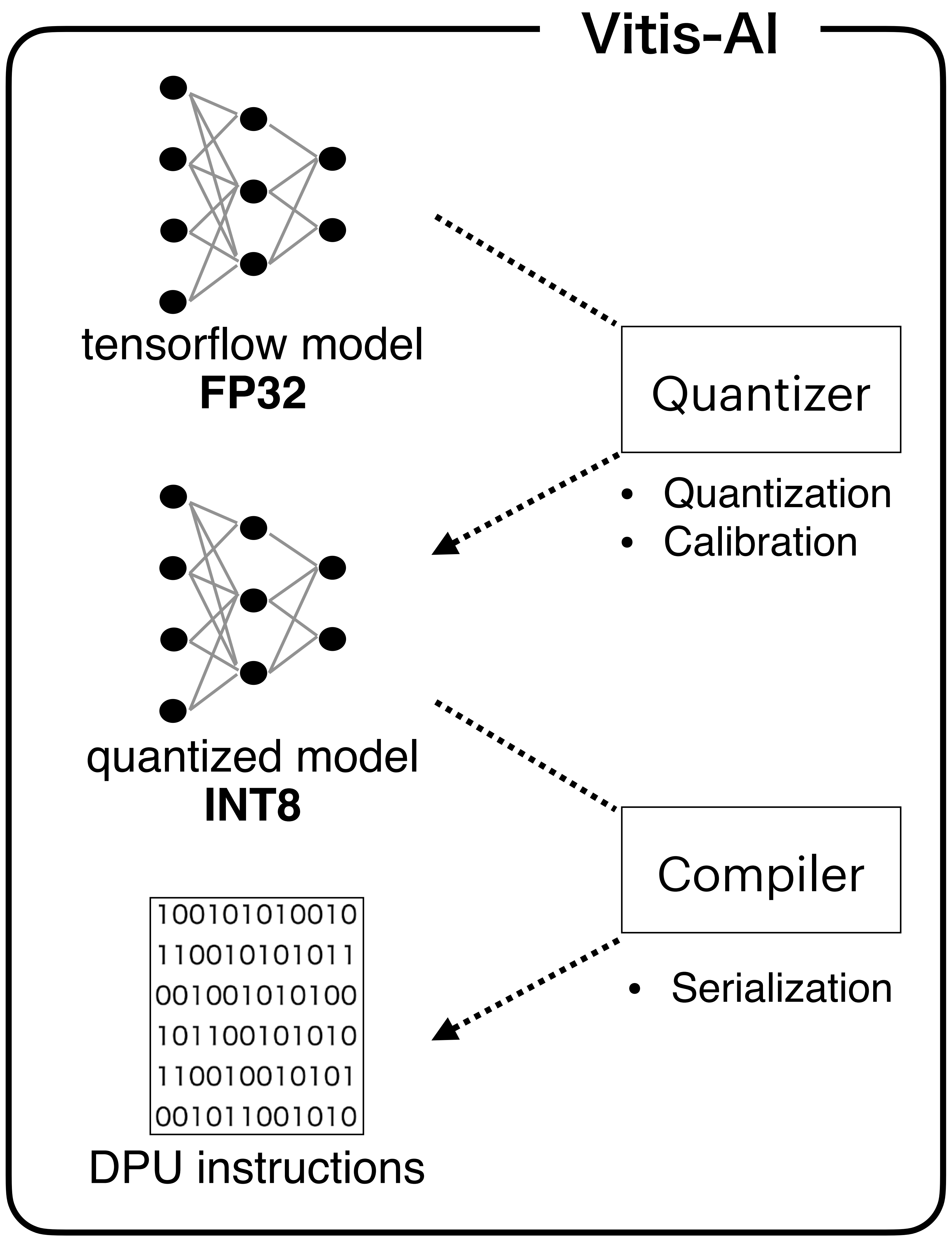
Vitis-AI Development Environment

- An environment for accelerating AI inference on AMD (Xilinx) hardware platforms

Optimization of classification model

Optimize the model evaluated using software-based methods.

- **Quantizer**：Simplification and lightweight processing of calculations through integer conversion
- **Compiler**：Serialize to a format supported by DPU



Quantization and compilation workflow for classification models using Vitis-AI

Firmware and software development for MPSoC

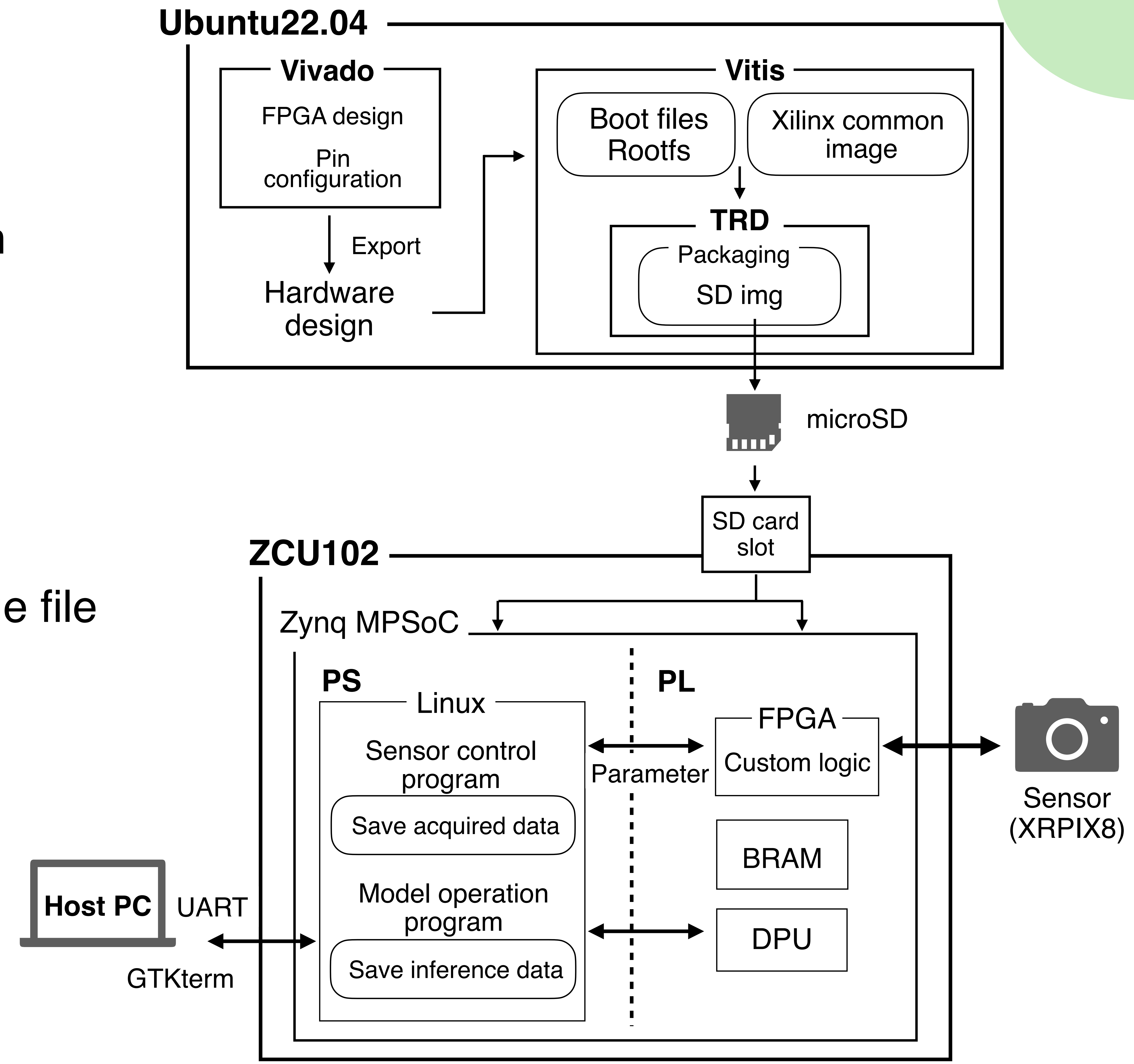
Firmware and software development

- Using **Vivado** and **Vitis** provided by AMD (Xilinx)
  - **Vivado**：FPGA design and external pin configuration
  - **Vitis**：Software design, DPU integration, packaging

SD card boot on ZCU102

- Booting the Linux OS from SD card containing an image file
  - **PS**：Sensor control, model operation program
  - **PL**：Custom logic, memory, DPU

- Control the PS via serial communication from the host PC
- Particle identification using a DPU model on data acquired in real time



Overview of firmware and software development on Zynq MPSoC

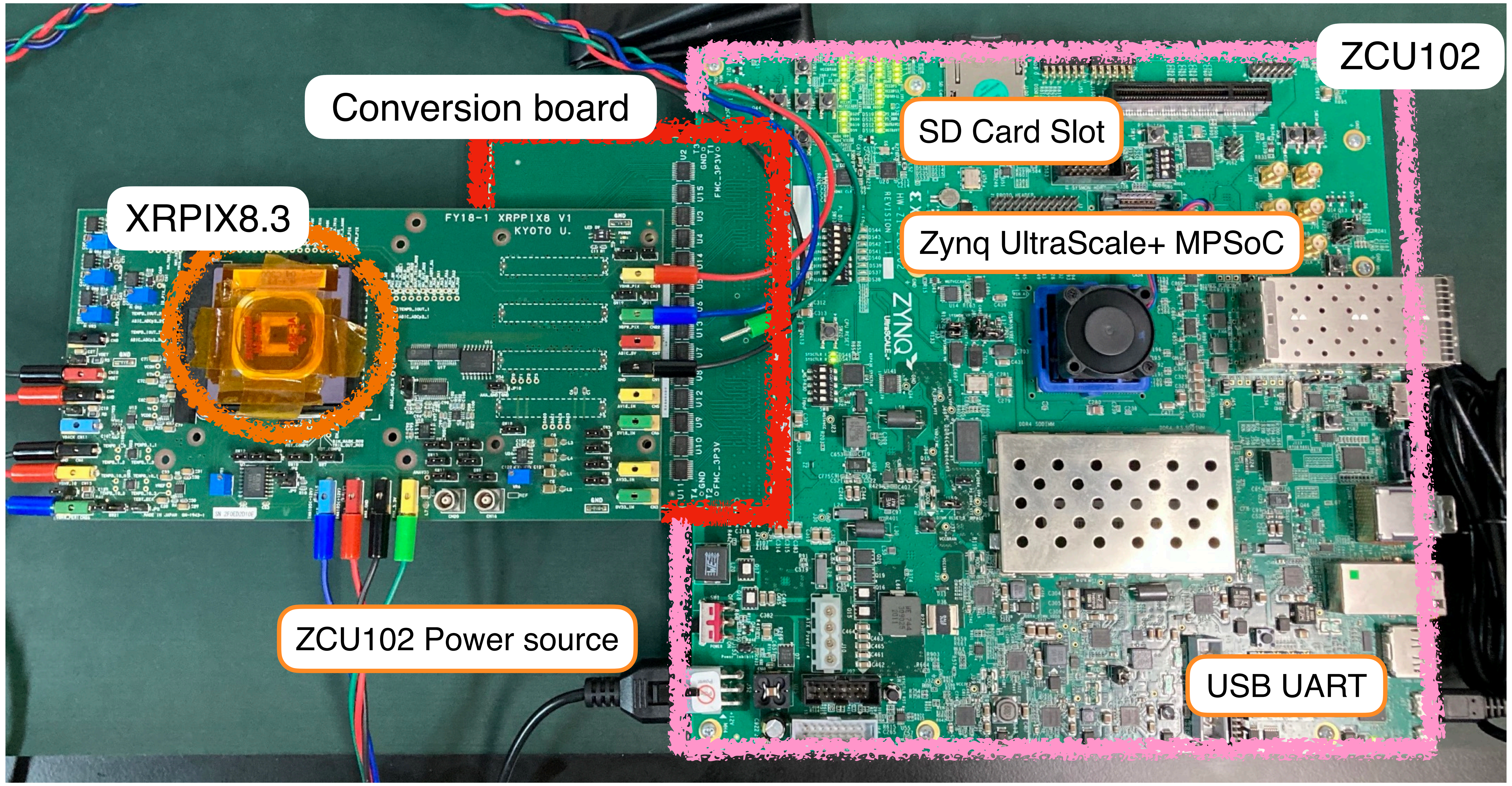
Experimental setup

Experimental condition

- Connected the sensor board and ZCU102 with conversion board.
  - XRPIX8.3
  - Two types of radiation sources
    - ^{90}**Sr** : β-ray
    - ^{241}**Am** : X-ray、α-particle
  - Acquire 10K frames per particle

Evaluation method

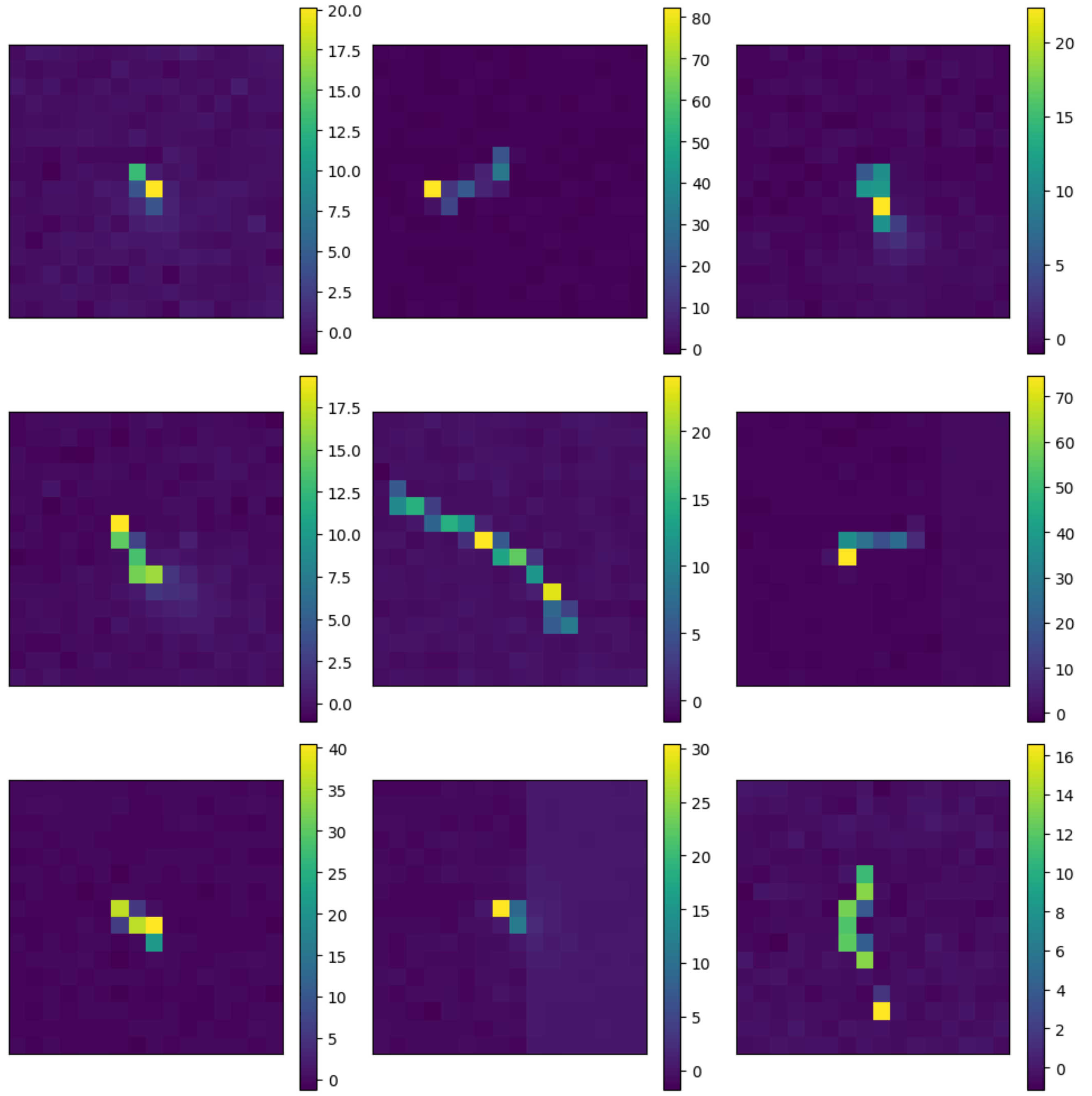
- Evaluation of data by label after particle classification
  - Check the 2D energy distribution
  - Check misclassified data



Experimental setup

Result

- Particle classification results is shown below (2D and the proportion of each particle).



β-ray （^{90}Sr）

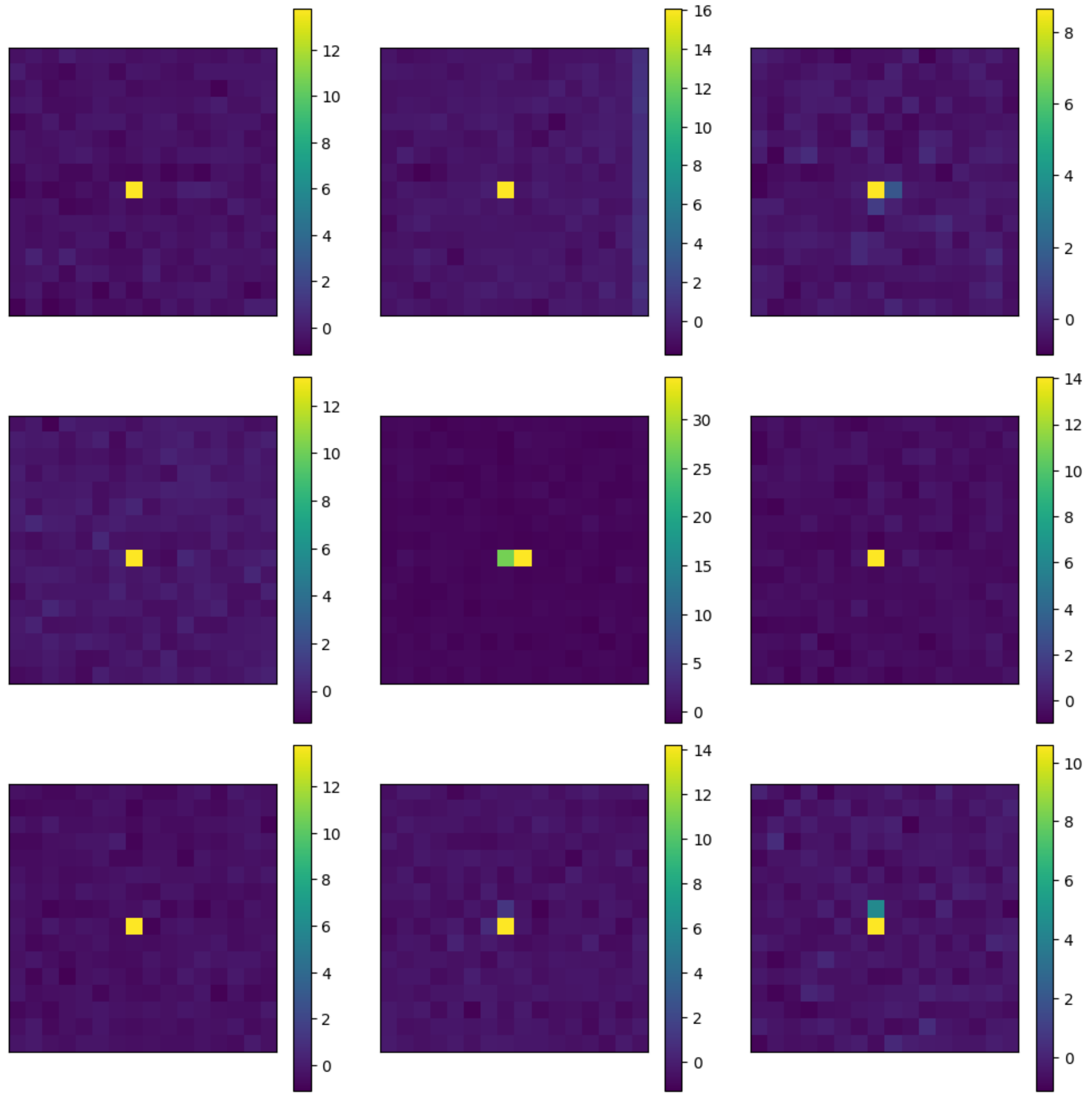
2D energy distributions

Classification results for ^{90}Sr

β-ray：84.23%

X-ray：15.68%

α-particle：0.09%



X-ray （^{241}Am）

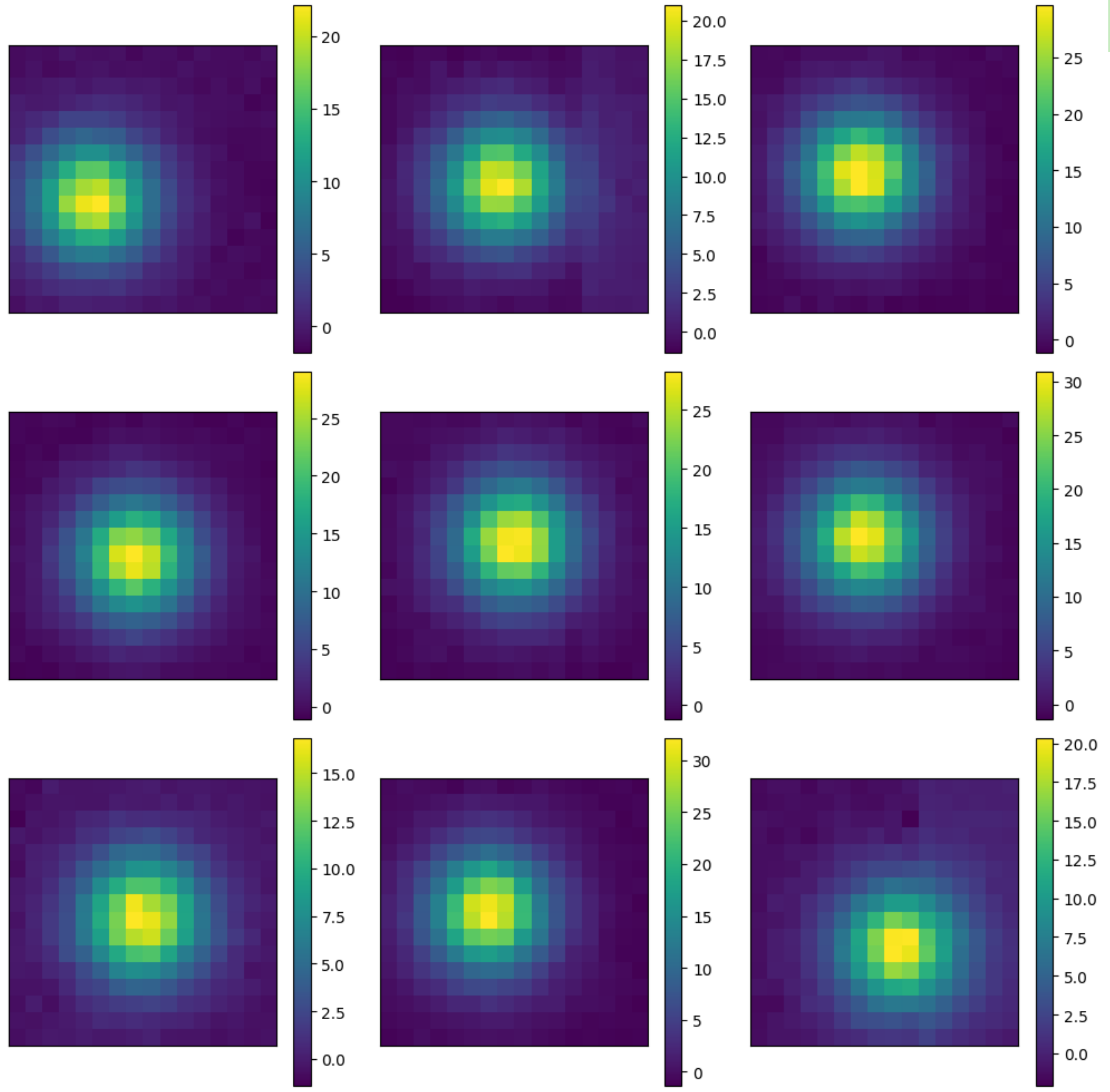
2D energy distributions

Classification results for ^{241}Am

β-ray：5.64%

X-ray：94.36%

α-particle：0.00%



α-particle （^{241}Am）

2D energy distributions

Classification results for ^{241}Am

β-ray：0.97%

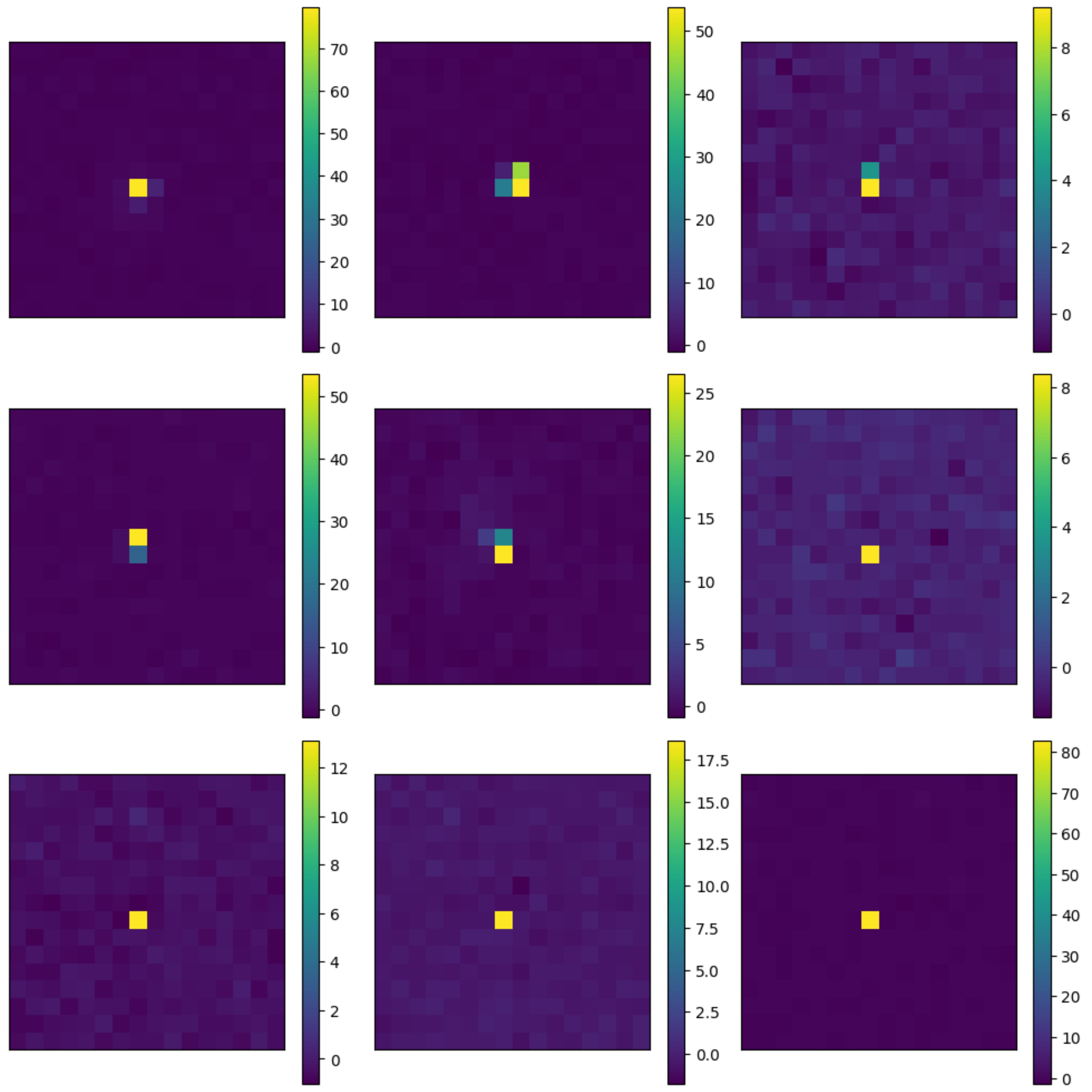
X-ray：1.71%

α-particle：97.32%

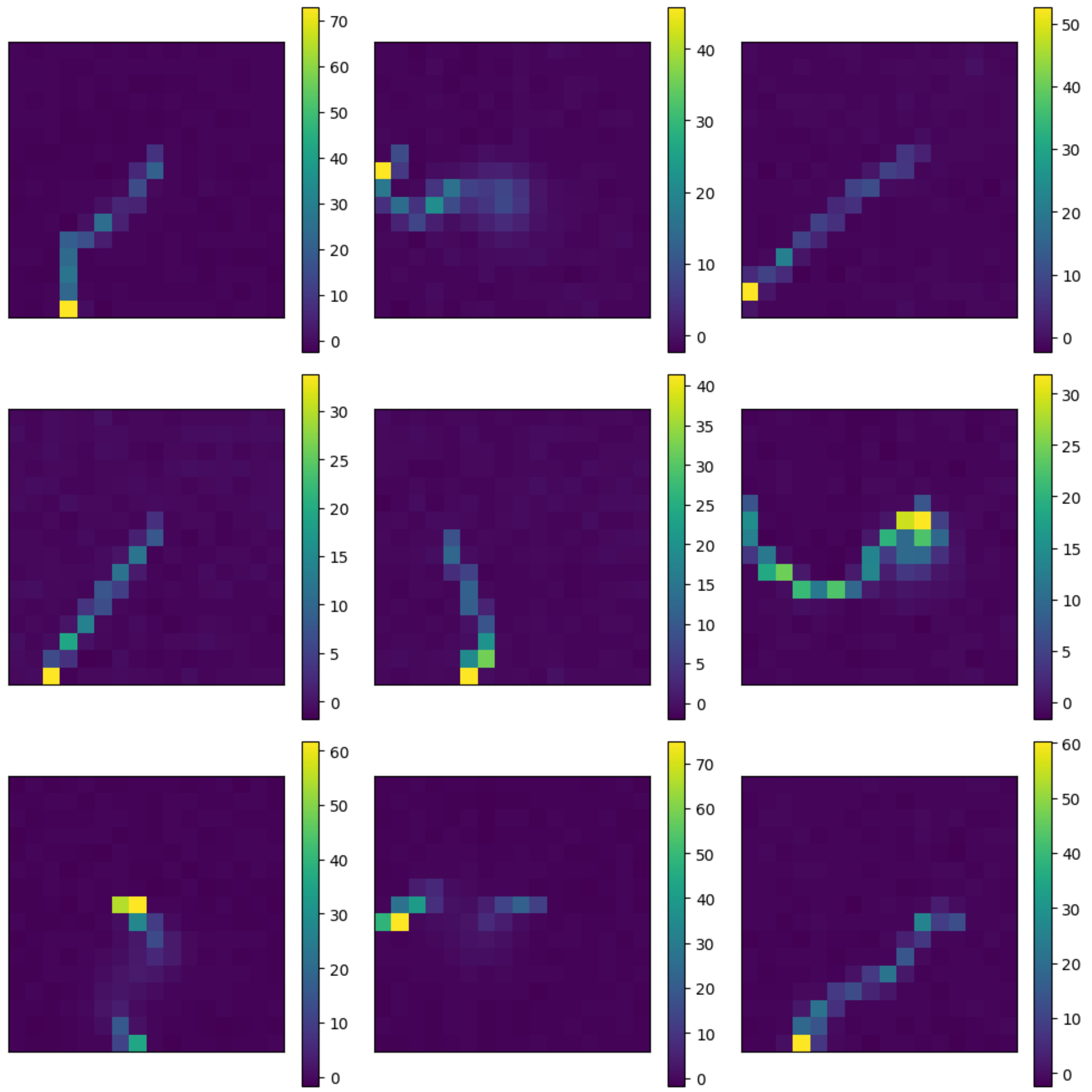
- Particle data can be classified based on differences in energy distribution.
- **Particle classification model successfully classified the characteristic energy distribution patterns of each particle.**

Result

- The misclassified data for ^{90}Sr β-ray are shown below.



β-ray misclassified as X-ray



β-ray misclassified as α-particle

Classification results for ^{90}Sr
β-ray：84.23%
X-ray：15.68%
α-particle：0.09%

- The partial overlap in the energy distribution between particles is the cause of these misclassifications.

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- **Particle classification using the DPU model demonstrates high performance despite some misclassifications.**
- Improved train data is required for reliable operation.

Summary

Establishing a development methodology for detector systems using the ZCU102 Evaluation Board with Zynq MPSoC and demonstrating the feasibility of particle classification processing

Particle classification model development and optimization

- Create a learning model using neural networks
- Achieved over 99% accuracy through software-based evaluation
- Quantization and compilation by Vitis-AI

Firmware and software development on Zynq MPSoC

- Vivado：FPGA design、Vitis：Software design
- Booting the Linux OS from an SD card
  - PS：Sensor control, model operation program
  - PL：Custom logic, memory, DPU

Demonstration of particle classification processing

- High performance despite some misclassifications
- Improved train data is required for reliable operation

We established a new detector system development methodology and evaluated the feasibility of particle classification processing.

Based on this foundational technology, applications to other quantum imaging fields are also expected.