

Research on Robust Intelligence for MTCA.4 Platforms with Simulation-Based Pre-Training and Multi-Task Modular Deployment

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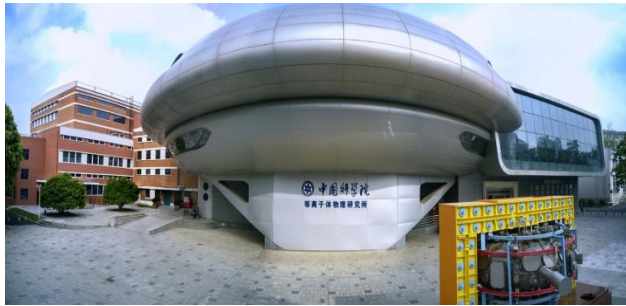
Content

- **Introduce of ASIPP and ZOONENG Corporation**
- MTCA Technology and Industry Progress
- Robust Cross-Detector γ -ray Nuclide Identification
Based on the MTCA Platform
- DDAQ Technology and System Architecture
- DDAQ-MTCA Integration for Future Fusion Systems
- Summary

Introduce of ASIPP and ZOONENG Corporation



- **ASIPP**: Institute of Plasma Physics, Chinese Academy of Sciences, founded in **Sept. 1978** in Hefei, Anhui Province.
- **Mission of ASIPP**: The research of **fusion energy** based on the **tokamak approach**.
- **ASIPP organization**: **14** Divisions, **3** Research Centers.
- **Human resource**: **>1500**



Science island

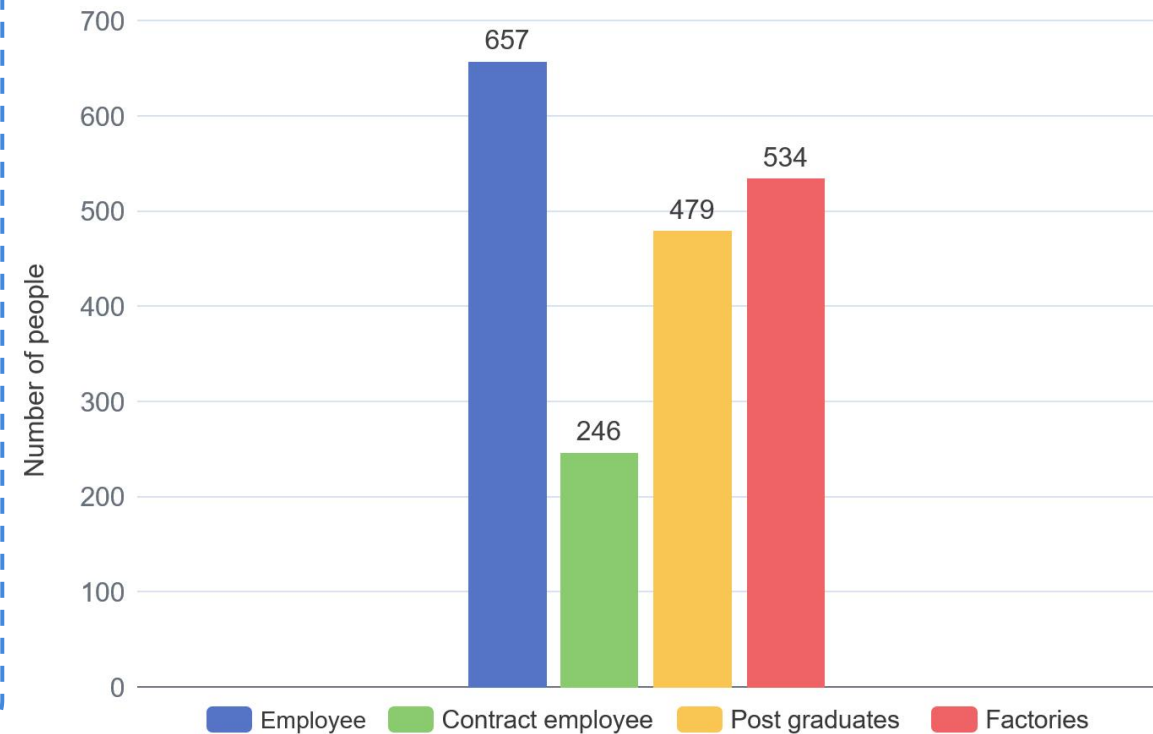


New Energy Research Center



CRAFT

Human Resources



Introduce of ASIPP and ZOONENG Corporation



~To Date: Experimental
Verification Phase

~2030 Engineering Technology
Verification Phase

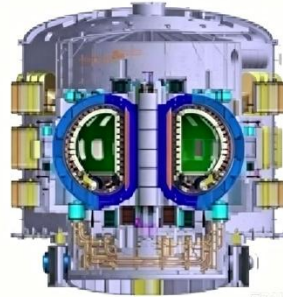
~2035 Engineering
Demonstration

2040~2045 Grid-connected
Power Generation



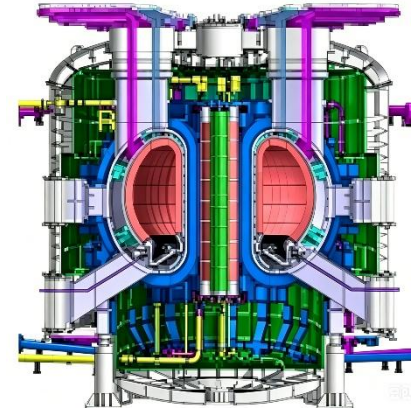
Experimental verification phase

- ◆ EAST ◆ Stellarator
- ◆ CRAFT ◆ FRC ◆
- ◆ Scientific Parameter Validation & Core Testbed Construction



Engineering Technology Verification Phase

- ◆ BEST ◆ ITER
- ◆ Key Physical & Engineering Technologies
- ◆ Deuterium-Tritium Experiment
- ◆ 20~40MW $Q=1$
- ◆ 100~200MW $Q=5$
- ◆ First discharge 2027, Power generation demo by 2030.



Fusion Engineering Demonstration Reactor

- ◆ Fusion power = 1.5-3GW
- ◆ Fusion gain $Q=20-30$ SSO
- ◆ TBR >1
- ◆ Safety
- ◆ Economy
- ◆ Continuous operating capability
- ◆ CFEDR completion expected by 2035.



Grid-connected power generation: the ultimate goal

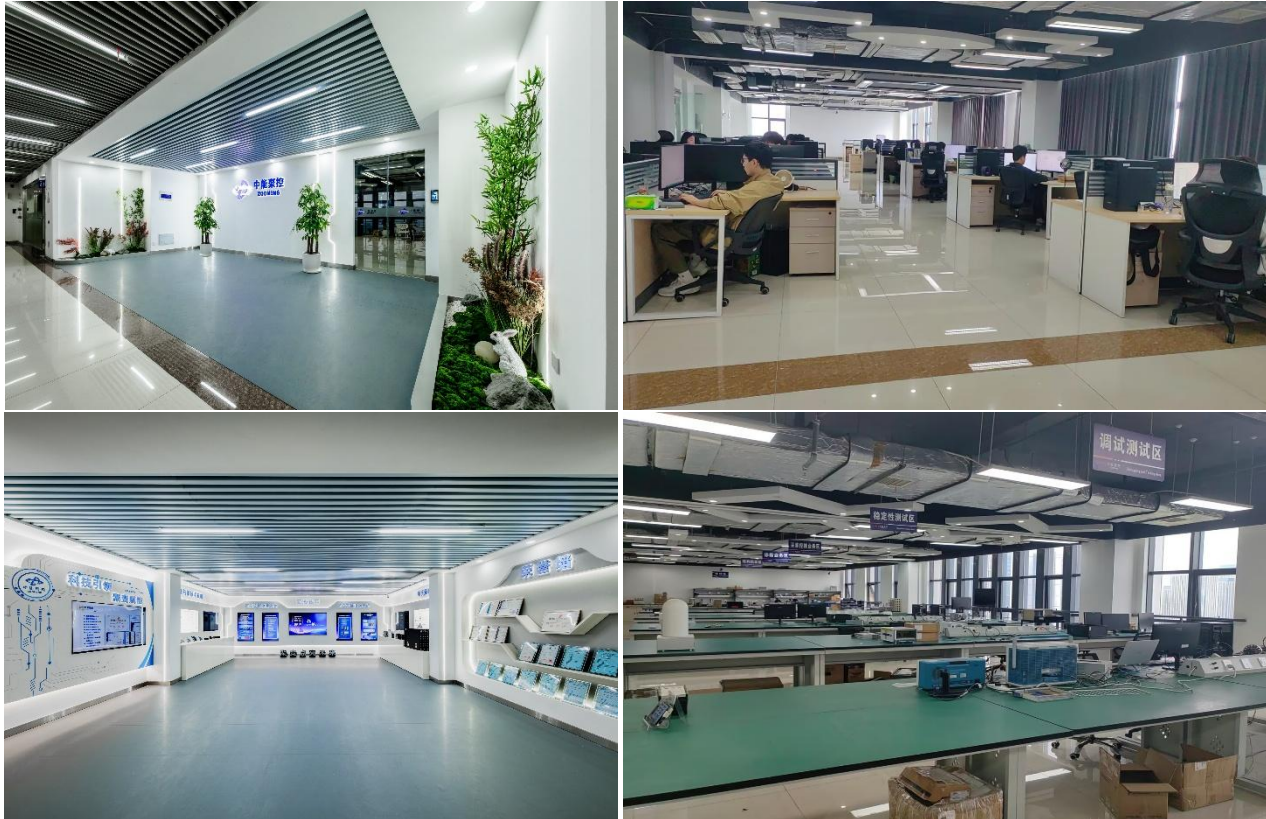
- ◆ Build a commercial demo plant and commercialize fusion energy.
- ◆ Expected to achieve grid-connected power generation around 2040-2045

- ◆ From EAST (foundation) to BEST (engineering validation) to CFEDR (demonstration), ultimately achieving grid-connected power generation.
- ◆ Interlinked stages together form China's grand blueprint for fusion energy development.

Introduce of ASIPP and ZOONENG Corporation



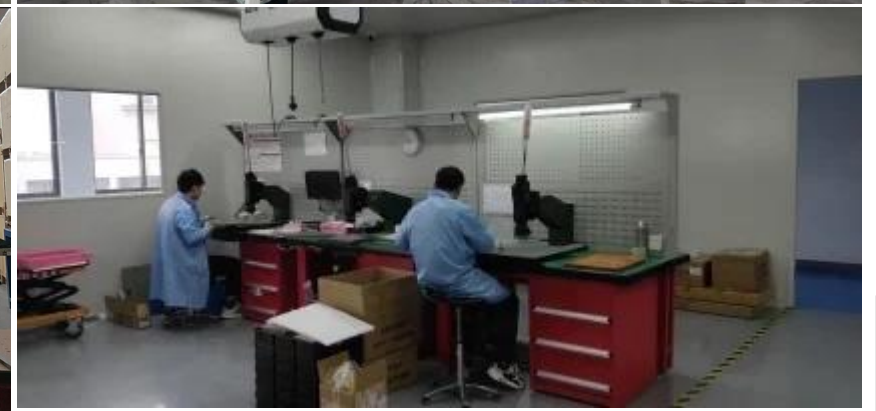
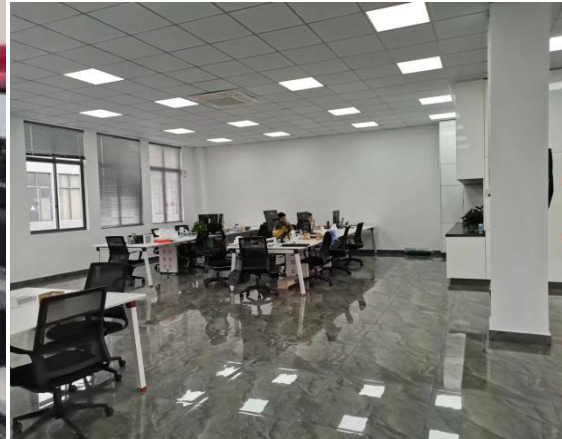
- **Zooneng:** Founded in 2022, it is a spinoff enterprise for innovation achievement transformation from the Institute of Energy, Hefei Comprehensive National Science Center.
- **Mission:** Plasma Diagnostic Electronics + High speed communication hardware platform.
- **Team Scale:** 40 Full-Time Members + 4 Core Directions (Hardware Circuit Design, FPGA/Embedded Systems, Software & System Platforms, Testing & Experimental Research)



Introduce of ASIPP and ZOONENG Corporation

- Workforce: >50 people, floor area: >5,000 m²
- Floor Layout

Floor 1: Production processing, Inspection; Floor 2: Storage; Floor 3: Assembly and testing; Floor 4: Design.



Content

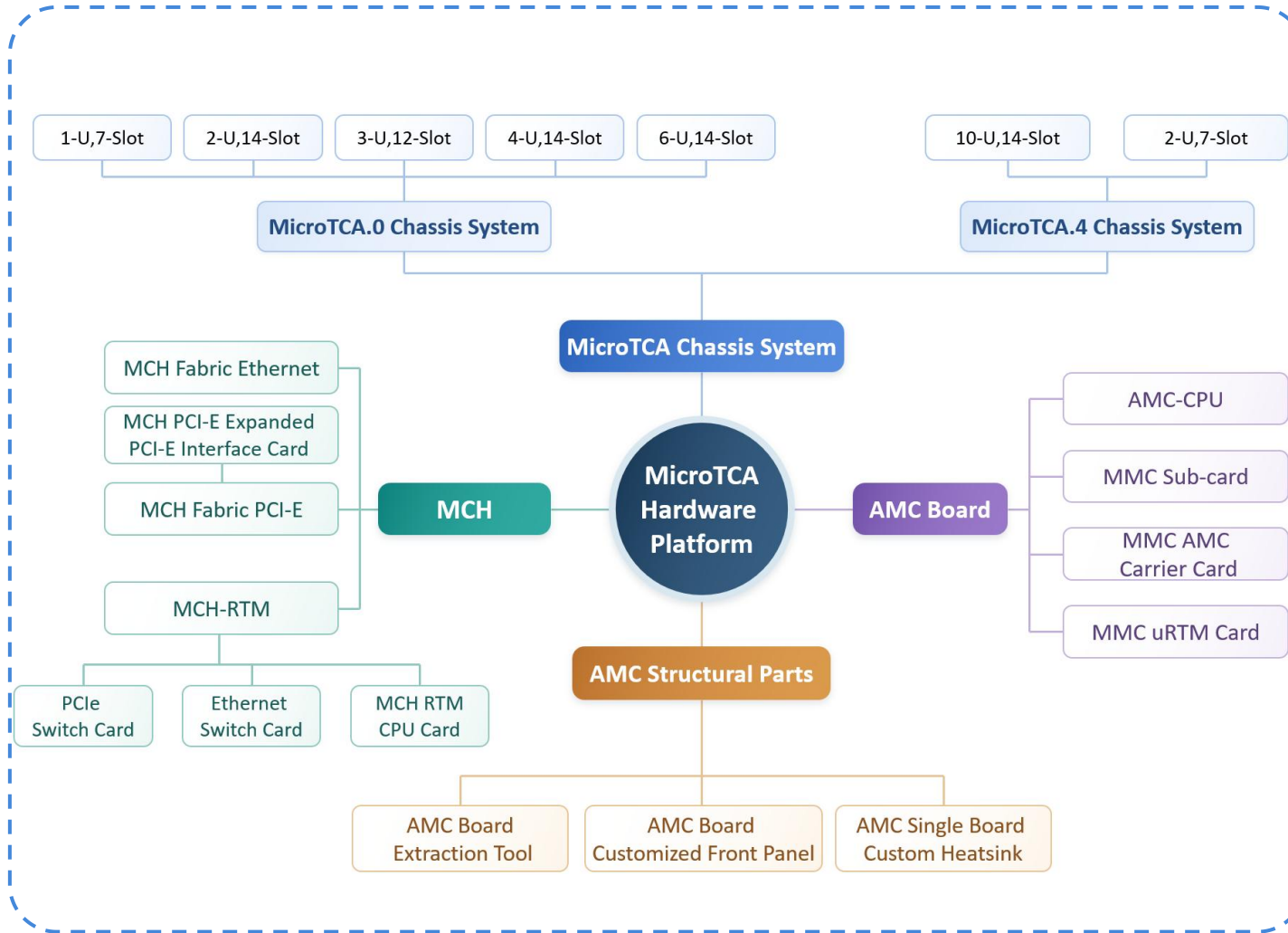
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MTCA Technology and Industry Progress

Full-platform Design Capability of MTCA Architecture

Technical Advantages

- Structurally reliable , easy to maintain
- Proprietary Power Design
- Modular Management Software
- Excellent thermal management
- Custom High-Speed Backplane
- Custom AMC Design & Manufacturing



MTCA Technology and Industry Progress

MTCA Chassis



MTCA Chassis + power(10U)



MTCA Chassis + power(3U)

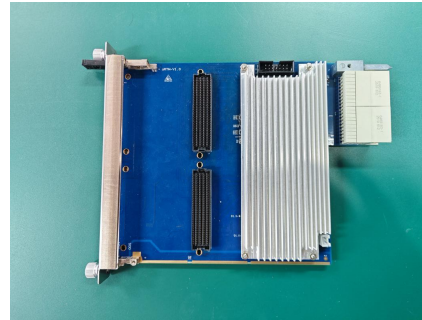


MTCA Chassis + power(2U)

AMC Card



uRTM Card



MCH Card



MCH Card
(Basic Configuration)



MCH Card
(with Optical Port)



MMC
module

CPU Card



AMC CPU



RTM CPU

FMC Card



MTCA Technology and Industry Progress

MicroTCA.4 Chassis System MTCS-3B00-01



Chassis:

- 19-inch chassis, 3U, 11 slots
- Front: 10 × 4HP AMC.4 slots + 1 × 6HP MCH slot; Rear: 4 × 4HP RTM slots + 1 × 10HP RTM CPU slot

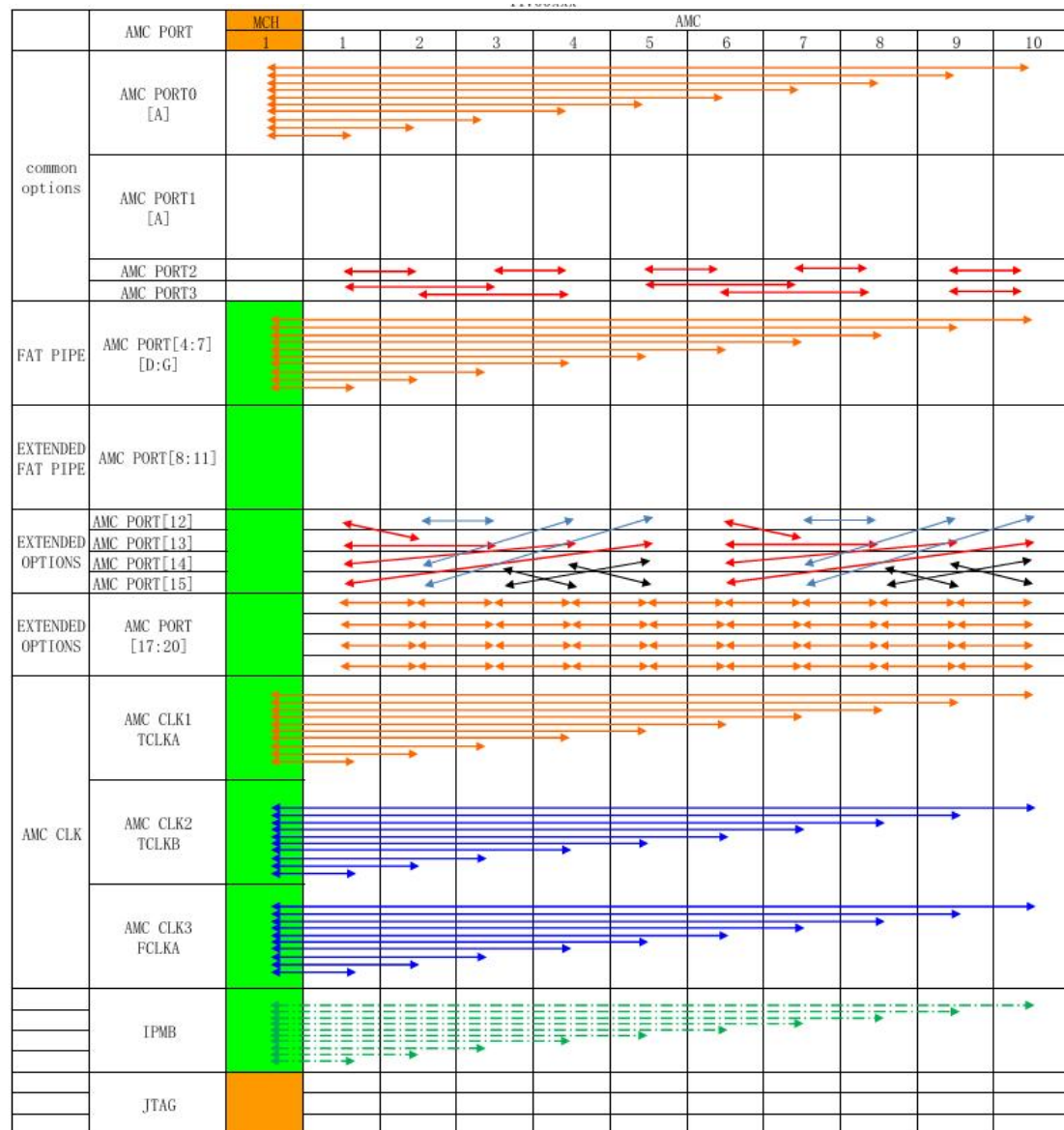
Backplane Link Rate:

- Backplane Link Rate: 10.3125 Gbps; supports PCIe Gen3

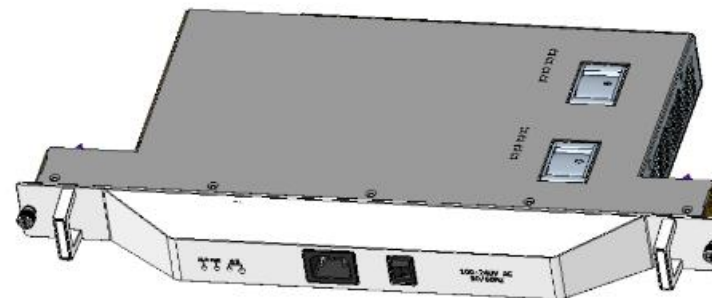
Chassis Management:

- Star-topology IPMB management bus
- One dedicated MCH slot
- Standard IPMI and custom I²C chassis management

MTCA Technology and Industry Progress



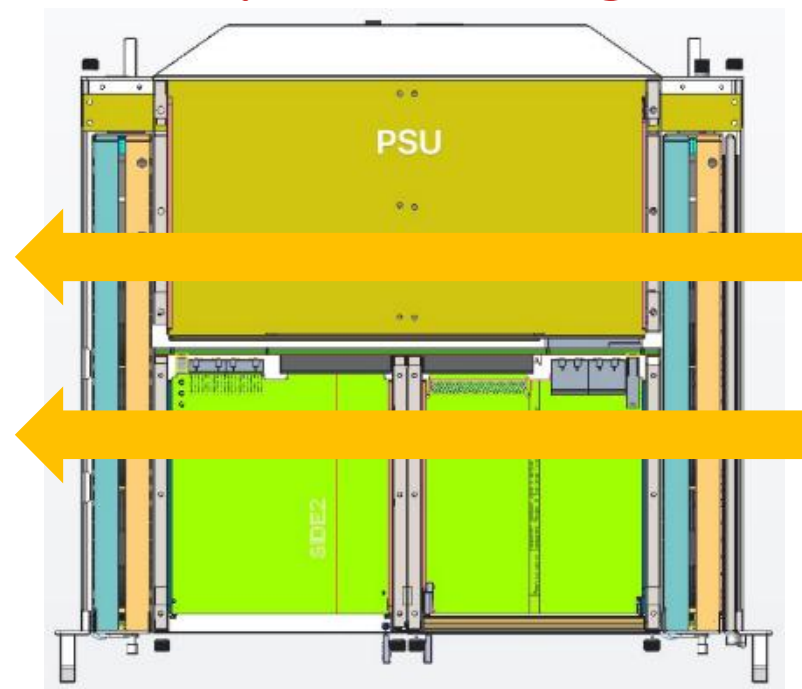
Power Supply



Power Input

- 220 V AC Input
- 2 × 1200 W PSU

System Cooling

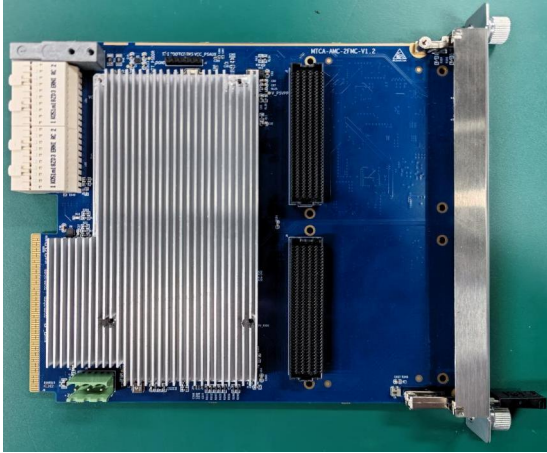


Cooling

- Front/rear card configuration; airflow: right-to-left
- Each side(left/right): 2 × 12038 + 1 × 8038 fans.
- PSU with cooling fan

MTCA Technology and Industry Progress

High-Performance AMC FPGA Board



Logic Resources:

- Industrial Zynq: 653k Logic cells, 2,928 DSP, quad-core Cortex-A53 @ 1.5 GHz, 4 GB DDR4 @ 2400 MT/s

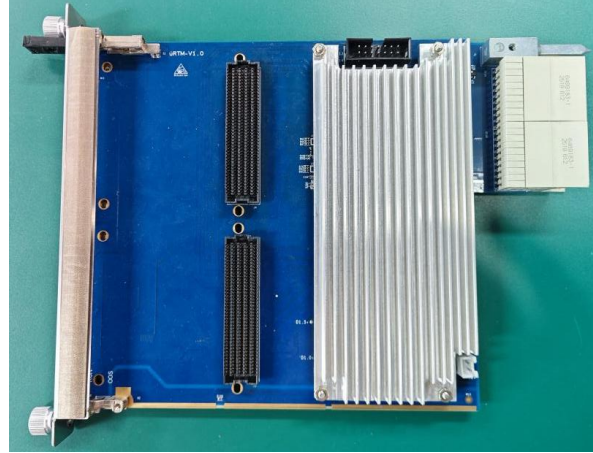
I/O:

- 2× FMC, 2× Zone 3, USB 3.0 Type-C, and bidirectional multi-source clock switching

Features:

- Flexible clocks and FMC expansion for complex DSP

High-Performance uRTM FPGA Board



Logic Resources:

- Industrial FPGA: 693k Logic cells, 3,600 DSP, 2,940 × 18 Kb BRAM

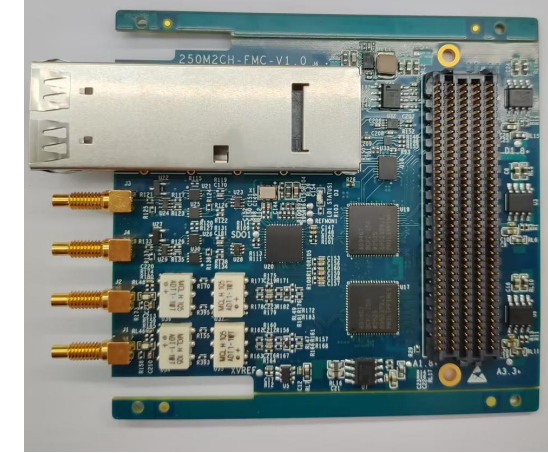
I/O:

- 2× FMC and 2× Zone 3

Features:

- High-performance MTCA.4 DSP with flexible FMC expansion

FMC Card



Logic Resources:

2× AD9467 and 1× EEPROM

I/O:

- 2-channel, 250 MSPS, 16-bit SSMA input, QSFP+
- 2-channel SSMA external clock, bidirectional selection

Input:

- Input range: ± 2 V / ± 20 V

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Robust Cross-Detector γ -ray Nuclide Identification Based on the MTCA Platform

AI algorithm for automating energy spectrum analysis (physical encoder framework)

| Targeting:

- Cross-Detector γ Energy Spectrum Intelligent Recognition Engine Operating on Embedded/FPGA Systems
- Single model training, multiple detectors directly reused
- Supports offline verification and online enhancement

| Shortcomings of current algorithms:

- Existing AI methods rely on cross-detector reuse, and their identification capability is limited when encountering unknown nuclides;
- After replacing the detector, it is usually necessary to retrain and adapt it.

| Key Achievements

27%

Enhancement of Abundance Quantification by Physical Driving

Poisson deviance

16.19 $\Rightarrow$ **11.82**

99.7%

Detection Rate of Unknown Nuclides

83–91%

Detection rate of medium- and high-energy nuclides

1.0

Residual Structure Separability

92.8%

Accuracy of detector parameter identification

- The physics-driven model enhances the accuracy of abundance quantification while retaining physical interpretability.
- Residual anomaly detection supports rejection of unknown nuclides
- An independent CNN can estimate the inherent characteristics of the detector from the energy spectrum

Implementation Steps

Algorithm Framework



Model Compression



Cross-Detector Robust Recognition

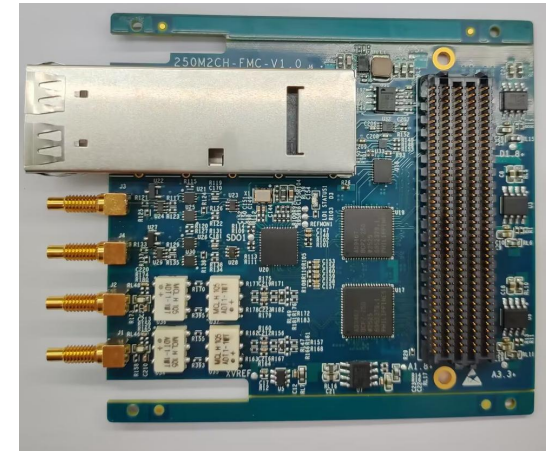
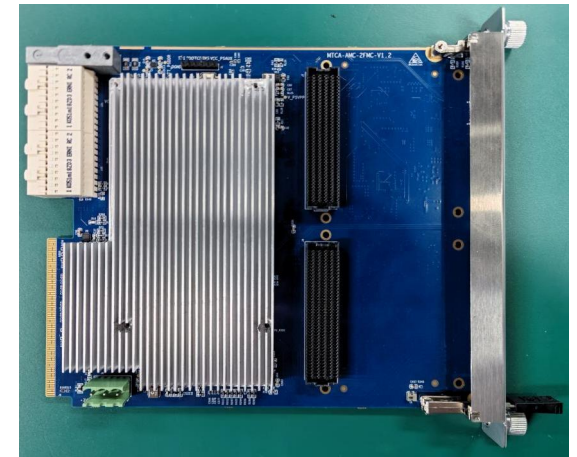


FPGA Deployment

Robust Cross-Detector γ -ray Nuclide Identification Based on the MTCA Platform

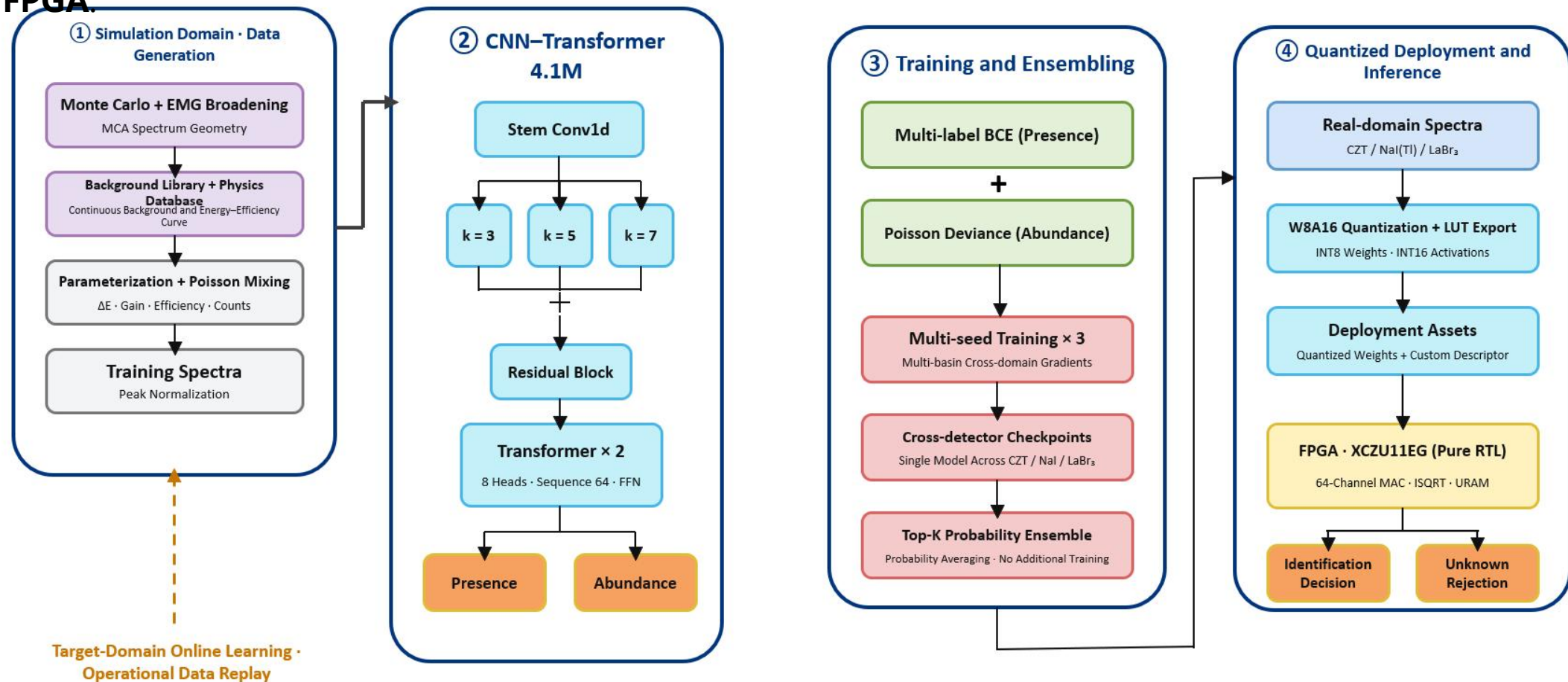
Why choose the MTCA platform

Comparison	MTCA.4	PXIe
Per-Slot Power Delivery	80–120 W per AMC slot; double-width modules support higher power for sustained FPGA/AI workloads.	Typically 30–45 W per slot, up to 60 W; high-power AI cards may throttle, limiting sustained workloads.
Cooling & Reliability	Directed forced-air cooling for continuous 24/7 operation and long-duration AI inference during experiments.	Limited cooling capacity; better suited to intermittent lab tests. Prolonged full loads may cause overheating.
Backplane & Interconnect	MCH-switched backplane enables high-speed peer-to-peer PCIe links; AI and acquisition cards exchange data directly, bypassing the CPU.	Tree-based PCIe topology routes inter-card traffic through the controller CPU, adding latency and bandwidth overhead.
Timing & Synchronization	High-precision clocks, PPS and triggers enable nanosecond-level module synchronization, ideal for coordinated acquisition and AI inference in fusion diagnostics.	PXI trigger bus available, but timing accuracy and synchronization are weaker than MTCA.4.
Expandability	Flexible slots support single-/double-height and single-/double-width AMCs, allowing multiple AI accelerators and digitizer cards.	Per-slot power limits make high-performance AI card expansion difficult.

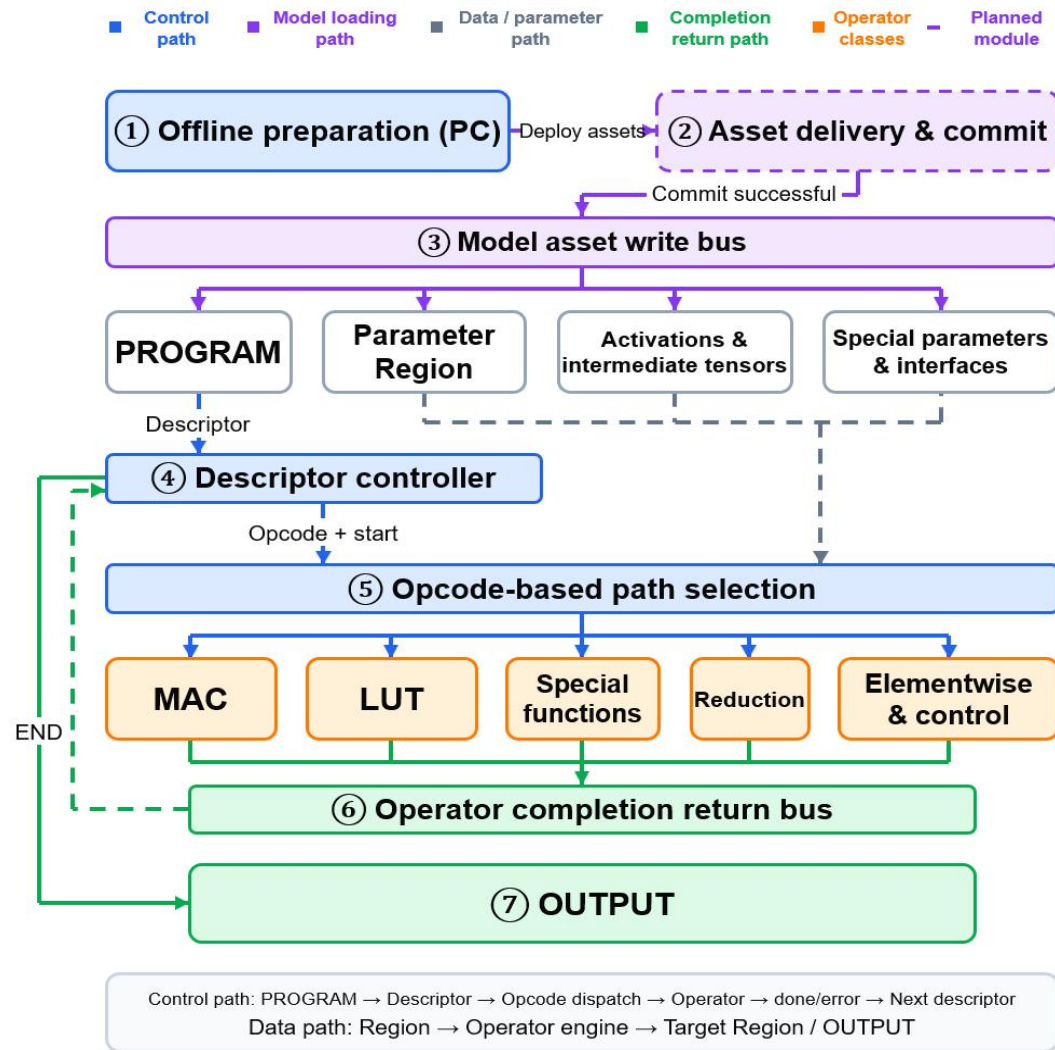


Robust Cross-Detector γ -ray Nuclide Identification Based on the MTCA Platform

This study adopts an integrated framework: **physical parameterized simulation data are generated to construct the training set**; a **CNN-Transformer** serves as the base encoding network; the **inference side use multi-seed probability-level ensemble** to enhance cross-detector generalization performance. The three modules collaborate to accomplish zero-shot γ nuclide recognition. After achieving the desired expectations, the model is quantized and deployed to **FPGA**.



Robust Cross-Detector γ -ray Nuclide Identification Based on the MTCA Platform



Specific implementation steps:

- Hardware logic is pre-fixed, no need to re-synthesize the FPGA project.
- The PC completes model training, quantization, and compilation offline, generating model assets (instructions + weights).
- The descriptor controller parses instructions and schedules hardware operators to perform neural network inference.

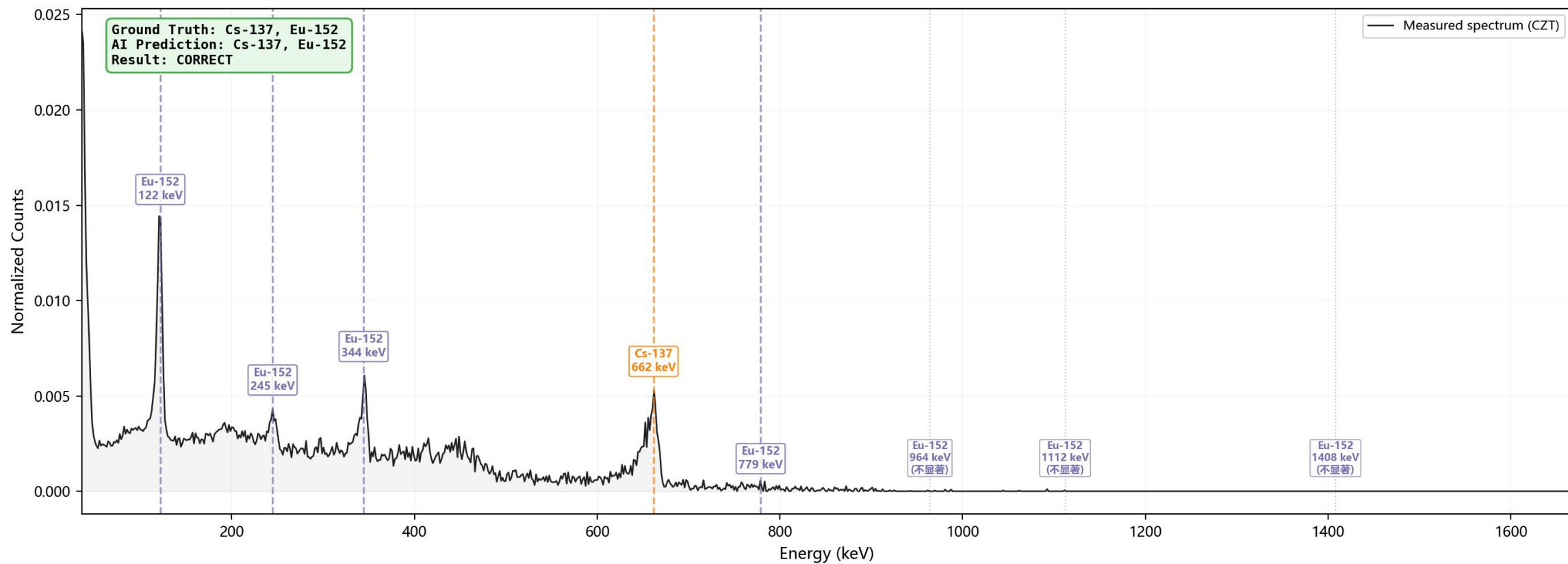
Advantages:

- Quickly switch between different models, adapting to multiple sub-probability ensemble inferences.

Overall Logical Architecture for Neural Network Inference Deployment on FPGA

Robust Cross-Detector γ -ray Nuclide Identification Based on the MTCA Platform

AI Nuclide Identification – Measured Spectrum from a Real CZT Detector



Measured-Data Validation:

- 74 CZT spectra, 98.6% accuracy (73/74), 90 nuclides, 1 false positive, and 0 misses.
- The Cs-137 + Eu-152 two-nuclide result shown is correct.
- F1 0.8–1.0 across three detectors
- Abundance +27% (16.19 to 11.82)
- FPGA matches reference 100% (740/740)

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DDAQ Technology and System Architecture

DDAQ-Z2601 (1U)

For fusion diagnostics, plasma control, high-energy physics experiments, and industrial measurement.



Up to 160 synchronous channels per single chassis, each channel with a 2MS/s sampling rate and 16-bit ADC resolution.

Integrated High-Performance Data Acquisition and Feedback Control Platform

Multi-Function Support:

- Supports five standard FMC modules
- Simultaneous operation of multi-channel AI, AO, DIO, and other modules

Low-Latency Data Transmission:

- 10GbE + DPDK enables microsecond-scale feedback for acquisition and control

High-Performance Processor:

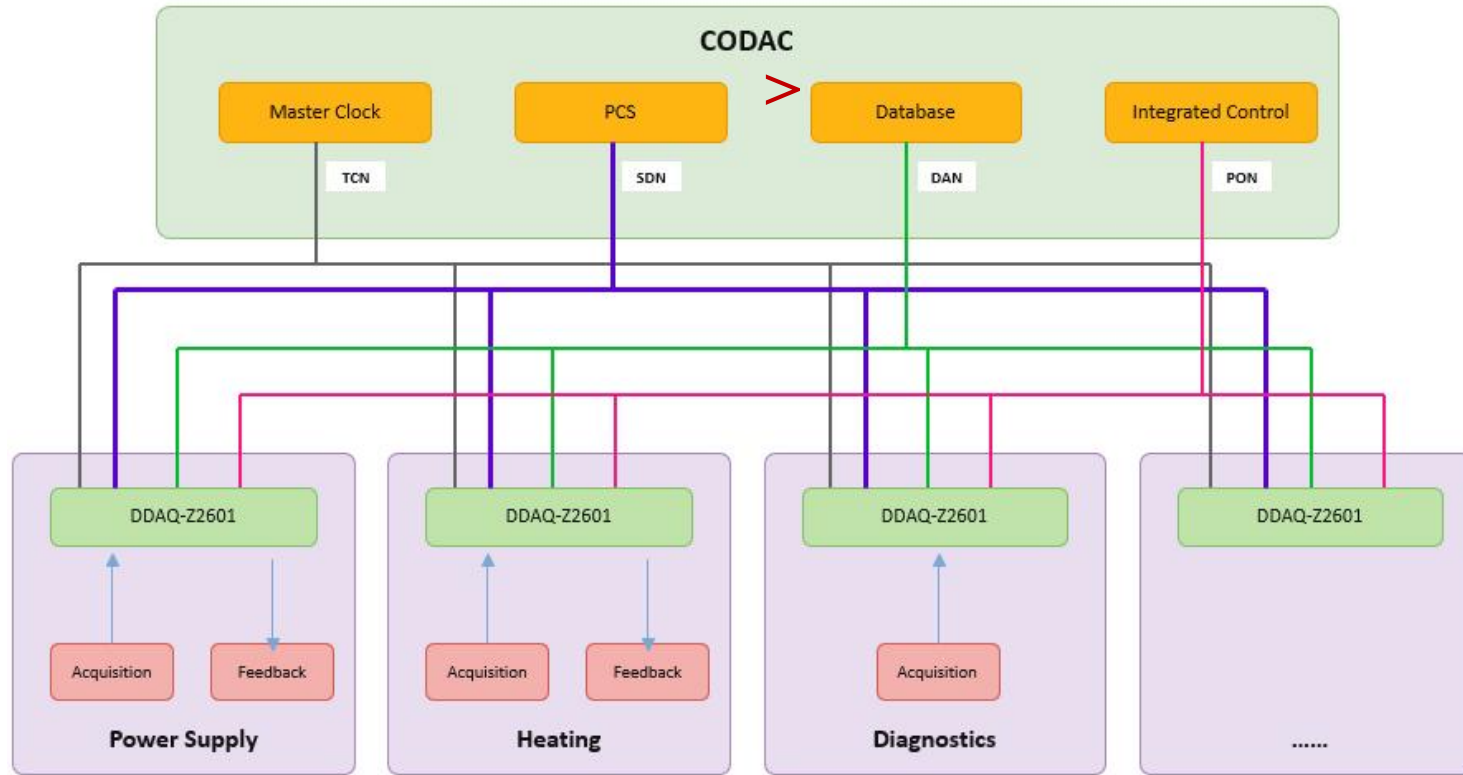
- FPGA secondary development and embedded system deployment
- AI model deployment
- High-speed data streaming to disk

Interfaces:

- 2 × SFP+ optical data ports
- 1 × 10/100/1000BASE-T RJ45, 1 × 1000 SFP control port

DDAQ Technology and System Architecture

System Networking: Distributed Acquisition and Control System under Unified Clock



DDAQ nodes are distributed across power, heating, diagnostic, and other subsystems

TCN Time Synchronization:

- PTPv2 aligns the time reference

SDN Synchronized Data Bus:

- Exchanges real-time control data

DAN Data Archiving:

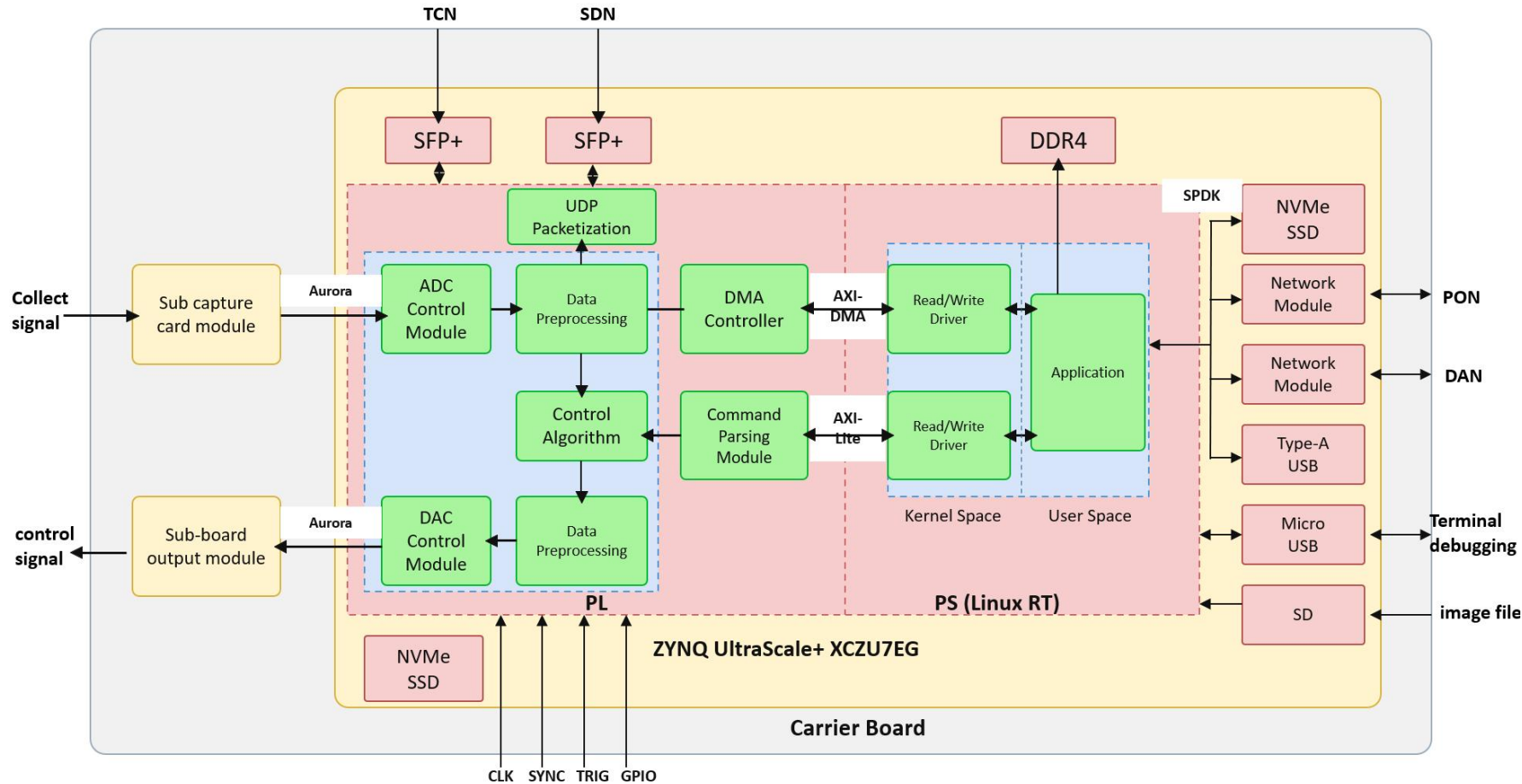
- Aggregate acquired data

PON Operation Management:

- Parameter configuration and remote monitoring

DDAQ Technology and System Architecture

Internal Architecture: PL Real-Time Data Transmission and PS Software Collaboration



Zynq UltraScale + MPSoC

PL: Acquisition & Feedback

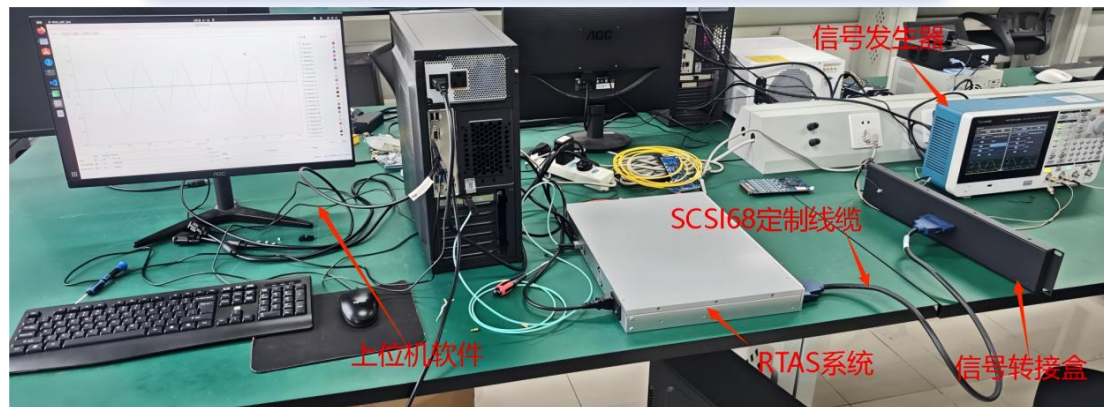
ADC / DAC control
Data preprocessing and control
UDP packet assembly

PS: Software & Management

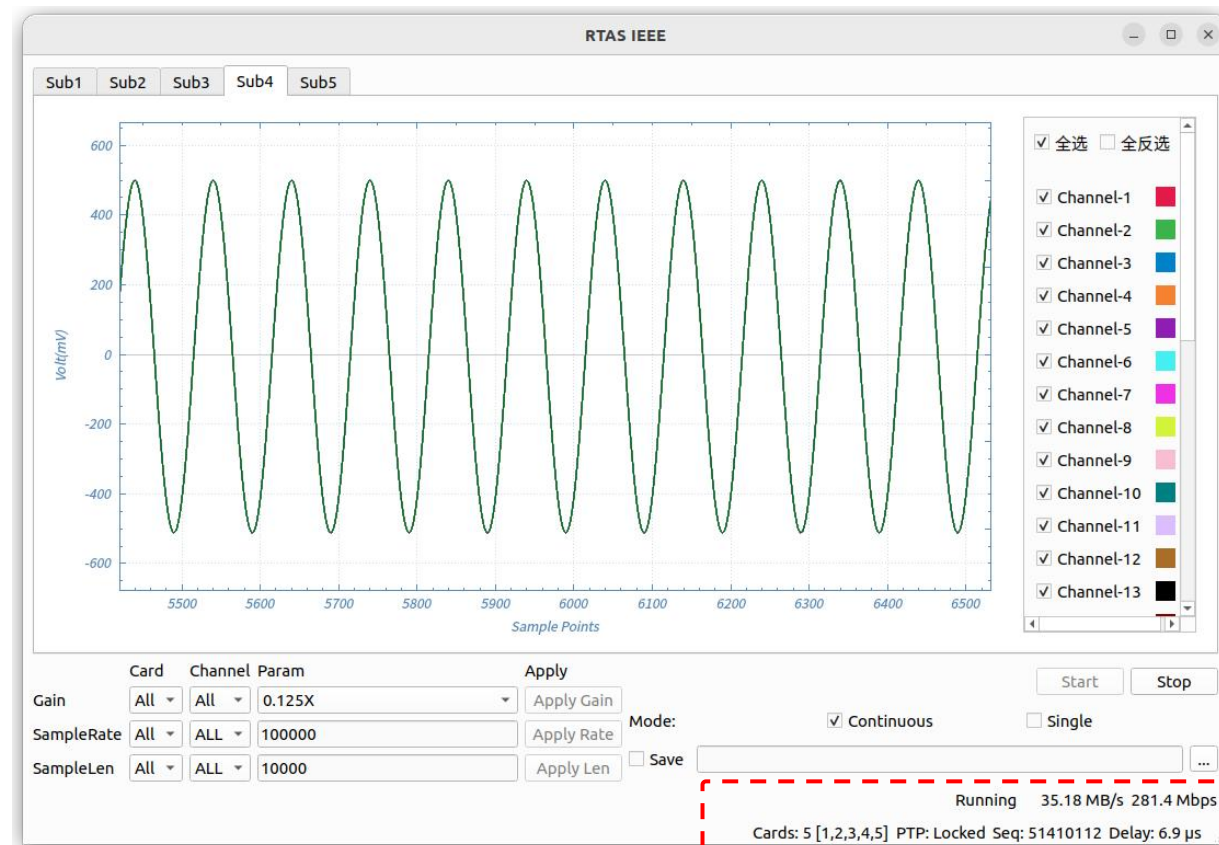
Linux RT Apps & Drivers
Networking & DDR4 Buffer
NVMe Disk Streaming

DDAQ Technology and System Architecture

software data acquisition link



Software: Setup, Waveforms, and Recording



DPDK

- High Throughput
- Low Latency
- Low Interrupt Overhead
- Multicore&Memory Efficiency

Technical Benefits

**DPDK + 10GbE +
Jumbo Frames**



**Stable Low-Latency
Transfer, 160
Channels**



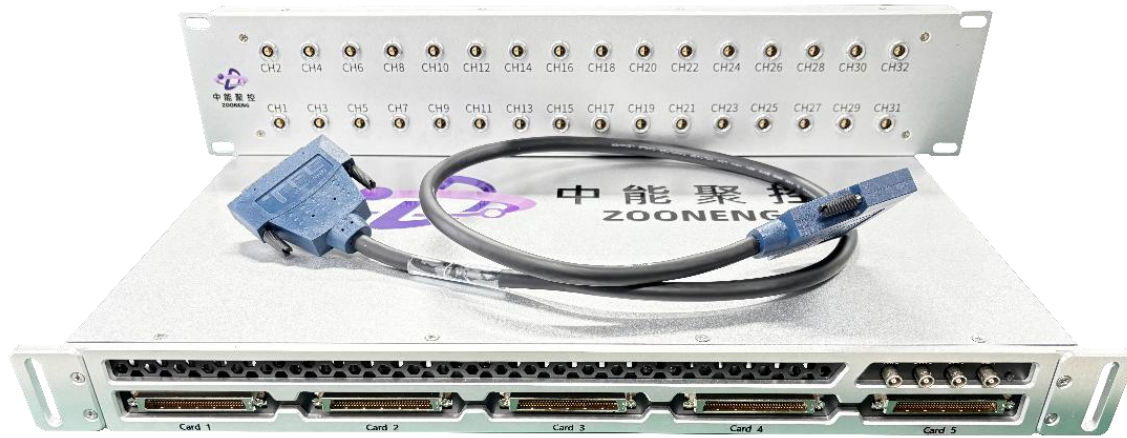
Running 35.18 MB/s 281.4 Mbps
Cards: 5 [1,2,3,4,5] PTP: Locked Seq: 51410112 Delay: 6.9 μs

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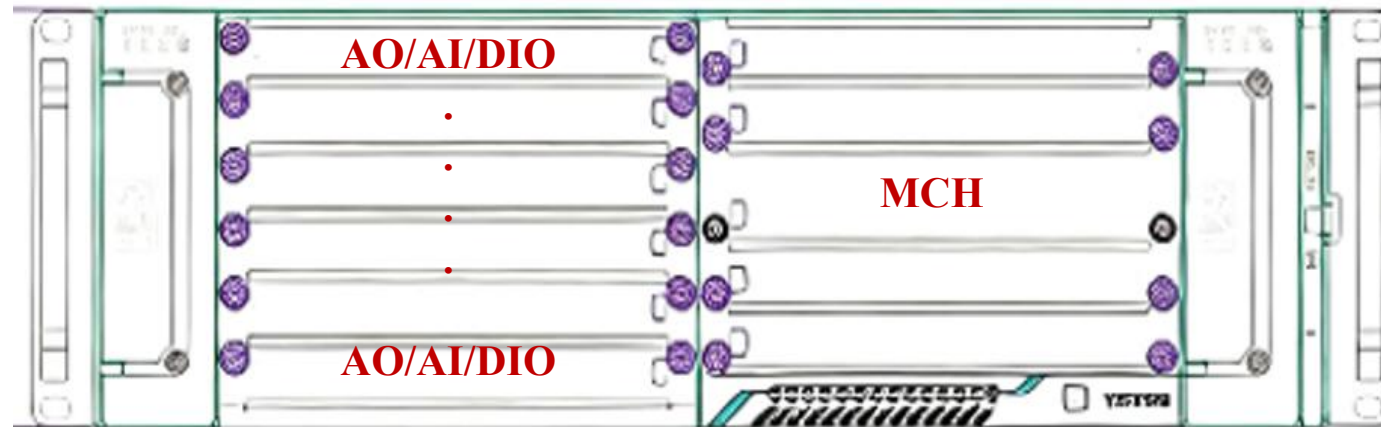
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DDAQ-MTCA Integration for Future Fusion Systems

MTCA-Based Data Acquisition and Closed-Loop Plasma Feedback Control System

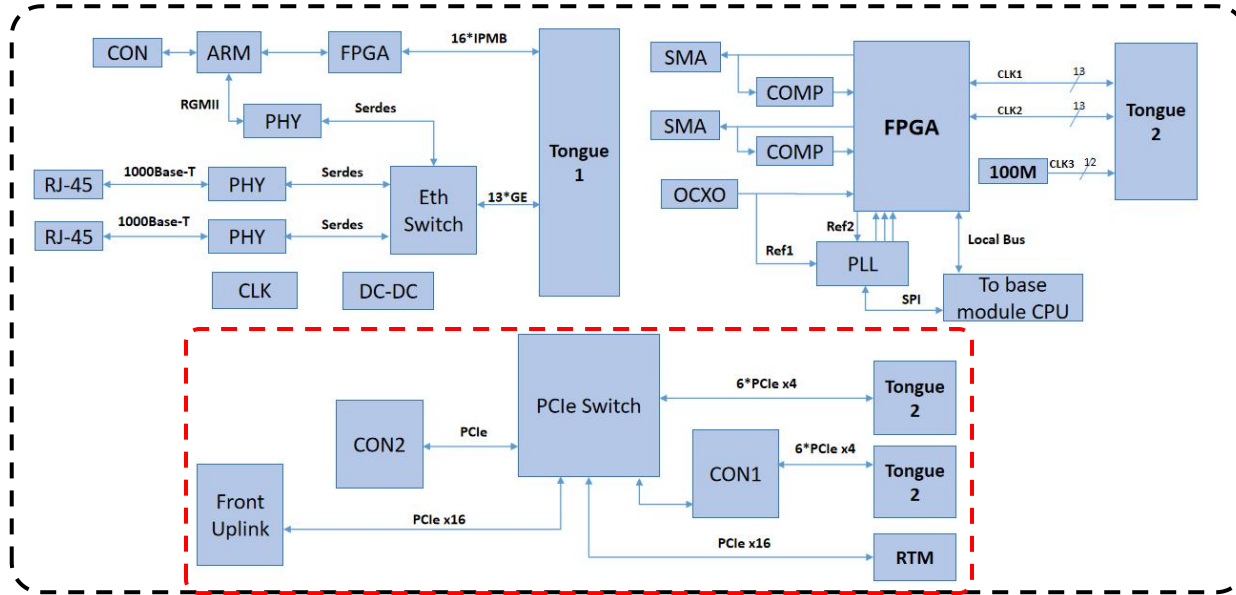


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DDAQ-MTCA Integration for Future Fusion Systems

MCH Functional Block Diagram

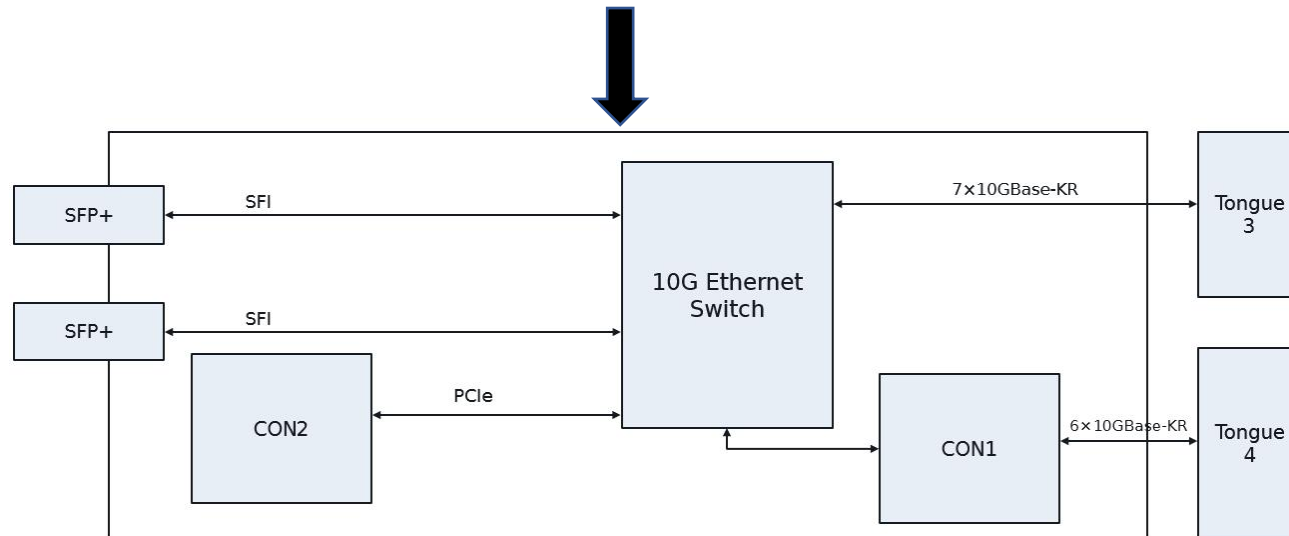


Product Concept:

- Build MTCA into an integrated platform for large-scale fusion data acquisition, real-time processing, and feedback control.
- A 10GbE switching architecture is introduced in the MCH, enabling high-speed aggregation and transmission of AMC board data via backplane 10GBASE-KR links and front-panel SFP+ interfaces.

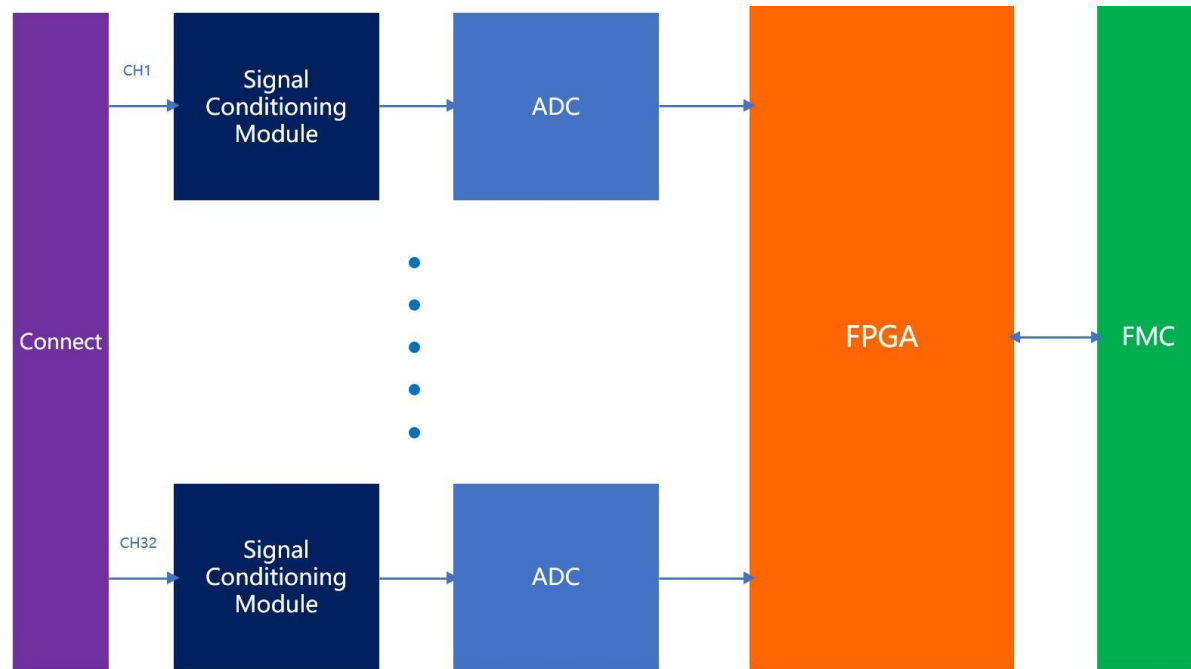
Advantages:

- Multi-channel synchronous acquisition
- Unified clock, synchronized triggering, and time alignment across boards ensure multi-channel acquisition consistency.
- Supports AI, AO, and DIO boards for both diagnostic signal acquisition and control signal output.
- Large AI models can be deployed.

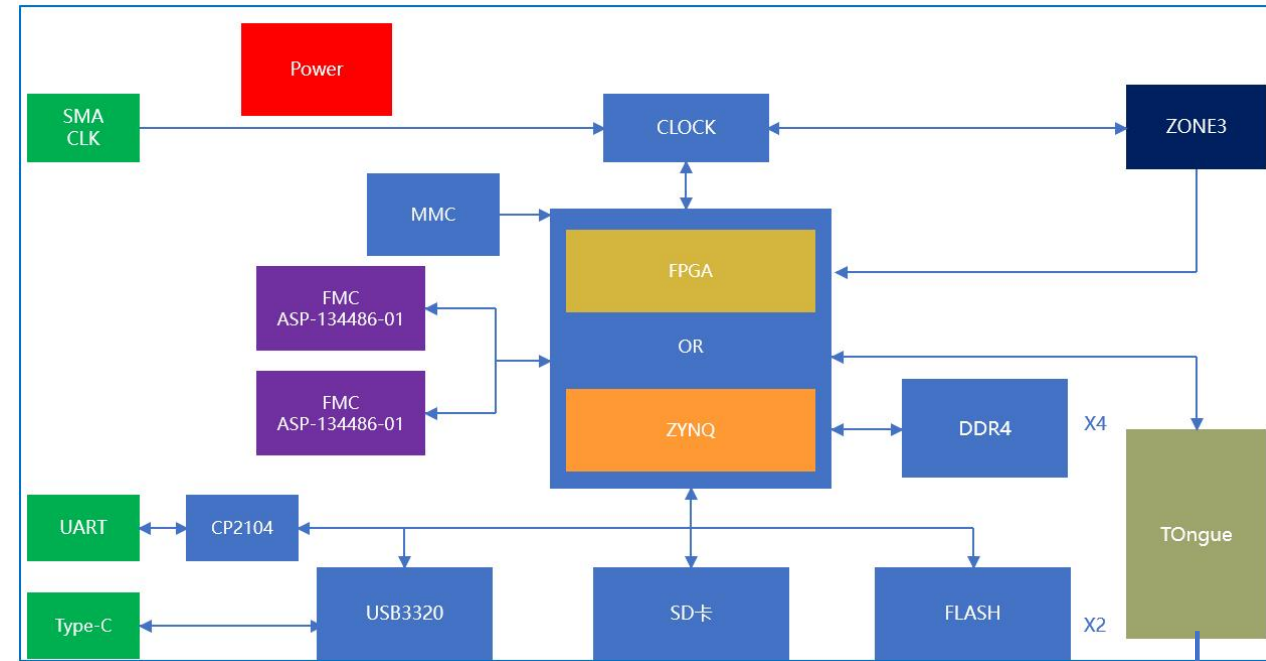


DDAQ-MTCA Integration for Future Fusion Systems

DDAQ Topology



MTCA Topology



Combination Scheme of DDAQ and MTCA



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Summary

High-speed acquisition and intelligent processing for plasma diagnostics are key to the stable and efficient operation of nuclear fusion. With MTCA as the core, combined with DDAQ's high-speed data acquisition, low-latency transmission and real-time feedback, we build an integrated acquisition-processing-recognition-control system that delivers high-bandwidth, scalable, stable and reliable hardware and software support.

- For the large volume of diagnostic data generated in fusion experiments, it can integrate high-performance processors and large-scale storage units to support real-time data processing and analysis.
- With its modular design, it allows rapid hardware expansion based on experiment scale and diagnostic requirements, adapting to various diagnostic subsystems of fusion devices and reducing the complexity and cost of system upgrades.
- Integrating multi-channel acquisition, real-time processing and closed-loop feedback, the system supports FMC module expansion including AI, AO and DIO, and accommodates large-scale plasma scientific data acquisition together with microsecond-scale low-latency feedback control.

Thank you for your attentions!

Comments and questions are welcome

