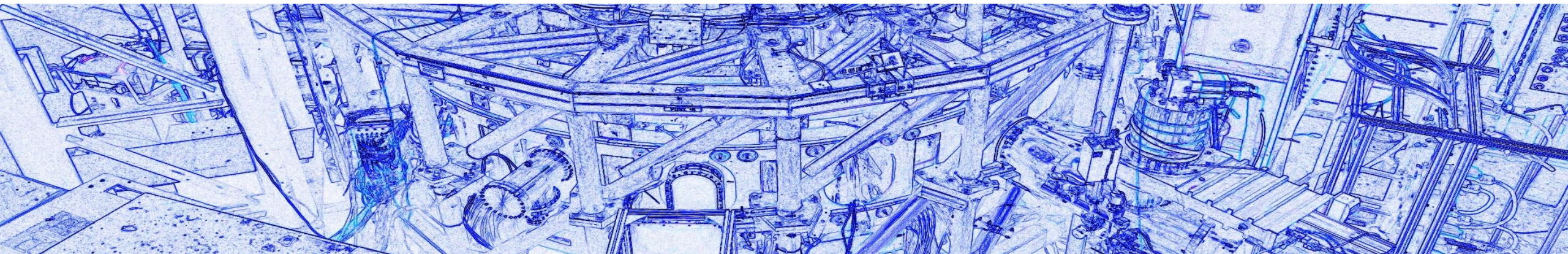


DDAQ: A Multifunctional Real-Time Digital Platform for Fusion Diagnostics and Control

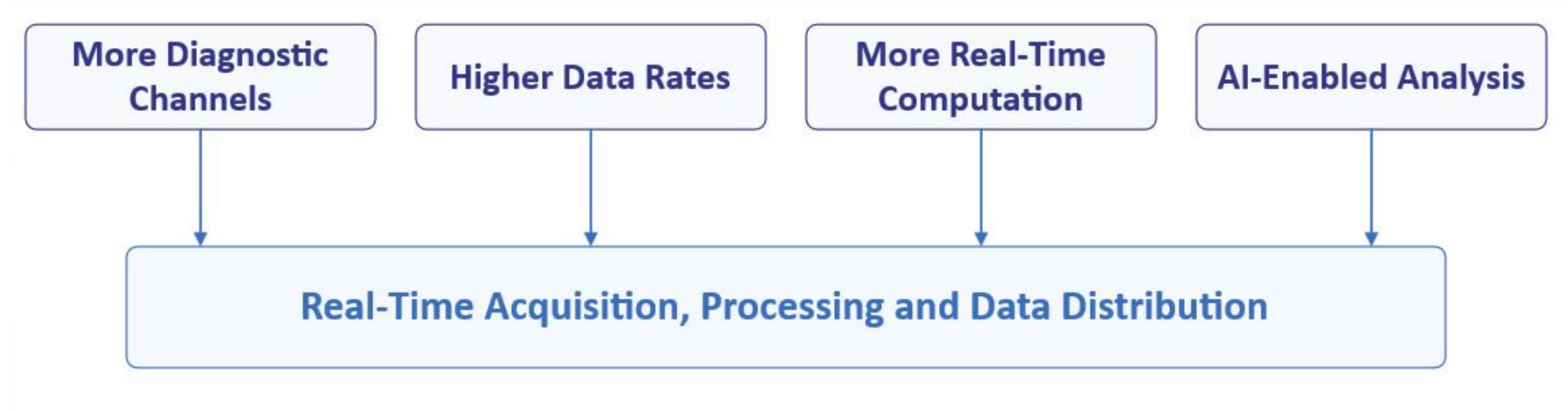
Ziwen Jiang, Zhengyang Shao, Weijie Ye, Jian Yu, Hongrui Cao
Huazhong University of Science and Technology, ZOONENG



Contents

- **Motivation**
- Design
- Applications
- Outlook

Diagnostic information is becoming part of the real-time computation loop



From a small set of control variables to data-intensive diagnostic information

AI / real-time control: Seo et al., Nature 626, 746–751 (2024), doi:10.1038/s41586-024-07024-9

High-rate / multichannel DAQ: Salim et al., Fusion Eng. Des. 87, 2174–2177 (2012), doi:10.1016/j.fusengdes.2012.03.047

Reflective Memory



Hardware-replicated shared data

- Low-latency, deterministic data exchange
- Simple shared-memory abstraction
- Specialized hardware and topology constraints

Ethernet-Based Fast Controller / SDN



Distributed real-time data exchange
SDN: Synchronous Databus Network

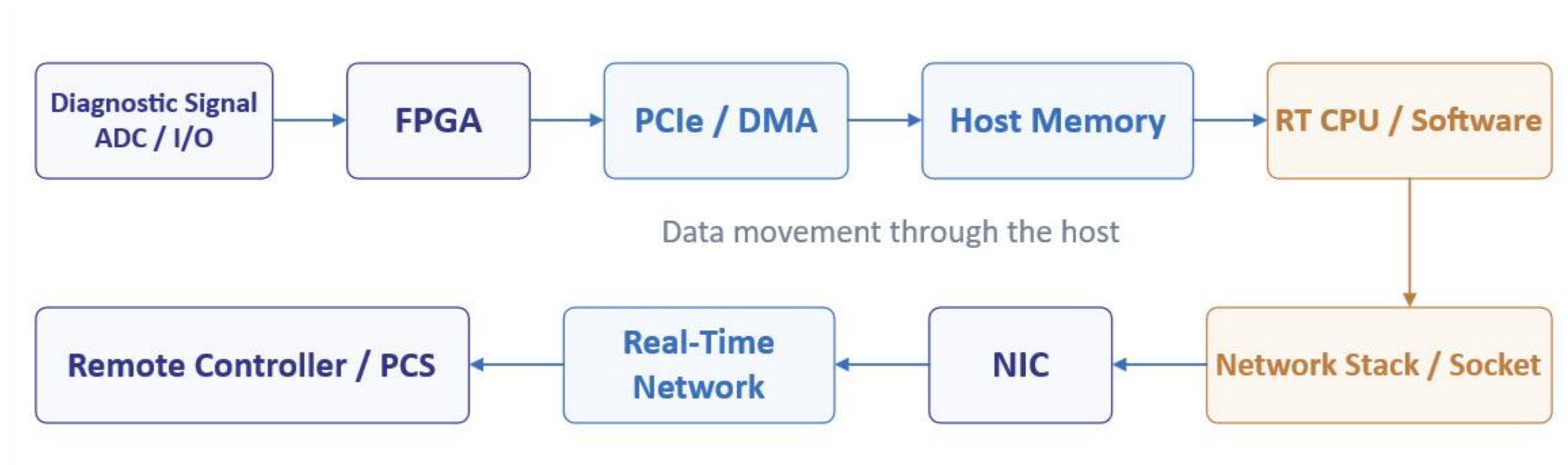
- Standard high-speed Ethernet
- Distributed real-time software and integration
- Host-based endpoints are commonly used

Mature infrastructures motivate further source-side endpoint optimization

Conceptual references: Abaco 5565; ITER (2021); IPFN FPSC; Fusion Engineering and Design (2017)

Motivation: The Critical Data Path Is Often Host-Centric

A typical acquisition-to-network implementation



The path traverses PCIe, host memory, CPU software and the network interface.

Can part of this critical path be moved closer to the data source?

Representative host-centric endpoint path; not a standard implementation of any specific real-time network.

Contents

- Motivation
- **Design**
- Applications
- Outlook

Design: Move the Critical Data Path Closer to the Source



FPGA-Centric

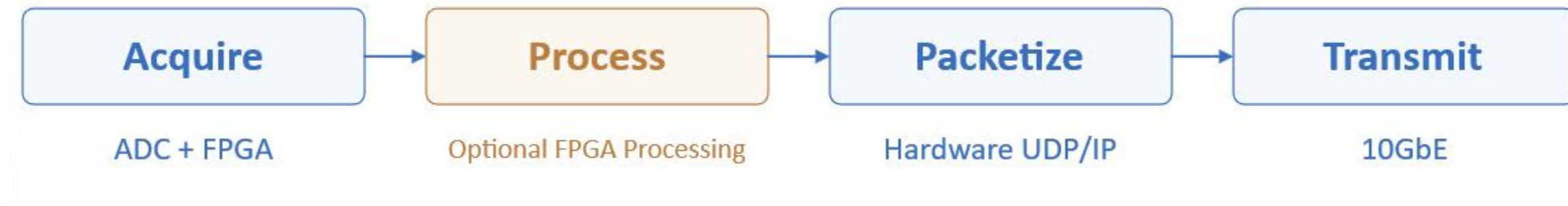
Real-time processing and routing close to the source

Direct

Hardware packetization and direct 10GbE transmission

Multifunctional

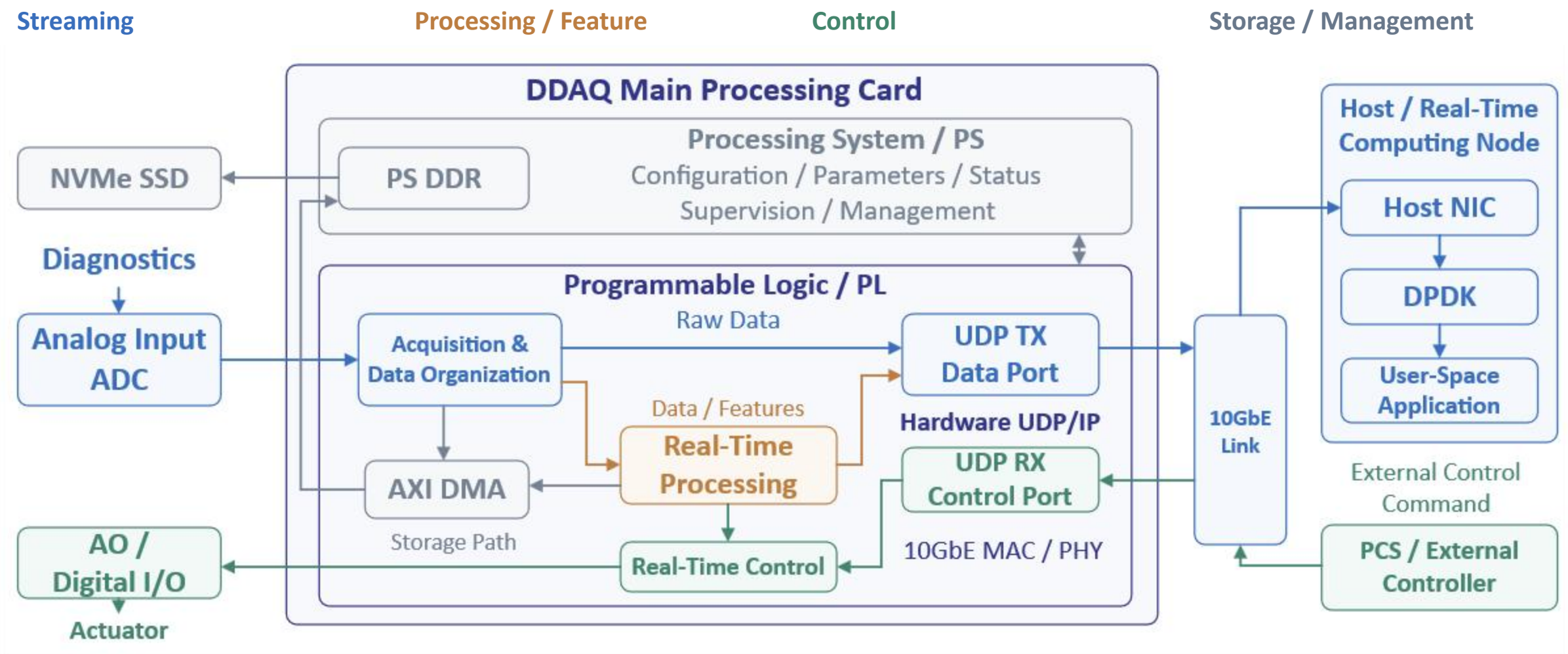
Acquisition, processing, networking, storage and control



Raw data can also be streamed directly.

Move real-time processing and data routing closer to the data source

Design: DDAQ Architecture and Data Flows



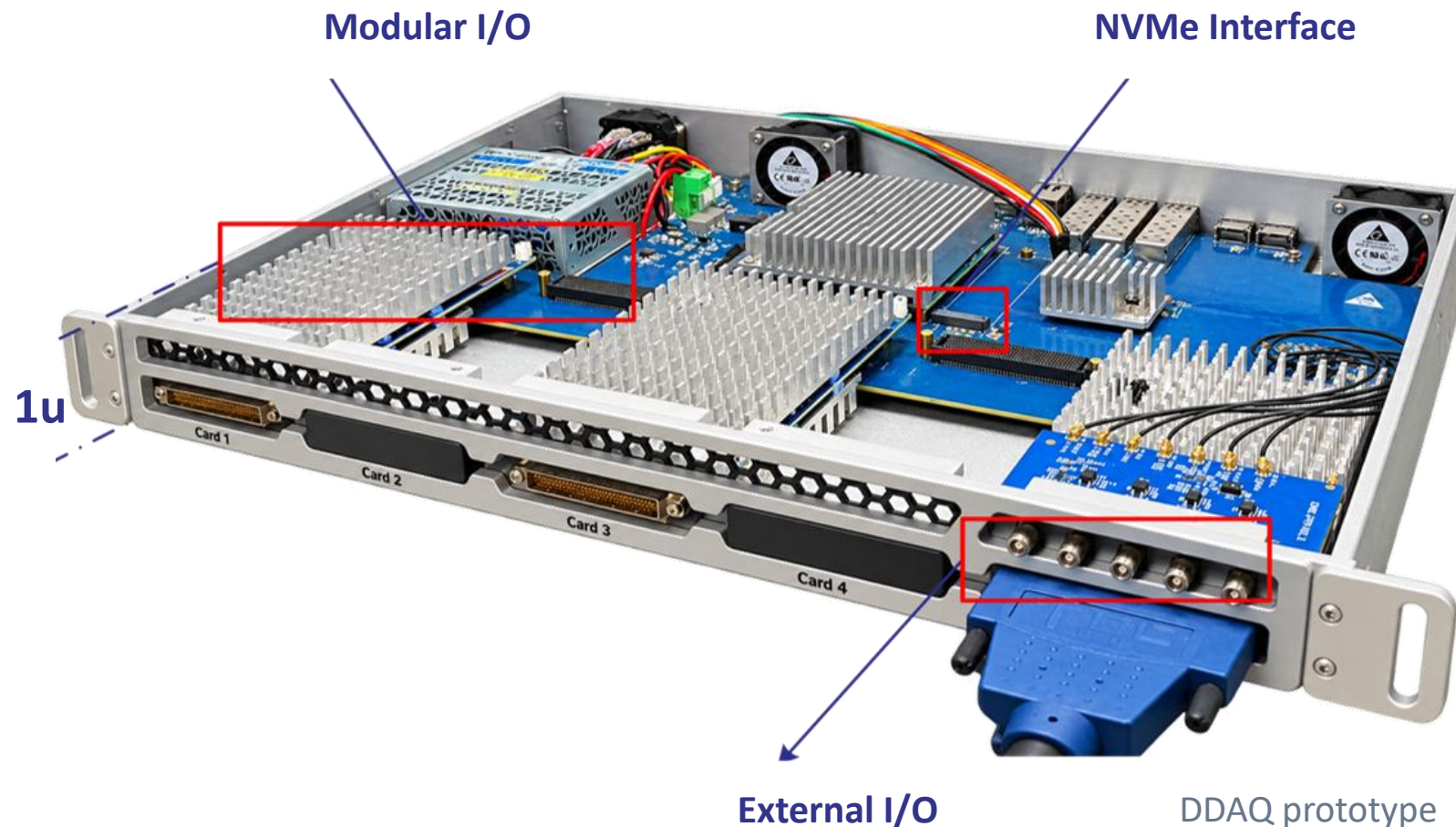
PL: critical real-time paths PS: configuration, supervision and management

Main Processing Card + Modular I/O

Analog Input Modules

2 MSPS $\times$ 160 channels
80 MSPS $\times$ 20 channels

AO and Digital I/O
10GbE networking
NVMe SSD support
External clock / trigger



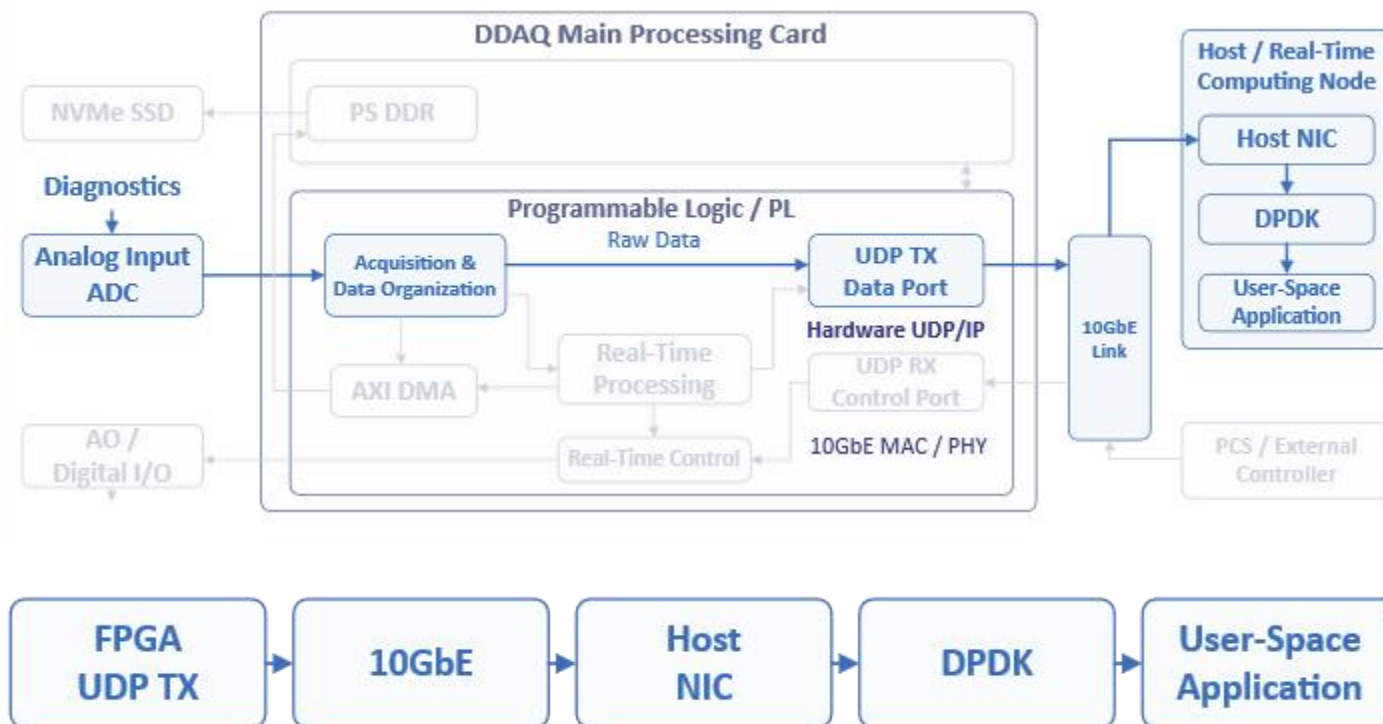
Configurable hardware for different fusion diagnostics and control tasks

Contents

- Motivation
- Design
- **Applications**
- Outlook

FPGA packetization → 10GbE → NIC → DPDK → User-Space Application

Streaming Path



Application Scenarios

01 Real-Time Diagnostic Streaming

High-rate diagnostic data delivered directly to remote computing nodes

02 Multi-Diagnostic Data Fusion

Multiple streams for centralized real-time processing

03 Real-Time CPU / GPU Computing

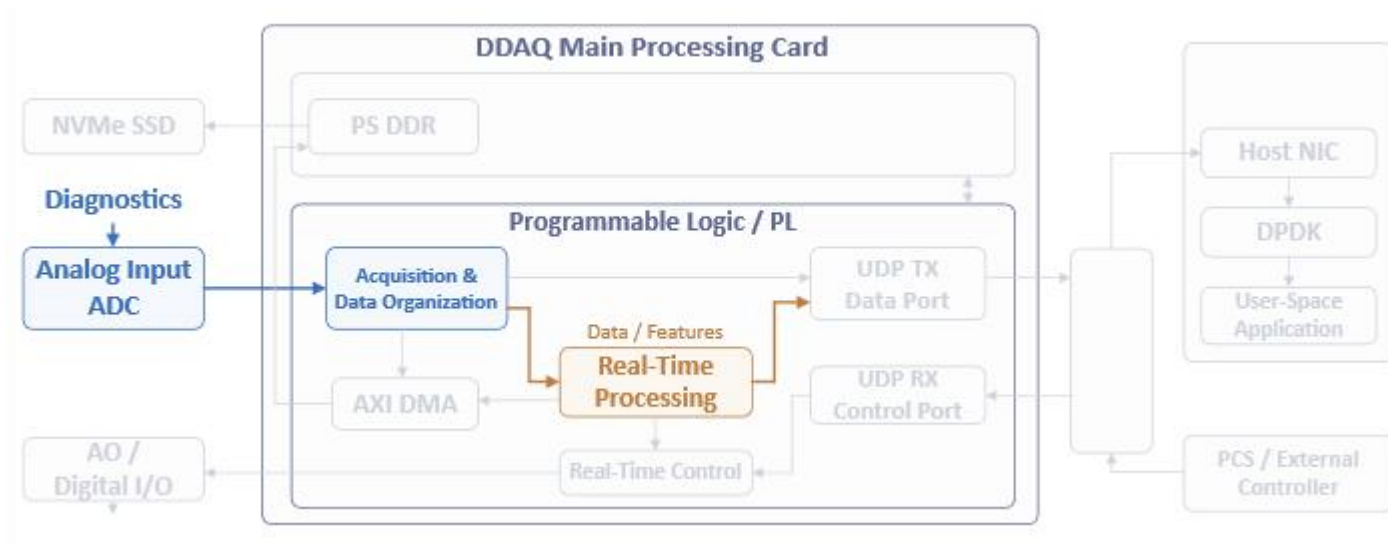
Intensive real-time analysis
Target example: disruption prediction

DDAQ turns the acquisition front end into a direct real-time data source for distributed computing.

DPDK uses user-space packet I/O and bypasses the traditional kernel networking stack.

Virtual Channels: real-time information derived from raw diagnostics

Processing Path



DDAQ can transform raw diagnostic data into real-time information close to the data source.

Example Processing Tasks

01 Signal Preprocessing

Filtering, normalization and basic transformations

02 Feature Extraction

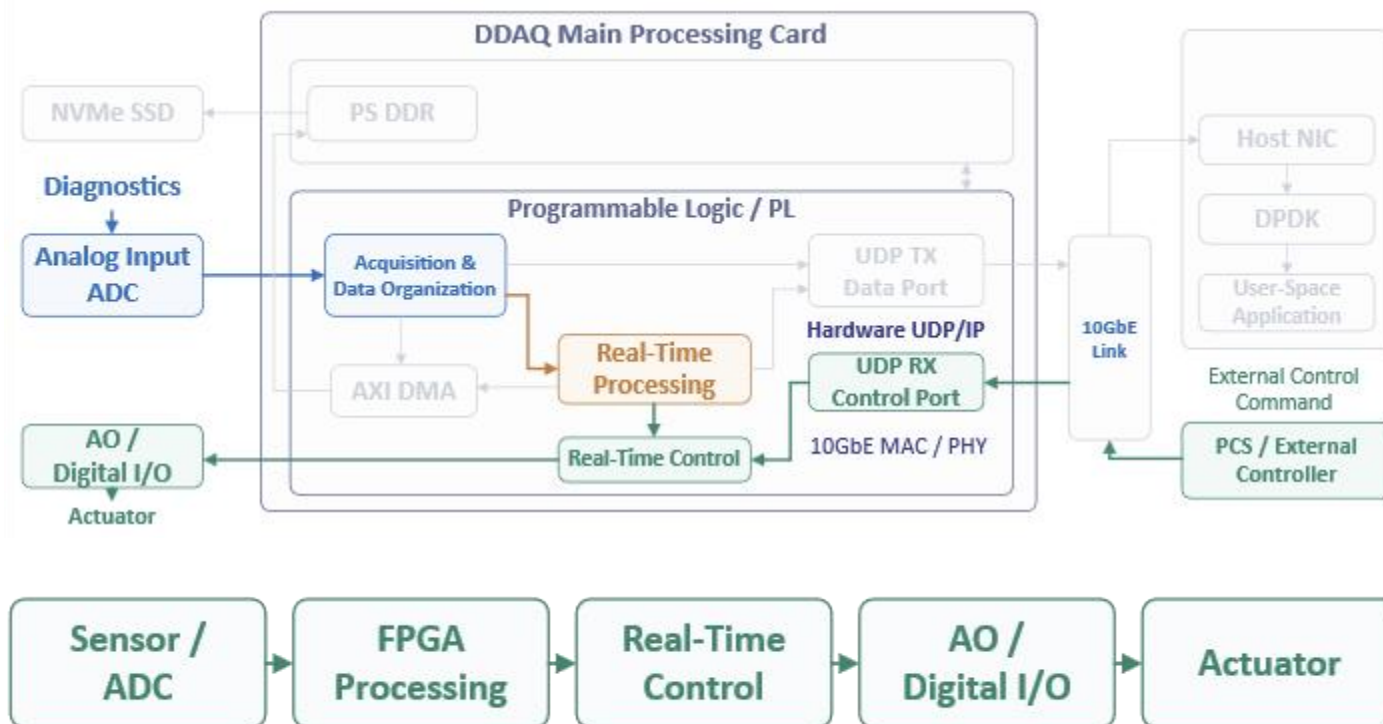
Amplitude, phase, density and mode features as virtual channels

03 Lightweight AI Inference

Optional FPGA-side models
Outputs for networking or control

Sensor → FPGA → Actuator

Control Path



For suitable fast-control tasks, sensing, computation and actuation can remain within the FPGA-centric path.

Fast Control Tasks

01 RMP Control

Resonant Magnetic Perturbation

02 Plasma Feedback

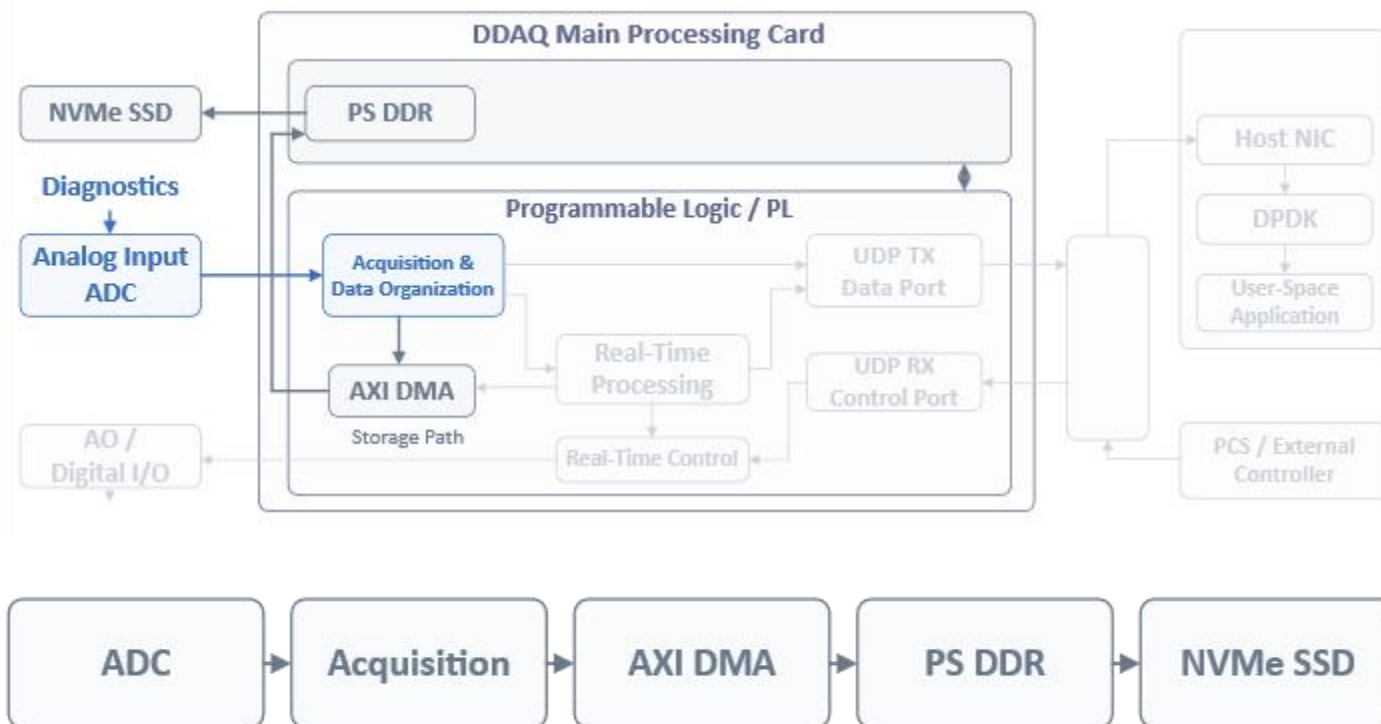
Vertical instability control
Density feedback

03 Power-Supply / Actuator Control

Target tasks close to the front end

Diagnostics → ADC → Acquisition → AXI DMA → PS DDR → NVMe SSD

Storage Path



Scientific Data Recording

01 Raw Diagnostic Data

Local recording of acquired signals

02 NVMe-Based Storage

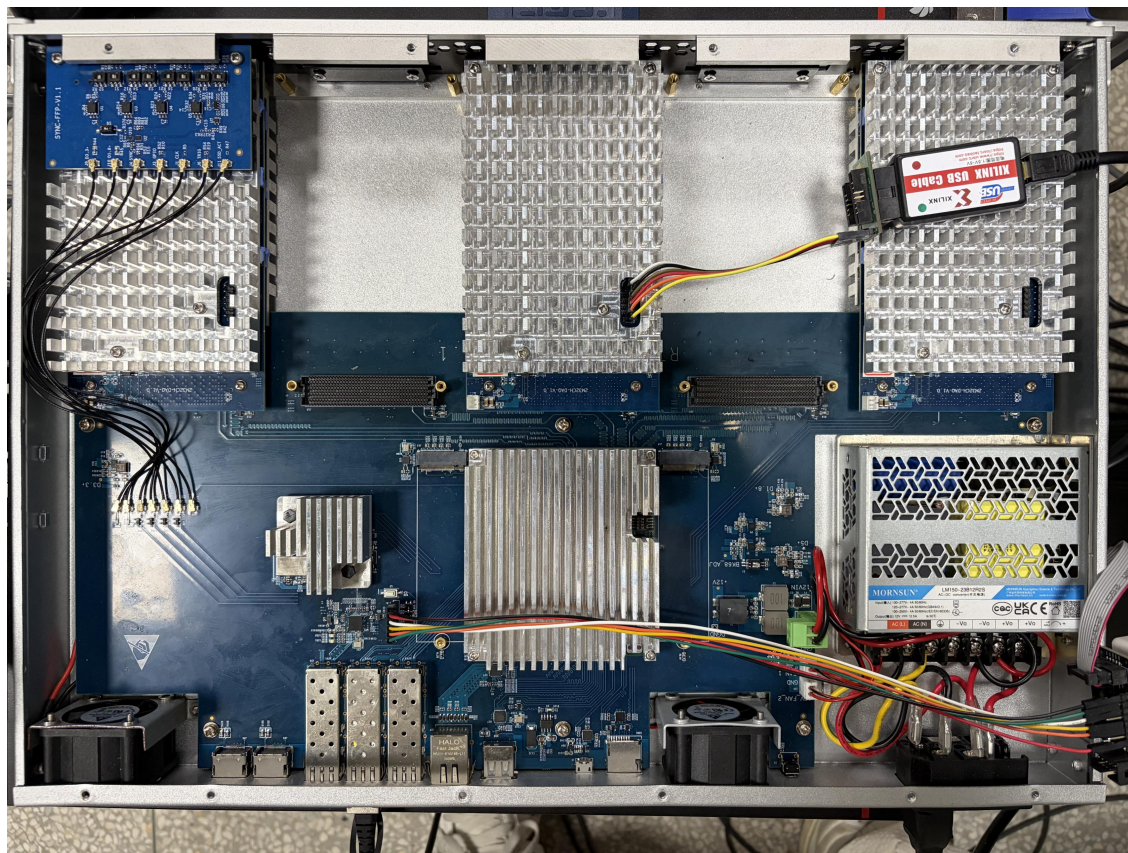
Local scientific data recording

03 Post-Shot Analysis

Recorded data for offline analysis and algorithm development

The same platform supports both real-time functions and local scientific data recording.

DDAQ Prototype — Top View



Streaming + Processing + Control + Storage
organized on the same configurable platform

Target Applications

Diagnostics

High-channel-count acquisition
Real-time feature extraction

Real-Time Computing

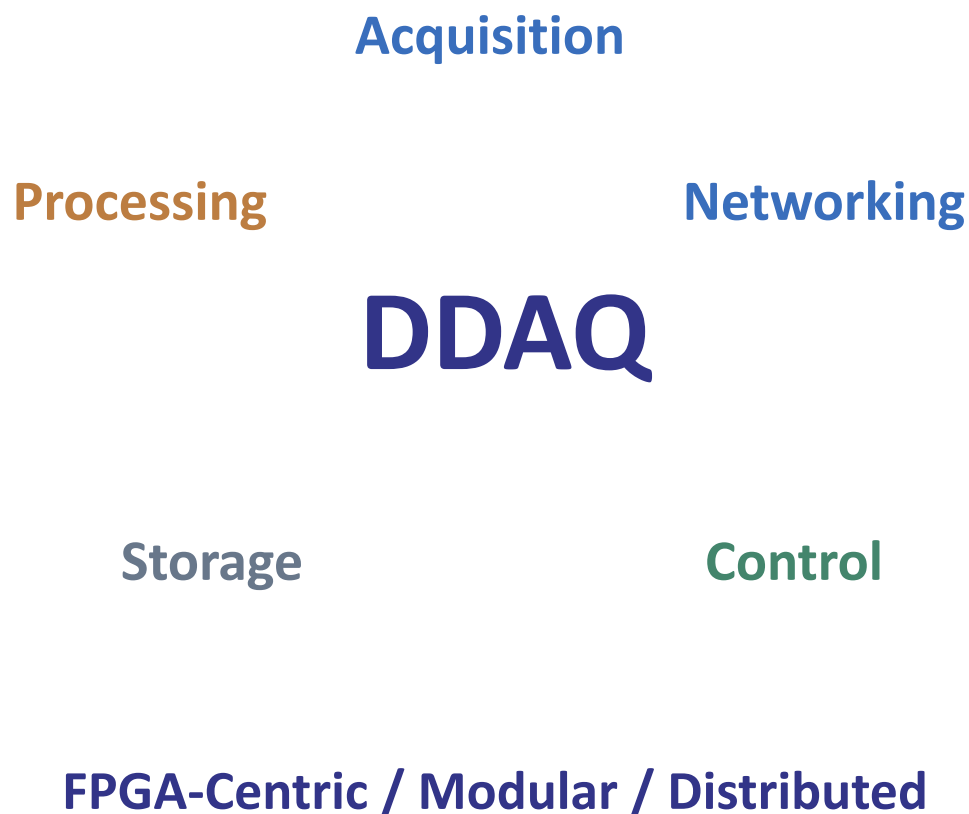
Data streaming, lightweight AI
and disruption prediction

Control

RMP, vertical instability
and density feedback

Contents

- Motivation
- Design
- Applications
- **Outlook**



Outlook

More Real-Time Algorithms

More Intelligent Edge Processing

Broader Integration with
Fusion Control Systems

**An FPGA-centric source-side platform
that can complement PCS, CODAC
and real-time network infrastructures.**

Bringing computation and data routing closer to where fusion data are generated

Thank you for your attention!