PPPL PRINCETON PLASMA PHYSICS LABORATORY

Scalable Real-time Diagnostic Infrastructure Supporting Disruption Prediction and Avoidance

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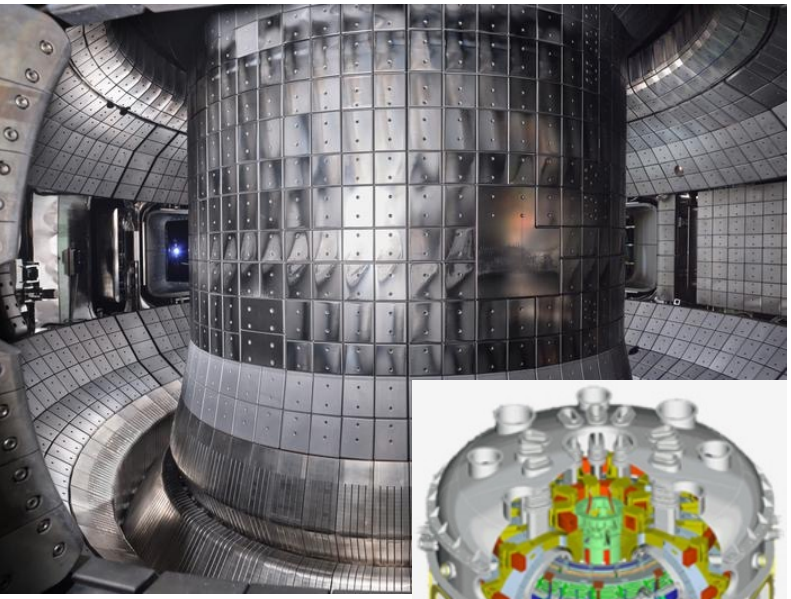
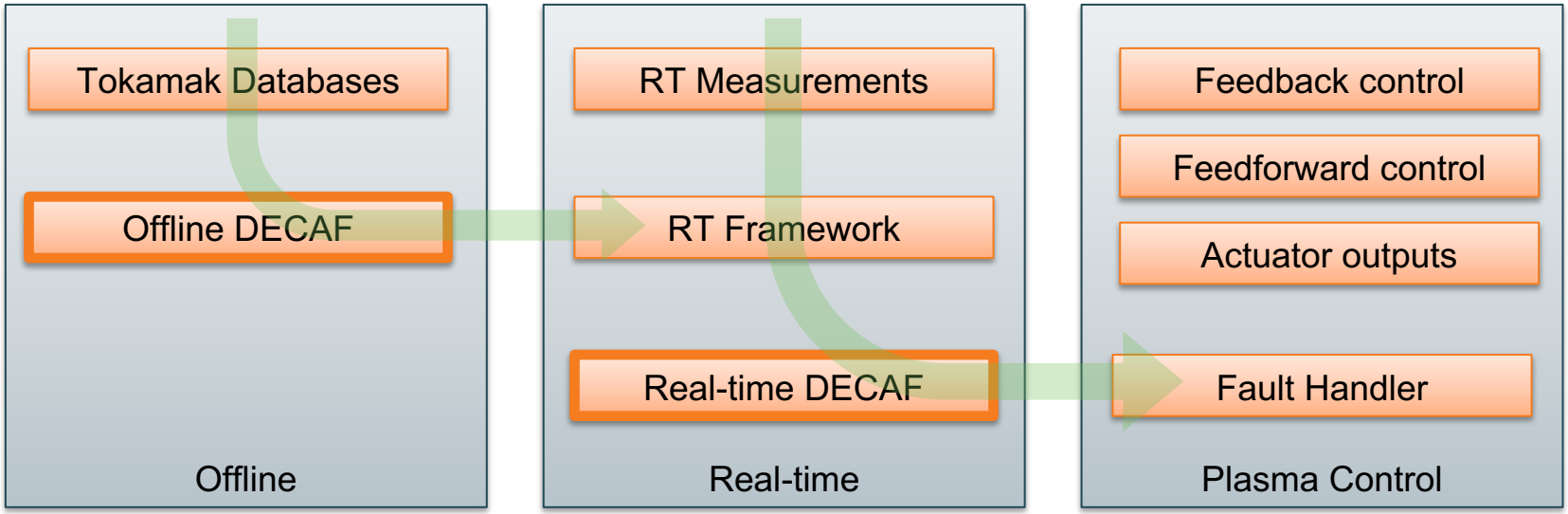
Accurate disruption prediction and avoidance (DECAF*) on KSTAR requires real-time diagnostics in Plasma Control



- KSTAR is a leading long pulse tokamak providing key research towards demonstration fusion reactors
- Large (expensive!) tokamaks require increasingly complex protection directly coupled to plasma control
- Recent **Disruption Event Characterization and Forecasting** (DECAF) research has produced high accuracy results (98%+) for large databases
- Real-time measurements of various types (magnetic, kinetic, rotation, etc. including 1D and 2D) are required to generate best accuracy in disruption prediction

*DECAF: S.A. Sabbagh, et al., Phys. Plasmas **30** (2023) 032506; https://doi.org/10.1063/5.0133825

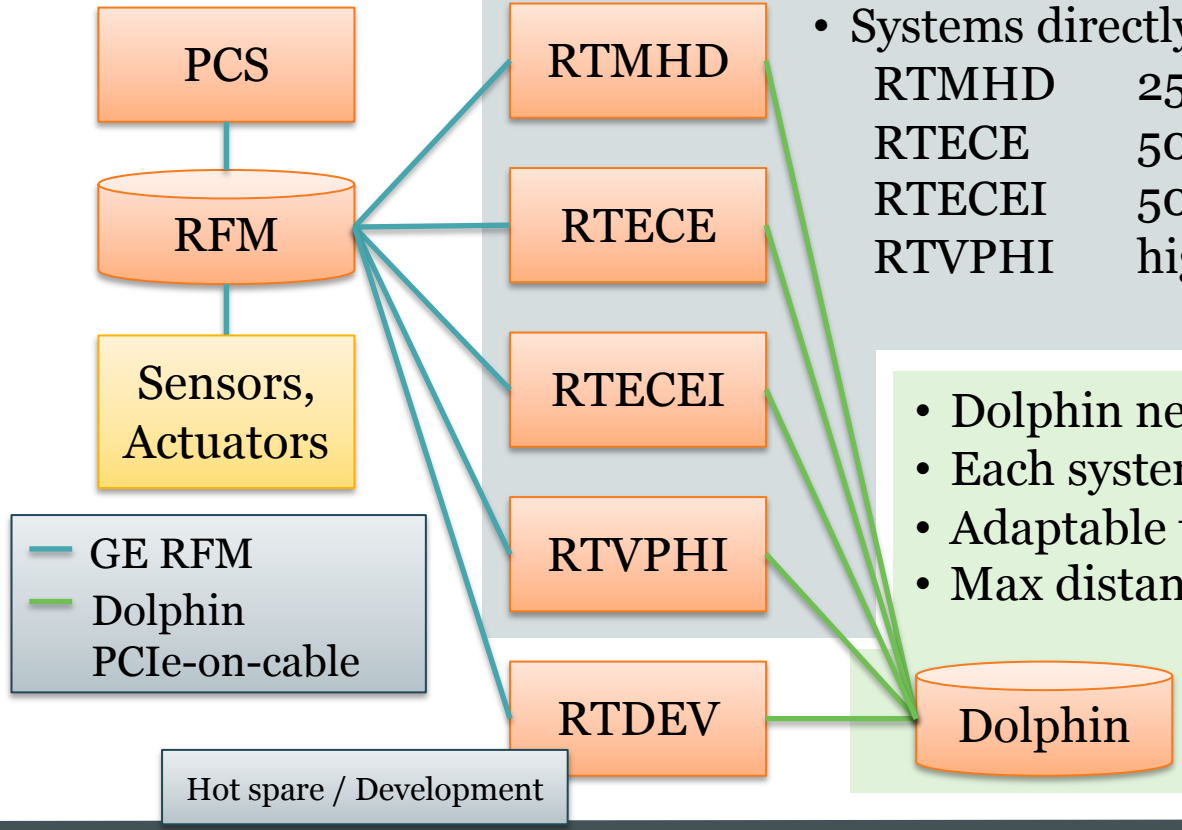
DECAF Data Analysis Workflow



Offline research informs real-time processing that drives the tokamak operation

*DECAF: S.A. Sabbagh, et al., Phys. Plasmas **30** (2023) 032506; https://doi.org/10.1063/5.0133825

KFE – Columbia – PPPL RT Diagnostic Layout



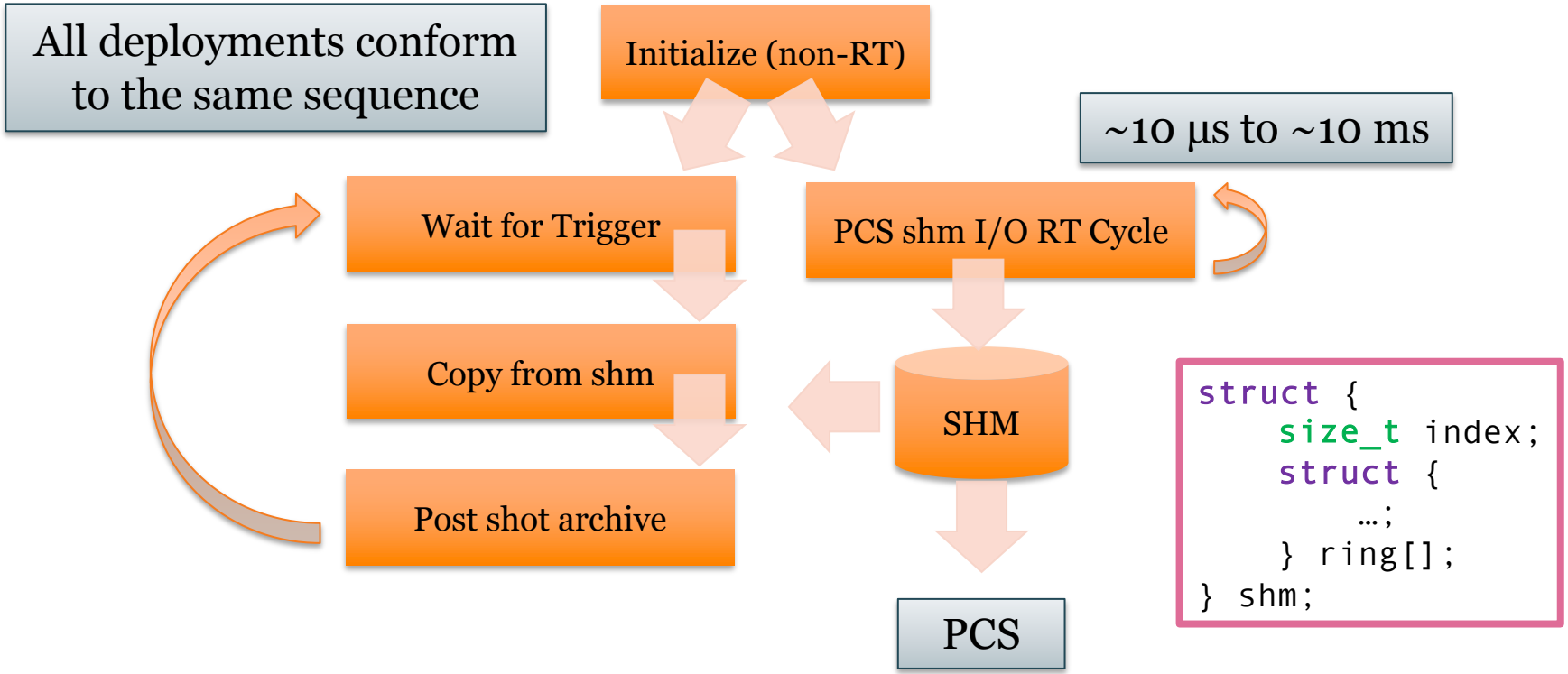
- Systems directly attach to hardware diagnostics:
  - RTMHD 250 kHz digitizers + FPGA
  - RTECE 500 kHz digitizers (local)
  - RTECEI 500 kHz digitizers (remote)
  - RTVPHI high speed camera, spectrometer

- Dolphin network runs outside of PCS, RFM
- Each system supports PCIe Gen3
- Adaptable to PCS memory region interface
- Max distance from switch to host: 100m

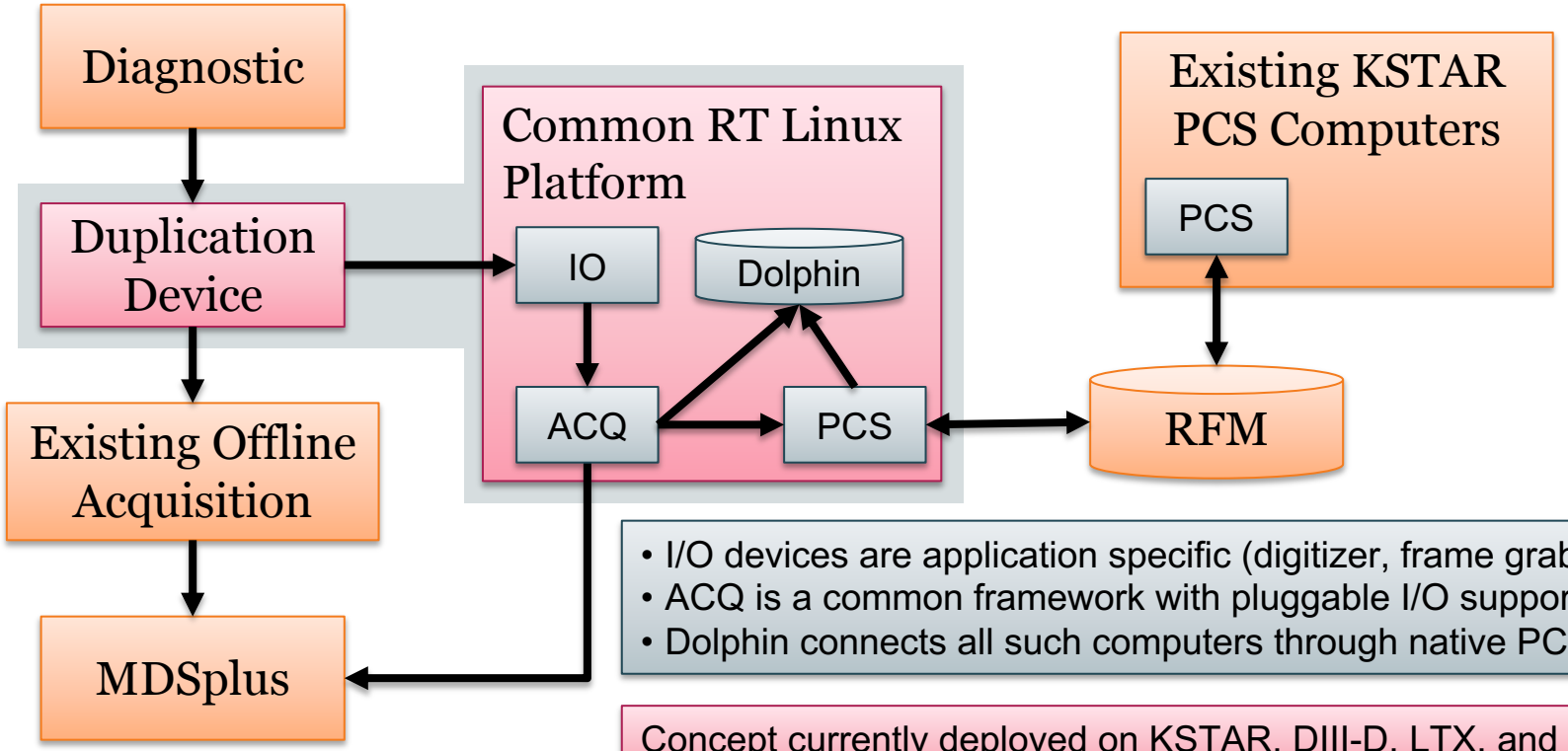
Scalable Platform Features and Limits
Unix philosophy: Do one thing, do it well

What it is	What it is not
• RT OOP with C++17	• General algorithm platform (PCS provides that)
• OS, platform abstraction	• Dynamic user interface (configured per device, not per shot)
• Modular interfaces	• Language agnostic (no python, Matlab, etc)
• Hardware-specific classes	• Hardware agnostic (HW abstractions are reusable but required)
• Command line configuration	• **High level**
• Diagnostic specific	
• I/O centric	
• **Low level**	

RT Software Framework Pulsed Workflow



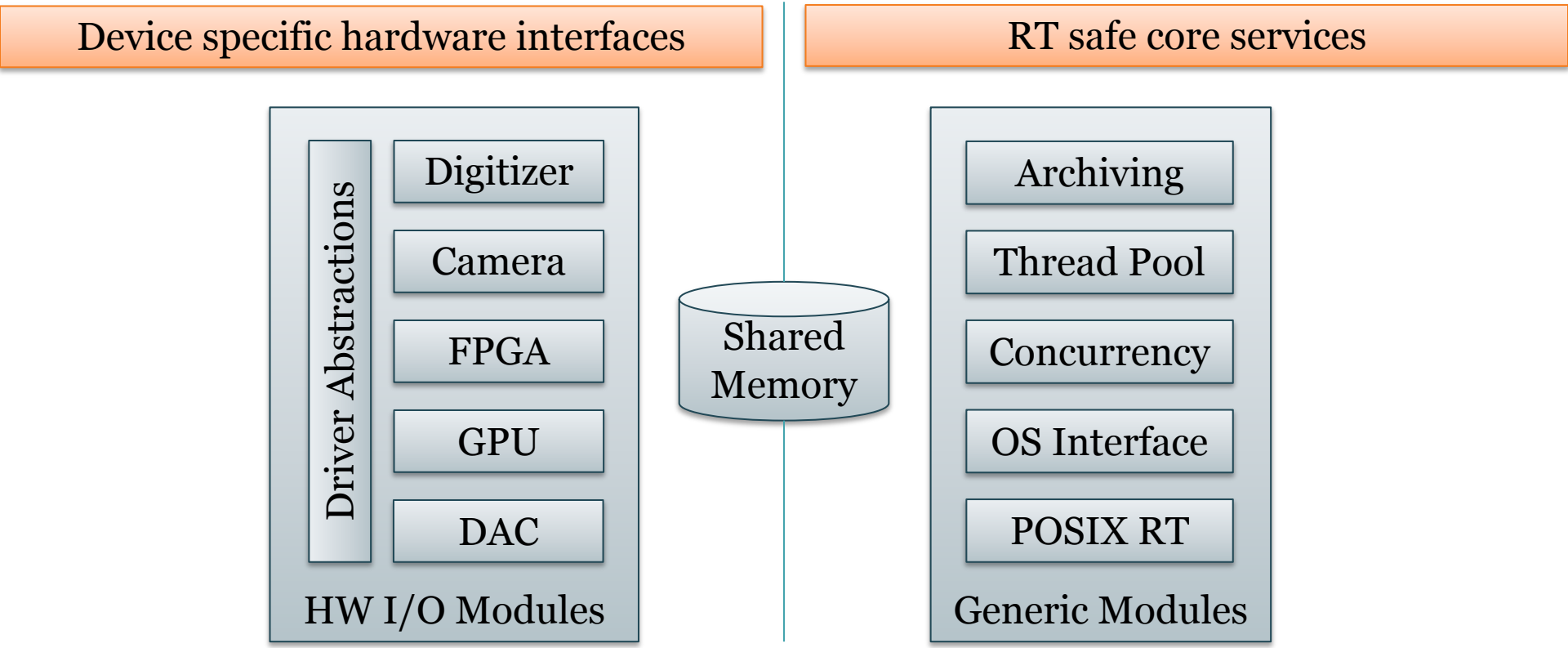
Scalable Platform Enabling Flexible RT Acquisition



- I/O devices are application specific (digitizer, frame grabber, etc.)
- ACQ is a common framework with pluggable I/O support
- Dolphin connects all such computers through native PCIe

Concept currently deployed on KSTAR, DIII-D, LTX, and NSTX-U

RT Software Framework Components



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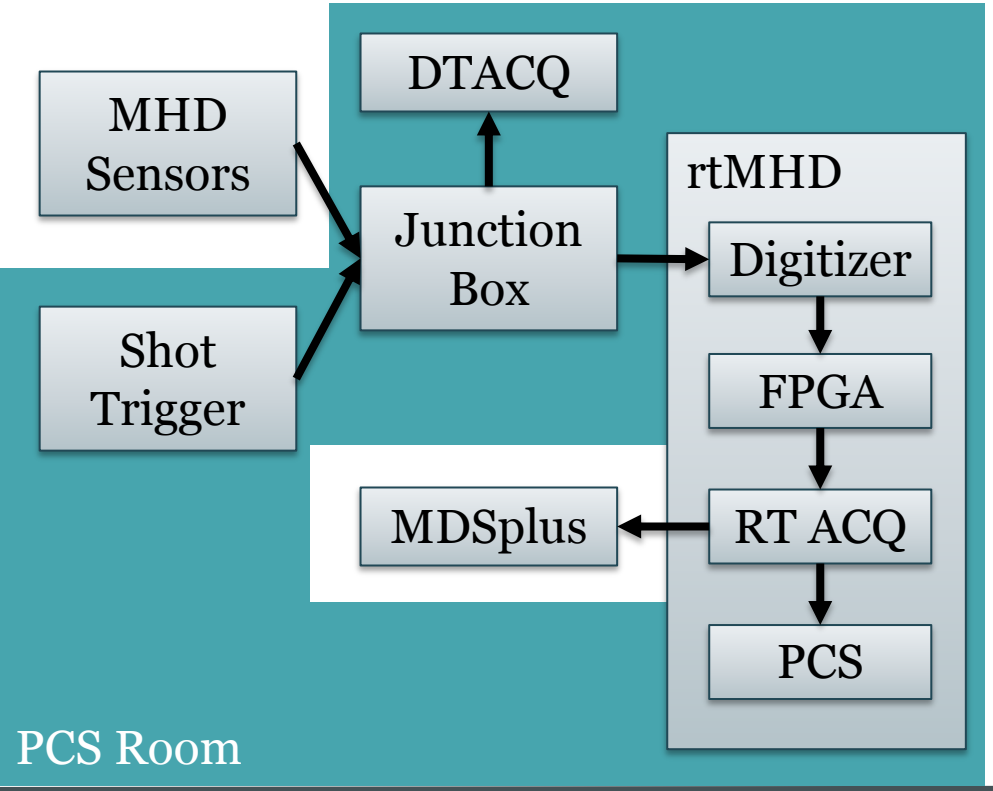
Individual RT Diagnostic Implementation

rtMHD Block Diagram



Data replicated to existing offline acquisition

RT digitizer sends 250 kHz data to FPGA

FPGA assembles 512 sample FFTs

FFT result + raw data sent to RT CPU software

Data stored for post shot archiving

Data sent to PCS at 2048µs intervals ± 1µs!

rtMHD Hardware Components

Timing Unit

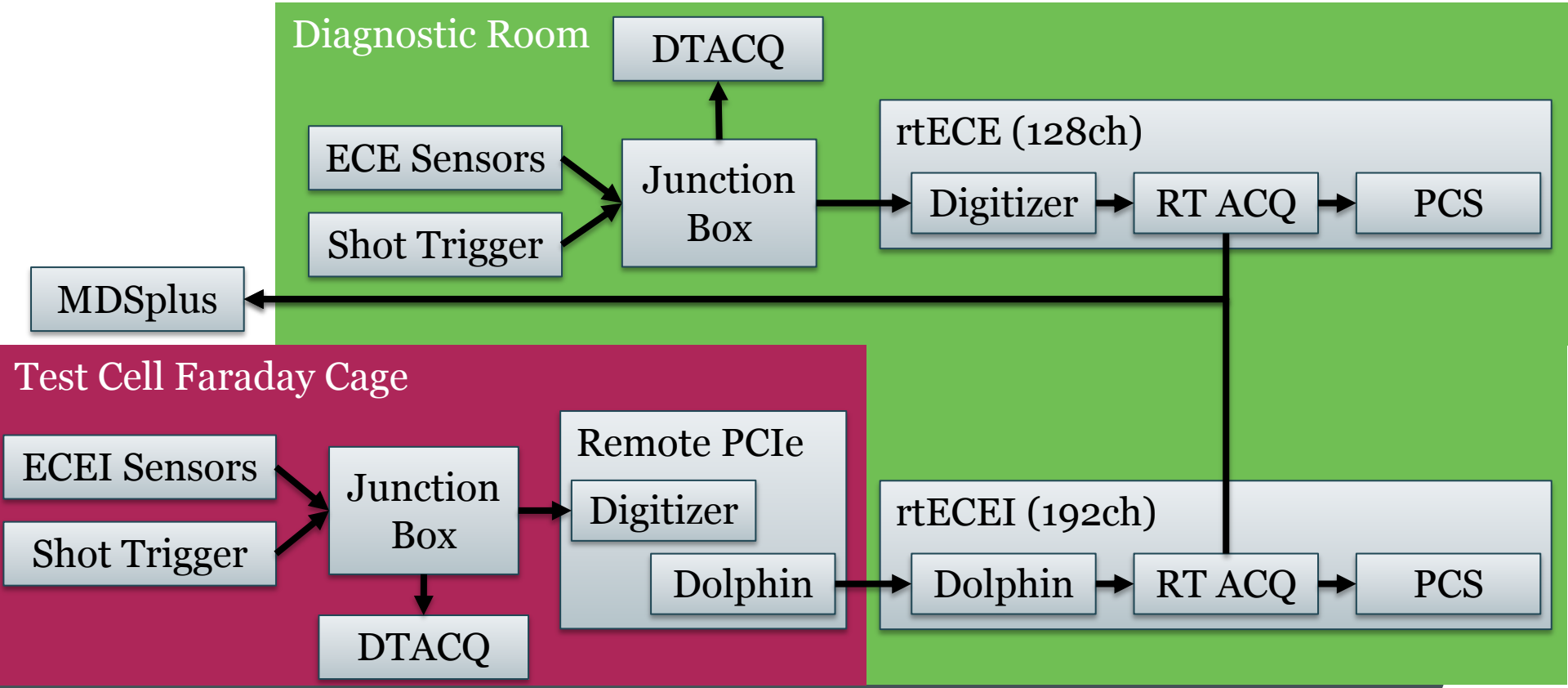
Junction Box

RTMHD

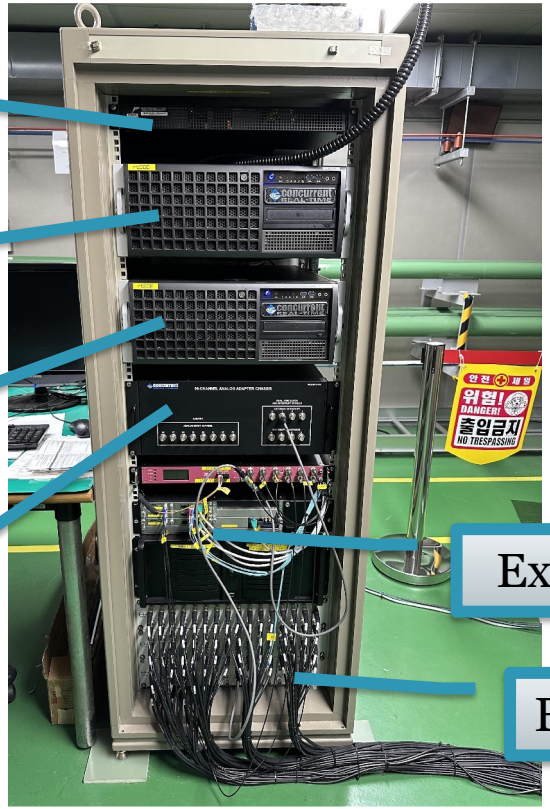
Existing I/O

- System lives in PCS room
- Patch panel uses 14 of 16 LEMO
- Additional digital I/O available
- Clock trigger synchronized with FFT

rtECE and rtECEI Block Diagrams

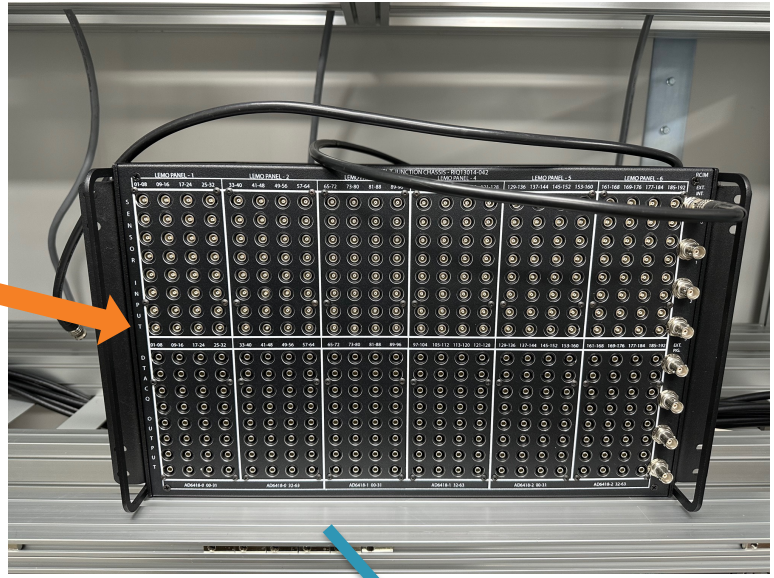


Diagnostic Room Rack Configuration



ECEI Diagnostic: Test Cell Faraday Room

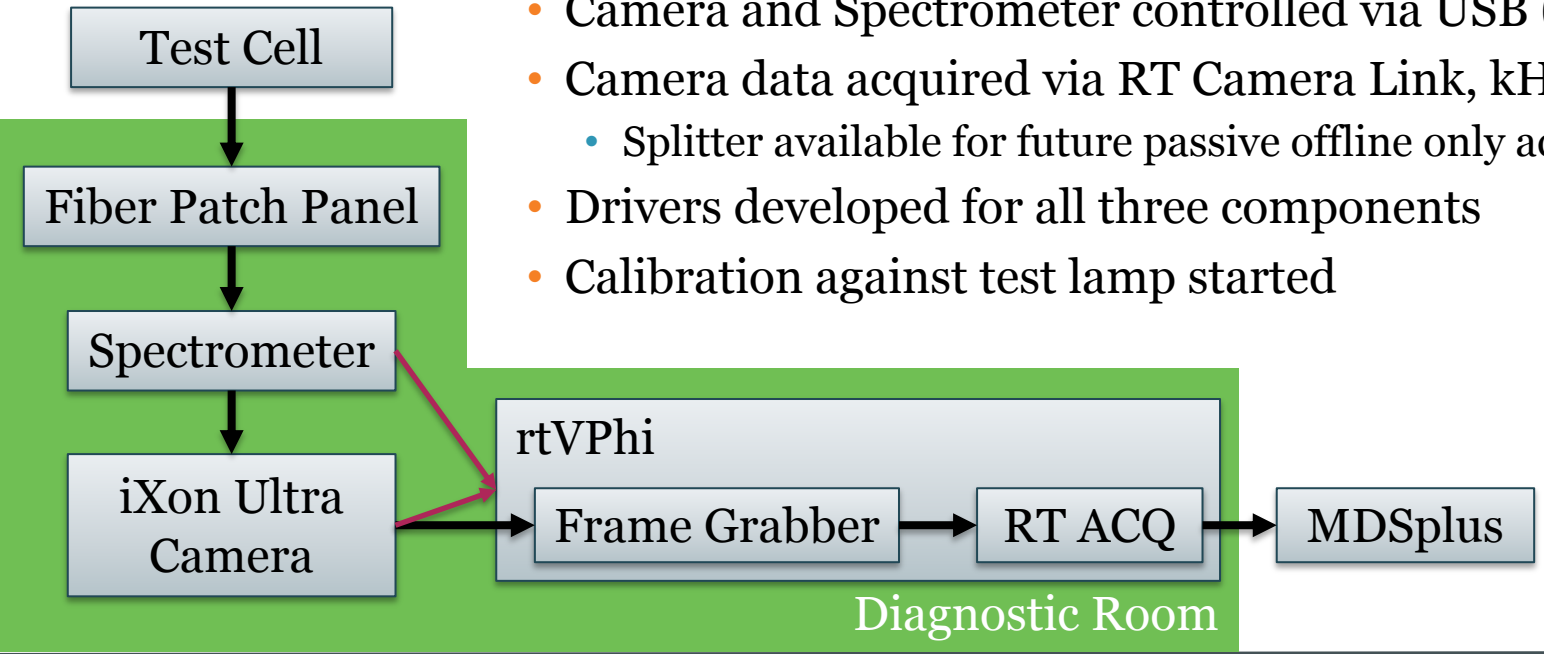
Faraday cage under construction



Patch Panel

rtVPhi Block Diagram and Current Status

- rtVPhi configuration differences
  - Frame grabber, no analog input digitizers
- Camera and Spectrometer controlled via USB (red line)
- Camera data acquired via RT Camera Link, kHz speed
  - Splitter available for future passive offline only acquisition
- Drivers developed for all three components
- Calibration against test lamp started

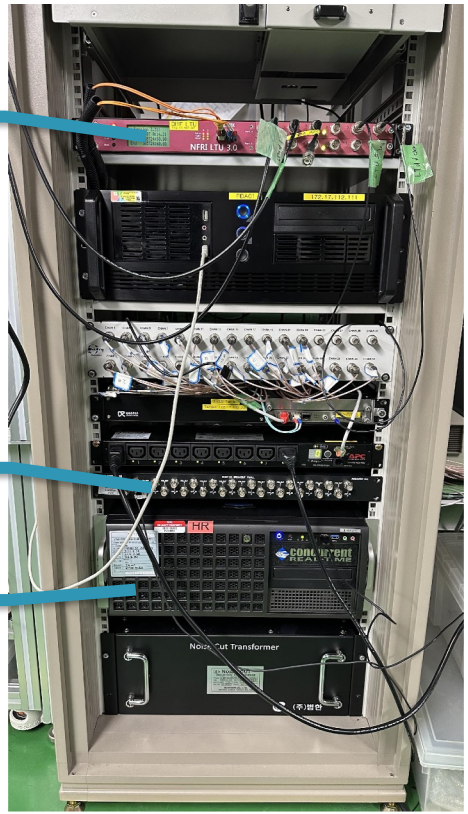


rtVPhi Hardware components

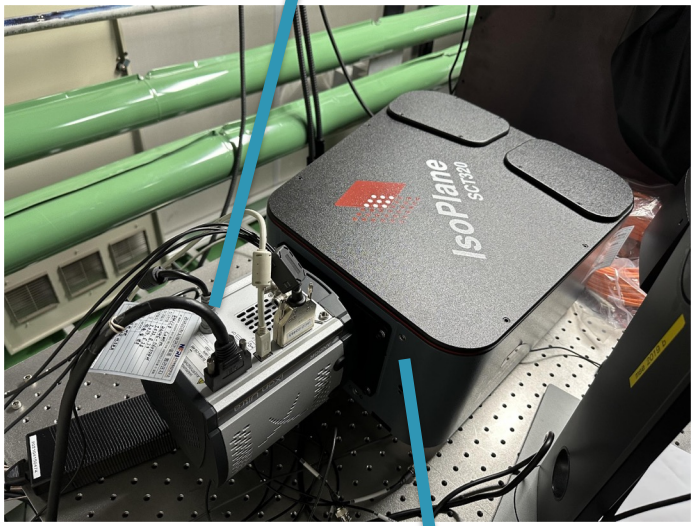
Timing Unit

RCIM Interface

RTVPHI

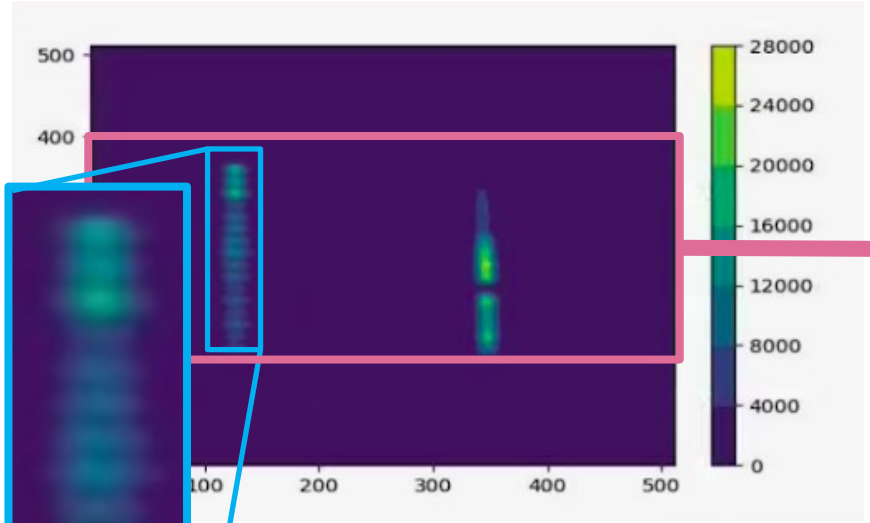


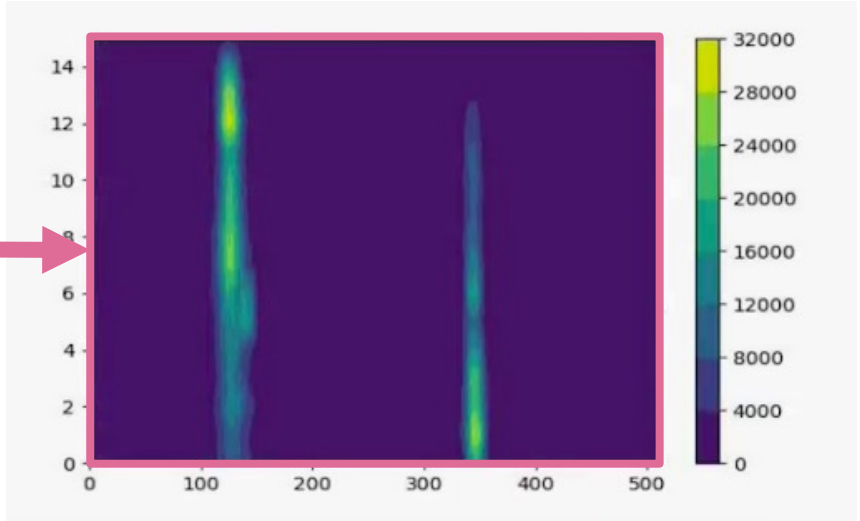
Camera



Spectrometer

rtVPhi Image Capture with FPGA Preprocessing





Full frame image, 512x512, 20.0ms
Each “blob” is an individual fiber

Binned image, 512x16, 2.2ms
Vertical combination on FPGA

KSTAR now has a scalable RT Diagnostic platform

Features

- Proven scalability of a common RT ACQ framework across disciplines
- High data rates, low latency, 24/7 operation, “lights out” management
- Shareable with others (ex. D3D) to leverage existing development efforts
- Team effort: KFE, Columbia, PPPL working together with common goals

Future

- Extend DECAF use of RT data and provide diagnostic data to all of PCS
- Create simulation modes to simplify testing and development
- Continue developing rtVPhi for use in CY24 campaign
- Expand with new, unforeseen RT diagnostic needs as they arise
- Port RT diagnostics from D3D, elsewhere to shared platform