Implementation of High-Speed Data Acquisition at DIII-D

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[1]General Atomics

Presented at the

14th Technical Meeting on Control Systems, Data Acquisition, Data Management and Remote Participation in Fusion Research

Instituto de Física da Universidade de São Paulo

July 15 - 18, 2024

Work is supported by US Department of Energy under DE-FC02-04ER54698 and DE-SC0010685

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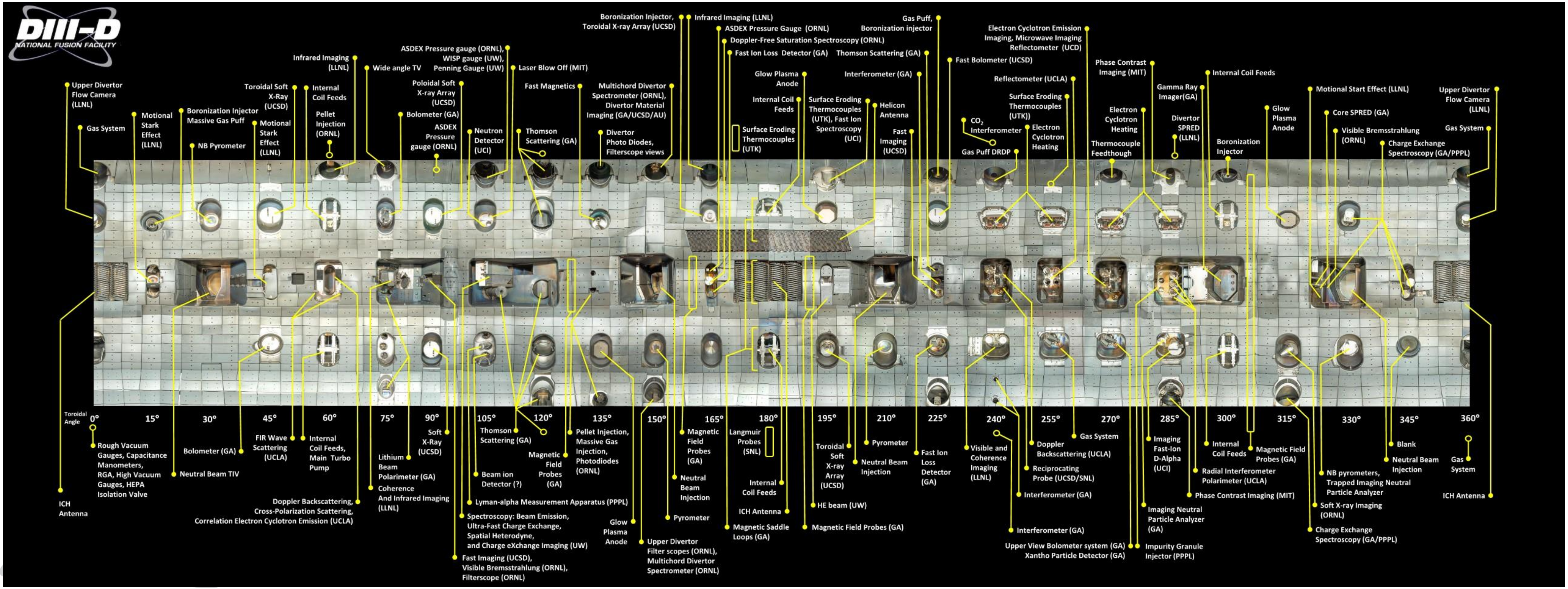
GENERAL ATOMICS

DIII-D Utilizes an Extensive Array of Diagnostics to Ascertain Vital Information from the Tokamak During Operations

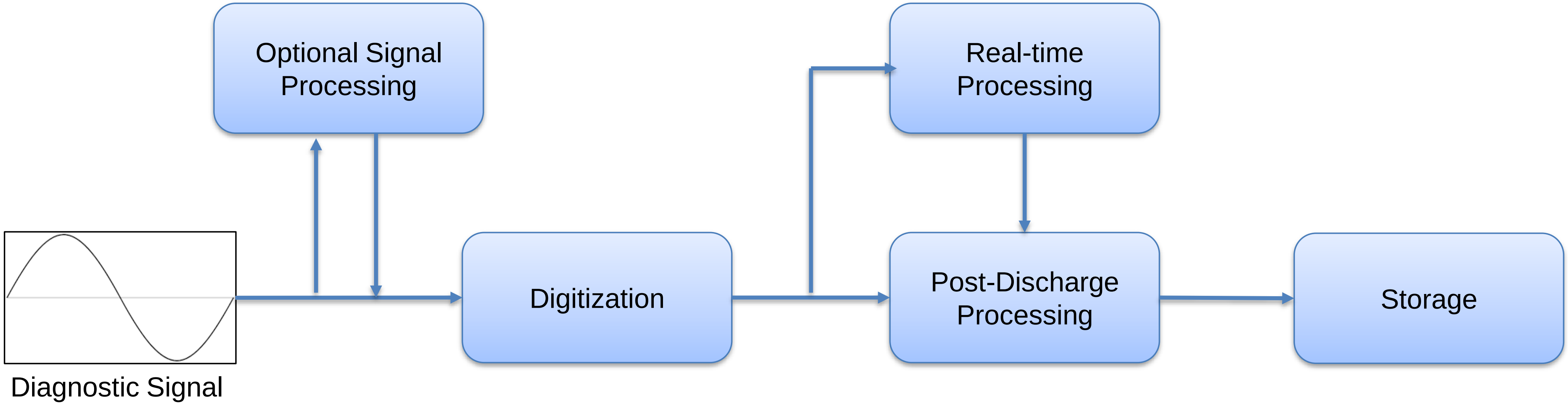
- **DIII-D is a DOE Office of Science User Facility for Fusion Research in San Diego, CA USA**
- **Experimentation focuses on short pulse (~10 second) plasma discharges**
- **Extensive array of diagnostics (87) to ascertain vital information from the Tokamak,** *R. J. Buttery, et al., Phys. Plasmas 1, 120603 (2023)*
- **Two main systems involved in raw data acquisition**
  - Plasma Control System (PCS) | Diagnostic Data Acquisition System



High-Speed Data Acquisition Involves Rapidly Collecting, Processing and Storing Diagnostic Data for Control or Analysis

- **Sample rates can range from thousands of samples per second (kS/s) to millions samples per second (MS/s)**
- **Most diagnostic systems output continuous analog signals, typically in the form of voltages, generating time-series data within/around the 10-second plasma discharge window**

<u>Diagnostic & plant system data flow</u>



High-Speed Data Acquisition is Critical to many Systems and Diagnostics at DIII-D

Capturing transient events *[100 – 250 MS/s]*

- Gamma Ray Imaging (GRI)
- Ion Cyclotron Emission (ICE)
- High-Frequency Doppler BackScattering (HFDBS)

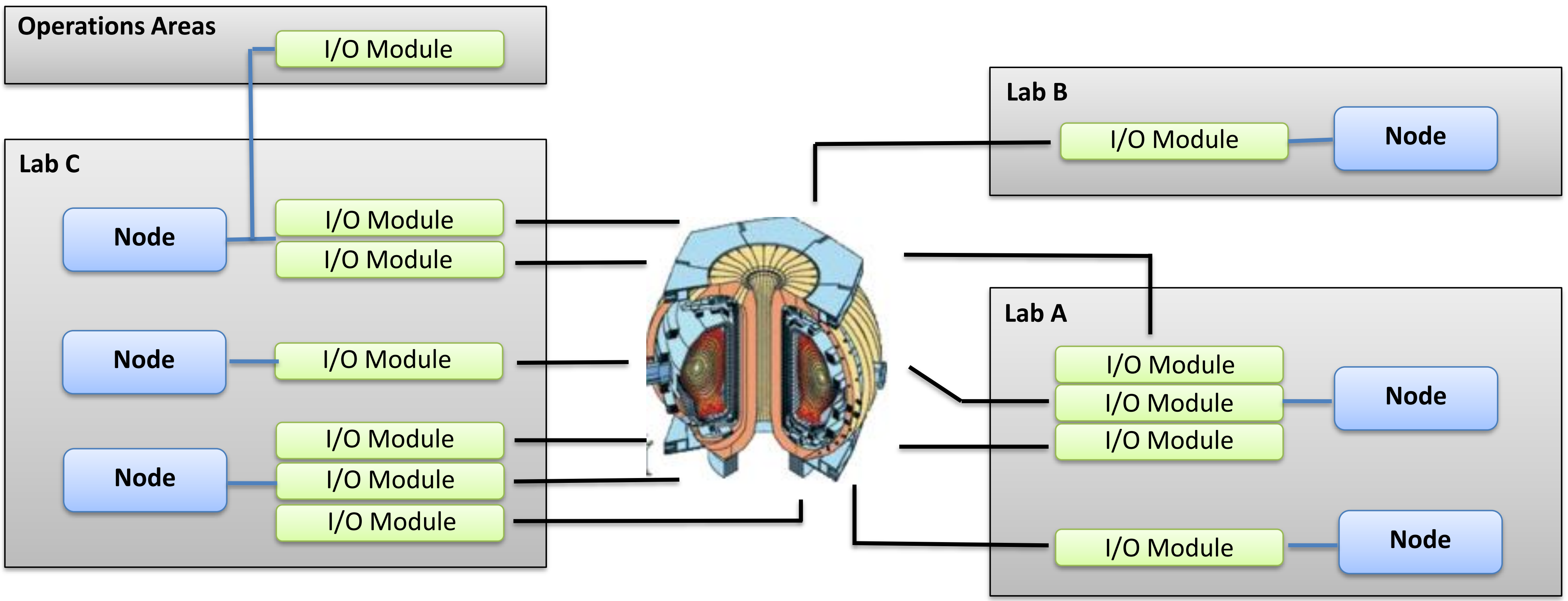
High-resolution temporal evolution *[500 kS/s – 50 MS/s]*

- Charge Exchange Imaging (CXI)
- Microwave Imaging Reflectometry (MIR)
- Beam Emission Spectroscopy (BES)
- Electron Cyclotron Emission Imaging (ECEI)

Real-time feedback control *[20 – 500 kS/s]*

- Plasma control system (PCS)
  - Equilibrium control (shape, vertical stability and divertor)
  - Resistive Wall Mode (RWM)

The Acquisition System is a Cluster Architecture Designed to Distribute Data and Processing Loads Across Multiple Systems



Hardware Continued…

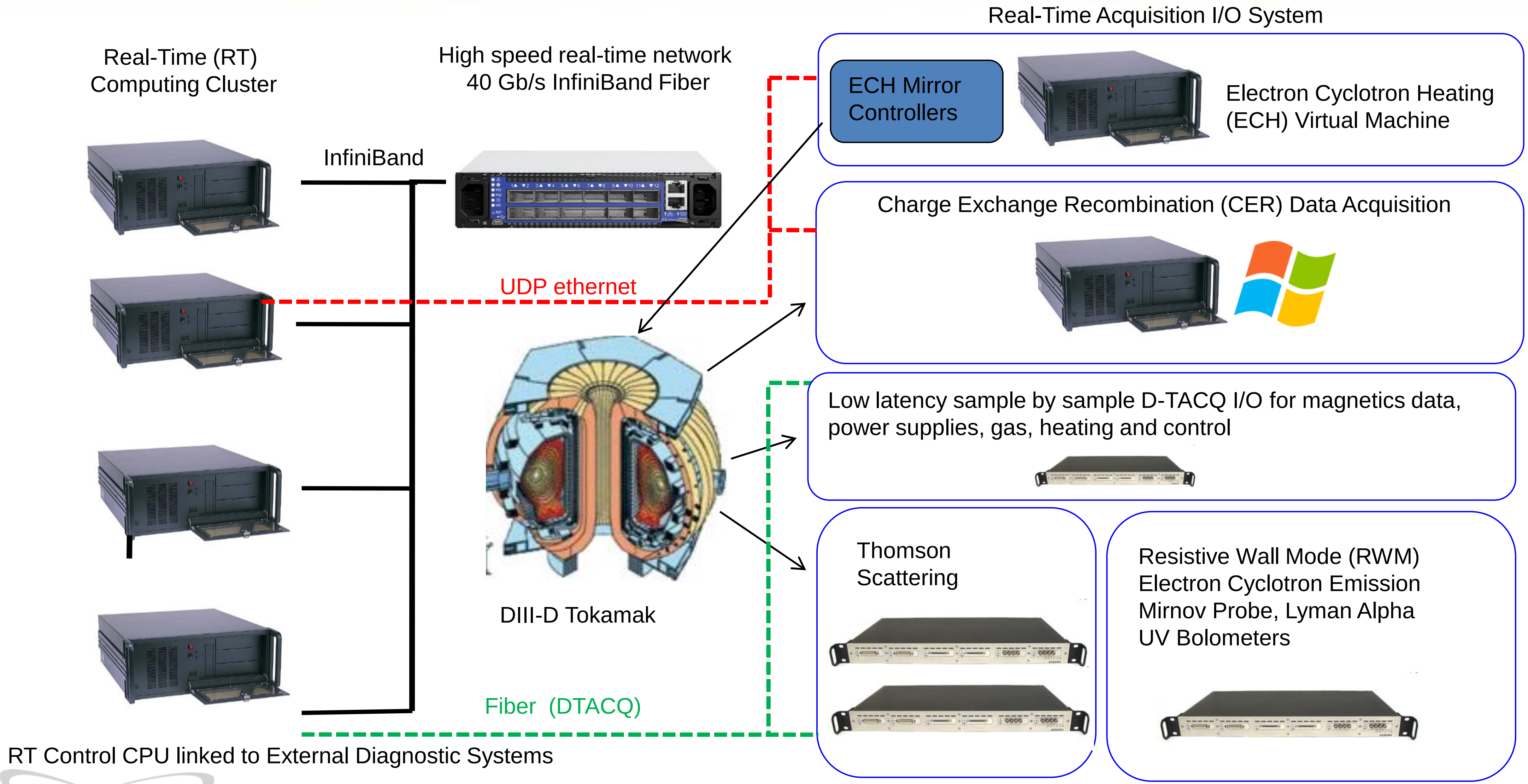
I/O Modules used at DIII-D

D-TACQ Solutions LTD

Spectrum Instrumentation

Alazar Technologies

PCS is Comprised of Multi-Core Compute Nodes, High Performance Network and Real-Time Acquisition and I/O systems



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The Acquisition Software Functions as an Intermediary Between the I/O Hardware and Application Layers

- **Both frameworks employ a similar top-down approach, where higher-level programs initiate lower-level commands to the I/O modules throughout the acquisition phases**

- **Following the typical acquisition procedure:**

Setup
- Configuration of each connected I/O module(s)
- Configuration of the acquisition node

Transmission
- Data is moved from the digitizer to the application space

Processing
- Real-time utilization of data
  - Running calculations
  - Sending to other nodes

Storage
- Formatting & archiving of data

The Setup Phase Configures all Aspects of the Hardware & Software Prior to Acquisition

- **Configuration of the I/O module acquisition parameters**
  - Bit resolution, trigger type, number of pre/post trigger samples, memory allocation per channel, and clocking rate

DAQ1	DAQ2	DAQ3	DAQ4	DAQ5
DAQ6	DAQ7	DAQ8	DAQ9	DAQ10
DAQ11	DAQ12	DAQ13	DAQ14	DAQ15

- **Configuration of the acquisition node**
  - Setting the FIFO scheduler & CPU affinity (high-speed systems)
  - Memory initializations

BDEF	B-Coil deflection	On
BDTC	Bottom Diverter TCs	On
BESF	BES Fast	Off
BESS	BES Slow	Off
BIMGFL	B-Coil Interconnect Mon	Off
BOLR	Bolometer Raw Data	On
BOLR_UD	Upper Diverter Bolometer	Off
BPS	B Power Supply	On
CECE	CRF/Doppler Reflct	On

- **The diagnostic acquisition framework is more generalized**
  - To support various hardware types and experimental setups with minimal or no adjustments to the higher-level framework
  - In the PCS, every computer and I/O module is integral to the Tokamak's operation, necessitating a more stringent approach to acquisition

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High-Speed I/O Modules Stream Data Directly to the Application Space for Real-time Analysis and Feedback Control

- **The acquisition application accesses data when a driver interrupt is received**
  - Interrupts are predefined to optimize the acquisition process
  - Asynchronous process begins after a set amount of data is streamed to the transfer buffer

- **This procedure is typically managed through direct memory access (DMA)**
  - Often facilitated by proprietary hardware to sustain the high data transfer rate
  - Ex. Spectrum Instrumentation

Acquisition Process

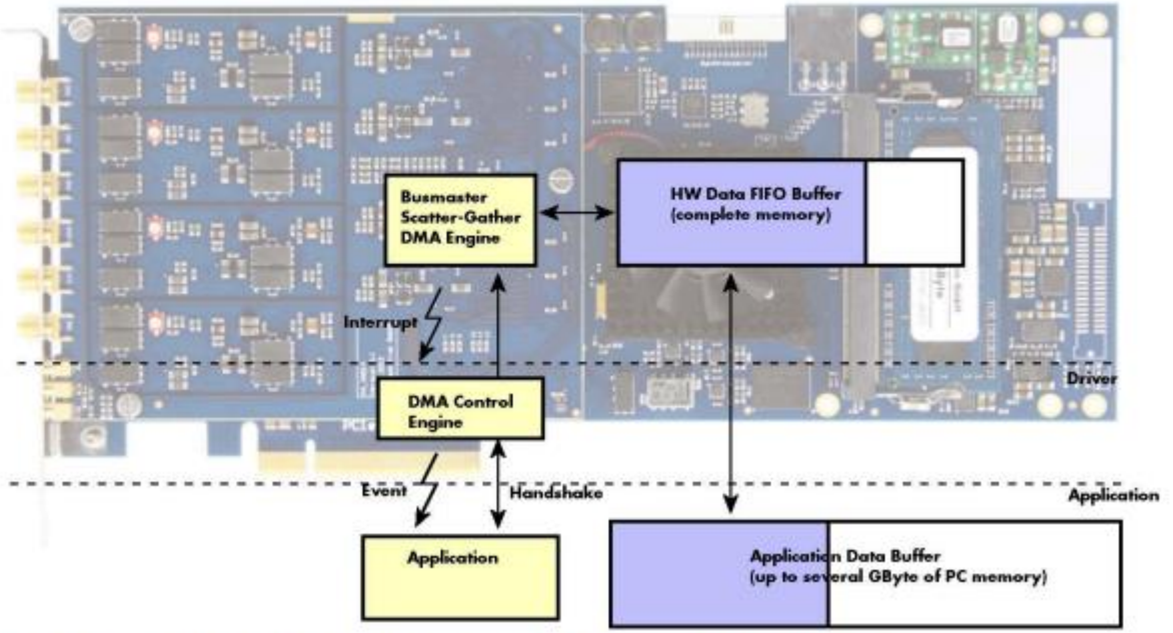
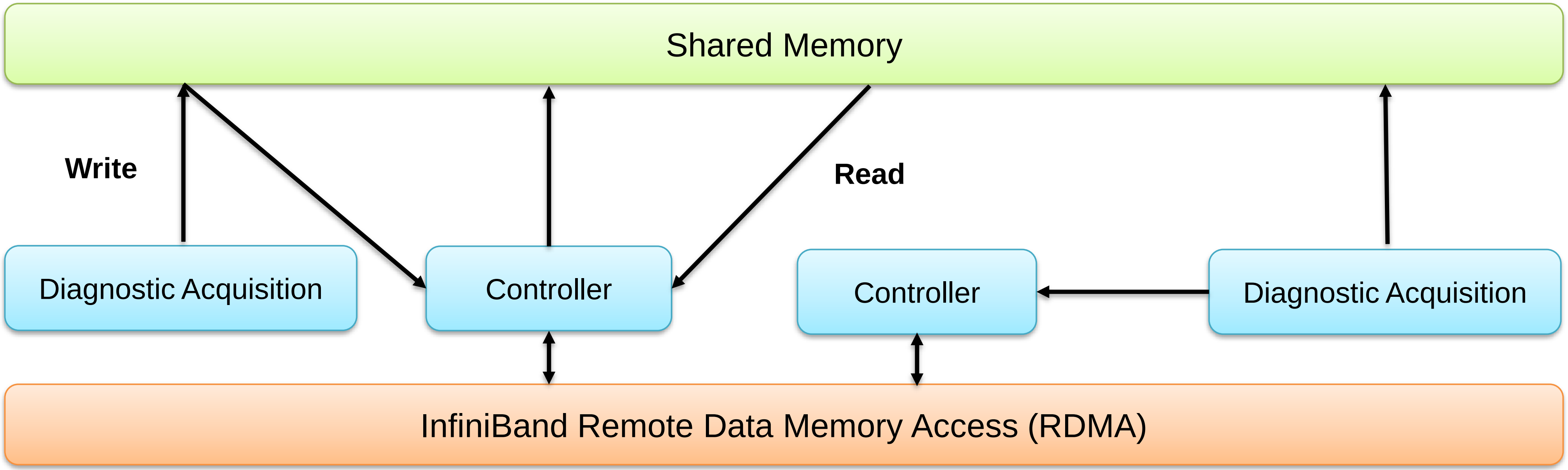


Image 53: Overview of buffer handling for DMA transfers showing and the interaction with the DMA engine

https://spectrum-instrumentation.com/dl/m4i44_manual_english.pdf

Real-Time Processing Requirements Dictate the Speed of Acquisition

- **Feedback control in the PCS is the largest use of real-time processing of acquired data at DIII-D**
- **Achieved by inter-process communication using shared memory and real-time networking**
  - These processes control actuators (coils, valves, mirrors, etc.) to control various aspects of the plasma structure



- **The diagnostic system nodes have minimal real-time processing due to the high throughput**

The Storage Format for Time-Series Data Varies Depending on the Data Type

Raw and Calibrated Data

- Contains the digitized data taken directly from the diagnostics
- Archived in PTDATA
- Allows for immediate access to the data post-discharge
- Is typically used for inter-discharge adjustments during experimentation

Derived Data

- Contains analyzed data calculated from one or more diagnostic measurements
- Archived in MDSplus
- Allows for all data (calibration data, setup, codes, etc.) to be stored in one hierarchical structure
- Is typically used for in-depth experimental analysis after experimentation

Implementing High-Speed Data Acquisition Systems Poses Various Challenges

Limitations

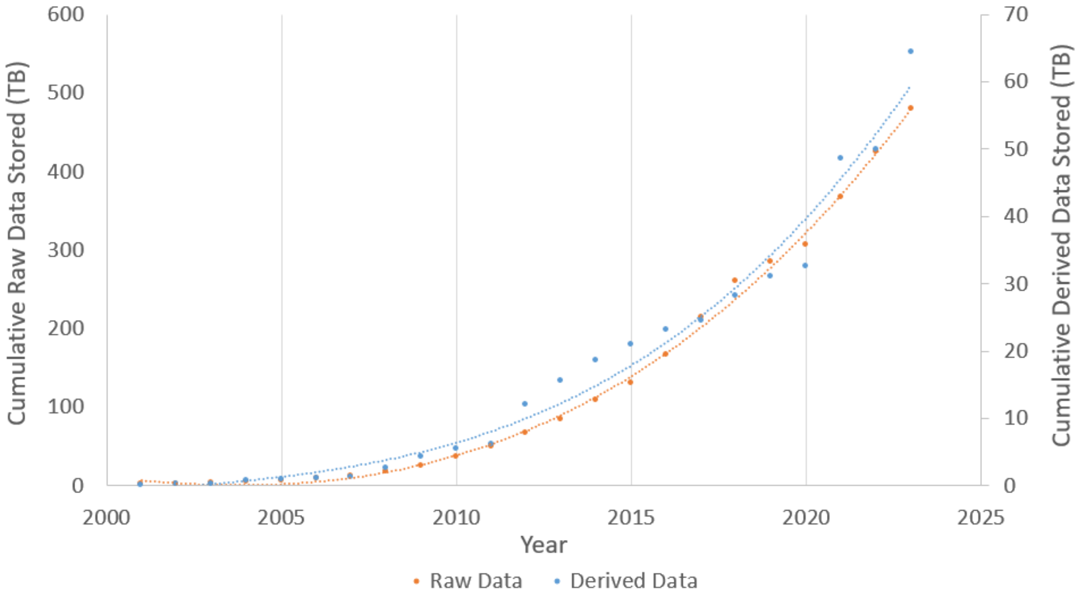
- Computer processing speeds
- Memory requirements
- Network bandwidth
  - Speed & deterministic performance

Data Formatting

- Scalability of DIII-D's raw data format (PTDATA)
- Formatting large datasets
- Efficient access to data

Storage System Lifetime

- All DIII-D raw data is stored in permanent redundant archives
- Accurately predicting future infrastructure requirements is challenging
  - Computer Systems Review (CSR)



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Production of High-Resolution Data is Required for Emerging Fusion Technologies

- **Developing/conceptualizing machine learning applications to detect and control plasma instabilities during real-time magnetic confinement**
  - Comparison of machine learning systems trained to detect Alfvén eigenmodes using the CO_2 interferometer on DIII-D, *Alvin V. Garcia et al 2023 Nucl. Fusion* ***63*** *126039*
  - Using Convolutional Neural Networks to detect Edge Localized Modes in DIII-D from Doppler Backscattering measurements, https://doi.org/10.48550/arXiv.2406.01464
  - Deep convolutional neural networks for multi-scale time-series classification and application to tokamak disruption prediction using raw, high temporal resolution diagnostic data, *Phys. Plasmas* 27, 062510 (2020)

- **Developing techniques for doing on-the-fly data reduction so that this data can be more easily utilized by the PCS**
  - Increases the feasibility the real-time detection and control

Conclusion

- **Reliable low latency high-speed data acquisition has been essential to DIII-D for many years and is now broadening in scope**

- **Recently large volume diagnostic data acquisition has become reasonably feasible**
  - Enabling deeper analysis of plasma phenomena

- **Requires optimized computational hardware, non-standard techniques and implementable software frameworks**

- **Production and reduction of high-resolution datasets will be a crucial next step in real-time control during magnetic confinement**

Questions?

Thank you!