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Advanced Real-Time Control Systems For Magnetically Confined Fusion Plasmas

Presented by

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On behalf of

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S8-5

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Preamble

Real Time Measurement and Control (RTMC) of magnetically confined plasmas is a critical issue for safe operation and high performance scientific exploitation of experimental devices on regimes beyond the current operation frontiers.

It is a broad task undertaken by most relevant devices and involving a large number of competencies:

-plasma physics, control, machine operations, systems, machine safety, software, hardware, communications engineering, computational mathematics, …

An interdisciplinary dialogue is required at several levels to integrate, consolidate and build-on all the expertise and knowledge available for the benefit of ITER.

Plasma control is essential for achieving the goals of the ITER experimental programme

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ITER Challenges: key areas

Plasma Control involves very many aspects and ALL must be addressed in a consistent and timely manner to allow an adequate model-based control design

Physics ⇒ The Objective
- Experiment

Modelling ⇒ The Description
- Theory & modelling of physics and engineering

Control Engineering ⇒ The Solution
- System specification, sensors, actuators, algorithms
- Control system software and hardware design
- Practical Implementation & Validation

Instrumentation and Information Technology ⇒ The Environment
- CODAC standards
- Signal IO: ADCs, DACs,
- Processors and operating systems, etc.
- Communications: process (continuous) & supervisory (occasional)
- Databases

ITER Challenges: Scientific Exploitation

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ITER will generate huge quantities of experimental data

– PBytes per year (but still less than LHC)

(e.g. 12 IR cameras data resulting from a 10 minutes shot: 1.728 TBytes)

ITER will provide tools for continuously accessing and analysing data during a pulse

- Requires data indexing by events

ITER will have a very strong flexible set of diagnostics and tools for optimising the performance during a pulse

- Adequate tools and methodologies need to be developed

ITER will have a limited number of pulse cycles and an unlimited number of ideas to be tested

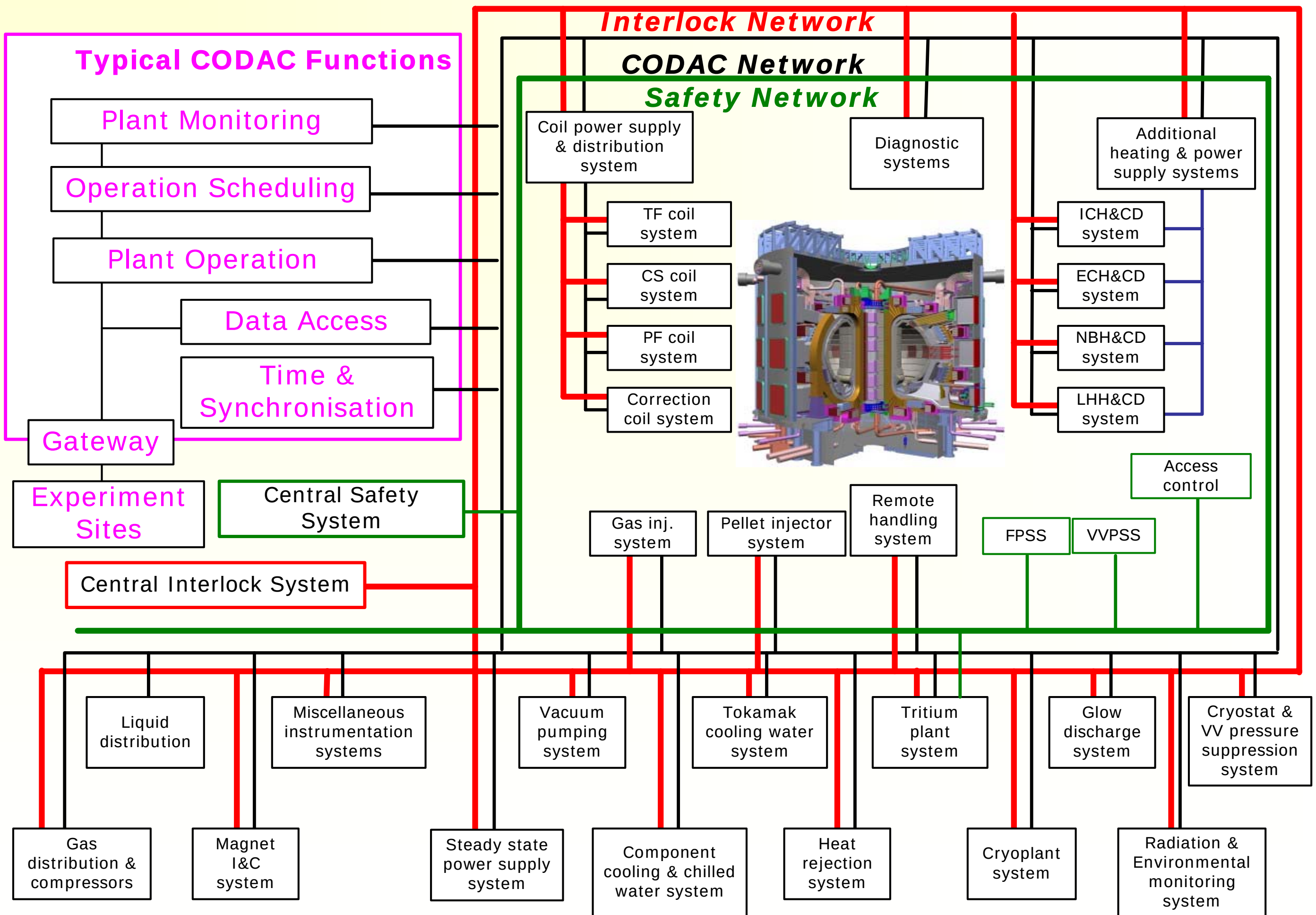
– Will schedule and reschedule many activities during a pulse

ITER will evolve both equipment and ideas over 20 years

– A lifetime of 30 years including procurement – evolution must be built into CODAC

ITER: as seen by CODAC

- CODAC integrates ALL ITER Plant Systems
- Many networks: operation, interlocks, safety
- CODAC functions are like present tokamaks



ITER Challenges: RT and CODAC

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RT control systems have specific technical issues which are different from the more general (and much wider) CODAC issues, though similar solutions are likely to be pursued.

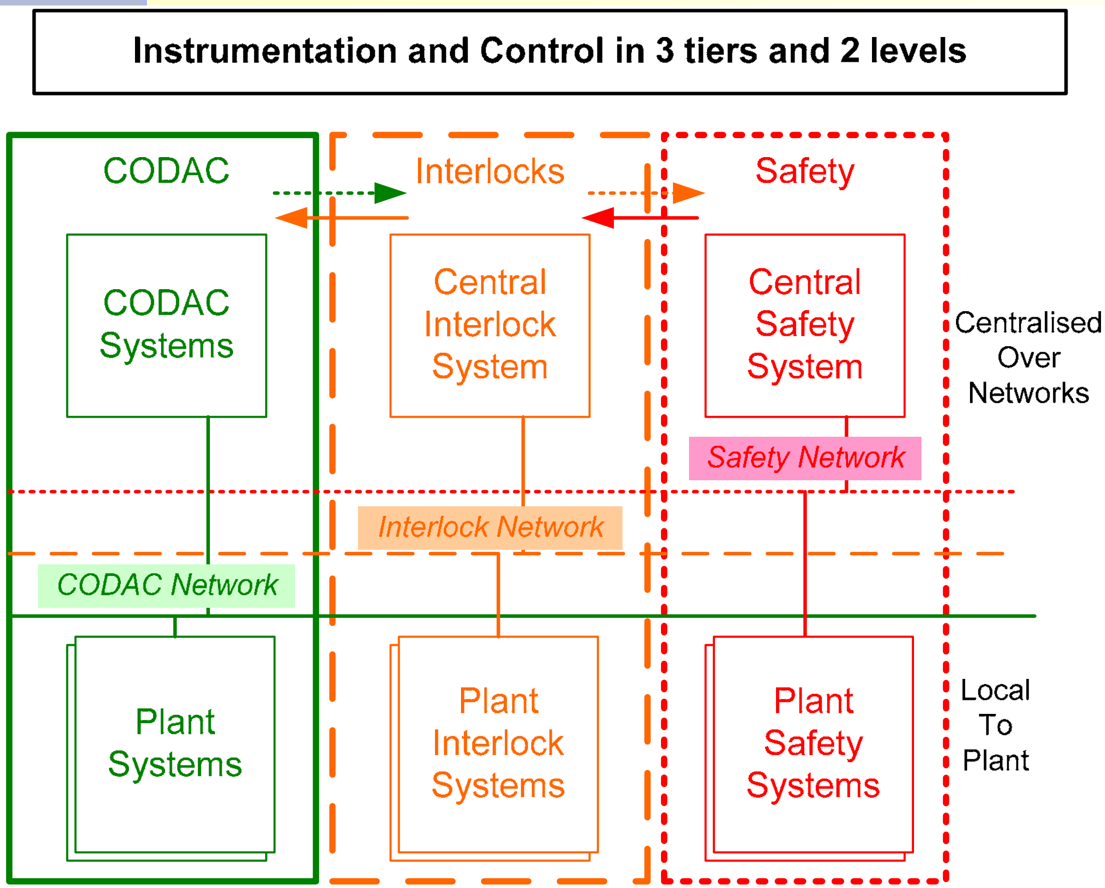
The ITER CODAC conceptual design is advancing towards peer review (not yet proposing technical solutions which would most likely be obsolete some years from now).

However, prototyping ideas is desirable and ALL concepts must be fully functional and exhaustively tested, well before it is essential for ITER

ALL CODAC functions/RT control systems must be proven on advanced facilities – existing tokamaks and/or ITER test stands

Near-term needs for RT control on existing devices may address issues of relevance for ITER-CODAC

Instrumentation and Control



I&C is in 3 clear tiers

- **Safety:** protects personnel, population and environment
- **Interlock**: protects ITER investment
- **CODAC:** operates ITER

I&C is in 2 layers

- **Plant Systems**: local responsibility
- **Networks** when responsibility lies across Plant Systems

- ITER operation will be complex
- The investment needs to be reliable
- The licensing has to be simple

ITER Challenges: Instrumentation & IT

Issues which need to be addressed for ITER

Assess design constraints and define requirements

Define standards and guidelines to avoid proliferation of solutions and technologies

- Which technologies, protocols, methodologies
  - technical integration and inter-operability ?
  - multi-party, international development ?

Design, develop and test appropriate solutions

Assess costs

Identify fusion specific needs

Choose long-life technologies for high availability and reduced maintenance

Dedicated time and funding will be required to address these issues

ITER Challenges:
Inherent Constraints

ITER site will be a Nuclear Registered site

- ITER environment between JET and a Nuclear power station in terms of quality, audit trails, ... etc.)
- To accomplish the scientific objectives will need control system architecture with freedom but within the licensing constraints
- Requires tools to guarantee safety, protection of investment (and a unique facility) and guaranteed operation
- Hostile environment for measurements, networks, electronics – human access will be restricted
- ITER will require a far higher level of availability and reliability than previous/existing tokamaks

IT security will be a major issue

- Security with transparency is required. What does this mean for Remote participation?

ITER Challenges:
Inherent Constraints

ITER is assumed to be totally legacy-free for hardware and software

- Methodologies will have to be tested and proved on existing fusion devices before implementation on ITER
- It will be necessary to take informed decisions based on technology progress
- Maintenance will be an issue and proliferation of technologies must be avoided

ITER is an international project

- In-kind procurement world-wide
- Integration of Plant Systems from all participants
- The implications of in-kind delivery of subsystems need to be recognised
- Powerful remote access networks
- Remote access security

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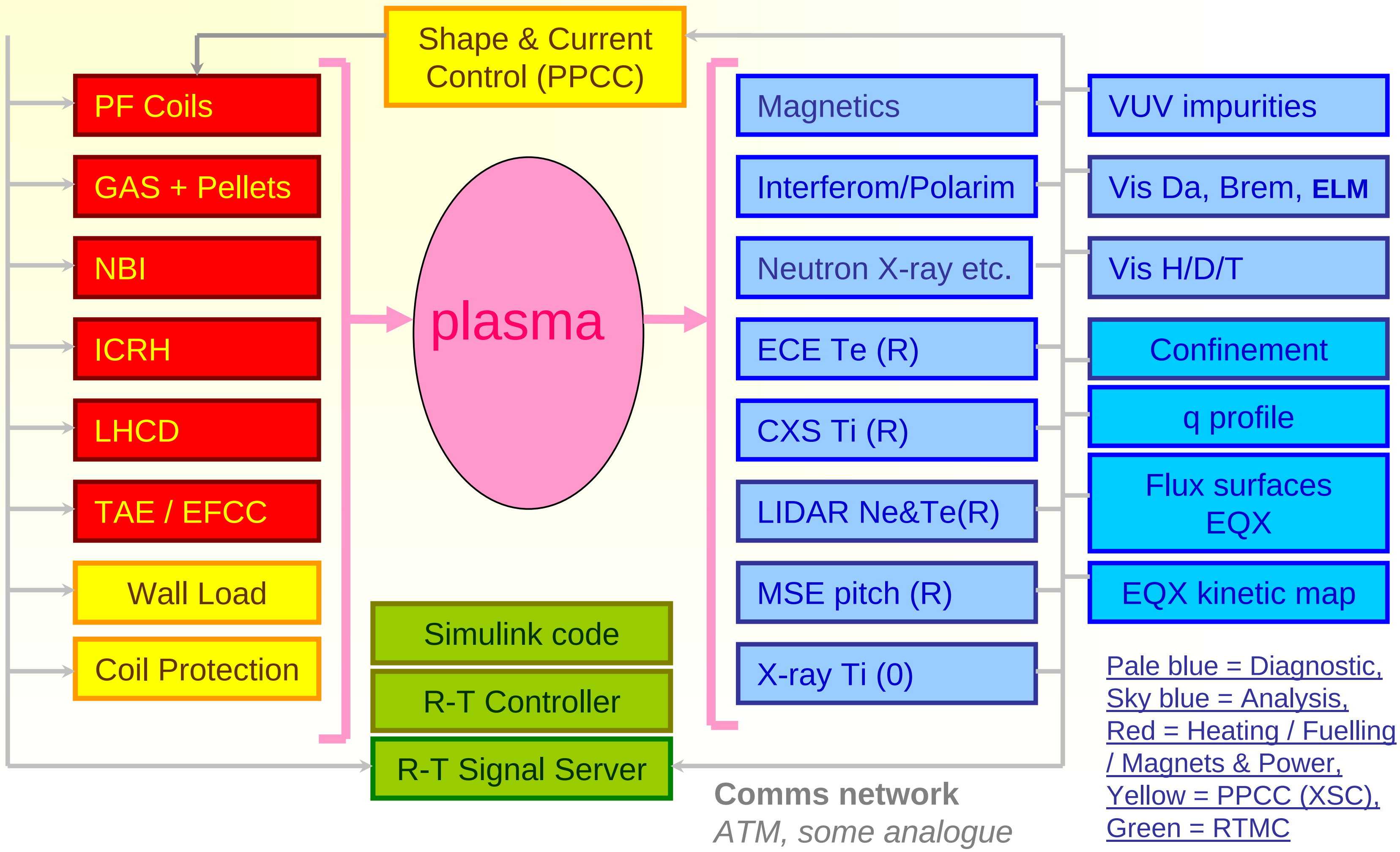
Control Systems: JET as an example

JET already has a wide range of Plasma Control Systems



Limitations of existing Control Systems: JET as an example

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High Maintenance

•Proliferation of interfaces

•Should converge on modern instrumentation, computer, etc. standards

Lack of commonality and functionality between different devices RTMC systems

•e.g. JET PPCC not simply exportable to other devices and vice-versa

Lack of flexibility

•Integration of new equipment and physics into the existing infrastructure is time-consuming.

Lack of good transport and integrated models and tools

•Integrated development environment and interchange formats

Future developments should acknowledge these issues

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The challenge: Control & Data Acquisition in Long Discharges

When the duration of the fusion plasmas increases, it is not convenient to acquire all data provided by all diagnostics

Therefore:

(i) Diagnostics are divided in two groups: technical and scientific;

(ii) Technical diagnostics are in continuous operation, connected to the data acquisition system (DAS) running in real-time algorithms for data analysis and control;

(iii) Scientific diagnostics driven by detection of an event. The DAS generates a signal that is distributed to all transient recorders to adequate their operation to study the detected event. The aim is data compression/reduction.

(iv) The transient recorders must have pre-trigger capabilities, aiming at not to loose any information

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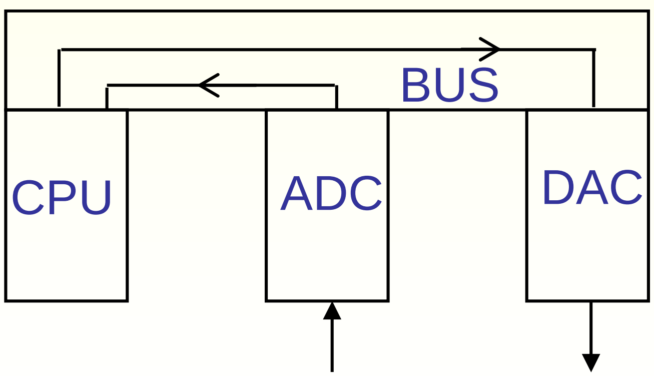
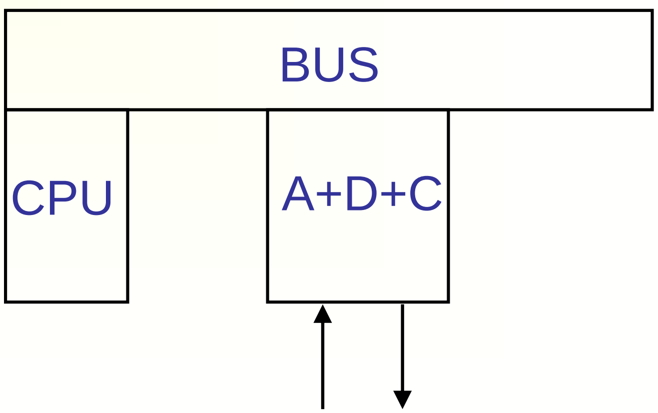
Traditional Architecture

• Control and data acquisition processes usually run on separate hardware platforms

• Data links for exchange of relevant data and events not always provide the bandwidth and low-latency adequate for real-time operation

• The large amount of raw data burdens the data links and the software based signal processing units





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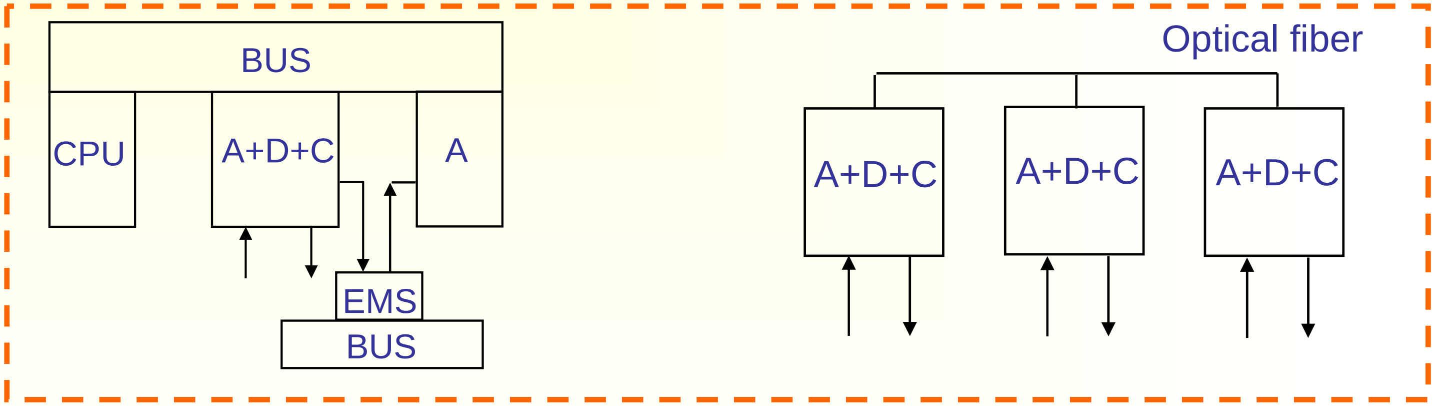
New Architectural Paradigms

New Real-time control systems are based on **intelligent modules**

- Control loop simple algorithm performed at the data acquisition level
  - reduced data rate flow output
- Low latency data link transmits reduced data to software signal processors and control signals back to the actuator units
  - Helps attaining low loop delays
- Integrated support for synchronization of processes an time is desirable



Highly efficient

- data acquisition,
- signal processing
- control tasks

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Aims

- decrease control cycle,
- Increase computer power
- deal with large amounts of raw data

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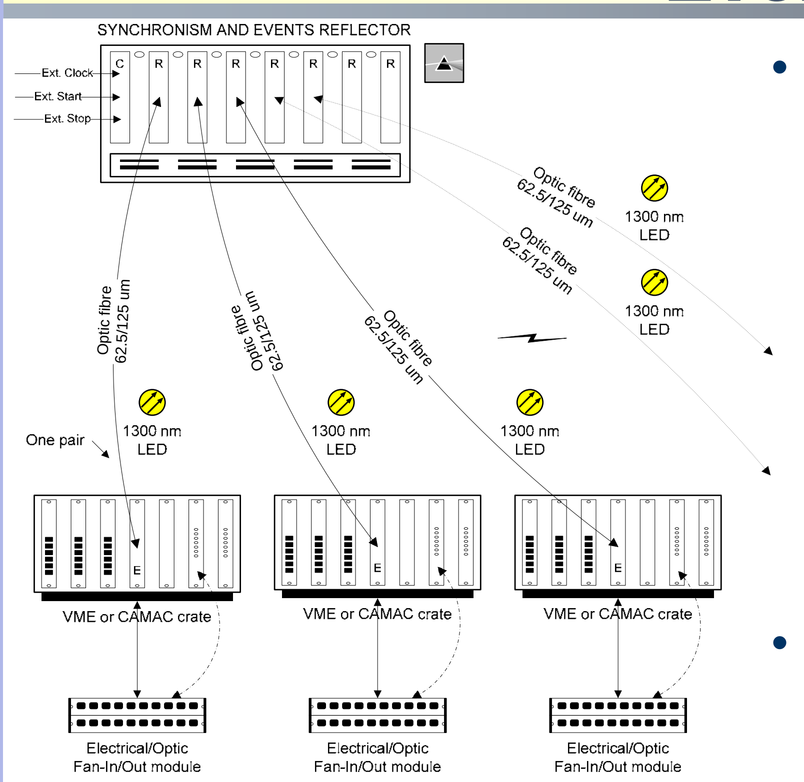
MAST Fast Timing and Event Management System



- **Main features**
  - Broadcasts timing and peer-to-peer events
  - Overall timing precision of the system is 1 µs
  - Events propagated in less than 2 µs
  - Up to 64k global distinct events
  - Up to 17 Reflector units and 256 EPN modules provide up to 2048 I/O channels
- **REFLECTOR unit**
  - Links up to 16 EPN (128 I/O channels) up to distances of 300 m through optic fiber at 1 GBit rate
- **EPN module**
  - Parallel Processing, DSP based,VME Module
  - 8 output timing unit; up to 10 MHz complex pulse patterns.
  - 8 input programmable event generator.

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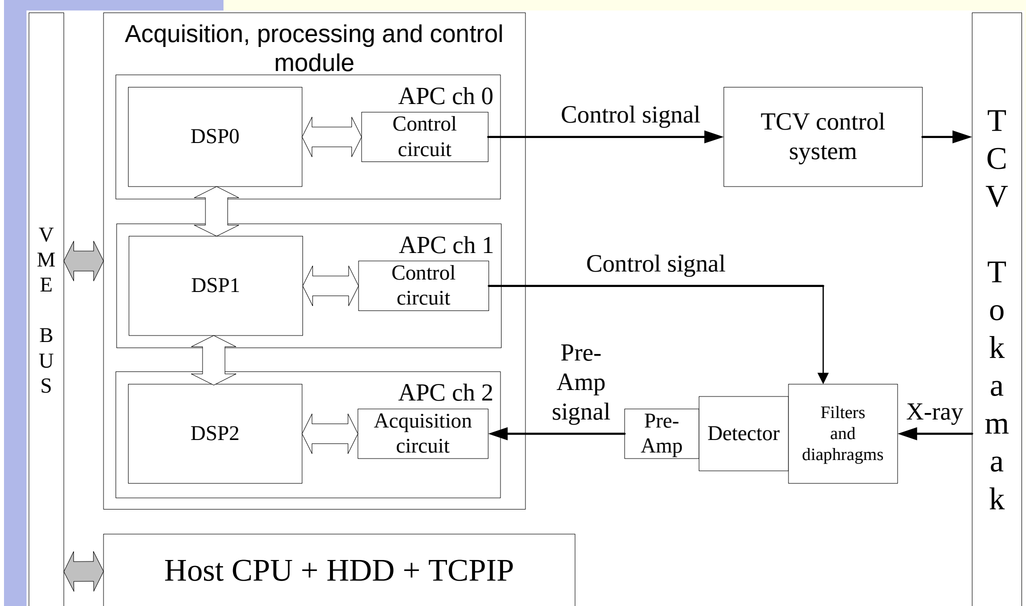
Real-Time Pulse Height Analysis X-Ray Diagnostic

TCV Diagnostic composed by detector, amplifiers and data acquisition system (multichannel analyser or transient recorder + software for data analysis).

Off-line capabilities:

- Determination of average plasma electron temperature
  - a) during the discharge (single value)
  - b) in several periods of the discharge (increasing the discharge duration and X-ray intensity).
- Identification of plasma impurities.



CFN's intelligent module allowed:

- **Real-time measurements** each 100 ms (300 kcounts/s)
- **Pile-ups avoidance** (real-time adjustment of diaphragm between plasma and detector).
- **Real-time control** of the gyrotrons used for plasma auxiliary heating

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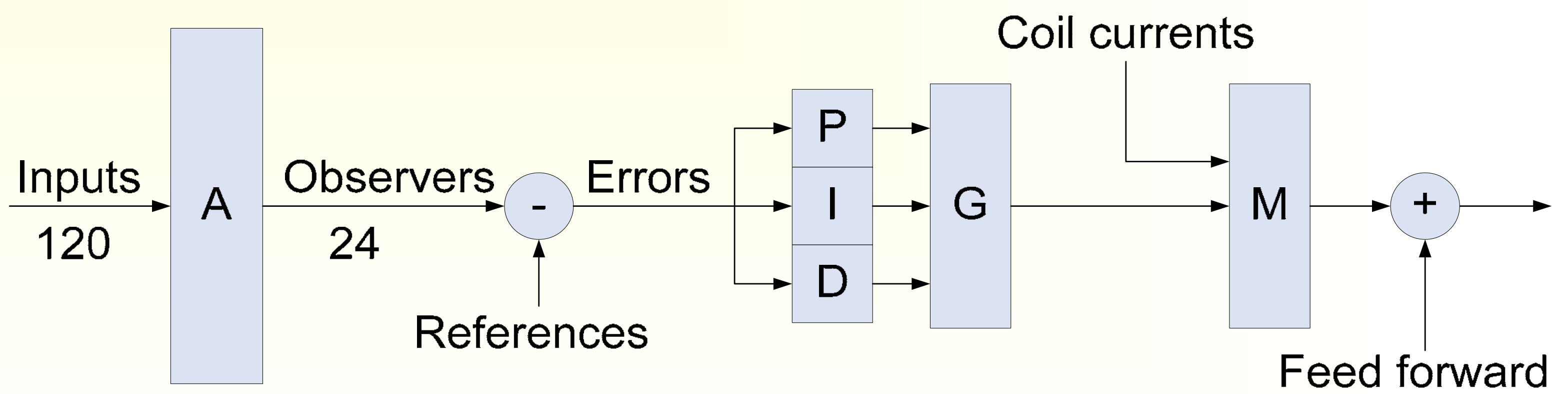
TCV Advanced Plasma Control System

TCV plasma control system had some limitations since was mainly based on analogue components:

(i) A, G and M matrices are based on analogue I/O, with digital coefficients provide by fixed gain PID (Programmable Integral Differentiator) controllers;
(ii) No real-time programming capability;
(iii) Only linear control algorithms could be implemented.



Reducing these limitations was particularly important to enhance the exploitation of a device designed for the study of plasma control in different plasma configurations.

TCV Advanced Plasma Control System

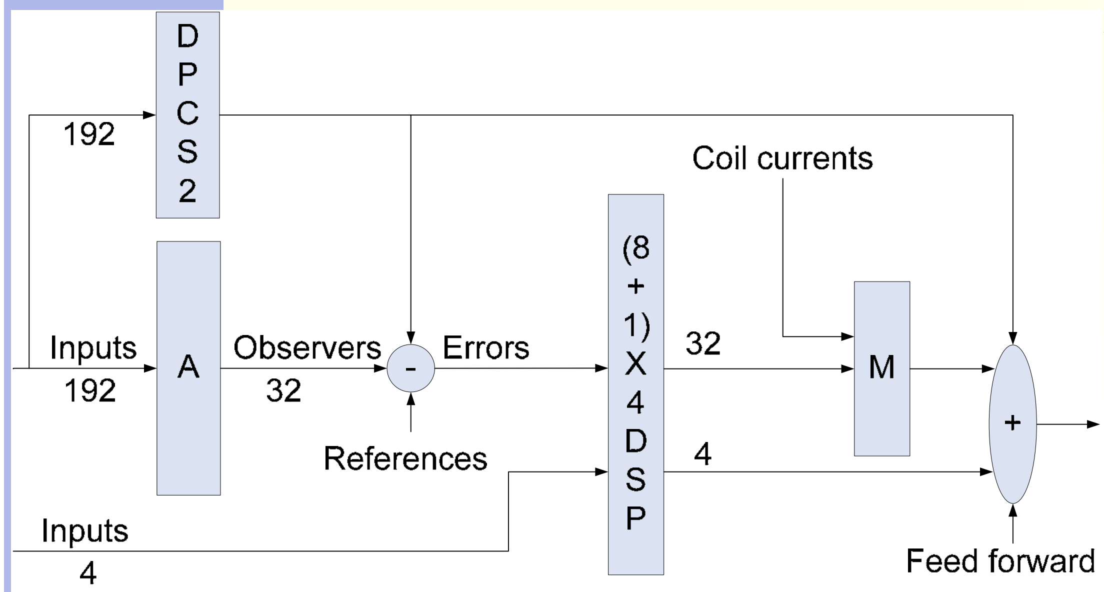
CRPP's new digital system based on CFN VME intelligent module

Designed for real time plasma control and event detection:

a) Slow control cycle of 25 μs for the electron cyclotron heating systems, plasma shape and current and gas injection system;

b) Fast control cycle of 5 μs for the plasma vertical position

c) Possibility of remote operation and modifications of the control parameters with the system powered on.



Architecture:

a) Mixture of analogue and digital matrices;

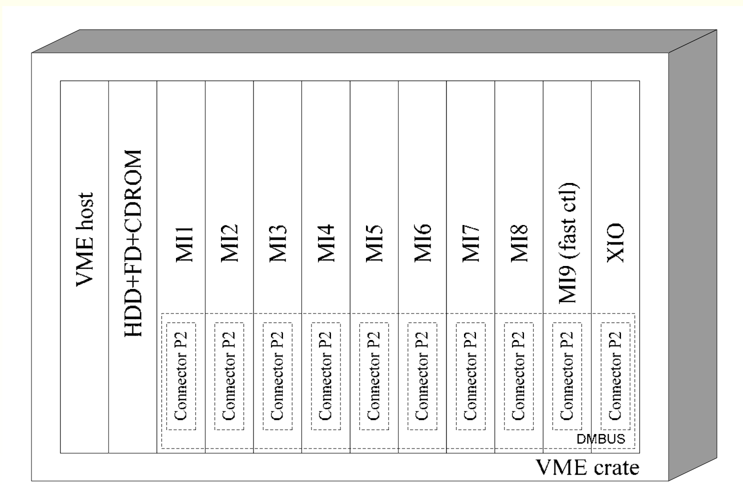
b) Replacement of PID controllers and G matrix by 36 interconnected DSPs;

c) DSPs running fast feedback control algorithms.

d) Each of 4 DSPs calculates a set of the output variables

TCV Advanced Plasma Control System

- The slow control has been implemented by 32 DSPs in 8 modules.
- The fast control has been implemented in 4 DSPs of one module
- Specially developed for this application:
  - -1 Extra digital inputs and outputs (XIO) board.
  - -1 DataMover bus (DMBUS) board.



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Real-Time Control Systems Test-Bench for JET

- Tests the operation of a real-time control system/tool:
  - Stimulates the inputs with the previously stored plasma variables or user defined waveforms
  - Simultaneously records the output variables

- Non-intrusive test method
  - Does not harm the machine to be controlled by unstable on-test control systems;
  - Permits to test all possible operation scenarios;
  - Allows faster test duty-cycles.

- First version of the system implemented in PCI:
  - 32 channels analogue stimulus generator;
  - 8 channels transient recorder;
  - Signals and parameters of previous experiments retrieved from a MDSplus server;

Towards the future:
Unified RT Control Data Acquisition & Hardware Platform

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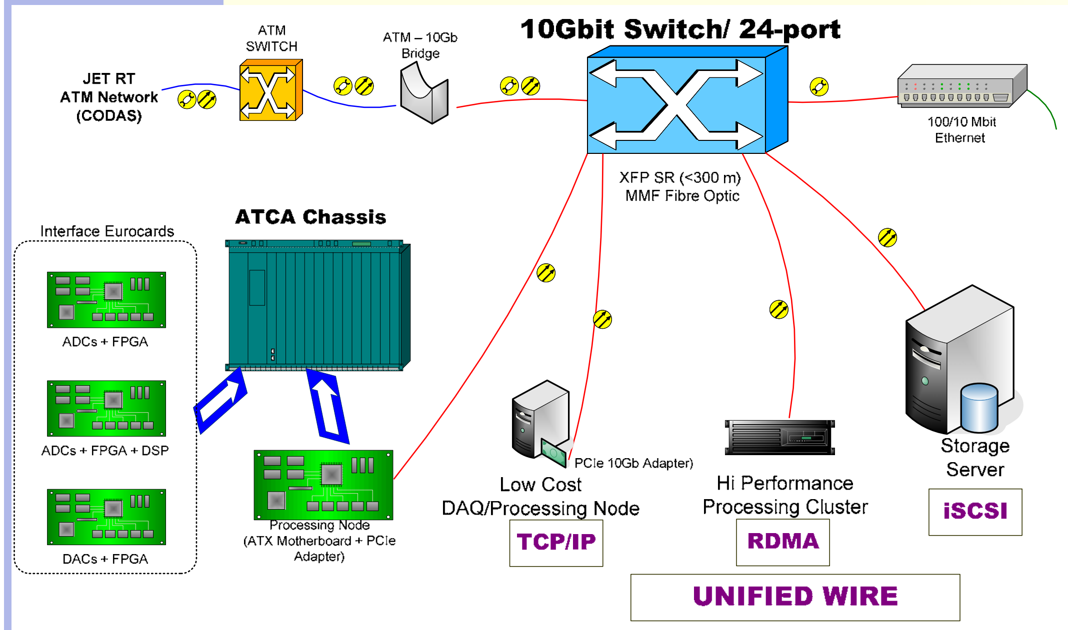
- Distributed signal acquisition, data routing, data processing, and signal generation
- All units connect through low-latency gigabit serial links
- Control cycles under 10 µs
- Sub-microsecond transport of signals and events



- Time synchronization over the 10 Gb Ethernet and PCI Express links
- Plug-n-play – each node provides a description of its features (XML)
- Standards compliant hardware
  - ATCA (Advanced Switching Computer Architecture)
  - PCI Express
  - 10Gb Ethernet with TCP/IP Offload Engine TOE

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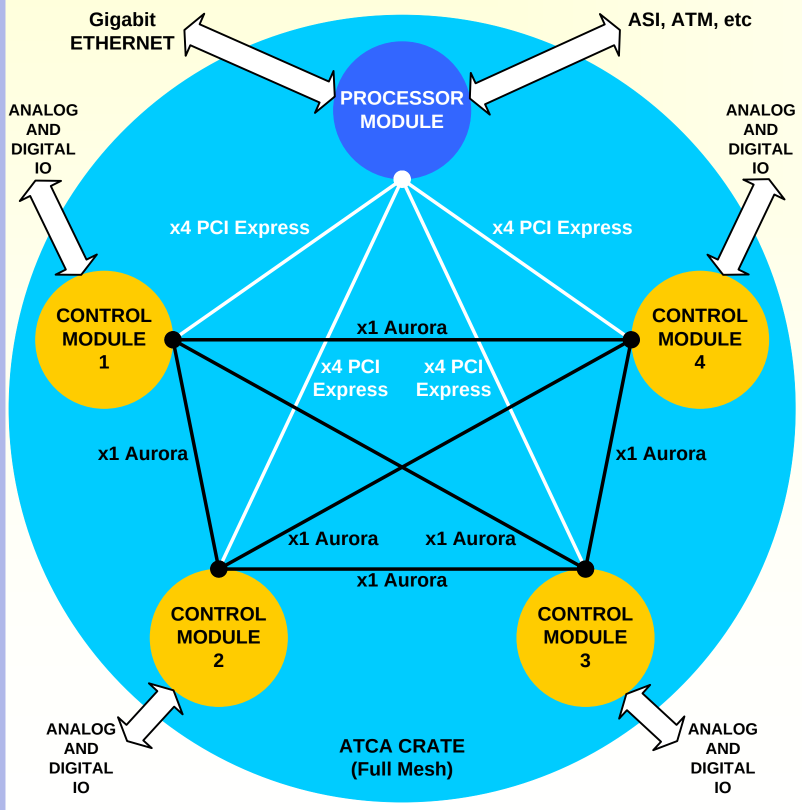
JET Vertical Stabilisation Upgrade

Vertical Stabilization Controller (input signals > 50):

• x86-based ATCA controller

• up to 12 DGP cards (PCIe links through the ATCA full mesh backplane)

• parallel execution on FPGAs for MIMO signal processing (Control loop delay < 50 μs, aim < 10 μs)



Specifications:

• Reduce delays on acquisition/generator endpoints and data interconnect links.

• High processing power near acquisition/generator endpoints and system controller.

• Synchronism of all digitizer/generator endpoints.

• Maintainability, upgradeability and scalability.

• Low cost per channel.

• Low risk of implementation and testing.

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FireSignal – Data Acquisition and Control System Software

- Highly generic Control and Data Acquisition System
- Provides a standard for hardware description
- Integration of new hardware in a plug and play, XML based, philosophy
- Remote hardware configuration through intuitive forms
- Easy access to acquired data by authorized personal
- Remote participation from anywhere in the world
- Personalized data viewers for different data types through a plug-in system.
- Data sharing between users
- Integration of any kind of database
- Implements a generic security access schema

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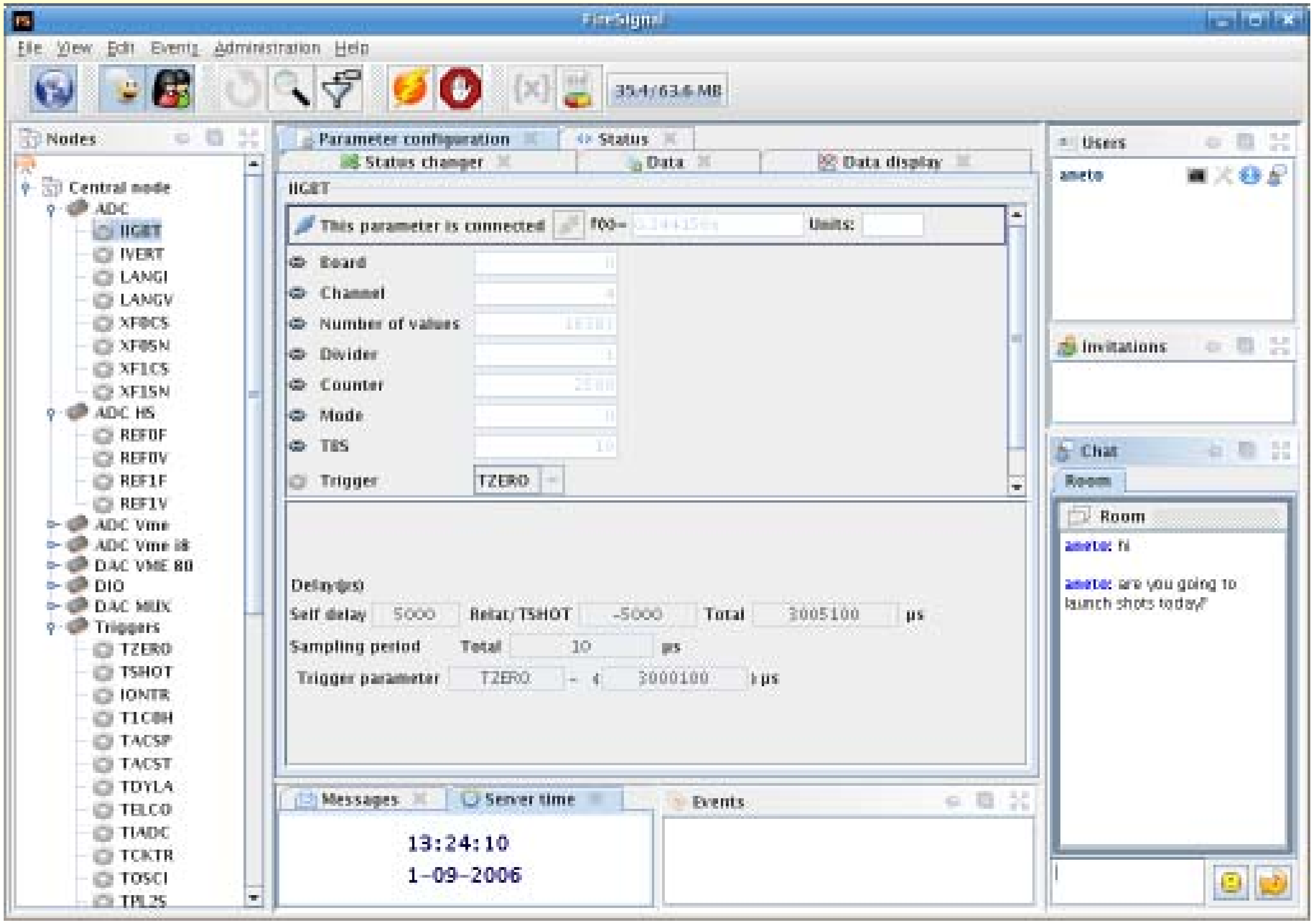
FireSignal – Data Acquisition and Control System Software

Successfully used at ISTTOK, ETE (Brazil) and CASTOR. Under tests at TCA/Br



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Shared Data Access System (SDAS)

- Provides a valid alternative for data indexing. Using events and time-stamps the system is prepared for the challenges of the near future, maintaining backward compatibility with the solutions of the past.
- SDAS libraries are easily integrated in programs such as MatLab, Mathematica and IDL, allowing users to retrieve data with only a few lines of code;
- Each experiment has a SDAS server where the software layer runs;
- A software layer provides the same data accessing functions in all experiments;
- The server communicates and translates the queries to the experiment's data ;
- The system was designed to be as generic as possible and can be adapted to any data storage mechanism.

Shared Data Access System (SDAS)

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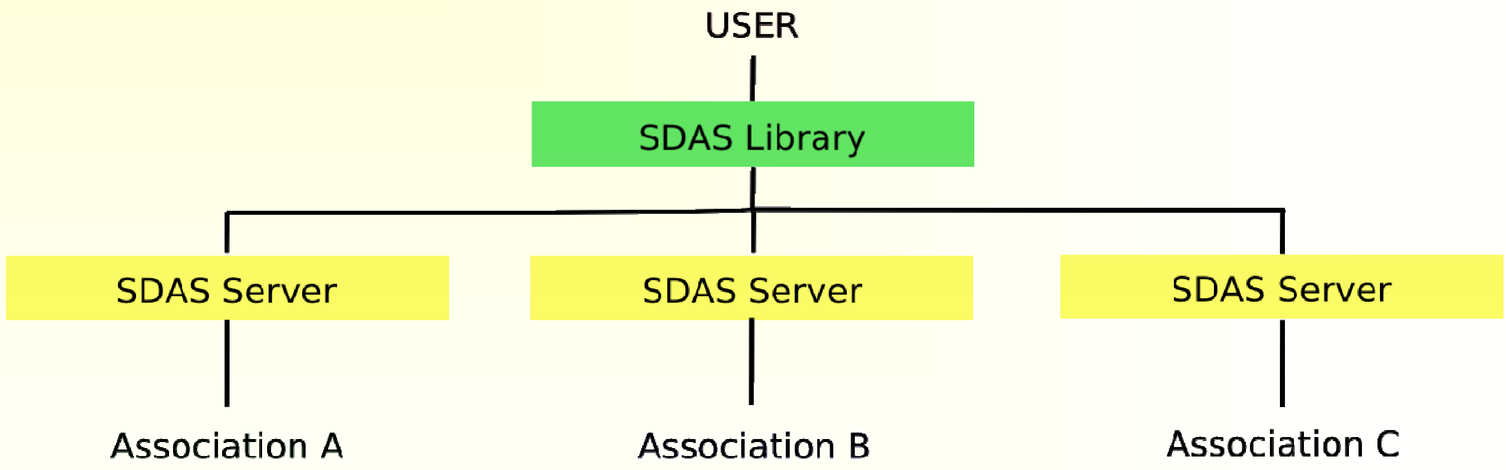
Allows scientists to focus only on data analysis without having to worry about data access procedures. The user's codes do not need to be changed to fit the host laboratory needs;



Data indexed by events and not by shot number (a shot number can also be seen as an event)

$\Rightarrow$ **Crucial for long-pulse operation (e.g. ITER)**

The way forward: Advanced Control system for COMPASS-D

The development of a control and data acquisition system for COMPASS-D represents an opportunity to test ITER relevant solutions

The following areas are relevant for testing at COMPASS-D as an ITER model

- Generic Plant Systems
- Self-description of Plant Systems
- Supervisory Control System, automation and remote requests
- Pulse schedule, editing and validation
- Data naming and data access

CFN developments address already some of these needs

CFN participation will build on previous developments towards ITER relevant solutions

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Summary

ITER Control and data acquisition will be challenging

Advanced Real-time control systems will be necessary and have to be timely developed

CFN has been actively involved in developing innovative control and data acquisition systems for several fusion devices

Some CFN developments approach ITER needs

CFN will extensively test the remote access tools in the 3rd Joint Experiment in ISTTOK organized in collaboration with IAEA (October 2007)

New machines (or enhancements of the existent) represent crucial opportunities to explore new concepts compatible with ITER requirements

CFN's future work will build on previous developments towards ITER relevant solutions

CFN (Association EURATOM/IST): a meaningful contribution

- Advanced Plasma Control Systems
- Fast Timing and Event Management System
- Shared Data Access System
- Generic Control and Data Acquisition System
- Hybrid (transient recorders and waveform generators) intelligent modules for CAMAC, VME, PCI, PCIe and ATCA standards;
- Unified RT Control Data Acquisition & Hardware Platform
- New concepts of data transmission and networks
- Remote operation
- Real-Time Control Systems Test-Bench
- Parallel processing techniques

Integration into small, medium and large fusion devices

Broader outreach by establishing new links with different plasma physics and fusion communities benefiting from IAEA activities