ATCA Advanced Control and Data acquisition systems for fusion experiments

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Abstract– **The next generation of large-scale physics experiments will raise new challenges in the field of control and automation systems and will demand well integrated, interoperable set of tools with a high degree of automation. Fusion experiments will face similar needs and challenges. In nuclear fusion experiments e.g. JET and other devices, the demand has been to develop front-end electronics with large output bandwidth and data processing, Multiple-Input-Multiple-Output (MIMO) controllers with efficient resource sharing between control tasks on the same unit and massive parallel computing capabilities. Future systems, such as ITER, are envisioned to be more than an order of magnitude larger than those of today. Fast-control plant systems based on embedded technology with higher sampling rates and more stringent real-time requirements (feedback loops with sampling rates > 1 kHz) will be demanded. Furthermore, in ITER, it is essential to ensure that control loss is a very unlikely event thus more challenging will be providing robust, fault tolerant, reliable, maintainable, secure and operable control systems. ATCA is the most promising architecture to substantially enhance the performance and capability of existing standard systems providing high throughput as well as high availability. Leveraging on ongoing activities at European fusion facilities, e.g. JET, COMPASS, this contribution will detail the control and data acquisition needs and challenges of the fusion community, justify the option for the ATCA standard and, in the process, build-up the case for the need of establishing ATCA as an instrumentation standard.**

I. INTRODUCTION

THE next generation of large-scale physics experiments will, raise new challenges in the field of control and automation systems and demand well integrated, interoperable set of tools with a high degree of automation [1]-[3]. New projects prominently feature solutions adopted from other laboratories [4], hardware and software standards and industrial solutions [5]. Modern physics experiments, e.g. LHC, ITER [6], are expected to deliver and process data at a rate of up to hundreds GBytes/s. R&D activities target self-triggered front-end electronics with adequate output bandwidth and data processing [6], Multiple-Input-Multiple-Output (MIMO) controllers with efficient resource-sharing between control tasks within the same unit [8] and massive parallel computing capabilities. The experimental control and data acquisition systems are distinguished from commercial systems by the significantly greater amount of I/O resources required between computational elements, as well as the unique and disparate I/O requirements imposed on their interfaces. Although both architectures have some similarities between them, commercial systems will only meet the basic requirements for advanced physics control systems, while Control and Data Acquisition systems are custom built to cater for those demands. Future systems are envisioned to be at least an order of magnitude larger than those of today. The biggest challenge will be providing robust, fault tolerant [9], reliable, maintainable, secure and operable control systems [10].

Convergence of computer systems and communication technologies yielded high-performance modular system architectures on based on high-speed switched interconnections. Simultaneously, traditional parallel-bus system architectures (VME/VXI, cPCI/PXI) are evolving to new higher-speed serial switched interconnections [11]-[13]. Traditional bus architectures have a relatively straightforward programming model, but are less effective in multiprocessor systems, especially when a low-latency, deterministic response is required. Bandwidth is one limitation of bus implementations, but even more important is contention between multiple processors for use of a shared bus. Predictable, deterministic response times are not possible when concurrent processors must wait to access a bus. Switch-fabric architectures offer a much better basis for multiprocessor systems, and provide several performance and usability benefits. Several high-performance switch-fabric standards have been developed. PCIexpress, 10 Gigabit Ethernet, and RapidIO are the most viable choices for high availability and high-speed applications, offering better overall backplane throughput with low-latency and deterministic delay.

II. CONTROL AND DATA ACQUISITION SYSTEMS FOR FUSION DEVICES

Real-time control of magnetically confined plasmas is a critical issue for the safety, operation and high-performance scientific exploitation of the experimental devices on regimes beyond the current operation limits [14]-[15]. The important and increasing role that real-time control is playing in the operation of fusion experiments is mainly due to the need to optimize plasma performance. For this optimization, adequate feedback-control processes, using an increasing number of plasma parameters, are demanded [16]. Active feedback control systems are used to control global plasma parameters such as plasma position, shape, heating, current drive,

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stabilization, and start-up and safe termination of discharges [17]. Furthermore, considerable effort is being made to enhance plasma confinement and achieve the so-called Advanced Tokamak regimes [18]. Such regimes are characterized by simultaneous high plasma pressure, long energy confinement time and non-inductively driven plasma current with a significant fraction provided by the self-generated bootstrap current. These steady-state configurations involve multiple fast-feedback loops. The feedback controls which act on global plasma parameters may use up to hundreds of inputs and take response time to control phenomena which evolve with time constants from tenths of microsecond to hundreds of millisecond, while controls acting on local parameters generally use fewer input signals but require response times of hundreds of millisecond [19]. For plasma instabilities with rapid rates of growth a very fast and low-latency response is necessary to combat its effects. In these cases the fast response times are measured in microseconds, thus the low-latency requirements of the real-time control systems are extremely important, e.g. resistive wall modes [20] and neoclassical tearing modes (NTMs) [21]. Current trends in fusion also indicate that future experiments will need intelligent and robust control and data acquisition systems due to their long duration pulses. The number of parameters and data volumes, used for plasma properties identification, scale normally not only with the machine size but also with the technology improvements, leading to a great complexity of the plant system. A strong computational power and fast communication infrastructure are needed to handle in real-time this information, allowing just-in-time decisions to achieve the fusion critical plasma conditions. These advanced control systems require a tiered infrastructure, including the hardware layer, signal-processing middleware, real-time timing and data transport, real-time operating system tools and drivers, the framework for code development, simulation, deployment and experiment parameterization and the human real-time plasma condition monitoring and management. Also, the increase of discharge duration towards steady-state operation forces the implementation of new philosophies of control and data acquisition [22]. These pulses may generate a massive amount of data that needs to be reduced and/or tagged before being stored in the database and usage of several specialized diagnostics, acquiring data only when particular phenomena occur, may be considered.

In addition, during tokamak operation hundreds of subsystems must operate correctly and simultaneously and, in modern tokamaks, the Plasma Control System is no longer expected to be only a plasma control tool, but has become an operation supervisor [23]. The control part of the system must be able to continuously monitor and control plasma activity, independently of the data acquisition part. Demanding safety procedures are required to operate close to unstable regimes and on not yet explored parameter ranges [24]. For that reason it is crucial to develop hardware which is less prone to faults and promote the usage of fault detection and isolation techniques.

These features are considerably hard to implement within existing control systems. The successful development of advanced operational regimes depends strongly on the architecture and processing capacity of the installed control system. Past developments for different fusion devices targeted different technologies (VME, PCI, ATCA), e.g. JET [47]-[48], COMPASS [49]-[49], TCV [51]-[55], MAST [56]-[57], ISTTOK [58].

A modern real-time control system for plasma control must be faster and demands larger computation power; besides it needs an intelligent strategy for real-time decision making which is only achievable by a digitally programmable system. The data acquisition and control tasks in the first feedback control systems have been carried out by separate digital hardware platforms, while the signal processing algorithms ran in the host CPU and data was exchanged using the instrumentation bus. Aiming at decreasing the control cycle, increasing the computing power and dealing with large amounts of raw data, the new generation of real-time control systems are based on intelligent modules that can perform with high efficiency the data acquisition, signal processing and control tasks. Taking into account the requirements for control and automation requirements of fusion experiments, a unified real-time control and data acquisition hardware platform is envisaged [46]. JET projects have been the stepping stones to develop this broader user base platform. At JET, the option towards ATCA was driven by the need to reduce the vertical stabilization digital control loop-cycle (down to 10 μs) and to improve the MIMO algorithm performance. Aurora and PCI Express communication protocols allow data transport between modules with expected latencies below 2 μs. For future experiments, e.g. ITER, MIMO controllers will be crucial for successful operation [59].

III. ITER

ITER is one of the best examples of globalization of science technology. This experimental magnetic confinement fusion device will be in most aspects similar to present tokamaks except for its size and energy content which imposes several restrictions to its operation. Furthermore, ITER is a nuclear facility and its operation demands an approach to safety which is not explored in present devices. Developing the ITER CODAC (Control, Data Acquisition and Communications) will be a challenging endeavour. It will be responsible for the orchestration of over 150 Plant Systems comprising 40 CODAC systems, one million of diagnostic channels, 300000 slow-control channels and 5000 fast-control channels. One single discharge, which can range from 400 seconds to one hour duration, will produce a data rate of about 5 Gb/s of data. This quasi-continuous operation demands technical solutions for data streaming, continuous storage and experimental data access during a pulse, also underlining the need for the development of intelligent data acquisition strategies based on real-time data processing. However, among ITER's major concerns is the requirement of a far higher level of availability and reliability than previous/existing tokamaks, in particular because the lost investment of a single prematurely aborted pulse or even a damaging event such as a disruption is very high. Redundancy is a key word for ITER systems, both on the networks involved on the device operation and on critical hardware.

Commercial technology and industrial standards will likely meet the basic requirements on which physics experiments such as ITER can leverage for building future control systems. But, more challenging will be providing robust, fault tolerant, reliable, maintainable, secure and operable control systems. ITER CODAC's Conceptual Design foresees fast control plant systems based on embedded technology with higher sampling rates and more stringent real-time requirements (feedback loops with sampling rates > 1 kHz). To attain the requirements of a MIMO architecture the hardware shall achieve a reduction of loop delay on the signal acquisition/generation endpoints, both on the data interconnect links from and to the processing unit and on the analogue signal path (analogue filters). Such reductions are only possible by having high processing power both on the acquisition/generator endpoints and on the system controller. Since fast-feedback control loops are expected, the synchronization of all digitizer/generator endpoints is also crucial. Furthermore, modern nuclear fusion experiments demand architectures designed for maintainability, upgradeability and scalability while targeting the specificities of the plasma controllers at low cost per channel. With the fast progression in the fusion community it is also essential to ensure a low-risk of implementation and testing of the systems.

Another key issue in a large-scale infrastructure such as ITER is the necessity to easily deploy and integrate systems with different degrees of complexity and provenience. The solution envisaged for this problem is enhanced by self-description of each system using structured data [60]-[61]. This procedure facilitates acceptance, commissioning, and integration of functionality at the remote production sites, while it also facilitates fault-recovery functions during operation and maintenance. Using an abstract description for the hardware interface (Plant system host - PSH), the development efforts are not replicated and the interfaces can be reused on other sub-systems.

IV. ATCA FOR PHYSICS APPLICATIONS

ATCA is the most promising architecture to substantially enhance the performance and capability of existing standard systems as it is designed to handle tasks such as event building, feature extraction and high-level trigger processing. It is the first commercial open standard designed for high throughput and availability (HA). The high-throughput features are of great interest to data acquisition physics, while the HA features are attractive for high up-time experiments. The ATCA standard [25] was originally conceived to specify a carrier grade-based system infrastructure for telecommunications. It was built from the ground up to support a wide range of processors. Compared to the VMEbus which was conventionally used in data acquisition systems, the ATCA standard offers advantages especially with respect to communication bandwidth and shelf management. The ATCA carrier-blade form factor supports well-balanced systems, delivering teraOPS of processing power in a single sub-rack. The architecture is flexible as to the types of processors that can co-exist in the system. One of the most critical aspects of implementing the ATCA architecture is the ability of high-performance blades to communicate with each other, so that vast quantities of data can be moved from board to board through the switch fabric within an ATCA system.

TABLE I. COMPARISON OF TECHNICAL FEATURES BETWEEN ATCA AND ITS DIRECT COMPETITORS

	ATCA	VPX	cPCI Express
Dimensions	8U	3U and 6U	3U and 6U
Nr analogue channels (front panel)	32	16	16
Fabric	Agnostic	Agnostic	PCI Express
Backplane	Full-mesh	Full-mesh	star
RTM	Yes	Yes	Yes
Mezzanines	Yes	Yes	Yes
Power dissipation/ slot	200 W	Shelf dependent	Shelf dependent
Redundant power supplies	Backplane level	External	External
Redundant cooling fans	Yes	No	No
Hot swap	Yes	Yes	Yes
Shelf management	Redundant IPMI	IPMI	IPMI
EMC shielding	Yes	Yes	Res
Availability	99.99%	-	-
Foreseen main application	Telecom industry	Military	industry

The ATCA platform is gaining traction in the physics community [26] because of its advanced communication bus architecture (serial gigabit replacing parallel buses), high availability n+1 redundancy, variety of form factors, very high data throughput options and its suitability for real-time applications [27]. Active programs are showing up most notably at DESY for XFEL [28]-[30] and JET [31] but also at other laboratories such as ILC [32]-[33], IHEP, KEK, SLAC, FNAL, ANL, BNL, FAIR [34]-[35], ATLAS [36] at CERN, AGATA [37]-[38], large telescopes [39] and also Ocean Observatories [40]. Both the CMS and ATLAS detectors are investigating ATCA solutions for future upgrades and ILC and ITER are setting up prototype experiments to test its potential. Most of these programmes put the emphasis on High Availability. In ITER, for example, ATCA is being considered for its performance but also because the systems will be located in areas of difficult access during operation.

To progress further it is essential to set up a more formal "ATCA for Physics Applications" collaboration between laboratories and industry to achieve broad sharing of information and interchangeability of module designs. ATCA has superior technical features (table I), for large physics experiments, than its strongest competitors VPX [41] and CPCI Express [42]. If an ATCA extension for instrumentation (xTCA for Physics) succeeds to appear in a short period of time, the ATCA will continue to have advantages over VPX and CPCI Express in spite of the associated evolution of VXI and PXI instrumentation.

V. DEVELOPING ATCA SYSTEMS FOR FUSION EXPERIMENTS

The JET Vertical Stabilization project [8] provides a good example where demanding requirements from a fusion experiment (JET) have driven the adoption of ATCA-based solutions. Elongated plasmas are vertically unstable, leading to loss of control if plasma reaches the vessel protecting tiles provoking considerable heat loads on JET's plasma facing components [43] . Therefore, dedicated MIMO systems are designed to make the plasma vertically stable allowing other controllers to successfully control the plasma position and shape. While at JET, a Vertical Displacement Event (VDE) can generate disruptions with a reduced impact in the machine, in ITER the loss of vertical plasma position control will cause thermal loads on Plasma Facing Components of 30-60 MJ/m^2 for ~0.1s. With the present knowledge, the Plasma Facing Components cannot be designed to sustain such (repetitive) thermal loads. Furthermore, VDEs also generates the highest electromagnetic loads: (i) A phenomenological extrapolation of horizontal forces from JET's worst cases implies horizontal loads ~45MN on ITER's vacuum vessel; (ii) The MHD wetted kink model developed to simulate the horizontal loads predicts ~20MN; and (iii) Vertical loads ~90MN. This leads to the conclusion that the plasma vertical position control in ITER must be robust and reliable to ensure that vertical plasma position control loss is a very unlikely event [43]. Therefore, JET project already had these stringent demands into consideration. In its specification it was required to aim at a reduction of: (i) the loop delay on the signal acquisition/generation endpoint (down to 10 µs); (ii) the data interconnect links from and to the processing unit; (iii) the analogue filter electrical path. It was also required high processing power on the acquisition/generator endpoints, on the system controller and for the improvement of the MIMO algorithm performance. The synchronization of all digitizer/generator endpoint was also required. There was a strong emphasis on choosing an architecture designed for maintainability, upgradability and scalability at a low cost per channel.

A Multi-Input-Multi-Output controller for the plasma Vertical Stabilization (VS) was implemented and installed on the JET tokamak. The system currently attains a control loop-cycle time of 50 µs using x86 multi-core processors but targets 10 µs via FPGA-based processing. The hardware, complying to the Advanced Telecommunications Computing Architecture (ATCA) standard, was specially designed to achieve such a performance [31] mindful of its suitability for ITER's needs. It consists of: (i) a total of 6 synchronized ATCA control boards, each one with 32 analog input channels, which provide up to 192 galvanically isolated channels, used mainly for magnetic measurements (Fig. 1). (ii) Each board contains 512 MBytes of DDR memory and an FPGA, which performs digital signal processing and includes a PCI Express communications interface; (iii) An ATCA Rear Transition Module, which comprises up to 8 galvanically isolated analog output channels for controlling the Fast Radial Field Amplifier (±10 kV, ±2.5 kA); (iv) An optical link to allow the digital control of the Enhanced Radial Field Amplifier (±12 kV, ±5 kA); (v) Up to 8 EIA-485 digital I/O channels for timing and monitoring information; (vi) An in-house developed ATCA processor blade~~,~~ with a quad-core processor, where the control algorithm is presently running, connected to the 6 ATCA control boards through the PCI Express interface. All FPGAs are interconnected by low-latency links via the ATCA full-mesh backplane, allowing all channel data to be available, in the control cycle, on each FPGA running an upcoming distributed control algorithm.

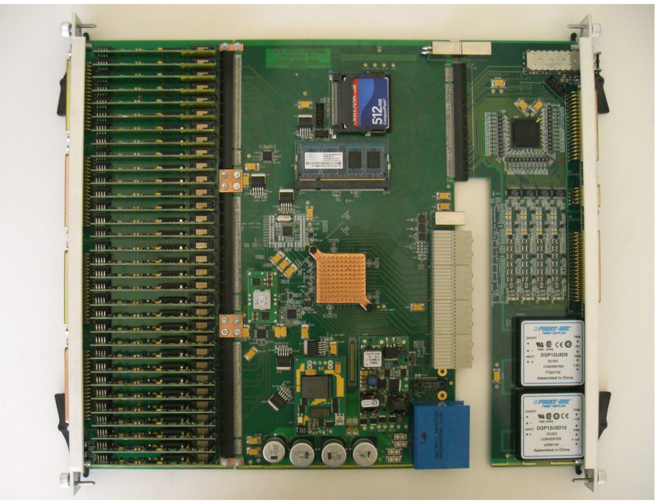

Fig. 1. IPFN´s ATCA-MIMO-ISOL card with 32 ADCs, 8 DACs and 8 DIO.

Another important requirement of modern data acquisition systems for fusion experiments is the capacity for real-time pulse processing. Such demand is required to reduce the amount of raw data stored in the experimental databases and will become particularly necessary for steady-state experiments such as ITER. An example of implementation of such system is the JET Neutron Camera Data Acquisition system where intelligent modules, along with FPGAs, are used for real-time data processing, e,g. Pulse height analyzer, pile-up rejection and pulse shape discriminator. The developed system is based on ATCA and contains a 6 GFLOPS ix86-based control unit and three transient recording and processing (TRP) modules interconnected through PCI Express links. TRP modules feature timing synchronisms, auto-trigger functionality, analysis/data reduction based on real-time algorithms and the possibility to choose from a set of preset sampling frequencies. The system is composed by 21 channels of 13 bit resolution with accuracy equal or higher than 11 bits to cope with the expected signal-to-noise ratio of the input pulses, and sampling rates up to 250MSamples/s, with the possibility to achieve 400 MSamples/s. Each channel will have 500MByte of local memory. The core of each TRP module are two FPGAs, able to perform real-time processing algorithms such as Pulse Height Analysis (PHA) and pile-up rejection of digitized pulses. These will allow data reduction by a factor of at least 8 and, possibly, spectra output in real-time [45].

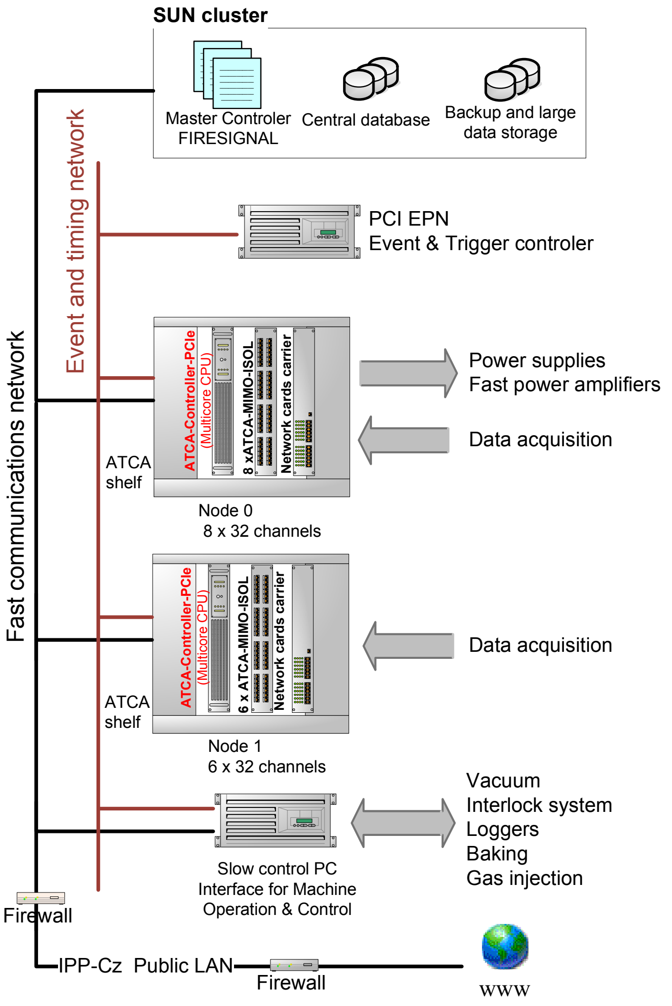

Fig. 2. Schematic of COMPASS tokamak control and data acquisition system. In this system the two ATCA systems are responsible for the fast control of the device and for the data acquisition. The large form factor of the ATCA allows accommodating boards with 32 ADC, 8 DAC and 8 DIO channels per board. In total 14 ATCA-MIMO-ISOL boards (developed at IPFN-IST) will be used.

For the Compass Tokamak, currently being installed in Prague, Czech Republic, its whole control and data acquisition system is being redesigned and built from scratch, based also on the ATCA standard (Fig. 2). The platform contains one ATCA controller with a Gigabit Ethernet interface, up to 12 ATCA Digitizer-Generator-Processor (DGP) cards and trigger and clock inputs, all on a 12U shelf. The multi-core x86-based General Purpose Processor (GPP) controller will be connected to the DGP cards by Peripheral Component Interconnect ExpressTM(PCIe) point-to-point links through the ATCA backplane. MIMO signal processing will be shared by the DGP cards using the built-in FPGA and the controller's x86 general processor. Eleven AuroraTM2.5 Gbit/s links allow further parallelization of the code execution among several FPGAs. In order to guarantee real-time execution of the control codes a framework based on Linux and the Real-Time Application Interface (RTAI) will be used. This will explore the features provided by the new multi-core technologies. Synchronization between the subsystems will be guaranteed by a real-time event network.

The interface to the system will be provided by the FireSignal control and data acquisition system. This will allow the operators and diagnostic coordinators to configure the hardware, prepare the discharges, pre-program events of interest and follow results from the discharge. FireSignal will also orchestrate the data flow coming from the different diagnostics into the database and to registered data clients.

For the previously described nuclear fusion systems the emphasis was put on performance. However, among the major advantages of using ATCA for such a demanding device as ITER, is the fault tolerance provided by the redundancy of power supplies and cooling fans and reliability on the shelf management by the redundant connection for the Intelligent Platform Management Interface (IPMI). It is through IPMI that the system's health is managed, allowing ATCA systems to achieve 99.999 percent high availability (HA) mark. So far, At the moment the potentialities of the IPMI have been disregarded for the nuclear fusion applications. Future developments will address this issue in order to ensure that a loss of plasma control (or loss of valuable experimental data) due to hardware failure becomes a very unlikely event.

VI. CONCLUSIONS

These days, building the best control and data acquisition system is only the price of admission on a very competitive market where several solutions are emerging. For large physics experiments, there are a few strong contenders like the VPX, CPCI Express and ATCA. As the complexity of the experiments increases the differentiating factor relies on the system robustness, resilience to faults, reliability, maintainability, security and operability. Considering the importance of such features for future fusion experiments, namely ITER, ATCA has been successfully used in fusion experiments, e.g. JET and COMPASS, for MIMO fast-control applications. However, in spite of its major advantages, ATCA was developed specifically for the telecom industry. Some issues need to be sorted out for physics applications, being essential a formal collaboration between laboratories and industry to achieve a broad sharing of information and interchangeability of module designs.

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