High-performance instrumentation for diagnostics and control in fusion devices

N. Cruz

On behalf of the Control and Data Acquisition Team*

Instituto de Plasmas e Fusão Nuclear, Instituto Superior Técnico, Universidade de Lisboa, 1049-001 Lisboa, Portugal

*(Coimbra) A. Combo, A. Fernandes, A.P. Rodrigues, B. Santos, M. Correia, N. Cruz, P. F. Carvalho, R. C. Pereira, (Lisboa) A. J. N. Batista, B. B. Carvalho, J. Sousa

Nuclear Fusion

Fusion of light elements like Deuterium and Tritium, hydrogen isotopes

These reactions free energy to obtain more stable nucleus

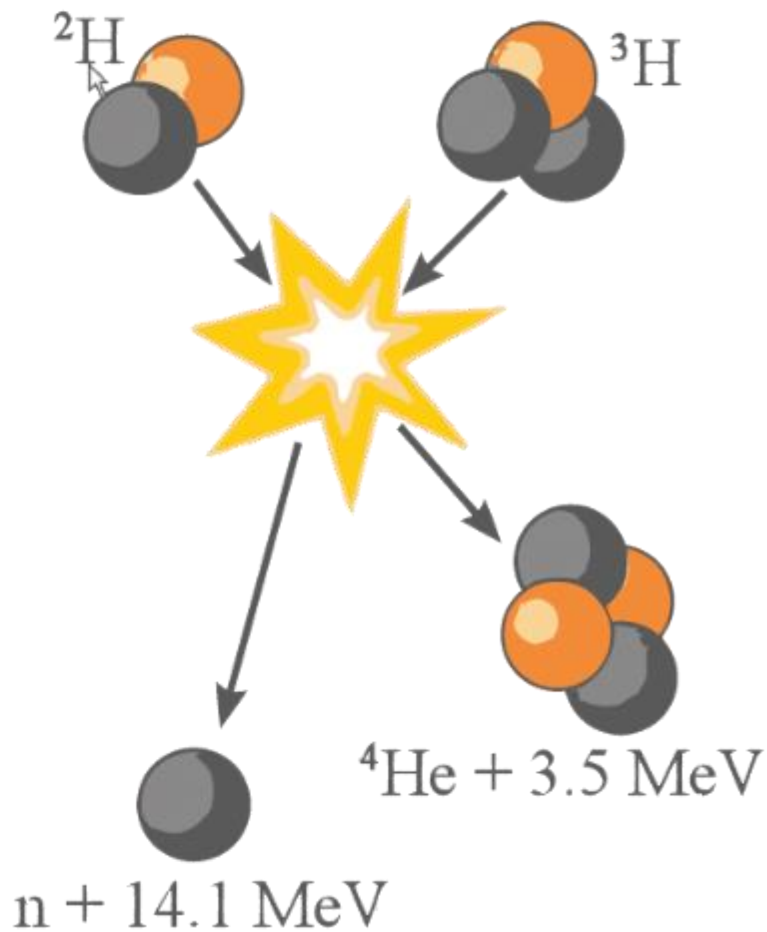
$$E = mc^2$$

$$D + T \rightarrow {}^{4}He + n$$

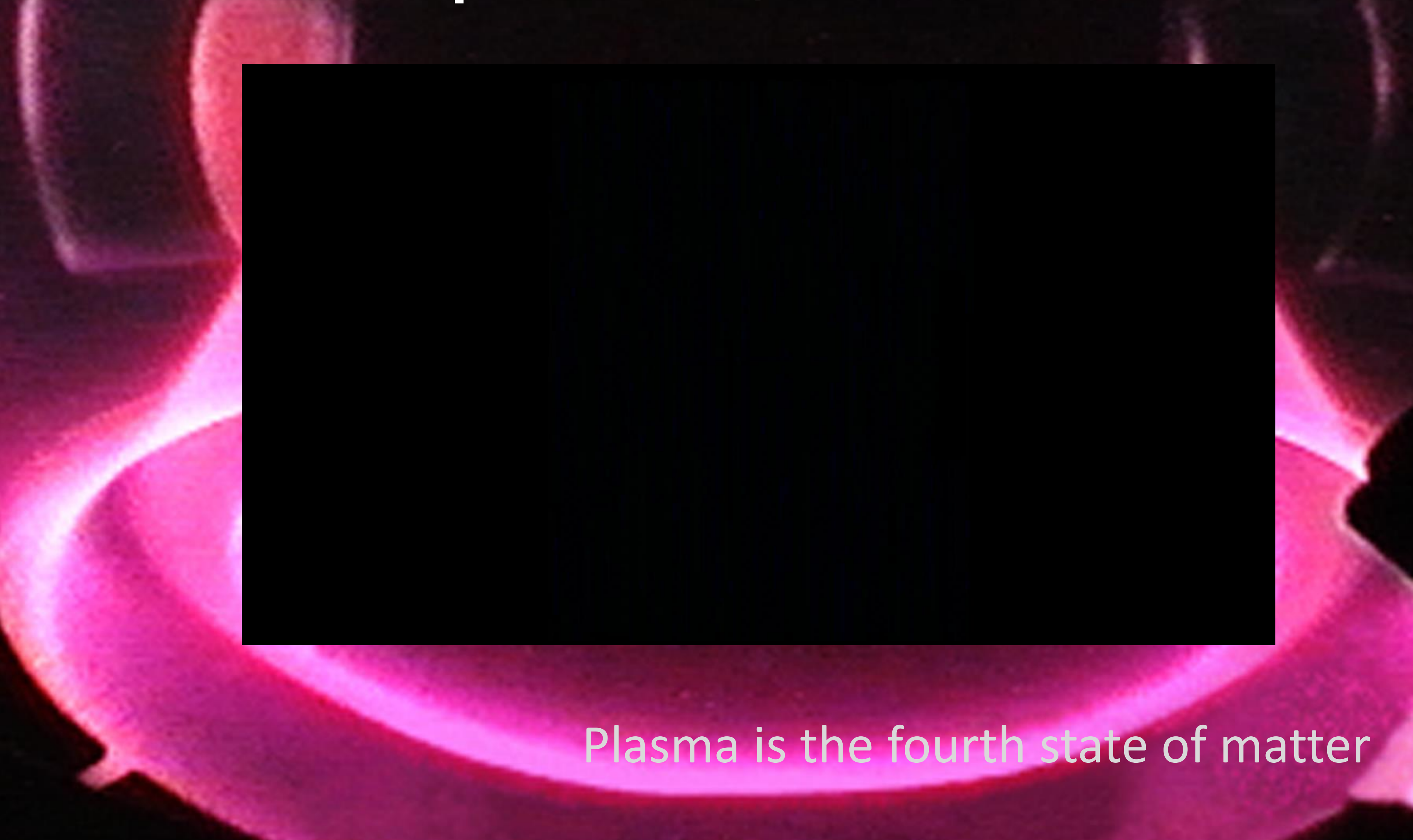
Tritium production

$$ {}^{6}Li + n \rightarrow {}^{4}He + T $$

$$ {}^{7}Li + n \rightarrow {}^{4}He + T + n $$



Fusion is the process occurring within the plasma core of our Sun, and inside the fusion experiments, like a Tokamak



Plasma is the fourth state of matter

Building a fusion device | JET

Vacuum chamber

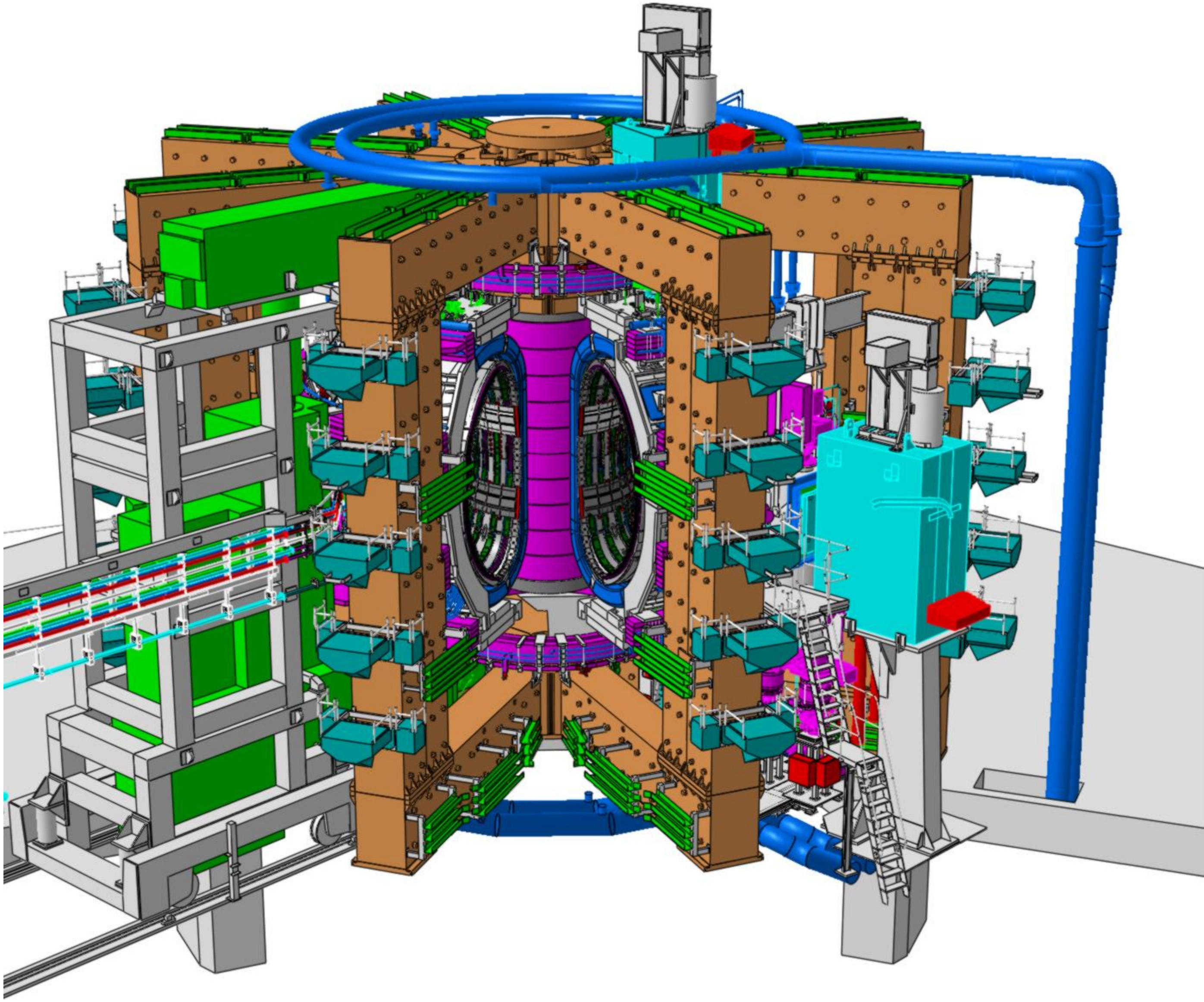
Toroidal coils

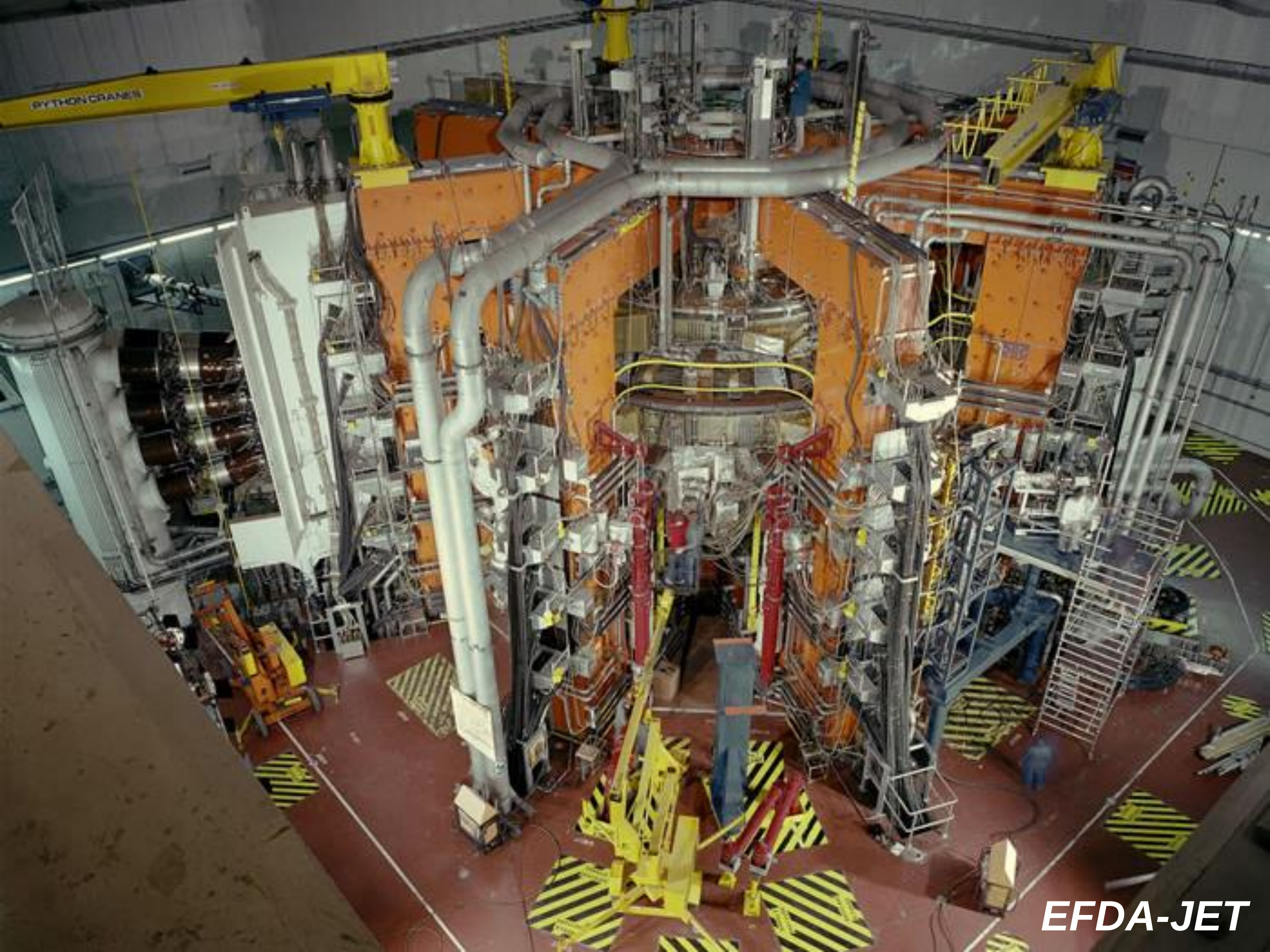
Support structure (2600 tons)

Poloidal coils

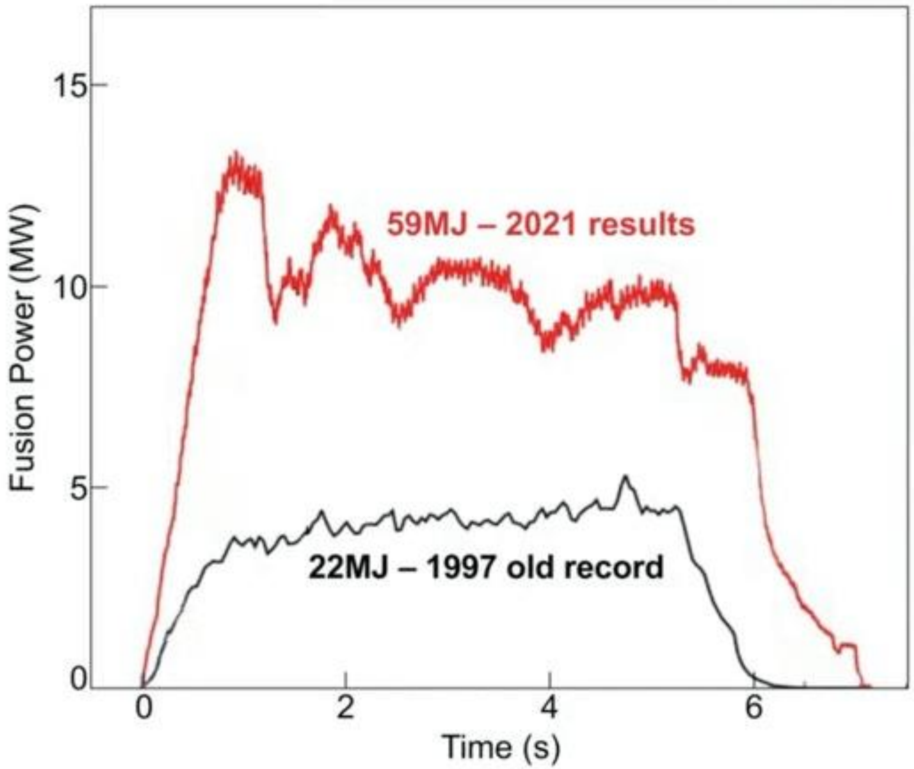
…etc

…. and fast electronics and diagnostics!




PYTHON CRANES
EFDA-JET

JET set new world record



EUROfusion

JET D-T experiments bring fusion energy closer

- We have prepared a new generation of scientists and engineers ready to transfer knowledge and skills to ITER
- We have tested D-T fusion in ITER-like conditions
- We now know more about burning plasma physics
- We have validated the models to extrapolate to the next fusion machines
- We have demonstrated highest ever fusion energy production

TÉCNICO LISBOA ipfn INSTITUTO DE PLASMAS E FUSÃO NUCLEAR

“A nuclear war cannot be won and must never be fought."

Geneva Summit on 19-20 November 1985

Secretary General Mikhail Gorbachev and President Ronald Reagan "emphasized the potential importance of the work aimed at utilizing controlled thermonuclear fusion for peaceful purposes and, in this connection, advocated the widest practicable development of international cooperation in obtaining this source of energy, which is essentially inexhaustible, for the benefit of all mankind." https://www.iter.org/newsline/-/2323

ITER: A Pathway to Fusion Energy

Mission:

Demonstrate the scientific and technological feasibility of fusion power for peaceful purposes

By:

Reaching 500 MW fusion power for >300 seconds with energy gain of 10

Demonstrating 'in-principle' steady-state operation with gain of 5 (>300 MW for up to one hour)

JET	
Size	~8 m
Magnetic Field	<4 T
Current	<4 MA

ITER	
Size	~17 m
Magnetic Field	5.3 T
Current	<15 MA

ITER Organization is responsible to construct and operate the ITER for the Members: China, EU, India, Japan, South Korea, Russia, USA

ITER | Mission

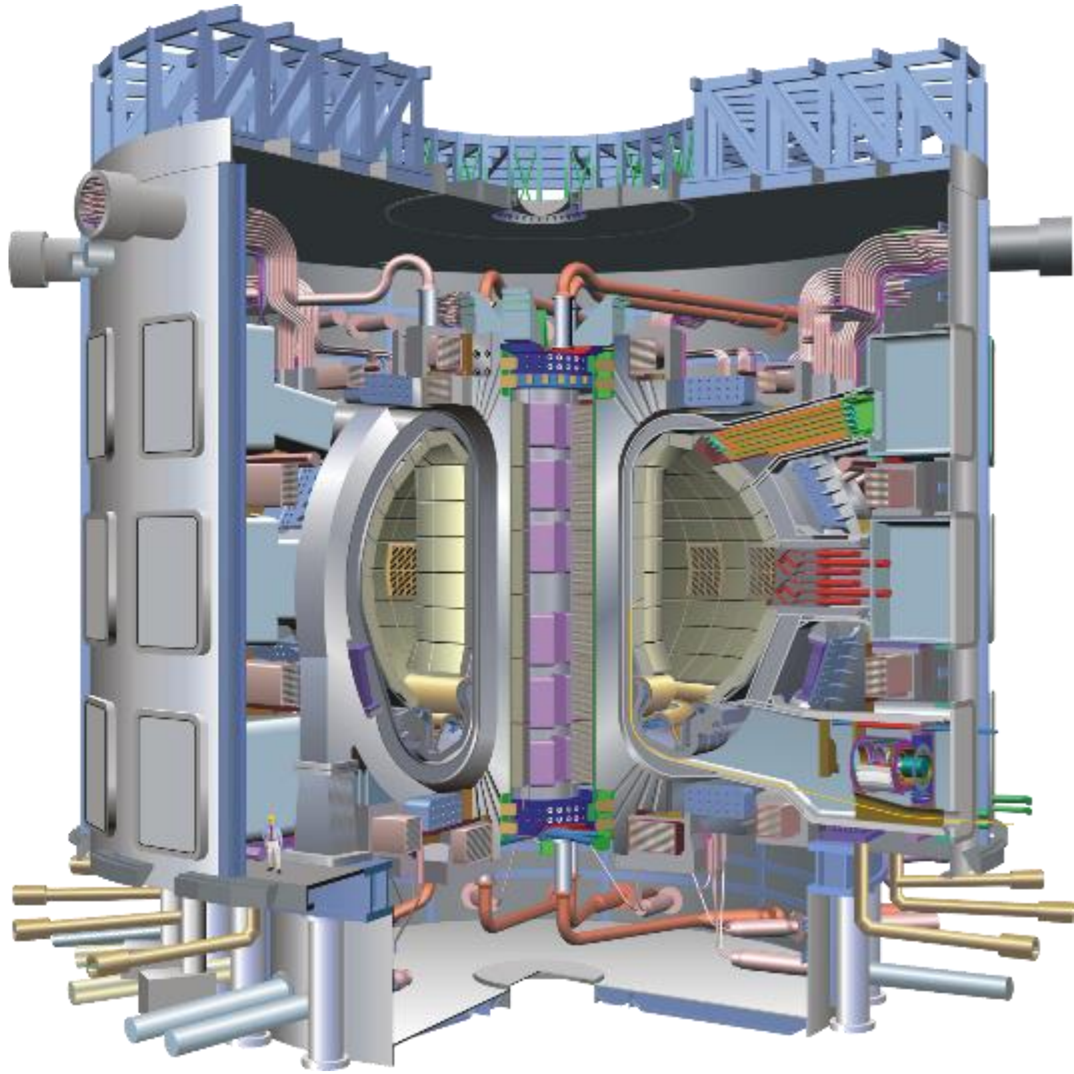
To prove scientific and technical viability of fusion

P = 500 MW

D = 300 s

Q = 10 – 20

To test integration of all technologies required for a fusion power plant



TÉCNICO LISBOA
ipfn INSTITUTO DE PLASMAS E FUSÃO NUCLEAR

ITER site @ September 2013

ITER site @ May 2021

TÉCNICO LISBOA

ipfn INSTITUTO DE PLASMAS E FUSÃO NUCLEAR

ITER “first” plasma

Motivation I&C IPFN Developments

- Fusion steady-state operation requirements
  - Reduced downtime - High availability
  - Redundancy at all possible levels
  - Very high data throughputs
  - Sophisticated remote monitoring, management and control
  - Data integrity at highly performant rates
  - Resilient and safe operation

Table 1
A_I targets per group, with details for “utilities”.

Function group	Main function	Availability for H		Availability for D–T	
		Target	Cumul.	Target	Cumul.
Safety and investment protection		96.1%	96.1%	96.1%	96.1%
Structure and support		95.6%	92.0%	95.6%	92.0%
Utilities					
	To supply Class I, II power	99.9%	91.9%	99.9%	91.9%
	To supply Class III power	99.9%	91.9%	99.9%	91.9%
	To supply Class IV power	99.0%	91.0%	99.0%	91.0%
	To perform control, data acquisition and communication	99.0%	90.2%	99.0%	90.2%
	To provide chilled water	99.0%	89.4%	99.0%	89.4%
	To provide vacuum	99.0%	86.2%	97.0%	87.0%

Availability targets for ITER

D. van Houtte et al., “ITER operational availability and fluence objectives”, Fusion Engineering and Design 86 (2011) 680–683

High Availability

- **N+M modular redundancy –** ATCA modules are, Field Replaceable Units (FRUs) controlled by the Shelf Manager Controller (ShMC), allowing spare modules for fault-masking.

- **Hot-Swap –** FRUs are inserted or extracted without the need of Shelf power-off, for seamless operation, minimizing downtime.

Board ACTIVATED (cannot be removed)

Board DEACTIVATED (cannot be removed)

Board safely removed

- Hardware **Fault detection –** redundant Shelf Manager (ShM) monitors for module health and manages alarms [1].

ATCA Shelf

ATCA-PTSW-AMC4
PCIe and timing switch
Cable interface to Host [2]

ATCA-IOP
Digitizer & data processing [3]

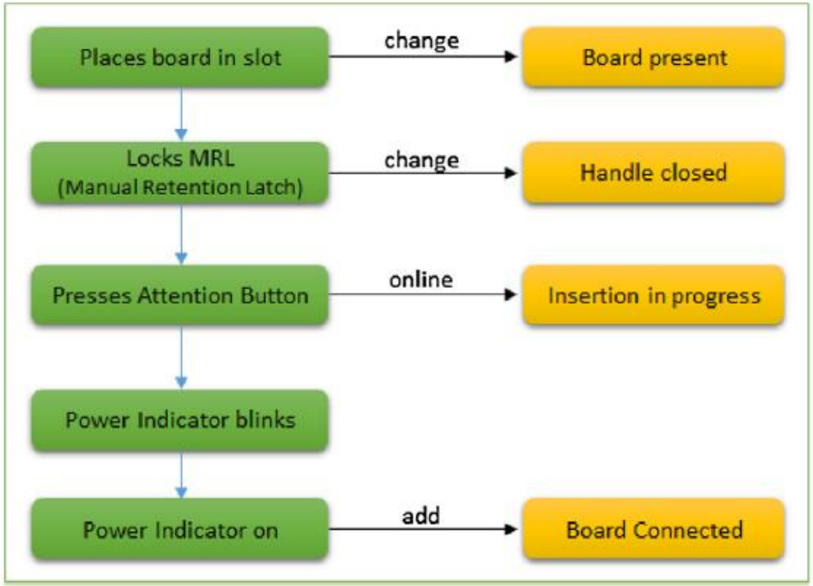
M. Correia et al, "High Availability methods in ATCA-based control and data acquisition for fusion diagnostics", 3rd ECPD European Conference on Plasma Diagnostics 6-9 May 2019,Lisbon, Portugal

[1] A. P. Rodrigues et al., "Intelligent platform management for fast control plant systems", IEEE TNS 58 (4) (2011) 1733 -1737
[2] M. Correia et al., "ATCA-Based Hardware for Control and Data Acquisition on Nuclear Fusion Fast Control Plant Systems", IEEE TNS 58 (4) (2011) 1701-1705.
[3] A. J. N. Batista et al., "ATCA/AXIe compatible board for fast control and data acquisition in nuclear fusion experiments", FED 87 (12) (2012) 2131-2135.

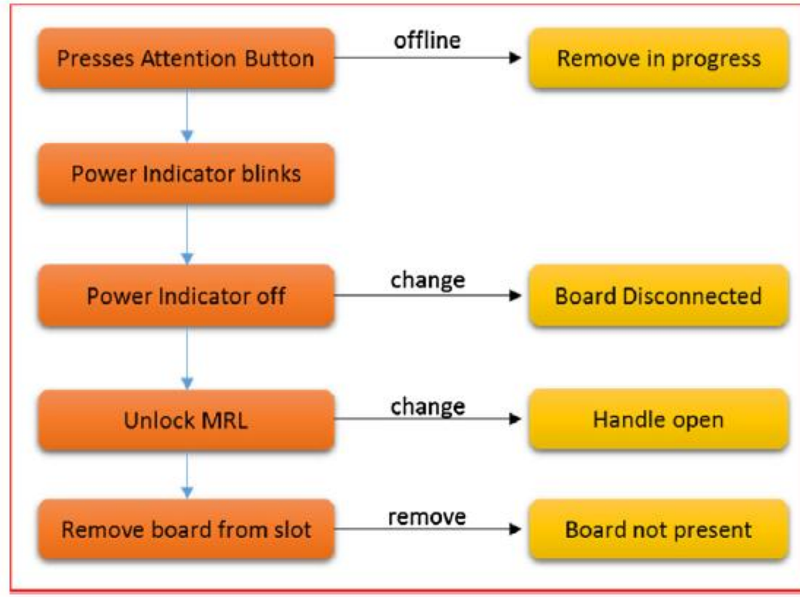
TÉCNICO LISBOA
ipfn INSTITUTO DE PLASMAS E FUSÃO NUCLEAR

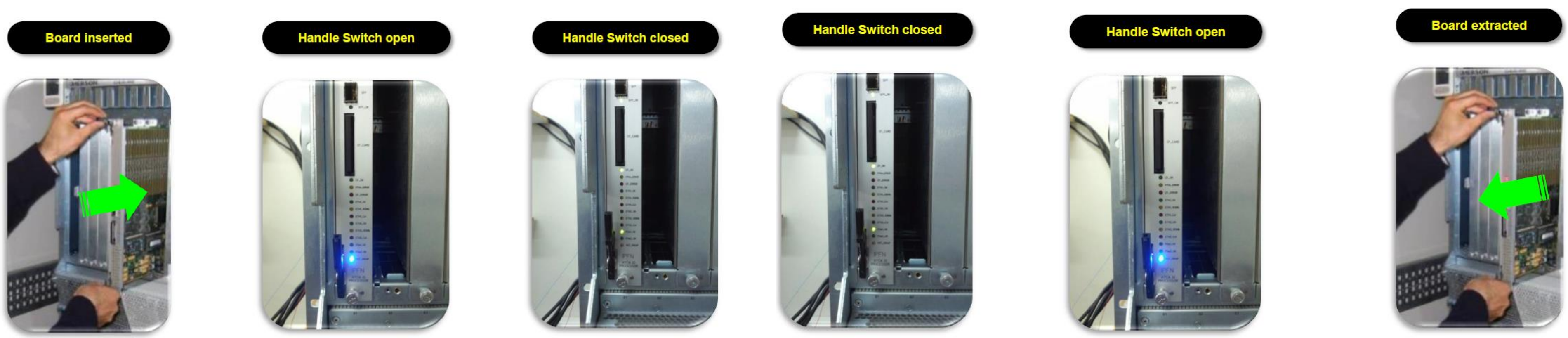
High Availability – Hot-plug features

Board Insertion



Board Removal





M0 Board Not Installed

M1 Board Inactive

M2 Activation Request
M3 Activation in Progress
M4 Board Active

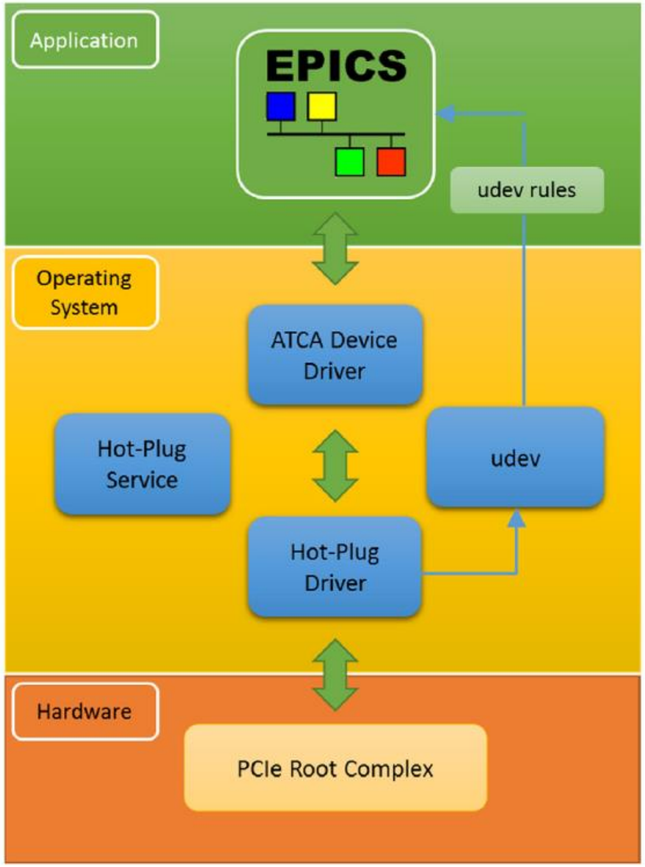
M4 Board Active

M5 Deactivation Request
M6 Deactivation in Progress
M1 Board Inactive (ready for extraction)

M0 Board Not Installed

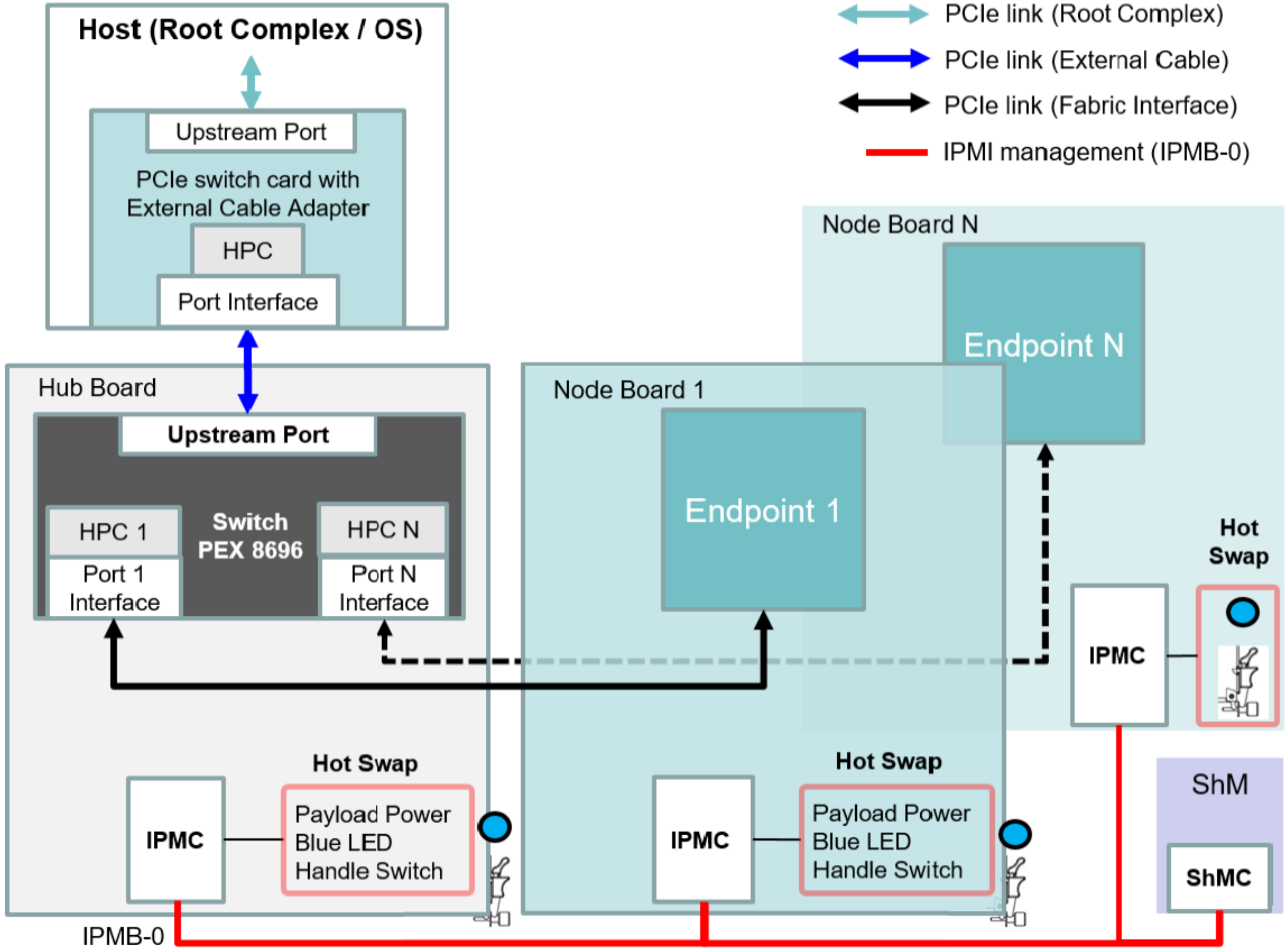
High Availability – Hot-plug features

Software Architecture



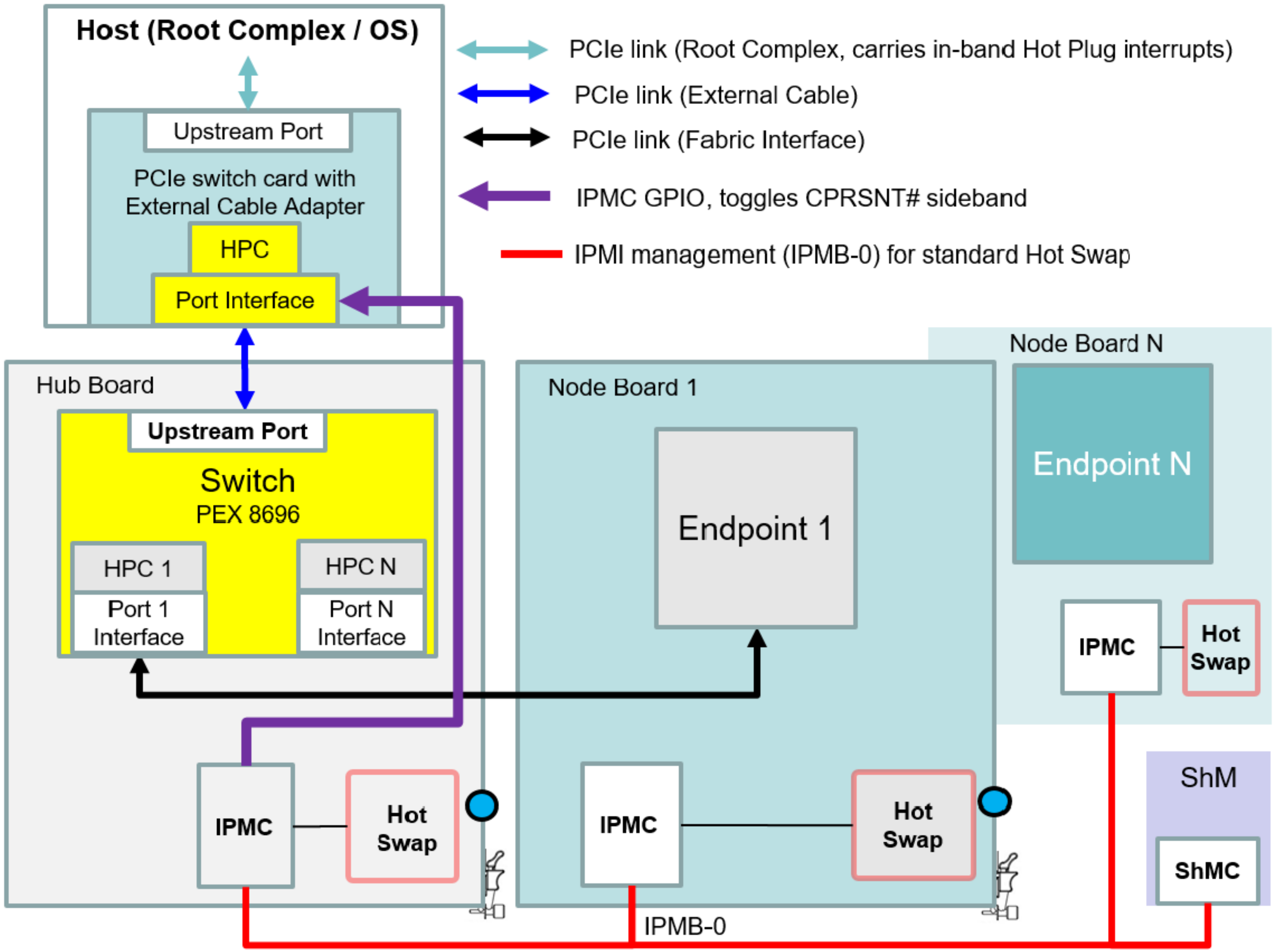
B. Santos et al, “EPICS device support for an ATCA CDAQ Board with hot-plug capabilities”, Fusion Engineering and Design 123 (2017) 732–736

High Availability – Hot Plug standardization



M. Correia et al, "PCIe Hot Plug support standardization challenges in ATCA ", 21st IEEE Real Time Conference 9-15 June 2018, Colonial Williamsburg, VA, USA

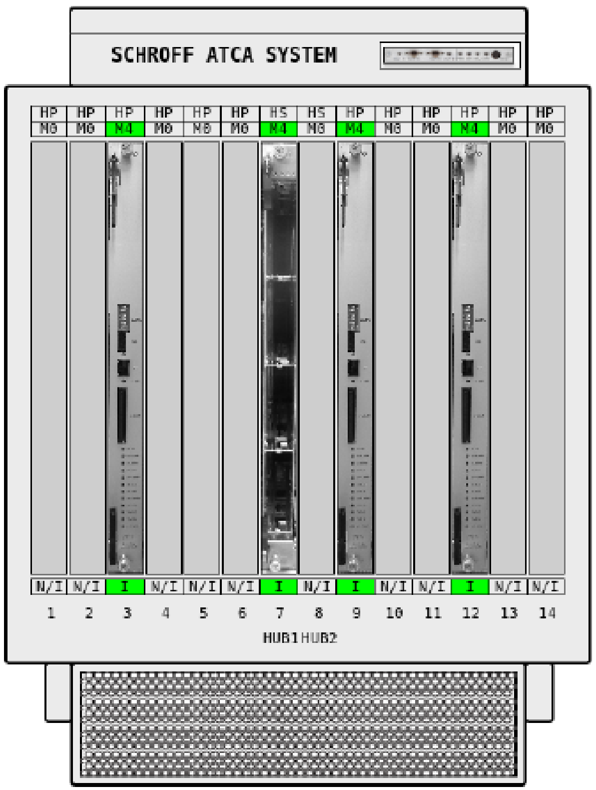
High Availability – Hot Plug standardization



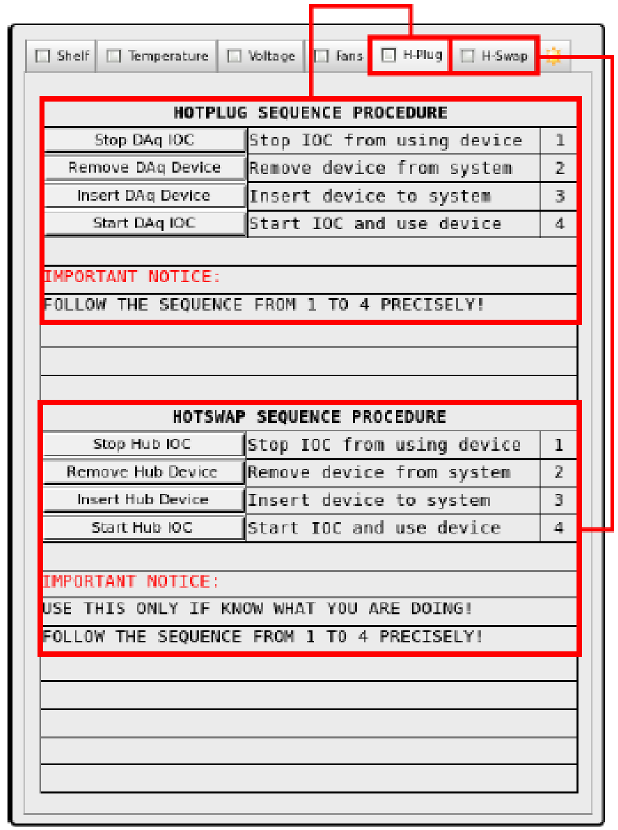
M. Correia et al, "PCIe Hot Plug support standardization challenges in ATCA ", IEEE Transactions on Nuclear Science (Volume: 66 , Issue: 10 , Oct. 2019)

Remote monitoring, management and control

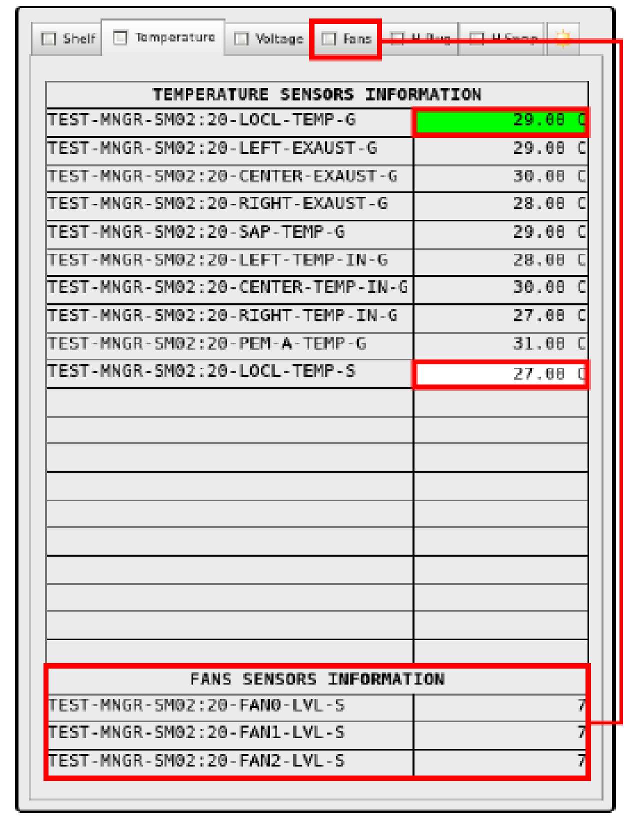
Remote ATCA shelf view



HOTPLUG Management



Temperature Status and Alarms



M. Correia et al, “High Availability methods in ATCA-based control and data acquisition for fusion diagnostics”, 3rd ECPD European Conference on Plasma Diagnostics 6-9 May 2019,Lisbon, Portugal

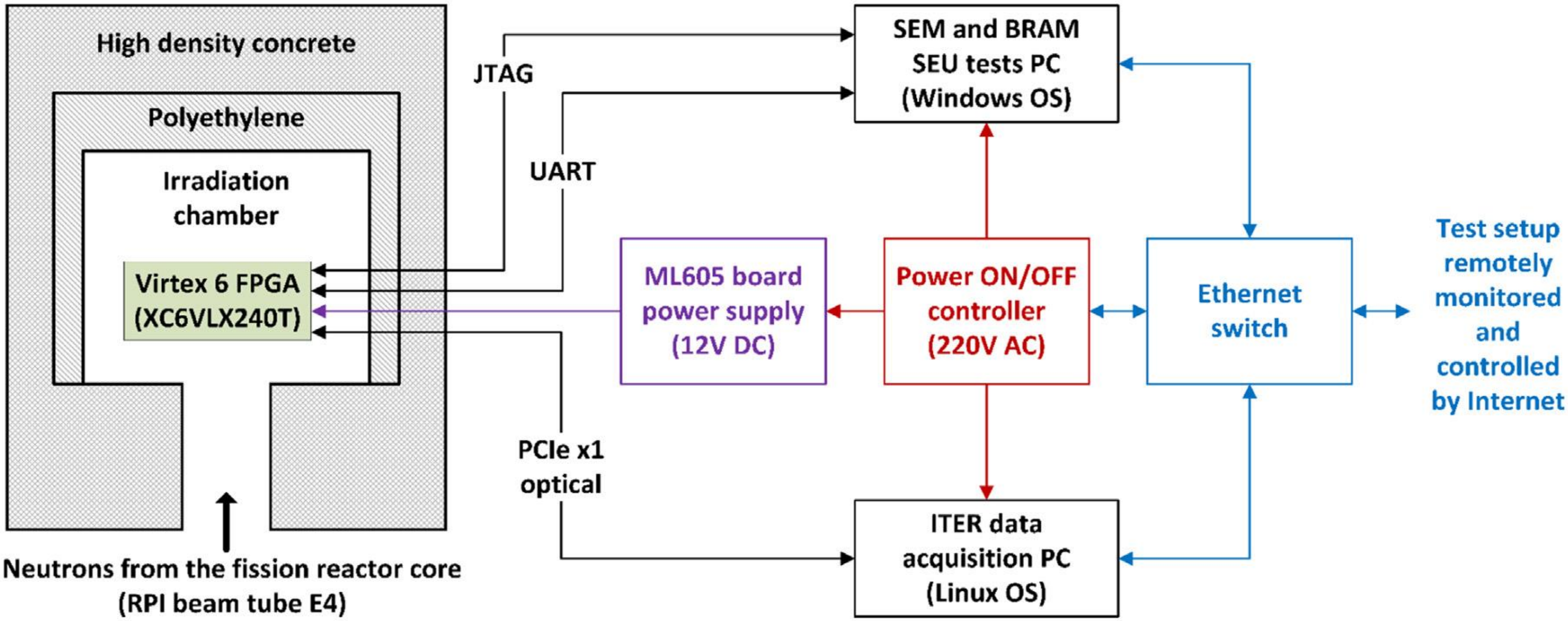
Safety and Data integrity

- Mitigation of Single Events Upsets (SEU) due to ionizing radiation
  - Hardware installed in ITER port cells will be irradiated by ionizing radiation (mainly neutrons)
  - Most equipment will be placed after bio-shield protection
  - Still, the influence of such radiation in FPGAs (functional state logic), Static RAM (configuration & program data), Block RAM (functional live data) can be mitigated using a Soft Error Mitigation (SEM) controller

Real-time mitigation of SEU can increase reliability and availability of data acquisition hardware for nuclear applications.

Antonio J.N. Batista et al, "SEU mitigation exploratory tests in a ITER related FPGA", Fusion Engineering and Design 118 (2017) 111–116

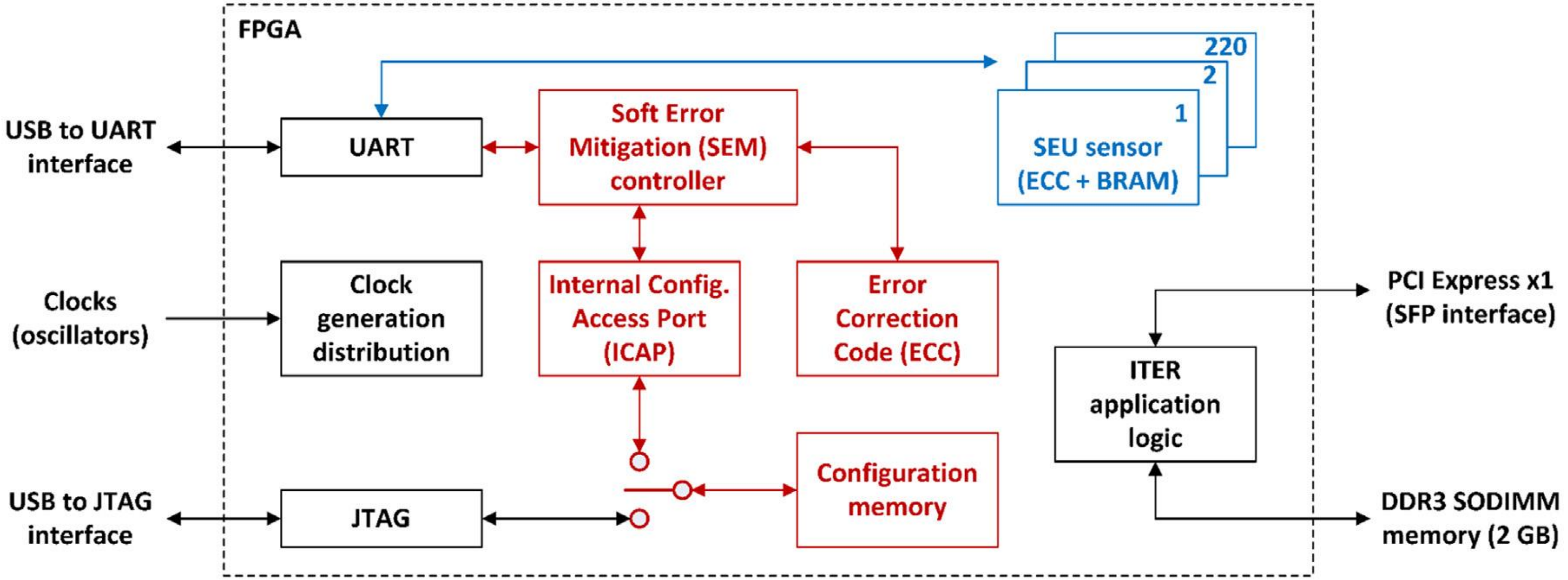
Safety and Data integrity



Experimental Setup

Antonio J.N. Batista et al, “SEU mitigation exploratory tests in a ITER related FPGA”, Fusion Engineering and Design 118 (2017) 111–116

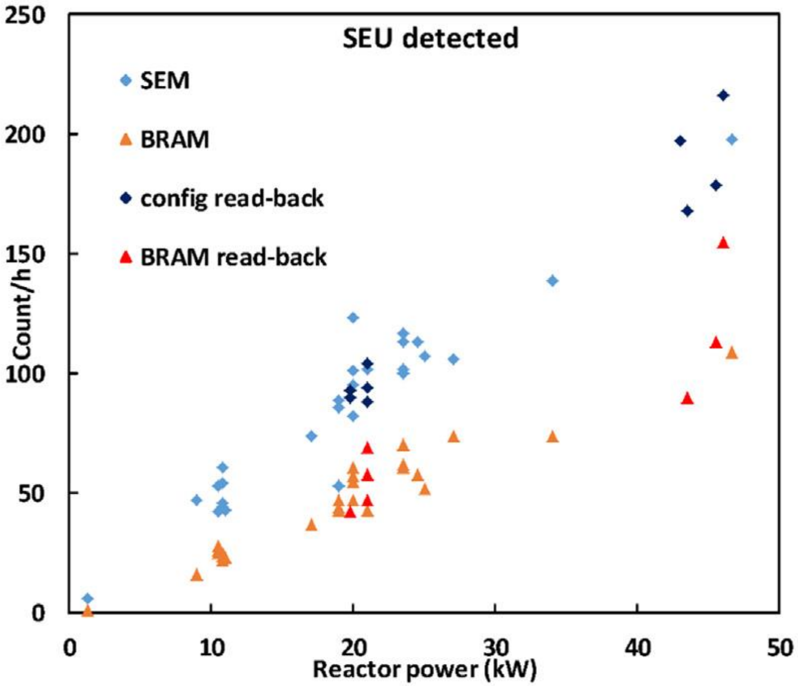
Safety and Data integrity



Firmware

Antonio J.N. Batista et al, “SEU mitigation exploratory tests in a ITER related FPGA”, Fusion Engineering and Design 118 (2017) 111–116

Safety and Data integrity



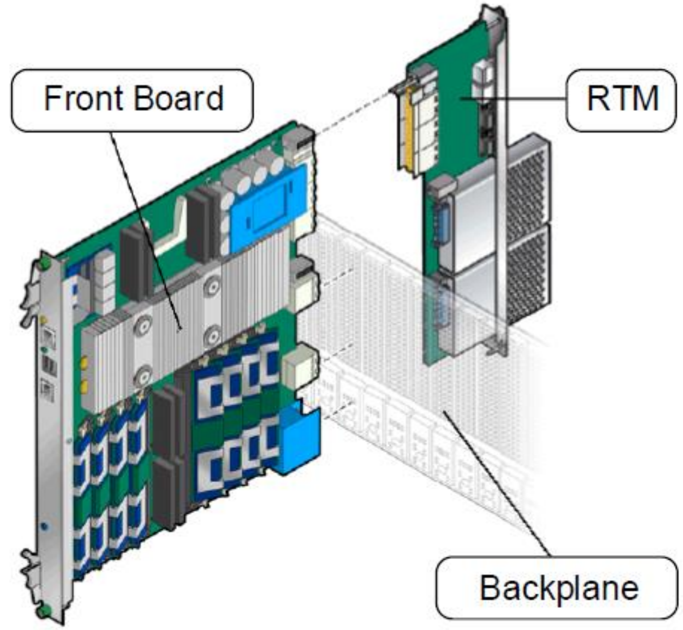
Main Results

- Worst case detection/repair time of an error was 26 ms
- BRAM repair is on-the-fly when data is read
- Real-time SEU mitigation is possible in relevant nuclear applications
- Future work is desirable to include SEU mitigation in all FPGA BRAM to improve statistics

Results show that the proposed mitigation technique is able to repair the majority of the detected soft-errors in the FPGA memory.

Antonio J.N. Batista et al, "SEU mitigation exploratory tests in a ITER related FPGA", Fusion Engineering and Design 118 (2017) 111–116

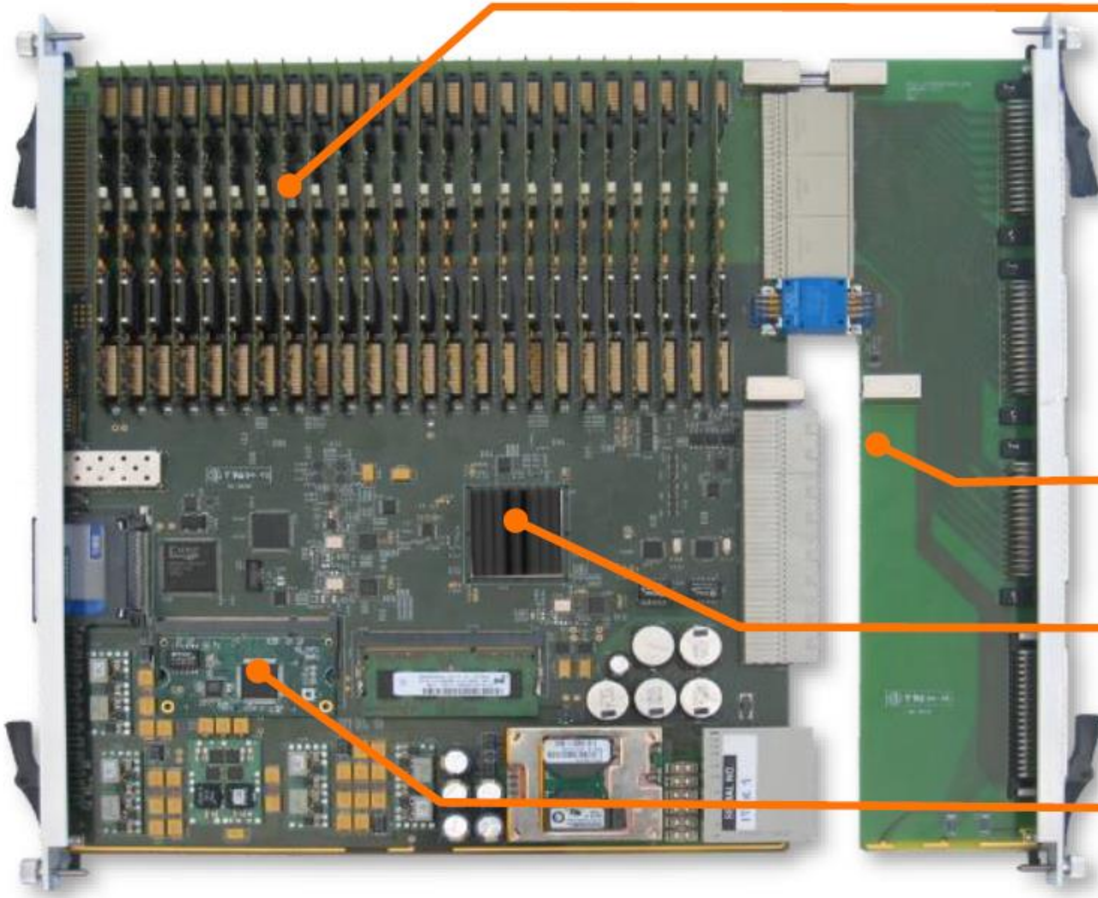
Hardware Solutions – ATCA



Designed for high levels of availability (≥99.999%)

- Modular - Field Replaceable Unit (FRU)
- Redundancy (Boards, Power Supply Units, Cooling Units, Shelf Managers, Backplane)
- IPMI-based management (Shelf Manager and IPMC)
- **Hot Swap** (Live insertion/extraction of FRUs)

Hardware Solutions – ATCA (DAcQ & Control)



ATCA-IO-PROCESSOR (IOP)

48 analog IO (ADC/DAC)

700V galvanic isolation

2 × DAC

2 × 1/2MSPS, 18-bit ADC

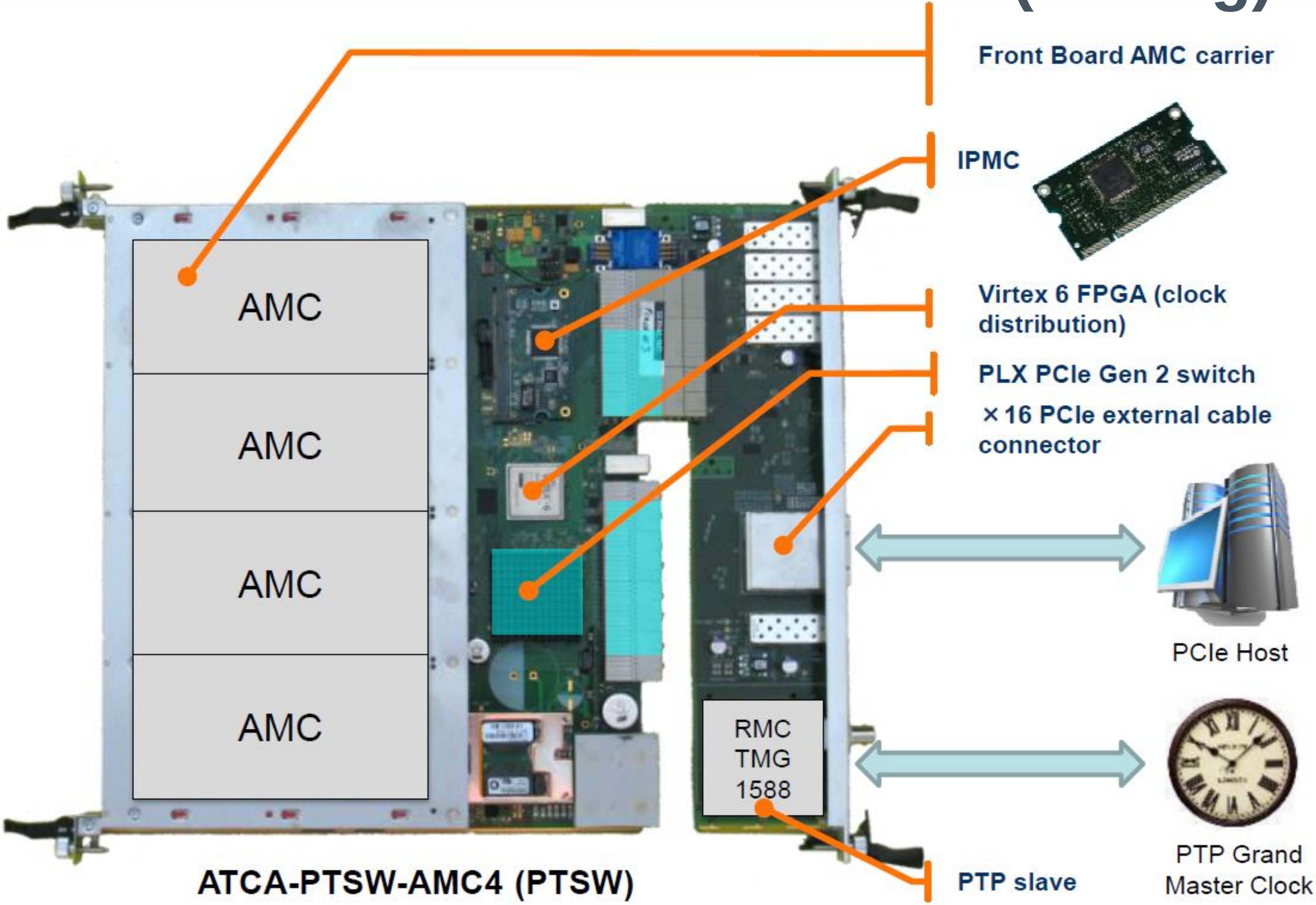
Passive RTM (Analog IO)

Virtex 6 FPGA

(PCIe endpoint)

CoreIPM OPMA2368 IPMC

Hardware Solutions – ATCA (Timing)



Hardware Solutions - MTCA

MTCA.0 System managed by IPFN's MCH hub controller

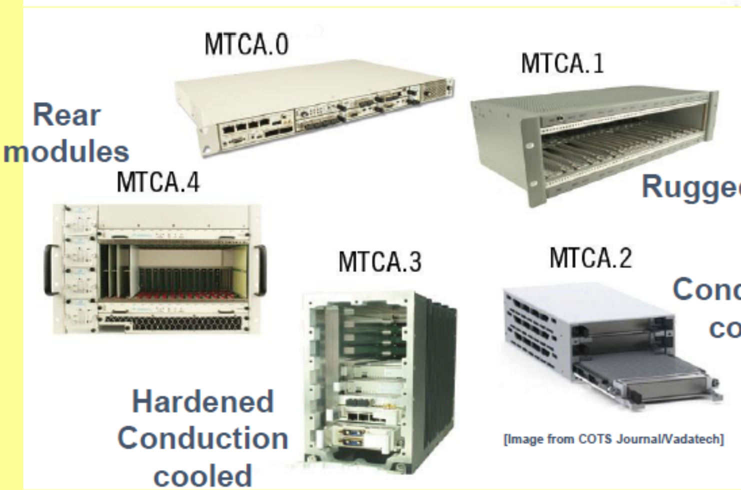
MTCA.0 system

- compact solution
- standalone or remote control/data processing
- lower number of channels than ATCA
- cost-effective instruments
- Various types of µTCA cards available from industry

MTCA.4 v. MTCA.0

- more channels
- rear modules: larger PCB area
- similar design: easy transition

MTCA.0 1U chassis
6-mid-size slots, 1 MCH



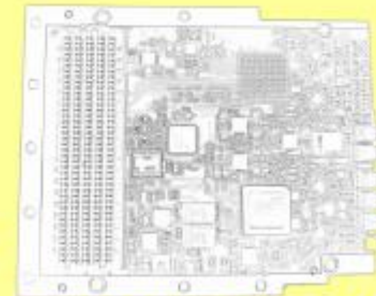
J. Sousa et al, "MicroTCA control and data acquisition platform for Plasma Diagnostics", 3rd ECPD European Conference on Plasma Diagnostics 6-9 May 2019,Lisbon, Portugal

Hardware Solutions - MTCA

Modular MicroTCA and FMC (ANSI/VITA 57.1) IPFN's digitizers

1 GSPS 8-bit FMC module

500 MSPS 14-bit FMC module (test phase)

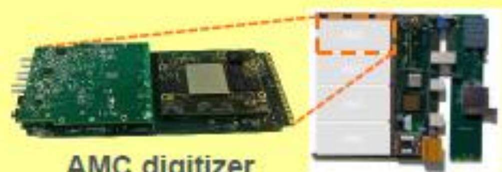


3 GSPS 14-bit FMC module (design phase)

1 GSPS+ 8+

- Thomson Scattering
- Linac and Low Level RF
- ITER Radial Neutron Camera

AMC FMC Carrier



AMC digitizer

500MSPS 14-bit

- X-rays, G-rays, Neutron spectroscopy
- Plasma Position Reflectometry

AMC FMC Carriers compatible with market available FMC solutions

J. Sousa et al, "MicroTCA control and data acquisition platform for Plasma Diagnostics", 3rd ECPD European Conference on Plasma Diagnostics 6-9 May 2019,Lisbon, Portugal

The ITER Radial Neutron Camera Diagnostic

The Radial Neutron Camera (RNC) diagnostic is a neutron detection system with multiple collimators aiming at characterizing the neutron emission that will be produced by the ITER tokamak:

- a primary role for basic and advanced plasma control measurements
- backup for system machine protection measurements.

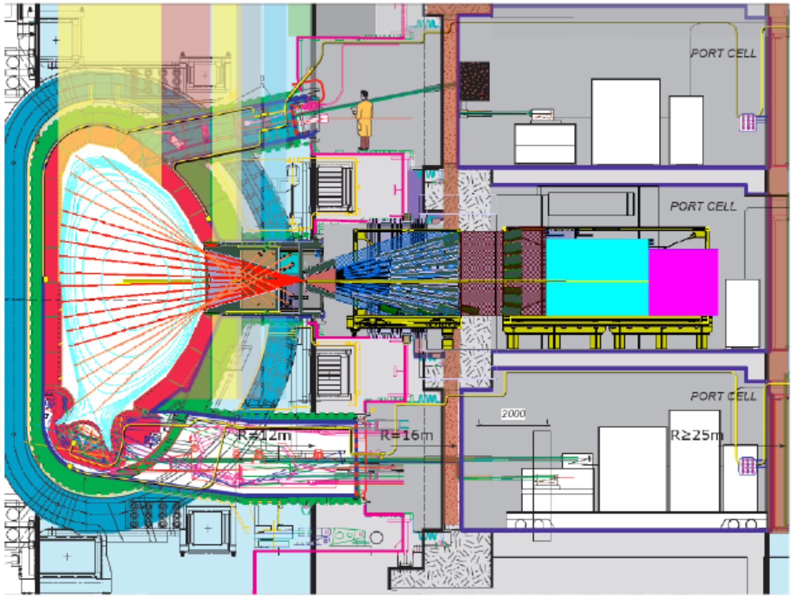
RNC diagnostic DatAcq needs

- acquire, process and store huge amounts of data per ITER discharge at high peak rates
- calculate real time measurements (neutron emissivity profile) on millisecond time scale

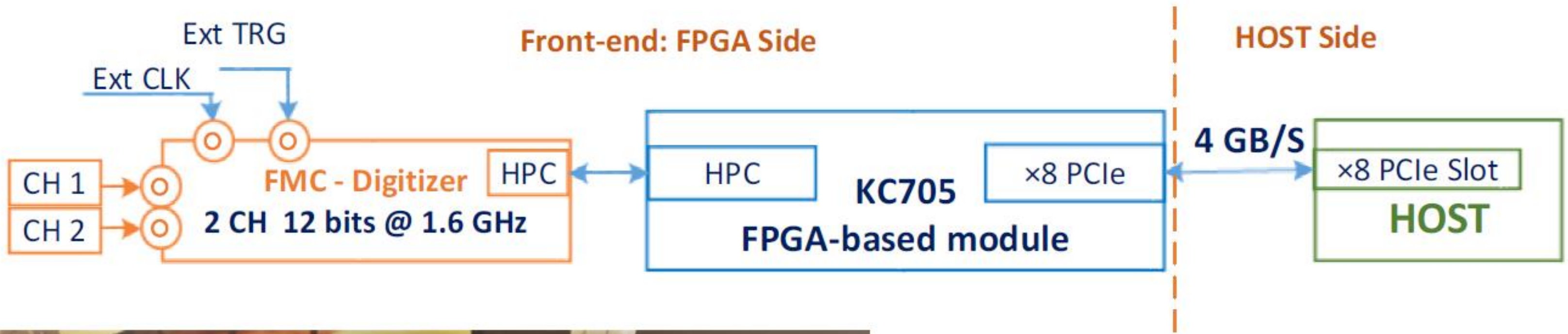
Technical challenges to the hardware, real-time firmware and software architecture design.

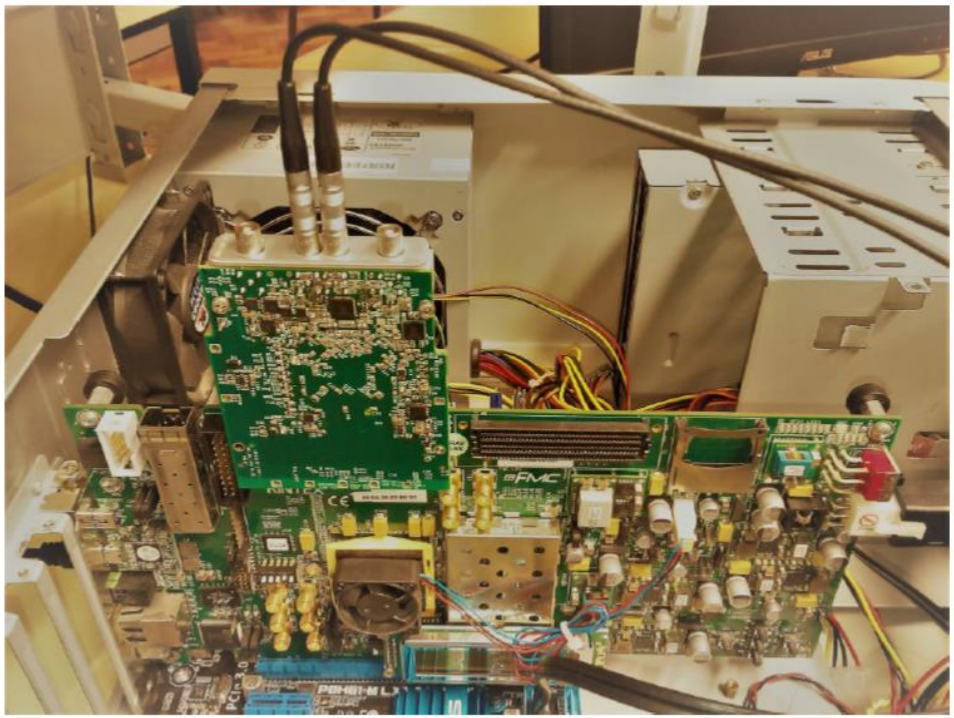
For the RNC system level design phase the following real time data processing algorithms were developed and tested:

- real time pulse processing (FPGA and host PC)
- real time calculation of the neutron emissivity radial profile
- real time pulse data compression block;



ITER RNC FEE Prototype





Host PC:

Intel(R) Core(TM) i7-5930K CPU @ 3.50GHz;

Scientific Linux 7;

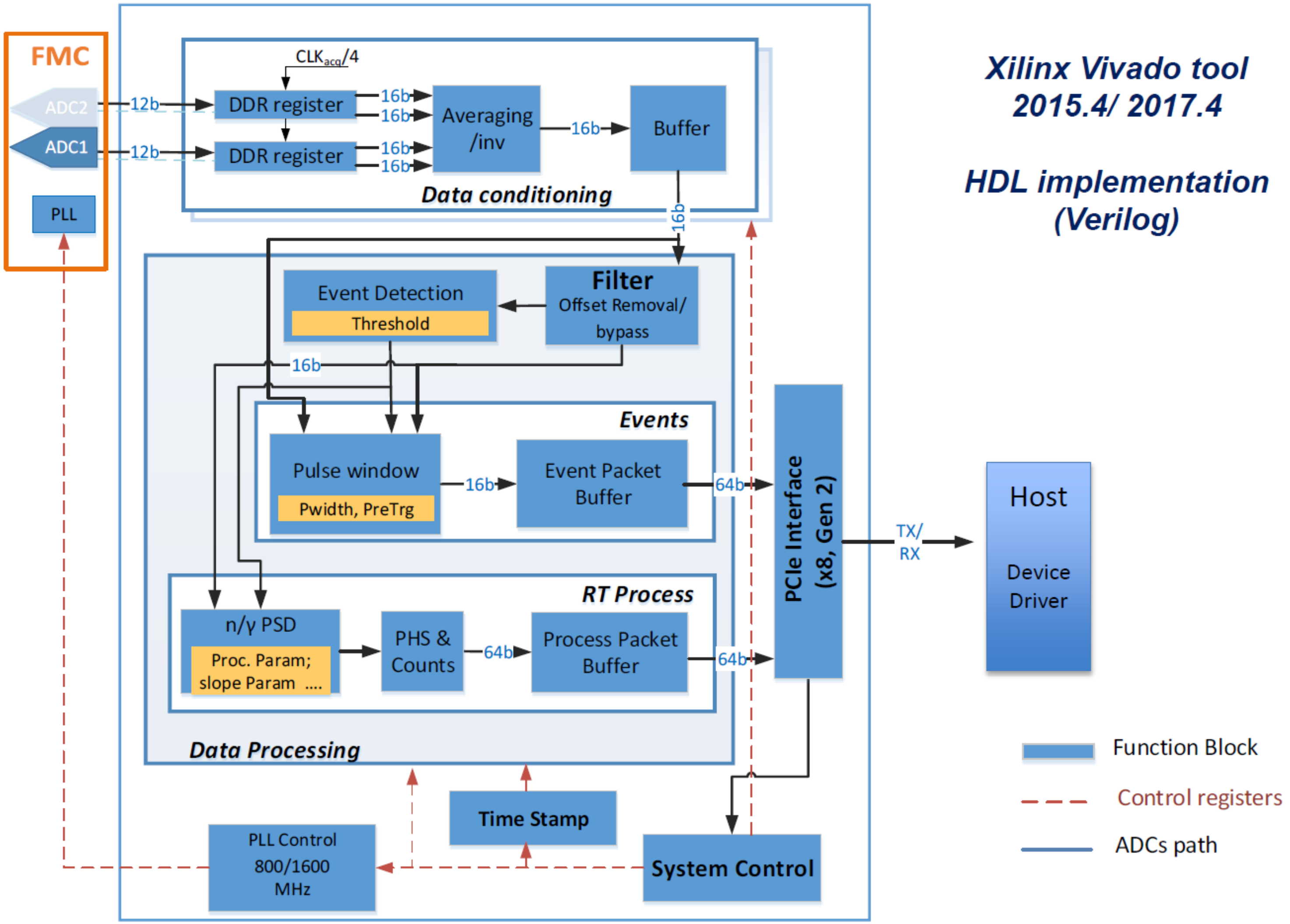
kernel: 3.10-rt

Digitizer:

Xilinx evaluation board (**KC705**); FPGA Mezzanine Card (**FMC-AD2-1600**) with 2 digitizer channels of 12-bit resolution @ 1600 MHz.

A. Fernandes, N. Cruz et al, "FPGA code for the data acquisition and real-time processing prototype of the ITER Radial Neutron Camera", 21st Real Time Conference, June 9th - 15th, Colonial Williamsburg, Virginia, United States

ITER RNC FPGA Code

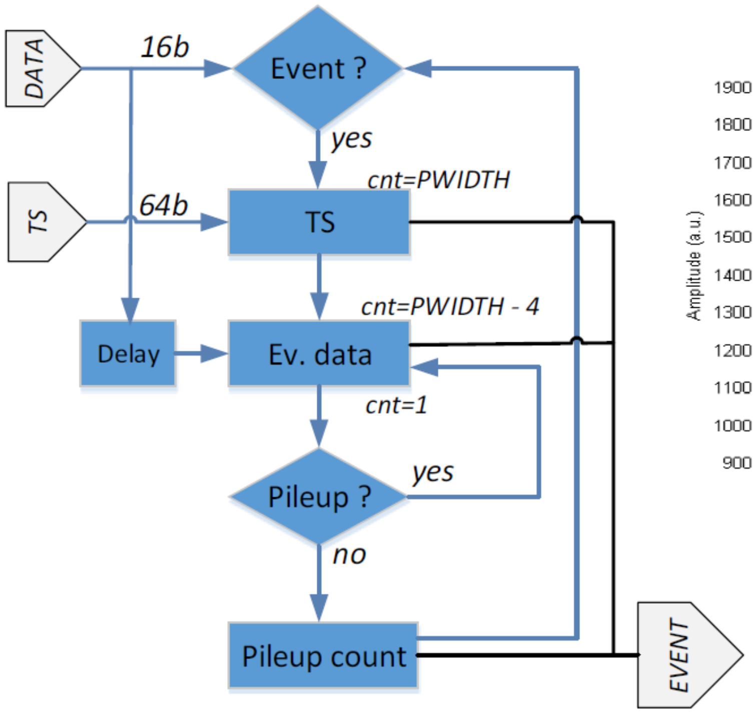


Xilinx Vivado tool 2015.4/ 2017.4

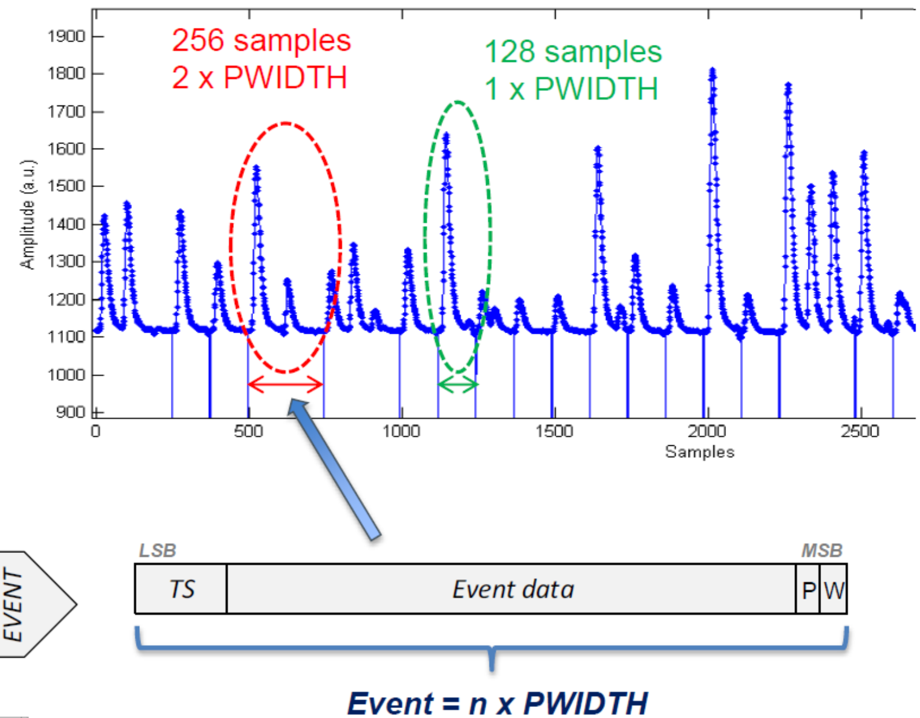
HDL implementation (Verilog)

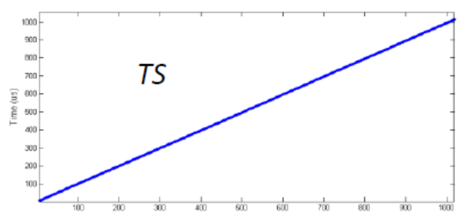
A. Fernandes, N. Cruz et al, "FPGA code for the data acquisition and real-time processing prototype of the ITER Radial Neutron Camera", 21st Real Time Conference, June 9th - 15th, Colonial Williamsburg, Virginia, United States

ITER RNC FPGA Data Processing
Event Storage



cnt – decreasing counter

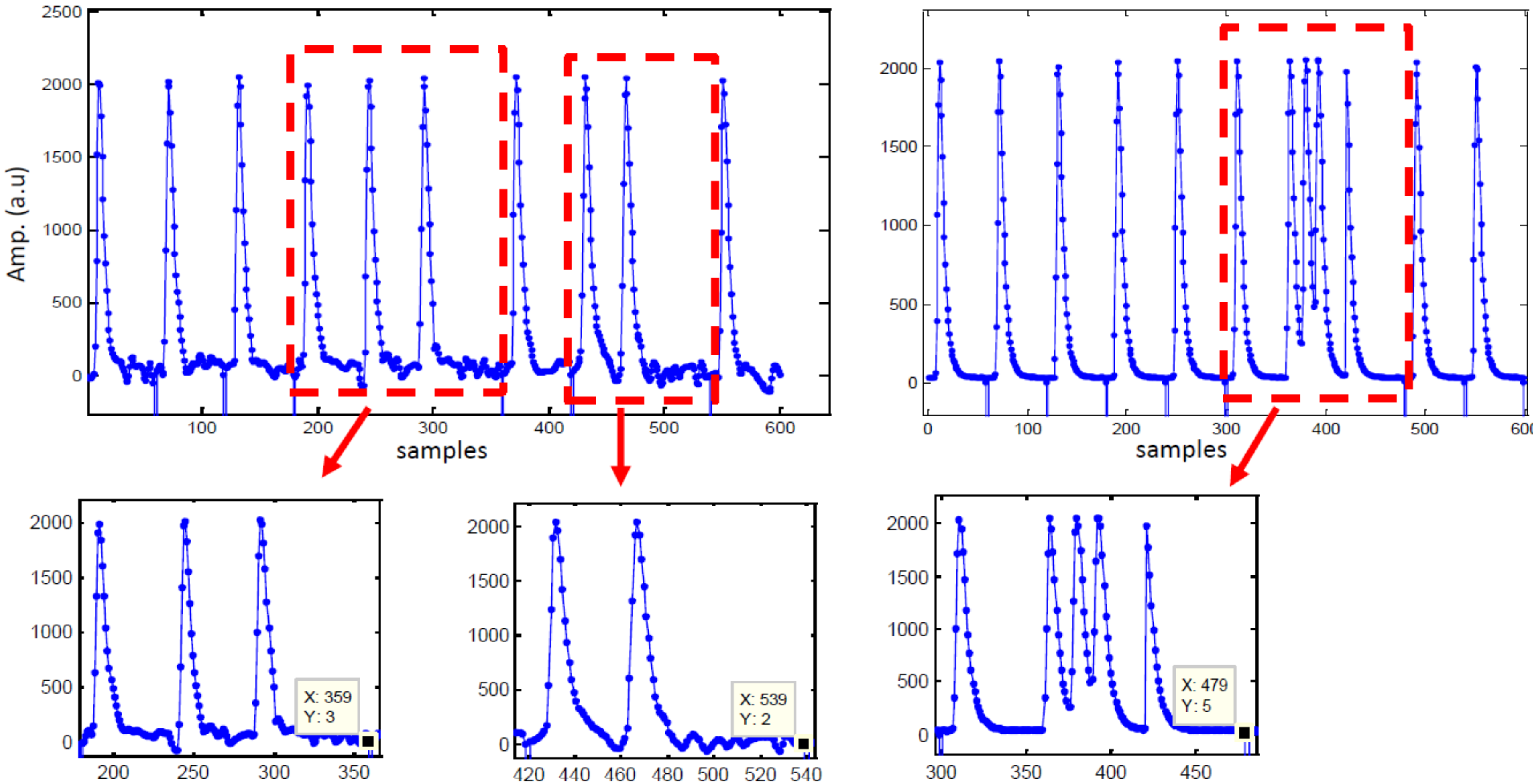




Synthetic input signal with several superimposed pulses (128 samples; PTRG 16 samples; THR. Level)

A. Fernandes, N. Cruz et al, "FPGA code for the data acquisition and real-time processing prototype of the ITER Radial Neutron Camera", 21st Real Time Conference, June 9th - 15th, Colonial Williamsburg, Virginia, United States

ITER RNC FPGA Data Processing
Event Storage



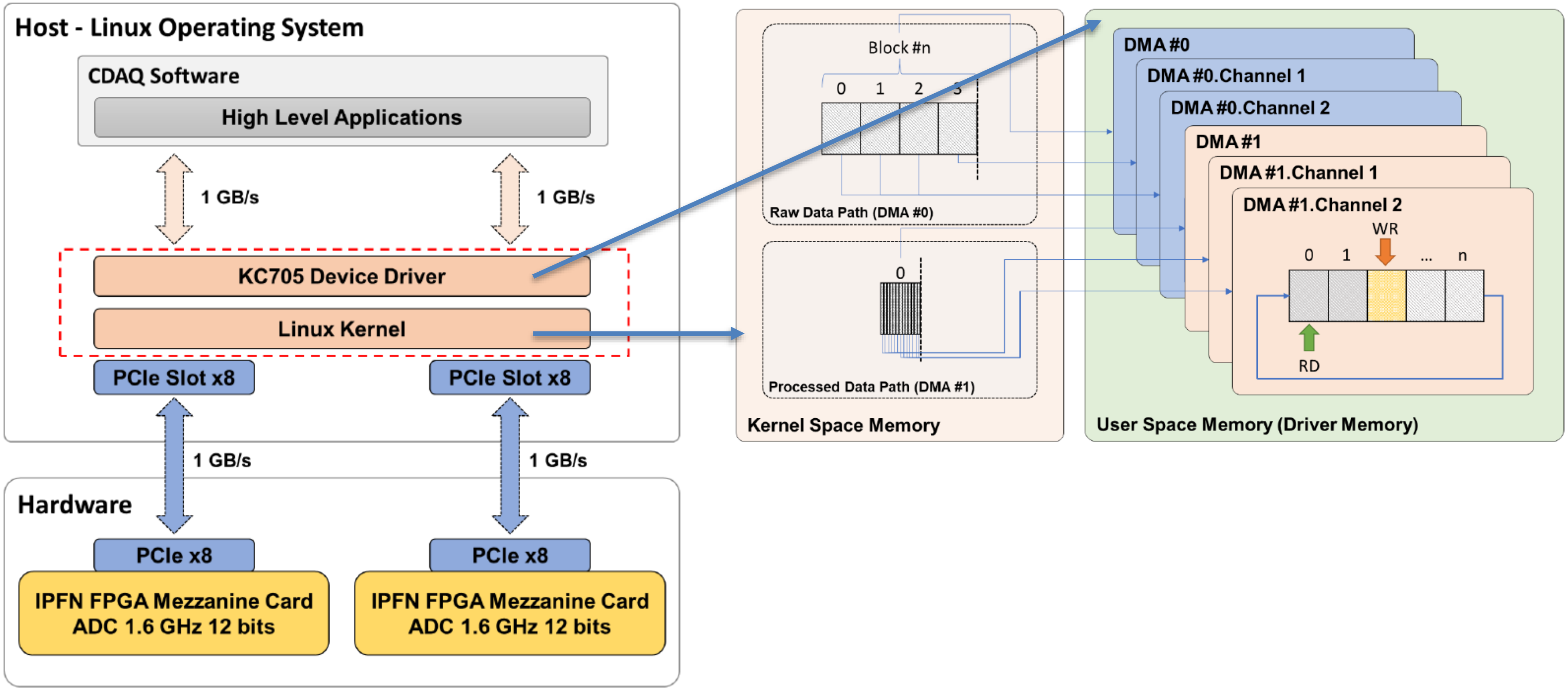
P. 3; Ev. 3 PWIDTH

P. 2; Ev. 2 PWIDTH

P. 5; Ev. 3 PWIDTH

A. Fernandes, N. Cruz et al, “FPGA code for the data acquisition and real-time processing prototype of the ITER Radial Neutron Camera”, 21st Real Time Conference, June 9th - 15th, Colonial Williamsburg, Virginia, United States

High Performance Linux Device Driver for ITER RNC Diagnostic



B. Santos, N. Cruz et al, "Linux device driver for Radial Neutron Camera in view of ITER long pulses with variable data throughput", 30th Symposium on Fusion Technology, 16-21 September 2018, Giardini Naxos, Sicily, Italy

High Performance Linux Device Driver for ITER RNC Diagnostic

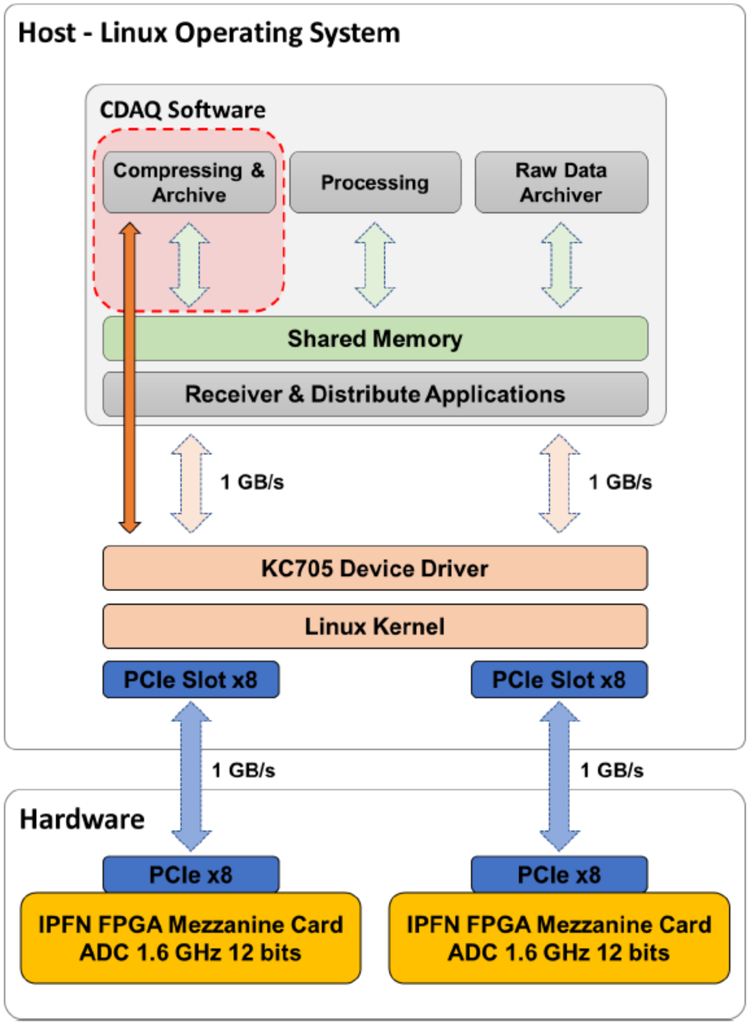
- The tests show a stable solution during 60 minutes acquisitions with data acquisition rates up to 1.5 GB/s.
- Using the interrupt approach (implemented and tested in a previous phase of the prototype), there are missing packets above 512 MB/s for single DMA #0 acquisitions, and above 64 MB/s for acquisitions from two DMAs at same time.

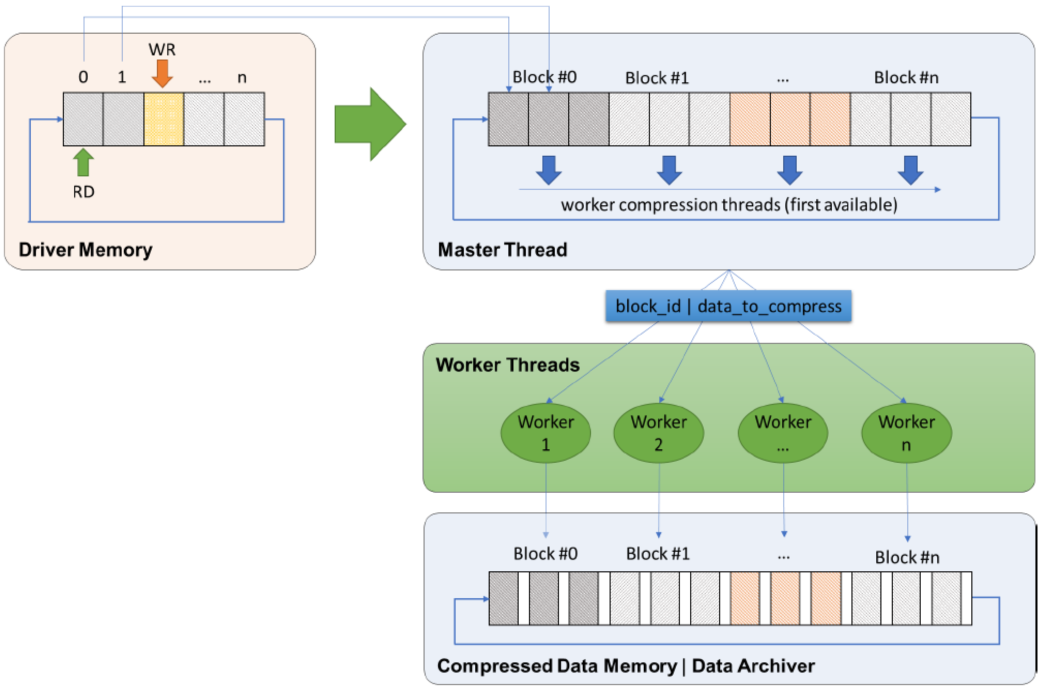
ACQ RATE (MB/s)	DMA #0			DMA #0 & DMA#1		
	Interrupt	Polling		Interrupt	Polling	
	Data Loss	Data Loss	Recovered Packets	Data Loss	Data Loss	Recovered Packets
64	0.0000%	0.0000%	0	0.0000%	0.0000%	0
128	0.0000%	0.0000%	0	0.0400%	0.0000%	0
256	0.0000%	0.0000%	0	1.4263%	0.0000%	0
512	0.0000%	0.0000%	0	2.3449%	0.0000%	0
768	0.0001%	0.0000%	0	-	0.0000%	0
1024	0.0019%	0.0000%	0	-	0.0000%	0
1536	0.0029%	0.0000%	0	-	0.0000%	2
Test Time	30 minutes	60 minutes		30 minutes	60 minutes	

- The packets recovered is a relevant issue to guarantee the data integrity, despite small impact.
- The usage of data transmission information can be a valuable contribution to solve problems when a traditional implementation of a Linux device driver based on interrupt handling or polling mechanisms cannot be used.
- The presented architecture is scalable and adjustable. Also, is data-agnostic because only the status information is considered to trigger the data to transfer.
- The presented solution implements an internal data transmission recovery algorithm, enabling the device driver to automatically check and recover missing data blocks in a transparent way for the host applications. Using a traditional approach, in which a block is transferred in each status changed, if some transition was missed the data would be lost.

B. Santos, N. Cruz et al, "Linux device driver for Radial Neutron Camera in view of ITER long pulses with variable data throughput", 30th Symposium on Fusion Technology, 16-21 September 2018, Giardini Naxos, Sicily, Italy

Real-Time Data Compression for ITER RNC





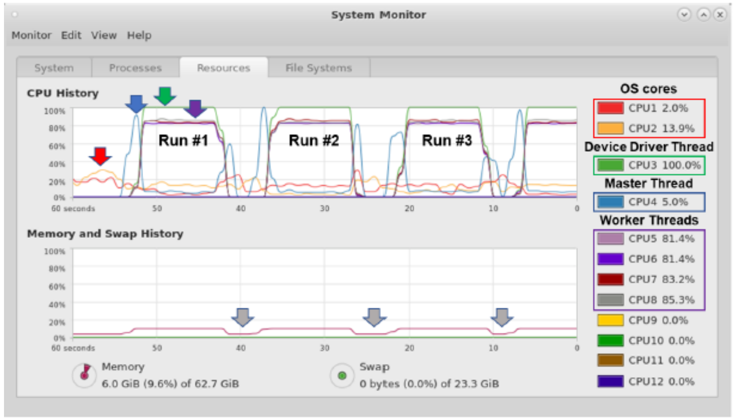
B. Santos, N. Cruz et al, "Real-time data compression for data acquisition systems applied to the ITER Radial Neutron Camera", 21st Real Time Conference, June 9th - 15th, Colonial Williamsburg, Virginia, United States

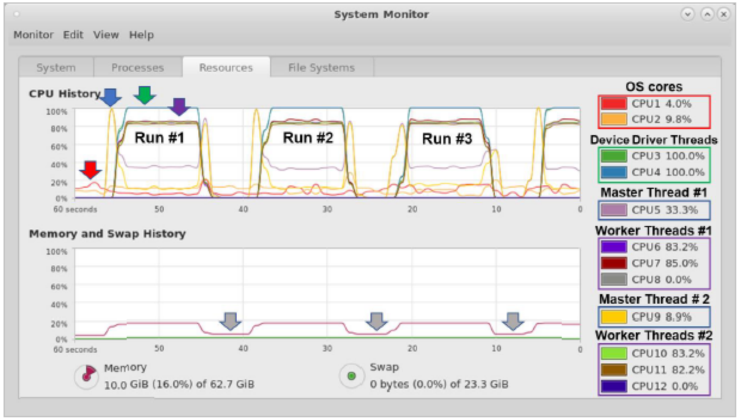
Real-Time Data Compression for ITER RNC

- The **minimum number of needed cores** per acquisition rate (with **no data loss**) is presented in the table below.
- The **device driver** and the **master thread** implement **algorithms to check the data loss**
- The input signal was a pulse type signal (gamma distribution) from a waveform generator with different pulse width using a 10 MB block size during 60 minutes.

Number of Channels	Pulse Width	Data Rate (MB/s)	Data Loss / Number of CPUS						CPU Load (avg/core)		Compression				
									Worker Threads	Master Thread	Speed (MB/s)			Ratio	Space Saving
			1	2	3	4	5	6			Avg	Min	Max		
1	32	128	0,00%	-	-	-	-	-	37,00%	0,54%	353,73	342,20	355,63	1,33	24,91%
1	64	256	0,00%	-	-	-	-	-	81,00%	0,59%	317,43	307,80	319,10	1,43	29,97%
1	128	512	40,68%	0,00%	-	-	-	-	84,00%	0,57%	302,76	294,87	304,23	1,55	35,61%
1	256	768	61,06%	22,33%	0,00%	-	-	-	86,00%	0,56%	297,74	280,02	299,04	1,63	38,47%
2	32	256	0,00%	-	-	-	-	-	73,00%	0,71%	352,35	340,90	353,41	1,33	25,07%
2	64	512	36,94%	0,00%	-	-	-	-	80,00%	0,57%	321,14	312,86	322,40	1,44	30,54%
2	128	1024	69,38%	38,83%	8,80%	0,00%	-	-	82,00%	2,75%	310,64	212,45	313,25	1,54	35,17%
2	256	1536	79,58%	59,27%	39,09%	19,12%	4,32%	0,00%	88,00%	25,64%	284,58	196,20	313,33	1,60	37,36%

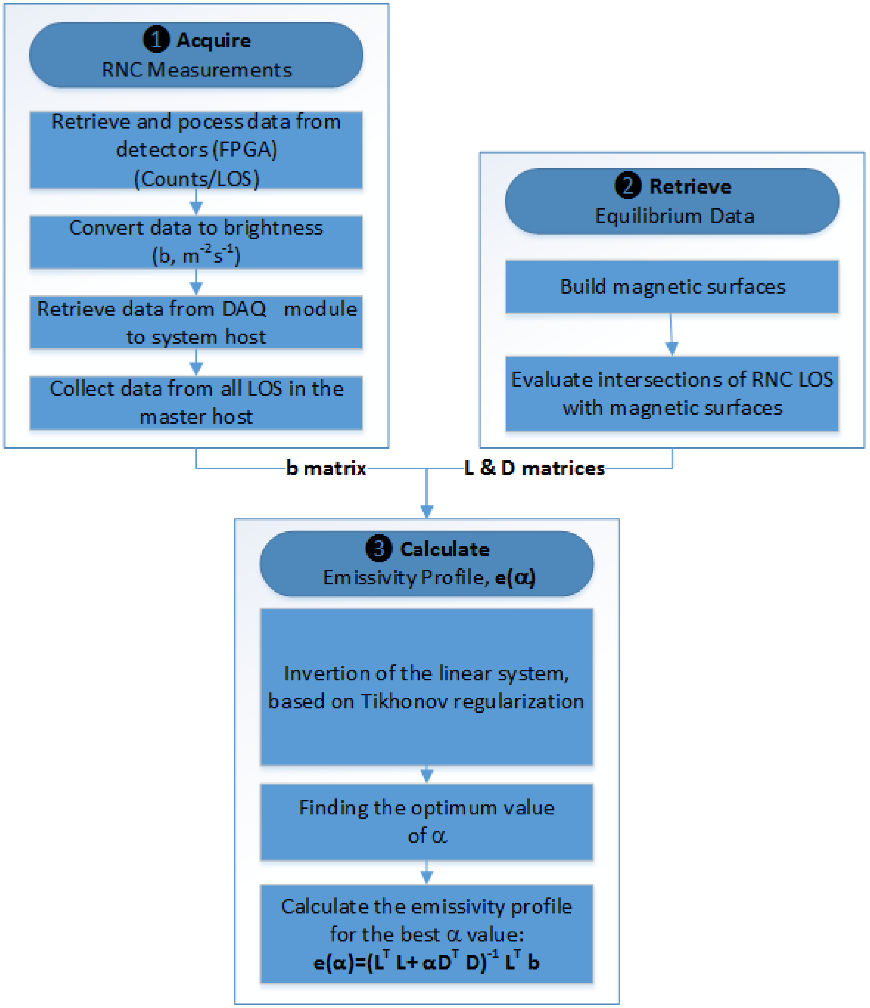
- The figures below present the **CPU and memory usage** during 3 runs of 10 seconds duration with 1024 MB/s of data acquisition rate. The **left** snapshot presents the state of the system during an acquisition from **one board** and the **right** from **two boards simultaneously** (512 MB/s per board).





TÉCNICO LISBOA ipfn INSTITUTO DE PLASMAS E FUSÃO NUCLEAR

ITER RNC Emissivity Profile Measurement

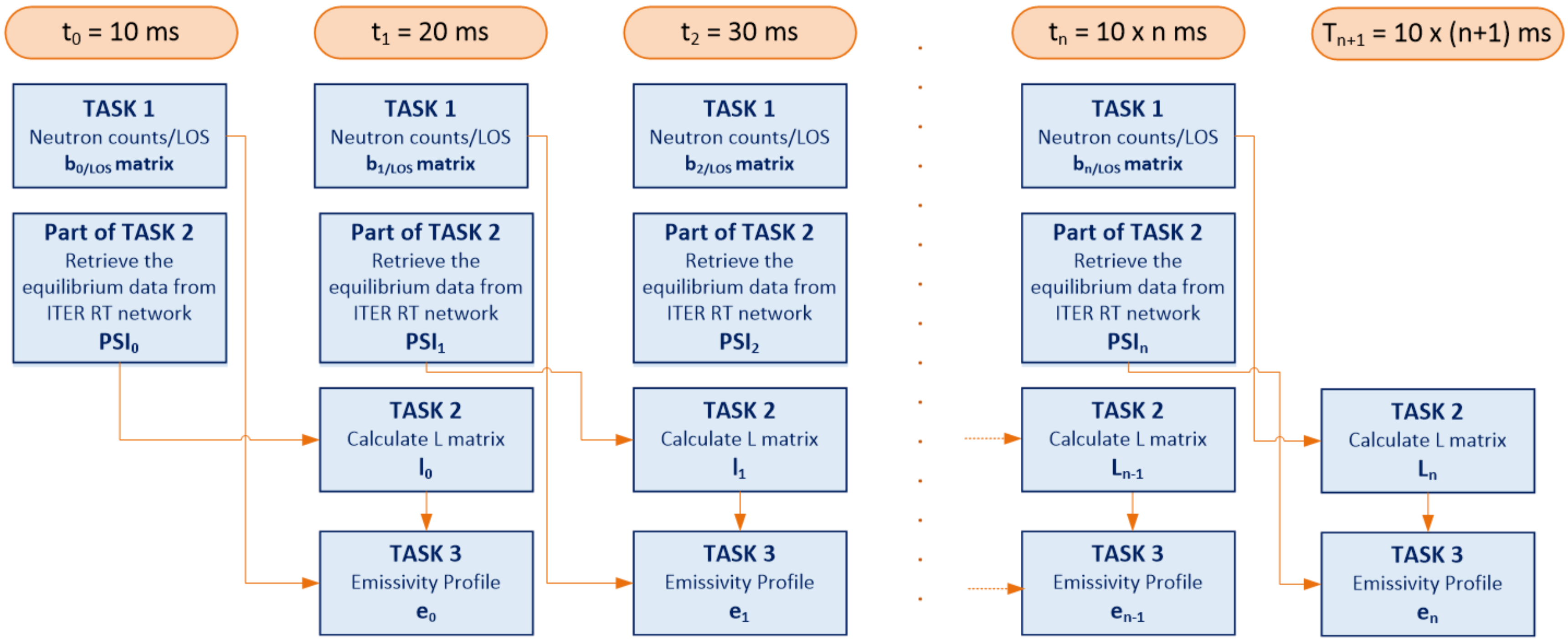


To obtain the real time measurement of the neutron emissivity profile 3 tasks were identified:

- Task 1 - Acquire and process neutron detector pulses;
- Task 2 - Retrieve and calculate the necessary inputs from the plasma equilibrium data;
- Task 3 - Calculate the neutron emissivity profile using Tikhonov inversion method.

N. Cruz et al, "The Design and Performance of the Real-time Software Architecture for the ITER Radial Neutron Camera", 21st Real Time Conference, June 9th - 15th, Colonial Williamsburg, Virginia, United States

ITER RNC - Real Time Control Cycle



Tasks distribution to perform the control cycle under 10 ms:

- Task 1 must run before any other for the complete period of a control cycle;
- Task 2 uses data retrieved in the previous control cycle and calculates the necessary inputs from the plasma equilibrium data in the present control cycle;
- Task 3 calculate the neutron emissivity profile using all the available data from previous and present control cycle.
- The 3 tasks run in parallel using different CPUs.

N. Cruz et al, “The Design and Performance of the Real-time Software Architecture for the ITER Radial Neutron Camera”, 21st Real Time Conference, June 9th - 15th, Colonial Williamsburg, Virginia, United States

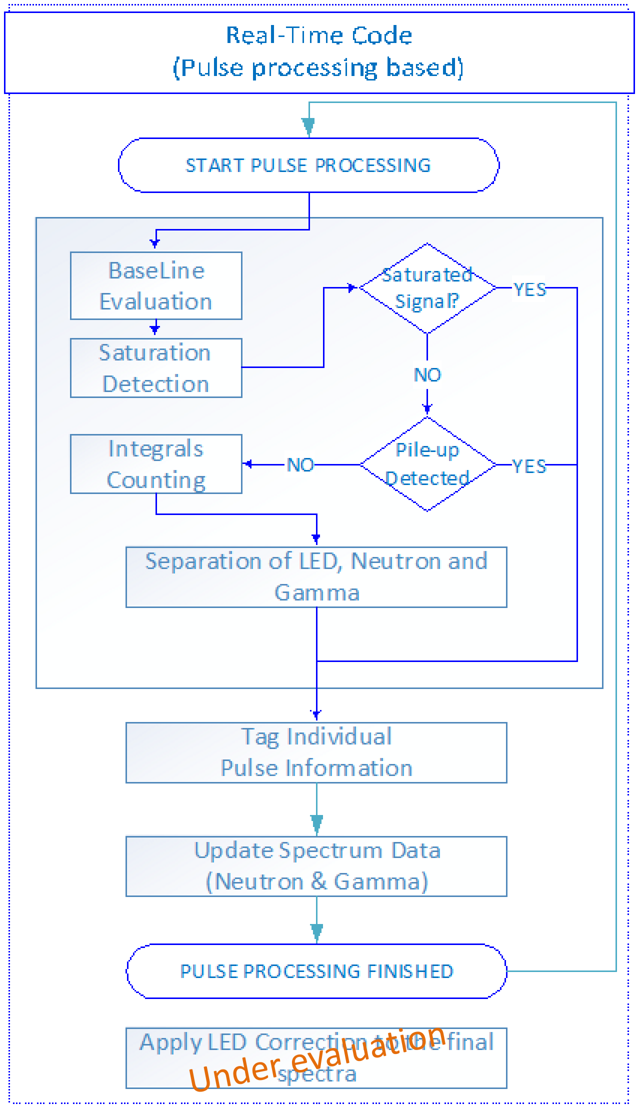
ITER RNC Host Pulse Processing

The real time pulse processing includes:

- Baseline evaluation
- Saturation detection
- Pile up detection
- Signal integration (energy calculation)
- Signal and particle separation

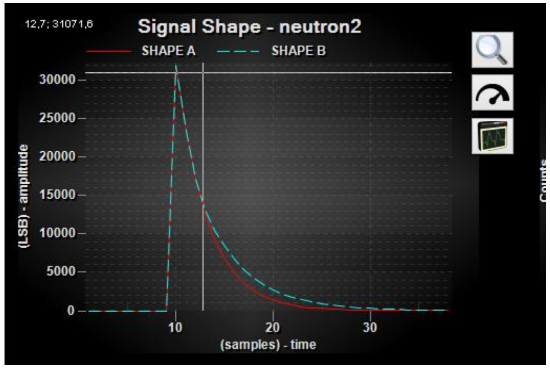
Real time spectrum calibration:

- The application of LED correction at the end of the control cycle to calibrate the energy spectra in real time is under evaluation.
- In former offline pulse processing, LED correction has been applied to each pulse individually.
- Pile-up and saturated signals detection is used for final spectrum count correction.

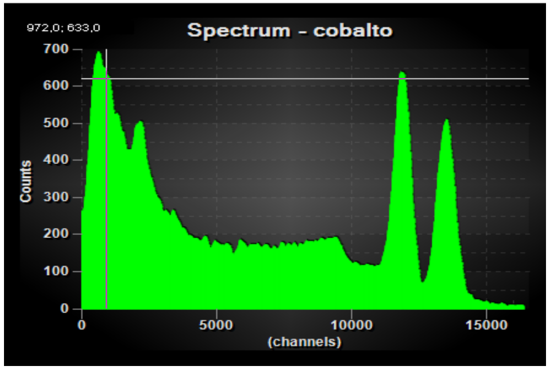


ITER RNC Validation Pulse Processing

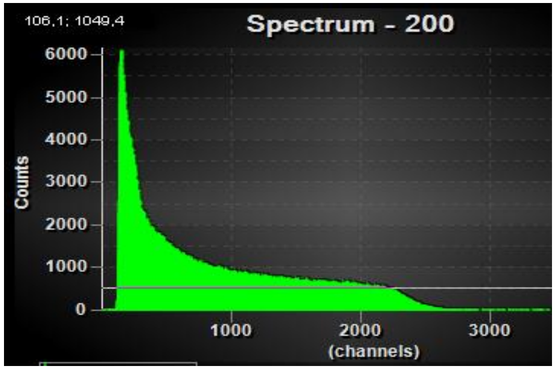
- Validation using known CAEN DT5800D generator



Pulse shape

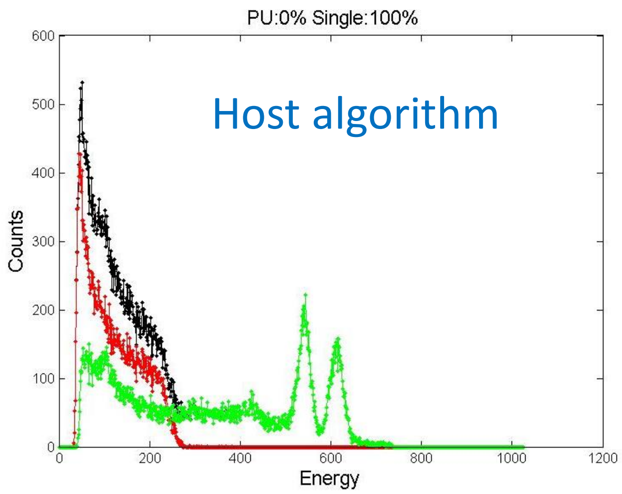


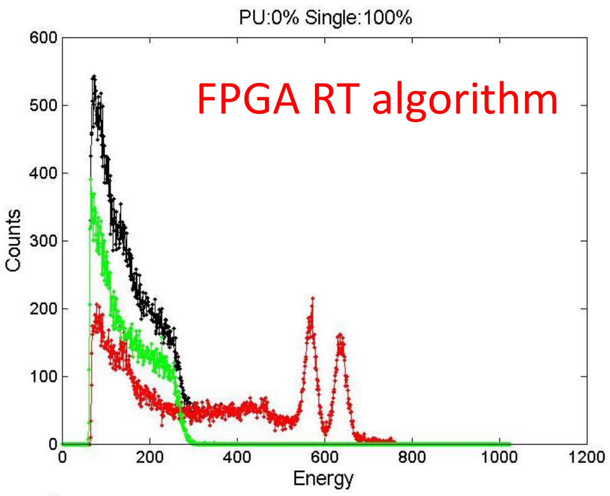
Gamma spectrum emulation



Neutron spectrum emulation

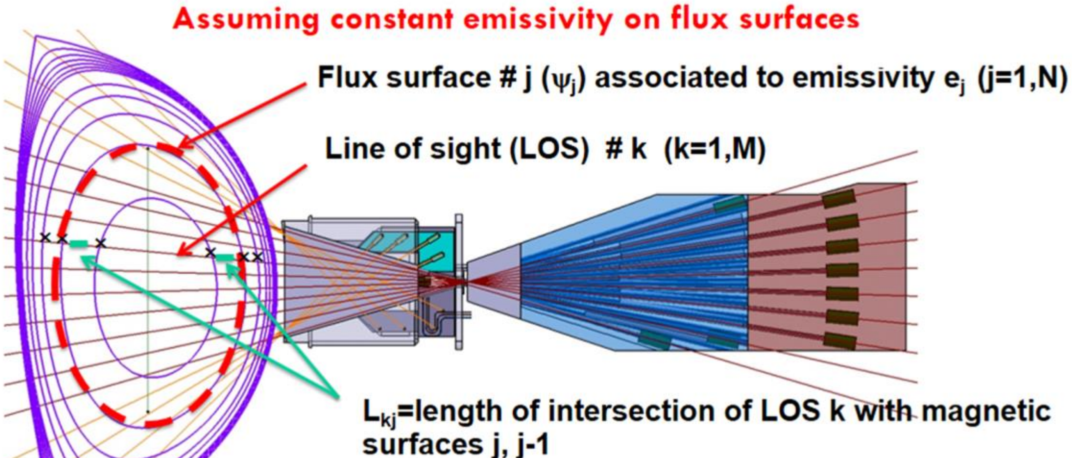
- Cross validation with FPGA code results





- Validation and performance measurements using Frascati Neutron Generator

ITER RNC Inversion Algorithm



b_k= line-integrated signal for LOS k

$$b_k = \sum_{j=1}^{N} l_{kj} e_j \qquad k = 1, M$$

$$b = L\, e \qquad (1)$$

Tikhonov regularization method

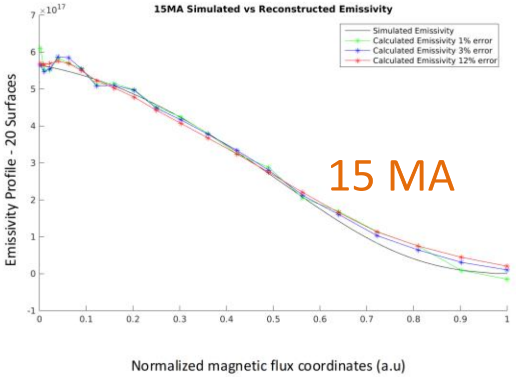
Solve the linear system using the procedure, based on Tikhonov regularization minimizing the functional

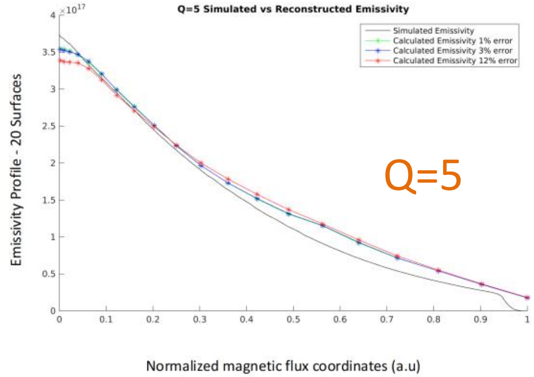
$$\left\| Le - b \right\|_2 + \alpha \left\| D\, e \right\|_2$$

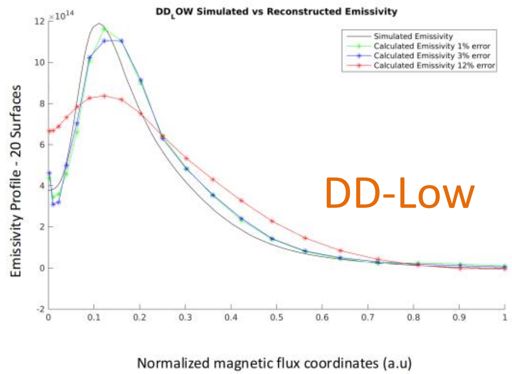
Regularization parameter to be minimized

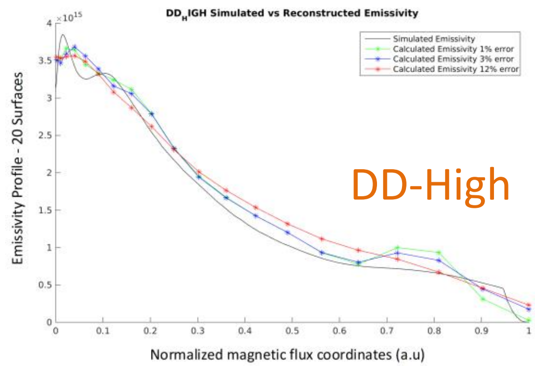
Regularization operator to impose physical constraints to the solution

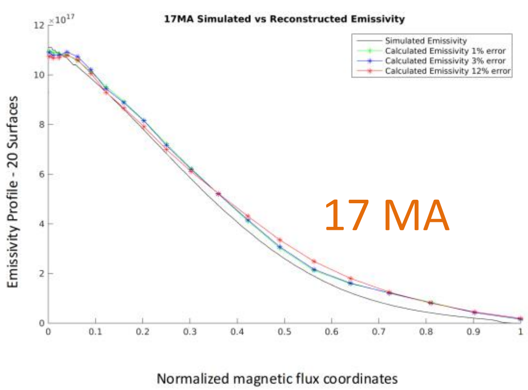
ITER RNC Validation of Inversion Algorithm

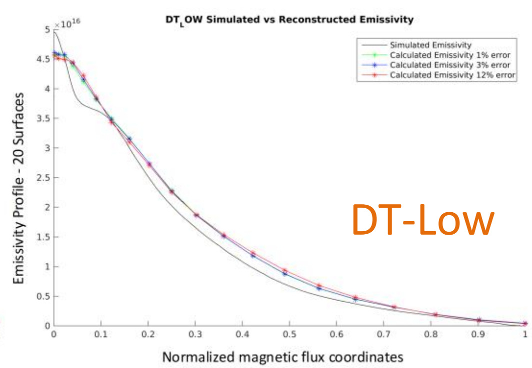












Validation for relevant ITER scenarios of the algorithm results was the first step to understand if the code run and converge with the correspondent simulated emissivity.

Crosscheck of the reconstructed emissivity, for different level of random noise (1%, 3% and 12%) using 20 magnetic surfaces, with the correspondent simulated emissivity was done for ITER relevant scenarios.

ITER Scenarios:

- 15 MA scenario;
- Q=5 scenario;
- DD-Low scenario;
- DD-High scenario;
- 17 MA scenario;
- DT-Low scenario.

Summary & Conclusions

- Different system architectures and studies have been executed to implement high performance systems aiming at:
  - High availability
  - Redundancy at all possible levels
  - Efficient system remote monitoring, management and control
  - Data integrity
  - Resilient and safe operation
- System prototypes have been designed to
  - Implement critical algorithms
  - Validate the results of the algorithms
  - Measure the systems performance
- Performance tests helped to retrieve valuable information to size the optimal system configurations and future developments design
- FPGA and CPU algorithms have been implemented successfully stressing the limits of high performant software architectures and hardware implementations

High-performance instrumentation for diagnostics and control in fusion devices

N. Cruz

On behalf of the Control and Data Acquisition Team

of

Instituto de Plasmas e Fusão Nuclear, Instituto Superior Técnico, Universidade de Lisboa, 1049-001 Lisboa, Portugal

*(Coimbra) A. Combo, A. Fernandes, A.P. Rodrigues, B. Santos, M. Correia, N. Cruz, P. F. Carvalho, R. C. Pereira, (Lisboa) A. J. N. Batista, B. B. Carvalho, J. Sousa