Overview of the TCV digital real time plasma control system and its applications

IAEA 13th Technical Meeting on Plasma Control Systems, Data Management and Remote Experiments in Fusion Research

Cristian Galperti

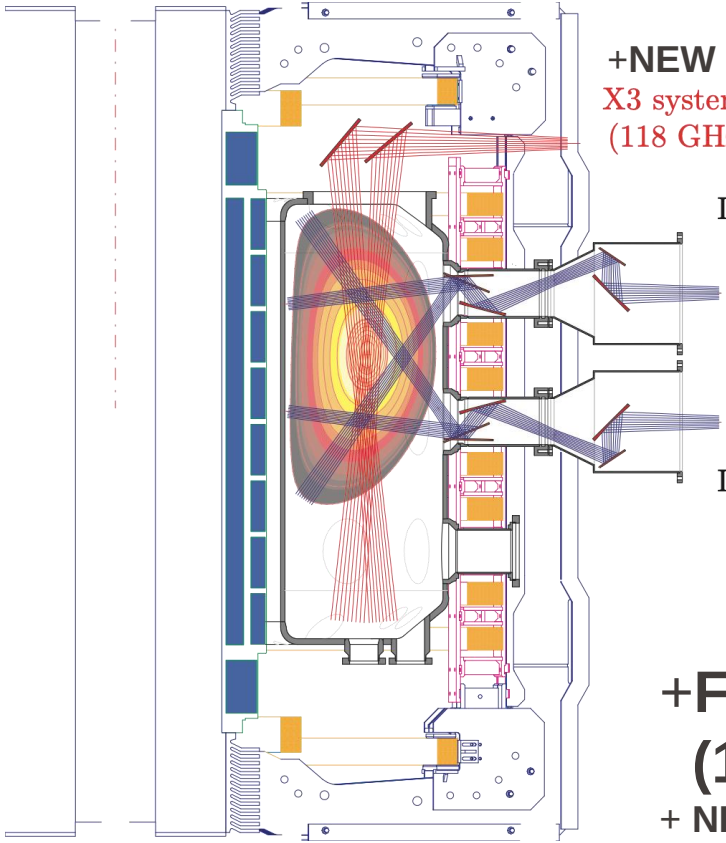
Federico Felici, Trang Vu, Olivier Sauter, Francesco Carpanese, Mengdi Kong, Gino Marceca, Antoine Merle, Alessandro Pau, Federico Pesamosca, Marcelo Baquero-Ruiz, Stefano Coda, Joan Decker, Basil Duval, Mateusz Gospodarczyk, Alexander Karpushov, Blaise Marletaz, Daniele Carnevale, Nicolo' Ferron, Jesse Koenders, Bob Kool, Gabriele Manduchi, Marc Maraschek, Peter Milne, Andre' Cabrita Neto, Arthur Perek, Emanuele Poli, Timo Ravensberger, Matthias Reich, Natale Rispoli

Swiss Plasma Center

06.07.2021

Galperti Cristian

The TCV tokamak



+NEW fast steerable antenna

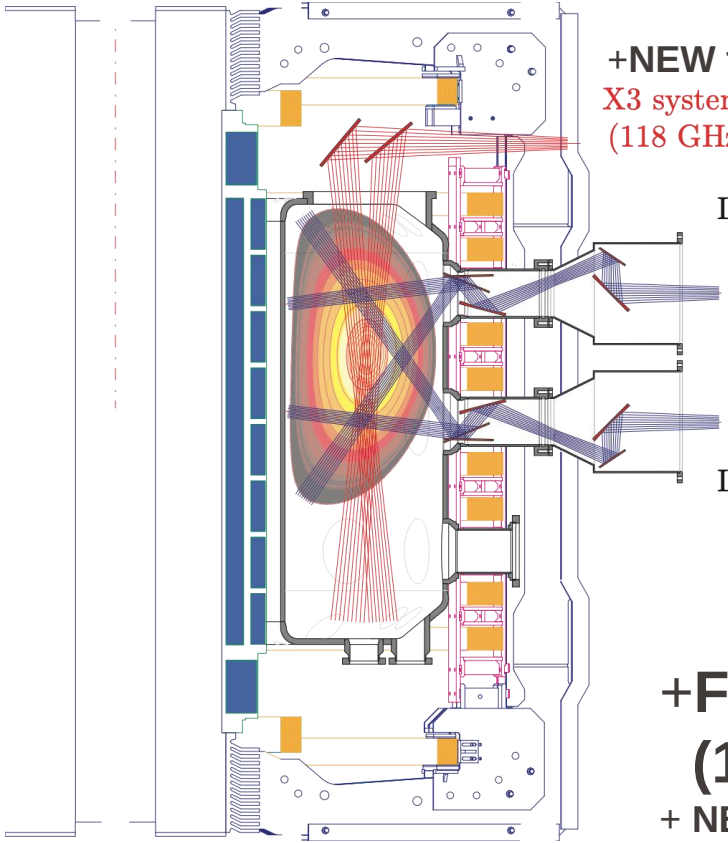
+NEW X3 (118GHz)

+Flexible digital control system (100% Simulink-programmable)

+ NBH (1 and new 2)

B_t = 1.5T, I_p<1MA, a=0.25m R=0.88m κ<2.8

The TCV tokamak



+NEW fast steerable antenna

+NEW X3 (118GHz)

- >390 signals at 10-250 kHz and >10 cameras at 1kHz to be interfaced
- Multi actuators experiment:16 PF coils, 2 Ohmic coils, 8 launchers, >3 gas valves, 6 gyrotrons, 2 NBHs
- Demanding constraint on main plasma control cycle time (<100 us, 10kHz)
- Plant-wide real-time distributed system
- Control research experiment: control system flexible and quick to implement new ideas but rigorous enough to maintain the good ones.

+Flexible digital control system (100% Simulink-programmable)

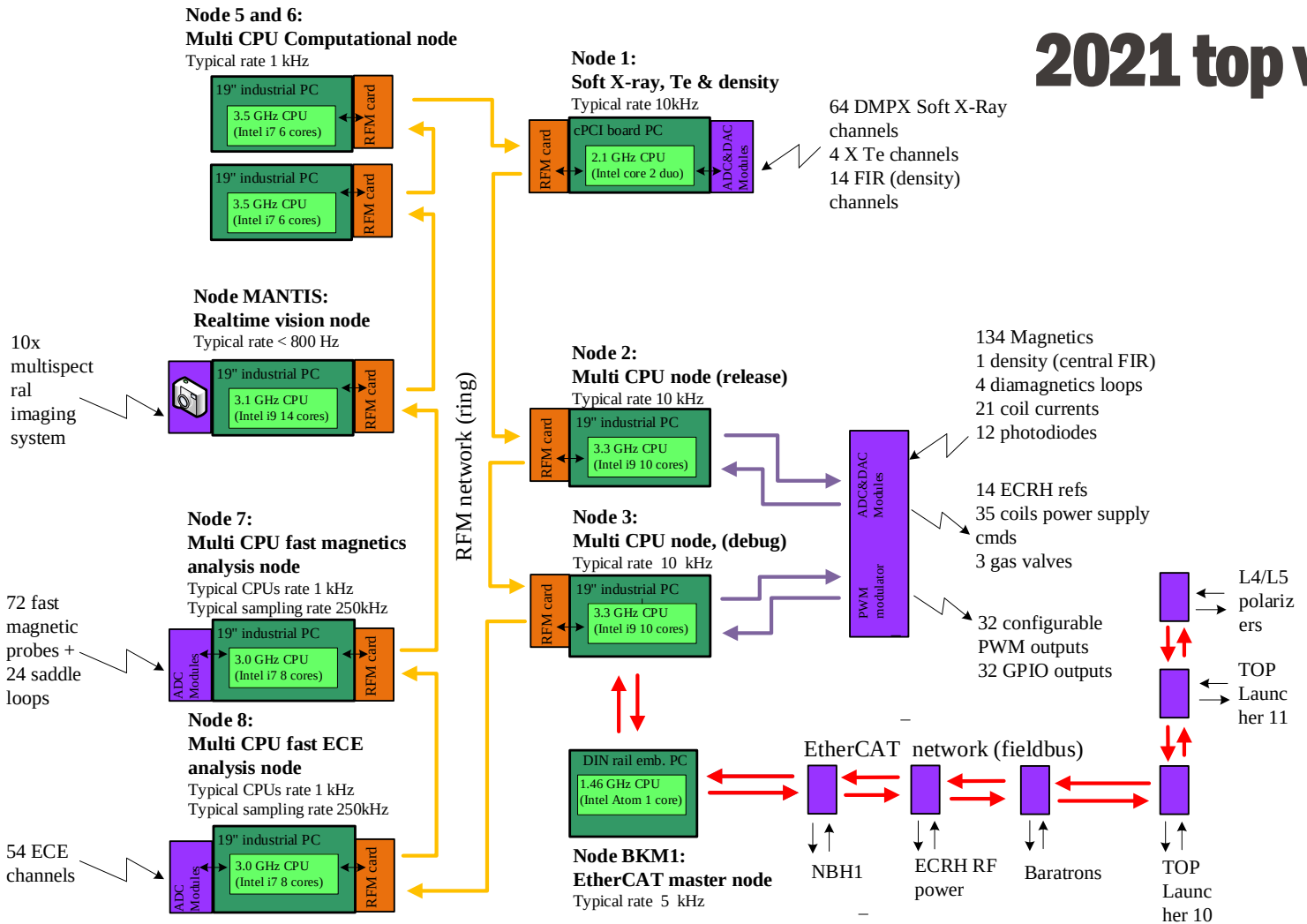
+ NBH (1 and new 2)

B_t = 1.5T, I_p<1MA, a=0.25m R=0.88m κ<2.8

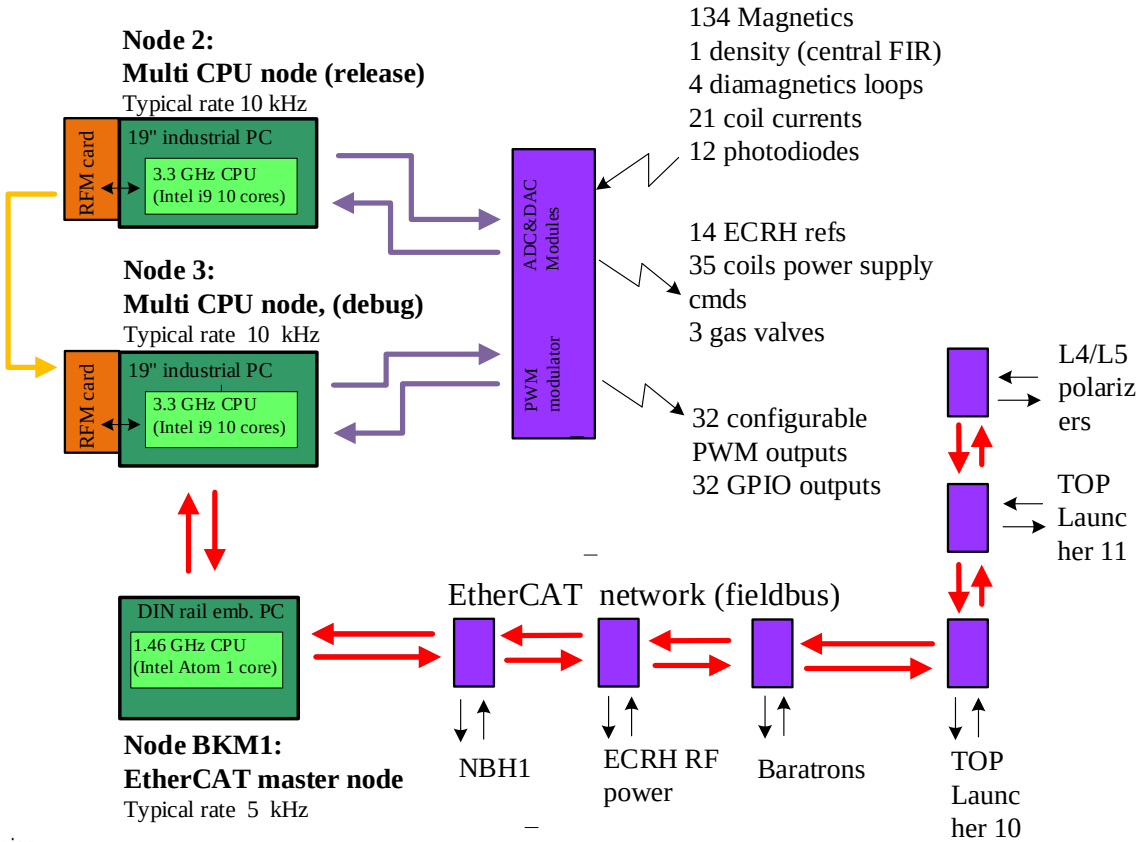
The digital real-time control system

- > 10 years continuous development -> mature system
- Control code mainly written and maintained in Simulink and autogenerated for MARTe2 capable systems, all data stored in MDSplus
- New: introspective generated code, fully and automatically interfaceable to MDS+ for its run-time configuration
- Various types of interconnected control subsystems:
  - Low latency systems for hard real time control at fastest rate
  - Oversampling systems for fast diagnostics acquisition followed by complex real-time analysis algorithms
  - Multi-core computational systems for CPU hungry codes
  - Real-time vision nodes for vision in the loop systems
- EtherCAT for fast, flexible, distributed and cost effective I/O interconnection

2021 top view



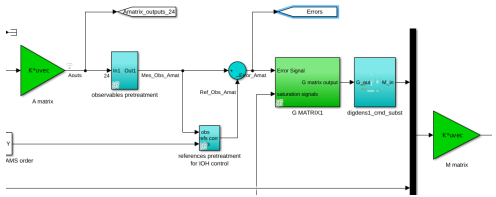
Hardware highlights



- Twin multi-core computer main machine control system
- The two computers can run real-time code in parallel on the same discharge (only 1 controlling it though)
- 10 kHz control rate on 192 inputs – 64 outputs system
- Articulated EtherCAT network for agile low bandwidth – low I/O systems interconnection

Control code handling

Simulink model



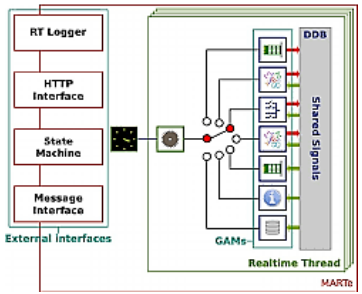
MDS+ parameters and waveforms DB

Common set of loader mechanism

Automatic code generation

Simulink simulation

=

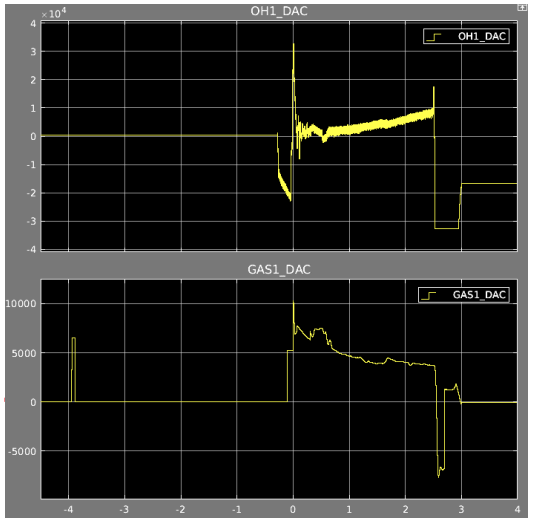


RT execution

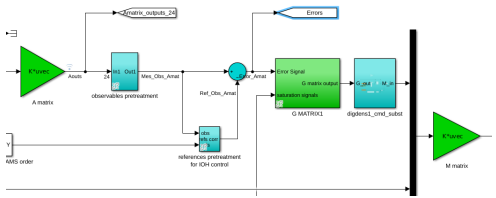
MARTe2 control system

Control code handling

Simulink simulation



Simulink model

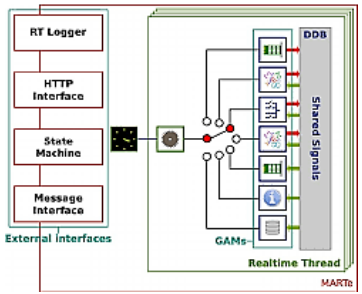


MDS+ parameters and real shot waveforms DB

Common set of loader mechanism

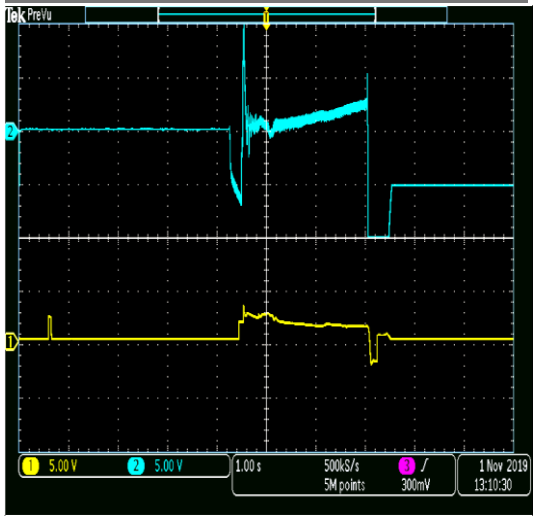
Automatic code generation

Functionally equivalent MATLAB and C++ loader classes



MARTe2 control system

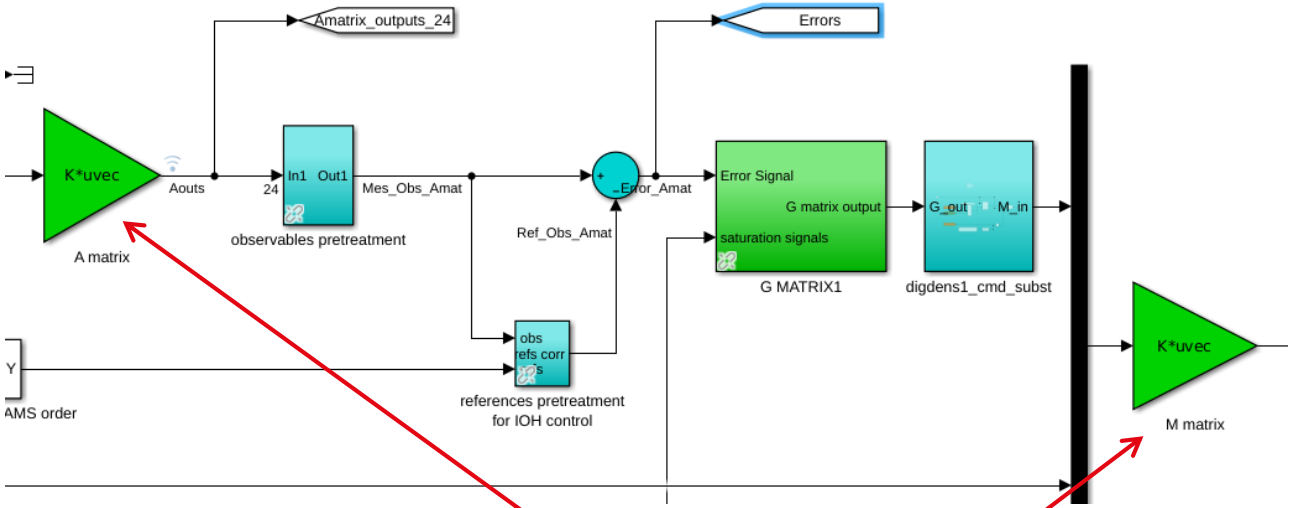
RT execution



Swiss Plasma Center

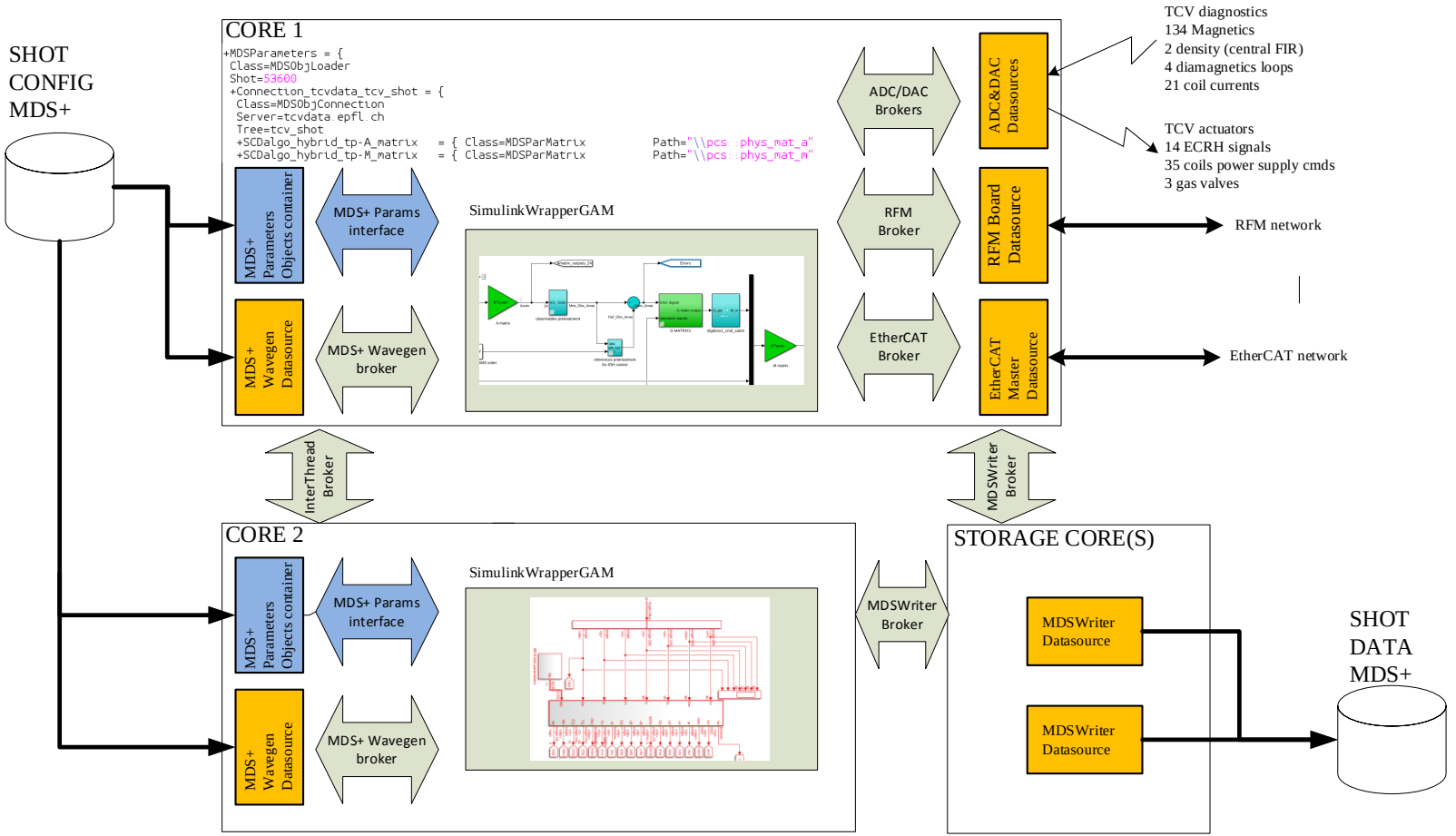
Galperti Cristian

MATLAB/Simulink MDS+ loader classes

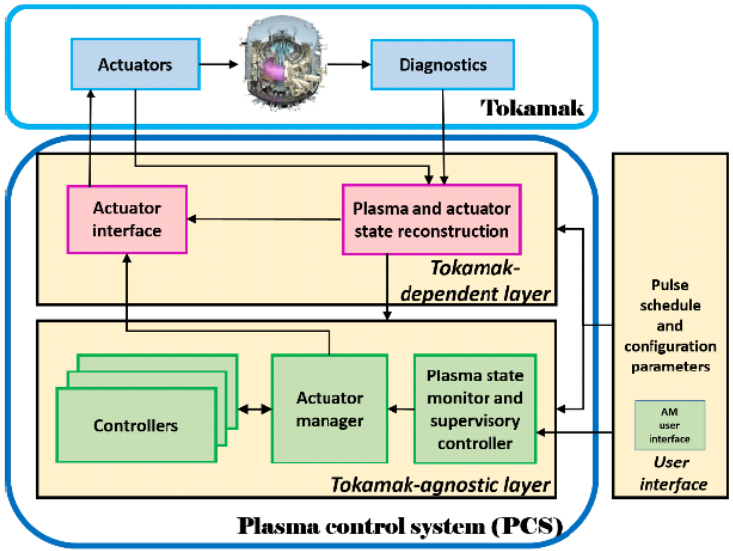



```
obj=SCDclass_algo('SCDalgo_hybrid');
obj=obj.settiming(-4.5,1e-4,3);
obj=obj.addtunparamstruct('SCDalgo_hybrid_tp');
obj=obj.addparameter(SCDclass_mdsparmatrix          ('\pcs::phys_mat_a',                  'A_matrix'    ));
obj=obj.addparameter(SCDclass_mdsparmatrix          ('\pcs::phys_mat_m',                  'M_matrix'    ));
obj=obj.addparameter(SCDclass_mdspar3Dmatrix        ('\pcs::phys_mat_g1',                 'G1_matrix'   ));
obj=obj.addparameter(SCDclass_mdspar3Dmatrix        ('\pcs::phys_mat_g2',                 'G2_matrix'   ));
obj=obj.addparameter(SCDclass_mdspar3Dmatrix        ('\pcs::phys_mat_g3',                 'G3_matrix'   ));
obj=obj.addparameter(SCDclass_mdsparfixdimvector    ('dim_of(\pcs::phys_mat_addresses:G)',  'G_time'    ,50));
obj=obj.addparameter(SCDclass_mdsparfixdimvectorint ('\pcs::phys_mat_addresses:G',        'G_order'   ,50));
```

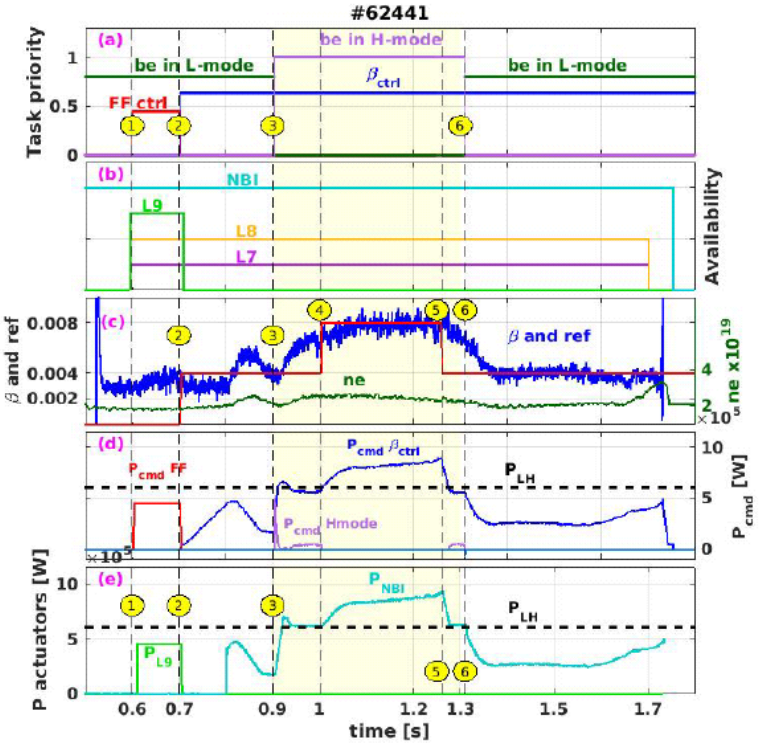
MARTe2 based control architecture



Supervisory actuator manager and off normal event handling



- Complete configurable plasma supervisory, actuator manager and off normal events handler to deal with multiple tasks and few actuators

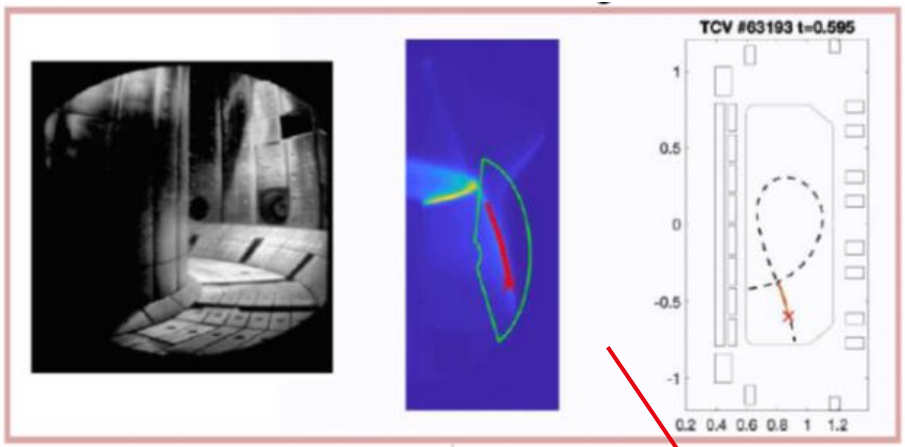


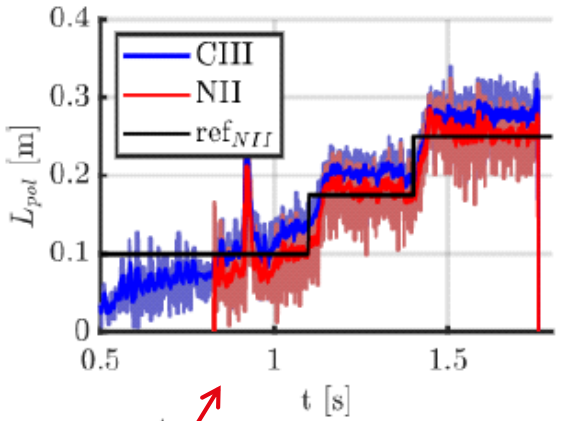
- Beta real-time control togther with confinement status (L/H) control via NBH 1

Swiss Plasma Center

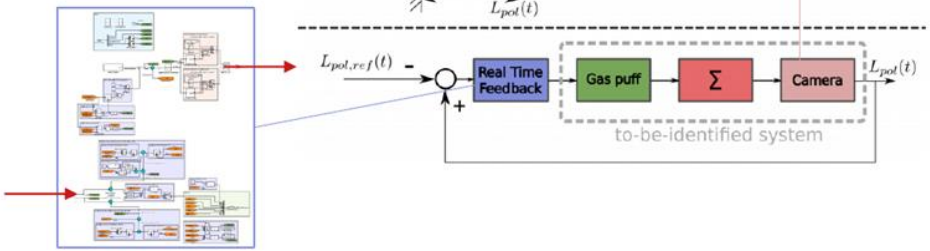
T. Vu et al. IEEE TNS 2021

Vision in the loop detachment control





- Divertor detachment front detected in real-time through vision processing algorithms
- 0D detachment signal used to control detachment via SISO controller acting on a fuelling or seeding valve



T. Ravensbergen et al., Nature Communications 12, 1105 (2021)
J.T.W. Koenders et al., 47th EPS Conference on Plasma Physics (Virtual), P1.1058, June 21-25, 2

Conclusions and outlook

- TCV has a state of the art, powerful and flexible digital control system
- Together with the extreme flexibility of the machine, this promotes TCV as a cutting edge facility for plasma control experiments
- A number of domestic and international control activities have been done and are ongoing on this topic
- Its software architecture is very general yet robust, it has allowed the seamless cohexistence of several control modules (e.g. basic plasma control together with advanced actuator manager)
- The system will be expanded in the future by adding additional diagnostics nodes (e.g. real-time Thomson scattering) alongside pure processing nodes

Thank you

cristian.galperti@epfl.ch

N. M. T. Vu et al., "Tokamak-agnostic actuator management for multi-task integrated control with application to TCV and ITER," Fusion Eng. Des., vol. 147, p. 111260, Oct. 2019.
F. Felici et al., "Integrated real-time control of MHD instabilities using multi-beam ECRH/ECCD systems on TCV," Nucl. Fusion, vol. 52, no. 7, p. 074001, Jul. 2012.
T. C. Blanken et al., "Model-based real-time plasma electron density profile estimation and control on ASDEX Upgrade and TCV," Fusion Eng. Des., vol. 147, 2019.
F. Felici et al., "Real-time physics-model-based simulation of the current density profile in tokamak plasmas," Nucl. Fusion, vol. 51, no. 8, p. 083052, Aug. 2011.
E. Maljaars et al., "Profile control simulations and experiments on TCV: a controller test environment and results using a model-based predictive controller," Nucl. Fusion, vol. 57, no. 12, p. 126063, Dec. 2017.
E. Poli et al., "TORBEAM 2.0, a paraxial beam tracing code for electron-cyclotron beams in fusion plasmas for extended physics applications," Comput. Phys. Commun., vol. 225, pp. 36–46, Apr. 2018.
H. Anand et al., "Distributed digital real-time control system for the TCV tokamak and its applications," Nucl. Fusion, vol. 57, no. 5, p. 056005, May 2017.
T. Vu et al., "Integrated real-time supervisory management for off-normal-event handling and feedback control of tokamak plasmas," IEEE Trans. Nucl. Sci., pp. 1–1, 2021.
M. Kong et al., "Control of neoclassical tearing modes and integrated multi-actuator plasma control on TCV," Nucl. Fusion, vol. 59, no. 7, p. 076035, Jul. 2019.
F. Carpanese, F. Felici, C. Galperti, A. Merle, J. M. Moret, and O. Sauter, "First demonstration of real-time kinetic equilibrium reconstruction on TCV by coupling LIUQE and RAPTOR," Nucl. Fusion, vol. 60, no. 6, p. 066020, Jun. 2020.
T. Ravensbergen et al., "Real-time feedback control of the impurity emission front in tokamak divertor plasmas," Nat. Commun., vol. 12, no. 1, p. 1105, Dec. 2021.
C. Galperti et al., "Integration of a Real-Time Node for Magnetic Perturbations Signal Analysis in the Distributed Digital Control System of the TCV Tokamak," IEEE Trans. Nucl. Sci., vol. 64, no. 6, pp. 1446–1454, Jun. 2017.
U. A. Sheikh et al., "Disruption avoidance through the prevention of NTM destabilization in TCV," Nucl. Fusion, vol. 58, no. 10, p. 106026, Oct. 2018.
Marceca G. et al, Proceedings, 47th EPS Conference on Plasma Physics: virtual conference, June 21-25, 2021
Carnevale, D., et al. "Runaway electron beam control." Plasma Physics and Controlled Fusion 61.1 (2018): 014036.
F Pesamosca et al, Model-based frequency decoupled control of plasma shape and position in the TCV tokamak, EPS 2021