Real-time magnetic control at JET tokamak

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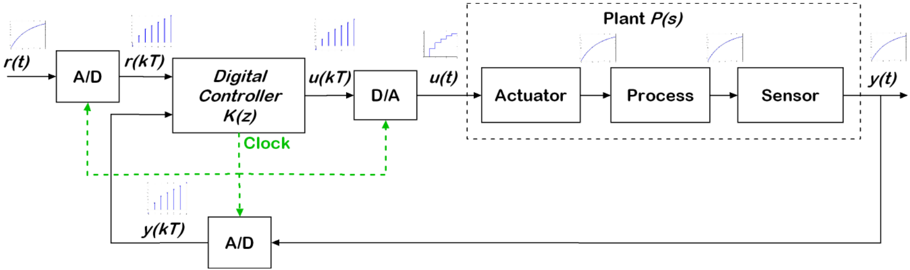
November 24th 2009

4th GOTiT High Level Course

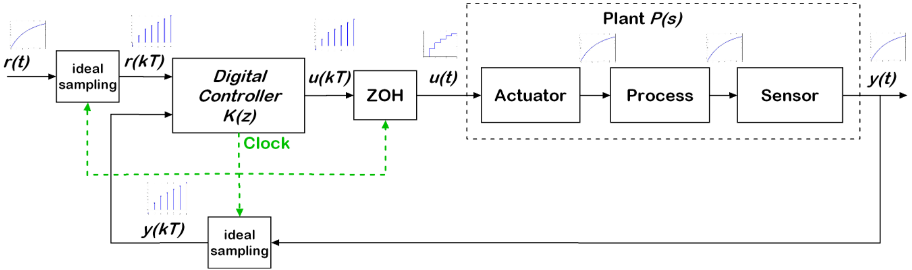
Magnetic Control of Tokamak Plasmas

Outline

Reference control scheme



Reference control scheme



Digital controllers

A linear time-invariant digital controller can be specified in the discrete-time domain by means of difference equations

$$\begin{aligned} x(k+1) &= Ax(k) + Be(k) \\ u(k) &= Cx(k) + De(k) \end{aligned}$$

or by the transfer-function in the $\mathcal{Z}$ domain

$$K(z) = C\big(zI - A\big)^{-1}B + D\,.$$

Reconstruction of sampled signals

Given a sampled signal $\{u(k)\}$ with sampling period $T = 1/\omega_s$, one possible way to reconstruct the signal is

$$u(t) = \sum_{k=-\infty}^{+\infty} u(k) sinc \frac{\pi(t - kT)}{T} . \qquad (1)$$

Equation (1) is *noncausal*.

In many communications problems the noncausality can be overcome by adding a phase lag, which adds a **delay** to the reconstructed signal.

In feedback control systems, delays are disastrous for stability! Therefore the *simpler* polynomial reconstruction is used. In particular a Zero-Order Hold (ZOH) is usually adopted.

Frequency response of a ZOH

The frequency response of a ZOH is

$$ZOH(j\omega) = e^{-\frac{\omega T}{2}} T sinc\left(\frac{\omega T}{2}\right) .$$

The scaling factor T is *absorbed* by the sampler.

If the bandwidth of the closed-loop system is smaller than the Nyquist frequency $\omega_N = \frac{\omega_s}{2}$ (it is usual to work with $\omega_B < \omega_N/8$), then

- the distortion in amplitude can be neglected
- BUT a phase lag equal to $e^{-j\frac{\omega T}{2}}$ MUST BE considered

Design approaches for digital control systems

- Design in the $\mathcal{L}$ domain (continuous-time) and digitization the controller
- Synthesis in the $\mathcal{Z}$ domain (discrete-time)

Design in the $\mathcal{L}$ domain

- This approach is suitable for SISO systems.
- The sampling frequency has to be choose in the proper way, so as to avoid aliasing, hidden oscillation, *ringing* of the controller, etc.
- The controller $K(s)$ is designed in the $\mathcal{L}$ domain taking explicitly into account the delay due to the phase lag $e^{-j\frac{\omega T}{2}}$ of the ZOH.
- Digitization of the controller $K(s)$ so as to attain a discrete-time approximation $K(z)$

Digitization of continuous-time controllers

Taking into account that

$$\int_{kT}^{(k+1)T} f(\tau)d\tau \cong Tx(kT)\,, \quad \text{Forward method}$$

$$\int_{kT}^{(k+1)T} f(\tau)d\tau \cong Tx\big((k+1)T\big)\,, \quad \text{Backward method}$$

$$\int_{kT}^{(k+1)T} f(\tau)d\tau \cong \frac{T}{2}\Big(x(kT)+x\big((k+1)T\big)\Big)\,, \quad \text{Trapezoidal method}$$

An discrete-time approximation $K(z)$ is obtained be simply replacing the argument s in $K(s)$ by s', where

$$s' = \frac{z-1}{T}\,, \quad \text{Forward method}$$

$$s' = \frac{z-1}{zT}\,, \quad \text{Backward method}$$

$$s' = \frac{2}{T}\frac{z-1}{z+1}\,, \quad \text{Trapezoidal method}$$

Digitization of continuous-time controllers

Matlab commands

`sys_d = c2d(sys_c,T_s,method)` - produces a continuous-time model `sys_c` that is equivalent to the discrete-time LTI model `sys_d`. `method` is a string that selects the conversion method (example `'Tustin'`).

Synthesis in the $\mathcal{Z}$ domain

Given the discrete-time plant $P(z)$, the controller $K(z)$ can be designed in the $\mathcal{Z}$ domain by

- pole-placement techniques based on
  - root locus
  - state space approach
  - polynomial approach (Ragazzini's method, Diophantine equations)
- optimal control approaches (suitable for MIMO systems)

Digitization of the plant

Given the LTI plant

$$\dot{x}(t) = Ax(t) + Bu(t)$$
$$y(t) = Cx(t) + Du(t)$$

a *sampled equivalent* is computed

$$x(k+1) = A_s x(k) + B_s u(k)$$
$$y(k) = C_s x(k) + D_s u(k)$$

with

$$A_s = e^{AT}\,, \quad B_s = \int_0^T e^{A\sigma} d\sigma B\,,$$

and $C_s = C$, $D_s = D$.

Suggested textbooks

- K. J. Åström and B. Wittenmark
  Computer-Controlled Systems - Theory and Design
  Prentice Hall, 1997
- G. F. Franklin, J. D. Powell and M. Workman
  Digital Control of Dynamic Systems
  Addison-Wesley, 1998

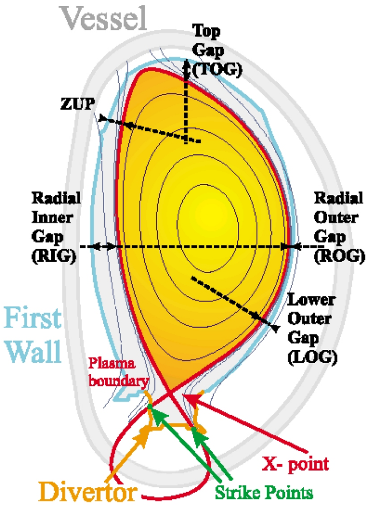
Plasma shape control

Controlled variables

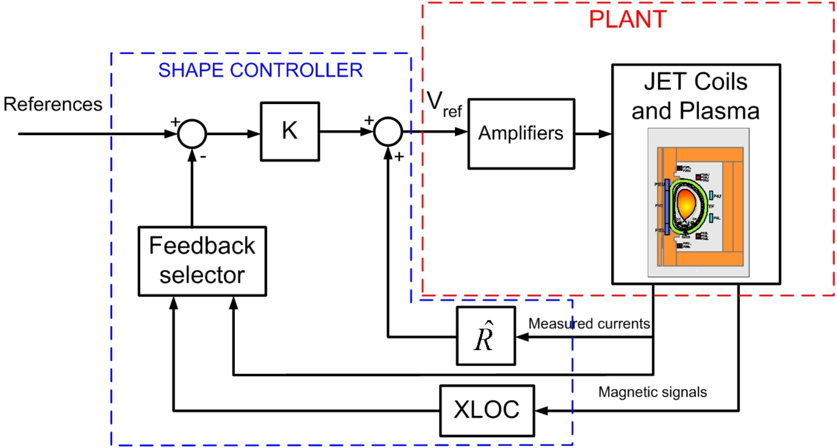
- Gaps
- Poloidal flux differences
- Other geometrical descriptors (e.g. triangularity and elongation)

Control variables

- PF coils voltages
- 9 independent PF circuits @ JET



JET Shape Controller - Controller Scheme



JET Shape Controller

Plant model without disturbances

$$\mathbf{V}_{PF} = \begin{bmatrix} L_1 & M_{12} & \dots & M_{1N} \\ M_{12} & L_2 & \dots & M_{2N} \\ \dots & \dots & \dots & \dots \\ M_{1N} & M_{2N} & \dots & L_N \end{bmatrix} \frac{\mathrm{d}\mathbf{I}_{PF}}{\mathrm{dt}} + \begin{bmatrix} R_1 & 0 & \dots & 0 \\ 0 & R_2 & 0 & 0 \\ \dots & \dots & \dots & \dots \\ 0 & 0 & \dots & R_N \end{bmatrix} \mathbf{I}_{PF}$$

Resistive compensation

$$\mathbf{V}_{PF_{ref}} = \hat{\mathbf{R}}\mathbf{I}_{PF} + \mathbf{K}(\mathbf{Y}_{ref} - \mathbf{Y})$$

Static relationship between PF coils current and controlled variables

$$\mathbf{Y} = \mathbf{T}\mathbf{I}_{PF}$$

Control Matrix

$$\mathbf{K} = \hat{\mathbf{M}}\mathbf{T}^{-1}\mathbf{C}^{-1} \text{ with } \mathbf{C} \text{ diagonal matrix}$$

JET Shape Controller

Closed-loop system

$$\mathbf{MT}^{-1}\dot{\mathbf{Y}} + \mathbf{RI}_{PF} = \mathbf{MT}^{-1}\mathbf{C}^{-1}(\mathbf{Y}_{ref} - \mathbf{Y}) + \mathbf{RI}_{PF} \Rightarrow$$
$$\Rightarrow \dot{\mathbf{Y}} = \mathbf{C}^{-1}(\mathbf{Y}_{ref} - \mathbf{Y})$$

By a proper choice of the **T** matrix it is possible to achieve:

- current control mode
- plasma current control mode
- gap control mode

F. Sartori, G. De Tommasi, F. Piccolo
The Joint European Torus
IEEE Control Systems Magazine, April 2006

JET Shape Controller

Summarizing...

- Each circuit is used to control a single variable (current, gap, flux)
- Up to 9 different variables can be controlled
- When plasma current is controlled up to 8 gaps can be controlled

eXtreme Shape Controller

SC in *current control mode*

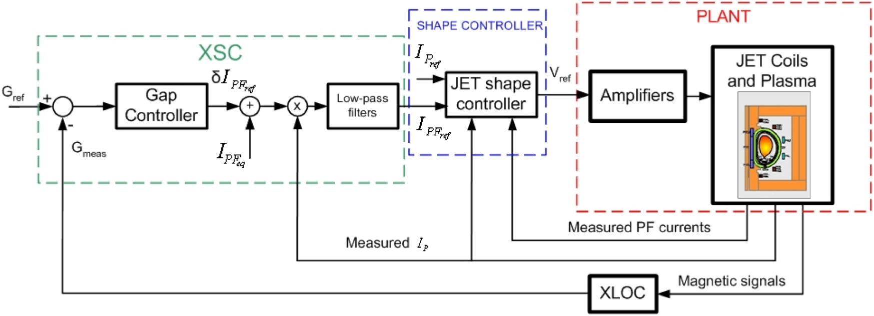
The XSC exploits the standard JET Shape Controller architecture. In particular it sets:

- the P1 circuit in *plasma current control mode*
- the other 8 PF circuits in *current control mode*

Model of the *current controlled* plant

$$\delta \mathbf{g}(s) = \frac{\widetilde{\mathbf{C}}}{1 + s\tau} \cdot \frac{\delta \mathbf{I}_{PF_{REF}}(s)}{I_P}$$

XSC - Controller scheme



eXtreme Shape Controller (XSC)

- The *eXtreme Shape Controller* (XSC) controls the whole plasma shape, specified as a set of 32 geometrical descriptors, calculating the PF coil current references.
- Let $\mathbf{I}_{PF_N}(t)$ be the PF currents normalized to the equilibrium plasma current, it follows that

  $$\delta \mathbf{g}(t) = \mathbf{C}\ \delta \mathbf{I}_{PF_N}(t).$$

  It follows that the plasma boundary descriptors have the same dynamic response of the PF currents.
- The XSC design has been based on the **C** matrix. Since the number of independent control variables is less than the number of outputs to regulate, it is not possible to track a generic set of references with zero steady-state error.

eXtreme Shape Controller (XSC)

- The XSC has then been implemented introducing weight matrices both for the geometrical descriptors and for the PF coil currents.
- The determination of the controller gains is based on the SVD of the following weighted output matrix:

$$\widetilde{\mathbf{C}} = \widetilde{\mathbf{Q}}\,\mathbf{C}\,\widetilde{\mathbf{R}}^{-1} = \widetilde{\mathbf{U}}\,\widetilde{\mathbf{S}}\,\widetilde{\mathbf{V}}^{T},$$

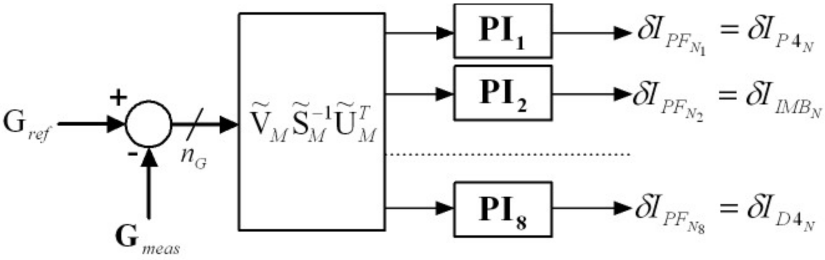
  where $\widetilde{\mathbf{Q}}$ and $\widetilde{\mathbf{R}}$ are two diagonal matrices.
- The XSC minimizes the cost function

$$\widetilde{J}_1 = \lim_{t\to+\infty} (\delta\mathbf{g}_{ref} - \delta\mathbf{g}(t))^T \widetilde{\mathbf{Q}}^T \widetilde{\mathbf{Q}} (\delta\mathbf{g}_{ref} - \delta\mathbf{g}(t)),$$

  using $\bar{n} < 8$ degrees of freedom, while the remaining $8 - \bar{n}$ degrees of freedom are exploited to minimize

$$\widetilde{J}_2 = \lim_{t\to+\infty} \delta\mathbf{I}_{PF_N}(t)^T \widetilde{\mathbf{R}}^T \widetilde{\mathbf{R}} \delta\mathbf{I}_{PF_N}(t).$$

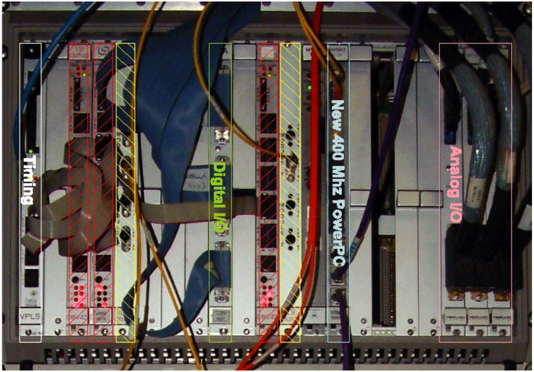
XSC - Gap controller



XSC - Hardware architecture

VME-based architecture

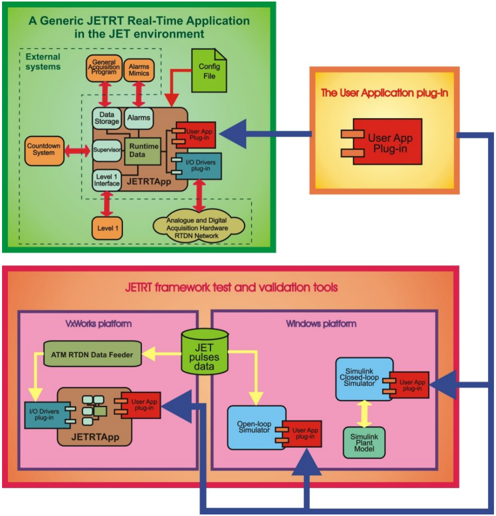
- PowerPC G4 400 CPU
- Analog and digital I/O boards
- ATM network



XSC - Software architecture

JETRT framework

- Modular *plug-in based* architecture
- Improves code reusability
- Substantial reduction of the time needed for the commissioning on the plant
- Non-expert can easily develop plug-ins



JETRT - Configuration file

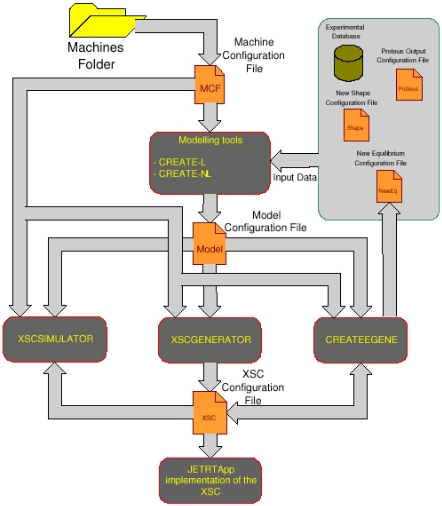
The system can be easily configured via a simple text file

```
...

RTApplicationThread = {
    DriverPool = {
        Driver0 = {
            BoardName=ATM4
            Class=ATMDrv
            MaxDataAge=1000000
            NumberOfInputChannels=128
            SyncroOnInputTimeout=1
            Vci=410
        }
        Driver1 = {
            BoardName=ATM3
            Class=ATMDrv
            NumberOfOutputChannels=116
            SyncroOnInputTimeout=1000
            Vci=406
        }

...
```

XSCTools


Machines
Folder
Machine
Configuration
File
MCF
Experimental
Database
Proteus Output
Configuration File
Proteus
New Shape
Configuration File
Shape
New Equilibrium
Configuration File
NewEq
Modelling tools
- CREATE-L
- CREATE-NL
Input Data
Model
Configuration File
Model
XSCSIMULATOR
XSCGENERATOR
CREATEEGENE
XSC
Configuration
File
XSC
JETRTApp
implementation of the
XSC

XSC - References

M. Ariola, A. Pironti
The design of the extreme shape controller for the JET tokamak
IEEE Control Systems Magazine, 2005

R. Albanese et al.
Design, implementation and test of the XSC Extreme Shape Controller in JET
Fusion Engineering and Desing, 2005

F. Sartori et al.
The system architecture of the new JET Shape Controller
Fusion Engineering and Desing, 2005

G. De Tommasi et al.
XSC Tools: a software suite for tokamak plasma shape control design and validation
IEEE Transactions on Plasma Science, 2007

Advanced Tokamak Scenarios

AT plasmas

An *Advanced Tokamak* (AT) plasma is a plasma with:

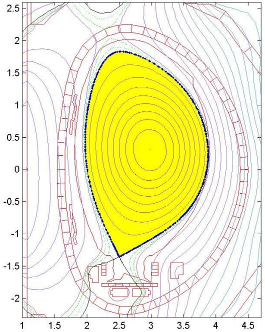
- high plasma kinetic pressure;
- a large fraction of self-induced current;
- a good particle and energy confinement.

- AT scenarios are aimed at allowing steady-state operation without a large amount of externally driven current.
- AT scenarios are aimed to increase the efficiency of a tokamak reactor.

Plasma shape control in AT scenarios

To achieve AT plasma performance, accurate shape control is needed:

- to obtain the shapes required to achieve high β;
- to optimize the coupling with the additional heating systems;
- to optimize divertor shape for pumping;
- ....

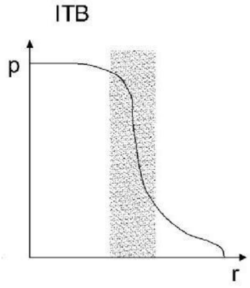


Plasma profile control in AT scenarios

Control of the plasma internal pressure and current profiles in AT regimes is needed:

- to improve the energy confinement;
- to increase the noninductive current fraction (*bootstrap current*).

- One way to increase the boostrap fraction is to generate an *internal transport barrier* (ITB), which also causes a reduction of turbulence and therefore an increase of confinement.
- ITB triggering strongly depends from the current density profile.



Plasma boundary flux control

- Steady-state scenarios should in principle be fully noninductive, and zero loop voltage should be maintained at the plasma boundary.
- Obtaining effective and routine boundary flux control is an essential step in AT regime.
- **An integrated approach for the control of the plasma shape and boundary flux has been developed at JET, and it has been tested on ITER-relevant plasmas.**

Plasma Boundary Shape Control at JET with XSC

- The boundary flux controller for the JET tokamak has been implemented using the XSC architecture.
- The actuator that has been chosen to control the plasma boundary flux ψ_b is the current in the *P1* circuit. The other circuits are much less efficient and therefore it is much worth to use them for the shape control.
- When controlling ψ_b, the control of the *P1* current is released to the XSC. A new actuator is then available to the XSC and it is used to control ψ_b, with negligible influence on the shape.
- When the XSC controls ψ_b the plasma current is not controlled, and it is left floating between given bounds.

Plant model

Plant model

In order to design the plasma boundary flux controller, a SISO model in the form

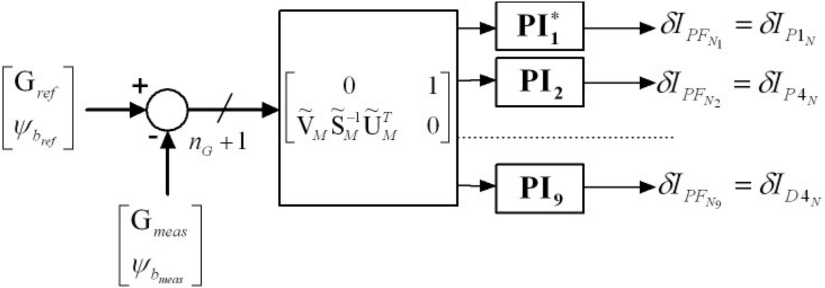
$$\delta\psi_b(s) = W(s)\delta I_{P_1}(s), \quad (2)$$

is needed.

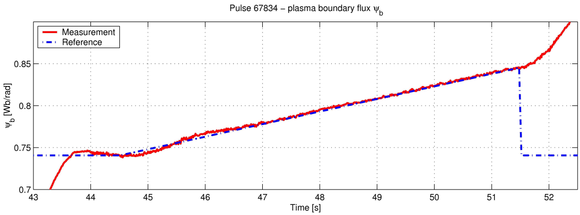
To obtain a model in the form (2):

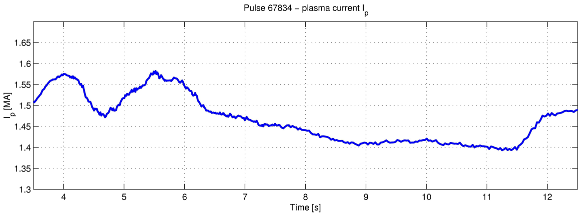
1. the loop consisting of the XSC and the plant model has been considered.
2. a model order reduction has been performed so that a low-order model is obtained. (A balanced model reduction has been performed, arriving to a model of the fourth order).

XSC with boundary flux control

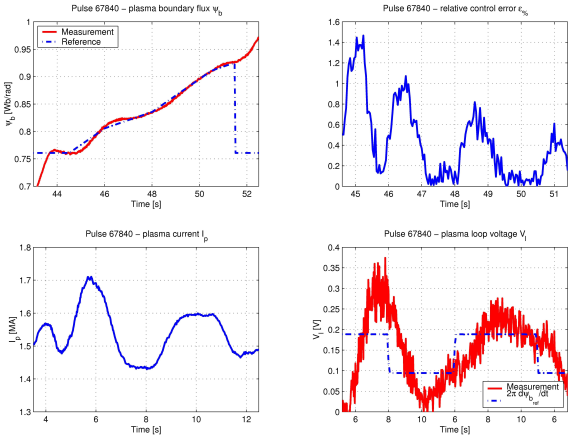


Constant v_{loop}

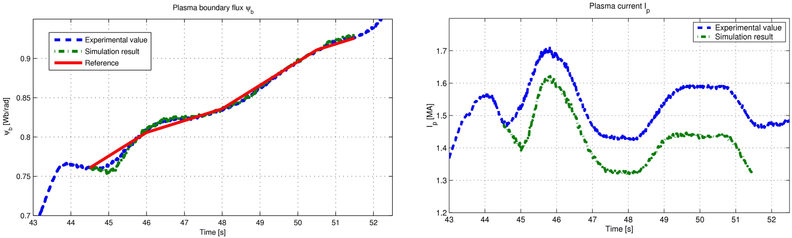




v_{loop} modulation



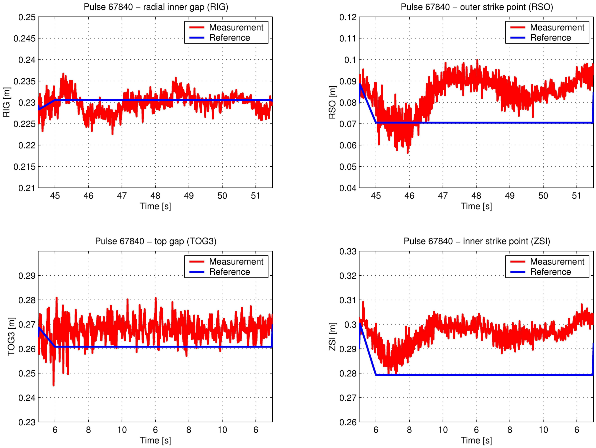
Simulation vs. experiment



(a) Plasma boundary flux $\psi_b(t)$. (b) Plasma current $I_p(t)$.

Figure: Simulation of the plasma loop voltage modulation experiment.

v_{loop} modulation - plasma shape



Conclusions

- In the future, the XSC with boundary flux control will be integrated in a more general scheme with the objective of obtaining a centralized controller for the plasma shape, boundary flux, current and pressure profiles.

References

M. Ariola et al.
Integrated plasma shape and boundary flux control at JET tokamak
Fusion Science and Technology, 2008

D. Moreau et al.
A two-time-scale dynamic-model approach for magnetic and kinetic profile control in advanced tokamak scenarios on JET
Nuclear Fusion, 2008

High performance plasmas and vertical position control in tokamaks

High performance in tokamaks are achieved for:

- **unstable** plasmas with elongated poloidal cross section
- maximization of plasma volume in the vacuum chamber

The plasma shape and position control system must guarantee good clearance between the plasma and the facing components.

This is especially true for future operation at JET with the beryllium ITER-like wall.

VS & JET PCU Project - 1

The **Plasma Control Upgrade (PCU)** project has increased the capabilities of the JET **Vertical Stabilization (VS)** system so as to meet the requirements for future operations at JET (ITER-like wall, tritium campaign, . . .).

The PCU project aims to enhance the ability of the VS system to recover from large ELMs, specially in the case of plasmas with large *growth rate*.

VS & JET PCU Project - 2

Within the PCU project, the design of the new VS system has included

1. the design of the new power supply for the FRFA circuit
2. the assessment of the best choice for the number of turns for the coils of the FRFA circuit
3. **the design of the new VS software, so as to deliver to the operator an high flexible architecture**

Why a new software architecture?

- Better fusion performance in tokamaks are achieved with highly elongated plasmas in presence of large ELM perturbations
- In these **extreme scenarios** a *general purpose controller* cannot guarantee the requirements
- To push the performance up to the desired level, it is usual to rely on a model based design approach which assures the needed control performance (e.g. eXtreme Shape Controller, XSC)
- **To optimize the system behavior in each *advanced plasma scenario*, it should be possible to choose**
  - **different estimations of the plasma vertical velocity**
  - **different adaptive algorithms for the controller gains**

Scheduling of optimized controllers

The *optimized controllers* can be scheduled by using either

time-driven policy - the whole experimental pulse is divided into a number of *time windows*, wherein different control algorithm can be chosen (as in SC/XSC architecture)

event-driven policy - since the controllers are optimized, there must be a safety logic that, in case of unexpected dangerous events, switches to the *general purpose controller*, so as to get a safe termination of the experiment

Modeling and Simulation Support

- New control algorithms are usually developed in a modeling and simulation environment (e.g. Matlab/Simulink), while are then implemented on a real-time target
- The new VS architecture should allow the user to check and validate the whole real-time code (including the control algorithm, communication interface with other systems, data acquisition, etc.) before test it on the plant
- Real-time prototype of the plant, based on detailed plasma models (such as CREATE L/NL), are needed to perform the offline validation

Requirements for the VS software architecture

New SW architecture for the VS system

Given the functional requirements introduced so far, it turns out that a **flexible and modular software architecture is mandatory for the VS implementation**, so as to successfully cope with the requirements given within the JET PCU project.

- The existing VS system, based on 4 Texas Instruments DSPs, has been dismissed, since it was not flexible enough to satisfy the requirements
- the new JET VS system has been developed exploiting the MARTe framework [1] and a the multi-processor ATCA hardware architecture [2]

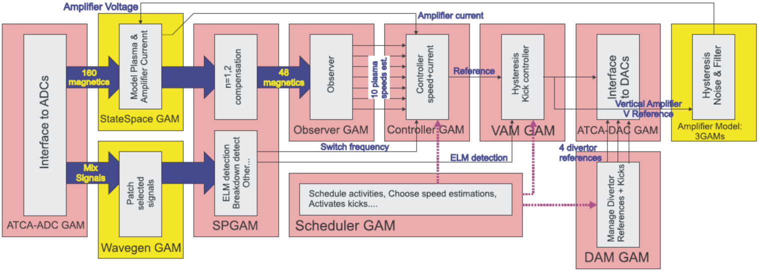
A. Neto et al.
MARTe: a Multi-platfrom Real-time Framework
Proc. 16th *IEEE NPSS Real Time Conference*, May 2009

A. J. N. Batista et al.,
ATCA digital controller hardware for vertical stabilization of plasmas in tokamaks
Rev. Sci. Instruments, vol. 77(10), 10F527, Oct. 2006

MARTe & GAMs

- The software architecture of the new JET VS system is a **user application** developed within the MARTe framework
- A user application is a collection of **Generic Application Modules (GAMs)**, which are specified by users and executed by a real-time micro-scheduler.
- It turns out that the new JET VS system is composed by a number of **plug-ins** executed by the MARTe real-time engine

JET VS Software architecture



Components Overview

- Input signals are acquired via ADCs, which are managed by the *ATCA-ADC GAM*
- *Signal Processing GAM (SPGAM)* computes the references waveforms for the control loops, starting from what it is specified in the user interface
- the compensated magnetic measurements are then sent to the *Observer GAM*, which computes ten different estimations of the plasma vertical velocity
- All the plasma velocity estimations, together with the power supply current and switching frequency, are sent as inputs to the *Controller GAM*, which is a container of four different control algorithms, which computes the voltage reference to ERFA
- All the request for the actuators (ERFA and divertors power supplies) are sent to the DAC by the *ATCA-DAC GAM*

Time windows and Scheduler GAM

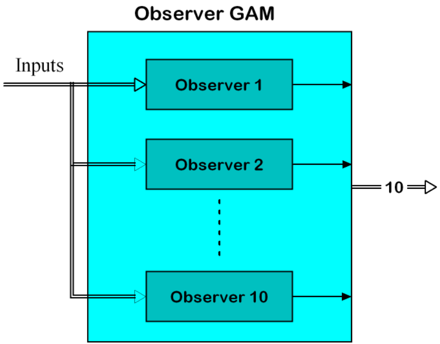
The JET discharge is logically divided into a number of *time windows*. In each time window the **Scheduler GAM** provides scheduling signals to the other modules (GAMs) so as to

- fed a specific estimation of the plasma velocity to each control algorithm
- choose which voltage requests generated by the controllers should be sent to ERFA
- perform either ERFA or Divertor kicks

Offline validation GAMs

- The new VS architecture allows the user to check and validate the whole real-time code (including the control algorithm, communication interface with other systems, data acquisition, etc.) before test it on the plant
- Real-time prototype of the plant, based on detailed plasma models (such as CREATE L/NL), are needed to perform the offline validation
- The three GAMs depicted in yellow have been specifically developed to simulate the plant so as to implement a complete close loop test-bench.

Observer GAM



An **observer** receives as input a set of measurements and a transformation matrix

The observer computational interface can be extended and specialized so as to implement state space model observer

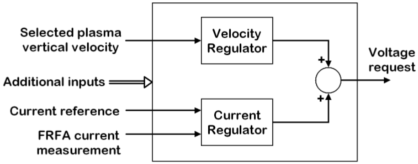
Controller GAM - 1

As for the Observer GAM, the **Controller GAM** has been conceived as a container of 4 different control algorithms

Hence, it is possible to meet the requirements by selecting the *optimal* controller in each phase of the pulse.

Furthermore this architectural choice permits to safely validate new control algorithms on the plant by running them in open-loop during the experiments.

Controller GAM - 2



Each control algorithms can implement any linear or nonlinear controller and must:

- control of the plasma vertical velocity, in order to achieve vertical stabilization;
- control the current in the FRFA circuit, so as to avoid current saturation and to reduce the thermal losses in the coil.

Vertical Amplifier Manager (VAM) GAM

The **VAM GAM** selects the desired controller outputs, on the basis of the scheduling signals. Before sending it to ERFA, the selected voltage request could be further processed by

- the *Dither* module
- the *Delay* module
- the *Kicks* module
- the *Relay Characteristic*

VAM Kicks

The **VAM GAM** allows the user to perform:

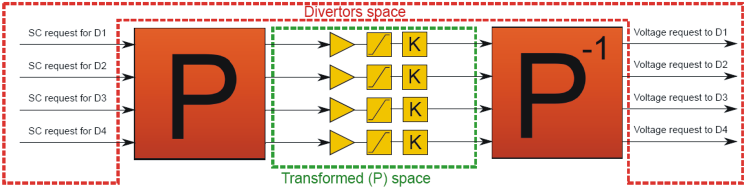
- **timed kicks** which are kicks applied at a precise time during the experiment, and which are used to simulate VDEs and to perform halo currents studies
- **periodic kicks**, used for ELM pacing
- **H_α kicks** which are triggered at the occurrence of an ELM, and which are used to switch off the controller during an ELM phase
- **saturation kicks**, which are used as protection system when the amplifier current reaches the safety threshold

Divertor Amplifiers Manager (DAM) GAM

The **DAM GAM** allows the VS system to act on the divertor coils, which are normally controlled by the Shape Controller

The **DAM GAM** made possible the application of voltage kicks to the divertor coils.

DAM GAM Architecture



P is a 4-by-4 invertible matrix which defines a linear transformation that maps the four divertor voltage requests into a custom *P-space*

In this space a gain and a saturation can be applied to each signal, and the transformed signals pass also through a *kick controller*

Thanks to its structure the DAMGAM can be effectively used to explore all the possible interactions and advantages of using also the divertors for the task of the vertical stabilization

Experimental Activities

- The commissioning of the new VS system (named **VS5**) has been done during C26
- During C27 the VS5 has been used
  - for the commissioning of the ERFA amplifier
  - to choose the optimum number turns for the coils in the FRFA circuit
- A new observer has been set as default in Mode-D. This new observer is a compromise among the following requirements
  - remove the contribution of discrete coils located behind the dump plate
  - guarantee scarce sensitivity to ELMs and fast plasma movements
  - have the same sensitivity as the old observer (ZPDIP) with quiescent plasmas
  - have the same dynamic response as ZPDIP to the amplifier voltage.