Exploitation of Modularity in the JET Tokamak Vertical Stabilization System

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The new architecture of the JET VS system
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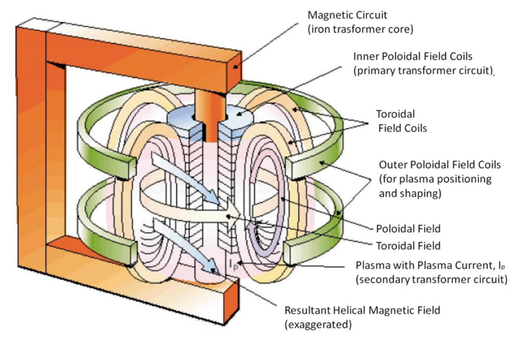
Tokamak



A tokamak is an electromagnetic machine containing a fully ionised gas (plasma) at about 100 million degrees within a torus shaped vacuum vessel. Poloidal and toroidal field coils, together with the plasma current, generate a spiralling magnetic field that confines the plasma.

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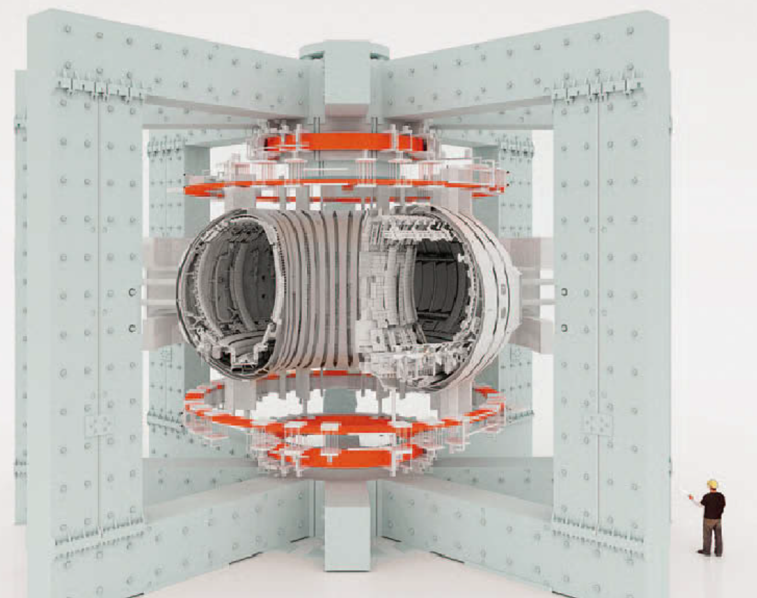
The JET tokamak - 1



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The JET tokamak - 2

- The Joint European Torus (JET) is an example of successful European collaboration.
- JET is still the world's largest tokamak
- JET has been built in the early eighties, and it was designed to allow the exploration of the plasma regimes in proximity of break-even, the condition at which the ratio between produced fusion power and input heating power is unity
- At the time of its construction, JET was a large step in scale from existing experiments, even larger than the one envisaged for the construction of the International Thermonuclear Experimental Reactor (ITER)

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Motivations

- Today's tokamak reactors are **experimental devices**
- The achievement of the required performance is strictly dependent on the **flexibility** and **reliability** of the real-time control systems that operate the plant

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Vertical Stabilization Problem

Objectives

- Vertically stabilize elongated plasmas in order to avoid disruptions
- Counteract the effect of disturbances (ELMs, fast disturbances modelled as VDEs,...)
- It does not control vertical position but it *simply* stabilizes the plasma
- The VS is the essential magnetic control system!

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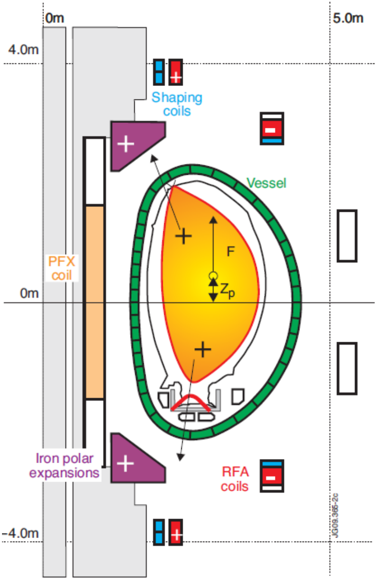
The JET Vertical Stabilization system

- A single power supply feeds the coils of the RFA circuit
- The control system drives the power supply voltage
- The controlled variables are the plasma vertical velocity and the current into the RFA circuit



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The JET VS control scheme before the enhancement

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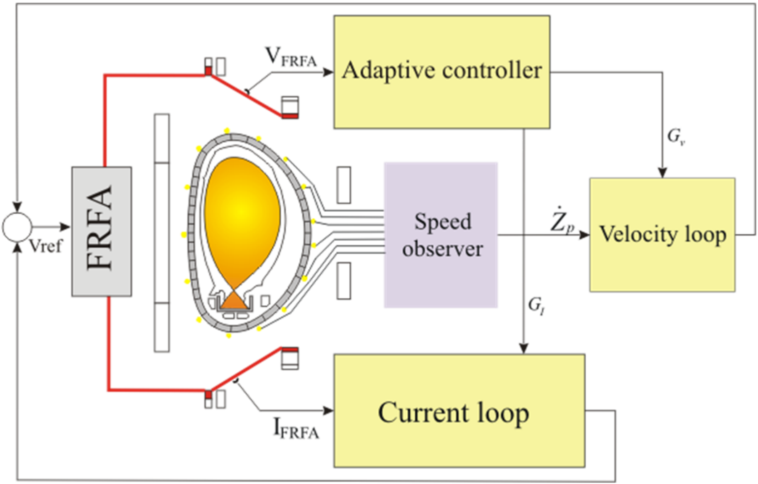

VS & JET PCU Project - 1

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

The PCU project aimed to enhance the ability of the VS system to recover from large perturbation.

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 RFA circuit**
2. the assessment of the best choice for the number of turns for the coils of the RFA circuit
3. **the deployment of a VS hardware, so as to increase the number of measurements and to increase the sampling time**
4. **the design of a new VS software, so as to deliver to the operator an high flexible architecture**

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VS & JET PCU Project - 2

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- **The PCU project has been successfully delivered in the course of 2010**

The new Vertical Stabilization

- 192 signals acquired by ADCs and transferred at each cycle
- 50 μs control loop cycle time with jitter $< 1 \ \ \mu s$
- Always in real-time (24 hours per day)
  - 1.728×10^9 50 μs cycles/day
  - Crucial for ITER very long pulses

Why a new software architecture?

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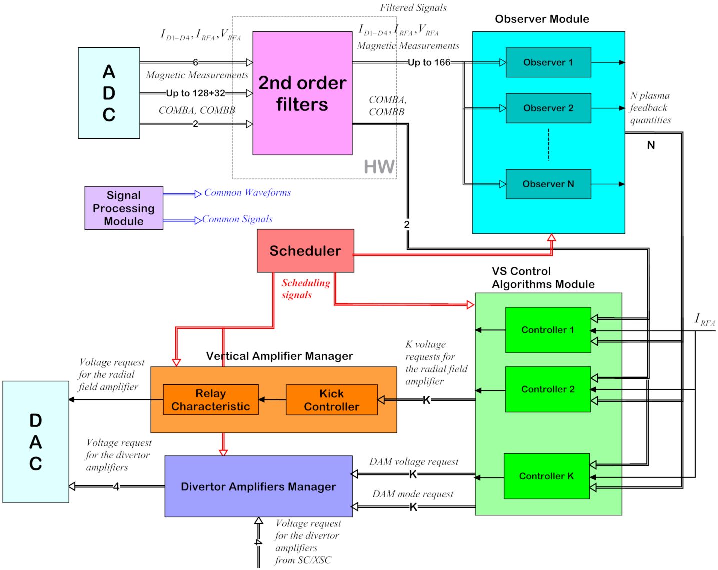
- Better fusion performance in tokamaks are achieved with highly elongated plasmas in presence of large perturbations
- In these **extreme scenarios** a *general purpose controller* cannot guarantee the requirements
- To push the performance up to the desired level, it is usual to rely on a model based design approach which assures the needed control performance
- **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**

The new architecture of the JET VS system



Observer Module

- **If reliable models are available the plasma unstable mode could be used the control control variable. Indeed, the unstable mode would be the more effective variable to be controlled to minimize the vertical displacement in presence of disturbances**
- The *Observer Module* has been designed as a *container* of up to ten different observers, giving the possibility of computing different estimations of the unstable mode to be used in different phases of the experiment
- Each observer receives as input a set of measurements and the resulting outputs can be used as inputs for other observers, in a daisy chain design, enabling the possible reuse and optimization of some calculations
- When only the feed-through matrix D of the observer is specified, an observer can be used as a *plasma velocity estimator*, i.e., it computes an estimation of $\dot{z}_p$ as a linear combination of the magnetic field measurements

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Controller Module - 1

- As for the Observer Module, the *Controller Module* has been conceived as a container of up to four different control algorithms which are available during the whole pulse.
- **This architectural choice permits to safely validate new control algorithms on the plant by running them in open–loop during the experiments**
- There are a number of inputs that are common to all the control algorithms (i.e., the Observer outputs and the current in the *RFA* coil). Moreover, each algorithm can have its own input signals
- **The selection of the plasma vertical velocity to be used for the control is made on the basis of the scheduling signal provided by the Scheduler**

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Controller Module - 2

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The control blocks can implement any linear or nonlinear control algorithm, provided that the computational effort is achievable.

Each controller must satisfy two basic requirements:

- control of the plasma vertical velocity or unstable mode, in order to achieve vertical stabilization;
- control the current in the *RFA* circuit, in order to avoid current saturation and to reduce the thermal losses in the coil.

Vertical Amplifier Manager (VAM)

- The *VAM* module selects the desired controller output, on the basis of the scheduling signals provided by the *Scheduler*
- **The VAM implements the Kicks module which is its most innovative component**
- **The Kicks module allows to apply voltage pulses of a given time length and amplitude to the coil used for vertical stabilization. These voltage kicks vertically move the plasma, and are used to trigger Vertical Displacement Events (VDEs), to perform halo currents studies, and for ELM pacing**

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Divertor Amplifiers Manager (DAM)

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- The *DAM* is a module created in order to let the VS system act on the divertor coils, which are normally controlled by either the plasma shape controller
- The *DAM* allows the user to perform kicks using the divertor coils
- **Experimentally this module turned to be useless at JET! (Because of the bandwidth of the divertor amplifiers)**

The Scheduler

- **The Scheduler allows the user to plan the experiment by setting the VS behavior in 25 time windows**
- In each time window, the user
  - chooses the estimation of the plasma vertical velocity to be controlled together with the desired control algorithm
  - sets the behavior of both the VAM and the DAM modules

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Profiling - 1

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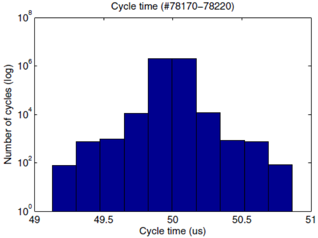
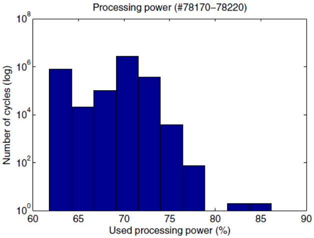
- One of the most important characteristics of any control system is that the execution of its algorithms is bounded to a well defined time period
- This requirement is particular important in the VS system, since the number of operations performed in a control cycle varies with the number of features enabled in a given time window

Profiling - 2

Even in the worst case conditions, where all the modules have all their features enabled, the system VS managed to execute and synchronize with the next control cycle within the prescribed 50 μs value



(a) Cycle time measurements. The jitter is always bounded to 1 μs



(b) Amount of time consumed to execute all the modules in a 50 μs control cycle, expressed as a percentage of this value

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Observer - 1

- A new plasma velocity observer had to be designed in order to take into account the field modifications imposed by the new ITER-like wall
- The Observer module has been designed to compare in the same pulse, albeit in open-loop, up to ten plasma observers in parallel
- The usage of a simulator, together with the CREATE-NL linear plasma models, provided excellent estimations of the expected behavior in the presence of fast disturbances, leading to the release of a new plasma velocity estimation

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Observer - 2

For the same ELM energy, the new plasma velocity estimation has a smaller plasma velocity variation, enhancing the controller response which requires a small current excursion to the power supply.

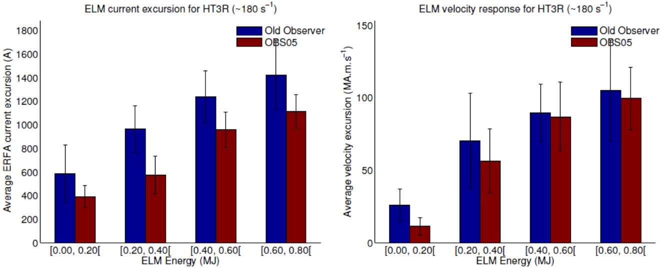

Figure: Comparison between the old VS observer and the new one in the response to ELMs.

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Regular operation

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- Once the commissioning phase was terminated, the new system was released as the official vertical stabilization system and successfully run for more than 1500 plasma pulses during several weeks of operation.
- The new vertical stabilization has demonstrated the capability of handling large ELMs ($>$ 1 MJ) at high plasma currents ($>$ 3 MA)
- As the culmination of the C27 campaign (end 2009), JET was operated for the first time since 1997, at a plasma current of 4.5 MA, with ITER relevant scenarios, confirming one of the project's major milestones.

Conclusions

- The robustness of the JET vertical stabilization system is vital for a safe operation of the experiment
- At the same time, the system is expected to provide advanced experimental features, enabling the exploitation of new scientific problems and the adaption to different experimental regimes
- In order to safely allow both modes of operation to co-exist, the new VS was designed using a modular and flexible
- Being able to switch the behavior of the single modules accordingly to the discharge phase, enables to test new features in safer plasma operational modes and to use special controller parameters when required
- Eventually, since its installation the new JET VS successfully controlled more than 2000 plasma pulses, with an extremely low failure rate (no natural VDEs or control failures during ELMs ever observed)

Thank you!

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