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REAL-TIME MEASUREMENT AND CONTROL AT JET
Experiment Control

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Abstract

Over the past few years, the preparation of ITER-relevant plasma scenarios has been the main focus experimental activity on tokamaks. The development of integrated, simultaneous, real-time controls of plasma shape, current, pressure, temperature, radiation, neutron profiles, and also impurities, ELMs and MHD are now seen to be essential for further development of quasi-steady state conditions with feedback, or the stabilisation of transient phenomena with event-driven actions. For this thrust, the EFDA JET Real Time Project has developed a set of real-time plasma measurements, experiment control, and communication facilities.

The Plasma Diagnostics used for real-time experiments are Far Infra Red interferometry, polarimetry, visible, UV and X-ray spectroscopy, LIDAR, bolometry, neutron and magnetics. Further analysis systems produce integrated results such as temperature profiles on geometry derived from MHD equilibrium solutions.

The Actuators include toroidal, poloidal and divertor coils, gas and pellet fuelling, neutral beam injection, radiofrequency (ICRH) waves and microwaves (LH). The Heating/Fuelling Operators can either define a power or gas request waveform or select the real-time instantaneous power/gas request from the Real Time Experiment Central Control (RTCC) system.

The Real Time Experiment Control system provides both a high-level, control-programming environment and interlocks with the actuators. A MATLAB facility is being developed for the development of more complex controllers.

The plasma measurement, controller and plant control systems communicate in ATM network

The EFDA Real Time project is essential groundwork for future reactors such as ITER. It involves many staff from several institutions. The facility is now frequently used in experiments.

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1 Introduction

The achievement of ITER relevant ELMy H mode, Steady State and Hybrid scenarios on JET requires active control of (a) plasma shape and current and (b) kinetic and magnetic radial profiles [1, 40, 41]. Plasma shape and current controls are covered by the eXtreme Shape Control system, described by Sartori et al [2]. The second group is the subject of this paper. All tokamaks have some central control system usually taking magnetic measurements and controlling the toroidal and poloidal magnetic fields. Most machines also have a gas or density controller. Over the last few years, EFDA JET has developed a more distributed data acquisition and data processing system (figure 3) for other key plasma diagnostics (section 2), controls (section 3), controllers (section 4). Substantial signal processing is done close to the diagnostic, and the physics results are sent over a real-time data network to an experiment controller and thence to the heating and fuelling plants. This distributed approach (section 5) has made it possible to incorporate new systems, progressively, without disturbing existing connections.

The EFDA JET project has co-ordinated developments in several laboratories, culminating in successful deployment and routine operation of the new systems for the EFDA JET programme (section 6) [3].

2 Plasma Diagnostics

The key measurements are electron density and temperature, ion temperature, q-profile, radiation, impurities, ELMs, and MHD [3]. Table I summarises the measurement capabilities. The existing Diagnostic control and data acquisition remains in use. Where a real-time signal processing cannot be done by the existing system, a new data acquisition system has been developed to run in parallel and process the data in much the same way as is done post-pulse. There is room here only for a few examples illustrating the range of signal processing.

The ECE radiometer now has 96 tuned heterodyne microwave receivers covering the much of the radial extent of the plasma, for most toroidal fields. To find the electron temperature in real-time (based on [4]), the system acquires and filters the 96 signals, applies calibration factors derived from cross-calibration with the absolute-reading ECE Michelson instrument on a similar shot, and sorts the channels into radial order, resulting in temperature profiles every 5 ms.

The LIDAR system sends short laser pulses across the plasma and records the Thomson backscatter echo at several wavelengths. At each instant in the echo, corresponding to radial position, the relative intensities at the different wavelengths are fitted to pre-calculated intensities depending on electron density and temperature. The real-time system processes the data in the same way as the post pulse in less than 10ms, resulting in 50 point profiles every laser pulse (250ms).

The MSE diagnostic now has a 32-channel ADC streaming data (250 kH sample/s) to 3 VME processors which all together implement 25 sets of 4 lock-in amplifiers and a polarisation/intensity calculator, resulting in 25 pitch angles at different radial positions every few milliseconds [9].

To simplify integrated plasma control, the Equinox Map system re-calculates various Te, Ti and q-profiles, with their different temporal and spatial sampling, onto the same poloidal geometry from the Equinox finite element analysis [7].

3 Heating and Fuelling

JET's coils, heating and fuelling systems have, from the first days of operation, been integrated in the CODAS hierarchical control systems. So they have a common architecture -

- **local** plant **control** (often a industrial Programmable Logic Controller (PLC)),
- a **sub-system manager** (a unix server, with unix workstations for man-machine interfaces)
- the JET machine **supervisor** (a unix server with unix workstations) which coordinate the sub-systems for JET pulse operations,
- common services : timing signals, safety interlocks, recorded data management

The sub-system manager can run the plant using either (a) operator-designed waveforms for power (heating) or gas flow (fuelling), or (b) instantaneous power (flow) request signals from the Real-Time Controller. This simple option gives the Real-Time Measurement and Control facility much of its operational flexibility.

JET has two sets of Neutral Beam Injectors (NBI), one with eight 120kV, 60A positive ion injectors (PINIs) and one with eight 80kV, 60A positive ion injectors. In each bank four PINIs beams run normal to the torus heating the core, and four run tangentially heating the outer plasma more, transfering some angular momentum and current drive. After the recent upgrades, the system provides more than 20 MW total power. In real-time control, sets of PINIs can be allocated to one of four groups, to achieve different heating effects.

The ion-cyclotron resonance heating system (ICRH) has eight 4 MW generators, tunable over 23 to 57 MHz, feeding four sets of antennae through pressurised transmission lines. The actual power delivered depends on the coupling with the plasma, and the high voltage capabilities of the lines, and is typically about 10 MW total. A new antenna is being developed for ITER-like shapes. For real-time control, the generators can be allocated to one of four groups .

The Lower Hybrid Current Drive system (LHCD) has 24 klystrons, operating at 3.7GHz, capable of 650kW for 10s or 500kW for 20s. For normal operations, the 24 klystrons are managed in six modules of four. The total power available is 12 MW for 10s or 4.8 MW for 20s. The Power coupled to plasma depends on launcher power handling and plasma conditions again. For real-time control, the modules can be allocated to one of three groups.

Up to four gasses can be injected through any of 10 piezo-controlled valves (Gas Introduction Modules). Tritium is injected though another dedicated valve. Each of these (a) can be opened according to a Session-Leader designed waveform, (b) coupled to a density feedback controller, or (c) can be opened according to a real-time request from the Real-Time Controller.

4 Real-time experiment controllers

The Real-Time Central Controller (RTCC) is a high-level programming facility [15]. A (trained) user can develop control algorithms, which read real-time signals, calculate feed-forward and feed-back components and write plant control signals to NB, RF, LH and gas systems, all in a 10 ms cycle. The signal processing blocks include analogue and logic, threshold, sample/hold, and standard process control functions (e.g. proportional integral and differential (PID) blocks). The feedback control schemes are modelled in Matlab + Simulink off-line, then the control is transcribed to the RTCC language, verified on-line and the experiment performed.

The controller has sufficient functionality for the simple real-experiments involving one or two inputs and one or two outputs, but it does not have the facilities to work well with multiple-input/multiple-output (MIMO) schemes. A new facility will integrate a Matlab + Simulink design workstation and a dedicated run-time engine into the RT Controller. Control experiments will then be able to designed and tested using historical or synthetic data off-line, and at the user's home lab, and then brought into the on-line facility for experimental sessions on JET.

5 Real-time data networks

The original Real-Time controller (c.1994) used analogue signals [15]. This was sufficient for global parameters such as plasma current, density, and neutron rate. Some of the analogue connections remain, but for advanced tokamak control with radial profiles, there would be hundreds of lines, and so a computer local-area-network technology was chosen. Each system acquires and processes its data, sending out datagrams of physics results (not raw data) every few milliseconds. The datagrams could be routed to one or more destinations so that analysis, control and recording systems can run concurrently.

Tests in 1998-2000 revealed that shared ethernet did not transport end-to-end reliably at the sub-10ms cycle time, and did not support direct one-to-many routing. We have found the ATM network (Asynchronous Transfer Mode) to be suitably fast, timely, flexible and reliable [16]. In particular, connections can be added or removed without disturbing other connections, and so the disturbance to JET operations is minimised.

6 Real-time control experiments

Numerous JET sessions have used the real-time facilities in Advanced Tokamak and ELMy H mode experiments – High performance ITB & q- profile with NBI, ICRH and LHCD, BetaN with NBI, grad(Ti) with NBI, ^{3}He concentration for ICRH mode conversion with ^{3}He gas, Radiated Fraction controlled by impurity seeding (Ar, N2 gas), and H98 controlled with D_2 gas, Pellets controlled by density limits, MHD controlled by NBI and burning plasma simulations using ICRH .

In the high performance ITB experiments, when a measure of the pressure gradient exceeds a threshold, the NBI heating is reduced, thereby avoiding an immanent disruption. For the ELMy H mode experiments both the radiation fraction and the confinement time are controlled with argon and deuterium gas injection respectively using 2-input, 2-output coupled PID scheme. In the q- and pressure profile experiments, the Te and the q-profile data are reduced to a few distributed terms and MIMO feedback controller adjusts NB, RF and LH power to achieve the target profiles simultaneously maintaining a good ITB [17, 18].

7 Conclusions

The EFDA JET real-time project has developed key measurement, communications and control systems for exploitation by the EFDA JET programme. All the systems use Commercial-Off-The-Shelf (COTS) equipment. The project has involved many laboratories, and the expertise is transferable to other existing and future tokamaks. The main problems arise in the Diagnostics and Fuelling systems, where the issues of the available lines-of-sight, in-situ calibration, and electro-magnetic, mechanical, thermal, vacuum and radiological isolation are considerable and compromise resolution and reliability.

Several important parameters or profiles are not available for real-time control e.g. high time/space resolution electron or ion density. The JET EP Diagnostics are addressing some of these, and real-time outputs will come in due course. Some of the parameters are not well controlled by existing heating and fuelling systems e.g. ICRH heating with ELMs. Work must continue (a) to exploit the existing systems (b) to integrate magnetic and kinetic controls and (c) to develop more comprehensive and effective systems and plasma scenarios.

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Figure 1 Real Time Measurement and Control

Plasma Diagnostics send samples of data (Te, Ti, etc.) over a network to RTCC. RTCC calculates the control signals using feed- forward and feed- back parameters supplied by the user, and then sends the control signals to the Heating and Fuelling systems (NB, etc.), over the network. RTMX runs matrix-based control codes based on the user's Matlab models.

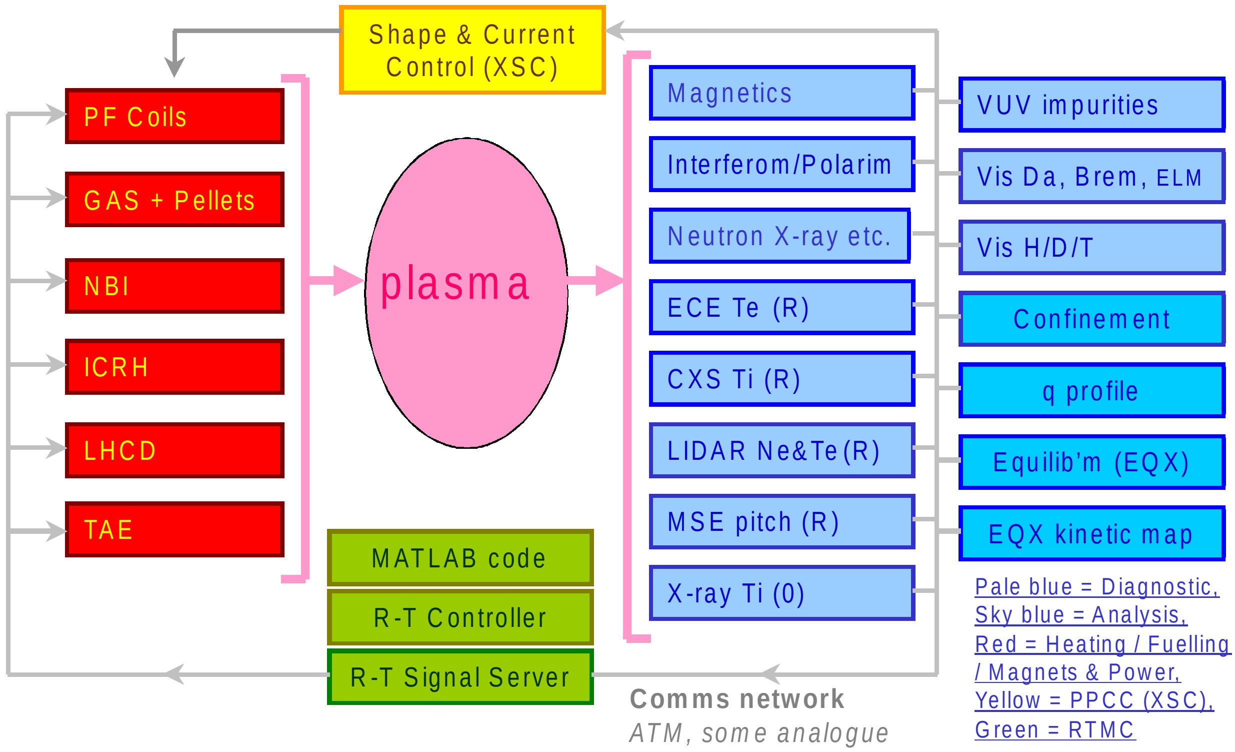

Table 1 Real-time Measurement and Analysis Capabilities

Physics	*Diagnostic*	*Size*	*Cycle (ms)*	*Ref,s*
Te (R)	ECE whole	48 96	2	4
ITBe (R)	ECE	48	2	4
Te (R)	LIDAR	50	250	
Ne (R)	LIDAR	50	250	
Ti (R)	CX	14	50	8
Vrot(R)	CX	14	50	8
ITBi (R)	CX	14	50	8
γ (R)	MSE	25	2	5
LID	FIR	8	2	9,10
FAR	FIR	8	2	9,10
LCFS	XLOC	100	2	14
β, l_i	Confinement	20	2	12
Flux	EQX	100	25	7
q r/a)	FIR / XLOC	10	2	13
q (r/a)	MSE / EQX	10	25	
ITB e (r/a)	ECE / EQX	10	25	
ITB i (r/a)	CX / EQX	10	25	
Rad'n	Bolometer	48	5	6
Imp'y	VUV	8	20	11
Imp'y	Vis.	16	20	11
ELM	Vis.	3*3	100	11
H:D:T	Vis.	4*3	20	11
Ti core	X-ray	8	20	11
Ipla	Magnetics	1	Analog	
MHD n=1	Magnetics	1	Analog	
MHD n=2	Magnetics	1	Analog	
RNT	Neutronics	1	Analog	
Hard Xray	Neutronics	1	Analog	
Density	FIR	1	Analog	

Table 2 Glossary

Term	*Description*
ECE	Electron Cyclotron Emission
CX	Charge Exchange Spectroscopy
MSE	Motional Stark Effect
FIR	Far Infra Red interferometry, and polarimetry
VUV	Vacuum Ultra Violet line emission
Vis	Visible Spectroscopy - D_α, C lines, etc.
ITB	Internal Transport Barrier
R	Radial co-ordinate, toroidal centre
r	Radial co-ordinate, poloidal centre
r/a	Radial co-ordinate normalised to plasma radius.
a	Plasma radius
Te (R)	Electron temperature profile
Ne (R)	Electron density profile
Ti (R)	Ion temperature profile
γ (R)	Mag. Field pitch angle profile
q (r/a)	q profile, normalised radius
ITB e	ITB using Te
ITB i	ITB using Ti
LID	Line integrated density
FAR	Faraday angle (polarisation)
LCFS	Last closed flux surface (plasma boundary)
XLOC	Plasma Boundary reconstruction
EFIT	MHD Equilibrium on grid
EQX	MHD Equilibrium on Finite Element Mesh, (Equinox code)
ELM	Edge Localised Mode
H:D:T	Relative composition, Hydrogen : Deuterium : Tritium
RNT	Total neutron rate