REAL TIME CONTROL OF LONG DURATION PLASMA DISCHARGES IN TORE SUPRA

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1 INTRODUCTION

In the field of fusion reactor studies, the Tore Supra tokamak explores the route of long duration plasma discharges. A plasma discharge of 4 minutes 25 seconds duration has been performed in 2002 with a world record of injected and extracted energy of 750 MJ. To achieve such performances, the in-vessel components and water cooling loop were fully renewed [1]. Furthermore each subsystem limitations were deeply analyzed and improved to meet the long pulse requirements, including the data acquisition system (DAS) and the real time plasma control system. New cross controls between subsystems has been developed to improve the level of safety and robustness of the machine operation. These aspects are detailed in the paper. It is worth noting that most of these improvements are relevant to operate tokamaks in a fully steady state regime.

2 DATA ACQUISITION SYSTEM

The limitations of the data acquisition system (DAS) has been firstly identified with the goal of a true continuous operation. The actual DAS design which fulfils the new requirements [2], includes the following major upgrades.

2.1 Continuous Data Acquisition

For a continuous data acquisition, the supervision, storage and timing tasks are now continuously running. For the last year long duration discharges, data from calorimetric sensors and from the toroidal field system were recorded. These information are of major importance for the physicist and for the operation. As an example, the one turn characteristic time of the water in the cooling loop being two minutes, temperature must be followed during typically 20 minutes after the discharge to work out a global energy balance between injected and extracted energies. The convective and radiated energy ratio is thus followed when plasma parameters evolve.

2.2 High Data Flow Rate Management

Some experimental units ask for a high data flow rate when special plasma events occurs. During 1-2 seconds, several times per discharge, the flow rate can reach 18 MB/s per front end unit. For these units, the raw data are transferred via a private 100 Mbit fast Ethernet link to separated powerful PC units where the data frames are build and then sent to the central real time server to be stored in the database.

2.3 Continuous Data Access and Processing

To avoid too many accesses to the central database, a large cache memory is used for data frames as well as discharge parameters. For a typical discharge the storage rate is 1.2 MB/s. Thus a reasonable memory size of 5 GB enables the storage of 4000 seconds of plasma, corresponding to 1-2 days of experiments.

The data access has also been upgraded to permit the data recall before the end of the discharge. The cache memory on the local servers is updated every second. Thus plasma analysis can immediately start at a quasi real-time level.

For the 4mn25s world record plasma discharge, the stored data were 285 MB including 58 % of MPEG1 and MPEG2 video files.

2.4 Real Time Data Processing

In the spirit of a full continuous operation, a ongoing effort is carried out to convert the post-discharge plasma analysis into real-time processes. This work takes advantage of the new powerful generation of processors. Nevertheless algorithms adapted to the real-time constraints must be developed and rewritten. As an example the plasma position control is presented in section 4. Moreover, some analysis need results from many other front-end units, or cross-validation, or end of pulse data to calibrate their data. A real-time sharing of the information becomes a necessity, and innovative data treatments must also be developed.

3 PLASMA CONTROL NETWORK

Several seconds plasma discharge needs active control of the plasma parameters to avoid drifts. Four feedback loops were initially implemented at Tore Supra:

- Plasma current, position and shape control, using magnetic sensors and acting the poloidal coil currents.

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- Density control, acting the gas and pellet injections to adjust the line density measured by infra-red interferometry system.
- Additional power controls of the two heating subsystems using high frequency waves. The feedback loops act to optimize the wave coupling to the plasma.

These control loops operate with response time of a few milliseconds, and are therefore software implemented in microcomputers (PowerPC unit in VME board).

To control the plasma in advanced regimes (not only the plasma position and density, but also its energy content, its temperature and current distributions…) and for long-duration plasma discharges, one needs to real-time react on several additional heating systems using information coming from different plasma diagnostics.

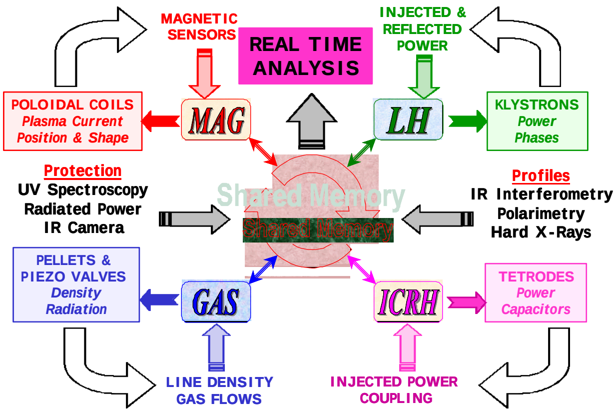

Figure 1: Tore Supra real time feedback network

The one to one connection between sensors and actuators of the initial control topology is no longer sufficient to fulfil these requirements. The sharing of information, not only some measured quantities but also computed parameters, becomes an essential issue. Therefore a fast dedicated network has been built (using SCRAMNet® boards from SYSTRAN Corporation), connecting together the four initial control units [3]. The sharing of information in real time insures a global and coherent operation of the sub-units. A schematic representation of this feedback network is shown in figure 1, where only the active control systems have been identified. Additional units only provide information on the plasma, with no mean of retroaction, except through one of the four active units. These front-end units can be separated in two classes :

- Those devoted to the protection and safety operation of the machine: UV spectroscopy, radiated power, Infra-Red cameras.
- Those needed to control the plasma in advanced regime in order to improve the plasma performance: IR Interferometry (density profile), Polarimetry (current profile), Hard X-rays (additional power deposition profile).

This shared memory topology is routinely used to demonstrate a precise plasma control in advanced and improved confinement regimes such as electron density profile, current profile [4].

Recently, PC units (INTEL Pentium® IV at 2.8GHz) have been connected to the ring using SCRAMNet® board in PCI standard. Taking advantage of the new CPU power, a full real time plasma equilibrium reconstruction is now routinely available. A C++ fast solver using finite element method is implemented [5], together with an online display developed using the OpenGL toolbox. Typical CPU time is 5ms per equilibrium and 3ms per displayed frame.

Up to now the magnetic data only are used for the equilibrium reconstruction, but the shared topology of acquisition units and the solver implementation itself enable us to add current profile as well as density and temperature profiles to constraint the solution. A feedback on plasma actuators (gas fuelling, additional heating…) will then become achievable to control the plasma profiles which is a key issue for future tokamaks.

4 POSITION AND SHAPE CONTROL

For power flux control and coupling of radio-frequency waves of heating systems an accurate positioning of the plasma boundary is required. A precision of a few millimetres is asked, smaller than the characteristic length (≈ 1cm) of power decrease in the evanescent plasma edge region. The real time control loop (Fig.2) solve the electromagnetic equations in the vacuum from magnetic coil sensors up to plasma boundary. The found boundary is then compared to the requested one and a feedback PI controller acts on the poloidal field (PF) power amplifier voltages to adjust the PF coil currents. The control loop cycle is 2ms, mastered by a central megahertz clock. The typical CPU time (VME PowerPC unit at 300Mhz) is 1.8 ms, including data reading and saving (0.4 ms) calibration (0.2 ms), boundary solver (0.9 ms) , feedback (0.2 ms) and safety control (0.1 ms).

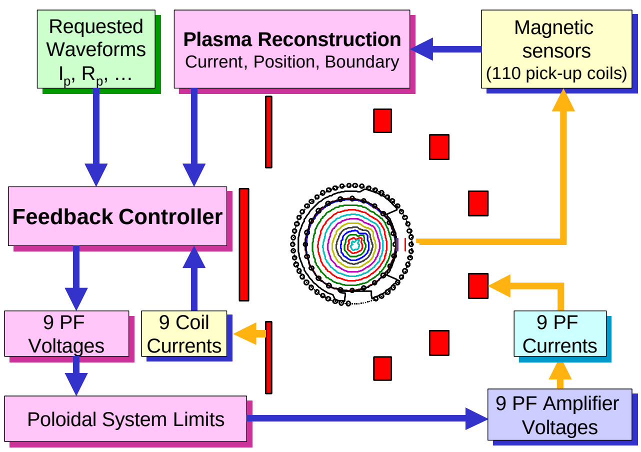

Figure 2: Current, position and shape feedback loop.

The typical response time is 8 ms, limited by the available power and voltage of the PF amplifiers. Absolute errors for the major radius R and vertical position Z are within 2 mm, fulfilling the requirements.

5 SAFETY OPERATION AND PROTECTION

Operation of powerful plasma discharges for several minutes needs advanced protection systems able to rapidly react on actuators. The main goals for designing such protections are:

- *Avoid machine damages.* The available heat flux can easily generate a water leak or an in-vessel wall melting. A robust plasma shutdown procedure is thus requested to softly stop the discharge before irreversible damages.
- *Operate as close as possible to the technological limits* of the systems. A fast safety controller including the limits, accurate measurements of the loads, and alternate conservative procedures will meat this requirement.
- *Avoid premature shutdown* of the subsystems when internal hardware limits are reached. An advanced protection controller is thus asked to re-dispatch the subsystem loads in order to increase the safety margin.

The SCRAMNet® network is used to exchange information devoted to the margin control of components. Figure 3 sketches the safety control system. The central controller can either authorize, modulate or forbid the additional power systems, request a plasma shutdown, or feedback on actuators. The surveyed subsystems and plasma parameters and the detection units are also drawn.

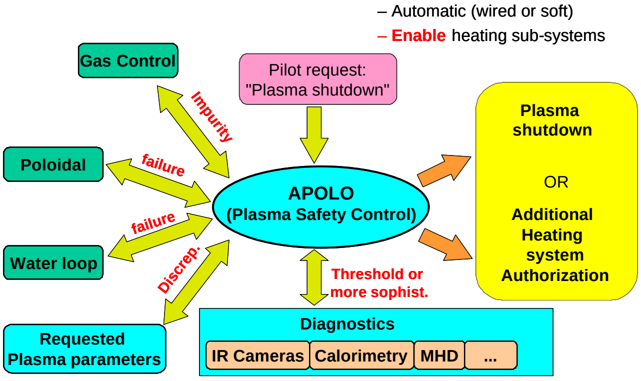

Figure 3: Plasma safety and protection system

6 LONG DURATION DISCHARGE

The new DAS, the improved plasma control system and the upgraded plasma safety controller system have been experienced for long-duration plasma discharges during the 2002 year. A powerful discharge (3 MW average additional power) at a plasma current of 0.52 MA has been controlled over 4 minutes 25 seconds duration. A corresponding energy of 750 MJ were exhausted by the water cooling loop.

Recently a full non inductive plasma discharge has been sustained for 3 minutes. Figure 4 shows the time evolution of its main plasma parameters. To achieve this non inductive discharge, two primary feedback loops have shared their information: plasma current was controlled by the lower hybrid additional power and the no primary flux consumption was adjusted by acting the main PF power amplifier voltage. The slow decrease of the LH power indicates a slight improvement of the current generation efficiency. This pulse demonstrates the capability for a tokamak to operate in a continuous regime, a necessary step towards a full steady state operation.

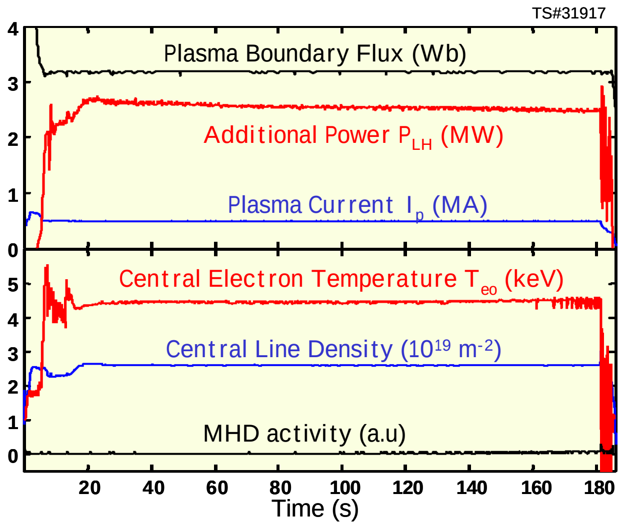

Figure 4: main plasma parameters of a 3 minutes fully non inductive discharge.

7 CONCLUSION

The tokamak operation for long-duration plasma discharges must integrate heterogen systems. An overall approach must be carried out to share the information at a real time level. The solution installed in Tore Supra, based on a SCRAMNet® network, has proved its flexibility (continuous addition of new nodes), and its robustness (no network failure during 7 years of operation). The possibility to share VME units as well as PC units enable us to strongly increase the available real-time CPU power. The development of advanced real-time plasma control algorithms becomes thus accessible. The real-time equilibrium reconstruction is a first example of such a new generation of algorithms. These developments are fully relevant for the new generation of magnetic fusion devices.

8 REFERENCES

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