RFX: new tools for real-time MHD control

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Abstract. RFX has been recently modified to improve its capability of controlling different MHD phenomena by means of fast, feedback controlled amplifiers and distributed radial field inductors.

The paper, after summarizing the principal results obtained in the past by means of active control of magnetic fields in RFX, describes the recent modifications to the machine and the improvements to the power supplies and to the magnetic diagnostics. The old thick shell has been replaced by a much thinner shell, whose electromagnetic time constants are much shorter than pulse duration, and a system of 192 radial field coils has been added, covering the whole torus surface.

Then the paper describes the models used to design the new real-time control system of RFX and gives some preliminary results obtained, with the same techniques, on the EXTRAP-T2R device. The basic choices about the technologies adopted for the new RFX control system are discussed with reference to the general problem of real-time control of MHD instabilities in magnetic fusion devices. Finally, the paper defines the main objectives of the RFX scientific programme aimed at exploiting these new tools.

1. Introduction

The RFX device [1] has been progressively modified [2, 3], in parallel to experimental campaigns, to evolve from passive control of the magnetic field configuration, mainly performed by eddy currents induced in the thick stabilizing shell ($\tau_{vertical} \sim 0.5$ s $\sim 2\ \tau_{pulse}$), to active control of the local field errors at the plasma boundary and of the m=0 field harmonics around the torus. In this way, we succeeded in reducing the localized plasma-wall interactions and, by dragging selected harmonics of the dynamo modes, to keep the phase-locked modes rotating with respect to the wall [4]. These results have considerably increased our confidence in the possibility of actively controlling the MHD dynamics on timescales much shorter than pulse duration [5].

After a long shutdown caused by a fire in the toroidal field power supply hall, RFX is now ready to resume operation. The reconstruction of the damaged plant has been completed, and significant improvements have been applied to provide a wider range of operating scenarios for current density profile and magnetic field control.

At the same time, the torus assembly has been substantially modified. The thick aluminium shell has been replaced by a thin copper shell, whose time constant is ten times shorter. The radial field at the plasma boundary is now actively controlled by a system of 192 saddle coils, covering the entire plasma surface, with each coil being independently fed by a fast amplifier.

Moreover, the new toroidal field power supply system is based on state-of-the-art power electronics that produces robust m=0 rotating field harmonics [6].

These new tools, and the experience gained in the first experimental phase of RFX with the active control of field errors and with the interaction between external fields and plasma instabilities, are the basis for a comprehensive experimental programme on MHD control.

Section 2 presents the most significant physics achievements resulting from the development of active control schemes on RFX. Section 3 discusses the rationale behind the basic design choices for the recent modifications and describes the system of magnets, power supplies and diagnostics that have been implemented for real-time MHD control. Section 4 deals with the models developed for the design of the controllers and shows some preliminary experimental results. Section 5 discusses the real-time control technologies adopted for this purpose.

Finally, the paper presents the scientific objectives of the first experimental campaigns.

2. RFX experience in active control of magnetic fields

Since the very beginning, it has been clear that the field errors caused by discontinuities (gaps) in the shell and by resistive inhomogeneities in the vacuum vessel were an important source of energy loss and of intense plasma-wall interaction on relatively small areas of the graphite armour. Later, it was found that in every pulse the internally resonant tearing modes were locked in phase and that the resulting magnetic perturbation was permanently locked to the wall, causing a further increase of heat flux in the locking zone [7].

The first attempt at reducing the field errors was the introduction of passive shielding elements on one poloidal and one toroidal gap. Subsequently feedback control of the equilibrium field and new saddle coils that actively control the error fields on both gaps have further reduced the local thermal flux [3, 8] . However, none of these improvements have prevented the wall locking of tearing modes.

In this respect, good results have been obtained by resorting to mode coupling. The MHD m=1 tearing modes, which are essential to maintain the RFP configuration, are non linearly coupled with the m=0 modes. A rotating m=0, n=1 magnetic perturbation has been generated by modifying the power supplies of the 12 groups of independently fed toroidal field coils.

The experiments have clearly demonstrated this kind of coupling and allowed to induce rotation of the wall locking position. This alleviated the thermal load on the first wall, so that both pulse length and plasma current could be increased. Moreover a reduction of the mode amplitude has been observed, due to the shielding effect produced by a non-fully penetrated conducting wall [2].

3. New features for MHD control

The recent modification of RFX [23] has been principally aimed to allow a direct magnetic interaction with the plasma m=1 and m=0 modes. The main tools to achieve this objective are:

- Replacement of the thick shell with a much thinner one;
- Installation of a new system of saddle coils, individually fed by fast amplifiers;
- Improvement of the toroidal field power supply;
- Improvement of magnetic measurements.

3.1 Machine modifications

The shell is necessary to reduce magnetic fluctuations at the plasma edge, and to stabilize macroscopic instabilities growing on a time scale faster than the characteristic response time of the control amplifiers. The first basic choice has been to install a new shell [9] as close as

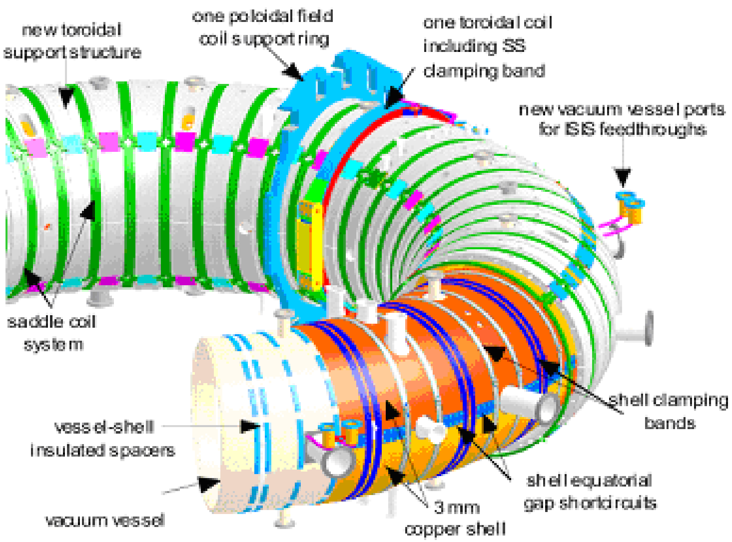

Fig. 1: CAD view of the new torus assembly: the shell is highlighted in orange/yellow and the saddle coils in green

possible to the plasma boundary and having a time constant for penetration of the m=1, n=0 mode of the order of 40-50 ms. This allows a good equilibrium control (the response time of relevant amplifiers is 20-30 ms) and offers a passive stabilization on a timescale of 10-20 ms of the characteristic m=1 internally resonant modes, ranging from n~7 to n~15. The shell is made of copper and is 3 mm thick.

Since the length of the plasma pulse is up to 250 ms, the shell will be almost fully penetrated by both the internal resonant modes and the resistive external non resonant m=1 kink modes like the Resistive Wall Modes (RWMs), that in RFX range from n=1 to n=5. Therefore the new RFX control system has been designed to interact with both of them and the theoretical feasibility of the concept has been recently assessed [10, 11, 12].

The plasma-shell proximity b/a has been reduced to 1.11 by reducing the thickness of the graphite tiles and by installing the shell as close as possible to the vessel surface (Fig. 1).

To reduce the field errors produced by eddy currents, the shell has only one poloidal gap and one toroidal gap. The poloidal gap, by far the most important source of stray fields, is overlapped for a toroidal span of 23° and the gap insulation is only 2 mm thick.

The design of the saddle coils [13] has been mainly driven by the requirements in terms of space resolution. As said before, the typical spectrum of MHD modes in RFX is m=0, 1 and n ranging from 1 to ~15. Therefore the minimum number of coils is $2m_{max}+1=3$ in the poloidal direction and $2n_{max}+1=33$ in the toroidal direction. Due to symmetry and assembly reasons and to minimize the amplitude of the undesired sidebands, the number of coils chosen for RFX is 4 in the poloidal direction and 48 in the toroidal direction (Fig. 1)

The saddle coils are made of 60 copper turns and are designed for a nominal current of 400A and a voltage of 650V. They are housed inside a new stainless steel toroidal support structure [9] and their poloidal branches lie immediately under the toroidal field coils.

3.2 Power supplies

Each saddle coil is fed by its own power supply, which performs independent control of the current and, consequently, of the local radial field at the plasma edge. The radial field at the plasma edge ranges from 40 mT in dc to 1.3 mT at 100 Hz when producing a n=8 harmonic.

The amplifiers have a switching frequency of 10 kHz, which allows a voltage response time lower than 1 ms. Particular care has been taken to avoid electromagnetic interference between converters and plasma diagnostics by means of proper output filters, designed to maintain a fast converter response in all operating conditions [14].

The toroidal field power supply has been modified [15] for a much better flexibility, to obtain improved confinement regimes by Pulsed Poloidal Current Drive and Oscillating Poloidal Current Drive, and to offer better performances in producing the m=0 rotating perturbation needed to drag the locked modes as described in Sect. 2. The 12 amplifiers feeding the 12 sectors of the toroidal field winding are able to generate rotating field waves with m=0, n=1-5. With a typical reversal parameter F=-0.2, the wave amplitude can be as high as 50 mT at low rotating speed; at higher speed it is mainly limited by the shielding effect of the shell.

3.3 Magnetic measurements

The extra-vessel probes, which are the basic source of feedback signals for MHD control purposes, measure all the three components of the magnetic field [16]. The poloidal and toroidal components are measured by pick-up coils located at the centre of each active saddle coil, the radial component is measured by saddle detection probes, mounted in the shadow of the active saddle coils. Two field components out of three are acquired in real-time for control purposes: 192 channels are dedicated to the radial field component and further 192 channels either to the toroidal or the poloidal component. The bandwidth is limited by the vacuum vessel eddy currents to about 1 kHz.

4. Modelling and test results

In recent years the need of designing active control systems of RWMs to achieve high β operation in Tokamaks has pushed the development of dynamic models using different approaches [10, 17] and first experimental results have been obtained [18]. Feedback stabilisation schemes have been also studied for Reverse Field Pinch plasmas [19, 11].

In RFX active stabilization of RWMs is required to extend the pulse duration beyond the new shell time constant. A full electromagnetic model has been developed, using state variable representation and multivariable control techniques [20]. It accounts for the interaction between saddle coils, plasma modes, passive conducting structures, integrating a lumped-parameter electromagnetic model of the saddle coil system (coil current dynamics & FFT) and a linear model of the evolution of RWMs (Plasma mode dynamics) [12]. The first describes the transfer function between the (m,n) Fourier harmonic components of the coil magnetic field at the coil radius and the total magnetic field at the sensor positions for a discrete set of coils and sensors. A MHD linear cylindrical stability code provided the growth rate estimate of the (m,n) modes for a RFP plasma in the presence of a resistive wall. A state space realisation has then been derived from the transfer function.

Figure 2 shows the scheme for the radial field component. A static controller and a processing block close the loop. The latter converts the output of the controller, proportional to the field harmonics, into voltage references to be applied to the saddle coils. In order to validate the

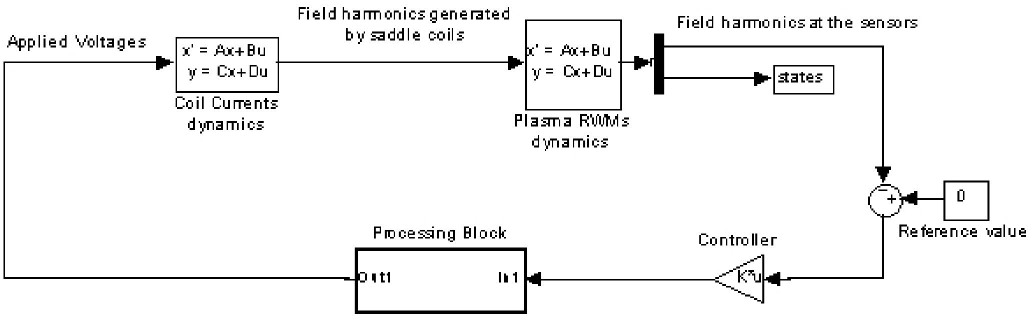

Fig. 2: closed-loop scheme of the RWM control system.

concepts, the model has been applied to the design of controllers for EXTRAP-T2R [21].

The flexibility of the digital control system allowed testing different control strategies, such as “virtual shell” and “mode control”. The former aims at cancelling the flux through each saddle detection probe, the latter at stabilizing selected MHD modes. Positive results in terms of pulse length [26] were obtained by testing a mode control scheme, named “wise shell”, in which all the measurable modes are suppressed except those related to equilibrium (in T2R n=0, ±1, ±2). Fig. 3 shows the measured amplitudes of the most unstable m=1 RWMs: almost all harmonics are lower in “wise shell operation” [23].

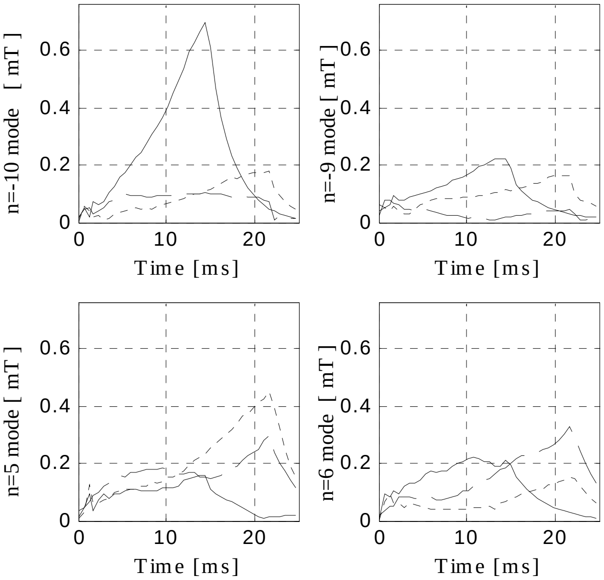

Fig. 3: time evolution of RWMs: reference shot without feedback #16365 (solid line), wise shell #16367 (dotted line), feedback on a subset of internally non resonant RWMs #16369 (dashed line).

5. Control technologies

Knowing the spatial structure of the magnetic field is crucial for any control scheme acting selectively on single MHD modes or groups of modes. In RFX the number of sensors installed allows the detection of MHD modes with orders m<2 and n<24. To cope with the large number of measurements and actuators and the computation load required to process the MHD signals, a distributed architecture has been chosen for the control system, using digital, computer-based electronics [24].

Figure 4 shows the implementation block diagram for the control of m=1 MHD modes. After sampling, two-dimensional Fourier analysis is executed on the measured field components and the control is selectively applied to single or multiple modes. The actual control is implemented in the frequency domain to track the reference mode $B^{m,n}_{ref,}$ aiming at cancelling the mode or at producing a static or rotating mode. After the controller, the field distribution required on the saddle coils is computed and translated into current/voltage requests.

Figure 5 shows the architecture of the control system, highlighting the key system functions: data acquisition and pre-processing, communication, control, power supply, measurement. It also shows the system layout, consisting of two computing nodes for data acquisition and pre-processing and three computing nodes to drive the power amplifiers. The number of computing nodes reflects the division of the system into more manageable sub-systems.

The selected hardware and software system components adhere as far as possible to formal or industry standards. The rationale behind this is that control systems in physics experiments must be designed to survive generations of hardware and software, and, at the same time, to continuously evolve for coping with new experimental developments. In real-time distributed systems, communication needs to be both deterministic and reliable (error free).

These requirements are generally in conflict, as error-free communication techniques imply re-transmission of lost or corrupted data packets, resulting in variable, non-deterministic transmission time. The communication layer for the real-time control was implemented by

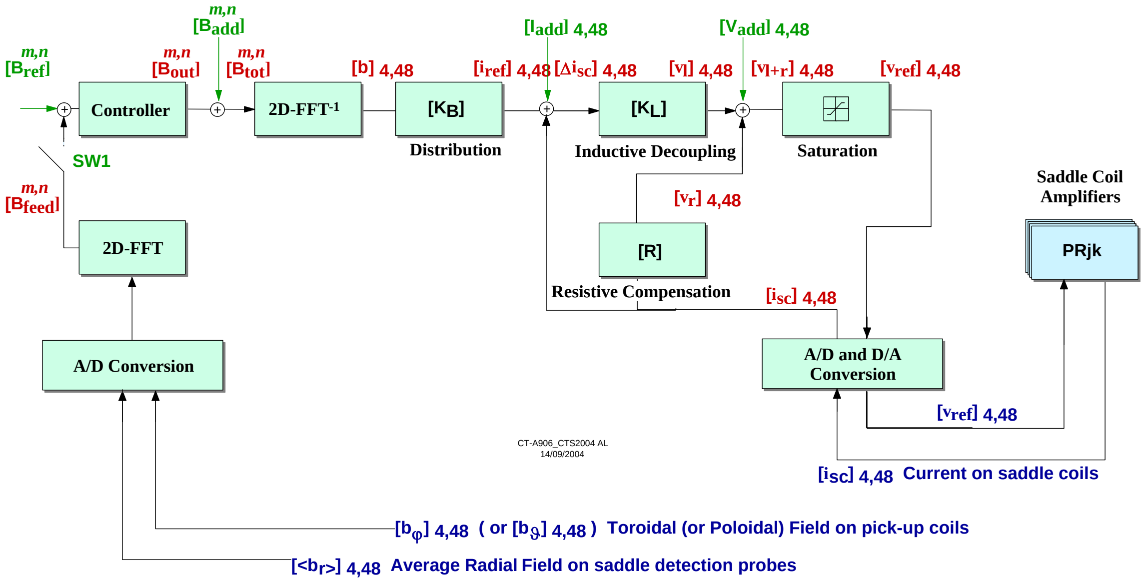

Fig. 4: block diagram for the control of m=1 MHD modes. Capital and small letters represent quantities in frequency and time domain, respectively.

using the UDP protocol (which has very limited error recovery) on standard Ethernet (100 Mbit/sec). An extensive measurement campaign validated this choice [24].

The measured system latency time (i.e. the time elapsed between acquisition of one sample of input signals and generation of the corresponding control references) is about 300 µs. This figure, obtained by careful optimisation of hardware and programming techniques, fulfils the control requirements for instabilities with growth time of the order of 10 ms.

The system software was implemented as a general, data-driven framework for real-time control, dealing with abstract concepts such as data packets, synchronisation events and state machines and is, as far as possible, independent of the underlying hardware. This approach allows minimising the software changes in case of future hardware modifications. Optimised programming techniques were used only in a few computation-intensive functions (such as

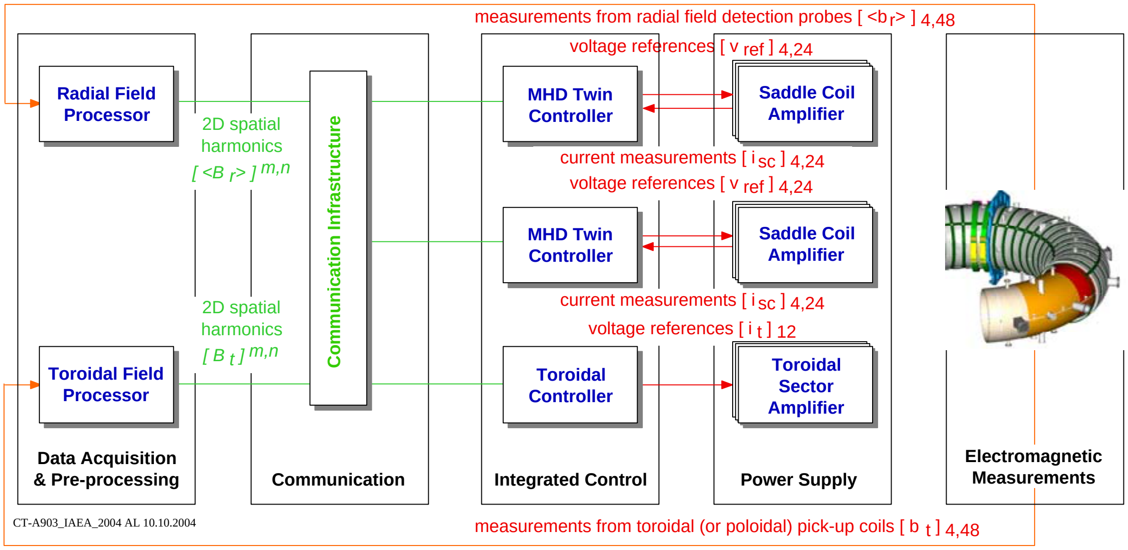

Fig. 5: system architecture for the control of the MHD modes.

2D Fourier analysis and matrix arithmetic, as they take advantage of particular features of the selected processors), because they affect code portability.

The main lessons learned in developing past and present real-time systems in RFX are:

- Algorithm processing can be made very efficient, as performing processors are available for intensive floating point arithmetic; in the MHD mode control system in RFX less than 20% of the cycle time is taken by the 2D Fourier decomposition algorithm;
- Communication is critical; in our application about half of the latency time is due to data transmission. Enhanced communication could dramatically help in real-time control systems. Standard communication is preferable to proprietary, more performing systems.
- Moving data between ADC/DAC and processors is critical. The performance figures of standard hardware platforms, such as VMEbus, are evolving, but not as fast as expected.
- Independence of software and hardware is the key concept to obtain enhanced portability and maintainability. Enhanced portability allows using the same real-time system software in different physics experiments and surviving hardware obsolescence.

6. Scientific objectives of experiments

RFX plasma experiments will restart by the end of 2004. The scientific programme aims at enhancing plasma confinement and allowing a deeper understanding of its basic phenomena, the main topics being MHD control, energy and particle transport, magnetic and electrostatic turbulence. Owing to the new tools, the main emphasis will be on MHD, where a variety of experiments are planned:

- Driven rotation of MHD modes, by non-linear coupling or by directly acting on individual field harmonics to induce differential rotation;
- Controlled formation of Quasi-Single Helicity [25] states by driving helical fields at the plasma boundary, or by keeping a flux surface coincident with the first wall;
- Feedback stabilization of RWMs;
- Simultaneous control of equilibrium, helical fields and rotating m=0 perturbations.

These studies will be not only relevant for RFPs but also for Tokamaks operating under advanced confinement scenarios. MHD control strategies will be developed and studied on a machine which offers a simple geometry and an excellent coverage of coils, where the effects of the actions on individual modes can be better assessed, resulting in a clear picture of the underlying physics.

7. Conclusions

The paper highlights that it is possible to design real-time control systems characterized by a large number of input/outputs and by a short latency time, to be suitable for feedback control of non-axisymmetric instabilities with high m or n periodicity in fusion machines.

Significant results have already been obtained on the RFP machine EXTRAP T2R [26]. This has improved our confidence that the RFX experiment, to be restarted at the end of 2004 and using similar hardware and algorithms, may offer a key contribution to the knowledge of the mechanisms underlying MHD mode control, which is relevant for the whole magnetic fusion community.

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