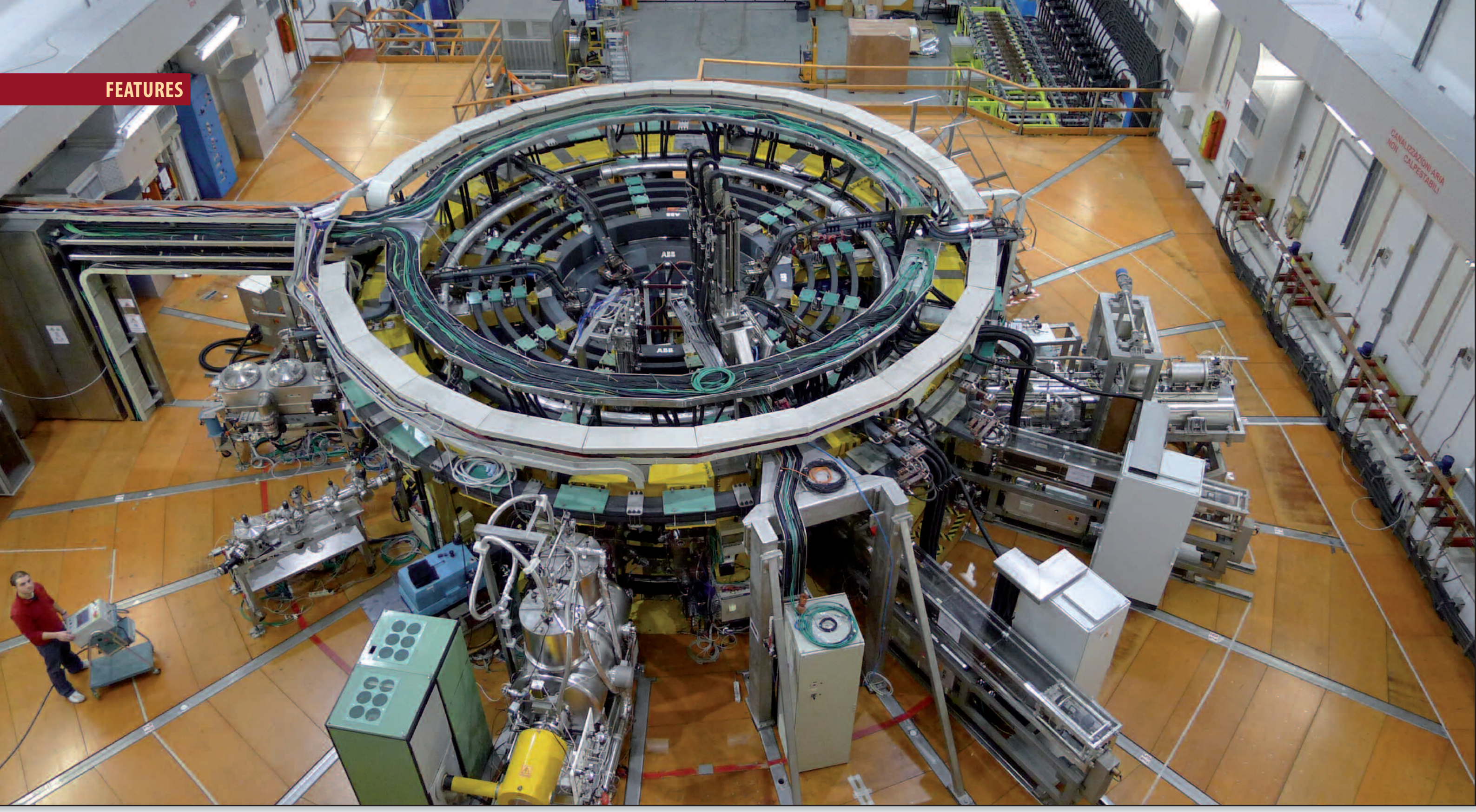

Feedback control in magnetic nuclear fusion

■ Piero Martin - piero.martin@igi.cnr.it - DOI: 10.1051/epn/2011607

■ Dipartimento di Fisica "G. Galilei", Università di Padova and Consorzio RFX-Associazione EURATOM-ENEA sulla fusione, Padova, Italy

Feedback control is part of our everyday experience. From the simple ambient thermostat in our homes to ABS in our cars, from the brightness self-adjustment of notebook screens to the more sophisticated cruise control systems in modern jetliners, feedback control is a ubiquitous ingredient of modern technology. Indeed, feedback control is a key process for life itself. It is therefore not surprising that a challenge like that of producing energy from controlled thermonuclear fusion strongly relies on feedback control for its success.

▲ The RFX-mod reversed-field pinch device. RFX-mod is equipped with the most complete system of coils for active control of MHD stability ever realized for a fusion device.

Living organisms, like humans, require feedback control mechanisms for maintaining internal stability in spite of environmental change. This ability is called homeostasis. It is, for example, responsible for maintaining blood pH or body temperature within rather narrow ranges – which, if trespassed, may lead to fatal consequences. Feedback control is also central for many technological tools, which are familiar to our daily life: from the simple one, like thermostats in our living rooms, to the more sophisticated like the Anti-lock Braking System (ABS) in the automobiles, or the control system in modern civil airplanes.

It may not be very surprising that one of the more ambitious scientific and technological challenges of mankind for this century, *i.e.* producing energy from controlled thermonuclear fusion, strongly relies on feedback control for its success.

The challenge of thermonuclear fusion

To produce energy with fusion, a hot plasma made by two hydrogen isotopes, deuterium and tritium, must be confined for a sufficiently long time within a reaction chamber. One possibility to achieve these conditions is using magnetic fields to confine the plasma (made by

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moving charged particles) within doughnut-shaped, toroidal containers. This is magnetic confinement fusion. For it to be successful, 'hot and dense' means orders of magnitude that for temperatures are ≈200 million °C and for densities ≈10^{20} particles per cubic meter (which corresponds to less than one millionth of the atmospheric density).

The ITER experiment [1] (ITER means "the way" in latin) is one of the largest science projects ever in the human history and is the front-runner in this challenge. ITER is supported by accompanying experiments in many countries of the world, which are necessary for its success. ITER is a 17 meters high, 830 m^3 plasma volume device, which is under construction in Cadarache, France as a joint project between China, European Union, India, Japan, Korea, Russia and USA. Its goal is to demonstrate the scientific and technological feasibility of fusion by producing 500 MW of fusion power. Its main parameters are listed in Table I.

Plasma major radius	6.2 m
Plasma minor radius	2.0 m
Plasma current	15 MA
Toroidal field at 6.2 m radius	5.3 T
Plasma volume	830 m^3
Fusion power	500 MW
Fusion power gain Q	≥10 (for 400 s inductively-driven burn)

▲ **TABLE 1:** ITER parameters [1] (more information at www.iter.org)

Reliability and performance: key to success

R&P, reliability and performance: these are two keywords to make fusion a successful story. Reliability is clearly a must for a commercial plant, which should be available 24/7 – except for short maintenance periods – and fault-proof. And performance, too: the quality of confinement is a basic requirement for fusion to happen, and to keep cost of electricity as low as possible. Getting R&P together is in general a challenge, as it is often easier to have one at the expenses of the other. Airplanes are typical examples: commercial attractiveness and social acceptance requires reliability and safety. In fact, intrinsic stability is one of the main drives for passenger aircraft design. But if performance is the prime requirement – as happens for example for military aircraft, where maneuverability and speed often define the metrics of performance – constraints on stability are relaxed, even to the point of relying completely on active stability control ("fly-by-wire") to fly intrinsically unstable airplanes. Part of the challenge for fusion is to simultaneously optimize both reliability and performance.

Reliability and performance in fusion plasmas are linked to stability. A key dimensionless parameter to define the metric of performance in magnetized fusion is β, which measures the ratio between kinetic pressure stored in the plasma (*i.e.* the product of density and temperature) and the magnetic pressure needed to confine the plasma [2]. Higher β means better performance (both in terms of fusion gain and capability of maintaining steady state conditions). But at higher β the plasma is more prone to instability [3]. Plasmas for magnetic confinement fusion are in fact systems with built-in free energy: pressure gradients, magnetic field, population of fast ions are all sources of free energy, which could give rise to unstable behaviour. Instability means either performance degradation or, in the worst case, severe threat to device integrity. A large part of plasma stability is described within the magnetohydrodynamic (MHD) model, which treats the plasma as a magnetized conducting fluid and uses mass, momentum and energy conservation equations. A number of these instabilities can be avoided by appropriately "navigating" the operational space, *i.e.*, by proper selection of the plasma regime to avoid "more dangerous" parameter regions. But navigation might not be enough to achieve the desired performance in the burning plasma if it is restricted to passively stable regions. Moreover, it may not protect against dangerous off-normal events. Therefore, active control is an essential ingredient for safe navigation beyond conventional stability limits, which would bring significant benefit in terms of performance and efficiency.

Examples of feedback control

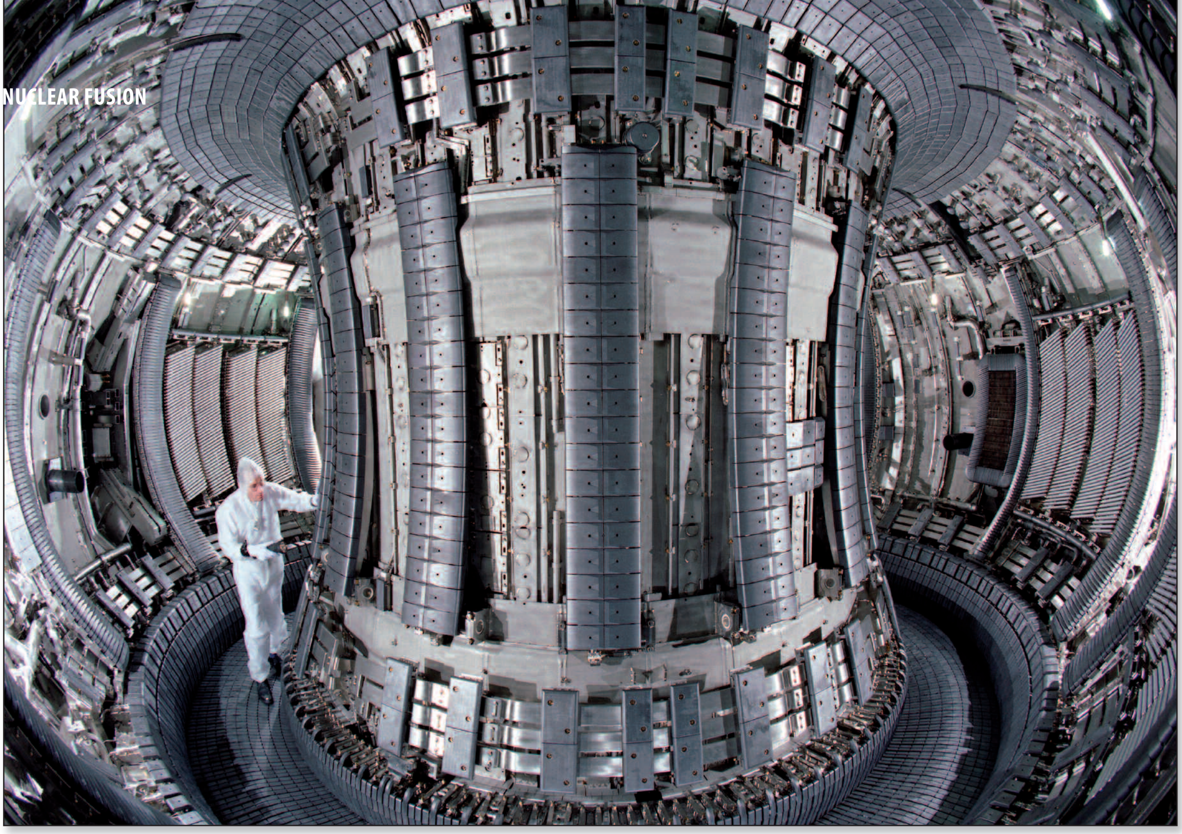
With clear awareness of the challenge, present-day fusion experiments are developing a successful program on feedback control of plasma stability, with a high level of integration and synergy between different approaches, all studied in view of applications to ITER and next generation of experiments. Interestingly enough, as we shall see, the science and technology of plasma control is being efficiently advanced in devices, which do not necessarily need to be tokamak, as ITER is.

Let's have a look at some examples, just to show what we mean by plasma stability control and its interplay with plasma performance. Due to space limitations, this is clearly not intended as a complete coverage of such a broad field.

The most mature problem in plasma control is controlling plasma shape and position. Both need to be controlled in a fusion device. The plasma has to be kept in the containment vessel, without having direct contact with it. Moreover, the particle outflow needs to be directed to a specific region, called divertor, where exhaust power

▼ **TABLE 2:** JET DESIGN parameters (more information at www.efda.org)

Major radius	2.96 m
Minor radius	2.10 m (vertical) 1.25 m (horizontal)
Toroidal magnetic field on plasma axis	3.45 T
Plasma volume	~ 90 m^3
Plasma current (max)	4.8 MA



▶ **FIG. 1:** Internal view of the JET vacuum vessel (image courtesy of EFDA JET)

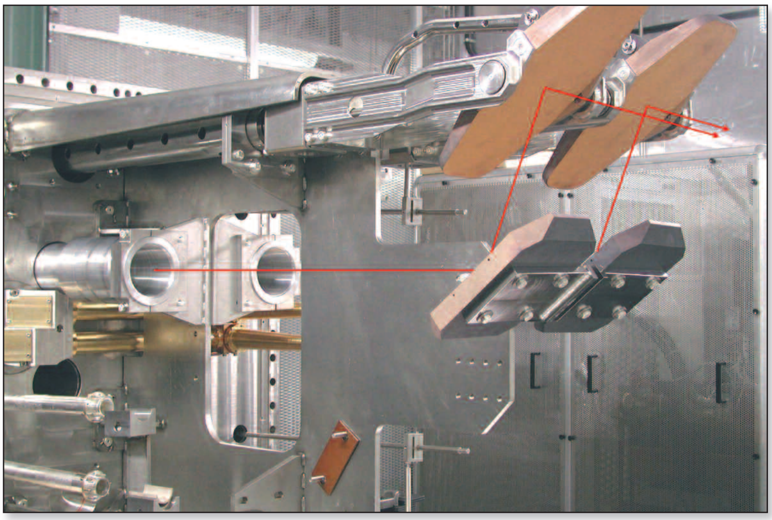
loads are managed. In addition, the poloidal plasma cross-section of a tokamak needs to be appropriately shaped to achieve higher performance. This means that the optimal cross-section is not circular, but vertically elongated. However, an elongated shape happens to be unstable against small vertical displacements, which are amplified and may lead to plasma termination. Therefore, also the vertical plasma position has to be controlled. Position and shape control is realized by acting on the plasma with external magnetic field.

The largest tokamak nowadays in operation, the European Joint European Torus (JET) device (see Figure 1 and Table II), works routinely with the eXtreme Shape Controller (XSC) [4]. This is a model-based, multivariable control system. Plasma shape is defined by 32 geometrical descriptors, which are basically distances (gaps) between the plasma and the wall and positions of particular plasma points. Magnetic sensors evaluate these descriptors. For each desired shape a set of such descriptors is preset. In real-time the differences between the actual and the preset optimal values of the descriptors are fed as input in the controller. Outputs are the voltages applied to coils, where a current flows to produce the required magnetic field to shape the plasma. The eXtreme Shape Controller calculates the smallest currents needed to minimize the error on the overall shape. It works efficiently also in presence of significant variations of other plasma parameter, not directly controlled by it, which may also influence shape. The eXtreme Shape Controller works very reliably, and allows for significant improvement in JET plasma operation. As an example, the average error on the 28 controlled plasma-wall distances is reduced down to 1 cm, to be compared with the larger radius of the D-shaped JET cross section, which is 2.10 m. The extreme Shape Controller is a valuable example to show the importance of having a good model of the process to be controlled, as the model used in the XSC. An accurate model can be either "ab initio", *i.e.*, based on a physics description of the process, or a "black-box", *i.e.*, identified by experimental data.

On the subject of plasma shape, a smaller tokamak device like the *"Tokamak à Configuration Variable"* "TCV" at the École Polytechnique Fédérale de Lausanne (EPFL) in Swiss [5] is explicitly designed to study the influence of shape on performance and stability.

As plasma performance is pushed, more free energy is available (in the kinetic pressure, for example) as a potential drive for instabilities. Active control provides a very efficient tool to overcome this problem, too. One option is to target directly the plasma current density and pressure, in order to tailor them in real-time in a more stable shape. The Tore Supra Tokamak at the Cadarache Center of the French *Commissariat à l'Energie Atomique et aux Energies Alternatives* (CEA) realized several successful experiments on this topic [6]. Another successful example is provided by Neoclassical Tearing

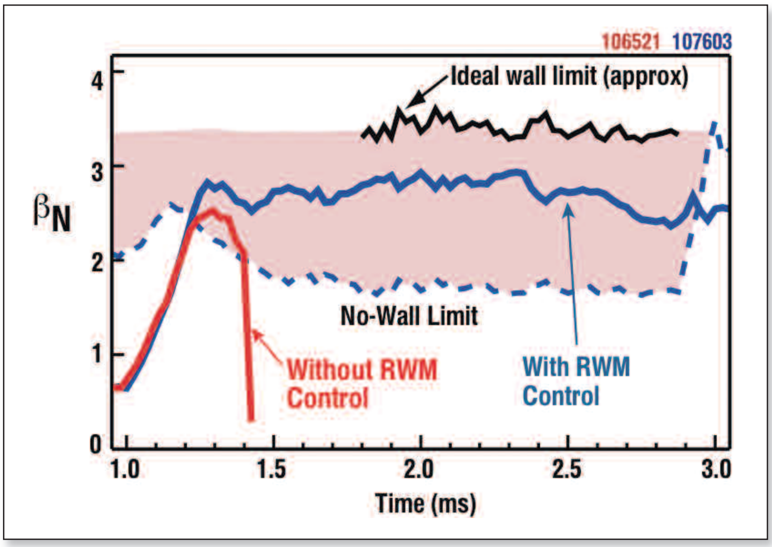
▼ **FIG. 2:** The real-time controlled mirror system in ASDEX (Axially Symmetric Divertor EXperiment) Upgrade. Mirrors are tilted real-time to focus a radio-frequency beam directly on the region where instability has to be cured. The pattern of the beam is also shown. (image courtesy of Max-Planck IPP)



Modes control. Neoclassical Tearing Modes are instabilities driven by plasma pressure, which cause the growth of nested sets of magnetic field lines within the main plasma, called islands. Islands may degrade plasma performance or cause its termination. Targeting them with beams of Radio Frequency (RF) waves, which resonate at the electron cyclotron frequency, was found to be an efficient method to heal them in tokamaks.

An example is provided by ASDEX Upgrade, a tokamak at the Max-Planck Institut für Plasmaphysik in Garching, Germany [7]. Here a system of mirrors – shown in Figure 2 – is controlled in real time with a typical response of 10-20 ms to track the target island and allow launching in it RF waves. These RF waves are produced by 6 gyrotrons with a total installed power of 6 MW (with 4 of them deliverable for up to 10 s). RF-based real-time feedback systems have been developed also for TCV [5] and for the TEXTOR experiment [8], operated in Jülich, Germany under the Trilateral Euregio Cluster. In TEXTOR the system combines an electron cyclotron emission diagnostic for detecting the instability in the same sight line with a steerable RF antenna. Event-triggered RF wave injection has also been demonstrated to be a powerful tool to avoid dangerous disruptions in the FTU tokamak in Frascati, Italy [9] or to control core instabilities like the so-called sawtooth (see [10] for a recent review).

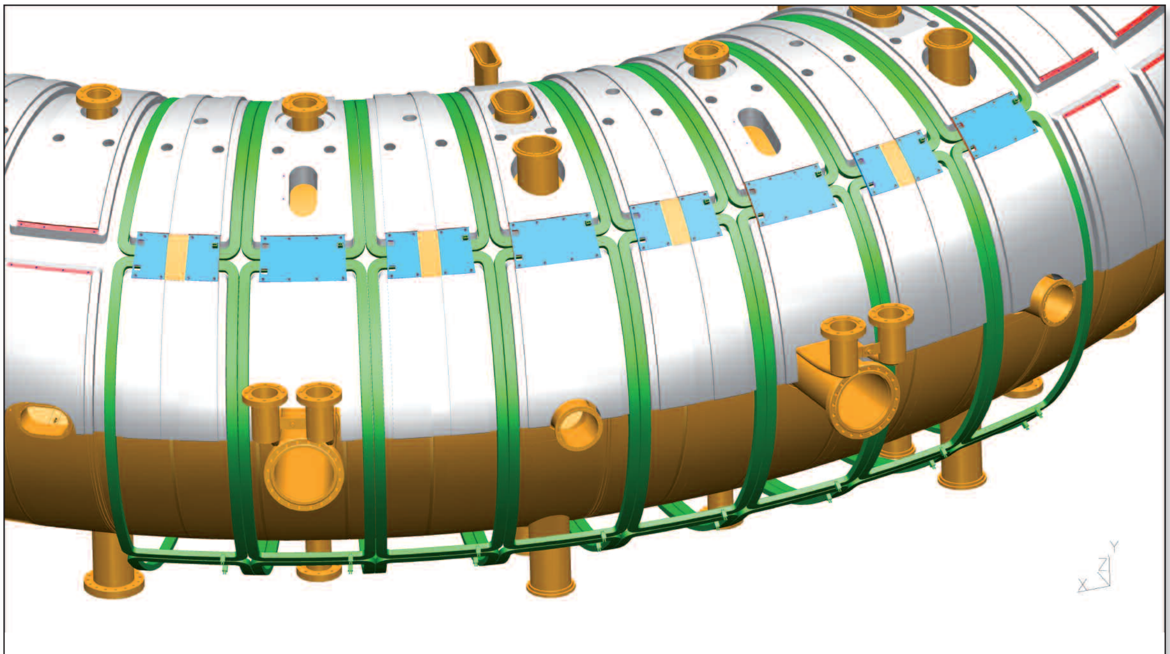
If one pushes performance even further, plasma instabilities known as Resistive Wall Modes perturb the equilibrium magnetic field. These perturbations can be sensed and used as input signals in a feedback loop, where the real-time actuators are a set of coils located at the plasma edge. These coils produce in fact a magnetic field, which cancels the perturbation. The technique is rather robust, and allows for running a tokamak plasma beyond passive stability limits. This was shown, for example, by the DIII-D tokamak [11], in operation at General Atomics, San Diego, California, see Figure 3. DIII-D is equipped with 18 feedback-controlled external coils, which have a key role in controlling magnetic field errors and perturbation caused by gross distortion of the plasma column, eventually leading to very high values of the plasma thermal content. RWM studies are conducted also in the NSTX device in Princeton, US. A new experiment, JT-60SA presently under construction in Japan under a joint programme between Japan and EU [12], will be particularly equipped with an active system to explore operation in high-performance, passively unstable regimes.



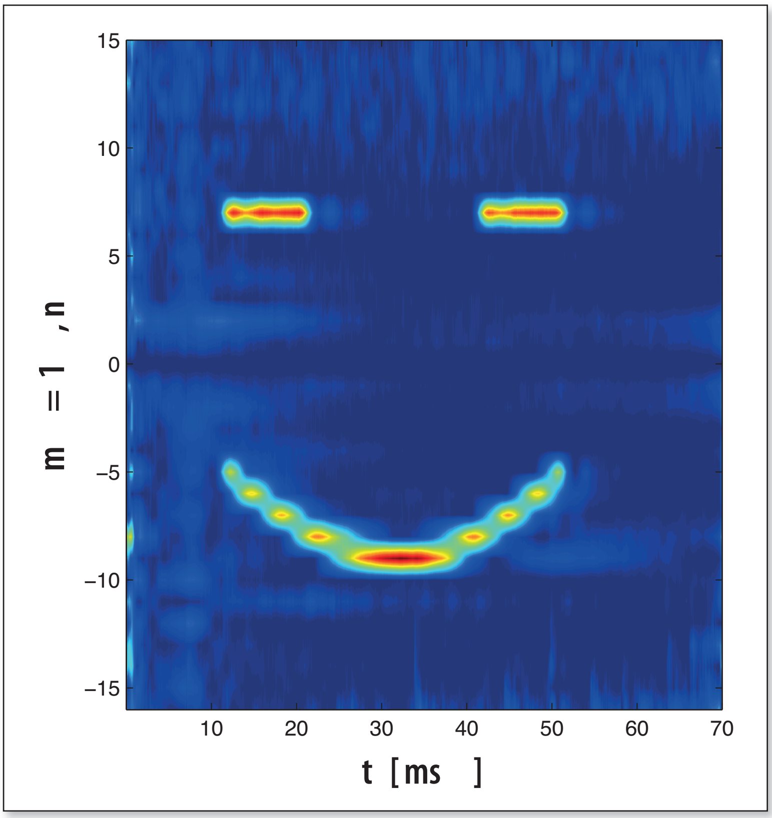
▲ **FIG. 3:** Time evolution of the β parameter (kinetic pressure divided by magnetic pressure, see text), here expressed with its normalized version β_N, in the DIII-D tokamak, with and without real-time control of magnetic stability. The dashed blue curve shows the boundary of the passively stable region: when a β-value higher than set by the passive stability boundary is reached, an instability called Resistive Wall Mode may grow and spoil plasma performance. This is shown by the red curve, where no active control was used. When real-time RWM control is used (solid blue curve) the plasma is actively kept stable and safely runs with higher performance. (Data taken from ref. [11]). Image courtesy of General Atomics-DIII-D

Coils: a robust tool for diverse experiments

Interestingly enough, flexibility in present devices is such that the same kind of coils are used in several tokamaks, like for example JET, DIII-D, ASDEX Upgrade, MAST ▸



◂ **FIG. 4:** In RFX-mod 192 saddle coils (some of them are shown in green) cover the whole plasma surface and are each independently controlled (image courtesy of *Consorzio RFX*) (at CCFE in Culham, UK) and TEXTOR, to actively produce appropriate magnetic perturbation which allow for the control of edge-localized instabilities and for a better mitigation of the plasma-wall interaction (see *e.g.* [13,14]). While plasma control is a challenging task, huge steps have been taken in recent years. Control tasks, which seemed unbelievable only a few years ago, are now performed. A good example is the experience of the European reversed field pinch devices, EXTRAP T2R [15] and RFX-mod [16]. Reversed Field Pinch (RFP) shares similarities with the tokamak, but is confined by a much smaller magnetic field. This has advantages – like an easier technology for coils – but also poses some issues in term of stability. RFPs are at the leading edge in the field of feedback control of plasma stability. For example, RFX-mod, in operation at *Consorzio RFX* in Padova, Italy, is equipped with 192 active coils, which cover the whole plasma surface (Figure 4). This system has allowed a significant improvement of the performance and in particular the discovery of the Single Helical AXis state [17]. Each of the coils is independently driven and feedback controlled, which allows enormous flexibility and control of several three-dimensional instabilities at the same time. The EXTRAP T2-R Reverse Field Pinch in Sweden is also contributing high leverage results (Figure 5). Reverse Field Pinches are providing a working example on how a complex control system can be designed, realized and used reliably. In addition, they prove the value of diversity, since flexible experiments, when cleverly designed, can provide key contribution to the tokamak main line even if they are not tokamaks.



▼ FIG. 5: A playful example of the capability of MHD real-time control in 'Reversed Field Pinch': the figure shows, as a function of time (*x*-axis), the Fourier spectrum (*y*-axis, toroidal mode number) of a magnetic perturbation deliberately imposed with external coils in the EXTRAP T2R device (image courtesy of EXTRAP T2R group, KTH, Stockholm).

Thanks to all this experimental and modeling effort the knowledge in this field is rapidly expanding, with a growing and cross-fertilizing interaction with control engineering world (see for example [18]), which also attracts new students in the field. ITER and the next generation of experiment will then be able to run in much safer condition and with higher performance. 3,2,1…take off. We are ready to fly! ■

About the Author

Piero Martin (1962) is full professor of physics at the Physics Department of the University of Padova, Italy, and head of the fusion science program of the RFX-mod experiment at *Consorzio RFX*. Since 2008 he is leading the Topical Group on "MHD stability and its active control" for the European Fusion Development Agreement (www.pieromartin.it). He is EPS Member and fellow of the APS.

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