Overview of RFX-mod Results with Active MHD Control

S. Martini, M. Agostini, C. Alessi, A. Alfier, V. Antoni, L. Apolloni, F. Auriemma, P. Bettini,
T. Bolzonella, D. Bonfiglio, F. Bonomo, M. Brombin, A. Buffa, A. Canton, S. Cappello, L.
Carraro, R. Cavazzana, M. Cavinato, G. Chitarin, A. Cravotta, S. Dal Bello, A. De Lorenzi, L.
De Pasqual, D.F. Escande, A: Fassina, P. Franz, G. Gadani, E. Gaio, L. Garzotti, E. Gazza, L.
Giudicotti, F. Gnesotto, M. Gobbin, L. Grando, S.C. Guo, P. Innocente, R. Lorenzini, A.
Luchetta, G. Malesani, G. Manduchi, G. Marchiori, D. Marcuzzi, L. Marrelli, P. Martin, E.
Martines, A. Masiello, F. Milani, M. Moresco, A. Murari, L. Novello, S. Ortolani, R.
Paccagnella, R. Pasqualotto, S. Peruzzo, R. Piovan, P. Piovesan, A. Pizzimenti, N. Pomaro,
M.E. Puiatti, G. Rostagni, F. Sattin, P. Scarin, G. Serianni, P. Sonato, E. Spada, A. Soppelsa,
G. Spizzo, M. Spolaore, C. Taccon, C. Taliercio, D. Terranova, V. Toigo, M. Valisa, N.
Vianello, P. Zaccaria, P. Zanca, B. Zaniol, L. Zanotto, E. Zilli, G. Zollino, M. Zuin

Consorzio RFX, Associazione EURATOM-ENEA sulla fusione, Padova, Italy

e-mail contact of main author: stefano.martini@igi.cnr.it

Abstract. The paper presents an overview of the main results from the modified RFX since its restart in December 2004. The new machine has a thin Cu shell with vertical field penetration time τ_s , lowered from 450 to 50 ms and shell/plasma proximity from b/a = 1.24 to 1.1. Toroidal equilibrium is feedback-controlled and new power supplies provide better B_{ϕ} control. Newly designed graphite tiles protect the vessel from highly localized power deposition. A mesh of 192 external saddle coils independently controlled by a digital feedback system, controls radial fields due to field errors and MHD modes.

A dramatic improvement of plasma performance was obtained by using the saddle coils to cancel all the radial field components, an operation mode dubbed Virtual Shell. The toroidal voltage was lowered by more than 10 V and the pulse length was tripled, i.e. up to 7 times the τ_s . Steady-state RFP pulses are now limited only by the applied volt-seconds. The improved magnetic boundary has also an effect on the tearing modes underlying the sustainment of the RFP, the dynamo modes, whose core amplitude is more than halved. This results in a 100% increase of the particle and energy confinement time relative to the previous experiment. RFX-mod is now a very flexible machine used for a variety of mode control experiments, such as Oscillating Poloidal Current drive and Quasi Single Helicity studies. One of the most important results obtained is the feedback stabilization of Resistive Wall Modes. Hence RFX-mod initial operation demonstrated the possibility to operate a large RFP without a thick conducting shell, actually greatly improving its performance in terms of plasma parameters and confinement and, moreover, opened the possibility to further develop advanced RFP scenarios.

1. Introduction

The need for a close-fitting thick conducting shell for stabilizing ideal kinks and resistive tearing modes [1] has often cast serious doubts on the RFP as a configuration for controlled nuclear fusion. On the other hand, previous experience with RFP operation with thin shells had been rather disappointing [2]. Extended studies on the behaviour and the control of locked MHD modes shed light on the nature of the problems encountered [3]. An important role is played by the "dynamo" modes: internally resonating tearing modes are intrinsic to the RFP. They arise even with a perfectly conducting close-fitting wall and with their saturated amplitude provide the dynamo which sustains the RFP profiles in steady state. Due to non-linear coupling, dynamo modes lock in phase between themselves creating an interference pattern, in the following dubbed locked mode (LM), where all m=1 modes maxima coincide and all the m = 0 nulls are in phase nearby [4]. Because of the finite conductivity of the structures surrounding the plasma, such as the vacuum vessel and the

shell, and due to the high n content of the spectrum, which entails a faster radial field diffusion through the shell, the LM has also a strong tendency to become wall locked [5]. Such LM worsens the power losses associated to magnetic field line stochastization by creating a toroidally localized loss channel [6]. Moreover it causes a non-axisymmetric perturbation of the plasma [7], which grows to several cm in fractions of the shell time constant for B_v penetration, τ_S , and results in a highly localized Plasma Wall Interaction, PWI (FIG.1) [8]. In addition, over timescales longer than τ_S , the RFP, similarly to the tokamak, is affected by Resistive Wall Modes (RWM) [9]. Such modes were first found on the HBTX-1C RFP [2]. In the RFP they are non-resonant current driven instabilities (in RFX typically m = 1, n > -7 or n > 0), and, contrary to the Tokamak, are not stabilized by plasma rotation. Recently, feedback stabilization of RWMs has been demonstrated on EXTRAP T2R [10].

A solution to the above problems [3] consists in relying on a thin conducting shell only for the stabilization of fast modes arising during the RFP setting up phase, and utilizing active feedback control by external coils to mimic an ideal shell afterwards, thus preventing the growth of RWM and mitigating the effect of dynamo modes. The concept of an "intelligent" shell for the RFP had been proposed in the 80's [11]. Modern digital feedback technology and present knowledge of RFP MHD dynamics made it possible to realize it on the RFX device [12], which has been modified [13] and resumed operation in December 2004 as RFX-mod [14].

The paper presents the results of the initial period of operation and highlights how the active MHD control led to a major progress in the plasma performance [15, 16] and to new advanced RFP scenarios. The organization is the



FIG.1 LM perturbation: perturbed plasma surface (top); localized plasma wall interaction (CCD camera, bottom left); magnetic perturbation (bottom right, color code refers to plasma-wall distance).

following: in Section 2 the main machine modifications are described; in Section 3 the initial "passive" shell and subsequent "active" MHD control operation are presented and compared to the previous performance; Section 4 presents the newly developed mode rotation schemes which permitted to perform experiments at plasma current up to 1MA; in Section 5 the results obtained for advanced RFP scenarios along with the RWMs control experiments are summarized; in Section 6 conclusions are drawn.

2. The RFX-mod experiment

The modifications of RFX (a/R = 0.46 m / 2 m; I \leq 2 MA) [13] where aimed at improving the plasma boundary, both in terms of plasma facing components and "passive" magnetic boundary, and at introducing an active MHD mode control capability. The first set of modifications entails a new conducting shell, which is thin (3mm Cu) and has one overlapped poloidal gap and one toroidal gap. The τ_s has been reduced from 450 to 50 ms and shell/plasma proximity from b/a = 1.24 to 1.1. Newly designed graphite tiles improve PWI by reducing the heat flux peaking on leading edges.

As for the plasma control, RFX-mod is equipped with a full coverage of 192 external saddle coils for MHD mode control and more flexible power supply for the toroidal field circuit. The

saddle coils are arranged in a regular mesh of 48 toroidal x 4 poloidal stations, each one independently fed and equipped with a sensor for radial, toroidal and poloidal magnetic field. They can generate magnetic field harmonics with m=0, n=0 \div 24 and m=1, n=-23 \div 24. The maximum radial field generated at the plasma edge is 50 mT DC and decreases to 3.5 mT at 100 Hz. A digital feedback system [17] controls toroidal and poloidal circuits, toroidal equilibrium and the saddle coils. For MHD control it performs the two-dimensional FFT of B_r and/or B_{φ} measurements, compares it with the preset waveforms and computes via inverse FFT the required references. This allows controlling the MHD modes selectively and has been used for several control schemes. In the selective Virtual Shell (VS) some modes are set to zero and other are left unperturbed (e.g. the m=1, n=0 equilibrium B_y). A second scheme, dubbed VS + rotating perturbations, adds a finite amplitude (static or rotating) reference to a selection of modes. This is used for mode rotation (Section 4) or for studying the controlled growth of some modes, e.g. for QSH studies (Section 5). Finally, the Mode Control (MC) scheme applies the regulators to the modes rather than to the individual sensors. In this way a "complex gain" can be preset to each mode, i.e. the feedback system applies an out-of-phase cancellation of the mode, realizing an alternative algorithm for mode rotation.

3. Experiments with passive and active shell

Initial RFX-mod experiments [14] at 300÷600 kA without active mode control ("passive shell") produced RFP pulses similar to those of RFX (FIG.2). Feedback control of toroidal equilibrium was effective, controlling the plasma shift within a few mm. Dynamo mode dynamics was also benign, with amplitudes and spectra similar to the past. On time scales of the order of τ_s , the penetration of the radial field components through the thin shell and the initial growth of RWMs led to enhanced plasma wall interaction and higher loop voltage (FIG.2). For the same reason also the peak temperatures were lower (FIG.3). The improved graphite tiles design partially countered this negative effect by spreading the power deposition over their plasma facing surface rather than on their edges and some benefit was also found by the Rotating Toroidal Field Modulation, RTFM [18], an active rotation of the LM by an external m=0 perturbation generated by the B_{ϕ} coils. Despite the improved shell proximity, in RFX-mod no spontaneous rotation of the dynamo modes was seen, even at low currents (200 kA) and low density (1·10¹⁹ m⁻³). In summary the passive shell operation proved that the thin shell of RFX-mod produces an RFP with performance close to that of a thick shell, with I_{μ} [kA]



300 Virtual Shell 250 No Virtual Sh T_e(0) [eV] 200 RFX 150 100 50 200 300 400 500 600 700 I_p [kA]

FIG.2: Plasma current (top) and on axis voltage (bottom) in reference pulses for RFX (green), RFX-mod passive shell + RTFM (blue) and RFX VS (red)



some degradation seen after one τ_s .

As soon as the saddle coils were used in VS mode, the radial field errors at the plasma edge reduced by one order of magnitude to fractions of 1 mT [17]. This quenched the radial bulging associated to the LM, as shown in FIG. 4, where it decreases from 4 to ≈ 0.5 cm for the m = 1 component and from 6 to ≈ 1.5 cm for the m = 0 one. As a consequence, a dramatic improvement of plasma performance was obtained. As



FIG.4 Plasma surface perturbation due to LM with VS (red) and without (black): m=1 component (left); m=0 one (right).

shown in FIG. 2, the loop voltage was lower by more than 10 V and the pulse duration was more than doubled. In practice, steady state RFP pulses are now limited only by the applied volt-seconds. The improved magnetic boundary not only results in a more uniform plasma-wall interaction, but also has an effect on the dynamo modes. By reconstructing the dynamo mode eigenfunctions in the plasma by means of a Newcomb solver code [8], we estimate a \geq 50% reduction the core radial fields associated to them, which is expected to entail less field line stochastization and better confinement. Indeed in FIG. 3 one sees that T_e in RFX-mod VS is systematically higher than in RFX. Moreover the profiles are characterized by steeper edge gradients and, in the best cases, they show some core peaking, with reduction of the thermal conductivity by a factor \approx 5 in the region r/a < 0.9. Overall we estimate a factor 2 improvement in particle and energy confinement [19].

4 Mode rotation and 1MA pulses

In RFX the lack of control of radial fields at the plasma boundary hindered operation at high current. Nearly 50% of pulses at $I_p > 0.9$ MA suffered "fast" terminations [20] and most of the remaining ones were plagued by carbon blooms due to highly localized PWI. In those conditions some relief was found by Oscillating Poloidal Current Drive (OPCD) [21] or rotating the LM by RTFM [18].

Conversely, the improved material and magnetic boundary of RFX-mod VS makes it



FIG.5 On axis toroidal loop voltage vs I/N in RFX and RFX-mod pulses at ≈ 1 MA

possible to perform long and well controlled 1 MA pulses, where the on axis loop voltage is in the range 20÷30 V, compared to the 30÷50 V of RFX pulses at the same current (FIG. 5). The temperature and the confinement time are also higher with a positive current scaling, which, contrary to the past, does not show any saturation at 1 MA [19], leading to $\tau_E \sim 1.5$ ms. Nonetheless, the incomplete field error correction by the saddle coils still causes the PWI to concentrate in the region of the LM. This results in a rapid deterioration of the wall conditioning, which calls for frequent sessions of H and He GDC.

A solution to this problem is to spread power deposition around the torus by externally induced the rotation of the MHD modes. To this end, RTFM can be used also in RFX-mod. The LM is rotated around the torus at 10÷20 Hz by applying an m = 0 n = 1 mode of a few mT in terms of $B_r(a)$. Unfortunately, although such values are lower than those needed in the

past, in RFX-mod with VS they cause an increase of a few volts of the loop voltage. This is explained by considering that the largest residual deformation of the edge magnetic surface with VS is due to the m = 0 component (FIG. 4). Hence, even the small additional error due to RTFM gives a non-negligible contribution to localized PWI.

On the other hand, we developed several new schemes for the rotation of internally resonant m = 1 modes by rotating m = 1 perturbations applied via the saddle coils. They take advantage of the direct coupling of each perturbation with the homologous mode, which occurs at the corresponding resonant surface. We used both MC with complex gains and VS + mode rotation schemes. As said in Section 2, the MC + complex gains applies a spatially out-of-phase correction to each mode, thus applying a torque that can be increased by increasing (in modulus) the phase of the complex gain. Of course the larger is such a phase, the higher is the residual field error, because of the incomplete correction. The scheme results in a rotation of the order



FIG.6: Footprint of LM maxima with active rotation: with MC + complex gains (top); with VS + rotating perturbations (bottom, path of an m=1 n=7 mode in red).

of $10\div20$ Hz. In the VS + mode rotation schemes the applied torque on each mode is proportional of the applied perturbation. We found that a B_r(a) perturbation smaller than 0.5 mT, i.e. comparable to the VS residual error, is adequate for mode rotation at frequency up to 40 Hz.

Both techniques are very effective, with some important differences. The complex gains scheme works with somewhat smaller field errors at the expense of a rotation velocity which "adjusts" itself to the plasma conditions. The latter feature is a drawback for LM rotation at high current. In fact when the complex gain is applied to several modes, because of their non-linear coupling, they all rotate at the same frequency. This results in a "poloidal rotation" of the LM (FIG. 6), which does not accomplish the desired toroidal spreading of the localized power load.

A more effective LM rotation is obtained via the VS + rotating perturbations schemes, which allow controlling the mode-mode relative phases. The best results are obtained rotating several modes with frequencies equally-spaced according to their n-number (e.g. n=-8 at 10 Hz, -9 at 20 Hz, -10 at 30 Hz and so on). The initial phase of each mode is set equal to the one present in the plasma (computed in real-time). In this way the modes are hooked up in the shortest possible time, their relative phases are maintained and



FIG.7: Superposition of 8 VS + rotating perturbation 1 MA pulses: a) plasma current; b) loop voltage; c) line average n_e ; d) central T_e ; e) LM toroidal angle.



FIG.8: T_e profile at 1 MA with VS + rotating perturbation (ensemble average of FIG.7 pulses) and with OPCD (pulse 19531)



FIG.9: QSH duration vs QSH probability in RFX-mod

the interference pattern of the LM is dragged helically along the path of a stationary m=1 mode (n= -7 in the case of FIG.6). Moreover, thanks to the combined non-linear coupling, the m=1 modes apply a rotating torque on the m=0 n=1 mode, which responds with occasional large toroidal "jumps" not normally seen in standard VS pulses.

The effectiveness of such LM rotation scheme is highlighted in FIG. 7, where 8 pulses lasting over 0.35 s are superimposed. As a result of a steady LM rotation, density control is not lost from pulse to pulse and plasma performance is very reproducible both in terms of plasma current, loop voltage, electron density and temperature. The T_e profiles are also very similar and broad (FIG. 8) with central values of 400 eV.

5 Advanced RFP Scenarios

The enhanced flexibility of the new toroidal circuit power supply along with the saddle coils system is also beneficial for advanced RFP scenarios aimed at confinement improvement by acting on the dynamo modes, such as Quasi Single Helicity states (QSH) [22], OPCD [21] and Self Similar Current Decay (SSCD) [23]. The QSH is an RFP state where the dynamo mode toroidal spectrum is dominated by a single n mode and which is characterised by higher central temperature and confinement. better core QSH states are often spontaneously occurring in RFX-mod, particularly when the edge error fields are minimized, i.e. when pure VS or MC with complex gains are applied. Long-lasting QSH states, where the hot helical core is seen for times much longer than τ_E , are more likely observed at high currents (FIG. 9) and shallow reversal ($F \le -0.1$). Moreover, by using the saddle coils with a proper feedback algorithm, it is possible control the onset of the QSH state and to study its properties through the pulse.

OPCD had been first tested on RFX [21]. It proved the possibility of improving the plasma confinement in steady state (oscillating) by the reduction of dynamo modes via inductive poloidal current drive [24]. In RFX it showed a



FIG.10: Standard (black) and OPCD (red) RFX-mod pulses at 1 MA: a) amplitude of m,n=1,-7mode; b) amplitude of other 1,-n modes; c) T_e ; d) reversal parameter F.

positive scaling with plasma current and a contribution to the improvement of plasma performance was also given by the periodic mitigation of localized PWI. The latter effect is less important in RFX-mod with VS, because of the improved magnetic boundary, therefore the confinement increase is not very large at low currents. Conversely, a recent set of experiments at 1MA shows that OPCD induces QSH by reducing the amplitude of secondary dynamo modes (FIG. 10). This results in central T_e increases of 30%, with the onset of a temperature gradient also in the plasma core (FIG. 8).

The Self-Similar Current Decay (SSCD) has been suggested as an interesting operation mode for the RFP [23]. The concept is that the dynamo should be "switched off" when the magnetic field is forced to decay with suitable rate at fixed radial profile. Numerical simulations predict a decrease of modes amplitude and stochasticity. The first experimental test of SSCD has been recently performed in RFX-mod. A regime, characterized by transient states close to the m=1, n=-7 single helicity, establishes. The magnetic regime induced by SSCD results in a 50÷100% increase of the energy confinement, as shown in FIG. 11.



600 kA (ensemble average)

Another important result obtained in RFX-mod has been the demonstration of full feedback stabilization of RWMs. This is highlighted in FIG. 12, where three pulses with different MHD control schemes are compared. When full VS control (12287 black line) is applied through the pulse, RWMs are completely stabilized. Conversely, when some RWMs are left uncontrolled (17301 red line), the most unstable one (m=1, n=-6 in figure) grows as expected from theory and leads to early pulse termination in $2\div3 \tau_s$. Finally, in the third case (17304)

green) the same mode is initially left free to grow and later stabilized. Remarkably, the mode is fully stabilized by feedback control in less than 10 ms, even after its growth to large amplitude. The MHD control system can also be used in open loop to investigate the so-called resonant field amplification involving marginally stable modes and resonant static or rotating field errors. In this way it is possible to assess the effect on RWMs growth of static error fields present during the setting-up phase.

6. Conclusions

The initial operation of RFX-mod clearly



FIG.12 RWMs stabilization: Plasma current (top) and mode m=1 n=-6 (bottom).

demonstrated the possibility to successfully operate a large RFP with a thin shell at MA current levels. Configuration set-up is not hindered and benefits by more flexible toroidal equilibrium control thanks to the faster penetration of the external vertical field. At later times of the pulse, feedback control in Virtual Shell provides a magnetic boundary better than that of a thick shell. As a consequence, plasma performance dramatically improves both because of better plasma wall interaction and of the reduced amplitude of core dynamo modes. RFP plasmas are sustained in steady state, as long as volt-seconds are available, toroidal voltage is reduced by \approx 30% and confinement time is doubled, up to 1.5 ms in standard 1 MA pulses. The demonstration of complete Resistive Wall Modes stabilization by pure feedback control

and with no plasma rotation effects is of interest also for the Tokamak. Moreover, the RFXmod high operational flexibility has been already used for a variety of advanced RFP scenarios. For instance Oscillating Poloidal Current Drive and Quasi Single Helicity states showed the onset of core pressure gradients and led to the highest central temperatures and the best confinement times. Initial Self Similar Current Decay experiments gave results in agreement with theoretical predictions. Several new mode rotation schemes have been successfully tested, which will permit to safely extend the current range beyond 1 MA.

Indeed future plans entail the exploration of the RFP performance at higher currents up to the 2 MA design value, along with the full exploitation of the MHD control. The Virtual Shell algorithm is being improved by including the shell transfer function, to compensate for the delay introduced by its interposition between coils and measurements. Moreover the Closer Virtual Shell is being implemented, where the control system is fed with error fields computed at the vessel first wall, rather than simply using measuring coils located at its outer surface. Progress is expected also in the m = 0 mode control, where the relatively limited correction capability of the saddle coils can be supplemented by integrated feedback control with the toroidal field coils. This will allow us to further develop advanced RFP scenarios and to perform more physics studies.

Acknowledgements: This work was supported by the European Communities under the contract of Association between EURATOM/ENEA.

References

- [1] ORTOLANI S. and SCHNACK D. D., Magnetohydrodynamics of Plasma Relaxation, World Scientific Publishing (1993)
- [2] ALPER B., et al., Plasma Phys. **31** (1989) 205
- [3] BARTIROMO R., Plasma Phys. 41 (1999) B143-B156
- [4] FITZPATRICK R. and ZANCA P., Phys. Plasmas 9 (2002) 2707
- [5] GUO S. C. and CHU M. S., Phys. Plasmas 9, (2002) 4685
- [6] SPIZZO G., et al, Phys. Rev. Lett. 96 (2006) 025001-1.
- [7] ZANCA P. and TERRANOVA D., Plasma Phys. 46 (2004) 1115.
- [8] ZANCA P., et al. 17th Proc. PSI, Hefei Anhui, China, 22-25 May 2006, P3.45
- [9] PACCAGNELLA R., et al., This Conference pap TH/P3-19
- [10] BRUNSELL P. R., et al., Phys. Rev. Lett. 93 (2004) 225001.
- [11] BISHOP C. M., Plasma Phys., 31 (1989) 1179
- [12] ROSTAGNI G., Fus. Eng. Design 25 (1995) 301
- [13] SONATO P., et.al., Fusion Engineering and Design 66 (2003) 161.
- [14] MARTINI S., et al., Proc. 32nd EPS Conf. on Contr. Fusion and Plasma Phys. Tarragona (2005), ECA Vol.29C, P-5.054
- [15] PACCAGNELLA R., et al., Phys. Rev. Lett. 97 (2006) 075001.
- [16] ORTOLANI S., et al. Active MHD Control Experiments in RFX-mod to appear on Plasma Phys.
- [17] LUCHETTA A. and the RFX Team, This Conference pap FT/P5-1
- [18] BARTIROMO R., et al., Phys. Rev. Lett. 83 (1999)1779.
- [19] INNOCENTE P., et. al., This Conference pap EX/P3-10
- [20] BARTIROMO R., et al., 27th EPS Conf. on Contr. Fusion and Plasma Phys., Budapest, ECA Vol. 24B (2000) 1380-1383
- [21] BOLZONELLA T., et al., Phys. Rev. Lett. 87, (2001) 195001.
- [22] ESCANDE D. F., et al. Phys. Rev. Lett. 85 (2000) 1662.
- [23] NEBEL R. A., SCHNACK D.D., GIANAKON T.A., Phys. Plasmas 9 (2002) 4968.
- [24] SARFF J. S., et al., Phys. Rev. Lett. 72 (1994) 3670.