Helical equilibrium in RFX-mod with feedback-controlled 3D boundary conditions at high plasma current and density

P. Piovesan[1], L. Marrelli[1], L. Piron[1], F. Auriemma[1], D. Bonfiglio[1], R. Cavazzana[1],
A. Fassina[1], P. Franz[1], M. Gobbin[1], E. Martines[1], A. Ruzzon[1], A. Soppelsa[1]
[1]*Consorzio RFX, Euratom/ENEA Association, Padova, Italy*

Helical states with improved confinement form spontaneously in all existing reversed-field pinch (RFP) experiments, in spite of different machine size and operating modes [1]. The probability to access a helical state, its persistence, and the amplitude of the dominant helicity - usually m=1/n=-7 in RFX-mod - steadily increase with plasma current, up to the highest value of 2MA recently reached in RFX-mod [2]. A residual level of secondary instabilities tends to perturb the helical flux surfaces, but their relative amplitude also decreases with plasma current. This correlates with the formation of helical internal transport barriers (ITB) and with an increase of the energy confinement [3]. While all the properties of spontaneous helical states scale favourably with plasma current, these states tend to disappear as the density is increased, typically above a Greenwald fraction $n/n_{GW}\approx0.3$ [4]. This effect is not fully understood at the moment, but it is likely due to high density peaking at the edge and consequent plasma cooling [5]. To realize high-performance, high-β RFP scenarios, methods to overcome this limit must be developed. This paper discusses one possible approach, based on feedback control of the helical equilibrium with external 3D magnetic fields.

In RFX-mod 1/-7 helical states can be robustly controlled and maintained in time by applying helical boundary conditions with the 192 feedback coils available in the machine [6]. The 1/-7 helicity corresponds to a nonlinearly saturated resistive kink-tearing mode. Both the edge radial magnetic field amplitude and phase of this mode are feedback controlled, so that either slowly rotating, $\omega_\phi<100$Hz, or static helical states can be obtained. Incidentally, similar experiments are being performed in RFX-mod also in low-current Ohmic tokamak discharges, applying 2/1 helical boundary conditions, with the same approach developed for the RFP [7]. Control of helical states via helical boundary conditions in the RFP and tokamak is shown to be feasible also in nonlinear 3D MHD modelling [8].

Recent experiments have shown that helical shaping with external 3D fields allows extending the density range where helical states exist up to $n/n_{GW}\approx0.5$, even at high plasma currents $I_P\approx1.7$MA. These results are presented for the first time in this paper. As an important outcome of this work, operation with a helical boundary opens the path to the development of helical divertors similar to stellarator ones to control the wall recycling [9], which may be considered for future upgrades of the machine. A better control of the plasma-wall interaction in turn may allow accessing even higher plasma current and density.

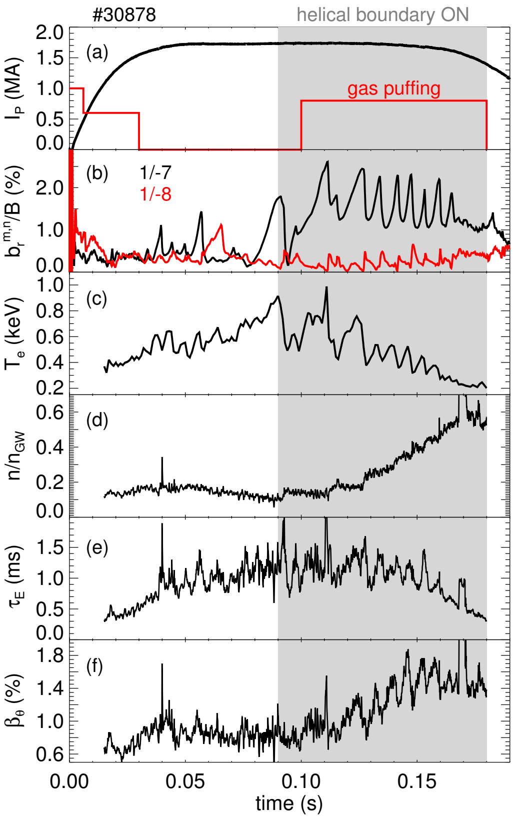

Figure 1. (a) Plasma current and gas puffing waveform (red), (b) 1/-7 and 1/-8 relative mode amplitudes at r=a, (c) core electron temperature, (d) Greenwald fraction, (e) energy confinement time, and (f) poloidal β for a 1.7MA discharge with helical shaping applied in the time interval indicated with the shaded grey band.

An example of a 1.7MA discharge with 1/-7 helical shaping is reported in figure 1. Here feedback-controlled helical boundary conditions are applied in the time interval 0.09-0.18s with reference $b_r(a)/B_\theta \approx 0.6\%$ and $\omega_\phi = 15$Hz. The density is increased by gas puffing in the second part of the flattop, as indicated by the red trace in figure 1(a). The helical state persists during this phase, which is evidenced by the 1/-7 mode amplitude in figure 1(b), up to an electron density of about 10^{20}m^{-3}, or $n/n_{GW}=0.5$. Without external 3D fields, the helical state would likely disappear at $n/n_{GW} \approx 0.3$. Note that this helical state is not really stationary, but it exhibits a sawtooth-like dynamics, which is observed also in the core electron temperature signal in figure 1(c).

Operation with a helically-shaped boundary is compatible with the high energy and particle fluxes reaching the wall at high current and density, as long as the edge 1/-7 radial field is maintained below $b_r(a)/B_\theta \approx 2\%$. In the discharge considered here, the energy confinement time does not change as helical shaping is applied, as shown in figure 1(e), while it starts decreasing at the highest density reached in the discharge. Confinement degradation may occur also at higher 1/-7 b_r/B_θ values, likely due to excessive plasma-wall interaction. On the other hand, β_θ increases with density up to $n/n_{GW} \approx 0.5$, as shown in figure 1(f).

The core electron temperature oscillation shown above reflects the formation and subsequent crash of a helical ITB, similar to that observed in spontaneous helical states [2, 3]. The ITB is associated with a region of good helical flux surfaces that forms in the plasma core. The ITB dynamics has been studied both with a 100Hz Thomson scattering diagnostic

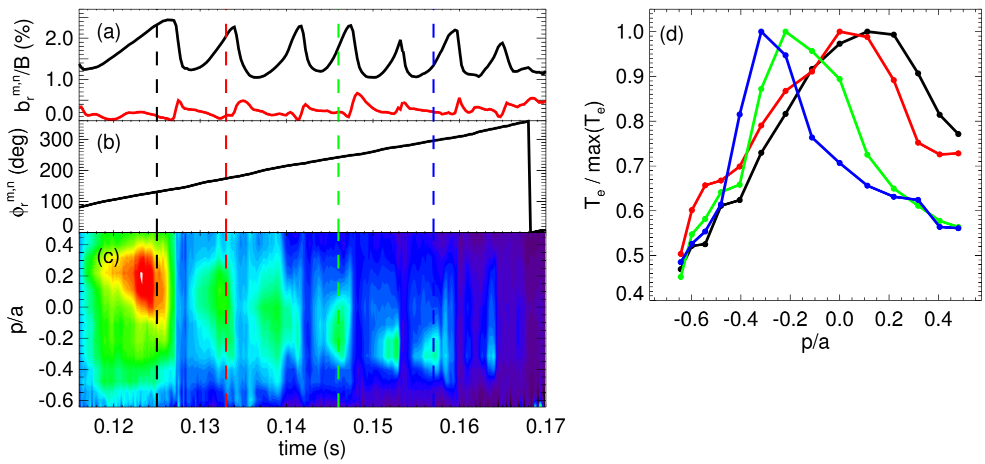

Figure 2. (a) 1/-7 and 1/-8 relative mode amplitudes, (b) 1/-7 phase, (c) contour plot of the electron temperature from the soft x-ray diagnostic vs chord impact parameter and time for the discharge of figure 1 during the interval with helical shaping. (d) Normalized electron temperature profiles corresponding to the times indicated with colored vertical lines in the left plots. The helical ITB shrinks as the density increases.

(not shown here) and with a new multi-chord, multi-colour soft x-ray diagnostic with temporal resolution of about 5kHz [10]. Figure 2 reports the time evolution of the electron temperature profile from the multi-colour soft x-ray diagnostic as a function of the chord impact parameter and time for the same discharge of figure 1. The ITB oscillates in phase with the 1/-7 mode amplitude, as expected. A series of normalized T_e profiles at times when an ITB is present are shown in figure 2(d) for increasing density, from $n/n_{GW}=0.1$ to 0.5. The low-density case is similar to the so-called SHAx ITBs described in [2]. Nevertheless, as the density grows, the ITB radial width decreases. This is likely due to the fact the secondary modes also increase at high density, as it will be better shown below. These modes can be responsible for the partial erosion of the good helical flux surfaces [11]. Transport analysis in helical coordinates, with the method described in [12], indicates that the heat diffusivity at the ITB radius decreases, due to the higher density at similar electron temperature gradient.

A series of similar discharges with (red circles) and without (blue circles) helical shaping are compared in figure 3 as a function of the Greenwald fraction. The helical state persistence, i.e. the flattop fraction when a helical state exists [2], collapses at $n/n_{GW}>0.3$ without helical shaping, while it grows to about 50% with helical shaping, as shown in figure 3(a). The energy confinement time and β_θ are plotted in figures 3(b) and (c), respectively, and the trends confirm the results described above. The relative secondary mode amplitude in figure 3(d) increases with density, probably due to a reduced Lundquist number, while the relative dominant 1/-7 mode amplitude stays almost constant (not shown here).

In summary, helical shaping allows to extend the density range where helical states exist up to $n/n_{GW}\approx0.5$. Helical ITBs similar to those forming in spontaneous helical states

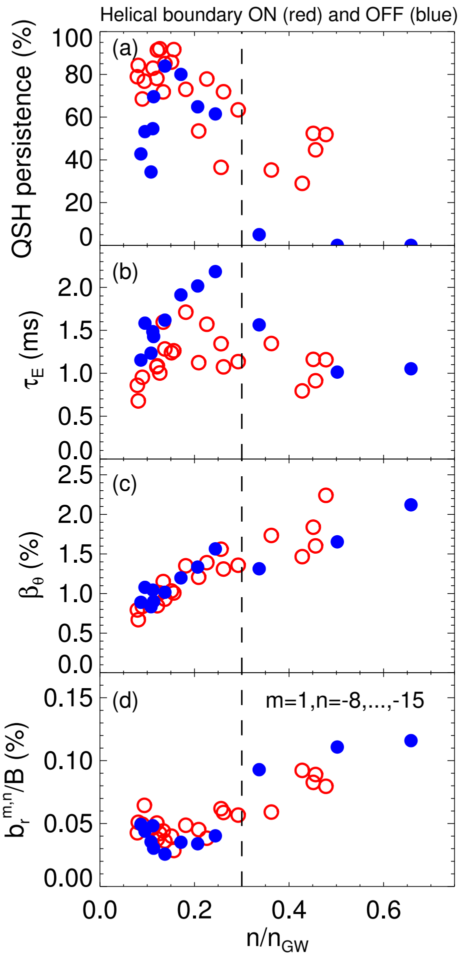

Figure 3. (a) QSH persistence, (b) energy confinement time, (c) poloidal β, and (d) relative secondary mode amplitude vs the Greenwald fraction for similar discharges with (red) and without (blue) helical shaping.

have been observed and studied with a new multi-colour soft x-ray diagnostic. As the density increases, though, the secondary modes also increase, probably due to the lower Lundquist number, which tends to erode the ITB and limits its impact on the global energy confinement. This may be not an intrinsic feature of this configuration, but it could be related to the present type of operation: with gas puffing and wall recycling, the particle source is located near the edge and the density profile is hollow. This tends to cool the plasma edge during high density operation. As an effect, the Lundquist number is reduced, which is likely the reason for the increase in the secondary mode amplitude. The optimization of helical states at high density thus requires the development of methods for a more efficient fuelling of the plasma, e.g. with pellets, NBI, or supersonic molecular beams, to produce density profiles more peaked in the core. This should go together with a better control of the plasma-wall interaction, e.g. with Lithium injection or a helical divertor. All these methods are in any case compatible with feedback control of the helical equilibrium using 3D shaping, as proposed in the present work.

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References

[1] P. Martin *et al.*, Nucl. Fusion **43**, 11855 (2003)
[2] R. Lorenzini *et al.*, Nature Phys. **5**, 570 (2009)
[3] P. Piovesan *et al.*, Nucl. Fusion **49**, 085036 (2009)
[4] M.E. Puiatti *et al.*, Nucl. Fusion **49**, 045012 (2009)
[5] G. Spizzo *et al.*, Plasma Phys. Control. Fusion **52**, 095011 (2010)
[6] P. Piovesan *et al.*, Plasma Phys. Control. Fusion **53**, 084005 (2011)
[7] P. Piovesan *et al.*, 18th Meeting of the ITPA MHD Stability TG, Padova, Italy, 4-7 October 2011
[8] M. Veranda *et al.*, 39th EPS Conf. & 16th ICPP, paper P4.004, Stockholm, Sweden, 2-6 July 2012
[9] E. Martines *et al.*, Nucl. Fusion **50**, 035014 (2010)
[10] A. Ruzzon *et al.*, 39th EPS Conf. & 16th ICPP, paper P2.023, Stockholm, Sweden, 2-6 July 2012
[11] R. Lorenzini *et al.*, Nucl. Fusion **52**, 062004 (2012)
[12] M. Gobbin *et al.*, 39th EPS Conf. & 16th ICPP, paper P4.094, Stockholm, Sweden, 2-6 July 2012