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H-mode Achievement and Edge Features in RFX-mod Tokamak Operation

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Abstract
The RFX-mod experiment is a fusion device designed to operate as a Reversed Field Pinch (RFP), with a major radius R= 2 m and a minor radius a = 0.459 m. Its high versatility recently allowed operating also as an ohmic tokamak allowing comparative studies between the two configurations in the same device. The device is equipped with a state of the art MHD mode feedback control system, providing a magnetic boundary effective control, by applying resonant or non-resonant magnetic perturbations (MP) both in RFP and in tokamak configurations. In the fusion community the application of MPs is widely studied as a promising tool to limit the impact of plasma filaments and ELMs on plasma facing components. An important issue is envisaged in the exploitation of the RFX-mod active control system for ELM mitigation studies.
As a first step in this direction, this paper will focus on the most recent achievements in term of RFX-mod tokamak explored scenarios, which allowed the first investigation of the ohmic and edge biasing induced H-mode. Among the others the realization of D-shaped tokamak discharges and the design and deployment of an insertable polarized electrode were accomplished. Reproducible H-mode phases were obtained with insertable electrode negative biasing stimulation in plasma shaped Single Null discharges, representing an unexplored scenario with this technique. Important modification of the edge plasma density and flow properties are observed. During the achieved H-mode ELM-like (Edge Localized Modes) electromagnetic composite filamentary structures are observed. They are characterized by clear vorticity pattern and parallel current.

Introduction

Thanks to its high versatility RFX-mod experiment recently had been operated as an ohmic Tokamak, with a toroidal field up to 0.55T, extending the parameter range explored by other devices, for example in the very low q (a) < 2 region, and allowing comparative studies between circular cross-section tokamak and reversed field pinch configurations in the same device [1]. RFX-mod is equipped with a set of 192 actively controlled saddle coils arranged in 48 poloidal arrays, each of them consisting of 4 coils, fully covering the vessel torus. This system represents the state of the art of MHD mode feedback control [2]. It allows a noticeable flexibility, so that the magnetic boundary can be effectively controlled and modulated by applying resonant or non-resonant magnetic perturbations (MP) both in RFP and in tokamak configurations [3,4]. The application of MPs is widely studied in the fusion community as a promising tool in particular to limit the impact of ELMs on plasma facing components [5]. RFX-mod is well suited to investigate the magnetic feedback control of the m=2, n=1 mode. The performed experiments have been fully successful for the stabilization of non-resonant RWM emerging in q(a)<2 plasmas [6]. The device allowed also the development of advanced MHD instability control algorithms [7], contributing to the advancement of runaway electrons studies [8] and disruption mitigation techniques by magnetic feedback control. A further important issue is envisaged in the exploitation of the RFX-mod active control system for ELM mitigation studies. As a first step in this direction, this paper will focus on the most recent achievements in term of tokamak discharge optimization, which allowed the first investigation of the ohmic and edge biasing induced H-mode in RFX-mod. In the last two years several developments have been performed to this end: in particular, the realization of D-shaped tokamak discharges (Single and Double Null) and the design and deployment of an insertable polarized electrode. The edge biasing technique was widely used in the past [9] to induce confinement improvements in fusion experiments. In recent experiments biasing was proposed for disruption avoidance due to the interaction of ExB flow with MHD modes [10]. In the RFX-mod experiments reported in this paper, the edge biasing is applied on circular and on SN shaped discharges, the latter representing an unexplored scenario. The optimization of the plasma shaping allowed studiyng the interaction between the edge features associated to the two configurations and the externally induced current flowing through the plasma and the biased electrode.

Experimental setup

The RFX-mod experiment is a fusion device born to operate as Reversed Field Pinch (RFP), with a major radius R= 2 m and minor radius a = 0.459 m, equipped with a first wall fully covered by graphite tiles. The development of reproducible and controllable tokamak operation in this experiment tooks advantage of the implementation of a real-time feedback control of the electron density [11] and of the plasma shape. Shape control has been possible thanks to the flexibility of RFX-mod power supply and magnet systems and to the design of a multivariable shape feedback control system based on a full model-based approach [12]. An algorithm to provide a fast and reliable plasma boundary reconstruction has been also developed [13]. The algorithm accuracy has been benchmarked against simulation results provided by the Grad-Shafranov solver MAXFEA [14] and proved to be robust against the noise observed in the experimental input signals.

The electrode setup used for biasing experiment is show in the fig.1 [15]. The electrode head consists of a graphite truncated ellipsoid (115x25x65 mm). It is connected to a manipulator and inserted inside the plasma from an access located on the bottom part of the device. Depending on the plasma position and shape, the tip of the electrode has been inserted up to 8 cm inside the Last Closed Flux Surface (LCFS). For the shots shown in this paper the electrode insertion was 7 cm inside the LCFS in both circular and SN plasma poloidal shaping. The biasing circuit scheme is also shown in fig.1 The electrode has been fed using one of the main power supplies of the machine, a single quadrant

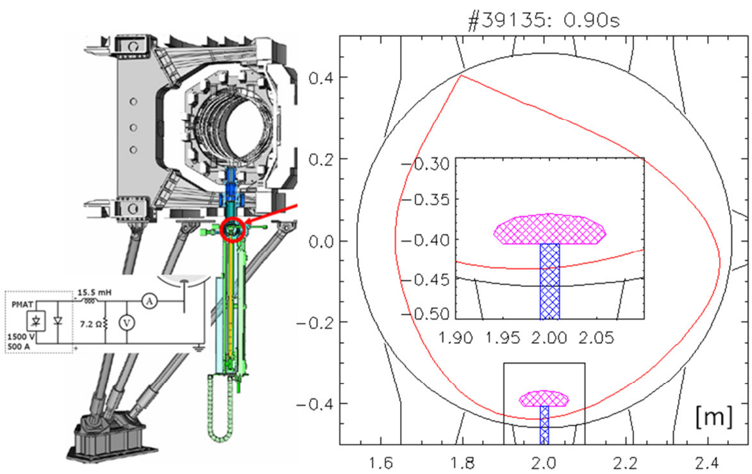

Fig. 1 Left : RFX-mod section at the toroidal position of the biasing electrode insertable system (colored parts). Electrical scheme used for the biasing. Right: polodal section of the vacuum chamber with the reconstruction of the LCFS (red line) and the corresponding electrode head (magenta) insertion for the shot #39135.

6 phases regulated bridge [16]. An L-R network is used to filter the fire sequence of the thyristors as shown in Fig. 1 (1.67 ms period). To preserve the electrode from damages, the electrode power supply was controlled through the MARTe real-time control system of RFX, programmed to turn off the power supply when the V-I curve was out of the expected range (i.e. arc occurrence). The temperature of the electrode was monitored by an infrared camera in order to avoid overheating.

Circular plasmas are operated with a 0.5-1 cm horizontal displacement towards the high field side, the inner first wall therefore acts as a toroidal limiter in this case. Features of performed circular discharges are plasma radius r_{plasma}=42-45cm, I_p=60-95kA, q(a)=2.7-4, n_e up to 8 $10^{18}m^{-3}$. Single Null (SN) discharges are characterized by the X-point distance from the first wall 0.5-2 cm. SN discharges are somewhat smaller, $<r_{plasma}>$=36-39cm, I_p=45-75kA, q_{95}= 2.5-4.5, n_e up to 5 $10^{18}m^{-3}$. As an example the plama shaping and the electrode inserted head is shown in fig. 1 for the SN shot #39135. The reconstructed position of the LCFS is shown in red. The effects of biasing electrode was monitored by using different diagnostics, ranging from spectroscopy to Soft X-ray Radiation and probes, fixed on the first wall and on insertable sistems. In particular in this paper are reported data from U-probe insertable head [25], equipped with 2D arrays of electrostatic pins and of tri-axial miniaturized magnetic coils, distributed on two identical towers poloidally spaced by about 6 cm. The system allows obtaining, besides the standard electrostatic characterization such as E×B flows, ion satuaration current I_{sat}, pressure, P_e, radial profiles, information also on two quantities not so commonly available such as the current density, δJ_t, and vorticity, $\delta\omega_t$, parallel to the local magnetic field [25].

H-mode achievement in RFX-mod tokamak

Indications of Ohmic H-mode were transiently observed during Single Null shaped plasmas, as attested by a decrease of the plasma-wall interaction, D_α decreases, and simultaneous increase of the soft X-ray (SXR). These transient states seem to be related to fast plasma current ramp-down [14], work is in progress on this subject.

The technique of edge biasing allowed instead to obtain more stable and reproducible H-mode phase, lasting for all the electrode switched on operation. It is worth noting that the explored electrode voltage, V_{el}, ranged from -800V to +350V with currents, I_{el}, up to 300A. In this paper we will focus on the results obtained with negative voltage biasing

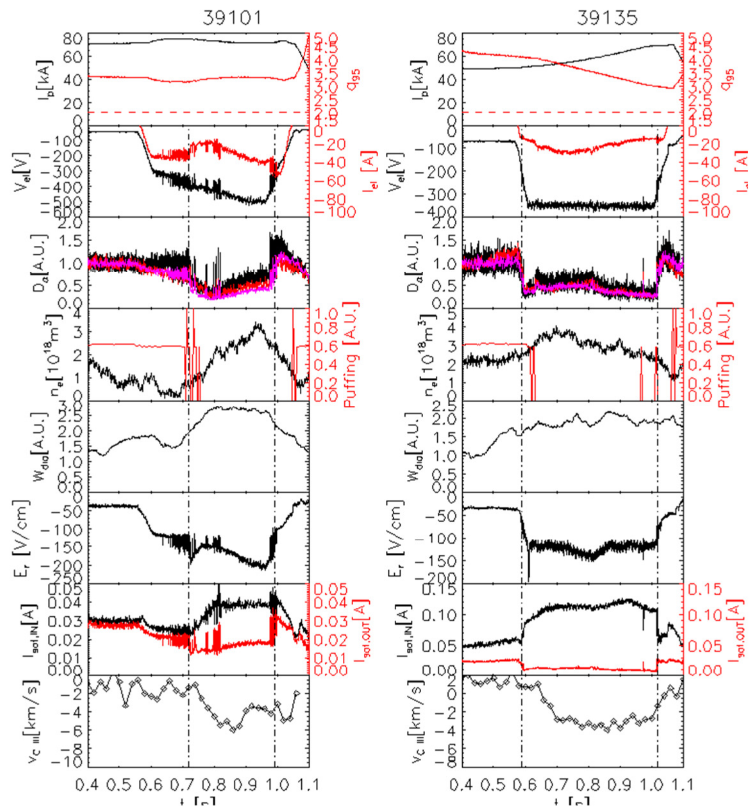

Fig.2 Time evolution of the applied V_{el} and I_{el}, of the main discharge parameters, and of some representative edge quantities. Circular shape #39101 (left) SN shape #39135(right).

with respect to the first wall. In this experimental condition circular and SN configurations will be compared.

The negative electrode biasing induced in a quite reproducible way the H-mode achievement. Two reperesentative shots were chosen, #39101 and #39135 respectively, operated in Deuterium. An example of plasma features modifications induced by negative electrode biasing is shown in fig. 2 for the two representative discharges. In both shots the signature of a transition to improved confinement, H-mode, is observed. This occurs when V_{el} overcome a threshold value around 200-300V and for enough high average plasma density, n_e=1-3 $10^{18}m^{-3}$ for I_p=70-80 kA. The achieved H-mode is characterized by similar behavior in the two configurations: an abrupt decreas of the D_α signals, measured along different lines of sight, an increase of the plasma electron density, n_e, though the puffing valve is switched off by the feedback system [11], the poloidal beta, not shown, and the diamagnetic energy W_{dia} also increase. The spectroscopically determined edge toroidal flow become more negative in agreement with the $J_r \times B_p$ force, with J_r directed inward. Important modifications can be inferred also in the edge radial profiles from the radial electric field, E_r, and I_{sat}, time traces measured in the LCFS proximity by the inseratble probe. In the following a more detailed analysis on the edge features will be shown.

In fig. 3 the V_{el}-I_{el} characteristic during the biasing electrode operation in the shot #39101 is shown. The blue triangles indicate the H-mode phase,

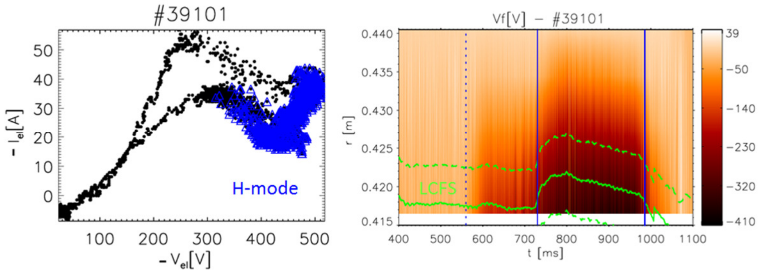

Fig. 3 Left: Electrode Voltage-Current characteristic during shot #39101, H-mode phase (blue triangles). Right: time evolution of $V_f(r,t)$ measured by one U-probe tower, local r_{LCFS} (green continuous line) and r_{LCFS} ± 5mm (green dashed lines).

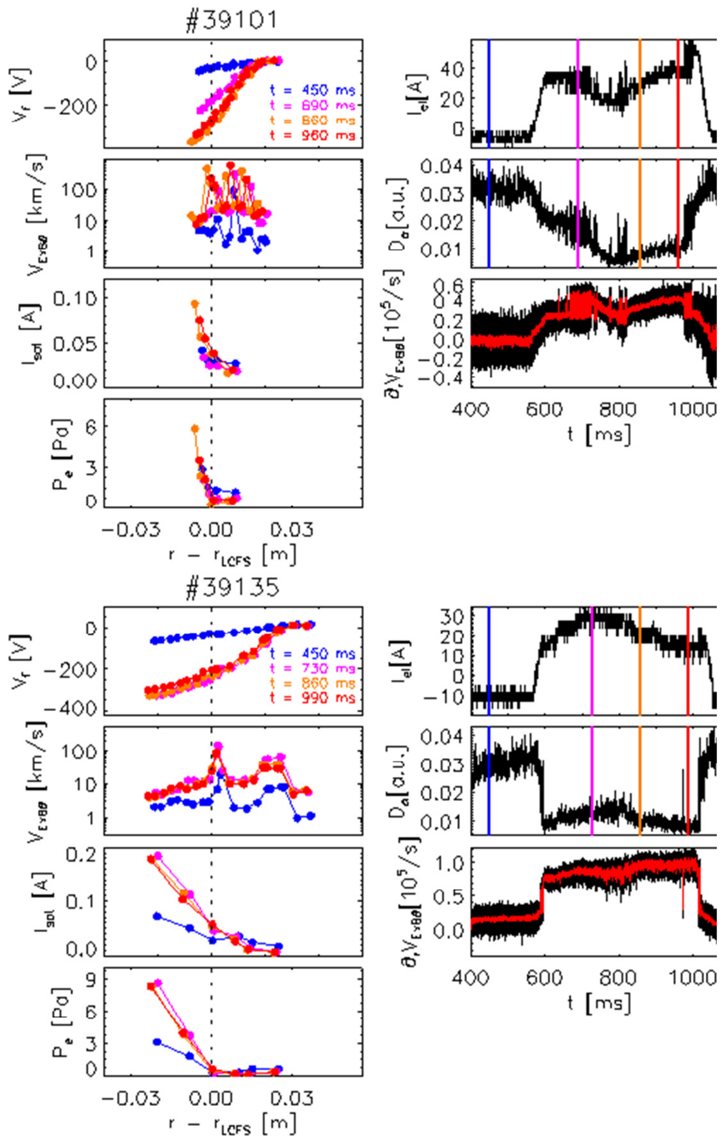

Fig. 4 Radial profiles of V_f, poloidal $V_{E\times B}$, I_{sat}, P_e at different times (left); time evolution of I_{el}, D_α and edge $dv_{E\times B}/dr$ measured at r=0.422 m during electrode operation (right); data from shots #39101 and #39135.

approximately from 710 to 990 ms, highlighted in fig. 2. It can be noted that the H-mode appears at V_{el}>250V and for a given V_{el} the collected current I_{el} is lower during H-mode, corresponding to an increase of the plasma impedance during the H-mode. It has to be noted however that a dependence of the I_{el}-V_{el} transition during the H-mode from the local plasma parameters as density and temperature is expected.

The floating potential radial profile time evolution $V_f(r,t)$ is shown on the fig. 3 right side, the vertical dashed blue line indicates the electrode swiching on while the continuous lines delimitate the H-mode phase. The $V_f(r,t)$ profile measured by 5 pins radially covering 24 mm is clearly affected by the electrode action, but this effect is by far larger during the H-mode.

This effect is clear and strong even accounting for the outer moving of the LCFS radial position, r_{LCFS}, (green line), then its approaching to the fixed U-probe radial location, releaved by the magnetic reconstruction during this phase.

To disentangle this issue the radial profiles of different quantities, as measured by the U-probe, are reconstructed as a function of the relative distance between the measuring pin and the local position of the LCFS, $r_m = r - r_{LCFS}$. Some selected results are shown in fig.4 for the two representative circular and SN discharges shown in fig.2.

The two towers of the U-probe are placed on the same poloidal section and are symmetrical with respect to the LFS equatorial plane. The profiles, as a function of r_m, (fig.4) of V_f, poloidal flow $v_{E\times B}$, ion saturation current, I_{sat}, and pressure $P_e = n_eT_e$ exploit data obtained from both towers. Looking at the circular case (#39101), the effect of the biasing induced transition to H-mode is clearly apparent from the $V_f(r_m)$ profiles. Different colors in the profiles (fig.4 left column) refer to average values over 80 ms centered at different time instants, the blue one is the low confinement (L-mode) reference obtained before the electrode operation. The same color code is used in the vertical lines during the time evolution of I_{el} and D_α (fig.4 right column). During all the discharge the $V_f(r_m)$ stay around V_f=0 (first wall potential) from r_m>1.5 cm. Going towards the plasma center, profiles exhibit more negative values and about 4 time lower during the H-mode. This behavior reflects on the abrupt change in the poloidal E×B flow, calculated from the radial electric field $Er_m \sim dV_f(r_m)/dr_m/B_t$ due to the negligibility of $dT_e(r_m)$, that increases of more than one order of magnitude in the region from -0.5 ÷ 1.5 cm. The E×B shear layer expected in biasing experiments [9] is then developed. Strong gradients are developed also in the $I_{sat}(r_m)$ and $P_e(r_m)$ in particular for in the r_m < 0. It can be observed that $\nabla_r P_e \sim 200$Pa/m during the L-mode increases up to $P_e \sim 700$Pa/m during the H-mode phase. In the right colum of fig 4 is show also an intersting quantity represented by the shearing rate, $dv_{E\times B}/dr$, measured at r=0.422 m. A clear jump is observed during the electrode operation and in particular during the H-mode, reaching values around 5 10^4/s.

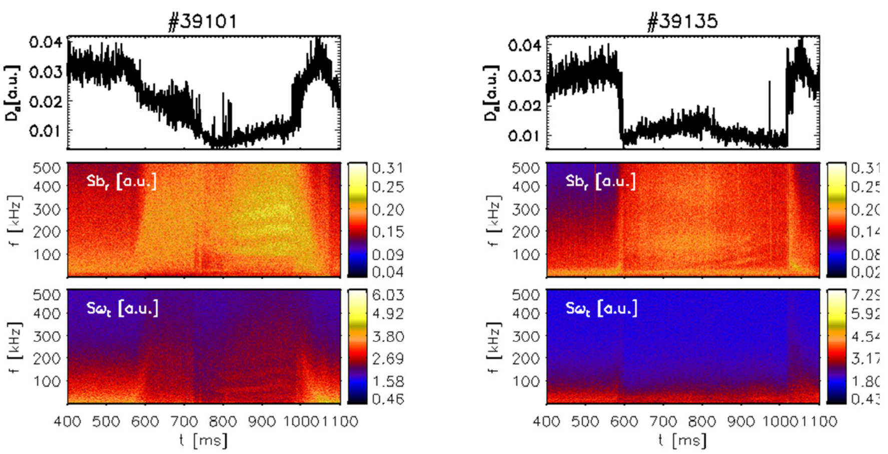

Fig. 5 Time evolution of D_α during electrode operation compared with spectrogram of δb_r and ω_t, data from shots #39101 and #39135.

Even if the U-probe has the same radial insertion, r, for the two shots, in the SN #39135 the region span across the LCFS is about double than the #39101. This is due to the poloidal

asymmetry of configuration in the SN case (see fig.1). This effect is apparent in the profiles of fig.4, where a wider region is explored around r_{LCFS} and in particular in the $r_m < 0$ side. Coming then to the SN case the V_f=0 position occurs about 1 cm outer with respect to the circular configuration, but the effect of H-mode inducing a steeper V_f profile is analogous. Noticeable values of poloidal E×B flow of the order of 10^4m/s and shear, 10^5/s measured at r=0.422m, are induced also in this case. The $I_{sat}(r_m)$ and $P_e(r_m)$ profiles exhibit as well strong gradients at the H-mode occurrence, reaching values inside LCFS $\nabla_r P_e$ ~150Pa/m in the L-mode increasing up to $\nabla_r P_e$ ~450Pa/m during the H-mode. It is found that the characteristic pressure length $L_{Pe} = |P_e/\nabla P_e| \sim 10^{-2}$m, double with respect to the circular case.
The H-mode phase is expected to reduce turbulence transport, so that in fig. 5 are investigated two quantities taken as representative of electrostatic and magnetic fluctuation behavior in the experiment under consideration. These are the parallel vorticity ω_t, calculated from the measurement of the U-probe pins arranged in a 2D array in the cross field plane, and the fluctuations of the radial component of the magnetic field, measured by one of the U-probe coils, δb_r. The ω_t spectrogram exhibits in both configurations a discontinuity in the H-mode phase, but while in the SN shot the higher frequency range is strongly depressed, the corresponding region in the circular case exhibit a mode at f~70 kHz, together with those that appears its harmonics at higher frequencies. A similar feature is found on its magnetic counterpart but at frequencies larger than 100 kHz. On the other side the magnetic spectrogram for the SN case shows the presence of modes during H-mode but at lower frequency. Work is in progress to investigate this features. It is worth mentioning that similar modes in magnetic fluctuations are observed in the inter-ELM phase of H-mode in the DIII-D [17] and COMPASS tokamak [18].

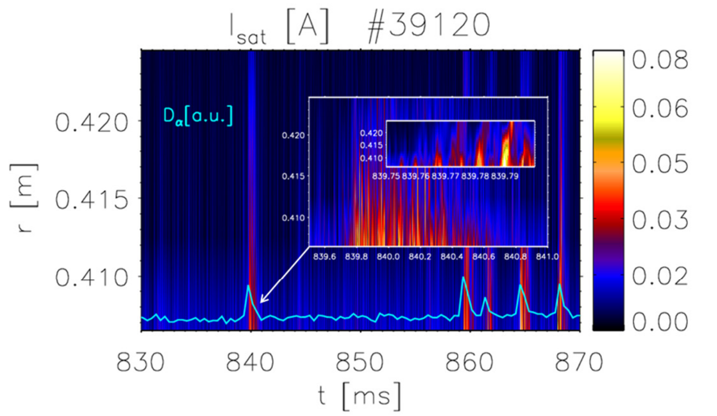

Fig.6 Time evolution of the $I_{sat}(r)$, at $r-r_{LCFS}$~1 cm, during H-mode with ELM-like events, compared with $D_\alpha(t)$; data from SN shot #39120 .

Transient events during H-mode

During the electrode induced H-mode phase strong peaks, lasting about 1 ms, are detected sometimes on the D_α signal. These peaks occur with a repetition rate ranging from 50 to 400 Hz in the explored conditions. In the tokamak experiments this behavior is usually associated to the presence of Edge Localized Modes [19], filamentary plasma structures, elongated along the magnetic field lines, characterized by a density higher than the surrounding plasma and ejected into the Scrape Off Layer region. The bursty behavior of the D_α monitor is related to the interaction of ELMs with the plasma wall or divertor plates. In general presence of ELMs is observed during ohmic or additional heating assisted H-mode[20], while the biasing induced H-mode and in particular with a SN configuration is a nearly unexplored experimental condition. A first observation from SXR measurements indicates that the revealed bursts are not correlated with the core sawtooth activity, suggesting an edge related behavior.
The sofisticated diagnostic equipment available in RFX-mod, allows a detailed investigation of their edge features. As an example in fig. 6 is shown the time evolution of D_α with bursts in

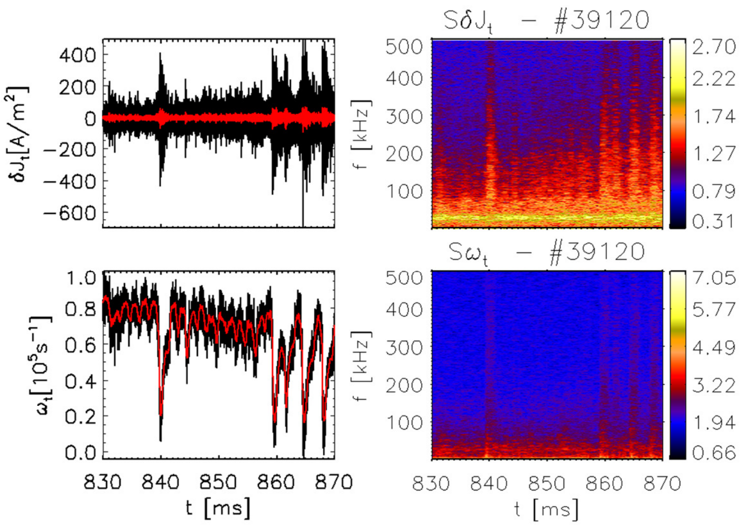

Fig. 7 Time behavior of ω_t, and δJ_t fluctuations, smoothed (red), and their respective spectrograms during the H-mode phase with ELMs-like events; data from SN shaped shot #39120.

a SN shot. D_α is compared with the $I_{sat}(r,t)$, providing a proxy of the local density, measured in the SOL at $r-r_{LCFS}\sim 1$ cm. A clear correlation with D_α of $I_{sat}(r,t)$ bursty behavior, involving the whole measured profile, is found. Fig. 6 shows also two inserts with increased magnification details of the same event. In this case a multiple fragmented density structure is observed. In the maximum zoom insert in fig.6 the detail on few of these fragments exhibits a behavior compatible with their radial propagation. A radial velocity of the order of 10 m/s is estimated, but on the other side this picture can be also interpreted as due to tilted structures.

Fig. 7 provides further details coming from the parallel vorticity, ω_t, and fluctuations of the parallel current density, δJ_t, associated to the D_α peaks. Their respective time behavior and spectrograms are shown in the same time window of fig.6. A first observation in fig.7 deserves the ω_t (t) spectrogram behavior, which exhibits a wide and abrupt spreading to all the frequencies with a clear correlation with the occurrence of D_α bursts. This result indicates the presence of localized structures crossing the probe location. In the $\omega_t(t)$ evident negative peaks are observed indicating that these structures are vortices, rotating in the cross-field plane. Similar feature was observed in the turbulent filaments in the edge region of all magnetic configuration fusion devices as well as in linear devices [21,22]. D_α correlated bursty spreading is also observed in the δJ_t spectrogram (fig 7), corresponding to the bipolar peaks observed in the δJ_t (t) evolution, left panel. The current density measured in this case is of the order of 0.5 kA/m^2.

These observations confirm also the electromagnetic (EM) features of the observed structures as expected for ELMs [23]. In particular they are current filaments as observed in the ELM structures in the COMPASS experiment [24], and for turbulence filaments as well [25,22]. Bursty behavior of $\omega_t(t)$ and δJ_t, correlated with D_α peaks, are observed in the Fig. 8, where events detected in the circular shaped shot #39101 are shown. Even if current density peaks are less apparent, similar feature to fig.7 are found. It can be noted in this case that the

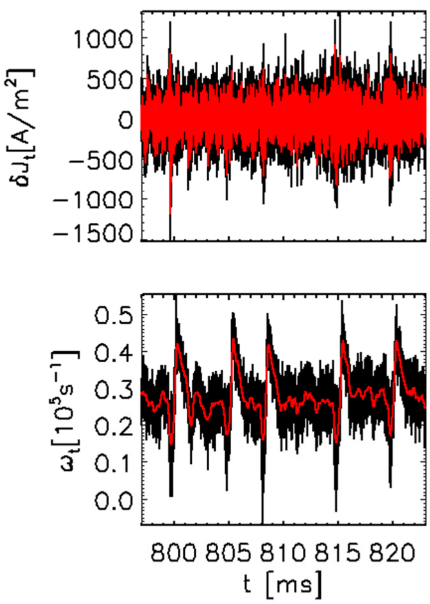

Fig.8 Time behavior of ω_t, and δJ_t fluctuations during the H-mode phase with ELMs-like events. Data from circular shaped shot #39101.

bursts on the parallel vorticity have a dipolar shape. This difference can be due to the different local velocity shear that was found to be effective in the vorticity selection [22,26].

Conclusions

Regimes with improved confinement were obtained in RFX-mod experiment operated as tokamak. The most reproducible H-mode conditions were obtained via edge biasing, with a negative bias with respect to the first wall. This operation corresponds to the enhancement of the naturally occurring poloidal E×B shear layer revelaed during the, L-mode. An abrupt increase of the edge radial gradient of plasma electron pressure and poloidal flow $v_{E\times B}$ were obtained in the surrounding of the LCFS, in both circular and SN shaped discharges. Within the incertitude of the separatix radial position, the characteristic pressure length is lower in the circular case and the point of null V_f is outer in the SN case. In both configurations, modes in the 70-100kHz range are observed in the magnetic spectrogram. On the other side only in the circular configuration a simulteneous presence of similar modes are detected in the electrostatic signals. In some cases, in both configurations, the presence of ELM-like structures are detected in the D_α signals. Those structures are found to be filamentary fragmented structures, with density features consistent with their radial propagation. Furthermore they appear as vortices rotating in the cross-field plane and exhibit EM features. It is worth noting that their associated local current density and vorticity fluctuations, parallel to the average magnetic field, were measured simultaneously for the first time.

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