Periodic collapse of a transport barrier induced by biasing experiments in the CASTOR tokamak

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An extensive experimental campaign has been performed on the CASTOR tokamak by applying a biasing voltage in the edge region of the plasma. The biased electrode has been inserted in the plasma inside the separatrix and a voltage of up to +300 V has been applied with respect to the vessel. The effects of the biasing have been investigated in details by using in particular poloidal and radial arrays of Langmuir probes. During biasing a clear and reproducible transition to an improved confinement is routinely observed along with the formation of an edge transport barrier which is characterized by a steepening of the time-averaged density gradient, a reduction in recycling and a substantial improvement of the global particle confinement. It has been observed that during biasing phase, when the electrode is deep enough inserted and biased at voltage larger than +230 V, a strongly sheared radial electric field is created within the Last Closed Flux Surface followed by an abrupt collapse of the potential and density gradients. The observed radial propagation of dense structures immediately following the collapse indicate the ejection of dense plasma towards the wall. This process repeats with a frequency of about 10 kHz during the biasing phase of the discharge. The described diagnostic system allows a fairly detailed investigation in space and time of this periodic behaviour.

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1 Introduction

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It is recognised that an effective way to control transport in the edge region of fusion experiments is to create a sheared flow layer, which suppresses the plasma turbulence reducing the radial transport. The result is to induce an edge transport barrier that characterises the improved-confinement regime, called H-mode [1]. Usually modifications of the edge $E \times B$ flow radial profile are achieved trough the modulation of edge radial electric field. With this aim several experiments have been performed on devices with different magnetic configurations, usually based on biased electrodes inserted inside the Last Closed Flux Surface: the biased electrode drives a radial current between itself and the vacuum vessel and the resulting $j \times B$ force enhances the naturally occuring shear of the $E \times B$ flow. An extensive review on the edge biasing experiments performed on fusion devoted experiments with different magnetic configuration can be found for instance on reference [2]. However in the tokamak, which is the major candidate configuration for the future fusion reactor, the H-mode is accompanied by the occurrence of the so called edge localised modes (ELMs). These phenomena occur periodically in the discharge and induce a noticeable plasma-wall interaction creating a privileged channel for particle and energy losses [3, 4]. Aim of the present paper is to provide a detailed characterisation of the modifications induced by biasing experiments in the edge region of CASTOR tokamak. Particular attention will be devoted to the study of relaxation events previously observed contextually to biasing [5, 6], which present characteristics similar to ELM phenomena. Thanks to its small size, the CASTOR device provides indeed a high versatility including the possibility to use numerous and insertable probes for a detailed investigation of the edge region.

2 Experimental setup

The CASTOR device is a small size tokamak experiment with major radius R=400 mm and minor radius a=100 mm, equipped with a poloidal limiter covering the poloidal section at $r > 85$ mm. During the present experiment a plasma current of 12 kA and a toroidal magnetic field of 1.3 T have been applied. The typical average plasma density was $10^{19} m^{-3}$, the discharge duration was 25-30 ms. A series of edge biasing discharges have been performed by using a graphite mushroom shaped electrode [7], which is 5 cm long in the poloidal direction, 3 cm wide in the toroidal one, maximum thickness 0.5 cm. The electrode has been inserted from the top of the machine at different radial positions, up to r=40 mm, and has been biased with respect to the vacuum vessel with a bias voltage of up to +300 V. The biasing phase lasts 5 ms during the discharge, generally in the time interval from 10 to 15 ms. A fairly complete and original set of diagnostics has been used for monitoring in particular the electrostatic and magnetic parameters in the edge plasma region and their modifications induced during the biasing phase.

Radial profiles of floating potential and ion saturation current have been measured by using the "double-rake" probe, inserted from the top of the torus. This diagnostics consists of two radial arrays of 12 pins, radially spaced by 2.5 mm, and the two arrays are poloidally separated by 2.5 mm. The probe has been inserted up to r= 50 mm, and different configurations have been used on a shot by shot basis. Detailed information along the poloidal direction have been provided by the

”SK-ring” [8], a full poloidal array of 96 Langmuir probes placed at the fixed radial position of r=87 mm, the pin length is 2 mm. The SK-ring is also equipped with a full poloidal array of 16 Mirnov coils, measuring the poloidal component of the magnetic field.

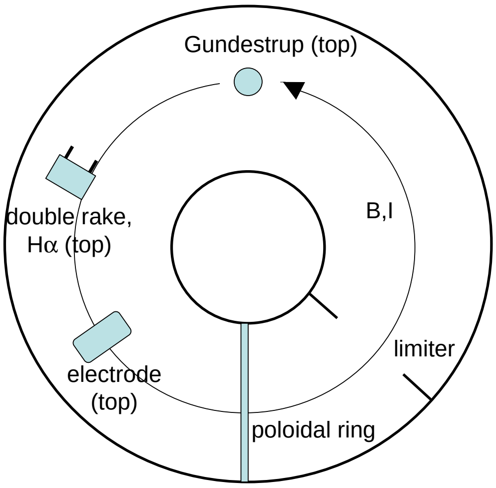


Fig. 1. Experimental layout scheme

The edge parallel and perpendicular flows have been measured by a Gundestrup probe [9], inserted from the top as well, equipped with eight copper plates distributed on a ring of 11.4 mm diameter over an active radial length of 2.2 mm. In some cases the local electron temperature and plasma density have been measured using a single Langmuir probe placed on the axis of the Gundestrup probe. Others diagnostics have been used, such as the Tunnel probe for measuring ion and electron temperatures, but the results will not be shown here. Data have generally been digitised with the high sampling rate of 1 MHz, for the SK-ring and the double-rake in some shots 0.3 MHz rate has been used. For the present experiment a H_α monitor has been used, placed on the top of the torus in the same toroidal location of the double-rake probe. The collected data have been digitally sampled at 40 kHz except for a certain number of shots where the sampling rate of 1 MHz has been used. The general layout of the biasing experiment is shown in the fig. 1.

3 Edge bias effects

3.1 Global parameters

The main parameters of the plasma discharge are shown in the fig. 2(a). From the top panel the time behaviour of the plasma current, of the average plasma density and of the H_α emission radiation are shown respectively, in the last two panels the corresponding voltage applied to the electrode and its current are shown. In this specific case a bias voltage of +300 V has been applied to the electrode with respect to the vacuum vessel, from 10 to 15 ms.

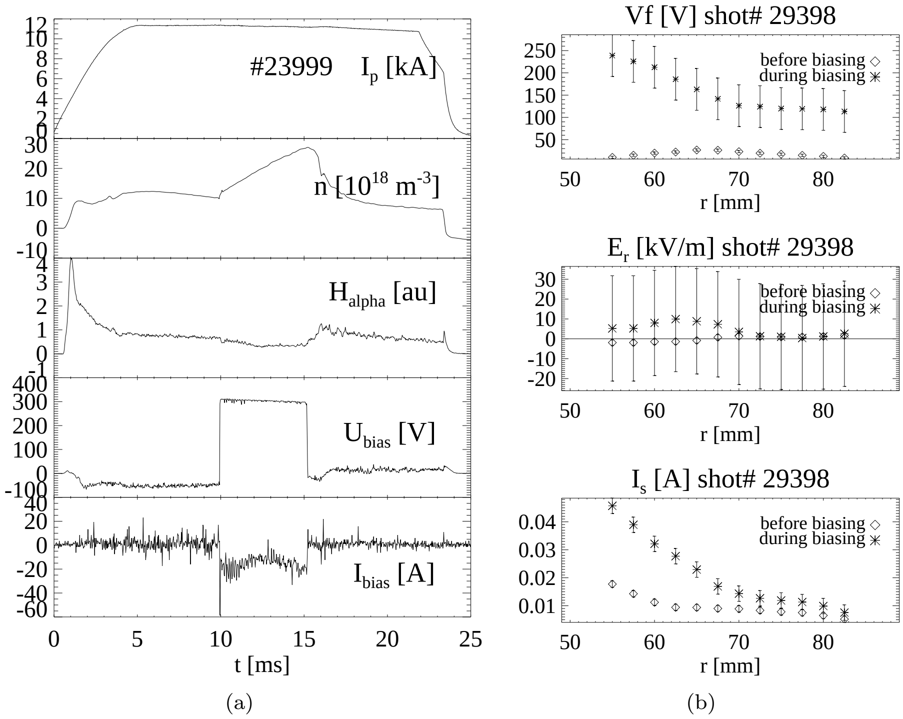


Fig. 2. (a): Global plasma parameters, electrode voltage, U_{bias}, and electrode current, I_{bias}, during the discharge. (b): Time average radial profiles of $V_f(r)$, $E_r(r)$ and $I_s(r)$ measured during a 4 ms time interval before and during biasing phase; in this case the electrode was at r=40 mm and biased at +250V.

It can be noted that during the bias phase a strong increase of the plasma density is observed and contextually the H_α radiation is reduced to about half of its value in the phase preceding the bias. These two observations provide a net increase of the ratio n_e/H_α, which can be interpreted as a net increase of the particle confinement induced by the electrode action [10]. Plasma density and H_α radiation recover their initial values after switching off the electrode bias at 15 ms.

3.2 Average edge profiles

The biasing effects on edge plasma parameters radial profiles have been monitored by using the double rake probe. In order to simultaneously investigate the radial profile behaviour on both floating potential, V_f, and ion saturation current, I_s, the probe has been configured to measure these two quantities. A comparison between the time averaged radial profiles of edge parameters before and during bias are shown in the three panels of fig. 2(b). In the top panel the strong modification induced by bias on the V_f radial average profile is evident: in the region within the Last Closed Flux Surface (LCFS), located in this case from r=65 mm to r=68 mm and corresponding to the position where the V_f profile before biasing is maximum [7], the radial gradient of V_f changes sign during biasing and undergoes a strong increase. Beyond the LCFS an increase of V_f is observed but without changes in the gradient, this modification is probably due to the not perfectly insulated electrode support. The modifications observed in V_f profile are reflected in those observed in the profile of the radial electric field, E_r, shown in the middle panel of fig. 2(b). In the edge region of CASTOR tokamak the radial gradient of electron temperature is negligible with respect to the radial gradient of floating potential [7], so that it is reasonable to estimate the radial electric field as $E_r = -\frac{dV_f}{dr}$.

It can be observed that E_r changes from -2 kV/m to up to +10 kV/m within the LCFS, indicating a poloidal flow which changes direction during bias and increases its value up to a factor 5. In the last panel of fig. 2(b) the modification induced by bias in the ion saturation current profile is shown: an almost doubled density radial gradient can be deduced.

The build up of strong gradients in the edge region together with the increase of the ratio n_e/H_α, provides an indication that the bias induces an improvement of the global particle confinement in the CASTOR tokamak.

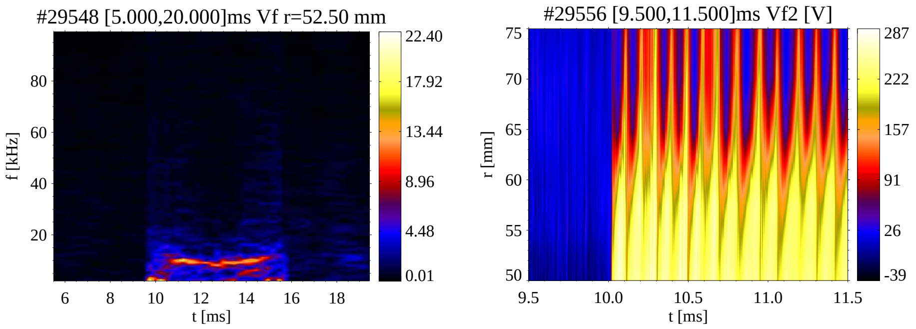
3.3 Relaxations

3.3.1 Radial profiles

The high time resolution (up to 1 MHz) used for the edge diagnostics allows to carefully investigate the time behaviour of the edge plasma parameters. In particular it has been observed that during the biasing phase, the floating potential signals exhibit an oscillating behaviour, with a typical period of 100 μs, not observed in the phase preceding the switching on of the bias. A visualisation of this phenomenon is obtained by plotting the spectrogram [11] of a V_f signal, i.e the power spectrum computed over a sliding time window, so that it is possible to provide its time behaviour.

An example of this kind of analysis is shown in fig. 3(a), where the spectrogram of a V_f signal measured at r=52.5 mm is shown. A qualitatively different behaviour of the power spectrum is observed during the bias, which is active from 10 to 15 ms. In particular a clearly defined peak appears at a frequency of about 10 kHz and lasts during the most part of biasing phase. The peak is not present in the phase that precedes or follows the biasing.

Even if the strong modification of average edge gradients appears in a wider range of cases, the oscillating behaviour is detected for particular conditions of biasing, i.e. when the electrode is placed in deeper position than r/a=0.5 and when a bias voltage larger then +230 V is applied.



(a) (b)

Fig. 3. Power spectrum of floating potential signal measured at r=52.5 mm, the bias was active from 10 to 15 ms (a); Time behavior of floating potential at the switching-on of the bias (b).

The onset of the oscillating behaviour is clearly related to the bias phase as it can be deduced also from the fig. 3(b). This figure shows the time behaviour of the V_f radial profile during a time interval including the switching on of the bias that occurs at 10 ms. It can be noted that an oscillating behaviour involves all the probes of the radial array, so that an abrupt modification of the profiles is observed at this time instant. Double rake probe measurements at different positions allow to conclude that this periodic modification of the radial profiles involves a radial region of few centimetres, external to the biasing electrode position.

The high time and radial resolution of the double rake probe provides a fairly detailed measurement of the time behaviour of the V_f radial profile as shown in fig. 4. In this figure a zoom on a time window of 0.4 ms during the appearance of the oscillations of V_f profiles is shown, in which three complete periods are evident (top panel). In particular it can be seen that the oscillation of V_f are associated to a periodic increase of the radial gradient followed by a crash. This feature is better highlighted by the picture in the middle panel of fig. 4, where the time evolution of the radial profile of E_r is shown. E_r reaches values up to 25 kV/m with a periodicity of about 10 kHz. A highly sheared region with a radial width of about 1 cm is periodically formed and radially propagates toward the wall before its crash. The radial velocity of this propagation towards the wall can be deduced from fig. 4 and is of the order of 0.2 km/s. In the same shot the second row of the double rake probe has been configured in order to measure the I_s radial profile. The result is shown also in fig. 4 (bottom panel). The 10 kHz periodicity is evident also on this quantity, with a radial propagation of the high density front, corresponding to the time instant of the crash of the high E_r sheared region.

In order to better investigate the behaviour of density during the relaxation phenomena, the time behaviour of the radial profile of the fluctuating part of I_s has been studied. The radial profile of $I_s - < I_s >$ is plotted in fig. 5(a). The radial

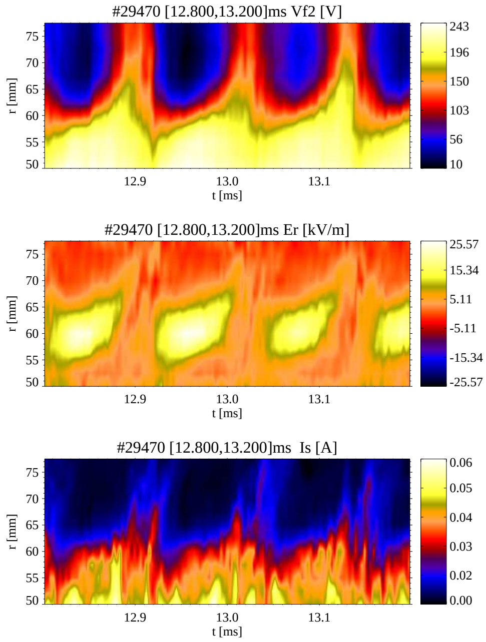
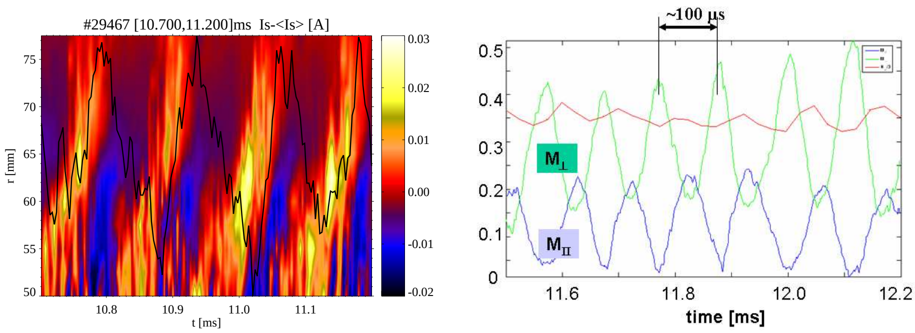


Fig. 4. Relaxations measured by double rake probe: V_f, E_r and I_s radial profiles



(a) (b)

Fig. 5. (a): Comparison between H_α emission, solid line, and radial profile time behaviour of I_s fluctuations; (a): time traces of $M_\parallel$ and $M_\perp$ measured during relaxations by Gundestrup probe, the red trace represents the $H_\alpha$emission.

propagation of the high density fluctuation front is visualized and occurs at each crash of the highly sheared velocity layer. An estimate of the radial propagation velocity for the density can be deduced and is of the order of 0.5 km/s.

In some cases fast measurements (1 MHz) of H_α radiation have simultaneously been performed with the edge plasma monitoring by Langmuir probe. It is interesting to note that concurrent 10 kHz oscillations develop also on the H_α signal and an example is shown in the fig. 5(a), where the continuous black line represents the H_α oscillations normalised to their maximum value. It results that these oscillations are well correlated to the periodic radial propagation of I_s fluctuations. It is worth noting that previous measurements [5], provided by high time resolution bolometer, indicates that plasma position during these relaxation phenomena essentially does not changes. Further information for the characterisation of these periodic relaxations of edge profiles is provided by the parallel and perpendicular flow measurements. An example of the time traces of these quantities measured by the Gundestrup probe are shown in the fig. 5(b). The figure reports a comparison between parallel, $M_\parallel$, and perpendicular, $M_\perp$, Mach numbers obtained using a validated one dimensional fluid probe model [12]. Mach numbers are defined as the ratio respectively of parallel an perpendicular velocity to the ion sound speed, which in the present case has been estimated 50 km/s. It can be observed that, contextually to the radial profiles, relaxations exhibit a strong periodic modification of flows is observed in the edge region. In particular the increase of the perpendicular flow is consistent with the build-up of the transport barrier as observed by the E_r profile measurements. The comparison between the $M_\parallel$ and $M_\perp$ time traces highlights a well defined π phaseshift between the two quantities. When the transport barrier crashes an increase of the parallel flow is observed, along with an increase of the H_α radiation due to enhanced influx of neutrals into the plasma, see also [13, 6].

3.3.2 Poloidal profiles

In order to extend the investigation on the spatial features of edge modifications correlated to radial profiles relaxations, an array of poloidally distributed probes has been used for measuring the poloidal distribution of electrostatic parameters in the plasma boundary. In the results reported in fig. 6 the active pins were configured for measuring V_f with a poloidal resolution of 11 mm at a radial position of 87 mm, covering the upper part of the poloidal sector from 70° to 170° (where the poloidal coordinate runs counter-clockwise and 0° correspond to the Low Field Side). The bias phase is from 10 to 15 ms. The fingerprint of relaxations is clearly visible also on poloidal profiles of V_f, see also fig. 4, and their poloidal distribution is almost symmetrical, suggesting that the detected relaxation of the edge radial profiles involves simultaneously almost the whole poloidal section and is accompanied by a periodical loss of particles.

3.3.3 Magnetic fluctuations

The quite particular set of diagnostics used for the present experiment allows also to investigate the magnetic activity modification, if any, induced by the relax-

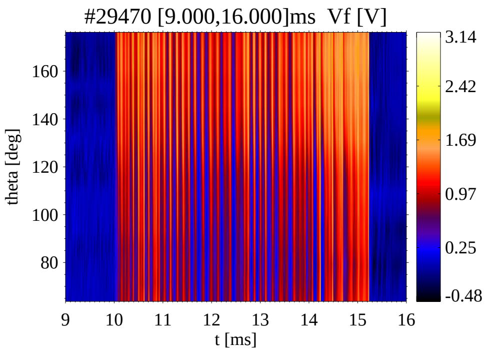


Fig. 6. Time behaviour of V_f poloidal profile

ations development. With this aim the full poloidal array of Mirnov coils has been used, measuring the time derivative of poloidal component of magnetic field, with a time resolution of 1 MHz. A certain correlation between the 10 kHz oscillations of V_f and the magnetic signals can be guessed, however clearer information can be obtained by a Fourier decomposition in the poloidal angle. This kind of analysis provides the graphs shown in the fig. 7, where the poloidal number intensity is shown as a function of frequency. The intensities are normalised to the maximum peak and the lighter colours indicate higher intensity values. It is worth noting that the plasma column is shifted towards the bottom of the vacuum vessel, so that the magnetic coils array is not perfectly centred to the plasma column, providing an uncertainty in the determination of the poloidal mode number, m.

The mode analysis performed in a time interval during the ohmic phase fig. 7(a) shows the presence of a magnetic island $m = 3$ at $f = 80$ kHz during the ohmic phase. During the relaxations fig. 7(b) a magnetic activity appears at $f \sim 10$ kHz with a poloidal mode number $m = 0 \pm 1$.

This result indicates that the observed relaxations have an electromagnetic nature suggesting a significant redistribution of current density profile during this phenomenon.

4 Discussion and conclusions

Biasing experiments performed on the CASTOR tokamak turned out to be effective in inducing an improved plasma confinement, characterized by steeper gradients of density and radial electric field.

High time and spatial resolution electrostatic diagnostics allowed a detailed investigation of relaxation events, destabilised during the biasing phase when the bias electrode is inserted at a radial position deeper than r/a=0.5 and the bias voltage is larger then +230 V. During these events critical gradients are periodically achieved, both on floating potential and plasma density, and E_r reaches noticeable

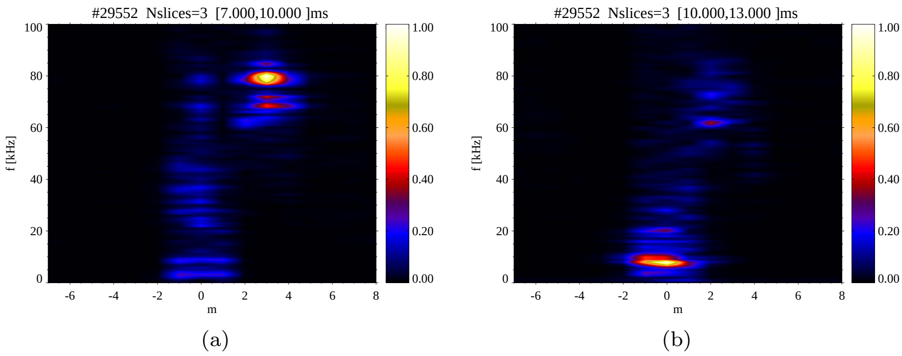


Fig. 7. Time averaged poloidal mode spectrum S(m,f) obtained during the shot ♯29552 before biasing (a) and during the occurrence of relaxations (b).

high values of 25 kV/m, a relaxation phase then follows and the entire process repeates with a typical frequency of about 10 kHz.

It has been found that these relaxation events are related to high density fluctuations radially propagating towards the wall and involving the whole poloidal section. Furthermore these phenomena are not purely electrostatic but exhibit also an electromagnetic feature, suggesting a not negligible redistribution of the plasma current during their appearance. Similar oscillations of edge profiles have been observed in the ISTTOK tokamak [14], however in the case of CASTOR the relaxation phenomena induce a periodic creation and crash of the transport barrier without providing a net improvement of confinement [6].

The observed relaxations, triggered by biasing experiments, exhibit features analogous to ELMs usually observed in large tokamak experiments [4], so that this kind of experiment can constitute an useful tool for investigating with high detail ELM-like events.

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