Statistics of Plasma Fluctuations in Runaway Discharges in TCABR Tokamak

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Received on 26 June, 2001

In this work we analyze the spikes in the H_α emission, and density turbulence in runaway discharges in the TCABR tokamak. For the plasma edge density fluctuations, we find a symmetric-recurrent-type turbulence, with the same statistics found in measures of low-dimensional recurrent chaotic systems. For the plasma core fluctuations, we note that the line density oscillations are synchronized to the H_α oscillations. In addition, we suggest that both the onset of the H_α spikes and the line density oscillations are triggered by a process similar to the bifurcation responsible for the firing of neurons.

I Introduction

The generation of runaway electrons during disruptions is a common feature of tokamaks [1]. They can be a severe problem in some experiments since their loss to the wall may cause severe localized surface damage. It is thus desirable to study plasma discharges with runaway production as well as methods to avoid this production.

A new regime of runaway discharges is obtained in TCABR initiating the discharge with low filling pressure and, after the initial current rise, maintaining a large filling rate [2]. The magnetic confinement is provided mainly by the runaway beam. In this regime the plasma profiles are kept approximately constant, the H_α emission increases substantially and shows strong spikes, possibly triggered by the relaxation instability typical of runaway discharges. As the filling rate increases further, the spike period decreases and its behavior changes in a transition similar to those observed in experiments in large tokamaks [3].

The discharges have a plasma current around 70 kA, loop voltage of 1 V, $Z_{eff} > 4$, $\beta \approx 0.1$. Plasma density of $2.5\text{x}10^{19} m^{-3}$ in the core and $1 \times 10^{19} m^{-3}$ at the edge.

In this work, we consider oscillations observed during approximately 10 ms of the stationary phase of eleven runaway discharges with constant loop voltage, mean plasma current, and plasma density. We analyze the sequence of sharp spikes in the H_α emission, correlated with positive spikes in the line density, negative and positive spikes in the loop voltage, small outward displacements in the radial plasma position, and bursts in the X-ray emission and magnetic activity. These spikes occur in whole plasma and their shape and repetition frequency change with the filling rate. For these discharges, we analyze also the line density oscillations simultaneously measured at the plasma edge and center.

The main interest of this work is to find invariant statistics in the reported new runaway regime. We choose to work with two types of data, one presenting turbulent behavior, the fluctuating density, and the other presenting a more regular, however, undetermined behavior, the H_α emission. At the plasma core, the density presents peaks of oscillation which happens in synchrony with the H_α peaks. As we measure this fluctuation away from the core, near the plasma edge, the density becomes more turbulent and not synchronized with the H_α peaks. The probability distribution of this density fluctuation is a symmetric Poisson-like and the data is recurrent. These properties are typical of recurrent low-dimensional chaotic systems that present a Poissson distribution for the returning times.

For the H_α emission we found some laws for the peaks shape that might give us indication of the physical process related to this line emissions. In particular we found that the relation between the width of the peaks and their heights follows a logarithmic law. A consequence of this law is that the spike should have an exponential decay. In fact, we observe that the H_α spike is similar to spike in neurons, what suggests that the dynamics behind the triggering of the spike in neurons might describe the H_α spikes (and also the line density at the core).

Moreover, the width of the distribution follows a linear law both with the time interval between spikes or with the spike heigth. Each law are characterized by two different coefficients, which reflect the change of oscillation frequency observed in the H_α emissions. In fact, for all the discharges analyzed, we see two regimes for the H_α emission. In the first half of the discharge, the time between the spikes are shorter and the peaks are smaller. On the second half of the discharge, the contrary happens, i.e., the time between the spikes are larger but the peaks taller.

II Statistical Analysis

The plasma in this high-density runaway discharge is characterized during the flat-top by stationary plasma profiles. As an example we show the plasma current profile in Fig.1.

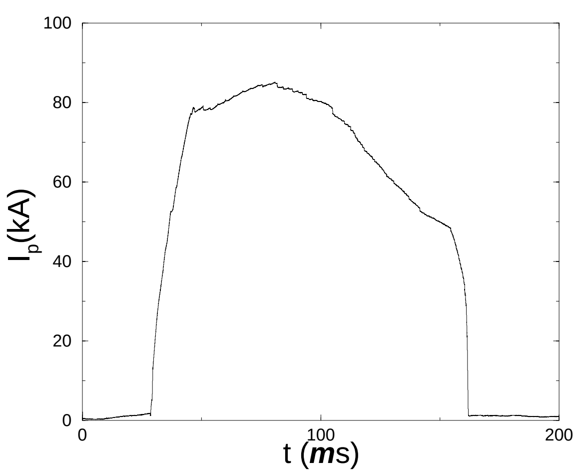

Figure 1. The plasma current for a runaway plasma shot.

We define D_n for the value of the density fluctuation $D(n\tau)$ at the time $t = n\tau$, where τ=4 μs is the sampling rate. Fig. 2 shows D_n for the plasma edge and for the plasma core. We define R_n as the difference

$$R_n = D_{n+1} - D_n. \quad (1)$$

The fluctuating difference is recurrent, i. e., its amplitude eventually come back to a reference interval of values with size of 2δ at χ=0. Next, in this figure, we define the returning time, T_n, as the interval of time in which R_n repeats a value inside a chosen reference interval. The probability distributions of T_n in normalized units $\rho(T_n)$, obtained for the data of Figs. 2(a-b), can be seen in Figs.3(a-b) respectively. We see that both data, from the plasma core and edge, have a distribution of the return time given by a Poisson [4] of the form

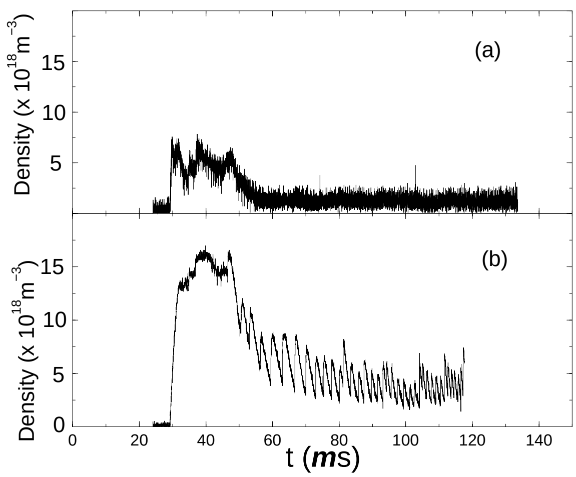

Figure 2. Plasma density at the edge (a) and at the core (b).

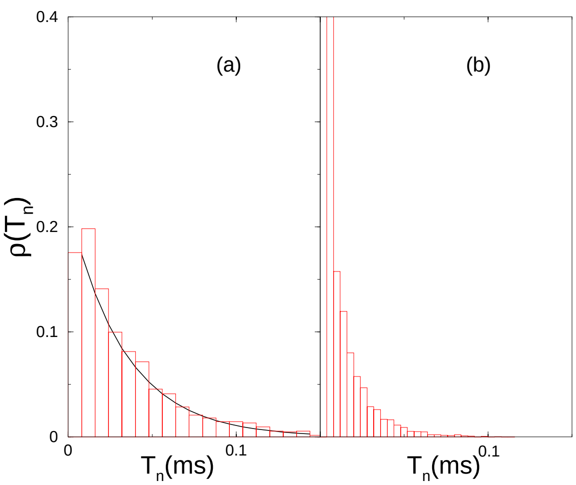

Figure 3. Distribution for the return time T_n in the plasma edge (a) and in the plasma core (b).

$$\rho[T_n(\epsilon)] = \frac{1}{2<T_n>} e^{-T_n/<T_n>} \quad (2)$$

Note that this Poisson distributions are invariant to different time intervals.

We also find that the probability distribution of R_n, $\rho(R_n)$, in the plasma edge shown in Fig. 4a is a a Poisson-like distribution represented as [4]

$$\rho[R_n(\tau)] = \frac{1}{2<R_n^+>} \exp^{-(|R_n-<R_n>|/<R_n^+>)}, \quad (3)$$

which corresponds to a sum of two Poisson distributions, where $<R_n>$ is the average of the R_n's and R_n^+ represents R_n bigger than $<R_n>$. This Poisson-like is characterized by the average width of the distribution which is equal to $<R_n^+>$. Note that the distribution form is invariant to different time intervals of the discharge. An unknown distribution is found for the density oscillation difference of the plasma core (Fig.4b).

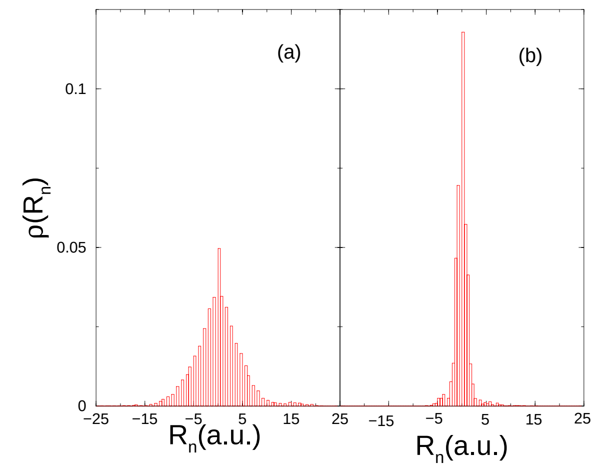

Figure 4. The probability distribution of R_n, for plasma edge (a) and core (b) density fluctuations, calculated respectively with the data of Fig. 2(a-b).

For the type of turbulence observed at the plasma edge, we can say that the return time T_n is statisticaly equivalent to the density difference, R_n. In addition, these variables are also statistically equivalent to the first Poincaré return time, which measures the time a chaotic trajectory takes to return to a given interval of values. In fact, for chaotic systems we are able to explain the reason for which the distribution of R_n is a symmetric Poisson-like distribution and also the reason for which the distribution of T_n is a Poisson. This approach considers that the observed recurrence is result of the existence of an uncountable number of periodic orbits embedded in the observed set. More details of this equivalence can be found in [5, 6].

Fig.5a shows the H_α emission. Once we are interested in analysing the shape of the spikes, we put the base of the spikes in to the same ground level. We do this by subtracting the data of the H_α with its running average calculated over a time interval of 100τ. The treated data can be seen in Fig.5b, where we indicate, in the small box, the reference value χ with which we calculate the time interval of the spike δT, and the time between two spikes, represented by ΔT. Note that the frequency of appearance of the peaks in Fig. 5a is the same of the abrupt change of the density profile in the plasma core of Fig.2b. Therefore, the density oscillation in the plasma core is phase synchronized with the H_α emission.

Much can be understood of the dynamics behind the H_α emission finding correlations between the time width of the spikes, δT (that we reffer as peak width), and the time interval between two spikes, ΔT, for a given χ. To improve the statistics of our analysis, we use a concatenated file with data from the eleven discharges. For $\Delta T > 1.57$ms, and $\chi = 0.05$, we found an exponential decay, with coefficient of -1.60 ± 0.09, for the probability distribution of ΔT as shown in Fig. 6. That means we expect most likely that time between spikes to occur at most within the time for the distribution to decay half. Therefore, we expect $\Delta T < 2.00$ms.

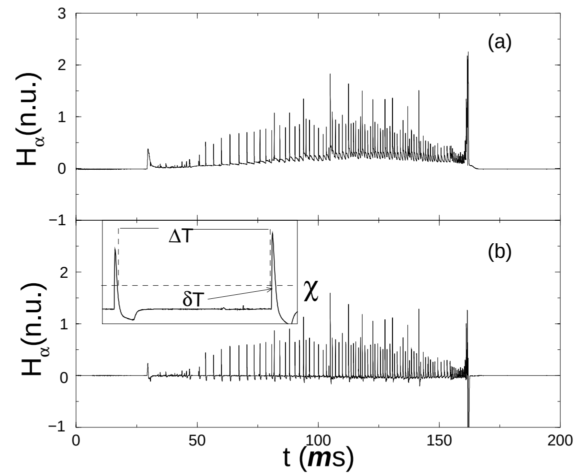

Figure 5. H_α emission (a) and normalized H_α (b) by running averages. In the small box of (b), for a given reference χ, the time in between spikes is represented by ΔT, and the time interval of the spike is represented by δT.

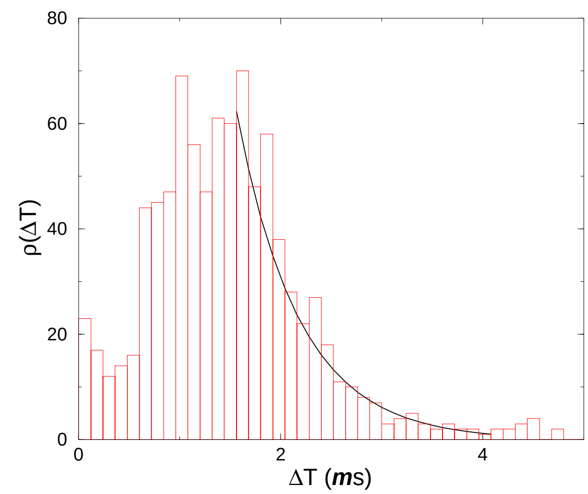

Figure 6. Distribution of time interval between two spikes ΔT, for 11 discharges in the runaway regime. The solid curve indicates an exponential decay for high ΔT.

Due to the fact that the spikes occur in two different frequency regimes, a more appropriate variable to look at is the difference between two time intervals, i.e.,

$$\xi_n = \Delta T_{n+1} - \Delta T_n. \tag{4}$$

This new variable has a symmetric Poisson-like probability distribution, shown in Fig.7, indication that the dynamics behind the triggering of the spike can be the result of low-dimensional systems.

It is interesting to understand the relation between the reference χ of the H_α peak emission with respect to the peak width (for that height), δT, and the time between spikes, ΔT. To improve our statistical analysis, we calculate averages values of ΔT and δT, denoted respectivelly by $< \Delta T >$ and $< \delta T >$, for a given χ along the 11 discharges. In Fig.8 we show three scalings relating $< \delta T >$ with respect to the reference value χ (a), $< \Delta T >$ with respect to χ (b), and $< \Delta T >$ with respect to $< \delta T >$. Note that (a) is a logarithmic law, while in (b-c) we have linear relations. This logarithmic dependence is consequence of the geometric shape of the spike. It is also worthwhile to comment that in both (b) and (c), we find linear laws with two different coefficients, which is a consequence of the fact that the time between spikes for the second half of the discharge is shorter than the one in the first half of the discharge.

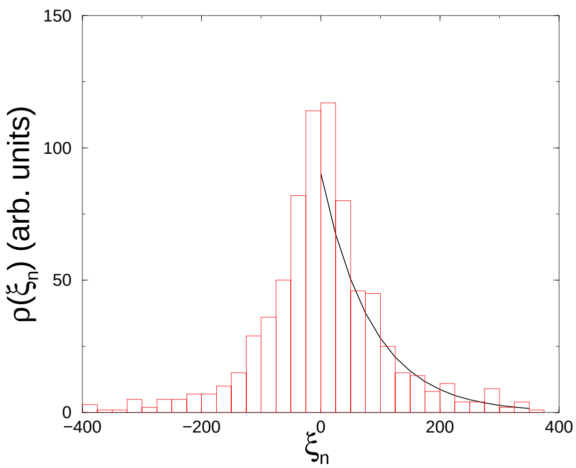

Figure 7. Distribution of the difference ξ_n, for 11 discharges in the runaway regime. The solid curve indicates an exponential decay.

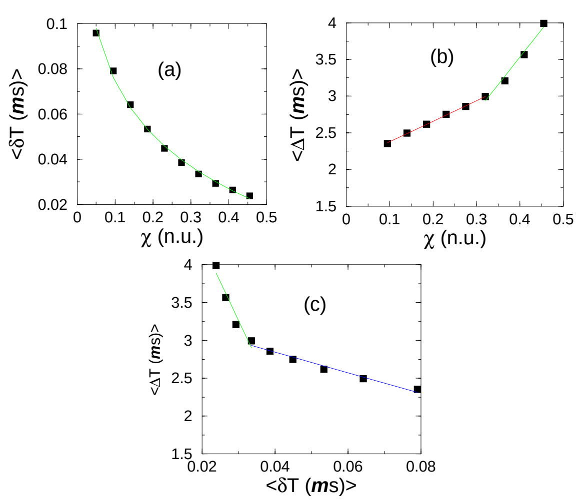

Figure 8. Scaling laws showing the logarithm dependence of $< \delta t >$ with respect to the reference value χ (a), the linear dependence of $< \Delta T >$ with respect to χ (b), and the linear dependence of $< \Delta T >$ with respect to $< \delta t >$.

The consequence of having a logarithmic law in Fig. 8a is that the H_α spike should have an exponential decay. Inspired by this observation, we fit the spike using the function $A \tanh{(Bt)} \times e^{-Bt}$. The result can be seen in Fig.9. The use of this particular fitting function is due to the fact that it fits well spikes in neurons. Therefore, this suggests that the dynamics (a bifurcation) behind the triggering of spikes in neurons [7] can explain the triggering of the spikes in the H_α emission.

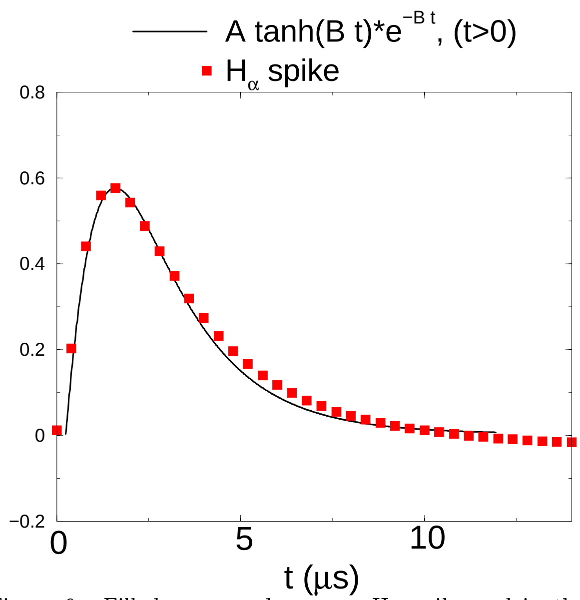

Figure 9. Filled squares shows one H_α spike and in the straight line the fitting function.

III Conclusions

There are four properties we notice as we compare the fluctuating plasma density on the core to that on the edge. Increase of fluctuation amplitude, symmetry in the distribution form of R_n, invariance of the distributions form for different time intervals, and preservation of short and long range correlations. The first three properties are discussed in this work and the last one is reported in Ref. [5].

The symmetry observed in the density plasma edge is named symmetric-recurrent-type turbulence. It is recurrent because of the symmetry of the probability distribution. It is recurrent because the statistics of the return time is equivalent to the statistics of return times of chaotic trajectories.

We see that the H_α spike is similar to spike in neurons. That suggests the dynamics that governs the triggering of the spike in neurons might describe the dynamics behind the triggering of the H_α emission. Further work could, indeed, prescribe procedures in order to be able to avoid such bifurcation, and therefore, avoid the onset of H_α emissions. In addition, once the H_α emission is syncronous to the density in the plasma core, this bifurcation process could also explain the reasons for the abrupt oscillations of the line density at the core.

Finally, the equivalence between the recurrence in dynamical systems and the recurrence in this special turbulent regime, allows us to describe the evolution of measurements in this type of turbulence with measures of low-dimensional dynamical systems.

Acknowledgements This work was partially supported by Brazilian governmental agencies FAPESP, CNPq, and CAPES.

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