Recent Results on the Search for Self Organization of Plasma Edge Fluctuations

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Large Helical Device heliotron (LHD) has achieved record <β> values up to 5\% [1] in its high-β regime. Fast camera experiments carried out during 2009 and 2010 experimental campaigns have revealed that this operational regime is characterized by the stochastic ejection of macroscopic structures [2]. The application of suitable statistical tools (waiting time and Hurst exponent) to the analysis of the ejection pattern of such structures shows that edge fluctuations possesses certain non-markovian self-similar properties which are considered an indication of non-diffusive transport in the edge, and to be in good agreement with several SOC theoretical models. The experimental layout employed is extensively explained in [2]: a Photron APX-RS fast camera was coupled to a 75 mm objective by a 4.5 m long coherent optical fibers bundle in order to protect it from the intense magnetic fields of LHD. As shown in Fig. 1 (left), the objective was placed on LHD 6-T tangential port, overlooking a region of almost 90º of the vacuum vessel. Pixel resolution varies with the sampling rate, ranging from 1024x1024 pixels up to 5 kHz to 192x136 pixels for 50 kHz. The actual resolution (in spatial units per pixel) depends on the distance of the observation region to the camera. In the divertor leg region analyzed in this paper, 1 pixel corresponds to some 5 mm. Visible radiation detected by the camera is produced by line radiation of light elements (essentially H_ and Carbon II), which takes place in relatively cold regions of the plasma, like the edge. Typical SOL is usually under the so called "ionizing plasma edge conditions" (Te under 100eV, $n_e \sim 10^{19}$ m^3 near the Last Closed Flux Surface). In such conditions, the excitation rate is essentially constant and the signal can be regarded as proportional to n_e and n_o in the point of emission, where n_o is the emitting element neutrals density. In Fig. 1 (right), a general view of a typical high-β discharge is displayed. A Poincaré plot of the vacuum magnetic field corresponding to the vertical plane defined by the blue line on the equatorial view on the left is superimposed. Interpretation of camera output is non trivial given the geometrical complexity and broad field of view (FOV), although several important features

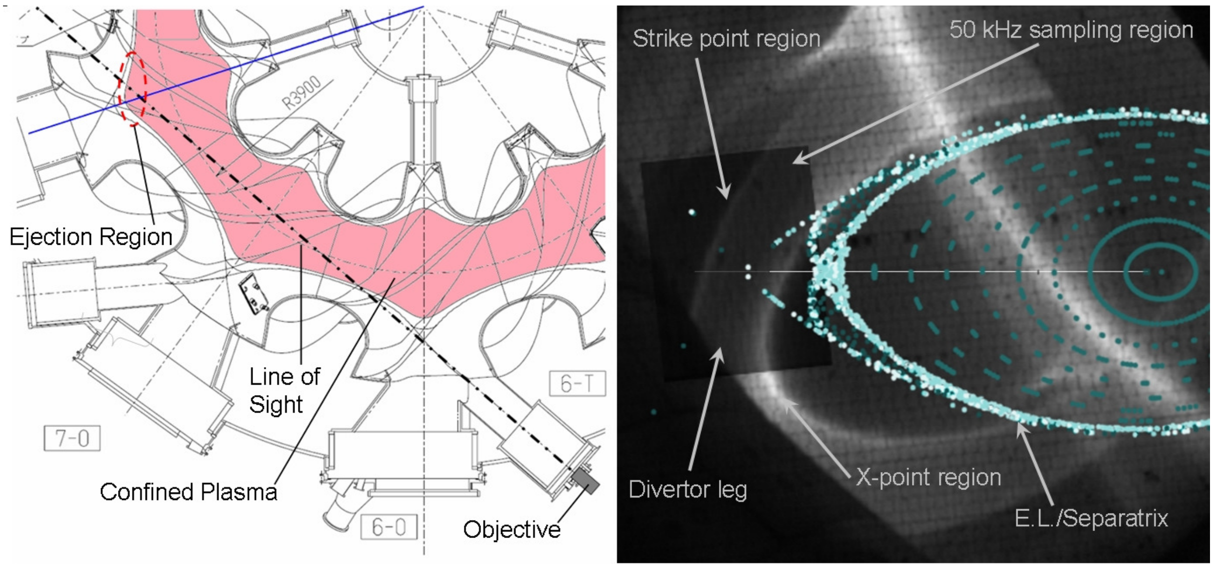

Fig. 1 *Experimental layout.* ***(Left)*** *top view of LHD equatorial section. Camera objective at 6T port and its line of sight are displayed. The region where filaments are observed is marked in red.* ***(Right)*** *General view of a typical high-β plasma.*

can be recognized (as highlighted in the figure): helicoidal illuminated curves correspond to the positions of the two X point regions. Between these and the bright curves on the wall indicating strike point regions (SP), the tenuous stripe of the divertor leg magnetic surface can be seen. Finally, the darkened region of figure corresponds to the FOV of the camera for 50 kHz operation. Analyzed areas signal is emitted at quite well determined magnetic regions (either the X point or the divertor leg) which almost never overlap on the camera FOV, reducing greatly line integration effects and thus allowing to identify the 3D position from a 2D view. It must be noticed how the area of maximum emission near the X point does not correspond with the external region of the ergodic layer, as would be expected, but it is shifted radially outwards some 15 cm. This can be explained as a result of the aforementioned increase of the ergodic layer width due to finite β. Moreover, a 15 cm shift is in very good agreement with HINT simulations in [1]. During high β discharges, filaments can be seen being ejected from the ergodic layer into the divertor leg surfaces. By collecting the raw data of a single pixel, a local density fluctuation evolution can be measured. This signal can be considered a good record of the size and duration of the ejected structures, in the range of several cm and some 100 μs, respectively. Although it is not a direct measure of the radial flux, it is related to the latter since it was found in previous work that the kind of macroscopic structures measured by the camera in the ergodic layer region always propagate radially outwards at similar velocities (in the range of 3-5 km/s) in this regime. In order to detect traces of long-term correlations and non-markovianity in the statistical behavior of the

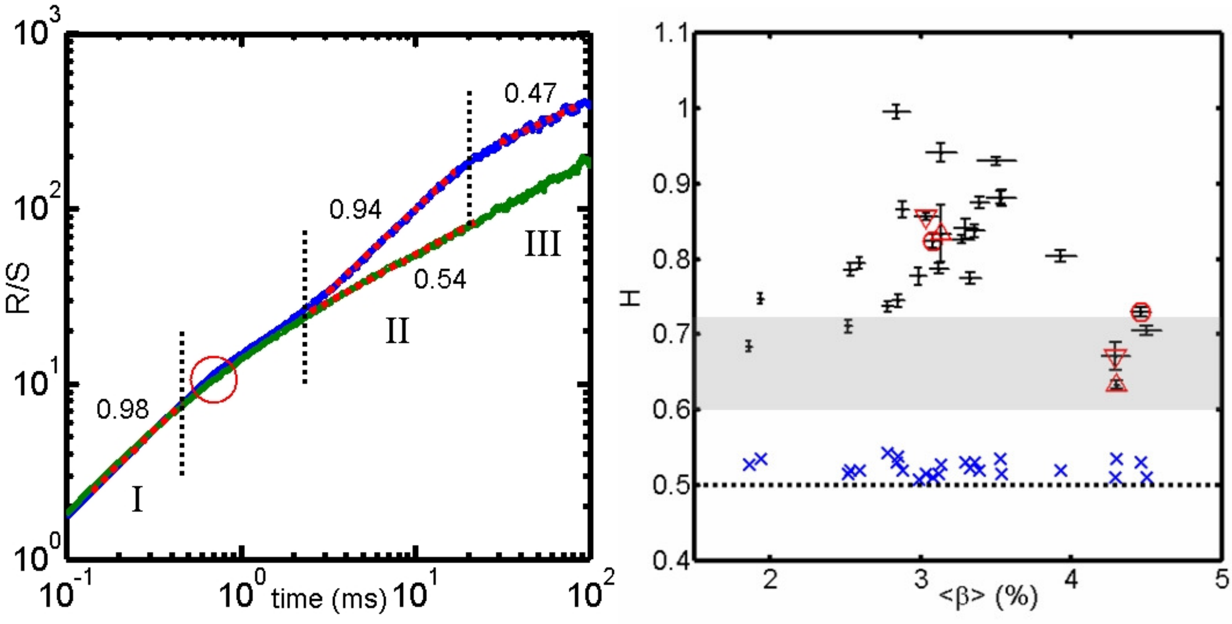

Fig. 2 (Left) *Typical result of an R=S analysis: the blue curve corresponds to the analyzed time series and the green curve displays the result of the shuffling test.* ***(Right)*** *Value of H in Region II for several <β> points with the same red symbol correspond to the same discharge. The values of H for the shuffled time series are represented by blue crosses.*

filament ejection (defined by the density fluctuation evolution in a point close to the ergodic layer), two statistical analysis are carried out. Firstly, the scaling with time of the square root of the second-moment of the signal, the so called *Hurst parameter* H, was determined. A robust way to compute H is to use the rescaled range or R/S technique [3]. A representative result of the R/S analysis in LHD high-β plasmas can be seen in Fig. 2 (left), where three different regions appear. Region I, ranging up to several hundreds of μs, has H ~ 1. However, this time scale corresponds to the duration of single events and its ballistic behavior is rather trivial [4]. Between regions I and II an elbow is found (red circle), followed by a flatter region. This time corresponds to the period of the m/n=2/3 mode activity (which can also be seen in the spectrum of the signal [2]) and the elbow is the characteristic signature of a coherent mode in [R/S](τ) [5]. Region II is the relevant one, the self-similar range exhibiting the non-trivial correlation between fluctuations at different times. In this region, which lasts around a decade, we find H = 0.94, which reveals strong persistence for large time lag in the time series analyzed. To ensure this, an illuminating test [4] is performed: the whole signal is divided in segments of the size of the events (200 μs) and then those segments are randomly shuffled. As expected, [R/S](τ) for the shuffled time series (green curve in Fig. 2) loses the persistent behavior in Region II This shows that the Hurst exponent found for the original time series in Region II is non-trivial. Region III possesses H ~ 1=2, probably due to finite-size effects in the time series [4] (the time scale is over the confinement time and the reliability of the R/S method is thus decreased in it). In Fig. 2 (right), the value of H in Region

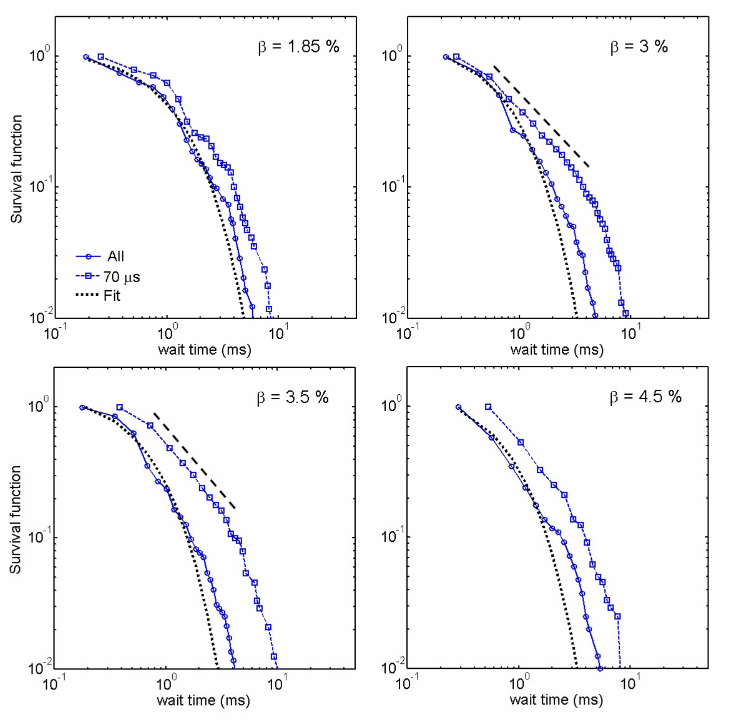

***Fig. 3** Waiting-time pdf for several values of <β> and computed with and without threshold in the event-size.*

II (i.e. the relevant time scale) as a function of <β> is plotted. For <β> < 2% one obtains the aforementioned usual values of H reported in the literature (shaded region). Then, H increases with <β>, reaches a maximum at <β> = 3% - 3.5% and decreases to the initial values for <β> ~ 4.5%. Again, to ensure the validity of the results, shuffling tests are performed, getting H = 1/2 for the shuffled time series at every value of <β>, as expected. As a complementary analysis aimed to give a further check of the non-markovianity found by the R/S calculation, the waiting-time [6] probability distribution function (pdf), i.e. the pdf of the time elapsed between two consecutive events, was studied. These distributions are closely related to the presence of long-term correlations: according to [6] the waiting-time of large events decays as a power law when long-term correlations are present. As displayed in Fig. 3, this is the case: only in the range of <β> ~ 3-3.5%, in which the value of H reaches a maximum, the distributions decay becomes algebraic when small events are discarded. These statistical properties seem to suggest that the increase of <β> introduces a change in the nature of the transport, which might become superdiffusive over a range of values. One possible interpretation of this might be some form of turbulence self-organization, such as SOC. This mechanism, although speculative, would be consistent not only with the aforementioned statistical results but also with additional analysis of TS pressure profiles, and in agreement with several theoretical models [7].

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