Characterization of edge and scrape-off layer fluctuations using the fast Li-BES system on COMPASS

A Bencze, M Berta, A Buzás, P Hacek, J Krbec, M Szutyányi and the COMPASS Team

1 Wigner Research Center for Physics, Budapest, Hungary
2 Szechényi István University, Győr, Hungary
3 Institute of Plasma Physics of the CAS, Prague, Czech Republic

E-mail: bencze.attila@wigner.mta.hu

Received 31 January 2019, revised 26 April 2019
Accepted for publication 24 May 2019
Published 21 June 2019

Abstract

Recently the Lithium-Beam Emission Spectroscopy (Li-BES) system on COMPASS has reached its full diagnostic power in terms of routine automatic operation in any kind of plasma scenarios and it is normally used as a standard tool for reconstruction of ultra fast density profiles in the edge region of COMPASS plasmas. The purpose of this study is to investigate the advantages and limitations of the COMPASS Li-BES system in characterizing plasma electron density fluctuations. We show how the atomic physics of plasma-beam interactions can affect the interpretation of the measurement at different radial positions and for different electron density profiles. We also demonstrate the usability of generalized sequential probability ratio test for automatic event detection. Using non-perturbative diagnostic, we verify the validity of the stochastic Garcia-model for scrape-off layer filaments and accompanying holes (density deficits).

Keywords: Li-BES, SOL filaments, intermittency

(Some figures may appear in colour only in the online journal)

1. Introduction

Tokamak plasma region defined as a narrow, few cm band around the last-closed-flux-surface (LCFS) is considered to be of crucial importance for understanding different transport phenomena determining both particle and energy confinement times and the strength of the plasma-wall interaction [1–5]. This is the region where the important and interesting physics of the L-H transition, the generation of turbulence induced mesoscopic shear flows takes place and where the scrape-off layer (SOL) filaments, known as ‘blobs’ are born. This region is well known to be rich in different stable and unstable modes like drift waves (DW), neoclassical tearing modes (NTMs), edge localized modes (ELMs) etc. The unstable modes through nonlinear mode couplings can and will lead to coherent structure formation. The kinematics and dynamics of these structures (which usually take the form of 3D filaments) is determined by the actual plasma parameters both global and local, the underlying shear flows and the interaction of filaments with the material components such as divertor and limiter structures. Theoretical descriptions of the coherent structure generation, structure propagation and detection statistics have reached different levels of sophistication and descriptive power. Some of the theories are competitive [6–9], therefore any experimental insight is of significant value. The number of publication aiming to compare experimental results with theoretical models is also increasing (see e.g. [10–12]). The overwhelming majority of experimental work is SOL plasma has been done using Reciprocating Langmuir Probes [13, 14], gas puff imaging systems [15–17] and fast visible cameras [18, 19].

The present work is intended to be a comprehensive contribution to the growing body of experimental data concerning the characterization of coherent structures: filaments or blobs in the SOL, holes or density deficits and other fluctuating phenomena in the plasma edge region. At the same time our intention is to place the recently built COMPASS Lithium Beam Emission Spectroscopy (Li-BES) system, on
the map of plasma turbulence studies, demonstrating its capabilities and uncover some of the interpretation issues that may arise during fluctuation data analysis.

The rest of this paper is organized as follows: in section 2, the experimental setup and the principles of Li-BES diagnostic are discussed. Section 2.1, qualitatively describes the raw data identifying the main noise sources. The effect of the plasma-beam interaction on the measured signal is described in details in section 2.2. Section 2.3 is devoted to the plasma-beam interaction on the measured signal is described in details in section 2.2. Section 2.3 is devoted to the fluctuation amplitude profiles and the variation of the auto-correlation functions with the radial position. Section 3 summarizes the analytic description of the Garcia-model (section 3.1) and presents the results of the synthetic diagnostic (section 3.2). Before analyzing the actual experimental data, two event detection techniques are compared (section 3.3). After presenting the experimental results in section 3.4, a summary is given.

2. Li-beam emission spectroscopy

Neutral alkali beams (Li, Na) are routinely used in a number of fusion-related devices (JET, ASDEX, Wendelstein-7X, COMPASS, KSTAR, EAST) as non perturbative diagnostics for time evolving density profile measurements [20–23].

Experimental data analyzed in the present article have been acquired by the COMPASS Li-BES diagnostic system (see figure 1) which consists of two main parts: the high energy (60 keV) diagnostic Li-beam [24] and the Li-light detection system [25]. The Li-gun ion source emits Li⁺ ions which are further accelerated in two stages (extraction and acceleration), in our case up to 60 keV. The ion beam is focused in the ion optics before entering the neutralization chamber where it gets neutralized by charge exchange processes induced by collisions with sodium atoms. The neutral beam reaches the plasma without any significant energy loss. During the plasma-beam interaction, through collisions with the plasma particles, Li-atoms are excited mainly to 2p state by the plasma particles. The excited 2p state decays with a τ_{life} ≈ 27 ns lifetime with the emission of a photon of characteristic wavelength (λ = 670.8 nm). These photons can be observed using an appropriate 2 nm wide interference filter and various detector systems (CCD camera, photomultiplier, photodiode or Avalanche photodiode (APD)).

For the present analysis we use the data acquired by a 18 channel APD-detector array [26] with observation volumes aligned along the major radius of the tokamak at the outer midplane. The distance of neighboring observation volumes is 10 mm. The actual radial resolution of the measurement strongly depends on the nonlocal nature of the light emission due to the finite lifetime of the exited Li(2p) states. The upper limit for this radial resolution can be easily calculated as:

$$\Delta r = \sqrt{\frac{2E_{\text{beam}}\tau_{\text{life}}}{m_{\text{Li}}}},$$  \hspace{1cm}(1)$$

where \(E_{\text{beam}}\) is the beam energy (most of our measurements were done using 60keV beam energy), \(\tau_{\text{life}}\) is the lifetime of the excited Li(2p) atomic state and \(m_{\text{Li}}\) is the mass of individual Li atoms. According to the equation (1), in our measurement \(\Delta r \approx 35 \text{ mm}\). This value sets a theoretical maximum for the smearing effect of the beam. The effective value of this non-locality is lower due to the collision induced de-excitation and ionization depending on the actual plasma density profiles [27]. In [28] a basic sensitivity study has been performed concerning the response of the light emission profile to the local perturbations of the density profile, concluding that the sensitivity is strongly suppressed at the maximum of the emission profile. Later in this paper we are going to analyze the effect of atomic physics on the statistical properties of fluctuating Li-BES signals.

The detected light intensity is—in the first approximation—proportional to the local electron density, therefore observing the time average intensity and its fluctuations along the beam, it is possible to reconstruct the density profile and the quasi-2D correlation functions of the electron density fluctuation [29, 30]. Using a pair of deflection plates the beam can be either chopped or poloidally delected (swept). Chopping the beam makes possible to correct for the background, while the poloidal deflection allows quasi-2D measurements [31]. The switching frequency of the sweeping/deflection system presently works up to 250 kHz. The poloidal resolution is limited by the \(\approx 2 \text{ cm}\) beam diameter. In the experimental campaign of which data are analyzed in this article, the quasi-2D measurement was not available.

2.1. Data characterization

Data analyzed in this work have been obtained in the experimental campaign CC18.18 dedicated to acquiring large sets of fluctuation data in identical discharges in order to provide good statistics for in-depth plasma fluctuation studies.
Medium density, L-mode plasmas were produced with a stable 150 ms flat-top. The main plasma parameters of the discharges are shown in figure 2. For our practical purpose we separate the outer region of the toroidal plasma in two parts: the edge plasma and the SOL. In this article we define the edge plasma as the region of closed magnetic surfaces just few cm inside the LCFS, meaning two observation channels \((R_{12} = 709.7 \text{ mm}, R_{13} = 719.4 \text{ mm})\) in the Li-BES system of COMPASS, while the SOL plasma is the region of open field lines and in this article we consider three Li-BES channels \((R_{15} = 738.7 \text{ mm}, R_{16} = 748.3 \text{ mm}, R_{17} = 758.0 \text{ mm})\) for our SOL analysis.

It is quite obvious that the quality of the Li-BES data is highly correlated to the reliability of the outcome results, therefore the assessment of data quality is very important.

In experimental physics the analyzed time traces are usually thought to consist of a series of instances taken from some statistical ensemble. The assumption is that the statistics is determined by the—usually nonlinear—dynamics of the physical system. In real world various noise sources can corrupt and hide the interesting statistics of the system under investigation. This is very much the case with the fluctuation data detected by the Li-BES system. In our case the interesting phenomena is the fluctuating turbulent plasma flow driven by local instabilities, while the main sources of measurement uncertainty can be identified as:

(i) Photon statistical noise.
(ii) Amplifier noise.
(iii) Pick-up oscillatory noise.
(iv) Fluctuations in the plasma background.

Figure 3 shows spectra of a typical Li-BES signal. The beam has been switched on and off with 20 ms period in order to assess the effect of plasma background and of the electronic noise. After the plasma discharge ends (after shot period, ASP) the beam observation continues. When the beam is off in the ASP, the pure electrical noise is detected (see the cyan line in figure 3, this is also the sum of items (i) + (ii) + (iii) in the list above), and some sporadic narrow peaks are seen in the spectrum. The same peaks are seen when the beam is on in ASP (see the red line in figure 3), showing that the presence of the beam does not introduce additional noise to the spectra. We should mention the resonance around 650 kHz which gets amplified and broadened when the high photon flux hits the detector during the discharge (see the green and blue lines in figure 3). These high frequency features are irrelevant from the point of view of edge turbulence studies, since we are interested in the 1–100 kHz spectral range. It can be also seen, that the background fluctuation levels are at least one order of magnitude lower then the beam light fluctuations in the relevant spectral range, assuring that the detected fluctuations are well localized at the beam position.

\[ \frac{d}{dz} N_i(z) = \sum_{j=1}^{5} [n_e(z)a_{ij}(T_e(z)) + b_{ij}]N_j(z), \]

where \(N_i\) is the occupation density of the \(i\)th excitation level, \(z\) is the coordinate along the lithium beam, where \(z = 0\) defines the position of the first measurement channel (called channel \(# 18\). The coefficients \(a_{ij} (i \neq j)\) describe the transition rate from level \(i \rightarrow j\) due to collisions with plasma electrons and ions. Attenuation of the \(i\)th atomic state due to charge exchange and ionization is included in coefficient \(a_{ii}\). The coefficients \(b_{ij}\) are the Einstein coefficients of spontaneous
emission. \( n_e \) and \( T_e \) are the electron density and temperature, respectively. This linear differential equation system describes the light emission of a Li-beam passing through a given plasma density and temperature profile.

Figure 4 shows an artificially constructed density profile (black curve) which consists of a tanh function smoothly merged to a linear function, matching the observed shapes of real density profiles [34]. The shape of the profile is controlled by two parameters: (i) the gradient at the inflection point (\( \alpha \) is the angle associated with the tangent line), (ii) the density value where the tanh function saturates (\( n_s \)). The density profiles constructed in such way have been perturbed with localized Gaussian density pulses (green curve). Using the collisional-radiative model \( \text{(2)} \) the light emission can be calculated (red curve). The calculations show some distinct features of the light emission response (see figure 4):

- amplification/attenuation of the perturbation amplitude
- radial shift of maximum perturbed emission
- radial broadening of the perturbation
- decrease in the emission behind the light profile maximum.

Recently it has been demonstrated that the relative emission response to density perturbation decreases with the radial position of the perturbation [28]. The present work expands on this idea as we examine the characteristics of the light response to various density perturbations of different density profiles.

Let us first examine figures 5(a)–(c) where the properties of light emission response are plotted against the perturbation amplitude. The subplot (a) reproduces the findings in [28]: the amplitude response is linear for small perturbations and a small deviation is observed for larger \( \delta n \). It is also clear that for a given perturbation strength the response decreases as we travel uphill the profile. According to figure 5(b) the maximum of the perturbation is shifted towards the center by a considerable amount of \( \approx 0.5 \) cm for low perturbation amplitudes. Less radial shift is observed for larger amplitudes and for larger \( r \) values. Depending on the amplitude and the initial position of the perturbation, a well localized perturbation gets broadened (smeared) due to the finite lifetime of the exited Li(2p) atomic states. Figure 5(c) reveals that larger \( r \) values favor localization.

Figures 5(d)–(f) present a situation when a fixed amplitude density perturbation is applied to the density profile at the radial position where the tanh profile reaches its inflection point (maximum gradient). The response has been calculated for two \( n_s \) saturation densities and different profile gradients \( \alpha \) (see figure 4). As the density profile becomes steeper the sensitivity to a given perturbation increases independently of the saturation density (see figure 5(d)), while the radial shift of the perturbation does not depend neither on \( \alpha \) nor on \( n_s \) as shown in figure 5(e). For low densities the perturbation broadening is quite large and it is basically independent of the profile gradient, on the other hand for higher density and shallow profiles the smearing is considerably smaller due to collisional deexcitation processes.

### 2.3. Fluctuation amplitudes and correlations

Before we turn to the detailed analysis of SOL structures (density filaments/blobs, holes), we shall describe the global characteristics of measured Li-light fluctuations (as a proxy for the electron density fluctuations). The relative and absolute fluctuation levels are plotted in figures 6(a)–(b) respectively, and are calculated as:

\[
\delta I_{\text{abs}} = \sigma_a - \sigma_b, \tag{3}
\]

\[
\delta I_{\text{rel}} = \frac{\delta I_{\text{abs}}}{\mu_a - \mu_b}. \tag{4}
\]

where \( \sigma_a \) and \( \mu_a \) are respectively the standard deviation and the time average of the signal \( S_a(t) = S_{\text{beam}}(t) + S_{\text{background}}(t) \). This is the superposition of plasma background emission and the Li-beam emission. \( \sigma_b \) and \( \mu_b \) are the standard deviation and the time average of plasma background signal \( S_b(t) = S_{\text{background}}(t) \) respectively. Applying a properly designed FIR bandpass filter, \( S_a(t) \) and \( S_b(t) \) contain only the relevant frequency components in the range of \( f \in [1, 100] \) kHz.

A clear difference between L-mode and H-mode fluctuation strength is visible in both absolute and relative fluctuation amplitude. The absolute fluctuation level in L-mode is as much as five times higher than in H-mode, while the relative fluctuation amplitude shows a factor of two difference. This behavior is well known and generally observed in all toroidal plasma devices (see e.g. [35] and the references therein). The lower plot in figure 6 shows the radial variation of auto-correlation function shapes. In the SOL fluctuations with 10%–40% relative level are seen with auto-correlation functions smoothly decaying with a decay length \( \tau_{\text{decay}} \in [20, 50 \mu s] \) decreasing towards the separatrix. In the fast closed flux surface region (plasma edge) the fluctuations are different as can be seen in figure 6(c). The observed wave-like...
fluctuations with $\approx 70$ kHz frequency are similar to the earlier Li-BES observations at Wendelstein 7-AS stellarator [36].

3. SOL plasma fluctuations

In this section we give a detailed description of the observed statistics of SOL fluctuations measured by Li-BES. Prior to the discussion of the blob detection and statistical analysis, we present the stochastic modeling of Garcia and a computer simulation based on this model, simulating both the density and Li-light emission fluctuations.

3.1. The Garcia model

In [37] Garcia presented a stochastic model describing the fluctuations of SOL plasma as perceived by single point measurements. The observed behavior is dominated by large-amplitude bursts, commonly referred to as ‘blobs’. The model represents the measurement as a random sequence of bursts:

$$\Phi(t) = \sum_k A_k \psi(t - t_k),$$

where $A_k$ is the burst amplitude, $t_k$ is its arrival time and $\psi(t)$ is a fixed waveform. It also states that bursts arrive according to a Poisson-process, which means that the waiting time between them follows an exponential distribution with rate $1/\tau_w$:

$$P_r(\tau) = \frac{1}{\tau_w} e^{-\tau/\tau_w}.$$
Calculating the cumulants of the signals probability density function (or PDF: $P_{fi}(\psi)$) yields formulas for its skewness and flatness, that show a parabolic relation, which is characteristic of systems that are dominated by intermittent fluctuations:

$$F = 3 + \frac{3}{2} S^2,$$

where $S$ is the skewness of the PDF, and $F$ is the flatness. This relation is in agreement with previous results from [37].

The possible origin of such quadratic relation has been discussed in [38]. For experimental consideration the burst waveform is taken as a 'step' rise followed by an exponential decay: $\psi(t) = \Theta(t) e^{-\tau}$ and exponentially distributed burst amplitudes. The connection between the skewness and flatness thus simplifies to:

$$F = 3 + \frac{3}{2} S^2.$$  

In case of short waiting times and slow decay ($\gamma = \frac{\tau}{\tilde{\tau}}$ is large) $P_{fi}(\psi)$ approaches a normal distribution while in the opposite limit it approaches Gamma distribution:

$$\lim_{\gamma \to 0} P_{fi}(\psi) = \lim_{\gamma \to 0} \frac{1}{\Gamma(\gamma)} e^{-\frac{\psi}{\Phi}}.$$  

In [14] a slightly refined version of the model was presented according to experimental results from Langmuir-probe measurements on the TCV tokamak. The shape of the bursts that dominate the signal have a double exponential waveform with amplitude and waiting time both fitting exponential distributions. The PDF of the signal fits a Gamma distribution which is in agreement with previous results [37].

### 3.2. Simulation and synthetic diagnostic

We created a MATLAB simulation of intermittent SOL fluctuations based on the Garcia model described in section 3.1. This simulation connected to the atomic physics model described previously serves as a synthetic diagnostic helping the interpretation of the Li-BES measurements. It basically models a single point measurement in a twodimensional (radial-poloidal) plane. The basic parameters of the emerging blobs are randomly generated: the arrival times at the first radial observation point and the blob amplitudes are drawn from an exponential probability distribution. Individual blobs are initialized at fixed radial position $r_0$ ($r = 0$ is the outer boundary of the simulation domain) and moved with velocities linearly dependent on blob amplitude, scattered by a normal distribution to simulate the findings in [14].

Blob wave fronts are propagated radially outward while their amplitudes are exponentially decaying. For each measurement point the passing through time (blob duration) is calculated for every blob, than an exponential rise and fall is added to the signal, creating double exponential waveforms.

The poloidal shape of individual blobs is described by a Gaussian function with FWHM = 3 cm. Then the perturbed signal is added to a radial density profile reconstructed from Li-BES measurements [32]. The amplitudes are scaled to match the relative fluctuation amplitudes seen in the experiment.

The average blob detection frequency is set so that larger blobs arrive at around 1 kHz. The shape parameters and the decay of the blobs is ascertained using conditionally averaged waveforms (conditional averaging will be explained in the next subsection) from COMPASS experiments as well. The radial velocity of the blobs is set to be around 300 m s$^{-1}$ as in e.g. [39]. The average blob amplitude is arbitrary as it can be scaled while maintaining statistics. After simulating a fluctuating density signal, the atomic physics of plasma-beam interaction is taken into account as it has been described in subsection 2.2. This way we get a synthetic signal similar to what we can obtain from real Li-BES measurements (see figure 7). At first glance two important features can be noted: (i) negative spikes appear at $r > r_0$, where $r_0$ is the radial coordinate, where all blobs are created (in this simulation $r_0 = 4$ cm). The negative spikes or holes are artifacts caused by the beam loss due to increased ionization in the higher density zone. (ii) the positive spikes at $r > r_0$, but closer to $r_0$ are the result of the smearing of the density perturbation by the finite lifetime of the excited Li(2p) states.

In figure 7, the subplot (a) depicts two time traces at different radial positions: the blue curve displays only positive fluctuations at $r < r_0$, while the red curve shows both positive and negative fluctuations relative to the average light profile. It is very important to realize that the appearance of holes as artifacts can corrupt our interpretation of the experimental results, therefore extra care is required during BES data analysis. Their contribution to the PDF (approximated by the amplitude histograms) of the signal also fits a Gamma distribution predicted by [37] (as seen on figure 8).

We applied a broadband Gaussian random noise to the simulated 'density' signal with standard deviation proportional to the signal RMS. This accounts for the different noises captured by the observation system, such as the electronic noise and the photon statistical noise in the limit of high photon fluxes. As a reference, in figure 9(a) the PDF of the 'pure' density signal is shown. A Gamma distribution fits

![Figure 7](image-url)
perfectly the simulation. The resulting PDF of the noisy synthetic measurement (Li-light fluctuations) is shown in figure 9(b), and exhibit a PDF with Gaussian center (red curve) and Gamma-like tail (green curve). We can conclude that applying the effect of collisional-radiative processes to the density does not change the amplitude distribution significantly, the change in PDF shape (observed in the experiments) is introduced by the detection noise. See figure 9(c), where scaled amplitude distributions are showed for the simulated noise-free density and light fluctuations. The Gamma distribution predicted by the Garcia model accurately fits the simulation density as well as Li-light data.

3.3. Event detection: two approaches

First, we present a widely used algorithm for SOL blob detection which is based on a predetermined, otherwise arbitrary threshold. This threshold is usually given in terms of the standard deviation $\sigma$ [14] and is set to discriminate between events of different amplitude. The detection algorithm scans the signal and finds the peaks above some prescribed $\sigma$ value. The detected peaks are considered to be part of individual filamentary events, therefore we can calculate the detection frequency, the amplitude distribution and the waiting time distribution. This approach is used in this article for conditional averaging (see section 3.3.2).

Another recently introduced approach to detect Edge Localized Mode (ELMs) events in different diagnostic signals is the generalized Sequential Probability Ratio Test (gSPRT) [40]. In the present work we applied, for the first time, the gSPRT technique to blob detection. It is a unique characteristic of the method that the event duration can be determined accurately according to the intrinsic statistics of the experimental data.

3.3.1. The gSPRT algorithm. The generalized approach described in [40] is based on the classical Sequential Probability Ratio Test [41], but adapt the local physics conditions and get the required parameters from the measured diagnostic signal. The SPRT algorithm is based on the assumption that the signal consists of two separate random processes and the algorithm can decide for each sample what is the logarithmic probability ratio of the two situations where the sample belongs to one or the other processes. This parameter, usually denoted by $\lambda_n$ (see its definition in [40]), depends on the probability distributions (PDF) of the two processes. Two decision levels are defined for $\lambda_n$, discriminating between two processes:

$$A = \ln \frac{\beta}{1 - \alpha},$$

$$B = \ln \frac{1 - \beta}{\alpha},$$

where we set $\alpha$—the probability of ‘false alarm’—to 0.2 and $\beta$—the probability of ‘missed alarm’—to 0.05. We have to note that the gSPRT method is not sensitive to small variations of these values. When $\lambda_n$ is below level $A$ the sample belongs to the first process (here inter-blob fluctuations), while it is above level $B$ the sample belongs to the second process (here the blob event).

For defining $\lambda_n$ directly from the experimental data we use the best fit two-parameter amplitude distribution (ADF) as a proxy for the PDF. We have found that the ADF of the inter-blob periods can be well described by the Gaussian
The calculated gSPRT signal (blue) together with the original signal (green) showing the starting and ending points as calculated by the gSPRT algorithm.

Figure 11. The observed linear correlation between the blob amplitude and the blob duration using the gSPRT method.

There has been observed a strong correlation between the blob velocity and the spatial distribution $G(\mu_0, \sigma_0)$. On the other hand, the best fit for the empirical ADF for conditionally averaged ‘blob event’ was the Inverse Gauss (also known as Wald) distribution $W(\mu, \lambda)$. We have found a strong correlation (>95%) between the maxima of the calculated gSPRT signal ($\lambda_0$) for each blob and the maxima of the original signal. As it is shown in figure 10 the gSPRT can determine the start and the end of the ‘blob event’.

When the gSPRT signal ($\lambda_0$) exceeds the decision level $B$, the blob event starts and when the signal falls below the level the event ends. Figure 10 also illustrates the problem of merged events. When two or more events overlap, the gSPRT signal could not fall below the decision level $B$ and the algorithm could not distinguish between the events. This problem can be handled by finding the local minima of the smoothed gSPRT signal within a given merged blob, and put the end and the start points there as it can be seen in the case of the 2nd and 3rd blob in the figure 10. We label the detected blobs according to their intensity (size). E.g. a ‘size 2’ blob has its maximal amplitude in the corresponding gSPRT signal in the interval $[B + 1 \cdot \Delta t, B + 2 \cdot \Delta t]$, where $\Delta t = (M - B)/n$ and $M$ is the overall maxima for the gSPRT signal and $n$ is the number of blob size labels we use (in the present analysis we use $n = 5$, therefore we have 5 different blob amplitudes in the analysis).

There has been observed a strong correlation between the duration time of blobs as measured by the gSPRT method and the blob intensity as shown in figure 11. We show the outlier point at the ‘size 1’ blobs as a warning sign which has to be taken into account when low amplitude blobs are considered. As the blobs (filaments) are considered to be ‘coherent structures’, the blob amplitudes, with good approximation are constant as they travel radially across the detection channel, therefore the measured blob duration is determined by the blob velocity. The analysis presented in figure 11 shows that with increasing blob amplitude the blob duration increases therefore the velocity decreases. Nevertheless we should note that the above statement does not necessarily imply a relation between the blob velocity and the spatial ($B_z$) blob size.

3.3.2. The threshold method and conditional averaging. As it has been mentioned above, the threshold-based event detection followed by conditional averaging (CA) is the conventional approach in the field of SOL fluctuation studies. In this section we briefly summarize our algorithm before we dive into data analysis. The algorithm starts with setting a reasonable threshold level, usually given in terms of standard deviation (e.g. $2.5 \times \sigma$, see figure 12), then the signal is being scanned starting from the beginning until a peak is found above the threshold. Around the peak the signal is cut out within a $\Delta t$ time window (in the case seen on figure 12, $\Delta t = 70(\mu s)$ and saved for further analysis.

This procedure is repeated for all peaks above the threshold. As a result a collection of $\Delta t$ long time series is created. Conditionally averaged blob is obtained after averaging over this ensemble of time series.

In figure 13 we show the result of the conditional averaging procedure applied to simulated density time traces. The comparison of the ‘density blob’ and the ‘light emission blob’ is plotted in terms of the conditional average waveforms.

The smearing effect of the plasma-beam interaction can be observed in the widening of the waveform. The rising exponent of the fitted exponential is increased by 72% while the falling by 37%.

3.4. Experimental observation of SOL fluctuations

In this section we present the results of basic statistical analysis of intermittent SOL fluctuations (blobs and holes) as measured by the Li-BES system at COMPASS.
After filtering the raw Li-BES data to the relevant 1–100 kHz frequency range, we calculated the amplitude histogram (PDF) of the Li-light fluctuations. It can be seen in figure 14 that the PDF is clearly positively skewed suggesting the presence of large amplitude events (filaments, blobs) in our experimental data. It is also clear that the experimental PDF does not fit the expected theoretical Gamma distribution described in [37]. Nevertheless it was possible to develop a fitting function as a convolution of two two-parameter distributions: a Gamma function and a Gaussian function which gave good fit to the data. Equation (13) shows the construction of the distribution function:

$$
\Phi(t) = \int_0^\infty \frac{1}{\Gamma(k)\theta^k} t^{k-1} e^{-\frac{t}{\theta}} \frac{1}{\sqrt{2\pi}} e^{-\frac{t^2}{2\sigma^2}} dt,
$$

where $\sigma$, $k$ and $\theta$ are the free parameters to be determined. $k$ and $\theta$ can be acquired by fitting a regular Gamma distribution to the tail of the PDF, while the parameter $\sigma$ representing the measurement noise was adjusted manually. It was also possible to deduce, directly from the experimental data, the input parameters for synthetic signal simulations, namely the waiting time distribution and the average blob duration. Running the simulation with such parameters, the resulting PDF is in very good agreement with the actual measurement (see the red points in figure 14), suggesting that our simulation approach is reliable. We have to note that the experimentally observed intermittency is lower than the Garcia-limit, yet the final conclusion of the model, that the signal PDF fits a Gamma distribution, still holds. As we have already showed in section 3.2, in the simulation hole artifacts can appear behind the maximum of the Li-light emission profile. This will present a challenge to experimental data analysis due to the fact that the real holes (density deficit) are expected around the separatrix, where the blobs are created.

Indeed, hole artifacts can be found in the experimental data as well, as it can be seen in figure 15, where we show the conditional average waveforms for different radial channels (figure 15(a)). Here the reference channel #15 is located in the SOL while channels #10 and #11 are behind the light profile maximum (channel #12). There is no time delay observed between conditionally averaged waveform maxima, showing that these events appear at the same time in the signal. The same conclusion can be drawn from the cross-correlation functions shown in figure 15(b). It is worth mentioning that reference channel is also #15 and time shifts relative to zero time lag can be observed for the SOL channels (#14, #16) indicating radial propagation of the blobs, but there is no shift for channel #11, which is consistent with the presence of hole artifacts.

In order to meet the challenge presented in the previous paragraph, the statistical analysis of the blob and hole events should start with a procedure sorting out the artifacts. This has been done based on the following process: if the algorithm finds a hole in a given channel and simultaneously finds a blob somewhere else it qualifies the hole as a fake. Fake blob appearance is also possible, if for some reason the density drops locally in the SOL, it can cause a simultaneous density increase behind the emission profile. As the analyzed discharges are made to be as much identical as possible, we are able to collect large amount of events (few thousand). In figure 16 we summarize the essential results about the statistical properties of these fluctuation events. In figures 16(a)–(b) the conditional average waveforms are plotted for blobs in the SOL and holes around the separatrix. The average blob duration is
$\leq 20$ $\mu$s while the hole duration time is $\leq 10$ $\mu$s. We have to note though that these values contain contributions from different size blobs, and as it was shown on figure 11 the higher amplitude blobs have longer duration times, which is the reason for the relatively large errorbars. Fitting double exponential to the conditional average waveforms, the rising and falling times can be obtained. As a general statement we can say that the blob/hole waveform rises approximately two times faster than it decays. The figures 16(c)–(d) shows the amplitude distribution for large events. According to Garcia model the amplitude distribution can be described by an exponential function, which indeed is the case for our Li-BES measurements. The above mentioned stochastic modeling predicts exponential distribution for the waiting times as well. Both the blobs and the holes detected in our experimental data have waiting times following exponential distribution as seen in figures 16(e)–(f). From the waiting time distribution the blob/hole detection rate can be inferred, this gives for blobs, $\lambda_{\text{blob}} \approx 3 \times 10^3$ s$^{-1}$ and for holes, $\lambda_{\text{hole}} \approx 13 \times 10^3$ s$^{-1}$.

4. Summary

We have demonstrated that the COMPASS Li-BES system can be used as a non-perturbative means for plasma fluctuation study, although the interpretation of the data is affected by the plasma-beam interaction.

Our sensitivity study shows that for given density profile shape with density perturbation applied at a given radial position, the amplitude response is proportional to the perturbation amplitude. On the other hand if we keep the perturbation amplitude constant, the light response is more sensitive to outer perturbations and for density profiles with larger gradients. We have also found that the localization (maximum shift and broadening) of the response is better for outer channel perturbations and it practically does not depend on saturation density.

We constructed a synthetic diagnostic based on two-dimensional numerical simulation of moving random structures with prescribed spatial and temporal shapes. From the simulated data, using a collisional-radiative model we have generated synthetic Li-BES signals. The analysis revealed the appearance of artificial events (holes and blobs) due to the plasma-beam interactions. These ‘fake’ events should not be included in the analysis. We have shown that the PDFs, therefore the statistics, are not affected by the atomic physics effects, but the photon noise and electrical noises change the statistics.

We have shown that beside the generally used threshold method, the sequential probability ratio test method can be successfully applied for blob detection, having the advantage of more accurate determination of event duration directly from the signal statistics.

We have also demonstrated that the Li-BES data of intermittent fluctuations in the SOL can be described by the stochastic Garcia model for convoluted PDFs assuming finite intermittency. It is also interesting to note that we have found a change in the correlation-functions of Li-light fluctuations as we approach the separatrix from the SOL. The origin of the
wave-like correlations at the last closed flux surface is not yet clear. Quasi-two dimensional Li-BES measurements are planned for further investigation of turbulence phenomena at COMPASS.

Acknowledgments

This work was partly supported by Czech Science Foundation Project No. GA16-25074S. This work was also partially supported by project No. CZ.02.1.01/0.0/0.0/16_019/0000768 and MEYS project LM2015045.

ORCID iDs

A Bencze https://orcid.org/0000-0002-4174-3893
J Krbec https://orcid.org/0000-0002-3780-6257

References

[1] Carreras B A 2005 Plasma edge cross-field transport: experiment and theory J. Nucl. Mater. 337–339 315–21 PSI-16
[2] Naulin V 2007 Turbulent transport and the plasma edge J. Nucl. Mater. 363–365 24–31 Plasma-Surface Interactions-17
[3] Krasheninnikov S I, D’Ippolito D A and Myra J R 2008 Recent theoretical progress in understanding coherent structures in edge and sol turbulence J. Plasma Phys. 74 679–717
[4] García O E 2009 Blob transport in the plasma edge: a review Plasma Fusion Res. 4 019
[5] D’Ippolito D A, Myra J R and Zweben S J 2011 Convective transport by intermittent blob-filaments: comparison of theory and experiment Phys. Plasmas 18 060501
[6] Carreras B A, Lynch V E and Zaslavsky G M 2001 Anomalous diffusion and exit time distribution of particle tracers in plasma turbulence model Phys. Plasmas 8 5096–103
[7] Sánchez R, van Milligen B P, Newman D E and Carreras B A 2003 Quiet-time statistics of electrostatic turbulent fluxes from the jet tokamak and the w7-as and tii-ii stellarators Phys. Rev. Lett. 90 185005
[8] Carralero D, Calvo I, Shoji M, Carreras B A, Ida K, Ohdachi S, Sakakibara S, Yamada H and Hidalgo C 2011 Influence of β on the self-similarity properties of LHD edge fluctuations Plasma Phys. Control. Fusion 53 095010
[9] Devynck P, Ghendrih P and Sarazin Y 2005 The origin of the long time correlations of the density fluctuations in the scrape-off layer of the tore supra tokamak Phys. Plasmas 12 050702
[10] Carralero D, Manz P, Aho-Mantila L, Birkenmeier G, Brix M, Groth M, Müller H W, Stroth U, Vianello N and Wolfrum E 2015 Experimental validation of a filament transport model in turbulent magnetized plasmas Phys. Rev. Lett. 115 215002
[11] Jorge R, Ricci P, Halpern F D, Loureiro N F and Silva C 2016 Plasma turbulence in the scrape-off layer of the istok tokamak Phys. Plasmas 23 102511
[12] Miliello F et al 2016 Multi-code analysis of scrape-off layer filament dynamics in MAST Plasma Phys. Control. Fusion 58 105002
[13] Xu G S et al 2009 and, Blob/hole formation and zonal-flow generation in the edge plasma of the JET tokamak Nucl. Fusion 49 092002
[14] Theodorsen A, Garcia O E, Horacek J, Kube R and Pitts R A 2016 Scrape-off layer turbulence in TCV: evidence in support of stochastic modelling Plasma Phys. Control. Fusion 58 044006
[15] Cziegler I, Terry J L, Hughes J W and LaBombard B 2010 Experimental studies of edge turbulence and confinement in alcor c-mod Phys. Plasmas 17 056120
[16] Fuchert G, Birkenmeier G, Carralero D, Lunt T, Manz P, Müller H W, Nold B, Ramisch M, Rohde V and Stroth U 2014 Blob properties in l- and h-mode from gas-puff imaging in ASDEX upgrade Plasma Phys. Control. Fusion 56 125001
[17] Zweben S J, Myra J R, Davis W M, D’Ippolito D A, Gray T K, Kaye S M, LeBlanc B P, Maqueda R J, Russell D A and Stotler D P 2016 Blob structure and motion in the edge and SOL of NSTX Plasma Phys. Control. Fusion 58 044007
[18] Kirk A et al (the MAST team) 2006 Filament structures at the plasma edge on MAST Plasma Phys. Control. Fusion 48 B433–41
[19] Ben Ayed N, Kirk A, Budson B, Tallents S, Vann R G L and Wilson H R 2009 Inter-ELM filament transport and turbulent transport in the mega-amp spherical tokamak Plasma Phys. Control. Fusion 51 035016
[20] Fiedler S, Brandenburg R, Baldzuhn J, McCormick K, Aumayr F, Schweinzer J and Winter H P 1999 Edge plasma diagnostics on W7-AS and ASDEX-upgrade using fast Li beams J. Nucl. Mater. 266–269 1279–84
[21] Zoletnik S et al 2018 Advanced neutral alkali beam diagnostics for applications in fusion research (invited) Rev. Sci. Instrum. 89 10D107
[22] Réfy D I, Brix M, Gomes R, Tál B, Zoletnik S, Dunai D, Kocsis G, Kálvin S and Szabolics T 2018 Sub-millisecond electron density profile measurement at the jet tokamak with the fast lithium beam emission spectroscopy system Rev. Sci. Instrum. 89 043509
[23] Anda G, Dunai D, Lampert M, Krizsanócz T, Németh J, Bató S, Nam Y U, Hu G H and Zoletnik S 2018 Development of a high current 60 keV neutral lithium beam injector for beam emission spectroscopy measurements on fusion experiments Rev. Sci. Instrum. 89 013503
[24] Anda G et al 2016 Lithium beam diagnostic system on the COMPASS tokamak Fusion Eng. Des. 108 1–6
[25] Berta M et al 2015 Li-bes detection system for plasma turbulence measurements on the compass tokamak Proc. 28th Symp. on Fusion Technology (SOFT-28); Fusion Eng. Des. 96–97 795–8
[26] Dunai D et al 2010 Avalanche photodiode based detector for beam emission spectroscopy Rev. Sci. Instrum. 81 103503
[27] Asztalos O et al 2017 Fluctuation response analysis of plasma turbulence with BES diagnostics EPS Conf. Proc.
[28] Willensdorfer M et al 2014 Characterization of the Li-BES at ASDEX Upgrade Plasma Phys. Control. Fusion 56 025008
[29] Fonck R J et al 1990 Plasma fluctuation measurements in tokamaks using beam-plasma interactions Rev. Sci. Instrum. 61 3487
[30] Zoletnik S et al 1998 Determination of electron density fluctuation via beam emission spectroscopy Plasma Phys. Control. Fusion 40 1399–416
[31] Zoletnik S, Bardocz I, Krümer-Flecken A, Xu Y, Shesterikov I, Soldatov S, Anda G, Dunai D and Petrivich G 2012 Methods for the detection of zonal flows using one-point and two-point turbulence measurements Plasma Phys. Control. Fusion 54 065007
[32] Krbec J, Háček P, Berta M, Seidl J, Hron M and Pánek R 2018 Fast density reconstruction of li-bes signal on the compass tokamak Rev. Sci. Instrum. 89 113504
[33] Schweinzer J et al 1992 Reconstruction of plasma edge density profiles from Li I (2s-2p) emission profiles Plasma Phys. Control. Fusion 34 1173

[34] Stefanikova E, Peterka M, Bohm P, Bilkova P, Aftanas M, Sos M, Urban J, Hron M and Panek R 2016 Fitting of the thomson scattering density and temperature profiles on the compass tokamak Rev. Sci. Instrum. 87 11E536

[35] Zweben S J, Boedo J A, Grulke O, Hidalgo C, LaBombard B, Maqueda R J, Scarin P and Terry J L 2007 Edge turbulence measurements in toroidal fusion devices Plasma Phys. Control. Fusion 49 S1

[36] Zoletnik S, Anton M, Endler M, Fiedler S, Hirsch M, McCormick K and Schweinzer J 1999 Density fluctuation phenomena in the scrape-off layer and edge plasma of the Wendelstein 7-AS stellarator Phys. Plasmas 6 4239–47

[37] Garcia O E 2012 Stochastic modeling of intermittent scrape-off layer plasma fluctuations Phys. Rev. Lett. 108 265001

[38] Guszejnov D et al 2013 On the effect of intermittency of turbulence on the parabolic relation between skewness and kurtosis in magnetized plasmas Phys. Plasmas 20 112305

[39] Lampert M, Zoletnik S, Bak J G and Nam Y U 2018 2d scrape-off layer turbulence measurement using deuterium beam emission spectroscopy on kstar Phys. Plasmas 25 042507

[40] Berta M et al 2017 Automatic ELM detection using gSPRT on the COMPASS tokamak Fusion Eng. Des. 123 950–4

[41] Wald A 1945 Sequential test of statistical hypotheses Ann. Math. Stat. 16 117–86