
Replies to Dr. Papp Gergely

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Dear Dr. Papp Gergely,

I would like to thank you for reviewing my PhD dissertation. Thank you very much for the endorsement, kind remarks and suggestions made in the review. First of all, I would like to address as few general remarks made during the review process:

- I have to agree on your comment of the work featuring not enough introductory descriptions to better detail certain phenomenon or signal processing methods used in my work. Due to the volume of results I wanted to present, I aimed to be brief in the introductions and provide as many references as needed. It is not a requirement but PhD dissertations submitted to my doctoral school tend to be in range of 100 pages. I aimed to be in the same order of magnitude, which meant shorting the descriptive and educative elements of my work.
- In hindsight and based on the critique of my other referee I will concede that my conclusion of a successful validation was a bit overzealous in the phrasing presented in the work. However, I found the defining the measure for success during the validation attempt of two imperfect representations of reality (HESEL and RENATE) with experimental difficult. The success of the validation effort presented in my work two motivations. Firstly, the noisy synthetic measurement features are much closer to the experimental ones, providing valuable insight into how the measurement process changes the features of the underlying turbulence. Secondly, I did get a good agreement in certain turbulence features such as filament frequency (see Fig 5.12A) as well as amplitude distribution in the far SOL. A full validation effort was not realistic goal for this work, so I did decisive positive steps towards that aim.

Questions:

1. Could you explain in a little more detail what “blobs” and “filaments” are, why they are important to study, and why are the tools used (such as skewness and kurtosis) adequate to characterize them?

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2. Could you elaborate on the unique value of BES in the context of plasma edge physics studies, which justified the great effort in working with this technique?

3. Could you discuss the differences between the full-f, gyro-kinetic, gyro-fluid and Braginskii models? Under what assumptions are they valid, what are the advantages and limitations compared to each other, and how do they compare from the perspective of a BES synthetic diagnostic? (i.e. does it matter which one we try to do experimental validation with?)

4. In figure 5.10 on page 102, the comparison of the simulated and synthetic signal spectra is shown. I'd argue there are two main discrepancies. In figure 5.10a the simulated density fluctuations (red) have a clear peak at $\approx$ 20 kHz, whereas in the experimental signal (green) a peak is found at $\approx$ 5 kHz. In figure 5.10b the shape of the spectrum as a function of frequency is very different between the HESEL density fluctuations and the experimental signals. The power fall-off is often a crucial part of turbulence studies. Can we expect that with adequate synthetic diagnostics these features can be "recovered" from an experimental signal, or do the results indicate that these will be lost due to the process of the measurement?

5. Page 114, equation (6.2). Perhaps I misunderstood, but how is the cross-section calculated? The text states that b_j are "the corresponding impact parameters randomly chosen following a uniform distribution in $[0; b_{max}]$." If b_j are random, 2π, T_N and b_{max} seem like constants, then how is this formula related to the physics? Which of these quantities comes from the CMTC calculation? How exactly is the cross-section derived in the CMTC method?

Answers:

1. To further expand on the description of filaments in the introduction of Section 2.3 and the subsection 2.3.1, filaments are regarded as coherent plasma density structures that is ejected from the confined plasma, onto open magnetic field lines, in the SOL region. The filament slowly dissipates in the SOL. While doing so, particle density and energy transport occurs along the magnetic field line, connecting the filament to the plasma facing component (PFC) and effectivly determining expected heatloads on specific locations of the "wetted" surface of the PFC. On a much slower timescale particle propagation across the magnetic field

lines occures into the far SOL, determining the reach of the filaments and subsequently the extent of the ”wetted surface” on the PFC. A very good overview is given by D’Ippolito *et al.* [1] on various filament types.

”Blobs” are filaments that are generated by pressure driven instabilities, based on the interchange mechanism. This occurs at the plasma boundary between a high density and lower density plasma. Depending on the relative direction of the pressure gradient and curvature, while interchange is more or less stabilized on the high field side, while instabilities on the low field side grow leading to the ejection of a chunk of plasma density, also referred to as blob or more generally filament. The filament dissipates due to the magnetic field aligned transport, while the ∇B and curvature drift induced $E \times B$ drift carries it radially outward.

ELM bursts, for example result in non ”blob filaments” as their generation and in general behavior is very different.

”Blobs” are intermittent by nature, therefore stochastic. Their statistics can be characterized by multiple factors, such as waiting time, amplitude, size and velocity, which all are all governed by individual distribution functions. Knowledge these functions gives a good description of SOL filament behavior, which in turn affects SOL width and divertor heat load. These quantities can be assessed by means of event identification. A more rudimentary interpretation is given by the moments of the distribution function (skewness) and auto power density spectra of the times signals where filament activity is expected. These values will not return any distribution functions but in turn give a first glance on the ”strength” of the filament behavior, typically providing the ground for further investigation.

2. Beam emission spectroscopy (BES) is a fast plasma density measurement, features of which were elaborated in the introduction of Chapter 2, complemented by a brief review in 2.3. To further elaborate, the unique nature of BES lies in the capability of the measurement system to produce light profiles, which can be used to infer plasma density and its fluctuation. The diagnostic system has a few limitations, most important of is the detected photon current, which limits the measurement frequency. The typical frequency range applicable for BES ranges between 100 - 1000 kHz, depending on the measurement setup. BES feature an optical resolution of 1 cm or less. The primary goal of BES diagnostics is the plasma density profile measurement in the SOL and edge region [2, 3], capable of resolving inter-ELM density

profiles with a high accuracy up to the pedestal top [4, 5]. This measurement capability is almost unique to BES. Sweeping reflectometry in the SOL-edge [6] features similar capabilities, however that measurement has somewhat historically struggled in low density plasma, such as the SOL. A secondary goal of BES diagnostics, is the study of plasma density fluctuations in the core, edge and SOL regions. A vast number of references for these observations are listed in Section 2.3. Other measurement methods commonly used for the study of turbulence and density fluctuations are gas puff imaging [7], Langmuir probes [8], reflectometry [9], phase contrast imaging [10]. The value of a well set-up BES system is its capability to provide 2D , well localized information on plasma fluctuations in the core - edge - SOL region allowing for the study of plasma transport and turbulence phenomenon over selected regions of the whole plasma range.

For a BES diagnostic system observing dedicated diagnostic alkali beams, a well set-up BES system provides fast density profiles of the plasma edge and SOL regions as well as 2D observation of density fluctuations of few cms spatial and microsecond temporal scales. Such a system provides valuable information on plasma transport and turbulence in the SOL and edge regions simultaneously.

For a BES diagnostic system observing a heating beam, a well set-up BES system provides a wide ranged 2D observation of plasma density fluctuations on multiple radial and poloidal channels providing information on plasma transport and turbulence phenomenon ranging from the SOL to the plasma core.

3. A few of the various codes and models discussing plasma turbulence are briefly described in Section 2.3.1. I would like to emphasize that the intricate nature of turbulence codes and models is not my area of expertise, during my work I relied on the expertise of the owners of such codes to generate the fluctuating density field, namely A.H. Nielsen of DTU to generate the HESEL [11] input for my synthetic diagnostic.

   That being said, plasma models evolving the SOL fall into three main categories. SOL transport codes such as the SOLPS suite of codes [12] are based on common fluid equations for the plasma, as derived by Braginskii [13] from the different moments of the distribution functions of electrons and ions. These models are based on equilibrium profiles which are evolved. These codes are relatively fast and do not have the capacity to resolve plasma fluctuations. Their variations and flavors vary considerably depending on what enhancements they feature, such as tokamak geometries, neutral particles, various boundary conditions. These models have an interplay with turbulence codes, as transport coefficients are derived from more detailed turbulence codes and fed into transport codes, which in turn generate the profile gradients necessary to model turbulence. These models are not featured in my work as they do not solve the time dependent features of SOL turbulence.

One level below the before mentioned transport codes, are the Braginskii based fluid descriptions for SOL turbulence. These models use a quasi neutral plasma models, accounting for drifts and currents, including collisional transport which gives rise to diffusion of particle density and momentum, removing the need to artificially introduce diffusion into the models. These models self-consistently evolve the full profiles of the dependent variables. These models require quasi neutrality to function and Maxwellian distributions. There is great variation in fluid based turbulence models depending on complexity. The ESEL [14], HESEL [11] and nHESEL [15] family are simple 2D slab geometry based models that use a drift-fluid approach by accounting for electrostatic forces, adding hot ions to the mix and account for plasma-neutral interactions, in this order. More complex models are 3D featuring variations of the above mentioned additions are STROM [16], GBS [17], TOKAMX [18] and GRILLIX [19], which are all computationally more intensive and solve SOL plasma turbulence.

The most detailed approach to plasma modeling is achieved by kinetic codes. These models have the advantage of describing a normal and momentum space of plasma particles and feature the ability to incorporate complicated atomic and plasma-surface interactions. These codes are designed to simulate the motion of many particles and simulate the motion of representative or all plasma particles and calculate all macro-quantities (like density, current density and so on) from the position and velocity of these particles. Such are the particle in cell codes like BIT1 [20]. The fully kinetic model allows a plasma description of the highest detail and in theory could be used to tackle almost any plasma physics related issue. The gyro-kinetic aspect is achieved by writing the Vlasov equation in gyro-center Hamiltonian, codes such as XCG1 [21], also follow a particle in cell approach.

A mix of gyro-kinetic and fluid codes are the gyro-fluid variant, such as GEMR [22] or GESEL [23]. The underlying principles of operation are very similar to that of the more classical fluid approach, notable differences being the gyrofluid moments are derived from the gyro-kinetic equations and from the Braginskii model allowing for a more correct plasma description over that of the more classical fluid approach. These methods are computationally less expensive than the gyro-kinetic ones but more expensive than the fluid ones.

The applicability of these models can be viewed from two perspectives in my opinion with regard to BES. From a theoretical point of view, any model from drift-fluid to fully kinetic is suitable for SOL turbulence modeling. While the more fluid models approach the SOL from a Maxwellian distributions the more kinetic codes can provide a better dynamic of SOL filaments, these features might all be detectable by BES as long as the density fluctuations are large enough.

From a pragmatical point of view, kinetic models take an immense computational time to render a relatively short representation of plasma behavior. From a point of view of SOL turbulence modeling: these methods can generate the time evolution of single filament with impressive detail, but generating a statistically relevant data set is not very realistic. Therefore the computationally cheaper models have a much better chance of validation to experimental measurements.

4. There is a significant discrepancy in the APSD between the modeled HESEL density (red) and the experimental observation (green) as seen in Figure 5.10 pointed out by the reviewer. The synthetic diagnostic demonstrates that during the measurement process a significant amount of information is distorted. A more relevant comparison to exactly understand the information transfer, would be rather between the HESEL density (red) and noisy synthetic signals (purple). The turbulence features are most likely lost. Most of the smaller density fluctuations are averaged out by the effective spatial resolution and covered by noise.

   However, I could imagine an attempt at reconstructing features of measurement signals. Such an endeavor would require a wide ranging database of density to synthetic data modeling. I could envision having some success using the amplitude information from the fluctuation response calculations or machine learning. The uncertainty and systematic error of such a reconstruction process would be significant.

5. The formula used for cross-section calculation by K. Tőkési:

$$\sigma^{(i)} = \frac{2\pi \mathrm{b}_{\max}}{T_N} \sum_{j=1}^{T_N^i} b_j^{(i)} \tag{1}$$

where T_N is the total number of trajectories computed with impact parameters less than b_{max}, T_N^i are the number of trajectories relevant for the investigated *i-th* channel with $b_j^{(i)}$ the corresponding impact parameters randomly chosen following a uniform distribution in $[0, \mathrm{b}_{\mathrm{max}}]$. This equation was also used in my work [24], heavily influenced by the work of K. Tőkési *et al.* [25] discribing the collisions between positronium and helium as a five body problem. The application of the formula by K. Tőkési dates back as far as 1996 [26].

To better understand it, consider the collision of 2 neutral particles described as a four body problem. A projectile featuring a positive core, in my case H^+ or Li^+ bound to an electron as well as a target featuring a positive core of H^+ or H_2^+ bound to an electron. First all exit channels have to defined, which in my case were the following:

(a) Direct: is a channel that describes elastic scattering.

(b) Target Ionization: is an exit channel that describes the target loosing an electron due to the collisions.

(c) Projectile Ionization: is an exit channel that describes the projectile loosing an electron due to the collisions.

(d) Target and Projectile Ionization: is an exit channel that describes both the projectile and the target loosing an electron.

(e) Capture to Target: is an exit channel that describes the projectile electron being captured by the target, realizing a negative ion as the target and positive ion as the projectile.

(f) Capture to Projectile: is an exit channel that describes the target electron being captured by the projectile, realizing a negative ion as the projectile and positive ion as the target.

(g) Exchange and rearrange: is an exit channel that describes the target and projectile exchanging electrons.

(h) Target Ionization and Capture: is an exit channel that describes the target ionization and subsequent electron capture from projectile, resulting in a neutral target with the projectile electron and an ionized projectile.

(i) Projectile Ionization and Capture: is an exit channel that describes the projectile ionization and subsequent electron capture from target, resulting in a neutral projectile with the target electron and an ionized target.

These are all the possible reaction outcomes, while keeping track of the electrons in the collision system. The b_{max} value is carefully set by repeating the CTMC model with a large enough impact parameter and searching for a value above which there are no significant inelastic collisions. The interval between $[0; b_{max}]$ is divided into a number of $b_i = \delta b$ intervals defined by the impact parameter resolution. Each classical trajectory simulation is initiated by randomly selecting a b_i impact parameter segment and initiating the collision with the corresponding impact parameter value. This process is repeated T_N times, as $N = 10^n$ trajectories are computed, where n is in the range of 7. Each i-th impact parameter segment (b_i) will have nine individual counters, one for each exit channel, thus keeping track of the outcome of each modeled collision. The final cross-section is derived by accounting for all the results related to each exit channel over all the b_i impact parameter segments. The T_N and b_{max} are indeed constants, b_{max} is chosen based on the initial CTMC performance, which is rooted in physics. The sum in essence is a representation of an integral of weighted b_i values from 0 to b_{max}. The physics aspect comes into play through the count distribution over the exit channels related to each b_i segment.

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