
Replies to Dr. George McKee

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Dear Dr. George McKee,

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 some of the remarks made during the review process:

- Q: It wasn't clear how the collection optics are being treated in the 3D geometry. Is the full optical throughput, with a light cone focusing on the neutral beam, but with finite extent considered, as this will naturally further enlarge the FSA relative to using line-of-sight "pencil beams". Faster, higher throughput (lower f/#) optics will naturally collect more light but at the expense of varying doppler shift across the optical elements and increasing FSA size.

  A: RENATE treats each detector element of the observation volume as a cone or volume with finite extent. The emission located outside of a specific cone is not accounted for, when total detected emission for a given detector is computed. The code features ray-tracing capabilities if a Zemax description is available. This feature is however rarely used due to its computationally expensive nature.

- Q: Also, DBES systems can suffer from impacts of very large edge/boundary turbulence $\frac{\tilde{n}}{n} \geq 20\%$ attenuating the beam (slightly), which is then detectable downstream, deeper in the plasma, as an out-of-phase fluctuations, which can rival or exceed that of the local fluctuations in the core. Has this been considered in the full model? The assessment indicates that, unlike alkali beams, there is little impact downstream for DBES systems.

  A: The effects of SOL/edge density fluctuations causing a negative emission response on DBES core observations is a feature that appears in the modeling, similarly to the LiBES case. It is not very accentuated as the studied observation geometry for EAST DBES is looking at the plasma edge and furthermore density perturbations were chosen to be $\frac{\tilde{n}}{n} \approx 5\%$. Fluctuation response calculations are quite expensive and a relative lower perturbation amplitude was chosen for these simulations.

A more extensive study is underway aimed at exploring a wider range of perturbation sizes and amplitudes.

- Q: Could a fast high efficiency (e.g., transmission grating based) spectrometer be used for largely unsifted beam emission, e.g., in the ITER core, to better filter out the recycling light and allow for spectral isolation of the desired by un-doppler shifted (but spread out spectrally via the motional stark effect sigma and pi components) and improved signal-to-noise compared with interference filters that have limits to the sharpness of spectral cutoff?

  A: The possibility of a fast spectrometer did not occur to me. The underlying assumption was a very low expected photon current in measurement window, thus the choice to spectrally integrate the emission in order to improve SNR. A follow-up paper is being drafted dedicated to the exploration of ITER fast BES measurements. This idea might be worthwhile exploring, though I fear the optical throughput of the entire ITER observation system is not ideal for fast spectral measurements.

- Q: Might fluctuations other than turbulence, e.g., from MHD, Alfven eigenmodes, still be usefully diagnosed in the ITER core with the poor (large) FSAs?

  A: Subsection 4.2.4 discusses the possibility of the ITER core BES system observing poloidal mode numbers. Assuming the SBR and SNR allow it, the large FSA should make it possible to observe mode number up to n = 35 or less around surface $\rho = 0.7$ and up to n = 16 or less around surface $\rho = 0.3$. Any mode number or density fluctuation beyond that might will most likely be averaged out due to the large FSA.

Questions:

1. This work comprehensively addresses fluctuation diagnostic design optimization. On the topic of detectors, however, little attention is paid to the noise contributions beyond photon noise, especially that of electronics, preamplifiers, etc. This is finally addressed in Chapter 5 on synthetic diagnostics; however, it doesn't appear to suffice for optimal detector choice, which is critical. Fully optimized, low noise, high gain (cooled) preamplifier electronics and noise therein, can change the decision of optimal detector choice, while subpar electronics may favor high-gain detectors (e.g., APDs), though these have other drawbacks.

The topic of excess noise factors in APDs isn't addressed. Can the best decisions on detector choice be made with these tools?

2. Consider the value of the thermal charge exchange emission for diagnosing fluctuations in plasma density. The edge recycling emission is non-local and a complicating background that needs to be spectrally removed, but does the charge exchange emission intensity from neutral beam on thermal hydrogenic ions enhance the overall useful signal and thereby enhance the ability to measure plasma fluctuations w/DBES? All filter designs appear to isolate and largely eliminate this emission.

3. The qualitative and quantitative comparisons of HESEL with synthetic and noisy synthetic signals is assessed as reasonably good, yet does not appear adequately address significant discrepancies between experimental and simulated quantities such as APSD, PDFs, etc. Can the author provide better justification for the positive assessment of the comparisons?

4. Can the author consider the potential value, strengths, and tradeoffs of a Lyman-alpha-based (n=2-1, lambda $\approx$ 121 nm) DBES system, in terms of signal strength, spatial resolution, diagnostic complexity, and feasibility?

Answers:

1. The noise modeling capabilities of RENATE-Open Diagnostics[1], which are featured in Chapter 5 of the PhD Thesis work, were developed based on the work of Dunai *et al.* [2] and feature the Gaussian approach to noise for the following detectors: APD (Avalanche Photodiode) [3], PMT (Photomultiplier Tube) [4], MPPC (Multipixel Photon Counter) [5] and PD (Photodiode), augmented by the Detailed noise model for PMT. The tool can provide hints and input information helpful for optimal detector selection.

   The aim and focus of Chapter 5 was to develop a BES synthetic diagnostic suitable for the processing of modeled, time-dependent, density and temperature fields into synthetic BES measurements. The initial stages of a validation exercise were featured using the HESEL [6] turbulence code on the AUG LiBES system [7], where parts of a study by G.Birkenmeier *et al.* [8] were reproduced on synthetic signals and compared to the experimental counterpart. Within this frame of reference, the Hamamatsu R928 PMT detector was modeled, because this one is operational on AUG, to demonstrate noise modeling effects and capabilities.

Other detector models are implemented and functional within RENATE-OD, such as APD detectors featuring low noise, high gain features as well as preamplifier noise, in order to accurately model the noise contribution to BES measurements on devices such as EAST, MASTU and others. The noise models of APD and PD detectors were not featured in current work, as it would have made the work very lengthy and missing the Detailed noise models for them.

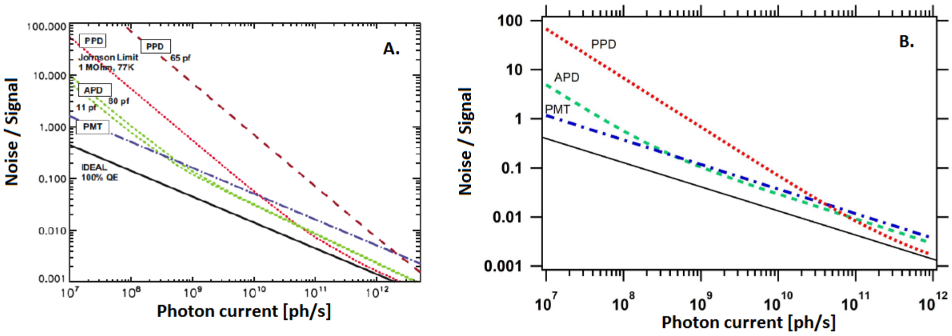

Figure 1: *Figure A shows the noise to signal ratio of various detector types based on the model of Dunai* et al. *[2]. Figure B shows the noise to signal ratio for the same detector types and input parameters by RENATE-OD.*

Figure 1 shows a benchmark of an established noise model for APD, PMT and PD detectors published by Dunai *et al.* [2] (Image A) and the noise model implemented in RENATE-OD for the same detector types and run with the same input parameters (Image B). Both images show the evolution of the noise to signal ratios for three detector types over a broad range of photon current values.

2. The work I performed on the feasibility of fast BES measurements observing the ITER diagnostic neutral beam solely focused on the detection of BES light, as pointed out by the reviewer as well. The filter optimization process was envisioned to allow as much of the BES light to pass and eliminate as much of the background, including charge exchange emission, as much as possible, due to the very unfavorable nature of the observation geometry.

   Allowing broader filters to include emission from either plasma edge CX or main ion CX along the beam path would inevitably have a deprecating effect on the BES SNR and SBR, leading to further difficulty in fluctuation BES signal processing.

That being said, recent work by M.R. Major *et al.* [9] explored the possibility of combining BES and charge exchange measurements. This aspect, the author hopes would be addressed by the dedicated CXRS diagnostic systems observing the ITER DNB in the same observation window, as seen in Figure 4.5B of the dissertation. The value of charge exchange fluctuations in the same frame of reference as the BES measurement I also considered as relevant, therefore the door was left open for an in depth further exploration of the issue, alluded to in the final paragraph of Subsection 4.2.2, on page 65 of the dissertation work. In this case, the leftover, unfiltered light of the BES observation could be collected separately and light fluctuations in different spectral ranges investigated on the same timescale as the BES measurement. An in depth study of such a method would be deserving of a dedicated study and a follow-up paper.

3. The reviewer is right in pointing out discrepancies in the comparison of the noisy and experimental signals, which cast doubt over the positive outlook of the comparison. The existing discrepancies were also pointed out at the end of Subsection 5.2.2 pointing out the need for a more extensive study of the validation exercise.

   The agreement between the experimental and synthetic signals is much better in the far SOL compared to that of the near SOL. This is especially true for the skewness (Fig.5.9) and the filament amplitude distribution (Fig.5.13). Other quantities such as filament frequency show a remarkably good agreement over the entirety of the SOL. It is clear from the APSD and the before mentioned quantities that a discrepancy exists and the combination of HESEL and the synthetic diagnostic does not fully reproduce experimentally measured features. This can be attributed to neither HESEL nor RENATE being fully correct or even both, leading to the observed discrepancy. I found the agreement in the far SOL filament frequency very encouraging, moreover the noisy synthetic signal further bridges the gap between experimental and synthetic measurements, which I considered a great result.

   Moreover, the synthetic diagnostic provides a unique insight into how the measurement artefacts impact and dampen the underlying features of turbulence.

   Furthermore, the author finds the expectation of a full agreement between a single measurement and its corresponding simulation as unlikely, precisely due to both HESEL and the synthetic diagnostic being an approximation of reality. To have a conclusive validation exercise multiple plasma discharges with various plasma parameters would be require. This issue was also addressed in the work at the beginning of Section 5.2, where criteria for validation are presented and the need for multiple plasma discharges and their simulation is required. This stage of the work was labeled as future effort.

I acknowledge, that a more cautious wording on the agreement and discrepancies might have been warranted.

4. Lyman alpha based beam emission spectroscopy diagnostic concepts were explored in a paper by G. McKee *et al.* [10] and further summarized by D.M. Thomas [11]. A more recent work done by Zhou *et al.* [12] provides an in depth exploration of possible L_α BES exploitation on the HL-2A tokamak.

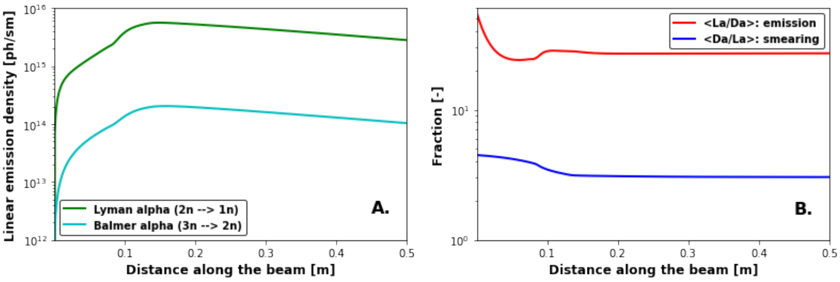

Figure 2: *Figure A shows the linear emission densities of the* L_α *(2n* → *1n) in green and the* D_α *(3n* → *2n) in cyan. Figure B shows the linear emission density fraction of the* L_α *over* D_α *along the beam path (red) and the emission smearing fraction of the* D_α *over* L_α *in blue.*

A common feature in these works is the much higher expected photon current of the Lyman α (L_α) emission compared to the Balmer α (D_α) emission. This is mainly due to a much higher electron population on the n=2 atomic level compared to the n=3. More intense emission from the L_α transition indicate better SNR and greater sensitivity to the detection of density fluctuations, compared to the performance of the D_α emission. Furthermore, an improvement in spatial resolution is projected for L_α observations, as the expected depopulation time of n=2 is less then that of n=3 resulting in less emission smearing aliong the beam. These features were also observed with Renate-OD [1].

To showcase the potential for Lyman α observation, consider the ITER DNB diagnostic system. Figure 2A shows the linear emission density for the ITER DNB in a fully inductive plasma for the Balmer α transition in cyan and the Lyman α transition in green. The simulations indicate more intense emission from the L_α transition in case of a 100 keV hydrogen beam. Image B in Figure 2 show the emission fraction of the $\frac{L_\alpha}{D_\alpha}$ intensities with red and the spatial smearing fraction of $\frac{D_\alpha}{L_\alpha}$ with blue. In case of the ITER DNB a switch to L_α observations would lead to an increase BES intensity of a factor of roughly 30 and an improvement in emission smearing contribution to the spatial localization of a factor of 3, which can be significant, depending on beam energy.

Another common feature discussed in the before mentioned papers, is the difficulty of realizing such a measurement, the main reason for which lies in the lower optical throughput for VUV (Vacuum Ultra Violet) spectra, compared to that of the D_α emission. This manifests in a clear trade-off between signal strength and optical throughput. A reasonable compromise for L_α centered observations might be a system with as few as possible optical elements to lessen the effect of lower optical throughput. For a device such as ITER, with metal first mirrors and multiple optical elements ensuring the beam emission being carried outside of the bio-shield, an increase of a factor of 30 in signal strength might not overcome the additional losses in signal throughput. This question further merits its own in depth exploration. For a much smaller machine, with higher optical throughput, this might a feasible diagnostic system.

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