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A Study of the Required Balmer-Lines for Integrated Data Analysis Systems in Tokamak Divertors

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Integrated data analysis (IDA) systems, based on Bayesian inference, offer the potential to describe entire divertor poloidal cross sections in terms of electron temperature, T_e, electron density, n_e, and neutral density, n_0 [1]. Such IDA systems rely heavily on heavily on multiple, wavelength-filtered, camera diagnostics owing to these diagnostics having a wide spatial coverage over the divertor. How accurately T_e, n_e and n_0 can be inferred depends on the combination of diagnostics included in the IDA. The complicated emission models of spectral lines, comprised of excitation and recombination emission (already simplified by provisionally ignoring plasma-molecule interactions), makes it challenging to decipher what information is held by different spectral line combinations in the IDA. To address that question, research has been performed to interrogate the information held by different Balmer-lines ($n \rightarrow 2$ Deuterium transitions) and so inform the lines required to be used in the IDA going forward.

Using SOLPS as a guide, different 'true' plasma conditions (that can be plausibly found in the MAST-U divertor: $(0.5 < T_e < 45)eV$; $(10^{18} < n_e < 3 \times 10^{21})m^{-3}$; $(10^{16} < n_0 < 10^{20})m^{-3}$) were used to simulate different data sets for Balmer line emissivities. The IDA, with different line combinations, was used to infer the maximum a posteriori (MAP) estimation of T_e, n_e and n_0 for each data set and these MAP estimations were compared to the 'true' plasma conditions that were used to make that data set. To quantify how much information is held by a combination of lines, an inference metric, ϵ^P_D, has been defined to be the percentage of, plausible, plasma conditions for which a MAP estimate of within 30% of the 'true' plasma value was achieved. Here, P is the inferred parameter and D is the diagnostics used.

It has been found that Balmer lines held more information on T_e ($\epsilon^{T_e}_{D_\alpha,D_\beta,D_\gamma,D_\delta,D_\varepsilon} \sim 92\%$) and n_e ($\epsilon^{n_e}_{D_\alpha,D_\beta,D_\gamma,D_\delta,D_\varepsilon} \sim 100\%$) than for n_0 ($\epsilon^{n_0}_{D_\alpha,D_\beta,D_\gamma,D_\delta,D_\varepsilon} \sim 27\%$). It was also found that the Balmer lines held more information for T_e in plasma existing in recombination-majority regions ($\epsilon^{T_e}_{D_\alpha,D_\beta,D_\gamma,D_\delta,D_\varepsilon} \sim 100\%$) than plasma existing in excitation-majority regions ($\epsilon^{T_e}_{D_\alpha,D_\beta,D_\gamma,D_\delta,D_\varepsilon} \sim 89\%$). This is deemed due to the excitation emission depending on n_0 and so n_0's inaccurate inference permits a range of possible excitation emissions and so reduces the information held on T_e in excitation-majority regions. With just two lines used in the IDA, it was found that in recombination-majority regions an $n < 5$ Balmer line is required to be used with an $n > 5$ Balmer line to provide the most information for all inferred parameters ($\epsilon^{T_e}_{D_\alpha,D_\varepsilon} \sim 80\% > \epsilon^{T_e}_{D_\delta,D_\varepsilon} \sim 40\%$). This is likely due to the IDA's tendency to assume all emission in a recombination majority region is from recombination alone (vice versa for excitation). $n < 5$ Balmer lines have a greater relative excitation contribution to their emission than for $n > 5$ Balmer lines [2] and so the provision of a line that has more excitation emission in a recombination-majority environment prevents the assumption of all emission being from recombination and so increases the information held on T_e and n_e (and vice-versa for the excitation-majority region).

Consequently, for adequate inference of T_e and n_e across the entire divertor region, minimally the D_α line and an $n > 5$ Balmer line is required. Further, additional information is required to accurately infer n_0. This is likely to become increasingly important when plasma-molecule effects are added to the emission models.

[1] C. Bowman et al., Plasma Phys. Control. Fusion **62**, 045014 (2020).
[2] K. Verhaegh et al., Plasma Phys. Control. Fusion **61**, 125018 (2019).