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

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Introduction

An integrated data analysis (**IDA**) system, developed to study the divertor region of **Nuclear Fusion tokamaks** [1], has been used to investigate the information carried by different combinations of Balmer lines.

- Spectral lines have complicated emission models, comprised of excitation and recombination emission (already simplified by provisionally ignoring plasma-molecule interactions)
  - Challenging to decipher what information is held by different spectral line combinations in the IDA
- Research 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

Motivation

IDA is desired to describe the **full 2D poloidal cross section** of the **divertor**.

- Described in terms of:
  - Electron temperature, T_e
  - Electron density, n_e
  - Neutral density, n_0
- Used to study the onset of detachment (which can drastically reduce the heat flux onto the tokamak's plasma-facing wall)
- The MAST-U tokamak is the focus of this research (due to it's focus on divertor physics via multiple possible divertor configurations)
- IDA incorporates:
  - Langmuir probe (many)
  - Thomson Scattering
  - Multiple, wavelength-filtered, camera diagnostic (MWI)
- Only the MWI offers a view of the entire divertor region
- Balmer-line ($n \rightarrow 2$ transitions) emission from excited hydrogenic species is available to the MWI and these are known to provide information on the deuterium-dominated divertor plasma conditions
- Maximising the information provided by these lines is crucial to the success of the IDA
- **What information is available to the IDA from a certain combination of Balmer-lines?**

IDA Structure

IDA utilises Bayesian inference to combine the available diagnostics.

- Solutions to the underlying plasma parameters may be found by **maximising the posterior distribution**
  - Posterior distribution asks: *what is the probability of the plasma having a certain combination of parameters given that a certain data set has been measured?*
- Posterior probability for one combination of plasma parameters $\underline{\theta} = \{T_e, n_e, n_0\}$ is given by,

$$P(\underline{\theta}|\underline{\mathcal{D}}) \propto P(\underline{\mathcal{D}}|\underline{\theta})P(\underline{\theta}), \quad (1)$$

  - $\underline{\mathcal{D}}$ is the vector of data measurements $\rightarrow$ for the MWI diagnostic corresponds to the different Balmer-line emissivities
  - $P(\underline{\theta})$ represents our prior belief in the plasma parameters: *Would this combination of parameters be expected to be found in the divertor?*
  - Likelihood probability, $P(\underline{\mathcal{D}}|\underline{\theta})$, found by forward modelling of the expected Balmer-line emissivities for the certain combination of parameters and comparing them to the measured data
- Emissivity for the transition $n \rightarrow 2$ can be modelled by,

$$\varepsilon_{n\rightarrow 2} = n_e^2 PEC^{rec.}_{n\rightarrow 2}(T_e, n_e) + n_e n_0 PEC^{exc.}_{n\rightarrow 2}(T_e, n_e), \quad (2)$$

  - $PEC^{rec.}$ and $PEC^{exc.}$ are the photoemissivity coefficients for recombination and excitation respectively
  - Coefficients, provided by ADAS [2], have complex dependence on T_e and n_e
- Hydrogenic plasma states (that leads to Balmer-line emission) occurs from either excitation or recombination processes, however, only total emission is detected by the MWI
- MWI diagnostic represents an ill-posed problem:
  - Many different plasma parameter combinations (representing a large region of plasma conditions) can give the same total emission and so the probability of which were the *true* plasma parameters is difficult to fix
- **Line combinations where the measured emission can be explained by a limited region of different plasma conditions corresponds to a lot of information in that region.**

References

[1] C Bowman et al., Development and simulation of multi-diagnostic Bayesian analysis for 2D inference of divertor plasma characteristics. *Plasma Physics and Controlled Fusion*, 62(4):045014, Feb. 2020.

[2] University of Strathclyde ADAS project, Open-ADAS. Website, 2018, url: http://open.adas.ac.uk; Last Accessed: 14.12.2021.

[3] S. Wiesen et al., The new SOLPS-ITER code package. *Journal of Nuclear Materials*, 463:480–484, 2015.

[4] K Verhaegh et al., Novel inferences of ionisation and recombination for particle/power balance during detached discharges using deuterium Balmer line spectroscopy. *Plasma Physics and Controlled Fusion*, 61(12):125018, Nov. 2019.

[5] K. Verhaegh et al., The role of plasma-molecule interactions on power and particle balance during detachment on the TCV tokamak. *Nuclear Fusion*, 61(10):106014, Sep. 2021.

Methods

The method for accessing the information provided by a certain combination of Balmer-lines is outlined in figure 1.

- SOLPS [3] used to predict many possible plasma conditions found in the MAST-U divertor
- Each combination of *true* plasma conditions used to simulate a data set of expected emissivities for various Balmer-lines ($3 < n < 7$)
- IDA permitted to use only a certain combination of Balmer-lines for it's inference
- IDA resultant probability distribution for the underlying plasma conditions compared to the *true* plasma conditions used to simulate the data set
- Percentage difference between the two used to classify how much information that combination of lines contained for this region of plasma conditions

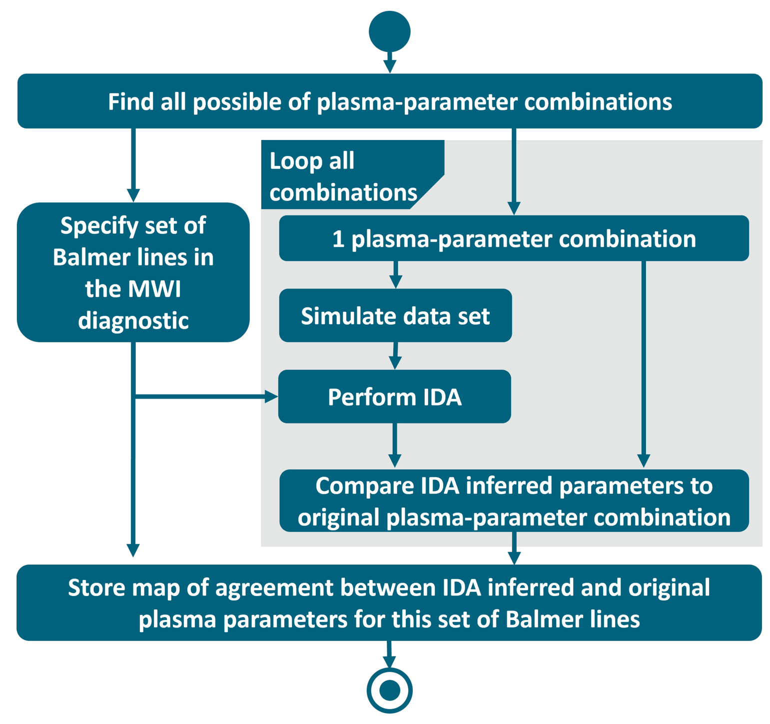

Figure 1: Flowchart of general method for accessing information available to the IDA from Balmer-lines.

- Map, over parameter space, of percentage difference (between IDA and *true* plasma parameters) created for each line combination
- Map split into recombination and excitation majority plasma conditions and investigated for different line combinations
- **Amount of information, for a certain plasma condition, provided by a line combination is found by comparison between IDA inferred parameters and true parameters.**

Results

- Above method was applied for various plasma conditions
- Plotted in terms of their *true* electron temperature and total hydrogen density
  - (linked to n_e and n_0 via a neutral fraction to temperature relation)
- IDA inferred maximum a posteriori (MAP) estimated value for each parameter compared to the *true* parameter value and percentage difference found
- Result for the T_e parameter, with Balmer-lines $n = \{3..7\}$ used by the IDA, is shown in figure 2
- Coloured regions have a percentage difference of $< 30\%$
- Certain parameter combinations excluded by prior (these conditions would not be expected in the divertor plasma)
- Repeated for multiple two Balmer-line combinations and shown in figure 3
- Percentage of plasma conditions that provide an inferred MAP value within 30% of *true* plasma parameter value (non-white regions in figure 2) calculated
- Performed separately for the recombination-majority and excitation-majority regions

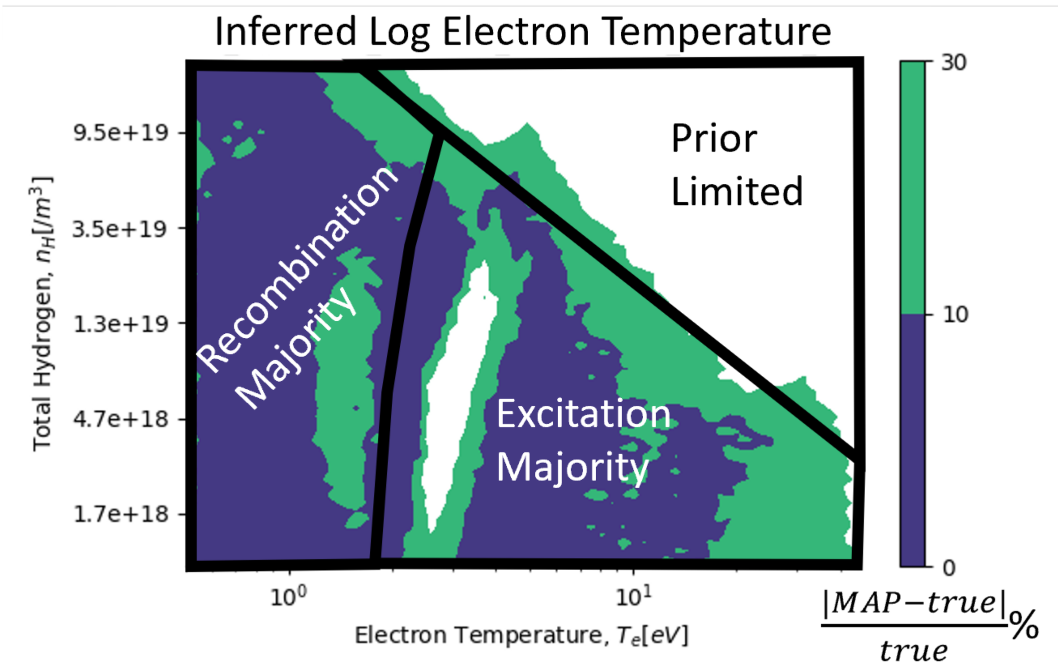

Figure 2: IDA inferred MAP estimate percentage difference to the *true* parameter value for the $\ln(T_e)$ parameter. X-Y axis are the *true* plasma conditions from which the data was simulated and the inference performed for subsequent comparison. Balmer-line combination D_α, D_β, D_γ, D_δ and D_ε used by the IDA.

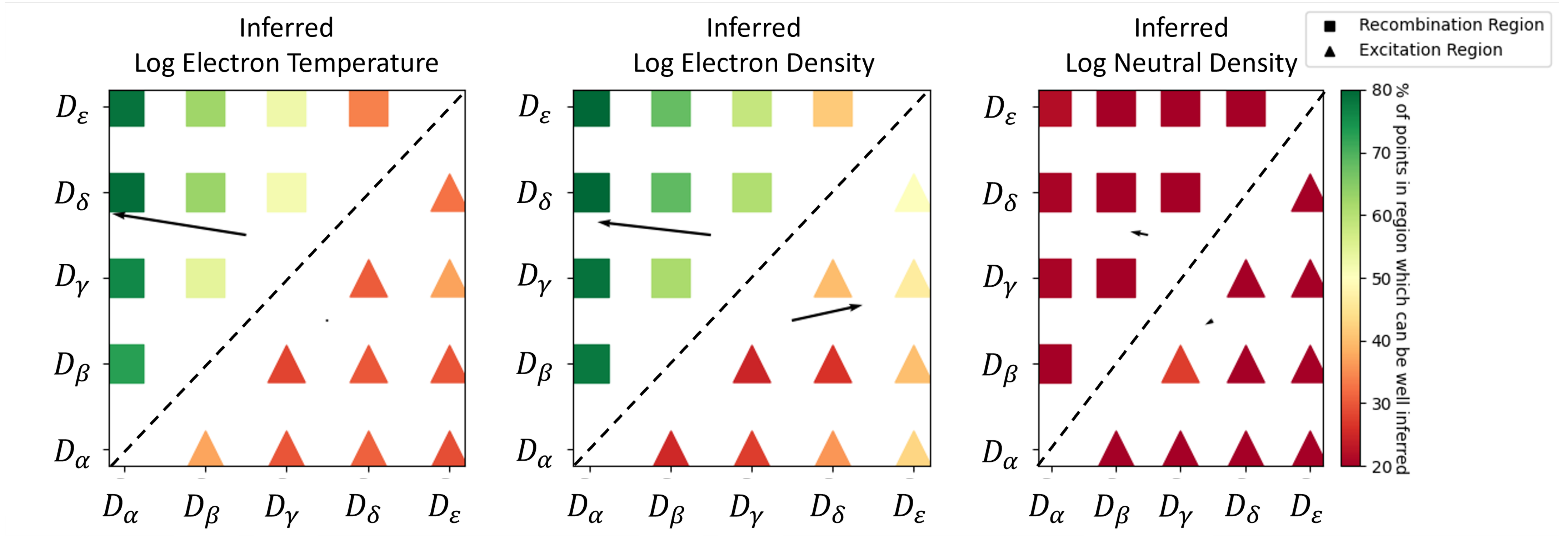

Figure 3: Effect of two different Balmer-lines on the IDA inferred parameter performance - as percentage of plasma combinations that could have MAP values inferred to within 30% of *true* parameter value for each parameter - across different plasma regions. X-Y axis represent the two Balmer-lines used by the IDA in the inferrence. Squares and triangles show results separately for the recombination-majority and excitation-majority regions respectively. Arrows represent general trend.

- **Information available in inferred regions separately considered for different line combinations.**

Discussion

- Figure 2 shows that a combination of all lines $D_\alpha..D_\varepsilon$ contains a lot of information in the recombination-majority region and a good amount of information for T_e in the excitation-majority region.
- Figure 3 shows that no two line combination contains significant information for n_0. In the excitation dominated region, D_α is minimally required to provide good information for T_e and n_e and it is best paired with a higher-n Balmer-line. The higher-n Balmer-line will also aid information for the electron density in the excitation-majority region.
- This result is likely due to the fact the emission, shown in equation 2, is frequently assumed by the IDA to arise from all recombination emission in a recombination majority region (vice versa for excitation) rather than from a balance of the two. $n < 5$ Balmer-lines have a greater relative excitation contribution to their emission than for $n > 5$ Balmer-lines [4] 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).
- This reliance on the D_α line is potentially problematic since it is known that molecular effects can impact the low-n Balmer-line emission in these plasma conditions [5]. Consequently, the emission model used in equation 2 must be adapted to include this affect.
- **The D_α line is required for good inference within the IDA and so molecular contributions will have to be considered in the IDA's MWI emissivity model going forward.**

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