Correlation of Hydrogen Emission and Electron Properties in Low Temperature Plasma Conditions Close to Divertor-like Materials

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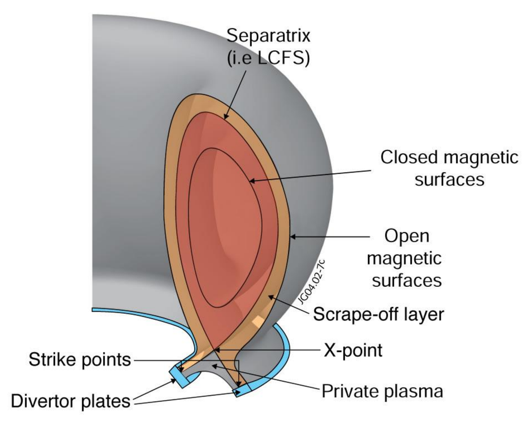
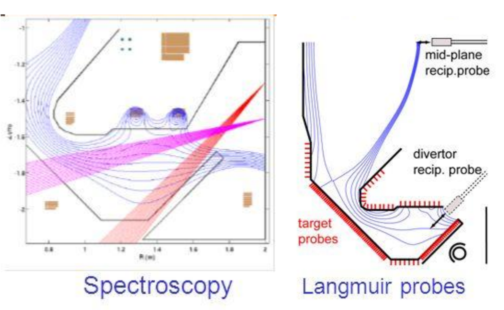
Motivation

- Studying the flow of energy and particles that come from the core plasma to the vessel walls is one of the key challenges for future fusion machines. [1]
- Detached regimes provide a solution to divertor material limitations, due to the reduction in temperature and density of tokamak divertor plasmas close to the divertor tiles. [2]
- In order to achieve divertor detachment, whilst maintaining the high-temperature high-density fusion conditions required in the core plasma, it is vital to understand the edge plasmas close to the vessel walls.



- The motivation of this work is to further understand the key atomic and molecular processes in partially ionised plasmas near divertor surfaces that influence detachment - a process vital for the successful operation of future fusion devices - and to inform predictive modelling codes on the key processes in edge plasma for improved exhaust control.
- The main objectives of this research centre on **improving the understanding of partially ionised plasmas close to divertor surfaces in tokamaks** by **investigating plasma-surface interactions of low-temperature plasmas with divertor-like surfaces,** including carbon, tungsten and nano-structured tungsten.
- Optical emission spectroscopy is utilised to study atomic and molecular emission in Hydrogen plasmas close to divertor materials using a heated sample mount. Emission trends are compared to plasma parameter data from Langmuir probes for a range of discharge and material conditions.



Experimental Setup

- Emission and plasma parameter data collected in the University of Liverpool Inductively Coupled Plasma (ICP) Discharge rig.
- 13.56MHz RF power matched via an impedance matching unit to a two-turn planar ICP coil.
- Hydrogen discharge gas produced using electrolysis of deionised water via a Hydrogen Trace machine and fed to the chamber through a MKS mass flow controller.
- Carbon, Tungsten and Nano-structured Tungsten 1" diameter samples mounted to sample heater via 3 tungsten clips and inserted into the vacuum chamber.
- Power and pressure varied to achieve a range of plasma parameters, 10-300W and 1-10Pa respectively, to give $T_e \sim$ 1-10eV & $n_e \sim 10^{13}$ - 10^{15}m^{-3}. Sample heater temperature varied from 100-1200C.

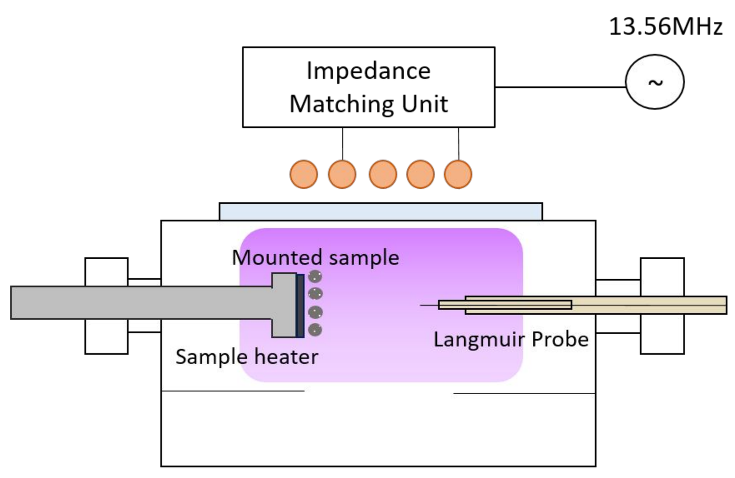


Figure 1: Diagram of UoL ICP discharge chamber.

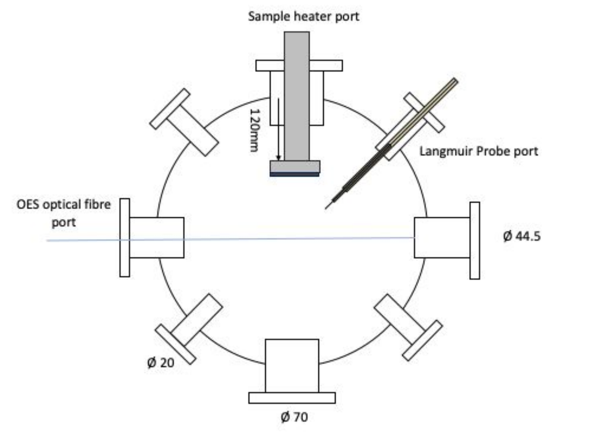


Figure 2: Cross section of ICP rig upper chamber, showing optical fibre and probe ports in relation to the sample heater.

Experimental results - OES

- Hydrogen plasma emission data has been collected in front of a heated sample mount.
- Carbon and nanostructured Tungsten samples were mounted to the sample heater and inserted into the plasma to study the effects on the atomic and molecular emission.
- **Atomic emission measurements -**
  - Data collected for the Hydrogen Balmer line series, H-α (656.27nm), H-β (486.13 nm) and H-γ (434.04 nm).
  - Balmer line intensities increase with RF power and electron density. Intensities measured with the Fuzzy W sample are higher than with the Carbon sample, and this increase is larger with increasing power above 100W as shown in Figures 6 & 7.
- **Molecular emission measurements -**
  - Hydrogen molecular data collected for H Fulcher band (580-650 nm). Figures 3 & 4 show molecular emission intensity peaks at 602 nm, 612 nm, 622 nm and 632 nm.
  - Fulcher band plots show molecular emission is dependant on sample temperature, with the emission intensity in the Fuzzy W sample case generally higher than when the C sample is inserted. As the sample temperature increases, the molecular emission increases gradually, and the ratio of the molecular lines varies with sample material and temperature. *These ratios will be further investigated for varying sample material.*

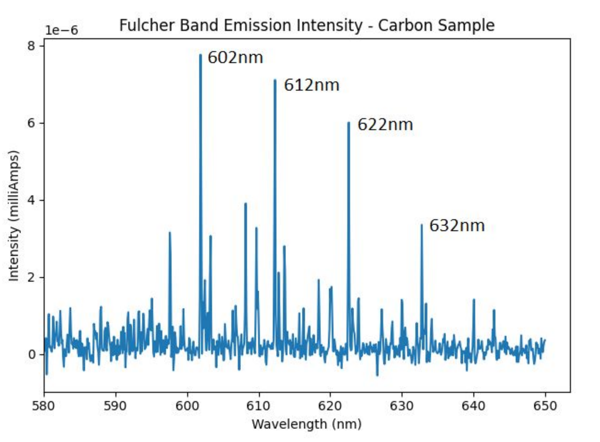


Figure 3: Annotated molecular Fulcher band emission intensity plotted against wavelength with a 1 inch Carbon sample inserted in the chamber. (Pressure = 10Pa, sample temperature = 100C, power = 300W).

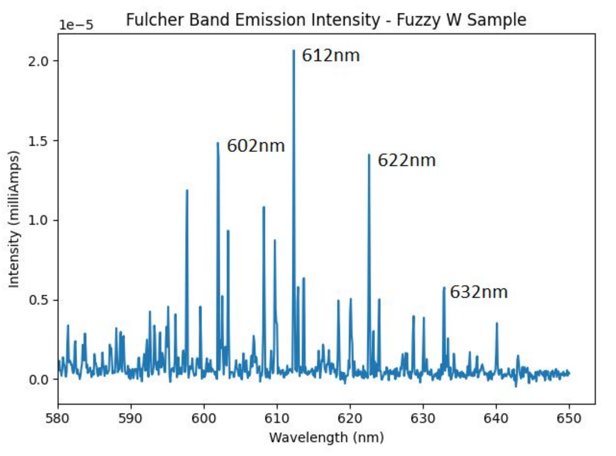


Figure 4: Annotated molecular Fulcher band emission intensity plotted against wavelength with a 1 inch nanostructured Tungsten sample inserted in the chamber. (Pressure = 10Pa, sample temperature = 100C, power = 300W).

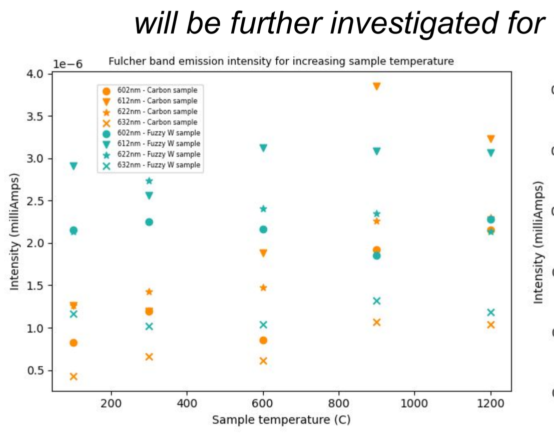


Figure 5: Fulcher band key line intensities for increasing sample temperature for Carbon and nanostructured W samples. Wavelengths shown - 602, 612, 622, 632nm. (Power = 100W, pressure = 10Pa).

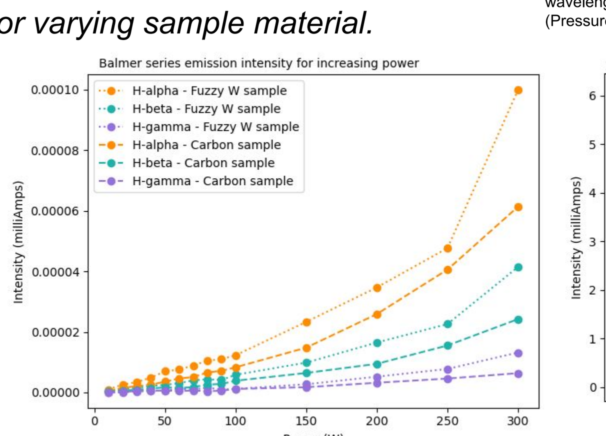


Figure 6: Balmer line intensities for varying RF power with Carbon and Fuzzy W samples inserted into the plasma. (Pressure = 10Pa, sample temperature = 100C).

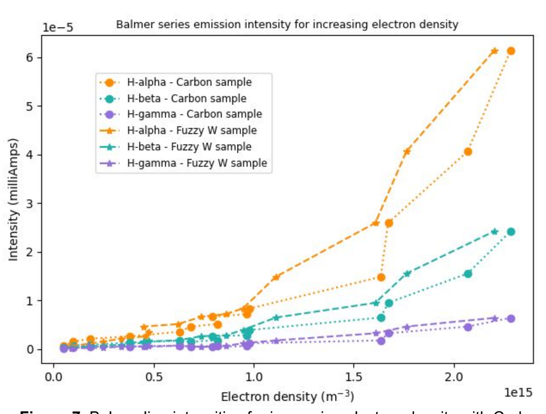


Figure 7: Balmer line intensities for increasing electron density with Carbon and Fuzzy W samples inserted into the plasma. (Pressure = 10Pa, sample temperature = 100C).

Experimental results - Langmuir Probes

- Plasma parameter data has been collected using a Langmuir probe close to the centre of the ICP discharge chamber, as seen in Figure 2.
- Current-voltage data is collected using a Langmuir probe ramp system and analysed using a Python LaFramboise theory analysis code.
- **Electron parameter measurements -**
  - Electron density increases with discharge pressure and RF power, for all three samples inserted in the plasma. These trends show the discharge transitioning from being capacitively coupled to inductively coupled.
  - Varying the sample inserted in the plasma doesn't change this general trend, but does influence the nature of the transition and where the sharp decrease in electron temperature occurs.
  - These measurements show generally higher electron densities and lower electron temperatures for the Carbon sample compared with the Clean & Fuzzy W samples for increasing RF power, as seen in Figure 8.
  - For increasing discharge pressure, the Carbon sample shows a higher electron temperature and lower electron density than both of the Tungsten samples up to 5Pa, at which point the nanostructured Tungsten sample data has higher electron temperature and lower electron density than for the same conditions with the Carbon sample, as can be seen in Figure 9.
  - Figure 10 shows a weak correlation between electron temperature and density with sample heater temperature for both samples.
    - The electron density trend in Figure 10 may be consistent with the sample heater heating the discharge gas, therefore causing a decrease of gas density in the central region of the discharge. The electron temperature dependence might be interpreted as showing that the sample heater helps the plasma change to inductively coupled - as low temperature is a characteristic of the inductive mode. These trends will be studied in further detail.
    - **These measurements will be repeated and studied in more detail with the probe closer to the sample surfaces to study the trends for increasing sample temperature.**

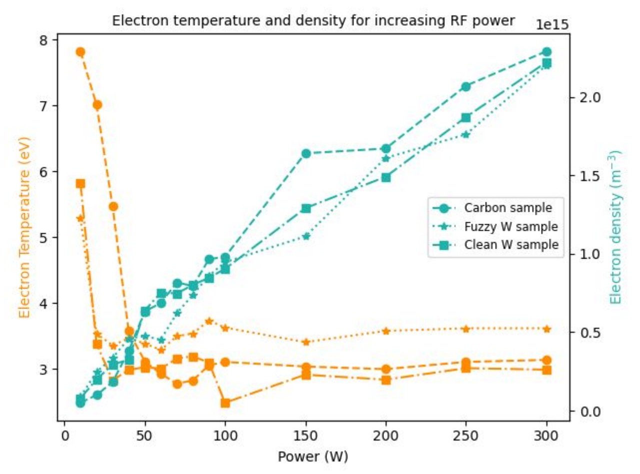


Figure 8: Electron temperature and electron density values for varying RF power with Carbon and Fuzzy W samples inserted into the plasma. (Pressure = 10Pa, sample temperature = 100C).

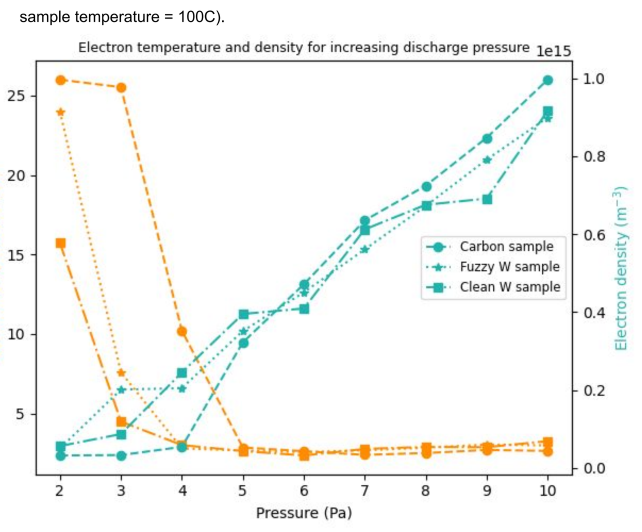


Figure 9: Electron temperature and electron density values for varying discharge pressure with Carbon and Fuzzy W samples inserted into the plasma. (RF power = 100W, sample temperature = 100C).

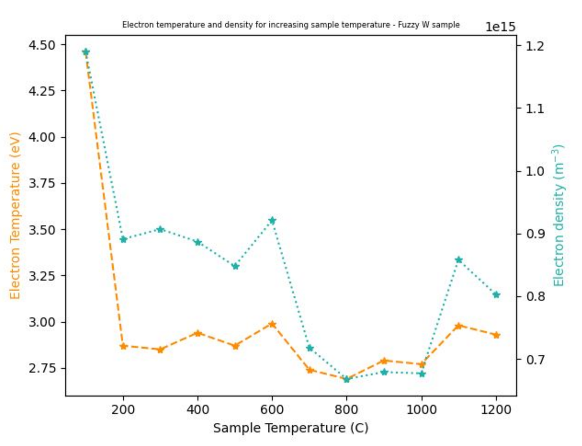


Figure 10: Electron temperature and electron density values for varying sample temperature with a 1 inch Fuzzy W samples inserted into the plasma. (Pressure = 10Pa, power = 100W).

Next Steps

Future work to extend this research will focus on:

1. Comparing emission and plasma parameter data for data taken with a clean Tungsten sample inserted into the ICP chamber.
2. Increasing the RF power to study the trends in emission and plasma parameters in both the ICP E mode and H mode, for powers > 300W.
3. Comparing Balmer line ratios with the electron energy distribution functions for varying plasma discharge conditions and material conditions.
4. Studying emission from MAST-U divertor experiments and comparing trends in emission with UoL discharge plasma data.
5. Extracting information about key processes in the low-temperature plasmas by comparing emission and plasma parameter data with 0D collisional-radiative model to understand the key processes behind trends in the data.

Summary

- A wide range of optical emission and plasma parameter data has been collected in the University of Liverpool Inductively Coupled Plasma discharge source for varying RF power, sample temperature and discharge pressure with Carbon, Tungsten and nanostructured Tungsten samples inserted into the chamber via a heated sample mount.
- Atomic Balmer line emission and molecular Fulcher band H emission has been studied and compared with plasma parameter data collected using Langmuir probes.
- For both Carbon and Tungsten samples, electron density increases with both RF power and discharge pressure, while the nanostructured W sample data showed generally higher densities and lower temperatures than with the Carbon sample.
- *Future work aims to analyse data further with clean W sample to study trends in detail. UoL data will also be compared with 0D collisional-radiative model to extract further information about atomic and molecular processes.*

References & Ackowledgements

[1] Asakura N, Shimizu K, Hoshino K, Tobita K, Tokunaga S & Takizuka T, 2013, "A simulation study of large power handling in the divertor for a DEMO reactor", Nuclear Fusion, Vol 53, no.12, pp. 123013

[2] Krasheninnikov S I, Kukushkin A S & Pshenov A A, 2016, "Divertor plasma detachment", Physics of Plasmas, **23**, 5

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