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CHARACTERIZATION OF THE 2.45 GHz DREEBIT ECRIS VIA OPTICAL SPECTROSCOPY

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Abstract

ECR ion sources are widely used at many research institutions to provide ions for various experimental setups. DREEBIT GmbH aims to industrialize this type of ion source technology. Our goal is to build table-top sized ion sources which can easily be handled and integrated into larger machine setups, thereby fulfilling high requirements on beam current, quality, stability and reproducibility in serial production. To achieve this, we had already optimized the microwave injection system and magnetic plasma confinement by introducing a simple method to allow for injection of circularly polarized microwaves and adjusted the magnetic field distribution which led to an 80 GHz increase of proton beam current [1]. In the present work, we show how optical emission spectroscopy was used to gain deeper information about the plasma of this specific type of ion source, independently from its ion extraction system. The plasma characterization includes studies of the electron density and temperature (n_e, T_e) and the density of atomic and molecular hydrogen (n_H, n_{H_2}) showing the performance of the 2.45 GHz DREEBIT ECRIS concerning plasma heating and proton production and indicating how the source performance can be enhanced in further steps.

INTRODUCTION

Electron Cyclotron Resonance Ion Sources (ECRIS) provide low, intermediate and highly charged ions for a broad range of applications, reaching from nuclear [2, 3] over materials [4] to medical physics research. In the future, they can be used in combination with particle accelerators or as part of irradiation facilities, e.g., for industrial semiconductor manufacturing or cancer therapy [5]. The goal of the present work is to characterize the plasma of the table-top sized 2.45 GHz DREEBIT ECRIS run with hydrogen in order to gain better understanding of the possibilities for source improvement. Using optical emission spectroscopy (OES) the intensities of the hydrogen Balmer and Fulcher lines depending on the power of the injected microwave and the phase shift of the two injected microwaves were studied. The electron density n_e, temperature T_e and ratio of atomic to molecular hydrogen n_H/n_{H_2} were deduced from the optical spectra using the Yacora solver [6].

EXPERIMENTAL METHOD

An Ocean Insight Flame UV-VIS Spectrometer was used for the optical spectroscopy setup. The spectrometer is sensitive in the wavelength range from 200 to 850 nm with a resolution of 1.37 nm. To couple the light into the spectrometer a reflective collimator with UV-enhanced aluminum coating with a diameter of $d = 8.5$ mm was employed. An optical cable with a fiber diameter of 200 µm couples the collimator to the spectrometer device. Intensity calibration was conducted on-site by using an Ulbricht sphere. The line of sight where the plasma was characterized is shown in Fig. 1.

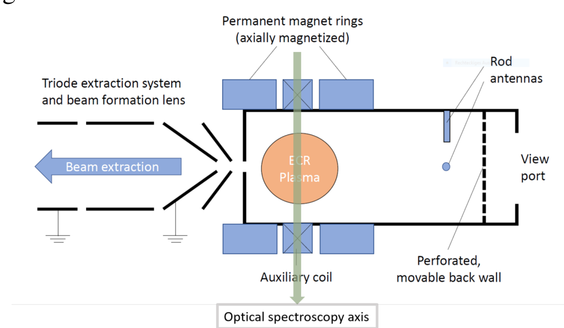

Figure 1: Experimental setup with optical spectroscopy axis marked in green.

The optical light emitted by the atomic and molecular hydrogen ions reveals information about the plasma. The Balmer line ratio H_β/H_γ relates to the electron density, the ratio between the Balmer line H_γ and the integrated Fulcher lines is a measure for the dissociation ratio, as the Fulcher lines are emitted during relaxation of excited vibrational and rotational states of the H_2 molecule [7]. While individual line ratios had been used to identify plasma parameters like the electron density directly in the past, this method was replaced by the Yacora solver, employing a collisional radiative model and identifying the best agreement between simulated and actual line ratios under variation of the desired plasma parameters.

RESULTS

In two separated measurement campaigns a scan of the microwave power and the phase shift of the two injected microwaves were performed. From this data set a range of the plasma parameters electron density n_e, electron temperature T_e and the neutral density ratio n_H/n_{H_2} were determined to characterize the plasma. The findings from the OES measurements are compared to measured spectra of extracted ions.

OES Measurements

Microwave Power Scan at 100° Phase Shift Figure 2 shows the results of the microwave power scan. Here, the intensity ratios of subsequent Balmer lines are shown as black (H_α/H_β), red (H_β/H_γ) and green (H_γ/H_δ) data points. Moreover, the previously discussed ratio of H_γ/H_{Ful}

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is shown in blue. It is visible that all line ratios increase with the microwave power. However, the red data points, which are a measure for the electron density, do not exhibit such a clear trend and the data is difficult to interpret. For this reason, the Yacora results are discussed in the next step.

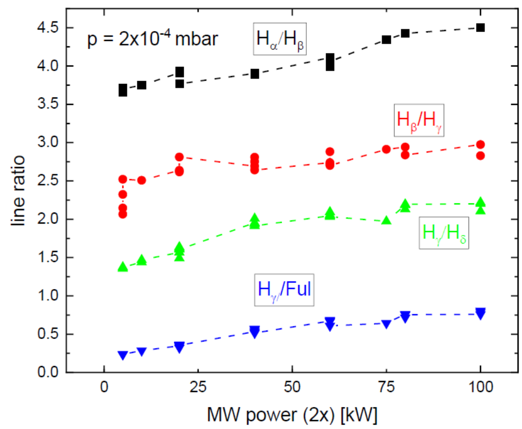

Figure 2: Microwave power scan at 100° phase shift.

Phase Shift Scan at (2x) 75 W Microwave Power Furthermore, the phase shift between the two injected microwaves was investigated by scanning the whole range of phase shifts, while maintaining the microwave power at (2x) 75 W and the pressure at $2 \cdot 10^{-4}$ mbar. Figure 3 shows the results of the phase scan. It is noticeable that there is almost no visible dependence of the line intensity ratios with the phase shift, which indicates that the plasma parameters are constant at the location of the optical spectroscopy axis.

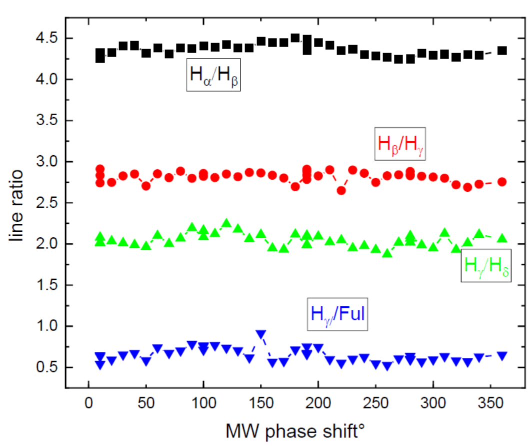

Figure 3: Microwave phase shift scan at (2x) 75 W microwave power and p = $2 \cdot 10^{-4}$ mbar.

Yacora Results

The electron density n_e, temperature T_e and the ratio of n_H/n_{H_2} can be reconstructed using the Yacora solver, which provides a collisional radiative analysis model for OES on hydrogen and helium plasmas. Yacora simulates the hydrogen line ratios under variation of the plasma parameters. By comparing the calculated results to the measured spectra the best match can be identified revealing the actual plasma parameters of interest. Among these parameters, the temperature T_e and the ratio n_H/n_{H_2} can not be reconstructed independently because they are strongly correlated due to their impact on line emission in the present parameter phase space. As a result only ranges of possible solutions can be determined, allowing for a coarse analysis of these parameters.

Figure 4 shows the electron density in dependence on the microwave power for a plasma length of $l_{plasma} = 5$ cm and $l_{plasma} = 10$ cm. The diameter of the plasma chamber is 10 cm, but the magnetic confinement compresses the plasma to a smaller volume, which is not exactly known. Therefore the electron density is specified for an educated guess of both limits of the possible plasma length as the precise length has not yet been determined. The electron density scales linearly with the plasma length and increases with rising microwave power until it reaches a plateau for values which are higher than 40 W. If assuming that the plasma is confined within a region which has half length of the plasma chamber (5 cm), the electron density is $n_e = 7 \cdot 10^{16}\,\mathrm{m^{-3}}$ at the plateau, a value which is close to the calculated critical density of a 2.45 GHz ECR source, resulting in $n_c = 7.45 \cdot 10^{16}\,\mathrm{m^{-3}}$.

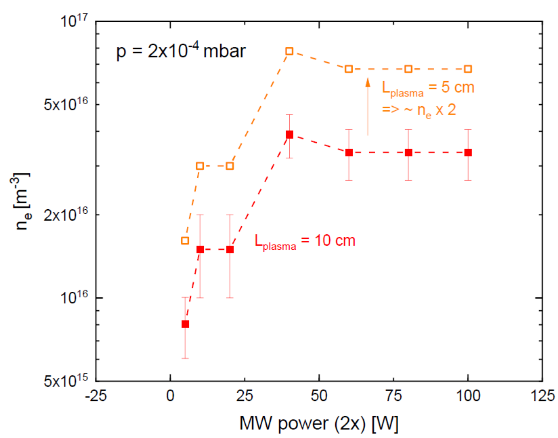

Figure 4: Yacora results for electron density n_e depending on the microwave power, considering 2 different plasma lengths of 5 cm and 10 cm.

Electron densities in other ECR ion sources around the world were found in the same order of magnitude around $10^{17}\,\mathrm{m^{-3}}$ [8–10].

Figures 5 and 6 show the dependence of the electron temperature T_e and the ratio of the atomic and molecular hydrogen density n_H/n_{H_2} on the microwave power. Since both parameters can only be reconstructed in combination, a wide range parameter variation was performed identifying the limits of the parameter space with values for the minima and maxima for T_e as well as n_H/n_{H_2}. Assuming individual values outside of these extrema, Yacora could not find any matching solution for the measured spectra at all, indicating that the actual values for T_e and n_H/n_{H_2} lie within the presented range. It is visible that the region for the electron temperature is quite large for microwave powers above (2x) 40 W. The upper limit is at the maximum of the phase space for the Yacora solver, indicating that an electron ensemble

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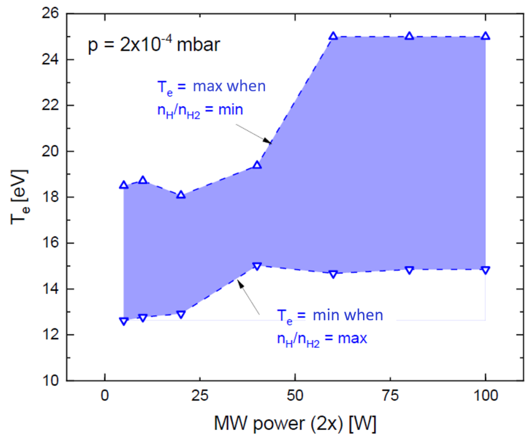

Figure 5: Yacora results for electron temperature T_e in dependence of microwave power.

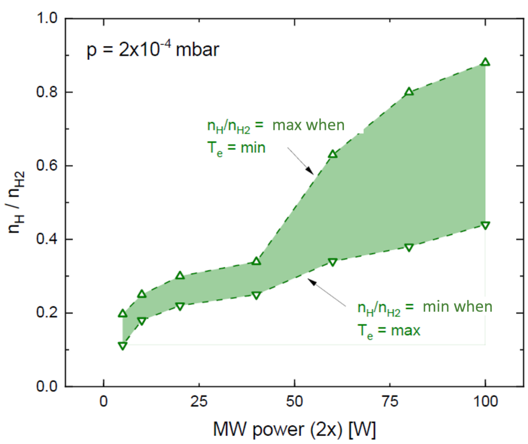

Figure 6: Yacora results for the ratio n_H/n_{H_2} in dependence of microwave power.

with an even higher temperature could lead to the observed line intensities. However, for temperatures higher than 25 eV the Yacora model is no longer accurate enough. The minimum of the temperatures is at 15 eV for a microwave power higher than (2x) 40 W. This lower limit of T_e is comparable with electron temperatures found by other research groups for a 2.45 GHz ECRIS [8, 10].

Extracted Ions

In addition to the analysis of the plasma emission via optical spectroscopy, it is also possible to extract ions from the plasma chamber and evaluate them using a dipole magnet, which separates the ions according to their mass to charge ratio. Extracted ions were measured in dependence on the microwave power and the phase shift of the two injected microwaves.

It was found that the intensity ratio of extracted ions I_H/I_{H_2} strongly depends on the microwave power, as shown in Fig. 7. At low microwave powers the ratio of molecular hydrogen corresponds to $I_H/I_{H_2} = 0.3$. With increasing power the ratio grows and becomes larger than 1 from 60 W on and reaches up to 1.4 for 80 W. A similar behaviour could be observed in the OES measurements, like shown in Fig. 6. Both the

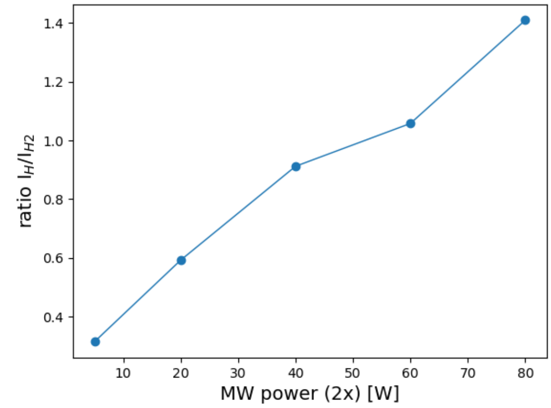

Figure 7: Intensity ratios of extracted atomic to molecular hydrogen I_H/I_{H_2} in dependence on microwave power.

minimum and maximum boundaries of the ratio n_H/n_{H_2} are increasing with the power. The upper limit is more trustworthy, since it is associated with the lower limit of the electron temperature. However, the absolute values of the dissociation ratio derived from the ion extraction measurements are higher than the OES results, even if the minimum electron temperature is assumed. Therefore, it is concluded that the differences in the extracted spectra and OES measurements originate from the different locations of spectroscopy and ion extraction within the plasma.

The OES data suggests that the phase shift has almost no influence on the ratio n_H/n_{H_2}. However, from the extracted spectra a slightly different picture is visible. The ratio is always above 1 for all phase shift angles, but the intensity ratio I_H/I_{H_2} is highest with almost 1.4 for phase shift angles between 10° and 100° and decreases to 1.1 for higher microwave phase shift angles, as shown in Fig. 8. This can also be explained with the fact that the extraction of ions and the optical spectroscopy happen at different locations in the plasma. While the spectrometer is looking through the center of the plasma chamber, the ions are extracted from a limited region behind the plasma aperture.

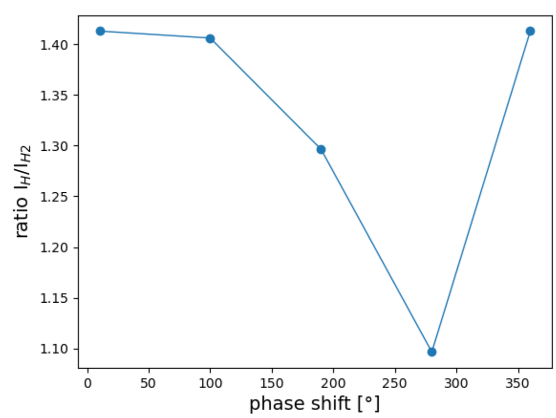

Figure 8: Intensity ratios of extracted atomic to molecular hydrogen I_H/I_{H_2} in dependence on microwave phase shift.

The polarisation of the injected microwave changes while the wave propagates through and interacts with the plasma. It is interesting to notice that while center of the confinement

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zone accumulating ions from a larger region along the ion source axis is not sensitive to the initial polarisation of the microwave, the region from where the ions are extracted is indeed sensitive to this parameter.

CONCLUSION

The present work focused on characterizing the DREEBIT 2.45 GHz ECRIS concerning the achieved plasma parameters electron density n_e, electron temperature T_e and dissociation ratio $n_\mathrm{H}/n_{\mathrm{H}_2}$. The plasma parameters were studied under variation of the injected microwave power as well as the phase shift, varying the initial polarization of the wave reaching the plasma.

The scan of the microwave power showed an increase in the electron density up to (2x) 40 W above which a plateau is reached with values between 3 and $7 \cdot 10^{16}\,\mathrm{m}^{-3}$. A more accurate value can be given once the effective length of the investigated plasma has been determined which will be done in the future. The results so far are in reasonable agreement compared to values recorded at other 2.45 GHz ECRIS with similar operation parameters.

The electron temperature T_e also rises with increased microwave power until (2x) 40–50 W. Within the range of possible resulting T_e it is most likely that the lower plateau limit of 15 eV reflects the conditions in reality as this corresponds to the maximum dissociation ratio values.

While n_e and T_e rise only up to a microwave power input of around (2x) 40 W, the dissociation ratio keeps rising up to the maximum power of (2x) 100 W given by the microwave generator, reaching $n_\mathrm{H}/n_{\mathrm{H}_2} = 0.9$. The same correlation is shown by ion extraction measurements although the absolute values for the dissociation ratio are even higher in this case, up to $n_\mathrm{H}/n_{\mathrm{H}_2}$ of 1.4. This is the first discrepancy shown between OES and ion extraction measurements. The second one is that while there is hardly any reaction to be observed via OES, the dissociation ratio does depend on the right phase shift between the two injected microwave signals defining the initial polarization of the microwave reaching the plasma. Both discrepancies can be explained by the different positions of OES and the region from where ions are extracted.

We conclude that while the electron heating and proton production have been optimized there is still room for improvement concerning the extraction of ions out of the plasma, the region from where ions are drawn to form the beam appears to be limited and does not reach the center of the plasma confinement where the OES line of sight is situated. In the near future, our R&D will focus on the optimization of the extraction lens system concerning beam current and emittance.

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