Model to self-consistently describe the RF coupling in low pressure high power hydrogen ICPs

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Introduction

In ion sources used for neutral beam heating systems in fusion devices, low pressure low temperature hydrogen or deuterium inductively coupled plasmas (ICPs) are sustained in compact cylindrical drivers [1]. To generate fusion relevant ion beams, high generator powers P_{RF} up to 100 kW have to be applied to a volume around 7.5 L yielding power densities of 13 kW/L and thus high plasma densities up to $10^{19}\,\mathrm{m}^{-3}$. To generate these high powers, currents around 100 A and voltages in the kV range are necessary which increase the probability for arcing among the RF components. This then could lead to system failures and thus reduces the reliability of the ion source, wherefore it is highly desirable to reduce P_{RF}. At the same time, the power that is absorbed by the plasma P_{plasma} should increase or at least remain constant. In other words, the RF power transfer efficiency $\eta := \frac{P_{\mathrm{plasma}}}{P_{\mathrm{RF}}}$ has to be maximized.

P_{plasma} and thus also η depend on the discharge and antenna geometries, RF frequency (1 MHz), pressure (≤ 0.3 Pa), on the used hydrogen isotope and on a magnetostatic stray field (≤ 2 mT) that is present in the driver. These properties span a huge parameter space making it virtually impossible to optimize η experimentally. Therefore a predictive model is needed, where parameters can be changed effortlessly and in a systematic way. The impact of each parameter on η can then be quantified, ultimately resulting in suggestions on how to optimize the system. Since multi-species fluid models provide a good compromise between retained physics and numerical efficiency, they are typically used to simulate ion source driver ICPs, cf. [2], [3], [4] and [5]. Each of these models has a different focus and therefore different physics is included, especially for the RF coupling. The aim of the present model is to include the RF coupling self-consistently under the conditions of low RF frequencies and low pressures, where the neutrals are depleted and the electrons are heated by a collisionless rather than a collisional mechanism [6]. Before the model can be used to make predictions, it has to be validated. This is done in two steps: First, the laboratory scale experiment CHARLIE [7] is used for a pressure variation in H_2 and D_2. It is well equipped with diagnostics such as Langmuir probes, opti-

cal emission spectroscopy and electrical measurements to quantify the plasma parameters as well as η. And second, benchmarks are done directly at the ITER prototype ion source of the BATMAN Upgrade test bed, where diagnostic access is not as easy as in CHARLIE.

In this contribution, the first validation step is presented. As a first application, the model is then used to study the isotopic effect, i.e. how changing the gas from H_2 to D_2 affects η in CHARLIE.

Model description

The present version of the time dependent model is cylindrically- and axially-symmetric, i.e. all quantities depend on the time and on the radius, which extends to the discharge wall. Hydrogen atoms and molecules are treated as a stationary background, i.e. the phenomenon of neutral depletion is not yet included self-consistently. The ideal gas law $p = n_\mathrm{a} k_\mathrm{B} T_\mathrm{a} + n_\mathrm{m} k_\mathrm{B} T_\mathrm{m}$ is used together with the measured atomic fraction $n_\mathrm{a}/n_\mathrm{m}$, pressure p and temperature $T_\mathrm{m} \approx T_\mathrm{a}$ to calculate the atomic and molecular densities n_a respectively n_m. For the charged species H^+, H_2^+, H_3^+ and electrons, the particle balances and momentum balances are solved. Ion inertia is retained, since at low pressures it plays a dominant role in the vicinity of the discharge walls. The equations are completed with zero-density boundary conditions for each ion species and a thermal flux boundary condition for the electrons at the walls. The electrostatic field in the bulk plasma is obtained from solving Poisson's equation, where the potential is set to zero at the walls. To model the RF coupling, a power balance is solved for the electrons, that are accelerated by a sinusoidally varying (denoted by a tilde) electric RF field $\tilde{E}_\varphi$. $\tilde{E}_\varphi$ and $\tilde{H}_z$ are obtained by solving Ampere's and Faraday's law in the frequency domain. The highly nonlinear coupling between the fluid and the electromagnetic equations is realized as RF power absorption term $P_\mathrm{pl} = \frac{1}{2}\mathrm{Re}\{\tilde{E}_\varphi \tilde{J}_\varphi^*\}$ in the electron power balance and as RF current density $\tilde{J}_\varphi = -e n_\mathrm{e} \tilde{u}_{\mathrm{e},\varphi}$ in Ampere's law. To reproduce the non-monotonic structure of the anomalous skin at low pressures and low RF frequencies, an effective viscosity approach that allows for diffusion of $\tilde{J}_\varphi$ is used, as developed by [6]. The losses in the RF matching network are calculated by using the measured network resistance, i.e. $P_\text{RF-network} = \frac{1}{2} R_\text{RF-network} I_\text{coil}^2$, while the power absorption by the plasma P_pl is calculated from the RF fields and plasma parameters. The system consisting of the plasma discharge and the RF network (hence $P_\mathrm{RF} = P_\text{plasma} + P_\text{RF-network}$) is excited and sustained by applying an RF current I_coil at the coil. This current is controlled by an integral controller such that the total generator power P_RF set by the user is reached and maintained for a stable plasma operation point. Hence, the RF coil current as well as the power absorbed by the plasma are outputs of the model and thus RF coupling is calculated self-consistently. In 1D, the RF coil current is expressed as $I_\text{coil} = \tilde{H}_z(R)/n$, where $n =$ number of coil windings / axial antenna length.

Model validation

As outlined in the introduction, the model is first validated against the laboratory scale experiment CHARLIE for a fixed $P_{RF} = 520\,W$ at different pressures in H_2 and D_2, as shown in Figure 1. The measured and modeled electron densities and temperatures show the same trends.

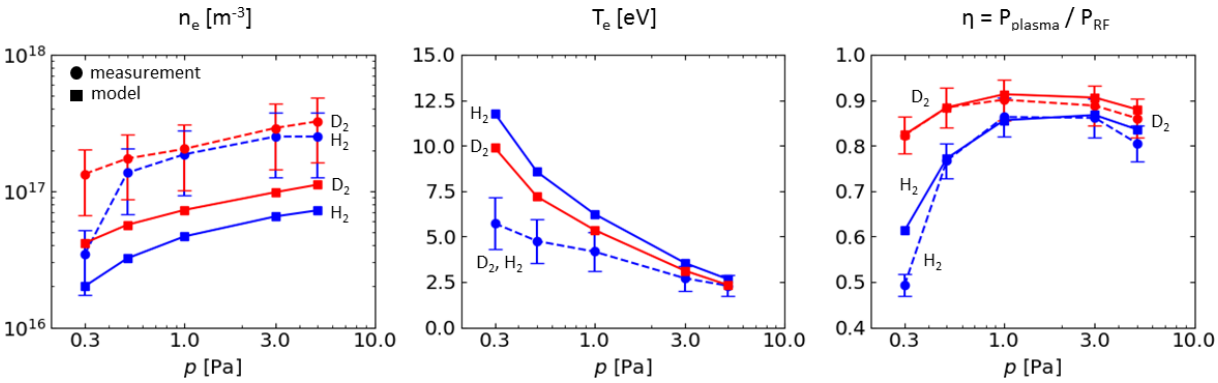

Figure 1: *Electron density n_e, temperature T_e and power transfer efficiency η at varying pressure for a fixed $P_{RF} = 520\,W$ at the laboratory scale experiment CHARLIE.*

However, the modeled electron temperatures deviate from the measured ones for $p < 1\,Pa$. This can be explained by the assumption of a Maxwellian EEDF which is used in this fluid model for the heat flux closure, electronic boundary conditions and to calculate all rate coefficients of (in-)elastic collisions. Moreover, the fluid model tends to overestimate the ion fluid velocities at low pressures, where the ion mean free paths are comparable to the discharge dimensions. This yields to an overestimated T_e compared to the experiment. η from the experiment and the model agree well throughout the whole pressure range, except for $p = 0.3\,Pa$ in H_2, where the measured η is roughly 10% lower than the modeled one.

RF skin effect and isotopic effect

For the validated low $n_e \lesssim 10^{17}\,m^{-3}$ regime, the model shows that at 1 MHz the RF skin effect is negligible, i.e. the RF fields $\tilde{E}_\varphi$ and $\tilde{H}_z$ are almost not affected by the plasma. Consequently, an increase/decrease in the electron density is equivalent to an increase/decrease in η. This fundamental mechanism has to be considered when different isotopes are investigated.

To switch from H_2 to D_2, three things are changed in the model. First, the dissociation cross-sections are slightly higher in D_2. Second, the experimentally measured atomic fraction $n_a/n_m \approx 0.2$ in H_2 and ≈ 0.4 in D_2. And third, the ion masses are doubled in D_2. Using the model to investigate each effect individually at 0.3 Pa, it can be shown that the effects of the increased dissociation cross-sections and atomic fractions are of second order. The former because the deviation in the dissociation rate coefficients in H_2 and D_2 is only $\approx 15\%$ at $T_e \approx 10\,eV$

and has therefore almost no effect on n_e and η. The increased atomic fraction in D_2 yields a decreased n_e by $\approx 15\%$. Since the skin effect is absent, this directly leads to a slight decrease in η. However, this effect is of second order, when compared to the dominant effect, which is the increased mass in deuterium. Its mechanism can be explained by using a simplified analytical picture, where the ions reach Bohm speed at the sheath boundary. Since for deuterium ions this is by a factor of $\sqrt{2}$ lower than in hydrogen, the surface losses are decreased. The particle balance then yields a lower T_e that is needed to sustain the discharge and the electron power balance shows that this corresponds to a higher n_e of a factor of around 2.5 at 0.3 Pa. This then directly translates to an increased η of roughly 20%, as shown in Figure 1.

Summary and outlook

A first 1D version of a time dependent multi-species fluid model that self-consistently simulates the RF coupling in low pressure low temperature H_2/D_2 ICPs is presented. As a first validation step, the model is benchmarked against the CHARLIE experiment in H_2/D_2. A pressure variation shows, that the n_e and T_e trends as well as the absolute values of η agree well. It is found from the model, that in the low n_e regime the RF skin effect is negligible and thus a higher n_e is equivalent to a higher η. The model reproduces the isotopic effect, i.e. η is systematically higher in D_2 than in H_2. For an exemplary pressure of 0.3 Pa, this is explained quantitatively by the increased ion masses in D_2 and the absence of the skin effect, while the effects of the dissociation cross sections as well as the atomic fractions are shown to be of second order. As next steps, the geometry is extended to 2D to model more realistic driver and antenna geometries and to include magnetic fields and neutral depletion.

References

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