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Predictive fluid model for self-consistent description of inductive RF coupling in powerful negative hydrogen ion sources

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Abstract. RF-driven negative hydrogen ion sources are typically operated at low frequencies around 1 MHz, gas pressures around or below 1 Pa and large power densities up to 10 Wcm^{-3}. Owing to these conditions as well as the current discharge geometries and antenna layouts, the RF power coupling is far from optimized, i.e. only a fraction η of the power delivered by the generator is absorbed by the plasma. This considerably limits the performance and reliability of RF-driven ion sources. To study the bidirectional RF power coupling a self-consistent fluid model is introduced. Taking into account the interplay between the nonlinear RF Lorentz force and the electron viscosity (usually neglected in state-of-the-art fluid models) a steady state solution is obtained, where the trends reflect the experimental data. Solutions calculated in hydrogen but with increased ion masses indicate that the latter are responsible for the systematically increased η, which is observed experimentally when deuterium instead of hydrogen is used as feed gas.

1. Introduction

Optimizing the RF power coupling in inductively driven radio frequency (RF) ion sources is a worthwhile task, since it can lead to significant improvement of the *RF power transfer efficiency* [1–6]

$$\eta = \frac{P_{\rm pl}}{P_{\rm RF}} = \frac{R_{\rm pl}}{R_{\rm pl} + R_{\rm net}}, \tag{1}$$

where $P_{\rm pl}$ and $P_{\rm RF}$ denote the power absorbed by the plasma and the total power delivered by the RF generator, respectively. Since only a negligible part of the electromagnetic energy is radiated away, the power is either lost in the RF network or it is deposited in the plasma. In the former, Joule heating of the RF coil produces undesired heat or eddy currents are driven e.g. in a Faraday shield (which is often present to suppress capacitive coupling) or in conducting support structures surrounding the discharge. These losses are conveniently combined in the network resistance $R_{\rm net}$, whereas the plasma resistance $R_{\rm pl}$ quantifies the power absorbed by the plasma, i.e. $P_{\rm pl} = \frac{1}{2} R_{\rm pl} I_0^2$, where I_0 is the RF coil current amplitude. If η is increased, $P_{\rm pl}$ can be held constant but at the same time the total delivered power $P_{\rm RF}$ can be decreased. This in turns relaxes requirements on the RF power generator (i.e. a cheaper model with smaller power output and space required can be used) as well as on the voltage holding and cooling

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of the various components of the RF network, such as RF coil, Faraday shield (if present) and matching system. RF ion sources are complex systems, wherefore several external parameters affect η. These are e.g. type of gas, filling pressure, power and driving frequency. Furthermore, different magnetic fields are typically present to increase the plasma confinement (cusp field) or to decrease the plasma density and temperature in specific regions (filter field). To study how and why the various parameters affect η, a numerical fluid model is developed. The challenges in simulating an RF ion source discharge are manifold. The used generator frequency f_0 is typically in the single digit MHz range, wherefore large RF magnetic fields are needed for producing induced electric RF fields comparable to the ones at higher frequencies of 13.56 MHz, which is the industry standard. Because of the high applied powers of up to 100 kW, the produced RF magnetic fields are even further elevated to values well above 100 G. To describe the RF coupling in this regime, an electron momentum balance is needed, where the RF Lorentz force has to be retained. However, solely retaining the Lorentz force leads to a compression of the plasma due to the DC component of the RF Lorentz force (ponderomotive effect). In state-of-the-art numerical models, this effect is so pronounced at the large RF magnetic fields in RF ion sources, that no steady state solutions are obtained [7]. It was recently found that the electron viscosity in the momentum balance mitigates the compression by the RF Lorentz force. In this way, self-consistent steady state numerical solutions are obtained for the first time. Further information about the self-consistent fluid model such as the used simulation domain, collisional processes and solved equations as well as boundary conditions can be found in [8].

2. Investigation of RF power coupling mechanism in RF ion sources

Experimental data from discharges of the ITER prototype RF negative ion source is used for the validation of the model. Typical operation is at a low filling pressure of 0.3 Pa, a driving frequency of 1 MHz and at large RF powers up to 75 kW [6]. The numerically obtained solutions are compared to values which are experimentally obtained from the plasma production region (driver). The comparison is exemparily performed in hydrogen as a variation of the total delivered power P_{RF} at a fixed filling pressure of $p_{\mathrm{fill}} = 0.3\,\mathrm{Pa}$. Shown in figure 1 are the RF coil current amplitude I_0 as well as the ratio of the electron density in the heating zone (in the vicinity of the radial wall) to the one in the driver center, $n_{\mathrm{e,h}}/n_{\mathrm{e,c}}$. As evident from the three trends, the model captures the trends of both quantities, and the absolute values are within or close to the experimental error bars, when the RF Lorentz force as well as the viscosity are retained. Note that the numerically obtained absolute values of the RF coil current are around 20% too small (compared to the experimentally obtained ones), when the RF Lorentz force and the viscosity are neglected. In this case the electron density ratio is overestimated by a factor of roughly two due to the missing compression effect. If only the RF Lorentz force is retained and the viscosity is neglected, the plasma compression by the RF Lorentz force is so strong, that no steady state solution develops (not shown in figure 1).

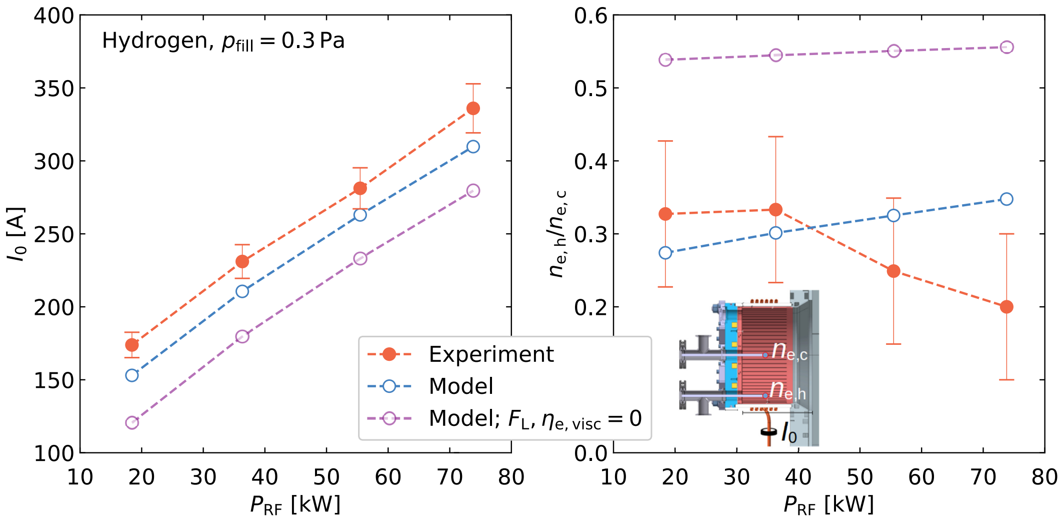

Figure 1. Validation of the self-consistent RF power coupling description of the model. Shown are the experimentally (full symbols) and numerically obtained (open symbols) RF current amplitude I_0 as well as the ratio of the electron density in the plasma heating zone to the one in the driver center, $n_{\mathrm{e,h}}/n_{\mathrm{e,c}}$. The total delivered power P_{RF} is varied from 20 to 75 kW. 'Model' denotes values calculated by the model, where the RF Lorentz force and the electron viscosity are retained. The points denoted by 'Model; $F_{\mathrm{L}}, \eta_{\mathrm{e,visc}} = 0$' are obtained by neglecting the RF Lorentz force as well as the electron viscosity. Figure adapted from [8].

3. Validation studies in hydrogen and deuterium

Negative RF ion sources used in fusion science are operated in deuterium as well. Hence it is interesting to study how the different isotopes affect the plasma parameters and the RF power coupling. Figure 2 shows at a fixed total delivered power of $P_{\mathrm{RF}} = 60\,\mathrm{kW}$ the RF power transfer efficiency η, the central electron temperature $T_{\mathrm{e,c}}$ and density $n_{\mathrm{e,c}}$ as well as the volume averaged atomic to molecular ratio $n_{\mathrm{H}}/n_{\mathrm{H_2}}$. In hydrogen the modeled trends of η and the plasma parameters $T_{\mathrm{e,c}}$ and $n_{\mathrm{e,c}}$ scale as the experimental ones. As expected from 0D global models, the electron temperature decreases, whereas the electron density increases with increasing pressure [9]. However the behavior of the RF power transfer efficiency η cannot be explained in this way. But the self-consistent power coupling model can be used to study the underlying physics effects. As demonstrated in figure 2, the trend of η agrees well with the experimentally observed one, i.e. the plasma's capability to absorb more RF power increases mostly because of the increasing electron density. Note that the calculated atomic to molecular ratios are by a factor of roughly two to four larger than the ones obtained by optical emission spectroscopy and collisional radiative modeling (CRM) [10]. The deviations are possibly caused by uncertainties in the input data (both in the numerical model and in the CRM evaluation) regarding atomic recombination coefficients of the wall material as well as opacity effects.

As a first step towards a model for description of deuterium, the masses of all heavy species from the validated hydrogen model, i.e. H, H_2, H^+, H_2^+ and H_3^+ are doubled, whereas everything else (such as e.g. collisional cross-sections) is left unchanged. This affects the flux of the ions to the discharge walls, which is in essence controlled by the Bohm speed $u_{\mathrm{i}} = (\mathrm{e}T_{\mathrm{e}}/m_{\mathrm{i}})^{1/2}$. For deuterium, the doubled ion masses yield a smaller flux towards the walls, when compared to hydrogen at the same pressure. A consequence of the decreased wall losses is a larger plasma density. The increased number of electrons in the volume available for the RF fields to couple to

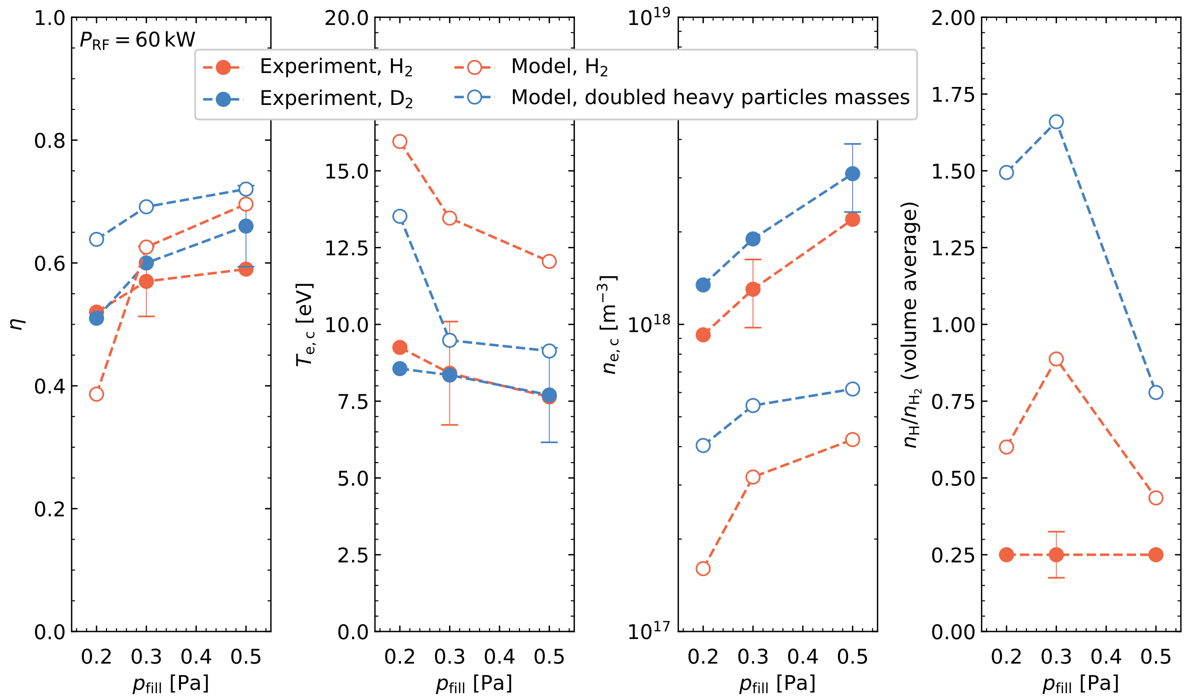

Figure 2. Comparison of experimentally (full symbols) and numerically (open symbols) obtained electrical and plasma parameters for hydrogen and deuterium at $P_{RF} = 60\,kW$ as a function of the filling pressure p_{fill}. Shown are the RF power transfer efficiency η, the electron temperature $T_{e,c}$ and density $n_{e,c}$ in the center of the driver as well as the volume averaged atomic fraction n_H/n_{H_2}.

consequently lead to an increased RF power transfer efficiency in deuterium. Interestingly, in the case of the increased mass, the model predicts that also the atomic to molecular ratio n_H/n_{H_2} will be systematically increased. The reason for this increase is a larger atomic production rate, since the latter is proportional to the electron density.

4. Conclusion

A mechanism for the RF power coupling in the RF negative ion sources operating regime (low applied RF around 1 MHz, high power densities up to $10\,Wcm^{-3}$ and low pressures around or below 1 Pa) has been validated with experimental measurements. Here it has been shown that the RF power coupling can be described by an electron momentum balance, where the RF Lorentz force as well as the viscosity are retained. The latter mitigates the ponderomotive effect caused by the RF Lorentz force. In this way steady state solutions are obtained for the first time. The numerical solutions scale as in the experiment. Moreover, the absolute values of the measured RF coil current and the intensity of the plasma compression match at almost all investigated operation points.

Further validation activities regarding the isotopic effect have been started by simply doubling the mass of all heavy species. This leads to a slight increase in the RF power transfer efficiency calculated by the model, which is in agreement with the experimental measurements. A plausible explanation for the increased η are the decreased plasma losses in the model that go along with larger plasma densities. However, increasing the ion mass can only be considered as a first step towards a comprehensive deuterium model. Here also cross sections for the elastic and inelastic collision processes as well as for various processes at the walls have to be exchanged.

The validated model can be applied to determine and optimize the external parameters that have the largest positive effect on the RF power coupling in RF ion sources. This is shown exemplarily in the contribution by S. Briefi et al. to this conference.

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