Alternative RF coupling configurations for H$^-$ ion sources

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Abstract. RF heated sources for negative hydrogen ions both for fusion and accelerators require very high RF powers in order to achieve the required H^- current what poses high demands on the RF generators and the RF circuit. Therefore it is highly desirable to improve the RF efficiency of the sources. This could be achieved by applying different RF coupling concepts than the currently used inductive coupling via a helical antenna, namely Helicon coupling or coupling via a planar ICP antenna enhanced with ferrites. In order to investigate the feasibility of these concepts, two small laboratory experiments have been set up. The PlanICE experiment, where the enhanced inductive coupling is going to be investigated, is currently under assembly. At the CHARLIE experiment systematic measurements concerning Helicon coupling in hydrogen and deuterium are carried out. The investigations show that a prominent feature of Helicon discharges occurs: the so-called low-field peak. This is a local improvement of the coupling efficiency at a magnetic field strength of a few mT which results in an increased electron density and dissociation degree. The full Helicon mode has not been achieved yet due to the limited available RF power and magnetic field strength but it might be sufficient for the application of the coupling concept to ion sources to operate the discharge in the low-field-peak region.

INTRODUCTION

Sources of negative hydrogen ions are used for neutral beam heating of fusion experiments (where the H^- ions are accelerated to high energies, neutralized and injected into the fusion plasma) as well as for proton accelerators where the negative ions are pre-accelerated and injected into a ring accelerator via stripping the two excess electrons by passing the H^- beam through a thin foil. The ion sources for these two applications greatly differ in size: for example, the ion source for the ITER neutral beam heating system is going to cover an area of 0.9×1.9 m^2 whereas the discharge vessel of the ion source for the Linac4 accelerator at CERN is only 5 cm in diameter −. But these sources have in common that they rely on plasma generation in a cylindrical discharge vessel via inductive coupling with a helical antenna (due to the large size the ITER sources is going to be equipped with 8 discharge vessels, the so-called drivers). However, in order to achieve the required H^- currents very high RF powers are needed: for the ITER source a maximum RF power of up to 100 kW per driver is foreseen (operating pressure 0.3 Pa, working gas hydrogen and deuterium, RF frequency 1 MHz, driver volume ≈ 7.5 l) [1, 2]; for the Linac4 source up to 100 kW are used (IS-02, operating pressure several Pa, working gas hydrogen, RF frequency 2 MHz, discharge vessel volume ≈ 0.25 l) [3]. These high RF powers pose strong demands on the RF circuit and generators which makes a reduction of the required powers very desirable. However, these plasma parameters which determine the negative hydrogen ion production and therefore the source performance (for the surface production process of H^- the density of atomic hydrogen and the density of the positive hydrogen ions [4]) must at least be retained. In order to achieve this goal, alternative coupling concepts such as Helicon coupling or inductive coupling using a planar antenna surrounded by ferrites are investigated.

Helicon coupling relies on wave heating mechanisms in magnetized plasmas which makes a cylindrical discharge vessel, an external magnetic field and a particularly shaped antenna necessary. The concept is generally known to produce rare gas discharges with very high efficiency [5, 6]. Another prominent feature is the enhancement of the coupling efficiency at a few mT external magnetic field strength, the so-called low-field peak [7], which could be enough improvement regarding the application at ion sources. For the utilization of Helicon coupling, the basic geometry of the ion sources has not to be altered, as both the driver in ion sources for fusion and the discharge vessel at ion sources for accelerators are cylindrical; only an additional magnetic field and a differently shaped antenna have to be applied. However, Helicon discharges are typically operated in long and thin discharge vessels using rare gases (especially argon). The applicability of Helicon coupling to hydrogen or deuterium has not been investigated

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systematically yet[1]. In order to investigate and optimize Helicon coupling for H_2 and D_2 the laboratory experiment CHARLIE (**C**oncept studies for **H**elicon **A**ssisted **RF** **L**ow pressure **I**on sourc**E**s) has been set up [9]. Measurements between 0.3 and 10 Pa pressure can be carried out which covers the relevant range both for ion sources for fusion and accelerators. In this paper, a comparison of important discharge parameters obtained at different pressures and external magnetic field strengths for operation with H_2 and D_2 are going to be presented.

For the second concept, enhancing inductive coupling with ferrites, a large scale planar RF antenna is foreseen for ion sources for fusion which offers the possibility to omit the drivers and thereby improving the plasma homogeneity. The coupling concept is based on a low pressure discharge for semiconductor manufacturing [10] where focus has been laid on increasing the RF field strength inside the discharge vessel as this increases the coupling efficiency. Applying a planar antenna at ion sources requires major changes in the design, therefore the fundamental feasibility is studied at the laboratory experiment PlanICE (**Plan**ar **I**nductively **C**oupled **E**xperiment) which is currently under assembly. A description of the concept, the setup and the foreseen diagnostic methods is given.

HELICON COUPLING

A sketch of the CHARLIE experiment is shown in figure 1. The discharge vessel is made out of quartz glass, has a length of 40 cm, a diameter of 10 cm and is attached to the vacuum system at the ends of the cylinder. As RF antenna a Nagoya-type Helicon antenna which couples to the $|m| = 1$ Helicon modes is applied [11]. The antenna is connected to the RF generator which operates at a frequency of 13.56 MHz via a matching network. All investigations presented in this paper are carried out at the maximum available RF power of 600 W. The external magnetic field which is directed parallel to the cylindrical axis of the discharge vessel is generated by a pair of Helmholtz coils (380 windings and 18 cm radius each) and reaches a maximum strength of about 12 mT. Typically, Helicon discharges are operated at RF powers in the kW range and at magnetic field strengths in the range of several 100 mT. However, for the first investigations the setup had been kept simple and water cooling of components had been avoided. In the next step, the discharge power is going to be increased to 2 kW at a frequency of 2 MHz in order to get closer to the operational parameters of ion sources. Also different antenna designs are going to be investigated.

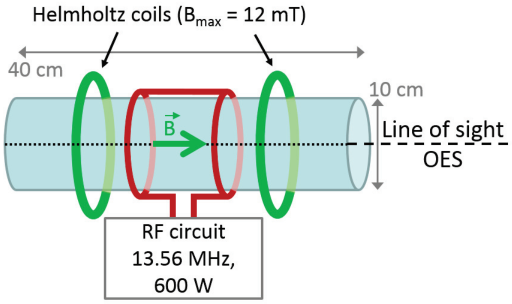

FIGURE 1. Sketch of the setup of the CHARLIE experiment.

As diagnostic method optical emission spectroscopy has been used. The measurements were performed with a high-resolution spectrometer ($\Delta\lambda_{\mathrm{FWHM}} \approx 50$ pm) along an axial line of sight (radially centered). As discharge parameters especially the electron density (as measure for the integrated density of the positive hydrogen ions) and the density ratio of atomic to molecular hydrogen $n_{\mathrm{H}}/n_{\mathrm{H}_2}$ (as measure for the atomic hydrogen density) are important with respect to the H^- production in ion sources [4]. Therefore these parameters and the electron temperature have been determined from the absolute emission of the Balmer lines and the molecular Fulcher emission via applying the collisional radiative models Yacora H for atomic [12] and Yacora H_2 for molecular hydrogen [13, 14].

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[1] Helicon coupling has already been studied for the plasma generation for future H^- ion sources for accelerators, but the motivation was different: a concentration of the plasma on the axis of the cylindrical discharge vessel should be achieved in order to reduce the losses at the vessel walls [8].

Pressure and B-field variation in H_2

In order to investigate the feasibility of Helicon coupling in hydrogen, variation of the magnetic field at different pressures are carried out. In figure 2 the measured emissivity of the H_β line (as an example of the atomic radiation) and the integrated emission of the Fulcher transition (as an example of molecular emission) is shown at varying magnetic field strength for pressures of 1, 0.5 and 0.3 Pa. In general, the application of a magnetic field decreases both the atomic and molecular emission compared to the case without magnetic field. This jump is attributed to a strong change in the spatial plasma distribution as without magnetic field, the discharge is concentrated under the antenna region. Applying a magnetic field leads to a much more uniform plasma distribution along the line of sight. However, a strong change in the profile cannot be considered in the evaluation of the OES measurements which makes the values obtained without magnetic field questionable. Due to this reason, the point at 0 mT is omitted in the following. A further increase of the field strength leads to a peaking of the emissivity (the so-called low-field peak which is more pronounced at lower pressure) followed by another increase at higher field strengths. At 0.3 Pa a stable operation of the discharge is not possible below a magnetic field strength of 4 mT as flickering and spontaneous quenching of the discharge occurs. However, this is not expected to be a general feature but rather caused by the limited RF power available.

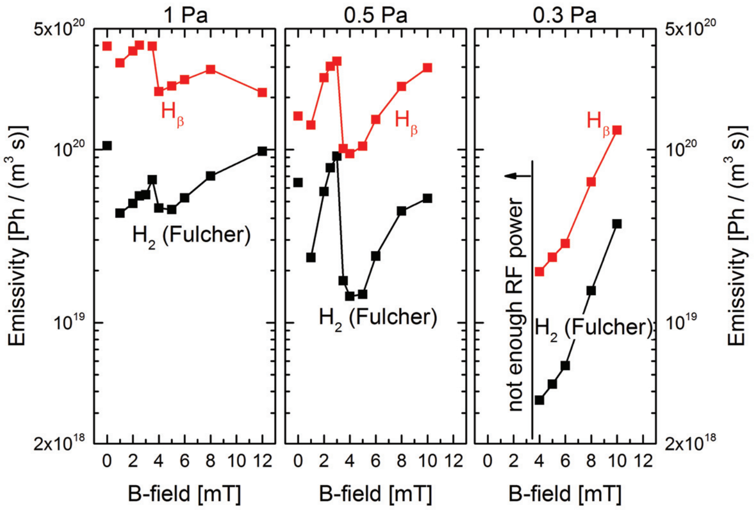

FIGURE 2. Measured emissivity of the H_β line and of the whole molecular Fulcher emission at varying magnetic field strength for a pressure of 1, 0.5 and 0.3 Pa. For 0.3 Pa a stable operation for $B < 4$ mT is not possible.

The electron density and temperature are shown in figure 3. For a pressure of 1 Pa, the electron density stays almost constant around 1×10^{17} m^{-3} with a slight increase in the region of the low-field peak and at high magnetic field strengths. A transition of the discharge into the high-density full Helicon mode which is accompanied by a large jump in the electron density is not observed which is attributed to the limited RF power and/or magnetic field strengths. For the electron temperature a variation of the magnetic field has very little influence as the values only drop from around 4.5±0.5 eV without B-field to around 4.0±0.5 eV at high magnetic fields for 1 Pa. At 0.5 Pa pressures, the general trends for n_e and T_e are retained but the low-field peak is more pronounced. For 0.3 Pa the electron temperature shows a linear increase from 2.5 eV at 4 mT to 4.2 eV at 10 mT at 0.3 Pa. Figure 4 shows the density ratio of atomic to molecular hydrogen determined for the above mentioned parameter variations. Applying a magnetic field leads to a decrease of the ratio followed by a peaked increase in the region of the low-field peak (again more pronounced at lower pressure) and another increase at high magnetic field strengths.

Comparison of H_2 and D_2

The propagation of Helicon waves is sensitive to the mass of the ions, therefore dedicated measurements have to be carried out for both hydrogen and deuterium in order to optimize Helicon coupling. The most distinct difference in the

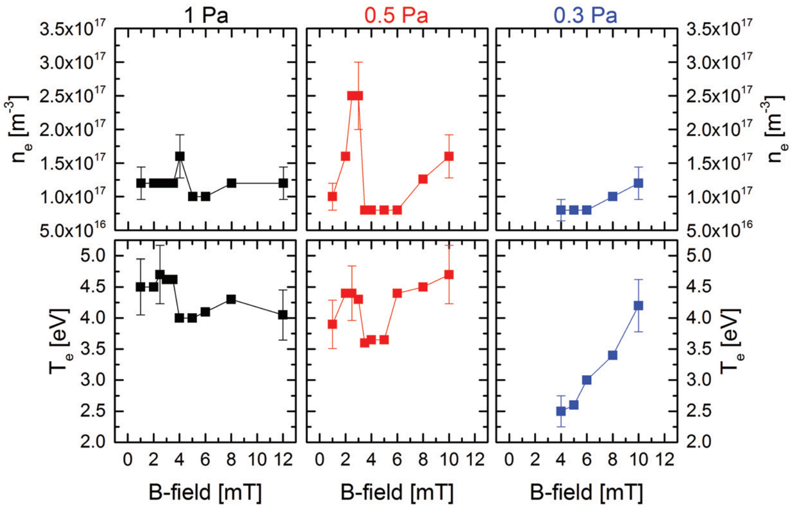

FIGURE 3. Electron density and temperature determined from the OES measurements via the collisional radiative models Yacora H and H_2 at varying magnetic field strength for a pressure of 1, 0.5 and 0.3 Pa.

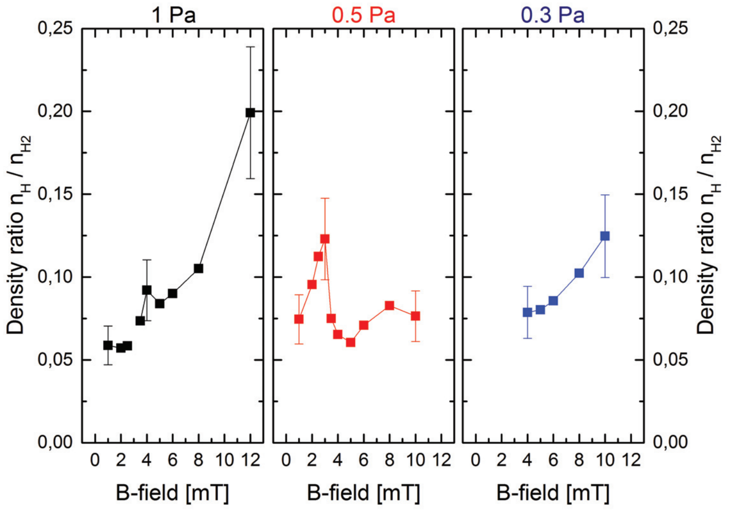

FIGURE 4. Density ratio of atomic to molecular hydrogen at varying magnetic field strength for a pressure of 1, 0.5 and 0.3 Pa.

measurements between H_2 and D_2 operation is the much higher value of n_D/n_{D_2} in deuterium which can be seen in figure 5. This can partly be attributed to the higher cross section for electron impact dissociation for deuterium [15]. Typically this leads to a factor of 2 increase [16] but here more than a factor of 5 is observed. The low-field peak is also more prominent in deuterium than in hydrogen: the local increase of the ratio reaches a factor of 2 to 4. Furthermore, at 0.3 Pa the discharge can be operated with lower magnetic field strengths in deuterium which reveals the position of the low-field peak at this pressure. Concerning the electron density, a slight increase is observed in deuterium whereas the electron temperature is basically not altered compared to hydrogen.

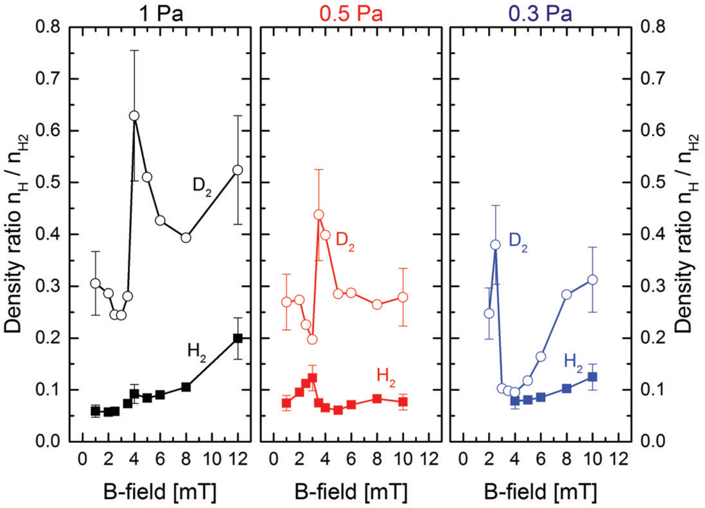

FIGURE 5. Density ratio of atomic to molecular hydrogen/deuterium at varying magnetic field strength for pressures of 1, 0.5 and 0.3 Pa.

Behavior of the low-field peak

Considering the application of Helicon coupling to ion sources, a promising point of operation is within the low-field-peak region. In this region, the electron density and the density ratio of atomic to molecular hydrogen are increased, especially for deuterium. The physical reason behind the occurrence of the low-field peak is still unclear. One possible explanation is, that the generated Helicon waves are reflected at the ends of the discharge chamber and the low-field peak forms if the length of the discharge vessel is a whole-number multiple of the B-field dependent Helicon wavelength which leads to constructive interference of the waves [17]. This means that the position of the low-field peak is dependent on the dimensions of the discharge vessel. For the presented measurement campaigns, the Helicon wavelength (calculated after [18]) is in the range between 30 and 50 cm at the low-field peak − dependent on the parameter variation − which means a clear consilience is not observed as the discharge vessel length is 40 cm. Another explanation for the occurrence of the low-field peak is that the RF coupling becomes more efficient if the Helicon wavelength is in the range of the antenna length [19]. In this case, the position of the low-field peak would depend on the size of the antenna. However, the antenna utilized in the current setup has a length of 10 cm which is smaller than the calculated Helicon wavelength. In addition, the position of the low-field peak is shifted to lower magnetic field strengths for lower pressure: for example for deuterium the low-field peak position is located at around 4 mT at 1 Pa, at 3.5 mT for 0.5 Pa and at 2.5 mT at 0.3 Pa. This behavior has also been observed in rare gas Helicon discharges [7] but the reason for it is still unclear as well.

PLANAR ICP WITH FERRITES

The enhancement of the RF coupling concerning this concept is twofold: First, immersing the planar antenna into the discharge vessel but separating it from the plasma by a thin dielectric window. The thickness of the window can be much thinner compared to conventional inductive coupling as it does not have to withstand atmospheric pressure. Therefore the distance between the antenna and the plasma can be decreased what substantially increases the RF fields that heat the plasma. Second, the RF radiation is concentrated into the discharge vessel via using ferrites that cover the planar antenna at the sides and the top.

An exploded assembly drawing of the experimental setup of PlanICE is shown in figure 6. The cylindrical discharge vessel is made out of stainless steel and has a diameter of 15 cm and a height of 10 cm. It is equipped with four quartz windows and four KF25 flanges for the connection with the vacuum system and for diagnostics. The water cooled

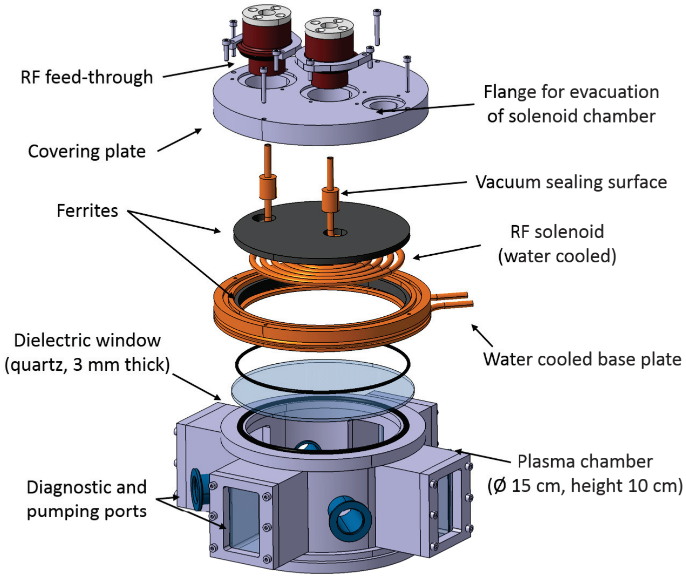

FIGURE 6. Exploded assembly drawing of the setup of the PlanICE experiment.

planar antenna which is made out of Teflon-insulated copper tube is surrounded by ferrites in order to concentrate the RF fields into the discharge chamber. In a first approach, the antenna and the ferrites were immersed into vacuum wax to avoid discharge ignition between the windings of the antenna and for vacuum sealing. However, after a few minutes of operation, the wax heated up and became soft which resulted in vacuum leaks. Therefore a redesign was carried out where the antenna chamber is evacuated and vacuum sealing is carried out via special RF feed-throughs (this setup is shown in figure 6). In order to facilitate discharge ignition a heated tungsten filament which is biased against the vessel wall is foreseen.

The RF generator which operates at 2 MHz (maximum power 2 kW) is connected to the antenna via a matching network. As diagnostic methods, optical and VUV emission spectroscopy, a horizontally and vertically movable Langmuir probe, microwave interferometry and energy resolved ion mass spectrometry will be applied. With these methods, not only the relevant plasma parameters such as n_e, T_e, $n_{\mathrm{H}}/n_{\mathrm{H}_2}$, the ion composition and temperature are going to be measured but also the profiles of the electron density and temperature are going to be deduced. The parameters are going to be compared for operation with and without ferrites at pressures between 0.3 and 10 Pa. Initially, no Faraday screen is applied in order to facilitate discharge ignition. However, as a Faraday screen is required for the application of the concept at ion sources, a screen is going to be introduced. In a next step also the size of the discharge vessel is going to be increased in order to demonstrate the applicability of the concept at larger scales.

SUMMARY AND OUTLOOK

Two different concepts are investigated as alternative RF coupling concepts of ion sources for negative hydrogen ions both for fusion and accelerators: enhancing inductive coupling using a planar antenna and ferrites or applying Helicon coupling. In order to investigate the feasibility of both concepts fundamentally two small laboratory experiments have been build up. The experiment PlanICE, where the planar ICP coupling enhanced with ferrites is going to be investigated, is currently under assembly. At the CHARLIE experiment Helicon coupling is investigated for hydrogen and deuterium. The full Helicon mode has not been achieved yet but it seems promising to operate the discharge in the range of the low-field peak which requires magnetic field strengths of a few mT. In a next step, an RF generator with a maximum power of 2 kW and a frequency of 2 MHz which is equal to the operating frequency of ion sources for accelerators and close to the 1 MHz used at ion sources for fusion is going to be applied to the CHARLIE experiment.

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