Negative ion density measurements in an inductively driven hydrogen discharge

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Abstract. The study presents experiments on the determination of the electronegativity and its axial variation in an inductively driven hydrogen discharge, performed by using the laser photodetachment technique. The results showing high electronegativity with nonmonotonic axial variations and a maximum next to the rf power deposition region provide an experimental indication that a design of an efficient source of negative hydrogen ions based on a single-chamber discharge might be possible.

1. Introduction
The plasma sources of negative hydrogen ions have formed a subject of extended research owing to their applications in the accelerator physics [1], ion implantation technology [2] and fusion plasma heating [3]. The volume production of the negative ions results from dissociative attachment of electrons to (highly) vibrationally excited molecules. In search for conditions for efficient production of negative hydrogen ions the idea for the tandem type of a design of the source has been reached [3]. In its modification into an inductively-driven rf plasma source [4] this concept has emerged to a design of the source as a two-chamber source with rf power deposition into the first – small-size – chamber and ion extraction from the second – large-size – chamber. However, recent theoretical studies [5, 6] show that the region of the rf power deposition – the driver region – sustains high concentration of negative ions due to their accumulation in the on-axis discharge region, and trace out a concept for a design of the source as a matrix of small radius discharges with a single hole extraction from each of them.

This study, being in the scope of recent work on small-size inductively-driven two-chamber negative-hydrogen-ion sources, extends previous experiments [7] on registration of the concentration of the negative hydrogen ions \( H^- \) in the second chamber of the source towards registration of the plasma electronegativity, i.e. the ratio of the concentrations of the negative ions and of the electrons, in the first chamber. The obtained axial variation of the electronegativity in the plasma region of the rf power deposition and in its vicinity shows nonmonotony with a maximum just outside the power deposition region and comes as an experimental support of the concept [6] for a rf-driven negative hydrogen ion source based on single-chamber discharges.

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2. Experimental arrangements
The experimental set-up (figure 1), described in more details in [7], is a two-chamber rf plasma source inductively driven by a cylindrical coil (a 9-turn coil). The first chamber of the source, a quartz tube, has a diameter of \( d_1 = 4.5 \) cm. The modifications, made here, concern the experimental arrangements for the laser photodetachment technique. In general, this technique [8] in its combination with a probe is a method for determination of the electronegativity \( \alpha = n_-/n_e \) based on measurements of the ratio of the pulse in the electron saturation current to the probe to its steady state value \( I_{e\text{(dc)}} \); in \( \alpha \), \( n_- \) and \( n_e \) are, respectively, the density of the negative ions and the electron density. The pulse is due to the extra electrons detached – by the laser beam photons (\( H^- + h\nu \rightarrow H + e \)) – from the negative ions and collected by the probe. As it has been done before [7], the second harmonics of a Surelite III-10 Nd:YAG laser is used. However, here, in accordance with the aim of the study – determination of the axial variation of \( \alpha \) – the laser beam path is aligned axially, centred at the discharge axis, as shown in figure 1. Respectively, the probe is axially movable over the entire length of the discharge, also centred at the discharge axis. The laser beam diameter is fixed at 1 cm by a diaphragm and the laser pulse energy is measured with a Gentec joulemeter. The relation of \( \alpha \) to the measured current ratio \( (I_{\text{ph}}/I_{e\text{(dc)}}) \) is \( \alpha = (I_{\text{ph}}/I_{e\text{(dc)}})/(\delta n_-/n_-) \), where the photodetachment fraction \( (\delta n_-/n_-) \) is obtained for the measured values of the laser pulse energy density \( W \), by using the well-established dependence of \( (\delta n_-/n_-) \) on \( W \) [7, 8].

![Figure 1. The experimental set-up.](image-url)

The probe is 8 mm in length, with a radius of 0.25 mm. In the measurements it is moved from the position \( z = 4 \) cm inside the second chamber till almost the middle of the coil \( (z = -12) \) cm. A second probe (a SmartProbe™ probe system) is used for measuring the ion saturation current which provides indications for the axial variation of the negative ion density \( n_- \). The results are in arbitrary units, since – at the current stage – the electron temperature (necessary for the determination of the plasma density) cannot be reliably determined.

3. Results and discussions
The results (figures 2 and 3) presented here are for the axial variation of the electronegativity \( \alpha \) and of the negative ion density \( n_- \) in a discharge sustained in the gas pressure range \( p = (4–10) \) mTorr in flowing gas (a gas flow of 20 sccm) by applying a rf power \( P = (700–1000) \) W at frequency of \( f = 27 \) MHz. In the figures, the \( (z = 0) \)-position is at the transition between the two chambers and, thus, the negative \( z \)-values are inside the first chamber where the driver is located. The vertical lines mark the position of the middle and the end of the coil.

The obtained axial variations of the electronegativity \( \alpha \) for different gas-pressure values are in figure 2. Nonmonotony of the axial profiles of \( \alpha \) is the main conclusion: starting with high
values in the plasma region under the coil, $\alpha$ decreases forming a minimum close to the end of the coil and then increases again reaching a maximum in the region between the coil end and the transition between the two chambers, followed by a decrease towards the second chamber. With the measured axial profile of the ion saturation current shown in figure 3(a), the axial profile of the negative ion density, though obtained only in arbitrary units (figure 3(b)), shows the same behaviour: high values of $n_-$ in the plasma region under the coil, minimum close to its end and a maximum towards the transition between the two chambers.

Clearly, the explanation of such a peculiar behaviour of the profiles of $\alpha$ and $n_-$ requires detailed theoretical and experimental knowledge of the plasma parameter distribution, still not available for two-chamber plasma sources. However, even at this stage the results give indications for locality in the $\text{H}^-$-balance established under the conditions of nonlocality in the formation of the discharge structure. A similar conclusion has been reached also before [7], in the experiments carried out in the second chamber of the source. Such a conclusion is supported also by the results from the model [9] of hydrogen discharges in a tandem source, with the same configuration and size as that in the experiment here, obtained, however, at higher gas pressures. The theoretical results show a strong decrease of the electron temperature $T_e$ and density $n_e$ from the driver of the discharge towards the second chamber of the source. However, whereas the axial $n_e$-decrease starts from the centre of the region of the rf power deposition, that of $T_e$ starts in the vicinity of the transition between the two chambers. As it is widely accepted, an effective $\text{H}^-$ production by electron attachment to vibrationally excited molecules ($e + \text{H}_2 \rightarrow \text{H}_2(v) + e$, Figure 2. Axial variation of the electronegativity $\alpha = n_-/n_e$ for different gas-pressure values $p$ and applied power of $P = 700$ W.

Figure 3. Axial variation of the ion saturation current to the probe in (a) and of the negative ion density, in arbitrary units, in (b) for $p = 6$ and 8 mTorr and $P = 700$ W.
e + H₂ (v → H⁻ + H) requires a combination of high Tₑ with high nₑ and N₂ (the concentration of the hydrogen molecules), for the vibrational excitation of the molecules, and a combination of low Tₑ with high nₑ, for the dissociative attachment of the electrons. Rovibrational excitation involving surface processes can also contribute to the H⁻-production [10]. The high values of α and n₋ (figures 2 and 3(b)) in the plasma region under the coil could be related to the high values of nₑ and H₂ (v) there, the minimum close to the end of the coil could be due to lower nₑ under the condition of still high Tₑ and the maximum outside the plasma region covered by the coil could be related to lower Tₑ there. High N₂ and lowering of the concentrations of the positive ions and of the hydrogen atoms outside the power deposition region [9] also favour sustaining high n₋ since the former supports the H⁻-production and the latter reduces the H⁻-losses. The shift of the position of the maximum of α with p calls for influence of effects of nonlocality, i.e. for contribution by H⁻-ions produced in the vicinity of the transition between the two chambers and accelerated to the position of the maximum in the dc potential drop towards the second chamber, which should be a pressure dependent process. However, the shift of the maximum with p is very slight and, thus, this effect is weak. The increase in the value of the maximum of α and n₋ with p is in conformity with the gas-pressure dependence of n₋, known from former experiments [11]. Increasing the rf power (up to 1 kW) preserves the structuring of the α-profile.

4. Conclusions
In general, the experimental results obtained showing high values of α and n₋ in the first chamber, moreover, quite higher than in the second one, come in conformity with the suggestion [6], stemming from theoretical results, for a design of a source based on the driver region and performed as a matrix of small-radius discharges with a single hole extraction from each of them. Moreover, with the registration of maxima of α and n₋ next to the region of the rf power deposition, the experimental results specify better the design of the source: The extraction of the H⁻ ions from the single discharge of the matrix should be from the position of the maxima of α and n₋, which is constructively better suited compared to extraction from the rf power deposition region itself.

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