# SELF-CONSISTENT MODEL OF AN INDUCTIVELY DRIVEN PLASMA SOURCE OF NEGATIVE HYDROGEN IONS

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In the one dimensional model of a low pressure cylindrical inductive discharge in hydrogen presented in the study, a gas-discharge fluid-plasma model description of free-fall regime discharge maintenance is coupled to nonlocal electrodynamics, i.e. to a kinetic model description of the rf power deposition in the discharge. The study is relevant to volume-production based sources of negative hydrogen ions. Former results for an accumulation of the negative ions in the on-axis region of the discharge obtained under the assumption for radially homogeneous power deposition are confirmed and shown not to be changed when the description of the power deposition is specified for a low-pressure inductive discharge.

## Introduction

The development towards big fusion machines motivates the active research on sources of negative hydrogen/deuterium ions, being the only possibility for neutral beam injection plasma heating in large scale tokamaks. The currently studied inductively driven rf sources with a two-chamber design and ion extraction from the expanding plasma volume of the source rely on surface production of the ions [1]. On the other hand, results from recent fluid-plasma model [2, 3] show (Fig. 1) that the active part of the discharge, i.e. the driver of the source, sustains high concentration of negative ions (even higher than that of the electrons) in its on-axis region when the discharge radius is small. This comes out from volume production of the negative ions over the entire cross section of the discharge and their accumulation in the discharge center due to their motion in the radial dc electric field formed in the discharge. This study confirms the above conclusion. The gas-discharge description in Refs. [2, 3] is extended via replacing the radially

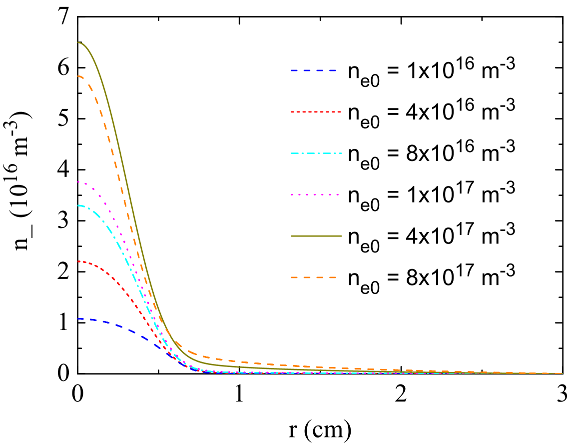


**Figure 1.** Radial distribution of the negative ion density $n_-$ for different values of the electron concentration at the discharge axis $n_{e0} = n_e(r = 0)$; gas pressure $p = 5$ mTorr, discharge radius $R = 3$ cm (from Ref. [3]).

homogeneous power deposition assumed there with a power deposition specifying cylindrical inductive discharges. In correlation with the low gas-pressure conditions and, respectively, the free-fall-regime gas-discharge description, the electrodynamics completing the model is nonlocal, described within the kinetic plasma theory.

**Model overview**

The model is one-dimensional and it couples fluid-plasma model description of free-fall regime maintenance of hydrogen discharges with nonlocal electrodynamics of cylindrical inductive discharges.

Electrons, the three types of positive ions ($H^+$, $H_2^+$ and $H_3^+$), negative ions ($H^-$), hydrogen atoms (H) and vibrationally excited molecules ($H_2(\nu)$, $\nu = 1-14$) are included in the model with their balance equations. The momentum equations of the charged particles, the Poisson equation, the electron energy balance equation and the expression for the gas pressure complete the initial set of equations of the gas-discharge part of the model [2, 3]. The conditions of a free-fall-regime discharge maintenance are specified by the inertia terms in the momentum equations of the positive ions and the inelastic collisions for particle production in the momentum equations of all types of charged particles. The production of $H^-$ is in the plasma volume, from the ($\nu = 4-9$)-excited states of $H_2$ and their losses are via collisions with electrons and atoms and recombination with the positive ions. In the electron energy balance, electron energy losses via conductive and convective fluxes as well as in collisions with H and $H_2$ and for maintenance of the dc electric field are in a balance with the rf power deposition to the discharge. In a way, the initial set of equations in the gas-discharge part of the model includes 25 differential equations.

The rf power deposition is obtained from the electrodynamical part of the model based on a solution of the wave equation written for the rf electric field ($E_\varphi$). In accordance with the low gas-pressure conditions of the discharge maintenance, the skin of the high-frequency (HF) transverse wave sustaining the discharge is anomalous which, together with the reflection of the electrons by the potential barrier of the dc field in the wall sheath, determines conditions for nonlocal conductivity. The integral form of the current density used for solving the wave equation is that [4] obtained from the solution of the Boltzmann equation for the oscillating part of the electron velocity distribution function.

**Results and discussion**

The results shown in Fig. 1 [3] are obtained with an assumption for a radially homogeneous rf power deposition to the discharge. For their check with respect to the influence of the manner of the rf power deposition on the radial variation of the macroscopic plasma parameters and, in

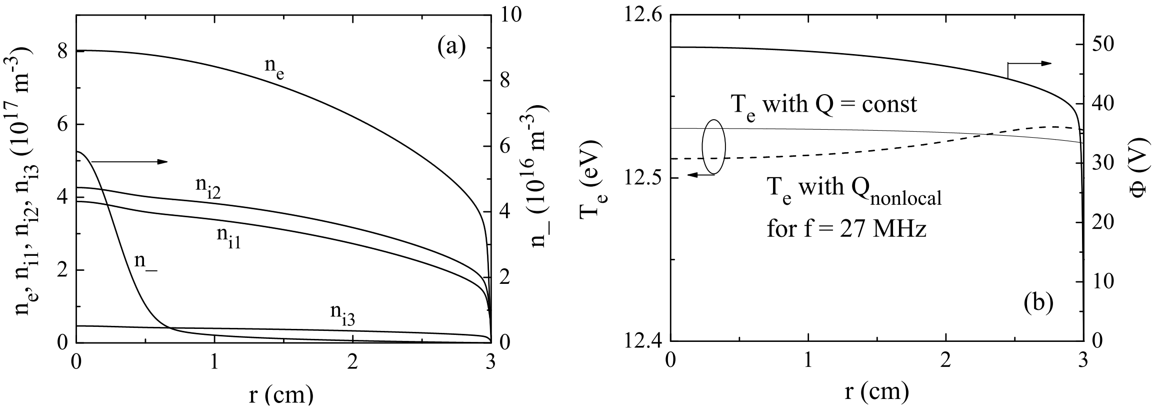


**Figure 2.** Radial distribution of the charged particle concentrations (a) and of the electron temperature $T_e$ and the potential $\Phi$ of the dc electric field (b), $p = 5$ mTorr, $R = 3$ cm, total applied power $P = 3 \times 10^4$ W/m (power per unit length).

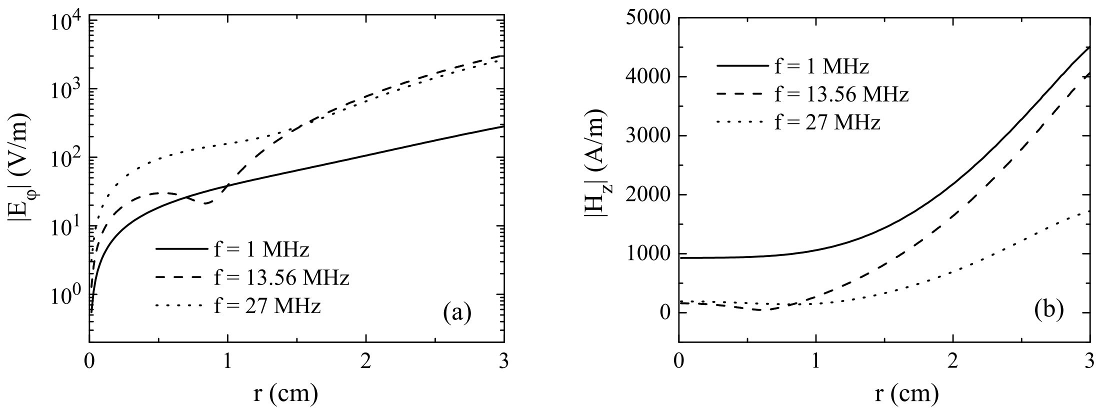


**Figure 3.** Radial distribution of the amplitudes of the azimuthal electric field $|E_\varphi|$ and of the axial magnetic field $|H_z|$ (b). The same conditions as in Fig. 1.

particular, on the radial profile of $n_-$, the case of $n_e\,(r = 0) = 8 \times 10^{17}$ m$^{-3}$ in Fig. 1 is picked.

The radial profiles (Fig. 2) of the concentration ($n_e$) of the electrons and of the potential $\Phi$ of the dc field show the typical – for a free-fall regime – well-pronounced wall sheath. Due to the accumulation of $H^-$ in the on-axis region of the discharge, the profiles of the densities of the positive ions ($n_{i1}$, $n_{i2}$ and $n_{i3}$ for $H^+$, $H_2^+$ and $H_3^+$) are slightly distorted there, ensuring fulfillment of the condition for quasi-neutrality.

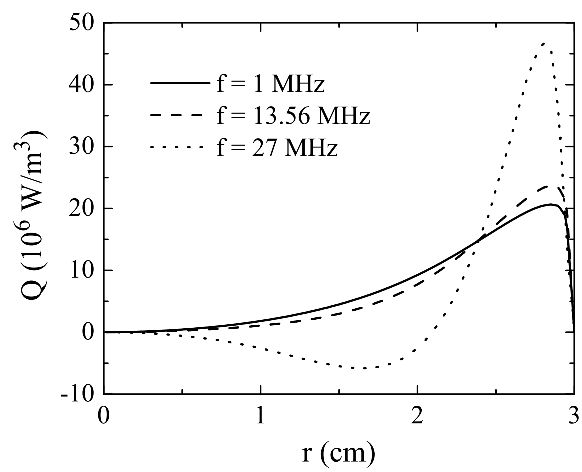


**Figure 4.** Radial distribution of the power density $Q$.

The results (Figs. 3 and 4) for the radial profiles of the amplitudes of the HF field components (the electric $E_\varphi$ and magnetic $H_z$ fields) and of the rf power density $Q$ show the effects of the nonlocal conductivity: nonmonotonic variations of the field amplitudes with formation of a hump towards the discharge axis and appearance of a region of a negative power deposition. Figures 3 and 4 also show a frequency ($f$-) dependence of the effect of the nonlocal conductivity.

Although the power density $Q$ strongly varies across the discharge radius (Fig. 4), the changes in the radial variation of the electron temperature $T_e$, compared to the case of a constant – across the radius – rf power deposition, are very weak (Fig. 2(b)), not showing evidence in the radial profiles of the charged particle densities (Fig. 2(a)). This could be associated with strong thermal-conductivity effects.

## Conclusions

The results presented here show that the accumulation of the negative ions in the on-axis region of the discharge is not affected by the type of the rf power deposition. But there is still an open question concerning the electron energy distribution function and expected deviations from the Maxwellian one. However, this could not influence the effect of the bunching of the negative ions in the on-axis region of the discharge since the latter results from macroscopic effects: The accumulation in the discharge center of the negative ions produced all over the discharge cross section is due to their flux in the radial dc electric field. This flux stays high when the discharge radius is small.

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