Production of Hydrogen Negative Ions in High Density Sheet Plasma

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Introduction

Negative ions are expected to play an essential role in particle accelerators, magnetic fusion energy research, and plasma processes. Research on a cesium-free negative ion source using sheet plasma has being carried out (Poster T4TU08). Hydrogen negative ions (H^-) are formed by the dissociative attachment (DA) of low-energy electrons e (slow) (T_e ~ 1 eV) to highly excited molecules H_2 (v" > 5), which are vibrated by the impacts of high-energy electrons e (fast) (T_e > 15 eV) in the plasma. The sheet plasma is suitable to produce negative ions, because the electron temperature in the central region of the plasma is as high as 10 -15 eV, whereas in the periphery of the plasma, a low temperature of a few eV is obtained.

In this study, we have carried out the experimental observation and modeling of molecular ions in hydrogen plasma in a linear plasma device, TPD-Sheet IV. The electron temperature and density were measured by Langmuir probe. The density of hydrogen negative ion was detected using an omegatron mass analyzer. The ground-state vibrational temperature of hydrogen molecules T_{vib} was deduced by applying the corona equilibrium model with VUV emission spectroscopy. The zero-dimensional, which is developed for solving the system of rate balance equations for ion and gas species, used to predict the measured density of hydrogen negative ion is discussed.

Reaction Processes in recombination plasma

Processes of negative ion

$H_2(5<v"<9) + e \rightarrow H^- + H^*$:(DA)

$H^- + H^+ \rightarrow 2H$:(MN) $H^- + e \rightarrow H + 2e$: (ER)

Electron-Ion Recombination(EIR)

$H^+ + e \Rightarrow H + h\nu$: (RR) $H^+ + e + e \Rightarrow H + e$: (THB)

Molecular Assisted Recombination (MAR)

$H_2(v) + H^+ \rightarrow H_2^+ + H$: (CNV) $H_2^+ + e \rightarrow H^* + H$:(DR2)

$H_2^+ + H_2 \rightarrow H_3^+ + H$: (CNV2) $H_3^+ + e \rightarrow$ 3H, $H_2 + H$: (DR3)

Molecular Assisted Dissociation (MAD)

$H_2(v) + H^+ \rightarrow H_2^+ + H$: (CNV) $H_2^+ + e \rightarrow H + H^+ + e$: (eD2)

Molecular Assisted Ionization (MAI)

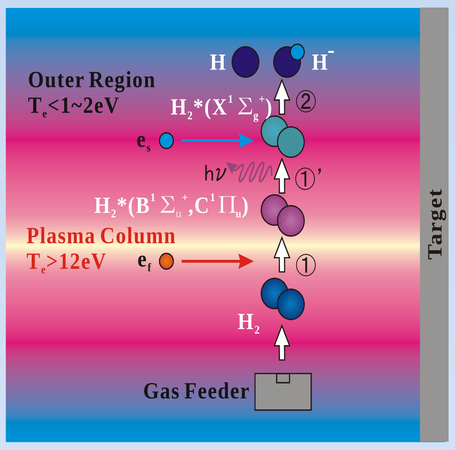
$H_2(v) + H^+ \rightarrow H_2^+ + H$: (CNV) $H_2^+ + e \rightarrow H^+ + H^+ + 2e$: (eDI2)

$H + e \rightarrow H^+ + 2e$: (eI) $H_2(v) + e \rightarrow 2H + e$: (eD)

$H_2 + e \rightarrow H + H^* + e$: (eDn) $H_2 + e \rightarrow H_2^+ + 2e$: (eI2)

$H_2(v) + e \rightarrow H^+ + H + 2e$: (eDI) $H_3^+ + e \rightarrow H_2^+ + H + e$: (eD3)

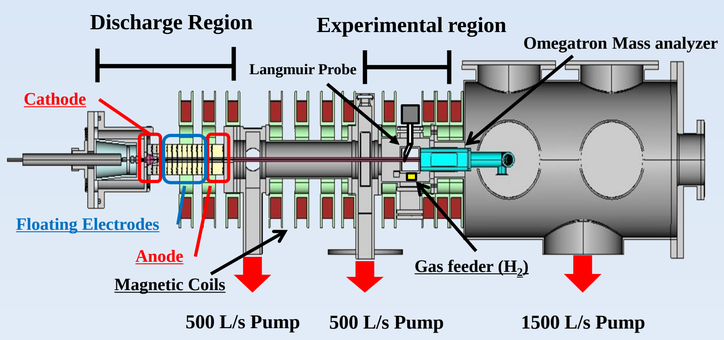
$H_3^+ + H \rightarrow H_2^+ + H_2$: (BCNV2) $H_2^+ + H \rightarrow H_2 + H^+$: (BCNV)



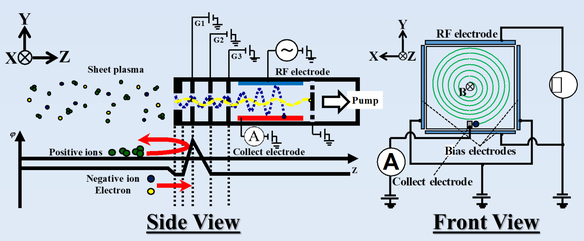
Schematic of negative ion product process

Experimental Apparatus

Linear Plasma Device TPD-Sheet IV

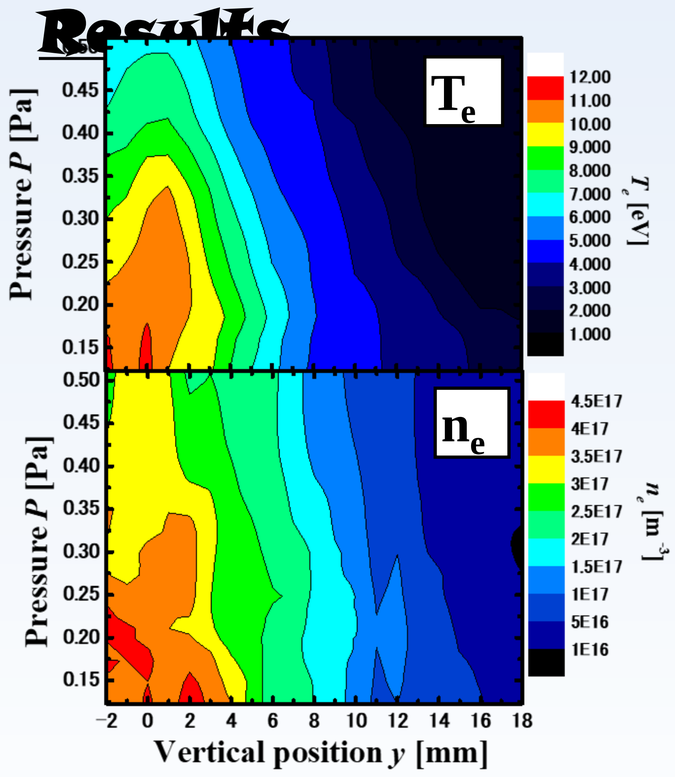


Omegatron mass analyzer

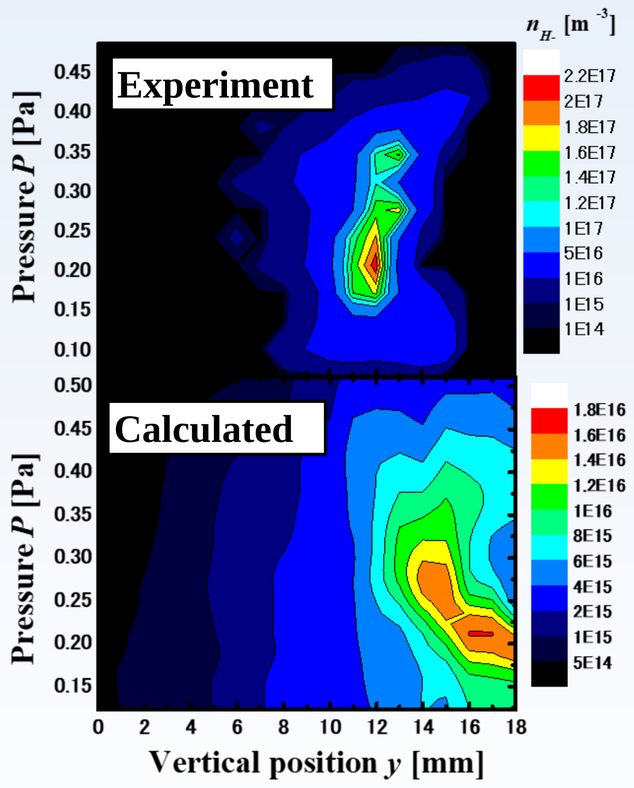


- Electron density and temperature (n_e,T_e) ··· Langmuir probe
- Hydrogen Negative ion density (n_{H-}) ··· Omegatron mass analyzer
- Vibrationally excited hydrogen molecules $H_2(v)$ ··· VUV spectroscopy

Experiment and Calculated Results



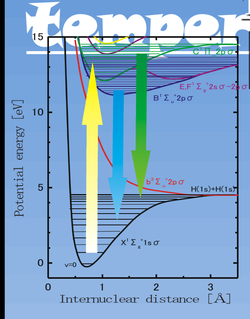
Probe measurement of electron temperature and electron density



Experimental and Calculated density of Hydrogen Negative ion

Calculation of vibrational temperature T_{vib}

Transitions of H_2



$H_2(X^1\Sigma_g^+, v") + e \rightarrow H_2(B^1\Sigma_u^+(v'), C^1\Pi_u(v'), D^1\Pi_u(v')\cdots) + e$

Cascade contributions

$X^1\Sigma_g^+ \rightarrow E, F^1\Sigma_g^+ \rightarrow B^1\Sigma_u^+$

Radiation trapping

$H_2(X^1\Sigma_g^+, v") + h\nu(VUV)$

Corona model

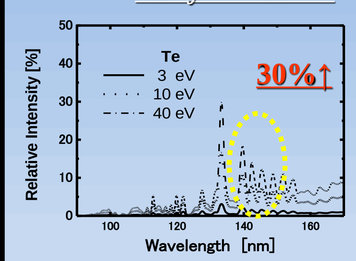
Electron impact excitation rate

$$c_{Xv}^{Bv',Cv',Dv'} = \langle \sigma_{Xv}^{Bv',Cv',Dv'} \upsilon_e \rangle = \frac{q_{Xv}^{Bv',Cv',Dv'} \exp\left(\frac{\Delta G_{B,C,D}(v)}{T_e}\right)}{\sum_{v'} q_{Xv}^{Bv',Cv',Dv'} \exp\left(\frac{\Delta G_{B,C,D}(v)}{T_e}\right)} \langle total\, \sigma_{Xv}^{Bv',Cv",Dv'} \upsilon_e \rangle$$

Calculated relative intensities

$$I_{Xv"}^{Bv',Cv',Dv'} = \frac{A_{Xv"}^{Bv',Cv',Dv'}}{\sum_{v'} A_{Xv"}^{Bv',Cv',Dv'}} \frac{hc}{\lambda_{Xv"}^{Bv',Cv',Dv'}} n_e \sum_v \left\{ c_{Xv}^{Bv',Cv',Dv'} n_{Xv} \exp\left[-\frac{G_X(v)}{kT_{vib}^X}\right] \right\}$$

Cascade contributions to Lyman-band



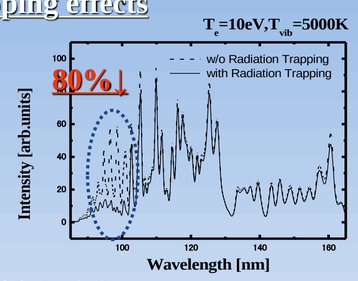
Radiation trapping effects

Escape factor g_0 $A_p^q \rightarrow A_p^q g_{0p}^q$ $(g_0 \le 1)$

$$g_0 \cong \frac{1.92 - 1.3/[1+(\kappa_0 R)^{6/5}]}{(\kappa_0 R + 0.62)[\pi \log_e(1.357 + \kappa_0 R)]^{1/2}},$$

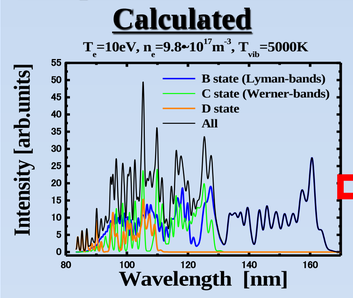
$$\kappa_0 = \frac{e^2}{4mc\varepsilon_0 \nu_p^q} \sqrt{\frac{Mc^2}{2k_B T_n \pi}} n(p) f_{p,q}$$

$n(p)$ is population density of level p,
$f_{p,q}$ is oscillator strength for transition $p \rightarrow q$

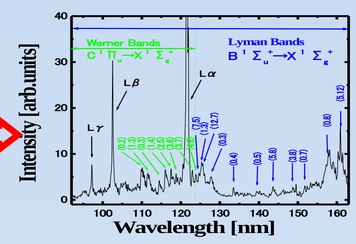


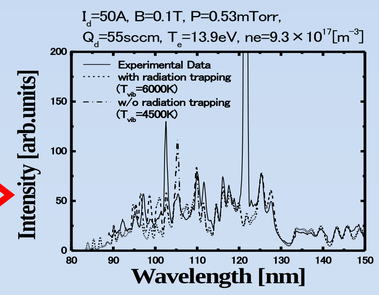
Comparison and calculated and measured VUV Spectroscopy

Calculated



Measured





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Rate balance equation of H^+, H_2^+, H_3^+ and H^-

$$\frac{\partial n_{H^+}}{\partial t} = 0 = n_{H^-} n_e S_{eI} + n_{H_2^+} n_H S_{BCNV} + n_{H_2} n_e S_{eDI} + n_{H_2^+} n_e S_{eD2} + 2 n_{H_2^+} n_e S_{eDI2} + C_{H^+}$$
$$- n_{H_2} n_{H^+} S_{CNV} - n_{H^+} n_e S_{Tbr} - n_{H^+} n_e S_{Rr} - n_{H^-} n_{H^+} S_{MN} - \frac{n_{H^+}}{\tau_i}$$

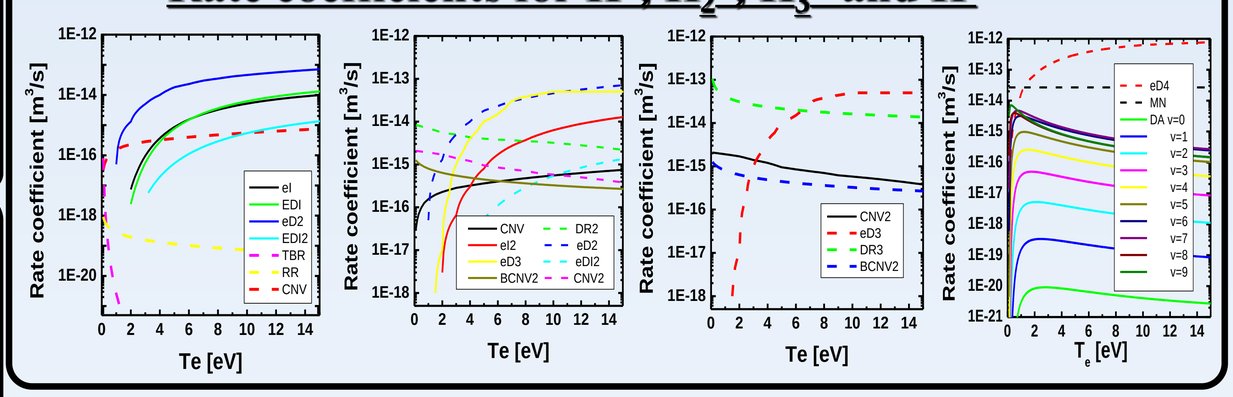
$$\frac{\partial n_{H_2^+}}{\partial t} = 0 = n_{H2} n_1 S_{CNV} - n_{H2+} n_H S_{BCNV} + n_{H2} n_e S_{eI2} - n_{H2+} n_e S_{DR2} - n_{H2+} n_e S_{eD2}$$
$$- n_{H2+} n_e S_{eDI2} - n_{H2+} n_{H2} S_{CNV2} + n_{H3+} n_e S_{eD3} + n_{H3+} n_H S_{BCNV2} - n_{H2+}/\tau_i,$$

$$\frac{\partial n_{H_3^+}}{\partial t} = 0 = n_{H2} n_{H2+} S_{CNV2} - n_{H3+} n_e S_{eD3} - n_{H3+} n_e S_{DR3} - n_{H3+} n_H S_{BCNV2} - n_{H3+}/\tau_i,$$

$$\frac{\partial n_{H^-}}{\partial t} = 0 = n_{H_2} n_e S_{DA} - n_{H^-} n_e S_{ED} - n_{H^-} n_{H^+} S_{MN} - N_{H^-}/\tau_i$$

※S:Rate coefficient, τ_i:ion lifetime, C_1:chamber influx rate of H^+

Rate coefficients for H^+, H_2^+, H_3^+ and H^-



Conclusions

- From the results of the electron temperature and density, it is found that the sheet plasma has both high electron temperature region(T_e >10eV) and low electron temperature region (T_e =1-2eV) when neutral pressure is 0.2-0.3Pa.
- The results of hydrogen negative ion density show that when neutral gas pressure is 0.2-0.3Pa, both calculated result (n_{H-} ≈10^{16}m^{-3}) and experimental result (n_{H-}≈10^{17}m^{-3}) have a peak of density at periphery region (y > 10mm).

Experiments and model calculations show that (DA) products negative ions at the periphery region of sheet plasma and the space and gas pressure profiles could be obtained.