Modeling and Measurement of Hydrogen Ion Species Fractions in a Penning Plasma Discharge

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INTRODUCTION

- **Main fields of proton ion source applications**
  - ✓ Accelerators
  - ✓ Nuclear fusion / Neutral beam injection for plasma heating or diagnostics
  - ✓ Neutron generators
  - → High beam current and high monoatomic fraction is essential.
- **Motivation of this research**
  - ✓ molecular ion beam such as H_2^+, H_3^+ → result in beam loss or reduce the reaction: high monoatomic beam is an important performance of proton ion source
- **Research objectives**
  - ✓ To establish a model to calculate the ion species fraction of hydrogen plasma → the change of the ion species fraction according to the plasma parameters & the direction to increase the monoatomic fraction
  - ✓ To measure ion species fraction and to compare with the model
    - Ion source type: PIG (*P*enning or Philips *I*onization *G*auge) ion source
    - Measure the ion species fraction: dipole mass analyzing magnet
  - → To suggest the improvement direction of the ion source

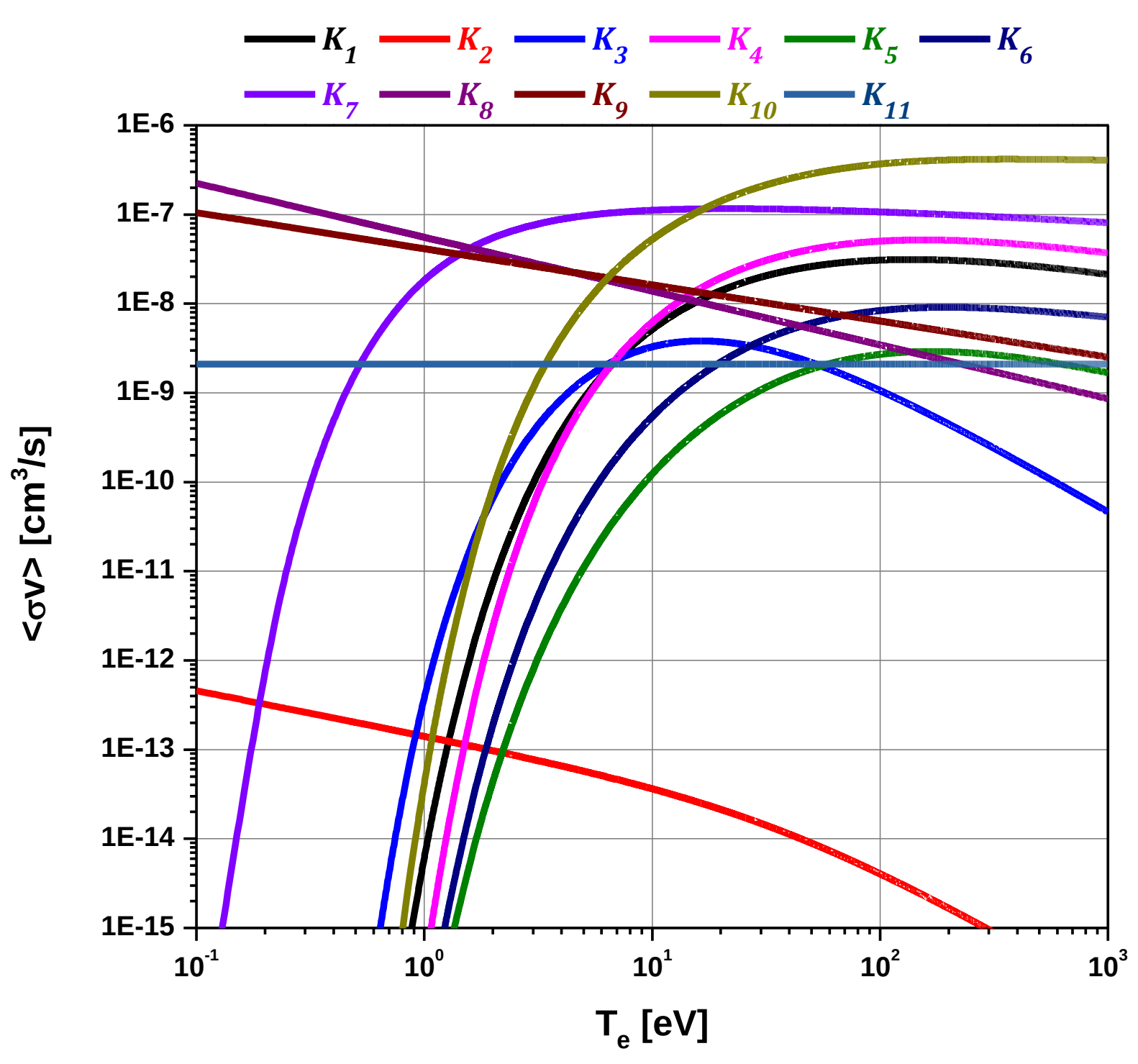
Numerical Model of Hydrogen Ion Species

List of process reactions

Reaction	Rate constants
$\mathrm{H} + e \rightarrow \mathrm{H}^+ + 2e$	K_1
$\mathrm{H}^+ + e \rightarrow \mathrm{H} + h\nu$	K_2
$\mathrm{H}_2 + e \rightarrow 2\mathrm{H} + e$	K_3
$\mathrm{H}_2 + e \rightarrow \mathrm{H}_2^+ + 2e$	K_4
$\mathrm{H}_2 + e \rightarrow \mathrm{H}^+ + \mathrm{H} + 2e$	K_5
$\mathrm{H}_2^+ + e \rightarrow 2\mathrm{H}^+ + 2e$	K_6
$\mathrm{H}_2^+ + e \rightarrow \mathrm{H}^+ + \mathrm{H} + e$	K_7
$\mathrm{H}_2^+ + e \rightarrow 2\mathrm{H}$	K_8
$\mathrm{H}_3^+ + e \rightarrow \mathrm{H}_2 + \mathrm{H}$	K_9
$\mathrm{H}_3^+ + e \rightarrow \mathrm{H}^+ + 2\mathrm{H} + e$	K_{10}
$\mathrm{H}_2^+ + \mathrm{H}_2 \rightarrow \mathrm{H}_3^+ + \mathrm{H}$	K_{11}
$\mathrm{H} \xrightarrow{(\mathrm{wall})} 1/2\,\mathrm{H}_2$	$K_{12} = \gamma D_{eff}^H/\Lambda_{eff}^2$
$\mathrm{H}^+ \xrightarrow{(\mathrm{wall})} \mathrm{H}$	$K_{13} = 1/\tau_{H^+} = u_{B,\mathrm{H}^+}A_{eff}/V$
$\mathrm{H}_2^+ \xrightarrow{(\mathrm{wall})} \mathrm{H}_2$	$K_{14} = 1/\sqrt{2}\tau_{H^+} = u_{B,\mathrm{H}_2^+}A_{eff}/V$
$\mathrm{H}_3^+ \xrightarrow{(\mathrm{wall})} \mathrm{H}_2 + \mathrm{H}$	$K_{15} = 1/\sqrt{3}\tau_{H^+} = u_{B,\mathrm{H}_3^+}A_{eff}/V$

γ: recombination coeff., D_{eff}^H: effective diffusion coeff., Λ_{eff}: effective diffusion length

τ_{H^+}: containment time of H^+, u_{B,H_x^+}: Bohm velocity of H_x^+, A_{eff}: effective area



Rate constants of volume process reactions

Equations

Particle balance equations (in steady state)

$$\frac{dn_i}{dt} = \sum_{j=1}^{N_p} a_j^p\, K_j^p \prod_{l=1}^{N_j^p} n_{jl}^p - \sum_{j=1}^{N_d} a_j^d\, K_j^d \prod_{l=1}^{N_j^{pd}} n_{jl}^d = 0$$

$$\mathbf{H}:\ K_2 n_{H^+} n_e + 2K_3 n_{H_2} n_e + K_5 n_{H_2} n_e + K_7 n_{H_2^+} n_e + 2K_8 n_{H_2^+} n_e + K_9 n_{H_3^+} n_e + 2K_{10} n_{H_3^+} n_e + K_{11} n_{H_2^+} n_{H_2} + K_{13} n_{H^+} + K_{15} n_{H_3^+} - K_1 n_H n_e - K_{12} n_H = 0$$

$$\mathbf{H^+}:\ K_1 n_H n_e + K_5 n_{H_2} n_e + 2K_6 n_{H_2^+} n_e + K_7 n_{H_2^+} n_e + 2K_{10} n_{H_3^+} n_e - K_2 n_{H^+} n_e - K_{13} n_{H^+} = 0$$

$$\mathbf{H_2^+}:\ K_4 n_{H_2} n_e - K_6 n_{H_2^+} n_e - K_7 n_{H_2^+} n_e - K_8 n_{H_2^+} n_e - K_{11} n_{H_2^+} n_{H_2} - K_{14} n_{H_2^+} = 0$$

$$\mathbf{H_3^+}:\ K_{11} n_{H_2^+} n_{H_2} - K_9 n_{H_3^+} n_e - K_{10} n_{H_3^+} n_e - K_{15} n_{H_3^+} = 0$$

Charge conservation equation

$$n_{H^+} + n_{H_2^+} + n_{H_3^+} = n_e$$

Particle conservation equation

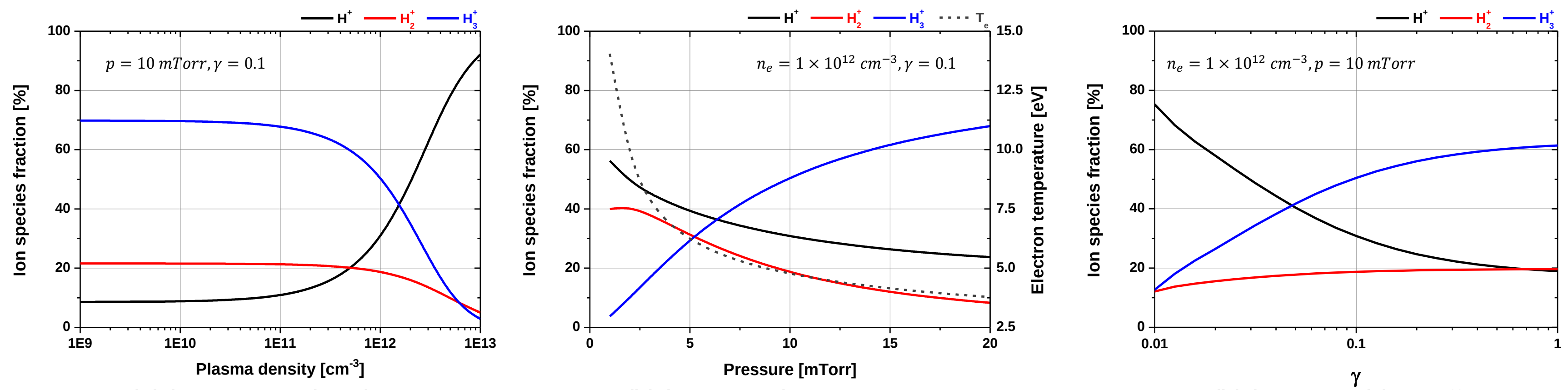
$$n_{H_2} + \frac{1}{2} n_H + \frac{1}{2} n_{H^+} + n_{H_2^+} + \frac{3}{2} n_{H_3^+} = n_g \left(= \frac{p}{k_B T_g} \right)$$

T_e and pressure relation

$$\frac{K_{iz}(T_e)}{u_B(T_e)} = \frac{1}{n_g d_{eff}}$$

$K_{iz}(T_e)$: ionization rate constant
$u_B(T_e) = \sqrt{k_B T_e/M}$: Bohm velocity
$d_{eff} = V/A_{eff}$: effective plasma size

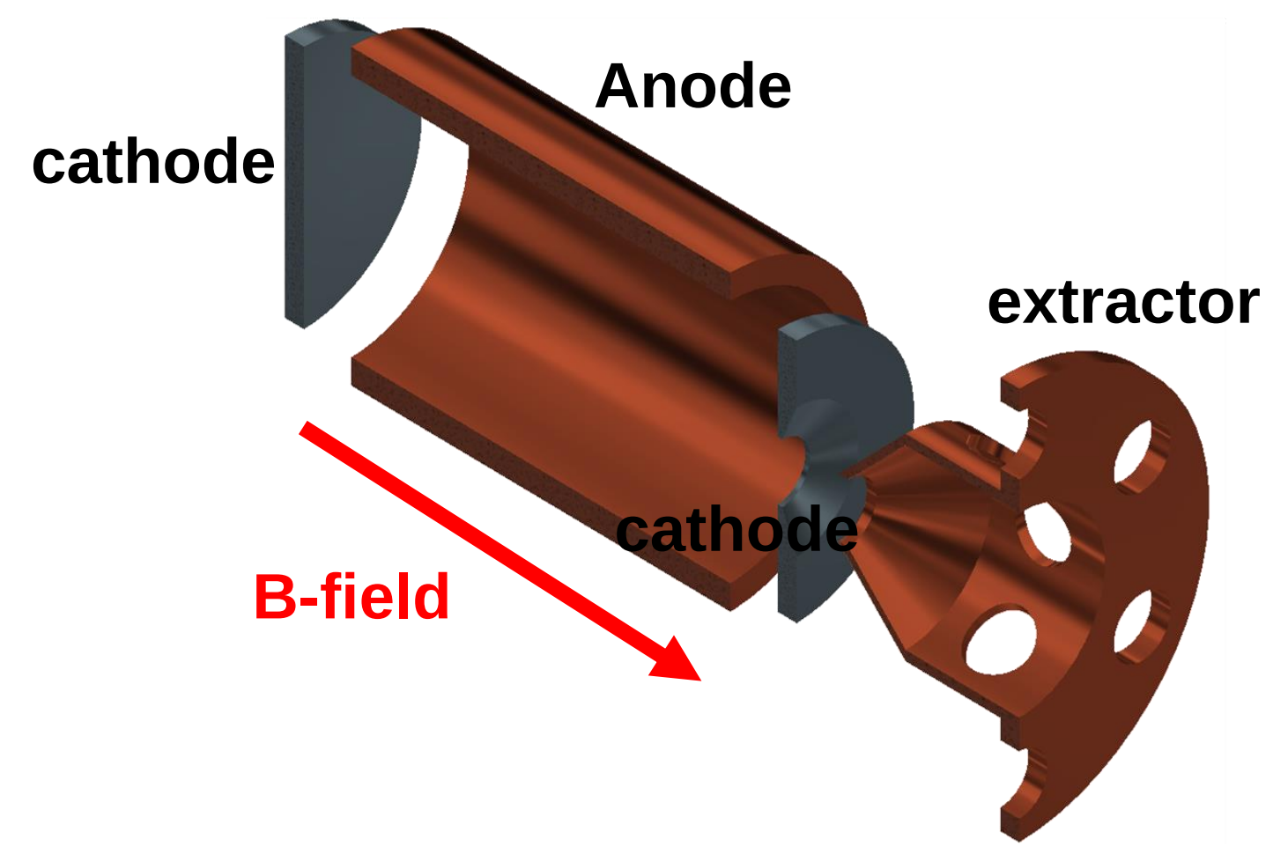
Modeling results



(a) by plasma density (b) by operating pressure (b) by recombi. coeff.

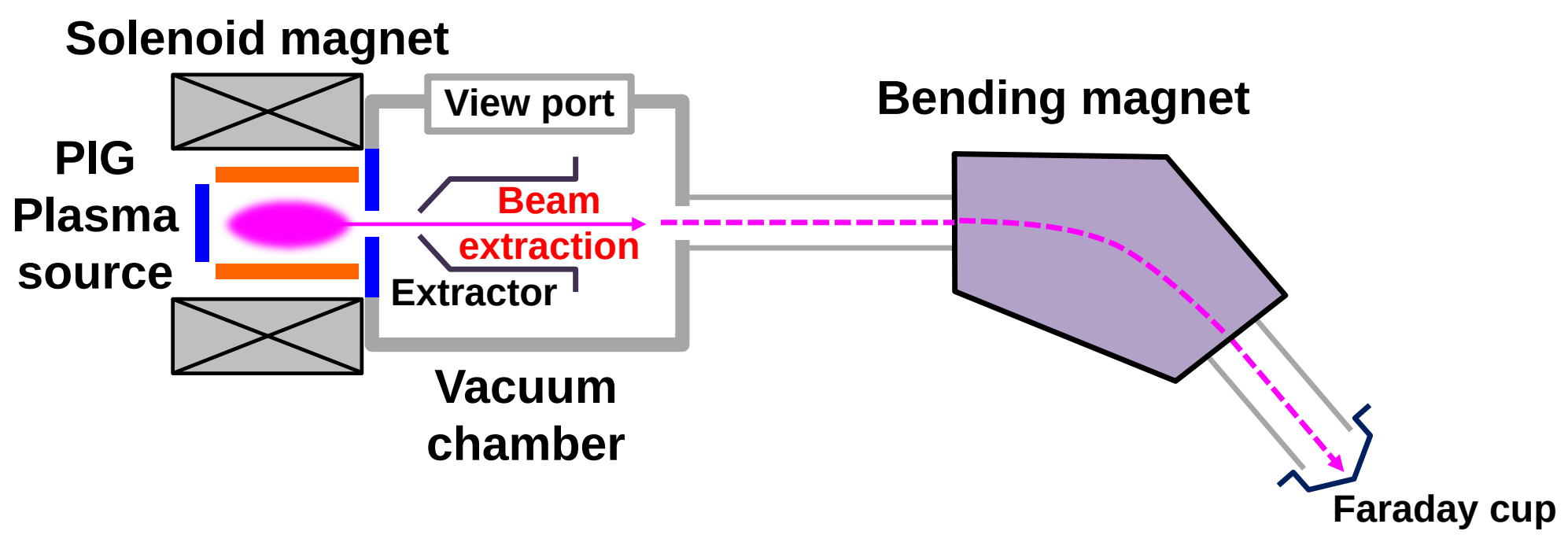
Experiments and Results

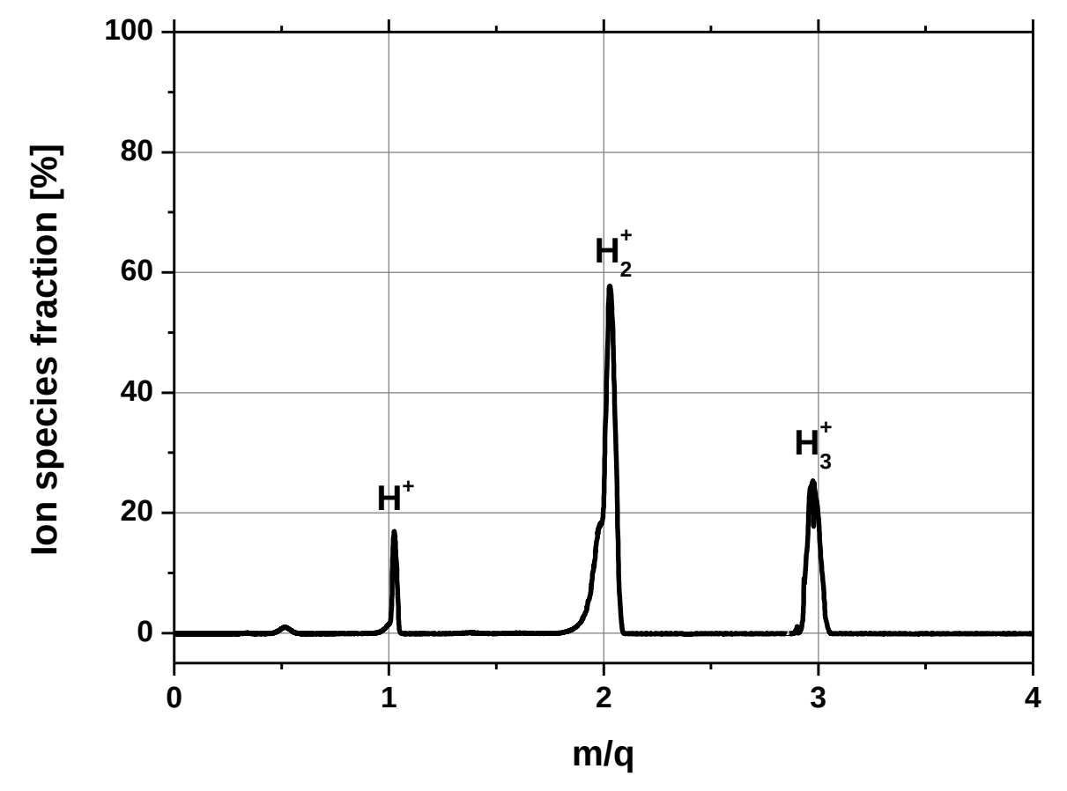
Structure of PIG ion source



Discharge volume: 25 mm(D) X 50 mm(L)
B-field: 400 – 1000 G
Gas: Hydrogen
Operating pressure: 2 – 20 mTorr
Discharge current: 10 – 400 mA

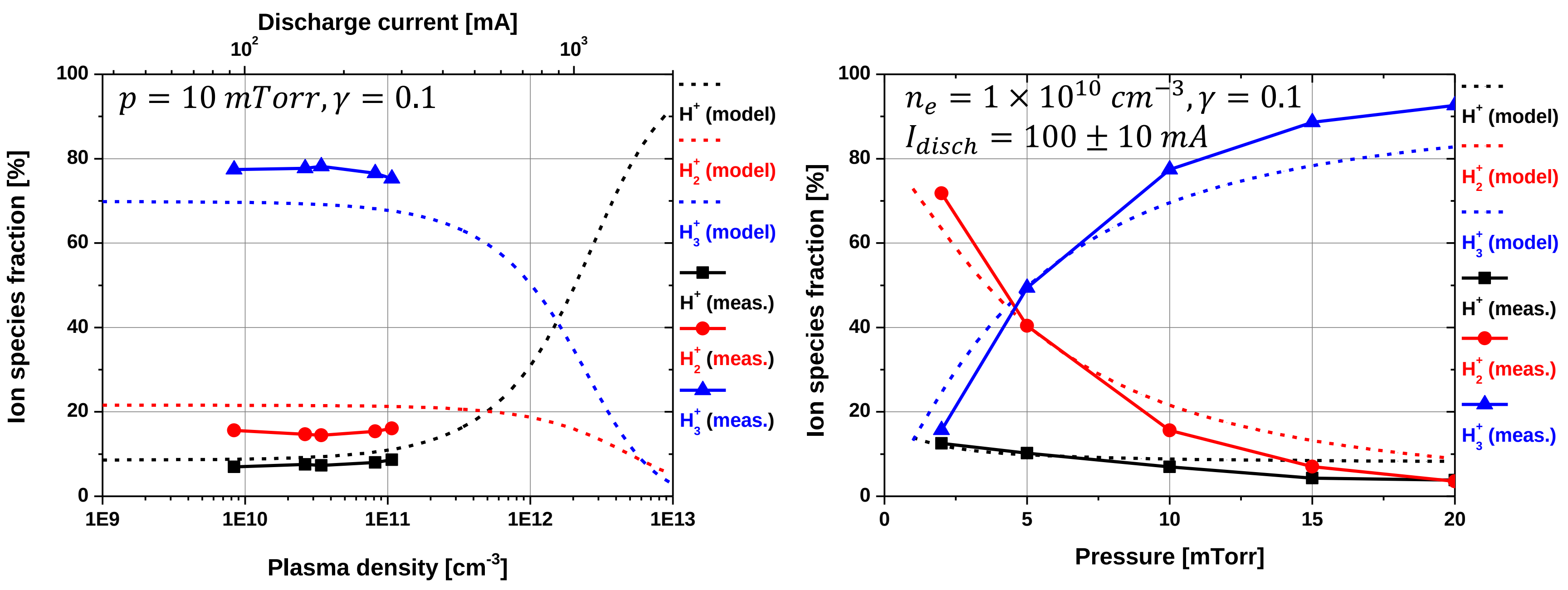
Ion species fraction measurement





An example of ion species data

Measurement vs. Model



(a) by discharge current / plasma density (b) by operating pressure

Conclusions & Future Works

- Model for the hydrogen ion species fraction
  - ✓ High plasma density and low operating pressure → increase the monoatomic fraction
- The hydrogen ion species fraction measurement at a Penning plasma discharge source
  - ✓ The model and the measurement agree well
  - ✓ The measured monoatomic fraction: about 10% or below
  - ✓ The discharge current and the density of the generated plasma is low → low monoatomic fraction
  - ✓ For a monoatomic fraction close to 90%, the plasma density → up to about 1×10^{13} cm⁻³ at 10 mTorr
- For high plasma density
  - ✓ Discharge regime: glow → arc (several amperes of the discharge current)
  - ✓ New power systems are needed.

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