Deuterium Plasma Diagnostics Using Collisional-Radiative Model Including Molecular Effects

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In order to diagnose electron temperature (T_e) and electron density (n_e) of deuterium plasma, spectroscopic method (line intensity ratio) based on collisional-radiative method was selected. CR-model based atomic process are configured and some molecular process of the dissociative excitation, mutual neutralization and dissociative recombination process for the low temperature were included in CR-model. Optical emission spectrum was measured by a monochromator (Czerny-Turner type, spectral resolution 0.313nm) and all of optical system including monochromator was calibrated with quartz halogen lamp. The transition lines of Balmer series (Balmer-α : n=3→n=2, 656.101nm, Balmer-β : n=4→n=2, 486.000nm, Balmer-γ : n=5→n=2, 433.928nm) were selected to diagnose the T_e and n_e of deuterium plasma. The diagnosed results by line intensity ratio were compared with electric probe diagnosis.

Collisional-Radiative(CR) Model

Atomic processes

1. spontaneous emission (A) $D(p) \rightarrow D(q) + h\nu$
   W.L.Wiese & J. R. Fuhr, J. Phys. Chem. Ref, Data, 38, 565 (2009)
2. excitation/de-excitation by electron collision (C) $H(p) + e^- \rightarrow H(q) + e^-$
3. ionization by electron collision (S) $H(p) + e^- \rightarrow H^+(q) + e^- + e^-$
4. three-body recombination by electron collision (α) $H^+ + e^- + e^- \rightarrow H(p) + e^-$
5. radiative recombination by electron collision (β) $H^+ + e^- \rightarrow H(p) + h\nu$
   R.K.Janev, JUEL-4105 (2003)

Molecular processes

1. dissociative excitation (γ) $H_2 + e^- \rightarrow H(p) + H(1) + e^-$
   T.Fujimoto et. al, J. Appl. Phys. 66, 2315 (1989)
2. mutual neutralization type 1 (δ_1) $H^+ + H^- \rightarrow H(p) + H(1)$
   M.Stenrup, Phys. Rev. A79, 012713 (2009)
3. mutual neutralization type 2 (δ_2) $H_2^+ + H^- \rightarrow H(p) + H_2$
   M.J.J.Eerden, Phys. Rev. A51, 3362 (1995)
4. dissociative recombination (ε) $H_3^+ + e^- \rightarrow H(p) + H_2$
   M. Larsson et al, Phys. Rev. Lett. 70, 430 (1993)

Rate equation for excited states of atom with molecular processes

$$\frac{dn(p)}{dt} = -\left\{\left(\sum_{q\neq p} C(p,q)n_e + \sum_{q<p} A(p,q)\right)n(p) + S(p)n_e n(p)\right\} + \left\{\left(\sum_{q\neq p} C(q,p)n_e + \sum_{q>p} A(q,p)\right)n(q)\right\}$$
$$+\{(\alpha(p)n_e + \beta(p))n_e n_i\} + \gamma(p)n_e n_{H_2} + \delta_1(p)n_i n_{H^-} + \delta_2(p)n_{H_2^+}n_{H^-} + \varepsilon(p)n_{H_3^+}n_e$$

atomic; de-populating; populating; molecular

Assume QSS(Quasi-Steady State) → $\frac{dn(p)}{dt} = 0\ (for\ p \neq 1)$

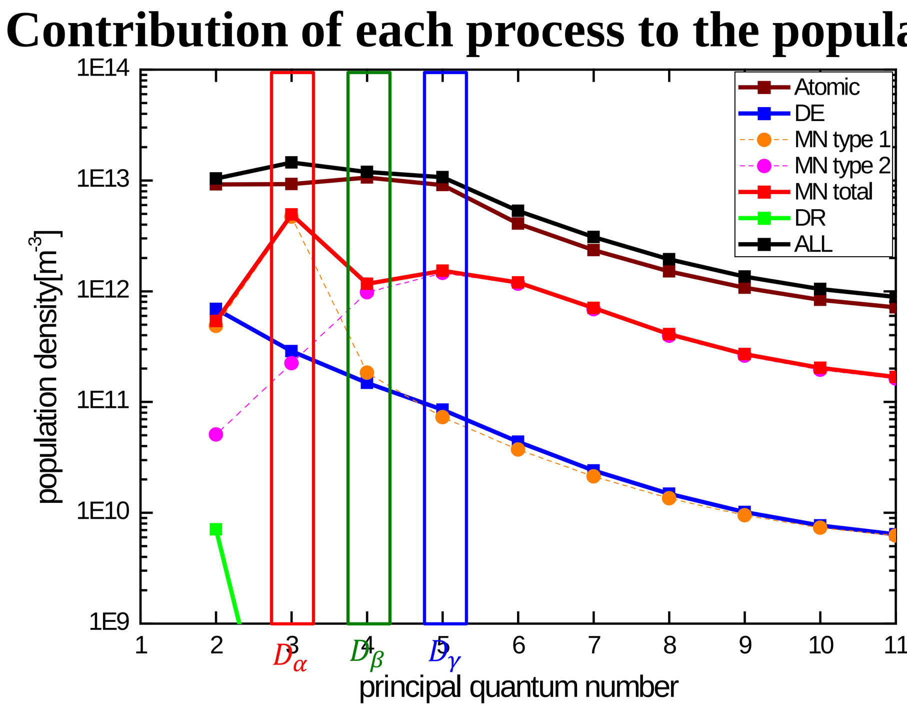
$$-\begin{pmatrix} X_{11} & X_{12} & X_{13} & \cdots \\ X_{21} & X_{22} & X_{23} & \cdots \\ X_{31} & X_{32} & X_{33} & \cdots \\ \vdots & \vdots & \vdots & \ddots \end{pmatrix}\begin{pmatrix} n(2) \\ n(3) \\ n(4) \\ \vdots \end{pmatrix} + \begin{pmatrix} \alpha(2)n_e+\beta(2) \\ \alpha(3)n_e+\beta(3) \\ \alpha(4)n_e+\beta(4) \\ \vdots \end{pmatrix} n_e n_{D^+} + \begin{pmatrix} C(1,2) \\ C(1,3) \\ C(1,4) \\ \vdots \end{pmatrix} n_e n(1) + \begin{pmatrix} \gamma(2) \\ \gamma(3) \\ \gamma(4) \\ \vdots \end{pmatrix} n_e n_{D^2} + \begin{pmatrix} \delta_1(2) \\ \delta_1(3) \\ \delta_1(4) \\ \vdots \end{pmatrix} n_{D^+}n_{D^-} + \begin{pmatrix} \delta_2(2) \\ \delta_2(3) \\ \delta_2(4) \\ \vdots \end{pmatrix} n_{D_2^+}n_{D^-} + \begin{pmatrix} \varepsilon(2) \\ \varepsilon(3) \\ \varepsilon(4) \\ \vdots \end{pmatrix} n_{D_3^+}n_{D^-} = 0$$

$$X_{pq} = -\left\{\sum_{q\neq p}(C(p,q)n_e + A(p,q)) + S(p)n_e\right\} \quad \text{for } p = q$$
$$= C(q+1,p+1)n_e + A(q+1,p+1) \quad \text{for } p < q$$
$$= C(q+1,p+1)n_e \quad \text{for } p > q$$

$$n(p) = r_0 n_e n_{D^+} + r_1 n_e n(1) + r_2 n_e n_{D_2} + r_3 n_{D^+} n_{D^-} + r_4 n_{D_2^+} n_{D^-} + r_5 n_{D_3^+} n_e$$

r : population coefficient

Contribution of each process to the population of excited states



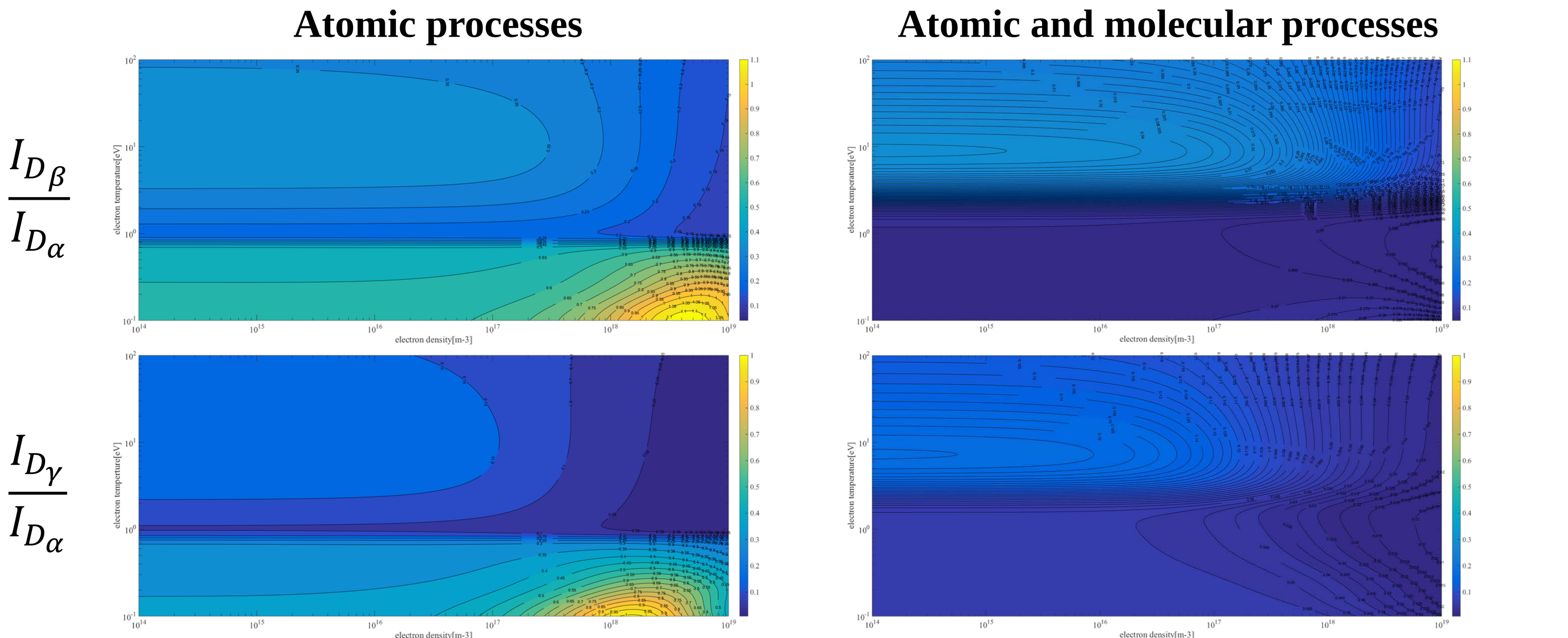
Conditions (U. Fantz et al, New J. Phys. 8, 301 (2006))
$n_{atom} = 1 \times 10^{19}\ m^{-3}$
$n_{H^+} = 5 \times 10^{17} m^{-3}$, $n_{H^-} = 5 \times 10^{16} m^{-3}$
$n_{H_2} = 5 \times 10^{19} m^{-3}$, $n_{H_2^+} = 1 \times 10^{16} m^{-3}$, $n_{H_3^+} = 1 \times 10^{15} m^{-3}$
$n_e = 5 \times 10^{17} m^{-3}$, $T_e = 3eV$

- The most influent process was mutual neutralization.
- Population density of n=3 state was the most increased by mutual neutralization (Balmer-α line intensity will be increased).

Calculated intensity ratio

Atomic processes | Atomic and molecular processes

$\frac{I_{D_\beta}}{I_{D_\alpha}}$, $\frac{I_{D_\gamma}}{I_{D_\alpha}}$



- Because of Balmer-α line intensity increase by mutual neutralization, intensity ratios were depressed at low electron temperature

Spectrum measurement and Balmer line intensity ratio

Observed radiation intensity $I_{pq} = \frac{1}{4\pi} h\nu A_{pq} n(p) V\Omega$

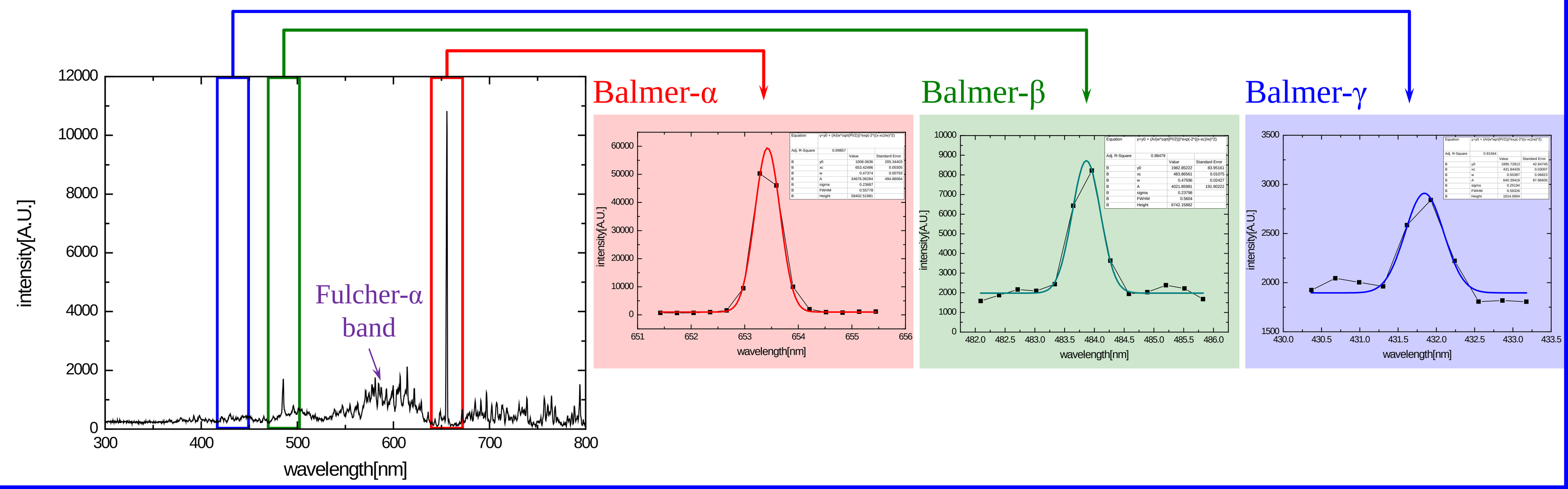
h : Planck constant
ν : frequency of emitted light
A_{pq} : radiative decay rate
$n(p)$: exited state atom density
V : measurement volume(defined by optics)
Ω : measurement solid angle(defined by optics)

Intensity ratio of deuterium Balmer line

$$\frac{I_\beta}{I_\alpha} = \frac{\nu_\beta A_\beta n(4)}{\nu_\alpha A_\alpha n(3)} \quad \text{and} \quad \frac{I_\gamma}{I_\alpha} = \frac{\nu_\gamma A_\gamma n(5)}{\nu_\alpha A_\alpha n(3)}$$

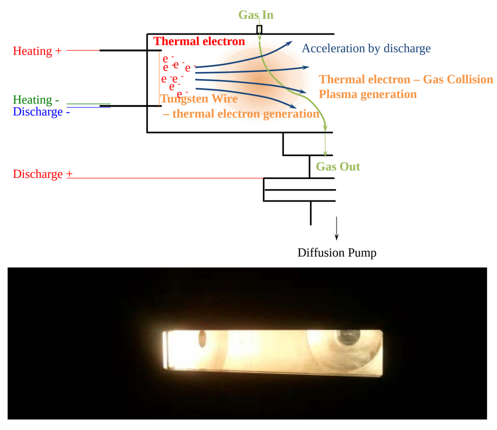
ν_α: 456.942 THz, ν_β: 616.872 THz, ν_γ: 690.898 THz
A_α: 4.41010 × $10^7\ s^{-1}$, A_β: 0.84193 × $10^7\ s^{-1}$, A_γ: 0.25304 × $10^7\ s^{-1}$

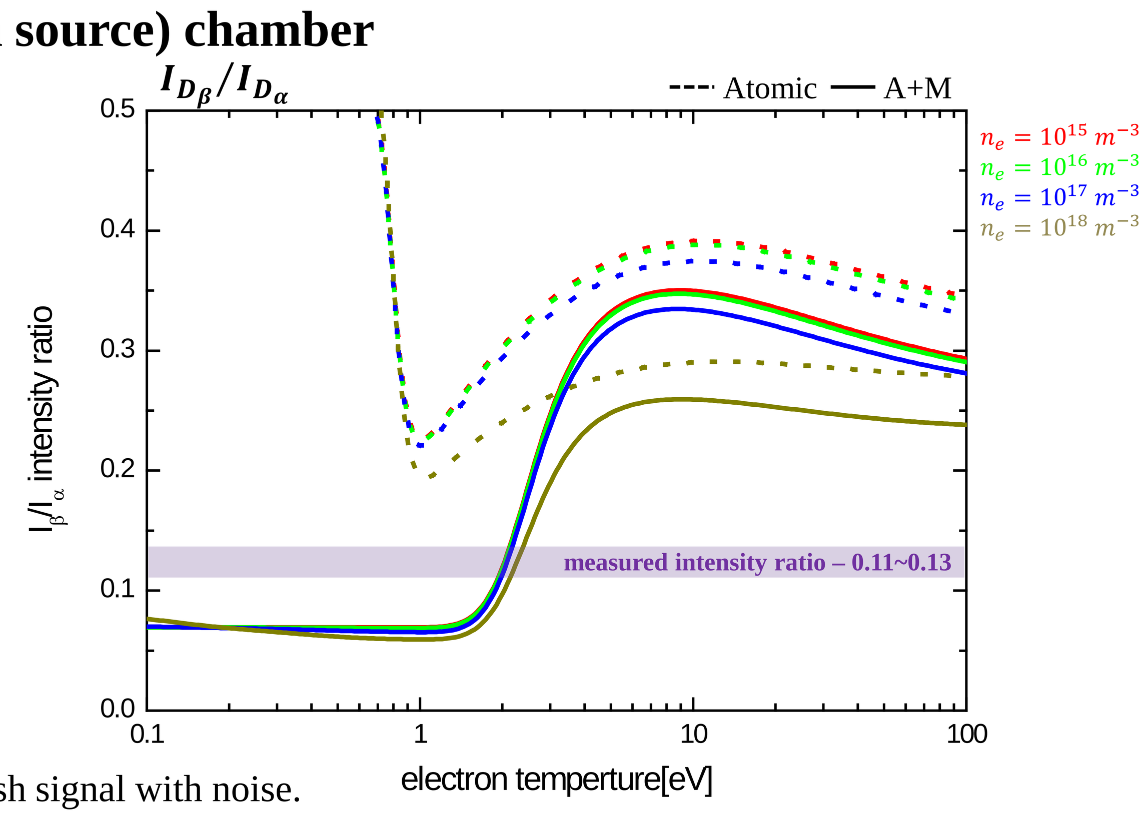
Typical deuterium spectrum of low temperature plasma in visible range



Plasma diagnostics

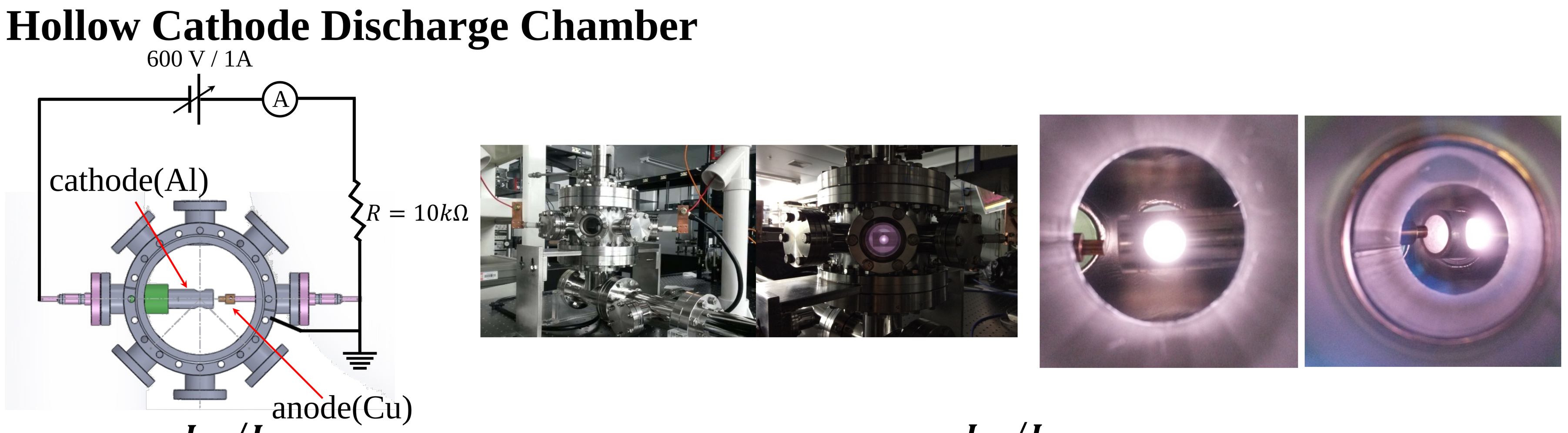
Filament (thermal electron source) chamber

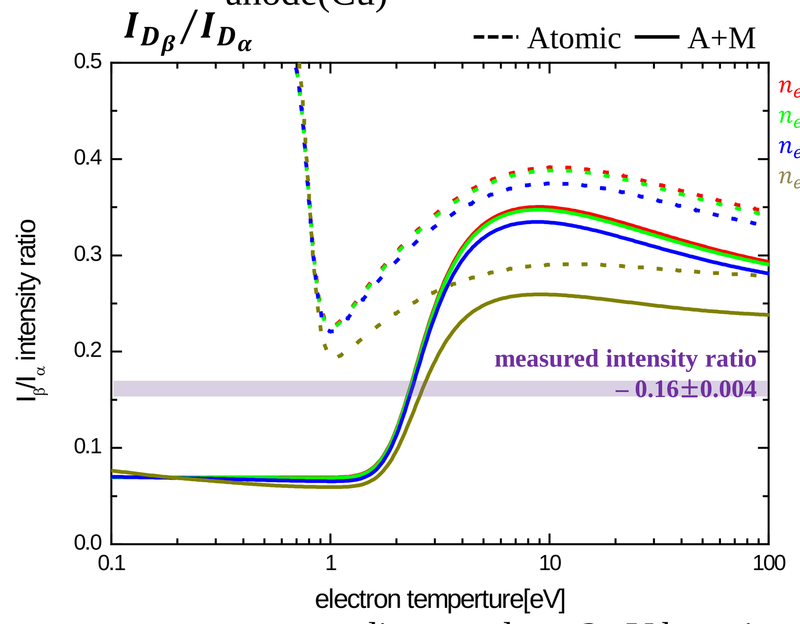


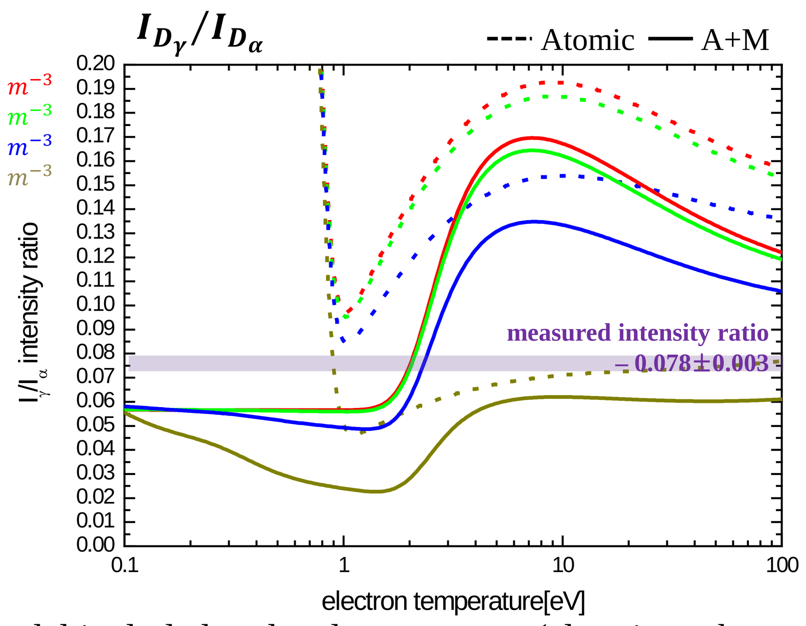


- D_γ peak was too small to distinguish signal with noise.
- Electron temperature (T_e) was not diagnosed using atomic CR model.
- T_e was diagnosed to ~1 eV by using CR model included molecular processes (electric probe - 1.24±0.09 eV).

Hollow Cathode Discharge Chamber







- Electron temperature was diagnosed to ~2 eV by using CR model included molecular processes (electric probe - 3.18±0.5 eV).

Results

- We diagnosed electron temperature more precisely by using CR model included molecular processes.
- In order to diagnose the plasma parameters more precisely, we will improve accuracy of the CR-model by concerning radiation trapping effect and another process.