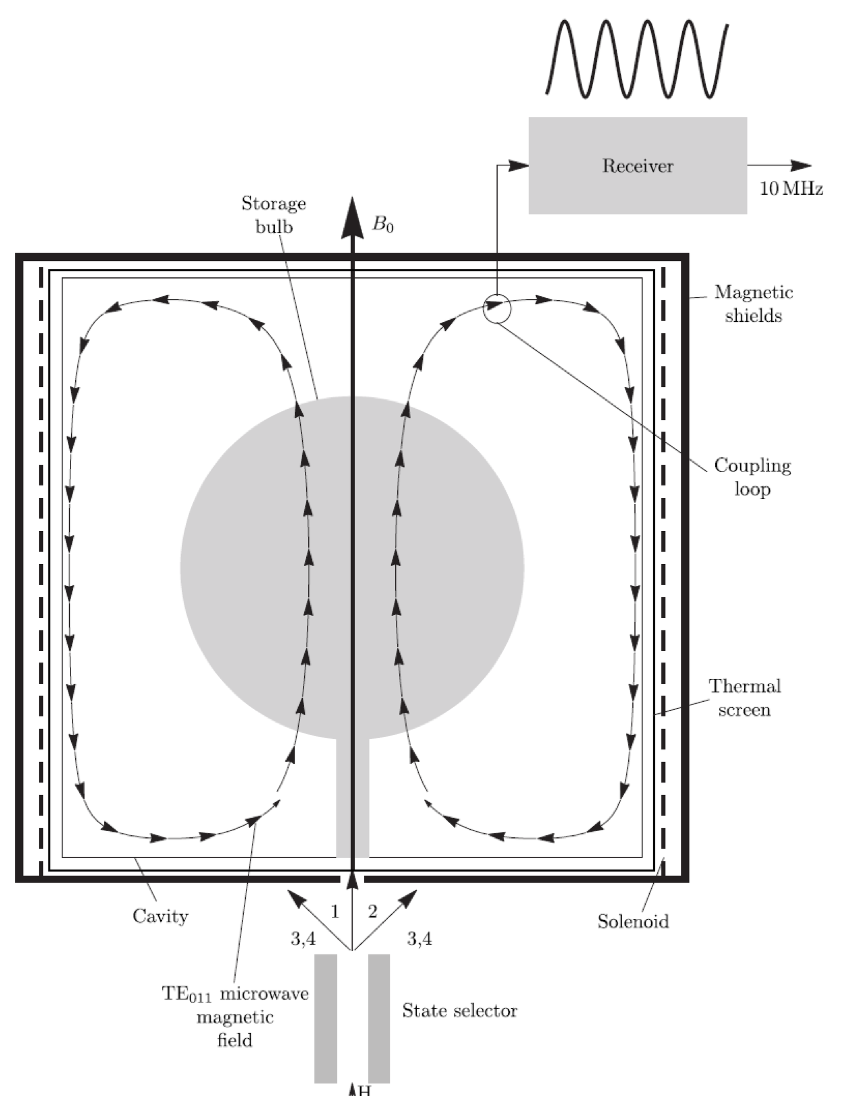
Detailed plasma source modeling for hydrogen masers

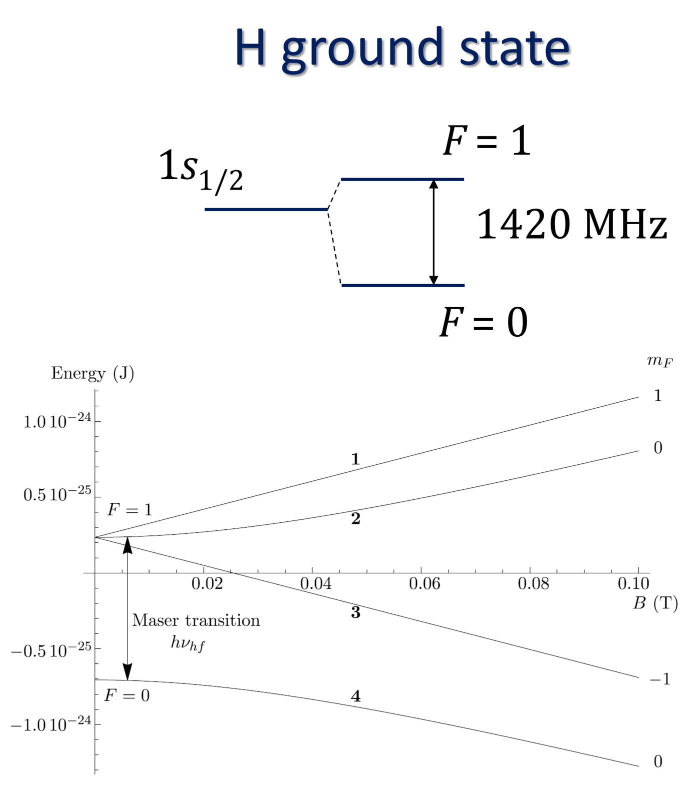
T. Bastin and D. Léonard

Institut de Physique Nucléaire, Atomique et de Spectroscopie, Université de Liège, 4000 Liège, Belgium

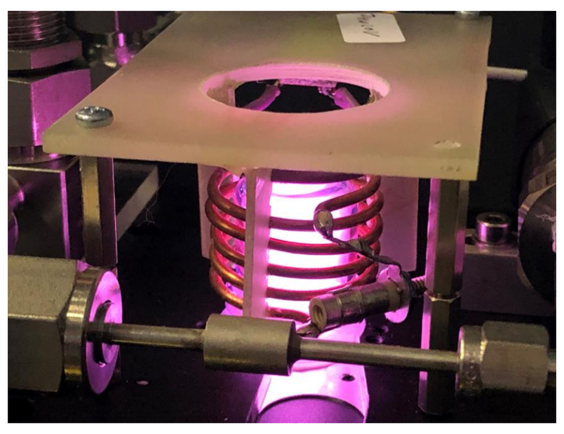
We report a detailed plasma source modeling for hydrogen masers and we show that low pressure plasma offers better performances with respect to molecular hydrogen dissociation. The role of ions H_3^+ and H^- in the discharge plasma is also discussed.

Hydrogen maser: scheme of principle



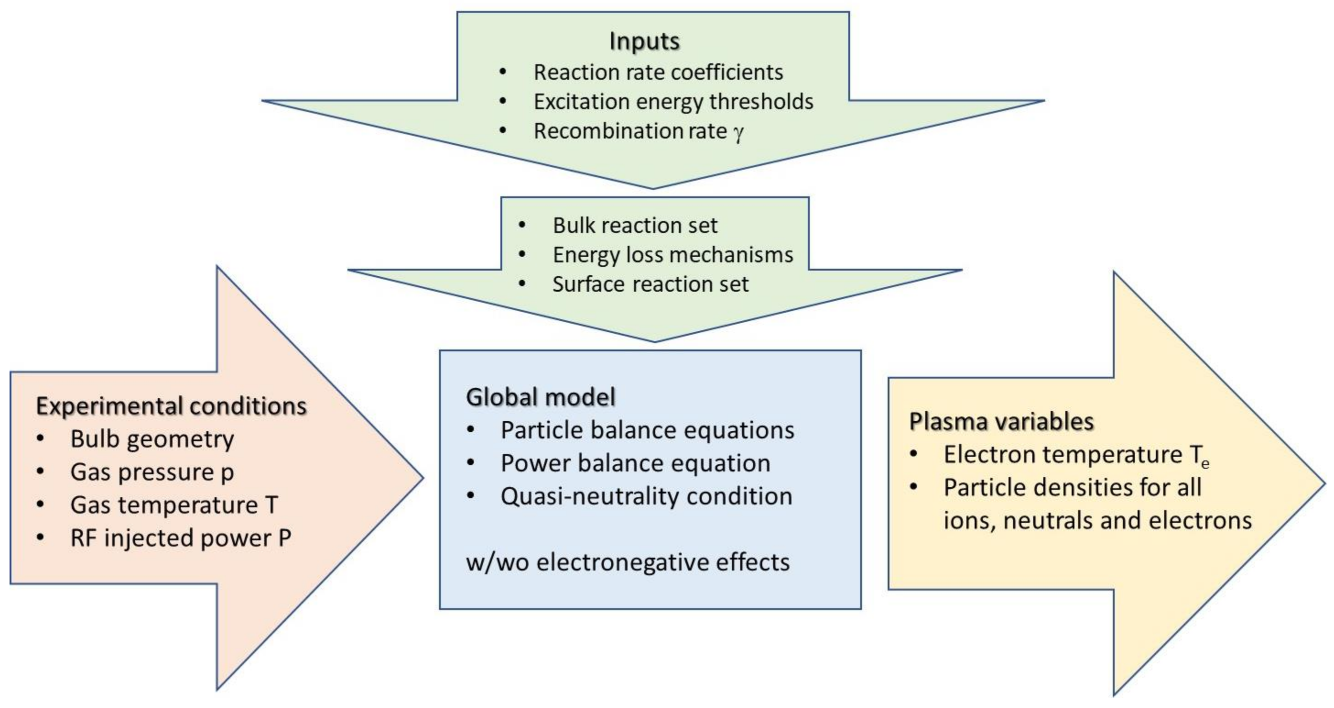


Discharge bulb in operation



H plasma

Plasma global modeling principle



Comprehensive bulk reaction set

1. $e + H_2 \rightarrow H_2^+ + e + e$
2. $e + H_2 \rightarrow H + H + e$
3. $e + H \rightarrow H^+ + e + e$
4. $H + H_2^+ \rightarrow H_2 + H^+$
5. $e + H_2^+ \rightarrow H + H^+ + e$
6. $e + H_2^+ \rightarrow H + H$
7. $H_2 + H_2^+ \rightarrow H + H_3^+$
8. $e + H_3^+ \rightarrow H + H + H^+ + e$
9. $H_2 + H^+ \rightarrow H_3^+$
10. $e + H_3^+ \rightarrow H + H + H$
11. $e + H_3^+ \rightarrow H + H_2$
12. $e + H_2 \rightarrow H + H^-$
13. $e + H_3^+ \rightarrow H_2^+ + H^-$
14. $H^+ + H^- \rightarrow H + H$
15. $H_2^+ + H^- \rightarrow H + H + H$
16. $H_3^+ + H^- \rightarrow H + H + H + H$
17. $e + H^- \rightarrow H + e + e$

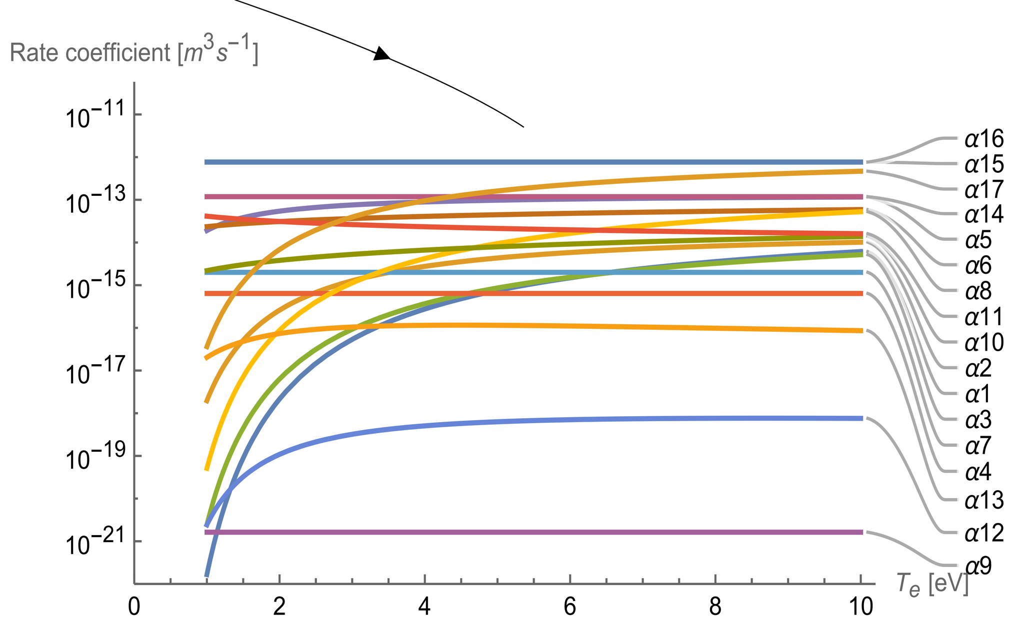
Bulk excitation processes

1. $e + H(1s) \rightarrow e + H^*(n = 2, \ldots, 5)$
2. $e + H_2(X\,^1\Sigma_g^+) \rightarrow e + H_2^*(b\,^3\Sigma_u^+, a\,^3\Sigma_g^+, c\,^3\Sigma_u) \rightarrow e + H + H$
3. $e + H_2(v = 0) \rightarrow e + H_2^*(v = 1,2)$
4. $e + H_2(X\,^1\Sigma_g^+) \rightarrow e + H_2^*(B\,^1\Sigma_u^+\ 2p\sigma)$
5. $e + H_2(X\,^1\Sigma_g^+) \rightarrow e + H_2^*(C\,^1\Pi_u\ 2p\pi)$
6. $e + H_2(X\,^1\Sigma_g^+) \rightarrow e + H_2^*(E, F\,^1\Sigma_g^+)$.

Surface reaction set

1. $H + H + wall \rightarrow H_2$
2. $H^+ + wall \rightarrow H$
3. $H_2^+ + wall \rightarrow H_2$
4. $H_3^+ + wall \rightarrow H + H_2$

See Refs. [1,2]



Particle balance equations (here, for all species X = H, H_2, H^+, H_2^+, H_3^+, H^-)

Variation rate of a species X density = sum of generation reaction rates* – sum of loss reaction rates*

→ Non-linear 1st order system of differential equations governing the time evolution of electron temperature T_e and particle densities → stationary state

Power balance equation

Expresses the balance between the injected RF power in the plasma and the power losses with elastic and inelastic collisions (mainly between free electrons and neutrals) and due to charged particle flow in the walls

+ Quasi-neutrality condition (the plasma is globally neutral)

electron density + sum of negative ion densities = sum of positive ion densities

Mass conservation condition

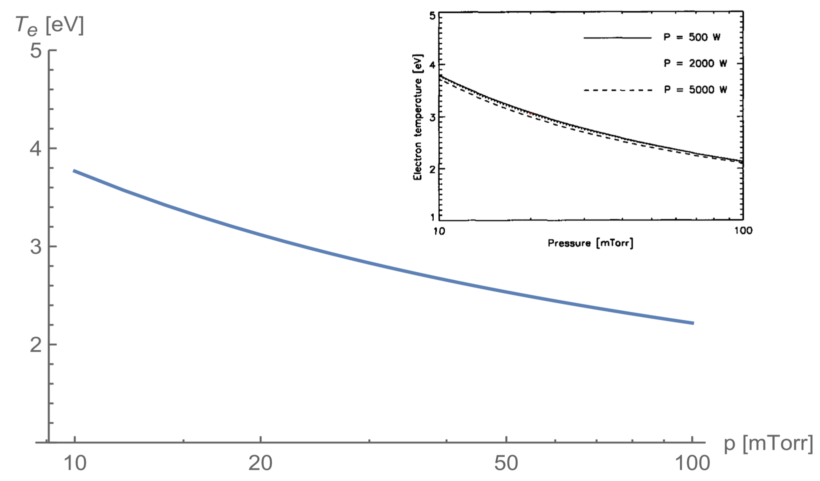
Weighed sum of plasma particle densities = initial H_2 gas density (p/k_BT)

*equal to the product of reactant densities and reaction rate coefficient α

Code benchmarking

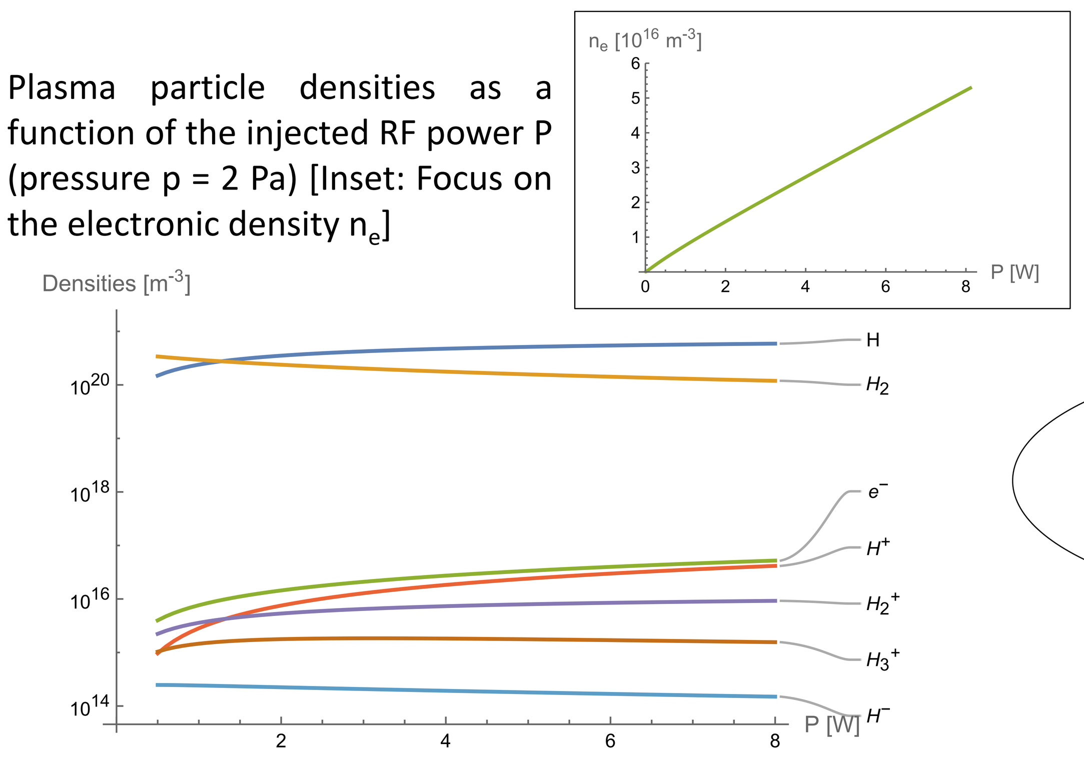
Comparison with existing plasma cell studies

Electron temperature T_e as a function of the gas pressure p for the discharge cell (9.8 liters) considered in Zorat's thesis [3] (Blue: Our model with P = 500 W, inset: Zorat's plot)



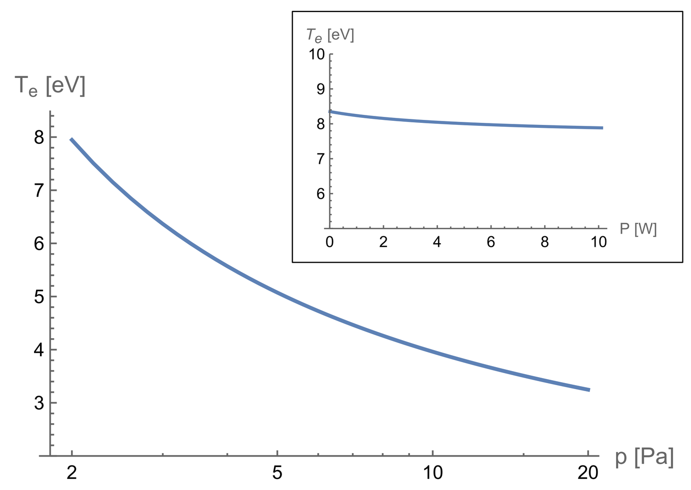
Plasma particle densities & e^- temperature

Plasma particle densities as a function of the injected RF power P (pressure p = 2 Pa) [Inset: Focus on the electronic density n_e]

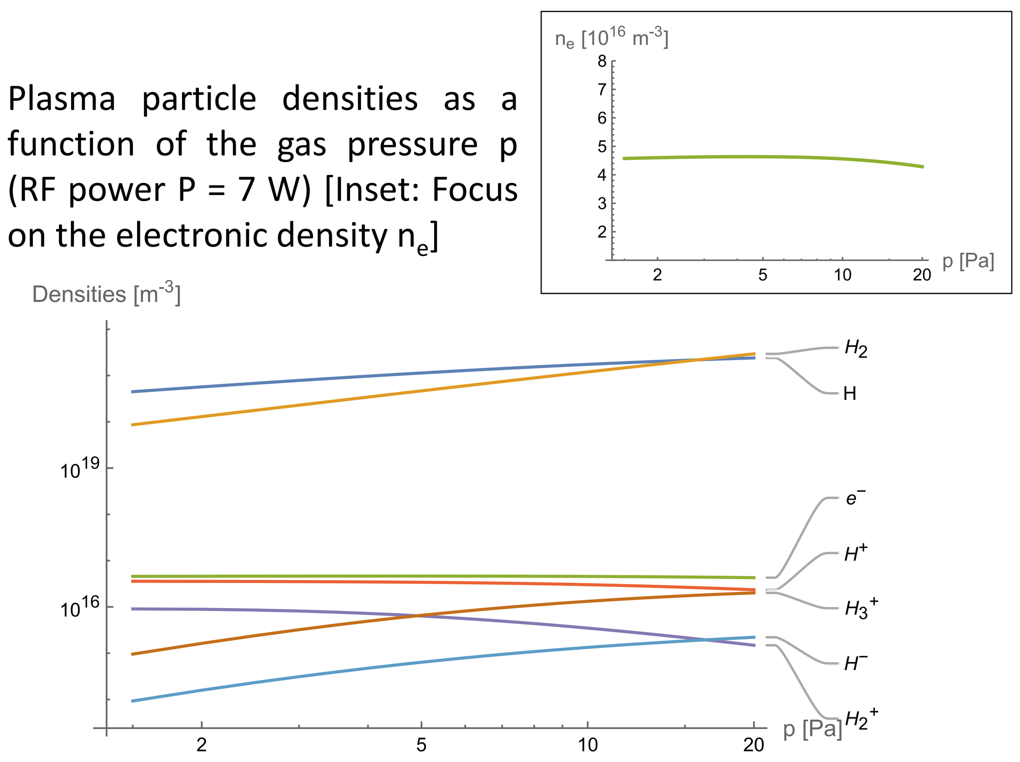


- Bulb radius R = 10 mm
- Bulb length L = 30 mm
- Plasma temperature T = 350 K
- Recombination rate γ = 0.001

Plasma particle densities as a function of the gas pressure p (RF power P = 7 W) [Inset: Focus on the electronic density n_e]



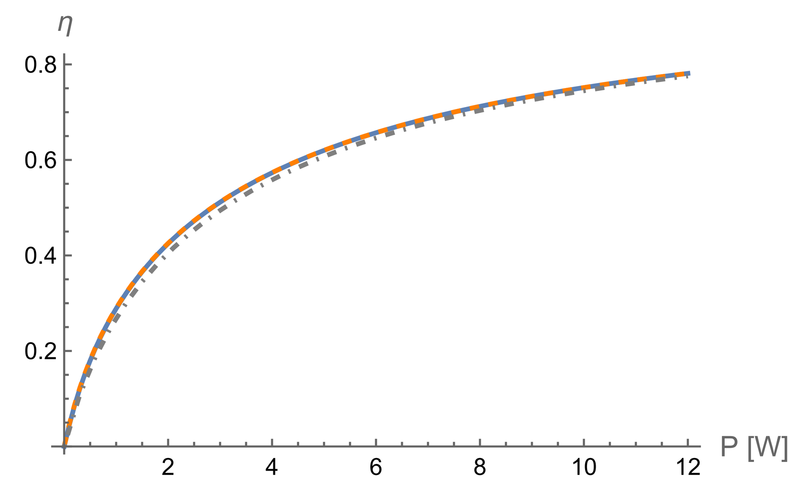
Electron temperature T_e as a function of the gas pressure p (RF power P = 7 W) [Inset: as a function of the RF power at 2 Pa]



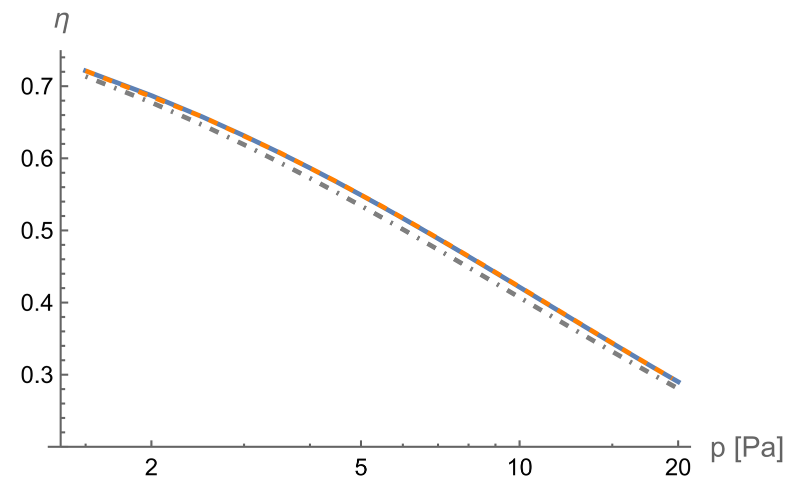
Dissociation efficiency η

$$\eta = \tfrac{1}{2} N_1/N_0 = 1/(1+2\,N_2/N_1) \quad (\text{since } N_2 + N_1/2 \approx N_0)$$

N_1 : H density
N_2 : H_2 density
N_0 : initial H_2 density



Dissociation efficiency η as a function of the injected RF power (pressure p = 2 Pa)



Dissociation efficiency η as a function of the gas pressure p (RF power P = 7 W)

Orange dotted: only processes 1-11 (no H^- processes)
Gray dotdashed: only processes 1-6 (no H_3^+ and H^- processes)

Conclusions

Both the injected RF power P and the gas pressure p act as two efficient ***independent*** *knobs on two distinct internal variables of the plasma. The RF power P forwardly tunes the electron density n_e with marginal effect on the electron temperature T_e, whereas the gas pressure p reversely tunes the electron temperature T_e, and so the hydrogen reaction rates in the bulb, with marginal effect on the electron density n_e. Both knobs act oppositely on the dissociation efficiency η: increasing the RF power P increases η (overall increase of the reactants, hence of their products), while increasing the gas pressure p decreases it (overall decrease of the reaction rates, hence of reactant products).*

→ *Better to work at 2 Pa than at 10 Pa*

- *H^- ion processes do not play any significant role*
- *H_3^+ ion processes do play a very minor role*

References

[1] A.T. Hjartarson *et al.*, Plasma Sources Sci. Technol. **19**, 065008 (2010); Samuel and Corr, Plasma Sources Sci. Technol. **25**, 015014 (2016).

[2] R.K. Janev et al., *Elementary processes in Hydrogen-Helium Plasmas: Cross Sections and Reaction Rate Coefficients*, Springer-Verlag Berlin (1987).

[3] R. Zorat, PhD thesis, *Numerical Modelling of low temperature radio-frequency hydrogen plasmas*, Dublin (2003).