Investigation of iodine plasmas for space propulsion applications

Laboratoire de Physique des Plasmas

Pascal Chabert

Laboratoire de Physique des Plasmas

CNRS, Ecole Polytechnique, France

Contributors for this talk

- PhD students : **Benjamin Esteves**, Pascaline Grondein, Romain Lucken, Nicolas Lequette, **Florian Marmuse**

- Colleagues :
  - Experiments : Ane Aanesland, Jean-Paul Booth, Cyril Drag, Valery Godyak
  - Modelling: Anne Bourdon, Alejandro Alvarez Laguna

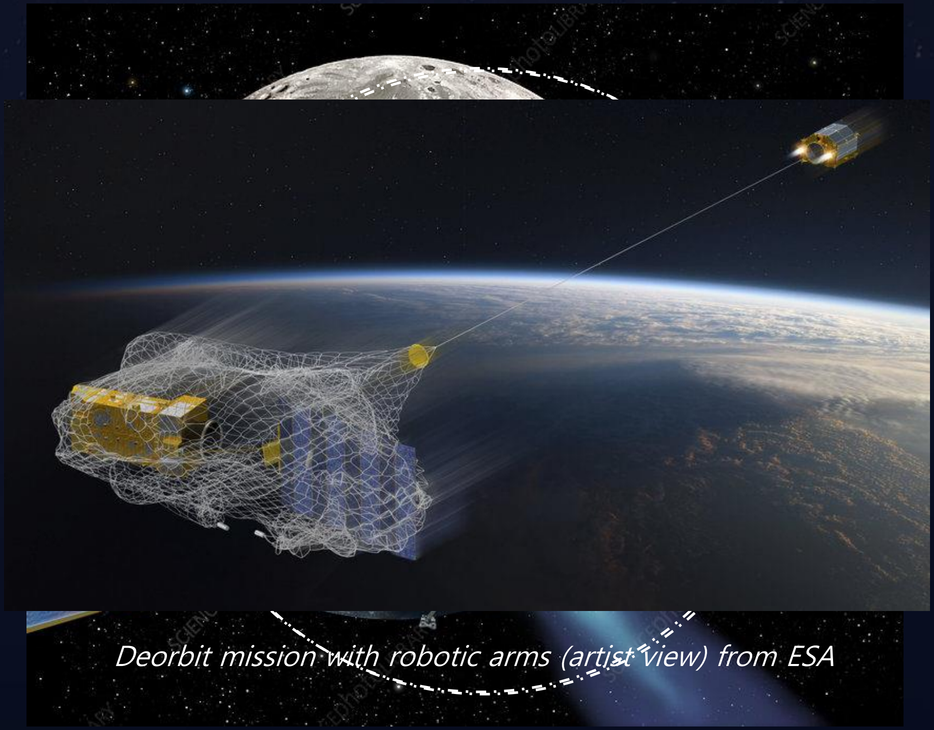
- Engineers : Garrett Curley, Bruno Dufour, Pascal Pariset, Jean Guillon,

Courtesy of Thomas Charoy

Space propulsion

Thrusters are needed

- Station keeping (atmospheric drag)
- Orbital change
- Space debris removal
- Deep-space exploration: Bepi Colombo (Mercury), Juice (Jupiter), etc.



Deorbit mission with robotic arms (artist view) from ESA

Artist view of SMART 1 (propelled by a Hall thruster) entering lunar orbit. Credit: David A. Hardy, Futures: 50 years in space, Science Photo Library

Propulsion basics: the rocket equation

- The Tsiolkovsky (rocket) equation :

$$\frac{dm}{dt}v_e = -m\frac{dv}{dt} \qquad Q_e = \frac{dm}{dt}$$

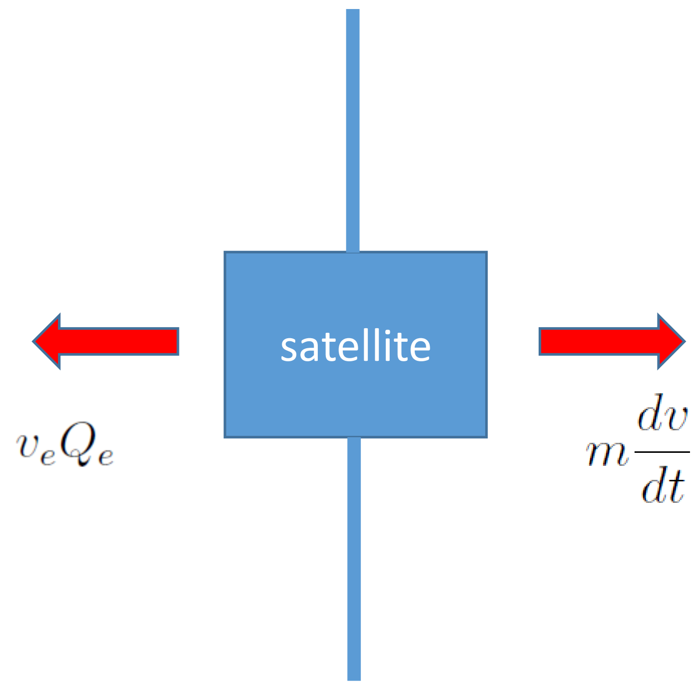
- The thrust and specific impulse are :

$$T = v_e\frac{dm}{dt} = v_e Q_e \qquad I_{\text{sp}} = \frac{T}{Q_e g_0} = \frac{v_e}{g_0}$$

- In a Plasma Thruster :

$$v_e = \sqrt{\frac{2eV_{\text{accel}}}{m_i}}$$

$$Q_e = \left(\frac{m_i}{e}\right) I_b$$



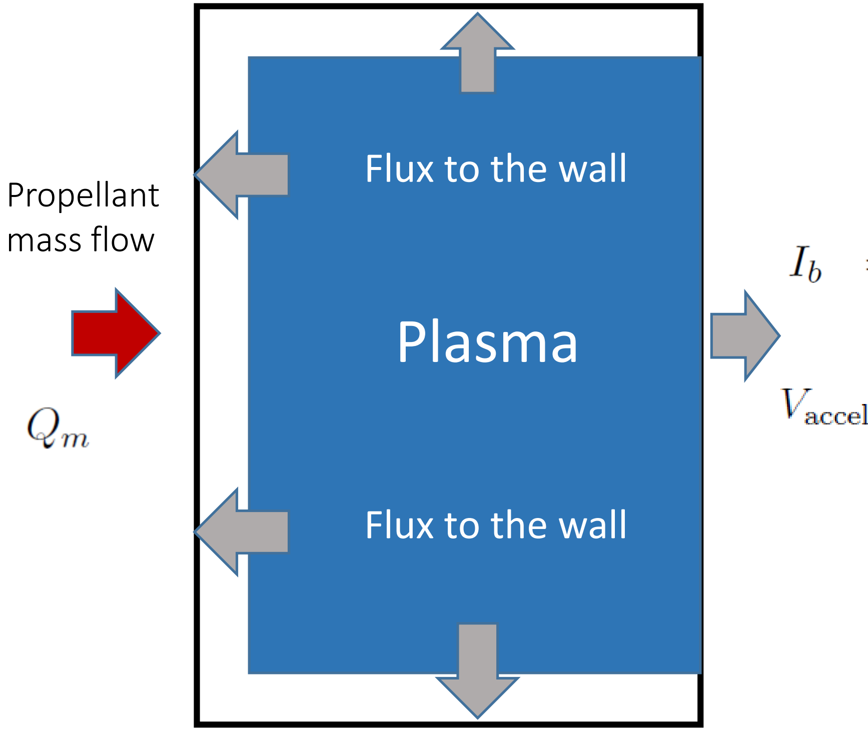
Thrust to Power ratio

- The thrust to power ratio is :

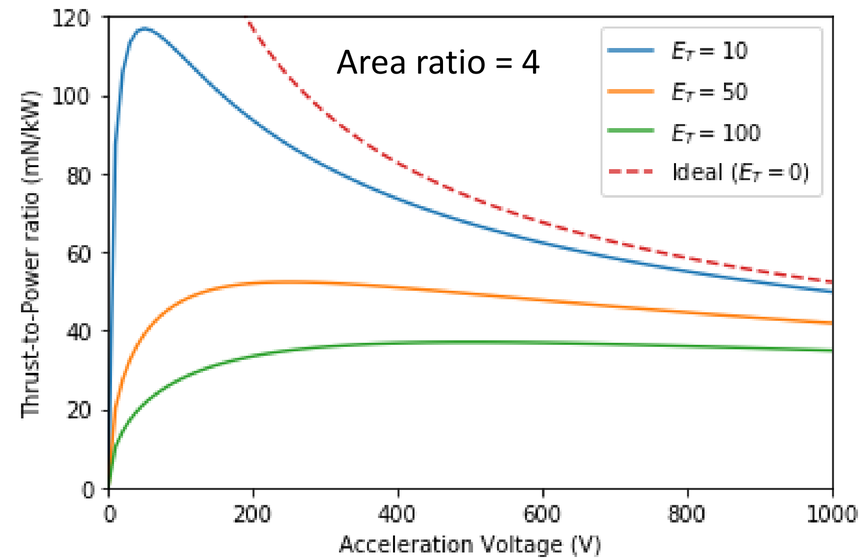
$$\frac{T}{P} = \frac{\Gamma_i A_{\text{open}} m_i v_e}{\Gamma_i \varepsilon_T(T_e)\left(A_{\text{open}} + A_{\text{wall}}\right) + eV_{\text{accel}}\Gamma_i A_{\text{open}}}$$

$$= \sqrt{\frac{2m_i}{eV_{\text{accel}}}}\left[1 + \frac{\varepsilon_T(T_e)}{eV_{\text{accel}}}\left(1 + \frac{A_{\text{wall}}}{A_{\text{open}}}\right)\right]^{-1}$$

Considers only thrust due to ions

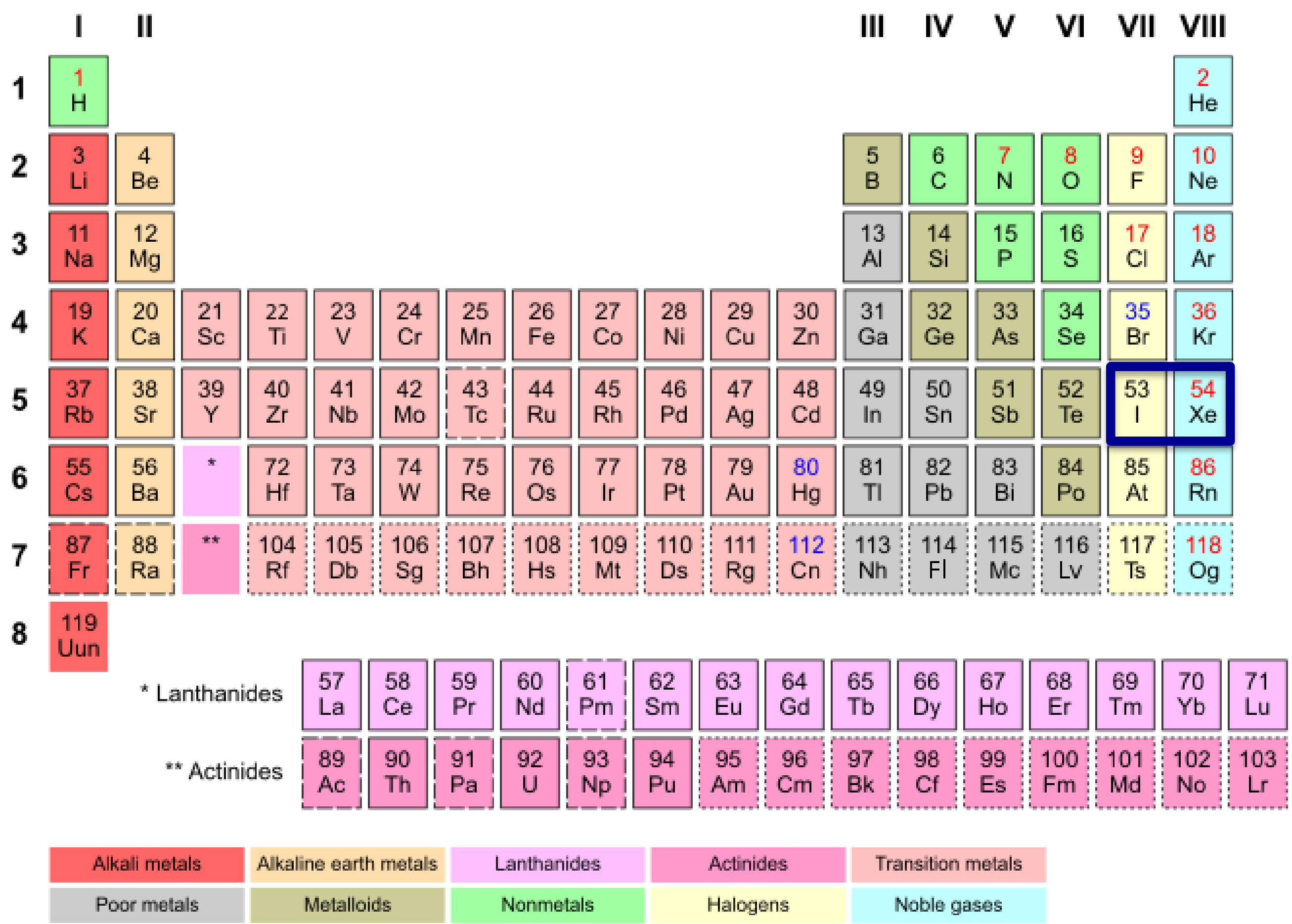


$$I_b = e\Gamma_i A_{\text{open}}$$



- Maximize the ion mass
- Minimize the ionization cost
- Note that thrust increases when the acceleration voltage increases

Iodine as an alternative to xenon



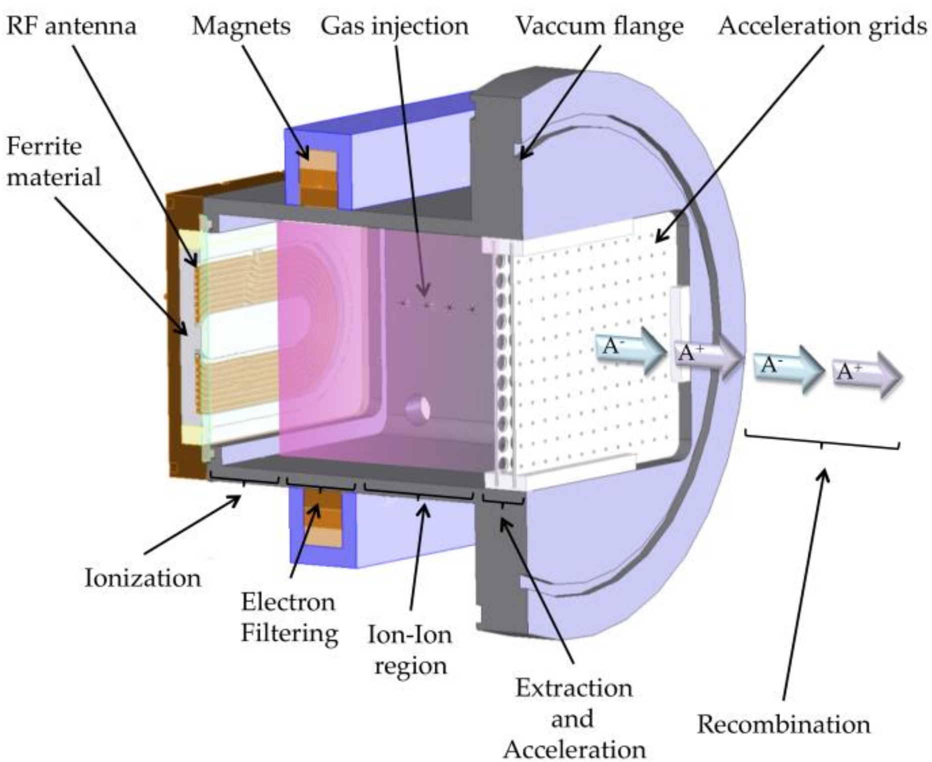
$$E_{diss} = 1.529\ eV$$

Mathieson and Rees, 1956

Iodine versus Xenon

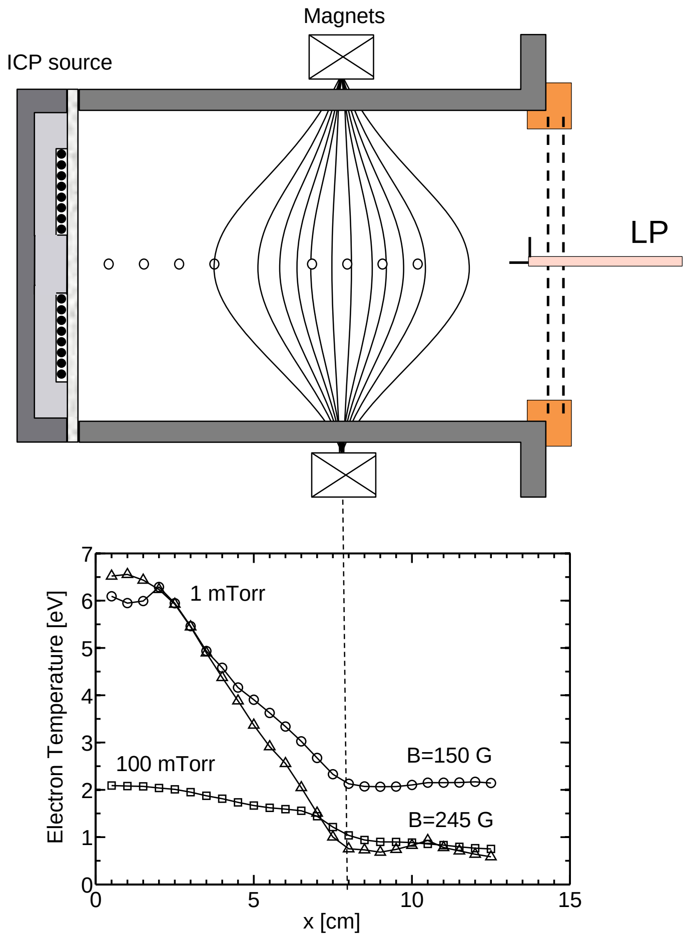
Xenon	Iodine
Heavy 131 amu	Heavy 127 amu (atoms)
Low ionization energy 12.1 eV	Low ionization energy 10,5 eV for I 9,41 eV for I_2
Xe+	I+, I_2+
Non corrosive	Corrosive
Expensive	Cheap
Rare	Larger stock on Earth
Gaseous form at STP	Solid at STP and High vapor pressure

The PEGASES prototype



P. Chabert
Electronegative plasma motor, WO/2007/065915 A1
publication date : 2007-06-14

A Aanesland, A Meige and P Chabert
J. Phys. : Conf. Ser. 162 (2009) 012009

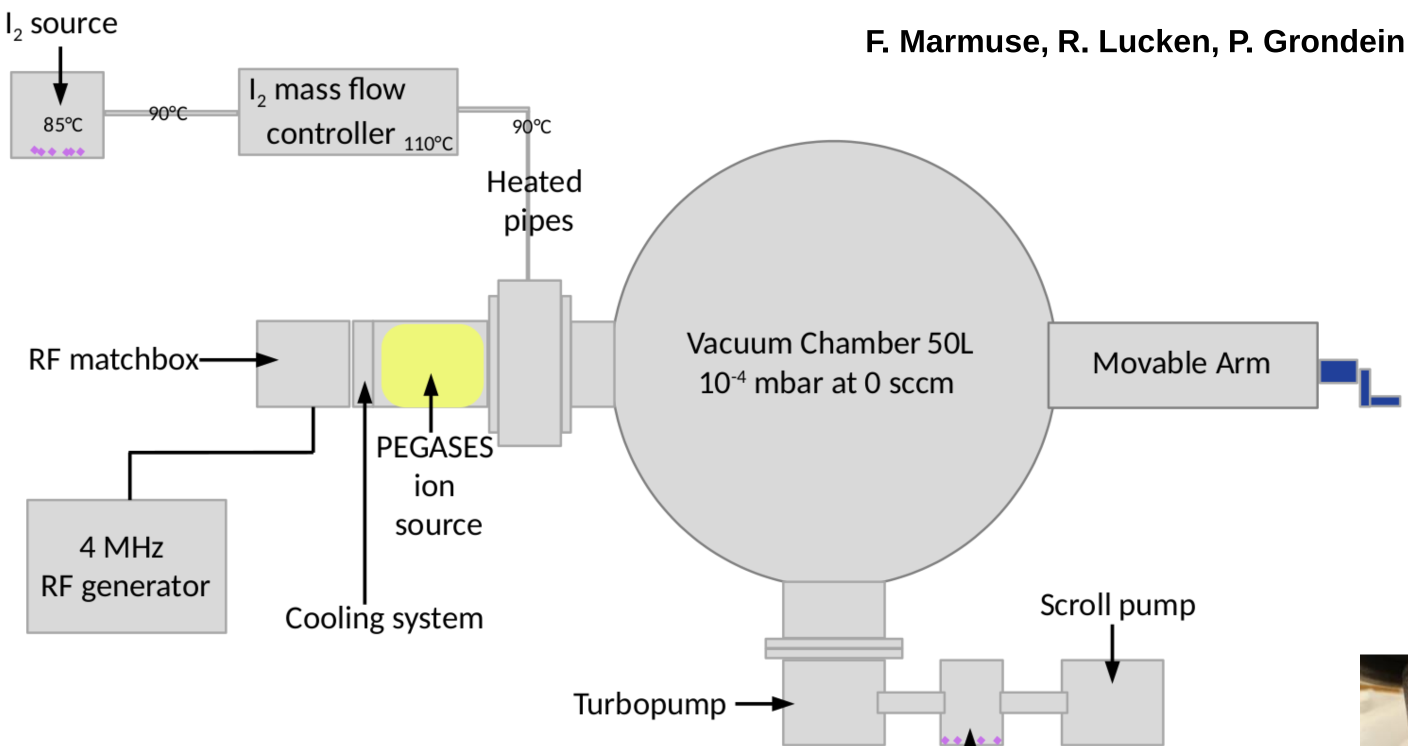


Aanesland, J. Bredin, P. Chabert, V. A. Godyak
Applied Physics Letters **100**, 044102 (2012)

Experimental setup

PEGASES thruster
without Magnetic Field

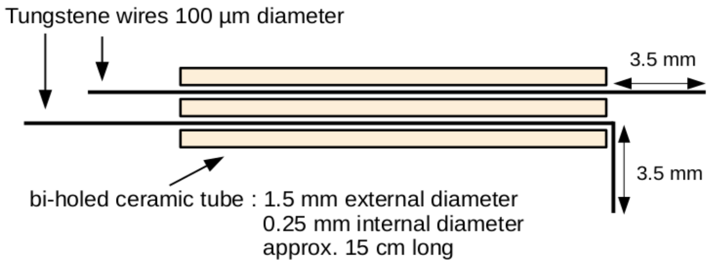
F. Marmuse, R. Lucken, P. Grondein PhD Theses

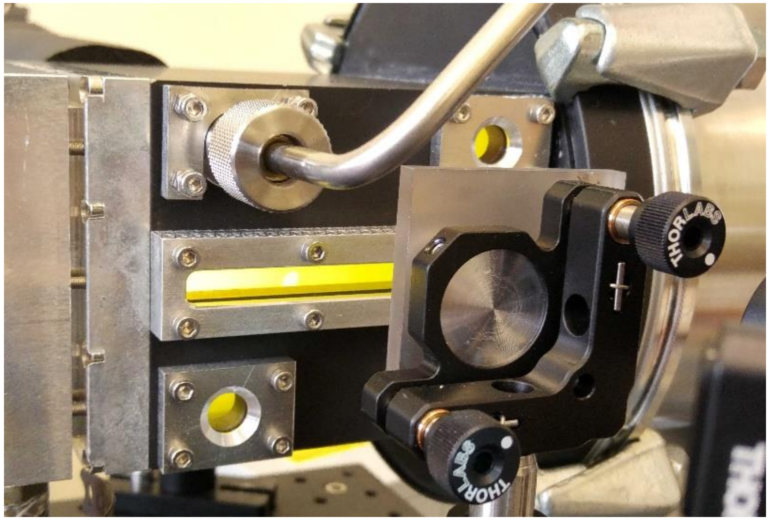


The **absorbed power** is calculated using the method detailed in:
Godyak, A. V., "RF discharge diagnostics: Some problems and their resolution," J. Appl. Phys. 129, 041101 (2021)

Electrons

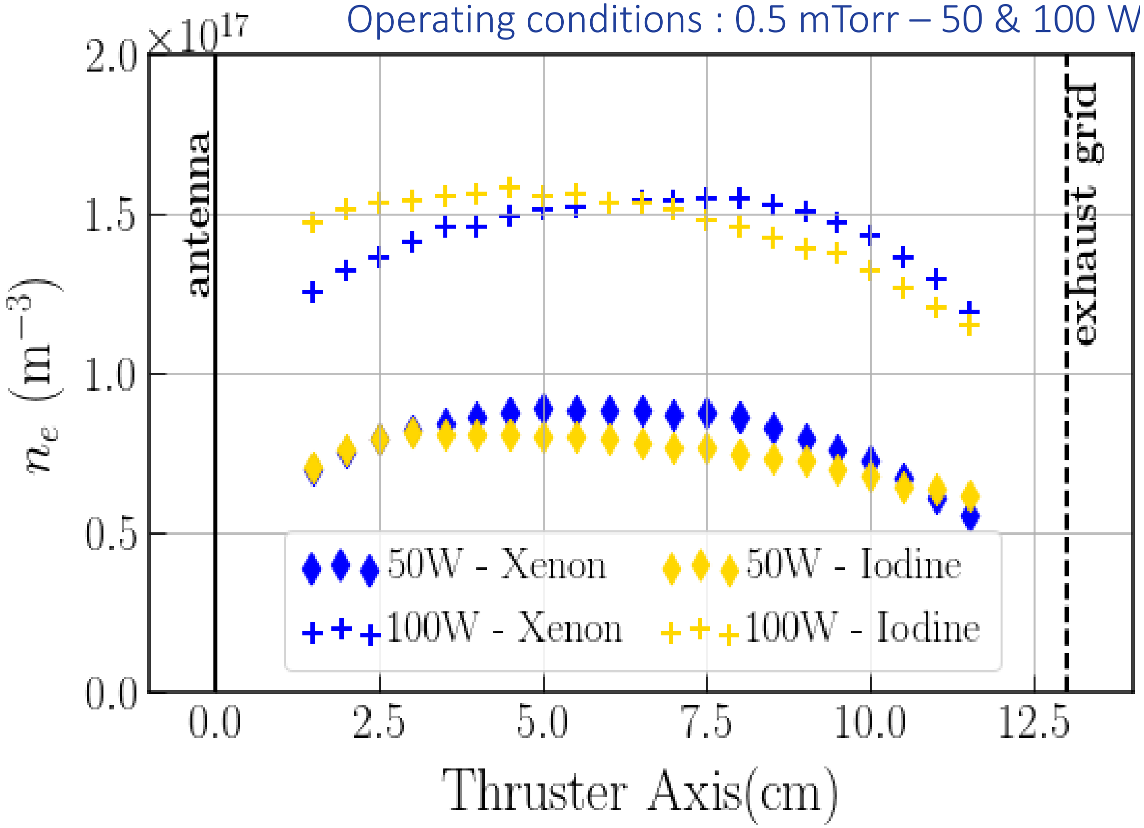
Laboratoire de Physique des Plasmas

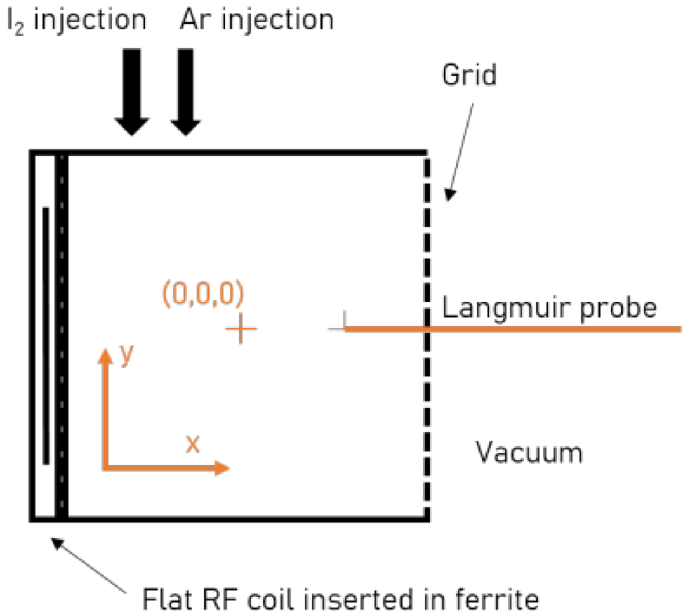


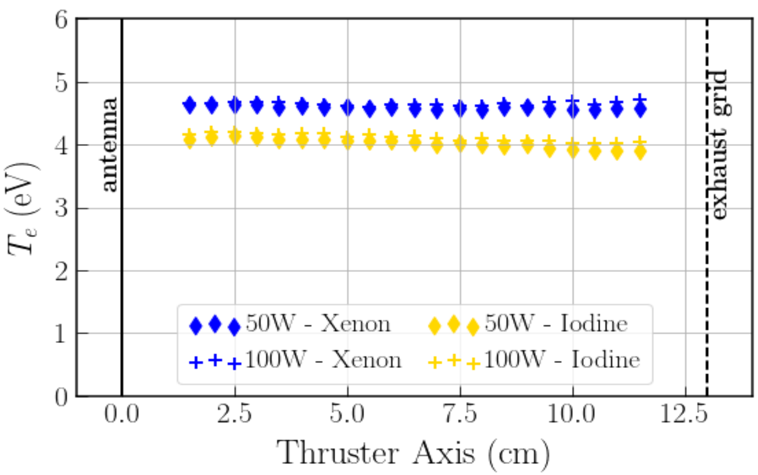


Iodine vs Xenon

Operating conditions : 0.5 mTorr – 50 & 100 W



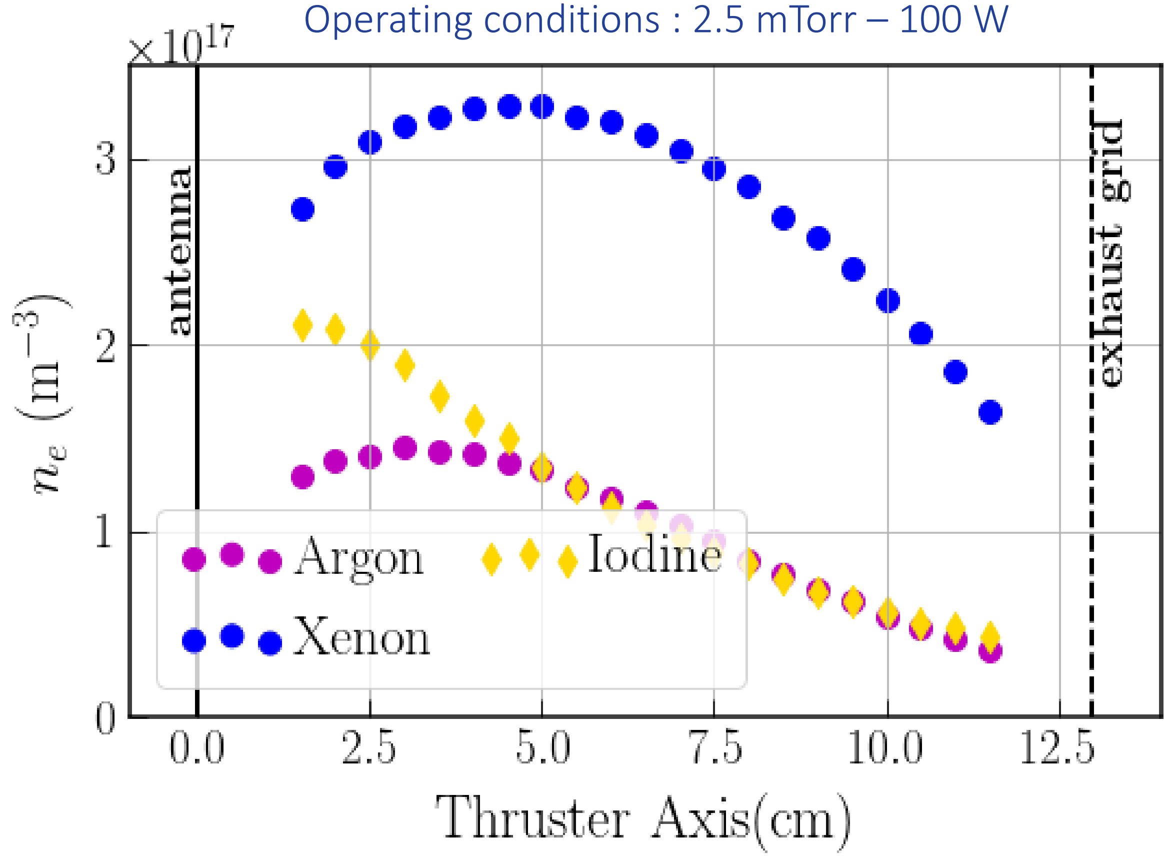


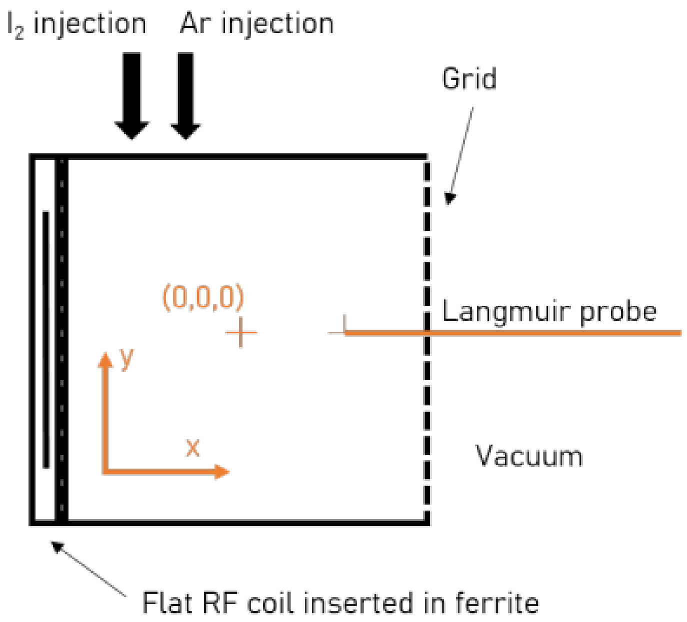


At very low pressure (thruster operating regime) **Iodine** produces plasmas densities **comparable to Xenon**

Iodine vs noble gases

Operating conditions : 2.5 mTorr – 100 W

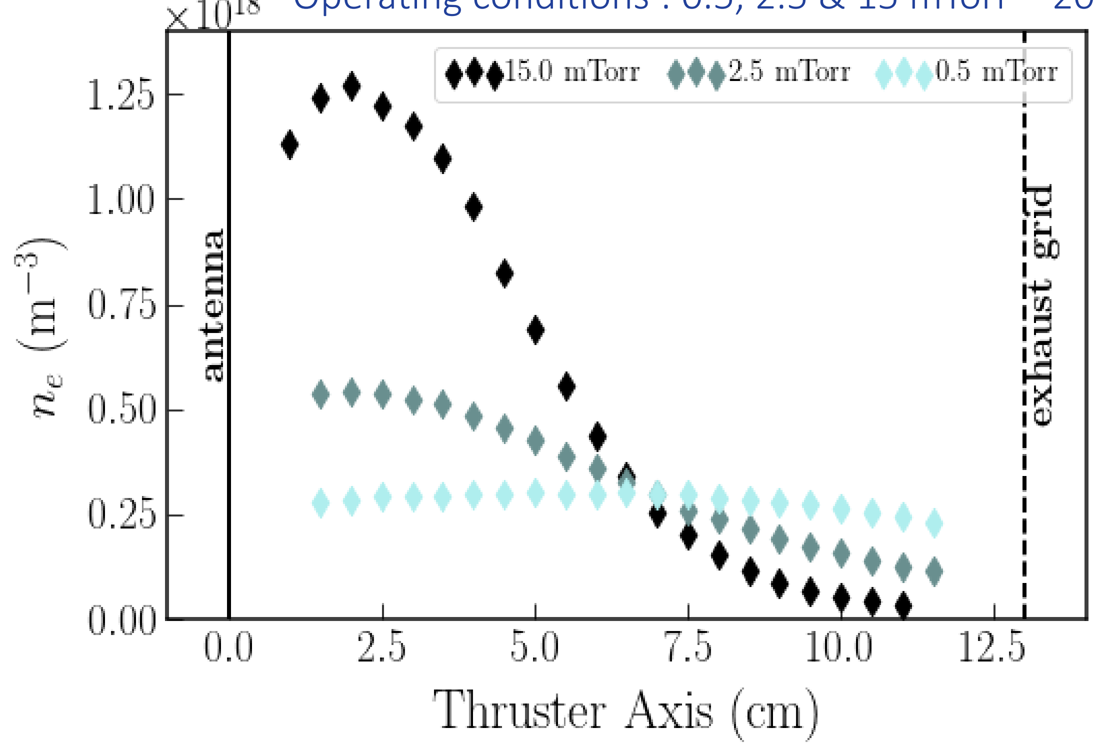


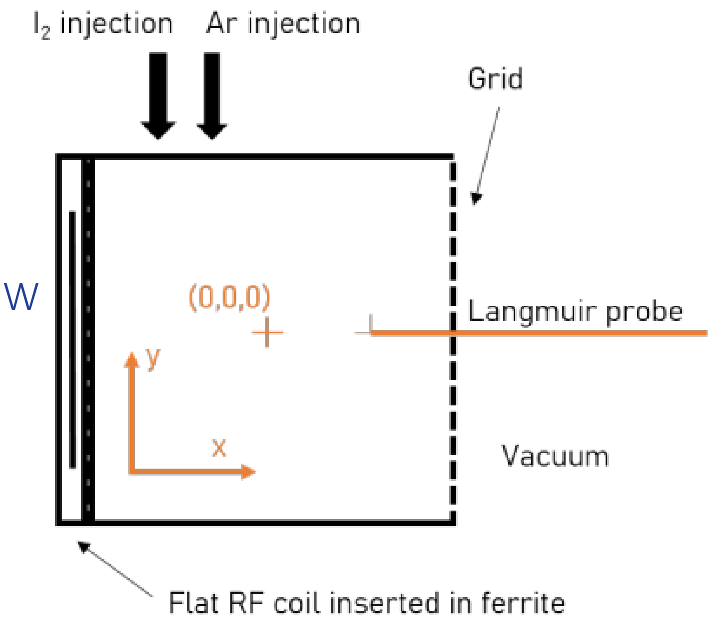


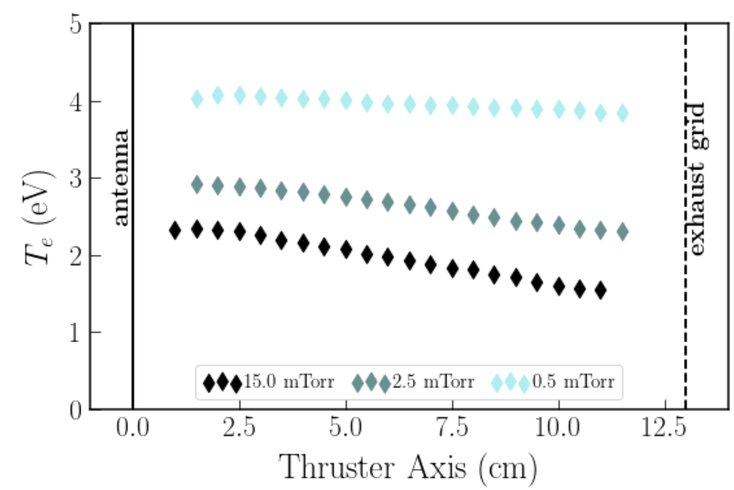
When pressure increases, **Iodine shows stronger localization** than noble gases

Iodine at higher pressures

Operating conditions : 0.5, 2.5 & 15 mTorr – 200 W



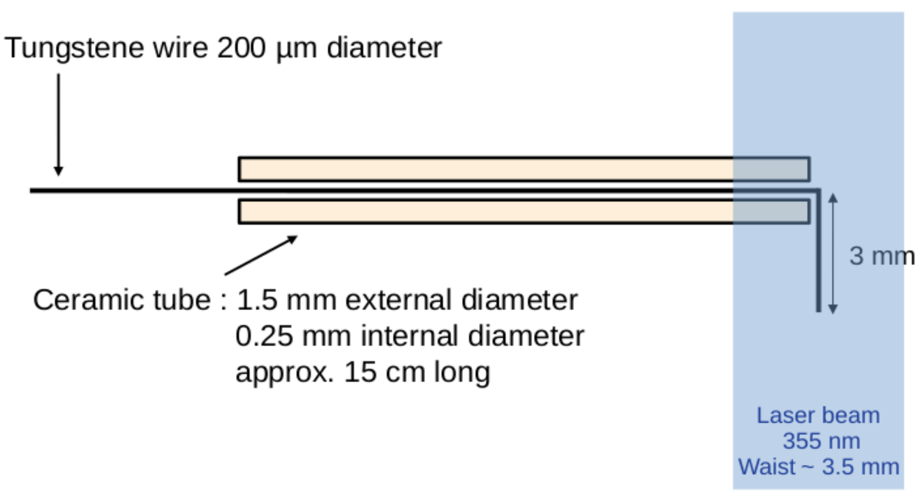


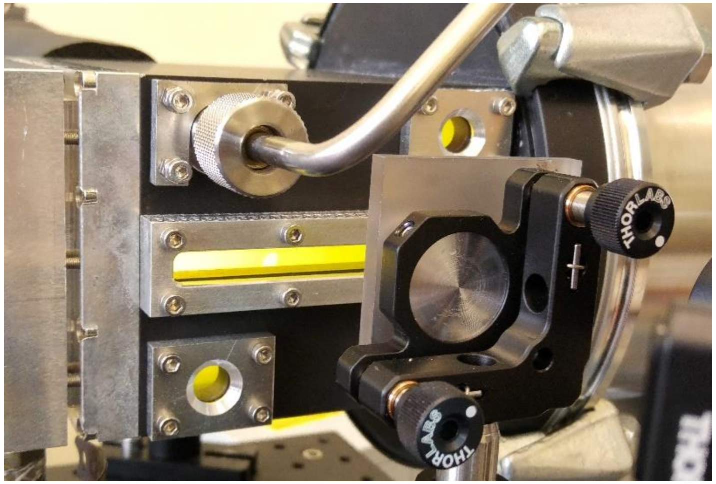


At higher **pressures**, very high density but strong gradients and fast decay away from the antenna.

Negative ions

Laboratoire de Physique des Plasmas





Negative ion formation in iodine plasmas

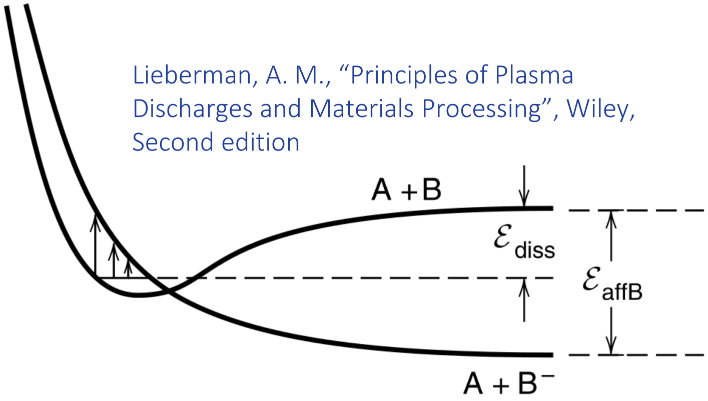
- Main process for negative ion formation is Dissociative Attachment:

$$I_2 + e^- \longrightarrow I^- + I^*$$

- Heavier negative ions could be formed at high pressure/low electron densities

- In iodine:

$$\varepsilon_{aff} = 3.06\text{eV} > 1.529\text{eV} = \varepsilon_{diss}$$



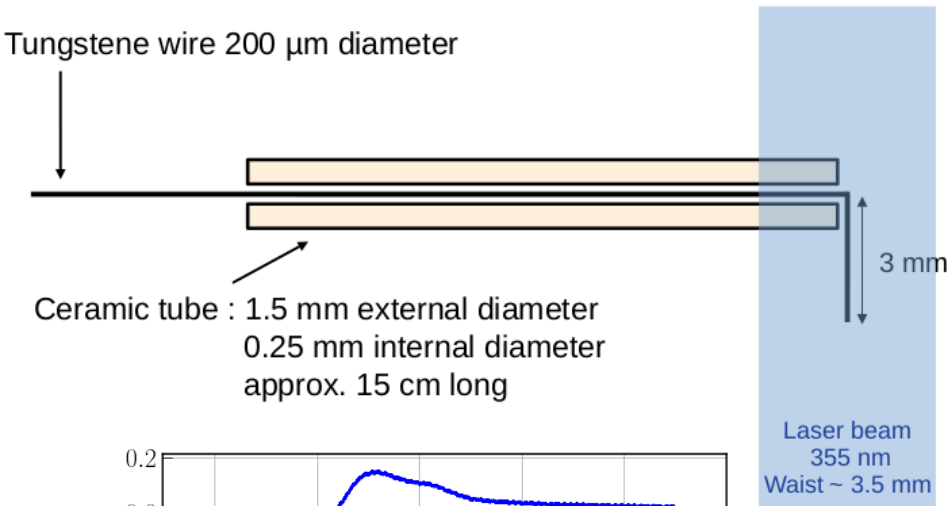
Lieberman, A. M., “Principles of Plasma Discharges and Materials Processing”, Wiley, Second edition

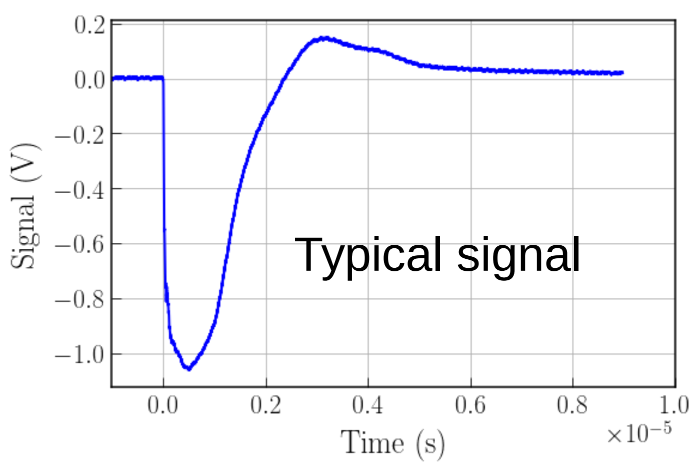
Generation of I^- starts at 0 eV electrons

Laser Photodetachment

Principle

Photodetachment process: $$I^- + h\nu \longrightarrow I + e^-$$





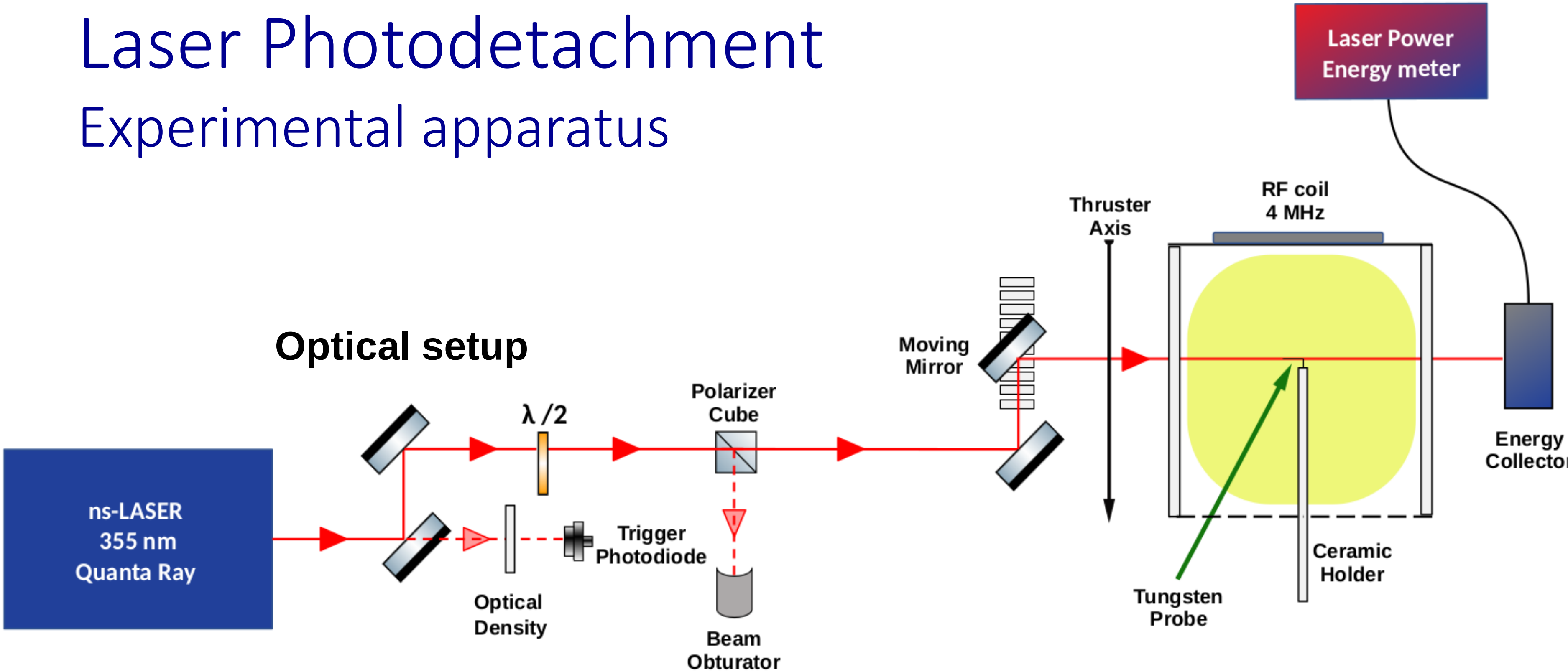
Principle :

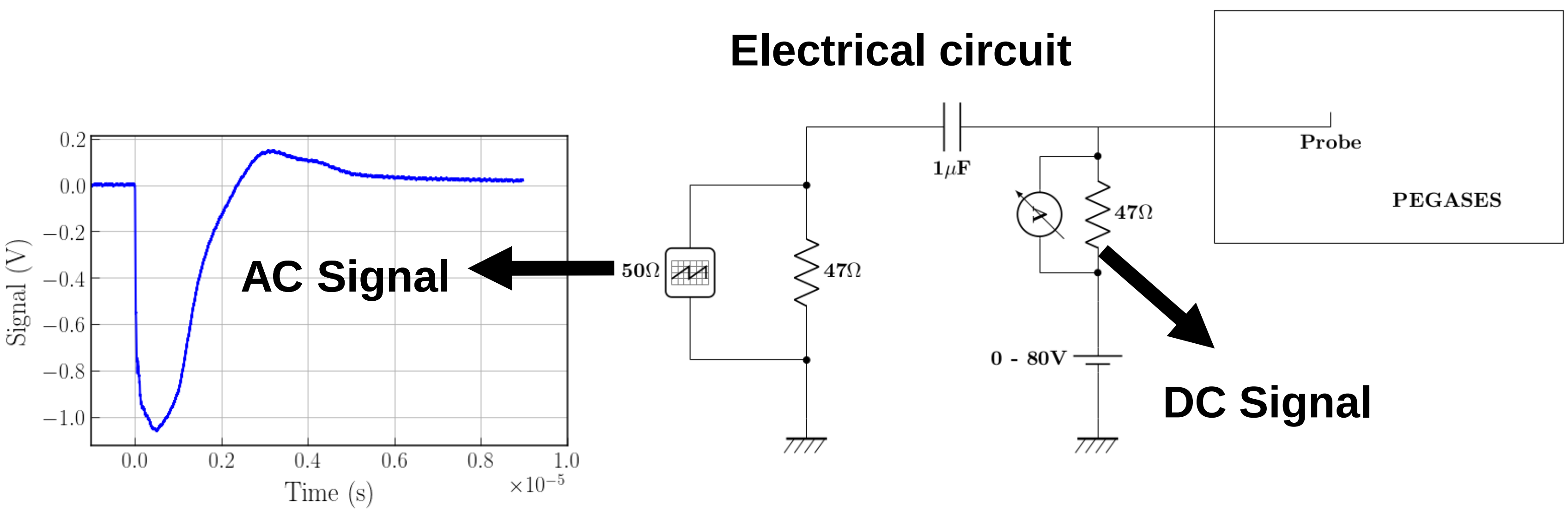
We bias the probe above the plasma potential and use a ns-laser to photodetach I^- ions in order to capture the newly created electrons.

$$\alpha = \frac{n^-}{n_e} = \frac{\Delta I_e}{I_{DC}}$$

Bacal et al., Rev. Scient. Instruments, 2000

Laser Photodetachment
Experimental apparatus

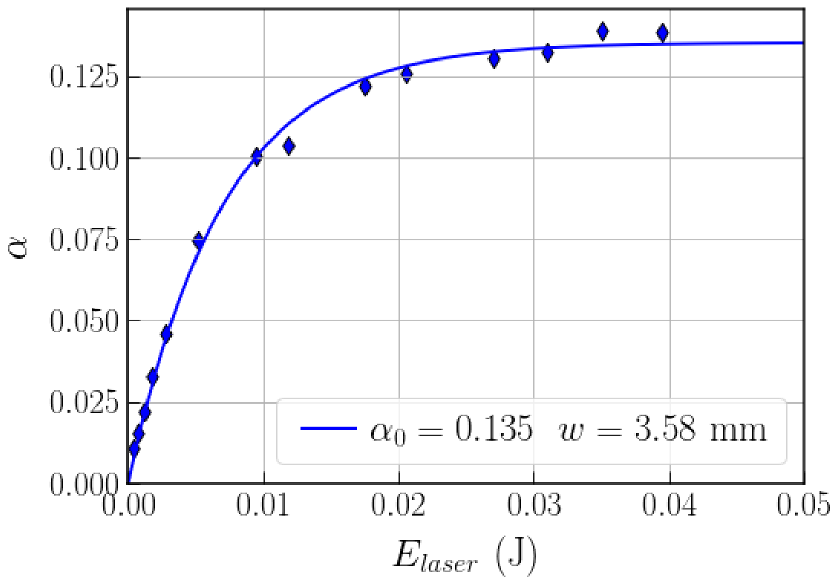




Laser Photodetachment

Mandatory verifications (Bacal et al., Rev. Scient. Instruments, 2000)

Saturation with the laser energy

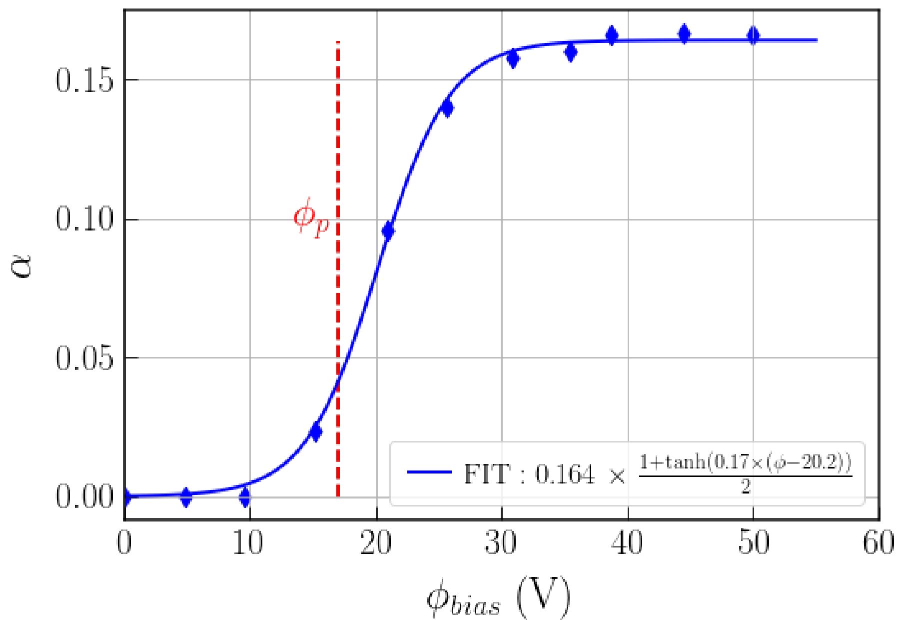


$$\alpha = \alpha_0 \left(1 - \exp\left(-\frac{\sigma}{2\pi w^2}\frac{E_{Laser}}{E_{phot}}\right)\right)$$

$$\sigma = 1.6x10^{-21} m^2$$

At this position and for these plasma conditions : **E_{laser} ~ 40 mJ**

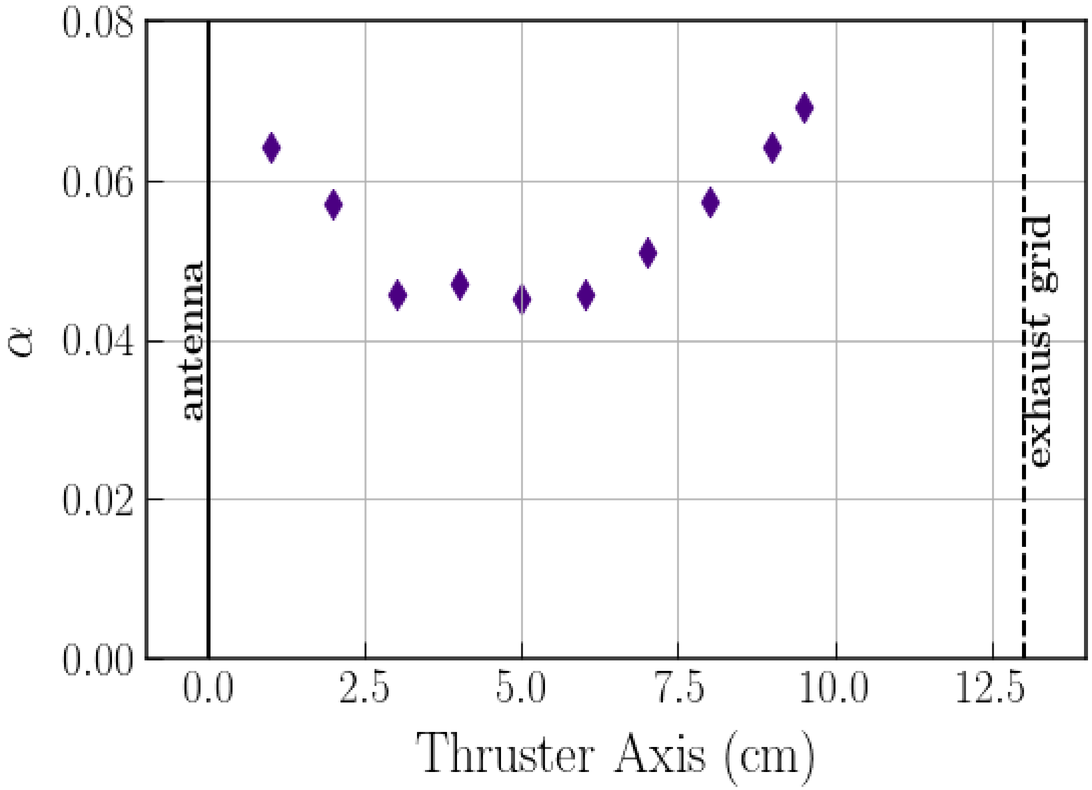
Saturation with the bias voltage



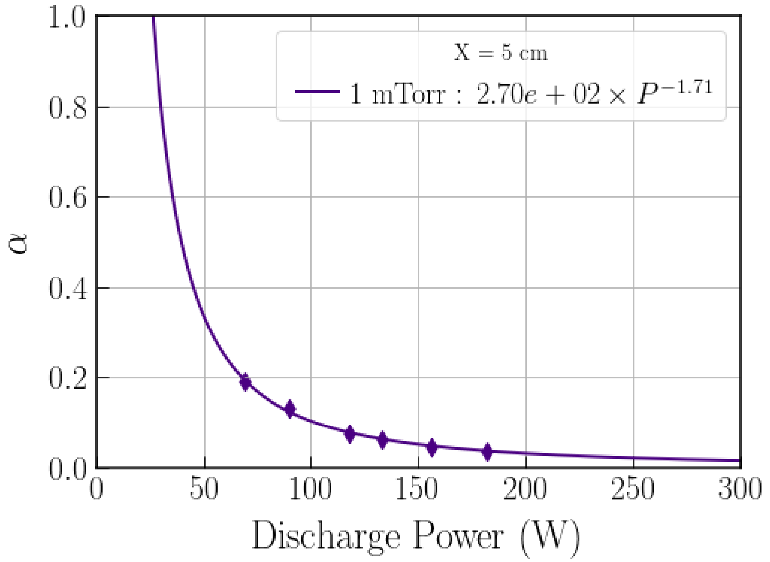
At this position and for these plasma conditions : **V_{bias} = 35V**

Electronegativity in typical «Thruster» regime

Operating conditions : 1 mTorr – 200 W



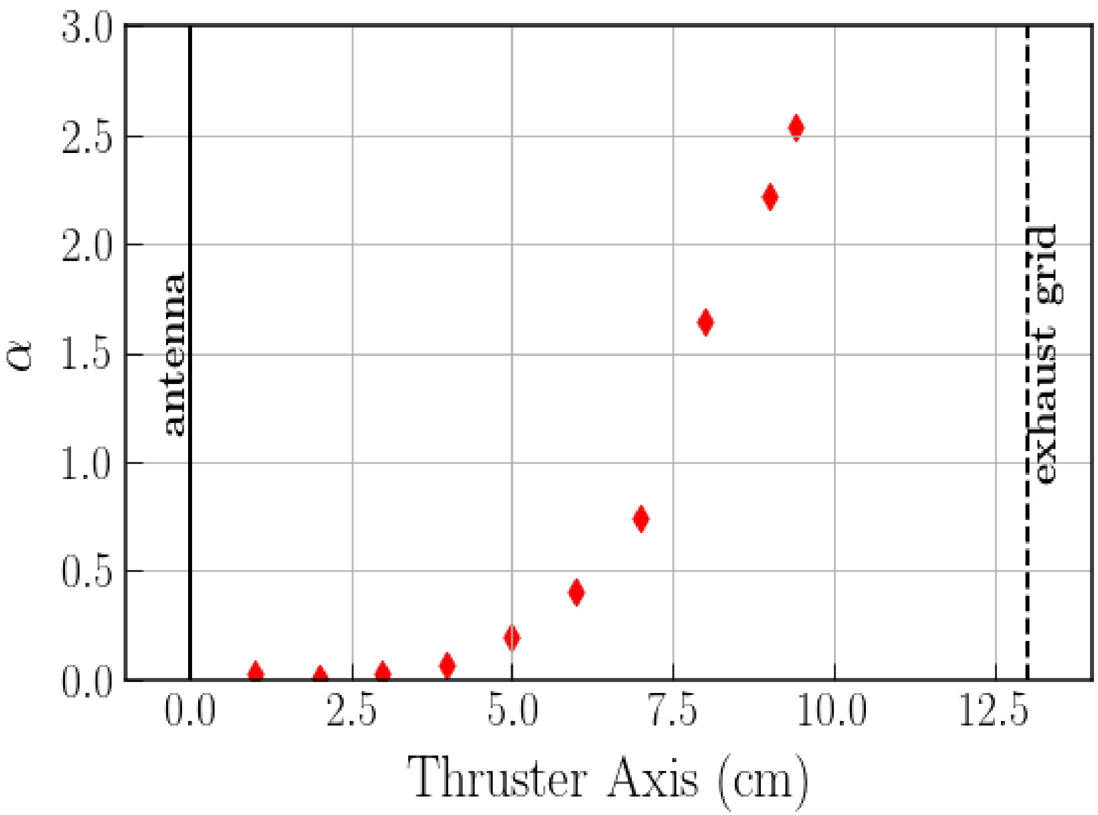
Electronegativity decreases with power



The electronegativity is very small at low pressure/ high power because iodine molecules are very efficiently dissociated

Electronegativity as pressure increases

Operating conditions : 10 mTorr – 200 W



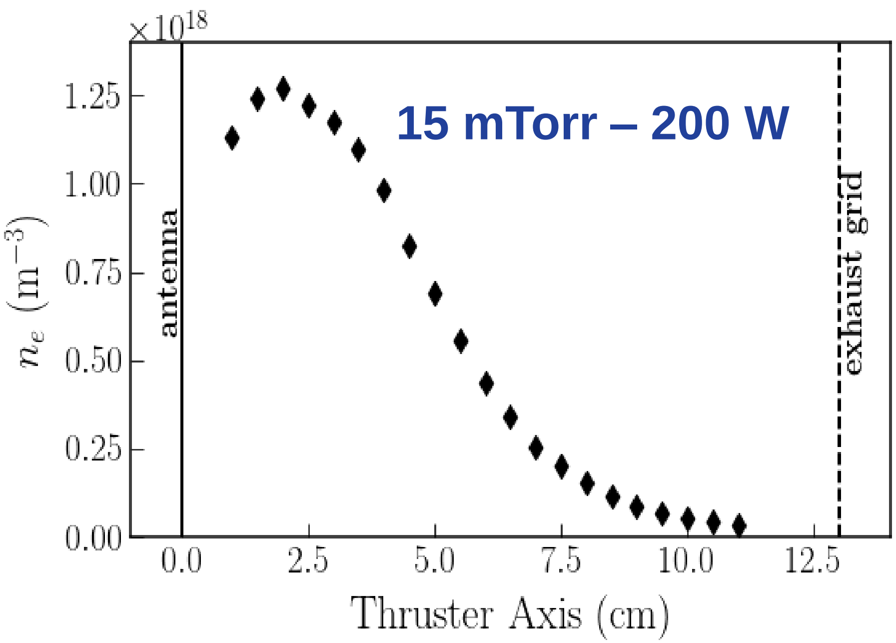
- Electronegativity increases rapidly as pressure increases
- Low electronegativity near the antenna where the electron density is high
- This suggests that negative ions are not in Boltzmann equilibrium

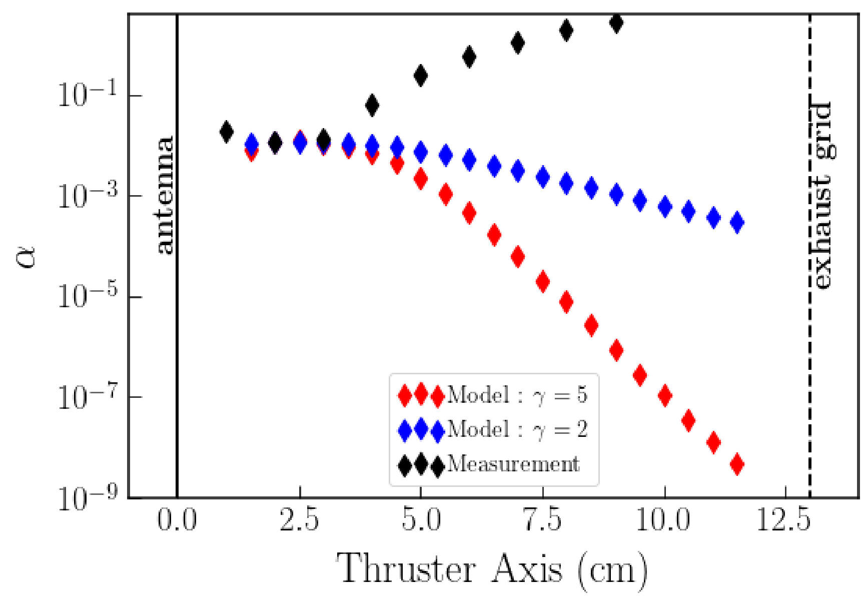
Negative ions are not in Boltzmann equilibrium

Assuming **isothermal electrons and ions** and Boltzmann equilibrium

$$\alpha(x) = \alpha_0 \left(\frac{n_e(x)}{n_{e0}} \right)^{\gamma - 1}$$

$$\gamma = \frac{T_e}{T_-}$$





Local balance :

$$I_2 + e^- \longrightarrow I^- + I^*$$

Creation : Dissociative attachment

$$I^- + e^- \longrightarrow I + 2e^-$$

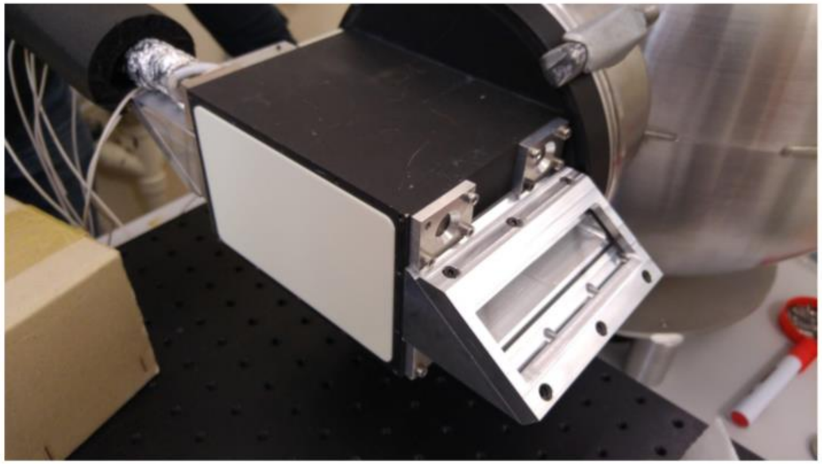
$$I^- + I^+ \longrightarrow 2I$$

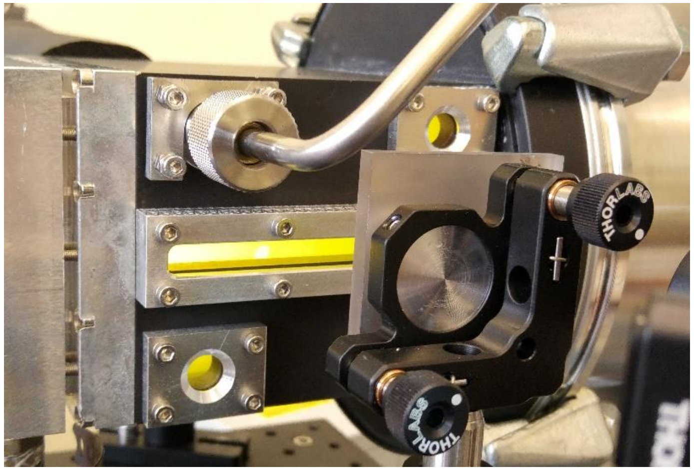
Loss : Electron detachment
Ion-ion recombination

Iodine atoms

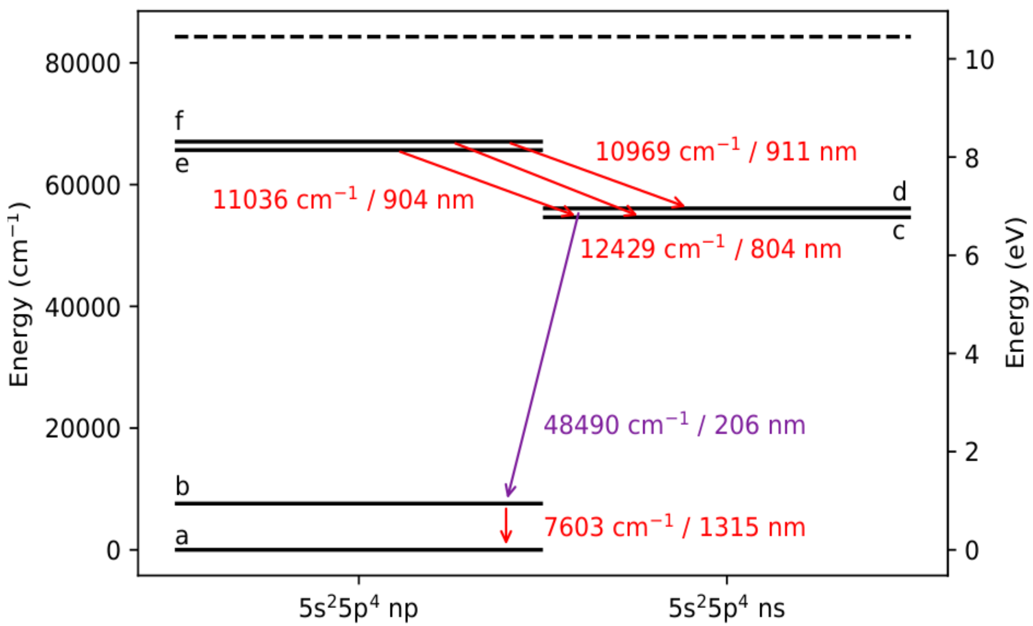
LPP

Laboratoire de Physique des Plasmas



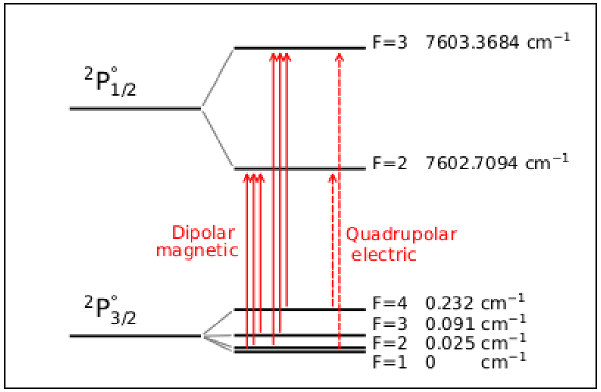


Iodine atom detection using laser absorption

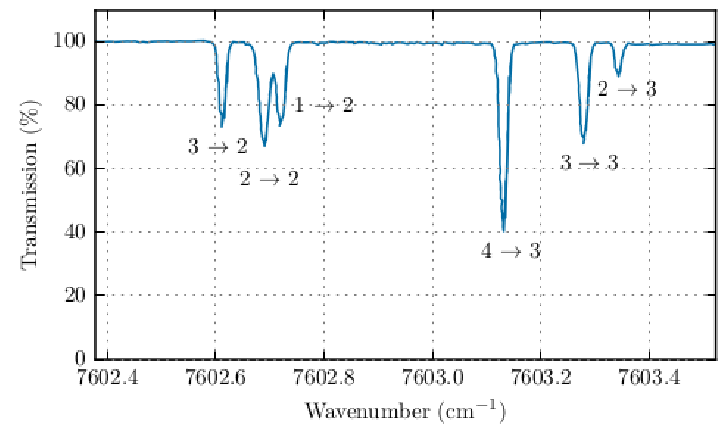


- Six lines from the dipolar magnetic part of the transition around 7603 cm^{-1} (IR)

- Very weak transition: multi-pass absorption is required



(a) I atom energy levels, focusing on the first transition at 7603 cm^{-1}. The lower state is the fundamental state, the zero energy fixed at $F = 1$.

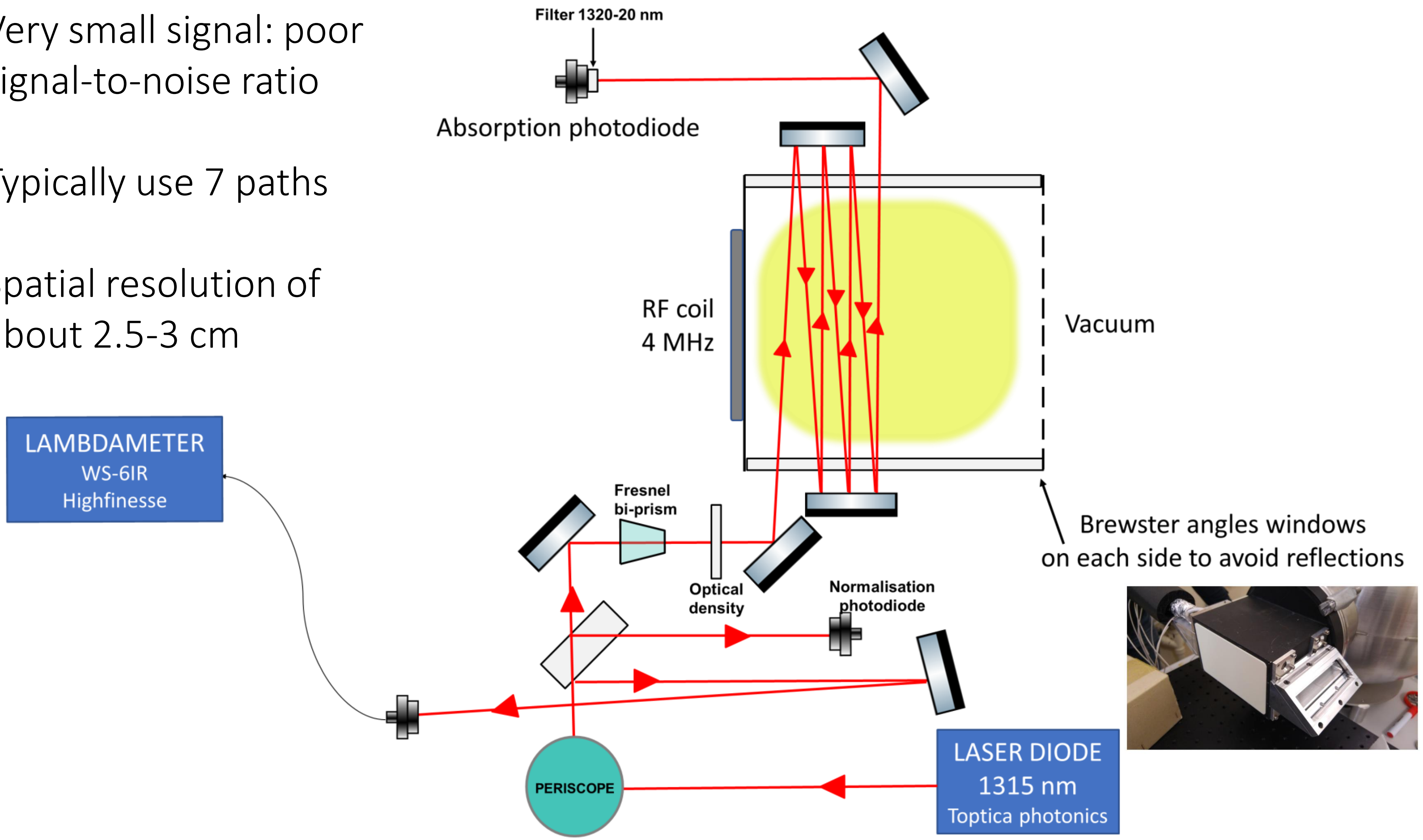


(b) Expected spectral transmission. Six lines from the hyperfine structure compose the dipolar magnetic part of the transition. The quadrupolar electric part is not detected, and was not included in the detailed analysis from Ha et al. [91] either.

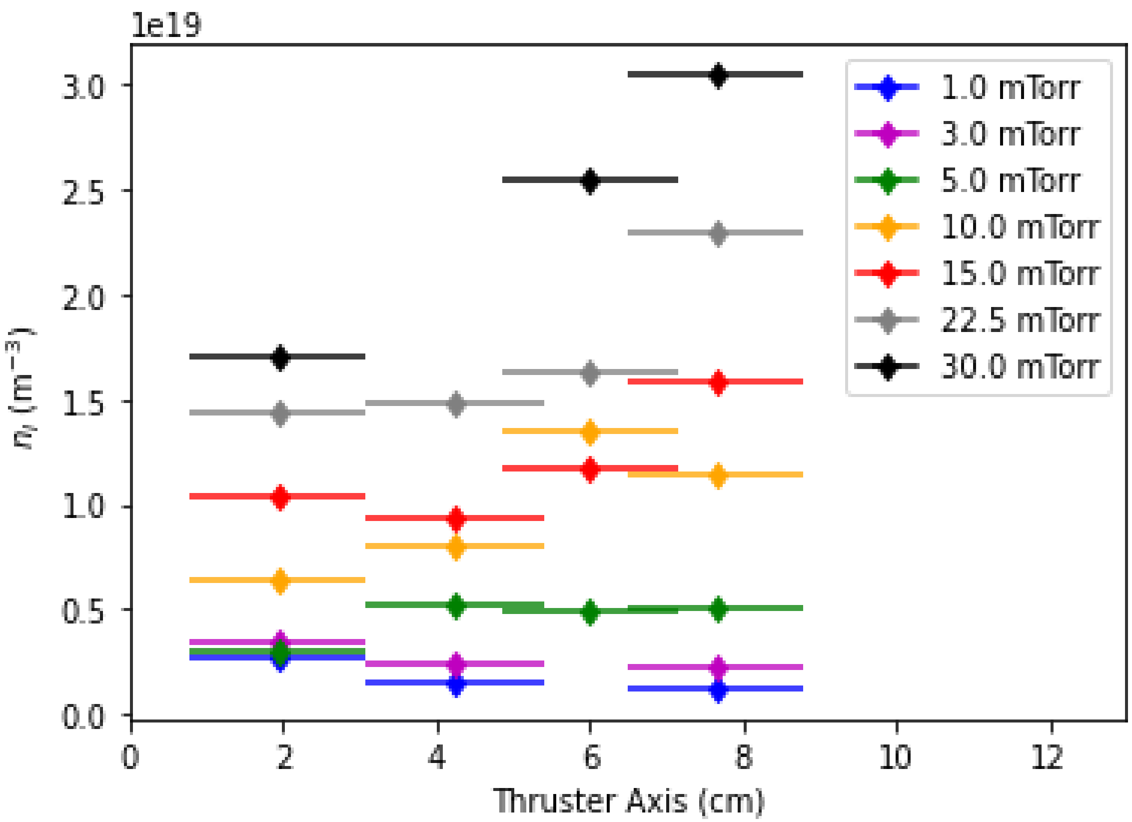
Figure 3.12: Data about the studied transition, available in the literature and reproduced from Ha et al. [91], He et al. [92].

IR absorption experimental set-up

- Very small signal: poor signal-to-noise ratio
- Typically use 7 paths
- Spatial resolution of about 2.5-3 cm



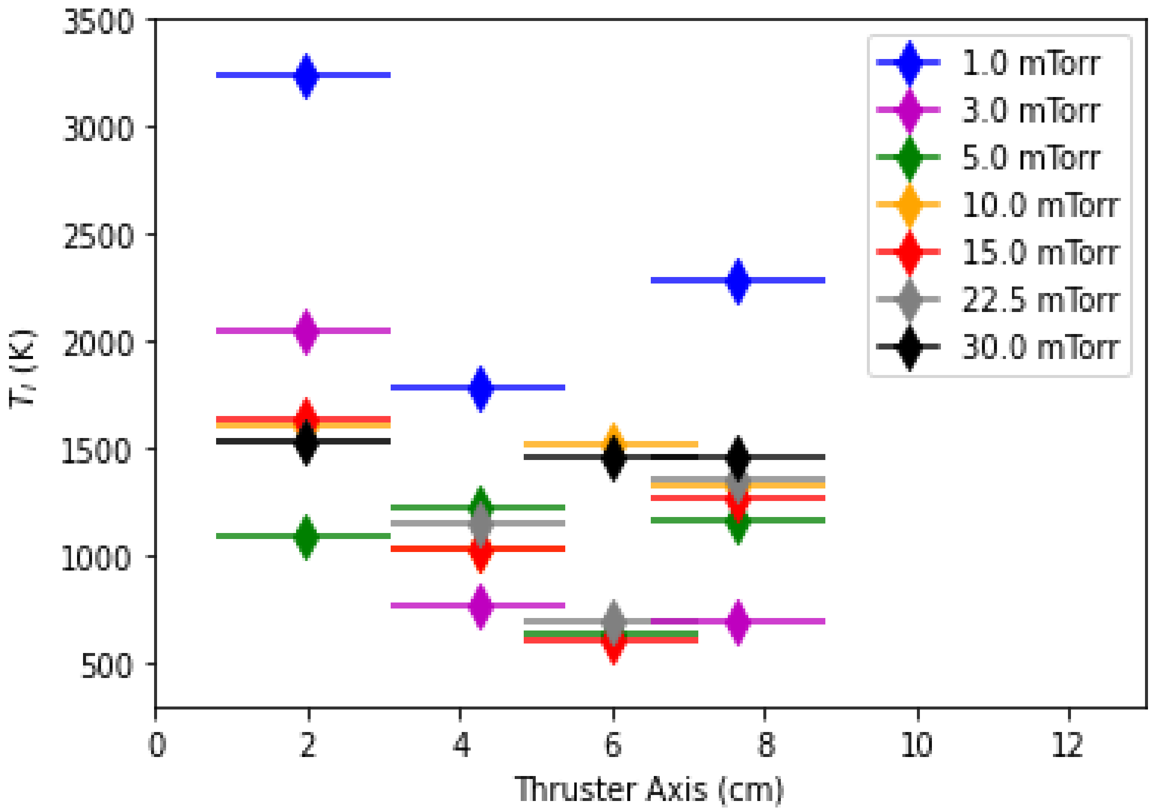
First analysis assuming negligible $^2P_{1/2}$ density



- Why would the atom density increase away from the antenna?
- Why is the atom density (and therefore the dissociation) so low ?

Is it due neutral gas depletion due to strong gas heating ?

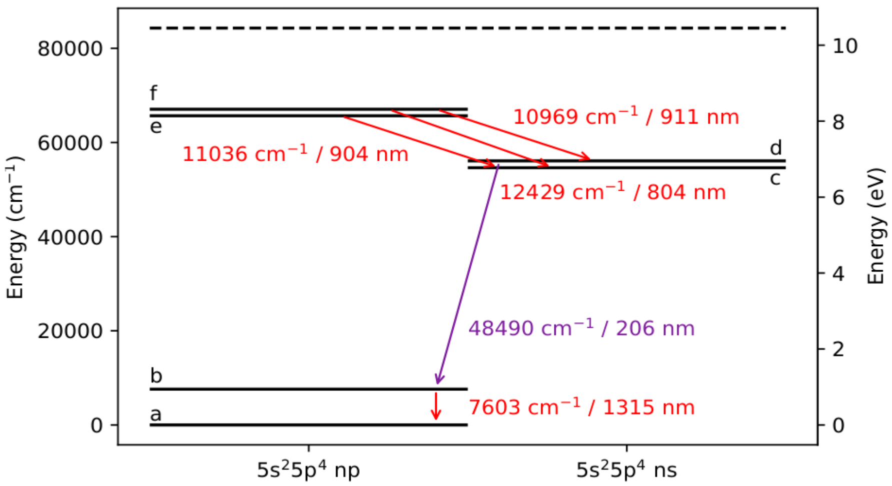
Iodine atom temperature from Doppler broadening

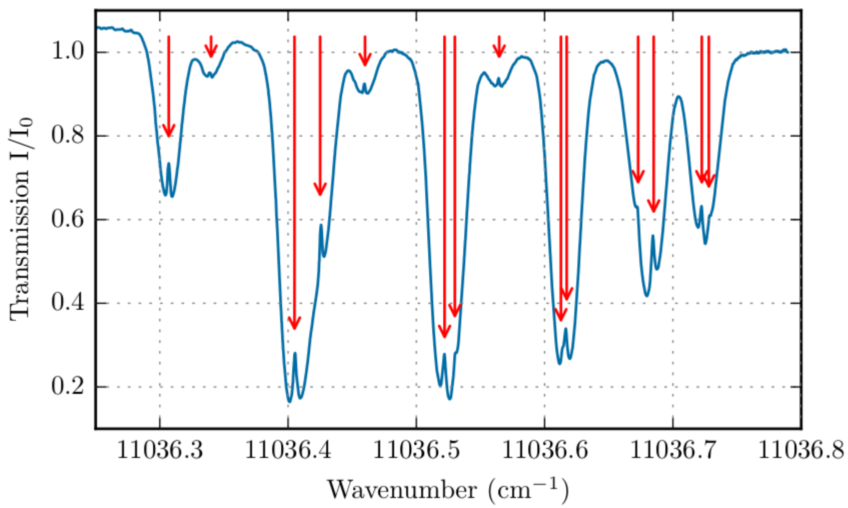


- Very small signal: poor signal-to-noise ratio
- Hard to trust these experiments at low pressure: very large error bars (not represented)
- No clear trends although the gas temperature seems rather high

Can we infer the gas temperature from another measurement?

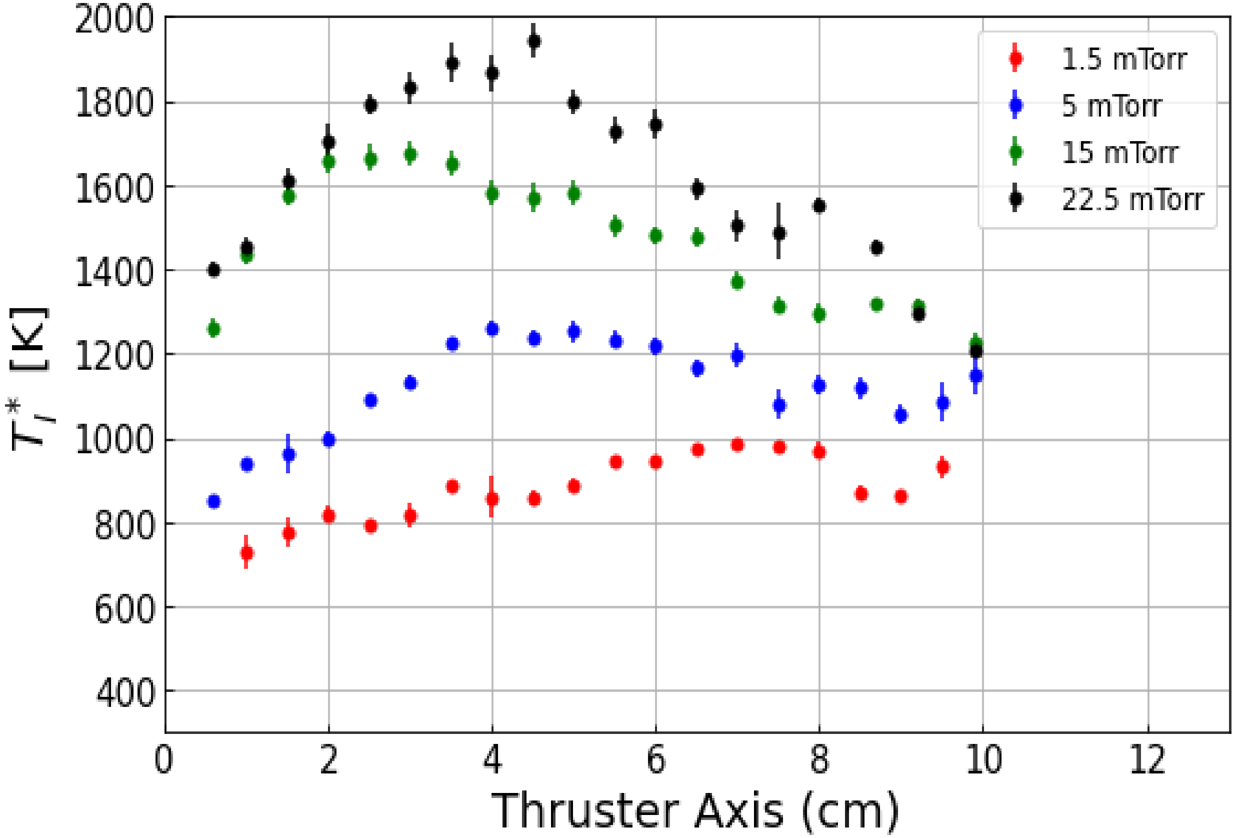
Iodine atom excited states temperature from a transition at 11036.415 cm^{-1}





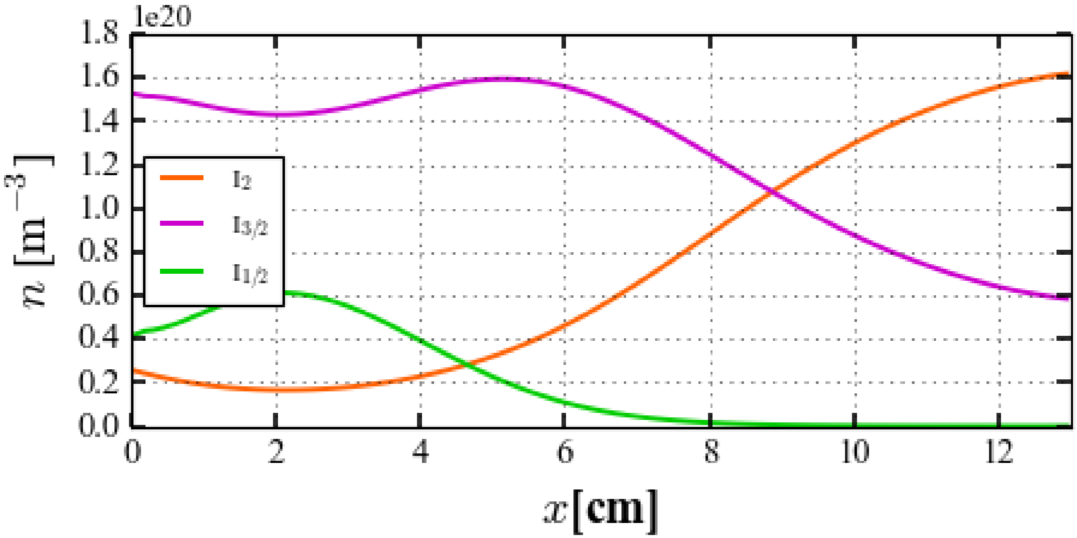
- Very good signal: excellent signal-to-noise ratio
- Only one path : strong spatial resolution
- Problem: there is no guarantee that the excited states are at the same temperature as ground state atoms

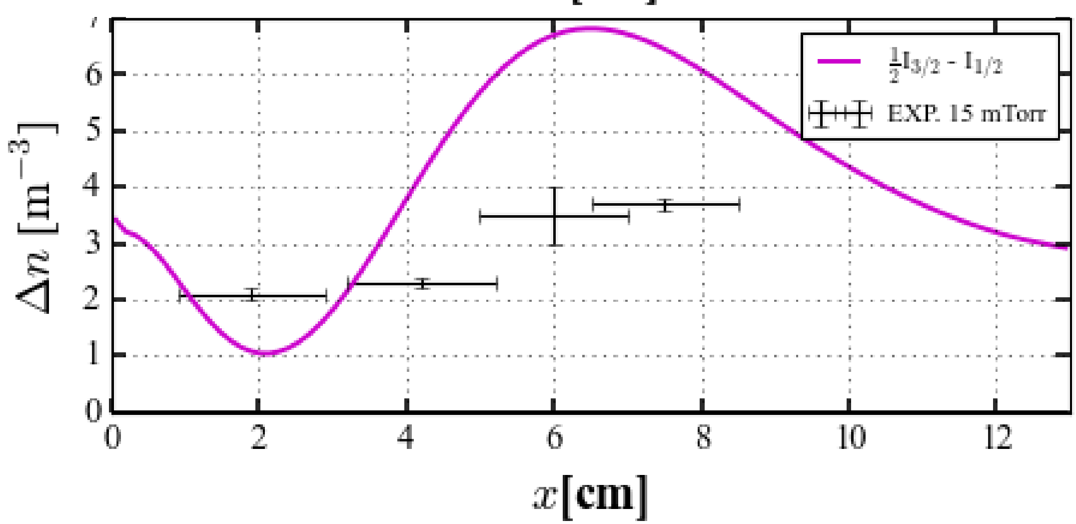
Iodine atom excited states temperature from a transition at 11036.415 cm^{-1}



Such a temperature profile cannot explain the atom density depletion near the antenna

The $^2P_{1/2}$ density is probably significant

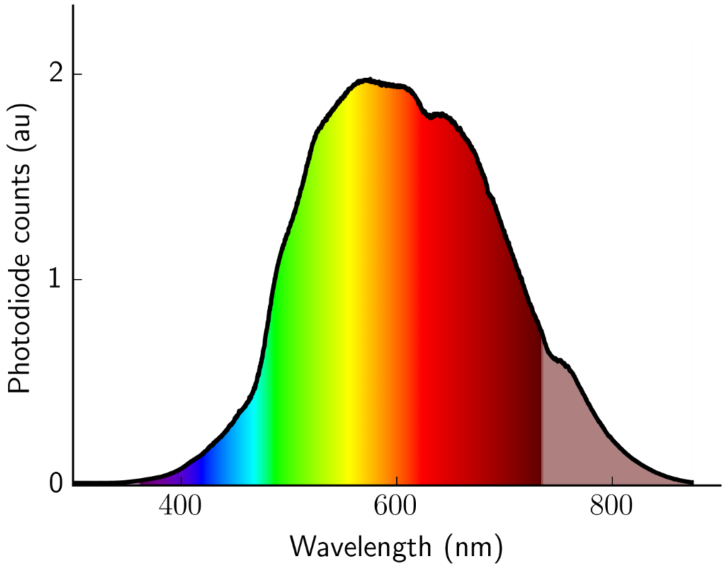


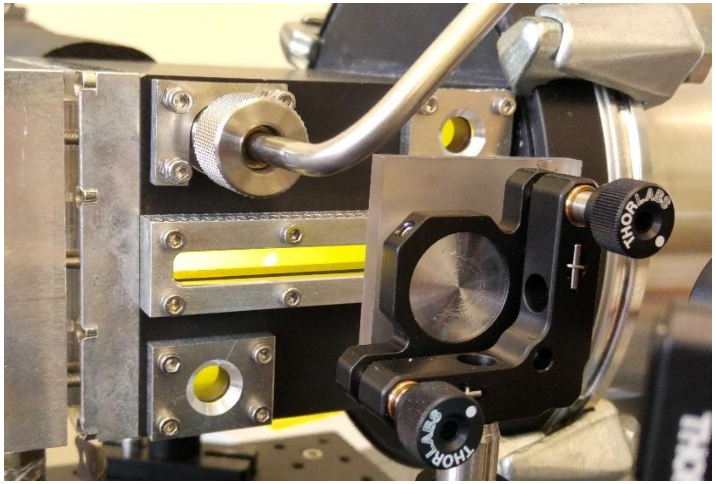


- A 1D fluid model tha solves for the neutral species dynamics (molecules, atoms in $^2P_{3/2}$ and $^2P_{1/2}$ states)
- Electron density and temperature profiles from experiments
- Assumes $^2P_{1/2}$ is produced by electron impact and destroyed by electron impact and quenching on molecules
- Assumes all atoms are generated in the $^2P_{3/2}$ state (from dissociation)

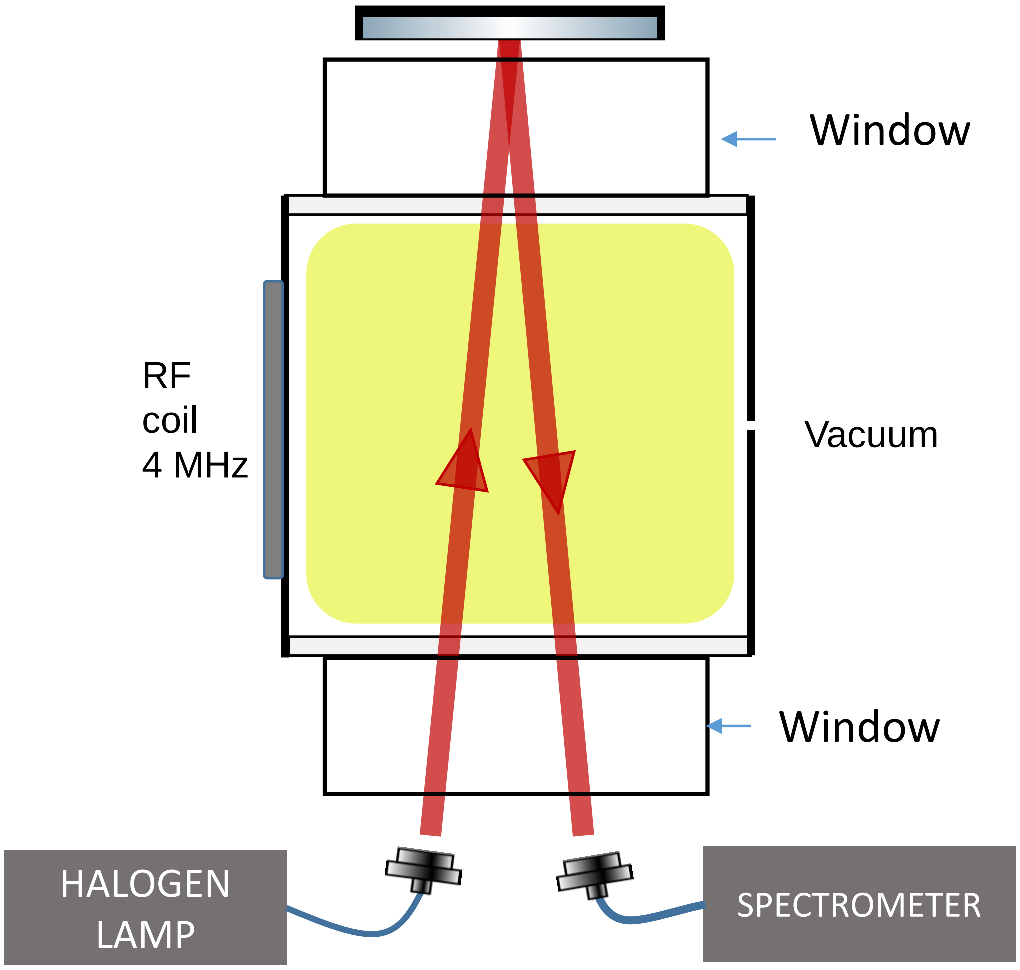
Molecules

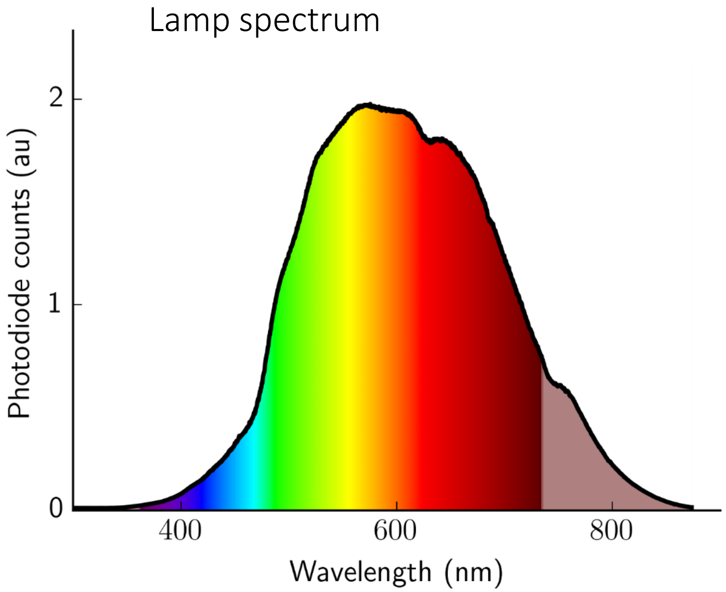
Laboratoire de Physique des Plasmas

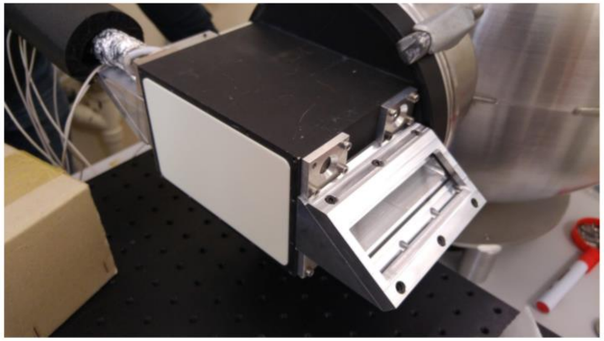




Iodine molecule density by broadband absorption

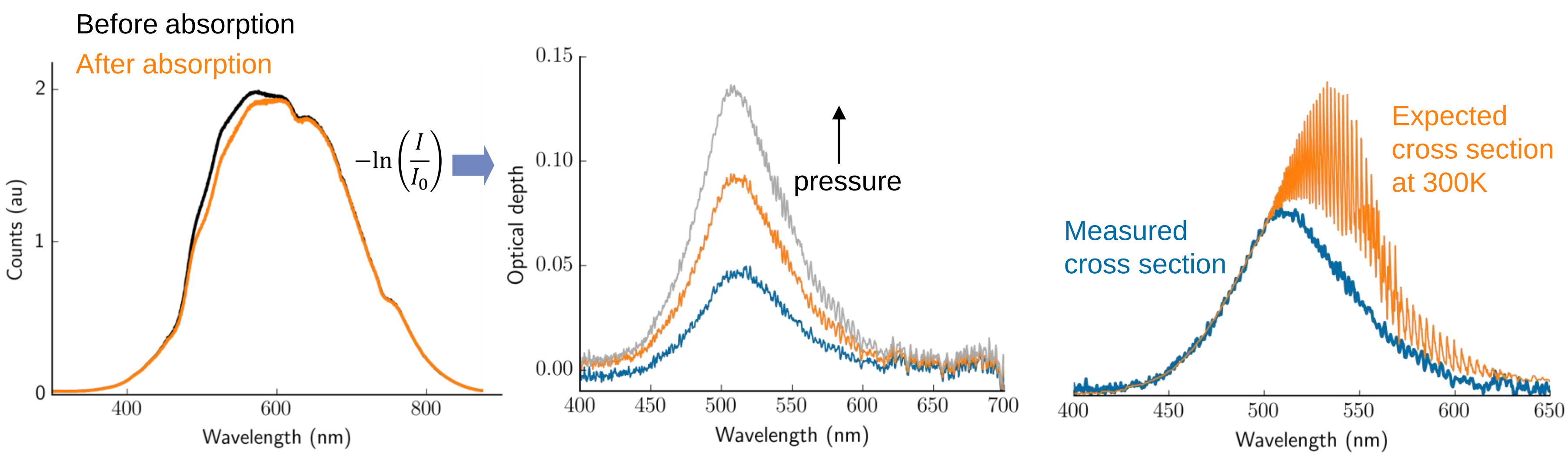




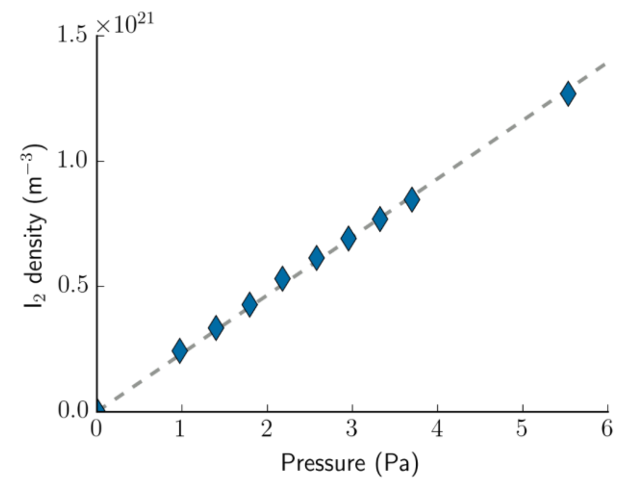


Iodine molecule density from broadband absorption: without plasma

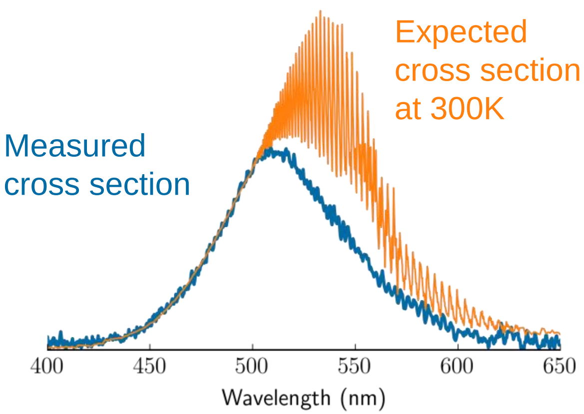
From Florian Marmuse PhD Thesis



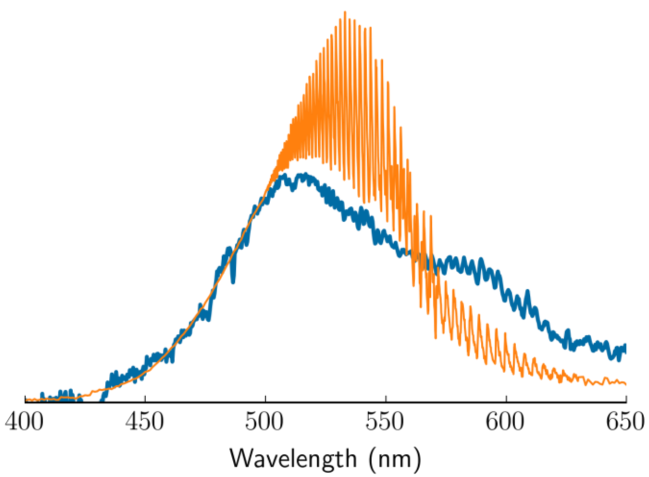
- Comparison with gas pressure measurements (Baratron gage)
- Good agreement with T=311 K when using the 450-500 nm range



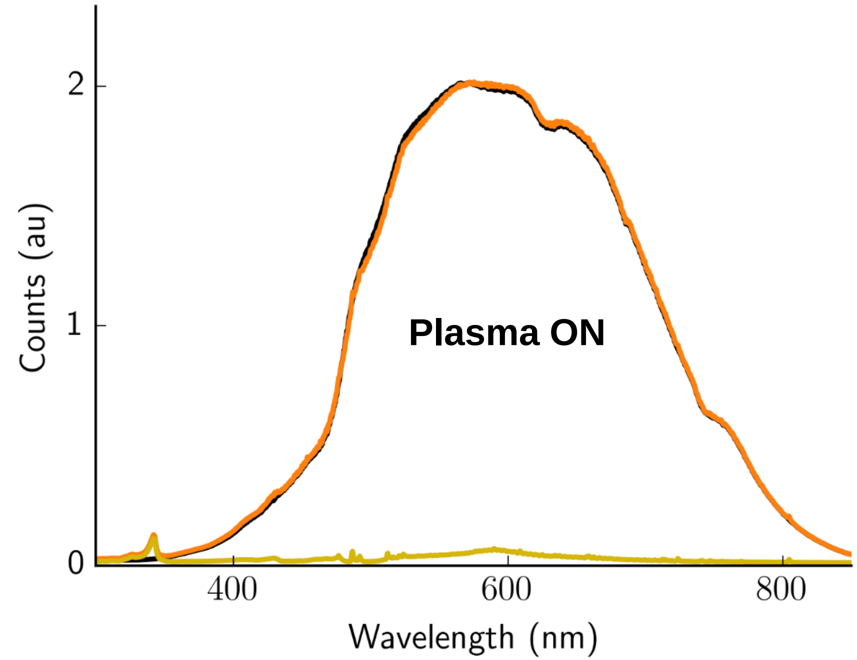
Iodine molecule density by broadband absorption: problems with plasma



Plasma OFF



Plasma ON



- When the plasma is on, plasma emission and absorption are of the same order of magnitude
- Vibrationnal excitation likely to be significant which would entirely change the cross section

Conclusions (1)

- Iodine (I_2) is a promising gas for plasma propulsion because:
  - It is heavy and easy to dissociate and ionize
  - Solid state at room temperature but easily sublimates

- At high power/low pressure (typical of plasma thrusters) iodine plasmas are comparable to xenon plasmas

- As pressure increases, the energy loss raises quickly and the molecular nature takes over: short energy relaxation length, attachment

- The electronegativity is negligible at high power/low pressure because negative ions are formed from dissociative attachment and efficiently destroyed by electron impact

- As pressure increases, the electronegativity raises quickly away from the antenna: negative ions are not in Boltzmann equilibrium

Conclusions (2)

- Iodine atom density in the $^2P_{1/2}$ state seems to be important. This makes atom density measurements difficult via the dipolar magnetic part of the transition around 7603 cm^{-1} (absorption in IR between the $^2P_{3/2}$ and $^2P_{1/2}$)
- Iodine molecules (I_2) are quite easily detected by broadband absorption when the plasma is OFF. When the plasma is ON, more work is needed to interpret the data
- From (somewhat questionable) first measurements, it seems that the plasma is highly dissociated near the antenna
- Iodine atom seems quite hot – heating coming from dissociation is probably quite important

Future work

- We plan to do Two-Photon Absorption Laser-Induced Fluorescence (TALIF) experiments to probe iodine atoms, both in the $^2P_{3/2}$ and $^2P_{1/2}$ states
- We also plan to do experiments with a magnetic filter (PEGASES configuration)
- We have a global model of iodine plasmas (Grondein et al. Phys. Plasma 2016) that is currently being compared to experiments – It will be used to test different chemistries (with increasing complexity). Cross section calculations (Quantemol, Klaus Bartschat) are also carried out
- Fluid simulations have recently been proposed (Levko and Raja J. App. Phys. 2021). We also plan to explore fluid modelling, in particular for neutrals species.
- 2D Particle-In-Cell simulations using LPPic2D will be performed (PhD thesis of Nicolas Lequette, started October 2021)