LABORATOIRE
D'ELECTROSTATIQUE
ET DE MATERIAUX
DIELECTRIQUES

L'apport de la spectroscopie d'émission dans la compréhension des décharges électriques dans les milieux denses.

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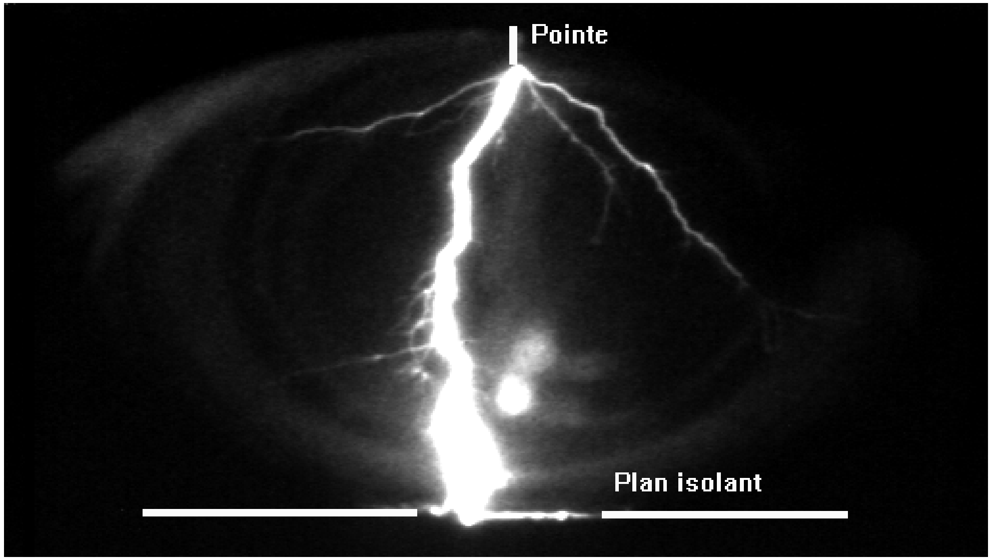
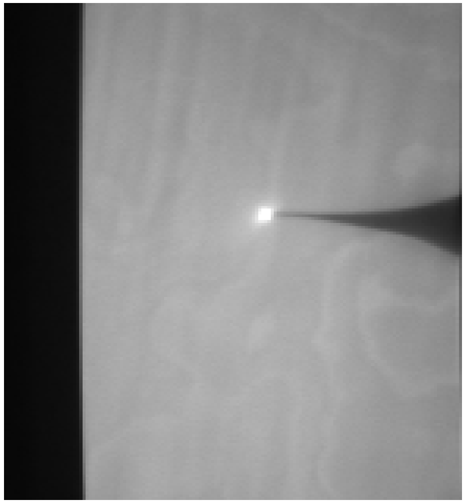
Laboratoire d'Electrostatique et de Matériaux Diélectriques

CNRS et U J F Grenoble FRANCE

Bref Historique



Streamer dans l’azote liquide

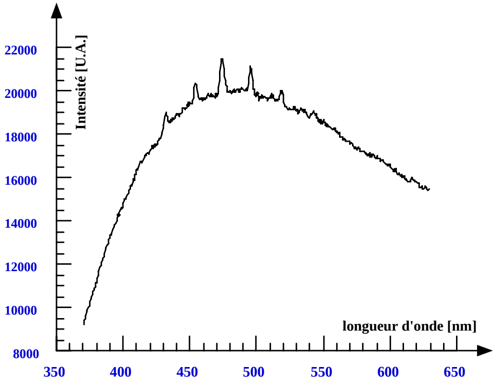


Décharge couronne dans l’argon liquide

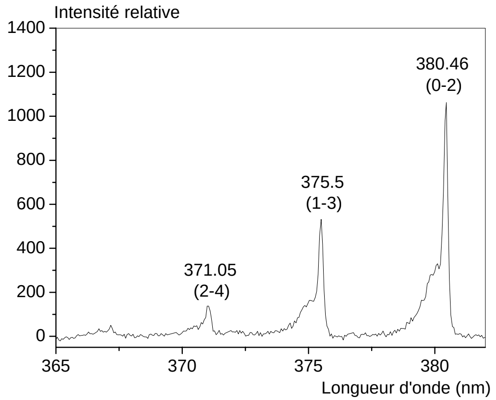
Spectroscopie d’émission

- **Densité Electronique Ne, Température Electronique Te**
- **Température cinétique du gaz Tk**
- **Densité du gaz N**

Continuum

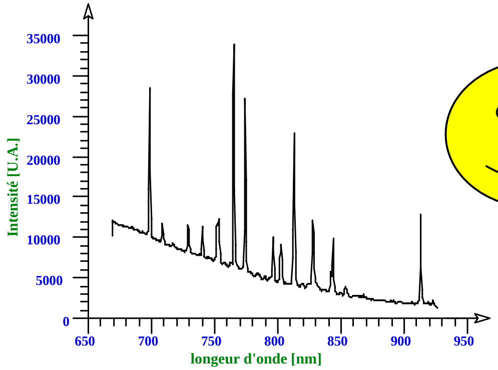


Molecular spectra



B. Pearse and A. G. Gaydon The identification of Molecular Spectra Chapman and Hall 1976

Atomic spectra



A. R. Stringanow and N. S. Sventitskii, Tables of Spectral Lines of Neutral and Ionized Atoms Plenum New York 1968.

Atomic Spectral Line Database http://cfa-www.havard.edu/

Remarques Préliminaires

Spectre Moléculaire : N_2, OH

Température vibrationnelle T_V

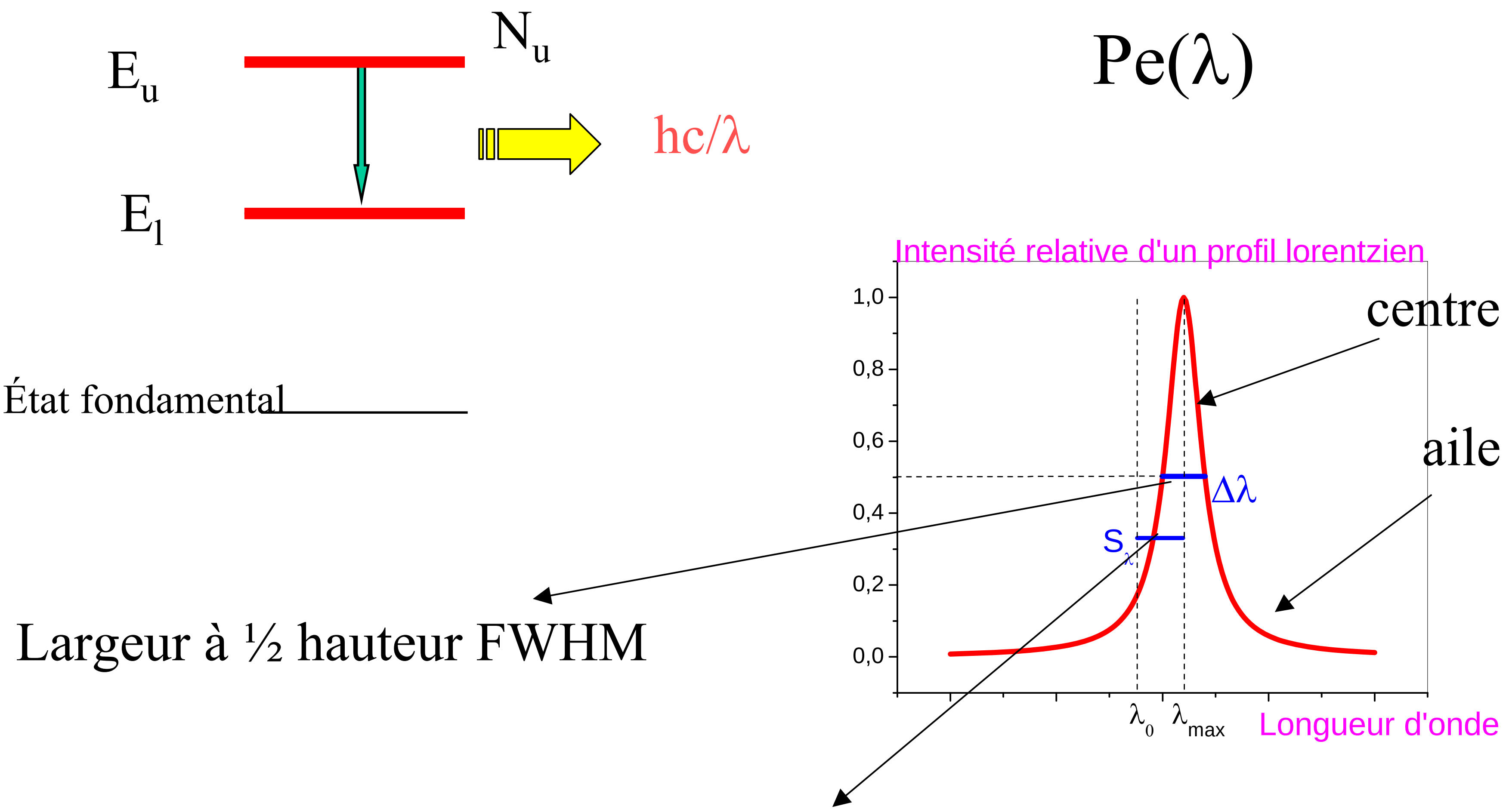
Température Rotationnelle T_r

$$I(J',J'')=D\,\nu^4_{J'J''}S(J'J'')\exp\left(-\frac{B_{v'}J'(J'+1)hc}{kT_r}\right)$$

T_r~Température cinétique des neutres

Méthode de simulation

Spectre atomique



$Pe(\lambda)$

centre

aile

Largeur à ½ hauteur FWHM

Déplacement

1 Élargissement Naturel

Durée finie des niveaux excités

$\Delta\lambda_{\mathrm{natural}}\xcancel{\sim 10^{-4}}$ Å

2 Élargissement Doppler

Mouvement de l'atome émetteur

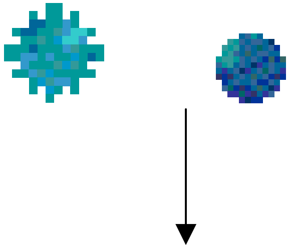
$$\Delta\lambda_D = 2\lambda\sqrt{\frac{2kT\ln 2}{mc^2}}$$

$\xcancel{10^{-2}}$ 10^{-4} nm

3 Élargissement de Pression

Élargissement de Pression

Interaction d’un atome avec les particules qui l’entourent



Le potentiel d’interaction

$V=hCp/r^p$

Profil de la raie

Théorie classique
Différentes Approximations

Approximation
d’impact

N faible
Centre de la raie

↓

Profil de la raie lorentzien

Approximation quasistatique

N élevée
Ailes de la raie

↓

Profil de la raie?

validité

Terme de densité

$$\rho_w = \left(\frac{\alpha_p C_p}{w} \right)^{1/p-1} = \left(\frac{1}{N_L} \right)^{1/3}$$

$N \ll N_L$ impact

$N \gg N_L$ QS

Terme de fréquence

$$\Delta\lambda_L = \frac{\lambda_{ul}^{\;2}}{2\pi c} \frac{w}{\rho_w}$$

$\Delta\lambda \ll 2\Delta\lambda_L$ impact

$\Delta\lambda \gg 2\Delta\lambda_L$ QS

Potentiel d’interaction

• Électrons , ions	Effet Stark
• Neutres	VderW, Resonant

Effet stark linéaire $V(r)=C_2/r^2$

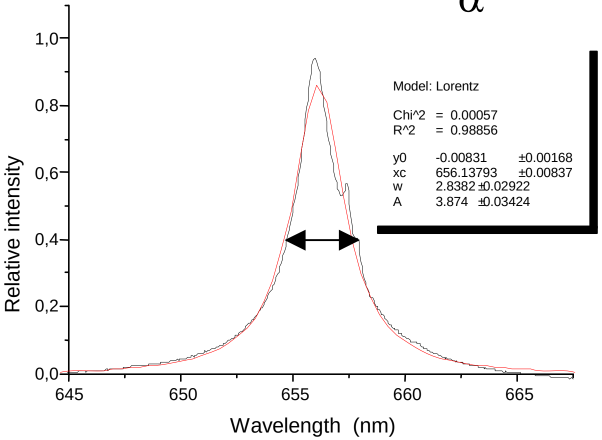
Cas de l'hydrogène atomique

Griem 1964,1974

$$N_e=C(N_e,T_e)*\Delta\lambda^{3/2}$$

Where $C(N_e,T_e)$ is in $A^{-3/2}$ cm^{-3}.

H_α 656.2 nm



```
Model: Lorentz

Chi^2  =  0.00057
R^2    =  0.98856

y0     -0.00831      ±0.00168
xc     656.13793     ±0.00837
w      2.8382 ±0.02922
A      3.874  ±0.03424
```

Effet Stark quadratique
V®=C_4/r^4

$$\Delta\lambda_{Stark} = \left(1+1.75\alpha(1-0.75r)\right)2\omega$$

$$S_{\lambda\,(Stark)} = d \pm 2\alpha(1-0,75r)\omega$$

ω proportionnel à Ne

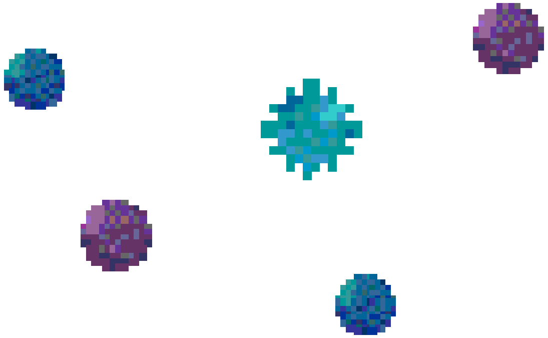
α

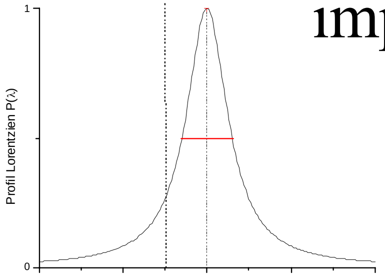
→ H .R. Griem, «Spectral Line Broadening by Plasmas », New York : Academic Press, 1974

→ **Ne**

Potentiel de Van der Waals
V®=$-C_6/r^6$

Perturbateurs neutres



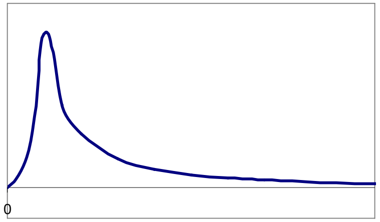


impact

$\longrightarrow$ $\Delta\lambda_{\mathrm{VdW}}\ \alpha\ N$

N ↗

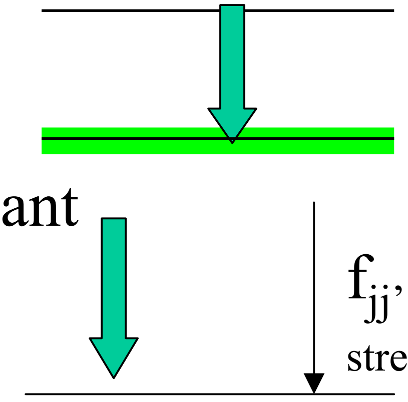
QS



$\longrightarrow$ $\Delta\lambda_{\mathrm{VdW}}\ \alpha\ N^2$

Potentiel de Resonance
V®=±C_3/r^3

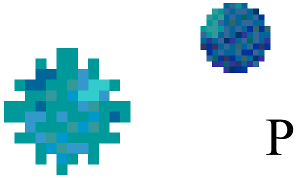
Niveaux excités couplés radiativement avec le fondamental



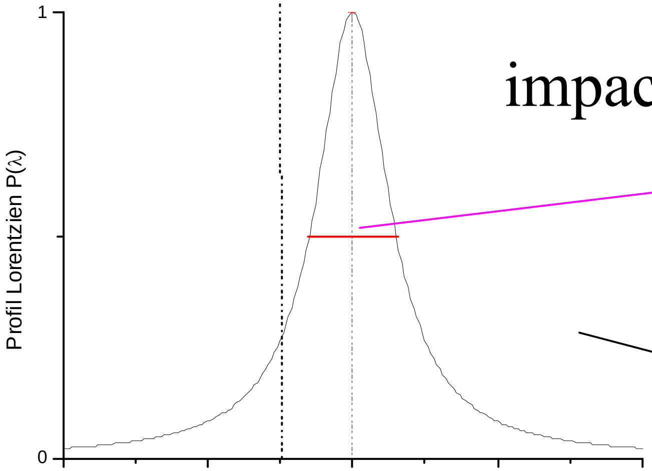
Niveau résonant

$f_{jj'}$ oscillator strength

Niveau fondamental



Perturbateurs de même nature que l'émetteur

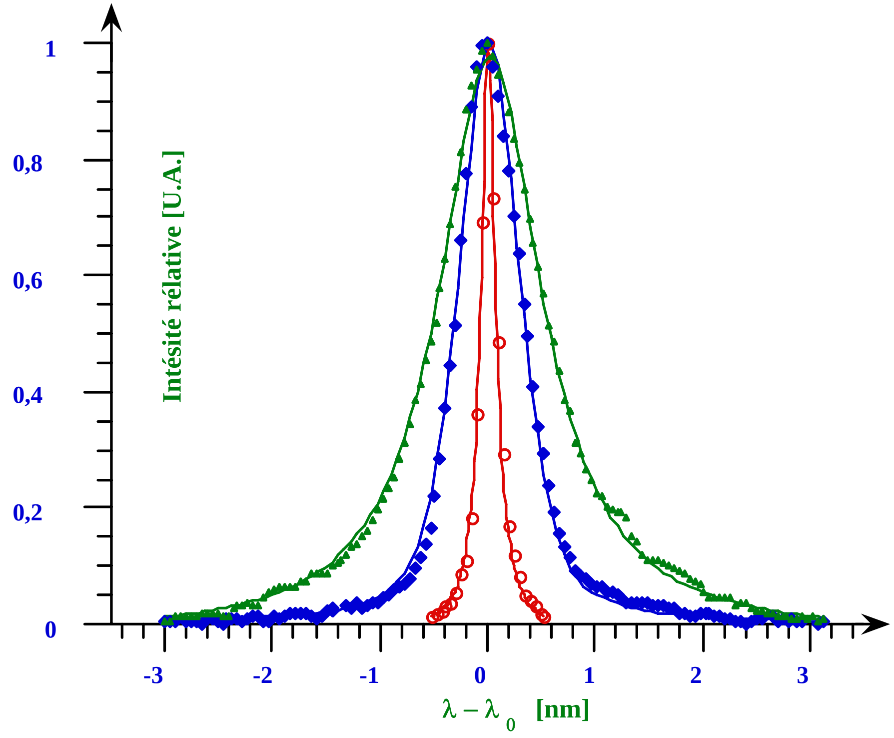


impact

$\Delta\lambda_{res}$ α N

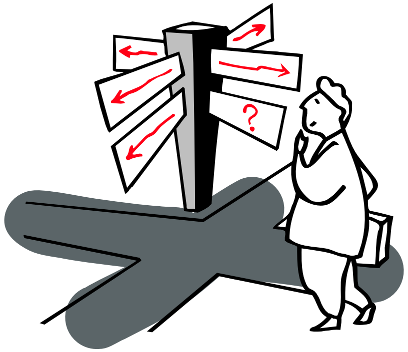
QS ?

$\Delta\lambda_{res}$ α N, □N…



→ Stark +Van der Waals +resonant

$$\Delta\lambda = \Delta\lambda_{stark} + \Delta\lambda_{VdW} + \Delta\lambda_{res}$$



Élargissement de pression

Classification Mathématique
Théorie classique
Différentes Approximations

Impact approx

$N<<N_L$

$\Delta\lambda<\Delta\lambda_L$

Quasi-static approx

$N>>N_L$

$\Delta\lambda>\Delta\lambda_L$

Classification Physique
Potentiel d'Interaction

Stark

N_e

Resonant

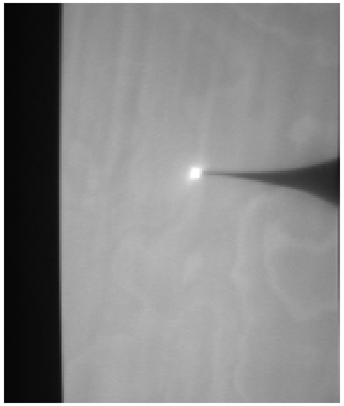
N

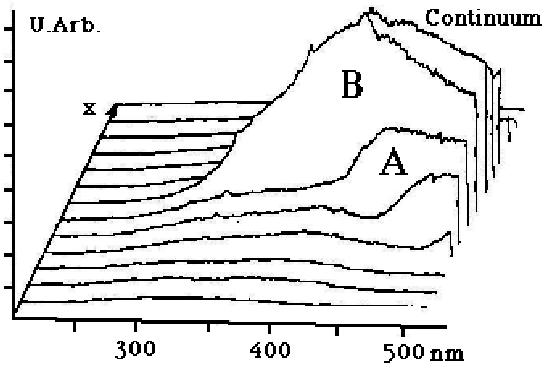
Van der Waals

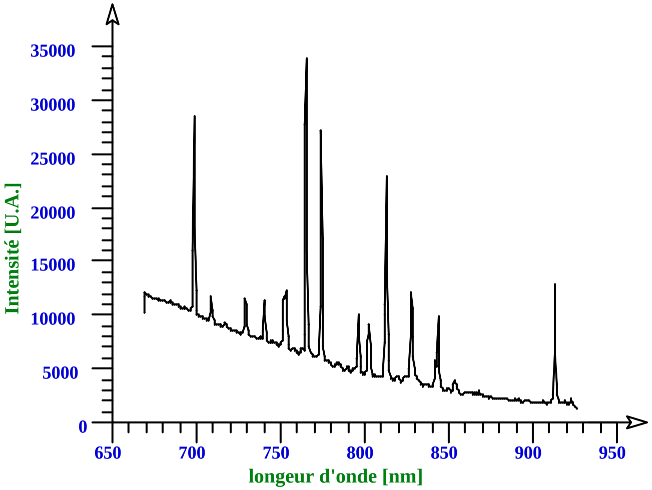
N

Exemples d’Applications

Décharge couronne dans l’argon liquide







Recombinaison

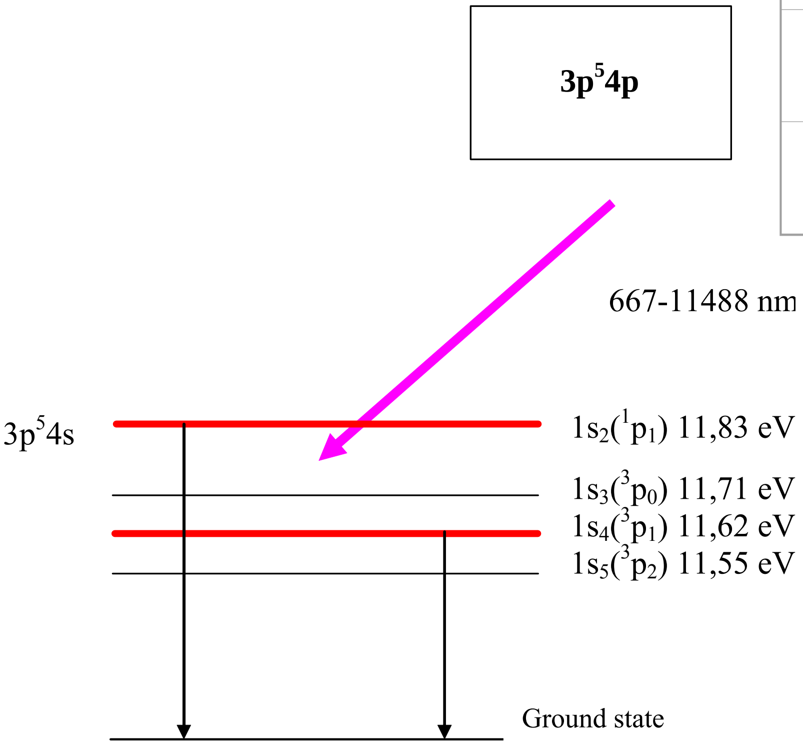
$Ar^{+}+e^{-} \longrightarrow Ar^{*}+h\nu$ N_e, T_e

$N_e \sim 10^{18}\ m^{-3}$ → ~~Stark~~

Décharge couronne dans l'argon liquide

Transitions 4p-4s

Wavelength λ (nm)	Transition Paschen Notation	Type of interaction
696.5	$1s_5$-$2p_2$	van der Waals
727.3	$1s_4$-$2p_2$	Resonance plus van der Waals
826.4	$1s_2$-$2p_2$	Resonance



$3p^54p$

667-11488 nm

$3p^54s$

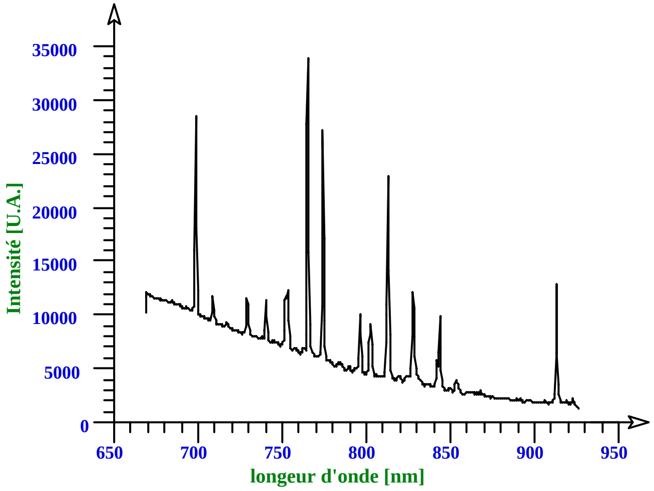
$1s_2(^1p_1)$ 11,83 eV

$1s_3(^3p_0)$ 11,71 eV

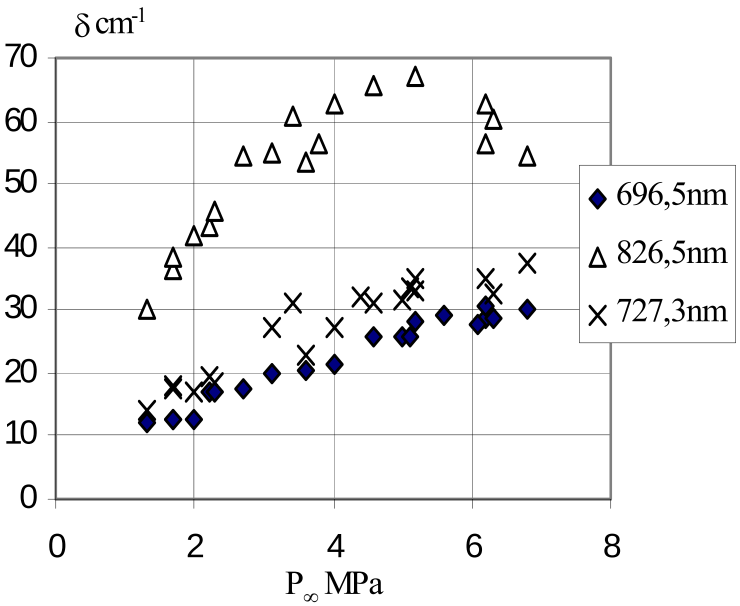
$1s_4(^3p_1)$ 11,62 eV

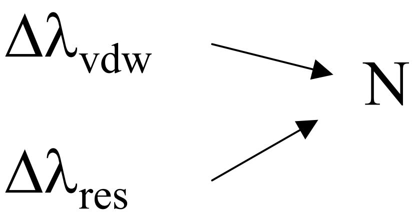
$1s_5(^3p_2)$ 11,55 eV

Ground state



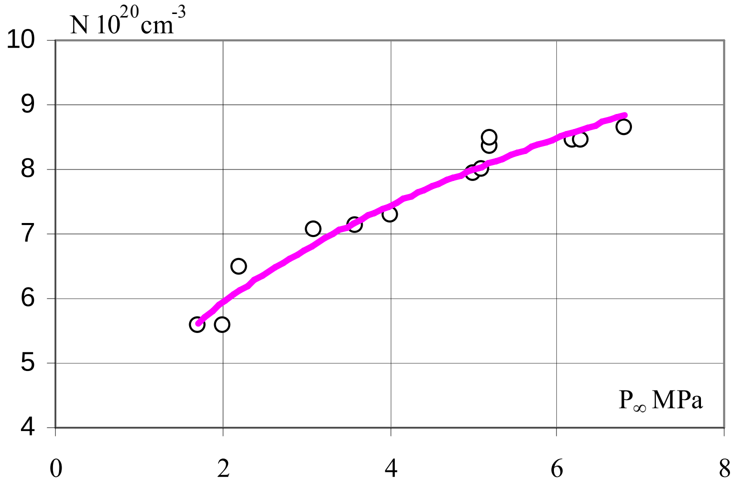
Décharge couronne dans l’argon liquide

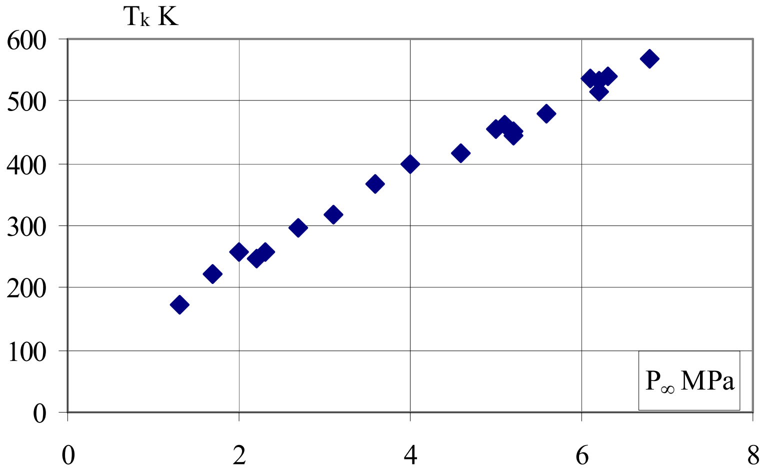



$\Delta\lambda_{vdw}$

$\Delta\lambda_{res}$

N



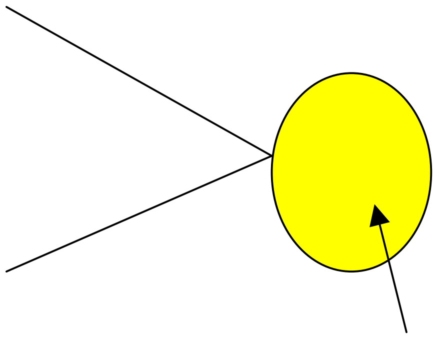


Décharge couronne dans l'argon liquide

$N = 2.1 10^{22} cm^{-3}$

$T = 88K$

$P = 1\text{-}6MPa$



$N \sim 5\text{-}9\ 10^{20} cm^{-3}$

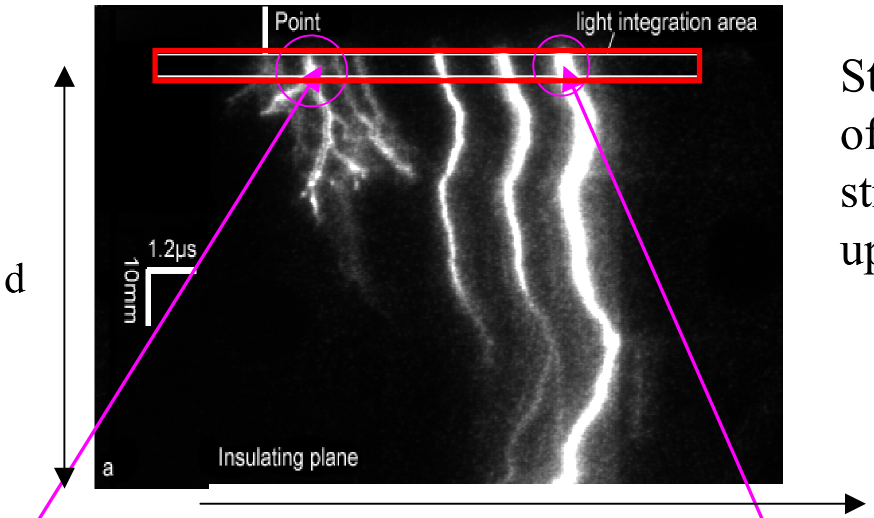
$T_k \sim 100\text{-}500k$

$N < N_{Lim}$

Approximation d'impact

Streamers filamentaires positifs dans l'azote liquide

2 phases distinctes



Streak photograph
of filamentary
streamer propagating
up to plane

La propagation
du streamer

The final jump

Émission de lumière faible

Émission de lumière intense

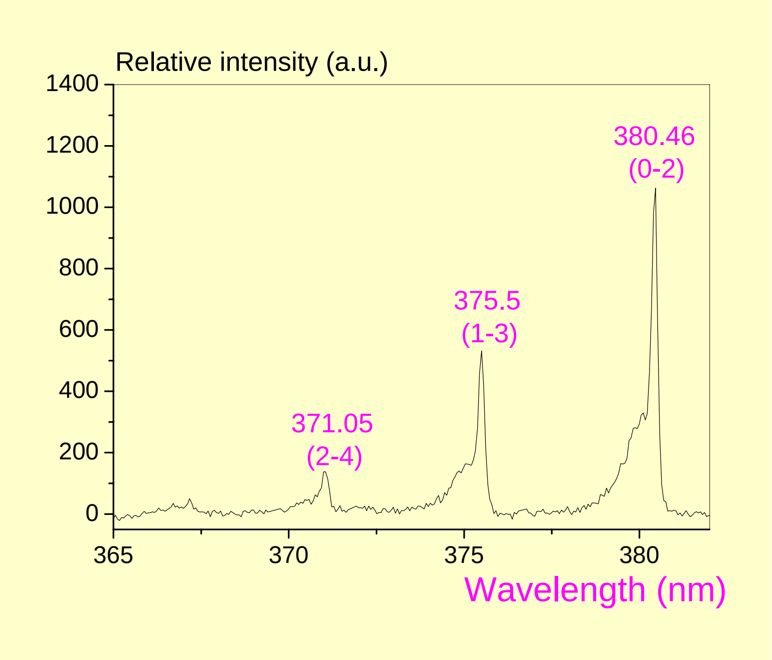
~100 streamers

1 streamer

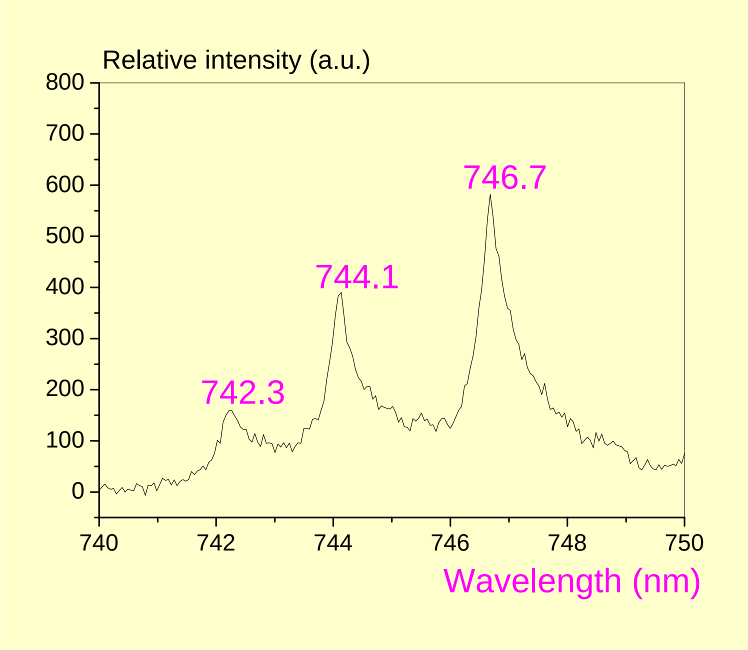
Streamers filamentaires dans l'azote liquide

Propagation

Second positif system of N_2
$(C^3\Pi_u \rightarrow B^3\Pi_g)$



Atomic line of NI
$(3s^4P\text{-}3p^4S^0$ and $3s^4P\text{-}3p^4P)$

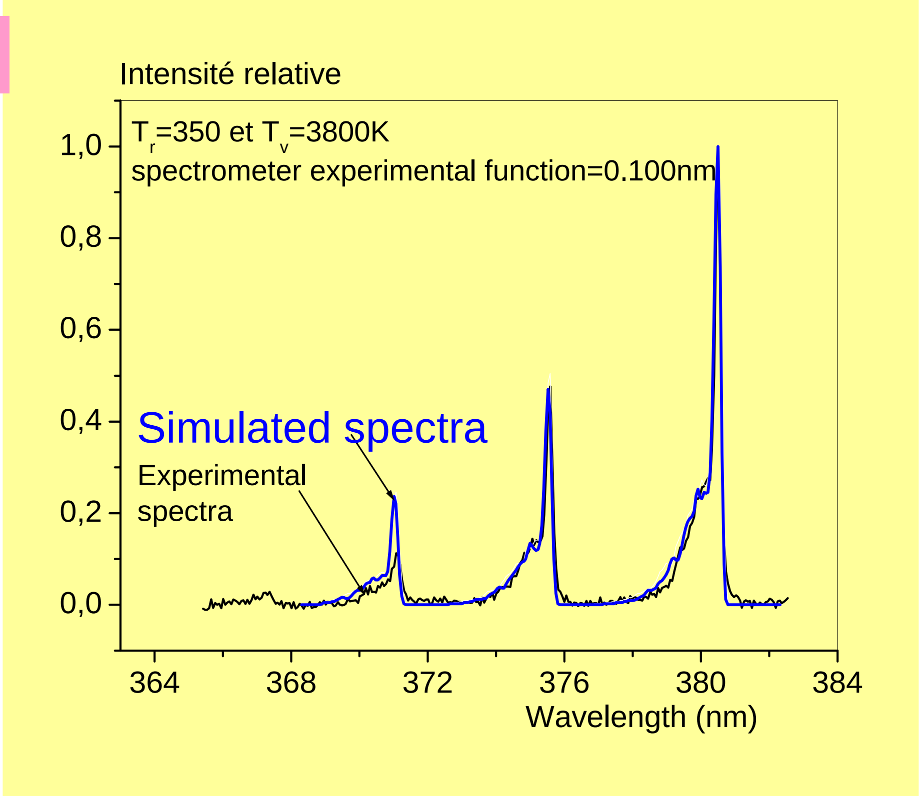


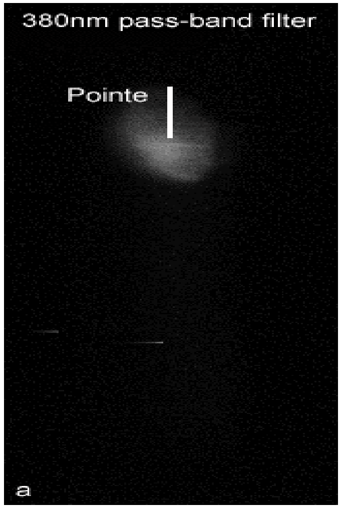
Streamers filamentaires dans l'azote liquide

Propagation

$T_v=3800$ K

$T_{rotational}=350$ K





Région périphérique $T_k \sim 350$K

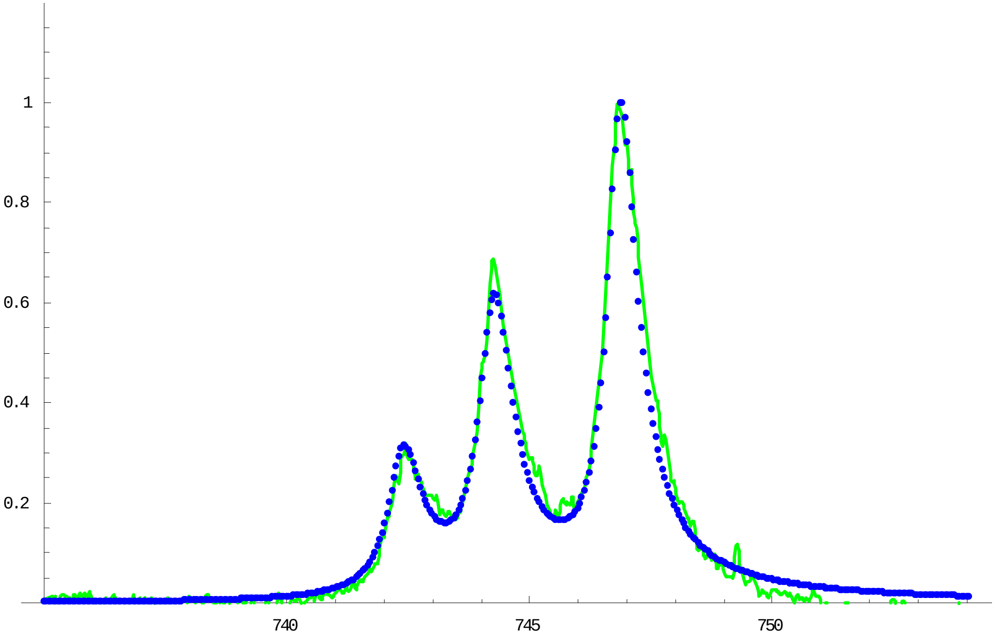
Streamers filamentaires dans l'azote liquide

Propagation

Stark	VderW	~~Res~~
Ne	N_{N2}	fr ≠ , Δλ(res) ≠

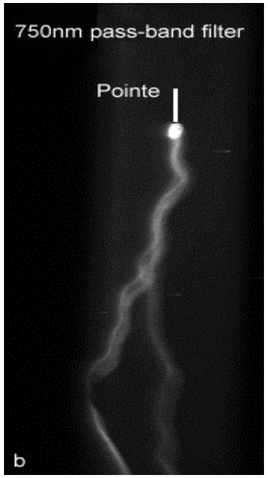
Ne impact
QS

$$P_T = \int_{-\infty}^{+\infty} P_1(\Delta\lambda - \zeta) P_2(\zeta) d\zeta$$



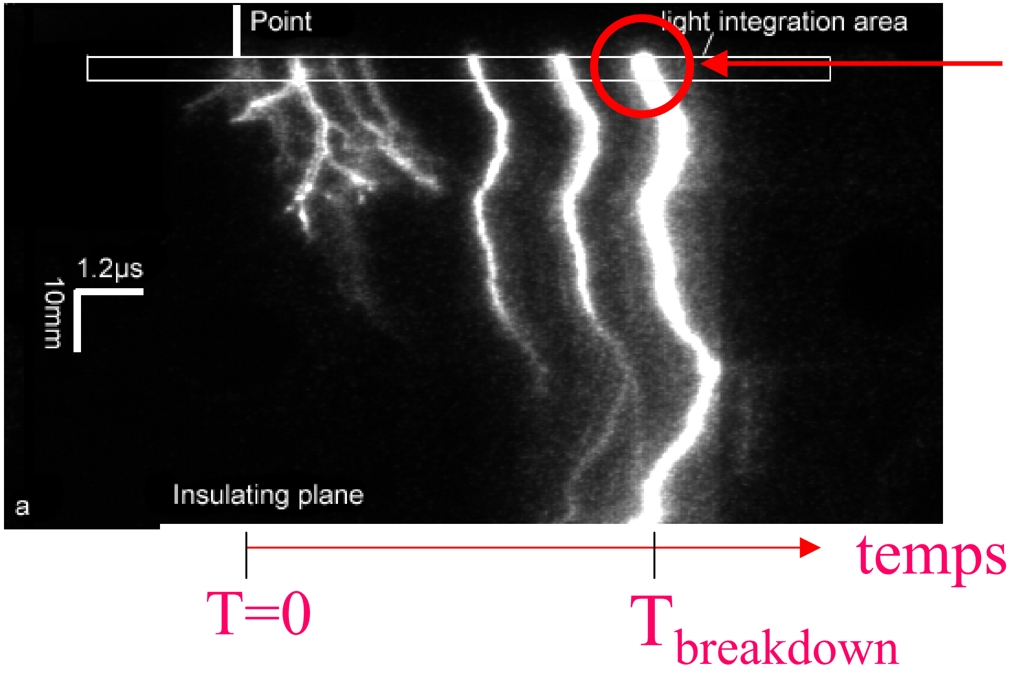
$N_e \sim 3\ 10^{23}\ m^{-3}$

$N_{N2} \sim 3\ 10^{26}\ m^{-3}$



Streamers filamentaires dans l'azote liquide

Final Jump



N I

($3s^4P$-$3p^4S^0$ and $3s^4P$-$3p^4P$ transition)

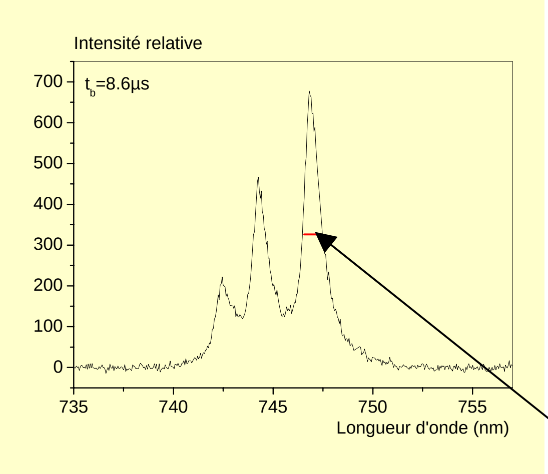
Absence d'émission N_2

2-9µs

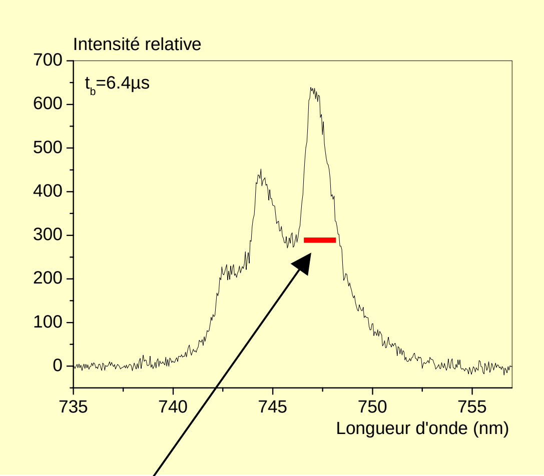
Streamers filamentaires dans l’azote liquide

Final jump

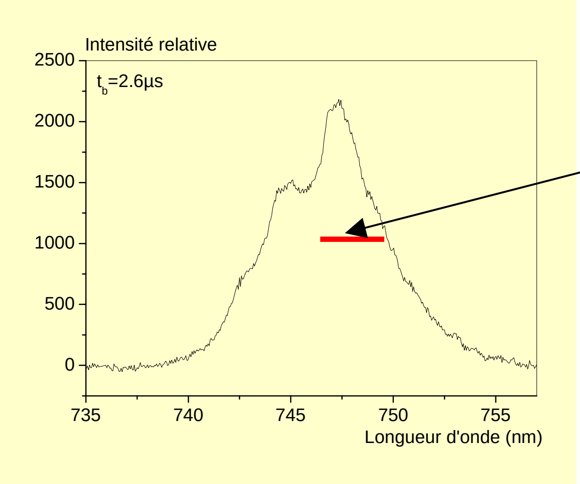
$T_{breakdown}$=8.6µs



$T_{breakdown}$=6.4µs



$T_{breakdown}$=2.6µs



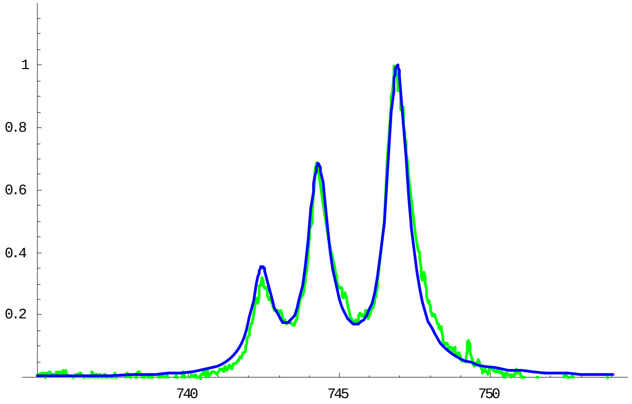
Élargissement de la raie atomique NI

Streamers filamentaires dans l'azote liquide

Final jump

Absence d'émission N_2

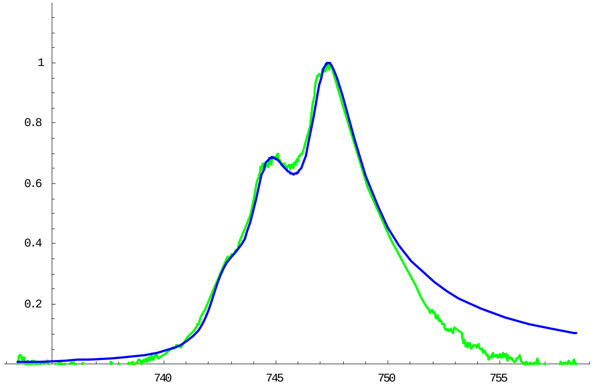
$T_{breakdown}=8.6\mu s$



$N_e \sim 0.6\,10^{24}\ m^{-3}$

$N_{N2} \sim 1\,10^{26}\ m^{-3}$

$T_{breakdown}=2.6\mu s$



$N_e \sim 1.10^{24}\ m^{-3}$

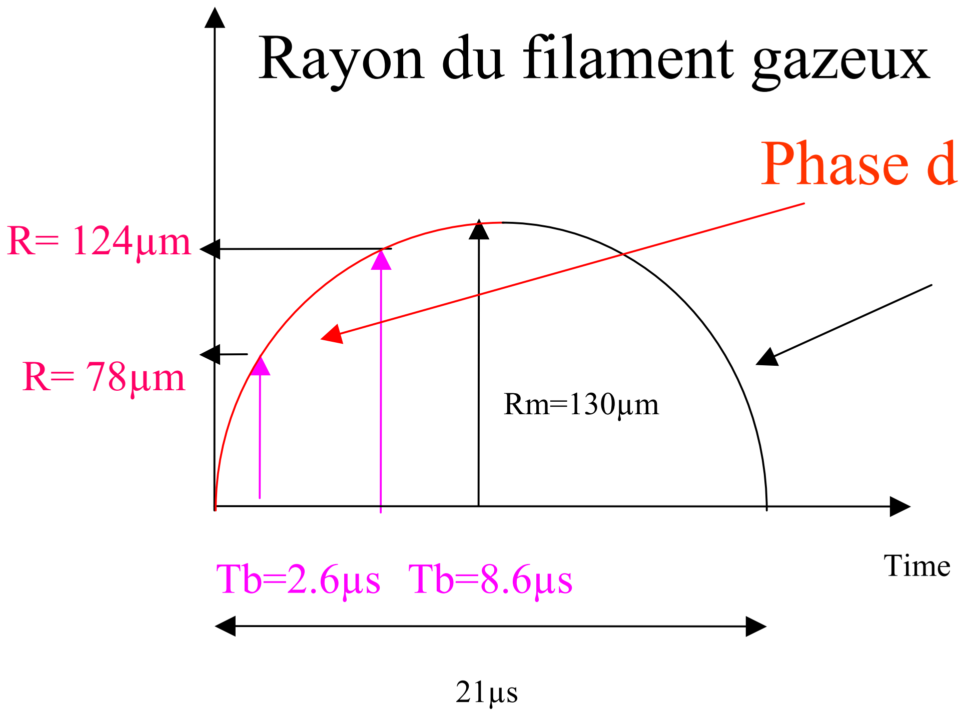
$N_{N2} \sim 7.10^{26}\ m^{-3}$

Streamers filamentaires dans l'azote liquide

Final jump

$Ng(2.6\mu s) > Ng(8.6\mu s)$ **?**

P Gournay and O Lesaint 1994 → R_m, τ



Phase d'expansion du filament gazeux

Collapse of gaseous filament

Tb ↗ Ng ↘

Streamers filamentaires dans l’azote liquide

Final jump

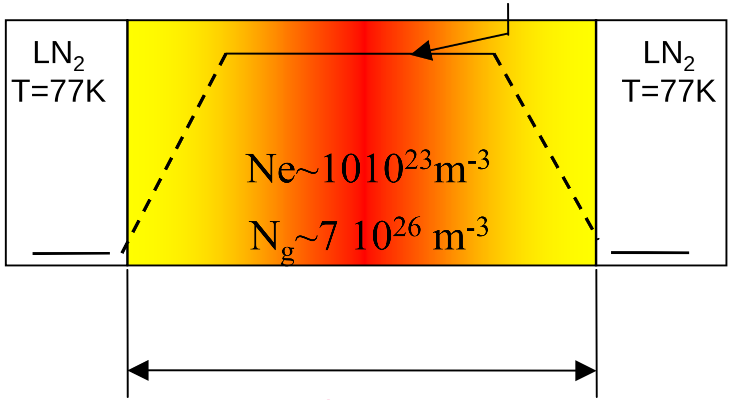
Schematic representation of gaseous structure

$T_k \sim 3000k$

$P=N_gkT$

$T_{breakdown}=2.6\mu s$

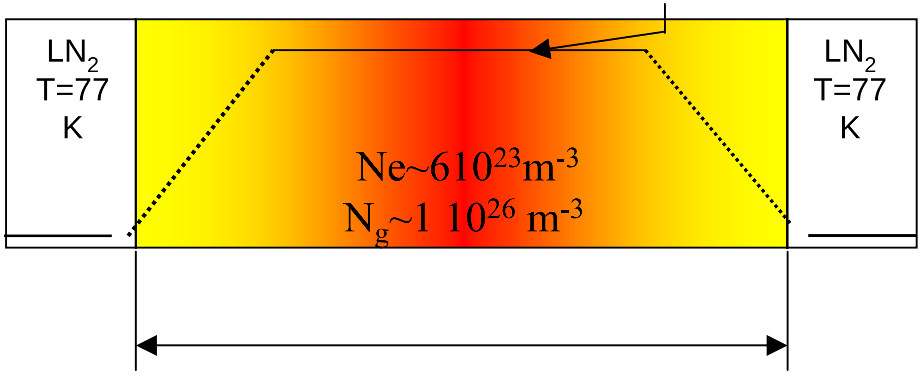
Pressure of the gas ~300 B



≅ 156µm

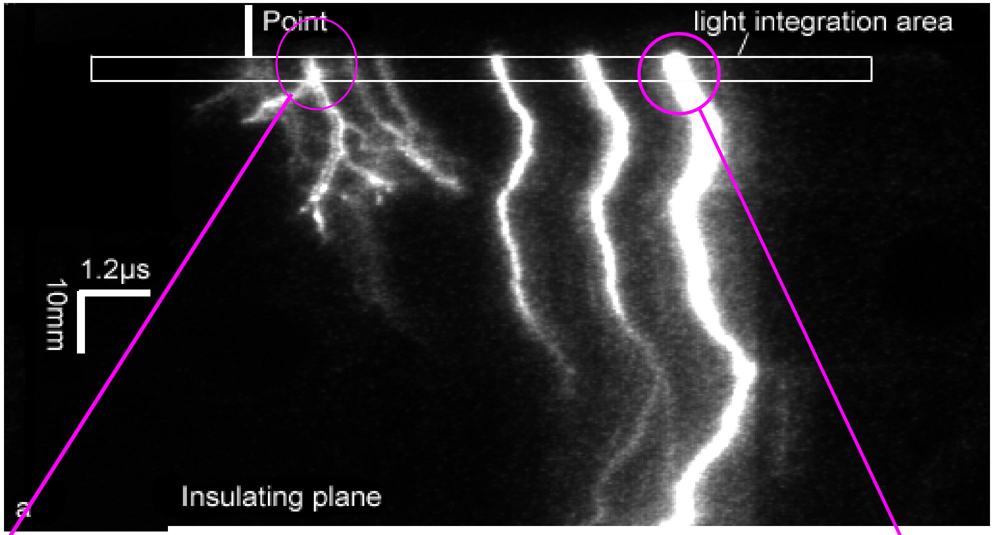
$T_{breakdown}=8.6\mu s$

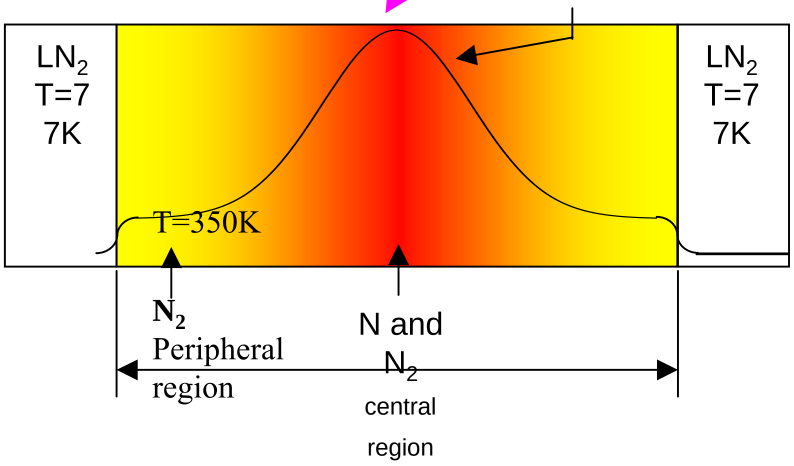
Pressure of the gas ~ 40B



≅ 250µm

Streamers filamentaires dans l’azote liquide





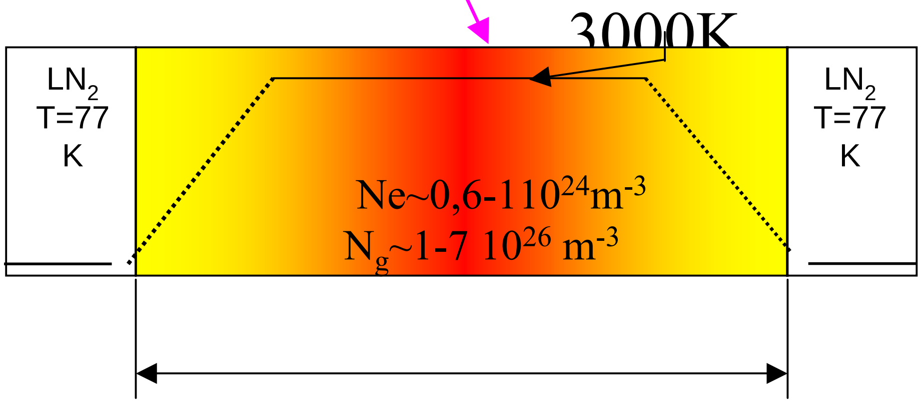
LN$_2$ T=77K

LN$_2$ T=77K

T=350K

N$_2$ Peripheral region

N and N$_2$ central region



3000K

LN$_2$ T=77K

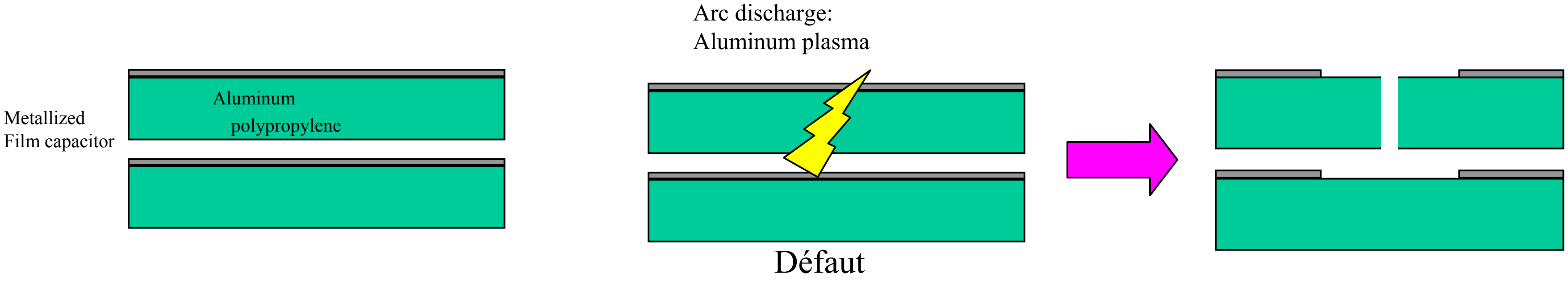
LN$_2$ T=77K

Ne~0,6-1 10^{24} m^{-3}

N$_g$~1-7 10^{26} m^{-3}

≅ 100-250µm

Autocicatrisation
Film de polypropylene métallisé



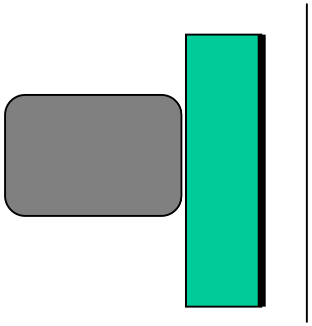
Arc discharge:
Aluminum plasma

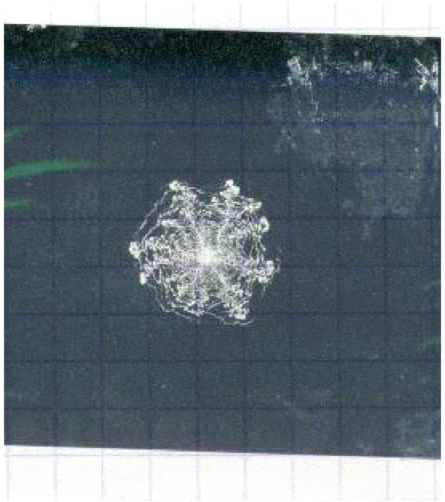
Metallized
Film capacitor

Aluminum
polypropylene

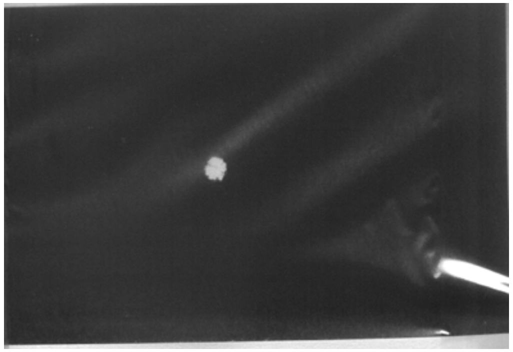
Défaut

verre



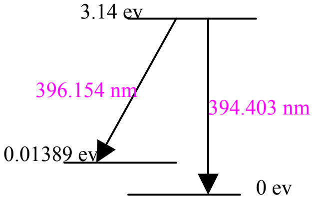


Décharge non confinée

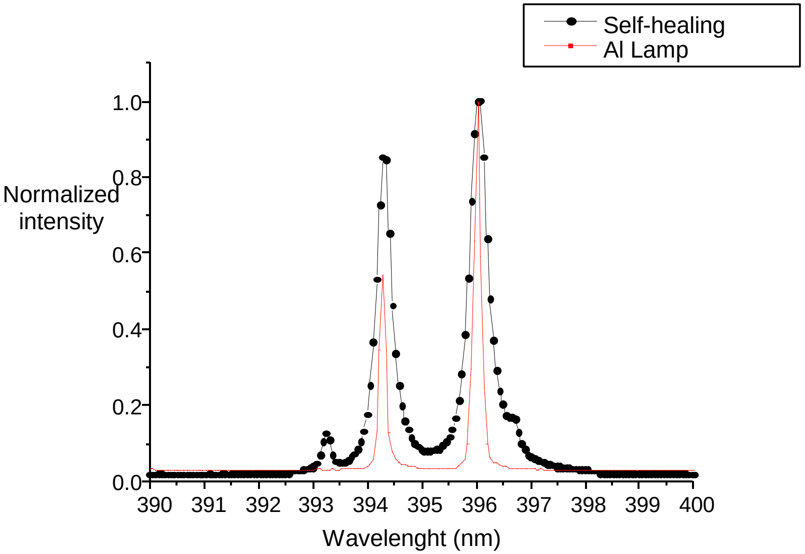


Décharge confinée

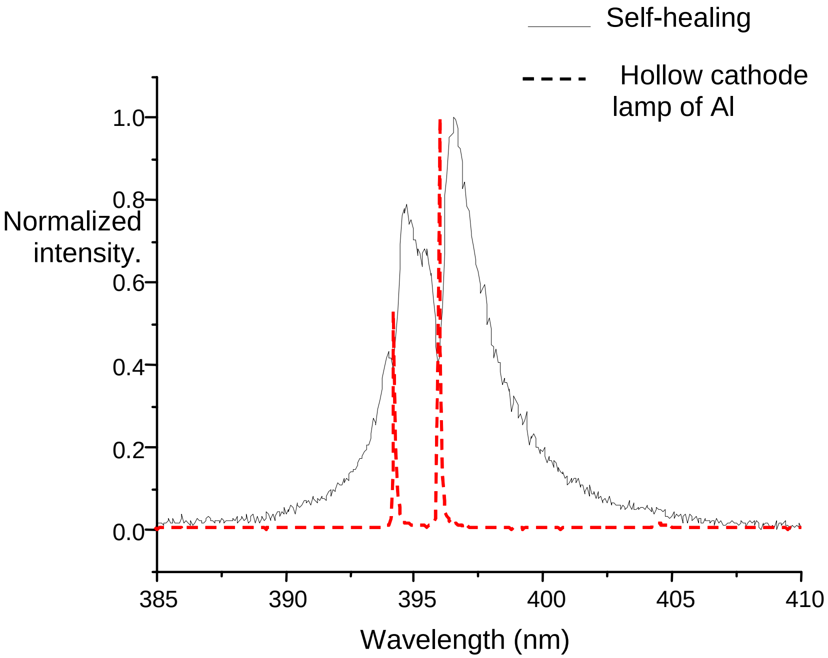
Autocicatrisation
Film de polypropylene métallisé



Raies Al autoabsorbées

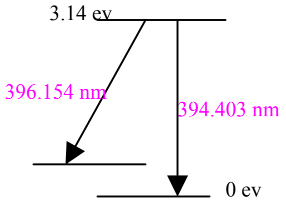


Décharge non confinée



Décharge confinée

Autocicatrisation
Film de polypropylene métallisé



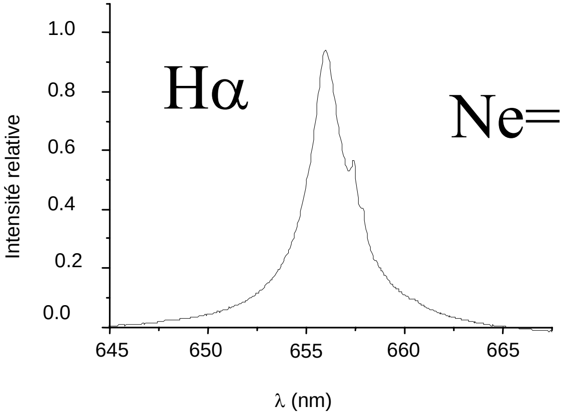
Décharge non confinée

$$\underbrace{\text{Res} \qquad \text{Stark}}_{\mathbf{L}}$$

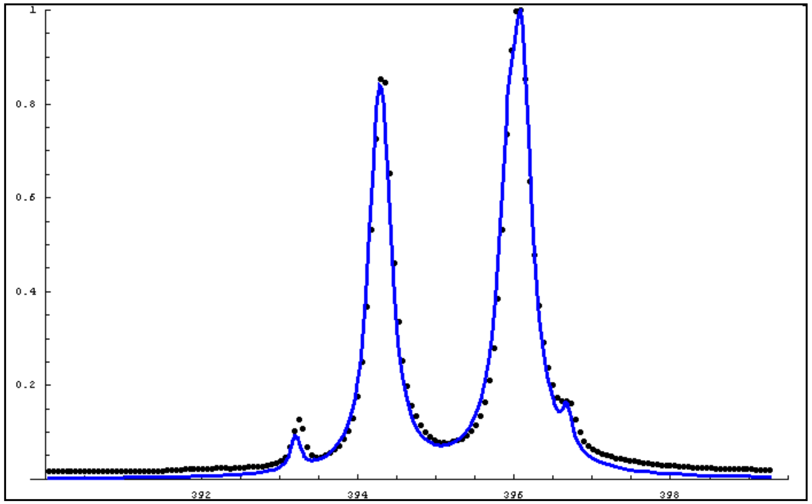
VdW

QS

$$\longrightarrow \quad P_T = \int_{-\infty}^{+\infty} P_1(\Delta\lambda - \zeta) P_2(\zeta) d\zeta$$



$N_e = 2.8\ 10^{23} m^{-3}$



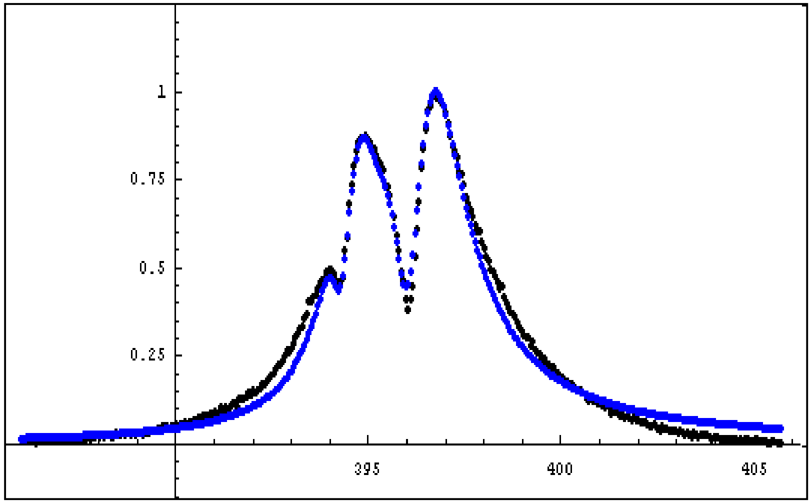
Autocicatrisation
Film de polypropylene métallisé

Décharge confinée

Res Stark VdW

$$P_T=\int_{-\infty}^{+\infty}P_1(\Delta\lambda-\zeta)P_2(\zeta)d\zeta$$

~~Hα~~



Equilibre
thermodynamique local

Loi de Saha Ne

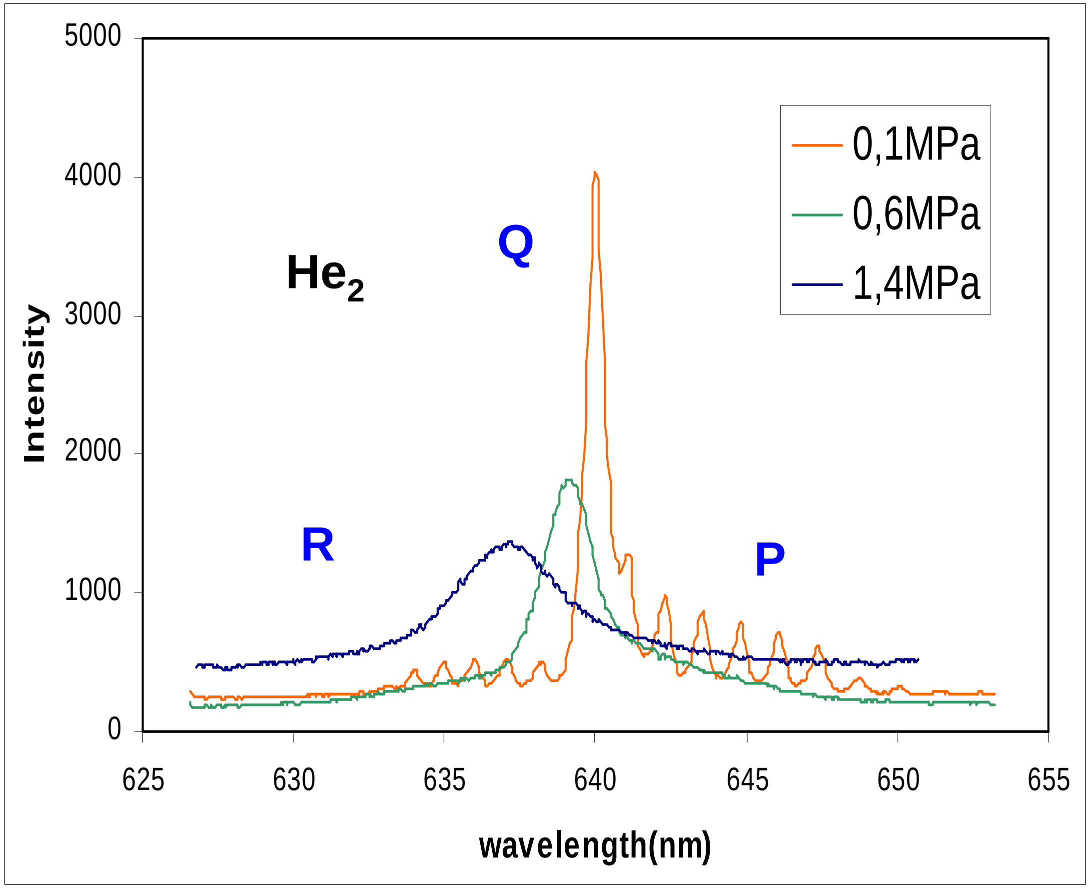
T(z)=(Tmax-Twall) cos[(z-lopt/2)(π/lopt)]+Twall

	Décharges non confinées		Décharges confinées	
	Nos résultats	Klein	Nos résultats	Thermodynamic Model2,3
T (K)	7200	4000-4500	6500-7000	3500
P (MPa)	0.1			10-30
N_g (m^{-3})	1x10^{24}		0.8-1.1x10^{26}	(2.1-6.3x10^{26}) [a]
N_e (m^{-3})	2.8x10^{23} (deduit de H_α)		2-2.8x10^{24} Valeur pour $T=T_{max}$	
l_{opt} (µm)	15		0.5-1	

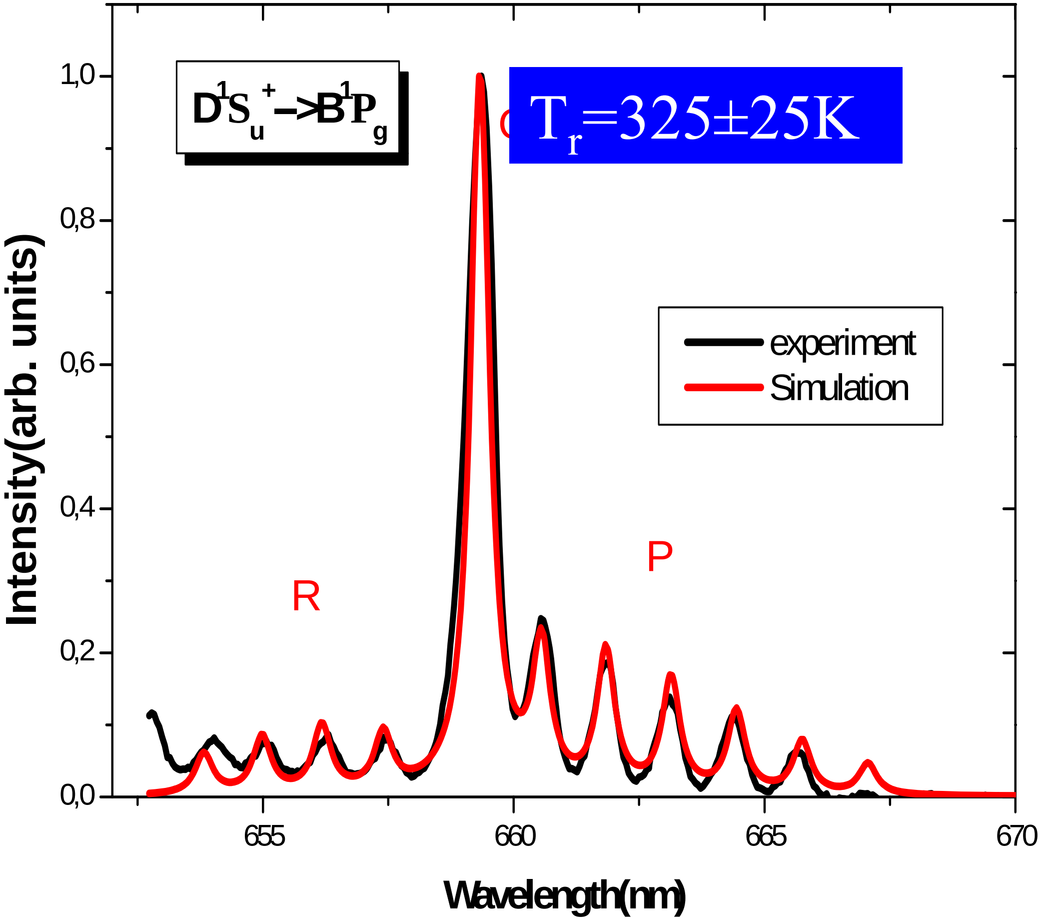
Applications en cours

Décharge couronne dans l'hélium liquide

Effet de la pression



Décharge couronne dans l’hélium liquide



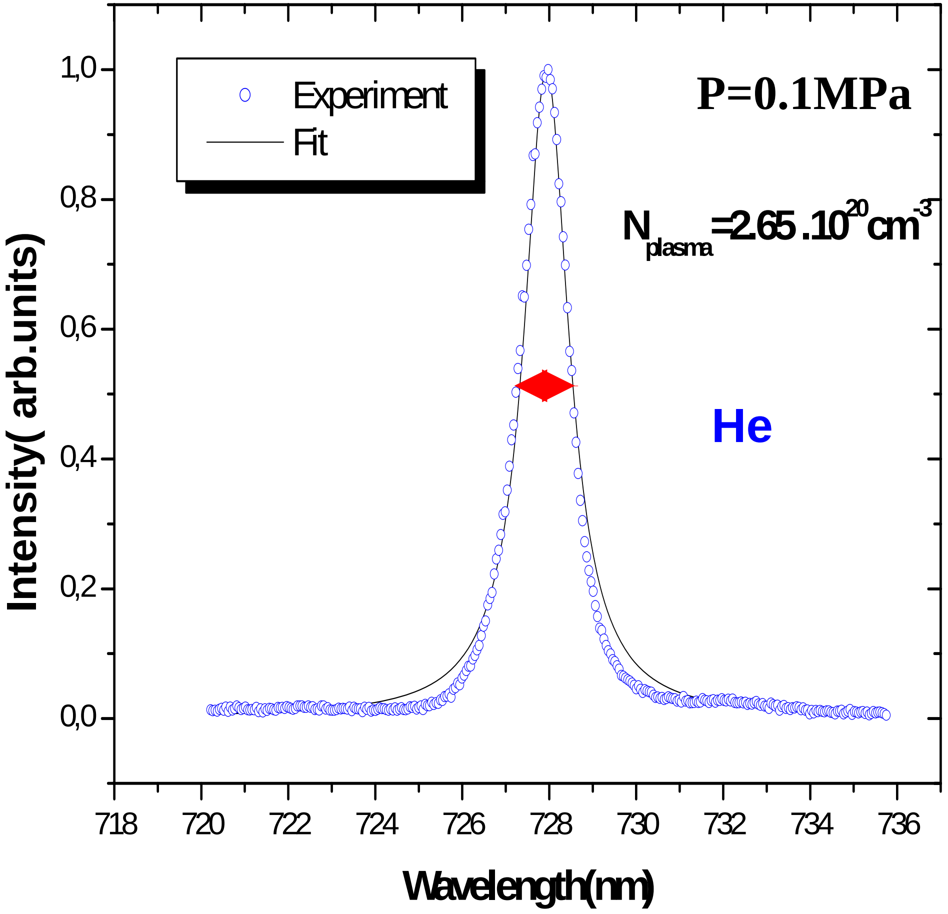
Molecular band

$D^1\Sigma_u^+ \rightarrow B^1\Pi_g$, 660nm

Décharge couronne dans l'hélium liquide

$$\Delta\lambda \propto N_{plasma}$$

☞ $N_{plasma} \approx 3*10^{20}cm^{-3}$



Déplacement/élargissement

- V®=+-C3/r^3
- V®=C_6/r^6, $C_{12}/r^{12}-C_6/r^6$

- Potentiels Moléculaires adiabatiques

Streamer dans l’eau

Traitement de l’eau

Pesticides,phénols

OH, H,O

Conclusion

La spectroscopie d'émission un outil de diagnostic des plus prometteurs des décharges électriques en milieu dense et trop peu utilisé.

Interprétation

Les milieux organiques formés de molécules polyatomiques

↓

dissociation, fragmentation, recombinaison…

↓

Ne,N,T ?

Champ de charge d'espace,   Champ macroscopique

Ne , E_{ce}