Interaction arc/ondes acoustiques dans une torche à plasma de projection. Obtention d'un mode résonant et applications

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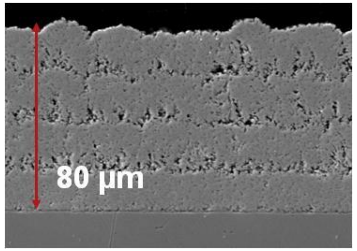
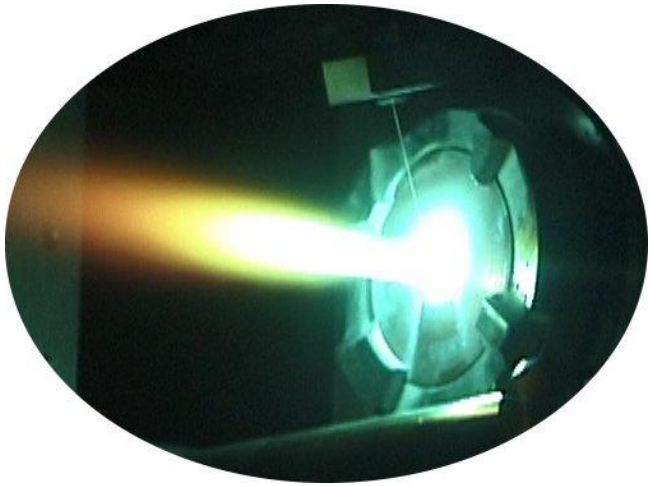
Projection par jet de Plasma de suspensions céramiques



Contrôle de l'architecture des dépôts

Piles à combustible (SOFC)

Barrières thermiques



Dépôts catalytiques

Résistance à l'usure

Electrolyse haute température

Procédés Plasma: une histoire de Transferts

-TORCHE

(conception, alimentation electrique …)

-GAZ

(composition, débit, propriétés thermo-physiques...)

-MATERIAUX

(injection, débits, propriétés)

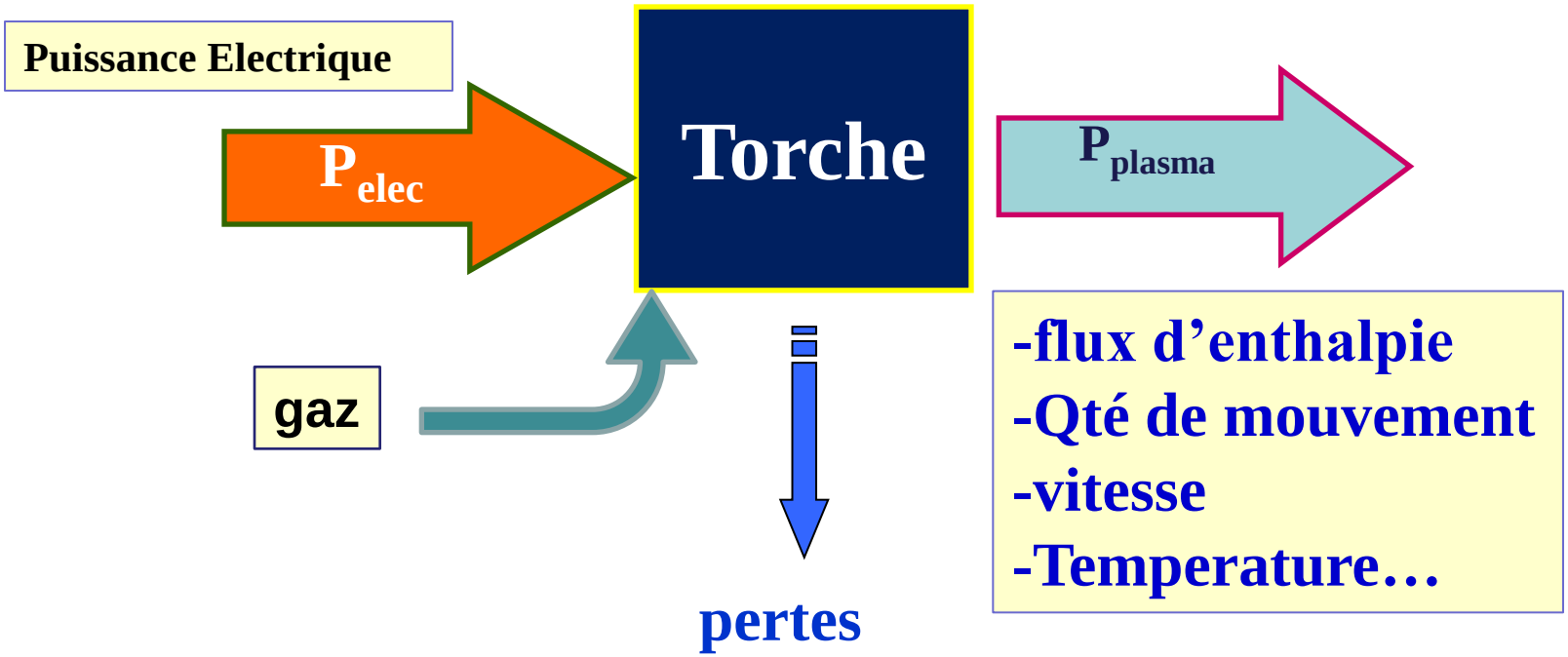
-CONTROLES

→ **interaction Plasma/ materiau** → **dépôt**

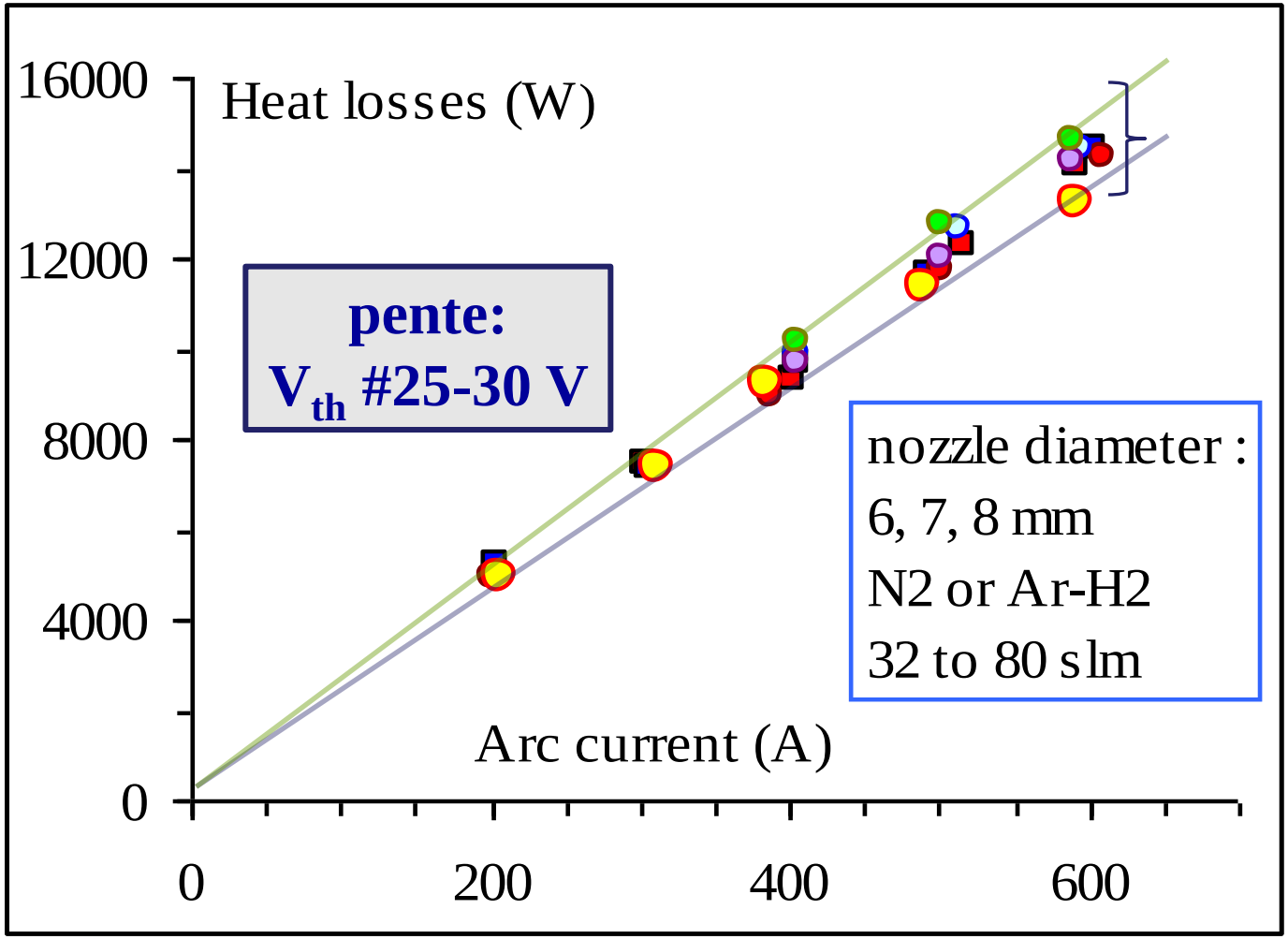
Accélération, Fragmentation, Vaporisation, fusion, Flux au substrat…

Distance de tir, Cinématique de déplacement, Contrôle Temperatures…

Bilan d'Energie



Pertes thermiques aux électrodes



Bilan d'énergie requis pour évaluer la dérive des performances de la torche

Ex : **Tension "*thermique*" équivalente : Vth#30 V**

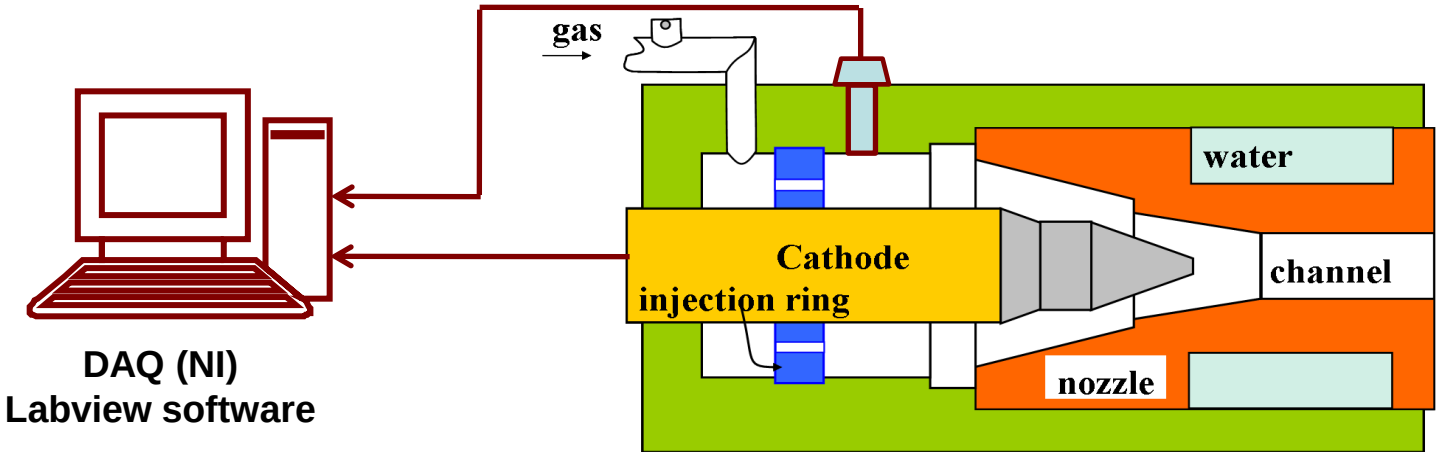
Dérive de la tension d'arc, U_{arc}: 70 V à 60V (errosion)

→ **Tension utile: (Uarc-Vth) : 40 to 30 V**

→ **Réduction de 30% de l'enthalpie massique**

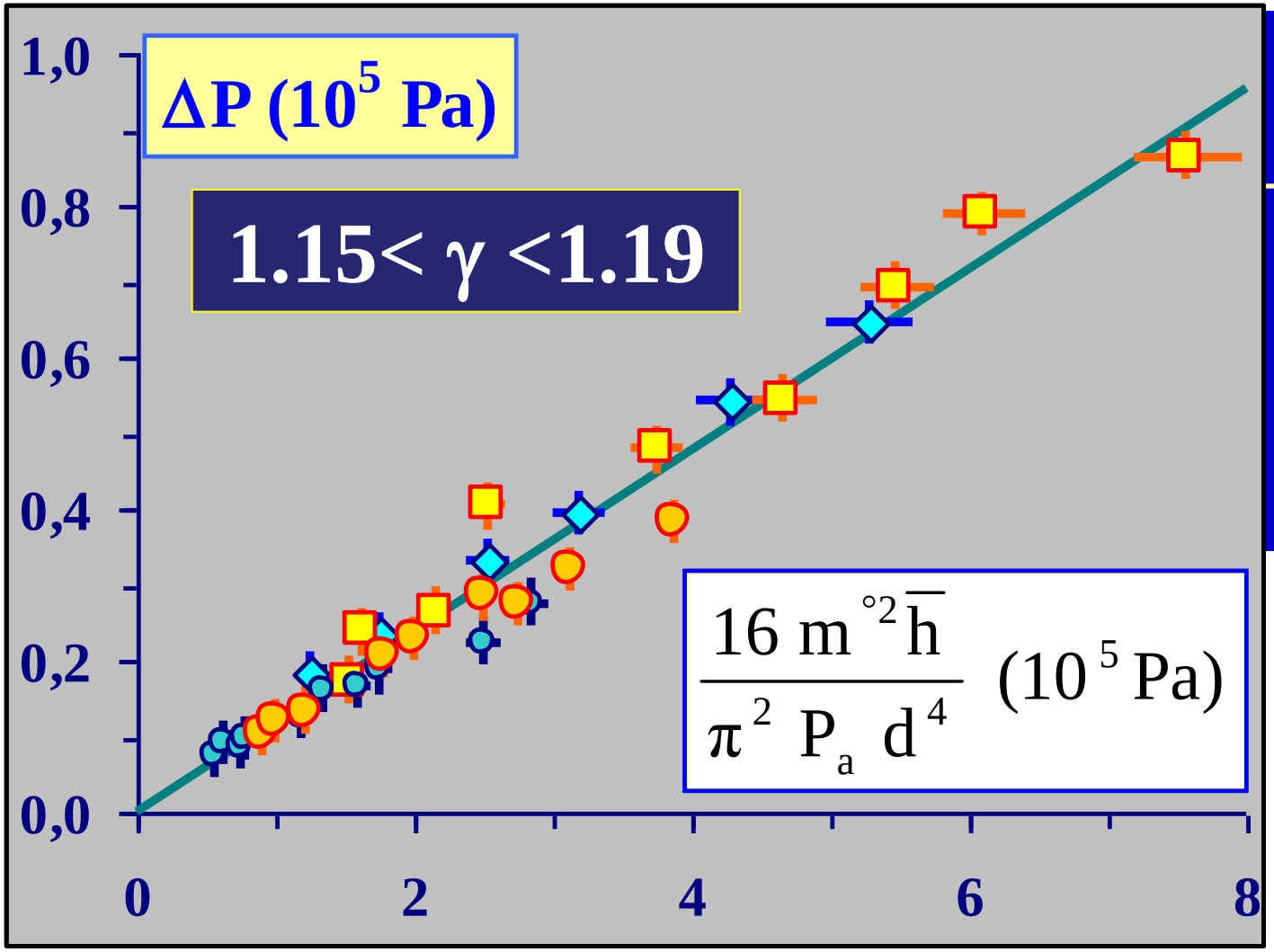
→ **Réduction significative de l' efficacité des transferts**

Mesures de pression dans la cavité cathodique



- capteur piezoresistif (ENDEVCO 8510C), Φ2mm, 320 kHz
- mise en évidence d'un couplage "pression -tension"
- Modèle analyique 0 ou 1D fondé sur pptés physiques du gaz

Ex: mesures de pression « statique » Ar-H_2 (75/25vol%)



m°: débit

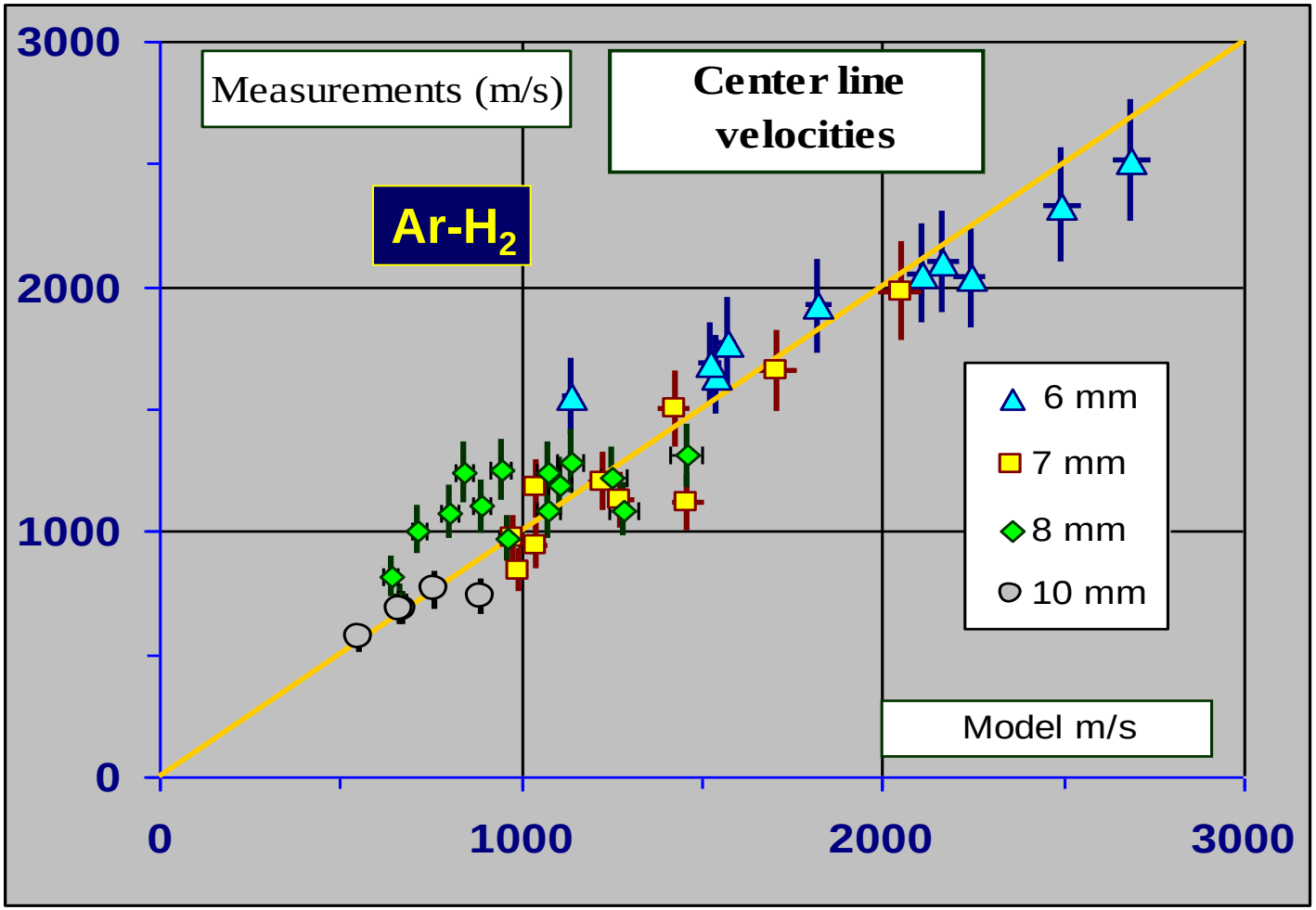
h : enthalpie massique

D: Diametre

P_a : pression de sortie

V. Rat and J.F. Coudert, J. Phys. D: Appl. Phys., 39, 4799 (2006)

Ex: Mesure de vitesses sur l'axe du jet



J.F. Coudert et al, Plasma Chem. Plasma Process., (1995) 15 n°1, pp 47-70

V. Rat and J.F. Coudert, J. Phys. D: Appl. Phys., 39, 4799 (2006)

Mesures résolues en temps:

- Tension
- Pression
- Imagerie synchrone

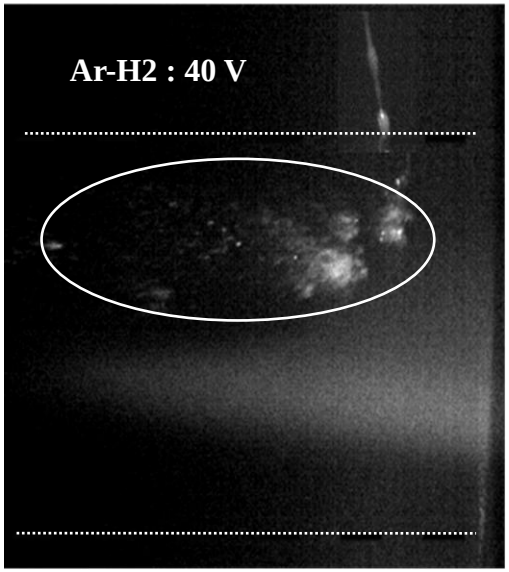
Comportement « dynamique »

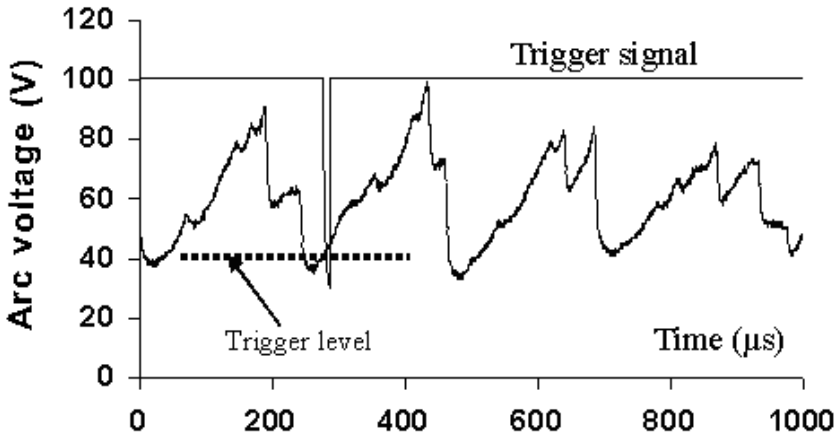
- Origine des instabilités

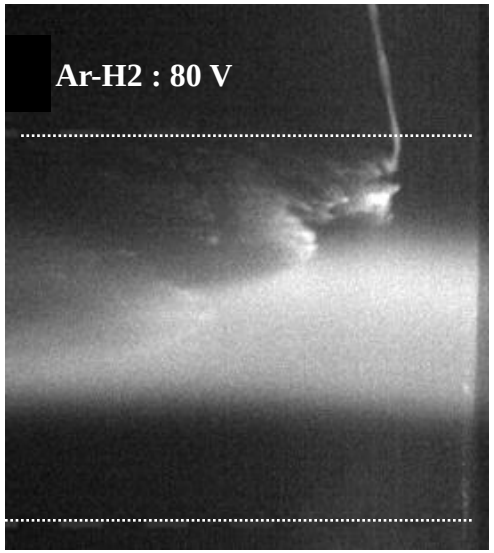
Projection plasma de suspension et instabilités de l'arc

Ar/H_2 (45/15) 500A **V_{inj}=27 m/s**

Instabilités de l'arc en projection de suspension

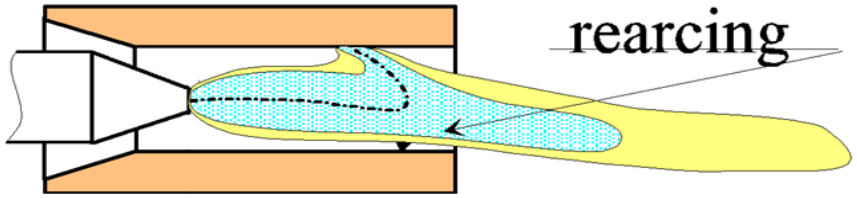




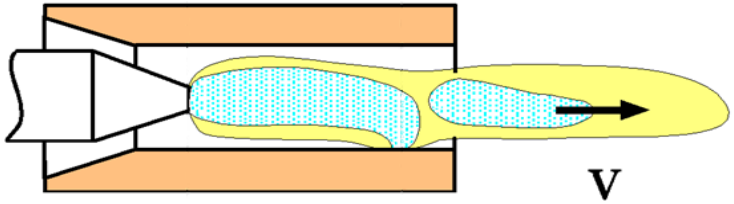


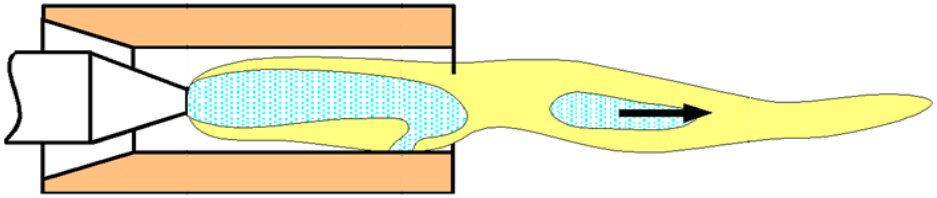
R. Etchart-Salas et al J. High Temp. Mat. Proces. 10, 407 (2006).

Instabilités de l'accrochage anodique

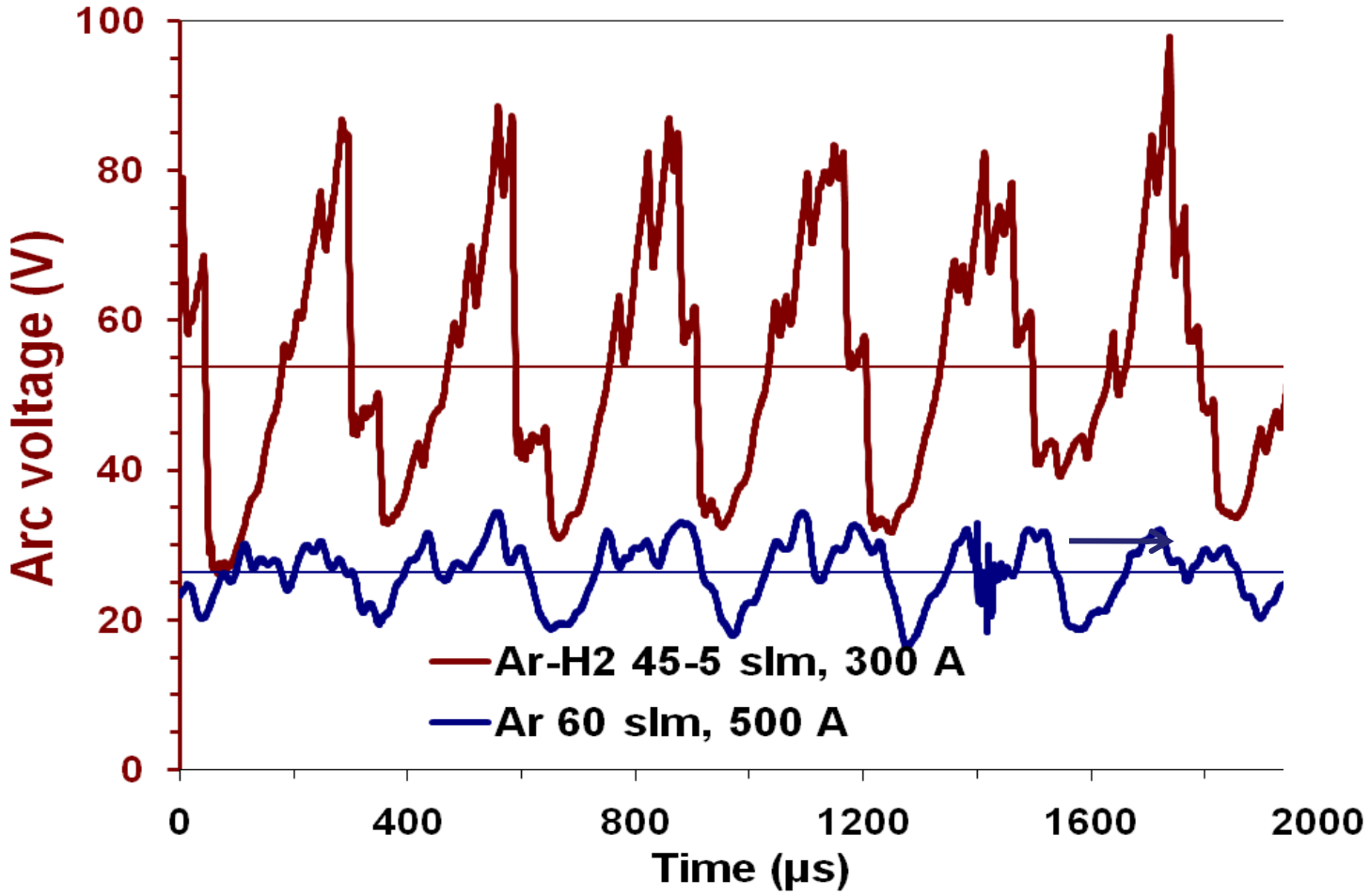


Anode nozzle



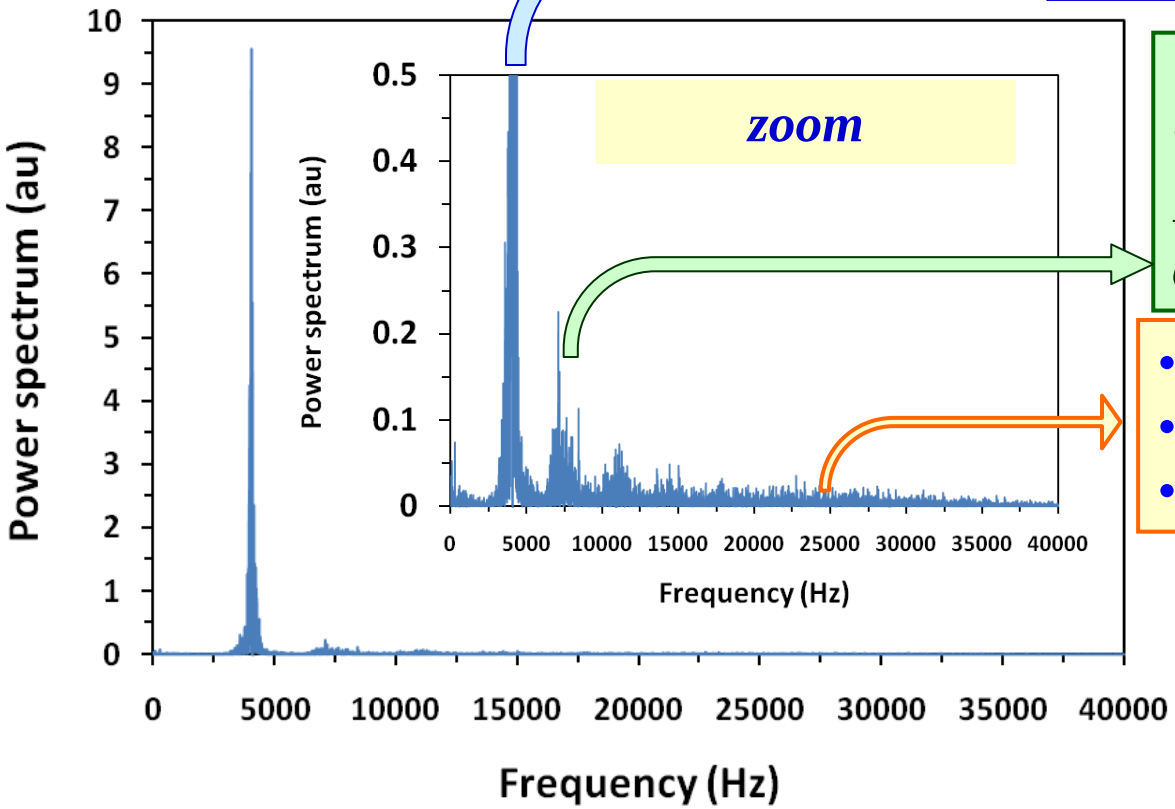


Ex: tension d'arc pour une torche de projection



Spectre de la tension d'arc

Ar-H_2 (45-5 slm) - 300 A



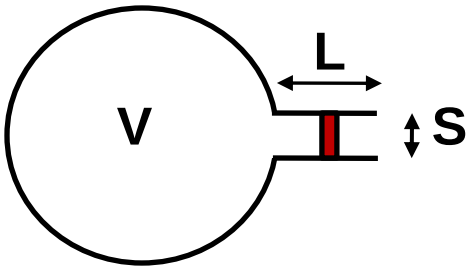
- "raie" étroite à ~ 4 kHz : Existence d'un oscillateur !

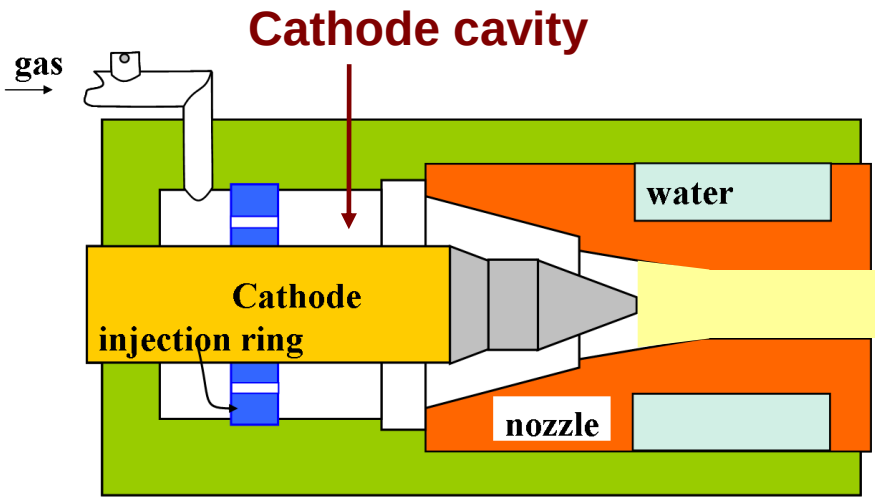
- présences d'autres "raies"
Faibles résonances acoustiques?

- Mode "restrike"
- *réamorgages aléatoires*
- *Bruit blanc*

Mechanical oscillator: Helmholtz resonator

- Oscillations due to compressibility effects of cold gas in volume V
- Mass-spring system
- Mass = plasma
- Spring = cold gas in cathode cavity



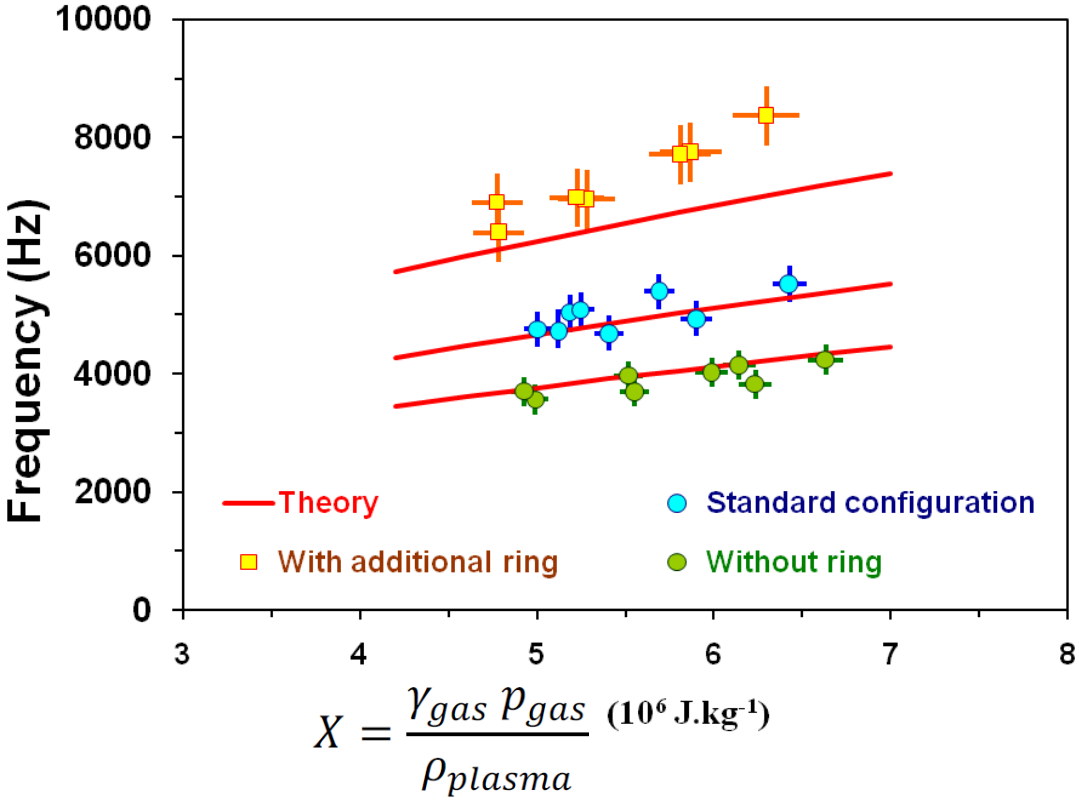


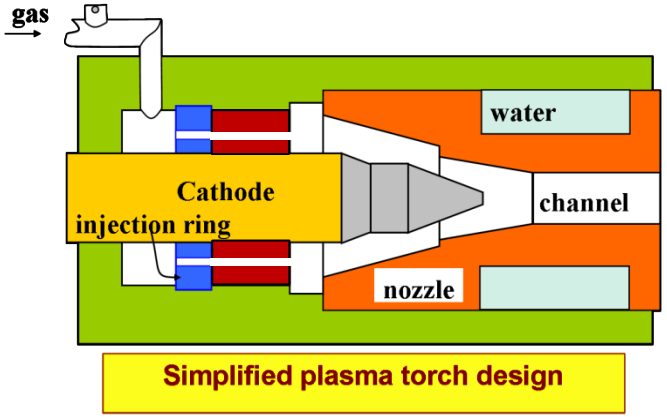
Simplified plasma torch design

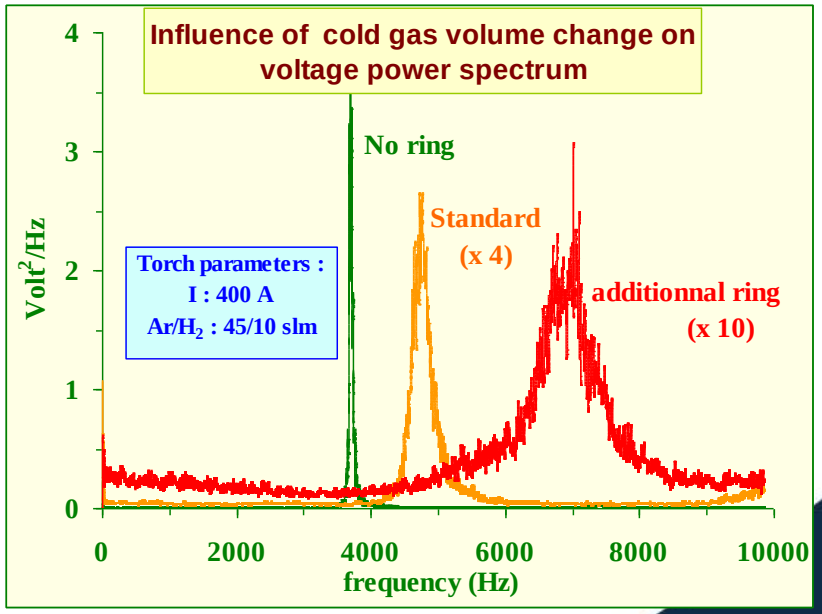
$$f_H = \frac{1}{2\pi}\sqrt{\frac{\gamma_{gas}\, p_{gas}}{\rho_{plasma}}}\sqrt{\frac{S}{LV}}$$

$$X = \frac{\gamma_{gas}\, p_{gas}}{\rho_{plasma}}$$

Mode de “Helmholtz”



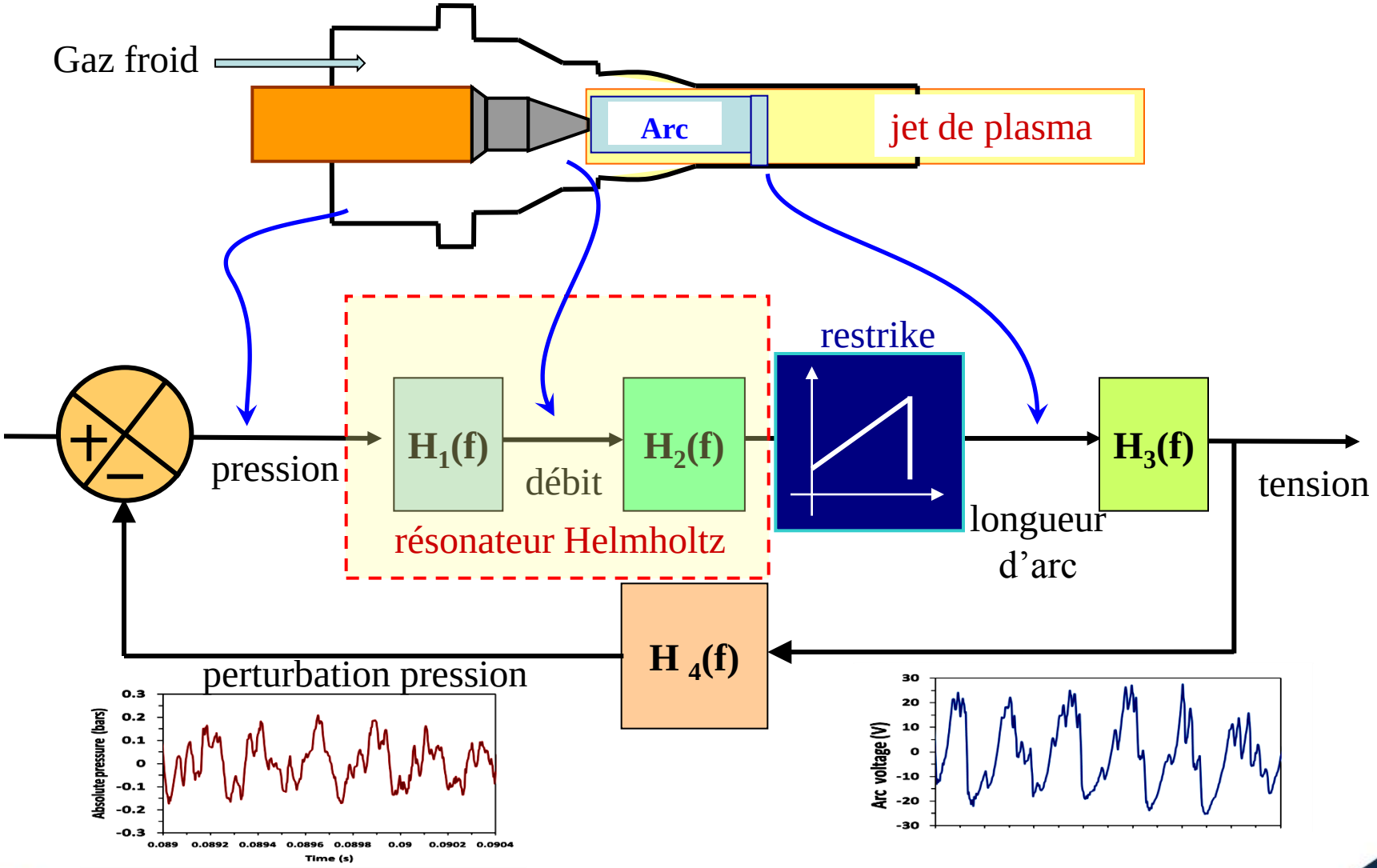




JF Coudert ,V Rat, D.Rigot, J. Phys D: Appl. Phys. ***40****, 7357 (2007)*
JF Coudert and V Rat, J. Phys D: Appl. Phys. ***41****, 205208 (2008)*

Université de Limoges

Principe de la dynamique de l'arc dans la torche

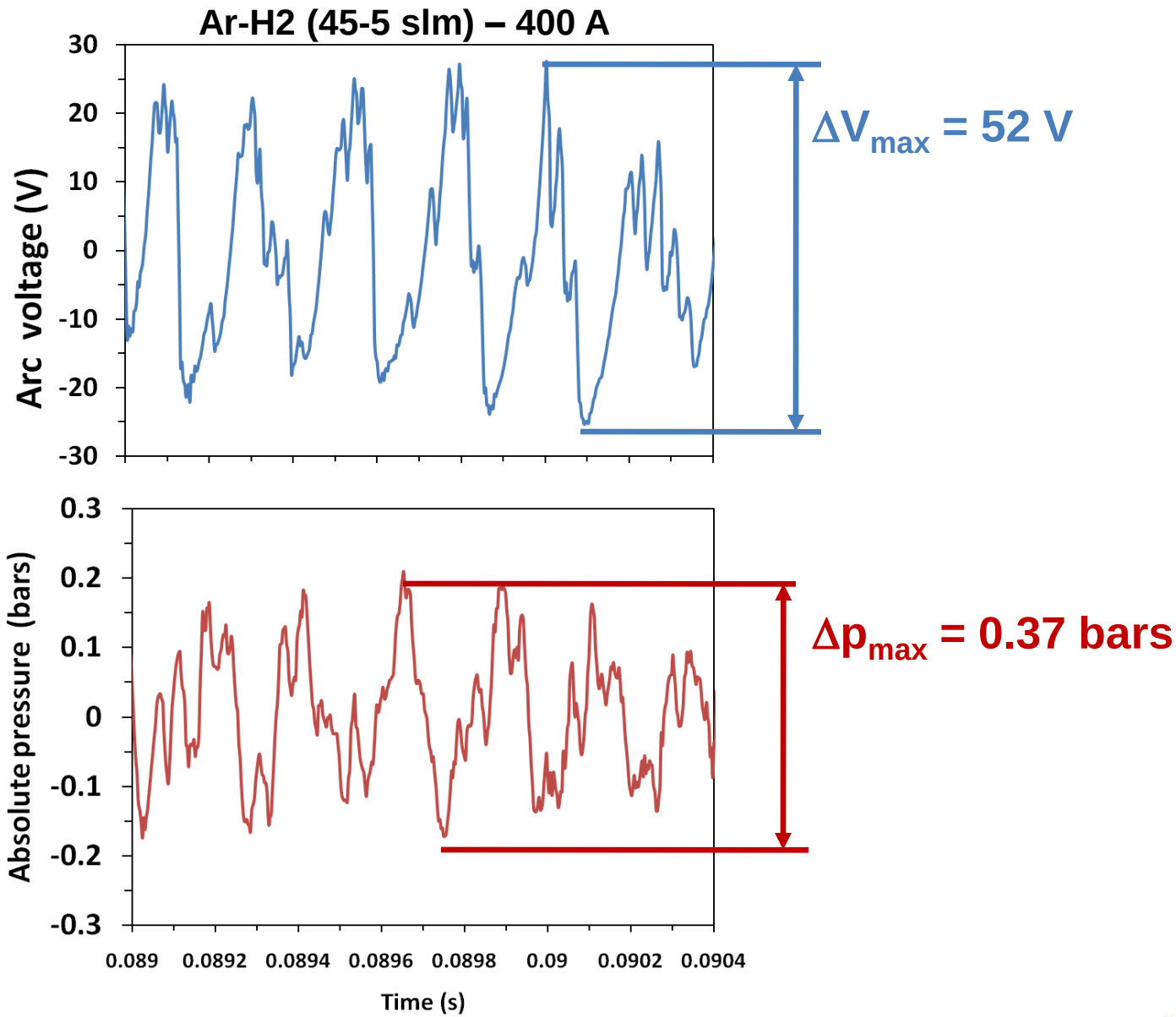


tension (Volts)

$$v(t) = \bar{v} + v'(t)$$

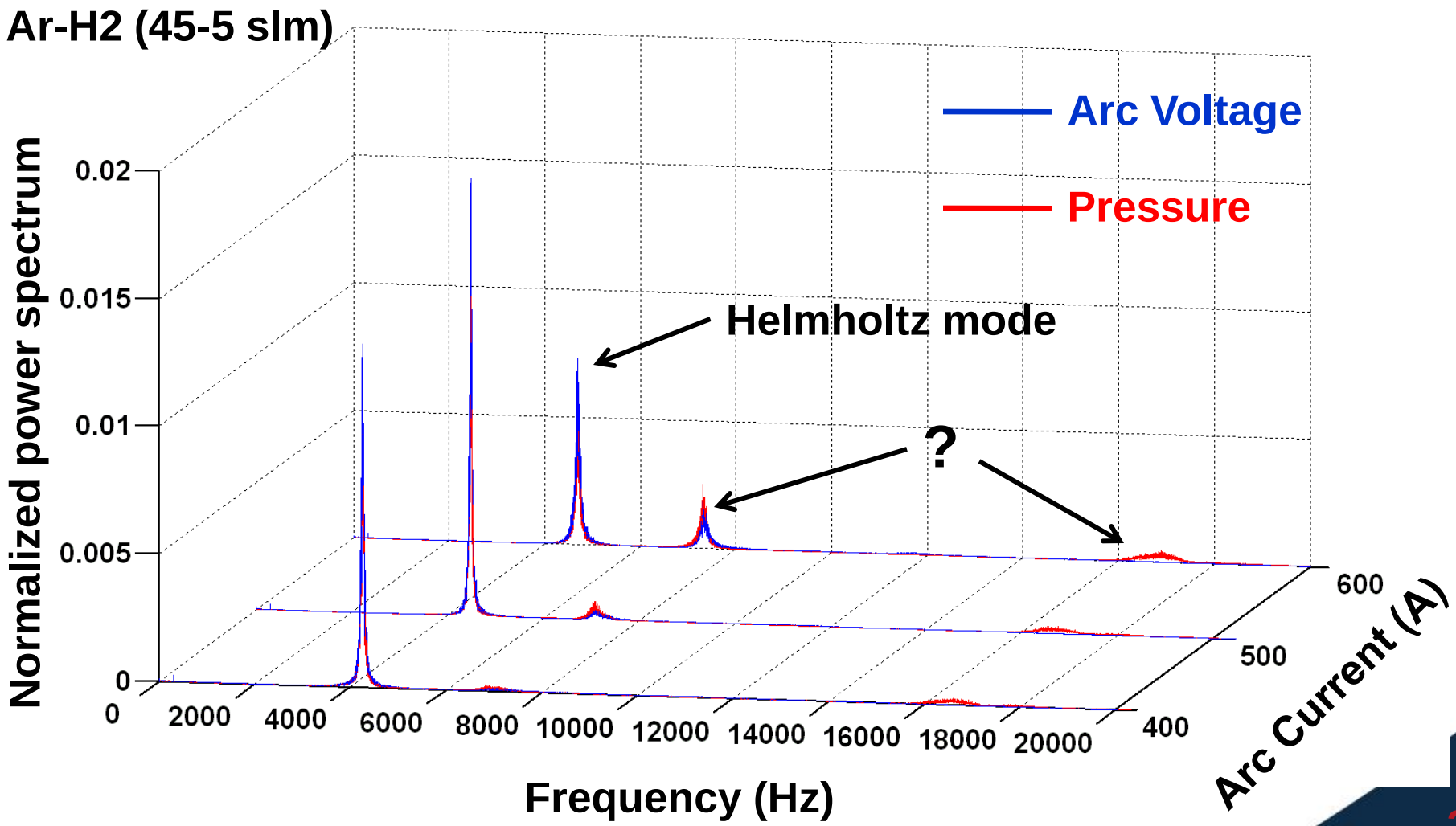
Pression (bars)

$$p(t) = \bar{p} + p'(t)$$



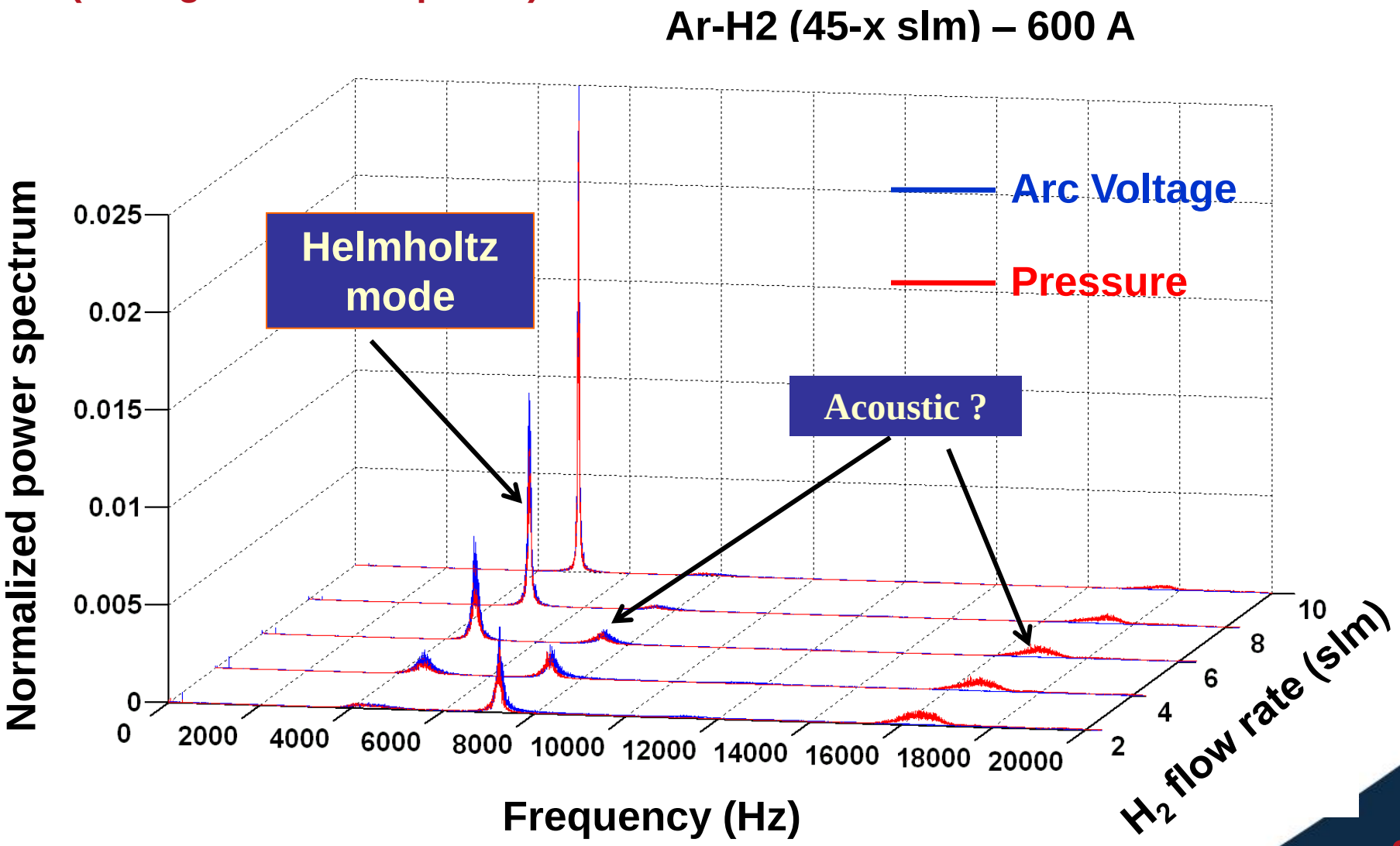
Power spectra – Influence of arc current

(averaged over 10 spectra)



Power spectra – Influence of H_2 flow rate

(averaged over 10 spectra)



- **Extraction par filtrage adaptatif**

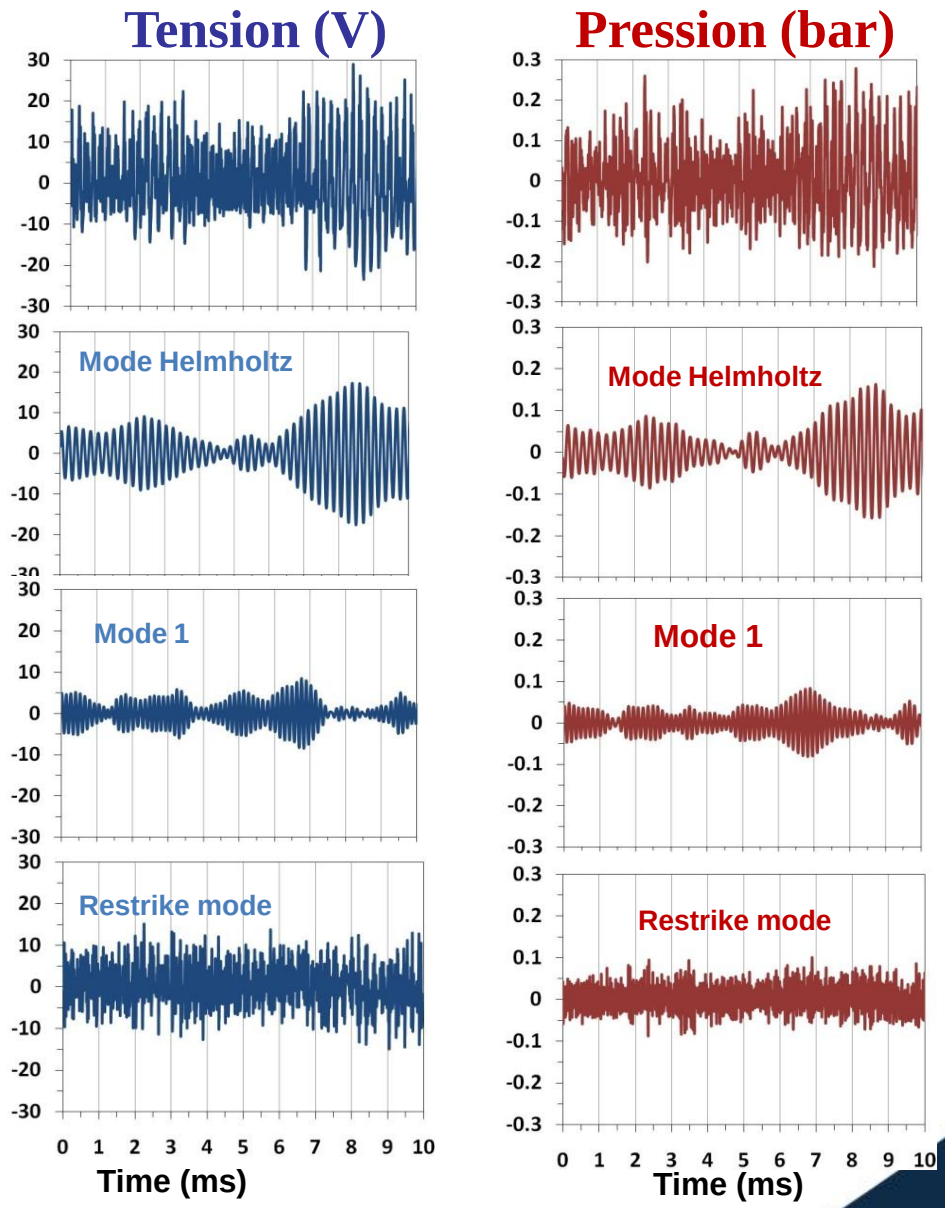
$$v(t) = \bar{v} + v_H(t) + v_R(t) + v_1(t)$$

$$p(t) = \bar{p} + p_H(t) + p_R(t) + p_1(t)$$

- **forte correlation V ⇔ p**

- **Torche = résonateur acoustique**

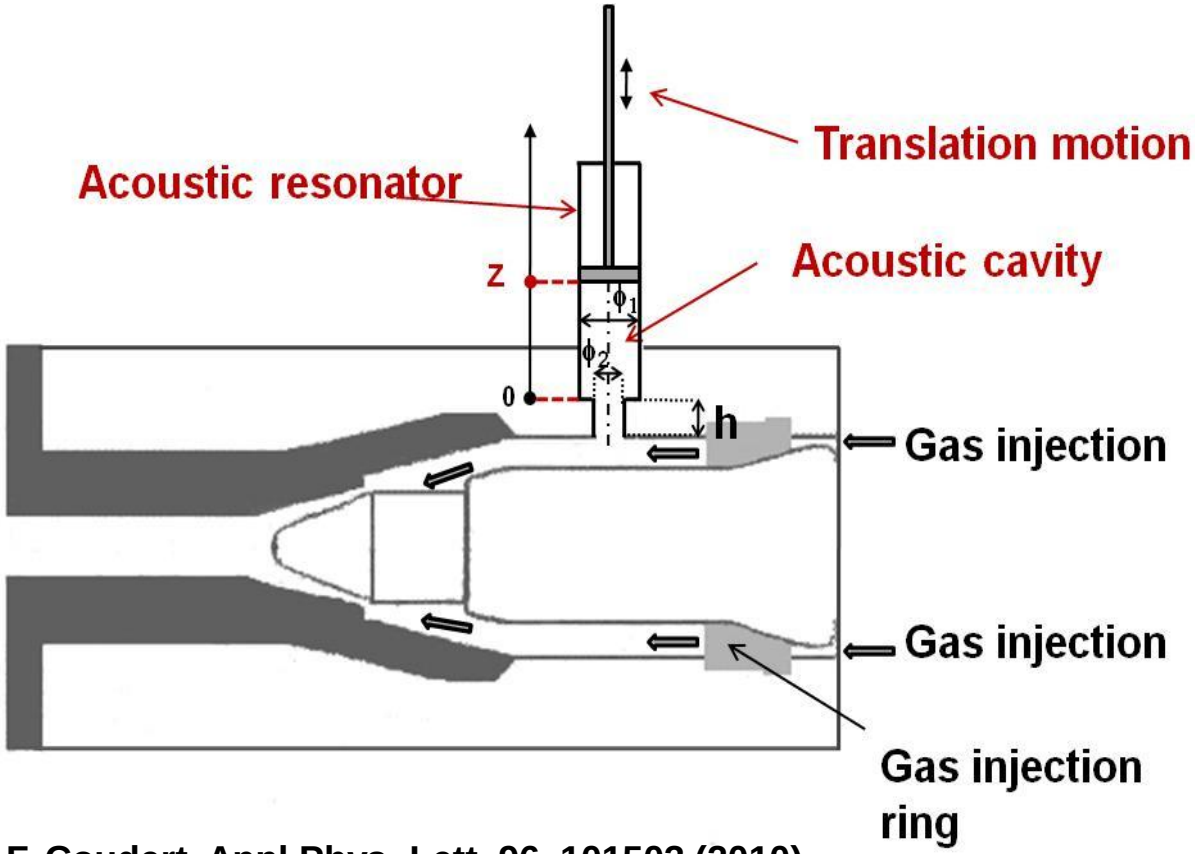
- $t_{Helmholtz} \sim 250\ \mu s$ $\quad t_{restrike} \sim 50\ \mu s$



V. Rat and J.F. Coudert,
J. Appl. Phys. 108, 043304 (2010)

Peut-on modifier les fluctuations de tension en jouant sur la pression?

Utilisation d'un résonateur externe : Le « Stub acoustique »



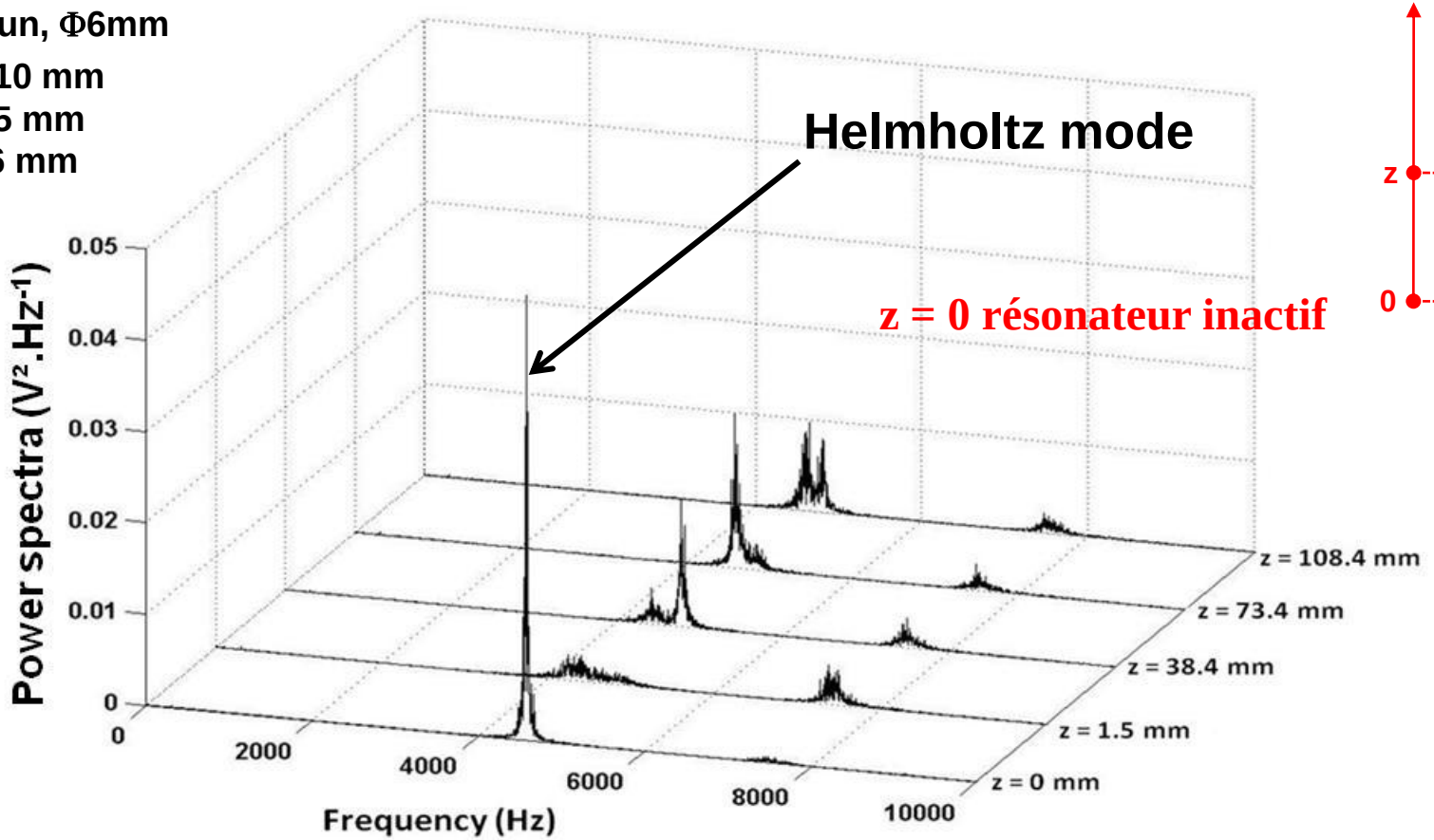
ϕ_1 = 10 mm
ϕ_2 = 4 - 6 mm
h = 6 mm

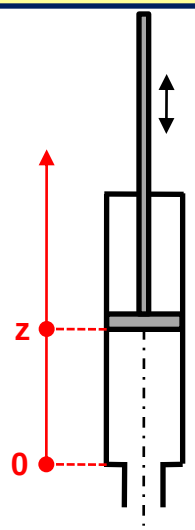
V. Rat and J.F. Coudert, Appl.Phys. Lett. 96, 101503 (2010)

Influence de la position du piston sur le spectre de tension

Ar-H_2 (45-10 slpm) – 500 A
F4 gun, Φ6mm

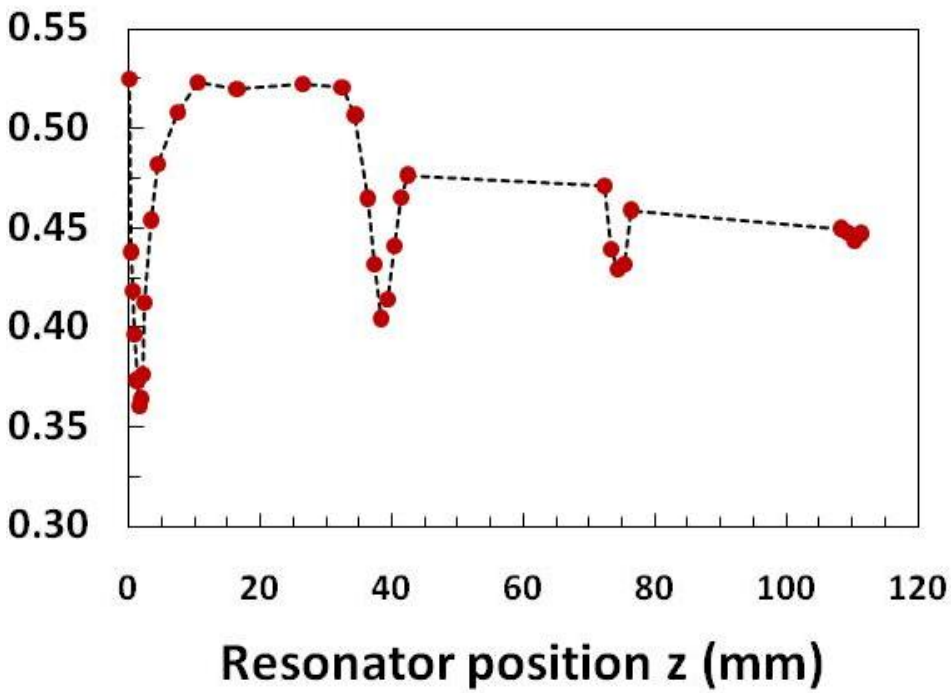
ϕ_1 = 10 mm
ϕ_2 = 5 mm
h = 6 mm



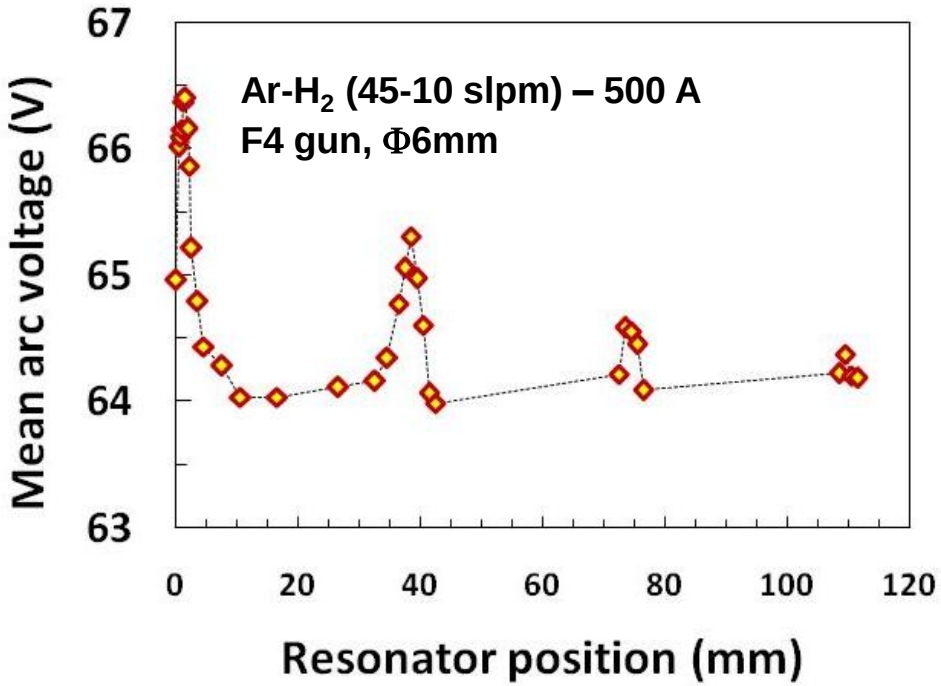


Réduction des amplitudes relatives en fonction de Z

$\Delta V/\bar{V}$



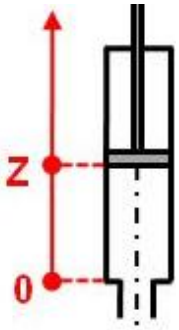
$\bar{V}$



$P_{net} = \eta\ VI = 19.20$ kW

$P_r = (\delta V)I = 1.25$ kW

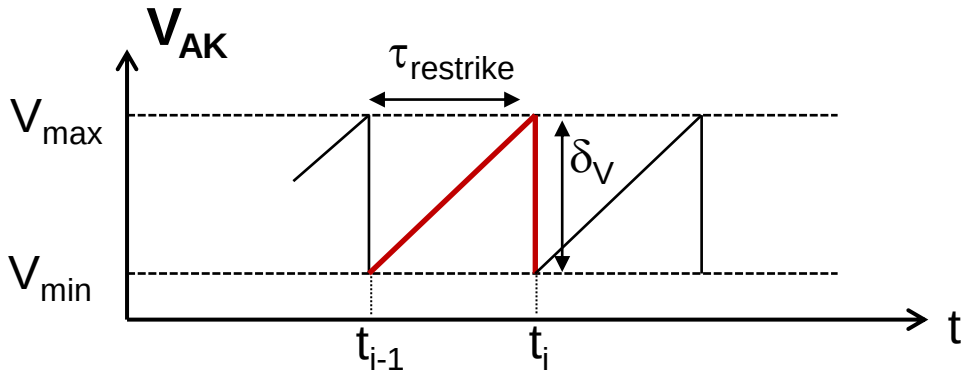
+ 6.5% in power



Peux-t-on coupler le mode de Helmholtz et le mode restrike?

-Le mode Helmholtz est très stable et est favorisé par une cavité importante.

- Le mode restrike est lié au déplacement du pieds d'arc et reste nécessaire pour limiter l'usure de l'anode. Il présente cependant des caractéristiques aléatoires.



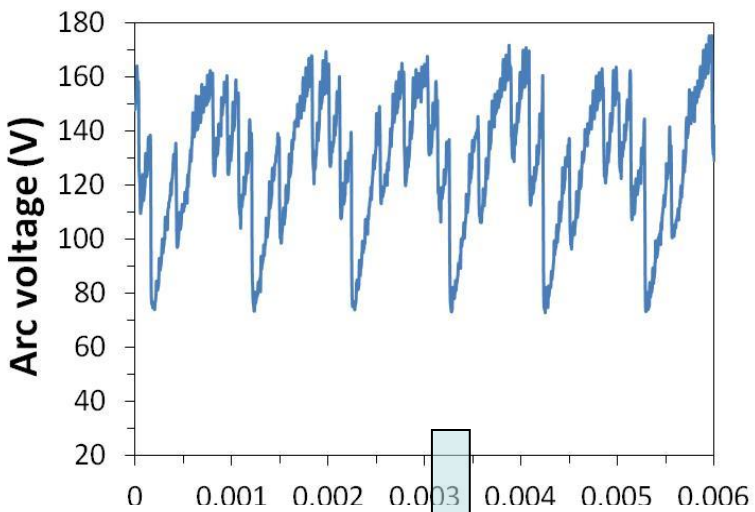
$$\left(\frac{dV_{AK}}{dt}\right) \propto \bar{E}\, u_{plasma}$$

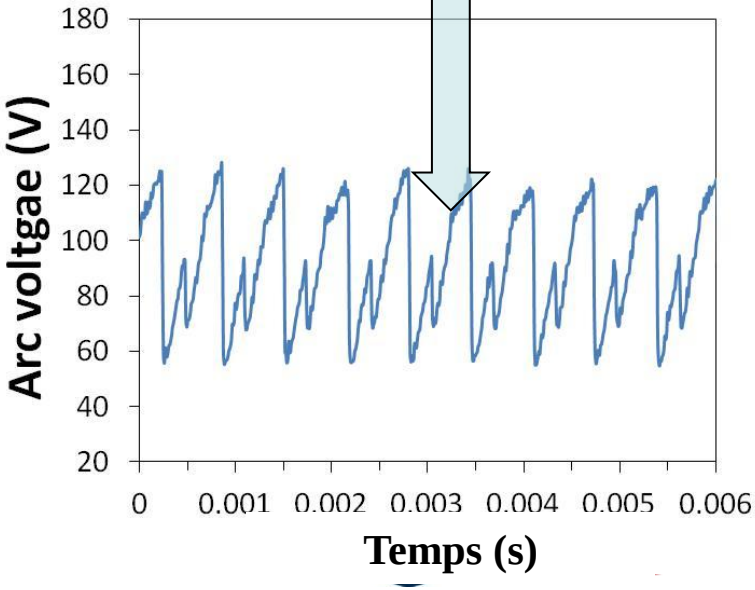
$$\left(\frac{dV_{AK}}{dt}\right) = f(I, \Phi, \dot{m})$$

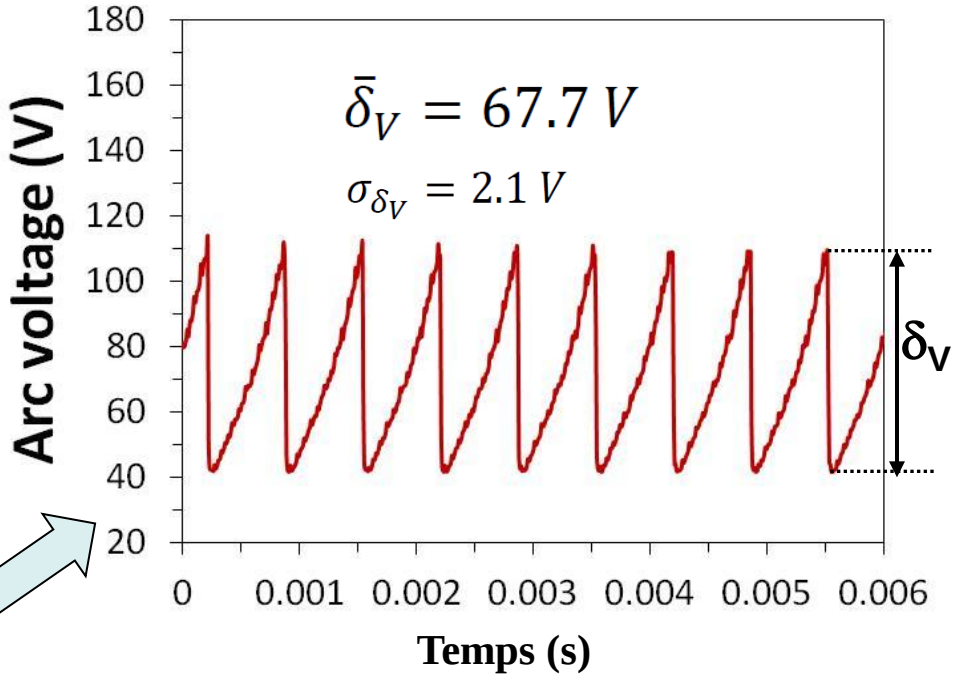
-Conception d'une torche à géométrie simplifiée pour limiter les modes acoustiques de haute fréquence

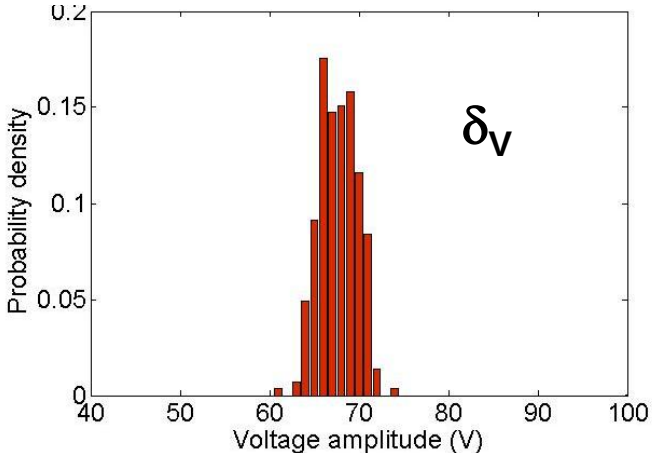
-On joue sur les paramètres de fonctionnement pour abaisser la fréquence du restrike jusqu'à atteindre celle du Helmholtz et « accrocher » ces deux modes.

Torche « simplifiée » fonctionnant à faible courant et faible débit



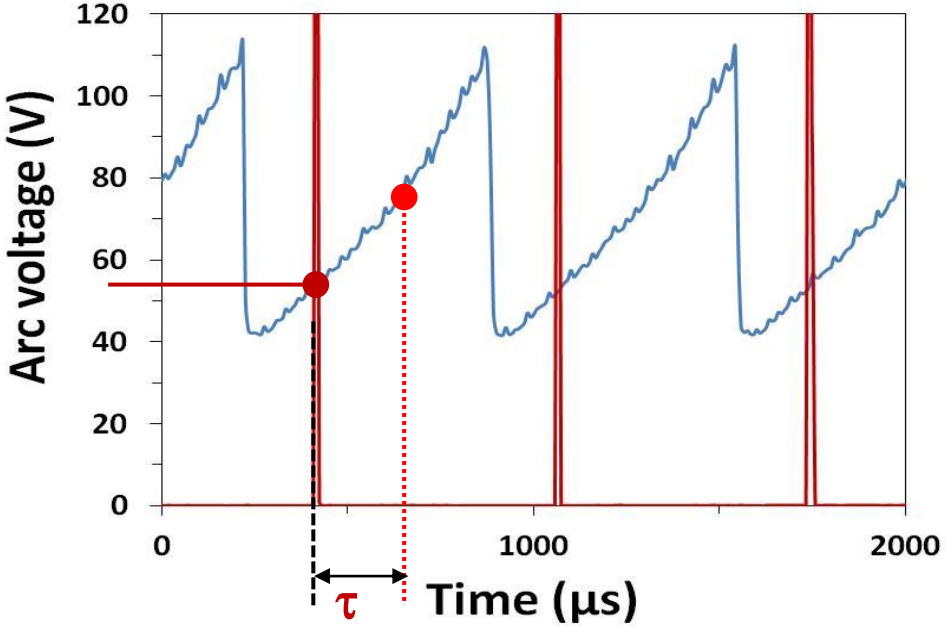


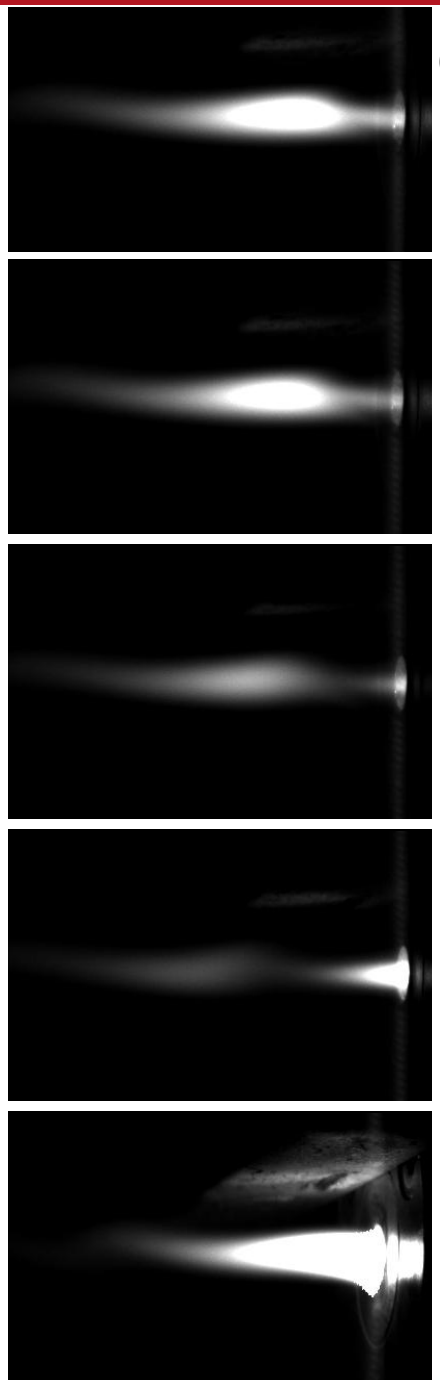




Jet de plasma pulsé…

I = 15 A, N_2 arc jet, 3 slpm,





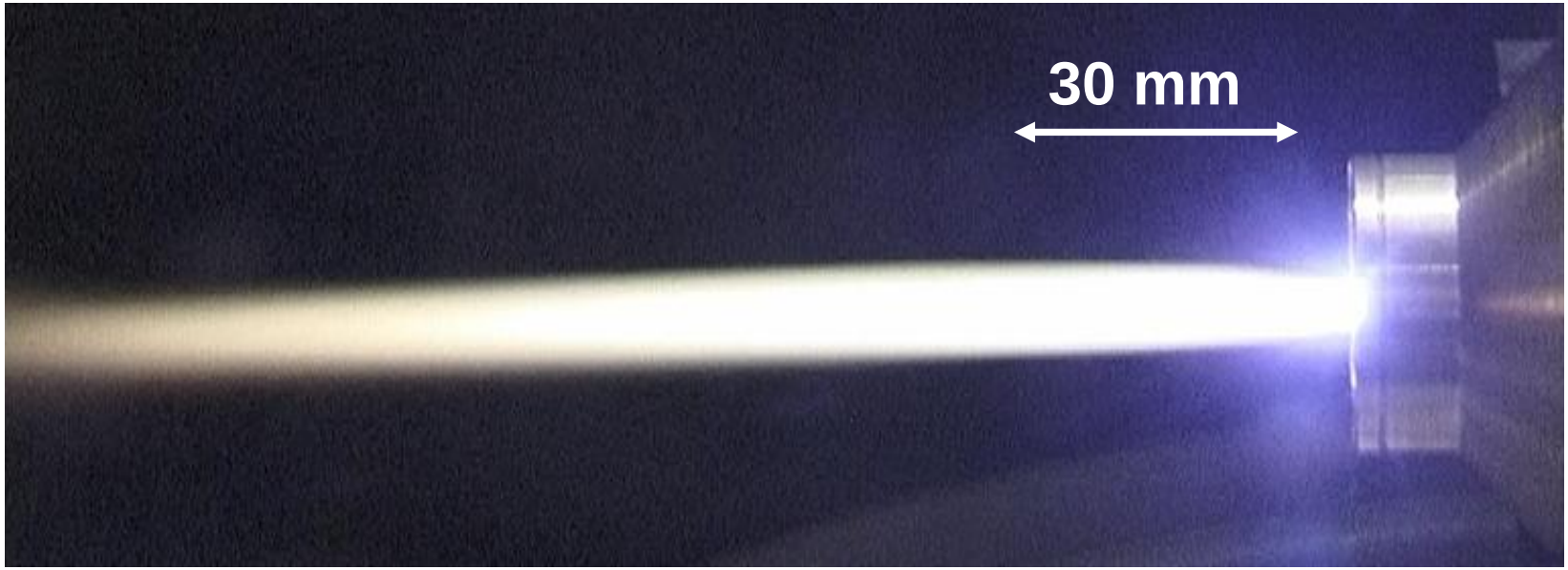
Ouverture caméra: 60 µs

1 Période : 800 µs

Forte modulation de l'enthalpie spécifique:

h_{max}/h_{min}=16 et h_{moy}=13.3 MJ.kg^{-1}

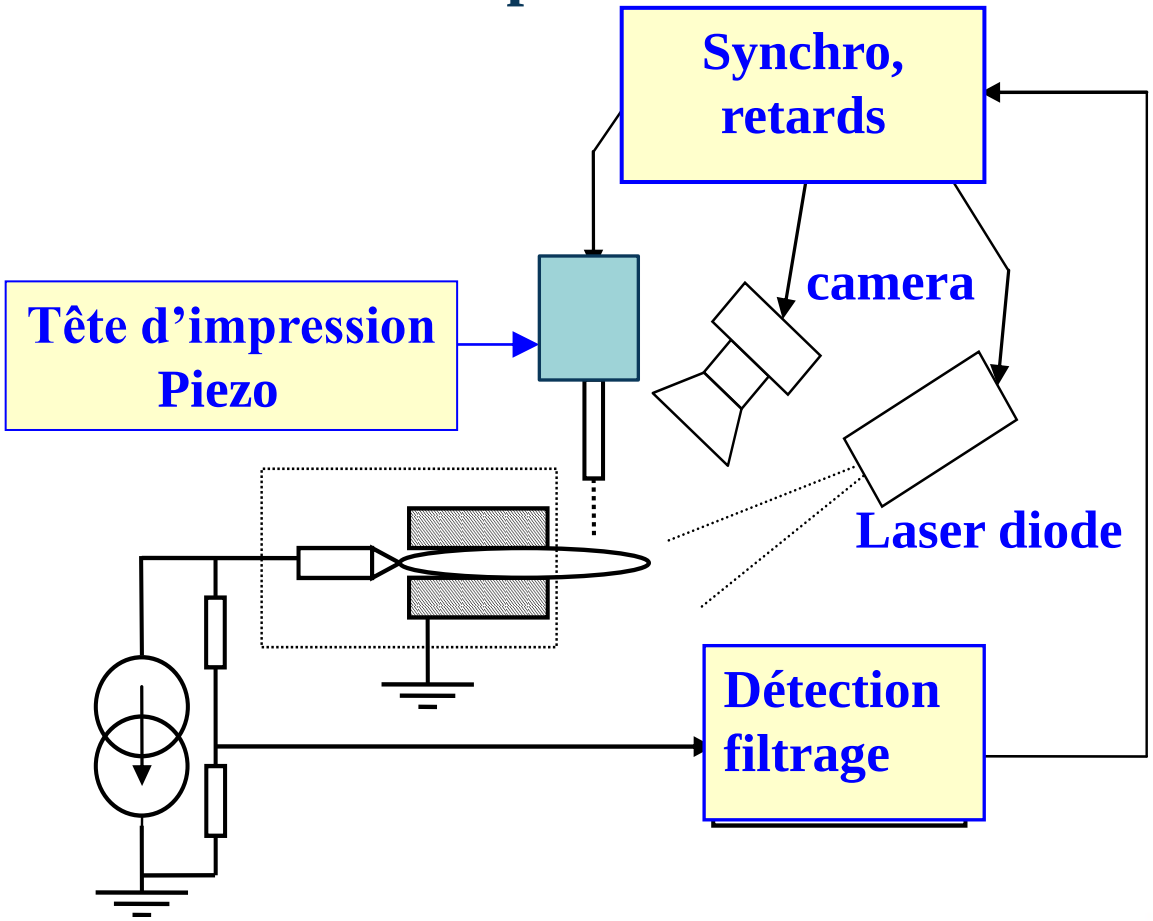
Temps d'obturation: 1/100éme s, soit 12 oscillations superposées



- I = 15 A, N_2 arc jet, 3 slpm, *laminar plasma flow*

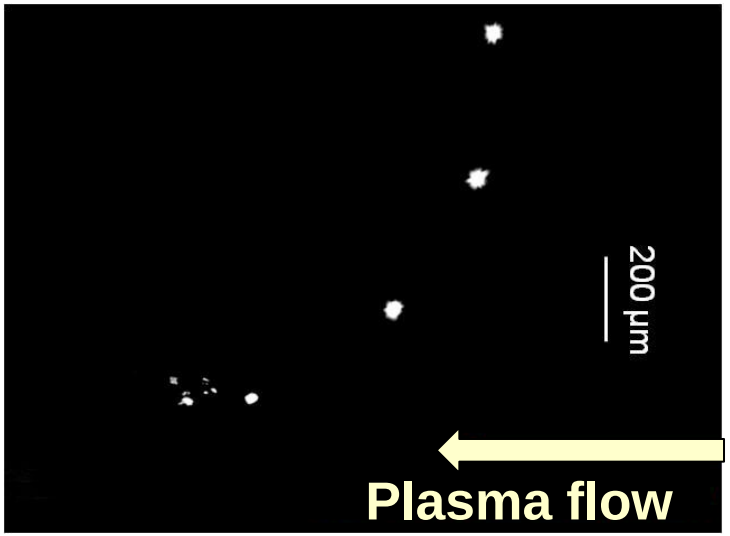
Injection synchrone de suspension céramique

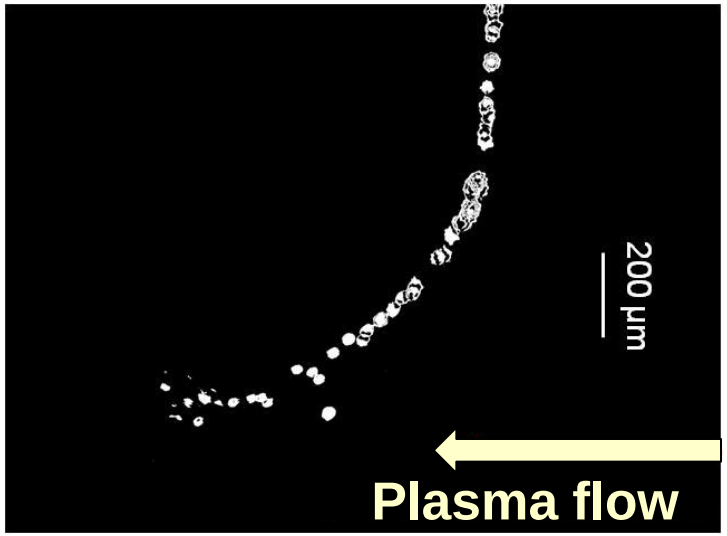
- Jet laminaire pulsé
- Injection de suspension TiO2 déclanchée à 1.2 kHz
- Imagerie laser résolue en temps



Injection dans le jet de plasma

Diamètre des gouttes: 50 µm, Vitesse des gouttes: 10 m.s^{-1}
Fréquence d'injection: 1.2 kHz
Taille particules céramiques: 200 nm
Temps illumination laser:10 µs
Temps ouverture caméra: 20 µs



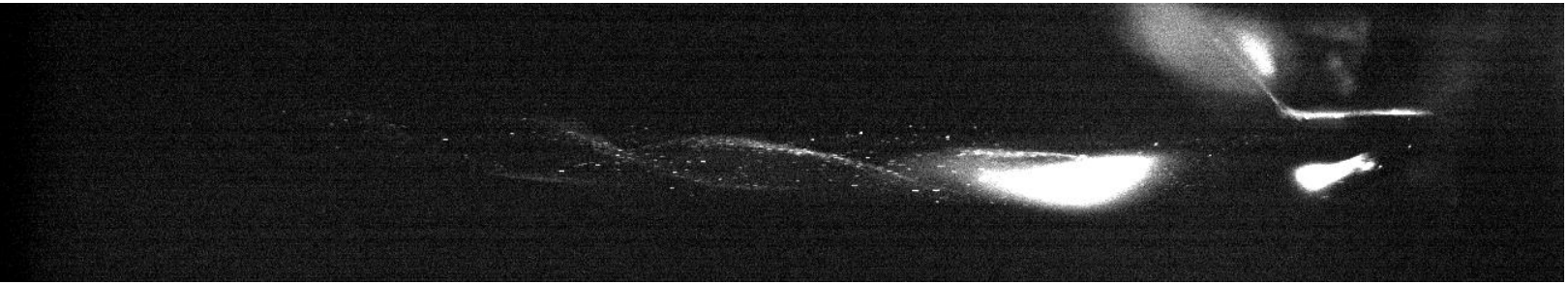


Superposition de 15 images

Time-resolved imaging (aperture time 5 µs)

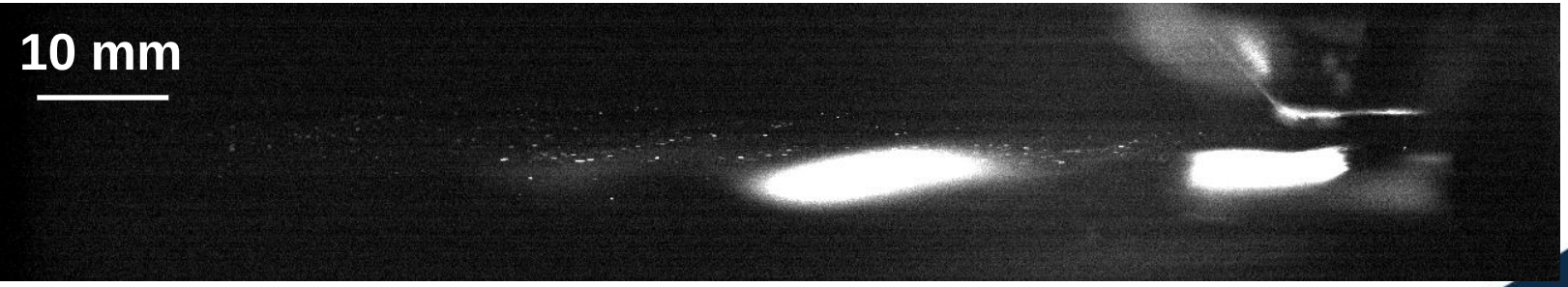
Plasma period = 680 µs

τ = 0 µs



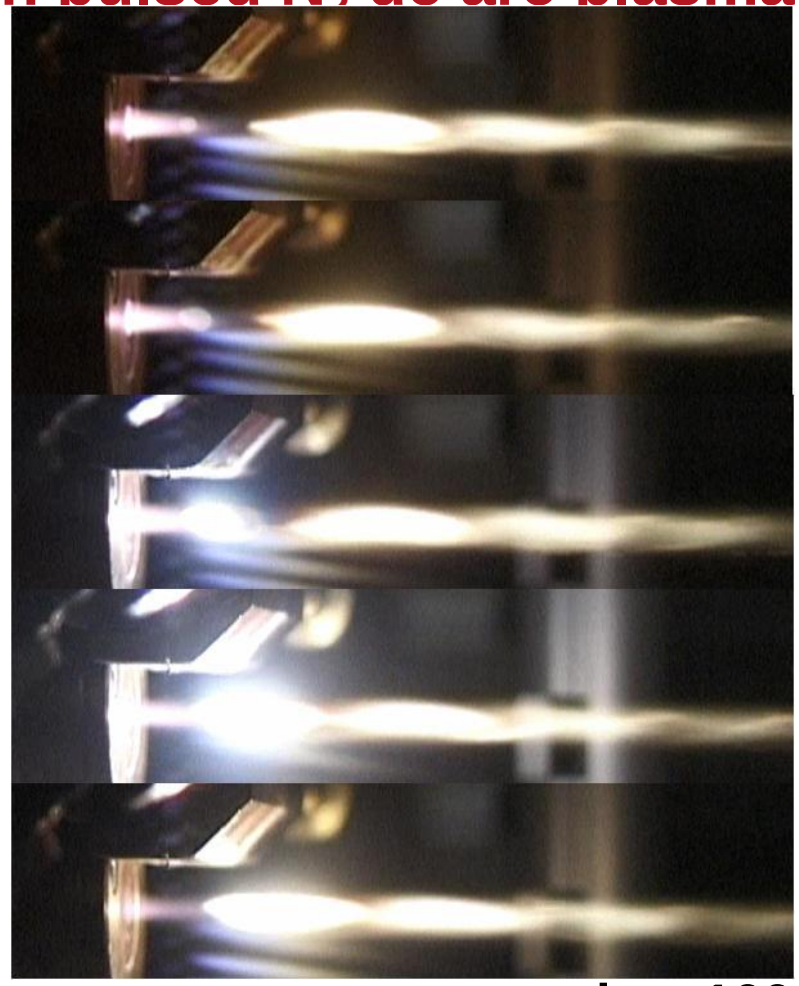
τ = 260 µs

τ = 480 µs



τ = 620 µs

Synchronized injection of TiO_2 suspensions in pulsed N_2 dc arc plasma jet



aperture time 166 µs
24 frames/s
Injection frequency 1.4 kHz

Merci pour votre attention

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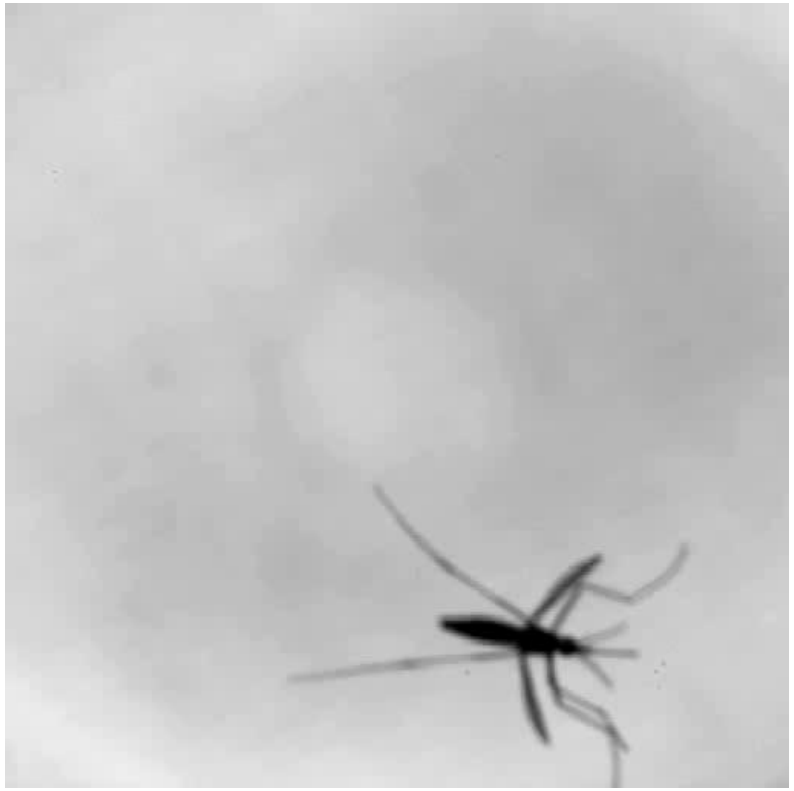

L.J. Cator *et al.*, Harmonic convergence in the love songs of the dengue vector mosquito Science, vol 323, 1077 (2009)