

Jets plasmas en interaction avec une cible

Eric Robert

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Plan de l'exposé

Jets plasmas ou pas ?

Propagation réacteur de décharge - air ambiant

Propagation/interaction avec une cible

Jets Plasma à pression atmosphérique

Plasma qui va s'étendre en dehors de la zone de création de la décharge (zone inter électrode)

La délivrance du « **plasma** » est induite par un flux de gaz ou est déterminée par la propagation du champ électrique

Terminologie très variée: APPJ, Plasma plume, Plasma Gun, Plasma Pencil, Plasma torch, micro plasma jet...

Baucoup de types d'excitation: DC, AC, RF (13.56 MHz), MW (2.45 GHz, 915 MHz) en modes continu or pulsé

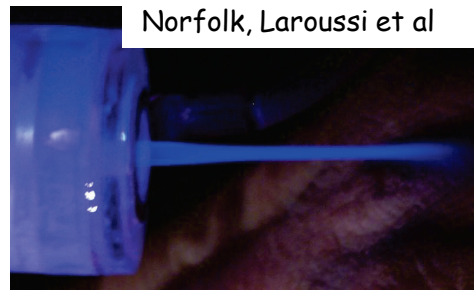
Les décharges sont initiées dans les gaz rares (Ar, He, Ne) purs ou avec adjonction d'oxygène/azote/eau ou dans l'azote ou l'air

Forte demande pour les applications biomédicales (Plasma médecine, décontamination, biomatériaux) et pour les interactions plasma matériaux (dépôt, gravure, fonctionnalisation...)

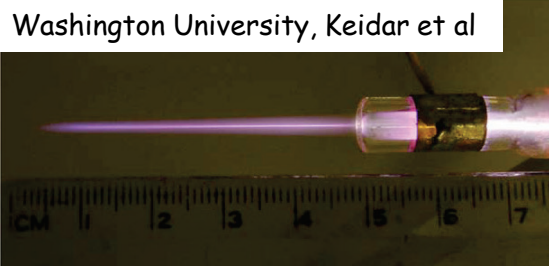
Le **Plasma** ou la « **post décharge/after glow** » sont délivrés sur les cibles



Osaka University

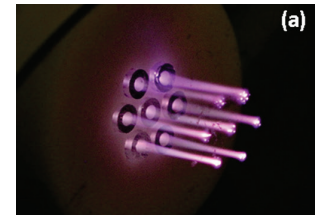


Norfolk, Laroussi et al

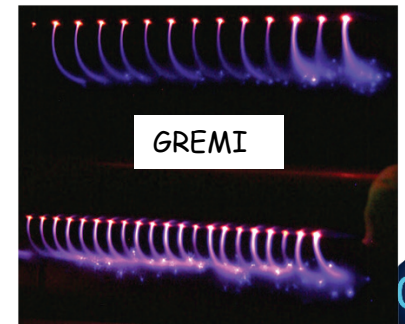


Washington University, Keidar et al

Z. Cao et al



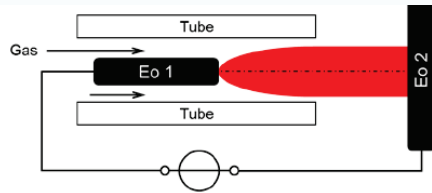
(a)



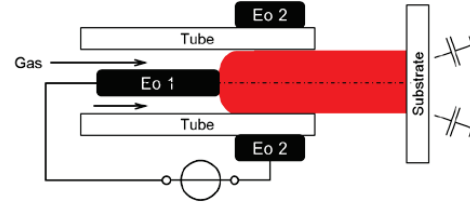
GREMI

Tous les « anciens » types de décharges à pression atmosphérique sont récemment devenus des jets plasma !

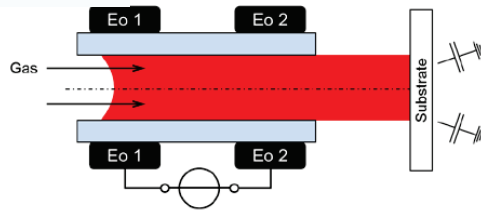
Transferred arc jets/
free expanding MW plasma torch



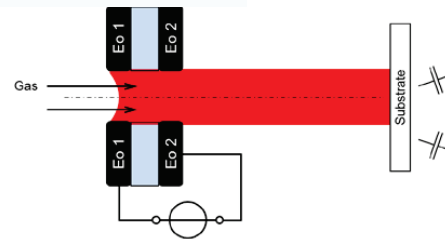
Non transferred arc jets, tube is conductive



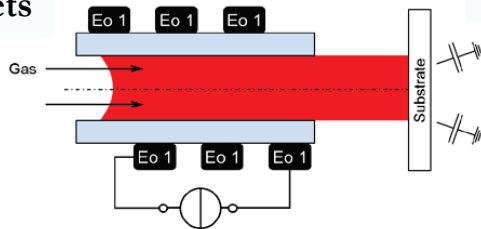
DBD plasma jets



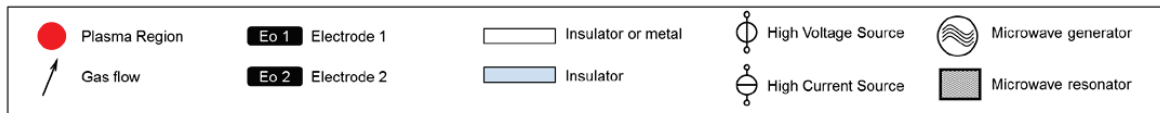
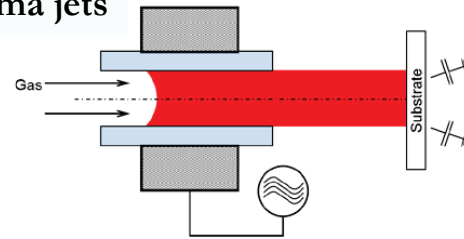
MHCD plasma jets



Inductive
plasma jets



MW plasma jets



Cross sectional views of the basic geometries of coaxial plasma jets

Un « APPJ » coaxial : 6 configurations!

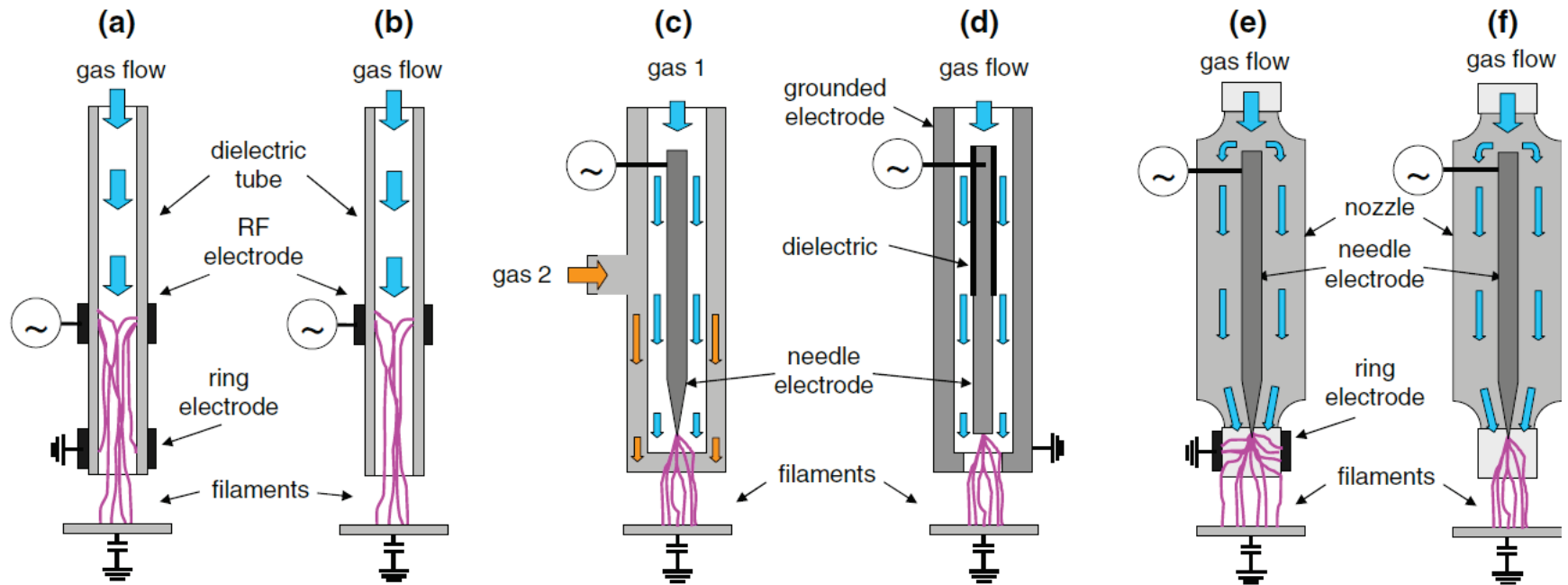


Figure 9. Principle designs for APPJs (a) using one powered and one grounded ring electrode, (b) without grounded ring electrode, (c) as a combination of two tubes where the inner tube is streamed with a noble gas for discharge ignition and the outer tube with a precursor, (d) composed of two coaxial electrodes with a dielectric in between (e) consisting of an inner RF-driven needle electrode and a grounded ring electrode, (f) without grounded ring electrode.

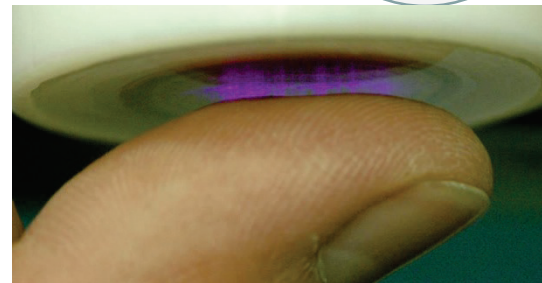
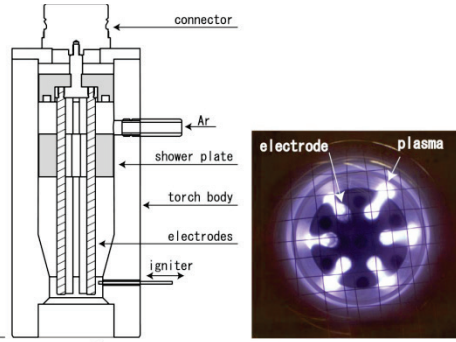
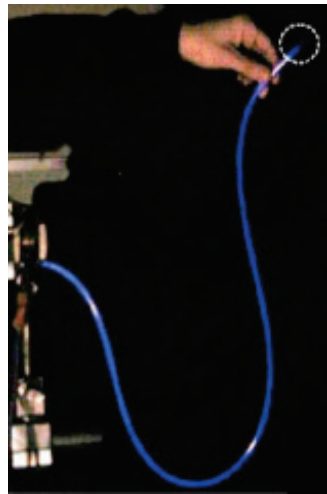
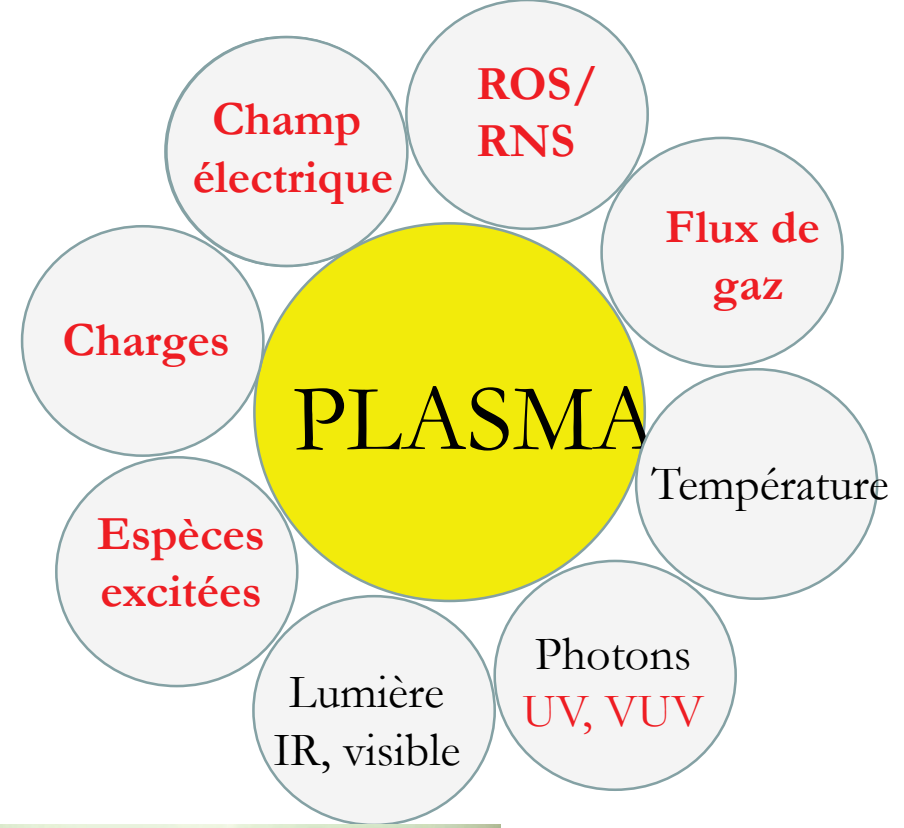
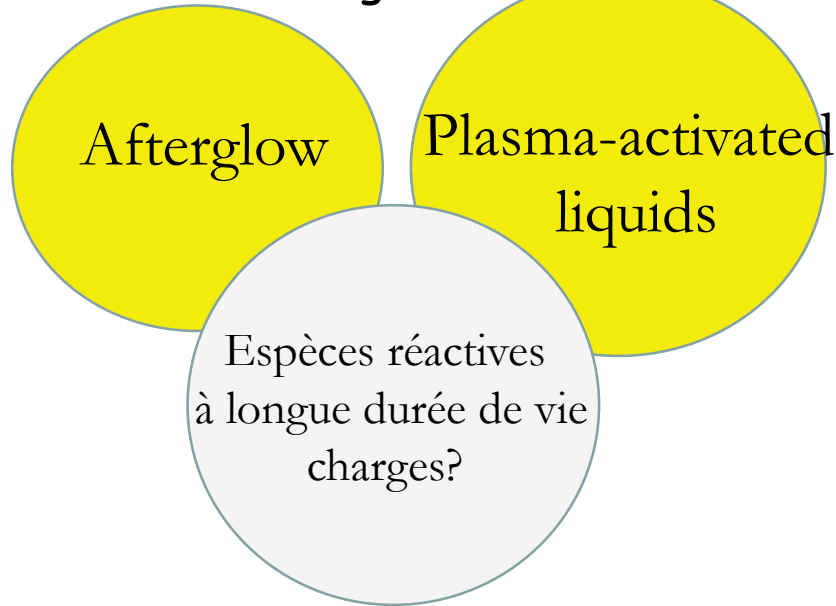
J. Phys. D: Appl. Phys. **44** (2011) 013002 J Ehlbeck et al

et pourtant:

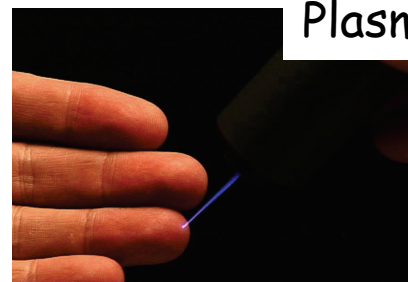
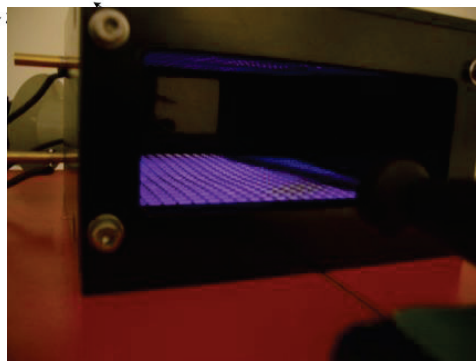
chacun se réclame avoir un jet plasma et même le jet plasma

et les biologistes utilisent UN JET PLASMA

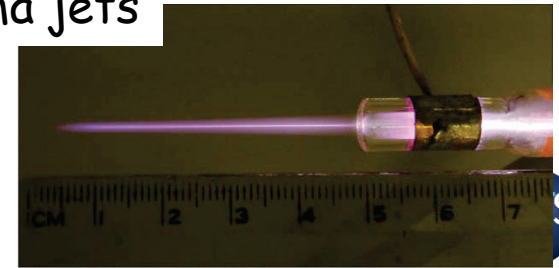
Plasma ou Afterglow



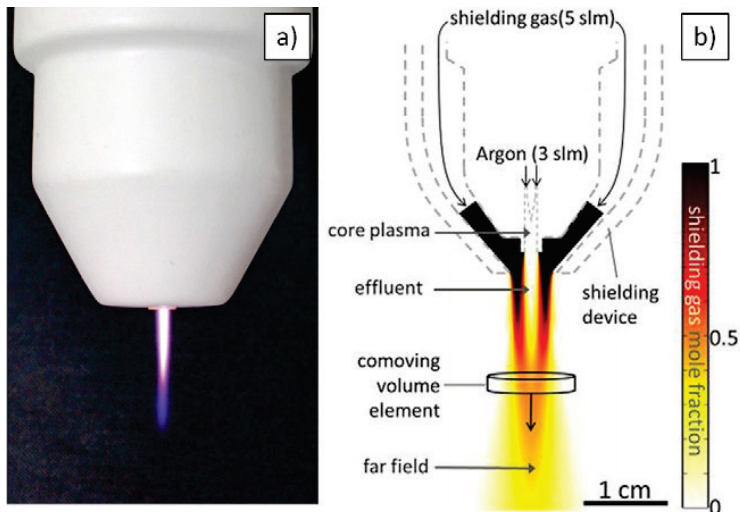
Dielectric Barrier discharge



Plasma jets



KinPen: Effluents/afterglow d'une torche plasma



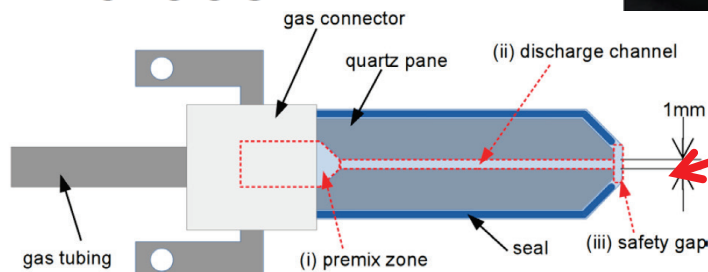
Visualization of kinpen plasma jet source with shielding gas. (a) photograph and (b) schematic and visualization of the shielding gas curtain by CFD simulation.

J. Phys. D: Appl. Phys. 49 (2016) 084003 (11pp)

doi:10.1088/0022-3727/49/8/08

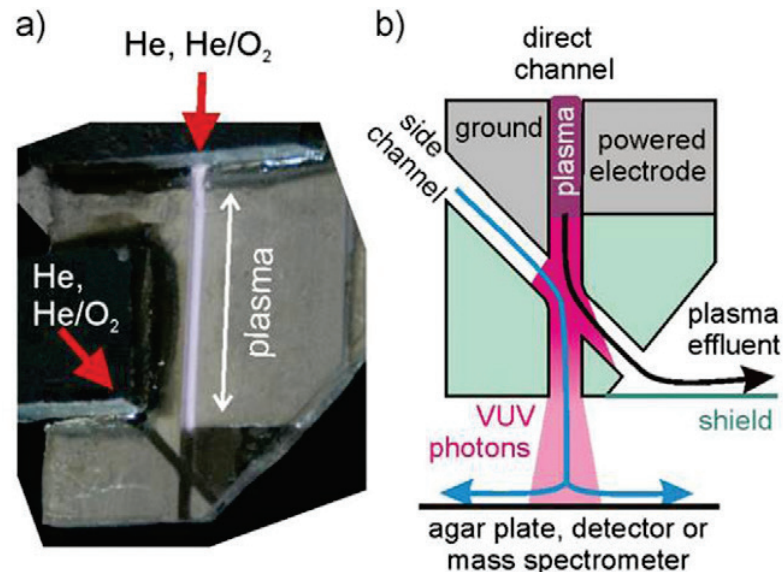
Concepts and characteristics of the 'COST Reference Microplasma Jet'

J Golda¹, J Held¹, B Redeker¹, M Konkowski¹, P Beijer², A Sobota², G Kroesen², N St J Braithwaite³, S Reuter⁴, M M Turner⁵, T Gans⁶, D O'Connell⁶ and V Schulz-von der Gathen¹

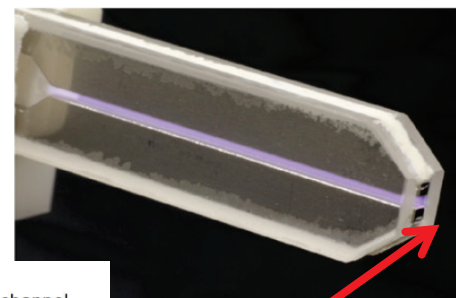


Effluent,
afterglow

μAPPJ: afterglow photons UV/espèces réactives



Photograph (a) and sketch (b) of the modified μAPPJ (so-called X-jet) setup.



Atmospheric pressure argon surface discharges propagated in long tubes: physical characterization and application to bio-decontamination

Zuzana Kovalova^{1,2}, Magali Leroy¹, Carolyn Jacobs¹, Michael J Kirkpatrick¹, Zdenko Machala², Filipa Lopes³, Christophe O Laux⁴, Michael S DuBow⁵ and Emmanuel Odic¹

Pulsed corona discharges were propagated on the inner surfaces of a quartz tube (8 mm inner diameter, variable length: 49 cm in the case of figure 1), in which argon (3.9 slm in dry argon conditions and 4.7 slm in a 760 ppm water vapor/argon mixture) was flowing at atmospheric pressure, from a tungsten needle placed at the tube inlet to a grounded counter electrode located at its outlet. The tungsten needle

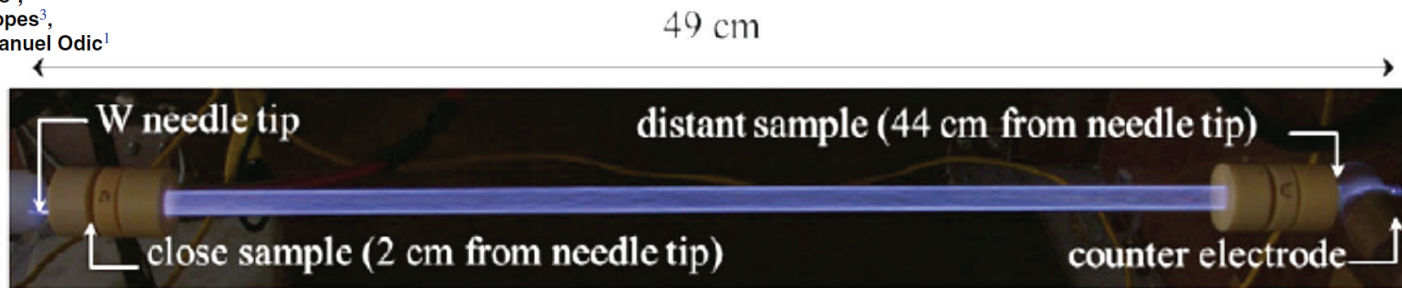


Figure 1. Photograph of the pulsed corona discharge propagating in argon gas inside an 8 mm inner diameter quartz tube over 49 cm between a charged tungsten needle and a grounded counter electrode. The bacterial sample locations at 2 and 44 cm are indicated.

Escherichia coli

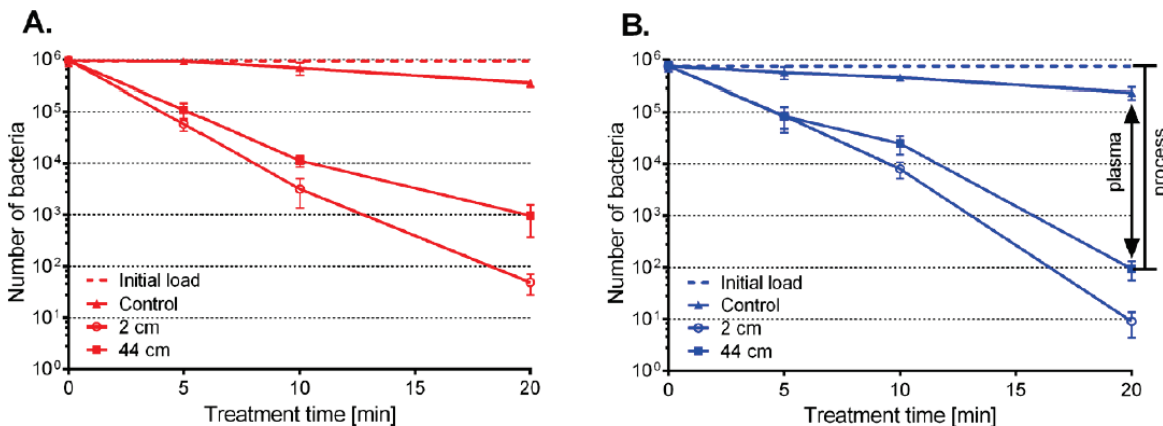


Figure 10. Bacterial viability reduction over increasing treatment times in (A) dry argon (red) and (B) humid argon feed gas (blue). No sample drying prior to treatment (liquid samples). Viable bacterial cells (colony forming units) recovered after 0 (initial bacterial load, dashed line) 5, 10, and 20 min of exposure to argon flow only (controls: triangle symbols for both locations) and argon plasma at 2 (circle symbols) and 44 cm (square symbols) from the source electrode. Assays were carried out in triplicates. Graphed: mean \pm SEM.

Réduction entrée/sortie:
5 log - 4 log

20 minutes

Implication:

Espèces à:

courte durée de vie (OH)

longue durée de vie (H₂O₂)

Photons:

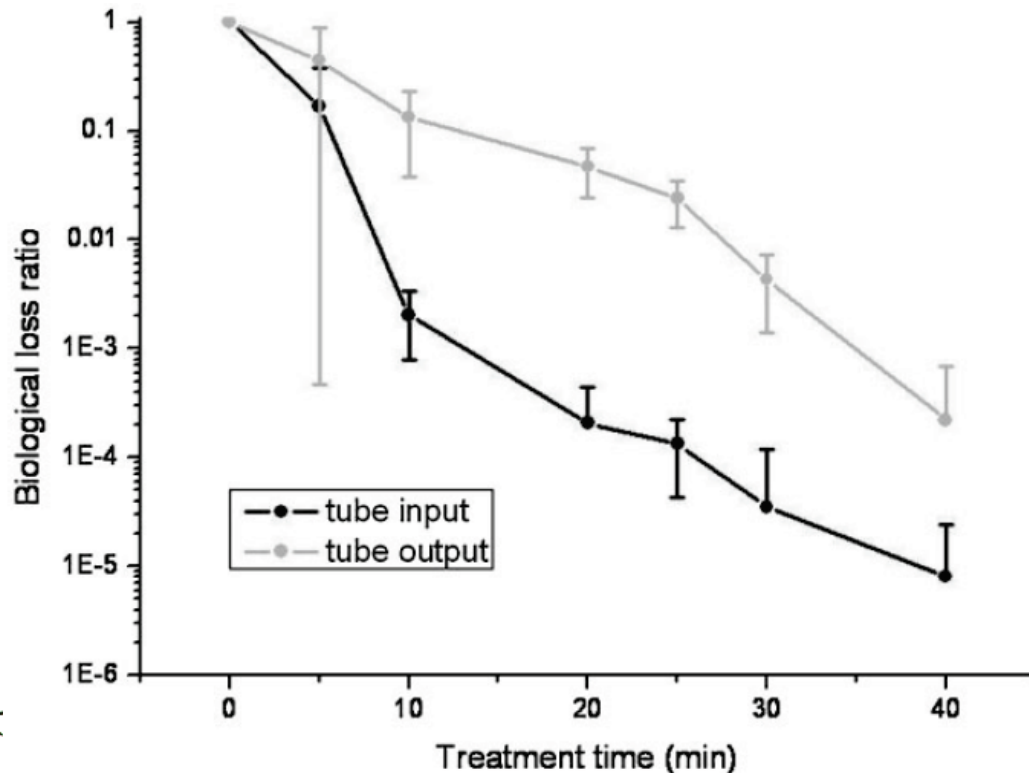
UVB

VUV

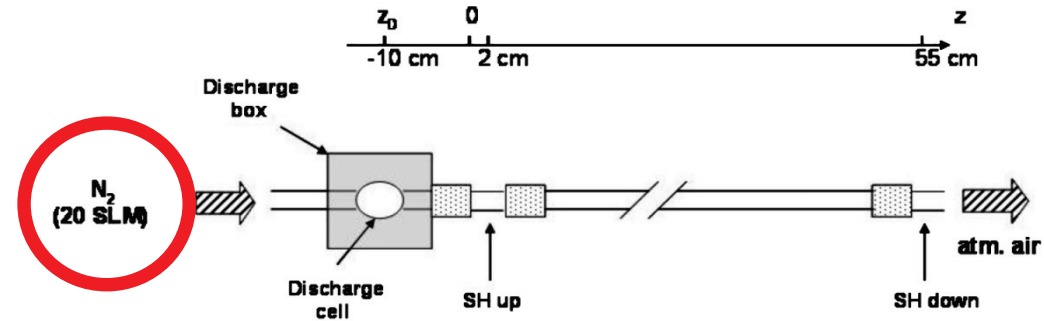
Bacterial Decontamination of the Inner Wall of Narrow Tubes by a Nitrogen Afterglow at Atmospheric Pressure and its Relation to Local Atomic Nitrogen Concentration

Soukayna Limam, Emmanuel Odic,* Michael J. Kirkpatrick, Anne-Marie Pointu

Escherichia coli



The device under study is shown in Figure 1. The discharge, described in Pointu^[11] was a point to point pulsed corona discharge at 14 W entrained by a high velocity gas flow of 20 SLM ($v \approx 6.63 \text{ m} \cdot \text{s}^{-1}$). The discharge atmosphere was



Réduction entrée/sortie:
4.5 log - 3.5 log

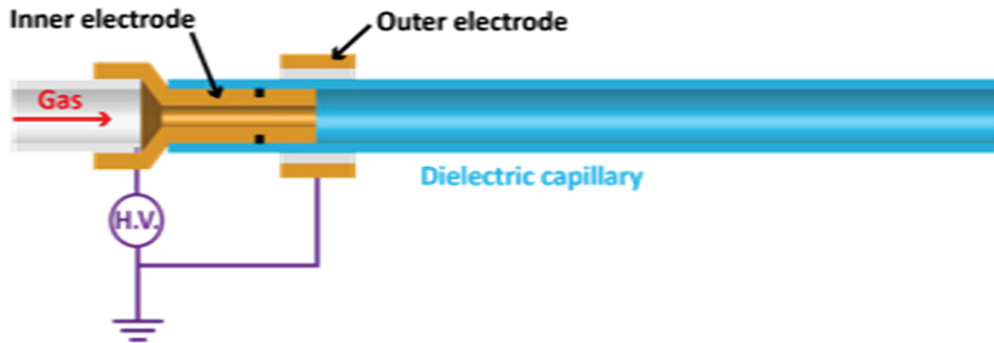
40 minutes

Implication:

espèce à longue durée de vie (N)

Propagation des plasmas de la zone d'initiation vers l'air ambiant

Dispositif Plasma Gun



Initiation du Plasma

Réacteur DBD,
Electrode H.T. interne creuse
Electrode externe: anneau à la masse

Débit He/Ne/Ar : 5– 5000 sccm

Propagation du Plasma

Tube quartz/borosilicate: diamètres int/ext: 4/6 mm
longueur: 5-350 mm

Beaucoup d'autres capillaires diélectriques possibles

Délivrance du Plasma

Génération d'une « Plume » plasma dans l'air:
longueur: 1- 100 mm

Jet libre dans l'air ambiant

Jets sur cibles *in vitro* et *in vivo*:
Étudiants, stagiaires, visiteurs et
Cultures cellulaire/ souris:
cancérologie/dermato-cosmétologie

μ s drivers

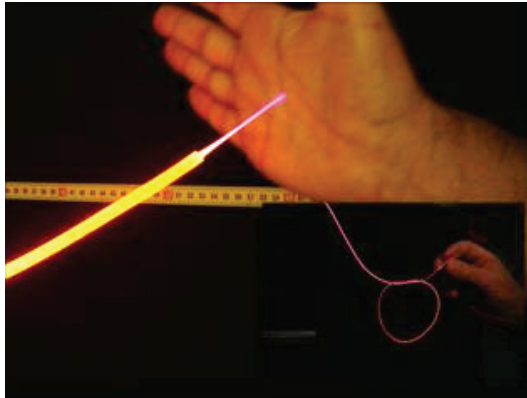
1-30 kV

Negative/positive polarity

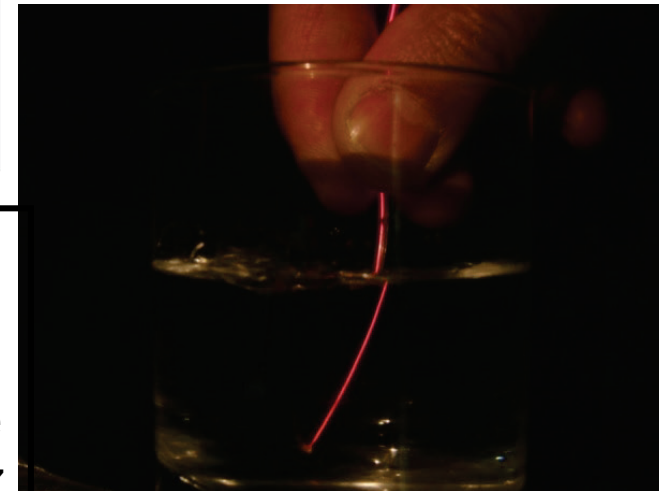
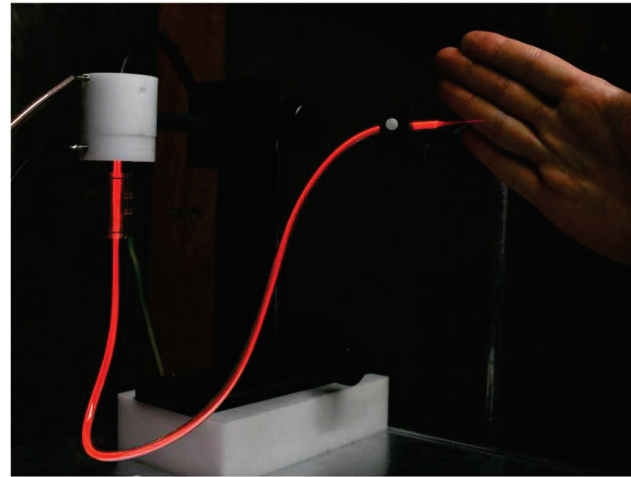
Single shot - 10 kHz

Plasma Gun

Production de colonnes plasma dans les gaz rares et mélanges à bas débits: 0,005 à 5 l/min



Guides diélectriques:
rigide/ flexible,
longueur: 5-350 cm
diamètre interne: 0.15 - 20 mm



Générateurs ns

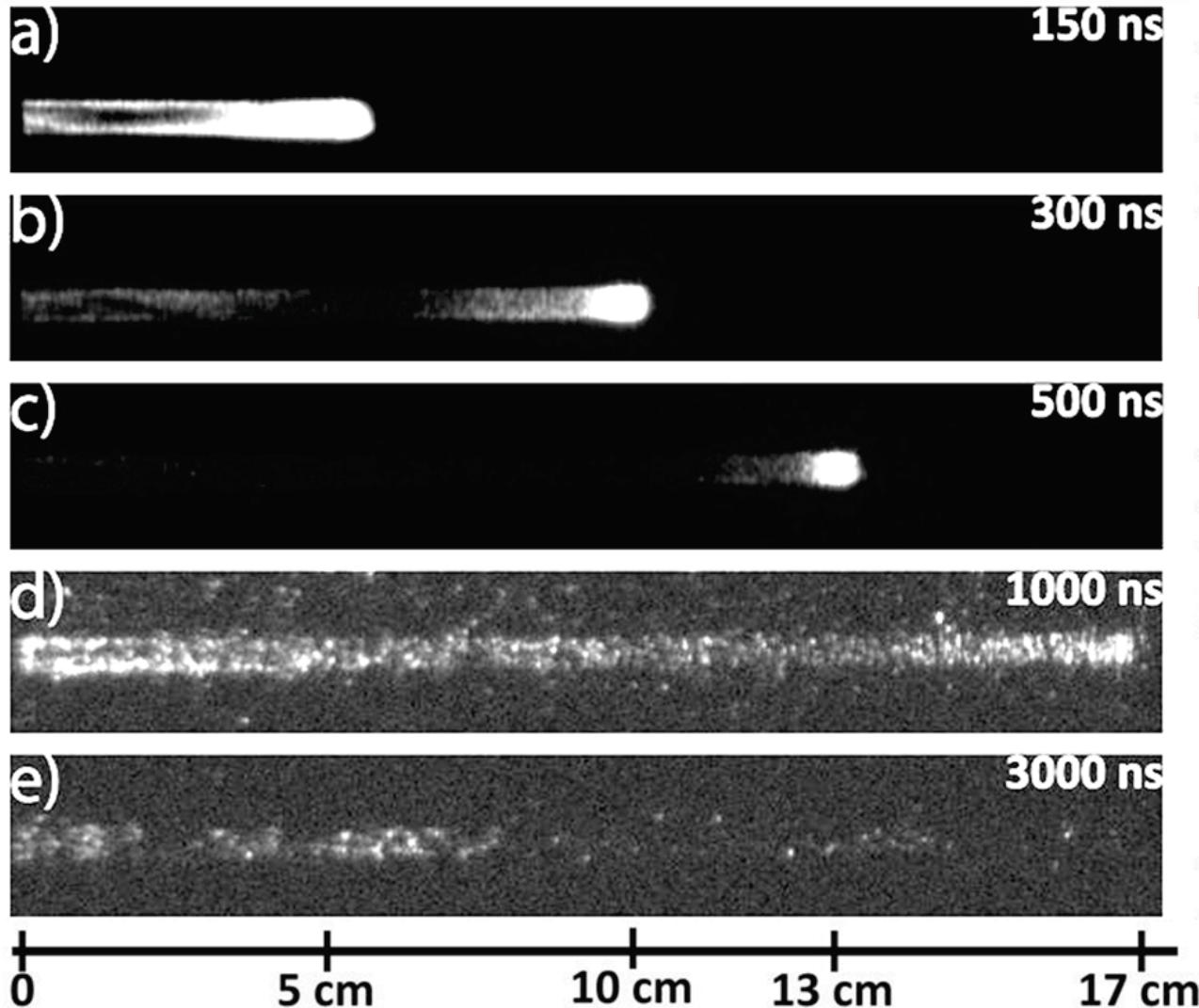
5-100 kV
Polarités: Négative/positive
Décharge unique à 200 Hz
Impulsion ns

Générateurs μ s

5-30 kV
Polarités: Négative/positive
Décharge unique à 20 kHz
Impulsion μ s

En immersion

Imagerie rapide (ns) par ICCD



« Filaments » Plasma sur les parois

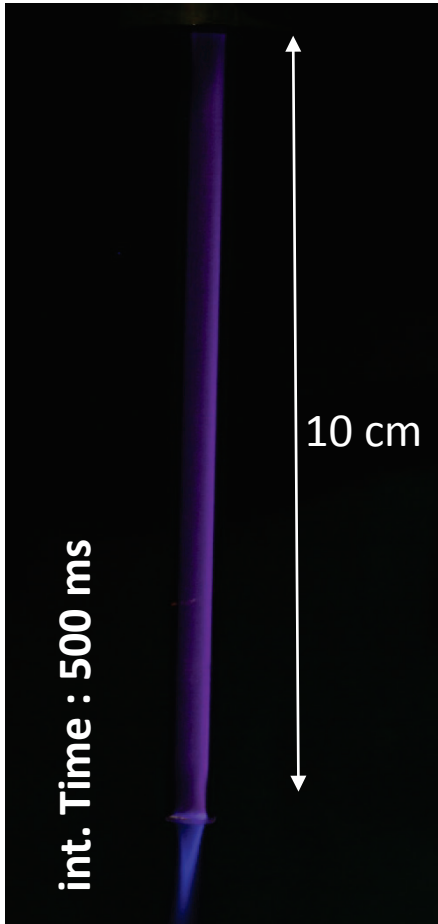
Emission intense à l'extrémité, le « front »

La « balle » plasma

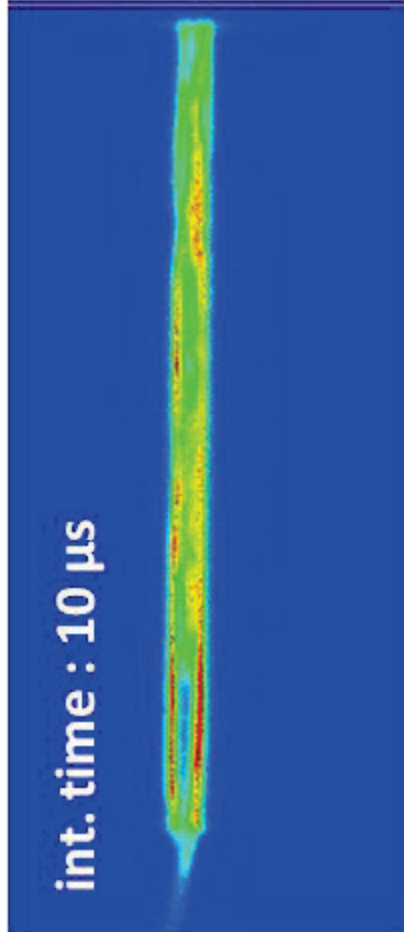
La colonne de plasma

Propagation du plasma: du réacteur à la cible

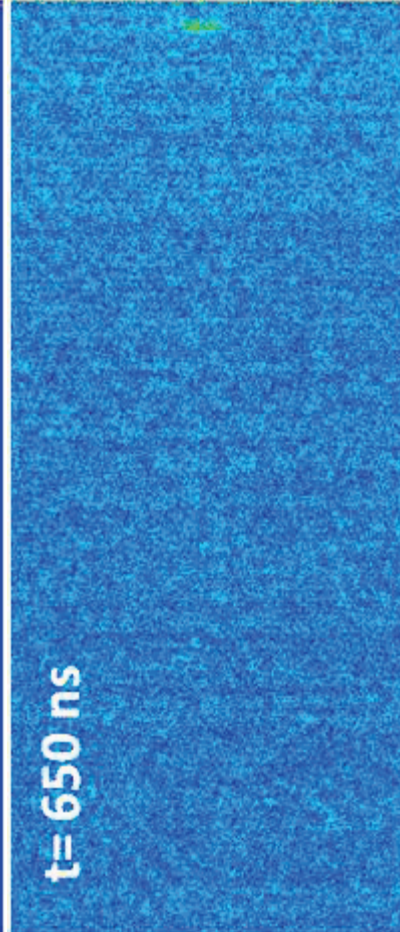
Plasma propagation : generation d'une onde d'ionisation avec un champ électrique local intense dans le front d'ionisation



Photographie: 500 ms



ICCD, temps d'intégration: 10 µs



ICCD, temps d'intégration: 10 ns

Front d'ionisation



Canal ionisé

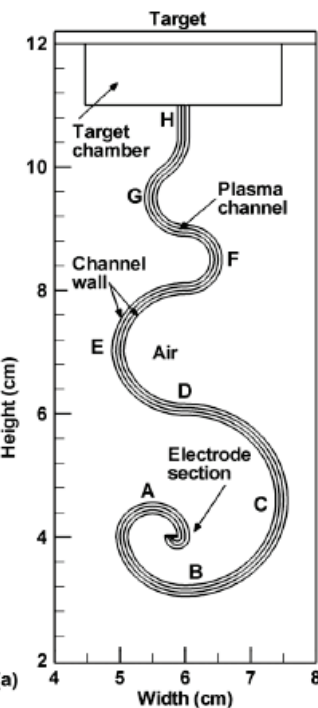


Colonne plasma ou PAPS
Pulsed **A**tmospheric
pressure **P**lasma
Streams

Pendant la propagation:
Le gaz est statique

Atmospheric pressure ionization waves propagating through a flexible high aspect ratio capillary channel and impinging upon a target

15 cm long channel
+/- ns voltage pulses

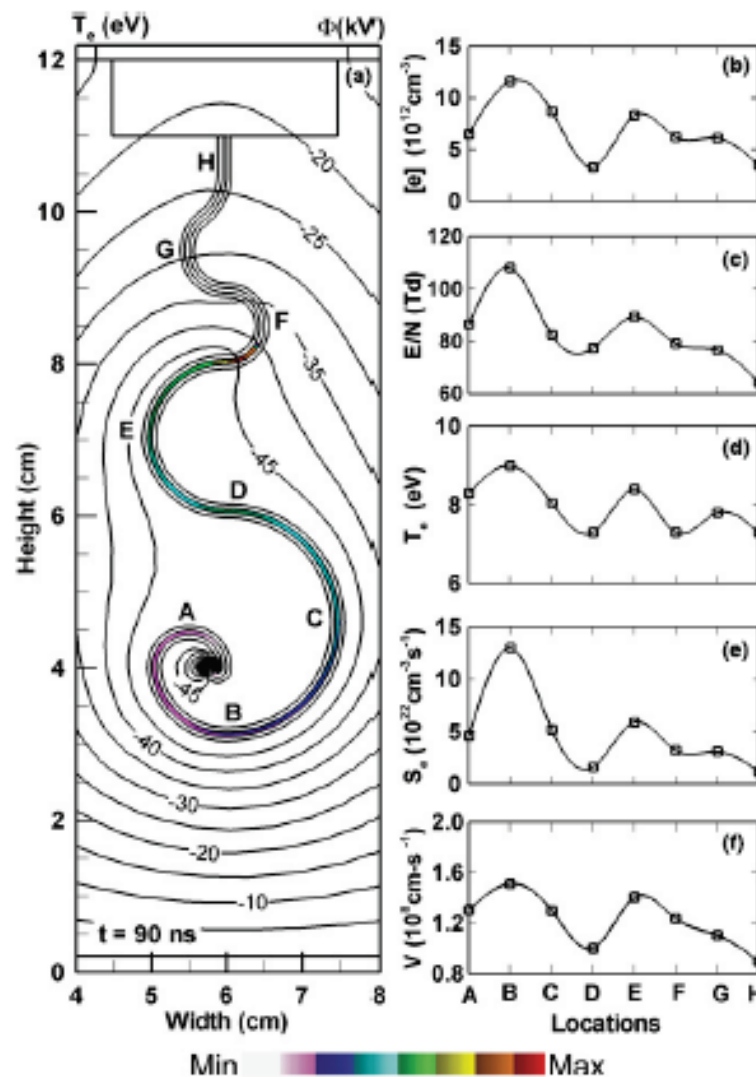


« Constrained » atmospheric pressure ionization wave

Ionization region extends up to several cm inside the channel

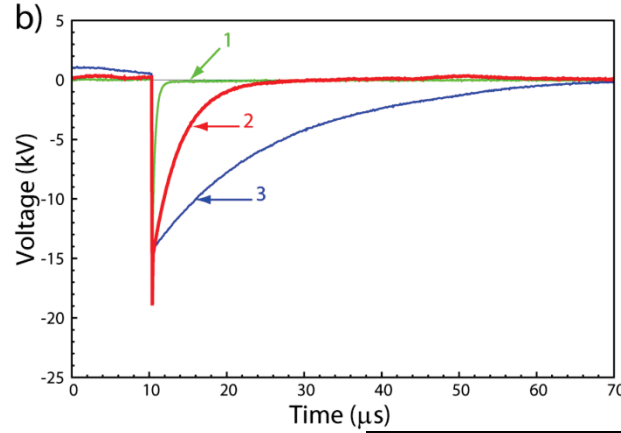
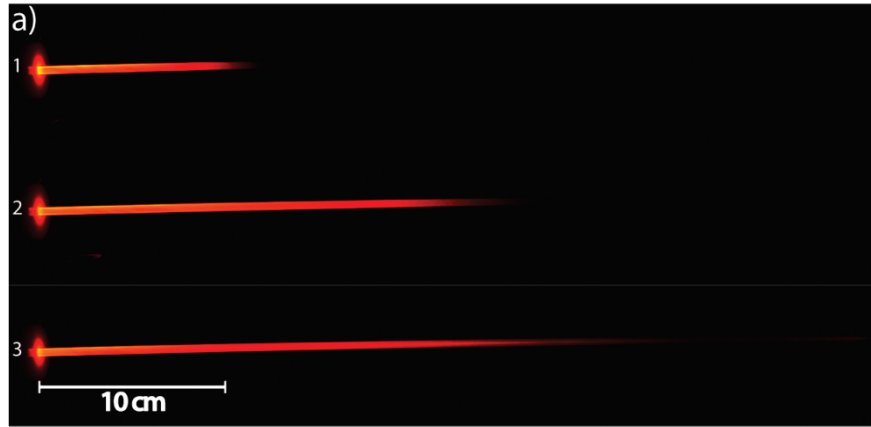
Slow variation of T_e and other parameters

Key roles of plasma tail impedance, wall charging

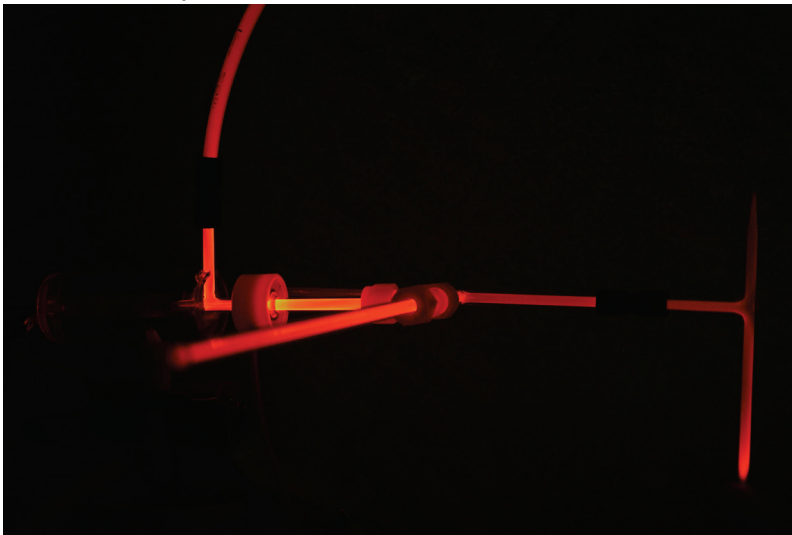


Propagations des PAPS

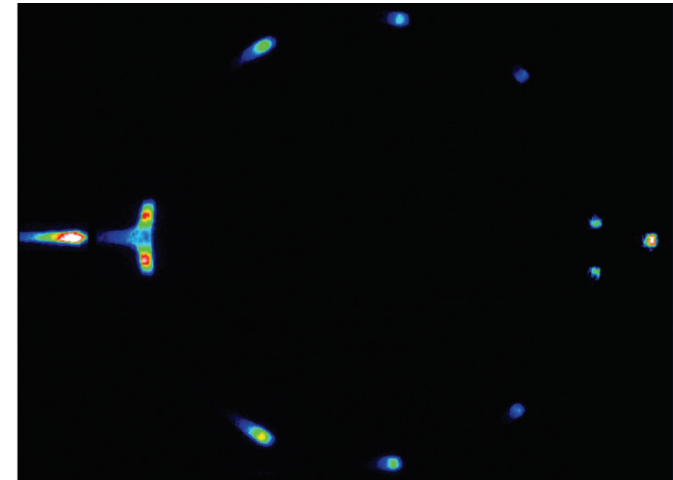
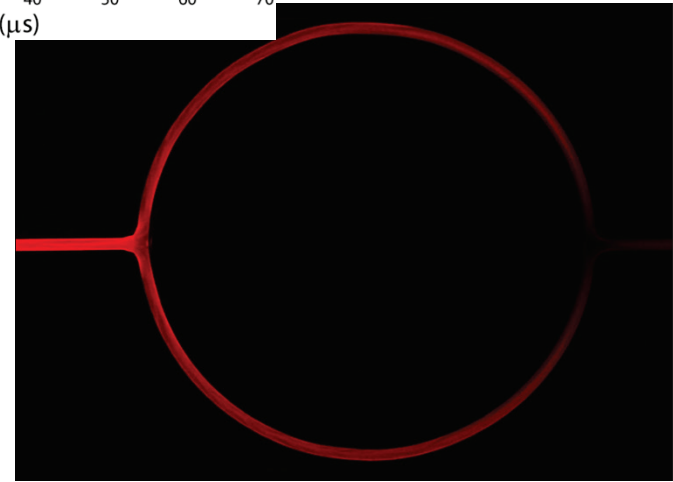
Propagation à longue distance



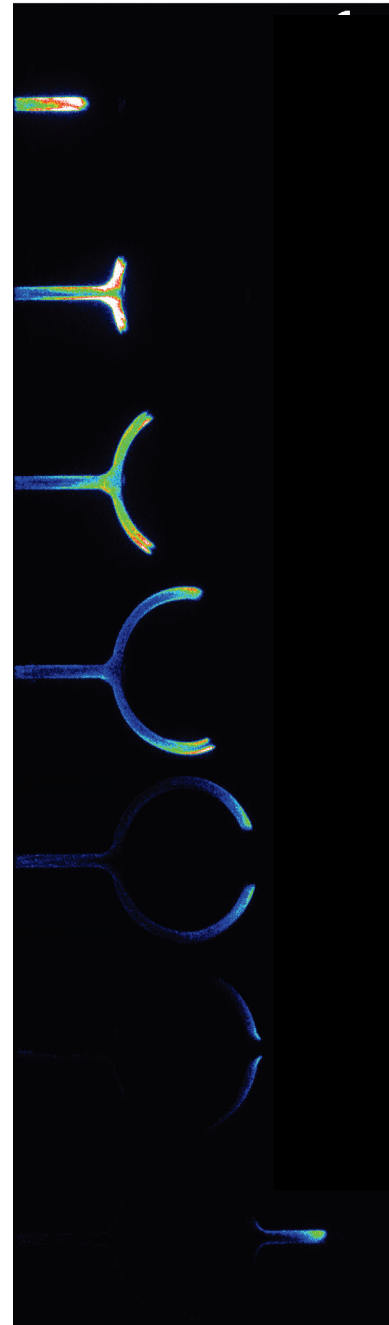
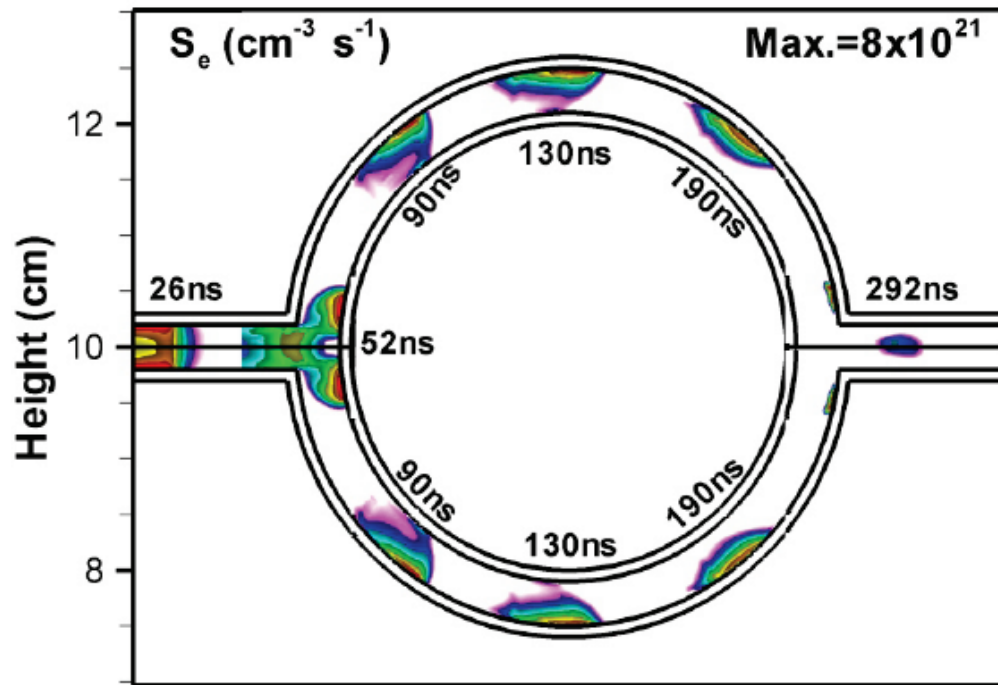
Propagation dans des capillaires ramifiés



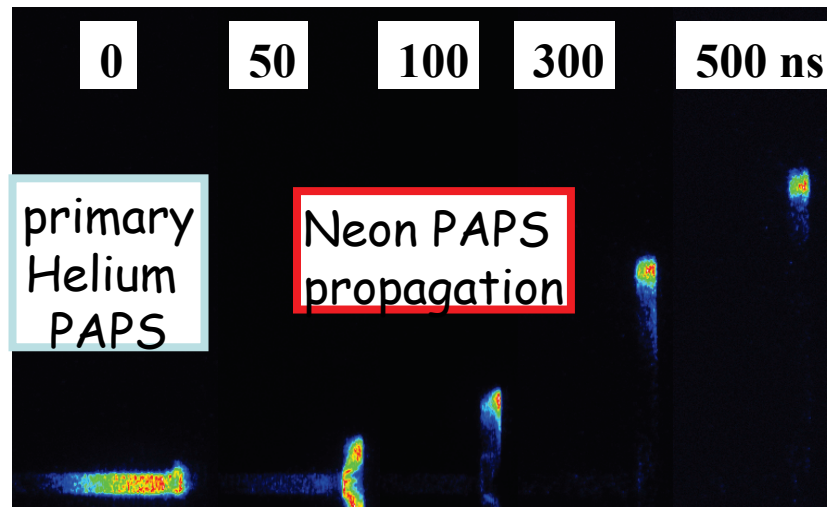
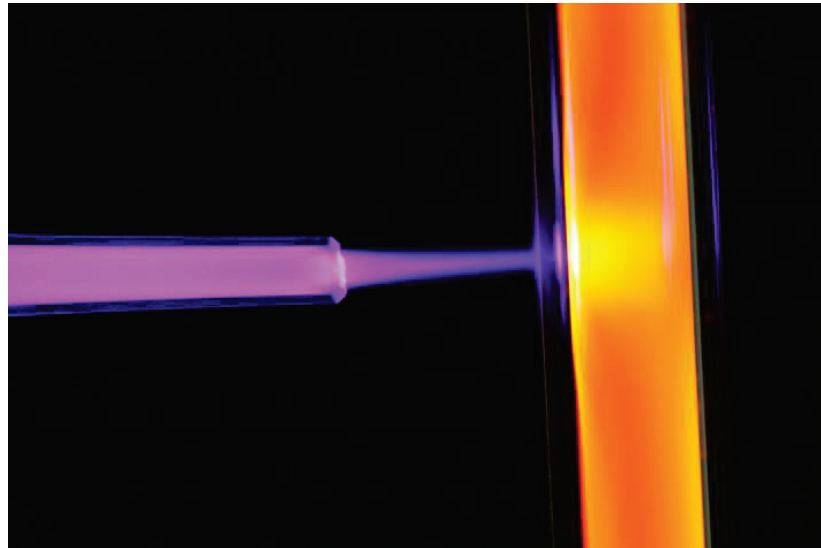
Séparation
et
mélange



Séparation et mélange



Transfert



Jets milli / micro / nano

Study of Cold Atmospheric Plasma Jet at the End of Flexible Plastic Tube for Microbial Decontamination

Plasma Process. Polym. 2015, DOI: 10.1002/ppap.201500125

Konstantin G. Kostov,* Thalita M. C. Nishime, Munemasa Machida, Aline C. Borges, Vadym Prysiashnyi, Cristiane Y. Koga-Ito

or regions with difficult access (e.g., mouth). Here, we report a device that allows ignition of cold He plasma jet at the tip of 1 m long, 3.5 mm diameter, flexible plastic tube. It is connected

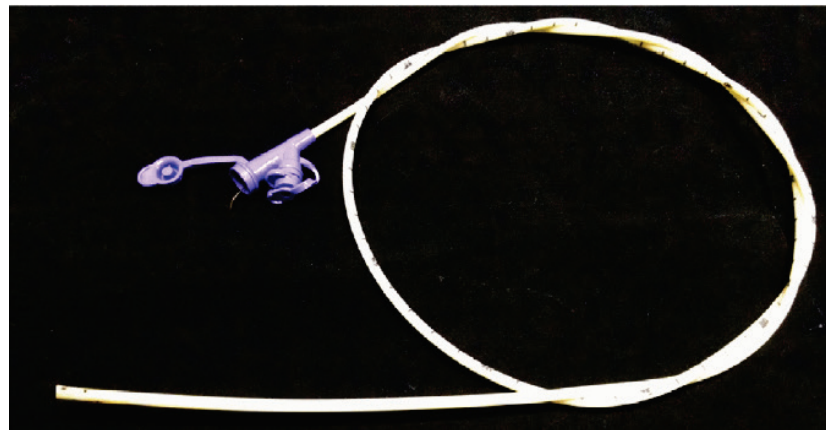
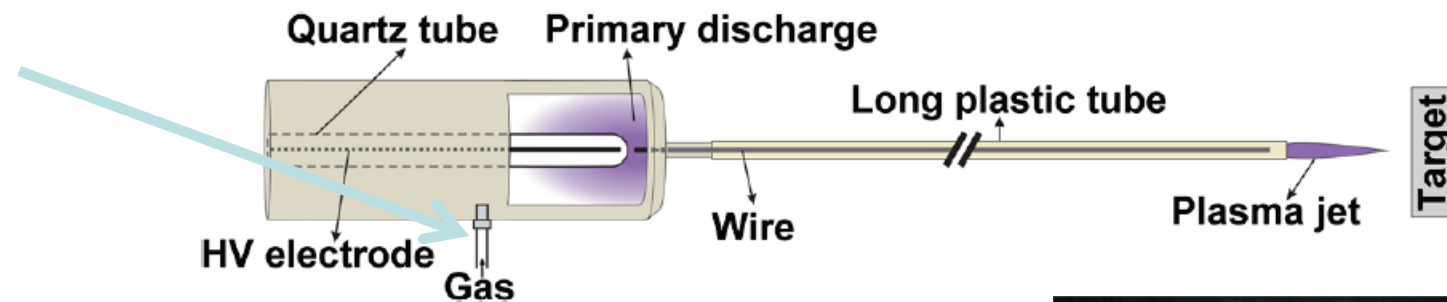
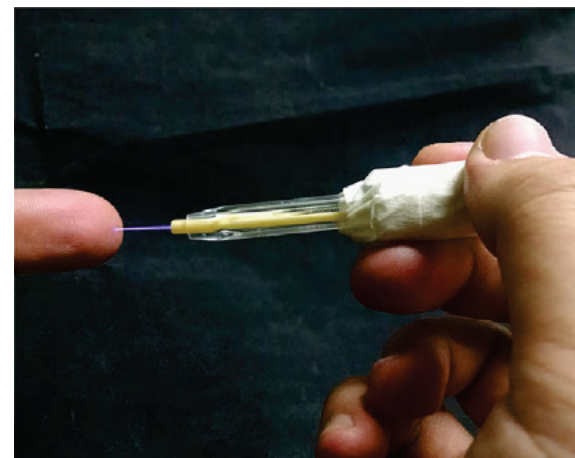
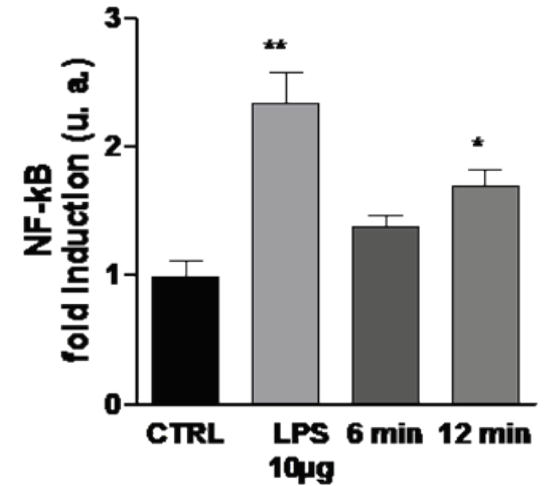
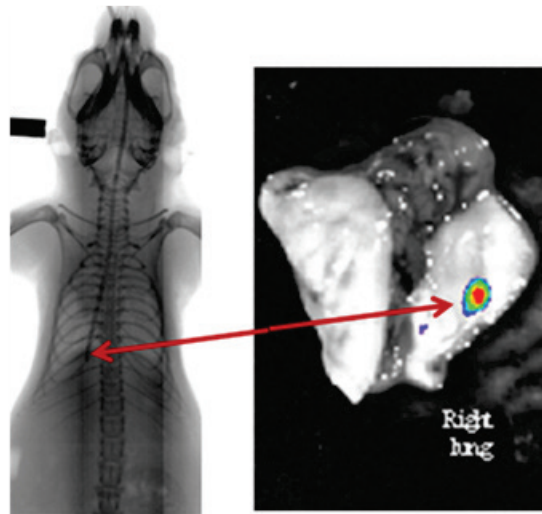


Photo of the polyurethane nasogastric feeding tube



Plasma jet emerging from the end of 1.0 m long plastic tube

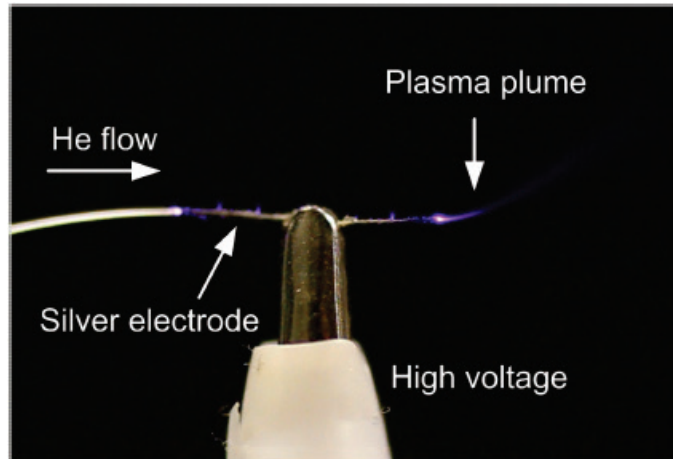
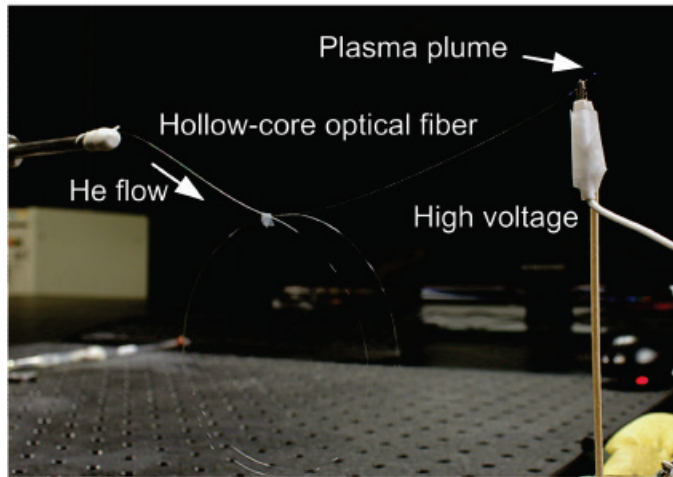
Plasma Gun sous endoscopie



capillaire 200 microns interne
Débit de gaz 20- 50 sccm

Single-Cell-Level Microplasma Cancer Therapy

*Jae Young Kim, Yanzhang Wei, Jinhua Li, Paul Foy, Thomas Hawkins, John Ballato, and Sung-O Kim**



small 2011, 7, No. 16, 2291–2295

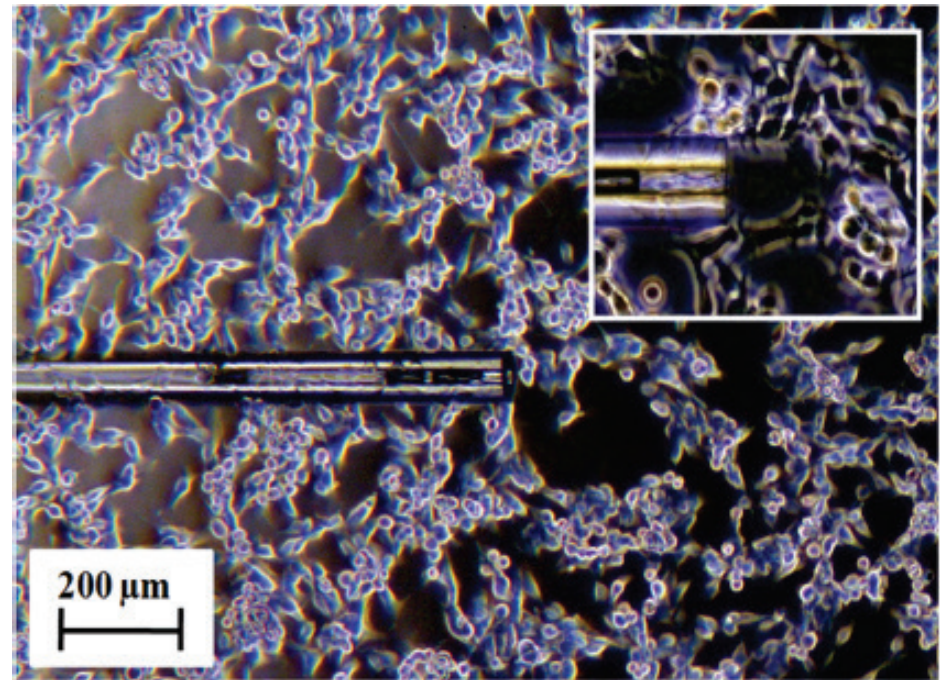


Figure 1. Single-cell-level flexible microplasma-jet device based on a hollow-core glass optical fiber. a) Plasma plume from the hollow-core glass optical fiber into ambient air. b) Highly flexible microplasma-jet device. c) Dimensional comparison between murine B160F melanoma tumor cells and the hollow-core optical fiber with an inner diameter of 15 μm . Inset: with 50 \times magnification. d) Optical emission spectrum of the atmospheric-

Nanocapillary Atmospheric Pressure Plasma Jet: A Tool for Ultrafine Maskless Surface Modification at Atmospheric Pressure

Iuliana Motrescu[†] and Masaaki Nagatsu^{*,‡}

DOI: 10.1021/acsami.6b02483

ACS Appl. Mater. Interfaces 2016, 8, 12528–12533

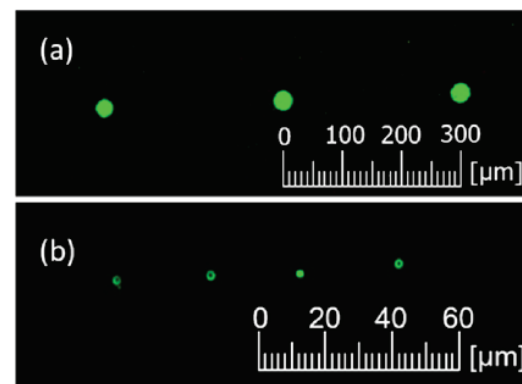
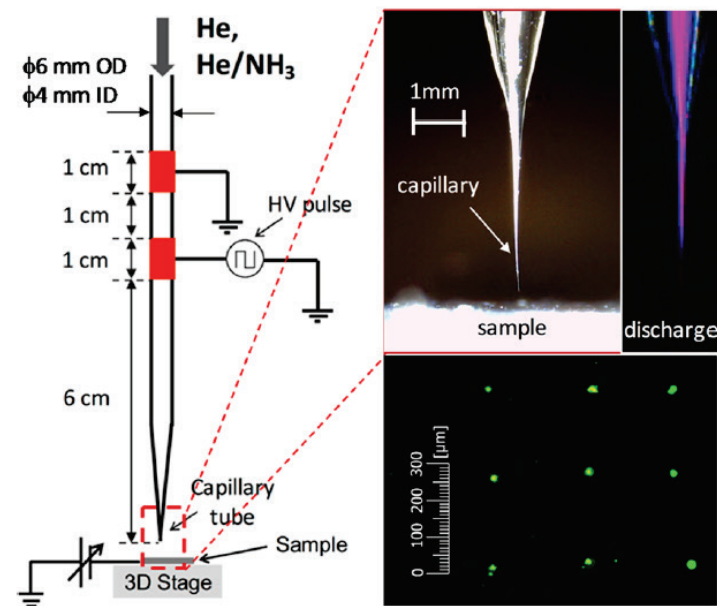
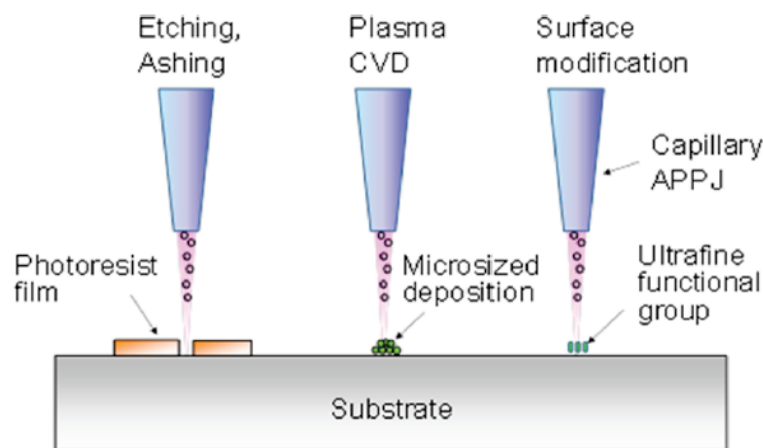


Figure 8. Fluorescence images examples of the aminated patterns obtained with CAPPJ with (a) 1 μm aperture and (b) 100 nm aperture for 0.1 s He plasma pretreatment (with a substrate bias of −500 V) and 3 s He/NH₃ plasma treatment.

Interaction jet de gaz/ décharge plasma

Interaction jets de plasma /cible

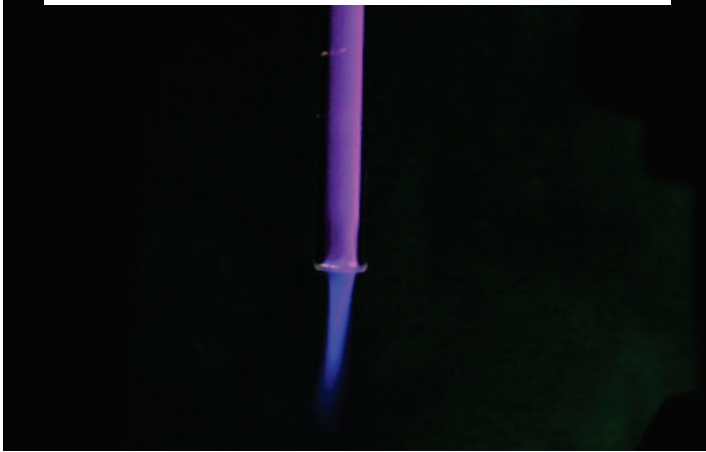
Initiation d'une onde d'ionisation dans le réacteur
Propagation dans le capillaire

Propagation dans l'air

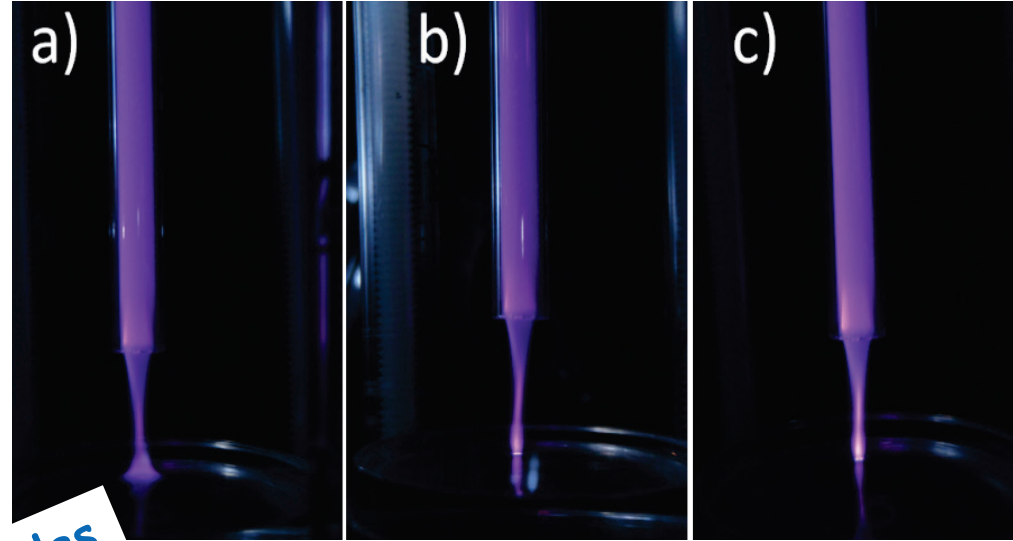
Interaction avec la cible

Et retour à l'expéditeur!

Jet libre dans l'air ambiant



- a) Eau distillée: 1.5 $\mu\text{S}/\text{cm}$
- b) Liquide physiologique (NaCl 9 g/l): 15 mS/cm
- c) Eau salée (NaCl 20 g/l): 35 mS/cm



Jet sur souris



Applications biomédicales

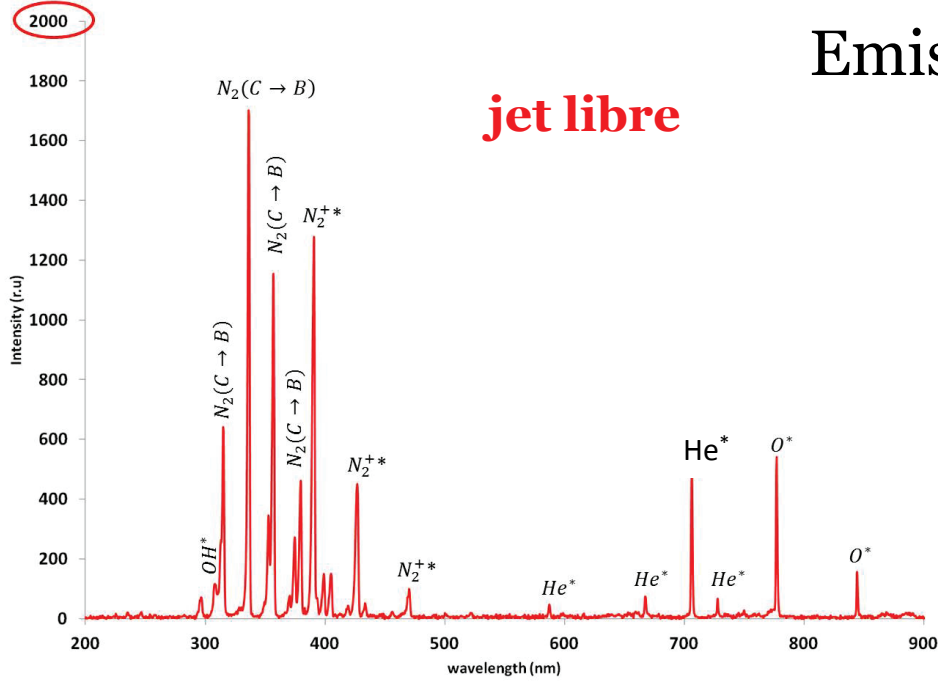
Plume plasma sur cible métallique



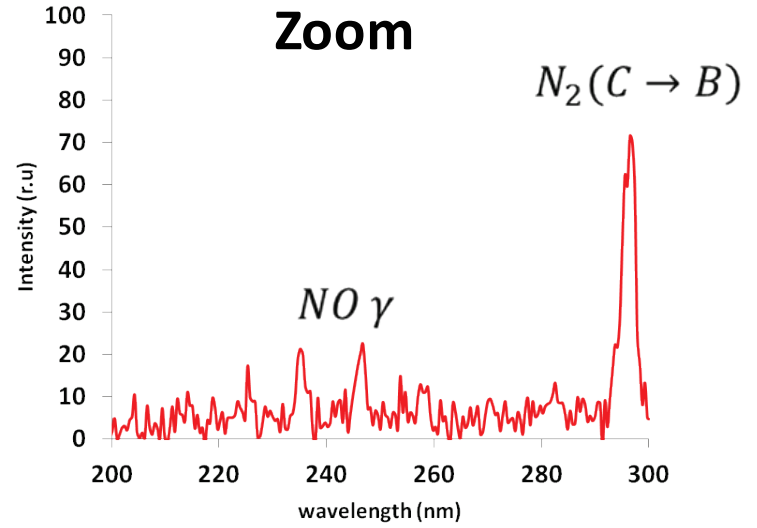
Des cibles ad hoc
pour délivrer et étudier le plasma

Emission de la plume plasma plume

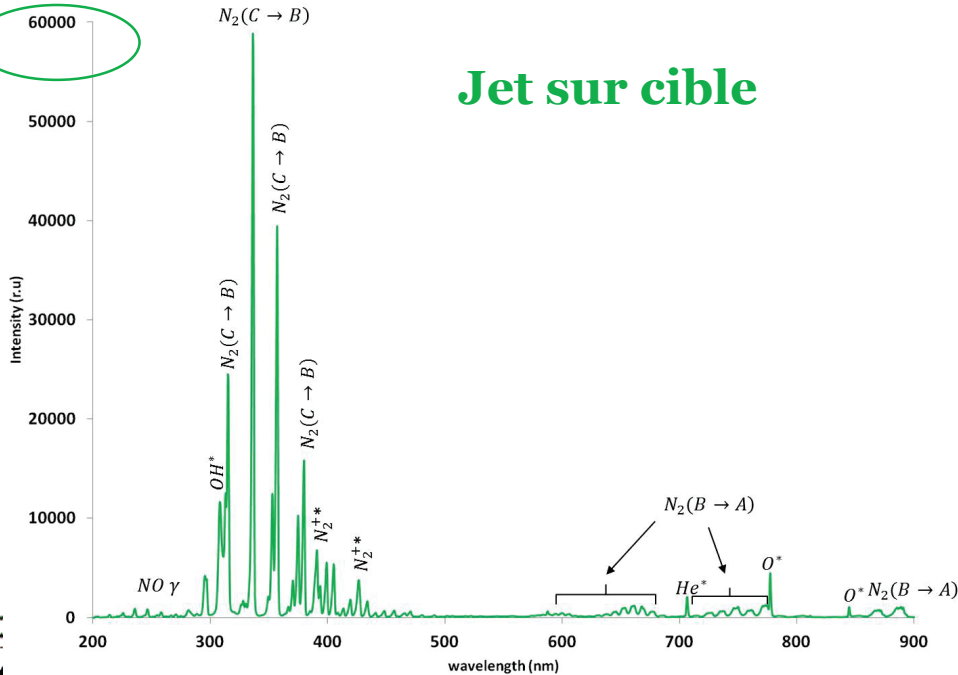
jet libre



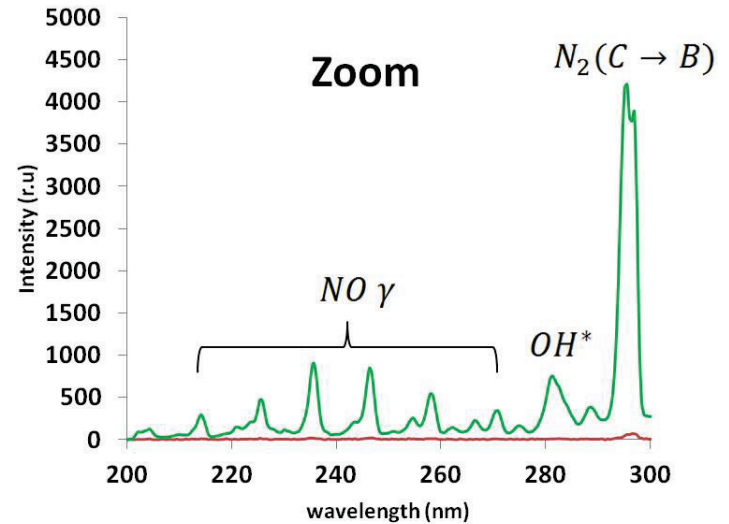
Zoom



Jet sur cible

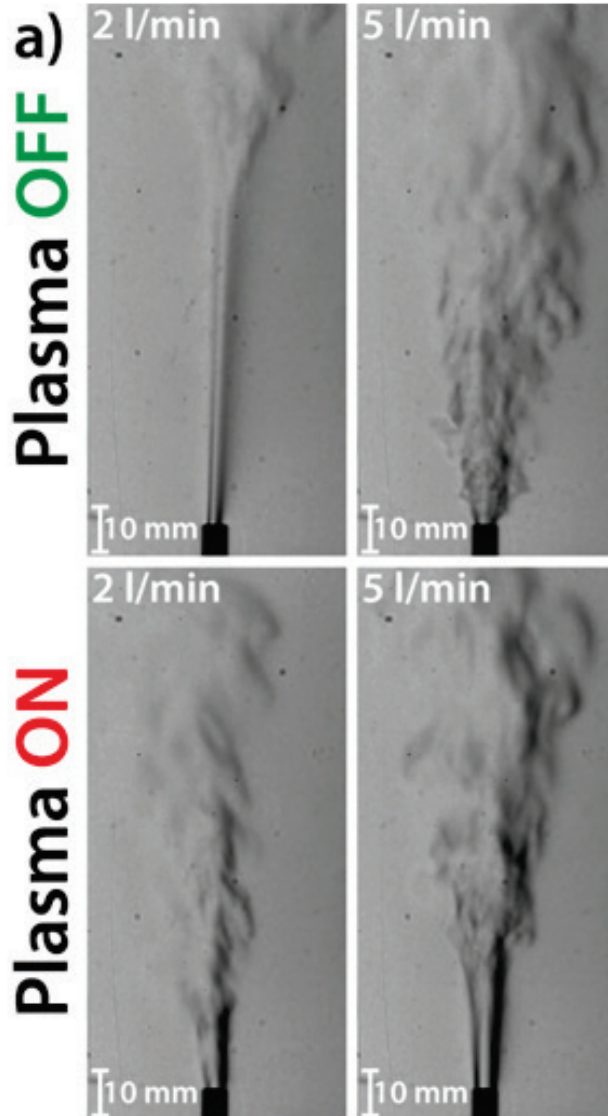


Zoom



Visualisation écoulement: Schlieren

Jet libre dans l'air

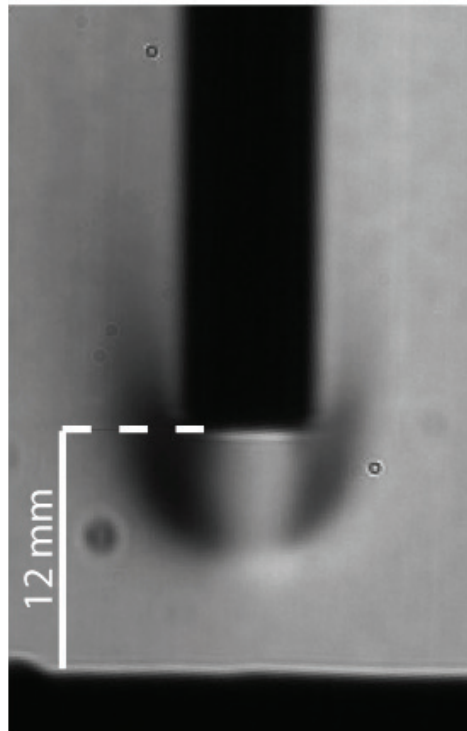


Décalage amont/aval du point
de transition
laminaire/turbulent

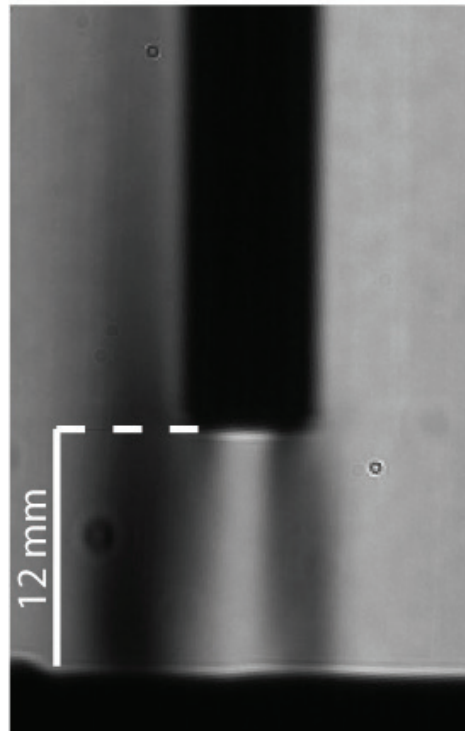
Visualisation écoulement: Schlieren

Helium 0.5 l/mn

Plasma **OFF**



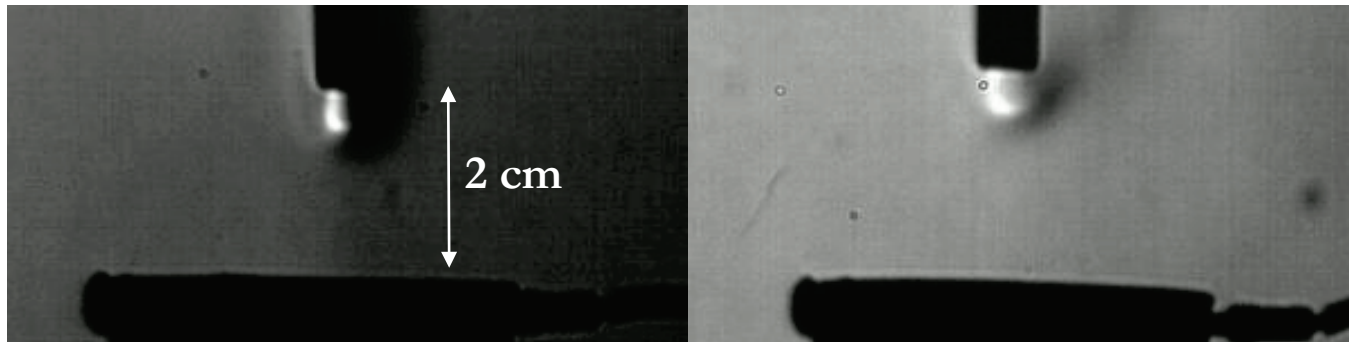
Plasma **ON**



Influence de la polarité

polarité positive

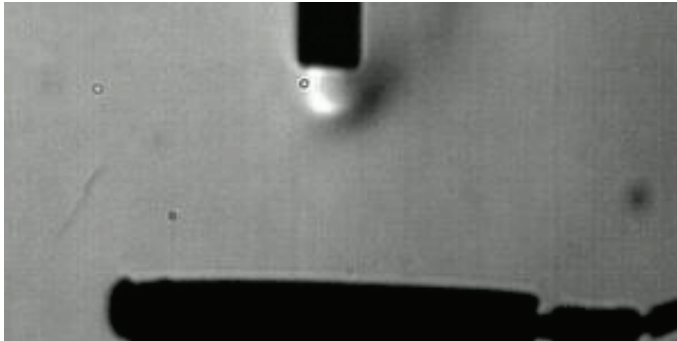
polarité négative



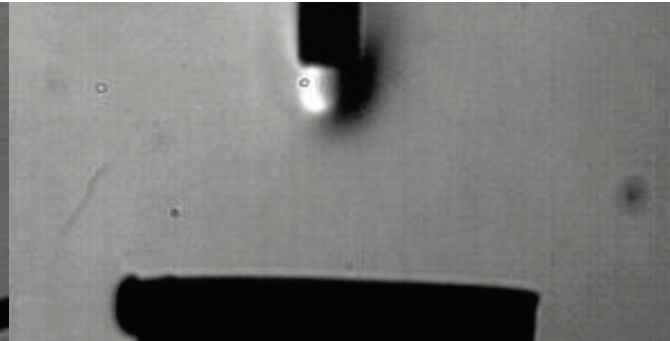
Construction d'un canal d'hélium de la sortie du capillaire
jusqu'à la cible

Influence du potentiel électrique de la cible

Cible à la masse



Cible au potentiel flottant



Schlieren High-Speed Imaging of a Nanosecond Pulsed Atmospheric Pressure Non-equilibrium Plasma Jet

Plasma Chem Plasma Process (2014) 34:853–869

M. Boselli · V. Colombo · E. Ghedini · M. Gherardi · R. Laurita ·
A. Liguori · P. Sanibondi · A. Stancampiano

Steady state
gas flow →

Steady state gas flow
with plasma ON →

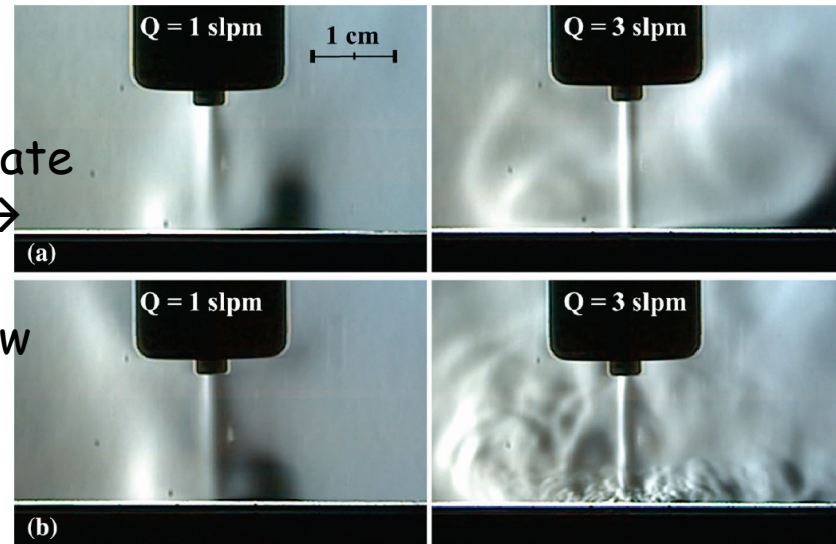


Fig. 13 Schlieren imaging of a jet impinging on a metallic substrate without (a) and with (b) plasma ignition. He mass flow rate set at 1 (left) and 3 slpm (right). PV = 14 kV and PRF = 1 kHz

← Gas flow dynamics on metal target

← Gas flow dynamics with dielectric layer

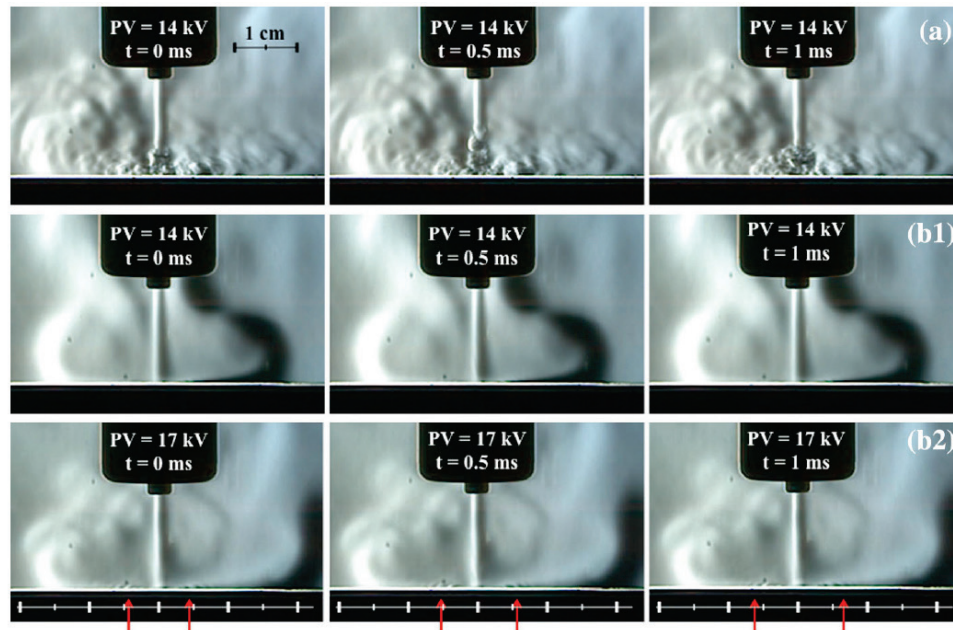
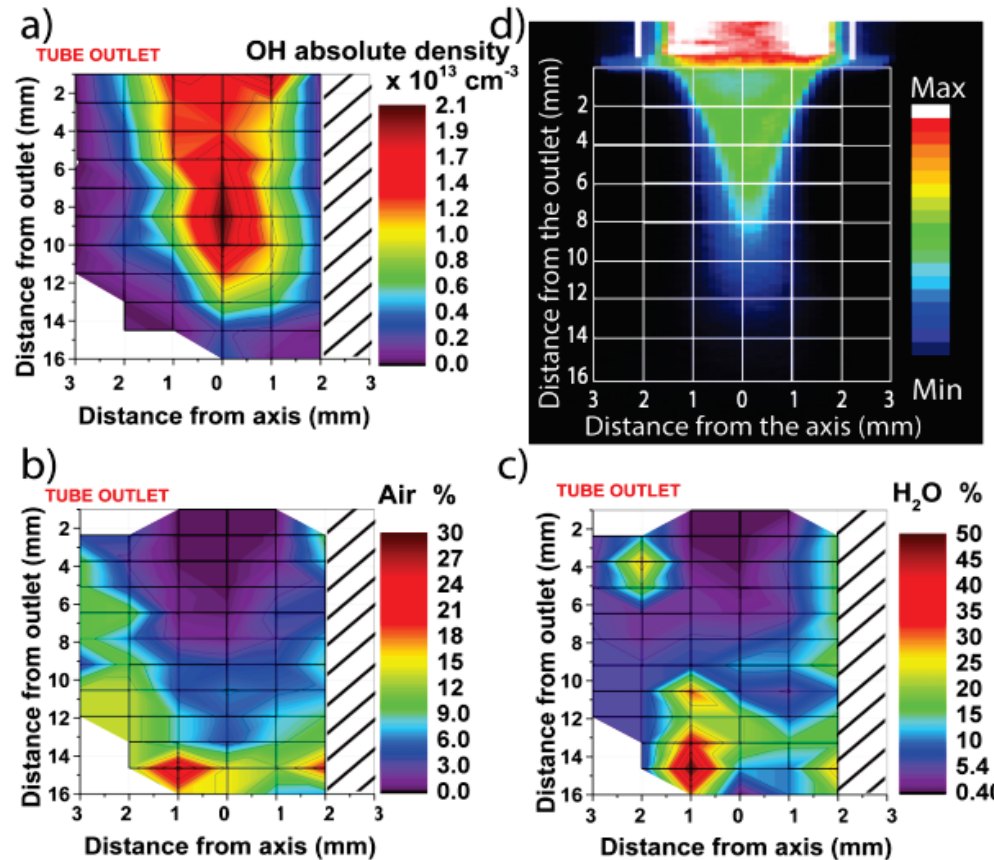


Fig. 15 Schlieren imaging of the plasma jet fluid-dynamics without (a) and with (b1, b2) a layer of dielectric material on the surface of a metallic substrate. PV at 14 (a, b1) and 17 kV (b2), He mass flow rate = 3 slpm, PRF = 1 kHz. Turbulent wave fronts are tracked by arrows. Voltage pulse at t = 0 ms

Fluorescence induite par laser sur radical OH Jet libre dans l'air

D. Ries *et al*, J. Phys. D: Appl. Phys. 47 (2014) 275401

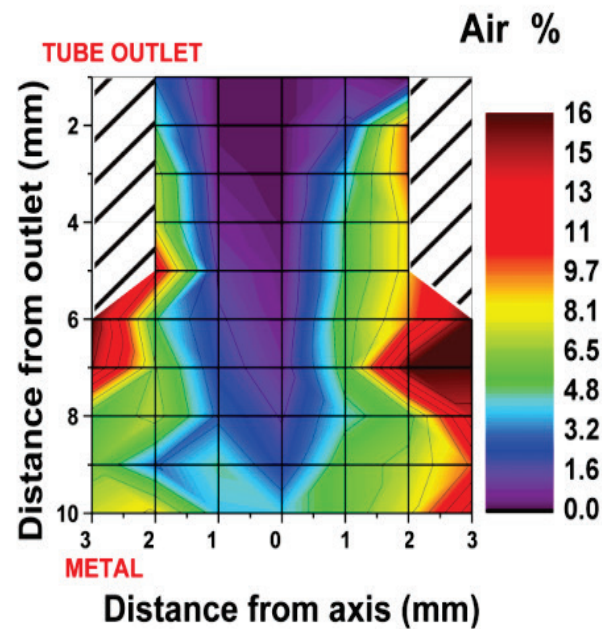
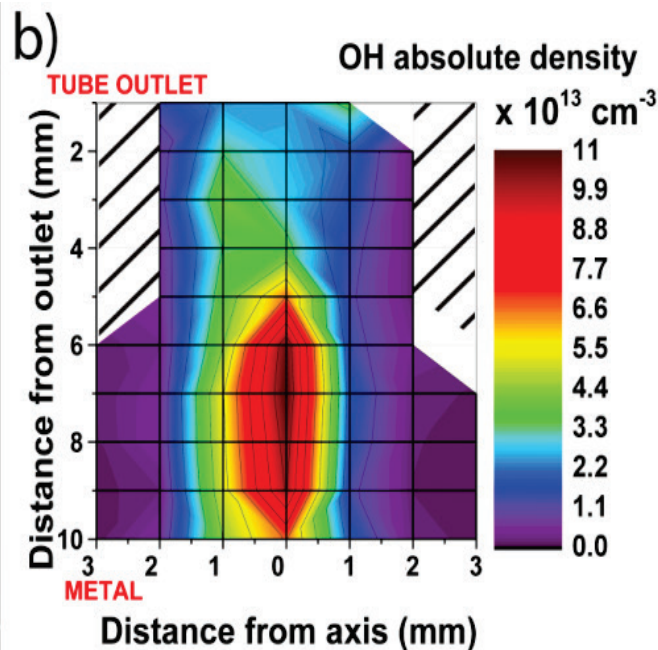
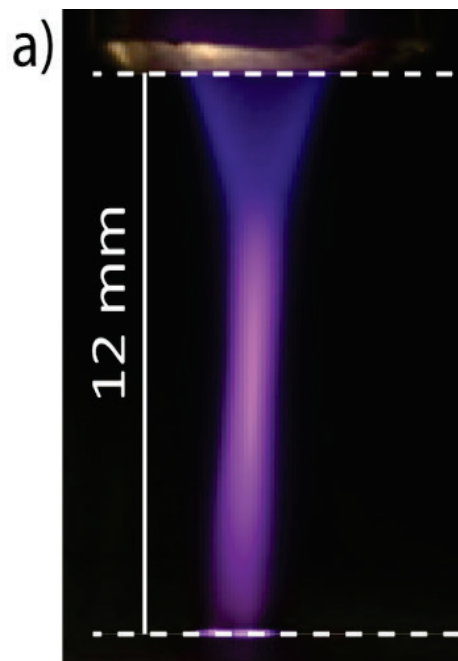


ICCD imaging and LIF results for [OH] and Air and H₂O partial pressures

Dilecce G. and De Benedictis S. 2011 *Plasma Phys. Controlled Fusion* 53:124006

G Dilecce 2014 *Plasma Sources Sci. Technol.* 23:015011

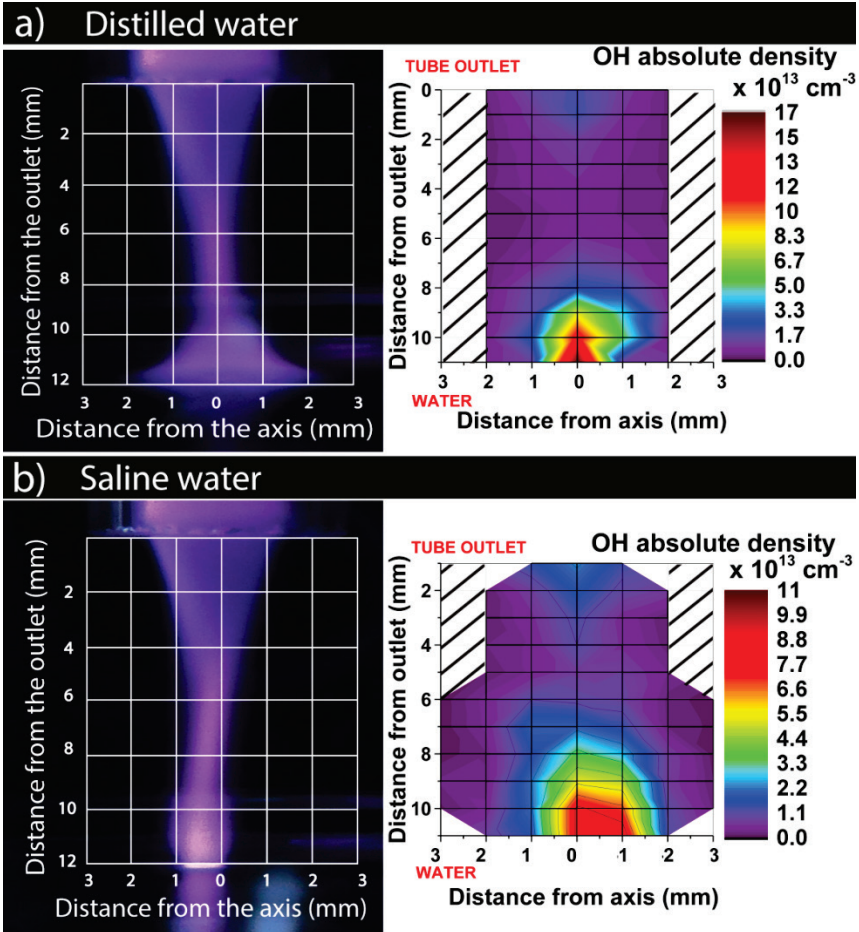
Jet sur cible métallique



Temps d'exposition
300 ms

14 kV

Jets sur cibles liquides de différentes conductivités



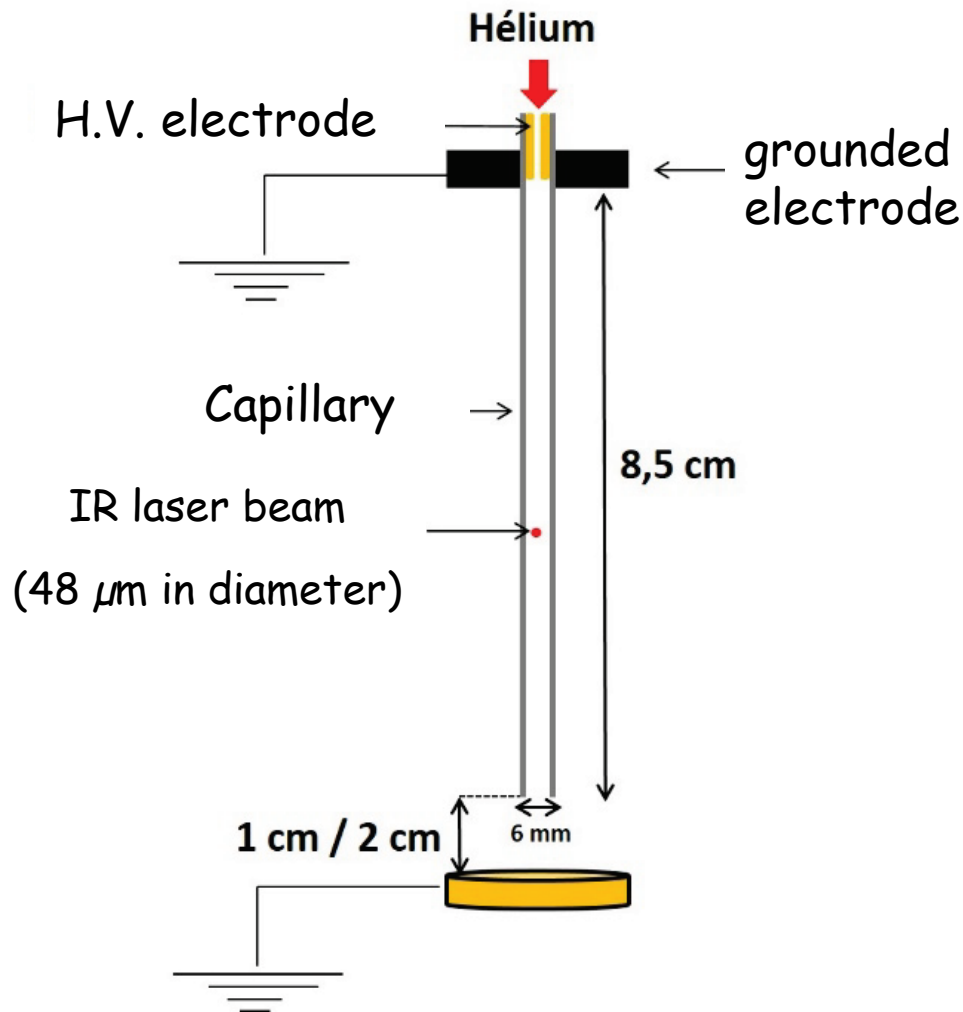
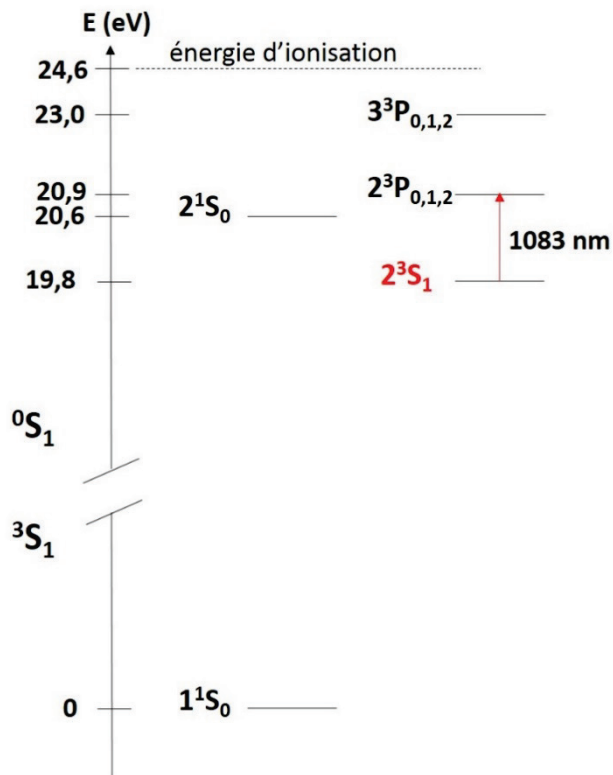
1.5 $\mu\text{S/cm}$

34.7 mS/cm

Solution de 10 mm de profondeur dans un puits placé sur une cible métallique

Mesure de metastable d'hélium He (2^3S) par absorption IR

Collaboration LPGP
V. Puech



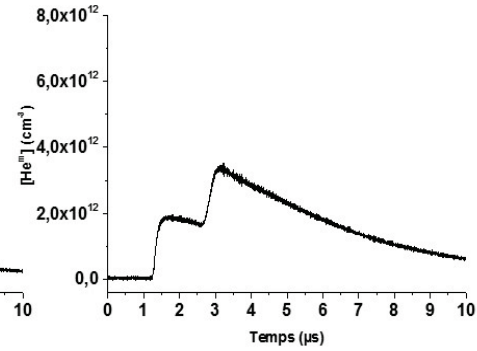
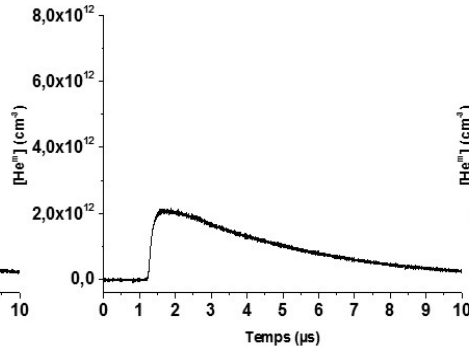
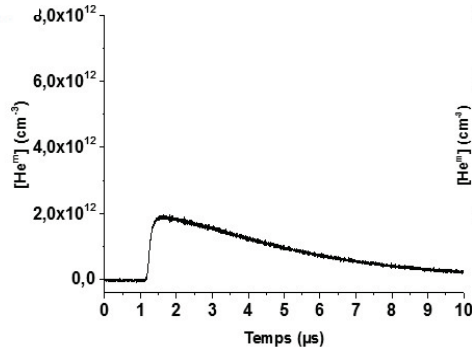
Distance to ground elec.

Jet libre

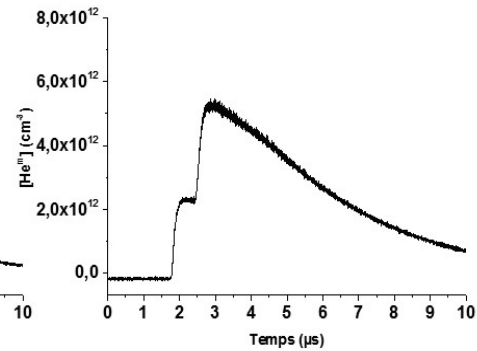
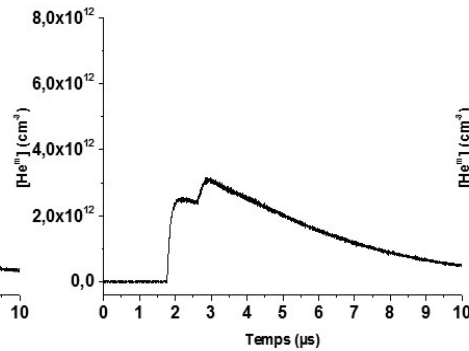
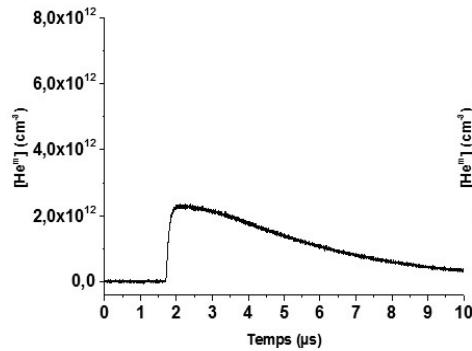
Cible à 2 cm

Cible à 1 cm

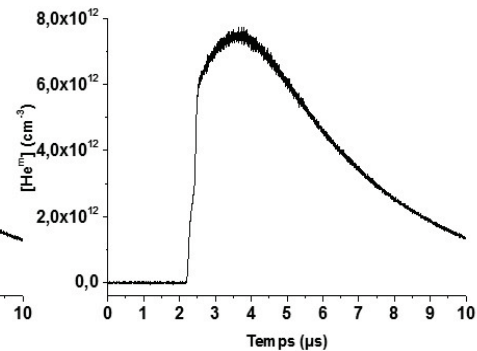
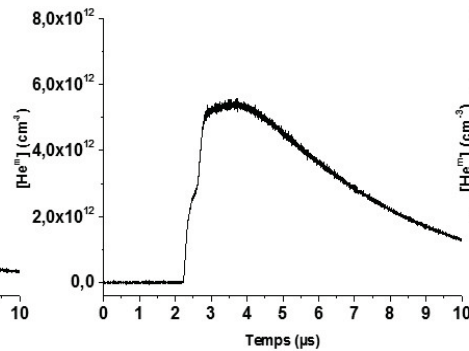
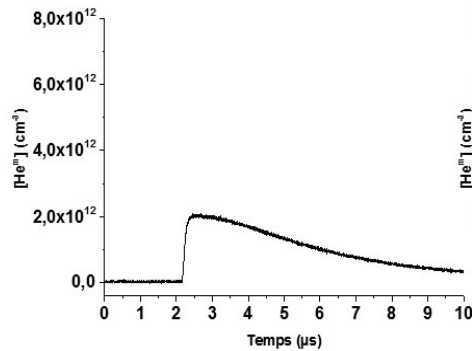
1,5 cm



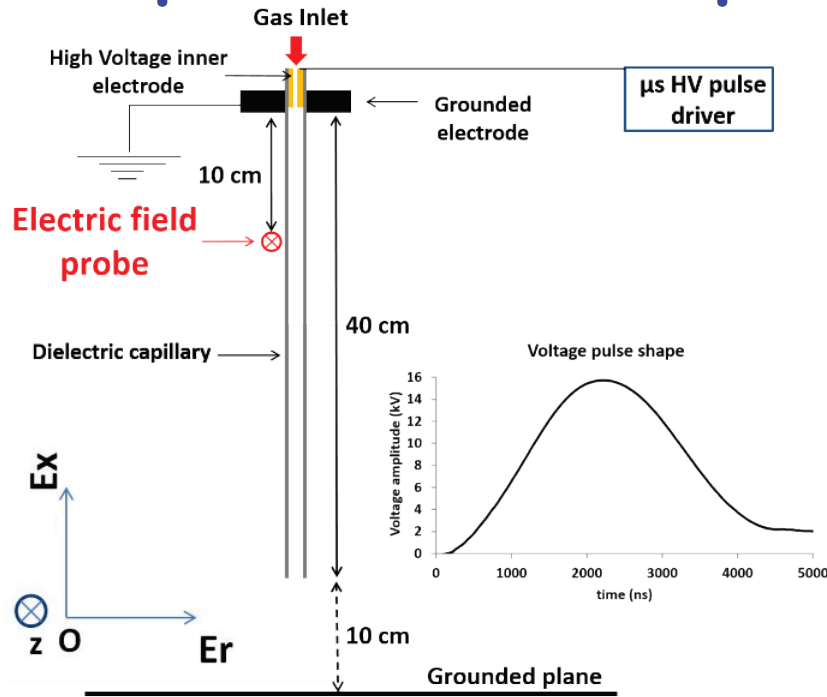
4,5 cm



7,5 cm

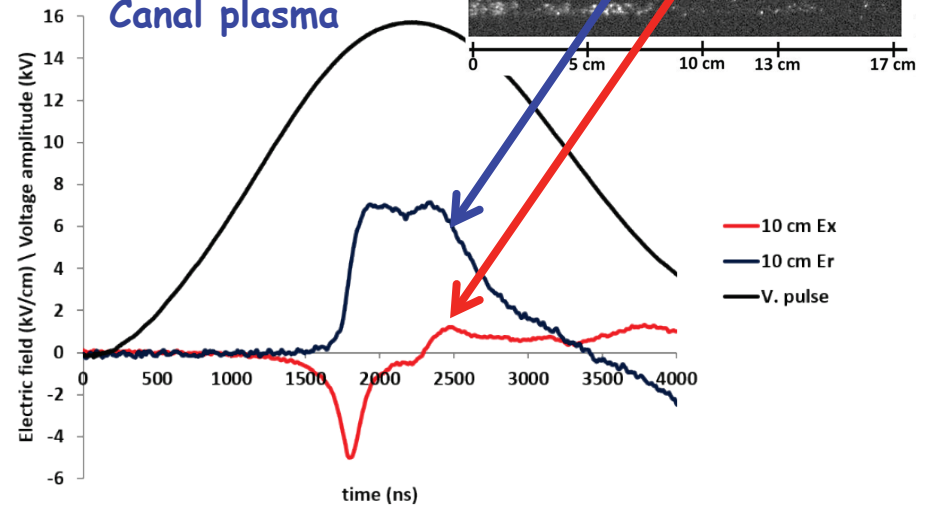


Jets plasma et champ électrique

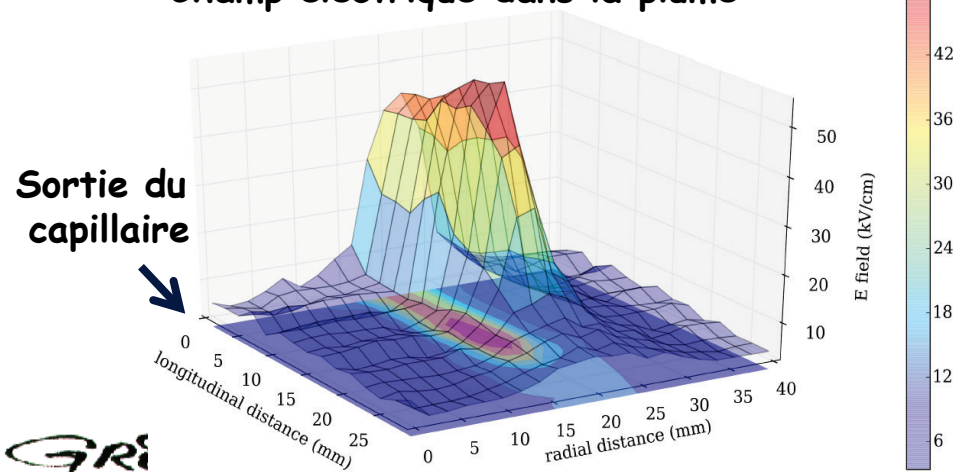


Champ électrique proche du capillaire

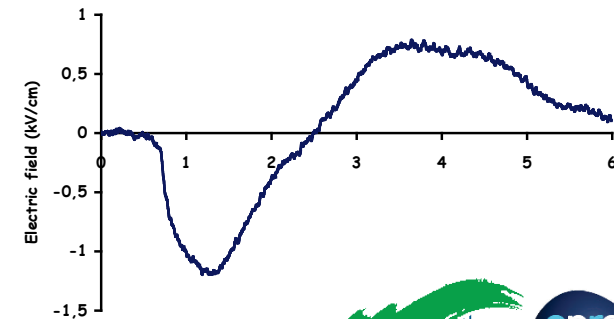
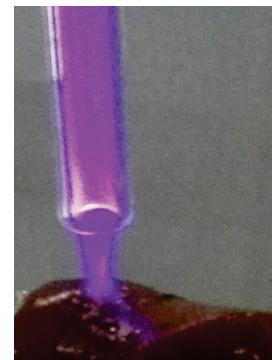
Front d'ionisation
Canal plasma



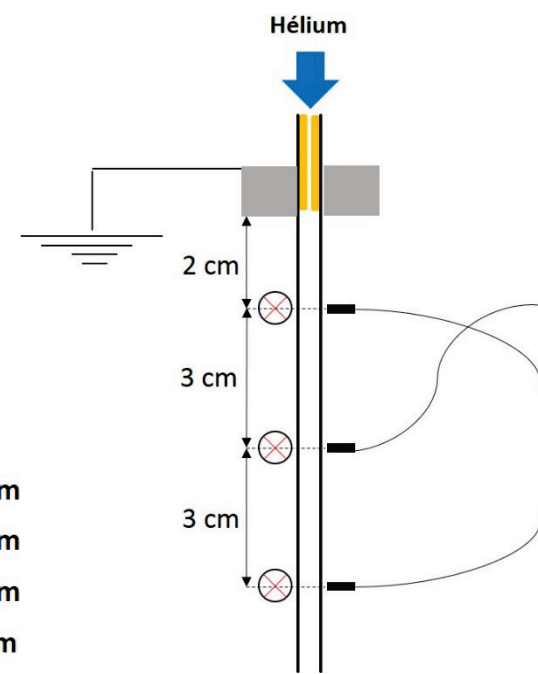
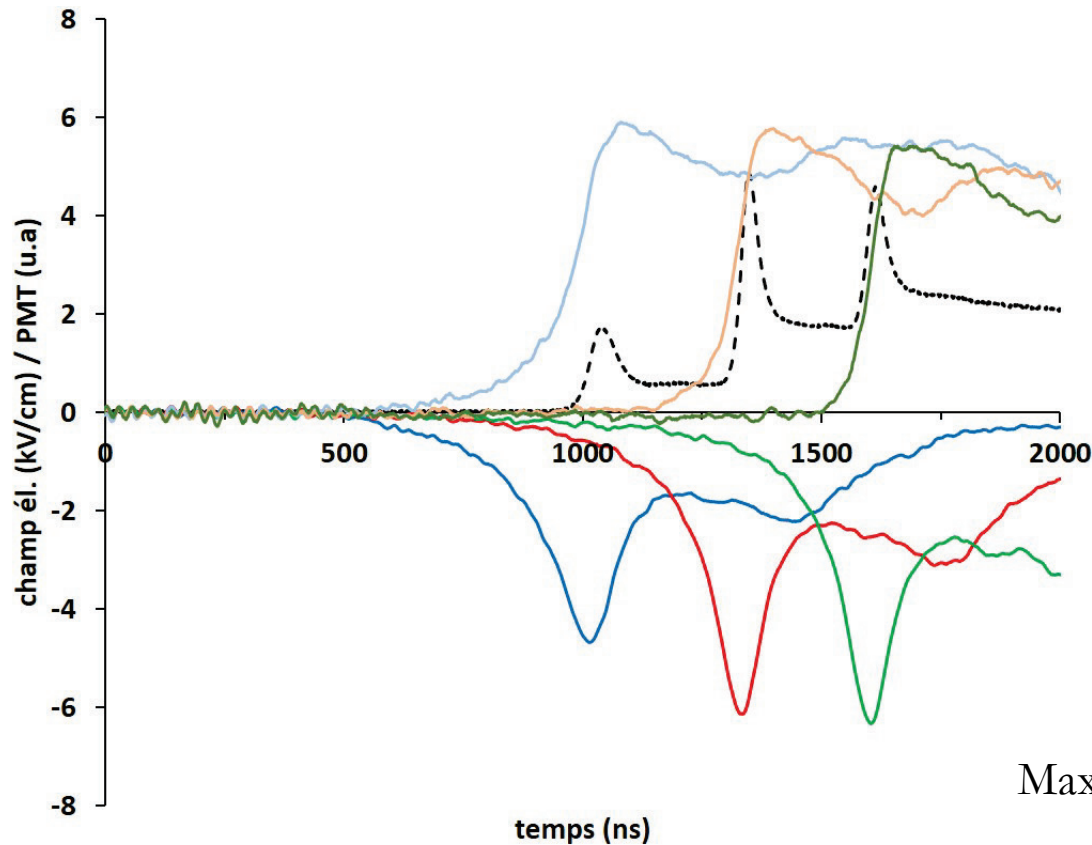
Champ électrique dans la plume



Champ électrique sous 3 mm de foie



Propagation du plasma dans le capillaire

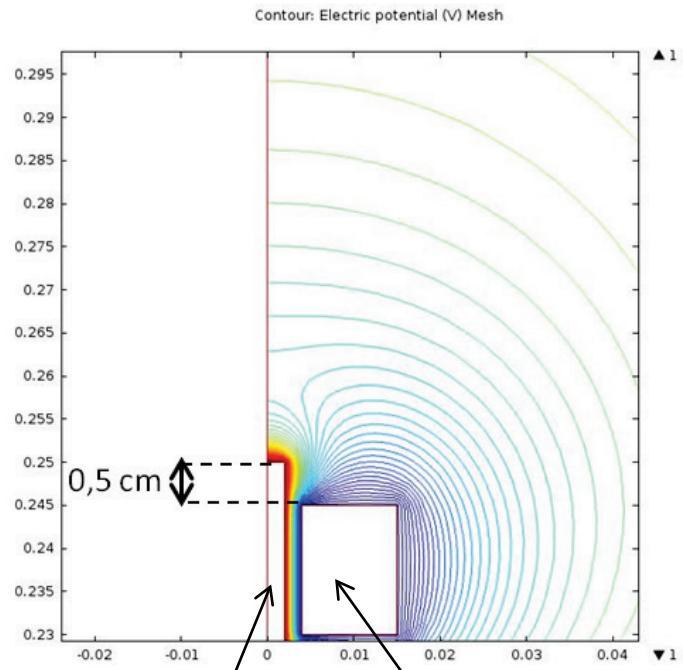


Max de Ex et Er proche de **6 kV/cm**

- ➔ Augmentation du champ **500 ns** avant la lumière du front d'ionisation
- ➔ **Max de Ex** et brusque augmentation de **Er** synchrones avec la lumière du front d'ionisation

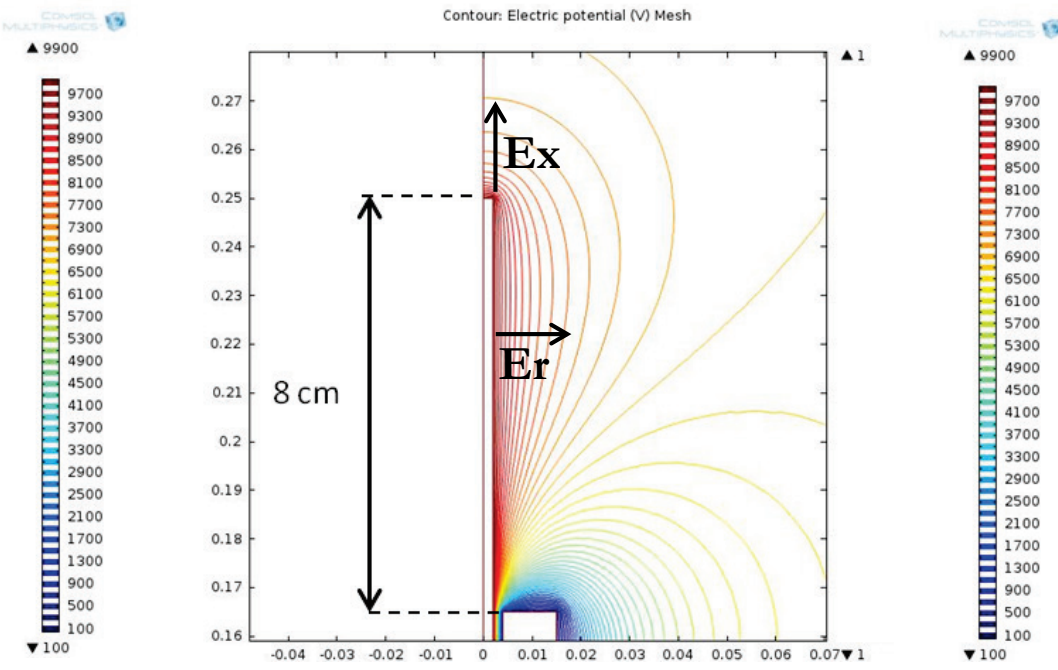


- ➔ Résolution de l'équation de Poisson en 2D axisymétrique
- ➔ Représentation simplifiée : Colonne plasma conductrice « tige métallique »
- ➔ Distribution des équipotentielles



10 kV
Electrode haute tension

0 V
Électrode de masse



Basculement radial le long de la colonne

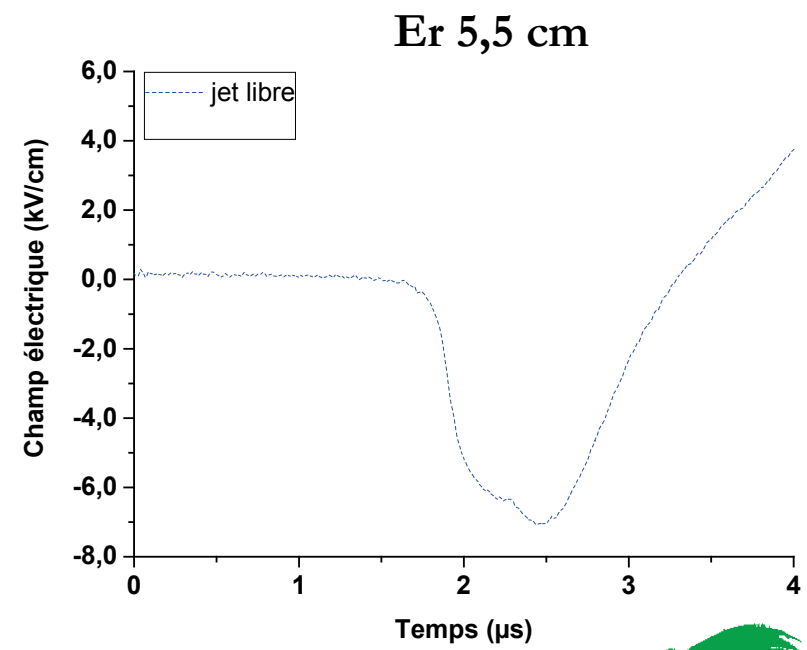
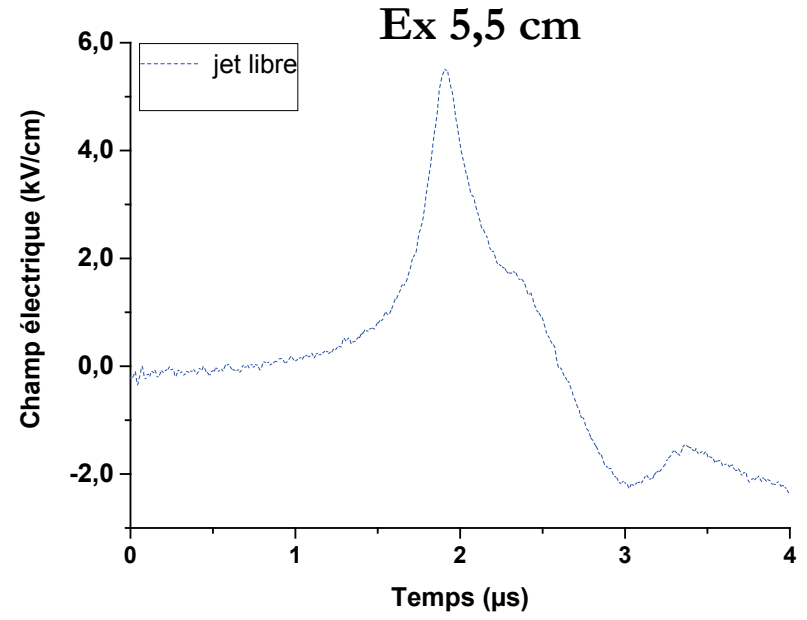
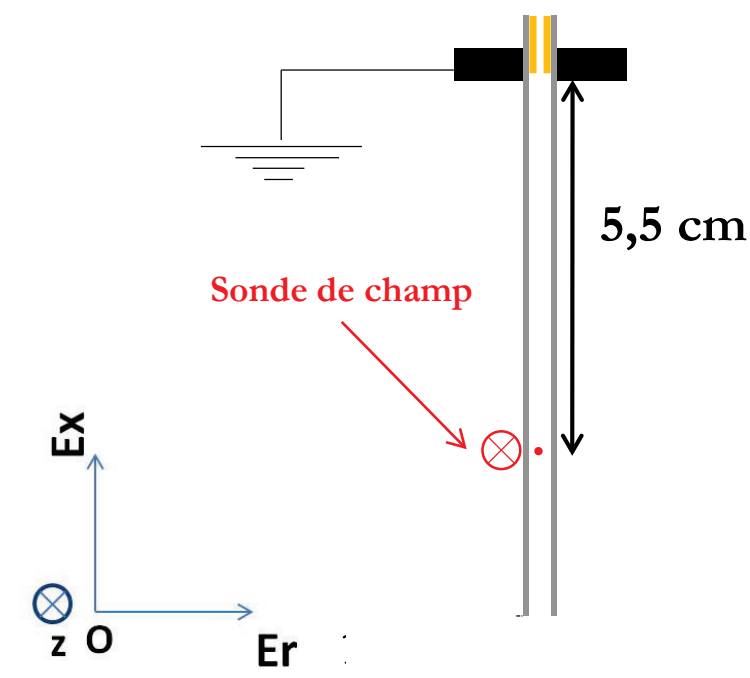
La **colonne plasma conductrice** transmet le potentiel de l'électrode interne



Interaction du plasma avec une cible conductrice

E_x : composante longitudinale du champ électrique

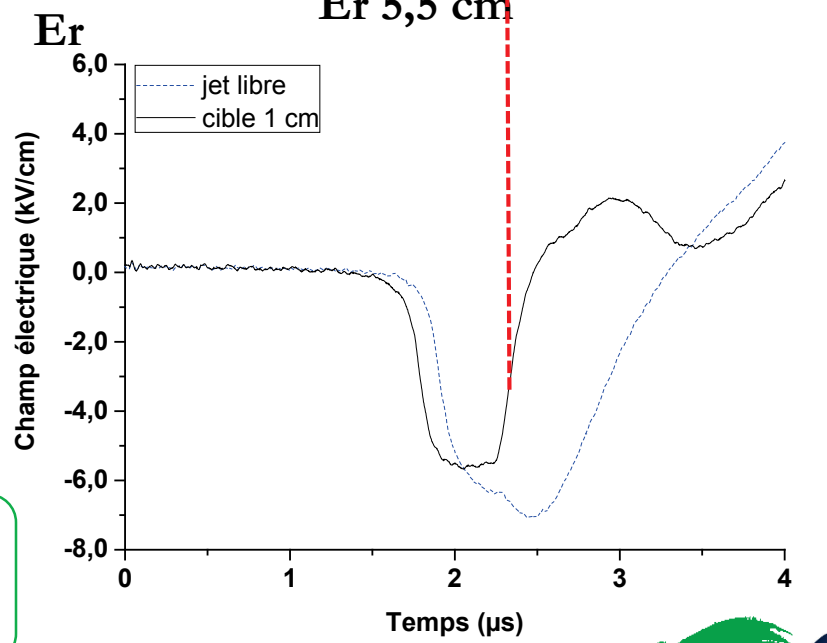
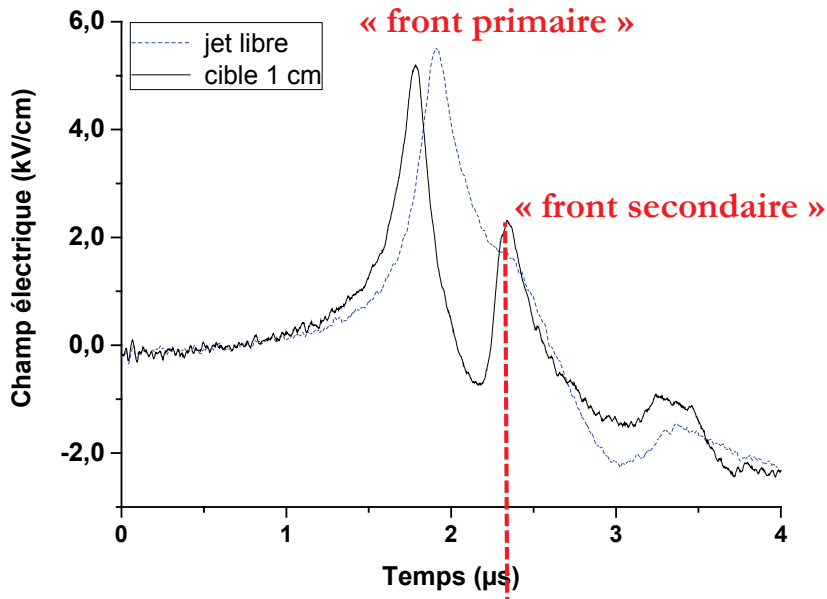
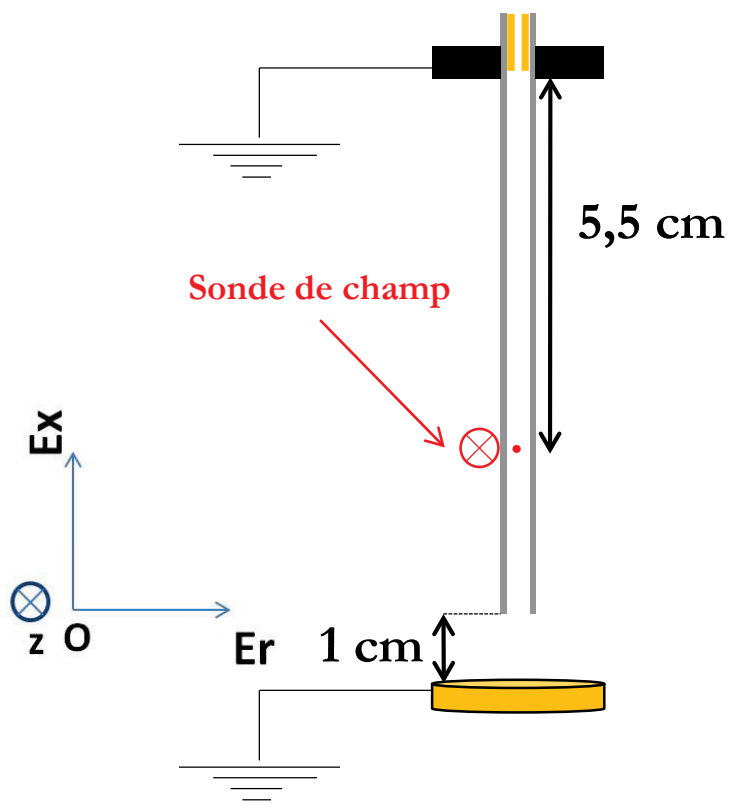
E_r : composante radiale du champ électrique



Interaction du plasma avec une cible conductrice

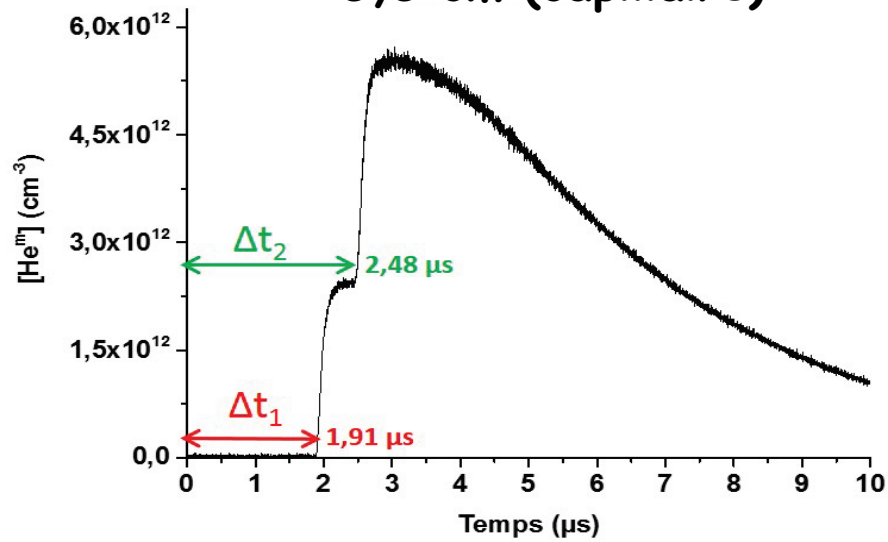
Ex 5,5 cm

Ex : composante longitudinale du champ électrique
Er : composante radiale du champ électrique

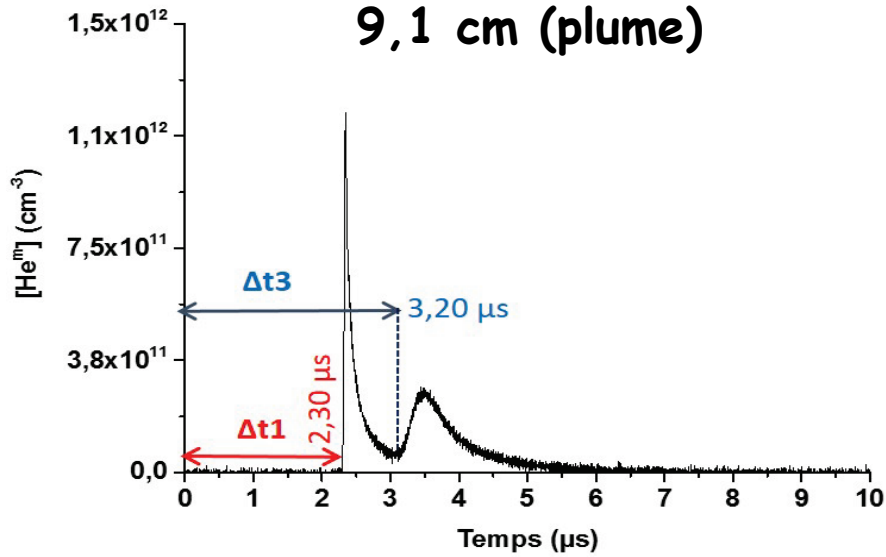


Front d'ionisation **secondaire** caractérisé par Ex et Er

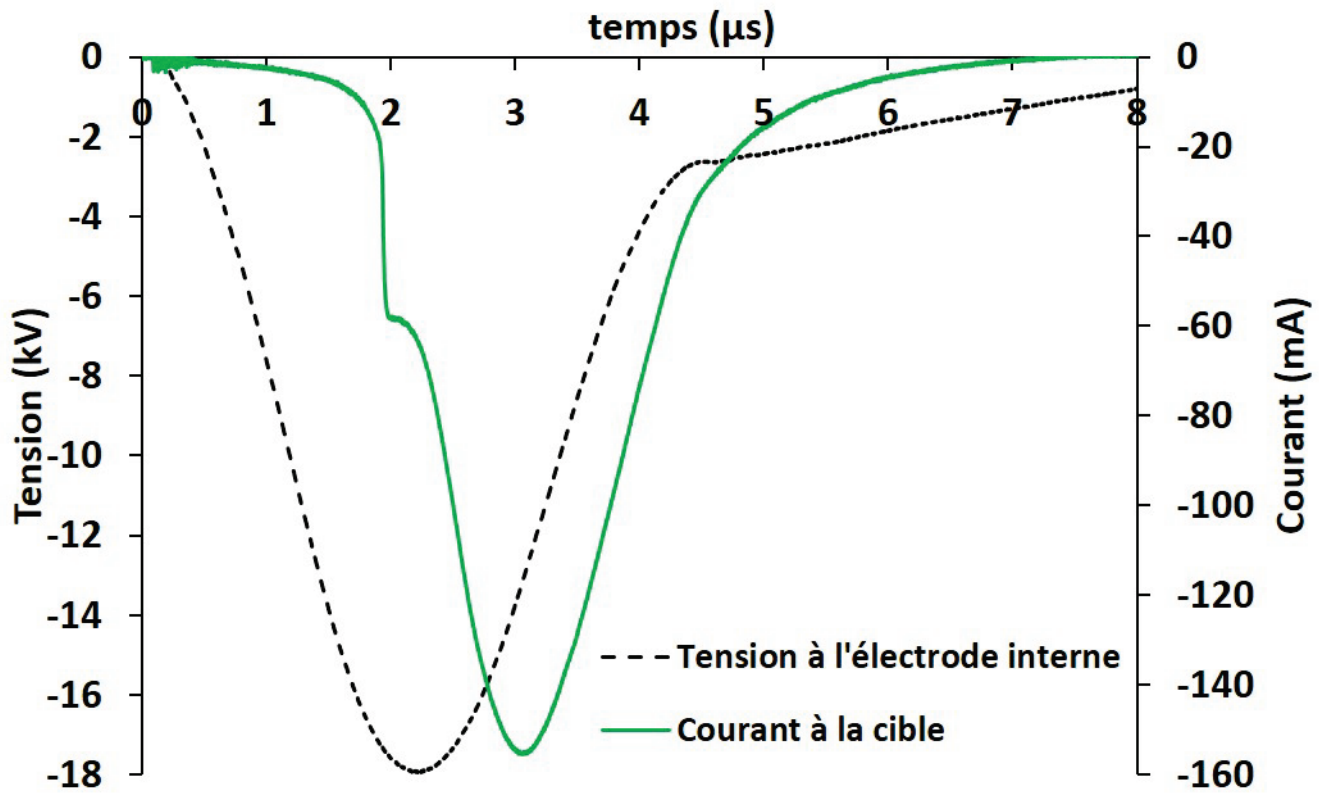
5,5 cm (capillaire)



9,1 cm (plume)



➔ **Mesure du courant** : résistance de 100 Ohm branchée en série sur la cible



➔ Max (140 mA) vers 3 μs (après la propagation des fronts primaire et secondaire)

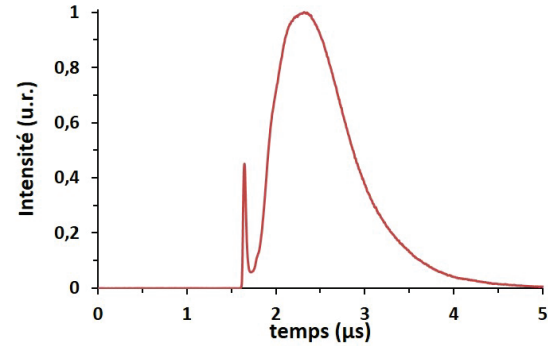
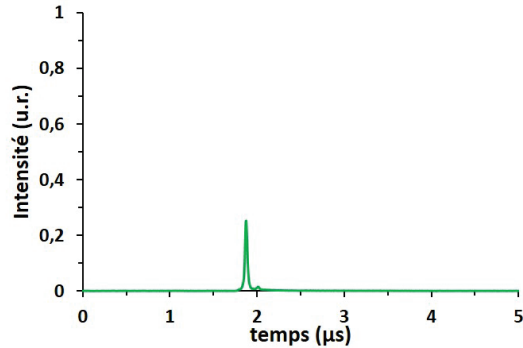
Jonction électrique entre la cible à la masse et l'électrode haute tension par la **colonne plasma conductrice**

→ Spectroscopie d'émission résolue en temps dans la plume plasma

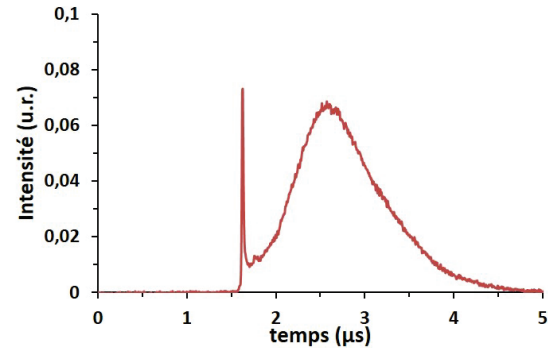
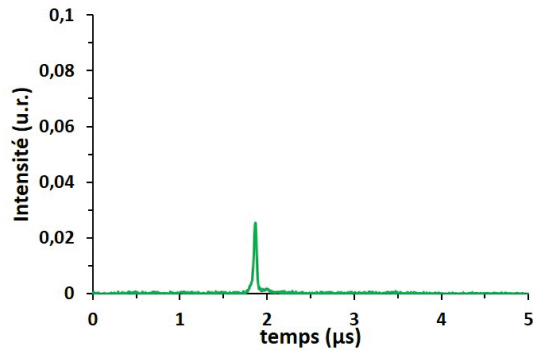
Configuration jet libre

Configuration cible 1 cm

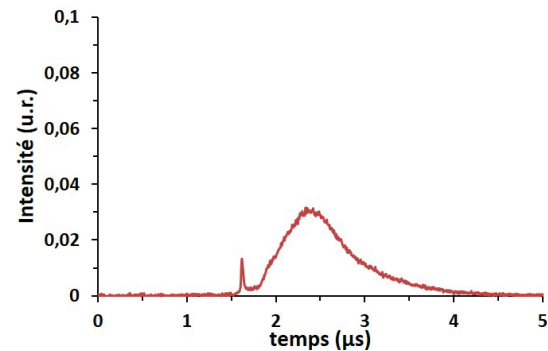
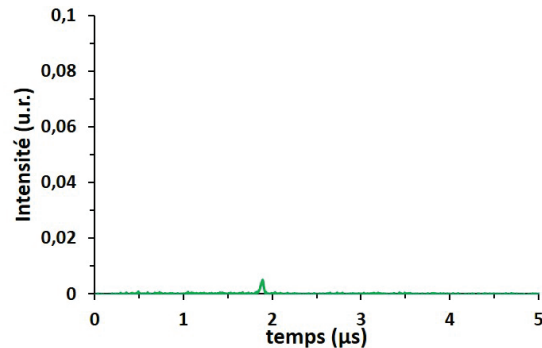
N_2^* * 337,1 nm



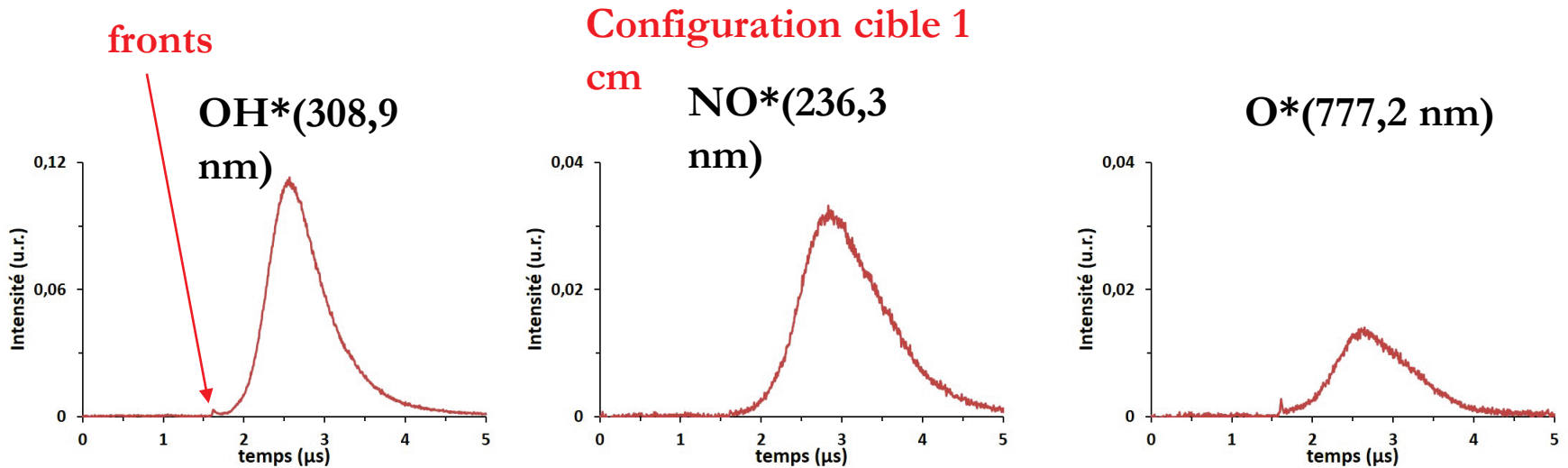
N_2^+ * (391,4 nm)



He*(706,5 nm)



→ Spectroscopie d'émission résolue en temps dans la plume plasma



toutes les espèces sont repeuplées sur des temps μ s après le passage **des fronts**

Jonction électrique entre la cible à la masse et l'électrode haute tension par la **colonne plasma conductrice**

Évolution vers une décharge de type **glow**

Distinction fondamentale entre un jet libre et un jet en contact avec une cible conductrice

Conclusions

Attention certains « jets plasma » sont des jets plasmas
d'autres des post décharges

Les deux sont intéressants mais n'ont pas a priori les mêmes effets

Il n'y a pas de balles plasma mais des plasmas avec un front d'ionisation
et une colonne ionisée reliant le front au réacteur de décharge

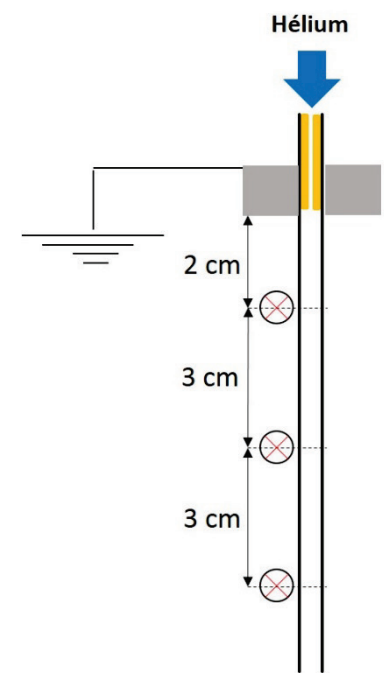
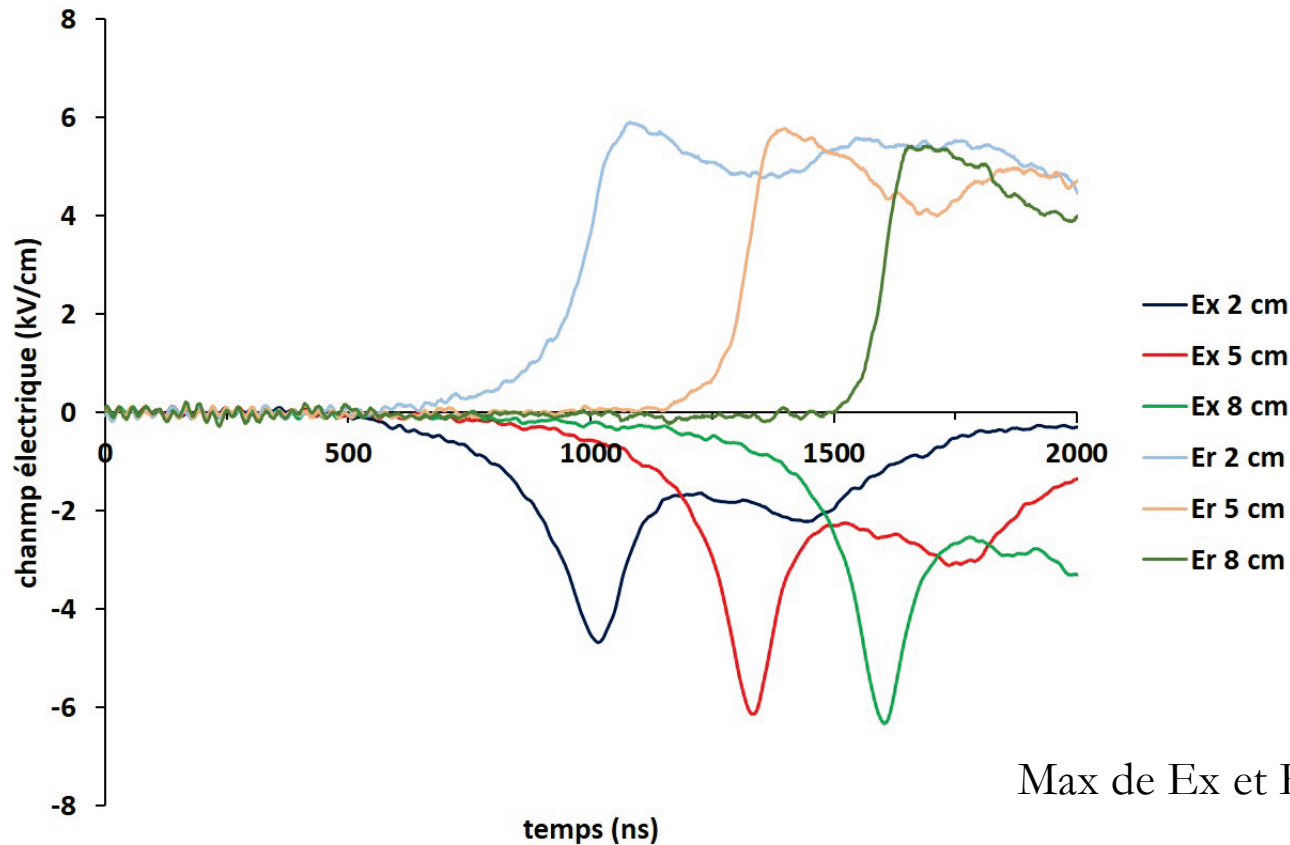
Les deux génèrent des champs différents

La colonne peut devenir suffisamment conductrice pour laisser passer
des courants importants.

Il y a des fortes interactions entre l'écoulement de gaz et la décharge
et entre le plasma et la cible

La caractérisation d'un jet libre ne permet pas de prévoir les conditions
d'utilisation des jets: espèces, champ, température...

Propagation du plasma dans le capillaire



Max de Ex et Er proche de **6 kV/cm**

- ➔ Augmentation du champ **500 ns** avant la lumière du front d'ionisation
- ➔ Max de Ex et brusque augmentation de Er synchrones avec la lumière du front d'ionisation

Avant passage du front : champ longitudinal en aval (4 cm)

Après passage du front d'ionisation, **maintien du champ radial par la colonne plasma**