



Physique des plasmas et alimentations impulsionales : un couple clef pour aborder les aspects fondamentaux et développer des applications innovantes

Sébastien DOZIAS et Eric ROBERT

2025 EPS Plasma Physics Division Innovation Award

- Pioneering work on atmospheric pressure plasma jets and demonstrations of plasma effects on cancer *in vivo*, synergetic effects of plasma treatment and chemotherapy, and plasma oxygenation of tissues, leading to hospital medical applications especially in cancer treatment and wound healing

This is the achievement of:

- Fifteen years of interdisciplinary work on biomedical applications of non-thermal plasma
- A continuous collaborative work between plasma physics researchers and electronic engineer
- The last development merging plasma physics with pulsed high voltage power supply



Two decades of non-thermal plasma applications based on high voltage pulsed power supplies

Teams and collaborators

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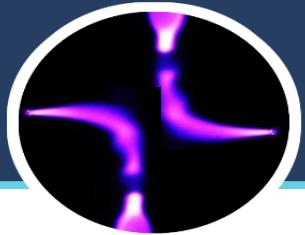
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Plan de l'exposé

- **Avant les jets plasmas:**
 - Sources rayons X, sources Extrême UV et éclairage sans mercure
- **Physique des jets plasmas**
 - Ondes d'ionisation, interaction plasma-flux de gaz et plasma-surface
- **Applications biomédicales: illustrations et verrous**
 - Action antitumorale des plasmas froids
 - Désinfection et soin des plaies
- **Conclusion**



Sources de rayons X

Applications: radiographie rapide (sans flou) d'éléments légers propres à la combustion (diesel, sprays cryogénique, supercritiques), et applications militaires

Pas de sources commerciales disponibles: impulsion brève (ns), rayons X de basse énergie (10 keV), source en rafale, dispositif utilisable sur des installations complexes ou sur le terrain

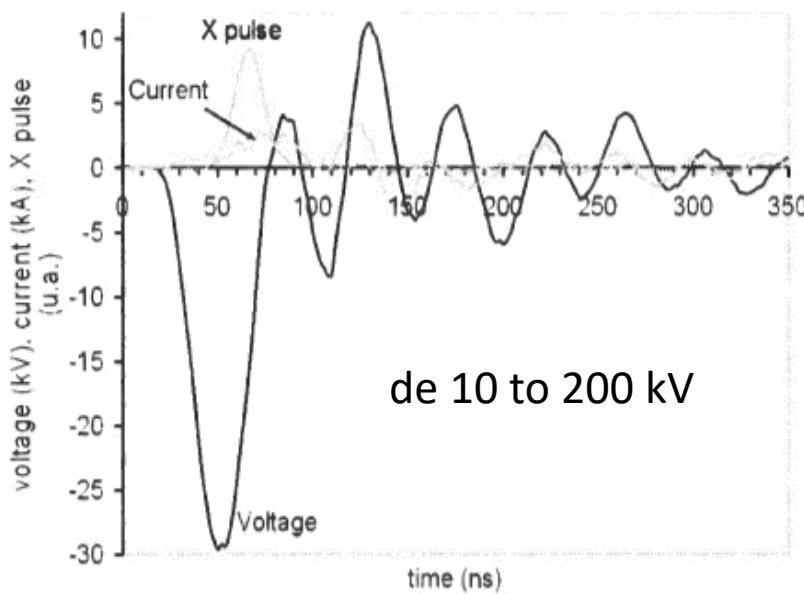
DEFIS

- Générer des électrons énergétiques pour produire des rayons X par bombardement anodique
- Produire des impulsions de très haute tension (10-500 kV) avec des fronts de montée rapides (ns)
- Mode impulsion unique ou répétitif (Hz-centaines de Hz), mode rafale (régime kHz)
- Adaptation d'impédance: ligne de stockage d'énergie - diode X (de l'infini à qqs ohms)
 - Tout ceci bien avant l'atelier couplage d'énergie !

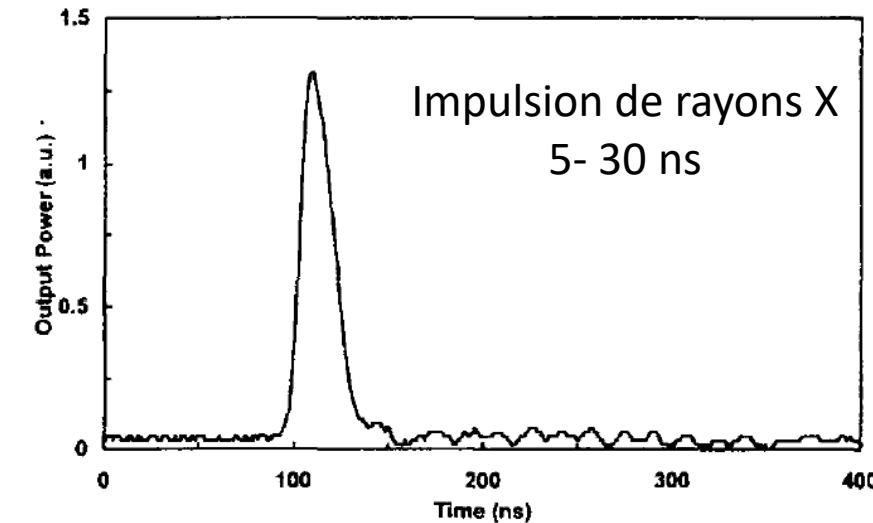


Impulsion de tension et de rayons X: illustration

10s-100s kV ns voltage waveforms

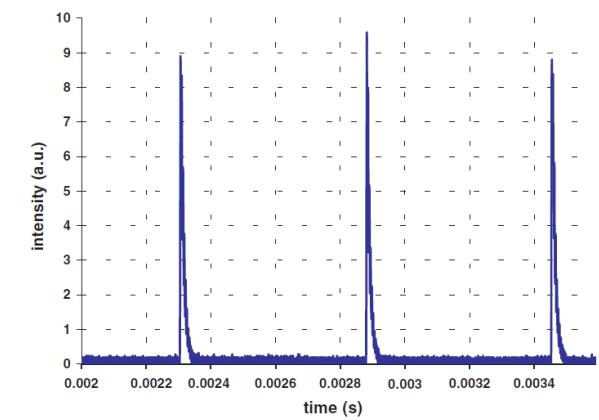
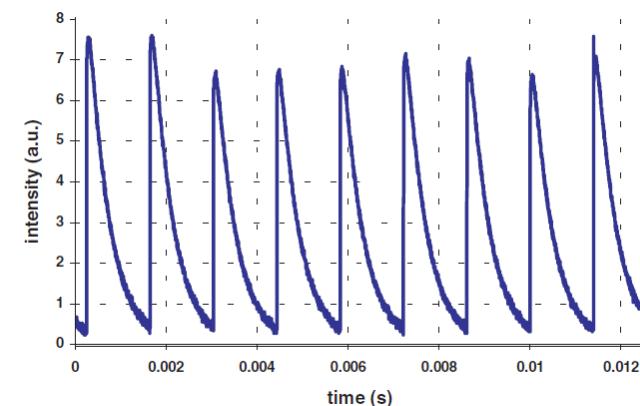


de 10 to 200 kV



Mode répétitif à 715 Hz, 200 kV

Mode rafale 2 kHz, 200 kV





Cinéradiographie

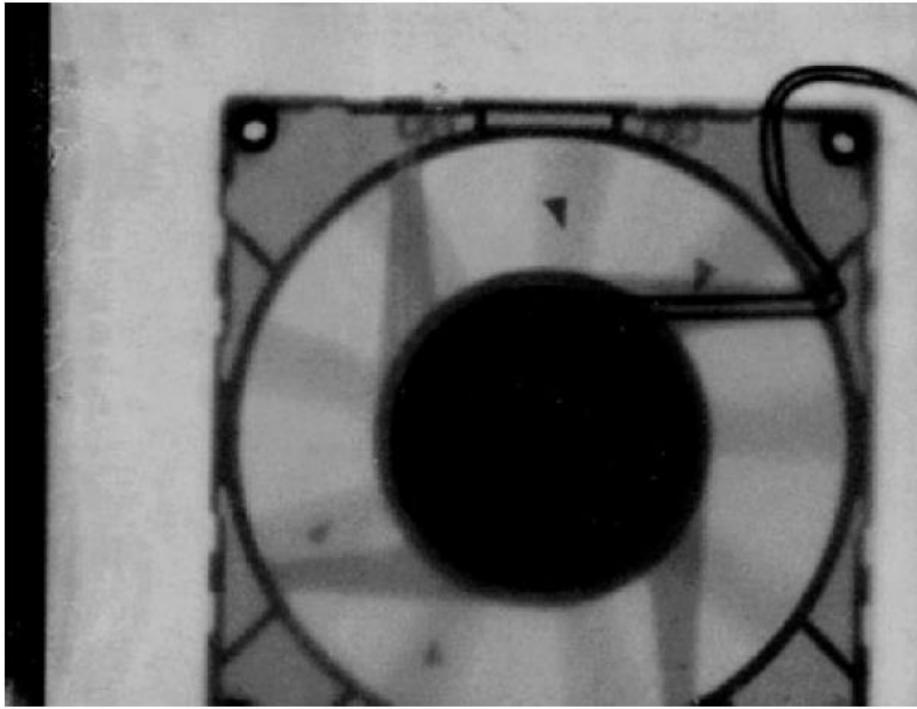


Figure 10. Radiography of a running fan with a burst of two x-ray pulses at 500 Hz. Small triangular pieces are made of lead.

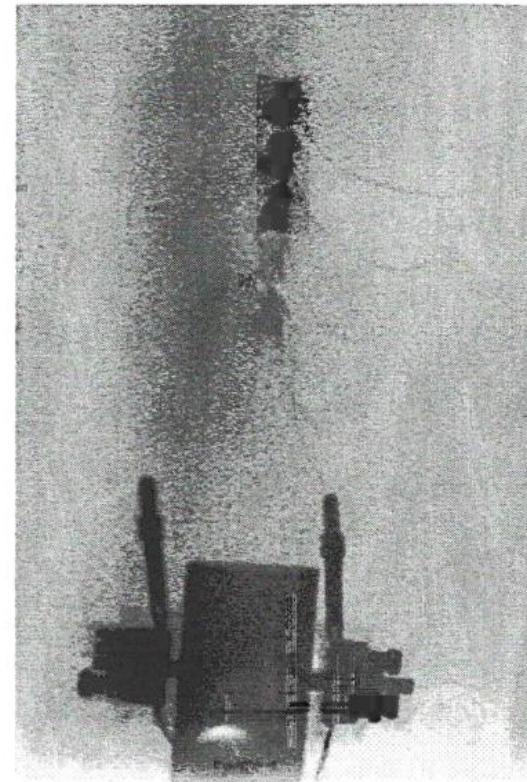
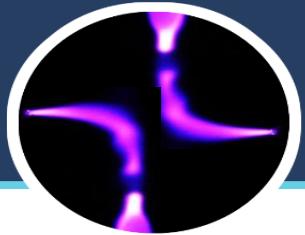


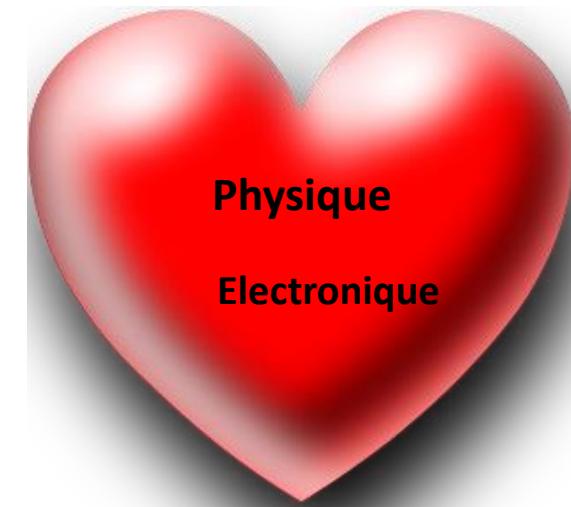
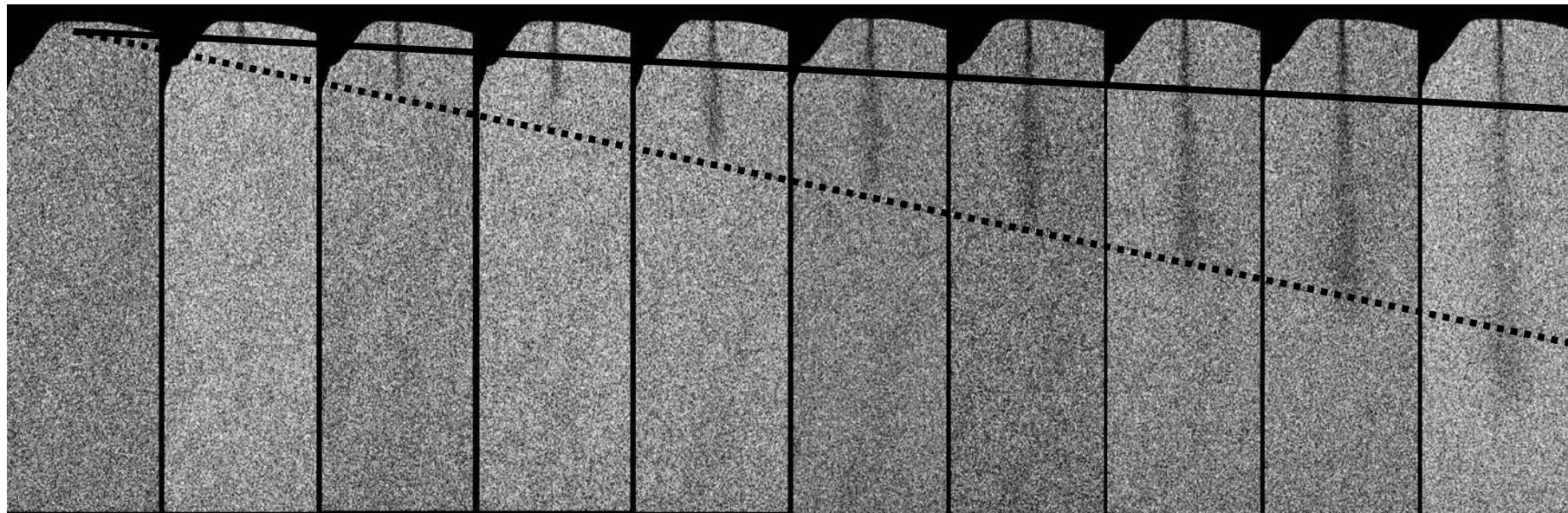
Figure 4. 20 : Radiographie d'un projectile de Plomb à 20 kHz



Injection diesel: condition réelles SPRAY A

Diesel injection (nozzle 100 μm , injection:500 μs)

t_0 + 10 μs + 20 μs + 30 μs + 40 μs + 50 μs + 60 μs + 70 μs + 80 μs + 90 μs



Deux composantes du spray avec des densités et vitesses de propagation différentes

Seule méthode alternative: rayonnement synchrotron



Lithographie EUV: années 2000

EUV lithography: generation of 13,5 nm radiation for chip processing

Au GREMI: plasma de xénon produit par décharges capillaires à forte densité de puissance

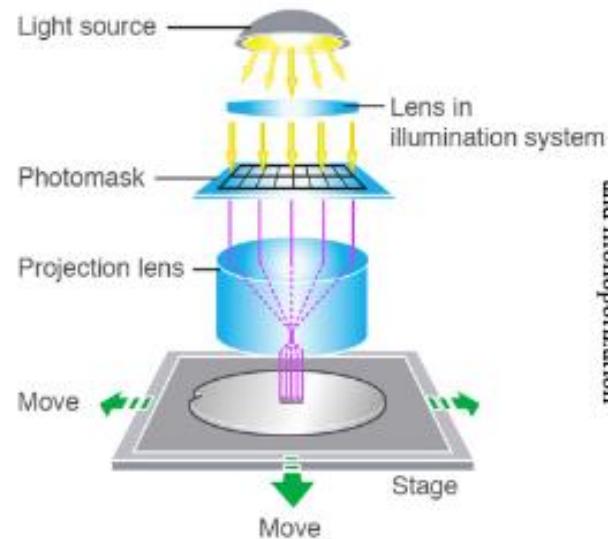
DEFIS

Efficacité énergétique

Forte puissance « in-band »

Source sans débris

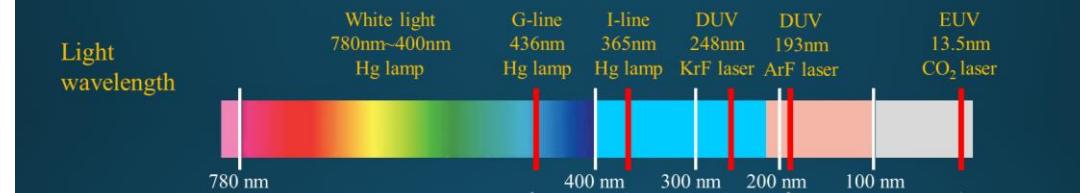
Stabilité du flux excellent (>99%)



<https://www.the-waves.org/2022/12/21/semiconductor-lithography-economics-fuelling-moores-law-and-market-power/>

Moore's Law: Playing games with wavelengths

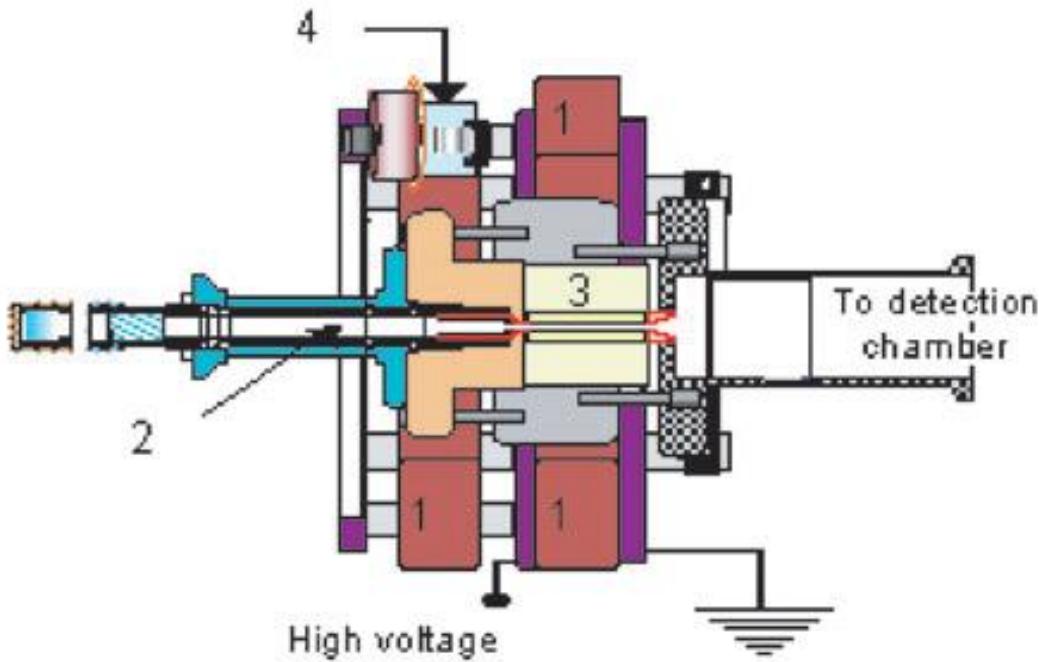
The light sources of lithography machines used by the semiconductor industry have progressed from white light to G-line/I-line, DUV, and now currently EUV.



<https://www.icometrue.com>



Décharge capillaire: pinch



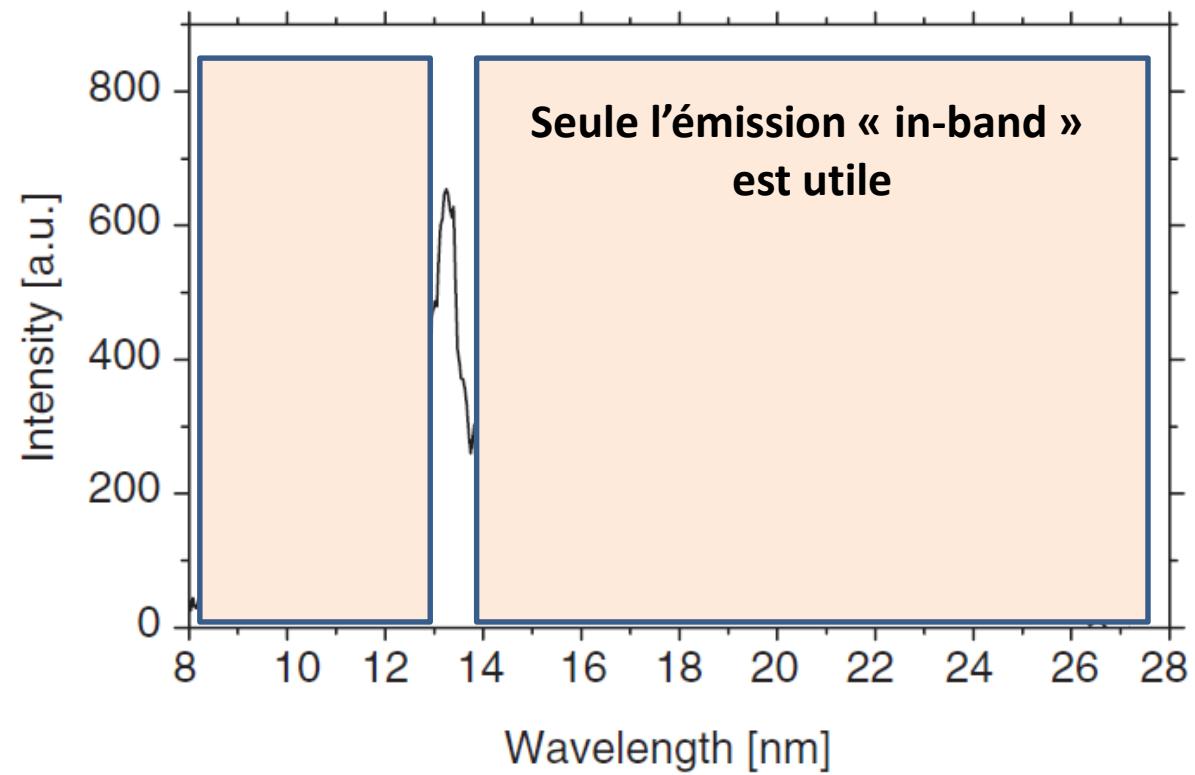
1. Knob capacitors

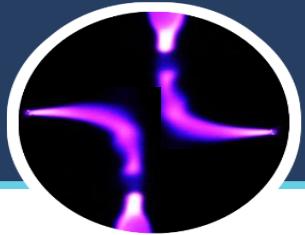
2. Gas inlet

3. Capillary

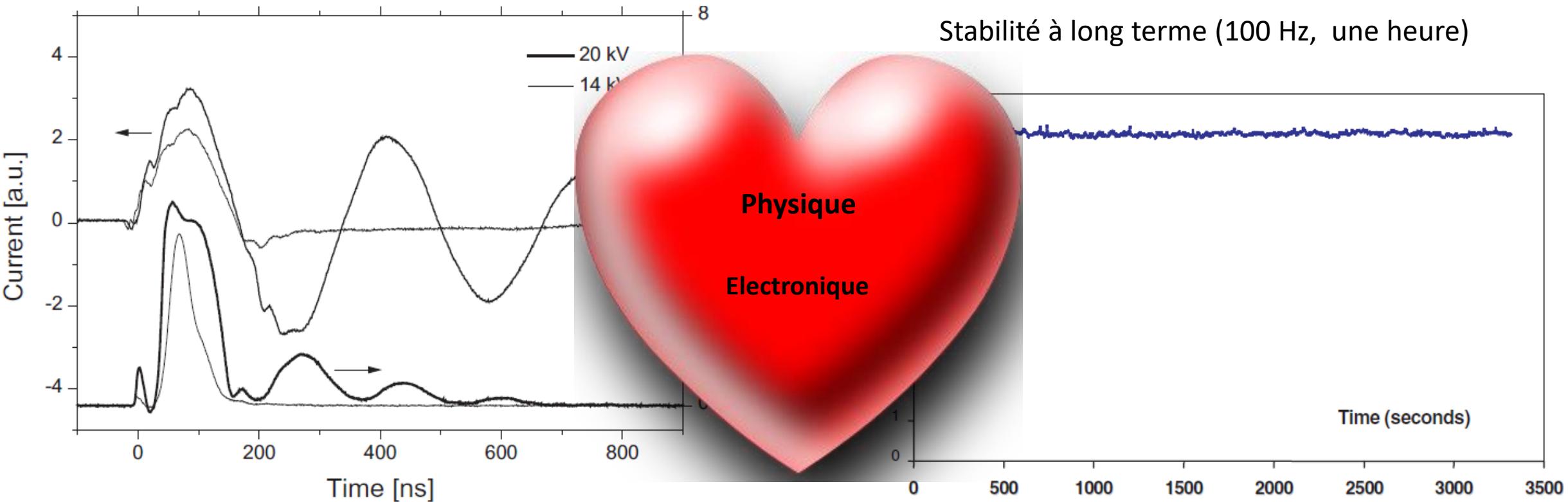
4. Fast Switch

Highly ionized levels up to Xe 12+





Couplage d'énergie



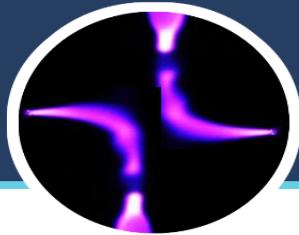
Impulsion de haute tension amortie pour prévenir
de l'ablation de l'électrode et du capillaire



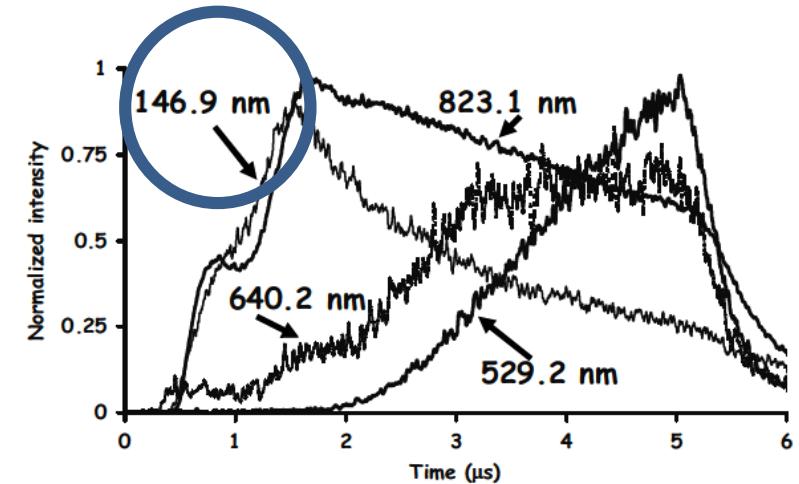
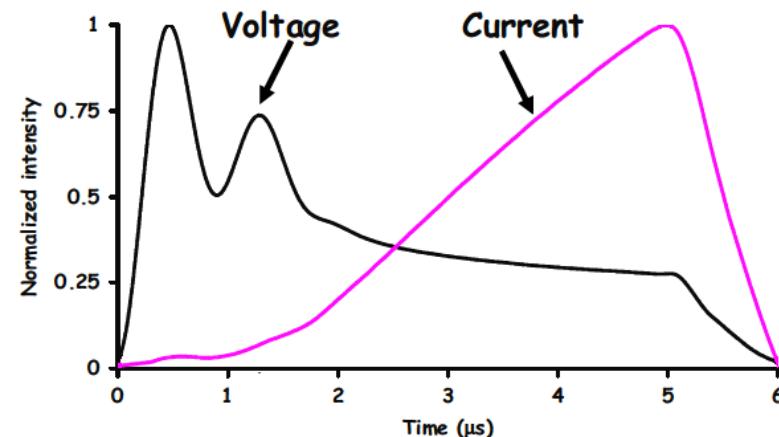
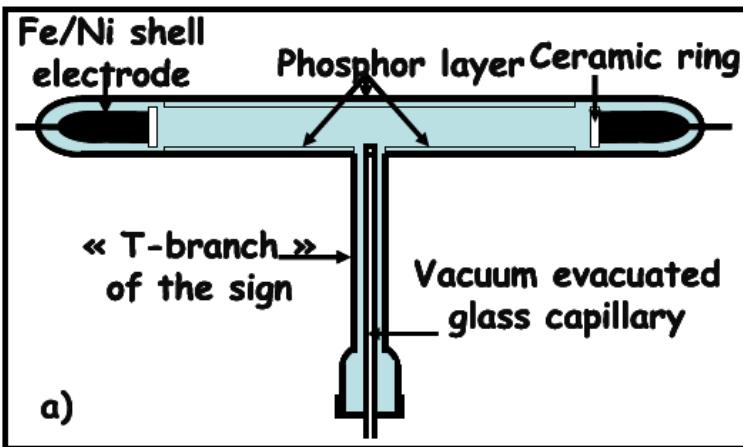
Eclairage sans mercure, années Ecran plasma

- DEFIS
- Génération de rayonnement UV-VUV dans des tubes fluorescents/ enseignes lumineuses
- Efficacité énergétique
- Durée de vie: milliers d'heures
pulvérisation des électrodes

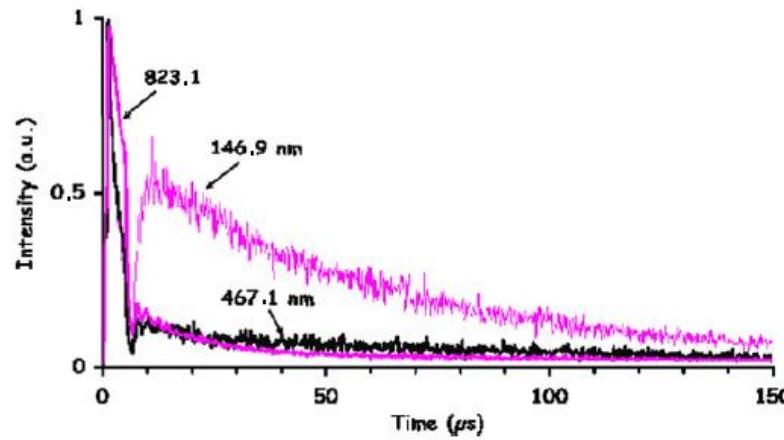




Une histoire d'impulsion: cinétique plasma



Largeur d'impulsion: paramètre clef



L'émission en post-décharge permet d'améliorer l'efficacité

Les ballasts conventionnels (AC) sont inefficaces pour générer les plasmas néon-xénon: saturation du flux pour quelques watt électrique

Alimentations impulsionales: lesquelles??

Optimisation de générateurs d'impulsions bipolaires (kV, kHz) de durée microseconde



Tout bon, juste avant les LED!

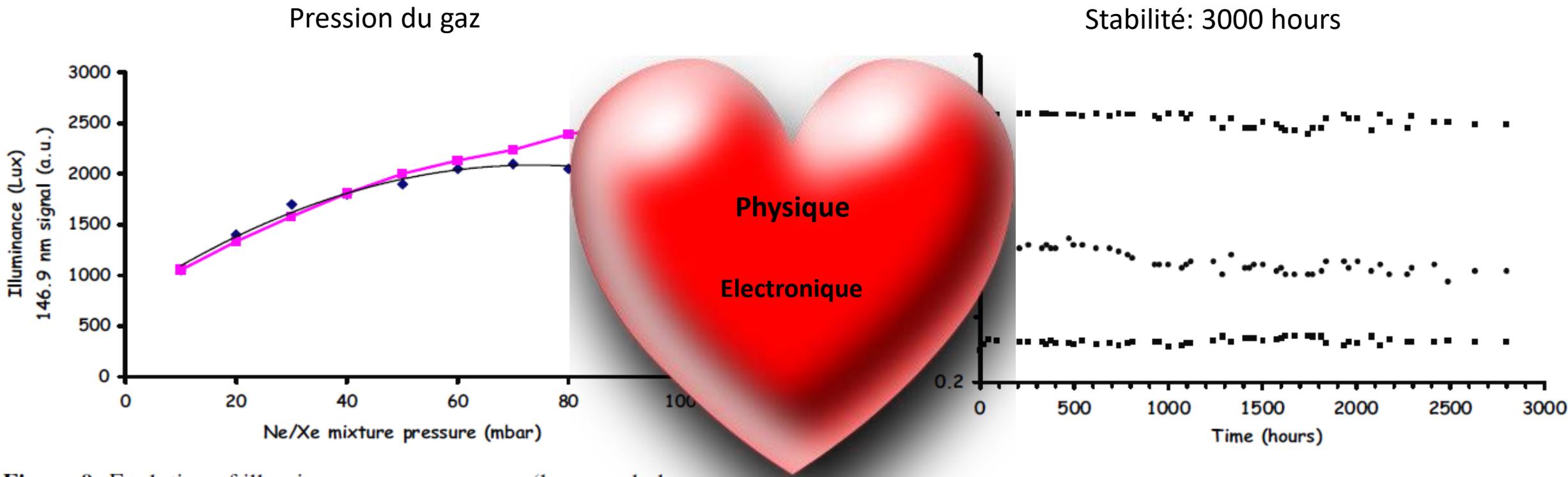
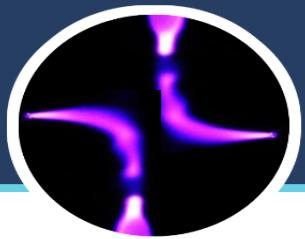


Figure 9. Evolution of illuminance versus pressure (lozenge dark fitted trace) and evolution of the 146.9 nm intensity with pressure (square grey fitted trace).

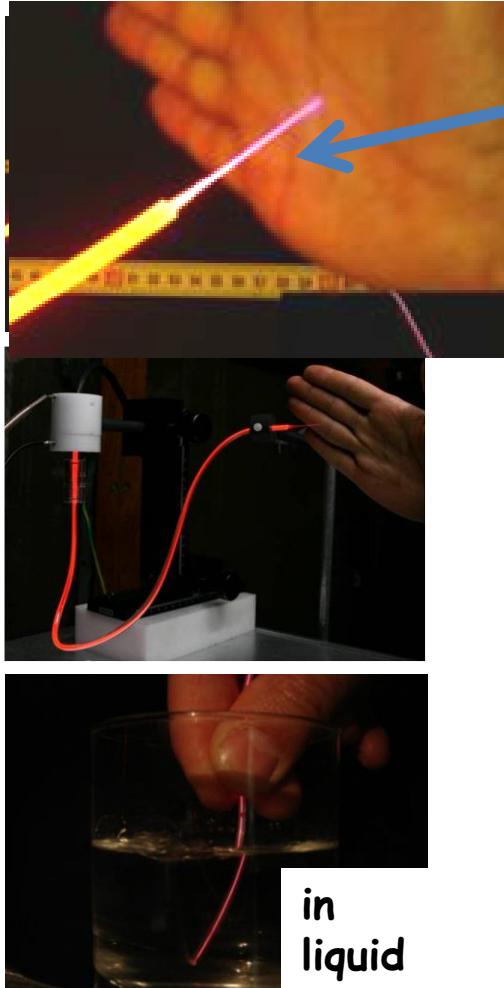
Figure 10. Evolution of chromatic coordinates (squares, x mean 0.26, y mean 0.60) and illuminance (dots, mean value 3850) for a 50 mbar Ne/Xe (100/5) sign.



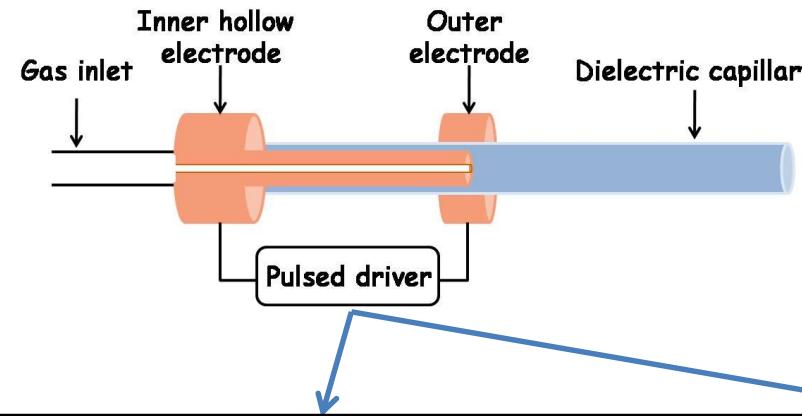
Plasmas froids et applications biomédicales



Jets plasmas: quelles impulsions électriques??



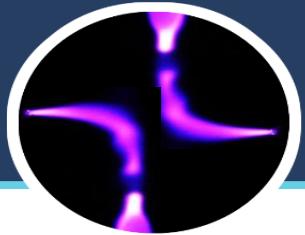
« Plasma plume, length 1- 100 mm
Reactive Nitrogen/Oxygen Species
generation



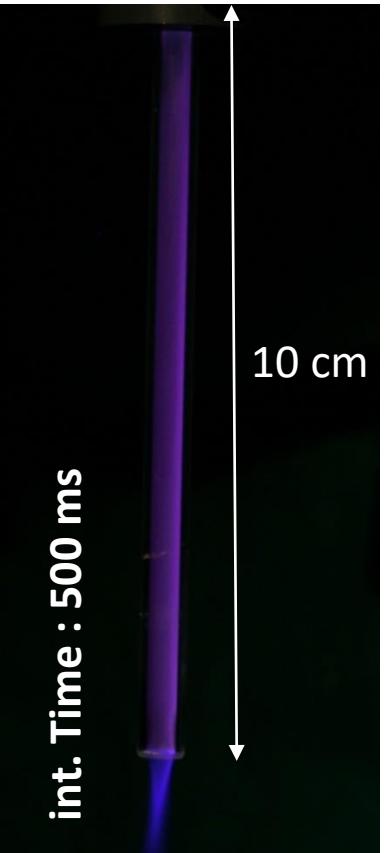
ns drivers
5-100 kV
Negative/positive polarity
Single shot - 200 Hz
ns pulse, ns damped trains of ns pulses
ns rising voltage front, μ s decay

DBD reactor, gas flow rate 5 - 5000 sccm
Dielectric guide:
rigid/ flexible,
length 5-100 cm
inner diameter 0.15 - 10 mm

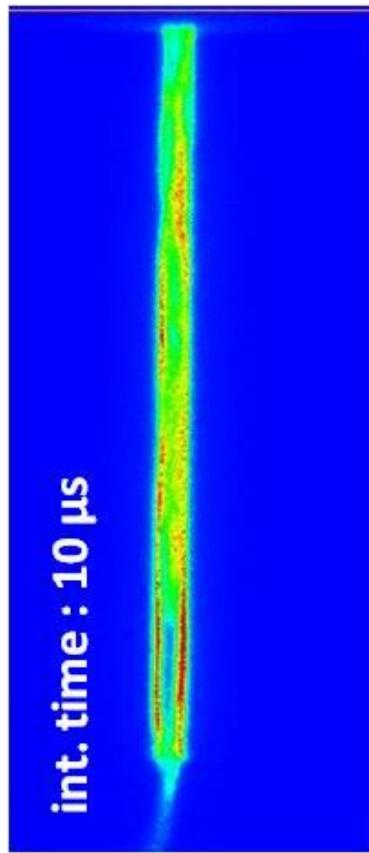
μ s drivers
5-30 kV
Negative/positive polarity
Single shot - 20 kHz
 μ s pulses



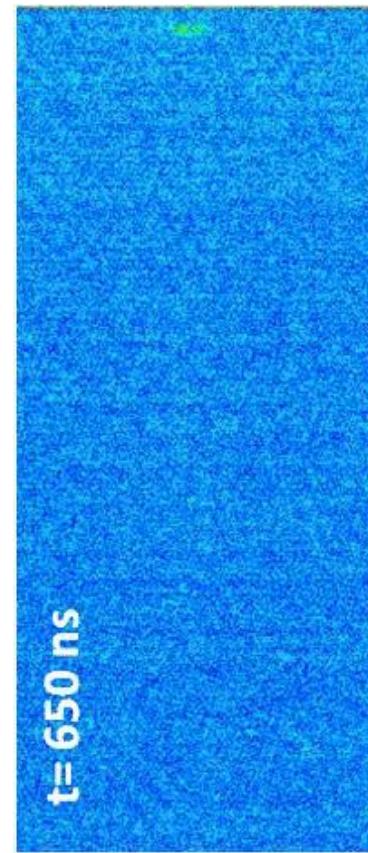
Ondes d'ionisation



Photographie : 500 ms



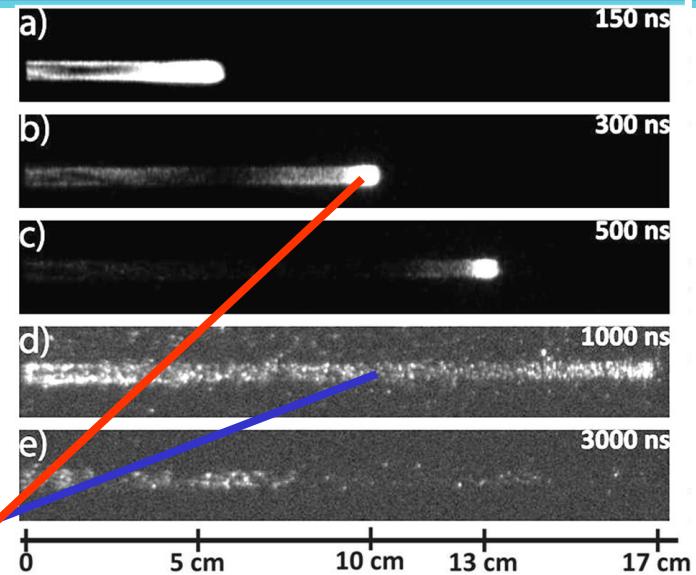
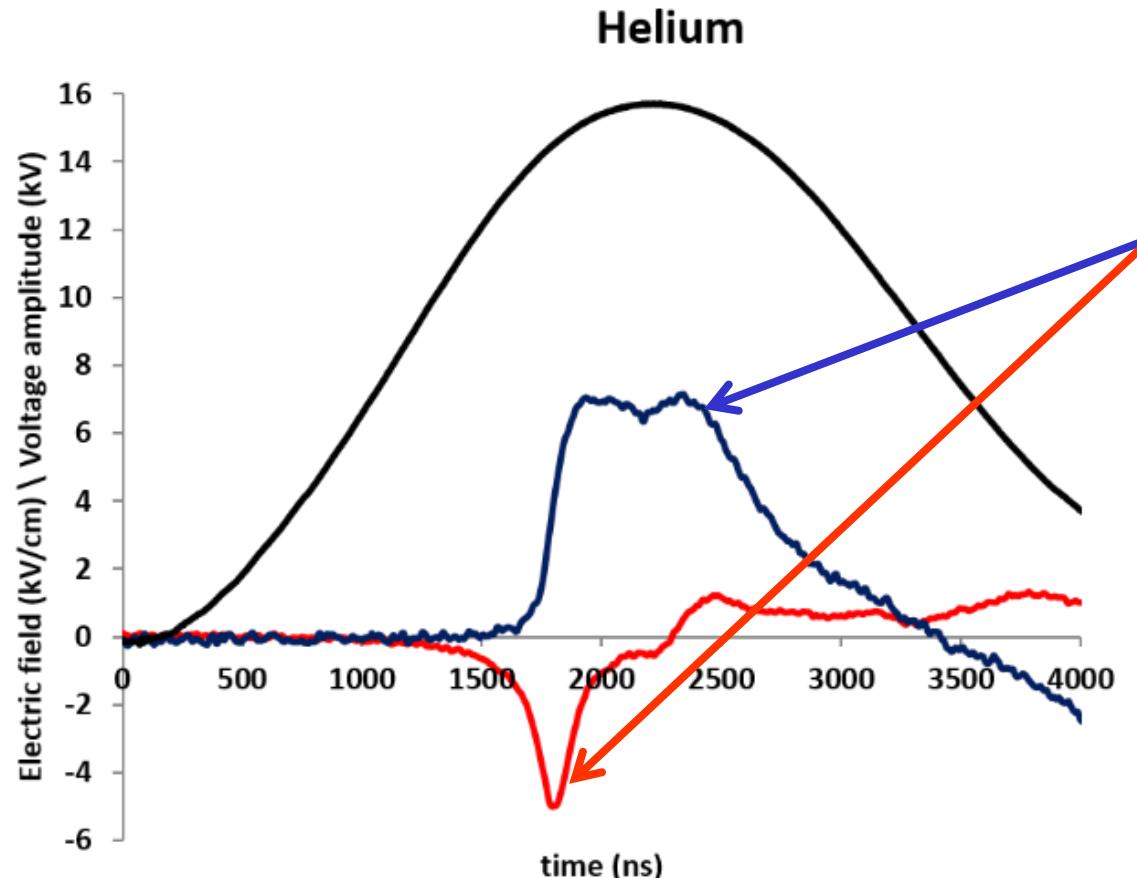
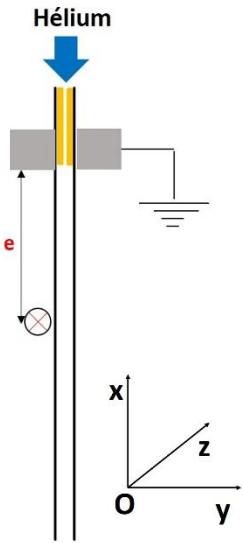
ICCD : temps
d'intégration 10 μ s



ICCD : temps
d'intégration 10 ns



Champs électriques: plasma et biologie

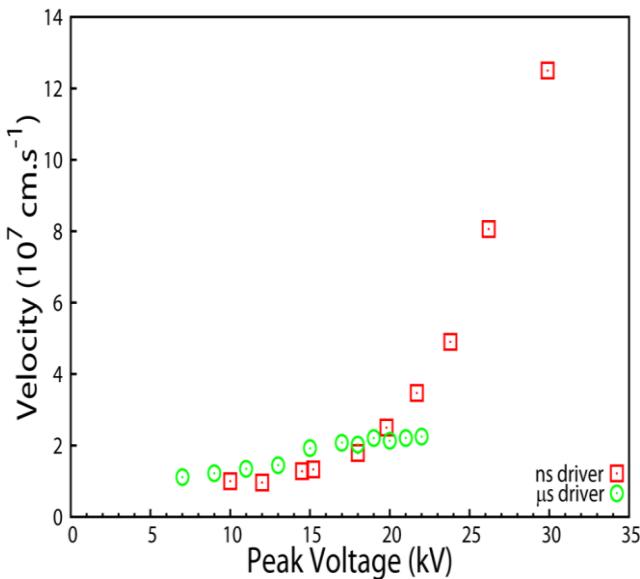


Front d'ionisation
Colonne Plasma



ns/μs

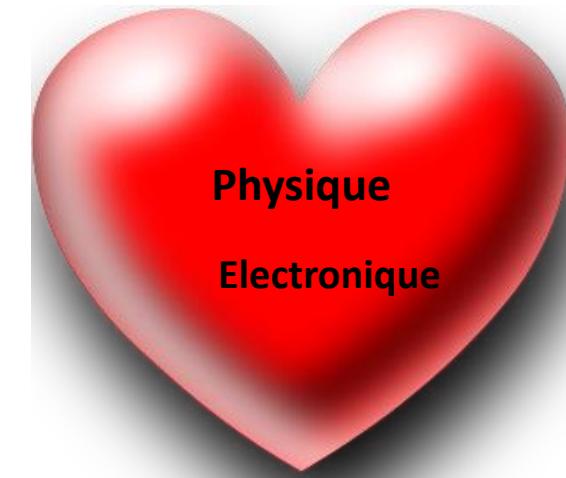
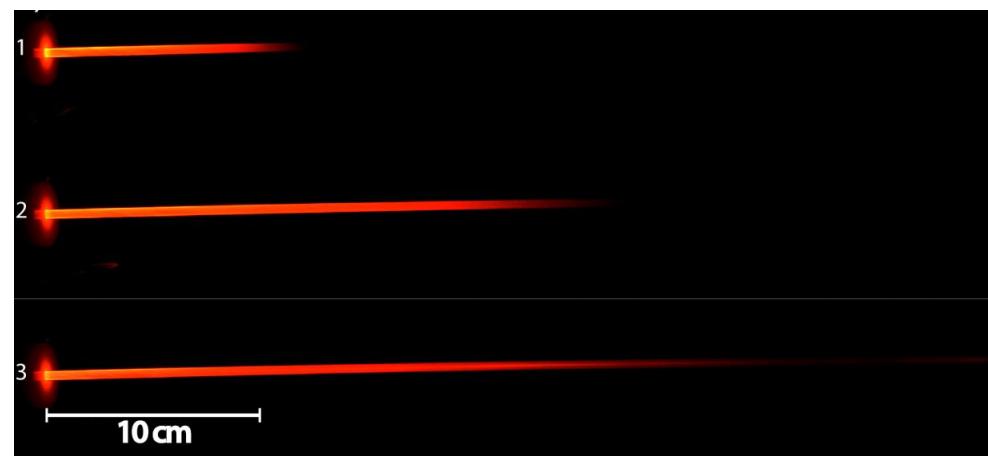
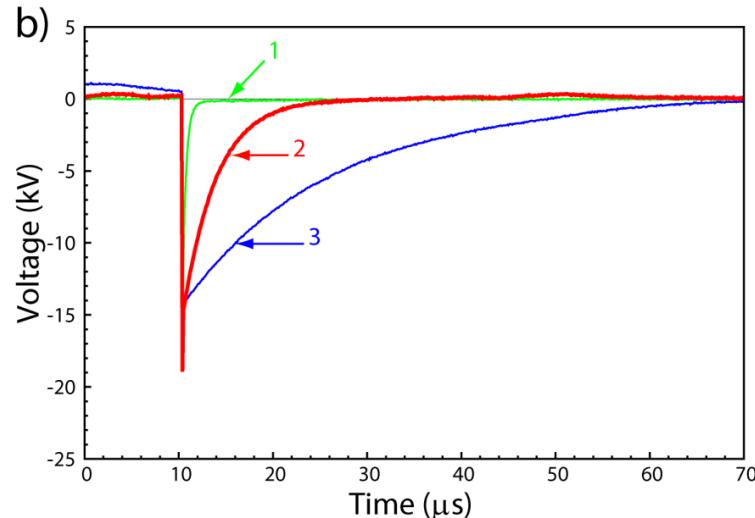
ns / μ s



L'amplitude crête de tension
contrôle la vitesse: pourquoi?

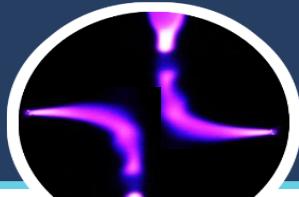
Les fronts rapides
permettent de dépasser les
tensions de claquage du gaz

La durée d'impulsion contrôle la distance de propagation



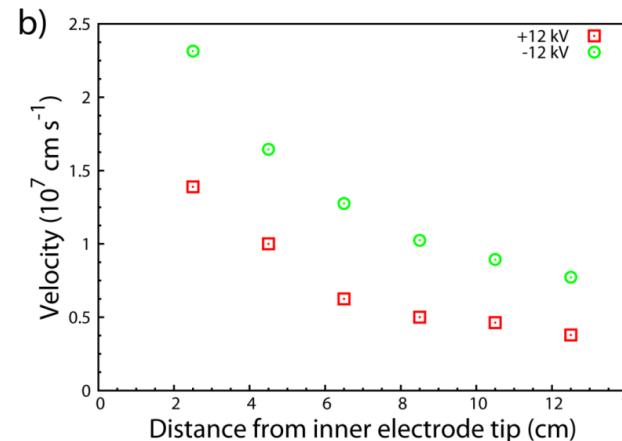
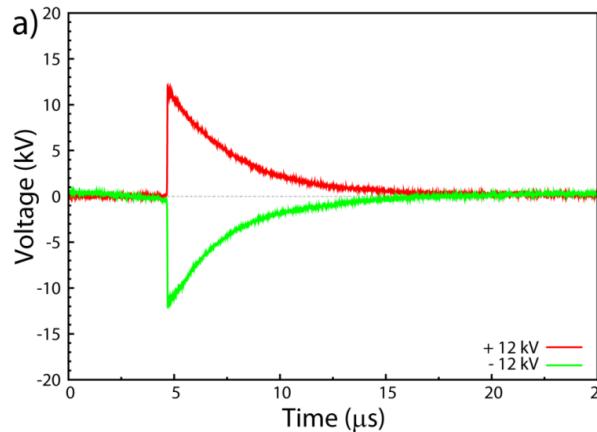
Endoscopie plasma

Brevet :
traitement de fibres/fils par
colonne de plasma



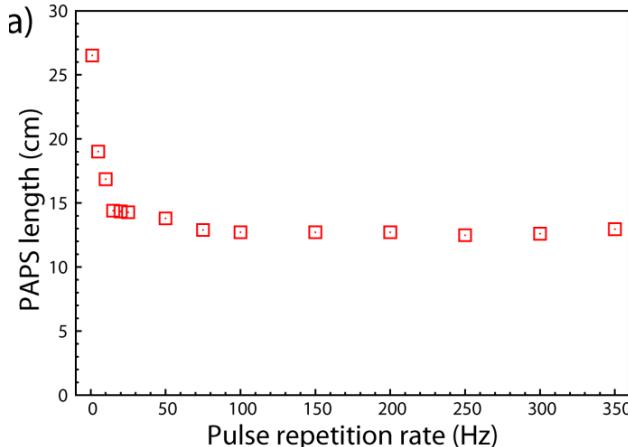
Physique de propagation: allo service électronique?

Impulsions de tension rigoureusement identiques mais de polarité inverse



Les ondes d'ionisation « positives »
se propagent plus vite que les
« négatives »

Impulsions identiques à toutes les fréquences



La longueur diminue puis se stabilise
quand la fréquence augmente

Aucun rôle du flux de gaz

Rôle des charges déposées?

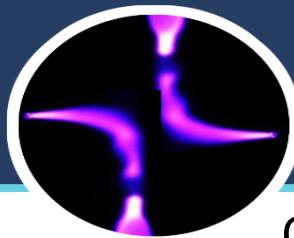
Verrous: expérience/modélisation

Rôle de la photoionisation ?

Résistance des colonnes plasmas ?

Charges en volume et surfaciques ?

Propagation en fonction de la fréquence

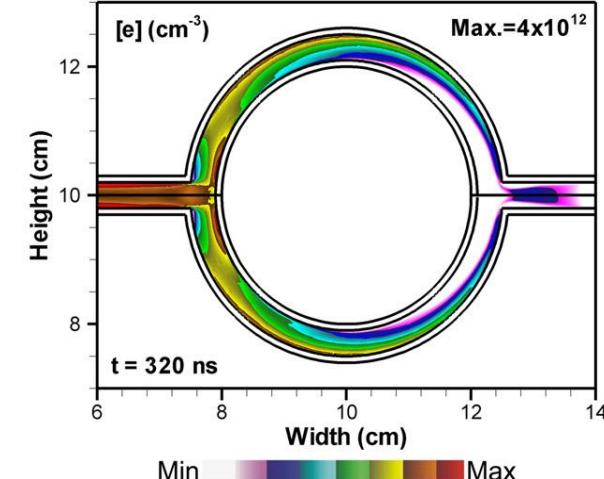
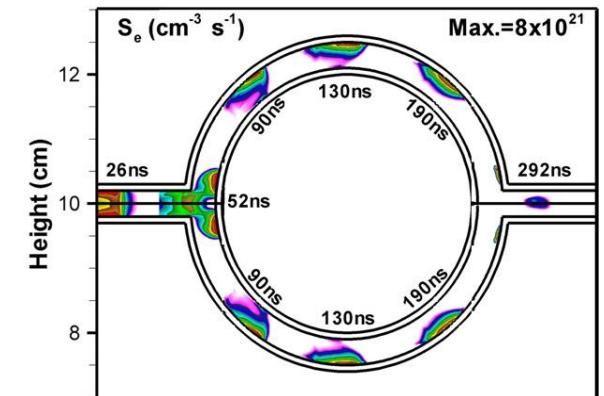
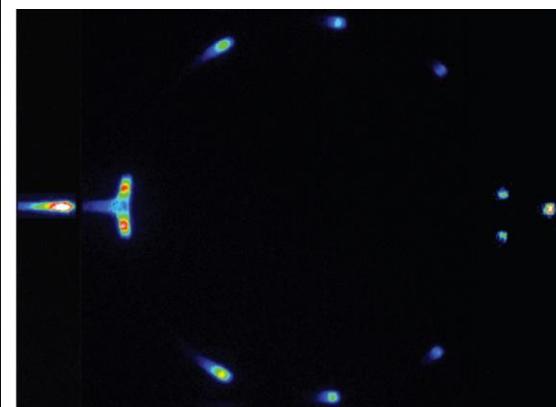
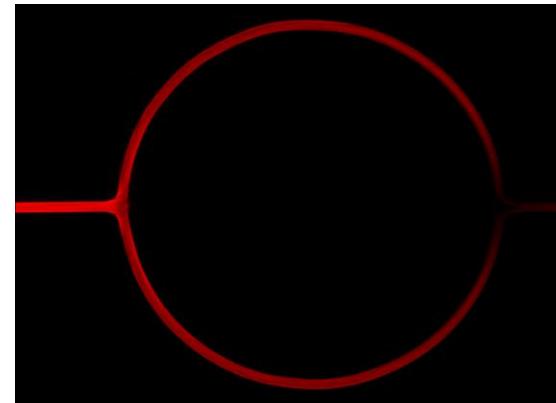
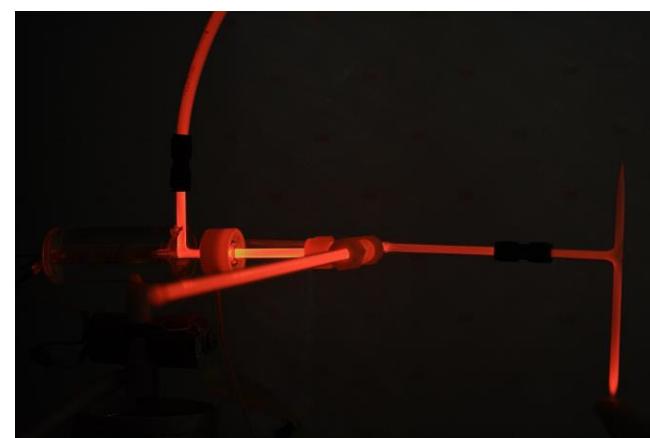
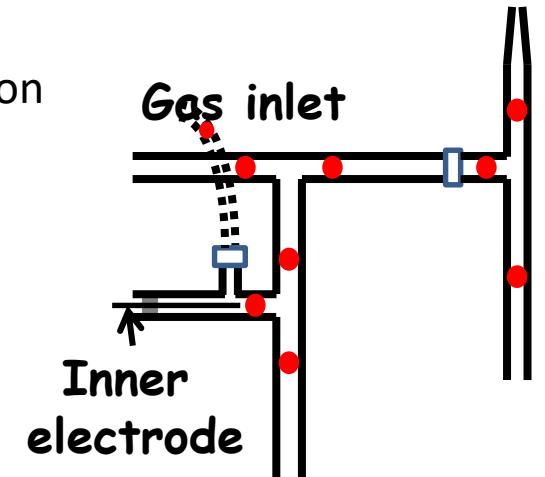
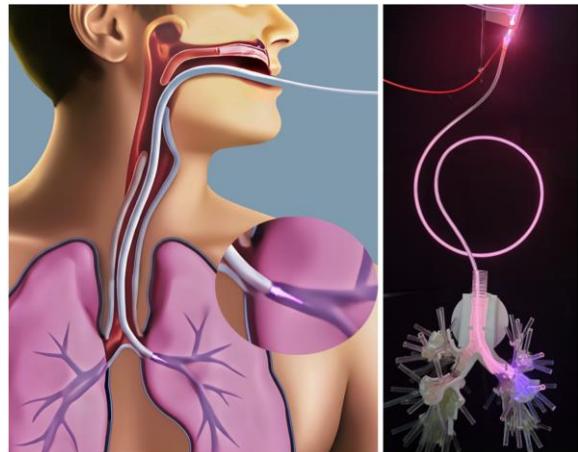


Recherche « fondamentale » d'origine applicative

Question: peut-on envoyer le plasma dans les poumons pour lutter contre les infections (avant COVID)

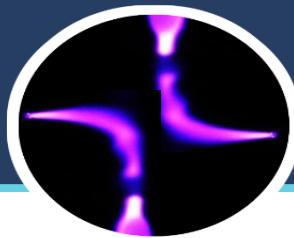
**Modélisation:
charges, champ électrique**

Branching and multi jets generation



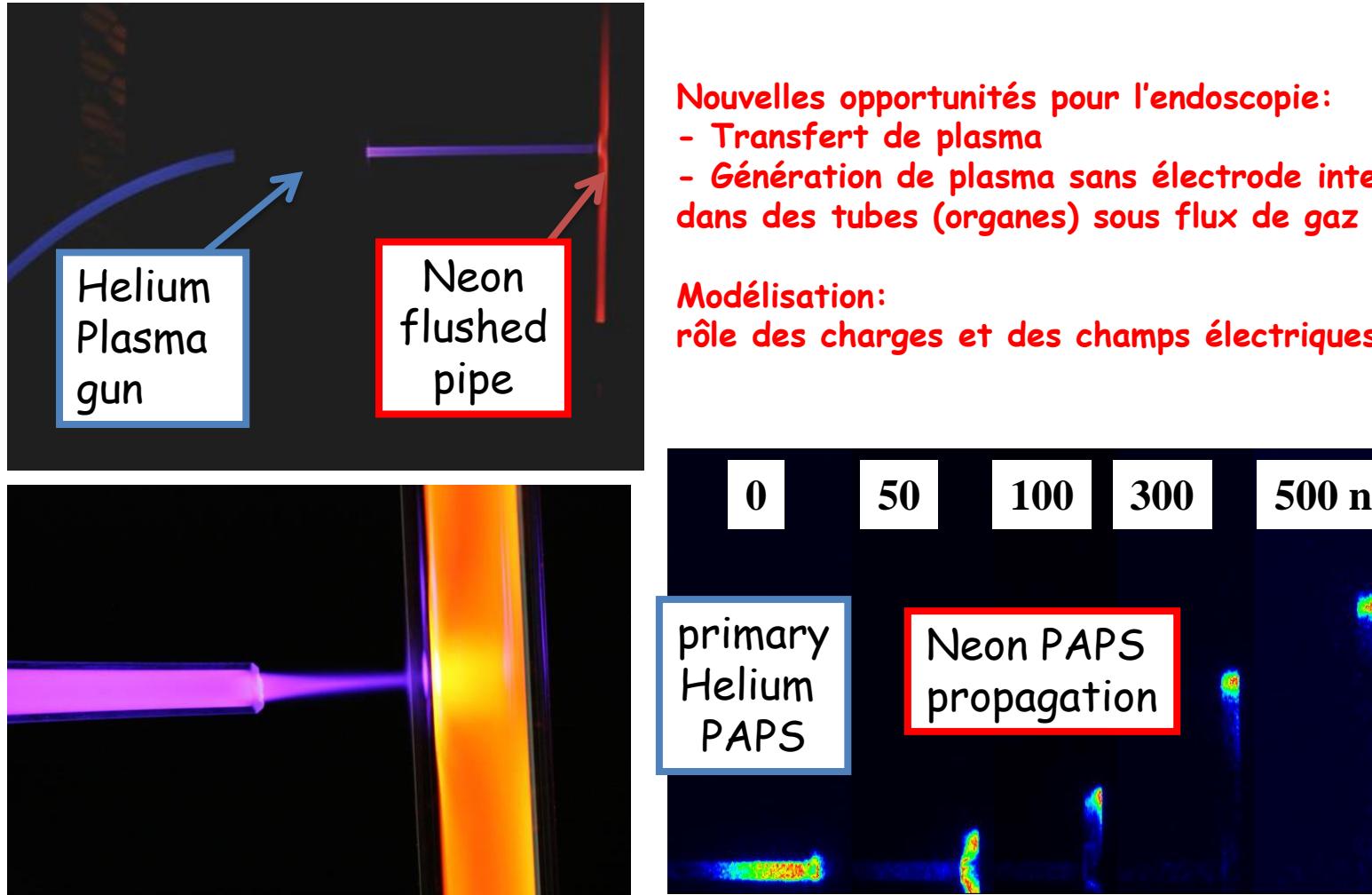
R. Liang et al, **First Published:**
1 July 2025

Z. Xiong et al 2012 J. Phys. D: Appl. Phys. 45 275201



Recherche « fondamentale » d'origine applicative

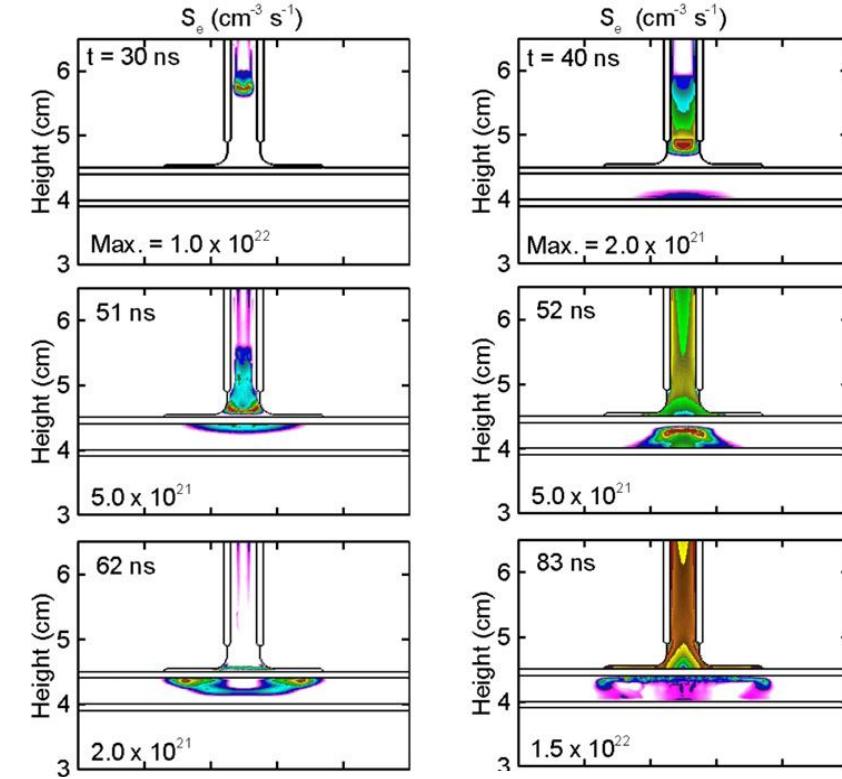
- Question: peut-on envoyer le plasma dans le colon pour détruire des cellules cancéreuses



Nouvelles opportunités pour l'endoscopie:

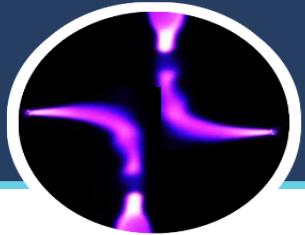
- Transfert de plasma
- Génération de plasma sans électrode interne dans des tubes (organes) sous flux de gaz

Modélisation:
rôle des charges et des champs électriques



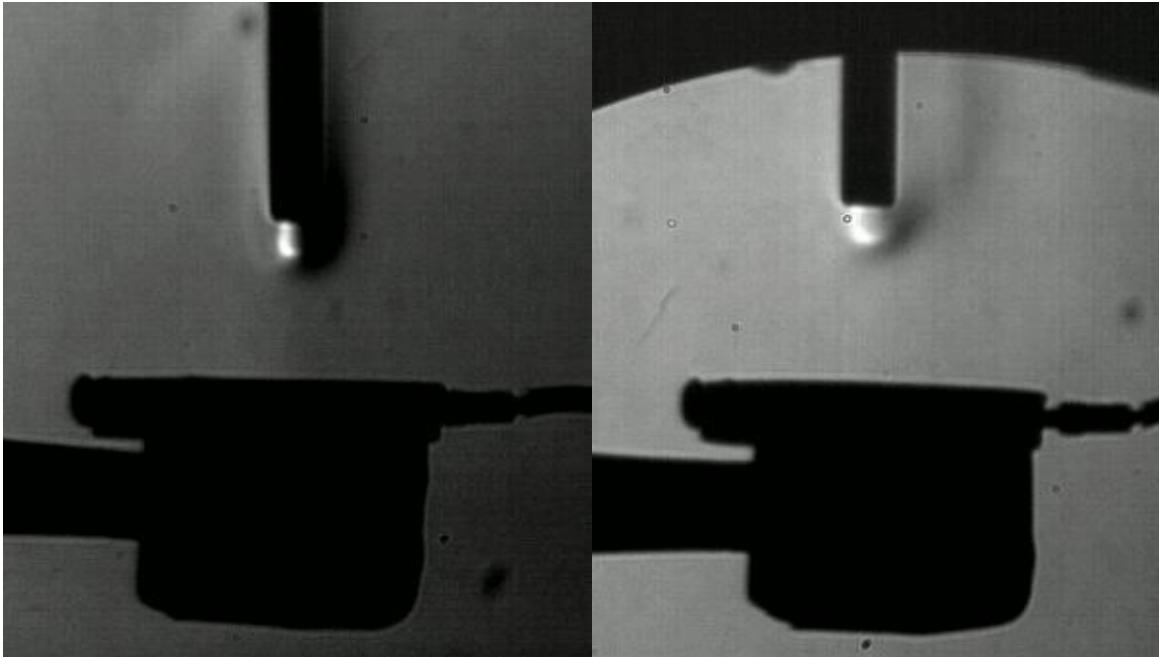
Primary IW propagates across the inter-tube gap and upon impingement induces two secondary IWs propagating in opposite directions in the transfer tube.

Z. Xiong et al 2013 J. Phys. D: Appl. Phys. 46 155203



Interaction décharge - flux de gaz

Polarité positive



Polarité négative

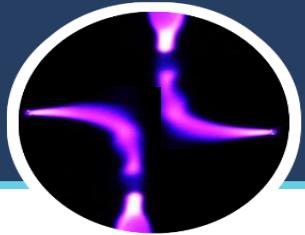
Canalisation du flux de gaz (hélium, argon)

Couche de gaz sur la surface

impact pour la délivrance d'espèces et de champ électrique sur des cibles

Impact lors du traitement de solutions liquides?

Contrôle de l'impulsion:
Amplitude
Polarité
Fréquence des impulsions

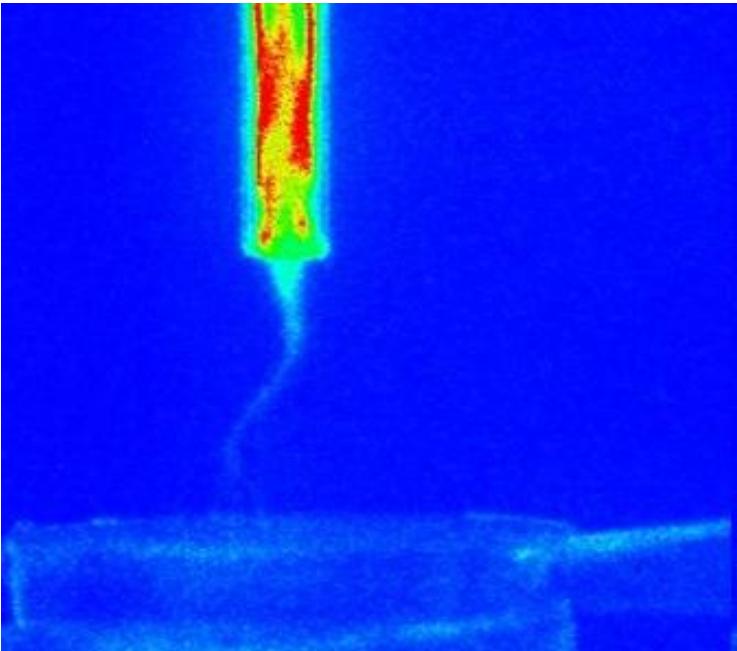


Et juste pour jouer ou plus...

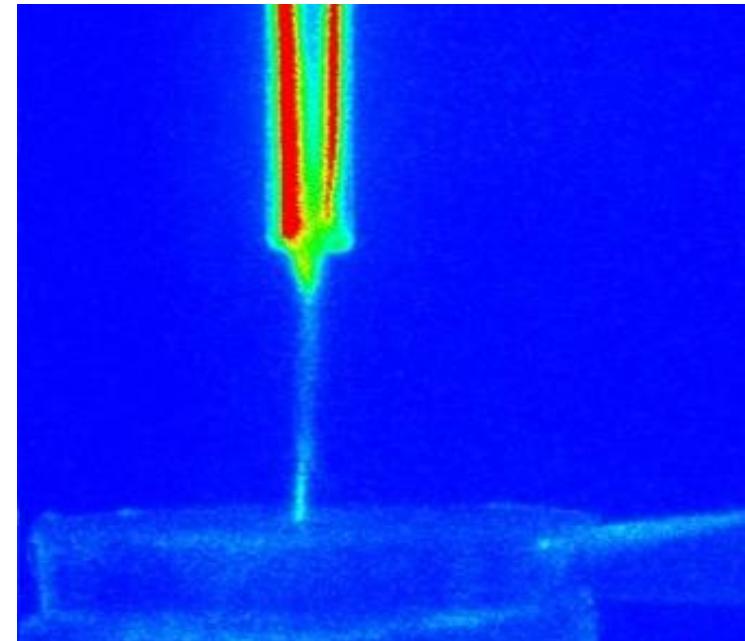
Manipuler la plume plasma avec le générateur d'impulsions

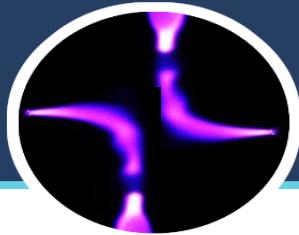
Plume plasma générée par l'application
d'une impulsion de polarité positive

Après 50 impulsions de polarité positive

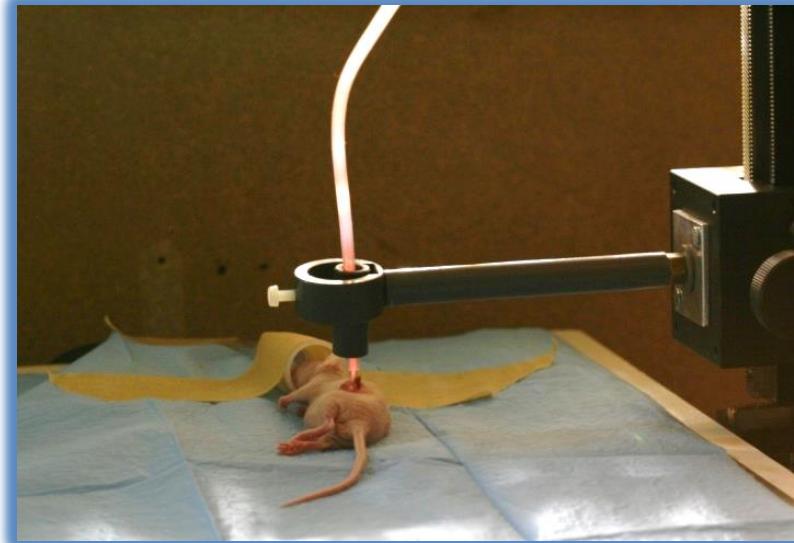


Après 50 impulsions de polarité négative





Recherche « fondamentale » d'origine applicative



- Interaction du plasma avec la cible?

Nécessaire pour développer les applications



Applications biomédicales: illustrations et défis



Effet antitumoral 2011, DBD

Antitumor action of DBD Plasma on heterotopic brain tumors



Key role of R

Verrou: pénétration ?

RNA damage, cell cycle arrest, apoptosis induction
and finally significant tumor activity and tumor volume growth rate reduction

Evidence for plasma « penetration » in the whole subcutaneously grafted tumor
while plasma is applied above the mouse skin

Vandamme et al.

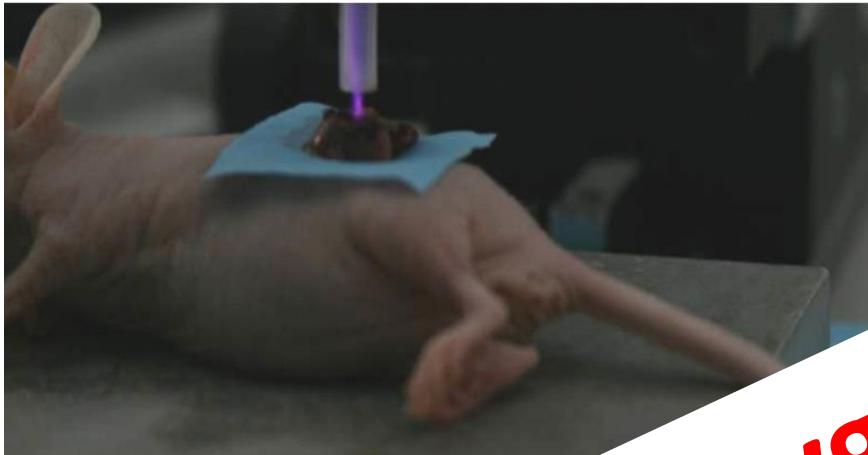
« Response of Human Glioma U87 xenografted on mice to non thermal plasma treatment », 2011 Plasma Med. 1, 27-43.

« ROS implication in a new antitumor strategy based on non-thermal plasma », 2012 Int. J. Cancer, 130, 2185-2194

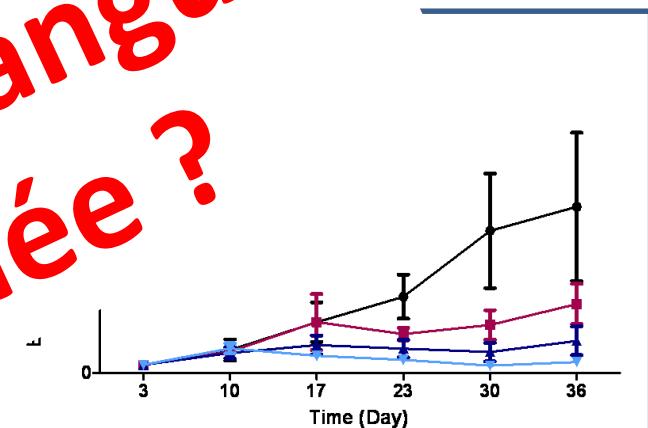


Effet antitumoral, couplage chimiothérapie

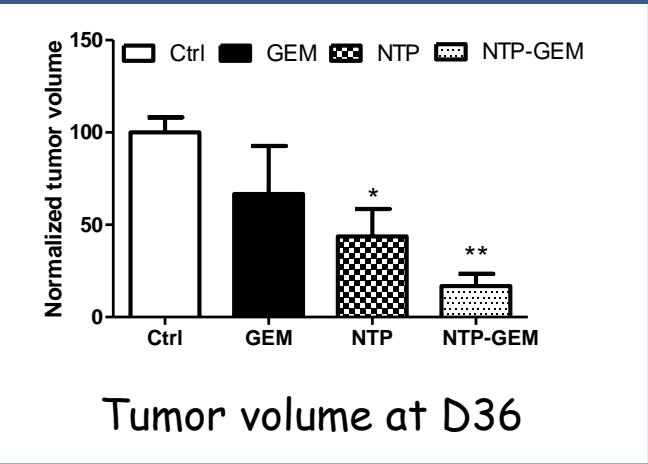
Antitumor action of Plasma Gun, second study



Chemo,
Plasma,
and (Chemo+Plasma)



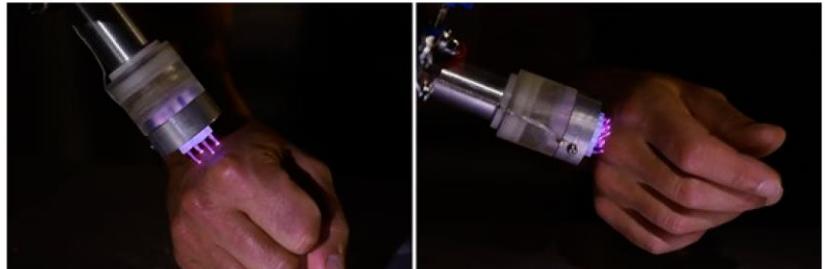
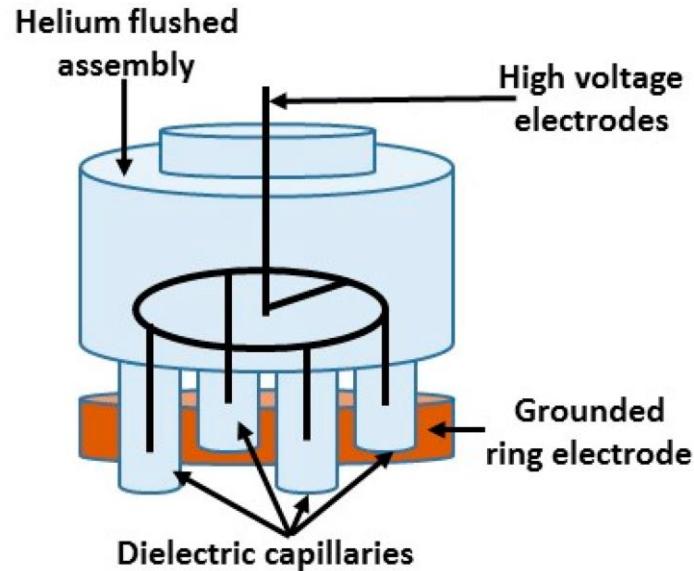
Tumor activity during study



Tumor volume at D36



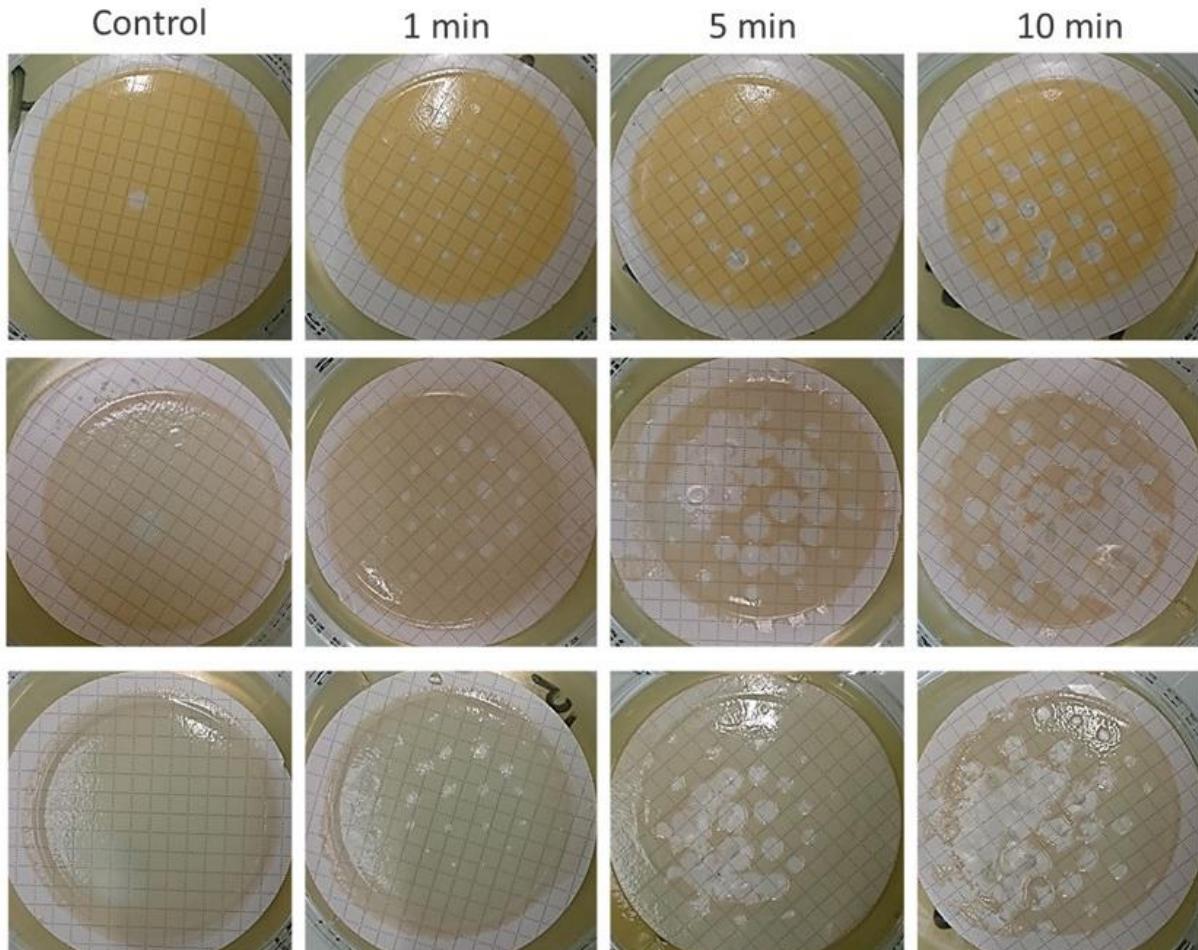
Action antibactérienne des multijets plasmas

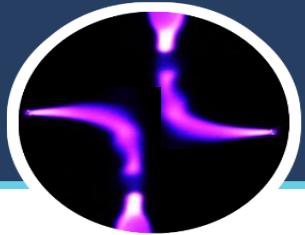


S. aureus ATCC9144
 10^3 CFU/ml

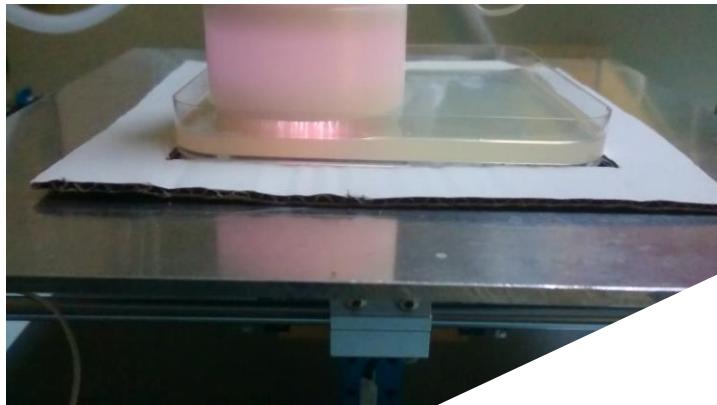
P. aeruginosa ATCC9027
 10^3 CFU/ml

P. aeruginosa resistant
(sensitive to aminoside only)
 10^3 CFU/ml



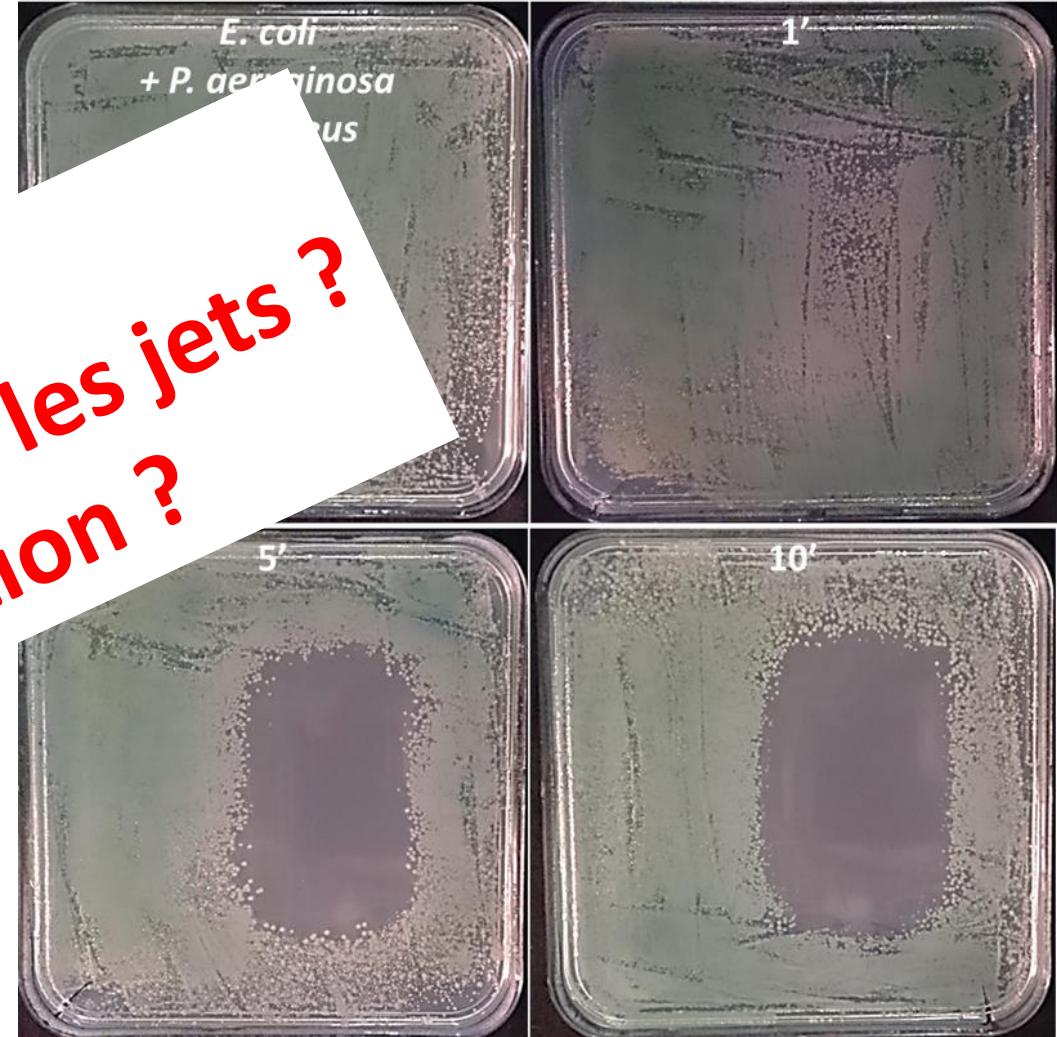


Décontamination de biofilms

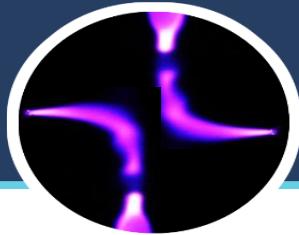


Pattern duration = 60 secondes
Repeated 1, 5 or 10 times

Verrou
Distribution entre les jets ?
Mode d'action ?



Appl. Sci. 2021, 11(20), 9598; <https://doi.org/10.3390/app11209598>

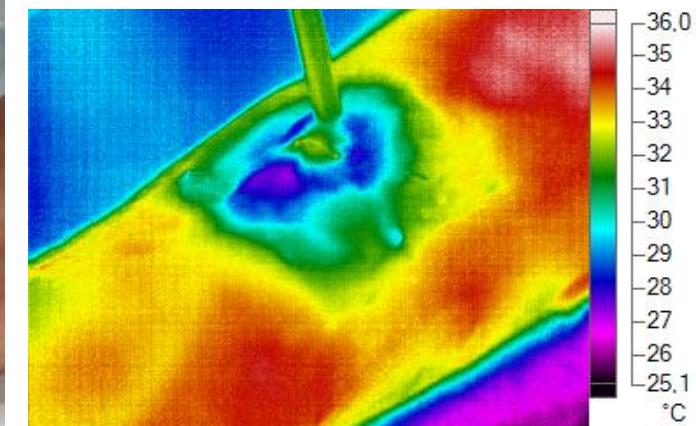


Application clinique: début 17/10/2025

2020 Case study: chronic wound treatment at Orleans Hospital

Protocol

- 5 patients with infected wounds (dia. 3 to 15 cm).
- 5 plasma treatment :
 - 1 min for each half square centimeter surface unit
 - Full time : 15 to 30 min, daily



Tolerance assessment

- Patients feelings during/after treatment
- Visuals controls by the nurse
- Monitoring of the temperature

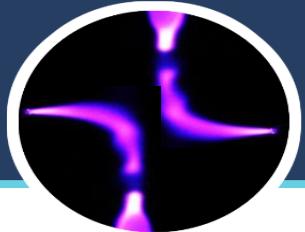
Absence of pain, burn or unpleasant feeling by the patient.
No inflammation, necrosis or degradation of the tissue.

2025 Etude clinique CHUO: 18 mois, 40 patients



Quels verrous pour toutes ces applications?

- Mesure/modèle des champs électriques in situ, dans les cibles: spectroscopies EFish, Stark , Pockels
- Mesures/modèle des courants: cible à la masse ou flottante, Rogowski?
- Mesure/modèle des ions et des charges déposées
- Mesure/modèle d'espèces réactives à courte durée de vie
- Mesure/modèle de température instantanée
- Mesures en temps réel pour l'implémentation du contrôle et de l'apprentissage automatique
- Quelle excitation: pulsée contrôlée, AC onde d'ionisation?
- Electrohydrodynamique en phase gaz et liquide
- Des jets à base d'air?



Merci de votre attention

