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Electric field and discharge properties of single and multiple arrangement of Pulsed Atmospheric Plasma Streams

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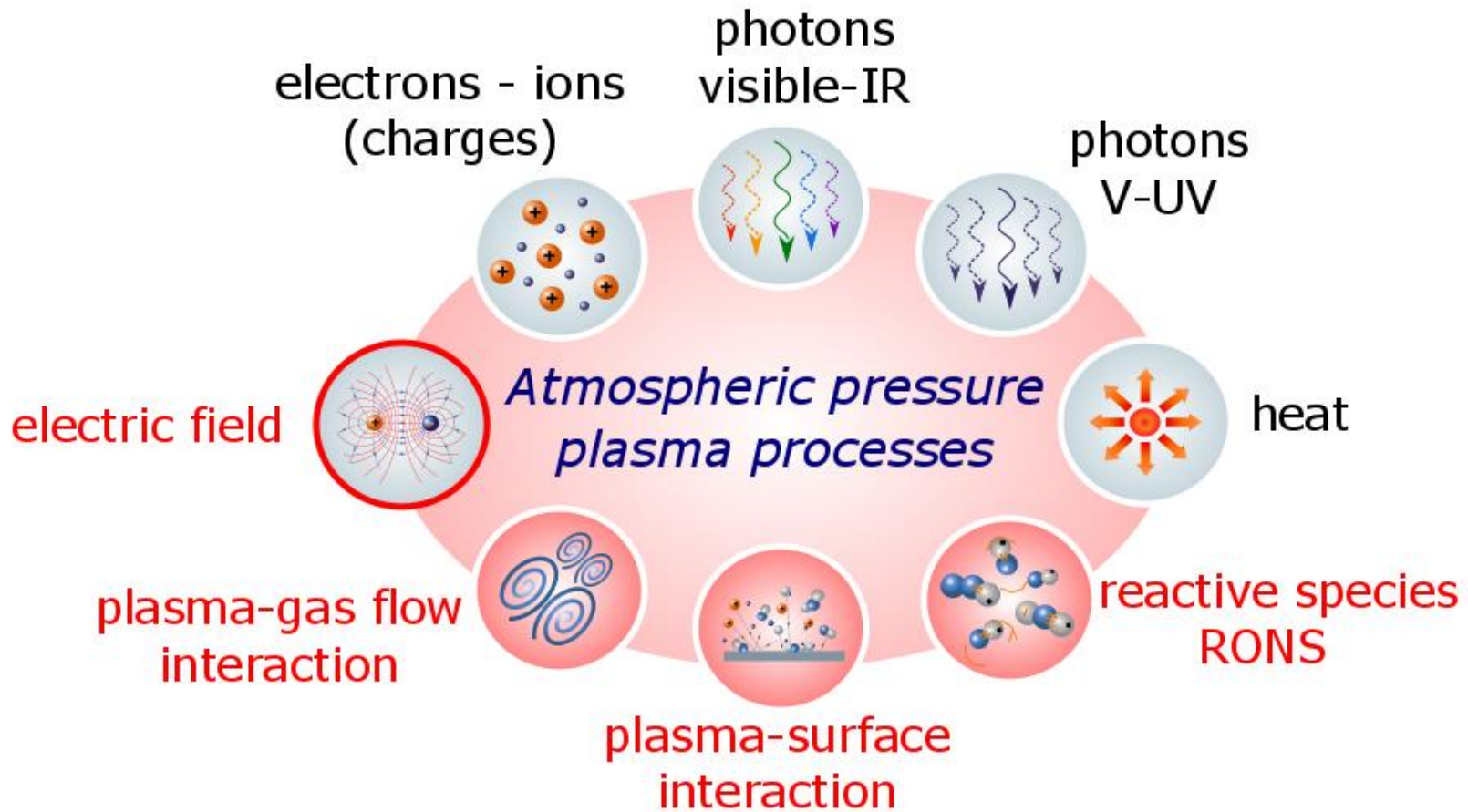
28th Summer School and
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the Physics of Ionized Gases

August 29 – September 2, 2016, Belgrade, Serbia

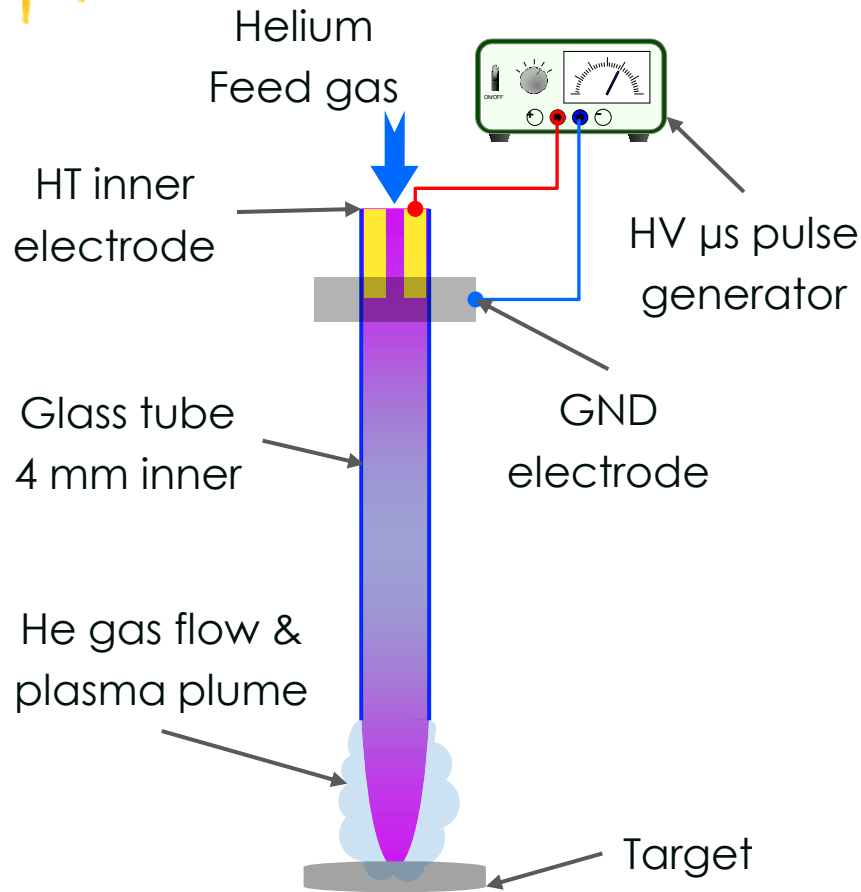


PHC Pavle Savic - #36216UA

What are we dealing with?

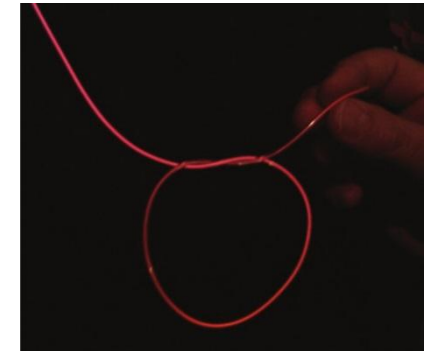
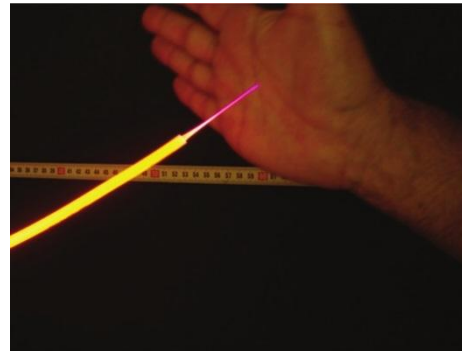


Plasma source: *plasma gun*



■ Applications

- Plasma medicine
- Plasma activated liquids
- Decontamination
- Surface functionalization



Robert E, et. al., 2009, *Plasma Process. Polym.*, 6, 12
Robert E, et. al., 2012 *Plasma Sources Sci. Technol.*, 21, 034017

Single Pulsed Atm. Plasma Streams



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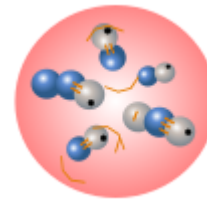
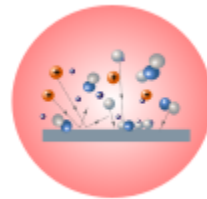
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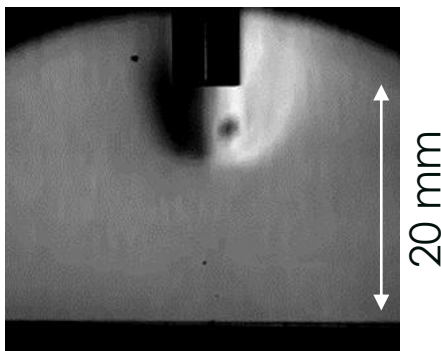
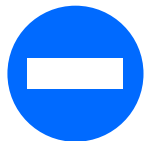
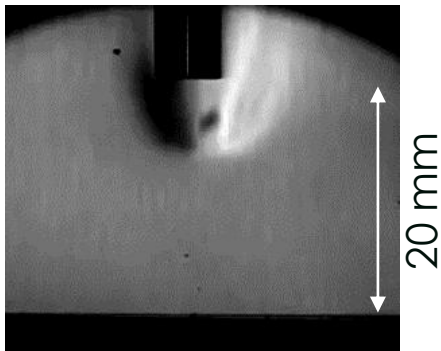
Some discharge characteristics



Plasma & gas flow interaction



Helium (AM: 4)

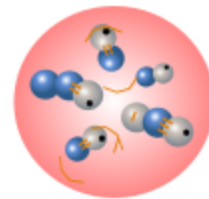


14kV / 4kHz, 0.5 L/min,
GND target

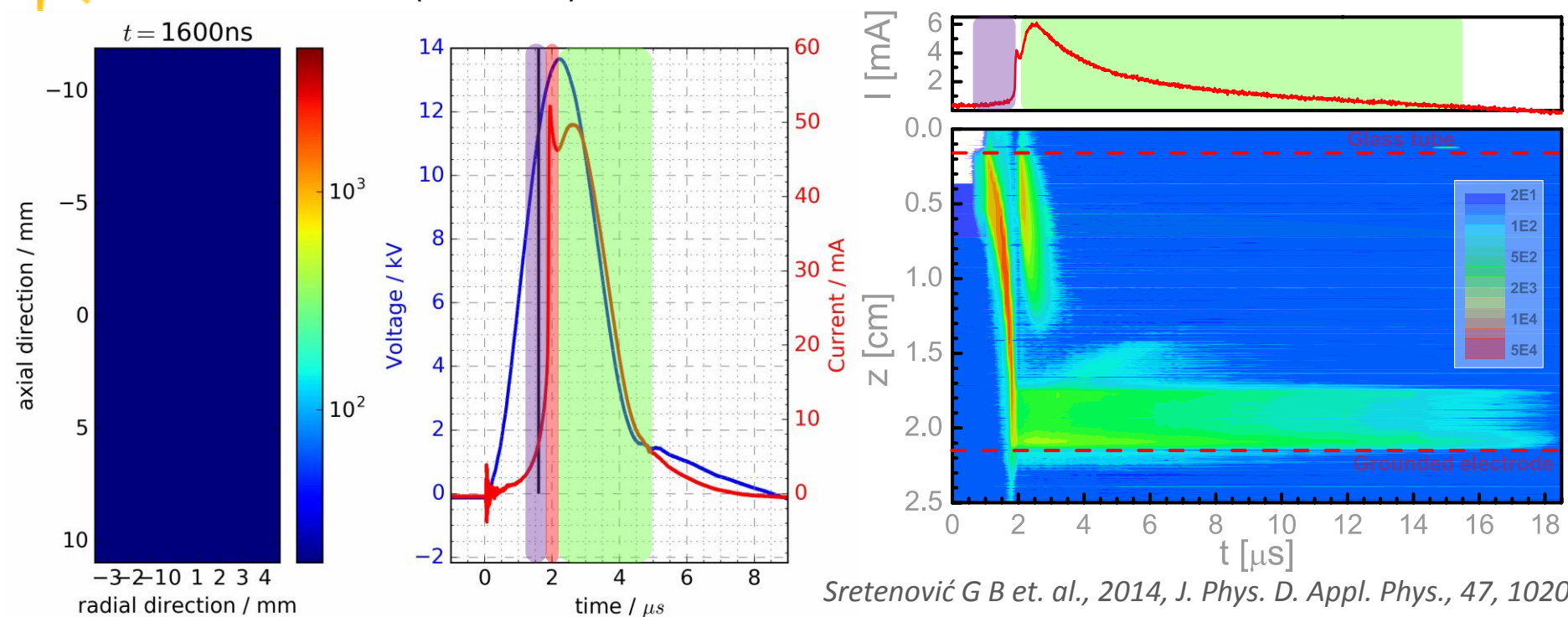
- Rare gas flow structuration
 - Pol. \oplus : flow perturbation / instabilities
 - Pol. \ominus : flow channeling / stabilization
- Motion of heavy gas
 - Ne(20), Ar(40) \Rightarrow universal feature?
- Plasma – substrate \Rightarrow central role!
- Ion wind
 - **charges (ions) & electric field**

Robert E, et. al., 2014, *Plasma Sources Sci. Technol.*, 23, 012003
Robert E, et. al., 2015, *Phys. Plasmas*, 22, 122007

Propagation towards a target



Helium (706.5nm)



Sretenović G B et. al., 2014, *J. Phys. D. Appl. Phys.*, 47, 102001

- 1st phase: cathode directed ionization wave streamer
- 2nd phase: anode glow, current rise ⇒ “rebound” ?
- 3rd phase: positive column of transient glow[†]

[†]Kogelschatz U, 2003, *Plasma Chem. Plasma Process.*, 23, 1–46



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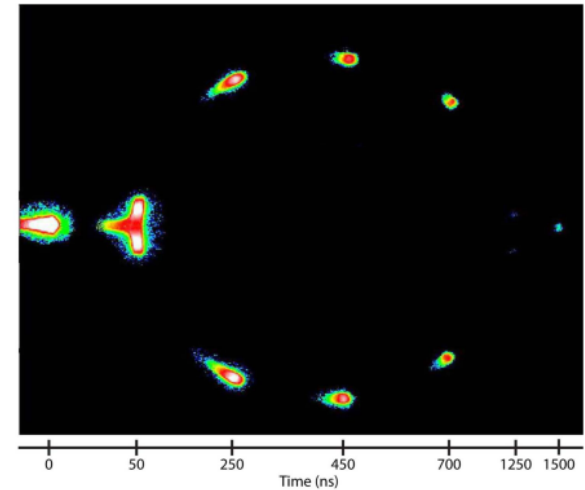
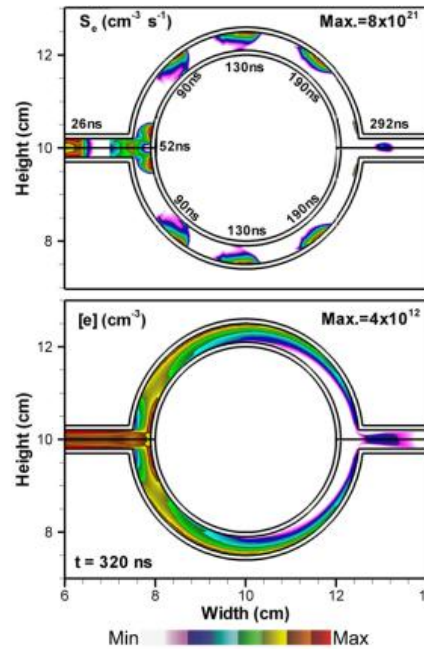
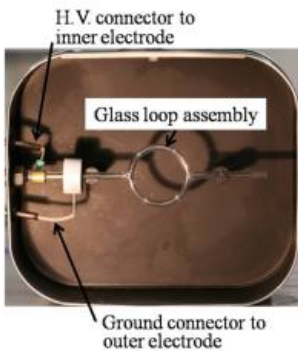
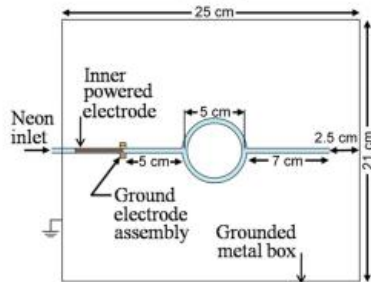
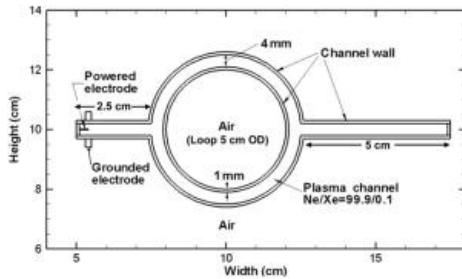
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Unique feature: split and merge

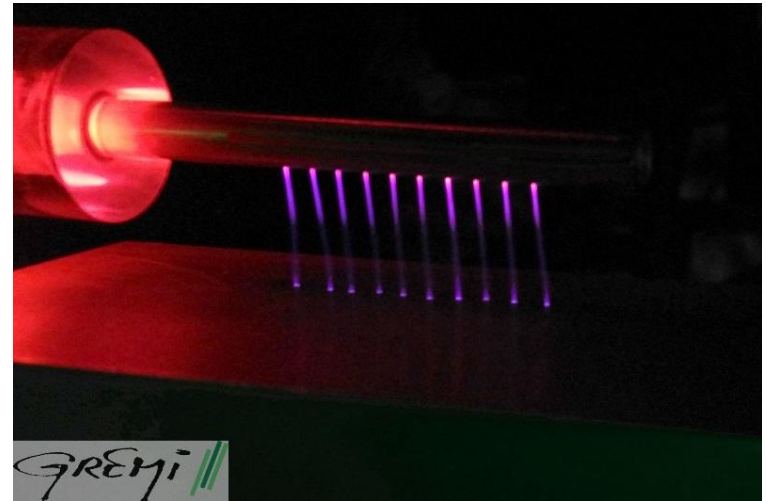
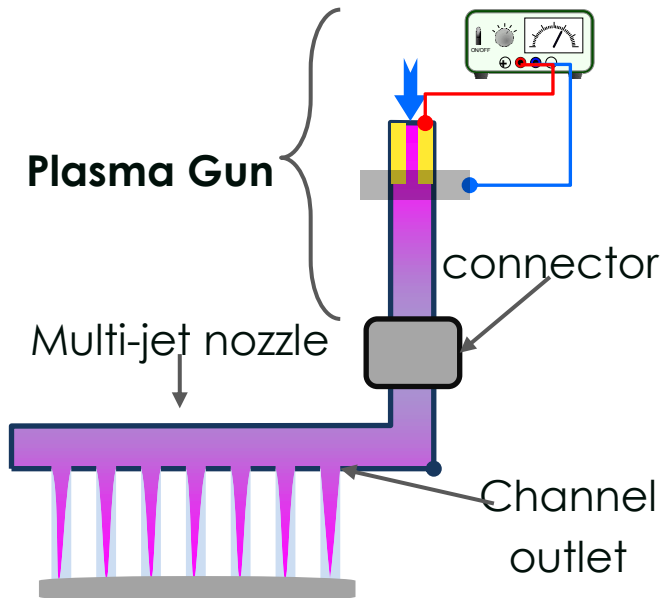


Sarron V, 2011, *IEEE Trans. Plasma Sci.*, 39, 2356-7

- Splitting - Merging
- Experiment
- Numerical Model

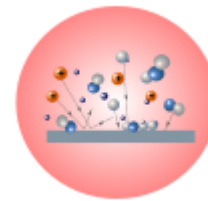
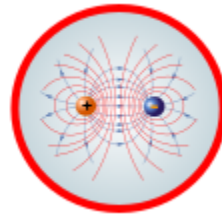
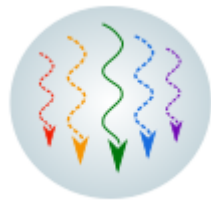
Xiong Z et. al., 2012, *J. Phys. D. Appl. Phys.*, 45, 275201

From single to multi jets plasma



- Robert E, Darny T, Dozias S, Iseni S and Pouvesle J M 2015, *New insights on the propagation of pulsed atmospheric plasma streams: From single jet to multi jet arrays*, Phys. Plasmas, 22, 122007.

Plasma jet and electric field

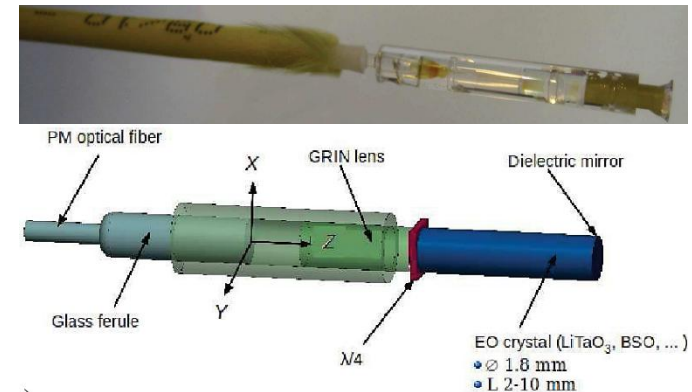


EF diagnostic in atm. plasmas

- Emission spectroscopy – Intensity ratio, N_2^+/N_2
 - Kozlov K V, et. al., 2001, *J. Phys. D. Appl. Phys.* 34 3164–76
- Stark effect – polarization-dependent Stark splitting and shifting (He I 492.19nm)
 - Kuraica M M and Konjević N, 1997, *Appl. Phys. Lett.* 70 1521
- Stark effect – Rydberg atom (H, He)
 - Doughty D K and Lawler J E, 1984, *Appl. Phys. Lett.* 45 611
- Four-wave mixing (CARS)
 - Gavrilenko V P, et. al., 1992, *JETP Lett.* 56 1-4
- Pockels effect – Electro-optic probe – Kapteos SAS
 - Gaborit G, et. Al., 2007, *Appl. Phys. Lett.* 90 241118

EF – Elec. Opt. probe

- Electro-optic sensor
 - Pockels effect
 - BSO crystal
 - $\varnothing = 1.8\text{mm}$, 1mm long
 - $\varnothing_{\text{probe}} = 4\text{ mm}$ (alumina)
- Transient E-field
 - 50kHz – 1GHz
 - 10 V/cm – 100kV/cm
- 2 orthogonal components simultaneously \Rightarrow vector
 - $\|\vec{E}\| = \sqrt{E_x^2 + E_y^2}$
- Absolute amplitude



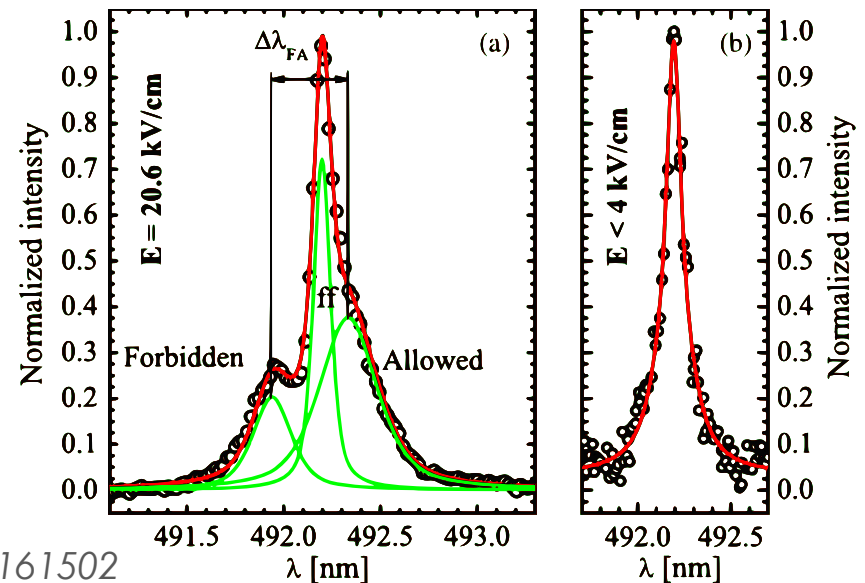
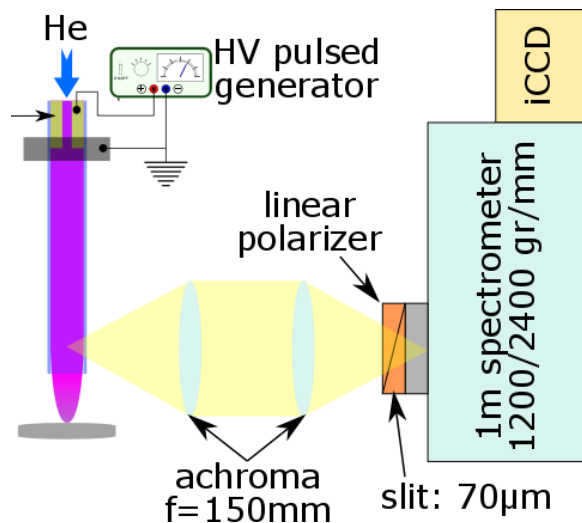
Gaborit, et. al., 2013 IEEE Trans. Plasma Sci., 41, 2851



Gaeremynck Y et. al., 2011, Appl. Phys. Lett., 99, 141102
KAPTEOS (SAS), 73800 Sainte H el ene du Lac, France

EF – Stark split & shift He I, 492nm

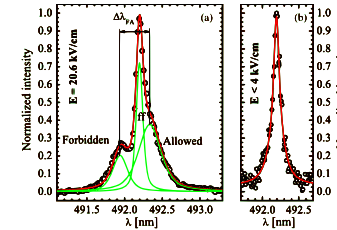
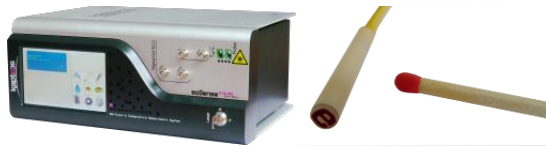
- OES technique
 - Non-intrusive
- Polarization dependent
- 1 EF component
- Time – space resolved
- Absolute ampl. $>4\text{kV/cm}$



Sretenović G B et. al., 2011, *Appl. Phys. Lett.*, 99, 161502

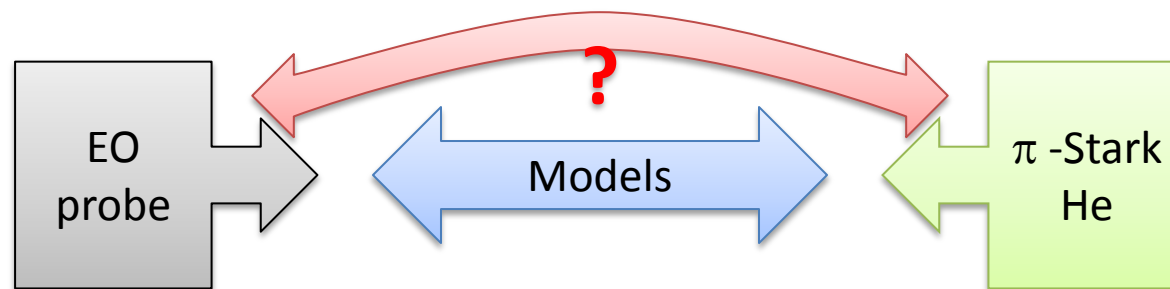
Sretenović G B et. al., 2012, *IEEE Trans. Plasma Sci.*, 40, 2870

Complementarity / Comparison



- Intrusive
- Measurement domain
 - Outside capillary vicinity
 - **Plasma plume?**
- Interaction plasma-substrate \Rightarrow application

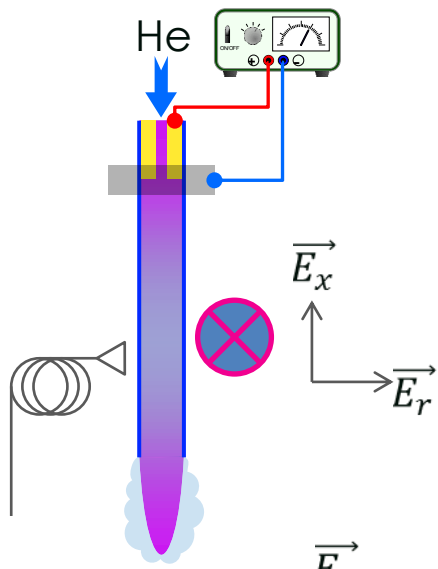
- Non-intrusive
- Measurement domain
 - **Exclusively within plasma volume**
 - Inside capillary
 - Plasma plume



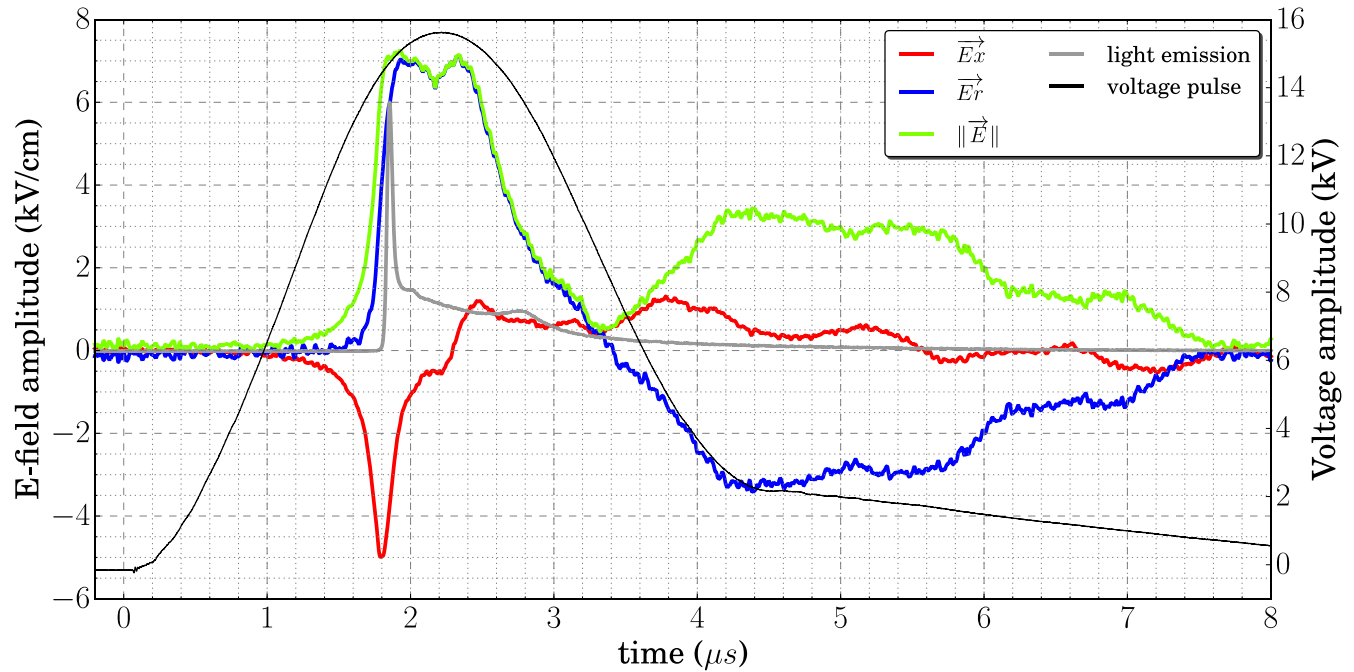
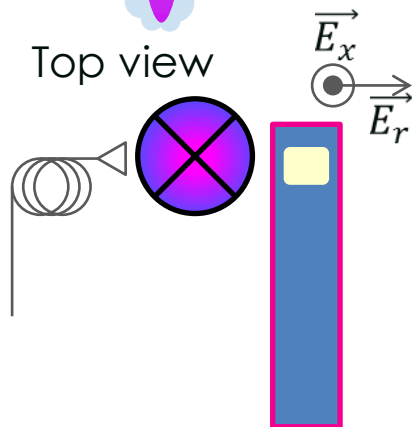
Ionization wave



Side view



Top view



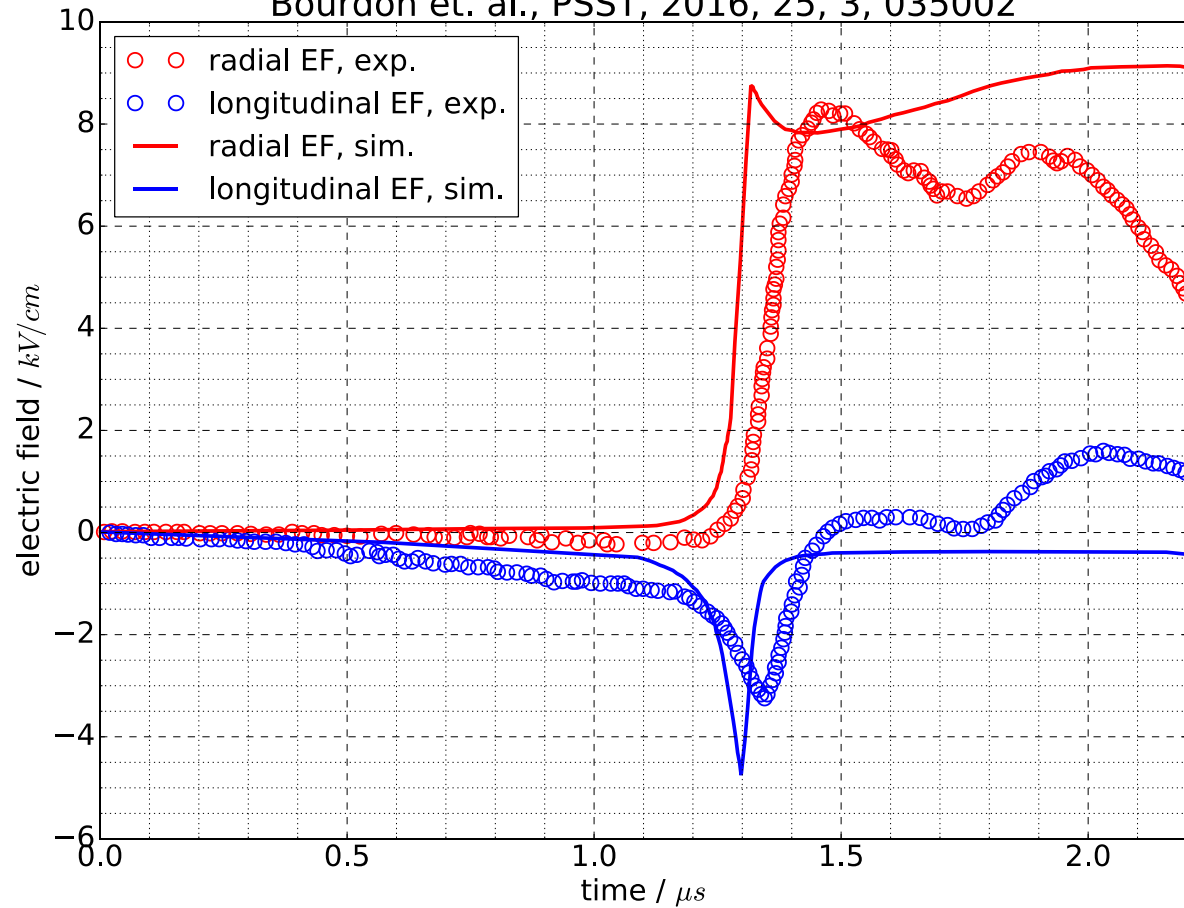
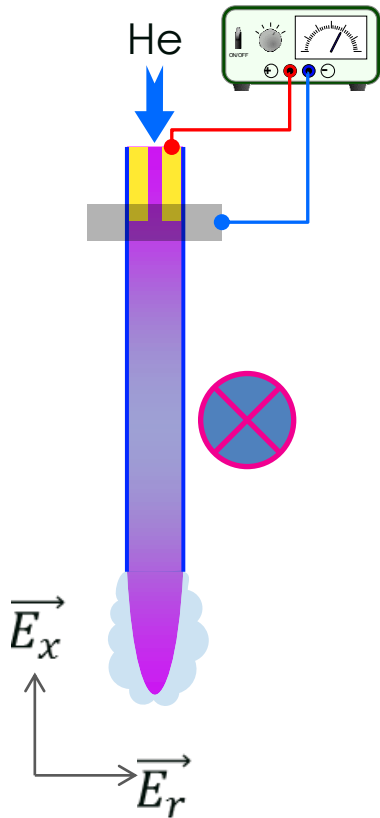
- \vec{E}_x and \vec{E}_r are well identified
- \vec{E}_x = ionization front 500ns before the light
- $\|\vec{E}\|$ in the order of 10kV/cm near the tube



Experiment vs model (I)



Bourdon et. al., PSST, 2016, 25, 3, 035002



Bourdon A et. al., 2016, Plasma Sources Sci. Technol., 25, 035002



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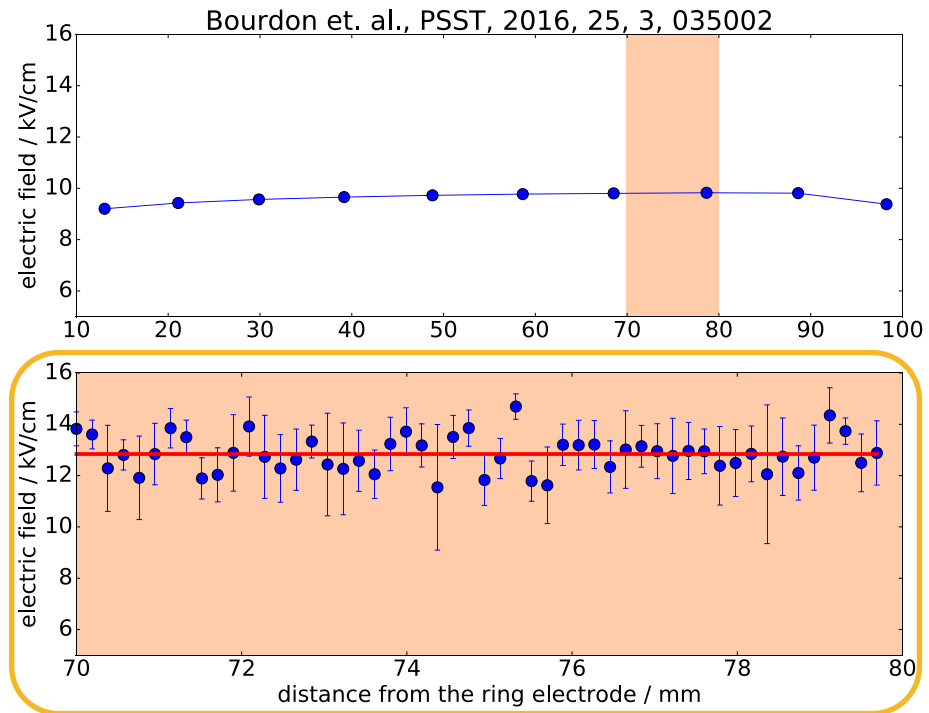
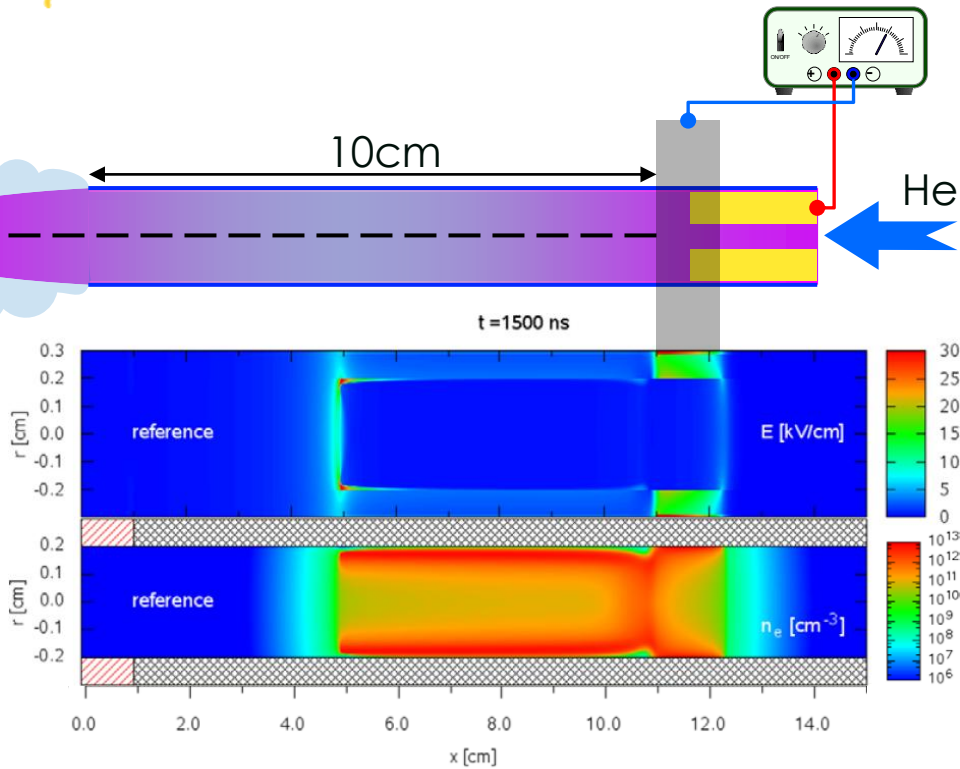
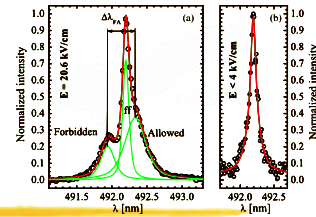
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Experiment vs model (II)



Measurement by π -Stark splitting and shifting (He I 492.19nm)

Bourdon A et. al., 2016, Plasma Sources Sci. Technol., 25, 035002



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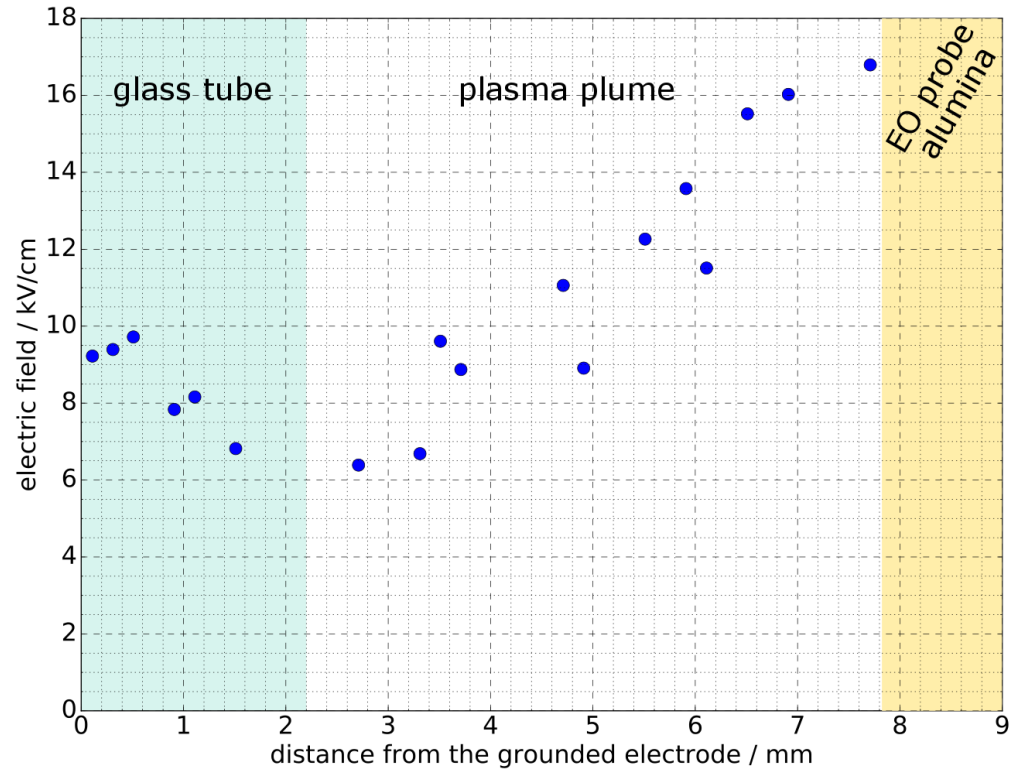
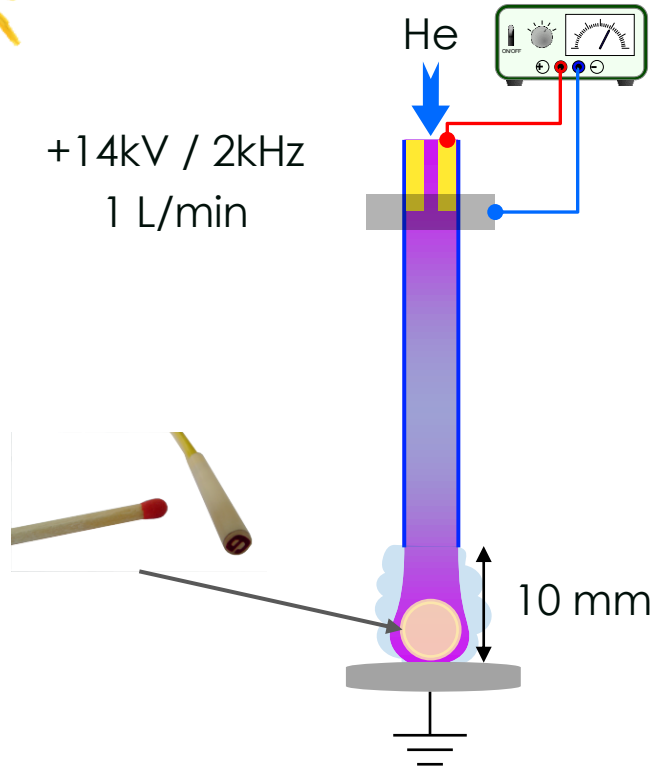
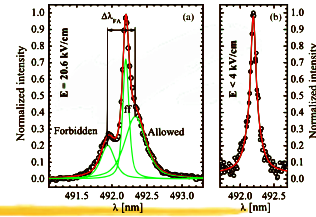
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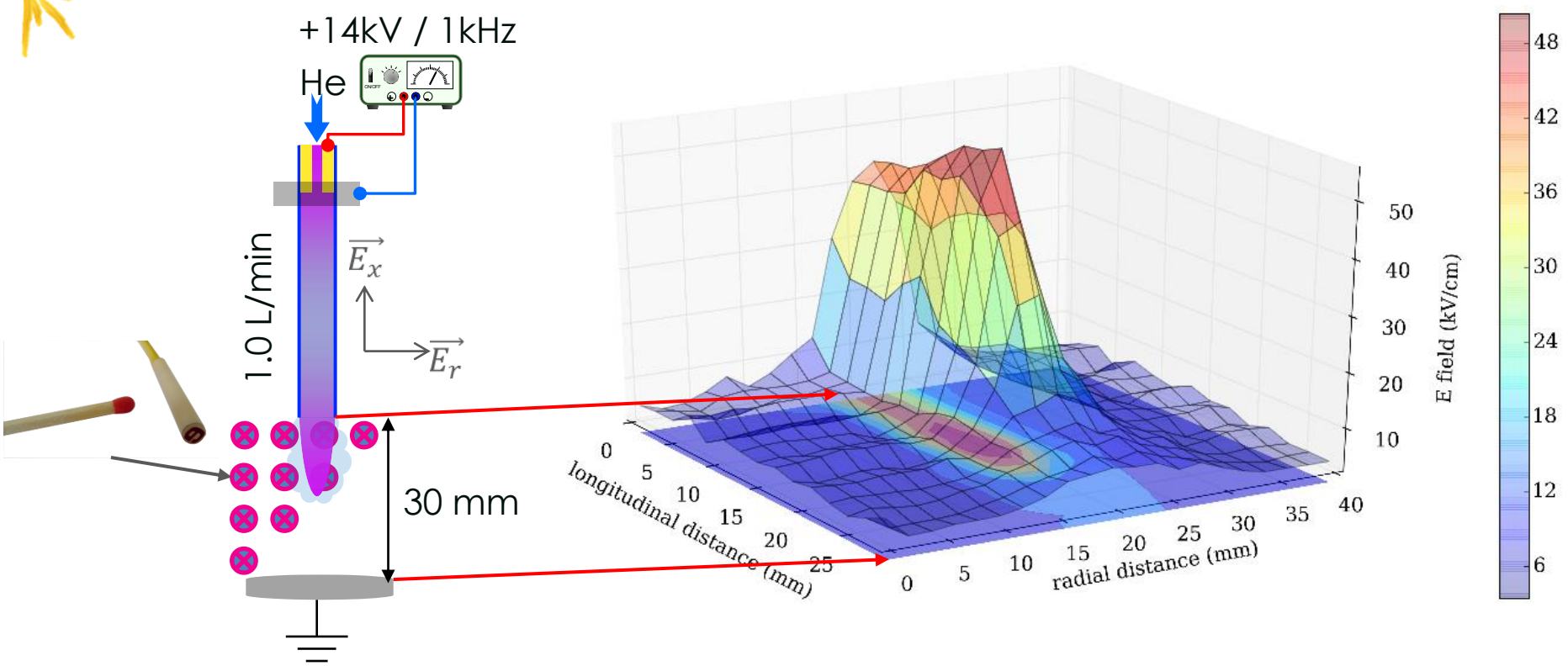
EF on EO probe surface



- Tentative of direct comparison...

- EF rises linearly in plume
- EF max : ~17kV/cm

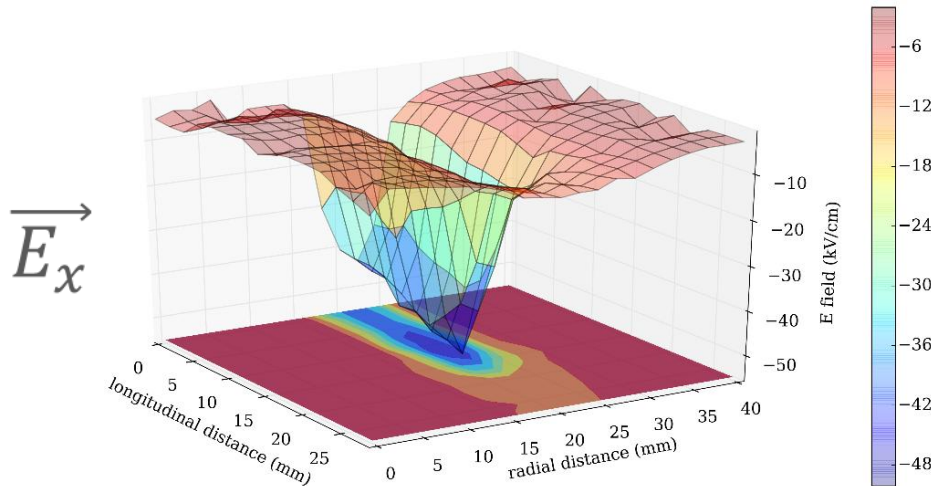
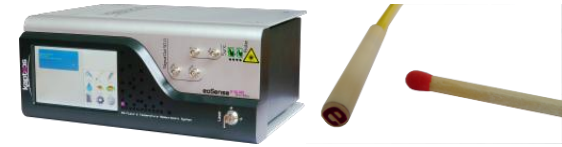
Plume EF distribution



- $$\|\vec{E}\| = \sqrt{E_x^2 + E_y^2}$$

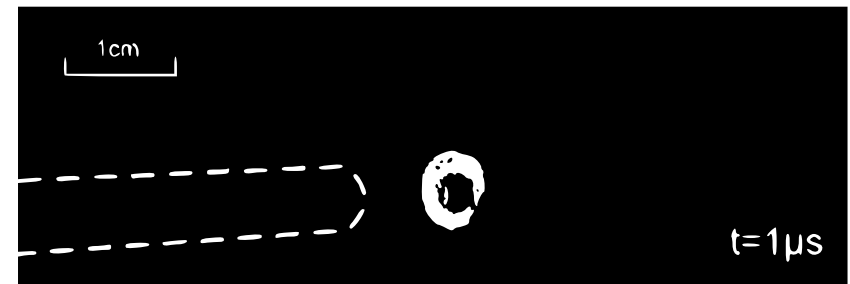
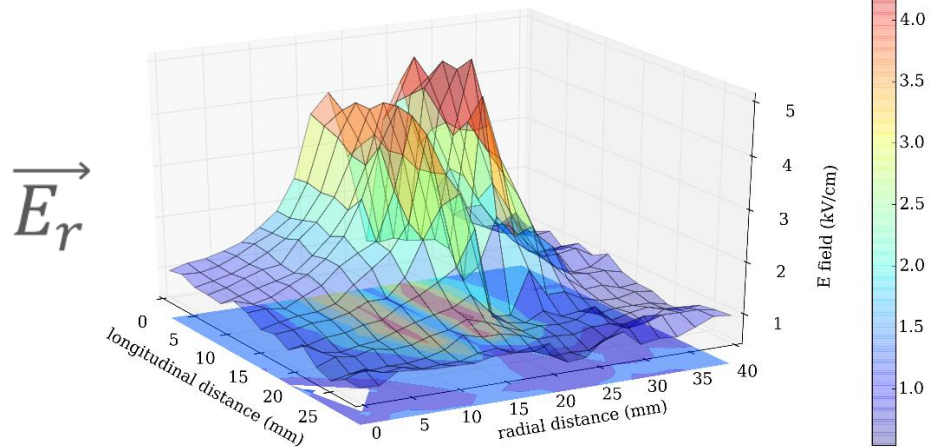
- EF rises in plume
- EF max : ~50kV/cm

E-field decomposition



- E_x is the major component
- E_r resembles a ring shape
- Consistent with the literature
 - π -Stark splitting and shifting (He I 492.19nm)
 - Numerical simulations

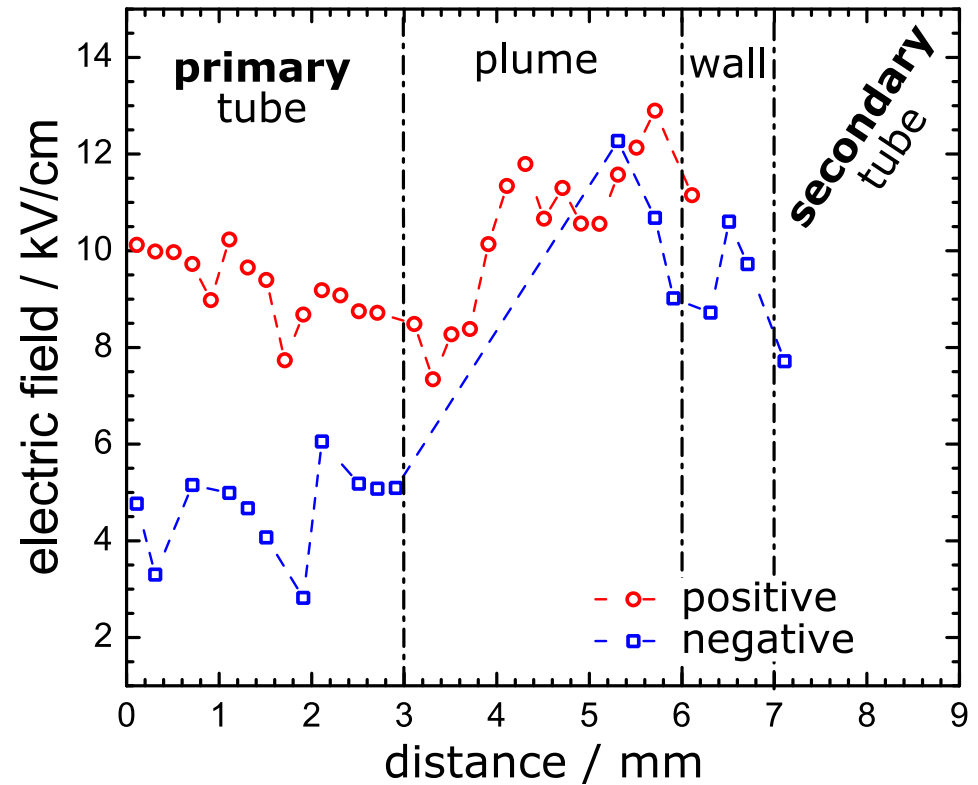
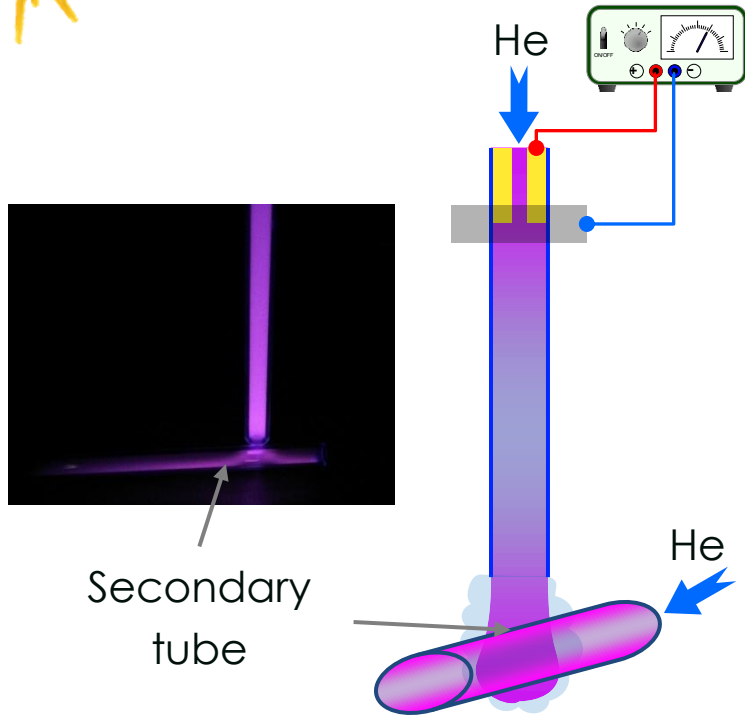
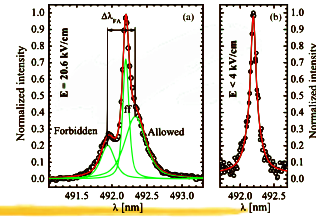
Sretenović G B et. al., 2012, IEEE Trans. Plasma Sci., 40, 2870



(b)

Teschke M, et. al., 2005, IEEE Trans. Plasma Sci., 33, 310-1

EF in a transferred PAPS

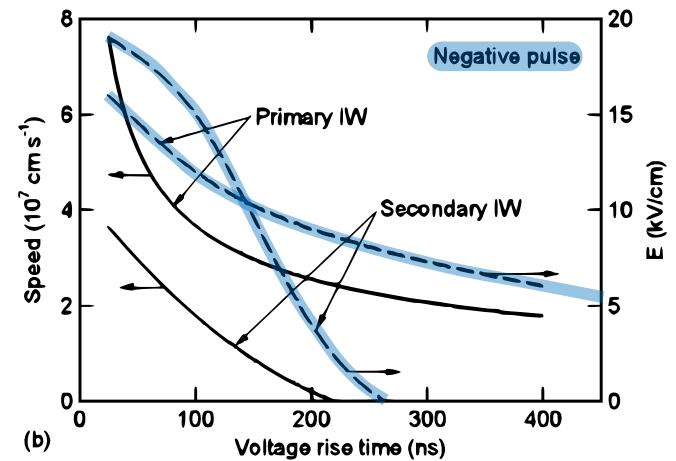
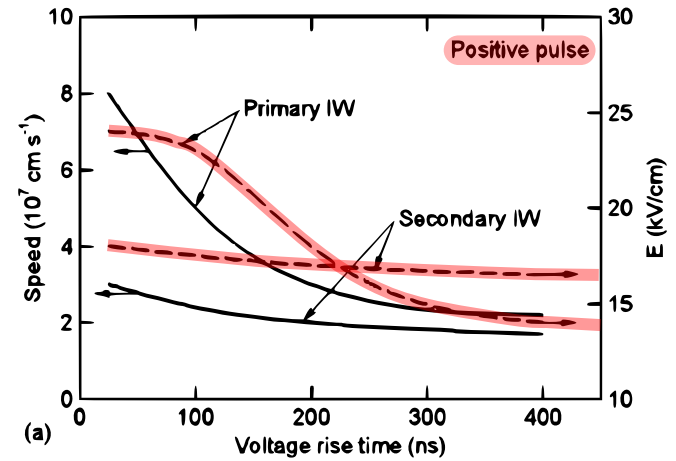
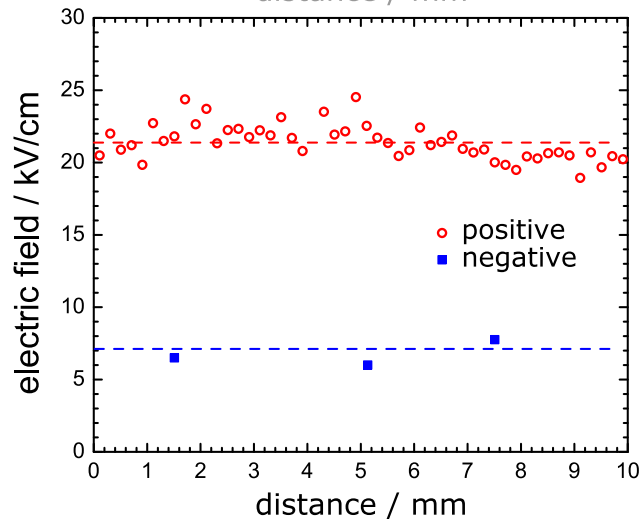
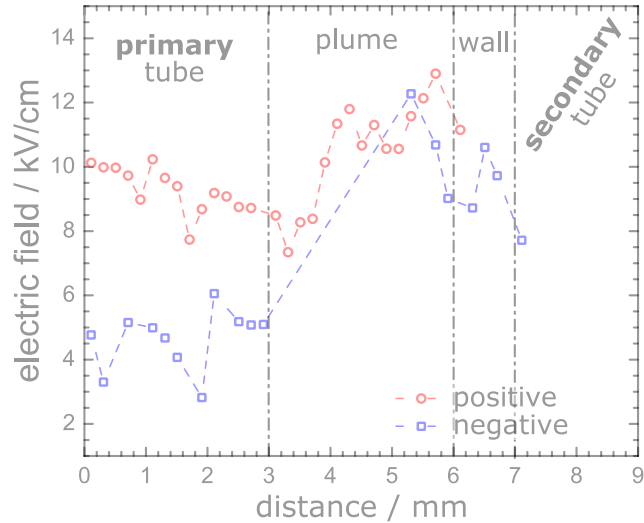
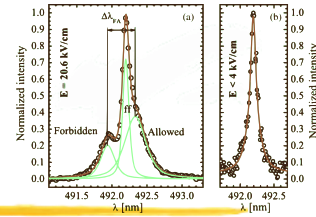


■ Influence of polarity

■ $|\vec{E}_x|_{\text{positive}} > |\vec{E}_x|_{\text{negative}}$

Naidis G V., 2011, Appl. Phys. Lett., 98, 141501

Secondary tube



Xiong Z, 2013, *J. Phys. D: Appl. Phys.*, 46, 155203

Concluding remarks

- ✓ Crucial role of the substrate \Rightarrow flow, propagation...
- ✓ E-field of ionization waves \Rightarrow successfully measured
- ✓ Consistent results \Rightarrow experiments vs modelling
- ✓ Complementary of both techniques
- ✓ E-field of several tens of kV/cm
- ✗ Mismatching of E-field *absolute* amplitude
 - ✓ Both techniques showed similar trends
 - ✗ Taking into account the surface material...
- ✓ *We will come back to Belgrade...*
 - ✓ 😊 😊 😊

Thank you for your attention!

