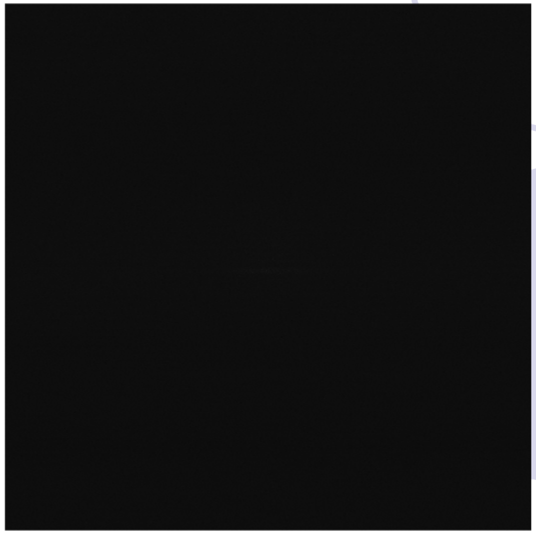
Plasmas froids, vent ionique et phénomènes électrofluidodynamiques : quand les plasma génèrent des écoulements



Eric MOREAU … and my colleagues and all my students !

Institut PPRIME, Equipe « Electrofluidodynamique », **Université de POITIERS, FRANCE**

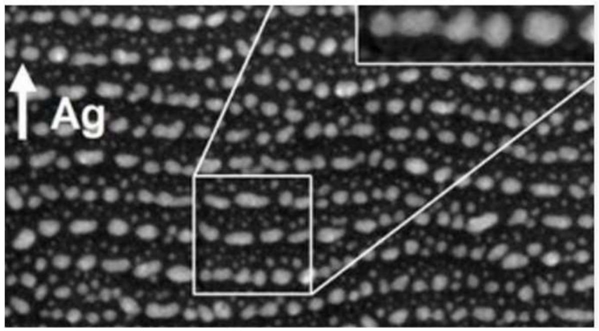
My laboratory ?

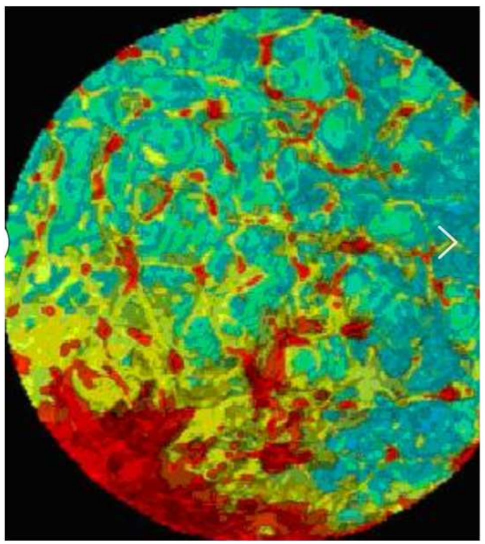
▶ **PPRIME Institute**

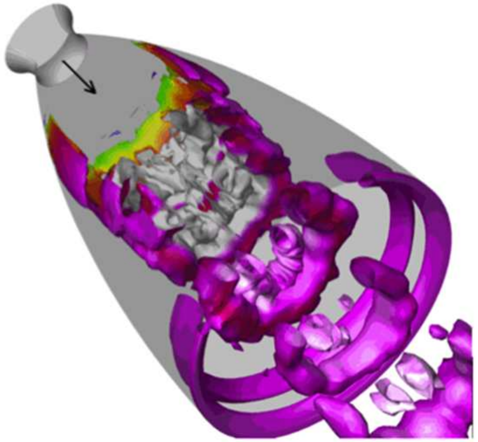
➪ **600 people: 230 researchers**, 240 PhD students and 120 enginners, technicians, administrative

➪ Three departments :

- Physics and Mechanics of Materials
- Mechanics and Robotics
- Fluid Mechanics, Thermal Transfer and Energetic → **Team « Electro-Fluid-Dynamics » (EFD)**







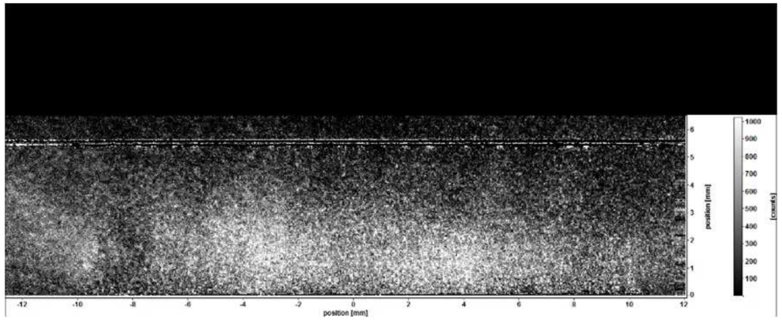
Team « Electro-Fluid-Dynamics »

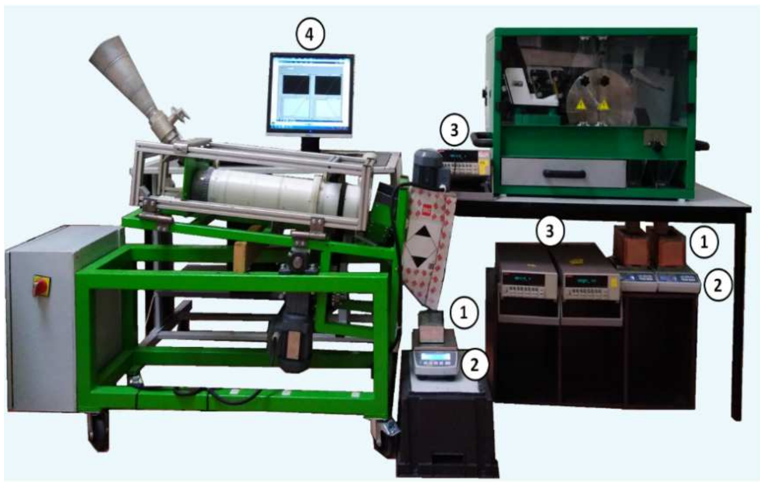
▶ **Topics**

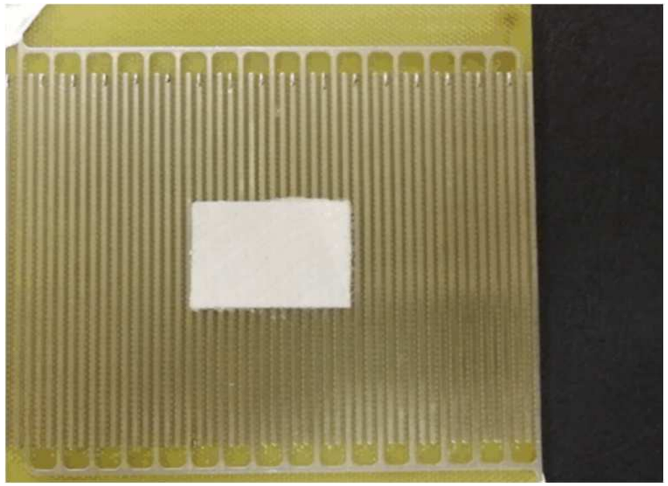
➪ **Link between electrical phenomena and fluid mechanics** (10 researchers)

➪ 5 main topics

- Flow electrification and electrostatic hazards (2)
- Electrostatics and tribology (2)
- EHD in liquids (1)
- Fuel cells and batteries (2)
- **EHD and Plasmas (Nicolas BENARD, Thomas ORRIERE and myself)**







My subjects of research

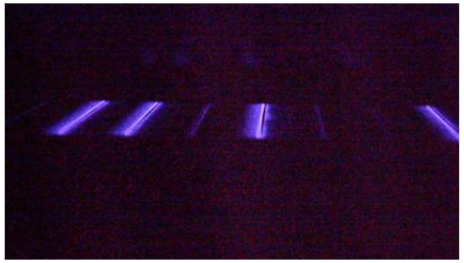
- **Since 1999**

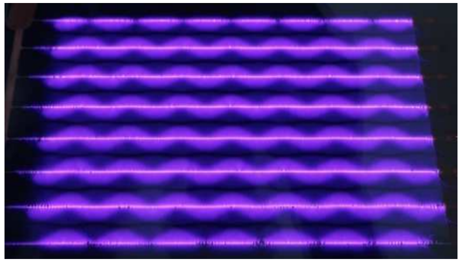
➪ Surface discharges and flow control by **plasma actuators** (1999 – present)

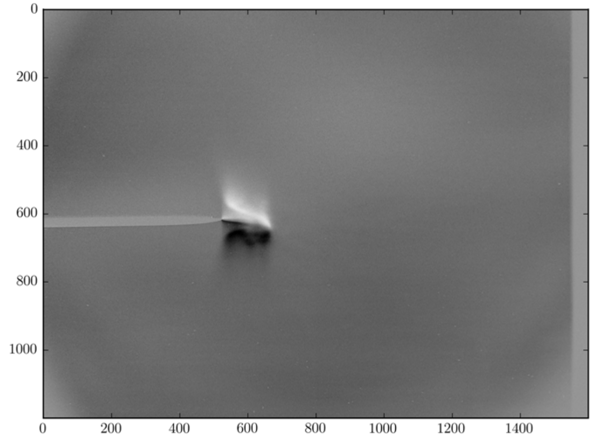
➪ Ionic wind produced by **corona discharges** (2015 – present)

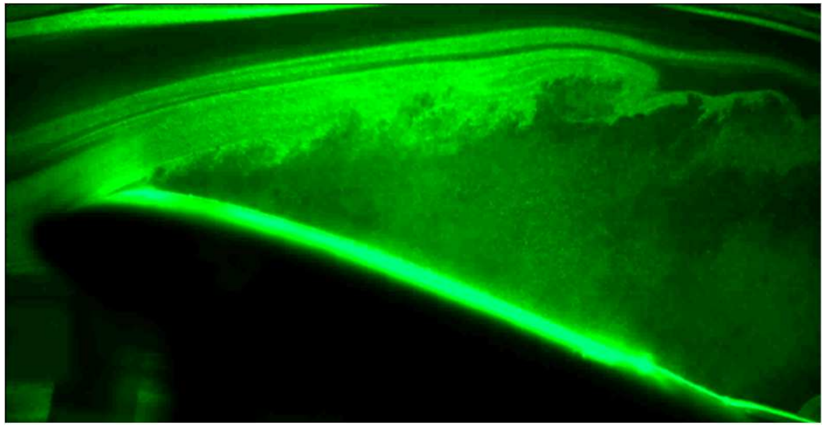
➪ **Liquid flows induced by plasmas** (2023 - present)

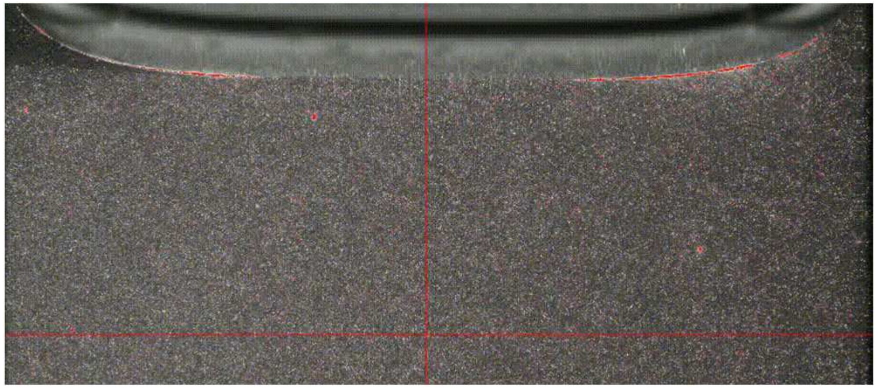
➪ Electrostatic precipitation (2005 – 2012)











Outline

1) Volume needle-to-plate corona discharges

2) Surface dielectric barrier discharges

3) Plasma-induced liquid flows

↓

A few examples of applications

Outline

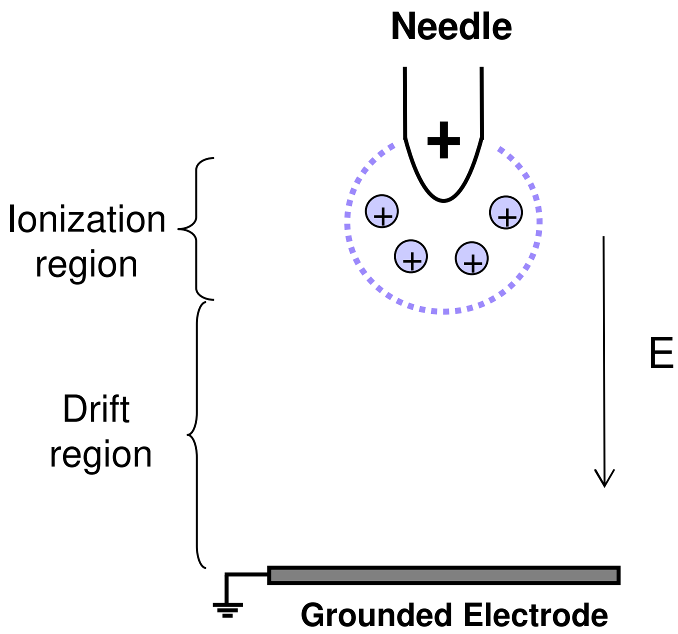
1) Volume needle-to-plate corona discharges

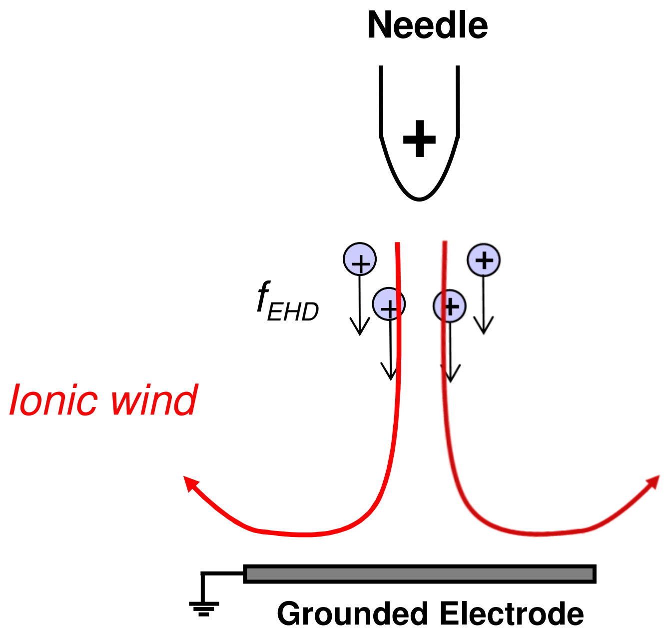
2) Surface dielectric barrier discharges

3) Plasma-induced liquid flows

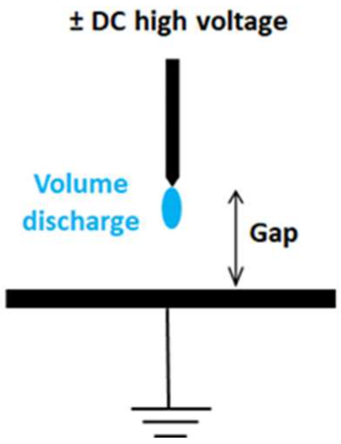
What is ionic wind?

- **Corona discharge**
  - **Flow generated by the motion of electrical charges in corona discharges**
  - Positive high voltage at the needle → positive ions around the needle
  - **Electro-Hydro-Dynamic (EHD) force** (N/m³) : $\vec{F}_{EHD} = \rho \times \vec{E}$
  - Sum of all the Coulomb's forces acting on every positive ions
  - Under f_{EHD}, ions drift toward the grounded electrode and exchange momentum with air molecules
  - All the ions, atoms and molecules are dragged → **ionic wind**

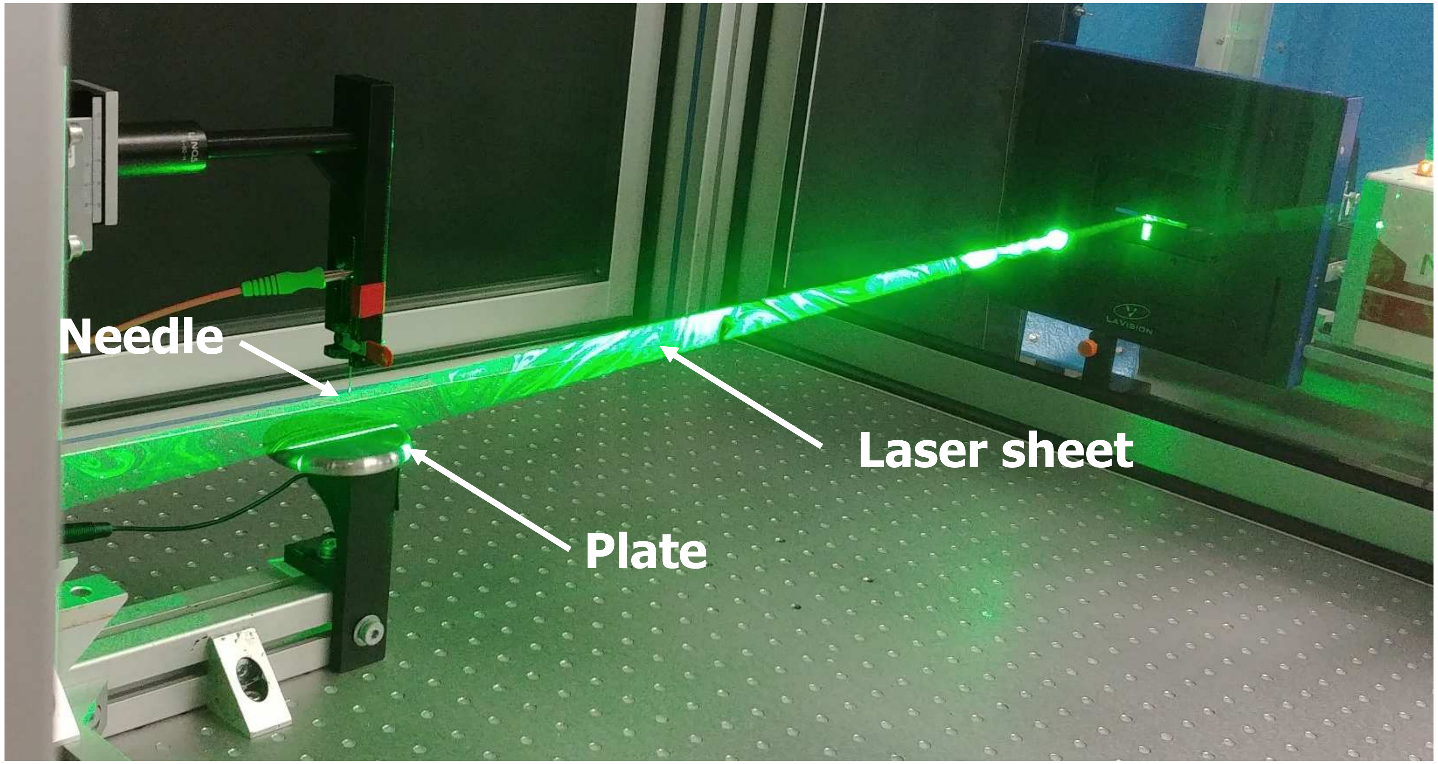




Visualisation of ionic wind



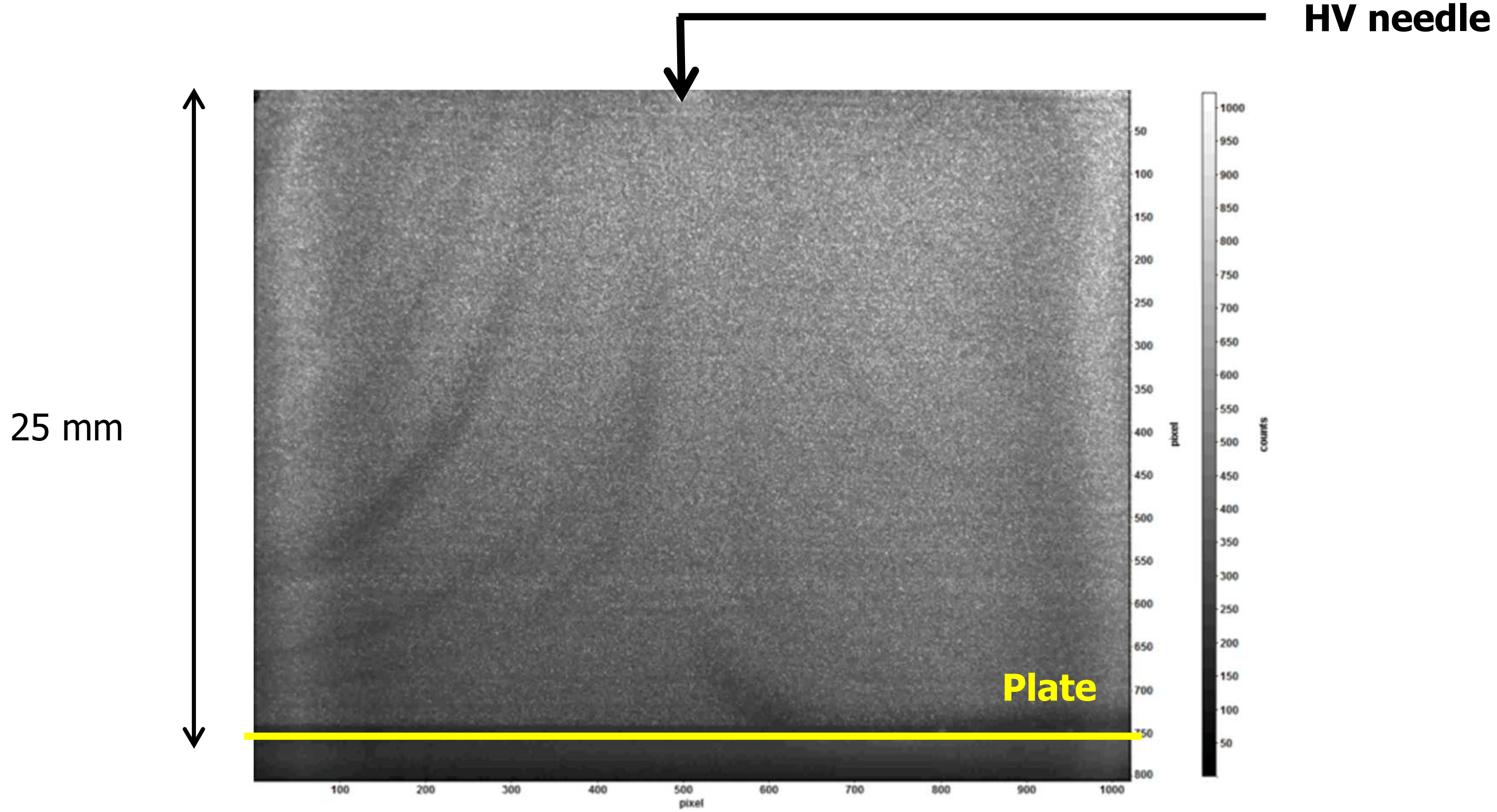
- **How ?**
- ⇨ We introduce seeding particles (0.3 µm) in a closed box (**in quiescent air**)
- ⇨ The 2D plane between the needle and the plate is lighted with a laser sheet
- ⇨ Switch on the discharge → the particles are dragged by the produced ionic wind
- ⇨ **We film the motion of the particles that follow the ionic wind**



Visualisation of ionic wind

- **Video at 20 kHz**
- **Positive needle-to-plate corona**
- HV is witched on → production of a jet from the needle

  → jet impacts the plate after a few ms

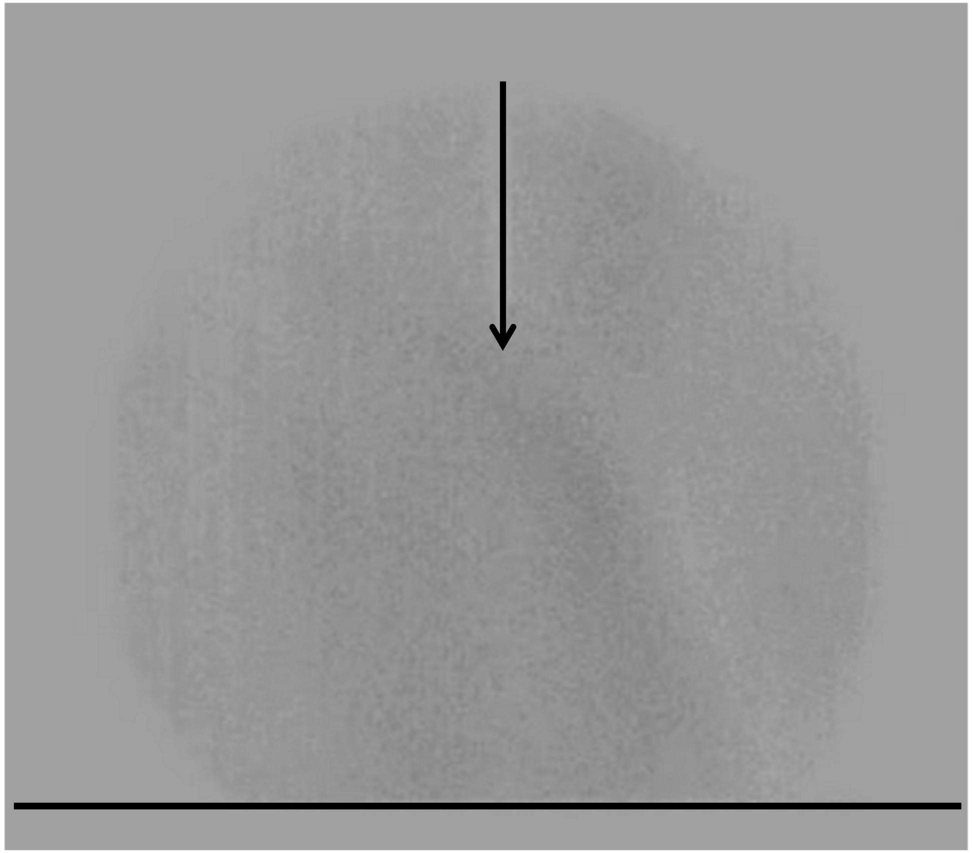


Schlieren visualisations

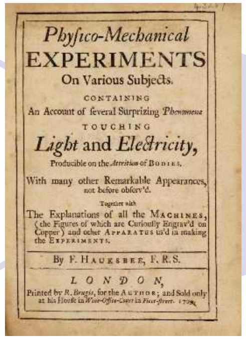
- **Time-resolved visualizations (2 kHz)**

⇨ **Allows us to see the density gradients** due to refraction indice variation

⇨ The discharge heats the air → the heated air is convected, resulting in density gradients due to the ΔT



History of ionic wind

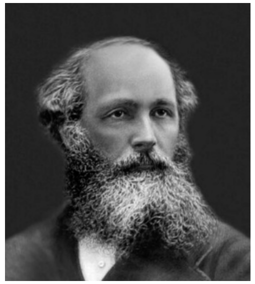


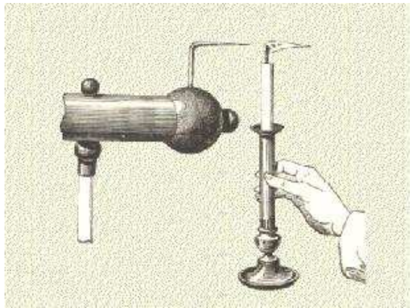
- **At the beginning …**

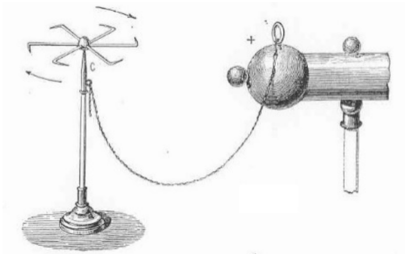
➪ Francis Hauksbee **made the earliest report of ionic wind in 1709**

➪ In 1838, **Faraday** explained that ionic wind was due to momentum transfer from charged particles

➪ **Maxwell** gave a more precise explanation of the phenomenon in 1876







> The charged particles of air tend to move off in the same general direction, and thus produce a current of air from the point, consisting of the charged particles, and probably of others carried along by them. By artificially aiding this current we may increase the glow, and by checking the formation of the current we may prevent the continuance of the glow.

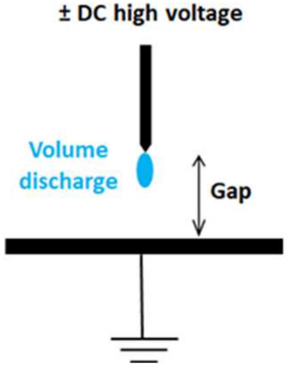
- **More recently**

➪ Well-known publications of Robinson in 60's (1961) on **electrostatic blowers**

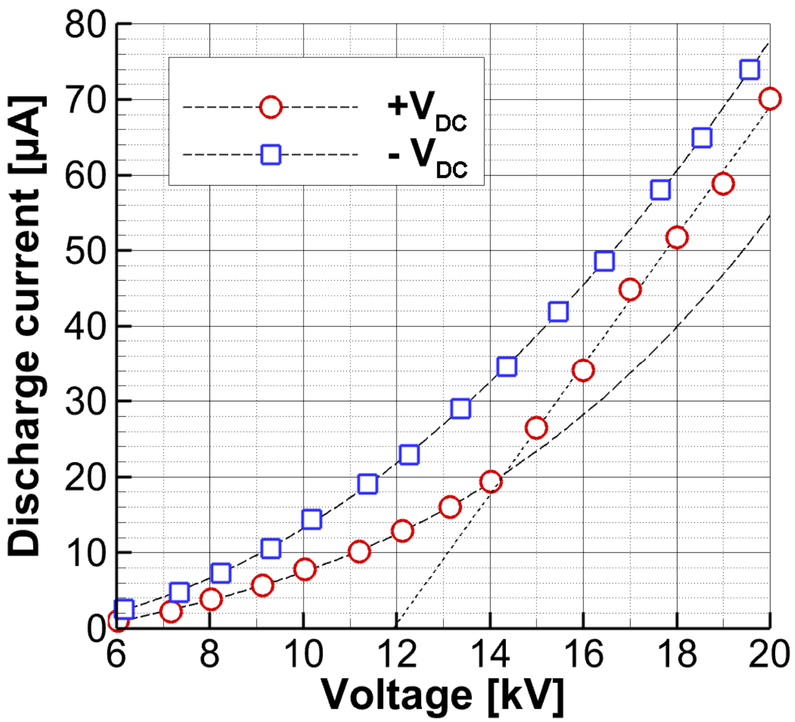
➪ But only the time-averaged phenomenon was described

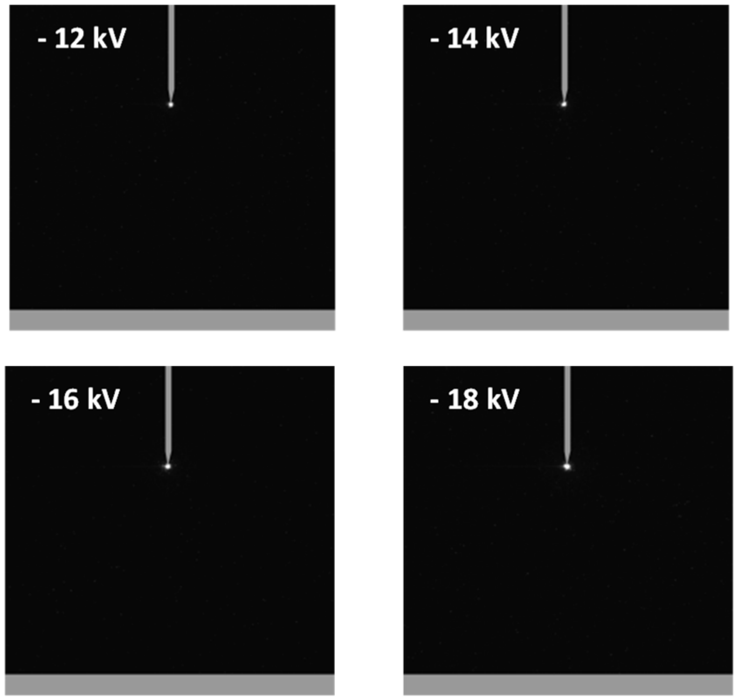
➪ Moreau E, « **On the phenomenon of ionic wind producec by corona discharges** », *J. of Electrostatics*, 2025.

Electrical and optical measurements



- **Negative corona**
  - I-V curve can be well fitted by Townsend law $I = C \times V\,(V - V_0)$
  - i(t) is constant (small Trichel pulses) $\rightarrow$ **negative glow discharge** (« corona » or « diffuse »)
- **Positive corona**
  - From +14 kV, **the measured current is higher than the predicted one** $\rightarrow$ **Why ?**



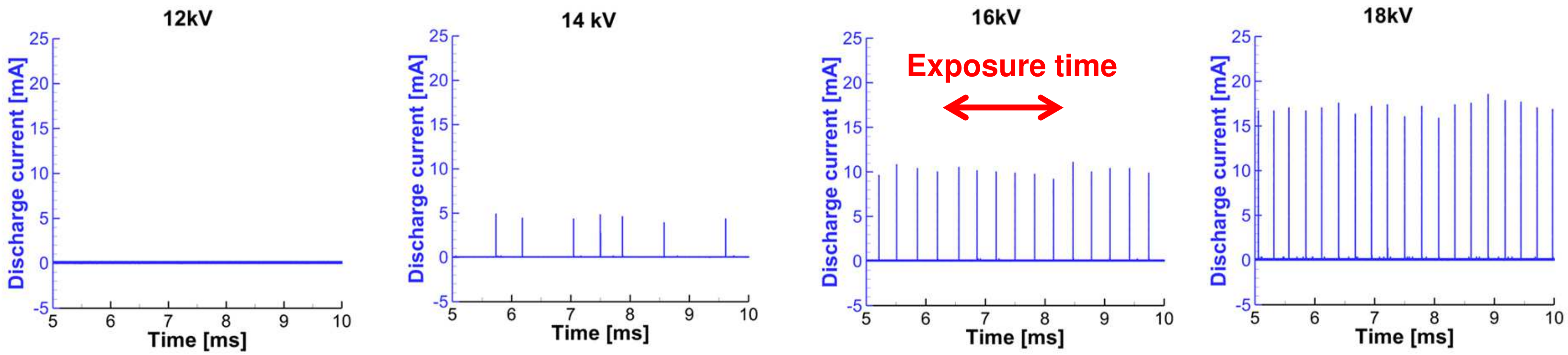


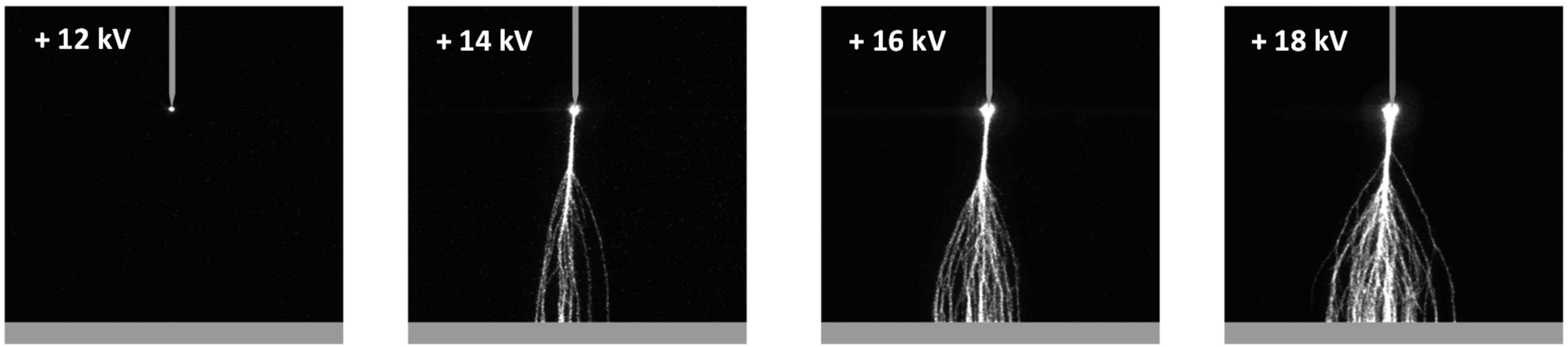
Positive corona discharge

- **<u>Current vs time and iCCD visualizations</u>**

➪ When V < +14 kV → discharge current is only composed of a dc component → **glow discharge**

➪ From V = +14 kV, current peaks → **breakdown streamer discharge**





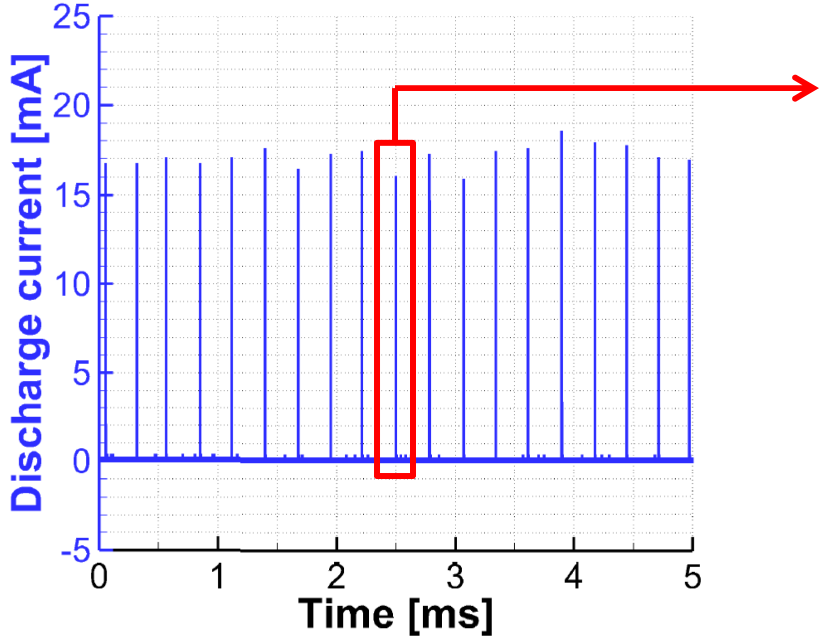
What about these current peaks ?

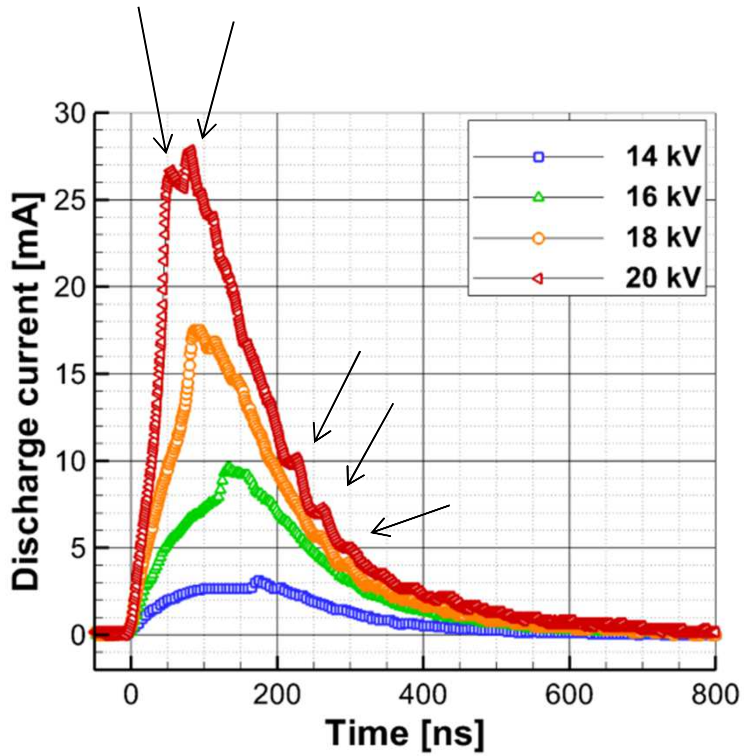
▶ **Zoom view**

➪ Streamer velocity ≈ 1 mm/ns (10^6 to 10^8 cm/s) → 25 ns to travel the gap of 25 mm

➪ In our case, current peak duration ≈ 300 ns → it cannot be only one single streamer

➪ **Primary and secondary streamers + branching**



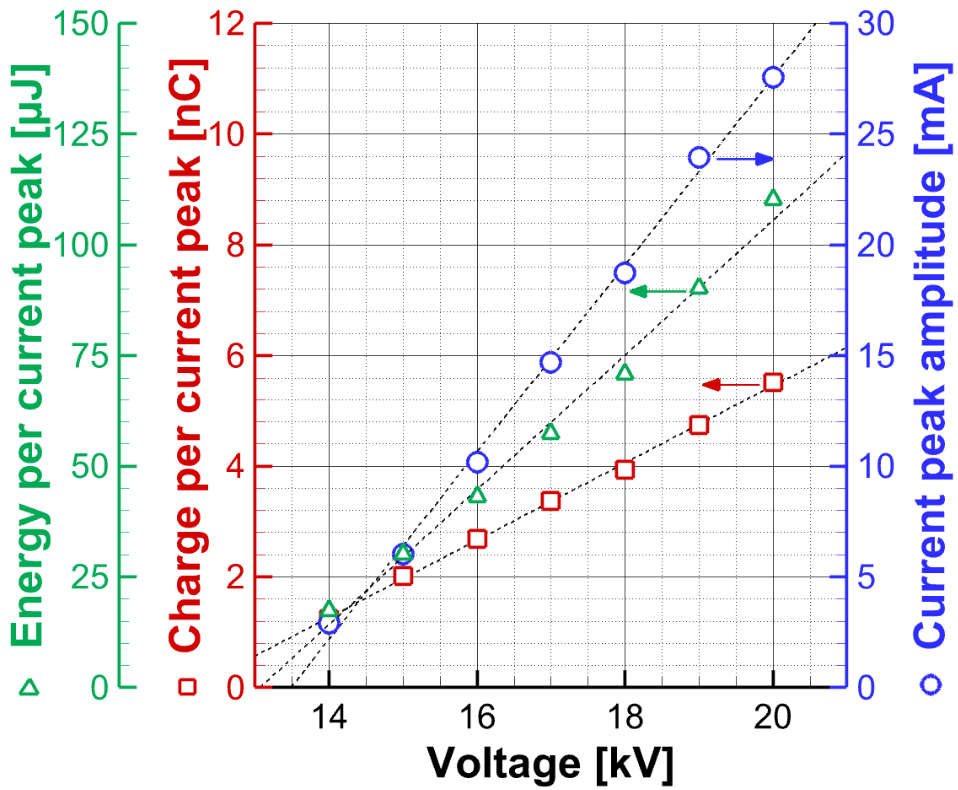


One peak

▶ **Positive corona**

⇨ Current peak amplitude, charge, energy ↗ linearly with DC voltage

⇨ At +16 kV → **current peak ≈ 10 mA, frequency ≈ 3 kHz**, Energy ≈ 40 µJ, Q ≈ 3 nC



PIV for ionic wind

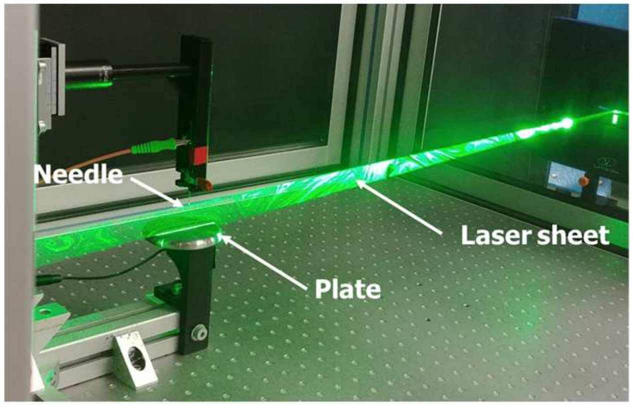
- **Particle Image Velocimetry (called PIV !)**

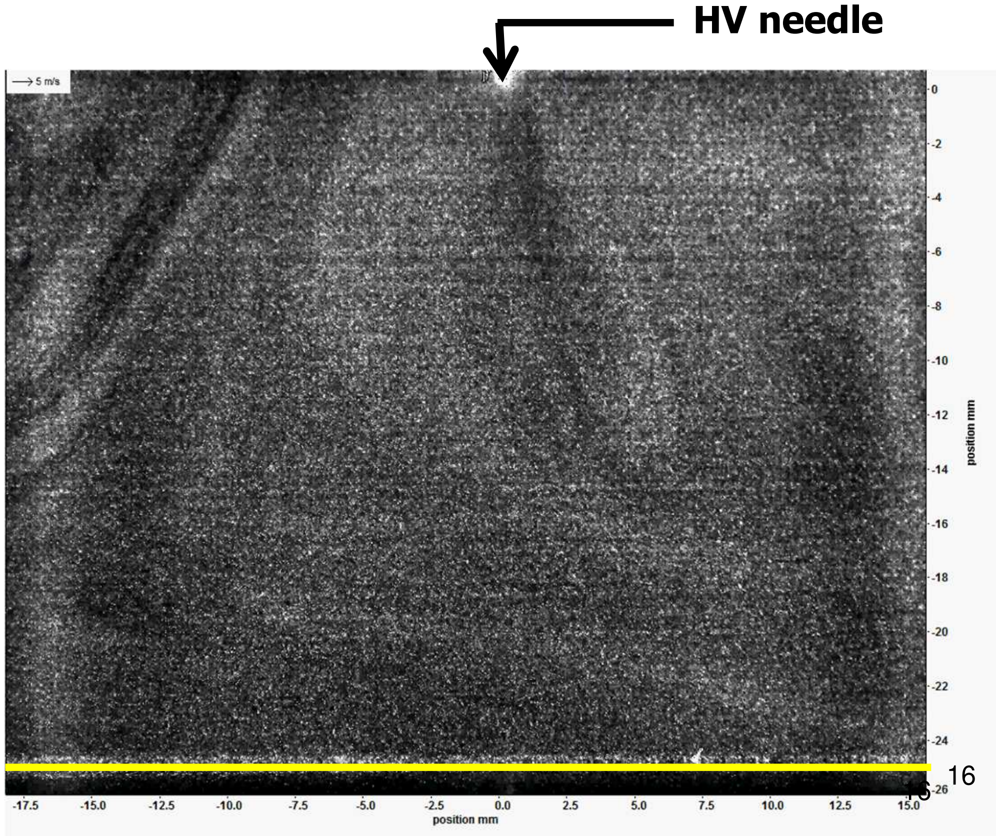
➪ High speed camera/laser at 20 kHz (**temporal resolution = 50 µs**)

➪ One films the particles that are dragged by the produced ionic wind

➪ **Post-treatment allows us to compute the velocity** (everywhere in the plane)

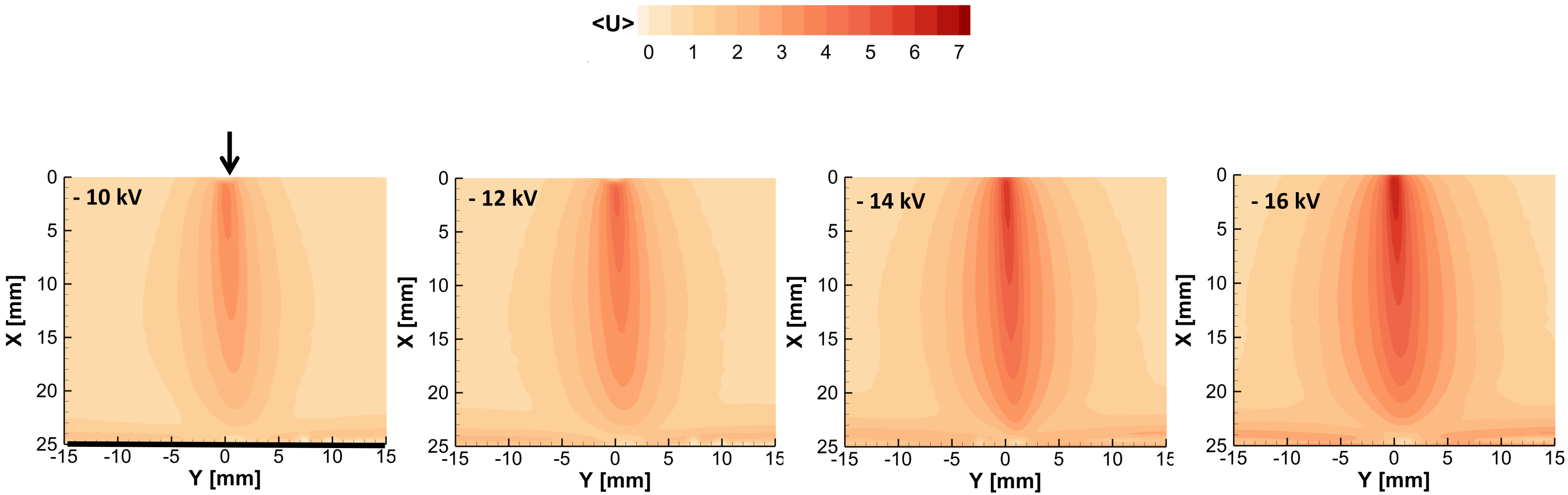
➪ Velocity up to 10 m/s, one 3D toroidal ring





Time-averaged velocity

- **Negative corona**
- ➪ Ionic wind velocity ↗ with voltage
- ➪ Maximum velocity around the needle → **EHD force takes place at the needle** $\vec{F}_{EHD} = \rho \times \vec{E}$



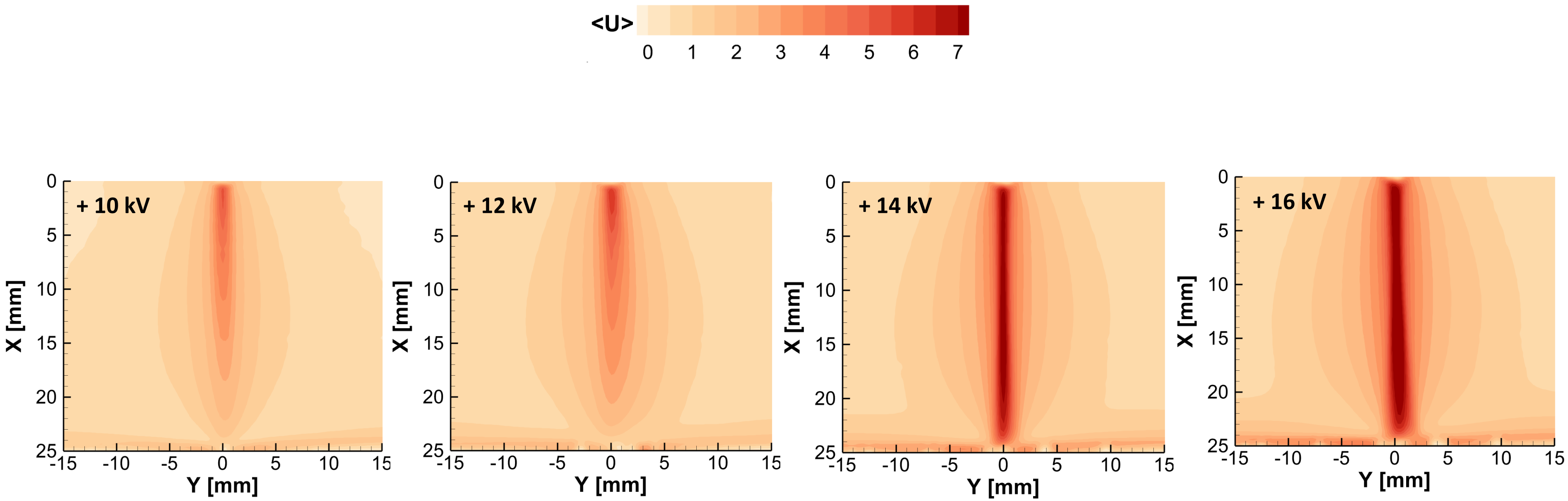
Time-averaged velocity

- **Positive corona**

➪ At V_{DC} = +12 kV, maximum velocity around the needle (as negative corona)

➪ From V_{DC} = +14 kV, constant velocity all along the electrode gap

➪ **EHD force is not limited to the ionization zone**

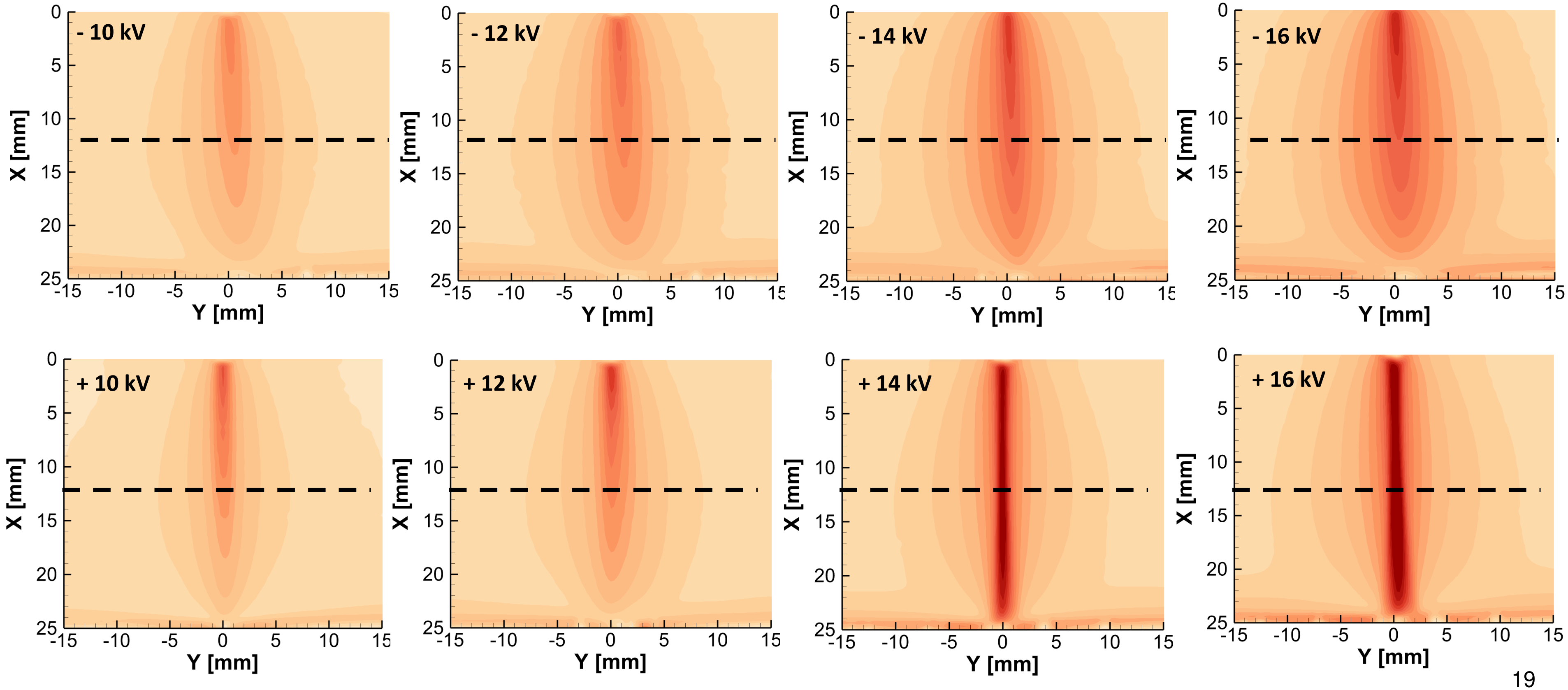


Time-averaged velocity

▶ **Comparison between both discharges**

⇨ In both cases, a jet from the needle toward the plate

⇨ Topology is different, especially for the positive corona from +14kV



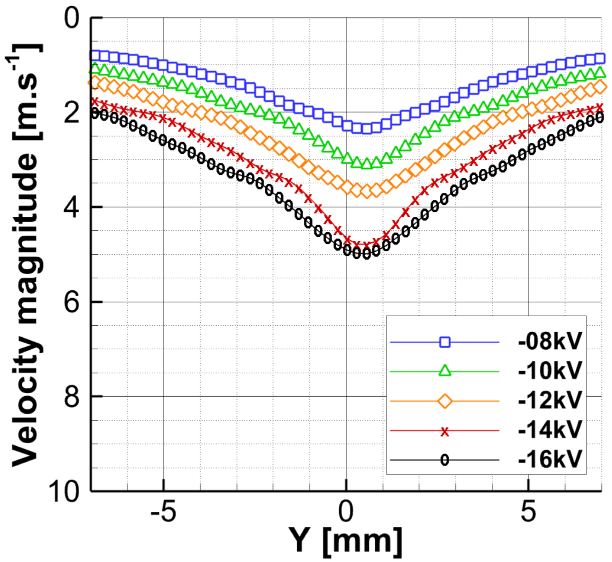
Time-averaged velocity

- **Velocity profiles**

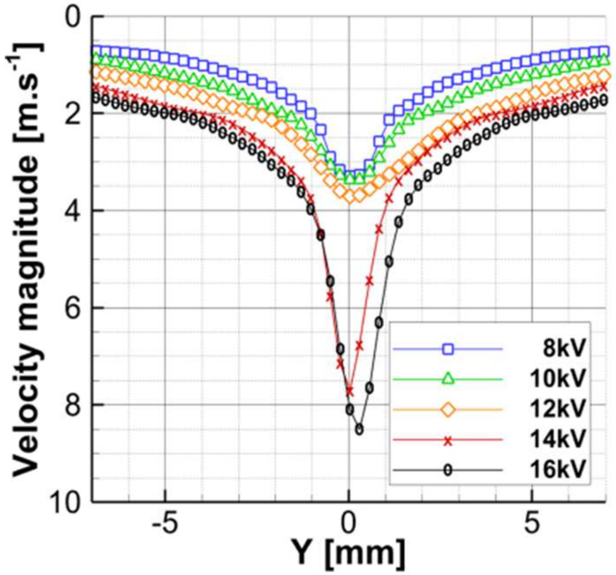
⇨ Negative corona → velocity limited to 5 m/s

⇨ Positive corona → jet is thinner but from +14 kV, velocity reaches 8 m/s

Negative

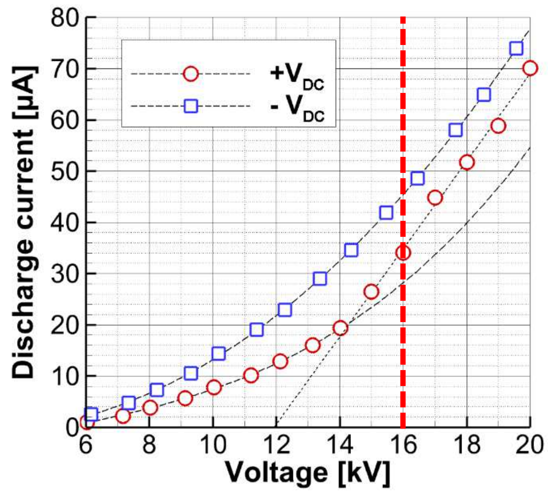


Positive

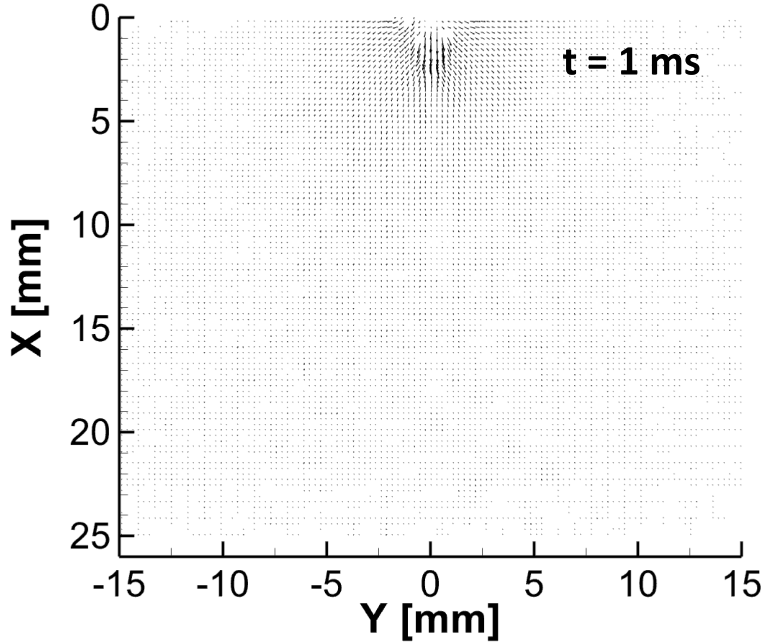


Time-resolved ionic wind

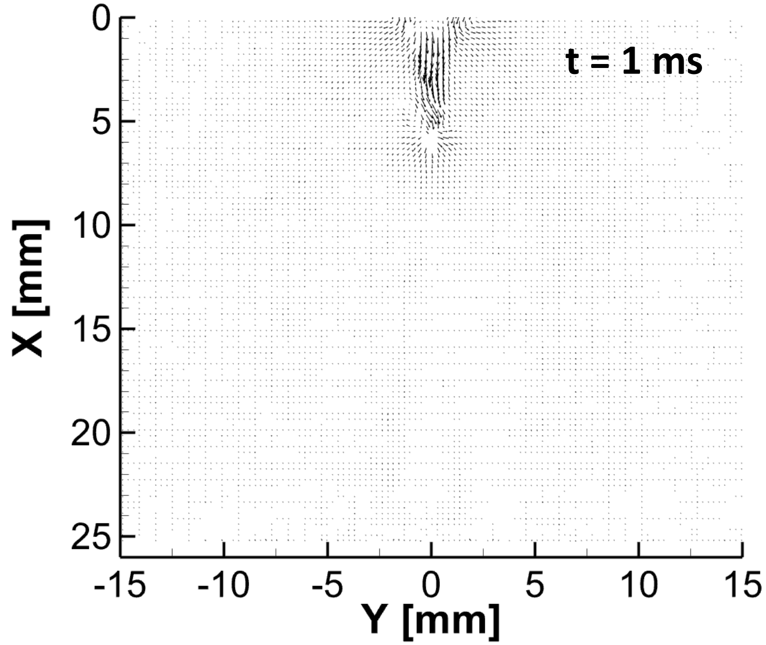
- **Voltage = ±16 kV**
- ➪ Instantaneous velocity fields (HV switched on at t = 0)
- ➪ **The positive ionic wind jet is faster and thinner**



Negative corona discharge



Positive corona discharge



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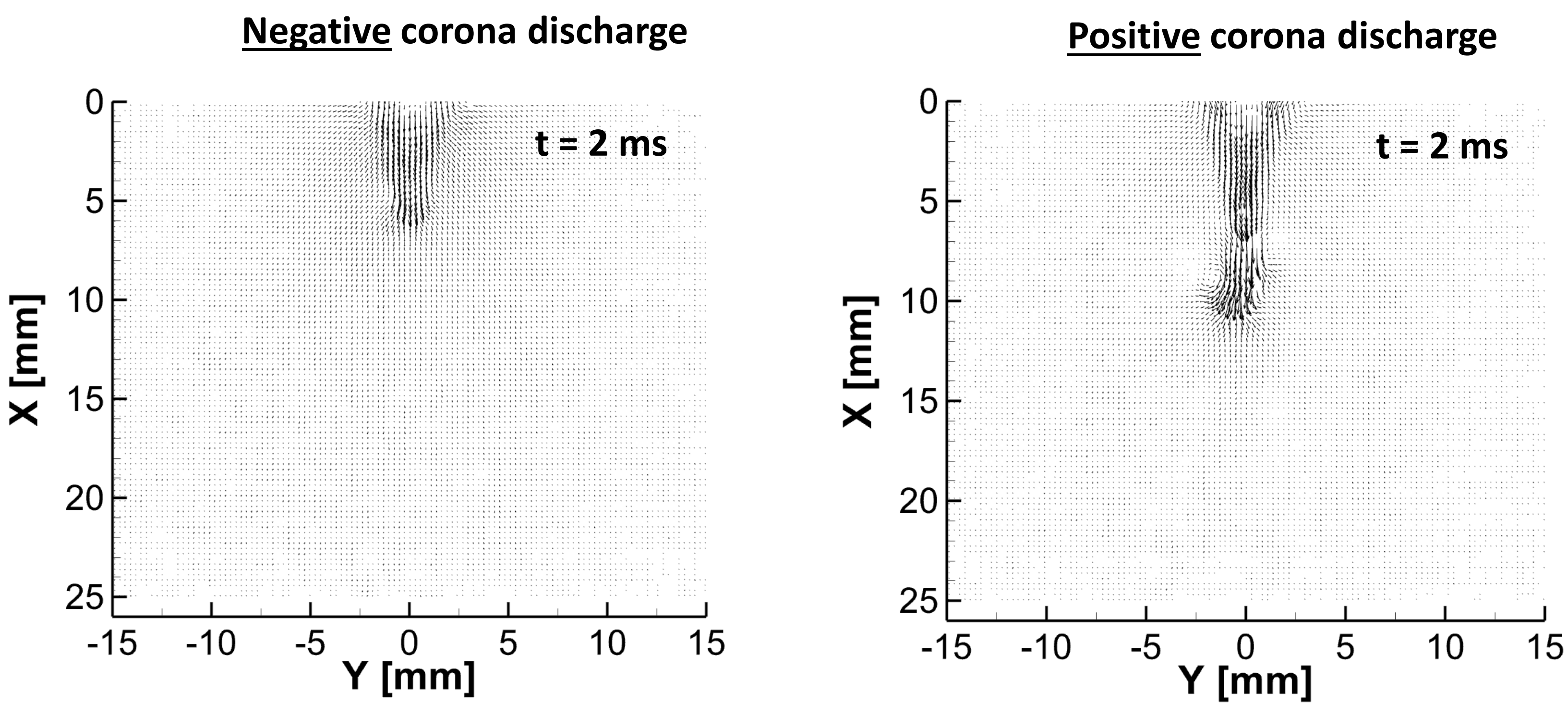

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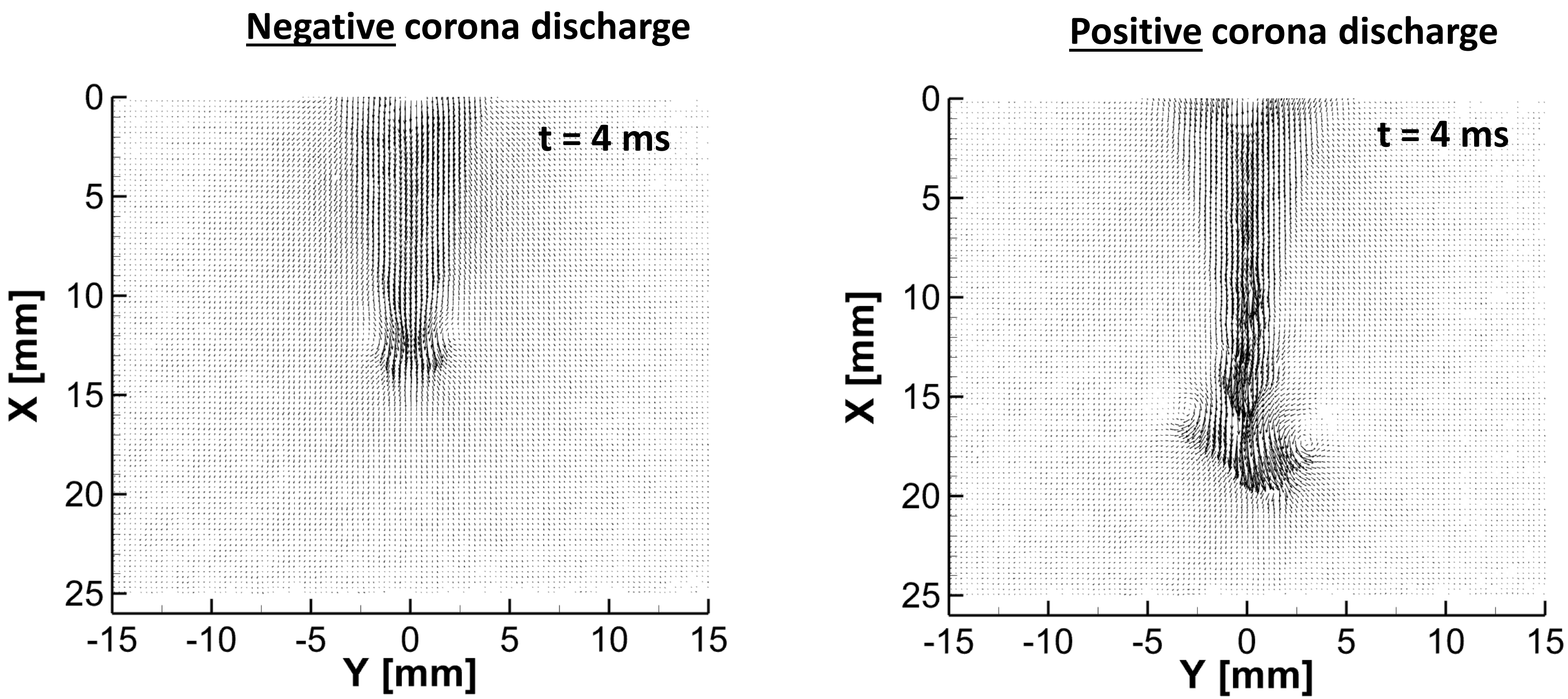

Time-resolved ionic wind

- **Voltage = ±16 kV**

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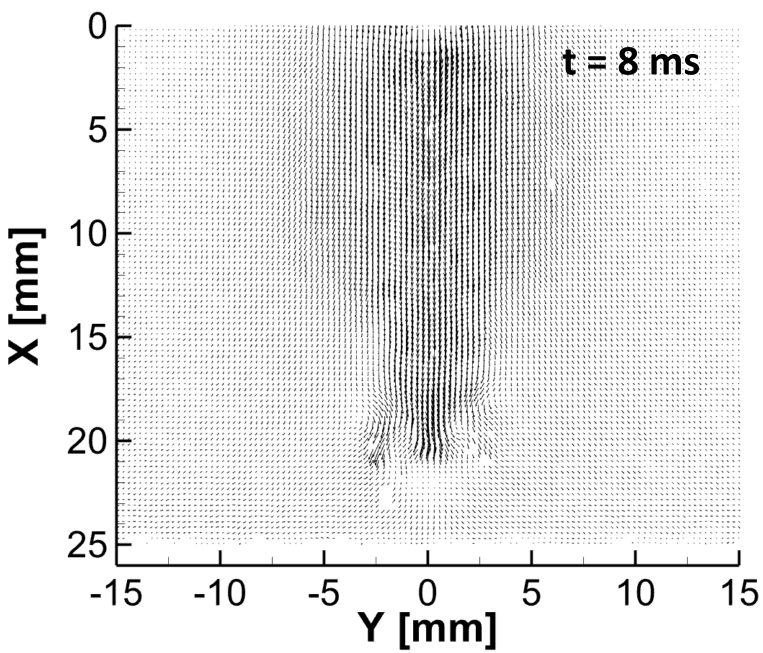
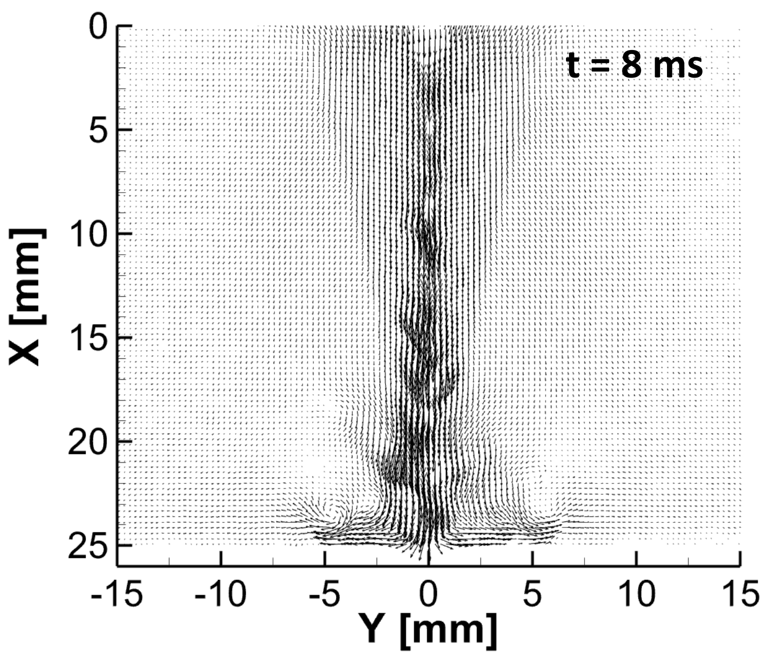
➩ **The positive ionic wind jet is faster and thinner *(and more turbulent)***

Negative corona discharge



Positive corona discharge



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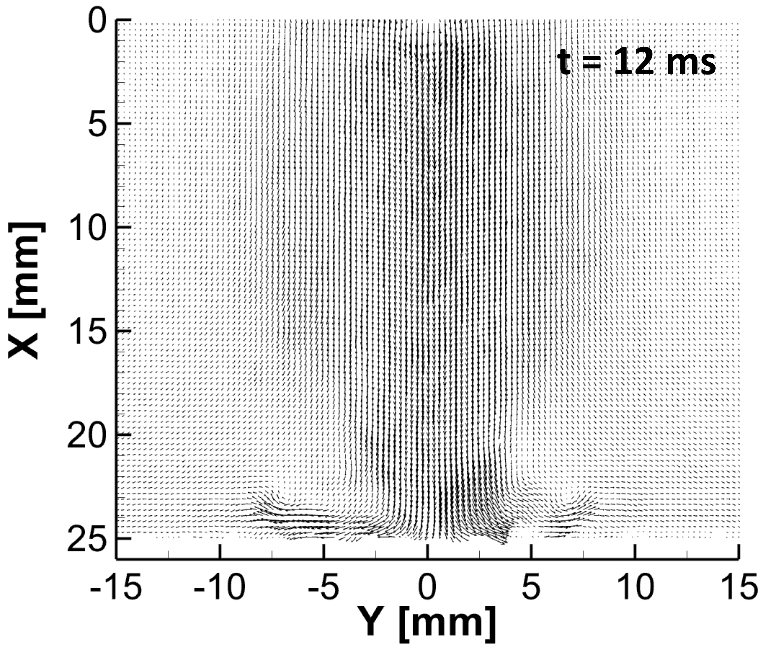
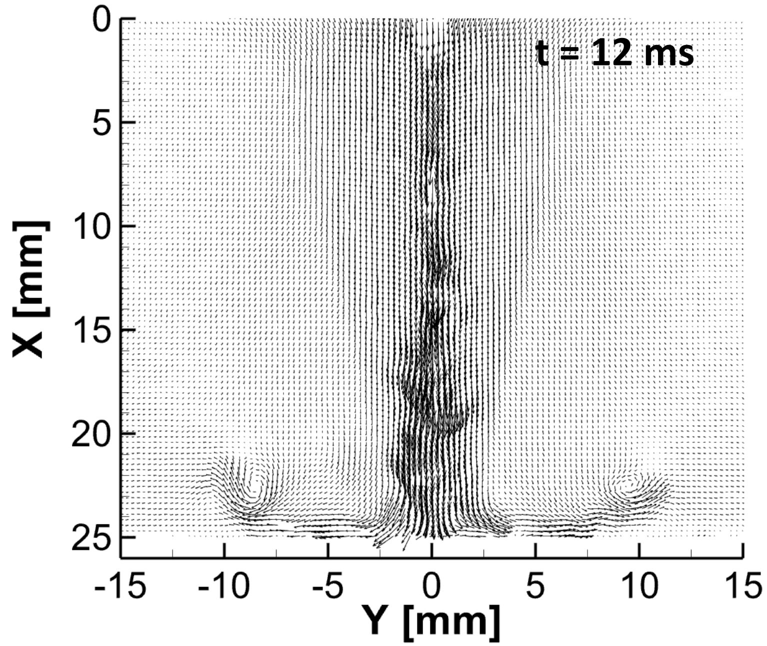


Positive corona discharge

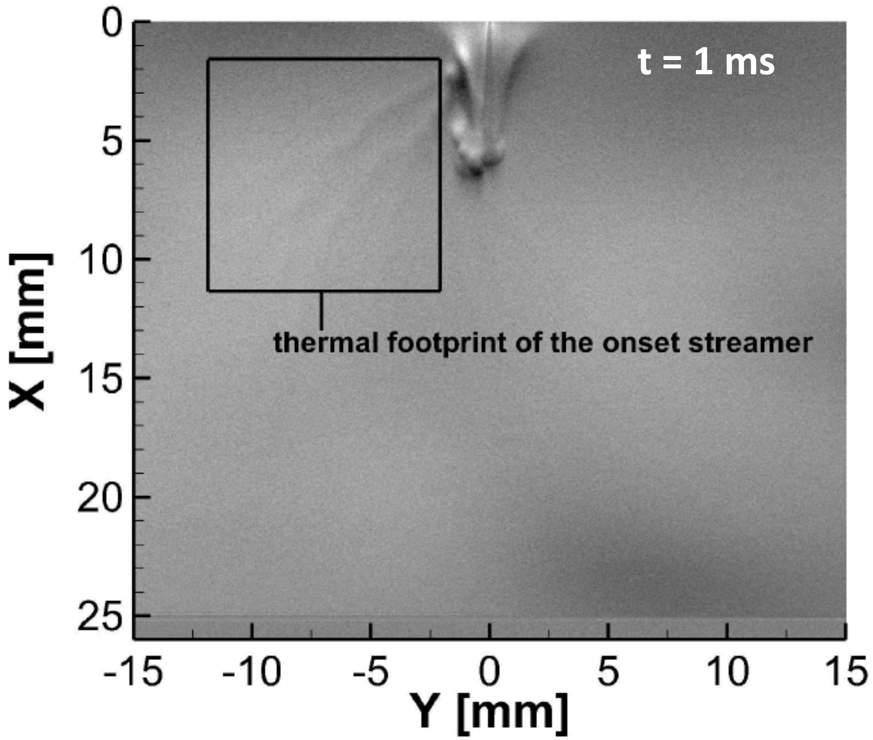


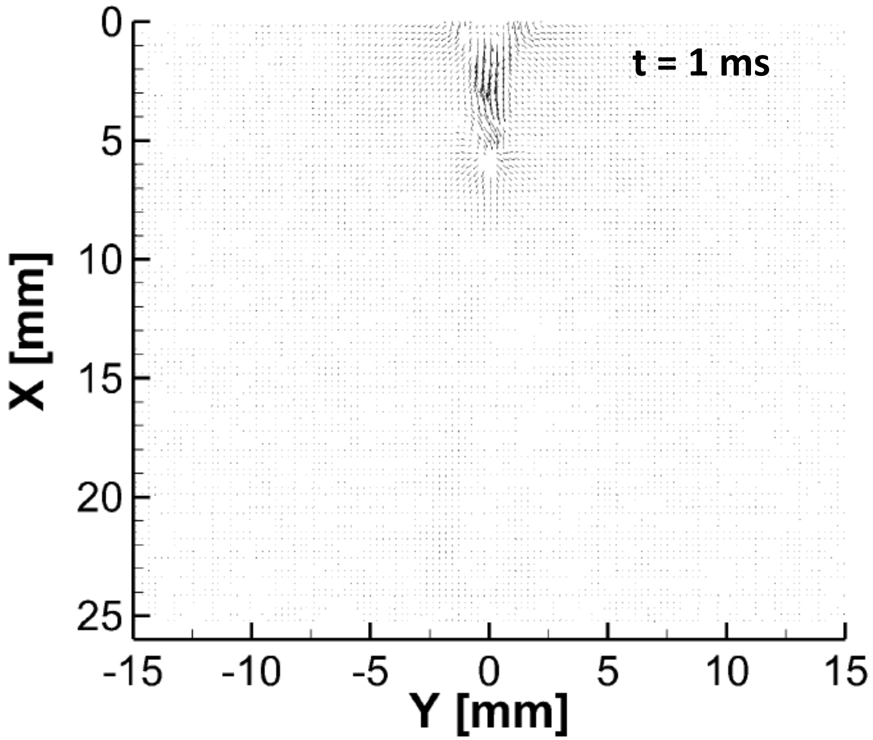
Schlieren vs PIV

▶ **Positive corona at +16 kV**

⇨ Comparison of instantaneous Schlieren visualisations (**no velocity !**) and PIV velocity fields

⇨ Schlieren visualizations do not require seeding particles that can be charged





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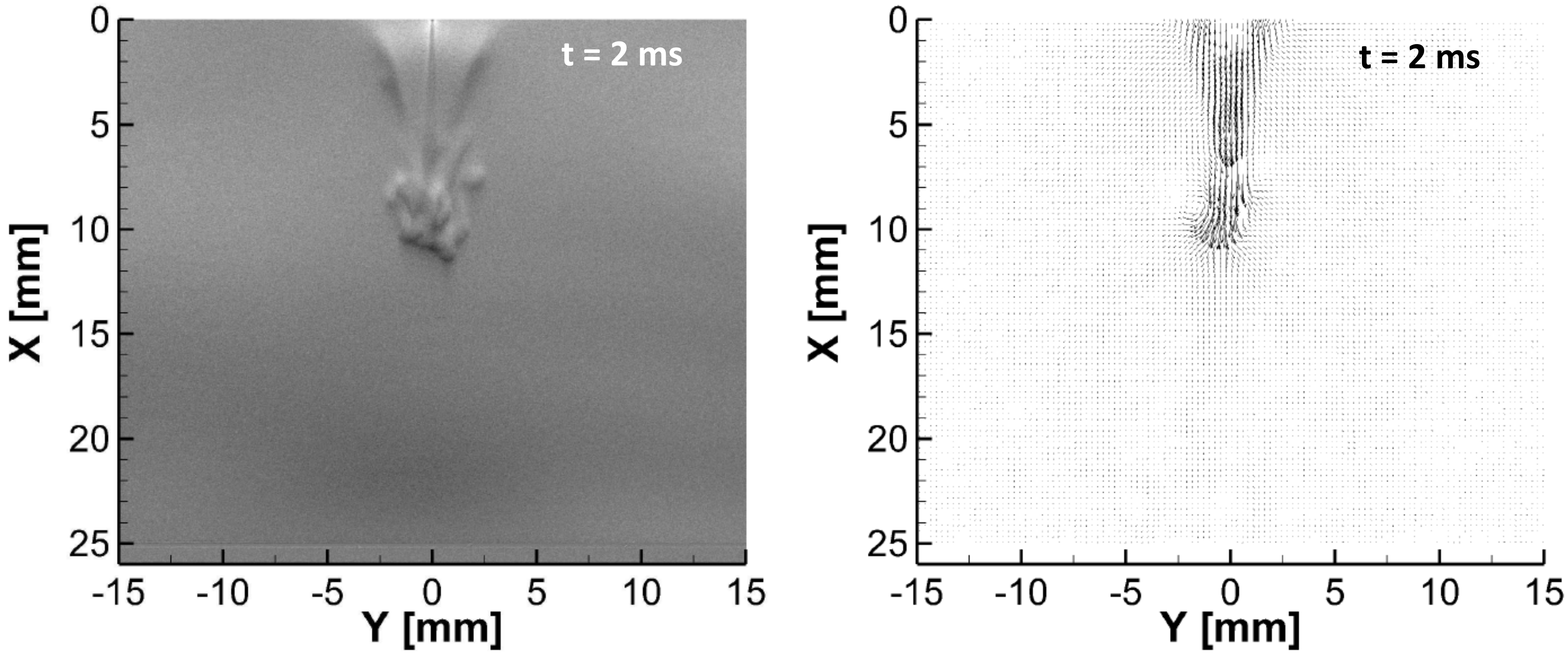

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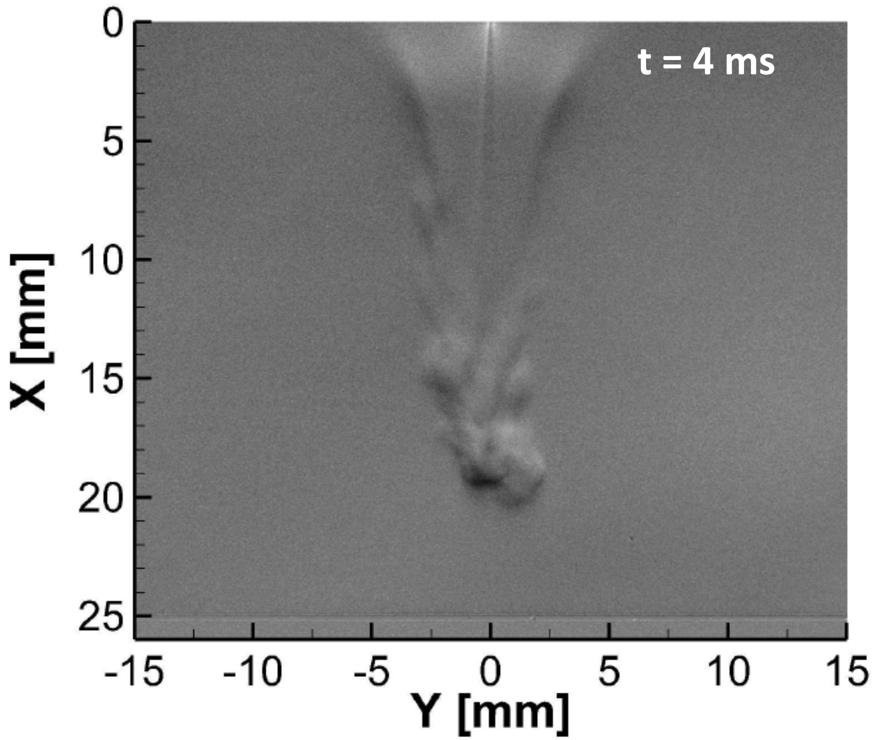
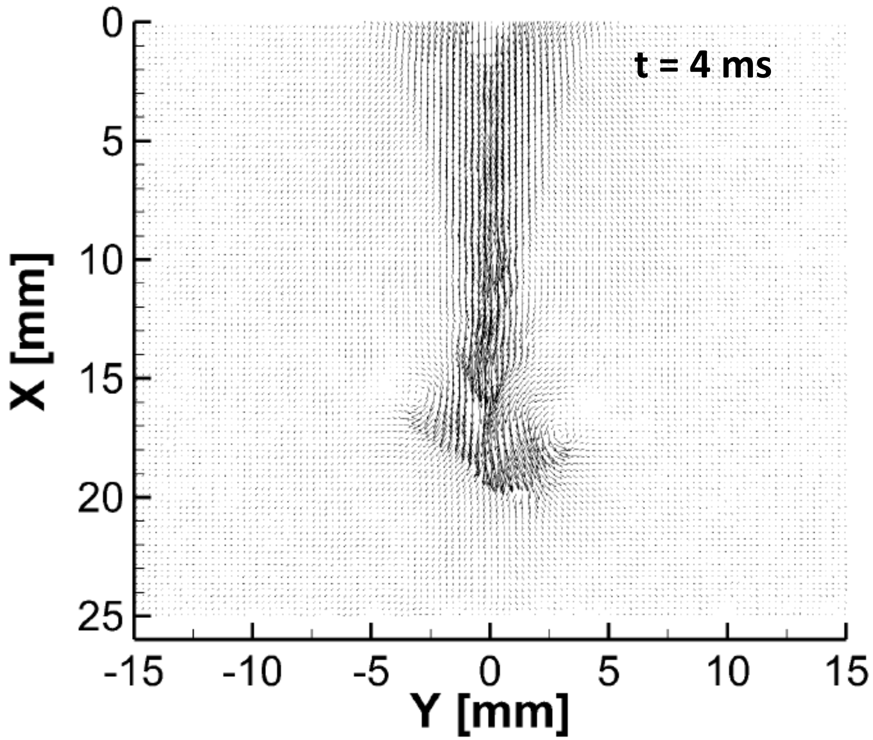




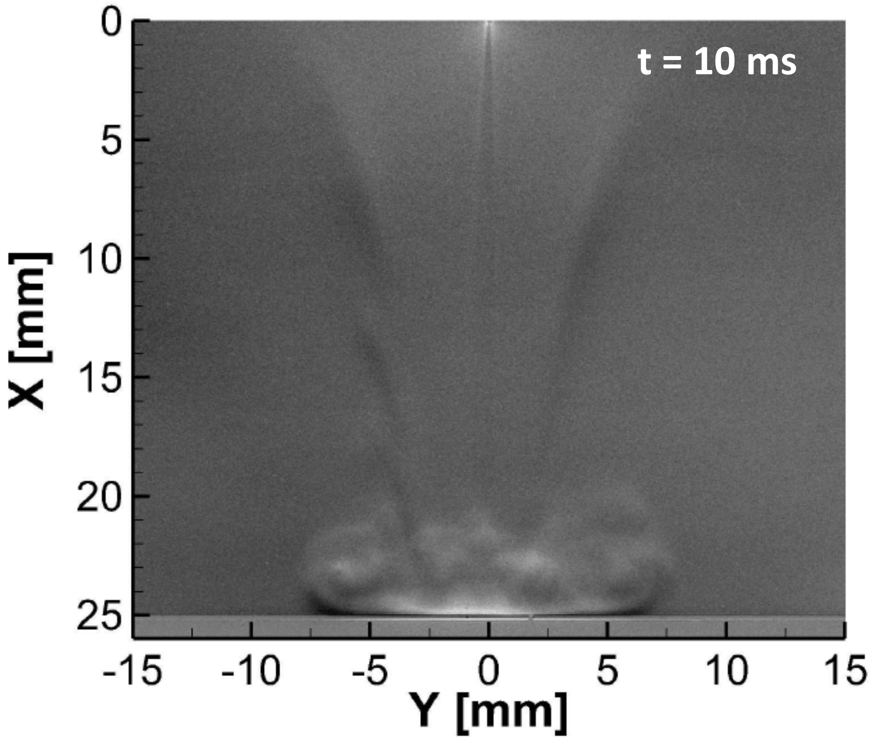
Schlieren vs PIV

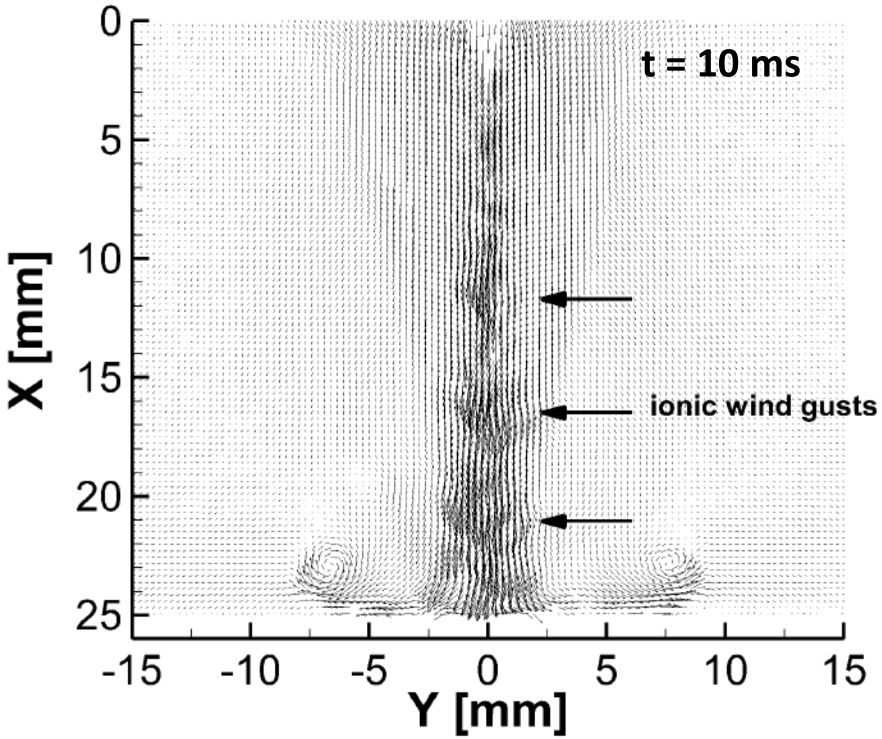
▶ **Positive corona at +16 kV**

➪ Comparison of instantaneous Schlieren visualisations and PIV velocity fields

➪ Schlieren visualizations do not require seeding particles that can be charged

➪ **When using PIV, particles follow the ionic wind trajectory (if well choosen !)**

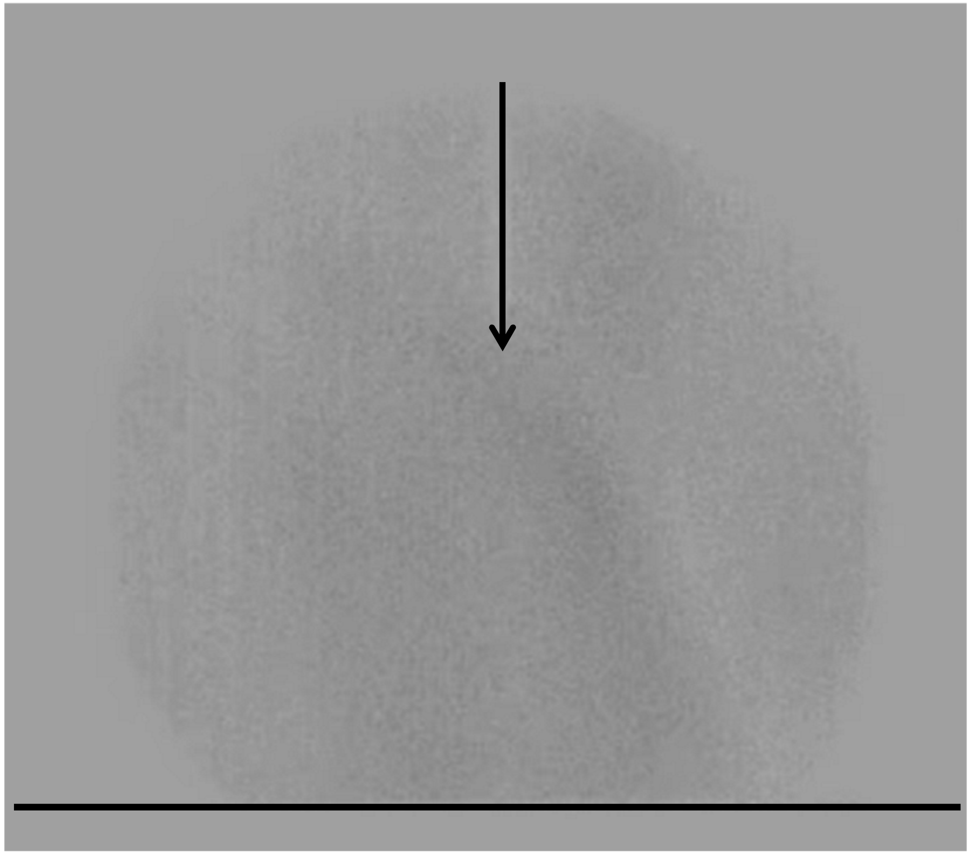




Schlieren visualizations

▶ **Time-resolved visualizations (2 kHz)**

⇨ Positive corona → we can see the « gusts »



Frequency of these gusts ?

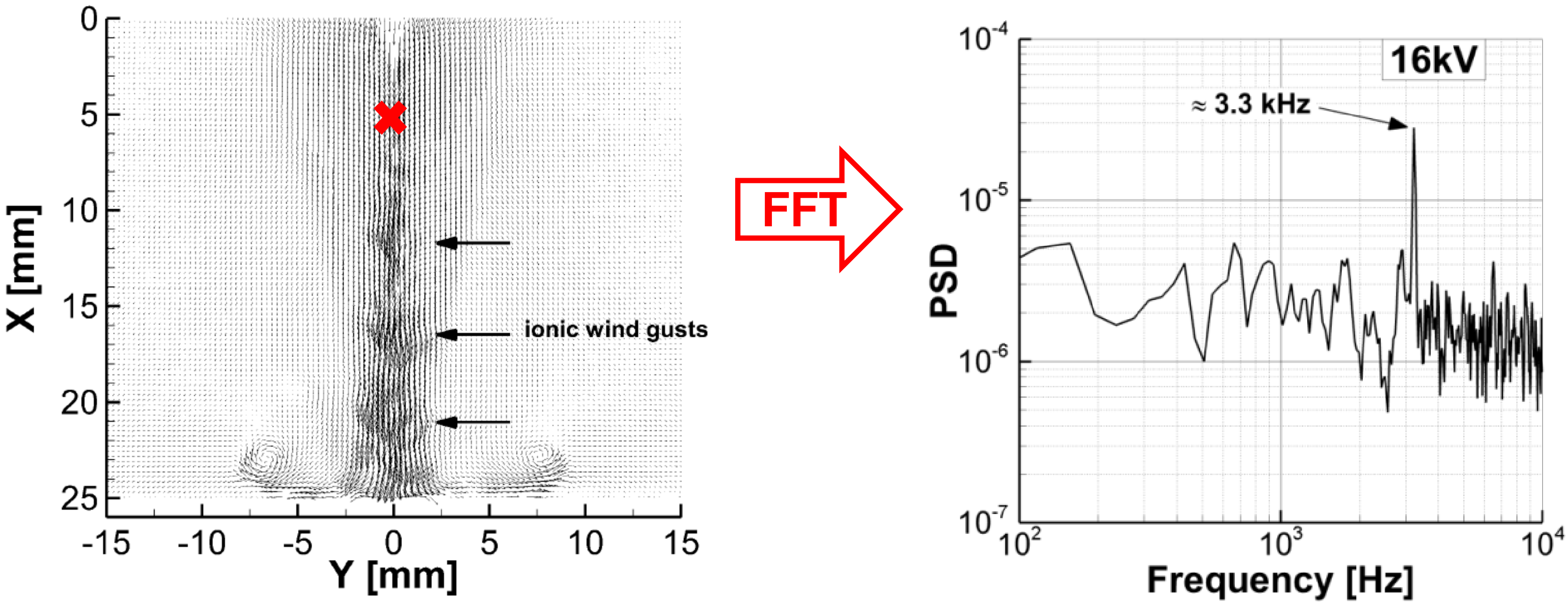
▶ **Power Spectra Density (PSD)**

⇨ Succession of gusts suggests that **the velocity is « pulsed »**

⇨ Fourier transform of ionic wind velocity versus time (PSD)

⇨ Peak at 3.3 kHz meaning that **the ionic wind is pulsed at 3.3 kHz**

⇨ **WHY** ?... It was the first time that this phenomenon was highlighted



Role of streamers in positive corona ?

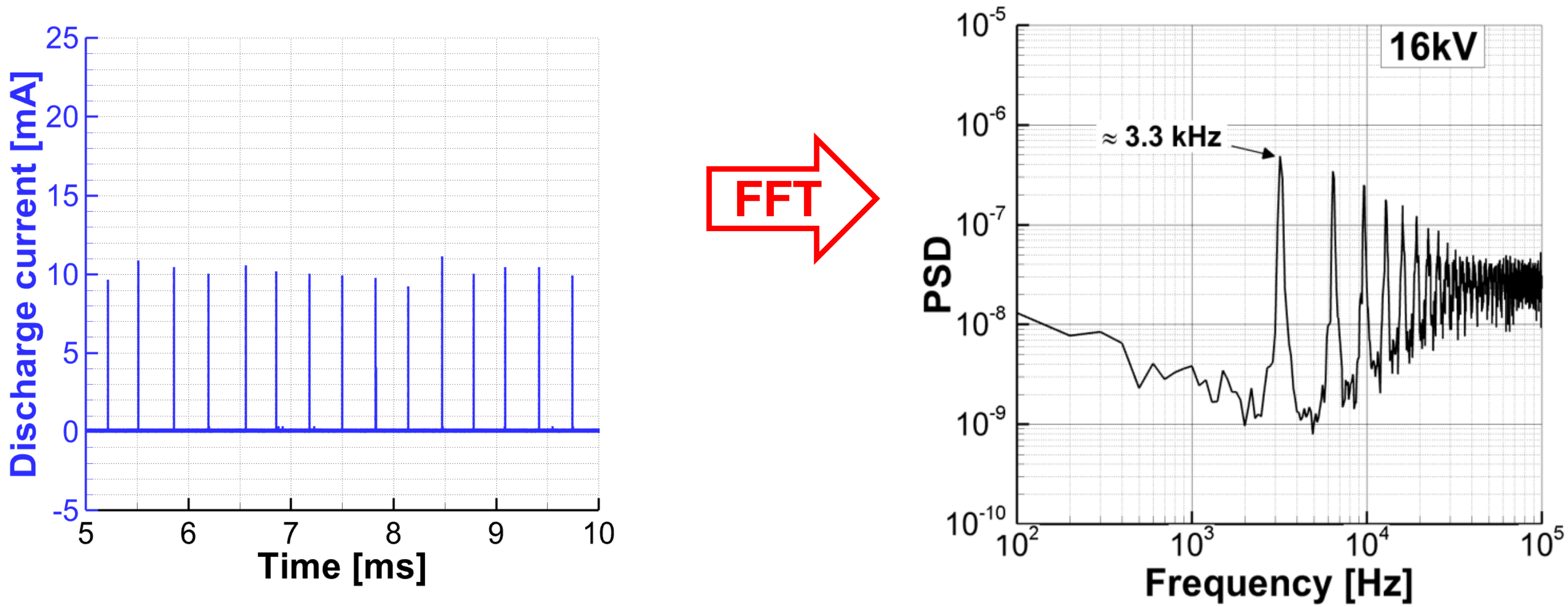
- **Discharge currrent**

➪ FFT of i(t) → spectrum with a peak at 3.3 kHz

➪ Ionic wind frequency = streamer frequency

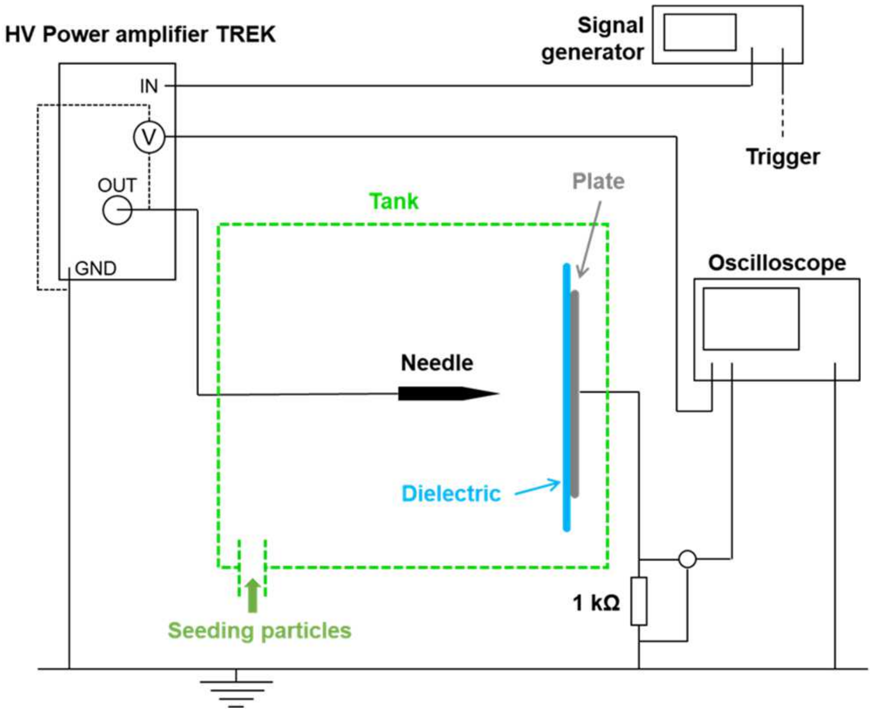
➪ **Every current peak → acceleration of ionic wind**

➪ **Debate → streamers are efficient to produce velocity !**



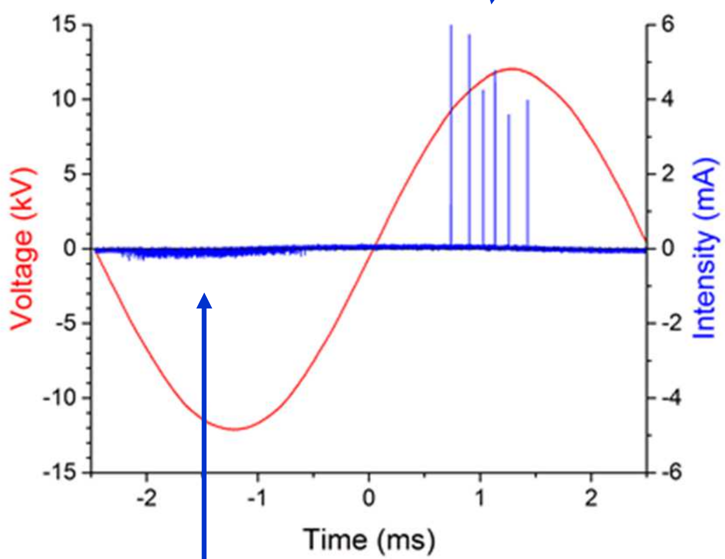
AC corona discharges

- ▶ **Corona with AC voltage**
- ➪ Plate covered with a dielectric, gap = 15 mm
- ➪ **Two discharges per voltage cycle**



Positive streamer discharge

(few mA, few kHz)



Negative glow discharge

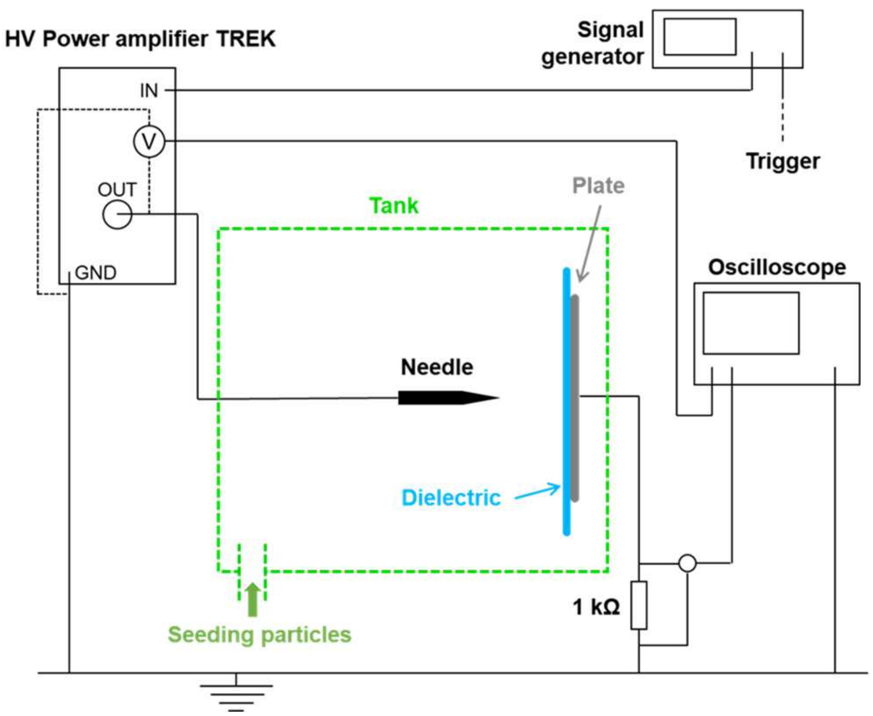
(< 200 µA, 200 kHz)

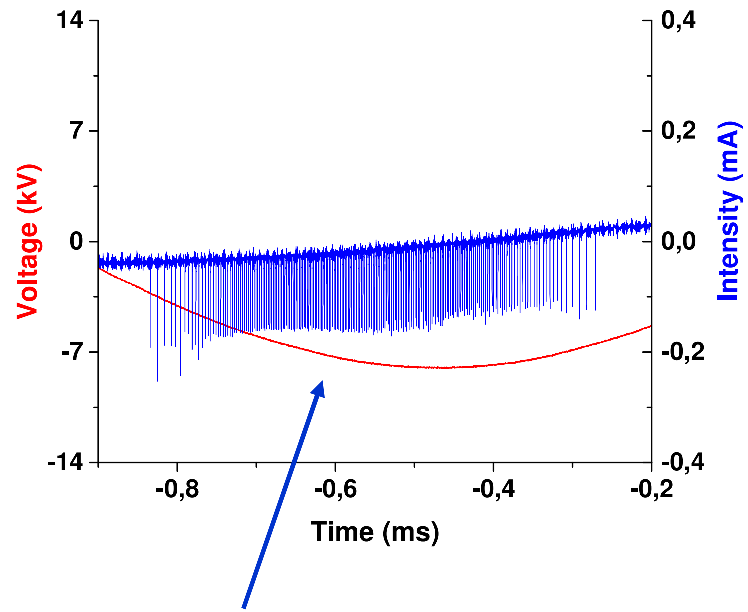
AC corona discharges

- **Corona with AC voltage**

➪ Plate covered with a dielectric, gap = 15 mm

➪ **Two discharges per voltage cycle**





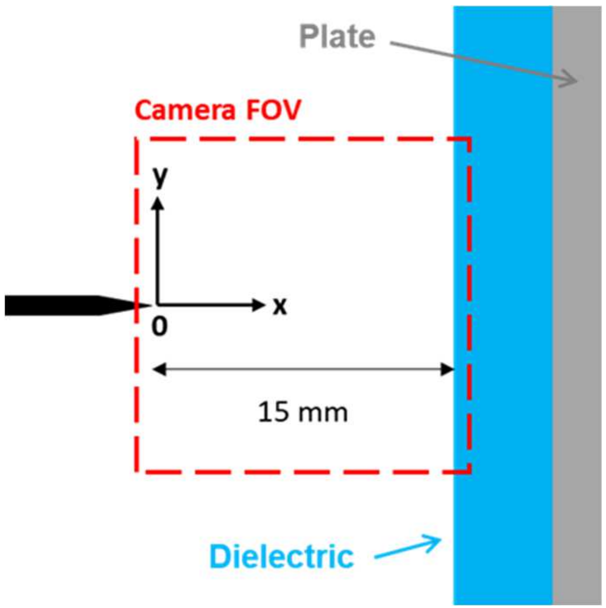
Negative glow discharge

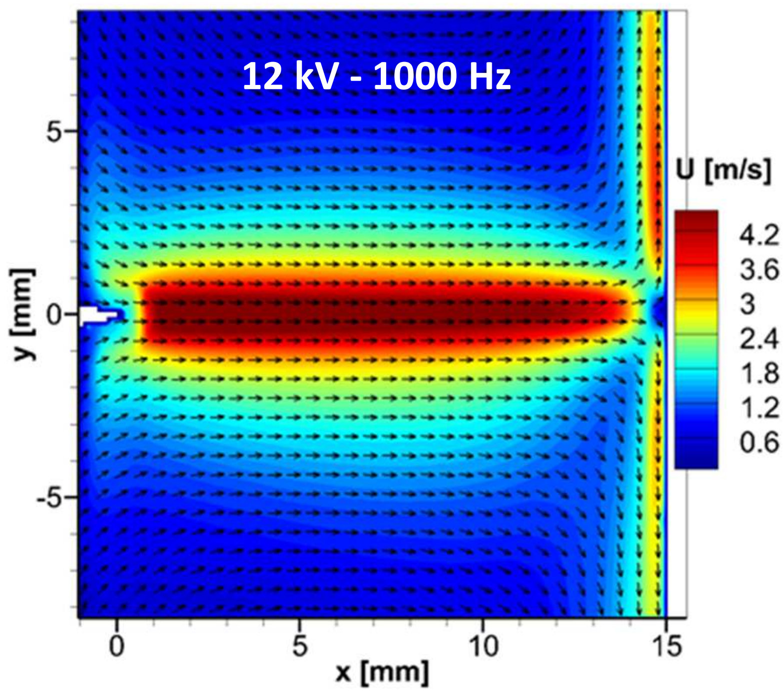
(< 200 µA, 200 kHz)

AC corona discharges

▶ **Corona with AC voltage**

⇨ Time-averaged ionic wind → jet from the needle to the plate, **as for DC**





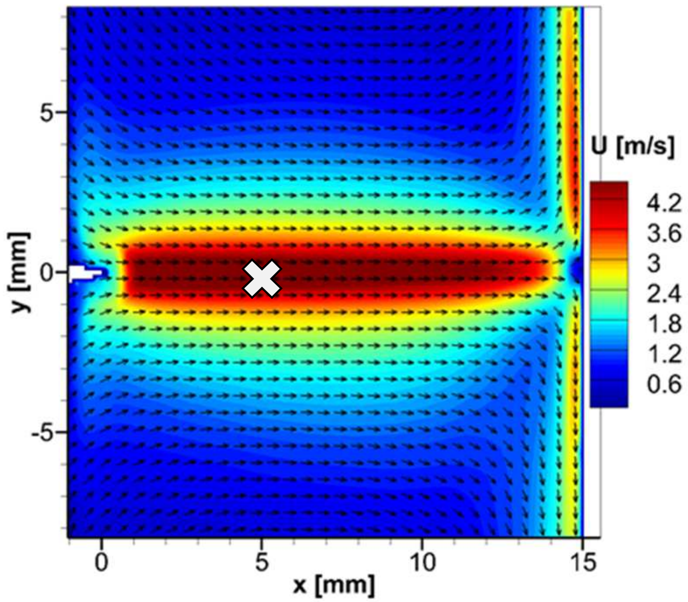
AC corona discharges

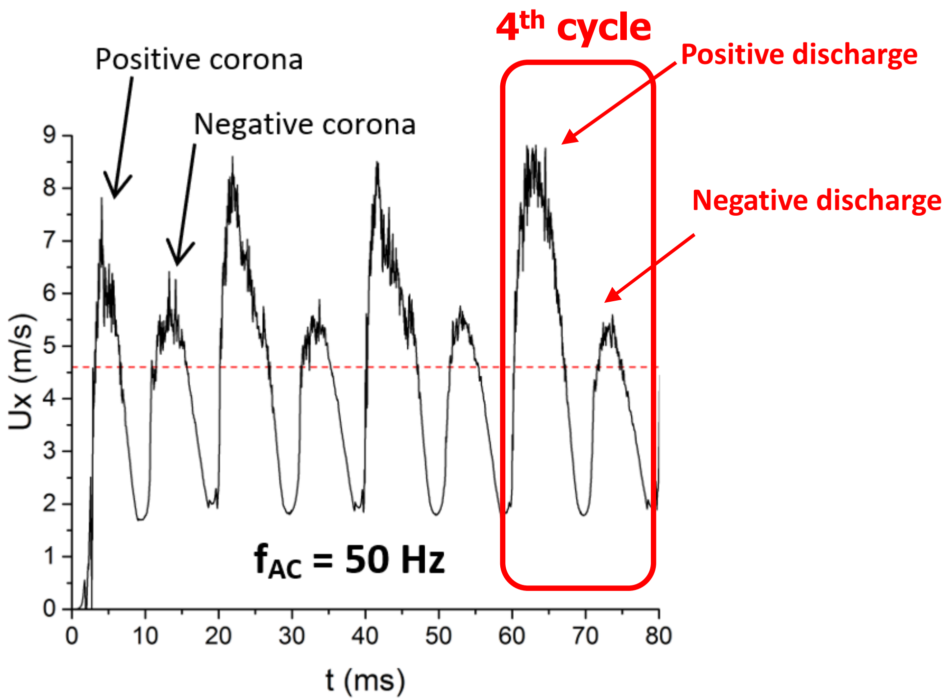
▶ **Ionic wind versus time**

➩ Local instantaneous velocity at x = 5 mm (HV switched on at t = 0, **four periods on the plot**)

➩ Two velocity bumps per sine HV period

➩ **The positive streamer discharge is more effective than the negative glow one**





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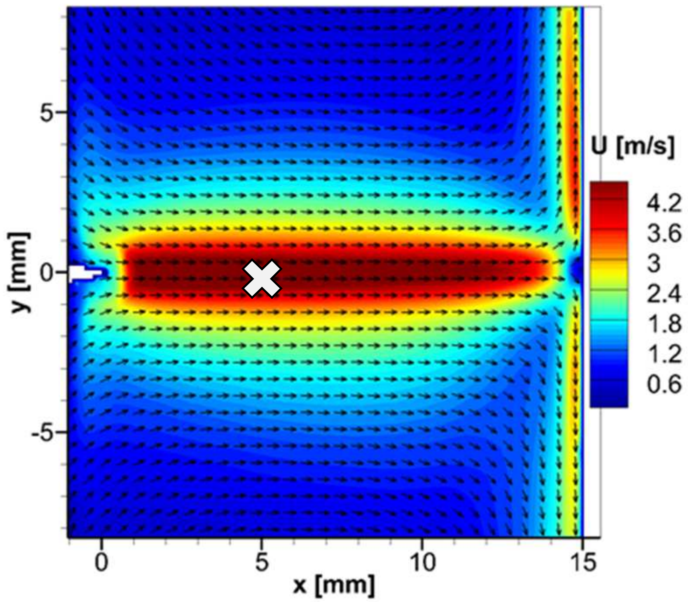
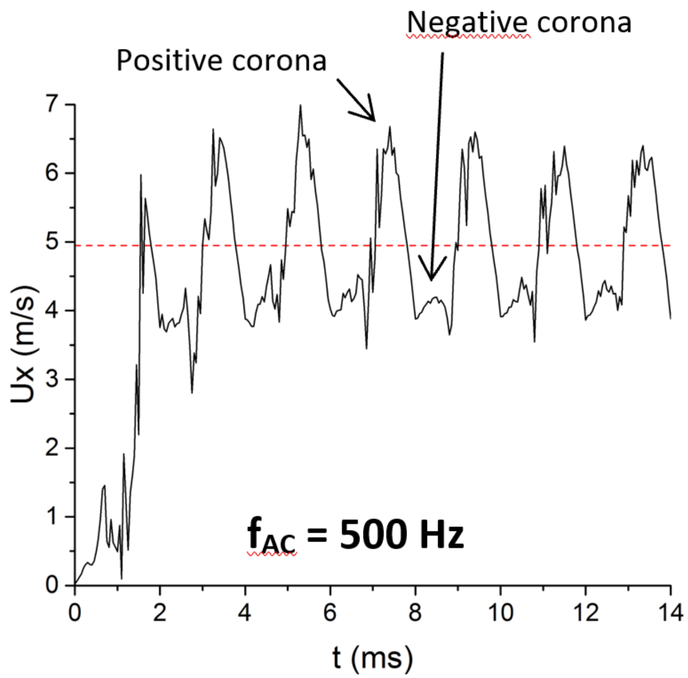


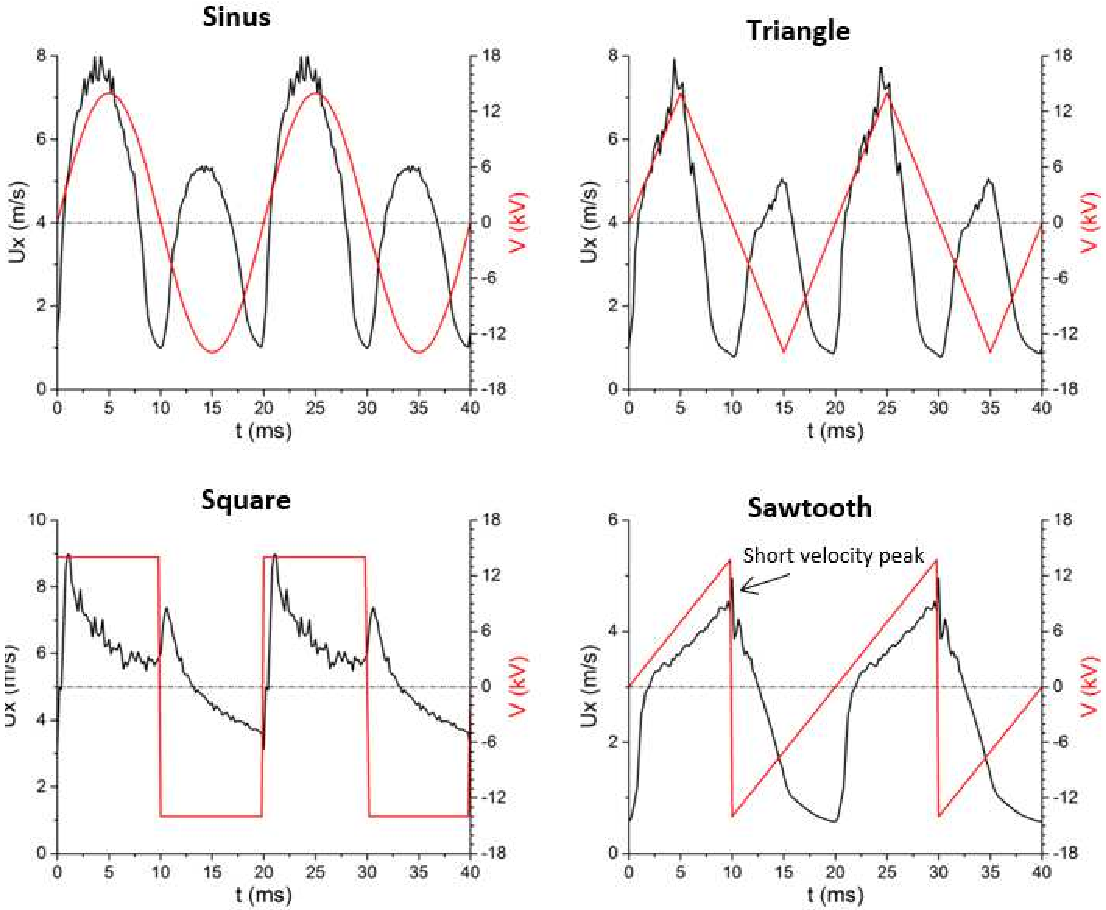


AC corona discharges

▶ **Influence of the HV waveform**

➪ The ionic wind vs time depends on the HV waveform

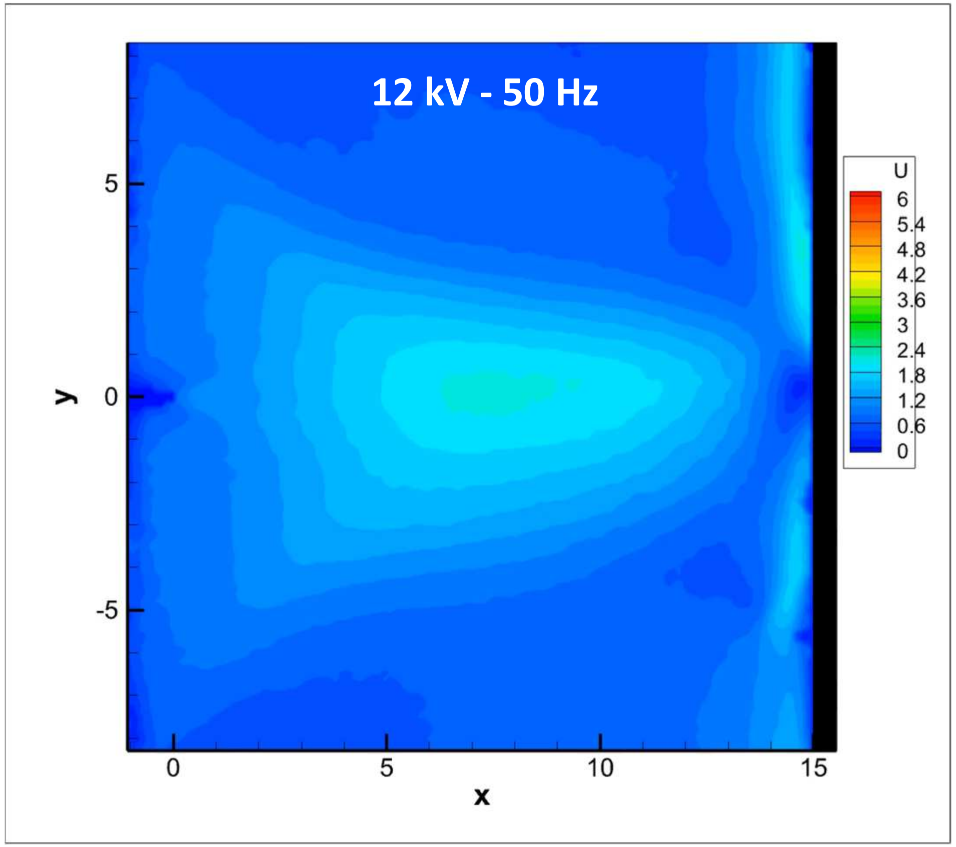
➪ **The streamer discharge is (always) faster than the negative one**



AC corona discharges

▶ **Ionic wind versus time**

➪ **The sine HV produces a « pulsed » ionic wind**



Outline

1) Volume needle-to-plate corona discharges

2) Surface dielectric barrier discharges

3) Plasma-induced liquid flows

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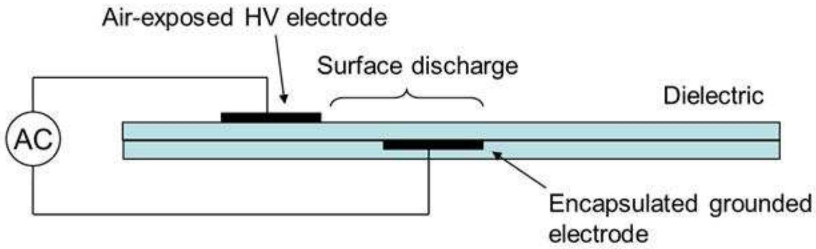
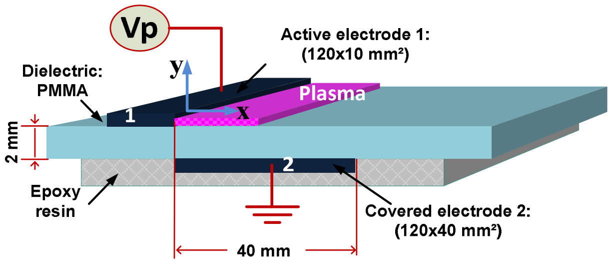
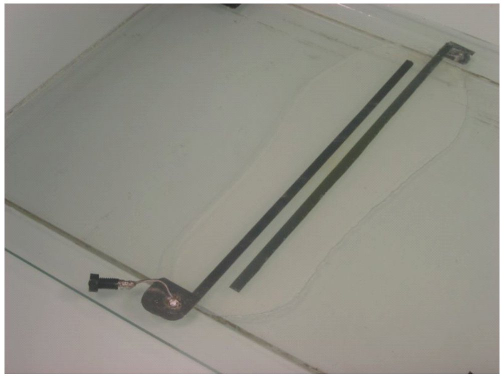
Single Dielectric Barrier Discharge (D.B.D.)

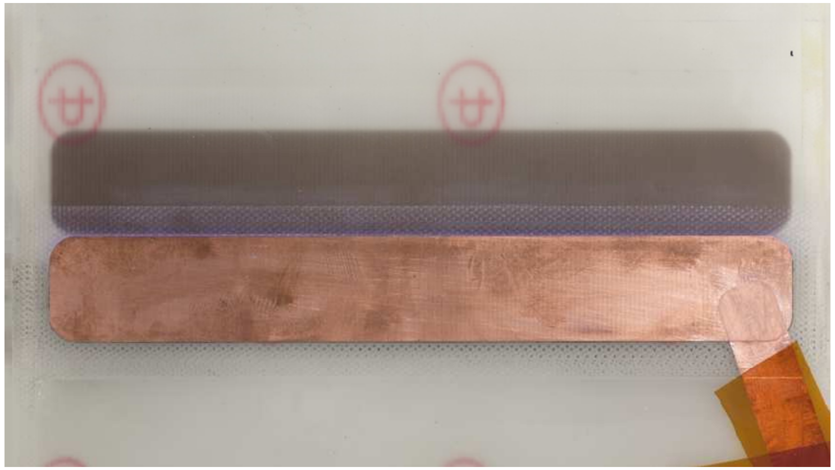


- **Actuator design**
  - **Two electrodes** on both sides of a dielectric
  - Thickness ≈ 50 µm to a few mm



- **Electrical parameters**
  - **AC HV** (5 - 30 kV, $f_{AC} \approx 1$ kHz) at the air-exposed electrode
  - **Power consumption < 1W/cm**





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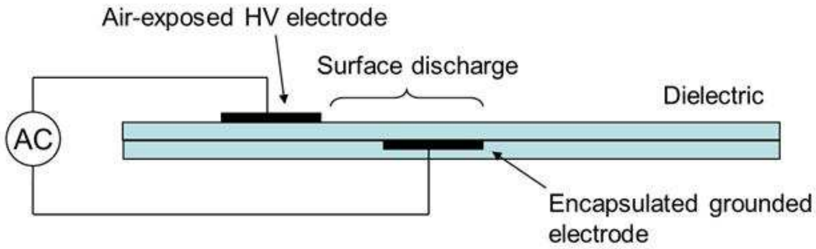

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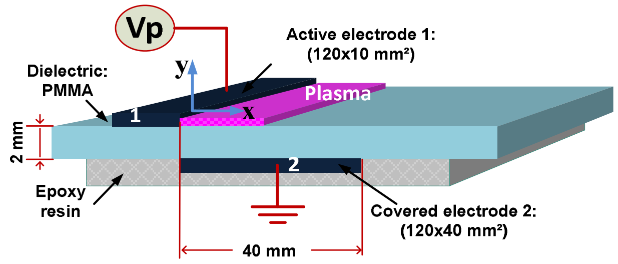

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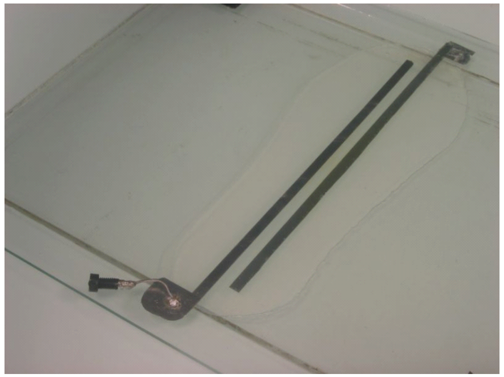

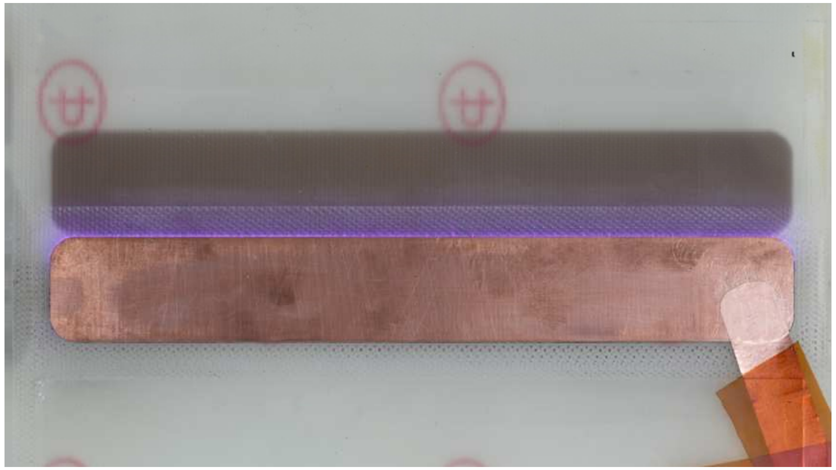

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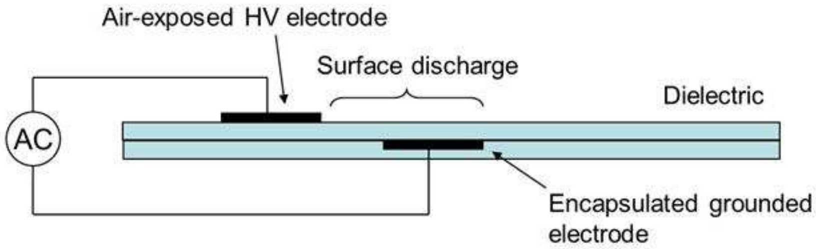

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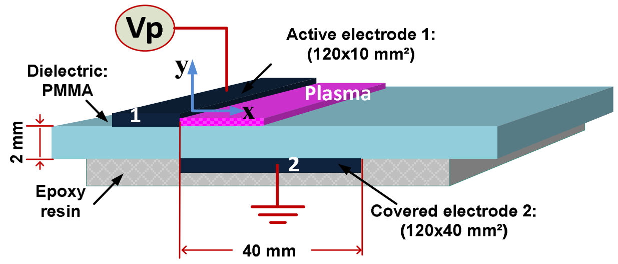
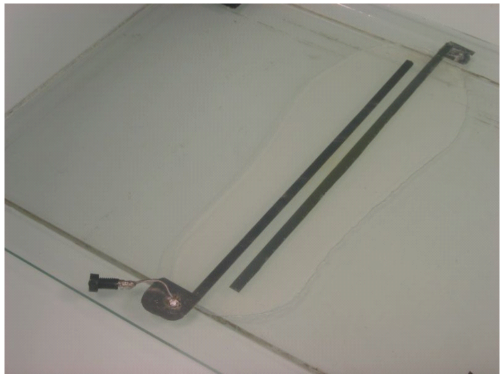
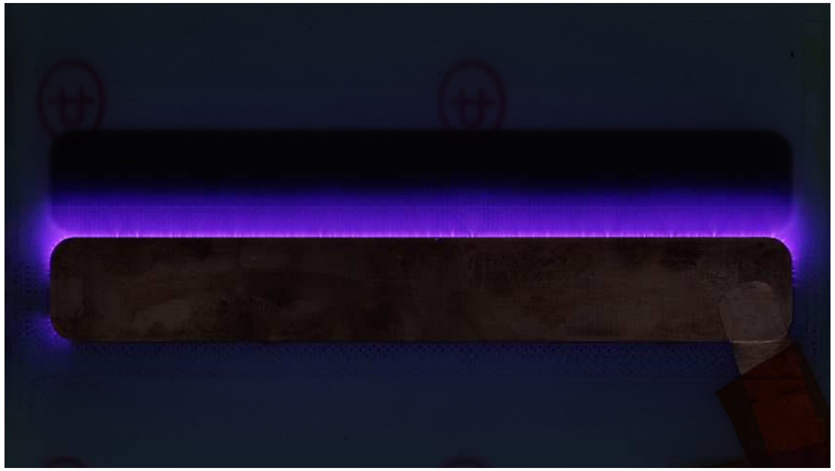
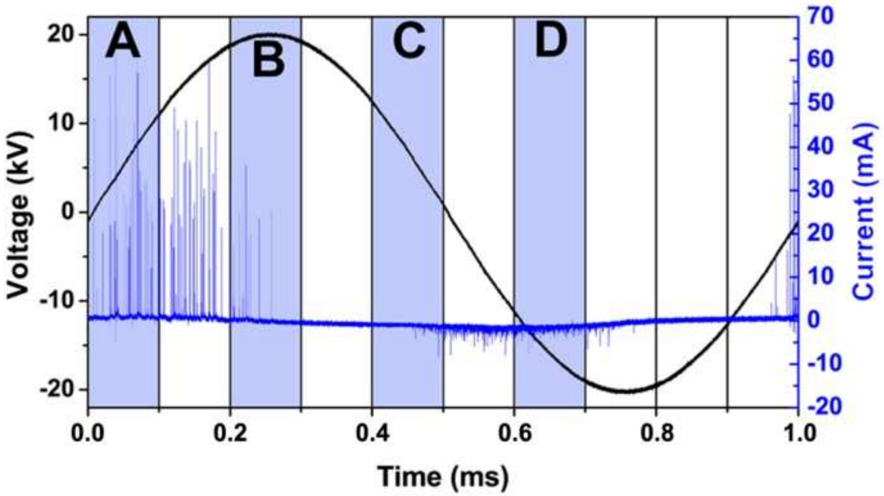


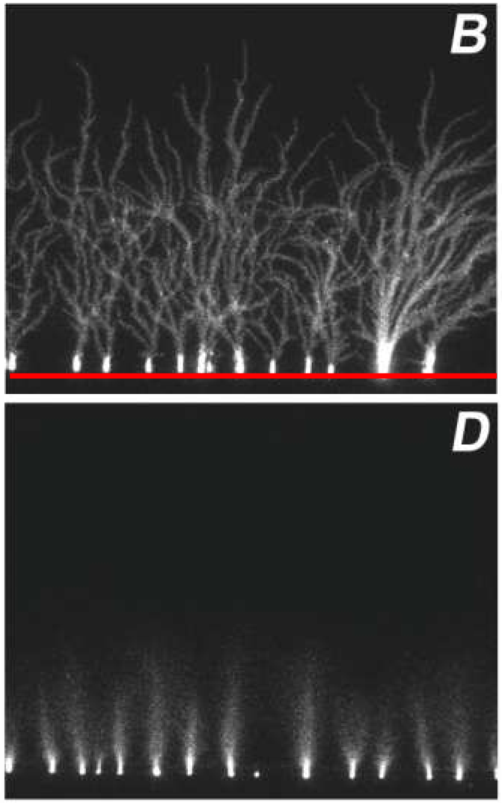




Plasma vs time

- **ICCD top views & current vs time**
- ➩ Positive-going cycle → **positive streamer discharge**
- ➩ Negative-going cycle → **negative glow discharge**
- ➩ There are two different discharges during one AC cycle





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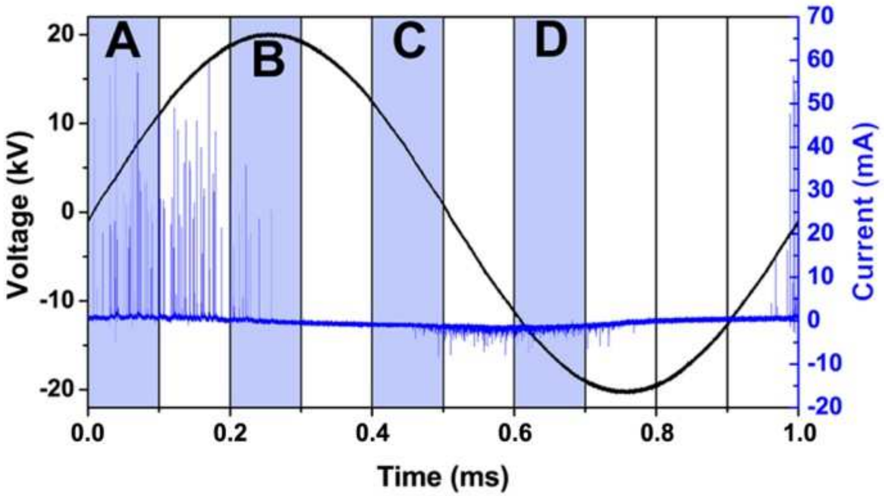

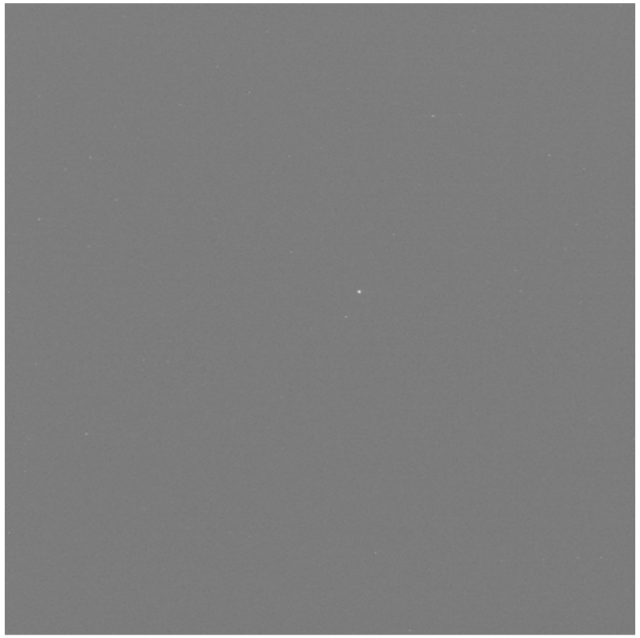

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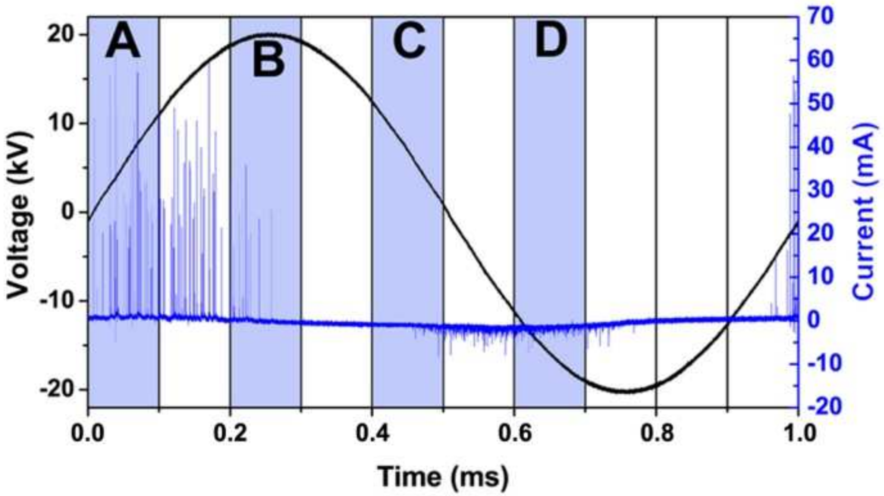
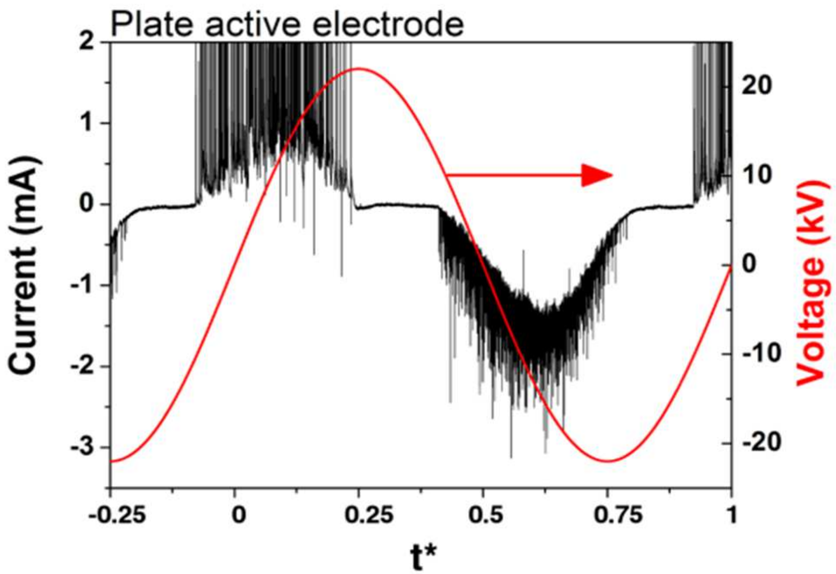


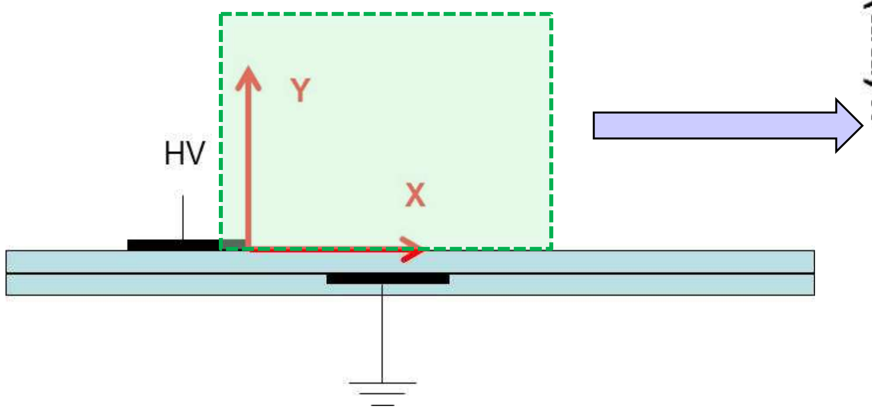


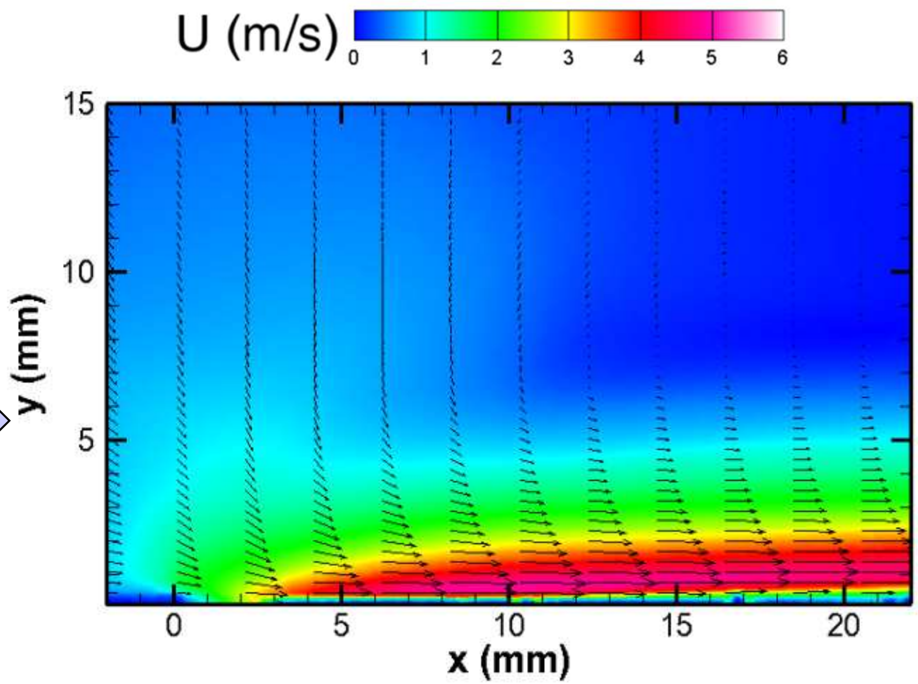
What about the ionic wind ?

- **Particle Image Velocimetry (PIV)**

⇨ **In quiescent air**

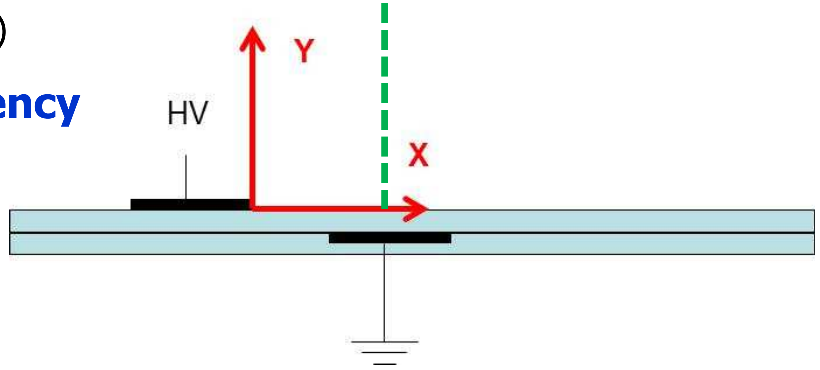
⇨ A jet is created from the active electrode edge with max **velocity of 6 m/s** @y ≈ 0.2-0.5 mm

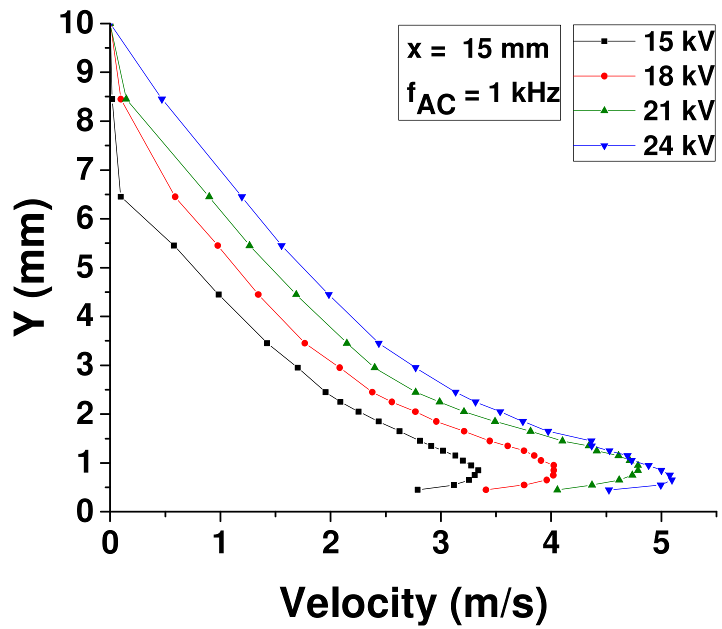


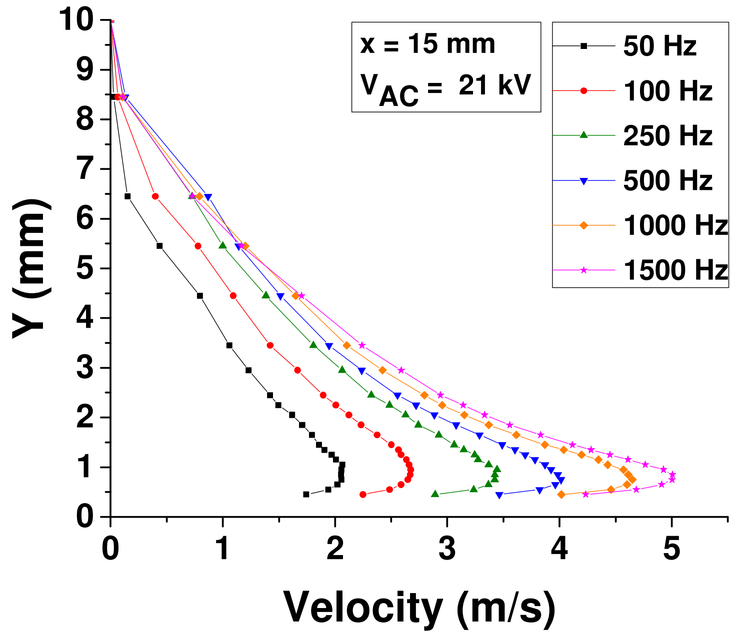


Velocity profiles by Pitot tube

- **Time-averaged velocity**
- ➪ Vertical profiles at x = 15 mm (with a glass « Pitot tube »)
- ➪ **Velocity increases with the HV and its frequency**
- ➪ Maximum velocity @x ≈ 10 mm → 6 m/s



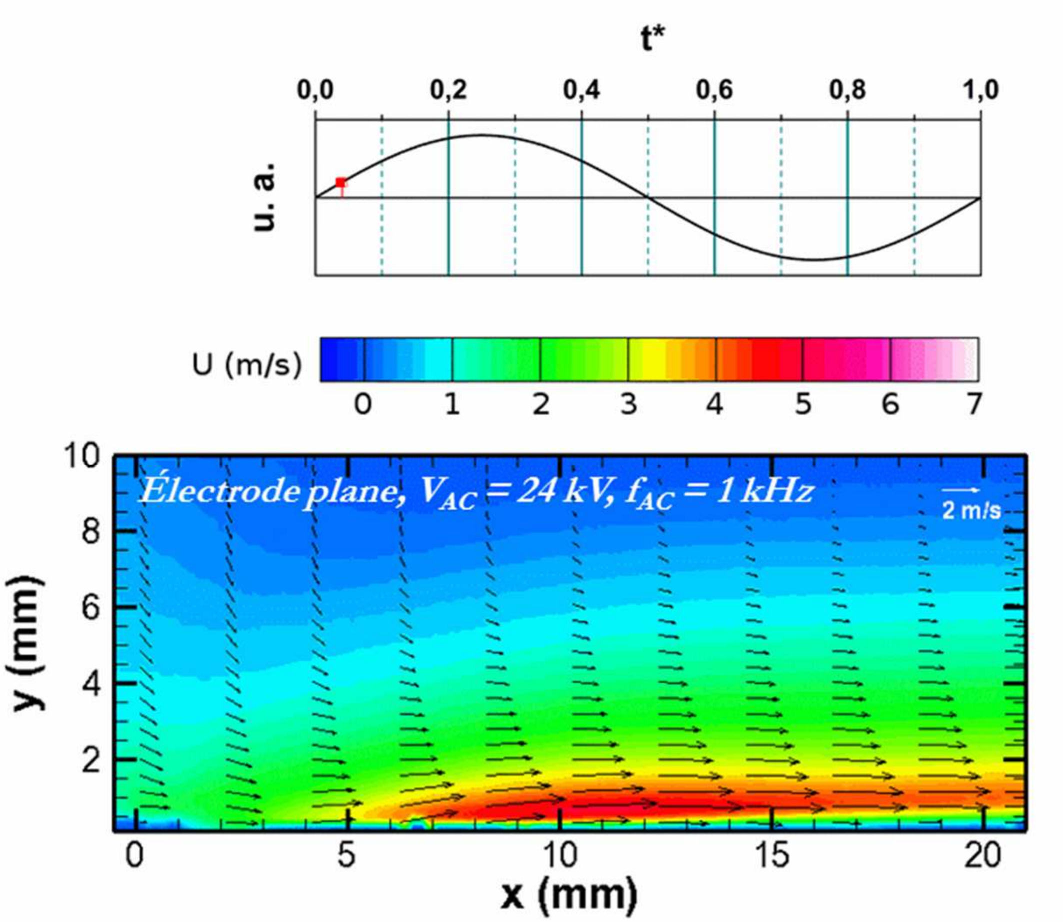




Ionic wind vs time

- **Velocity fieds vs time**

➪ The electric wind is strongly unsteady



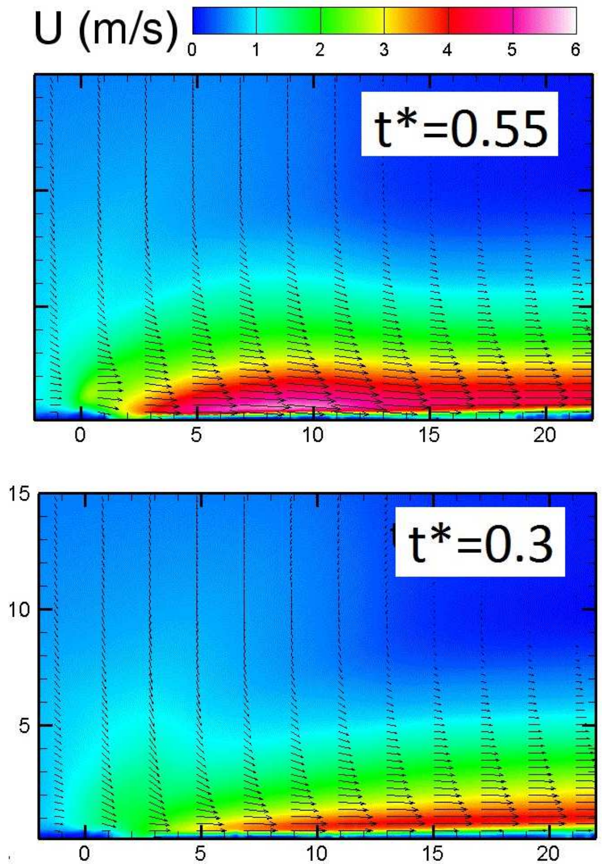
Velocity vs time

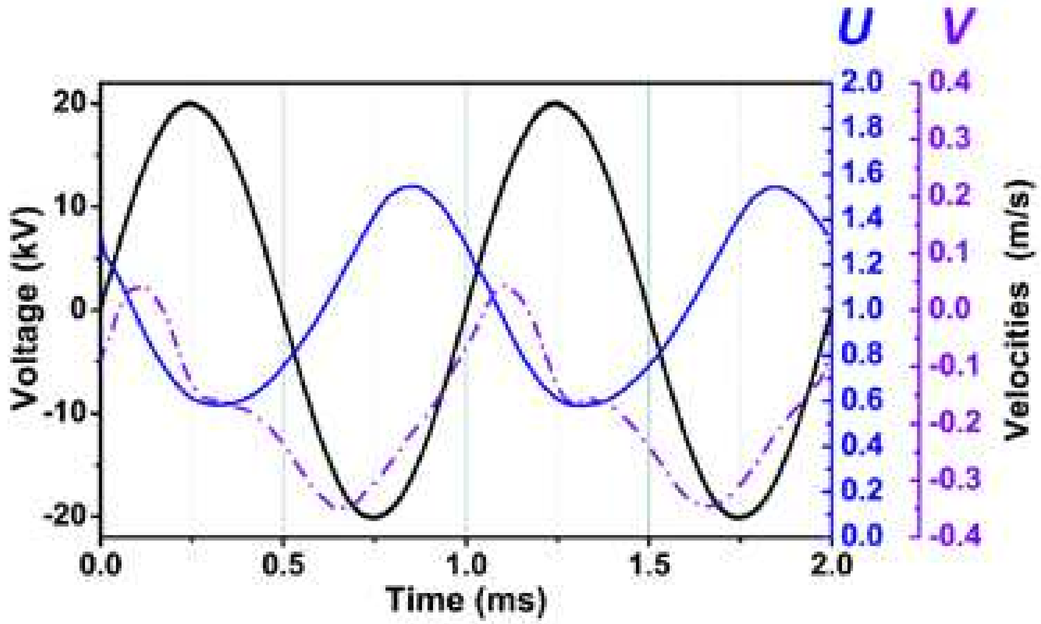
- **Velocity at x = 5 mm**

⇨ A sine HV at f_{AC} produces a « sine » ionic wind at f_{AC} with a phase-shift

⇨ **Contrary to volume coronas, streamers are not efficient to produce velocity !**

⇨ Force very close to the wall → skin-friction





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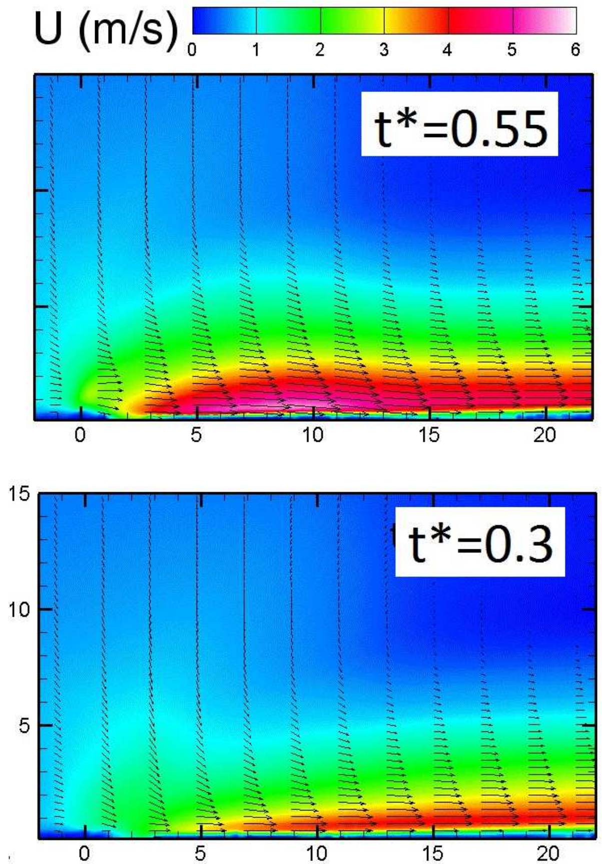
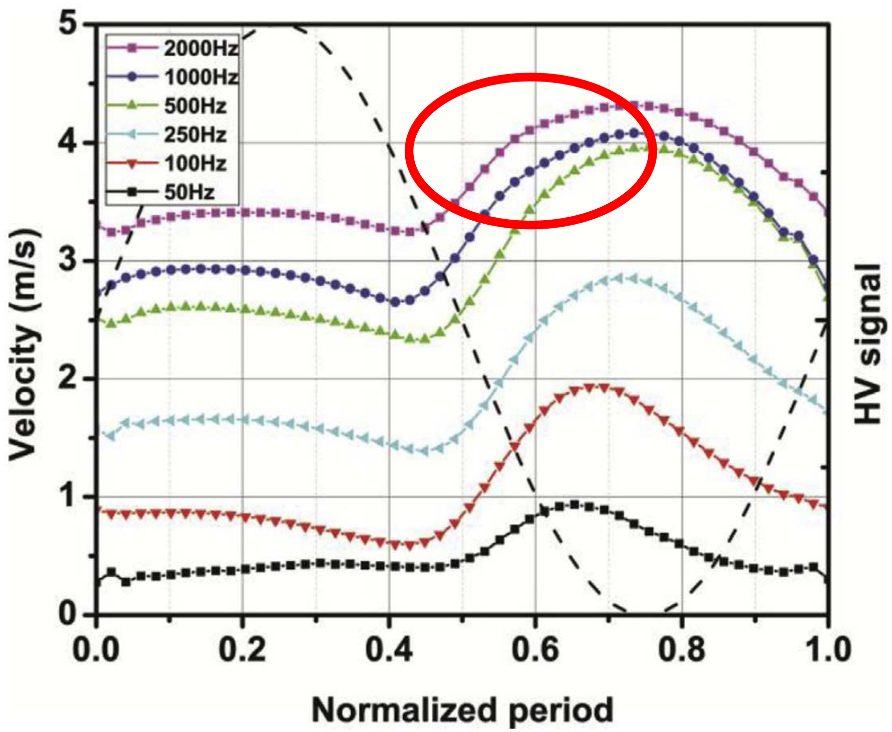
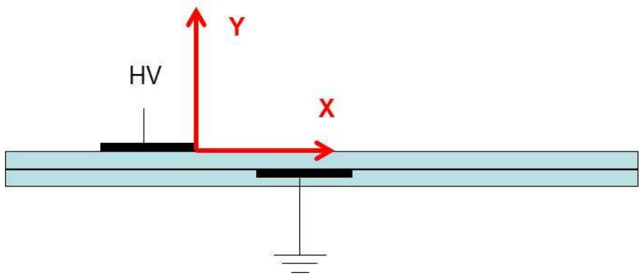


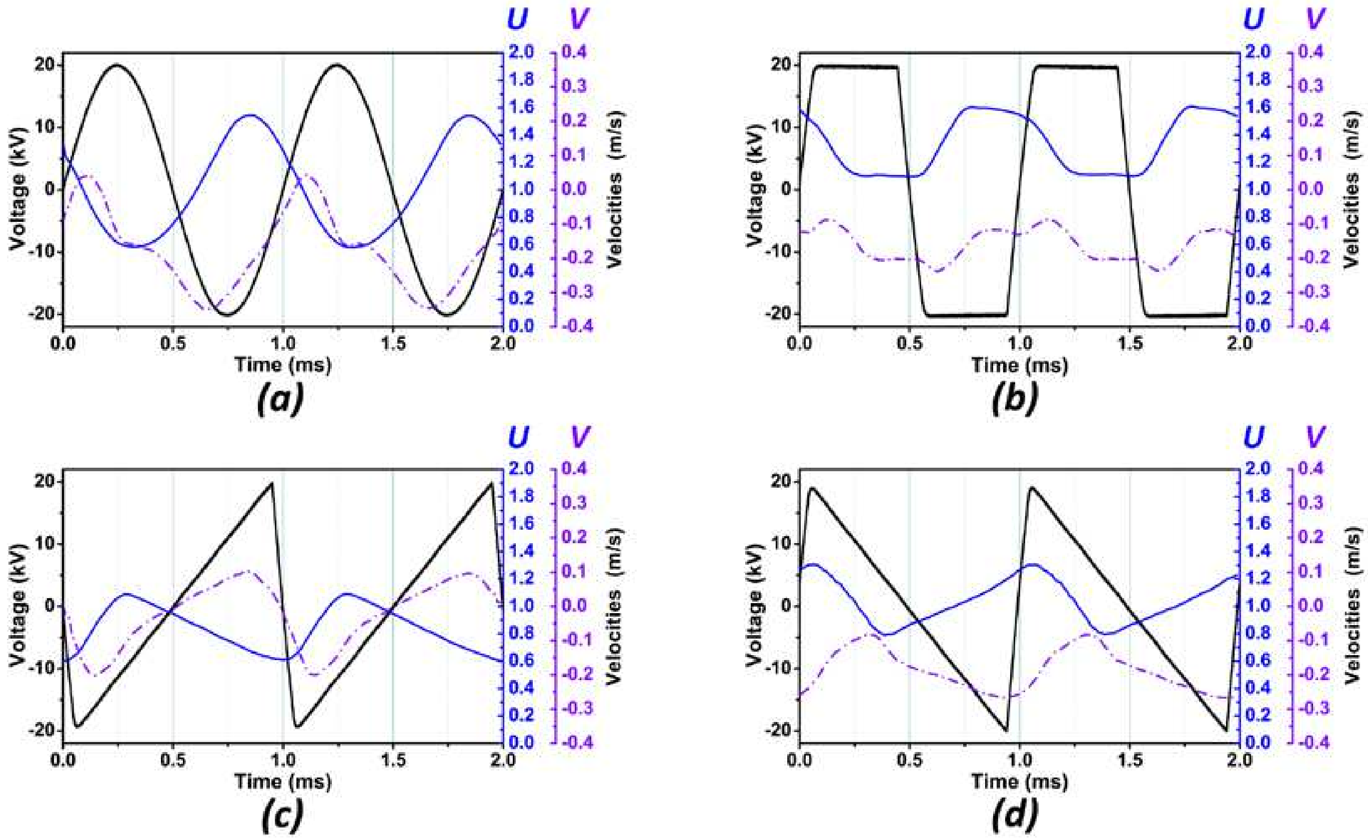


Influence of HV waveform



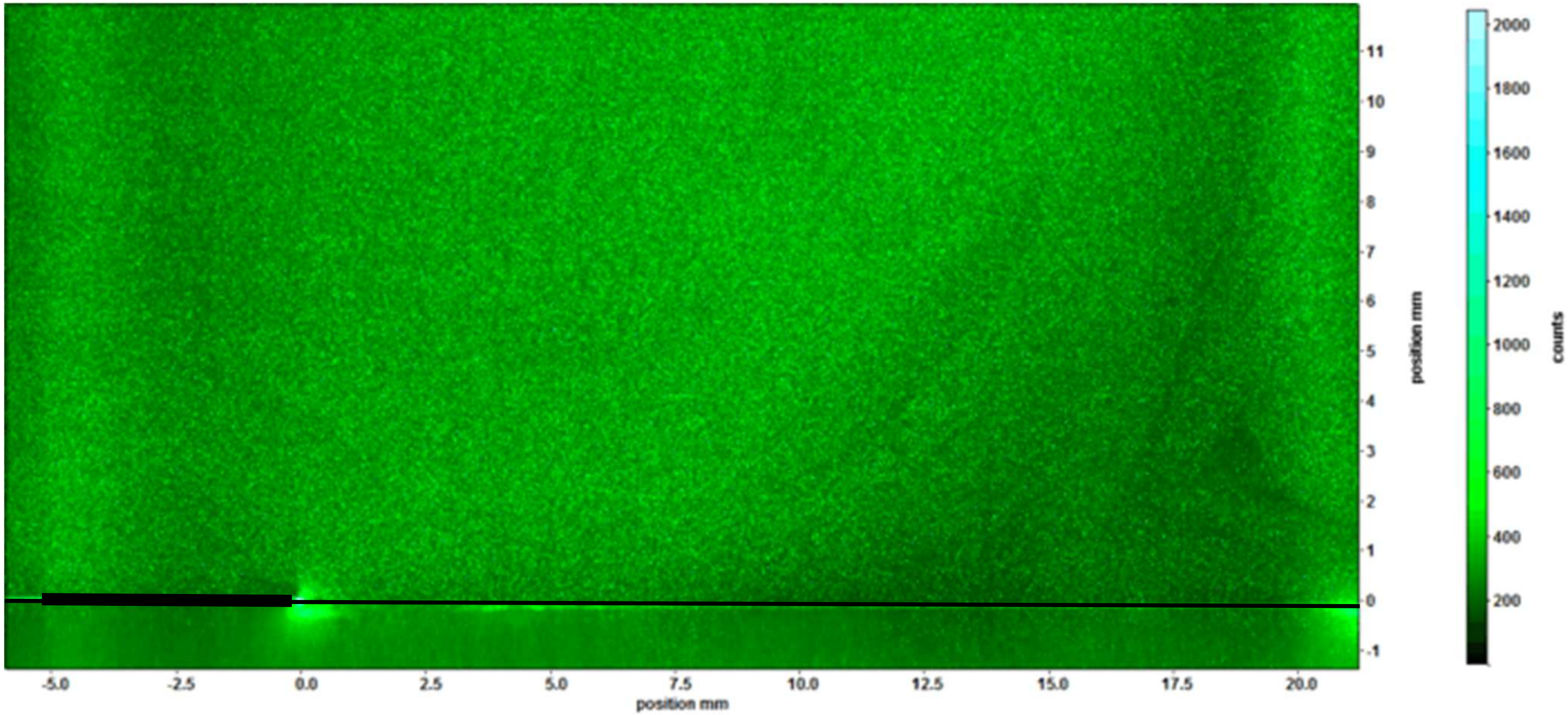
- **Different HV waveforms**

⇨ **The velocity « follows » the HV waveform → linear relation between HV and v_G**



Time-resolved video

- **40 kHz video – 1 kHz sine HV**
- ➪ One can observe velocity fluctuations at f_{AC}
- ➪ **As for the volume AC corona discharge, the ionic wind is strongly unsteady**
- ➪ Streamers are less effective than the glow discharge …

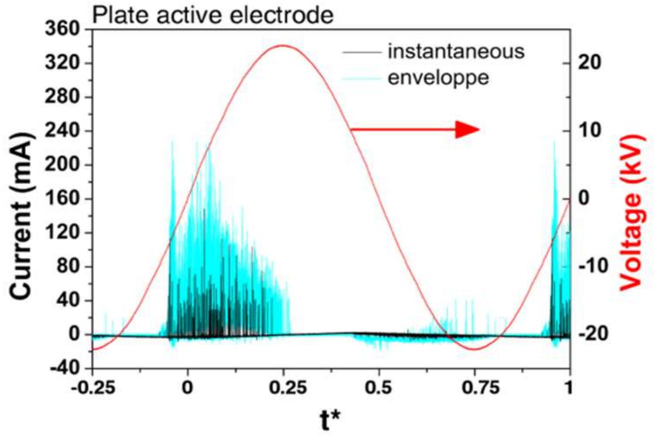


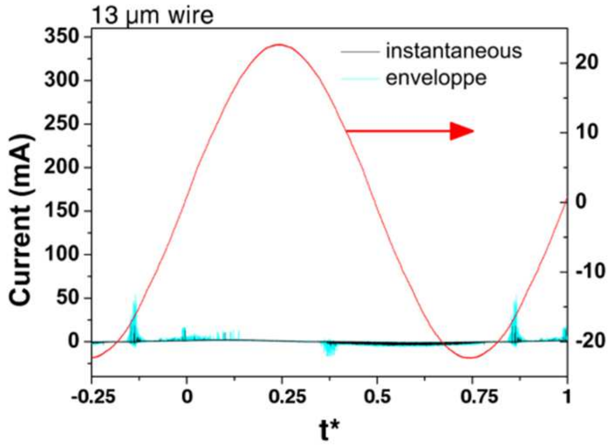
Influence of the air-exposed electrode shape

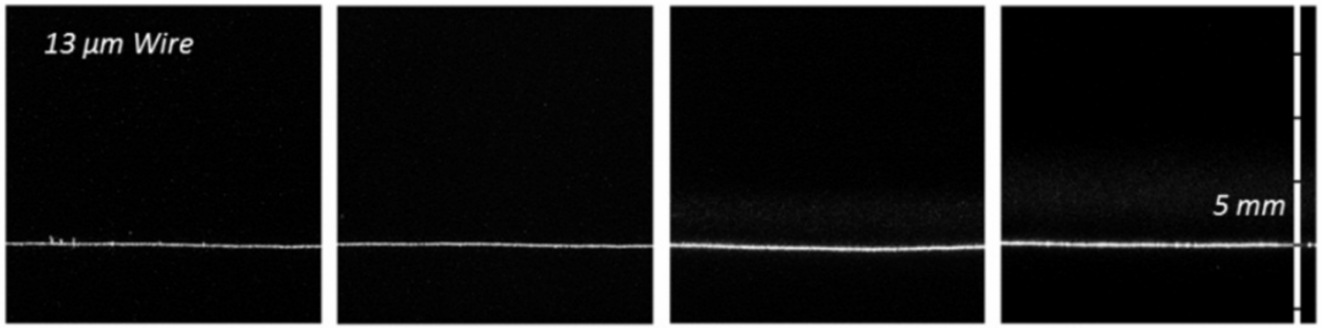
- **Wire electrode**

➪ Wires from 300 µm down to 13 µm (hot wires used in aerodynamics)

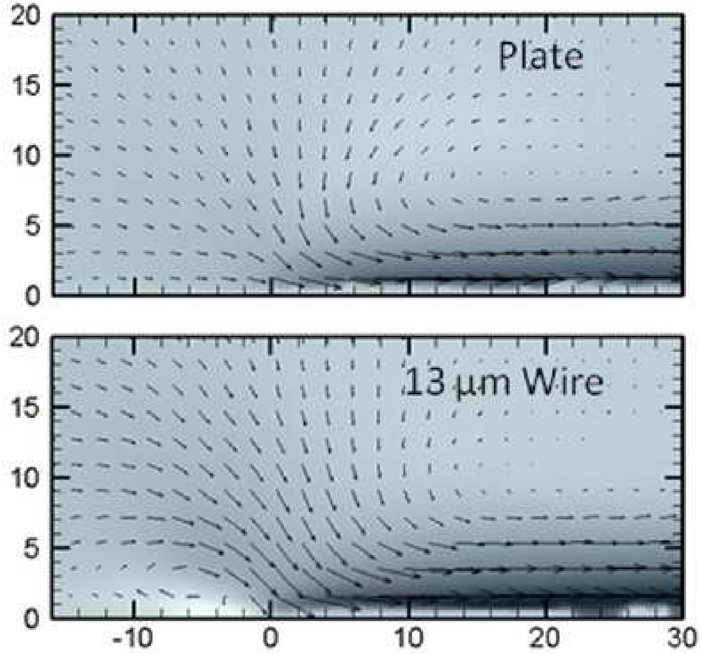
➪ Current and iCCD visualizations → **streamers are removed !**







Wire active electrode



- **Time-averaged velocity**

➪ Topology is fully modified

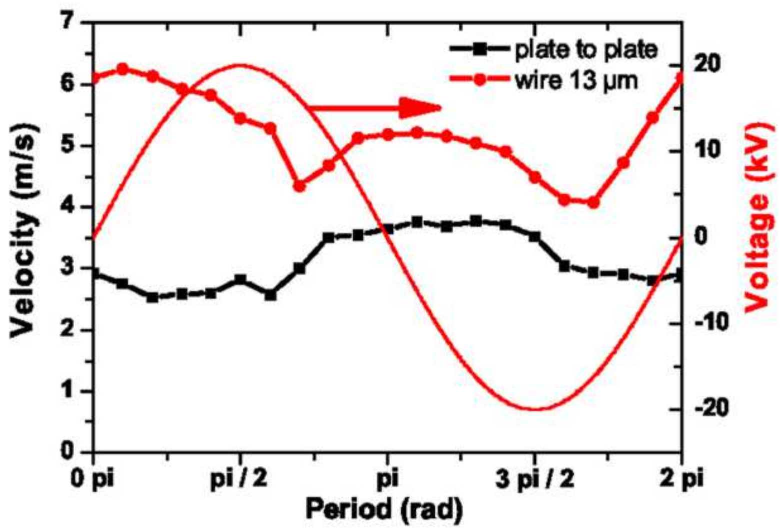
➪ **Suction effect and maximum velocity ↗**

- **Time-resolved velocity**

➪ Time-history of ionic wind is fully modified

➪ For a plate active electrode → negative discharge > positive discharge

➪ **With a wire, both discharges produces velocity (positive > negative)**



➪ **Streamers are not efficient !**

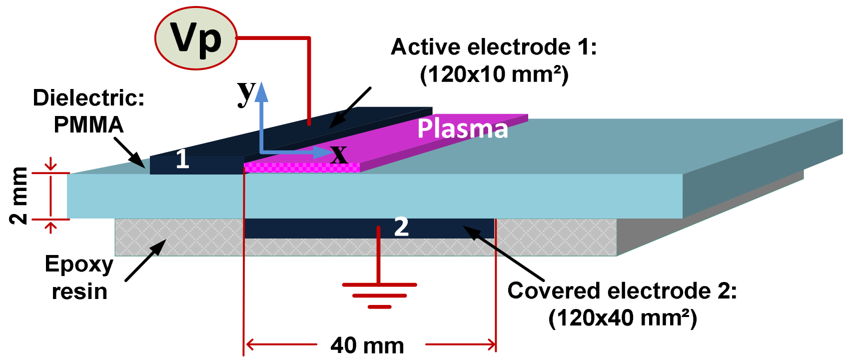
Nanosecond Pulse DBD

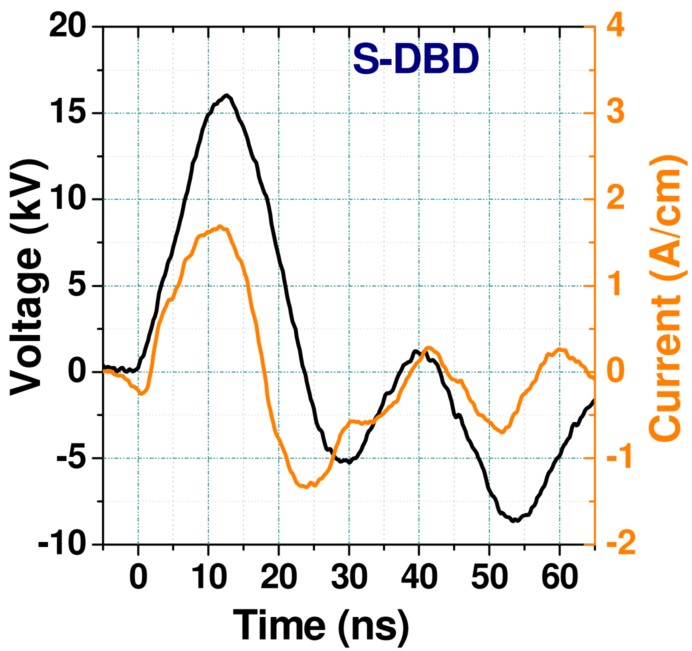
▶ **How it works ?**

➪ Surface DBD supplied a series of fast-rise (1 to 50 ns) **HV pulses**

➪ EHD force and electric wind are negligeable → pulse discharges act differently

➪ Thermalization of the gas at the dielectric wall → **Production of a local pressure wave**





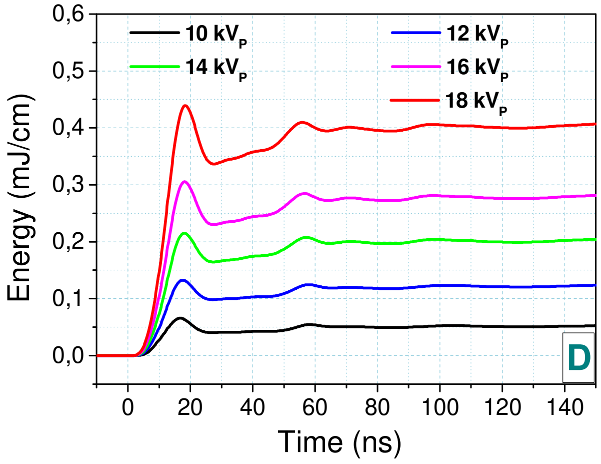
Nanosecond Pulse DBD

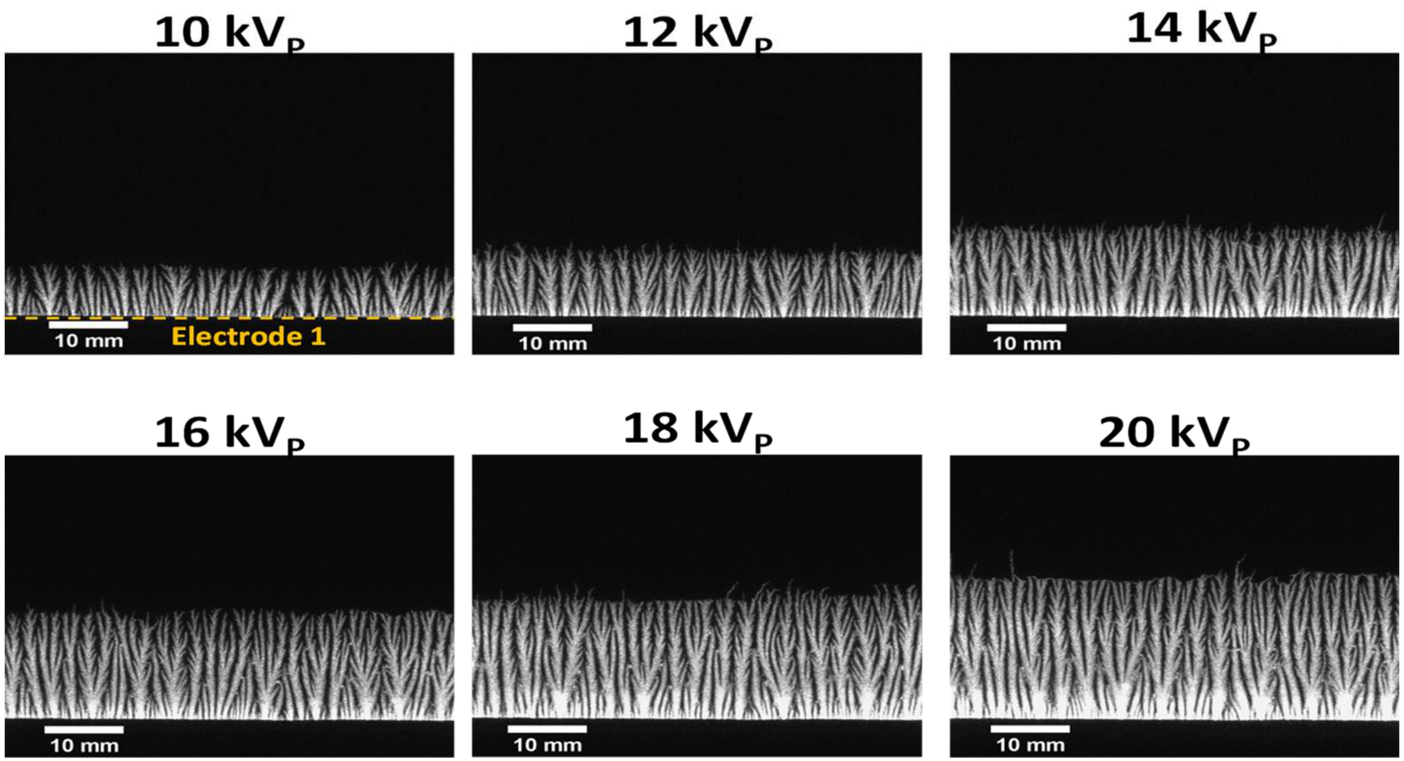
- **Energy and discharge at the wall**

⇨ Energy in the order of **1 mJ/cm** per pulse

⇨ iCCD top views → **streamers are very well-organized**

⇨ Discharge extension ↗ with V_p



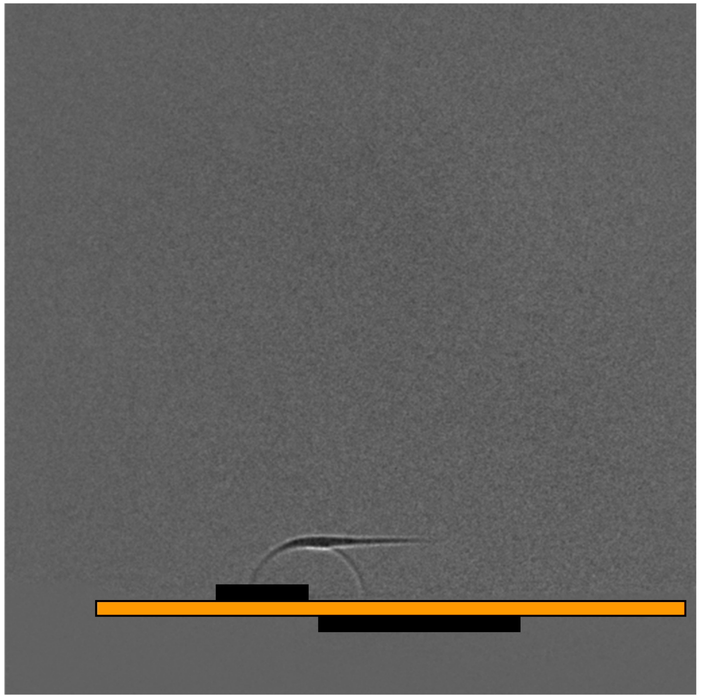


Nanosecond Pulse DBD

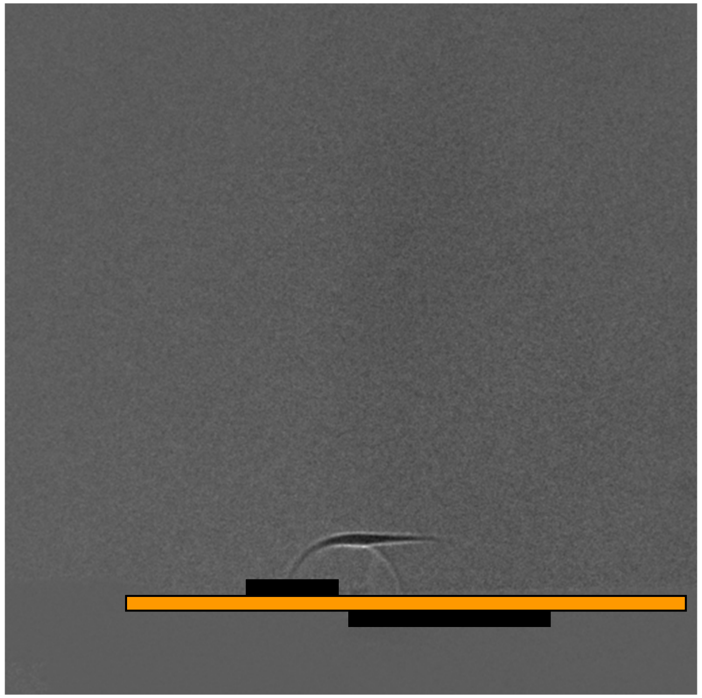
- **Schlieren visualisations**

⇨ Production of a **pressure wave** with a propagation velocity equal to sound one (343 m/s @20^{0}C)

⇨ Both negative and positive HV pulses produce a similar pressure wave



Positive pulse (10 kV, t_{rise}=50 ns, width 200 ns)
10 µs/image



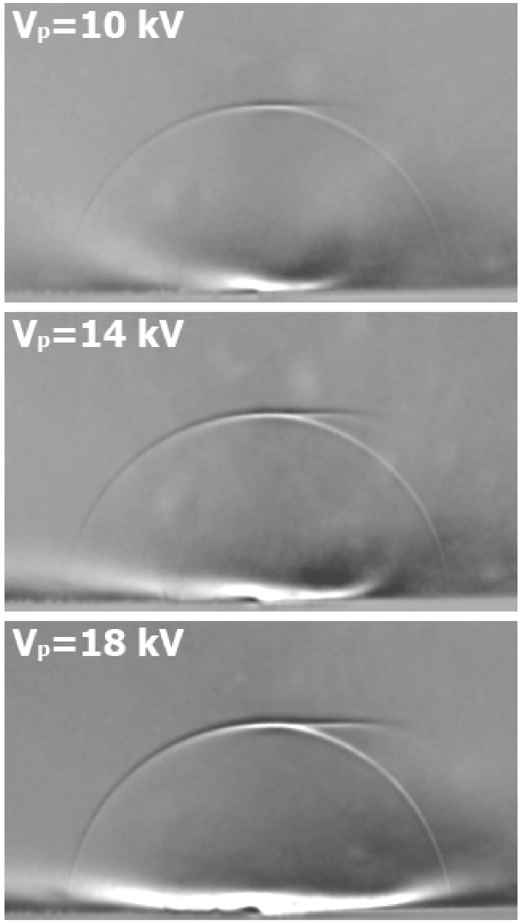
Negative pulse (10 kV, t_{rise}=50 ns, width 200 ns)
10 µs/image

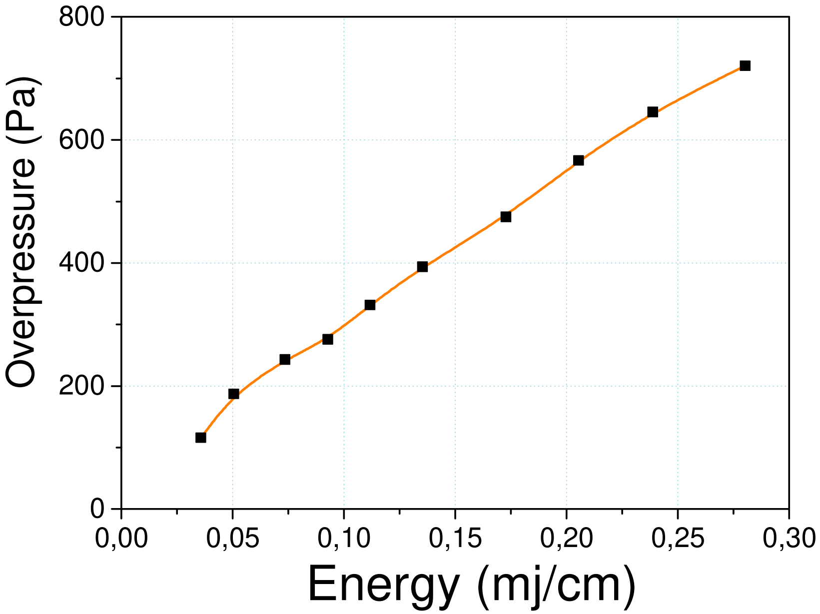
Nanosecond Pulse DBD

- **Schlieren visualisations & Pressure measurements**

⇨ The pressure gradient increases linearly with the consumed energy per pulse

⇨ **ΔP of 2.5 kPa per mJ/cm**





Sliding discharge

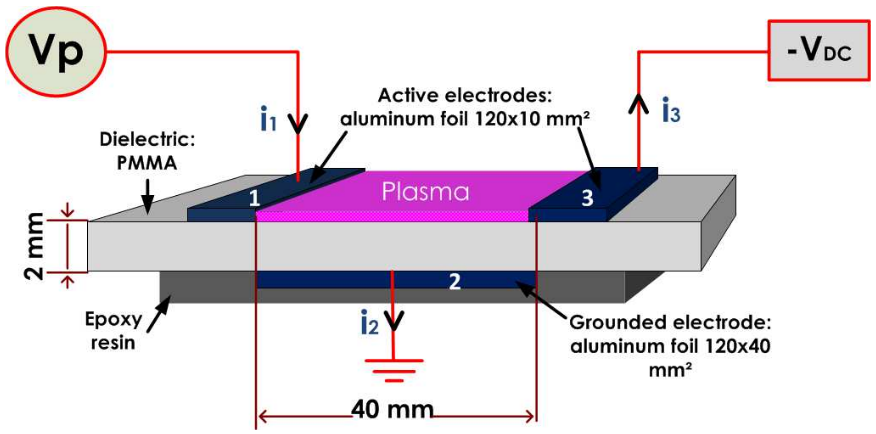
▶ **Three-electrode design→ « sliding discharge »**

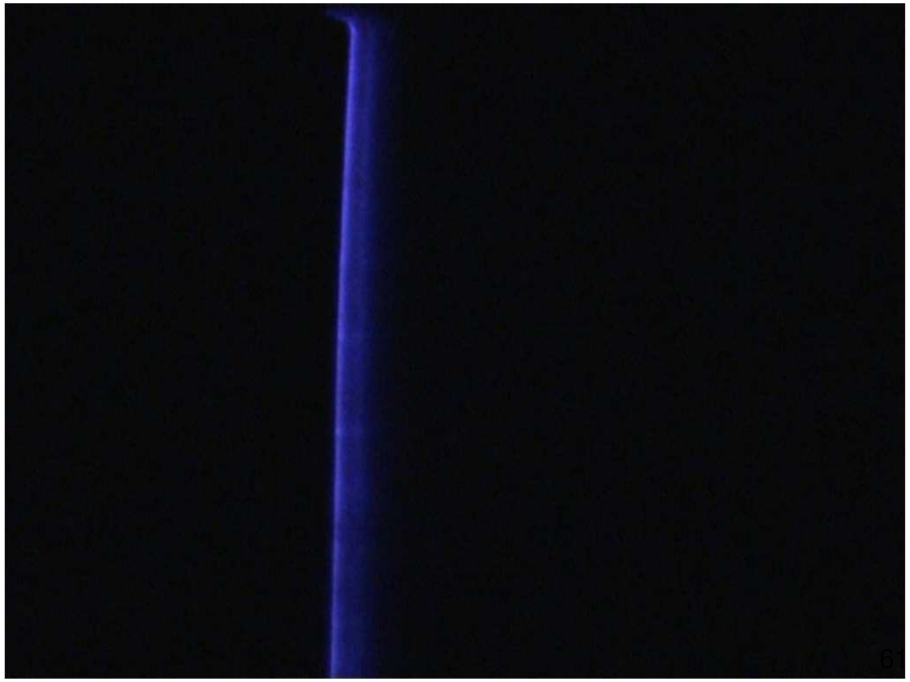
⇨ To add a third electrode with a negative DC voltage

⇨ V_P at the first air-exposed electrode and $-V_{DC}$ at the other (gap = 4 cm)

⇨ To « slide » the positive discharge from electrode (1) to (3)

⇨ **To increase the surface of plasma-flow interaction**





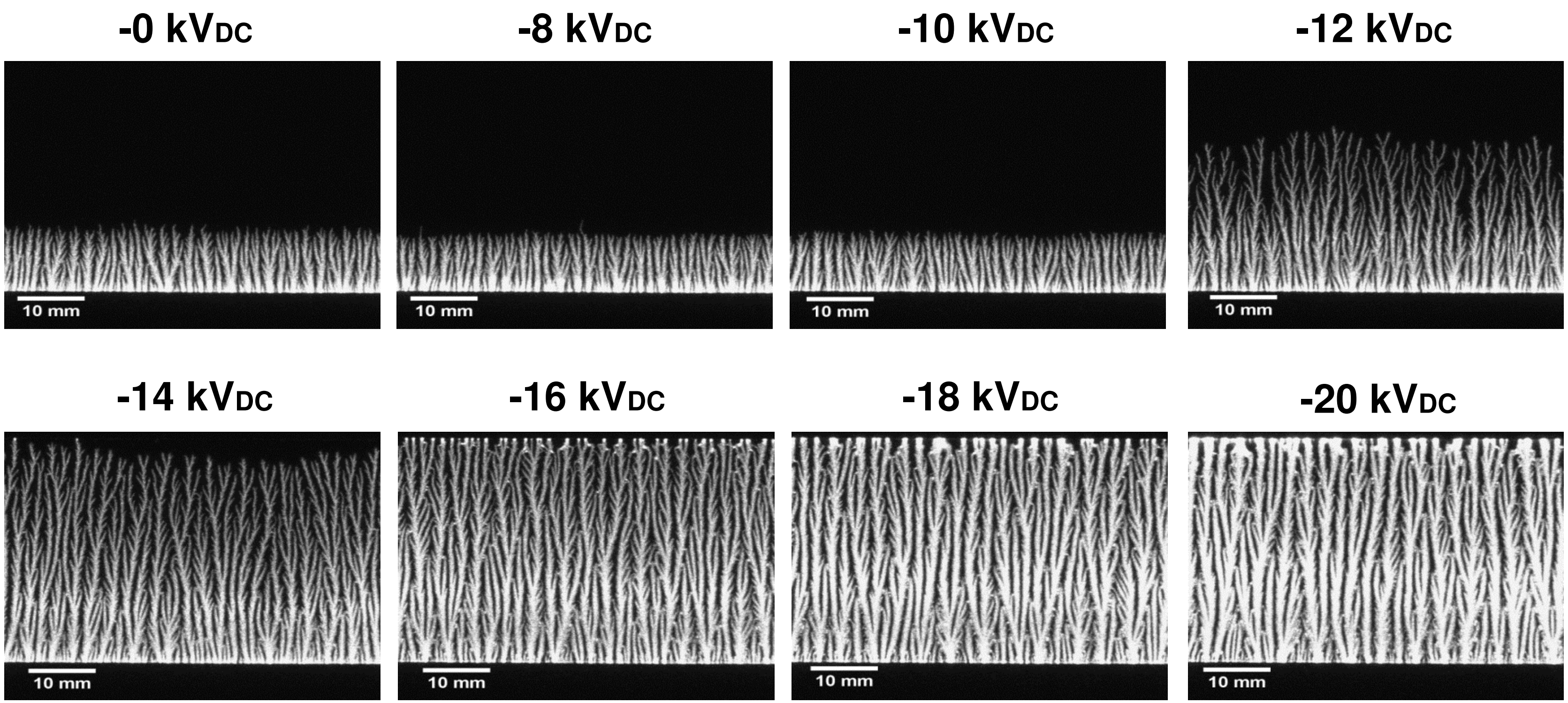
Sliding discharge

- **iCCD visualisations**

➪ V_P = 14 kV and V_{DC} is increased from 0 to -20 kV

➪ Under -10 kV → no effect (gap = 4 cm)

➪ **From -16 kV, streamers propagate up to electrode (3)**

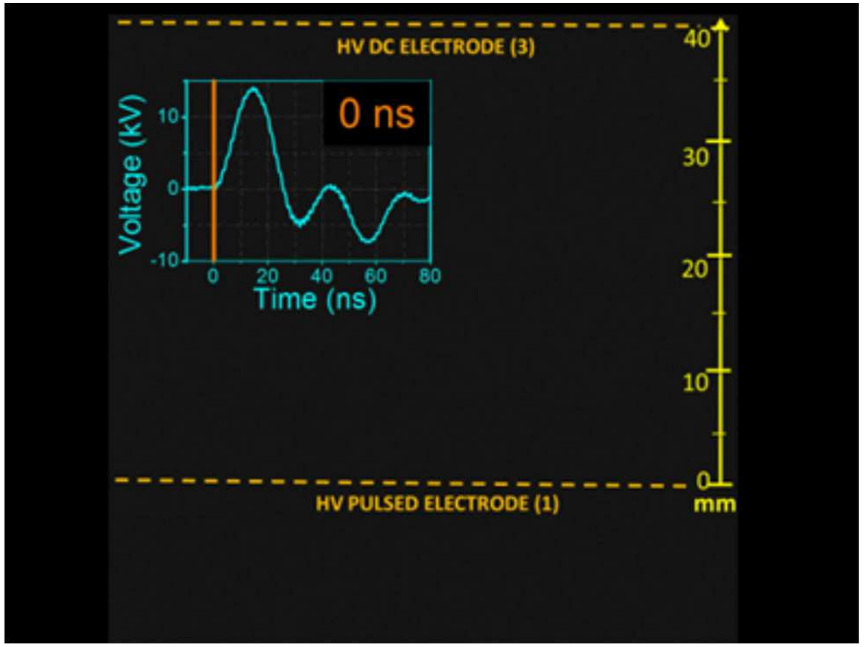


iCCD images of the discharges for Vp = 14 kV and various V_{DC}

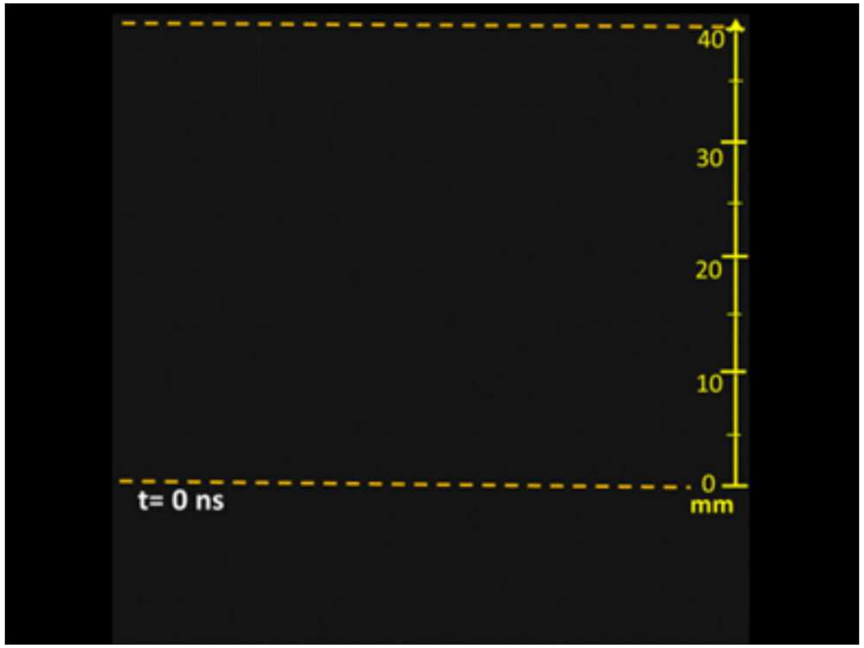
Sliding discharge

- **iCCD visualisations**
  - Time-resolved behaviour of the surface discharge propagation (t = 4 ns of exposure)
  - **Streamers propagation is extended up to electrode (3)**
  - Streamer velocity depends on V_{DC}

Single ns-DBD ($-V_{DC}$= 0 kV and Vp = 14 kV)



Sliding ns-DBD ($-V_{DC}$= -20 kV and Vp = 14 kV)



Sliding discharge

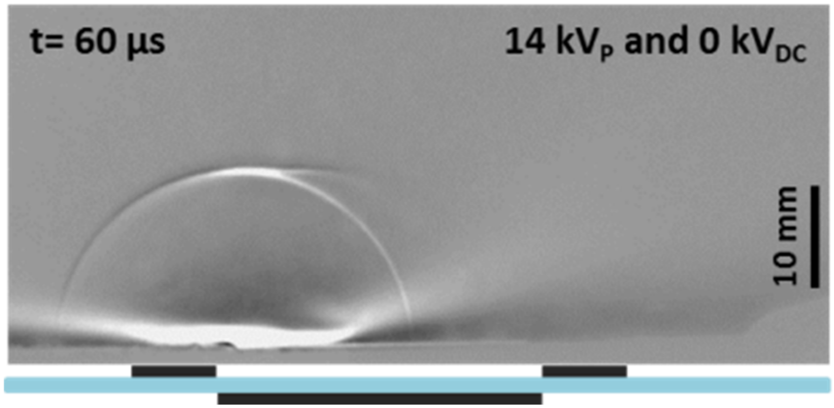
▶ **2D Schlieren visualisations**

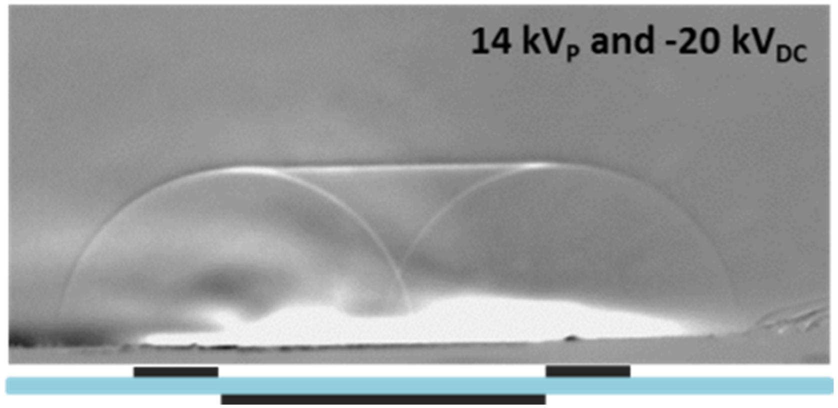
➪ A first « circular » pressure wave at electrode (1) due to **streamer ignition**

➪ A second circular wave at electrode (3)

➪ « Planar » pressure wave → **propagation of the streamers** between electrodes (1) and (3)

➪ Thermal signature at the wall

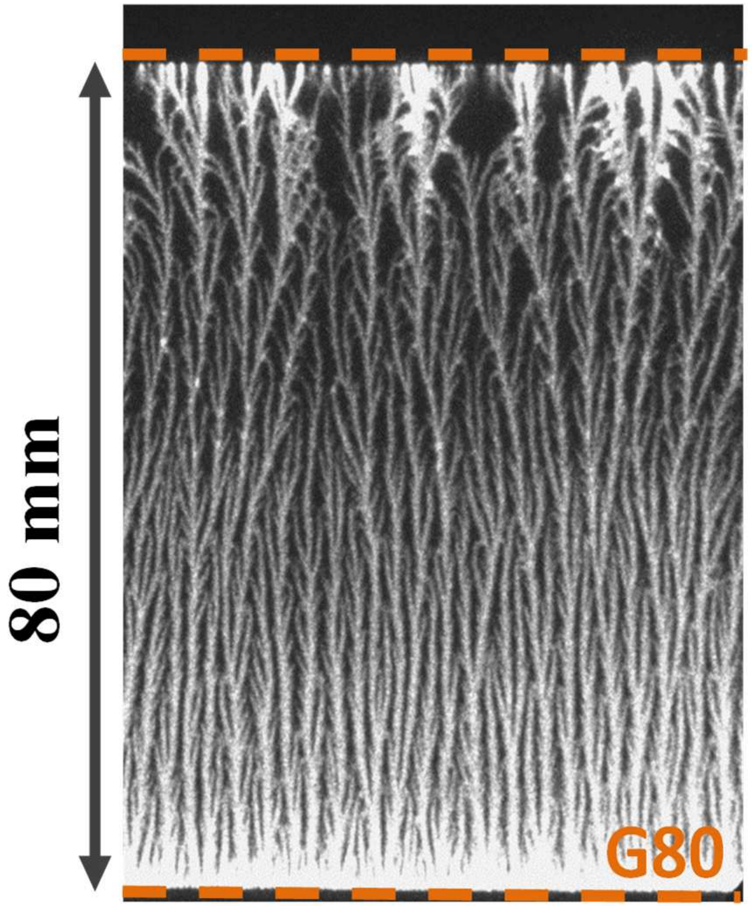


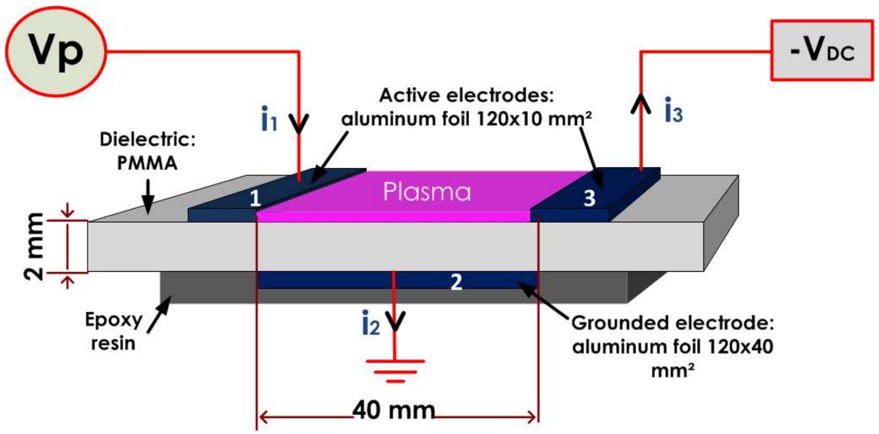


Sliding discharge

- **iCCD visualisations**

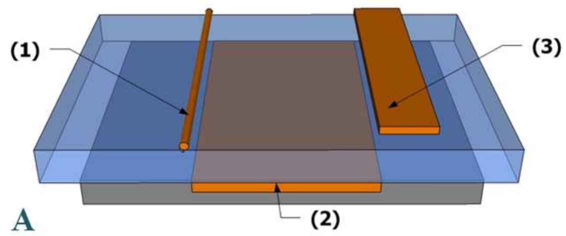
➪ **Gap is not limited (up to 80 mm here)**

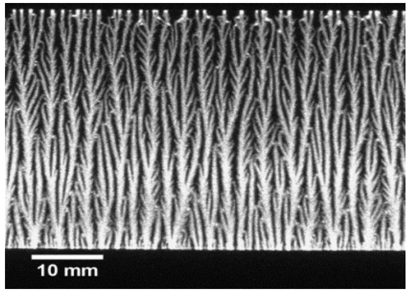




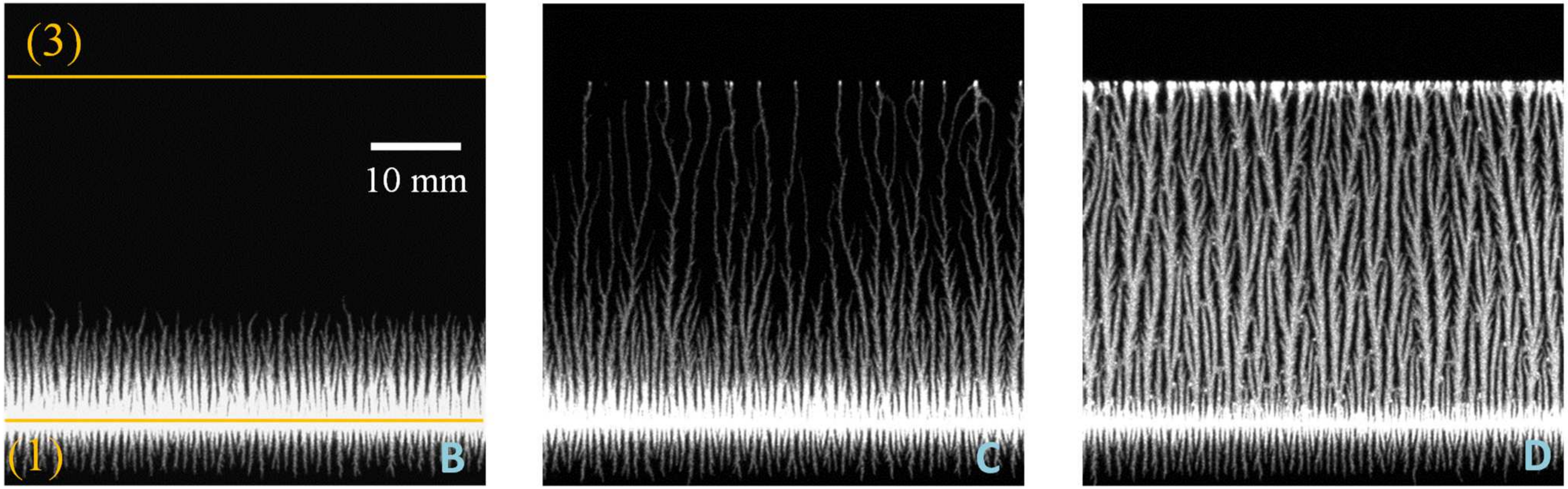
Sliding discharge

- **Effect of the active electrode shape**
- The plate electrode is replaced by a thin 13-µm wire
- **Similar**



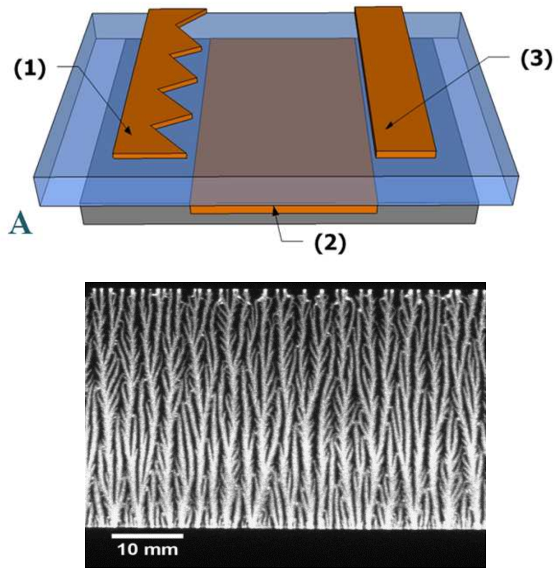


16 kV_P et 0 kV_{DC} — 16 kV_P et -10 kV_{DC} — 16 kV_P et -16 kV_{DC}

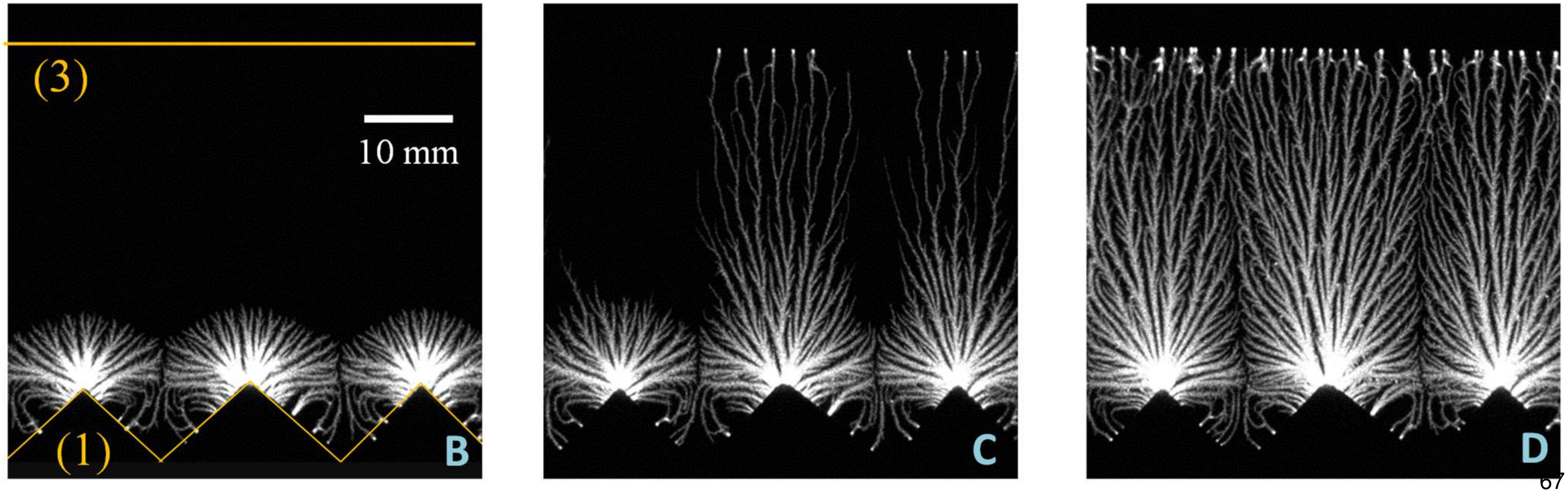


Sliding discharge

- **Effect of the active electrode shape**
- The plate electrode has a sawtooth edge
- **Streamers ignites at the needles**

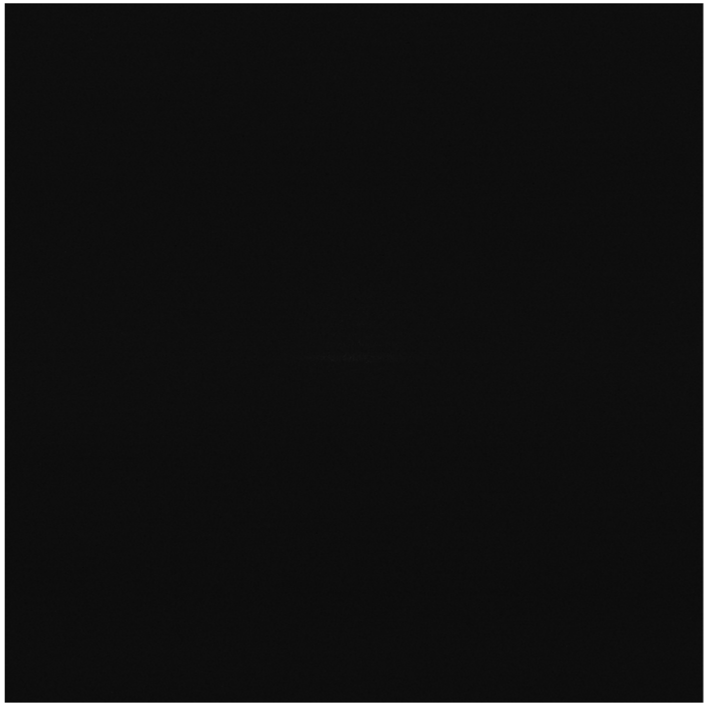


16 kV$_P$ et 0 kV$_{DC}$ | 16 kV$_P$ et -10 kV$_{DC}$ | 16 kV$_P$ et -16 kV$_{DC}$



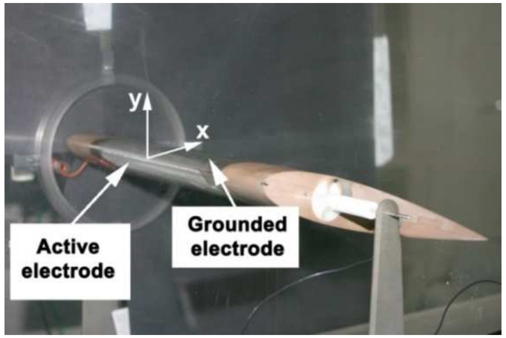
Sliding discharge

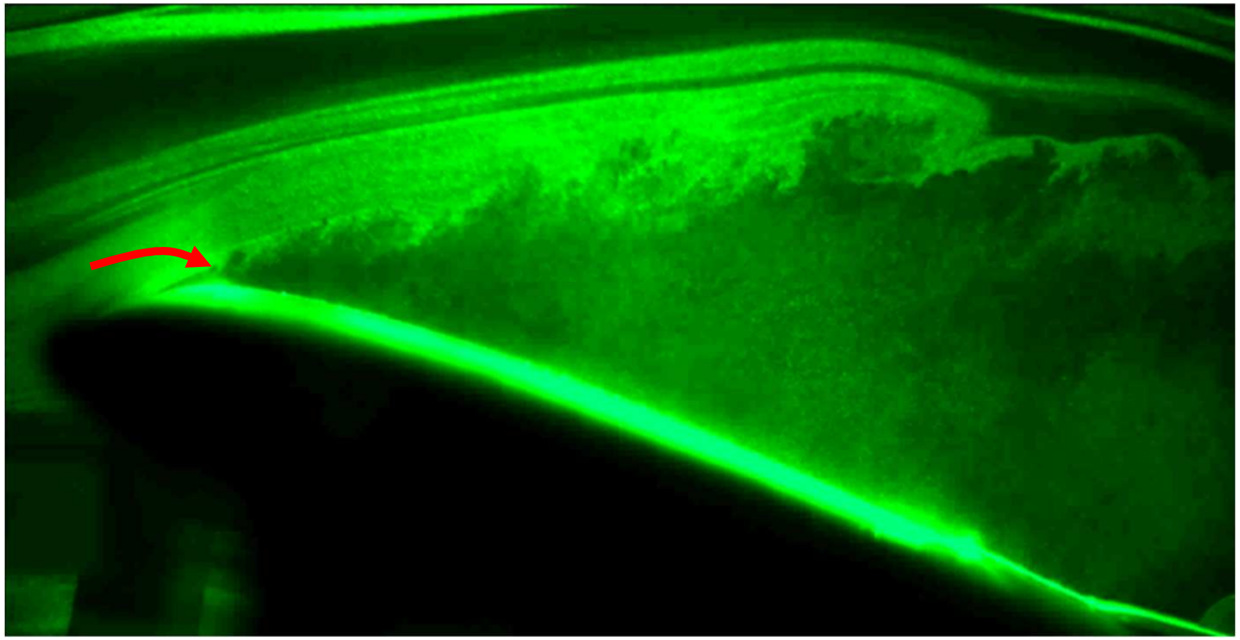
- **Effect of the active electrode shape**
- ⇨ Video of the streamer propagation (every 2 ns)



Airflow control by surface DBD

- **Our main topic since 1999**
- Airflow control → applications in fluid mechanics, noise reduction, thermal exchanges and combustion
- **« Crazy » idea → add velocity very close to the wall**
- Ionic wind at the wall → flow reattachment

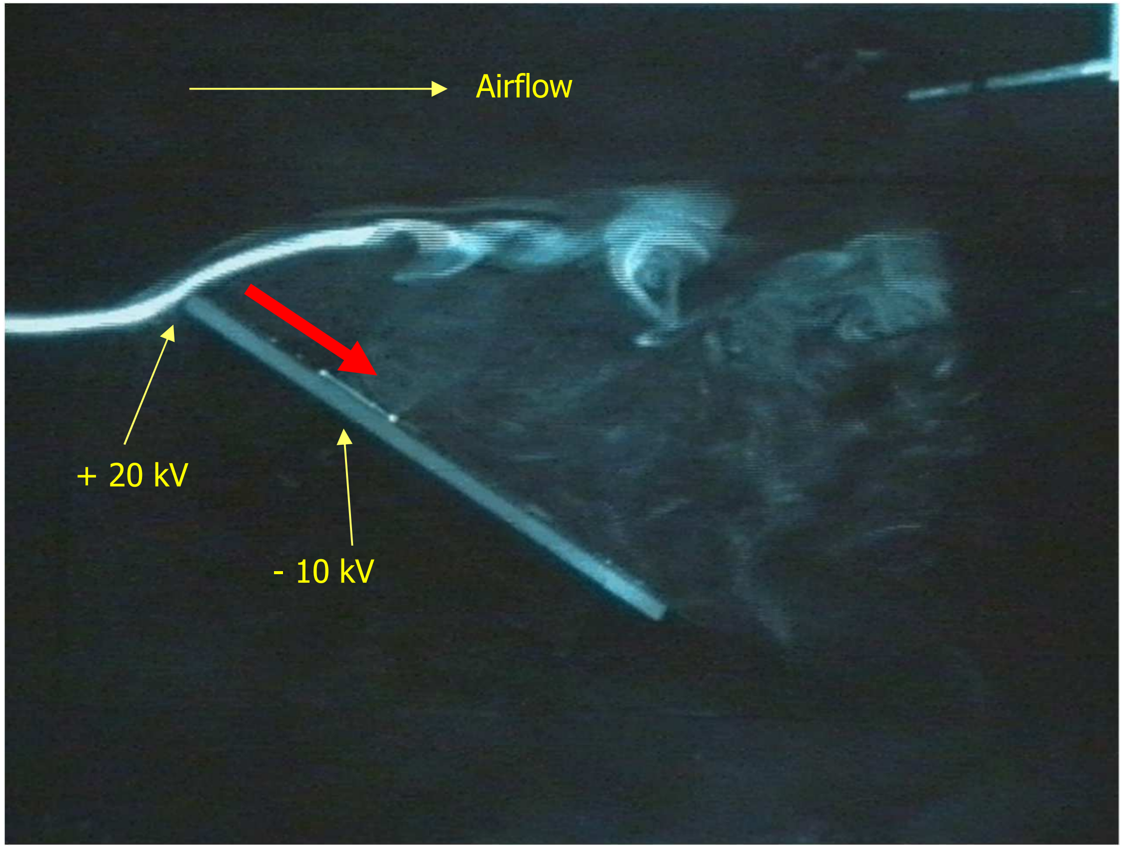




20 m/s, Re = 250 000, 3 kHz (25 s ⇔ 150 ms)

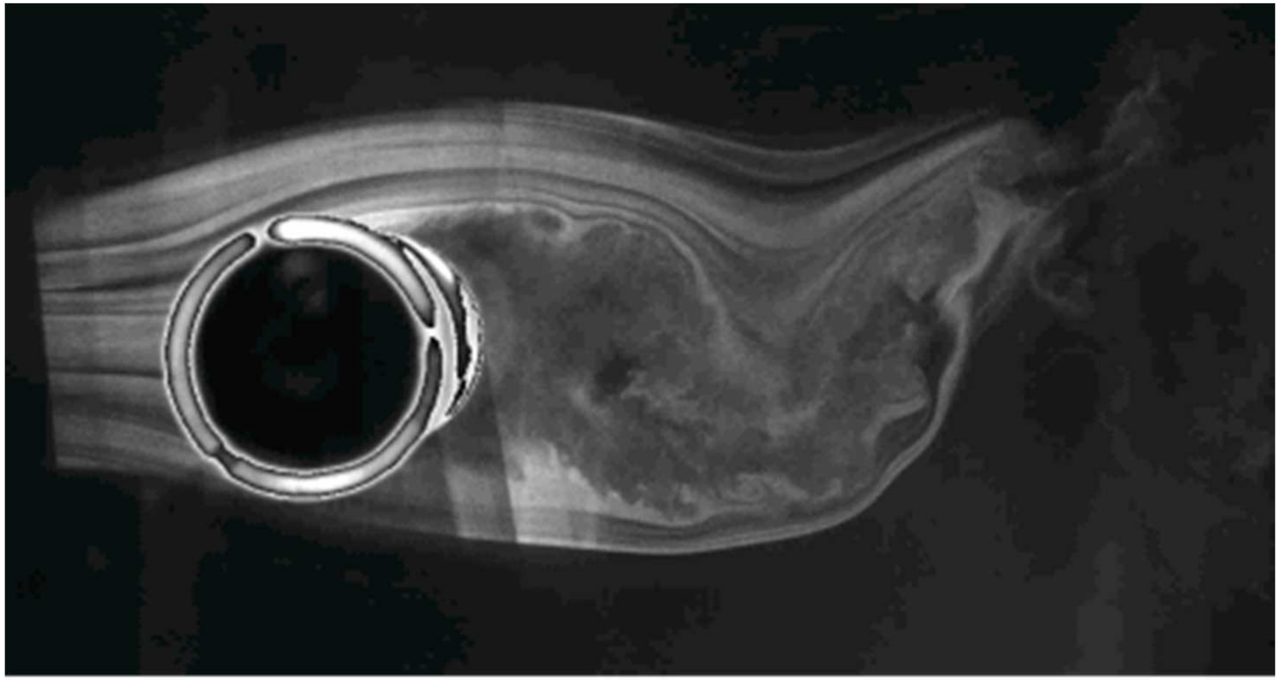
Our first video in 1999 ...

- **Flat plate**
  - U ≈ 2 m/s



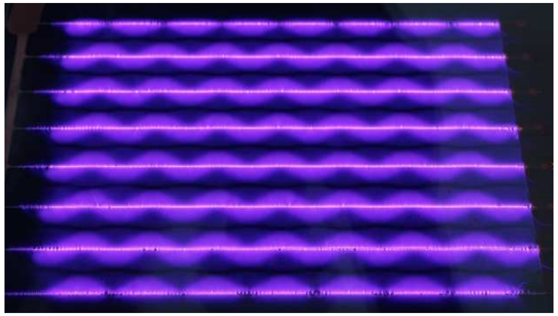
Cylinder

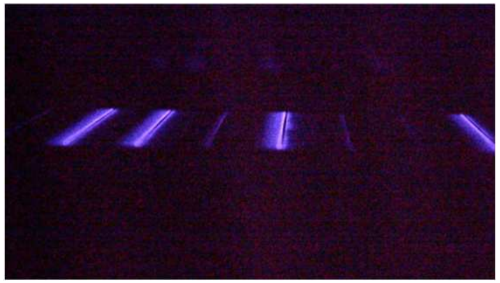
- **Experimental conditions**
- **1 kHz visualization, U_0 = 55 m/s (200 km/h, Re = 140,000)**
- Initially, discharge is OFF, and it is switched ON
- Vortex shedding is forced → **high flapping phenomenon downstream the cylinder**

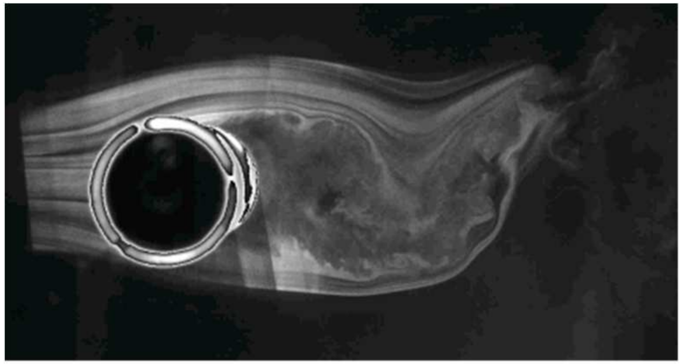


Airflow control by surface DBD

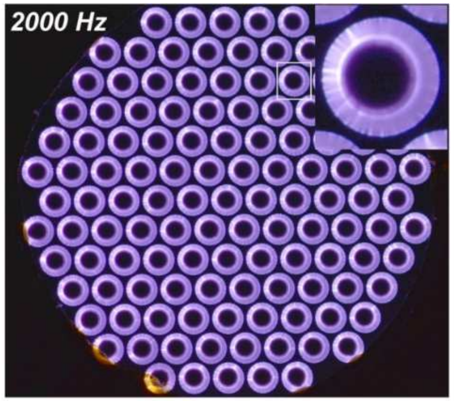
- **Lots of applications**
  - External flows (cylinder, backward-step, wing, flat plate) and internal flows (jets)
  - 3D spanwise forcing, multi-actuators

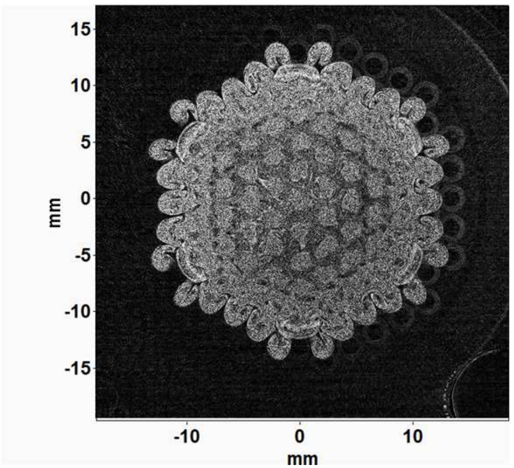


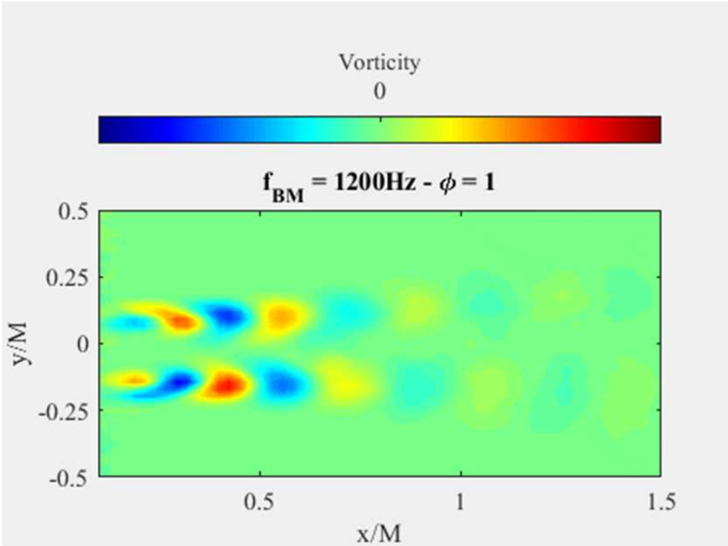




- **Mixing and combustion**
  - Plasma grid





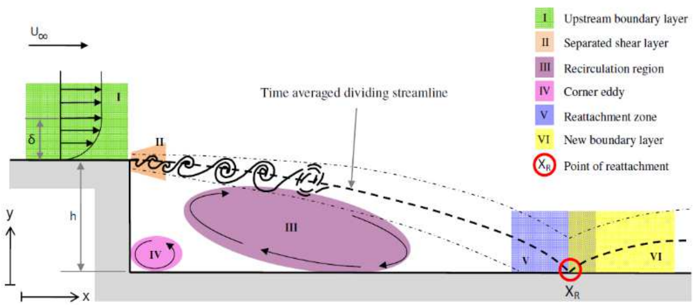


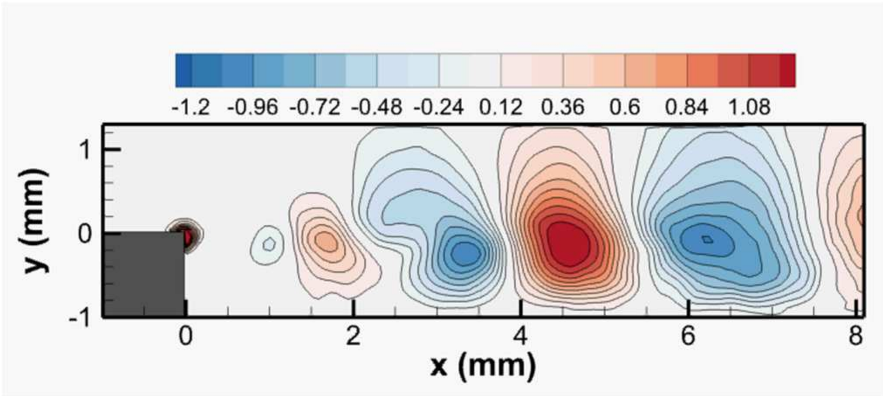
Example 1 : Backward-facing step

▶ **Shear layer**

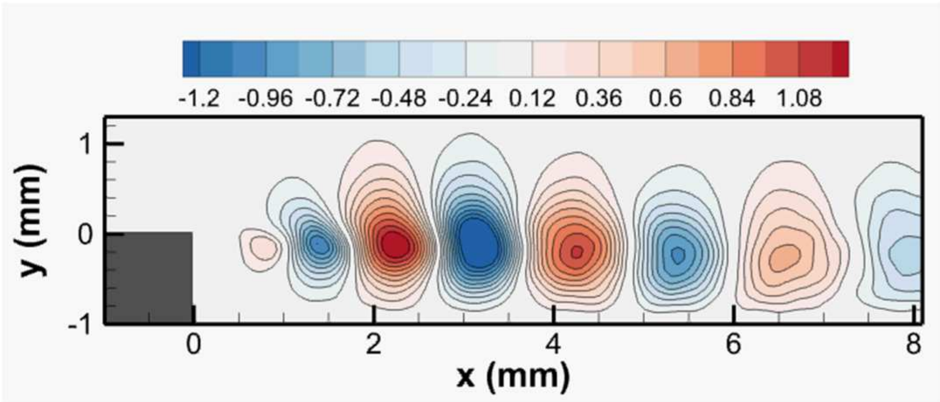
➪ The dynamics of the shear layer depends strongly on the actuation frequency f_{BM} (65 and 130 Hz)

➪ There is a lock-on phenomenon → **the shear layer frequency is fully driven by f_{BM}**





65 Hz



130 Hz

Example 2 : Free jet

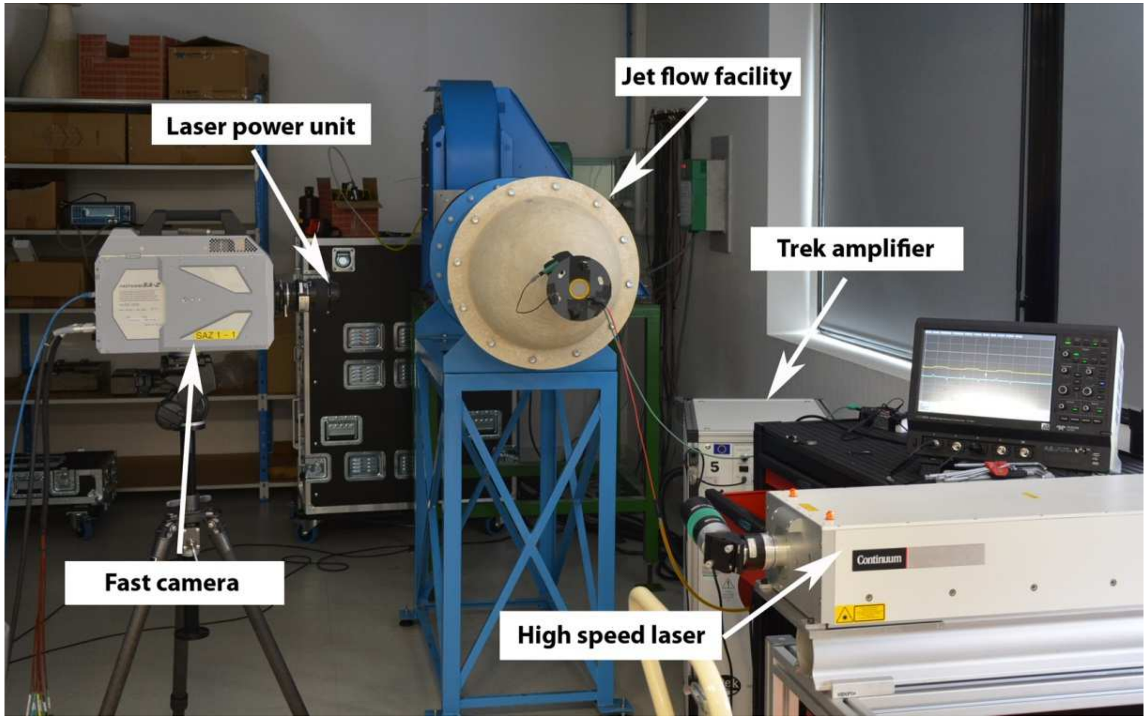
▶ **Airflow**

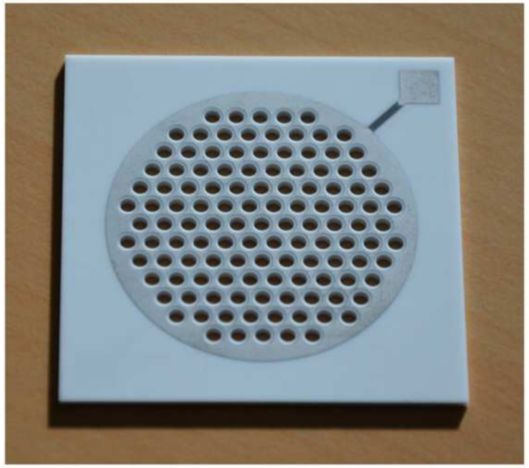
⇨ The perforated plate is implemented at the exhaust of a circular open-air type wind-tunnel

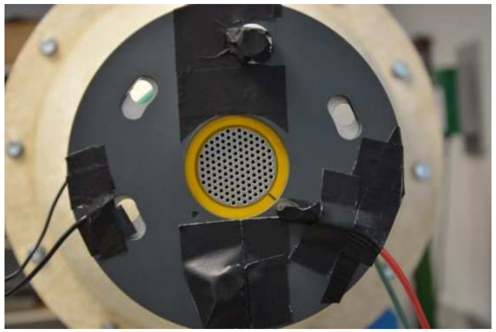
⇨ The main jet (D = 29 mm) is composed of 121 small jets (ϕ = 1.8 mm),

⇨ **Each jet will be controled by the discharge occuring at the exit of its hole**

⇨ Velocity from 5 up to 60 m/s



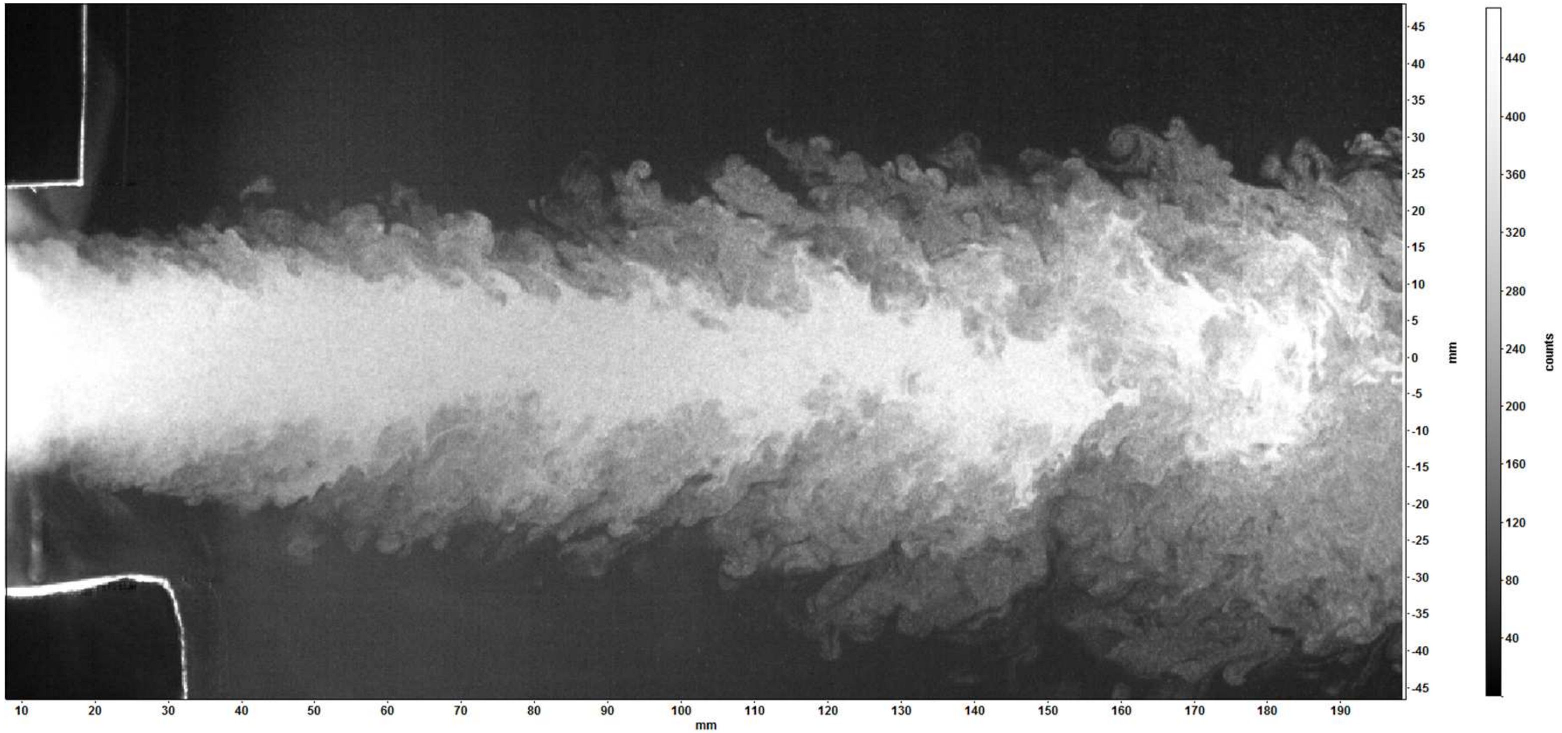




Flow control at 20 m/s

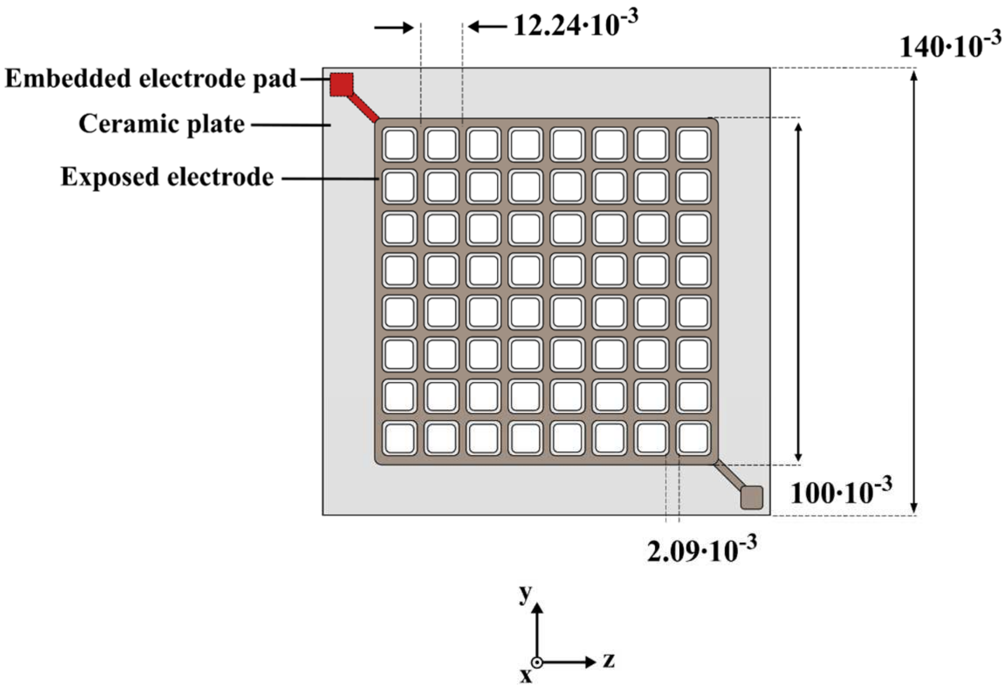
- **High speed video**

➪ Unsteady effect → **« pinching » effect that increases mixing and turbulence**



Grid turbulence & mixing

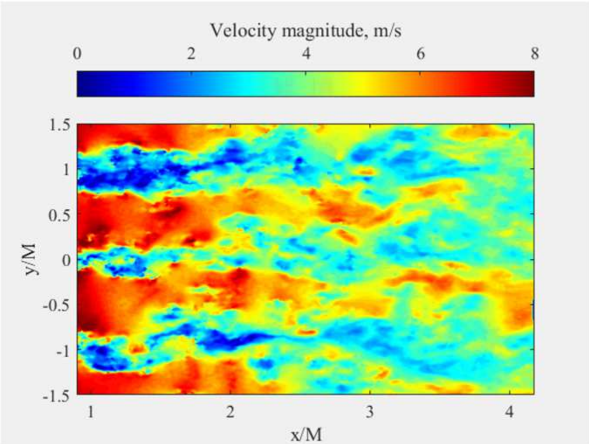
- **<u>Plasma-assisted grid for turbulence control</u>**
- ➪ Lots of applications in fluid mechanics → fundamental and mixing
- ➪ **3D actuation results in the wake control at the plasma frequency**

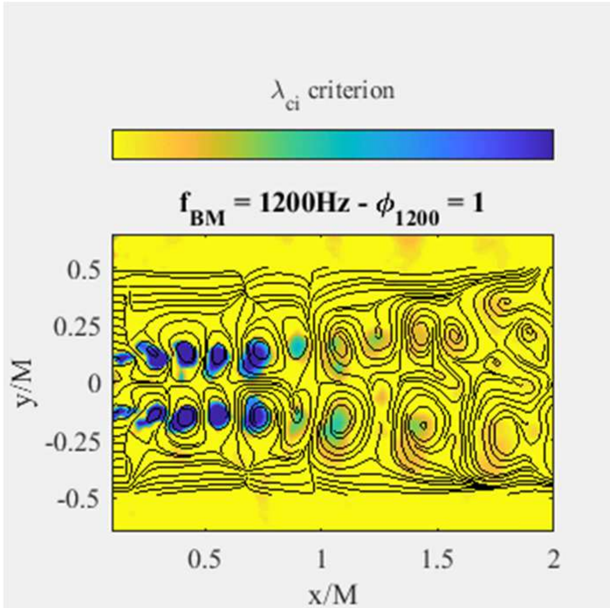


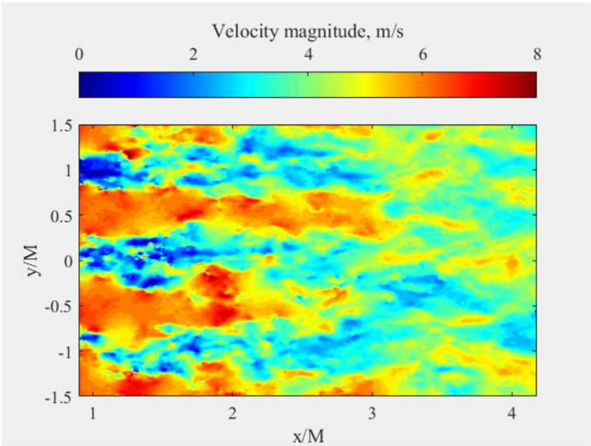
Vue de face
(a)

Grid turbulence & mixing

- **Plasma-assisted grid for turbulence control**
- ➪ Lots of applications in fluid mechanics → fundamental and mixing
- ➪ **3D actuation results in the wake control at the plasma frequency**







Outline

1) Volume needle-to-plate corona discharges
2) Surface dielectric barrier discharges
3) Plasma-induced liquid flows

Outline

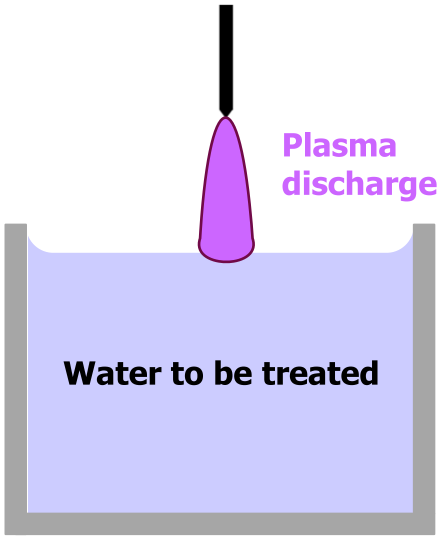
1) Volume needle-to-plate corona discharges

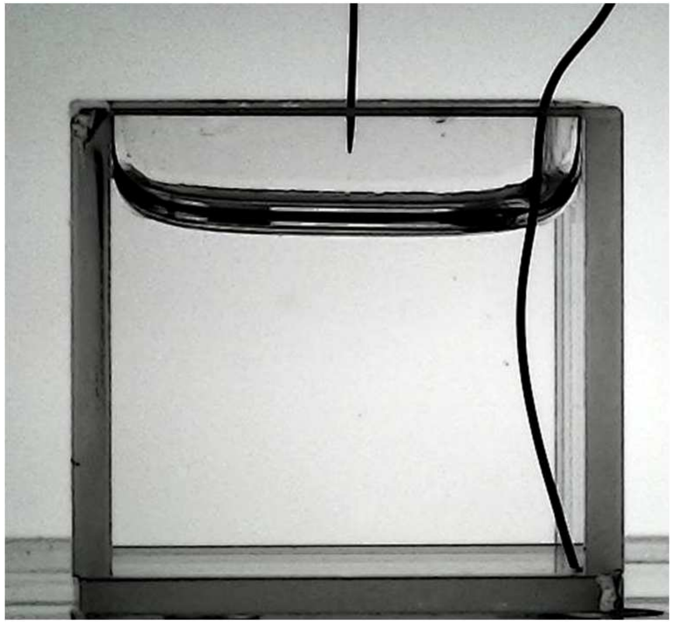
2) Surface dielectric barrier discharges

3) Plasma-induced liquid flows

Water treatment

- **New suject for 3 years**
- Discharge above the surface of a polluted water to treat it (it has been already done !)
- **Originality** : to characterize the role of the **EHD phenomena** on the chemical results
- Flow inside the discharge (ionic wind), deformation of the liquid surface, flow in the liquid
- **Depending on the discharge, these (EHD) phenomena are fully different !**





Water treatment by cold plasma

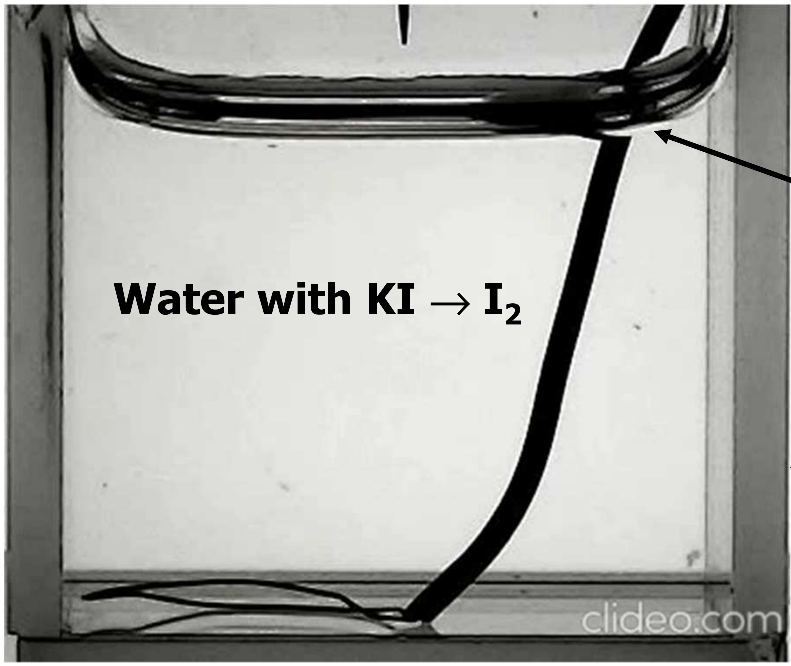
- **Chemical analysis**

➪ A easy **« chemical marker »** to characterize the chemical activity of the plasma treatment

➪ Potassium iodide (KI) converted in I_2 (by RONS as O_3 and H_2O_2)

➪ Its reaction with oxidant species is followed by a **change of colour (uncoloured to brown)**

➪ Accelerated video with a **DC corona discharge (≈ 100 mW)**



Water surface

Glass vessel

Water treatment by cold plasma

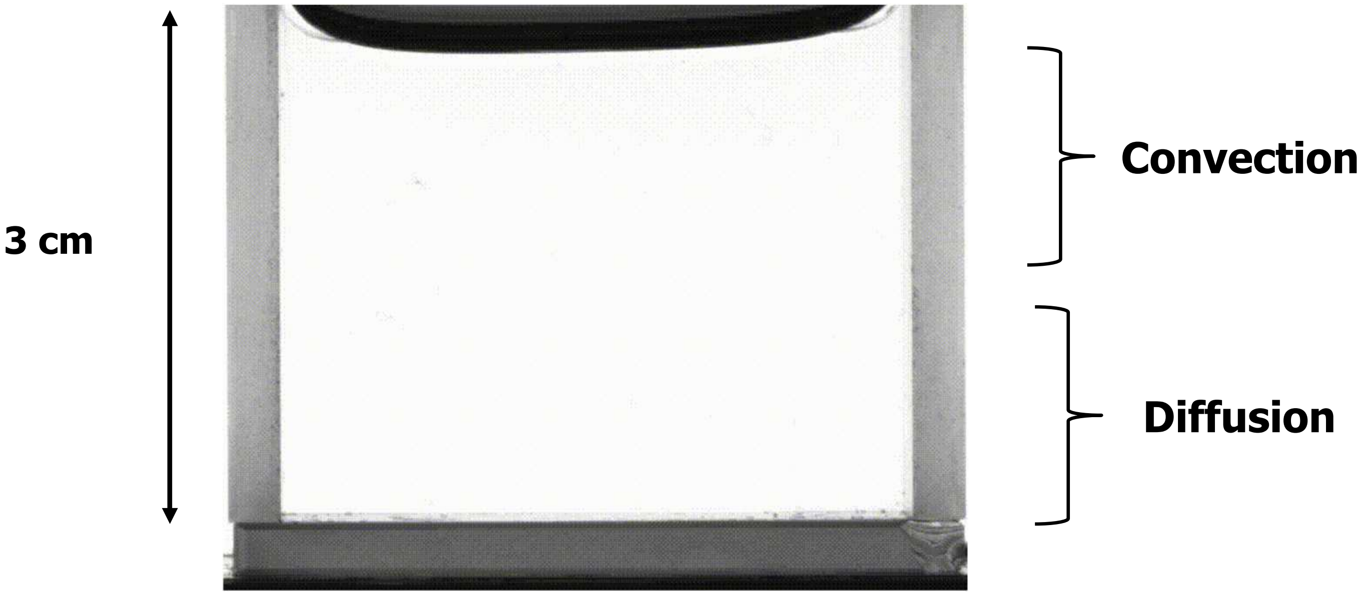
- **DC normal glow discharge (2 W)**

⇨ **Flow in the liquid !**

⇨ Two zones : convection of chemical species and diffusion → convection faster than diffusion

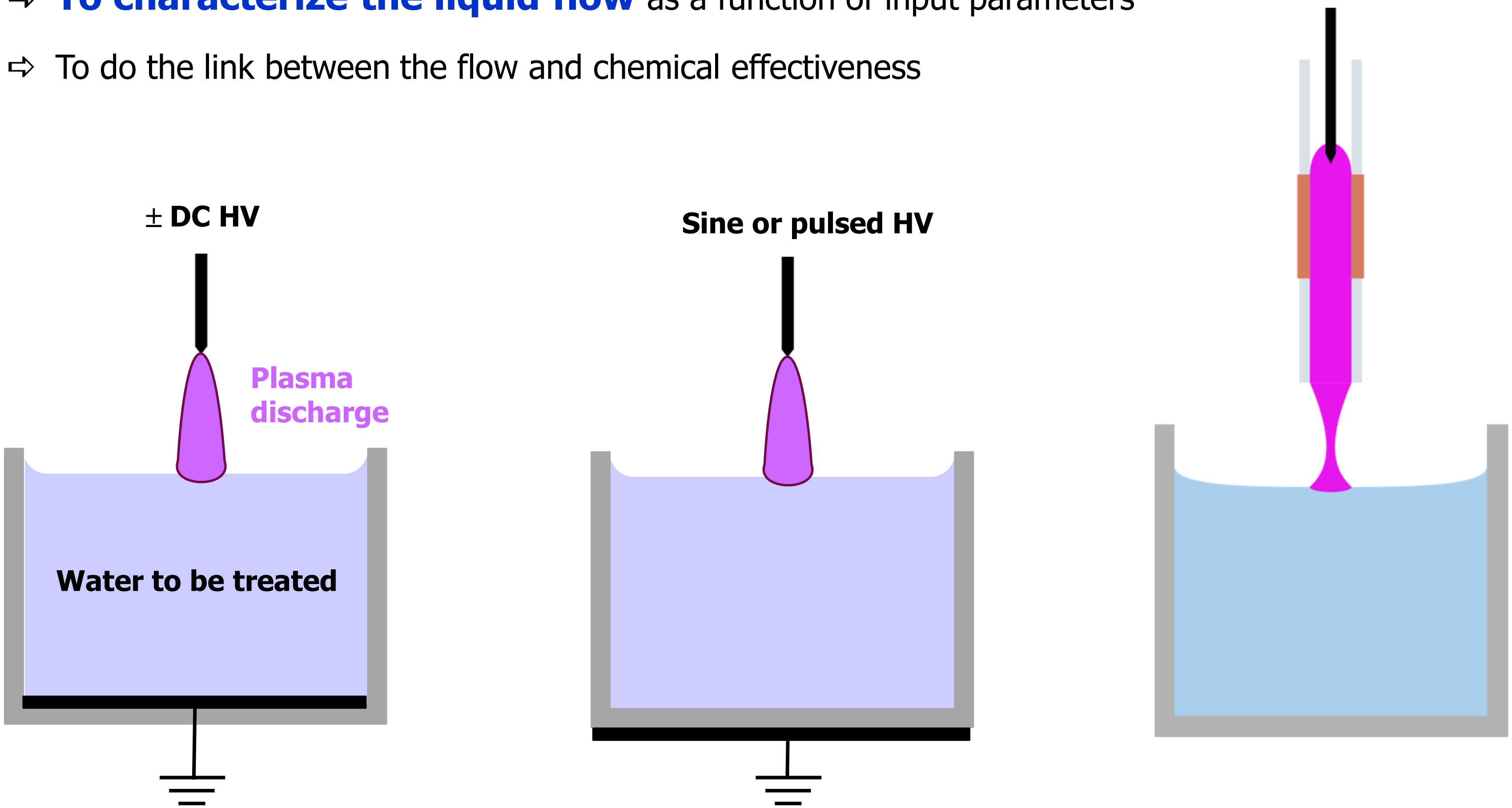
⇨ Interesting to mix the liquid **to improve the chemical results**

⇨ To study these cold **plasma-based liquid flows by PIV diagnostic**



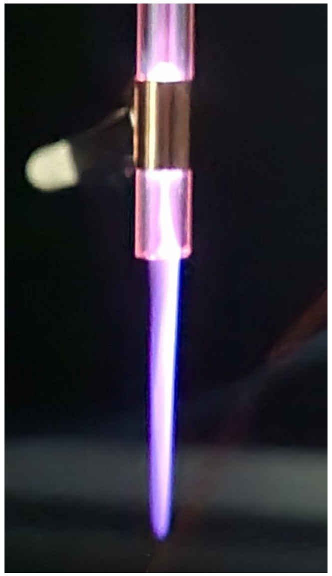
Water treatment by cold plasma

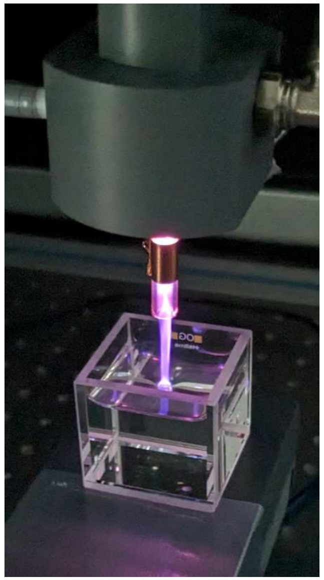
- **New subject for 3 years**
- ➪ Compare the effectiveness of different discharges (**DC, AC-DBD and pulsed DBD, plasma jet**)
- ➪ **To characterize the liquid flow** as a function of input parameters
- ➪ To do the link between the flow and chemical effectiveness

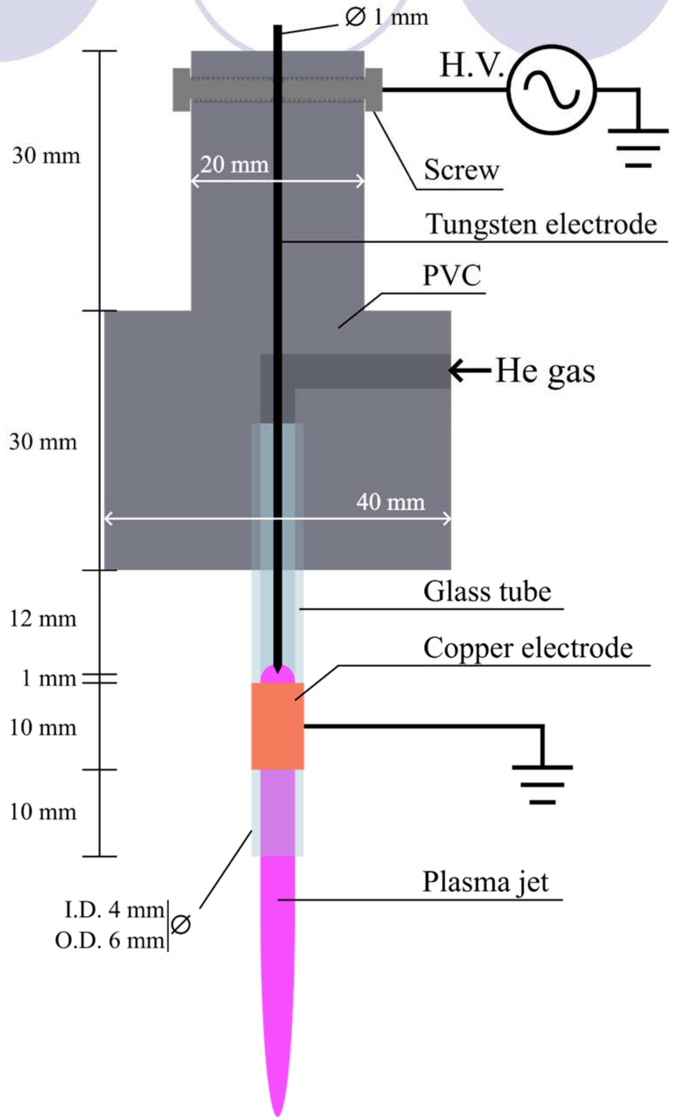


Plasma jet

- **DBD-based helium plasma jet**
- ➪ **Without helium flow** → DBD confined inside the tube
- ➪ **With helium flow → plasma jet of a few cm**

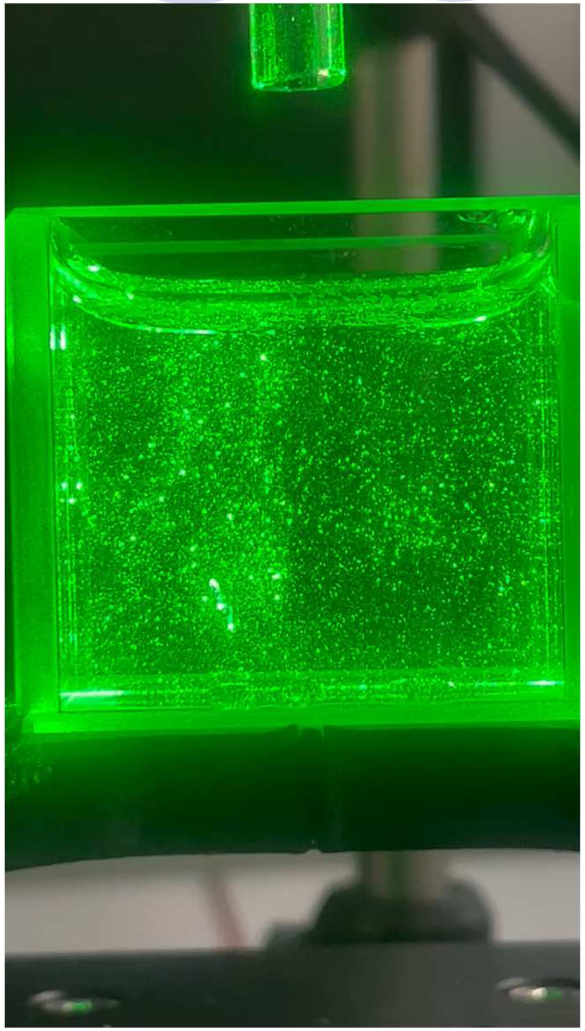




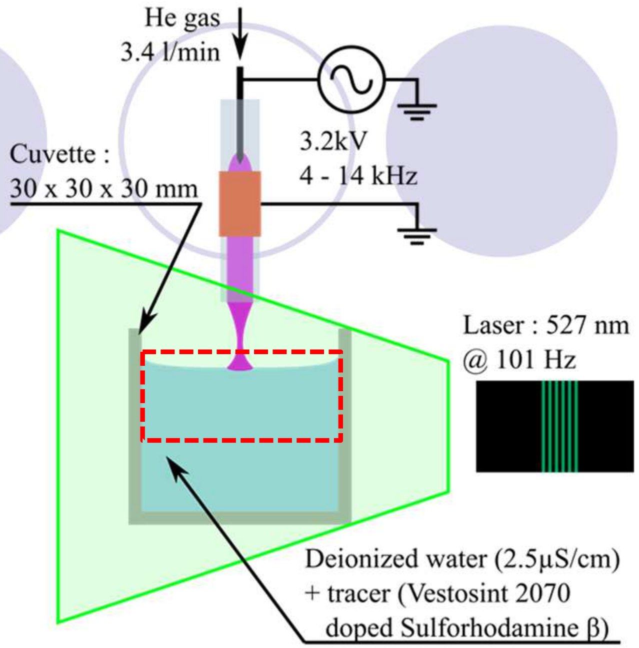


Flow visualization

- **Simple visualization**
- ➪ Vessel → 3 × 3 × 3 cm^3 (20 mL of water)
- ➪ Gap = 10 mm
- ➪ Plasma off → **water flow induced by the He flow**
- ➪ Plasma on → **velocity increase due to electric forces**



PIV measurements

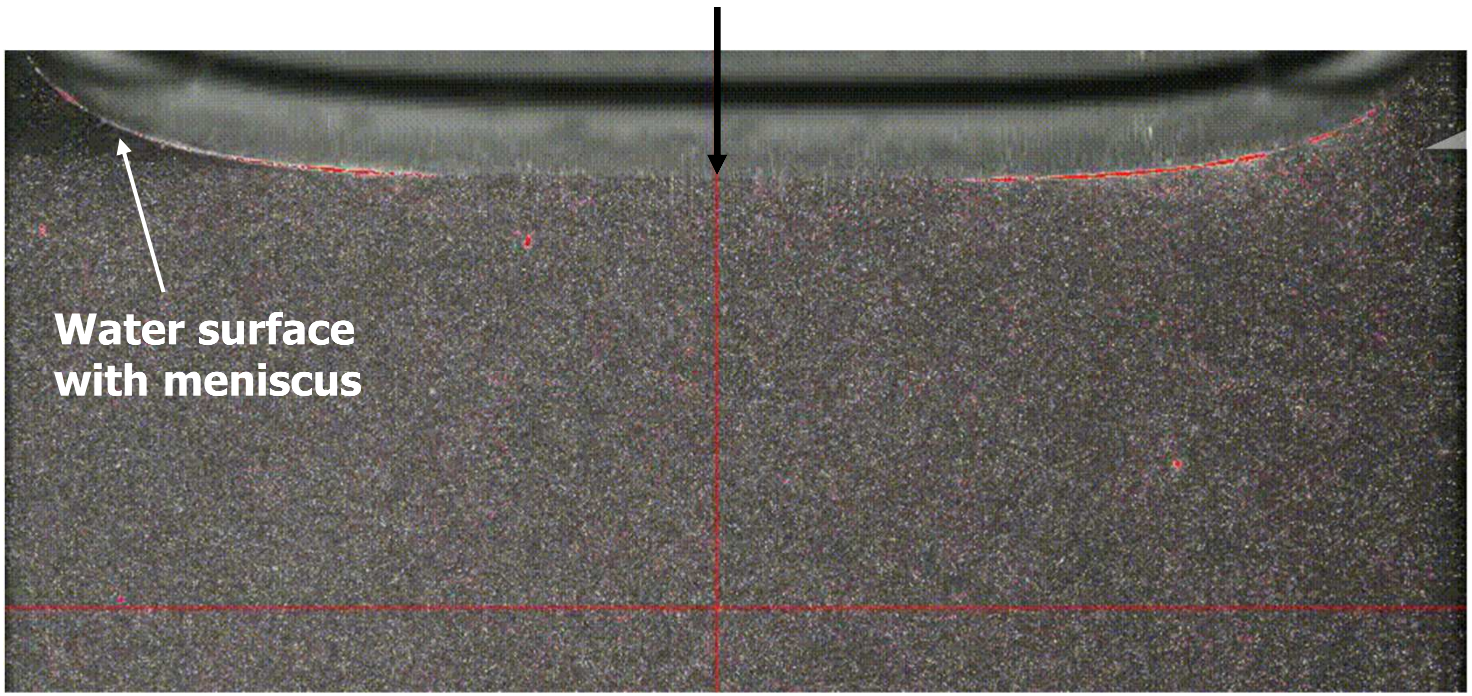


- **PIV pictures**

⇨ Images taken with the PIV camera (9 Mpixels, 101 Hz)

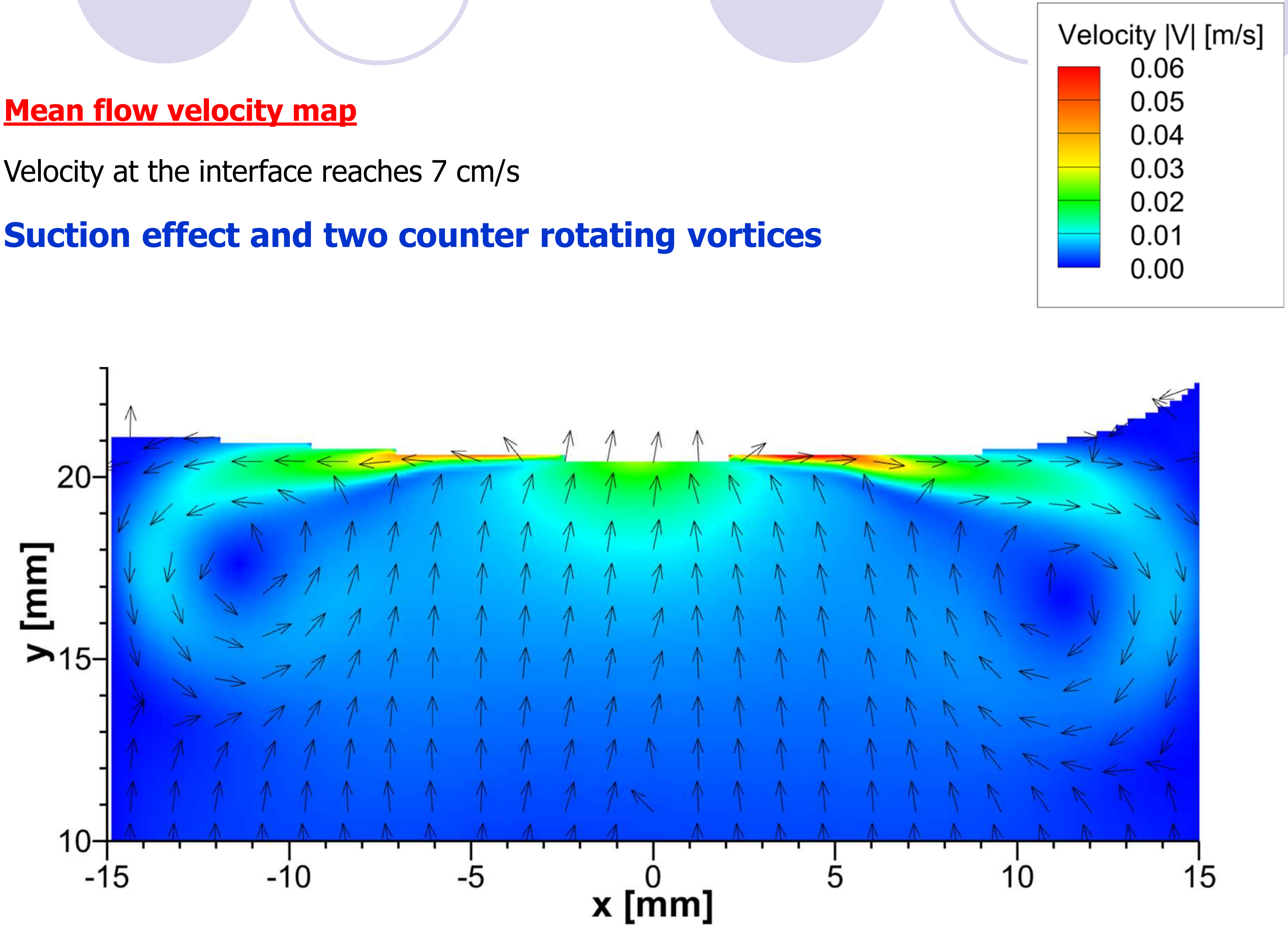
⇨ **High quality images** → good spatial resolution

⇨ **Two counter-rotating vortices**



Time-averaged flow

- **Mean flow velocity map**
- ➩ Velocity at the interface reaches 7 cm/s
- ➩ **Suction effect and two counter rotating vortices**



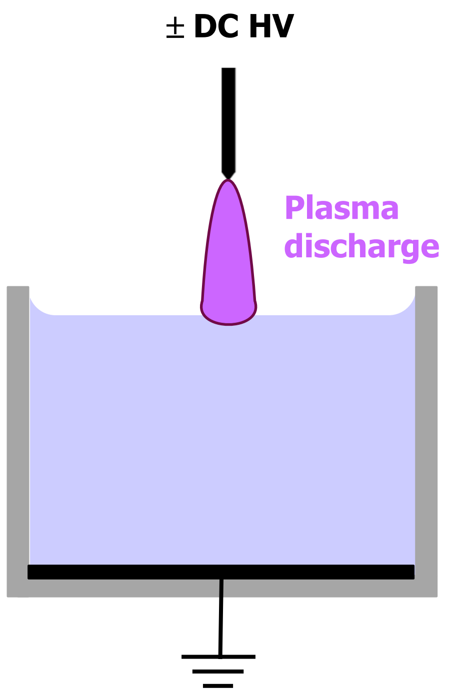
DC discharge

▶ **DC discharge**

➪ Needle located above the water surface (**gap =2 mm**)

➪ Grounded electrode immersed in the water

➪ **± DC HV at the needle**



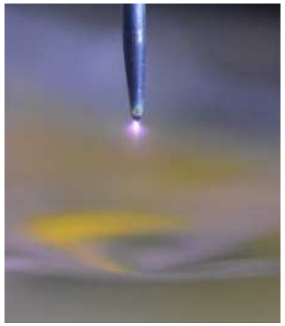
Discharge regimes

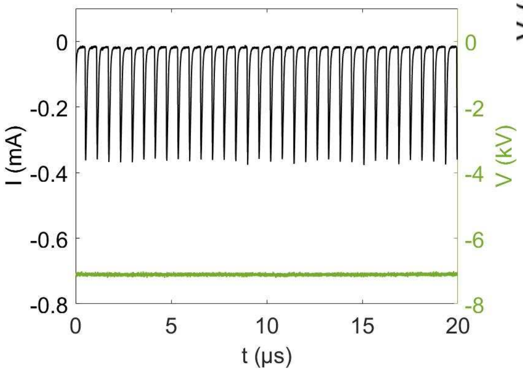
▶ **Corona, unstable glow and stable glow**

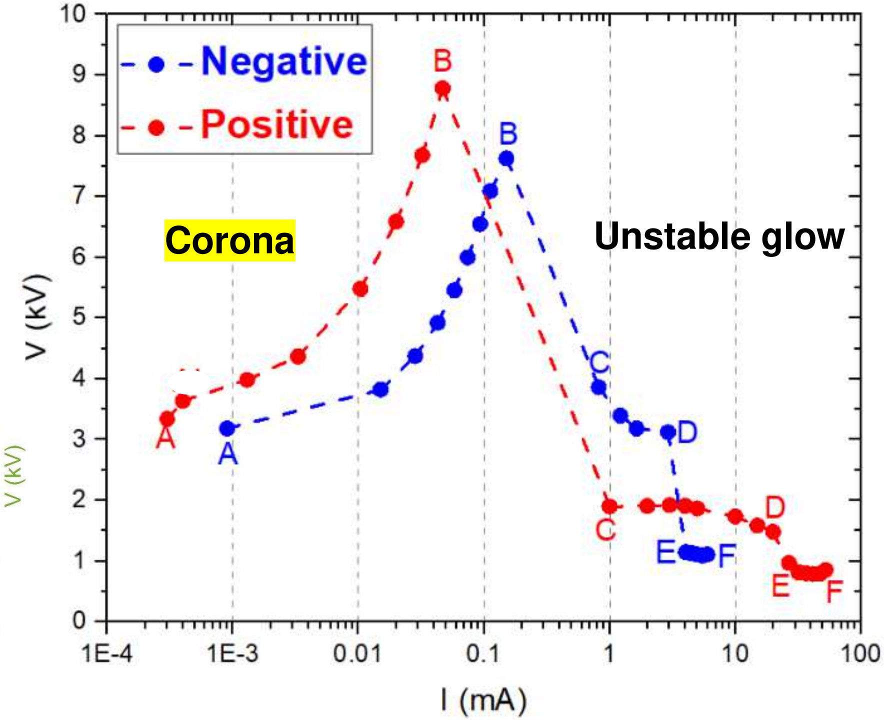
➪ **Corona discharge** (A-B) → current up to 150 µA (Townsend's law, as for point-plate, but higher current)

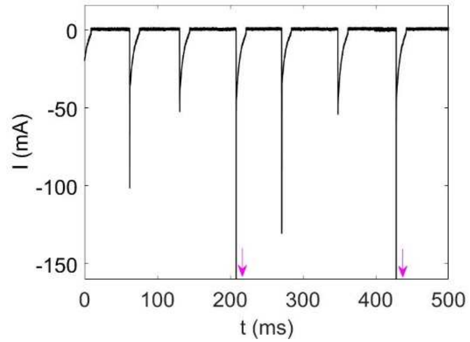
➪ Unstable **glow** → high current peaks, up to 200 mA

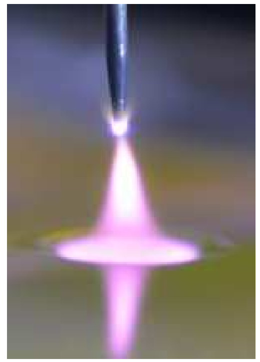
➪ From point E, stable **glow discharge** → constant current of a few mA











Stable glow

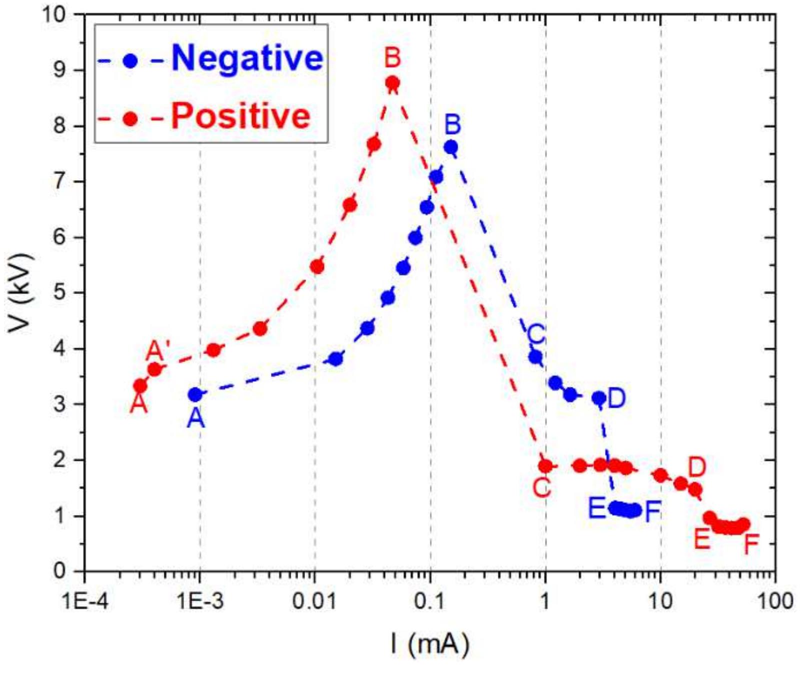
Discharge regimes

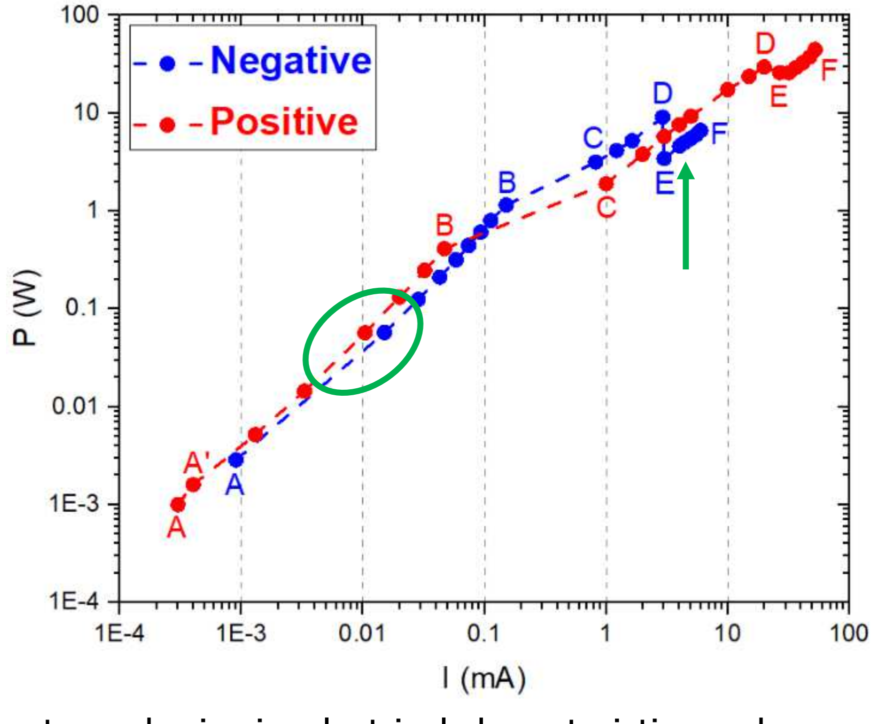
▶ **Electrical power and PIV**

➪ Electrical power → from mW to several dozens of W !

➪ **Corona discharge** → 7 to 30 µA (**< 100 mW**)

➪ **Glow discharge** → current fixed to 3.8 mA (**a few W**)





➪ Alomari et al., « Needle-to-liquid DC discharge in atmospheric air: electrical characteristics and impact on potassium halide solutions", *Plasma Chemistry and Plasma Processing*, 2025.

PIV system

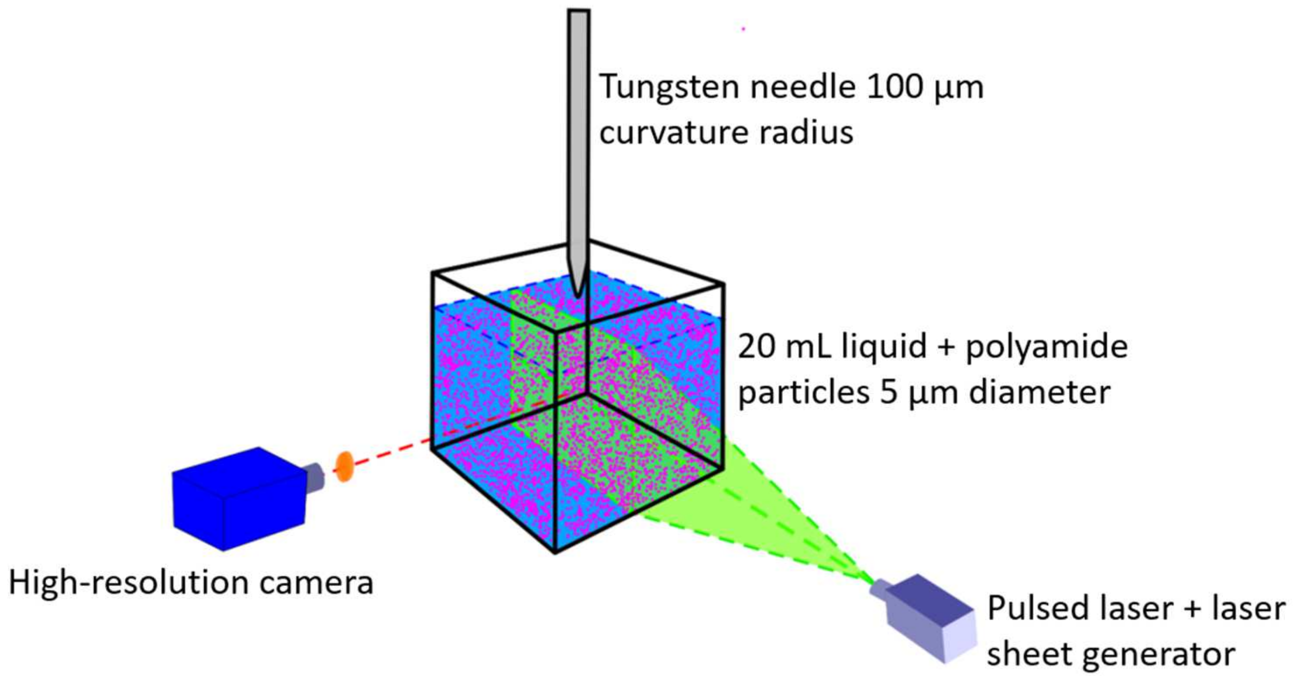
- **PIV**

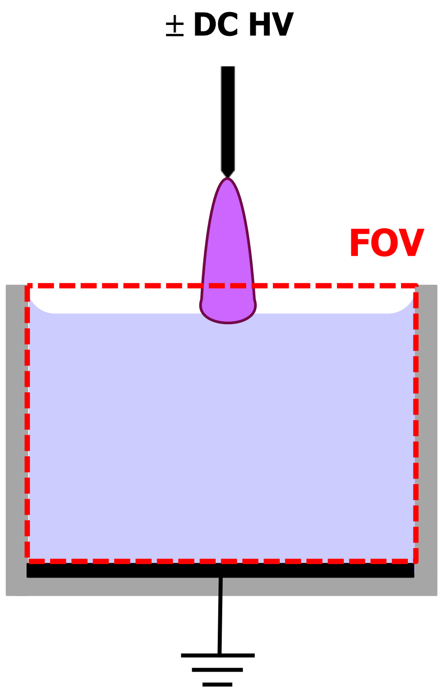
➪ **Particule Image Velocimetry is the liquid phase**

➪ Polyamide particles with rhodamine (diameter = 5 µm)

➪ 2000 images @101 Hz, 9 Mpixels camera → one vector every 100 µm

➪ **Time-averaged velocity fields**





PIV system

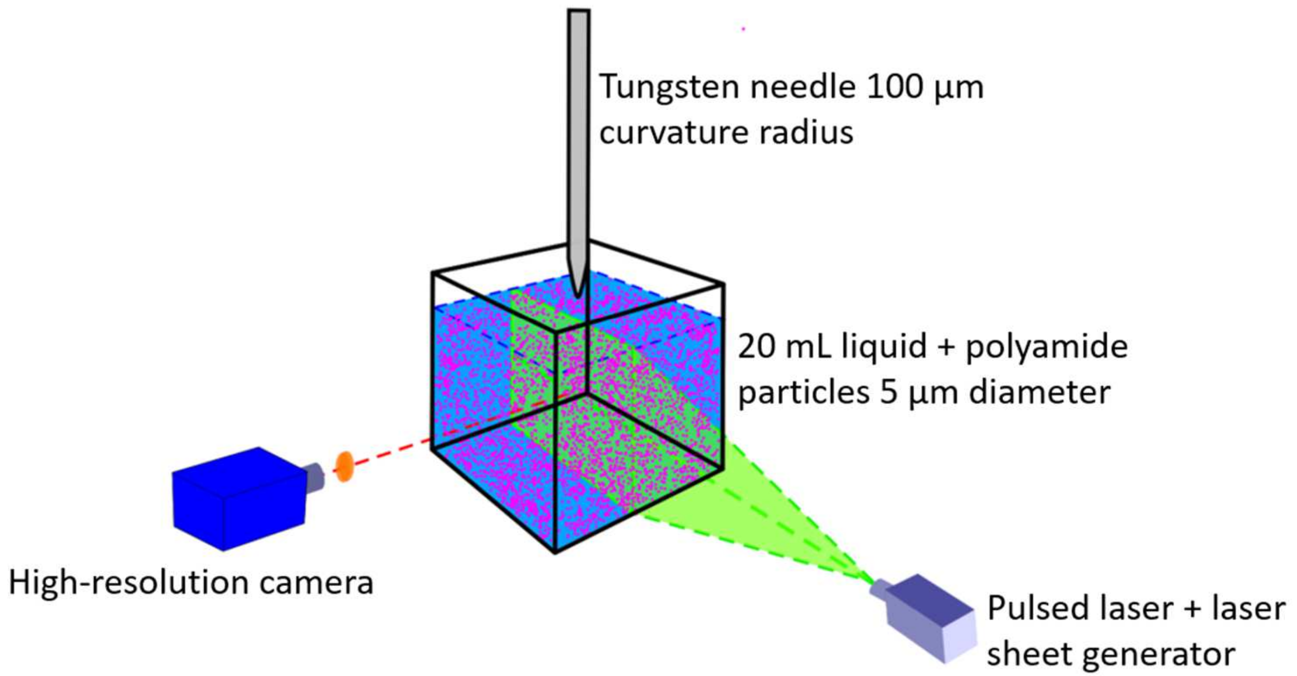
- **PIV**

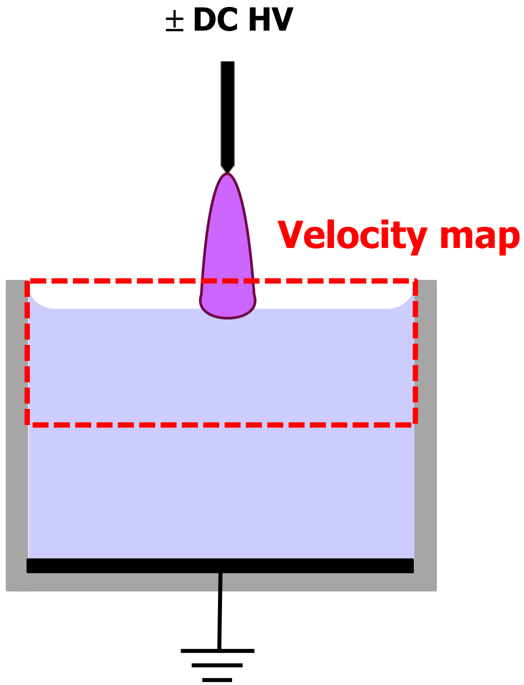
➪ **Particule Image Velocimetry is the liquid phase**

➪ Polyamide particles with rhodamine (diameter = 5 µm)

➪ 2000 images @101 Hz, 9 Mpixels camera → one vector every 100 µm

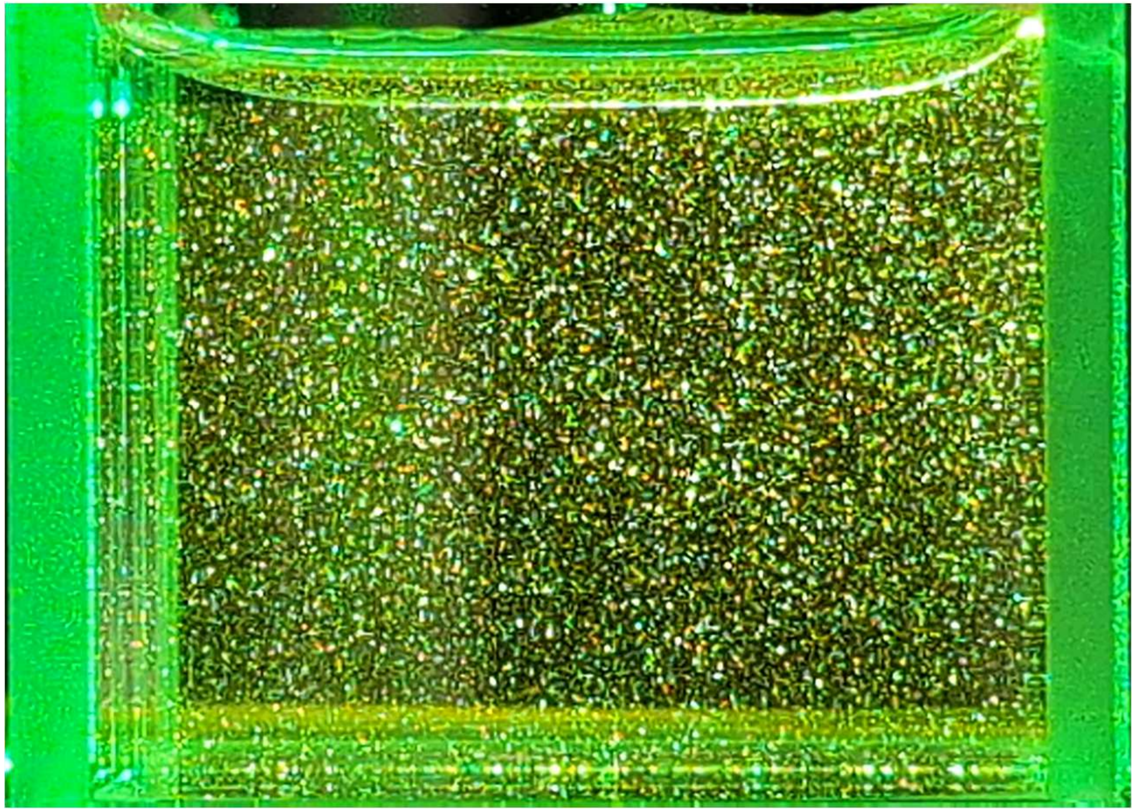
➪ **Time-averaged velocity fields**





Example of liquid flow

- **Positive glow discharge (a few W)**
- ⇨ Two strong and fast vortices !
- ⇨ **Upward force** and **outward force**



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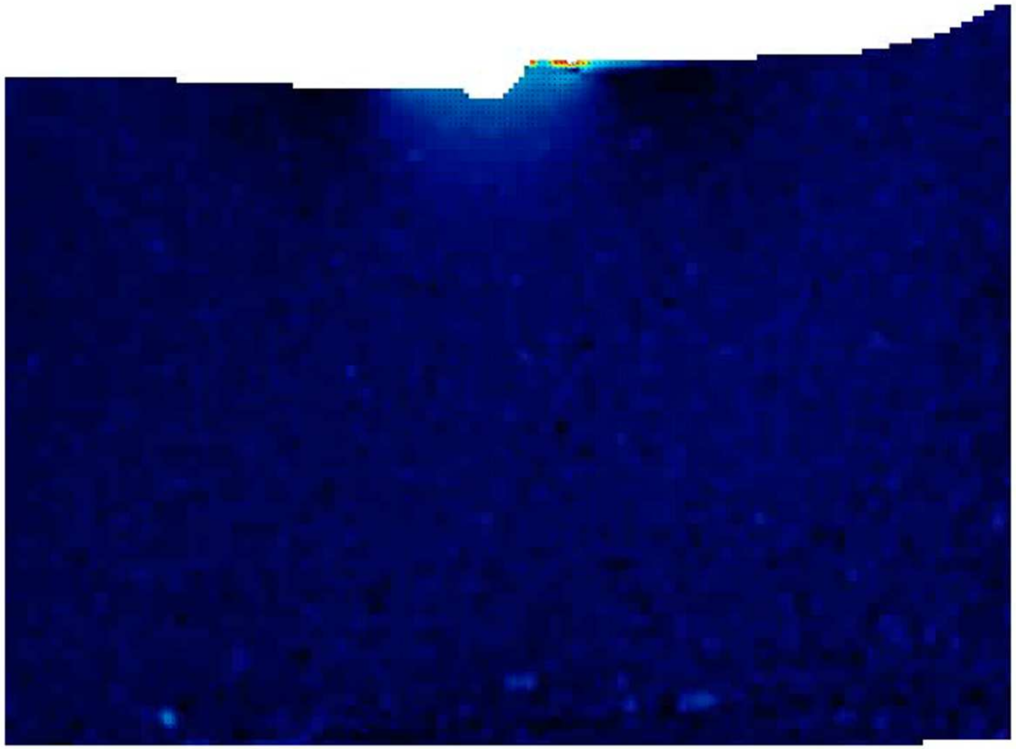
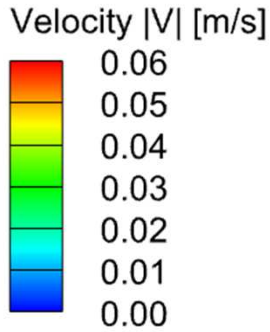
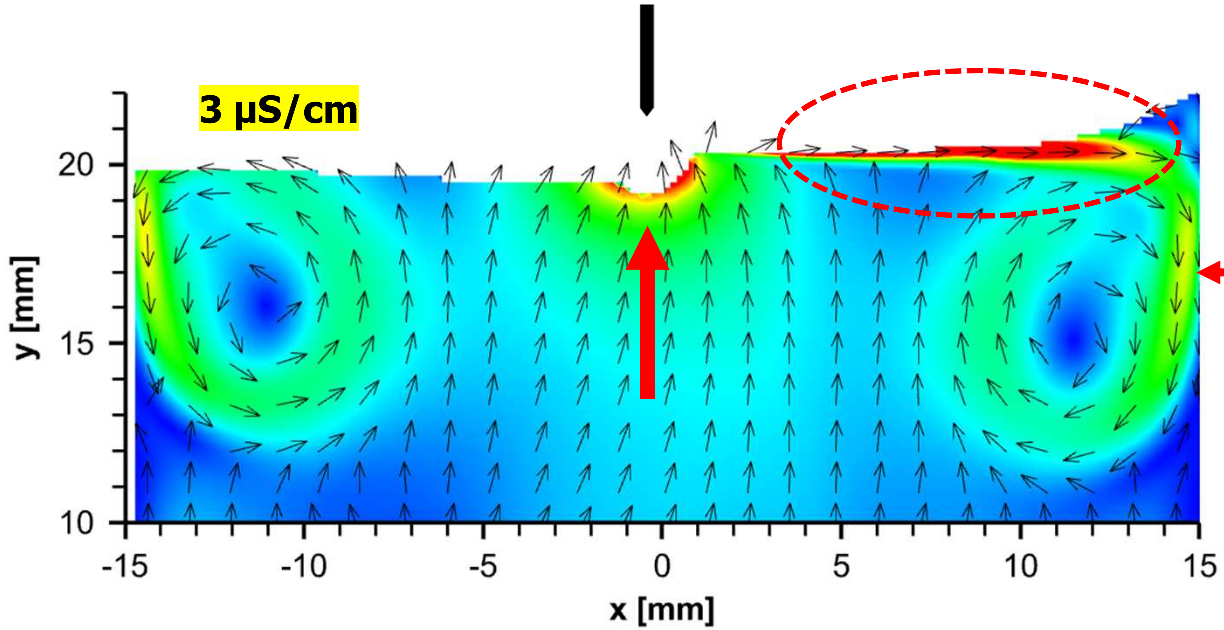
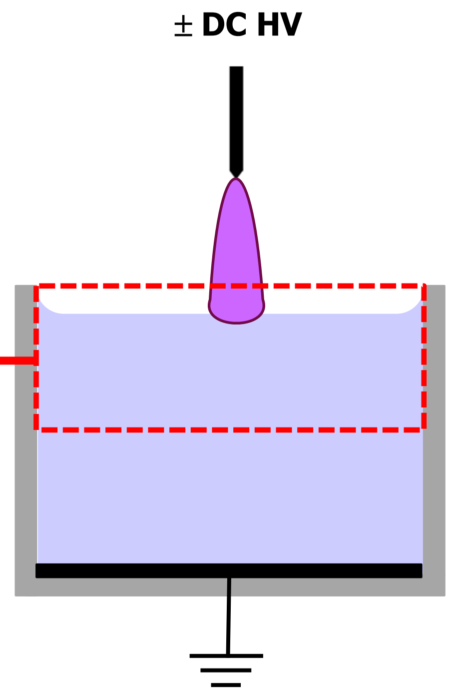


Glow discharge

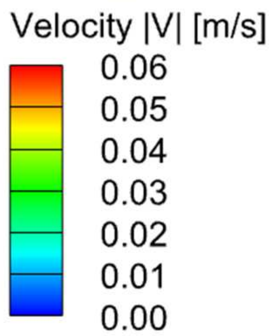


- **Positive glow (σ = 3 μS/cm, gap = 2 m)**
  - ➪ Deformation of the water surface → shadow region without velocity vectors
  - ➪ **Tangential flow** due to force at the interface → **two counter-rotating vortices**
  - ➪ **Upward flow** due to a volume force inside the water
  - ➪ Velocity up to **14 cm/s at the interface** (x ≈ 8 mm) → very speed compared to the vessel size !





Glow discharge



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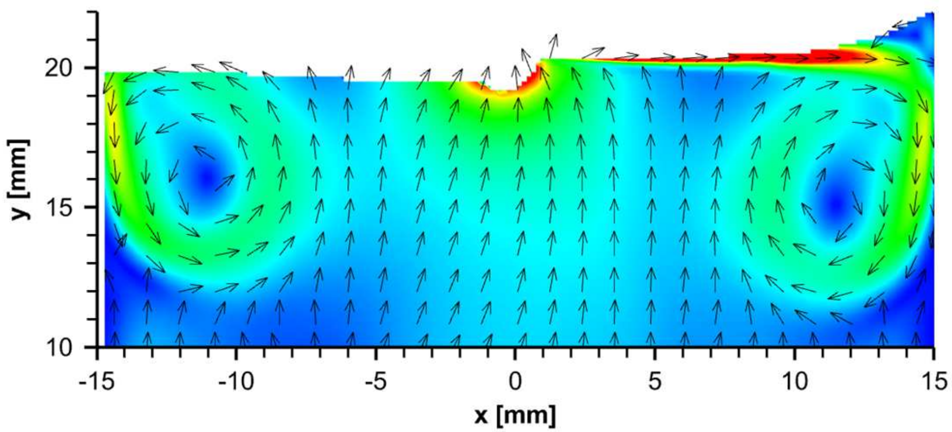
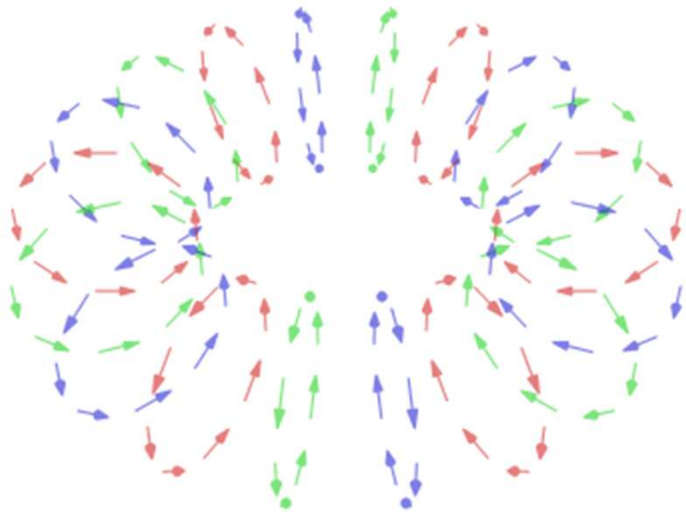
➪ Velocity up to **14 cm/s at the interface** (x ≈ 8 mm) → very speed compared to the vessel size !

➪ Cross-section of a single 3D toroidal vortex → **3D vortex ring**

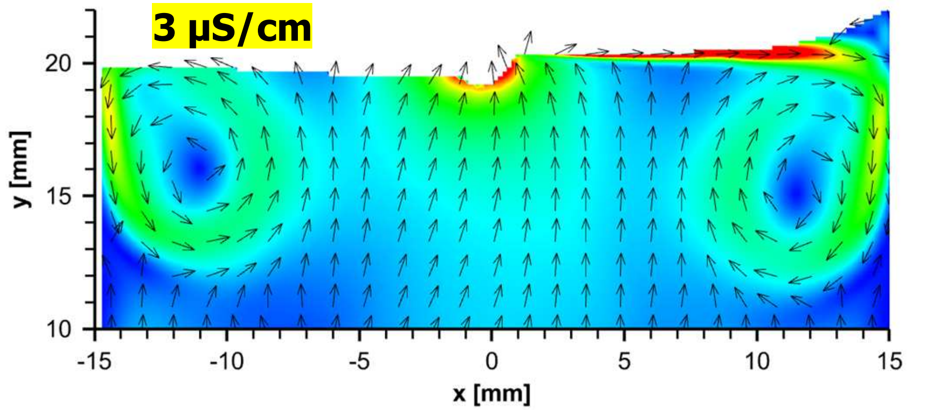


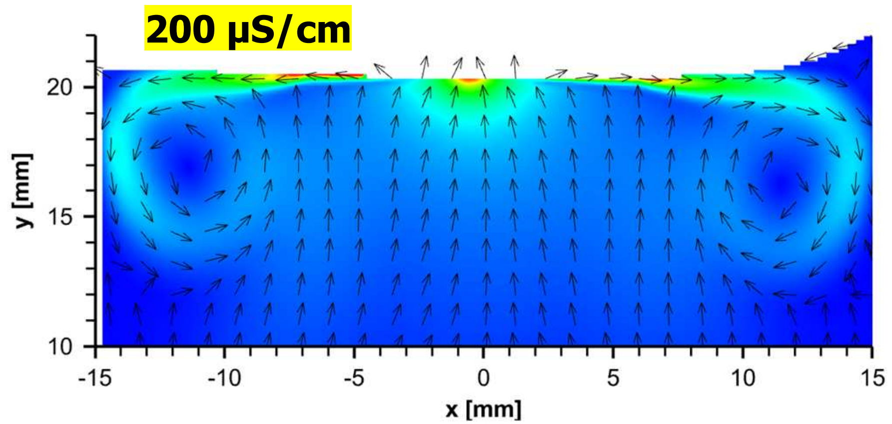


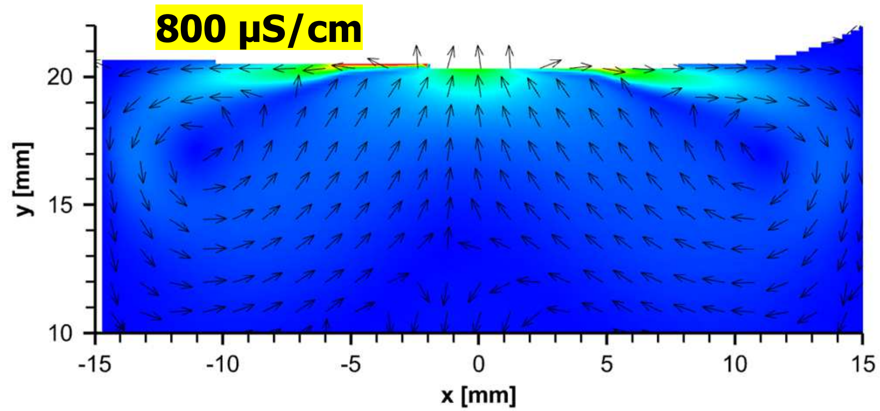
Glow discharge

- **Positive glow**

➪ **Velocity ↘ when conductivity ↗**





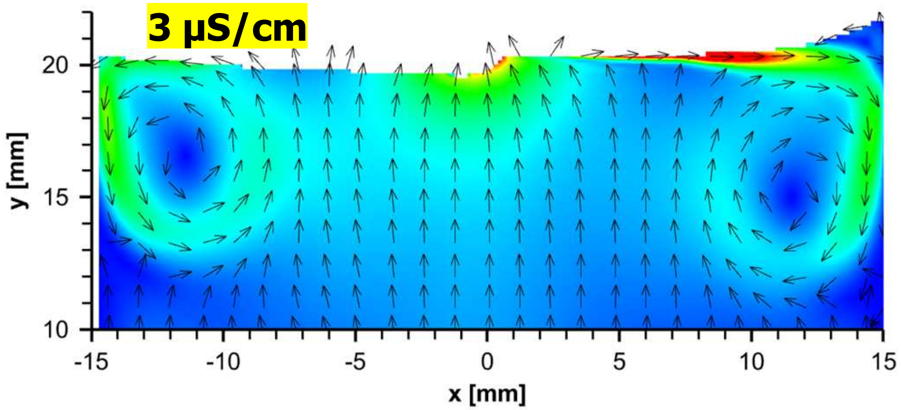


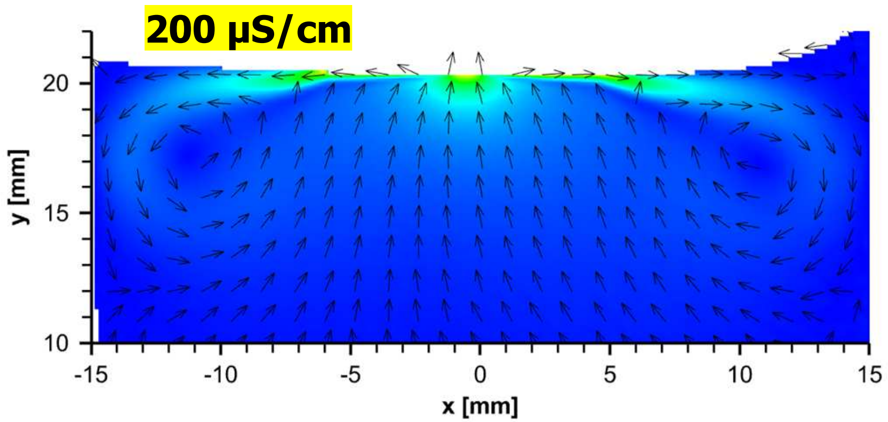
Glow discharge

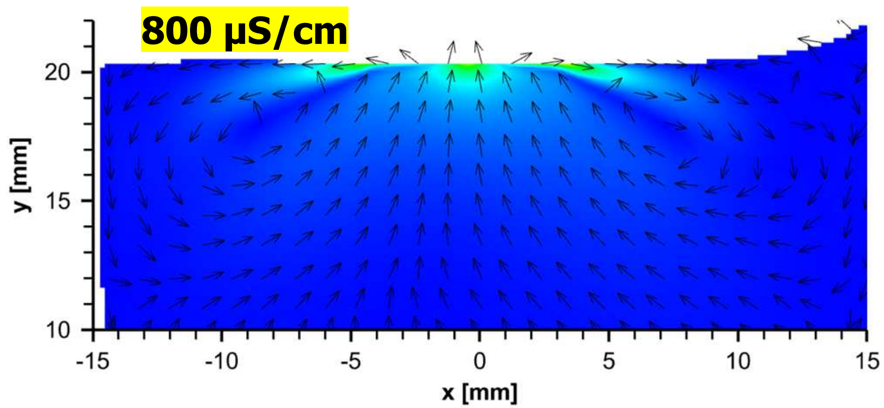
▶ **Negative glow**

⇨ Deformation is weaker, velocity ↘ when conductivity ↗

⇨ Velocity at the interface → **14 and 11 cm/s for positive and negative, respectively !**







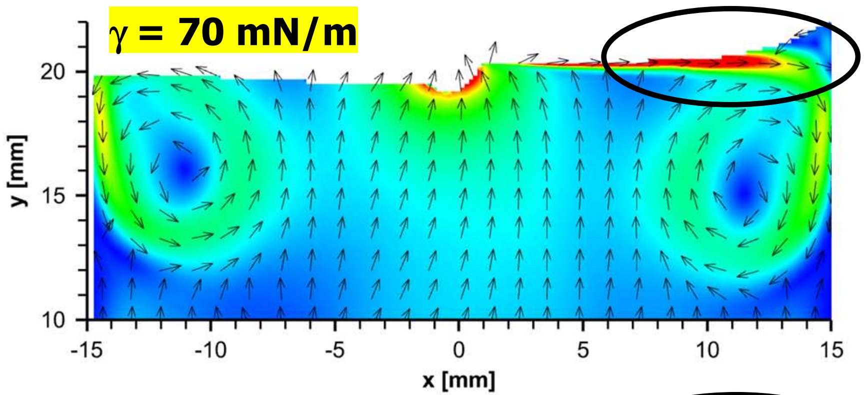
Glow discharge

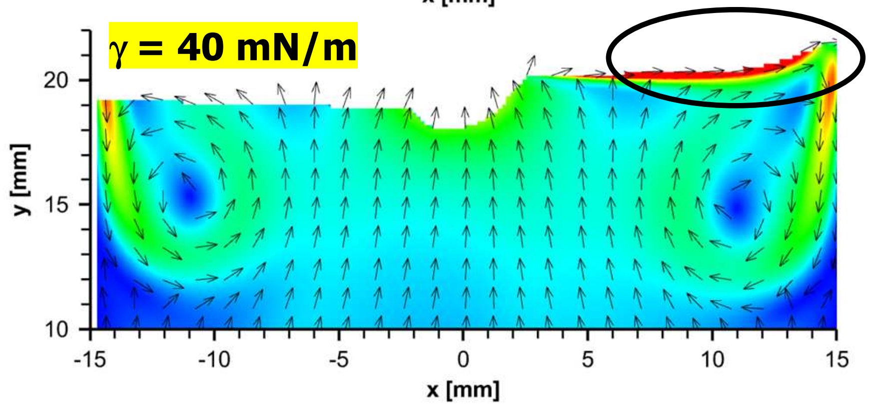
▶ **Effect of the superficial tension**

➪ σ = 3 µS/cm, **γ = 70 mN/m** (pure water) and **γ = 40 mN/m** (20% ethanol)

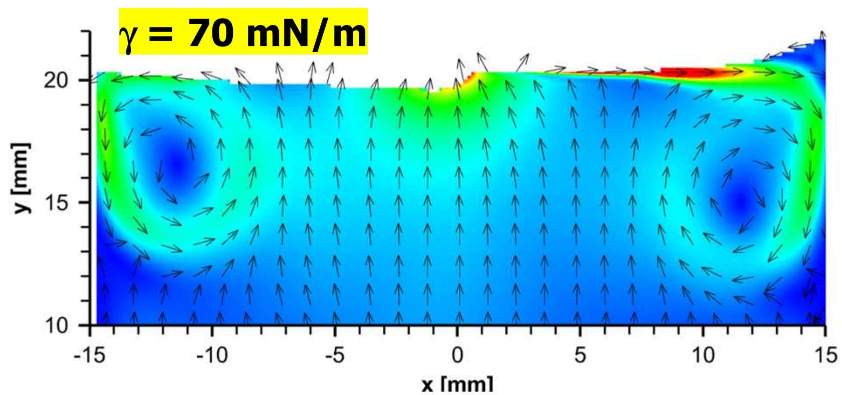
➪ **Decrease in γ → velocity propagate more along x**

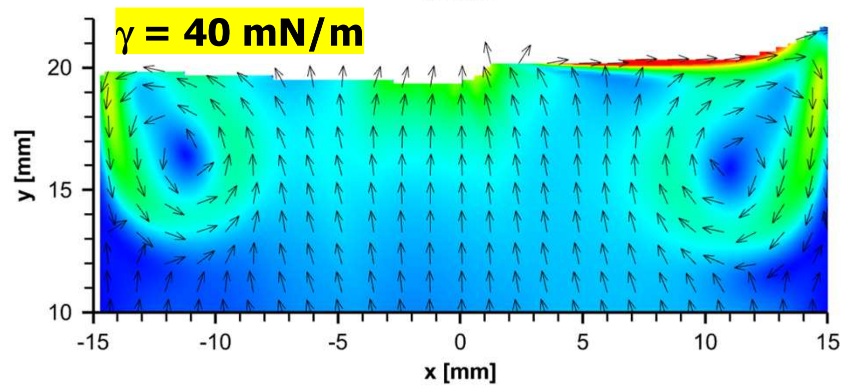
Positive glow



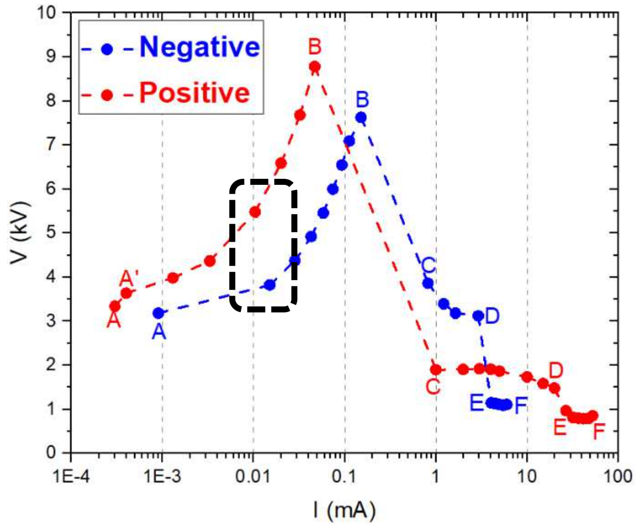


Negative glow

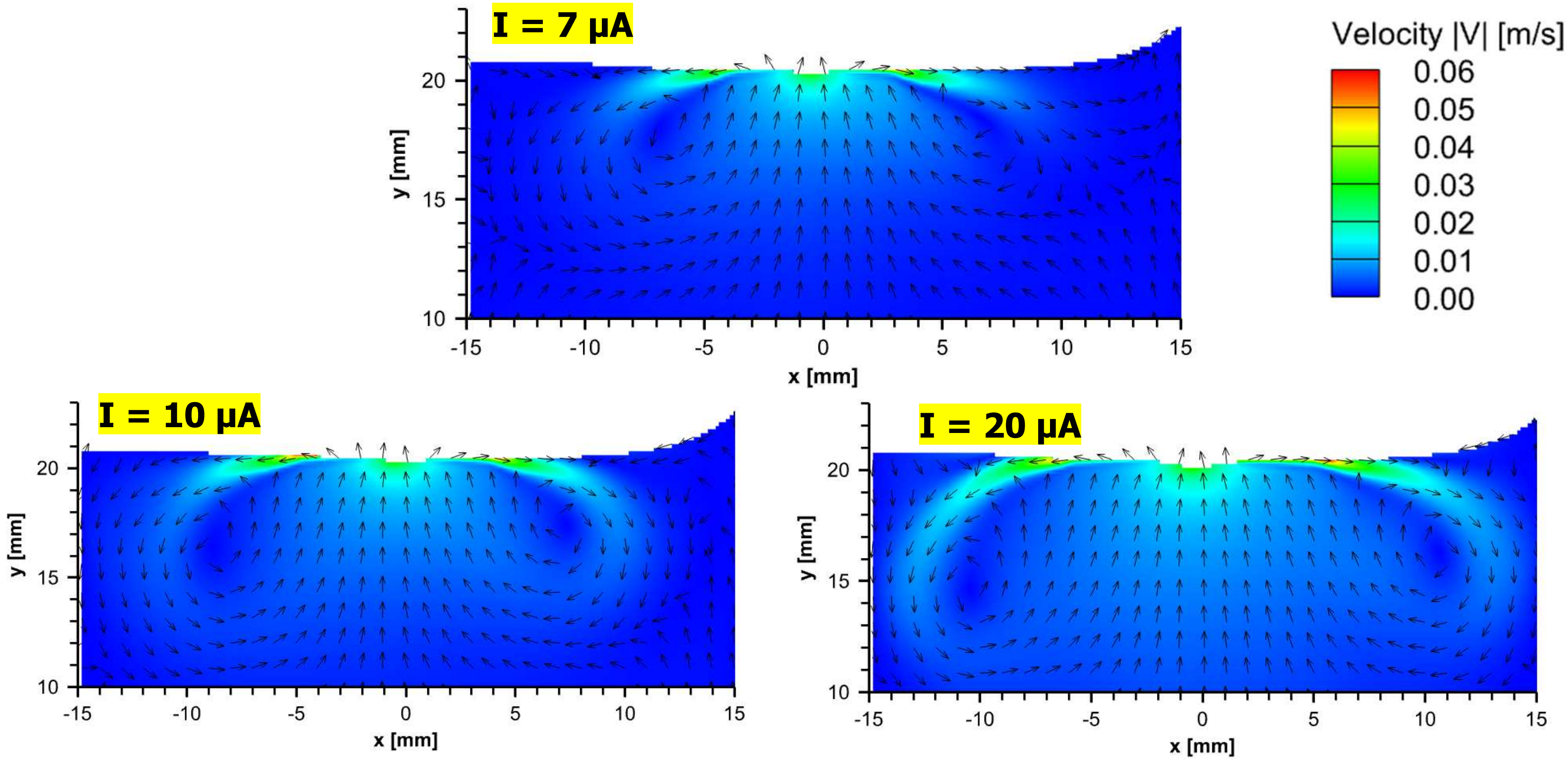




Corona discharge



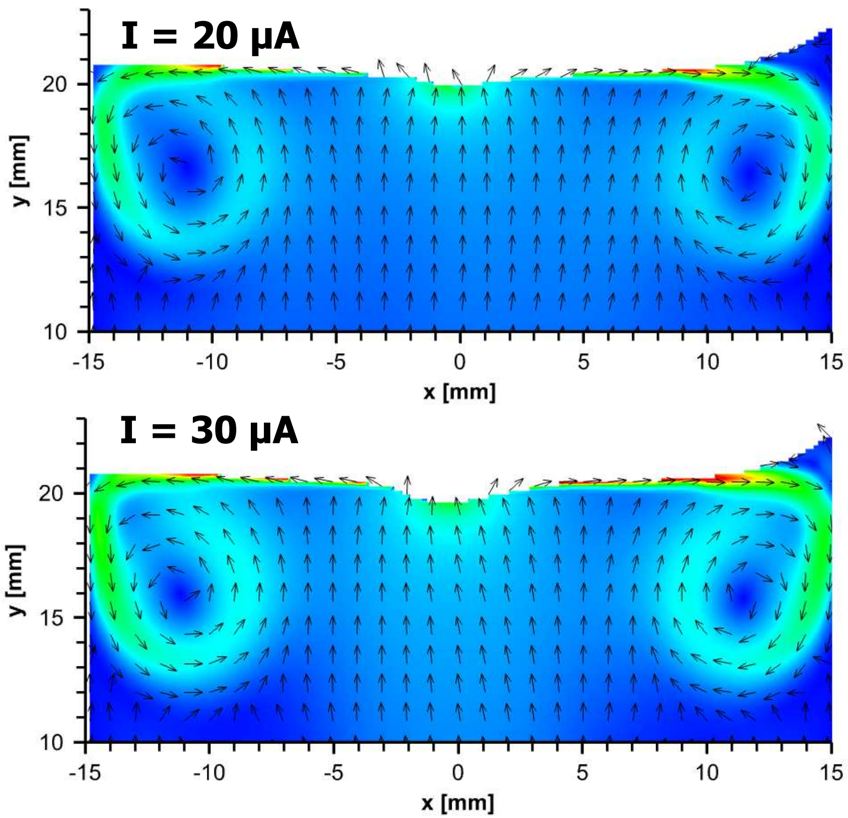
- **Positive corona (g = 2 mm)**
  - Velocity ↗ with I
  - **Significant flow even at I = 7 µA !**



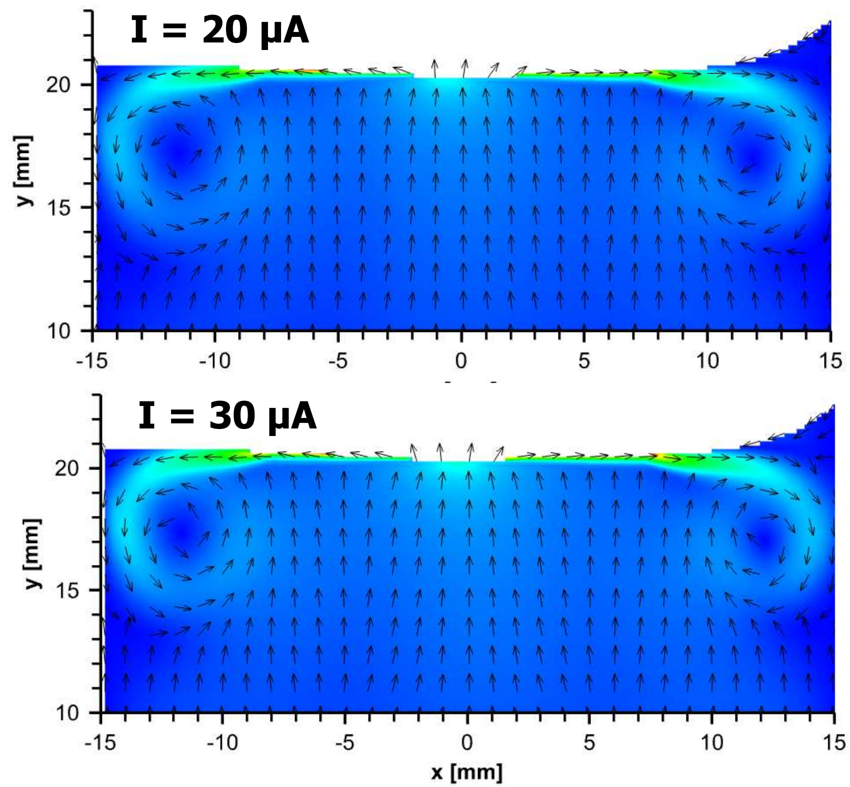
Corona discharge

- **Positive/negative corona (g = 4 mm)**
- Positive discharge is more effective
- **Velocity up to 8 cm/s for I = 30 µA !**

Positive corona



Negative corona

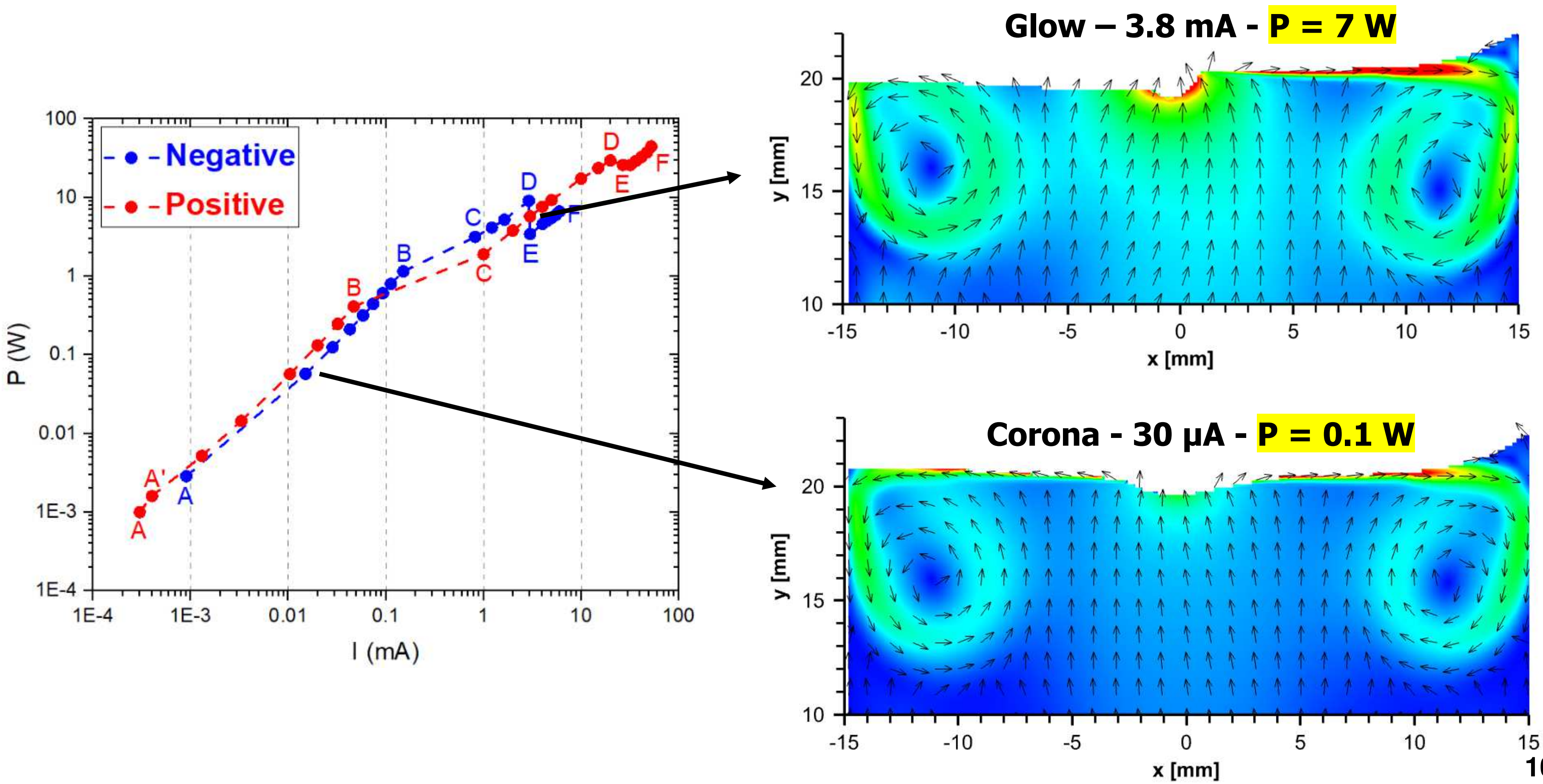


Corona vs glow

- **Conclusion**

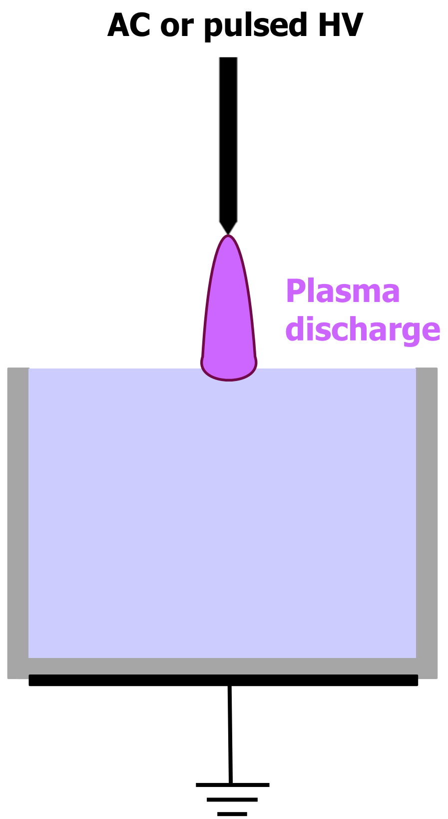
⇨ Positive discharge is always more efficient to produce a flow inside the liquid (corona and normal glow)

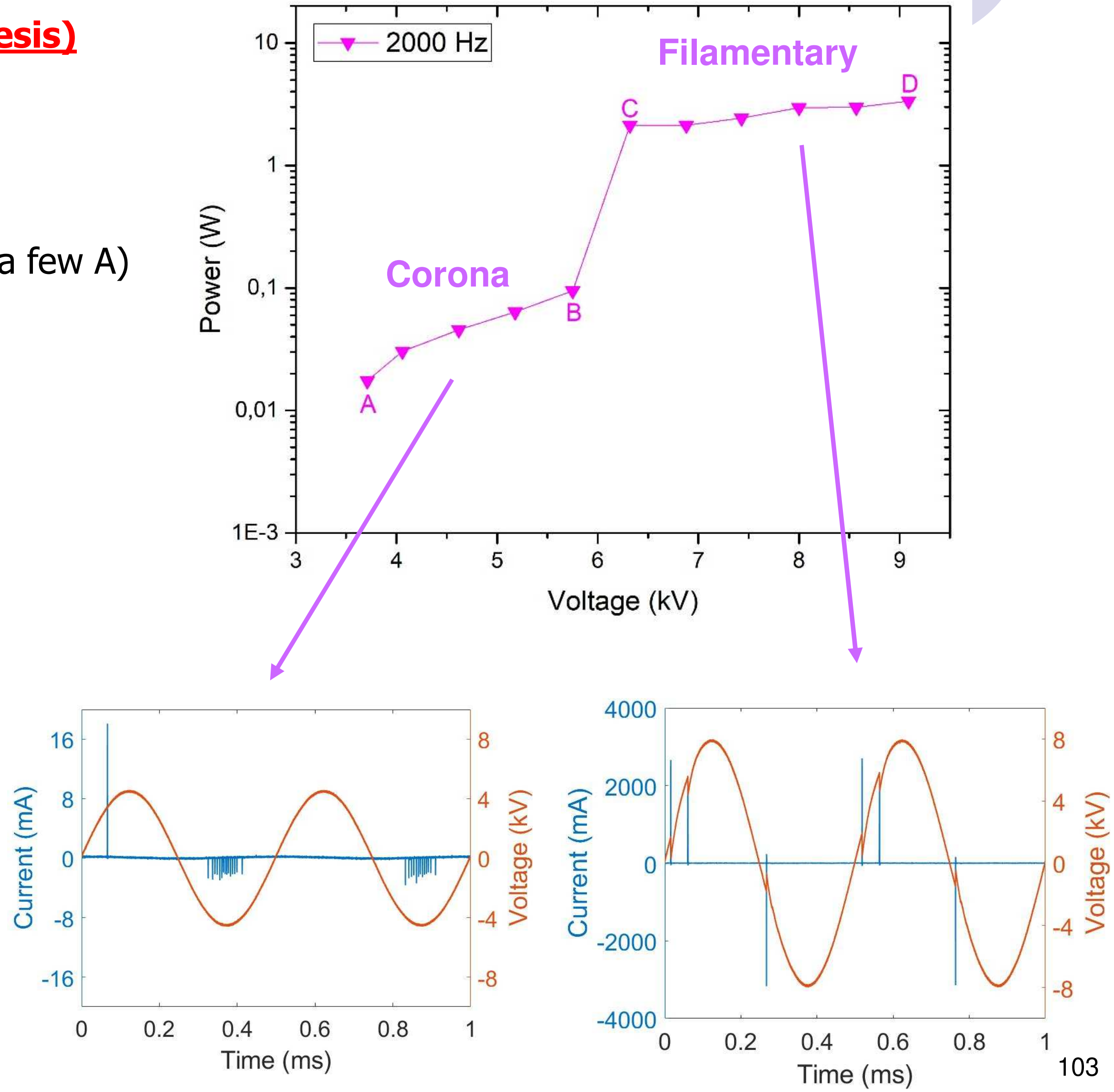
⇨ **It's not a problem of electrical power !**



Dielectric Barrier Discharges

- **AC-DBD (Lara ALOMARI's PhD thesis)**
- ➪ Grounded electrode under the vessel
- ➪ **AC-DBD** (sine HV)
- ➪ Corona and filamentary (pulses up to a few A)





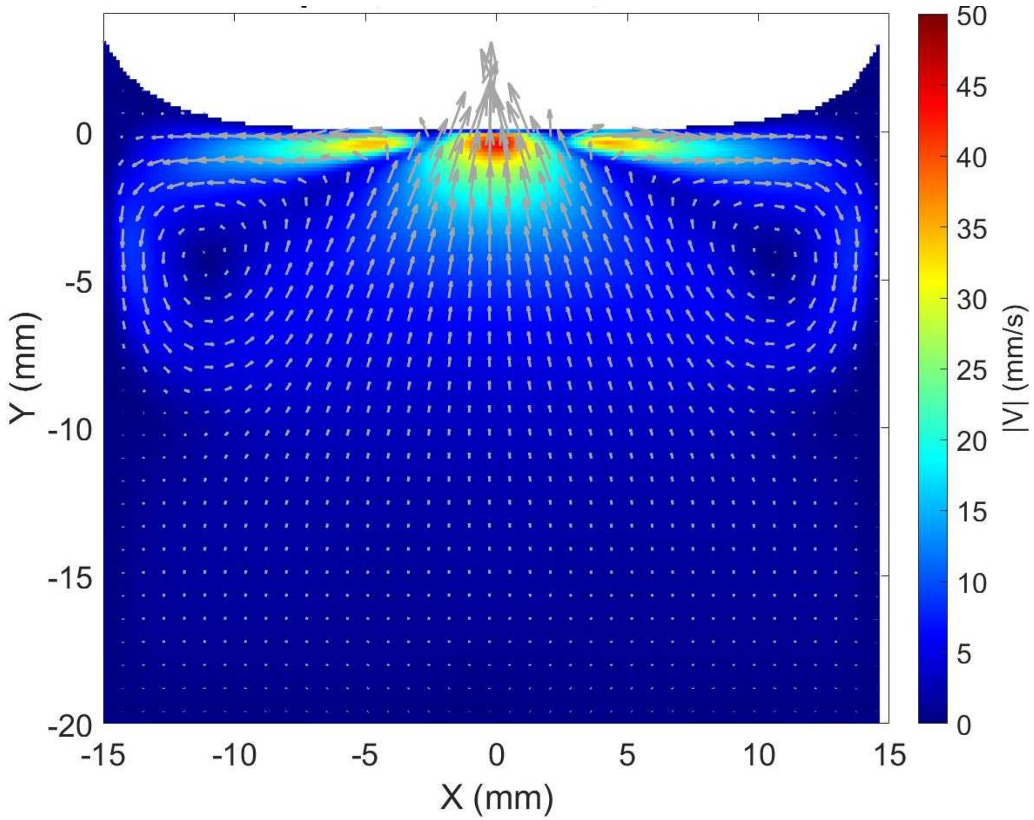
PIV measurements

- **Time-averaged liquid flow**

➪ Pure water, σ = 2 μS/cm, 8 kV, 4 kHz

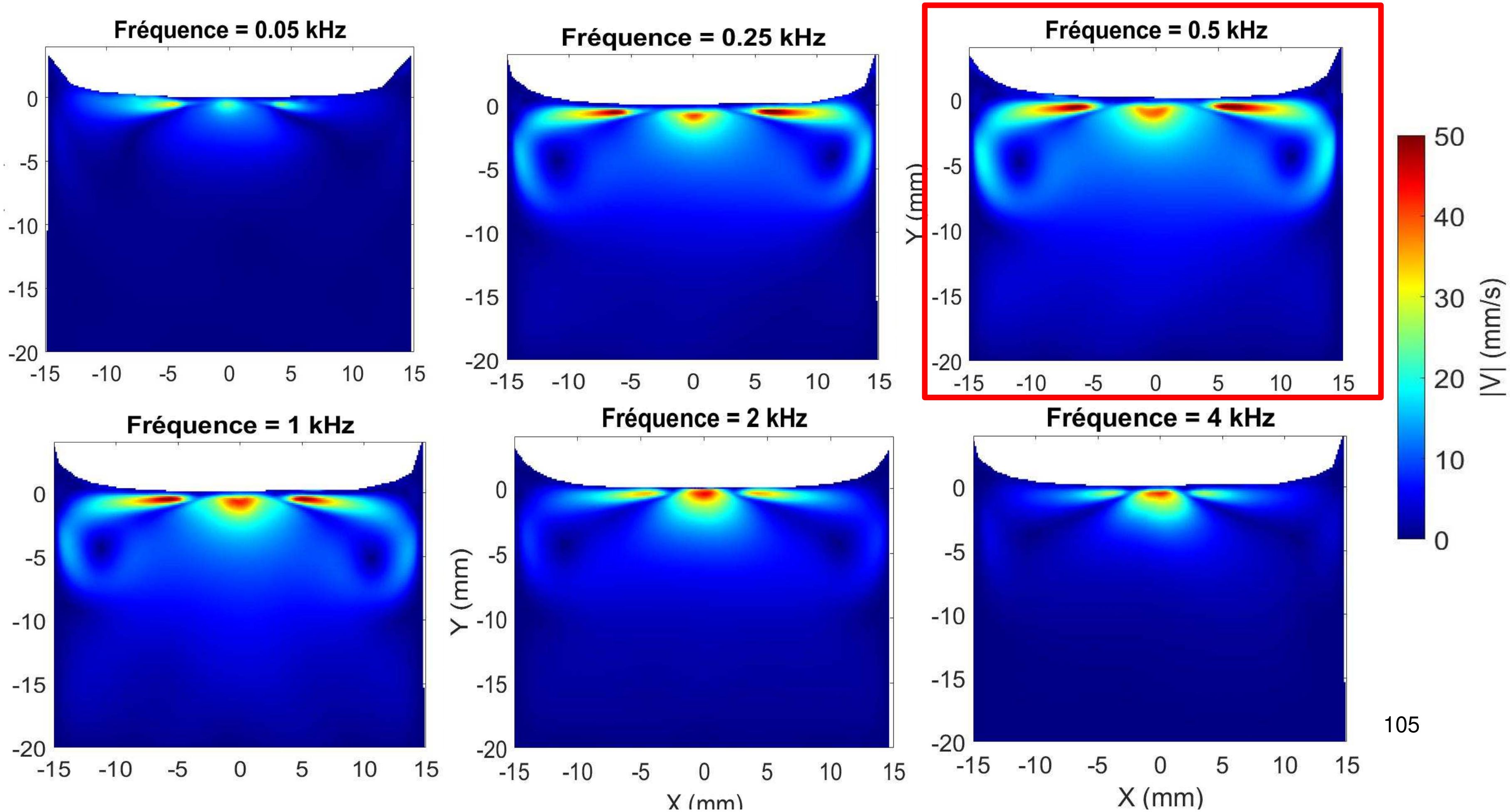
➪ Strong attraction in front of the needle → **upward volume flow**

➪ Two vortices → **outward surface flow**



Influence of the HV frequency

- **Time-averaged liquid flow**
- ➪ Frequency from 50 Hz to 2 kHz
- ➪ **Maximum velocity is obtained at 0.5 kHz …**

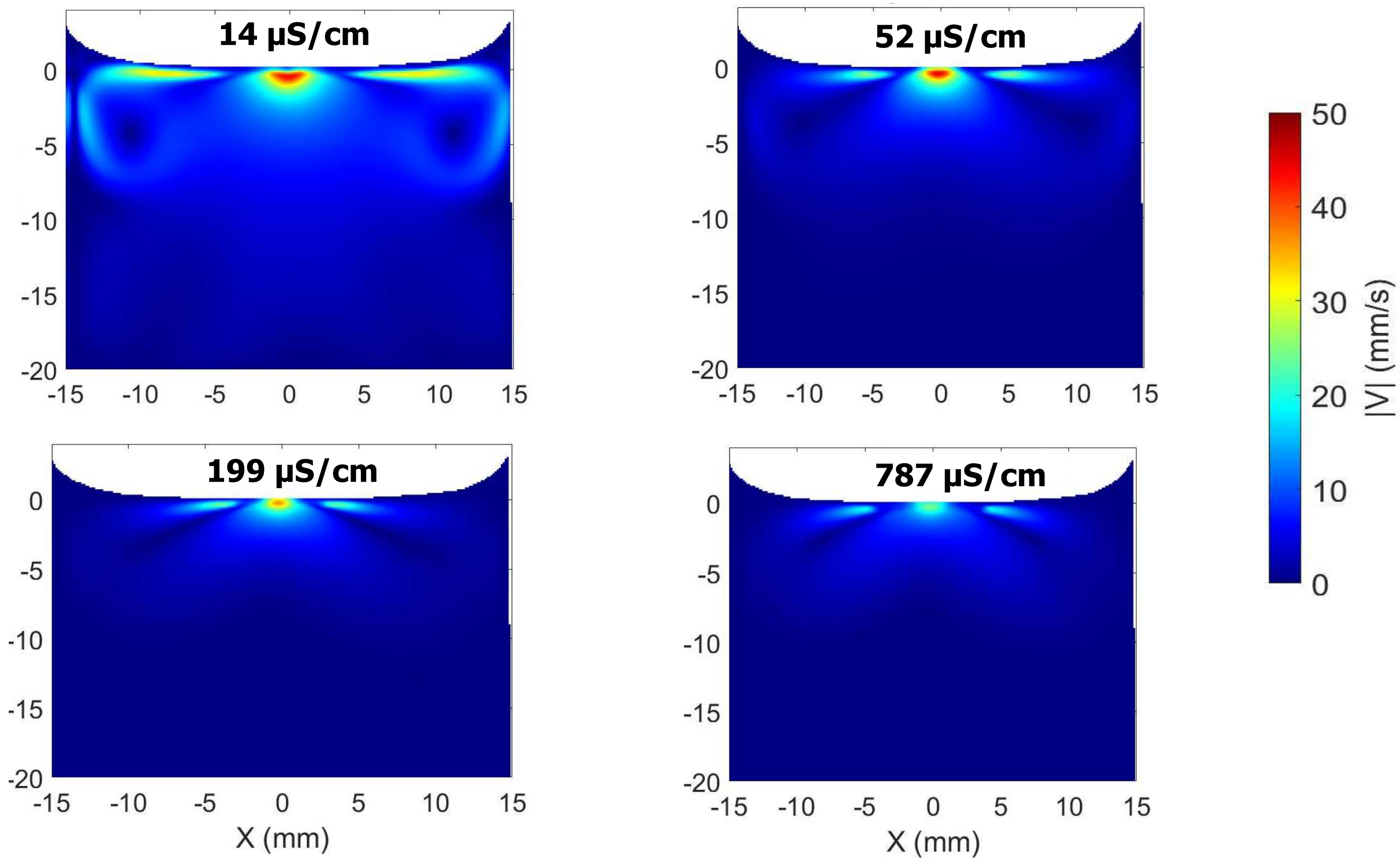


Influence of the water conductivity

- **Water conductivity**

➩ We add KCl in pure water to increase its conductivity (14, 52, 199 and 787 µS/cm)

➩ **The velocity decreases when σ ↗**



Influence of the superficial tension

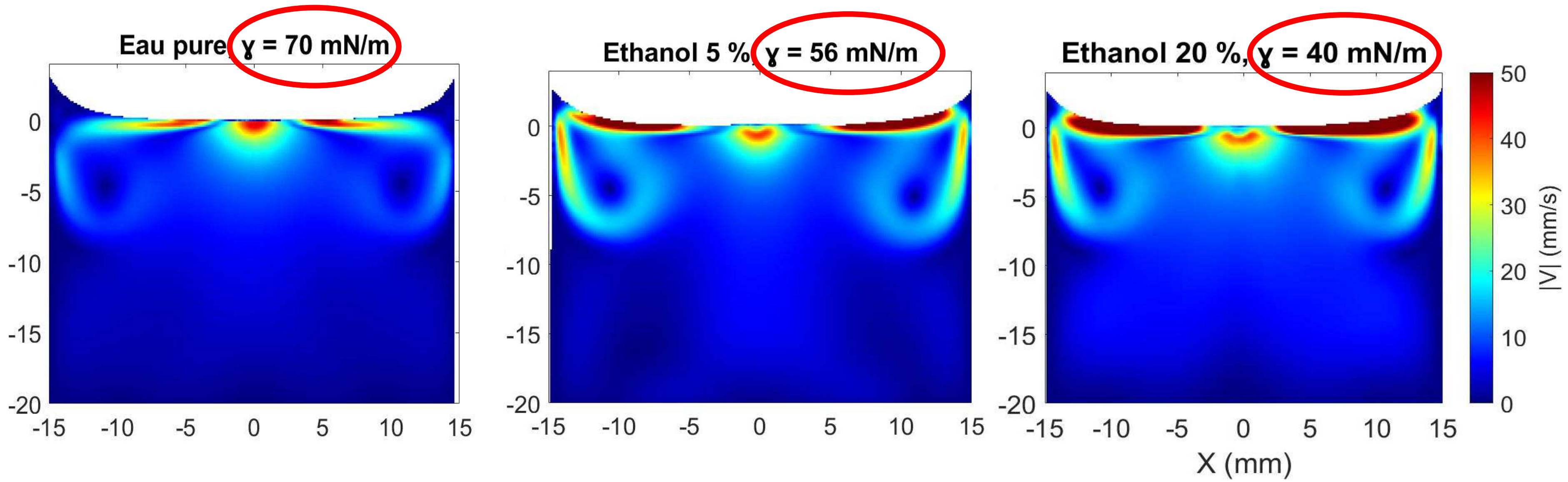
- **Superficial tension**

⇨ Ethanol to decrease the superficial tension γ (70, 62, 56, 50 and 40 mN/m)

⇨ The flow is significantly modified !

⇨ **The upward force is rather similar**

⇨ **But the force at the surface acts over a greater length**



Velocity field versus time

▶ <u>**Time-resolved velocity fields**</u>

➪ 9 kV, 2 kHz → **what's happen when the discharge is switched on ?**

➪ **The flow dynamics is different, and depends on the water properties !**

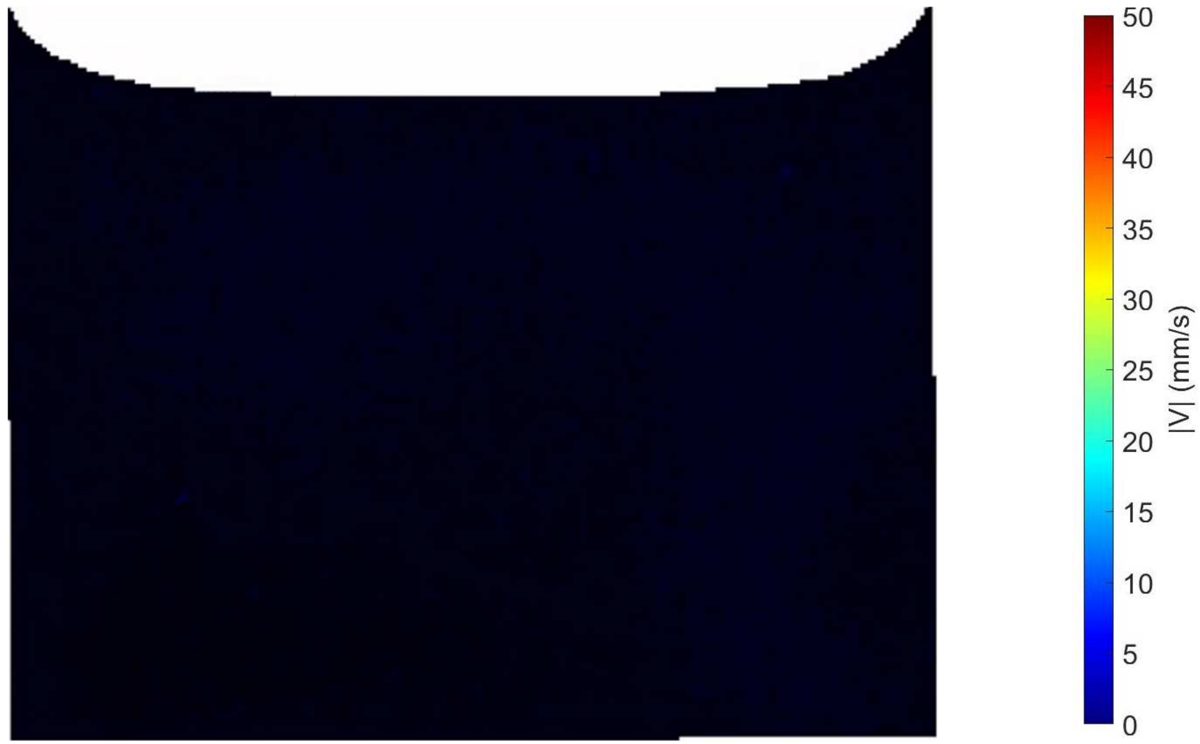
Pure water
2 µS/cm, 70 mN/m

Water with KCl
200 µS/cm, 70 mN/m

Water with ethanol
2 µS/cm, 40 mN/m

Example of liquid flow

- **Water with KCl (σ = 200 µS/cm)**
- Liquid flow is not fully time-resolved (camera frequency = 7 Hz)
- **Upward force** and **outward force**



Discussion

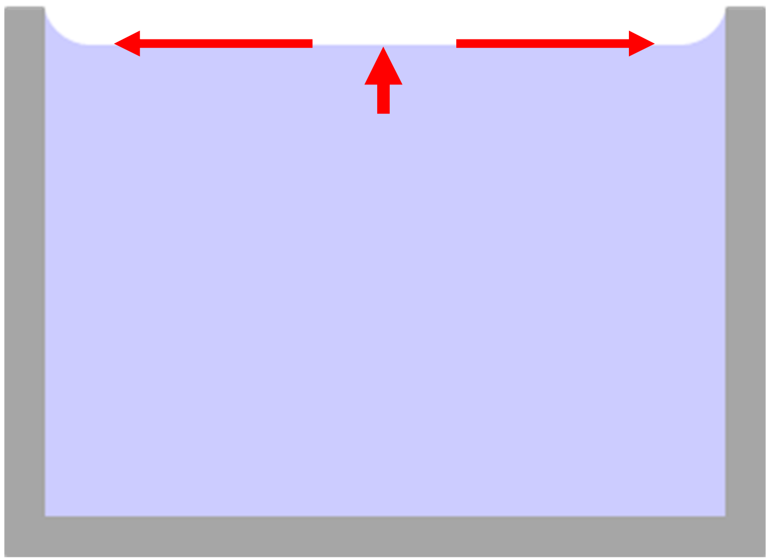
▶ **Thermal effect**

➪ Thermal gradient → variation of density → **buoyancy force** $\vec{F}_B = -\rho.\beta.(T - T_\infty)\vec{g}$

➪ **Thermal plume** → not predominant

➪ **Why ?**

- at I = 7 µA (corona discharge), 15 mW !
- computations show that F_B is weak (even for a few W) → maybe a weak contribution
- If yes, with DBD, the velocity should ↗ with P_{elec}



Discussion

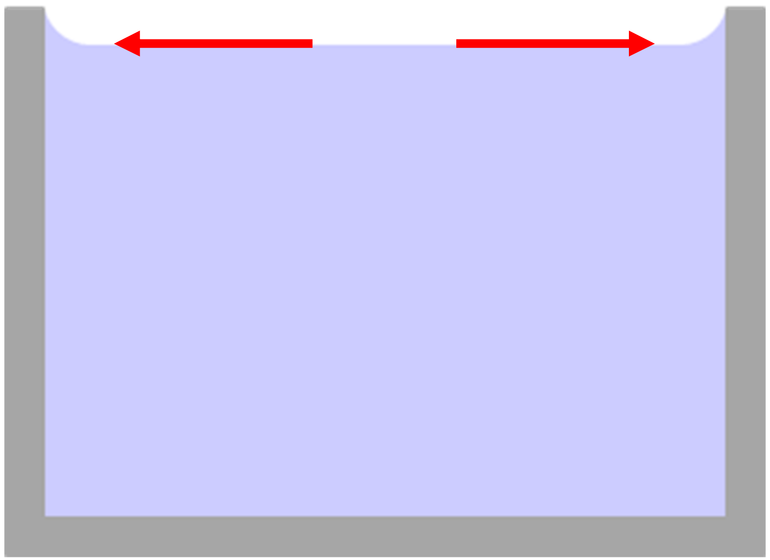
- **Marongoni effect**

⇨ Force from small γ to high γ → **surface force** $F_\gamma = \nabla_s \gamma$

⇨ Water → its γ ↘ when T° ↗ → surface force from the discharge impact … (at 100°C, γ ≈ 60 mN/m)

⇨ **But if Marongoni effect was dominant → velocity would ↗ with P_{elec}**

⇨ It can be the main effect in presence of a surfactant …



Discussion

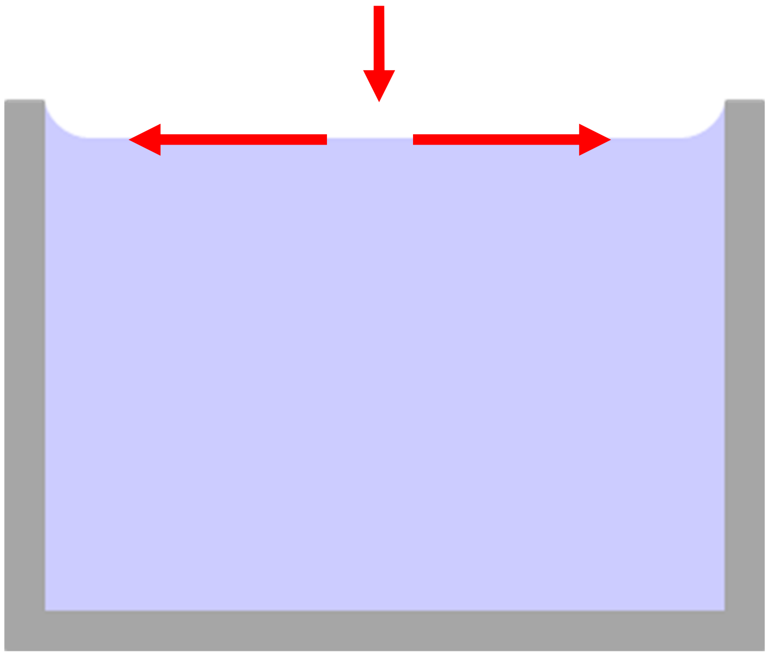
▶ **Shear force**

⇨ **Due to the gas flow along the liquid surface**

⇨ Corona discharge (ionic wind) and plasma jet (Ar or He jet)

⇨ But no for the DC glow discharge → no gas flow in this case

⇨ **The strongest flows with DC glow discharge !**



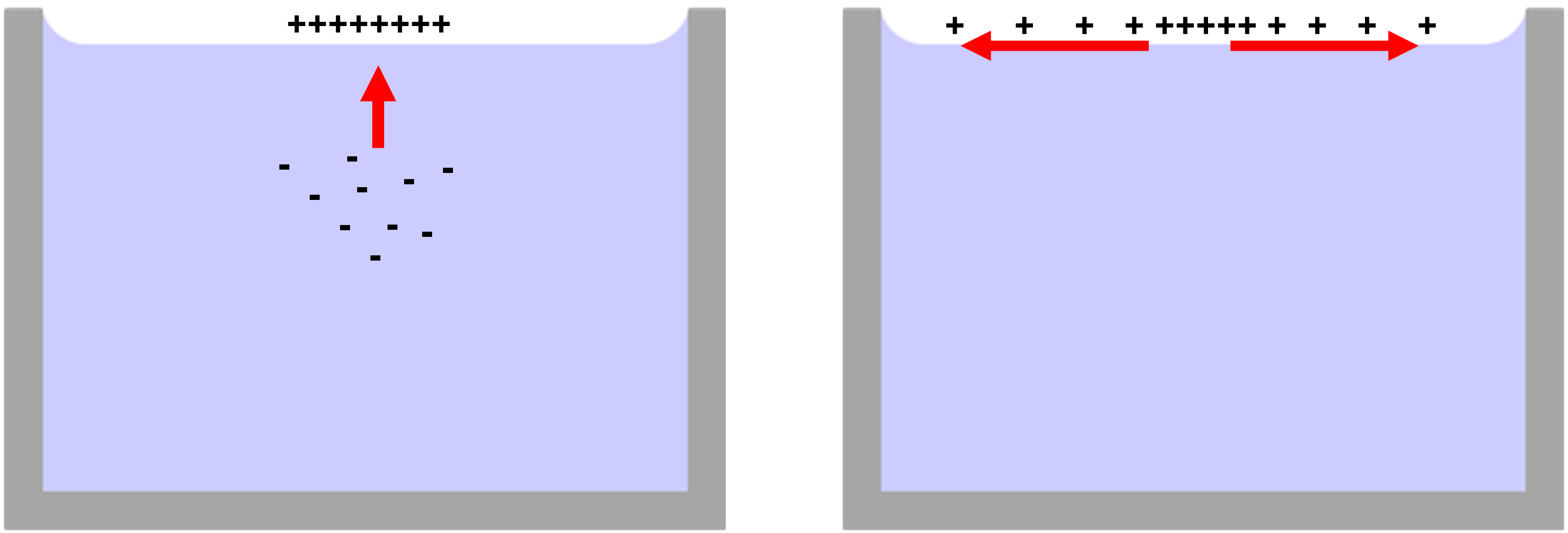
Discussion

- **EHD forces**

➪ **Volume EHD force** due to the deposition of charges at the interface

➪ **Surface EHD force** due to the repulsion between charges at the surface

➡ **This is consistent with our results as F_{EHD} ↘ when σ ↗**

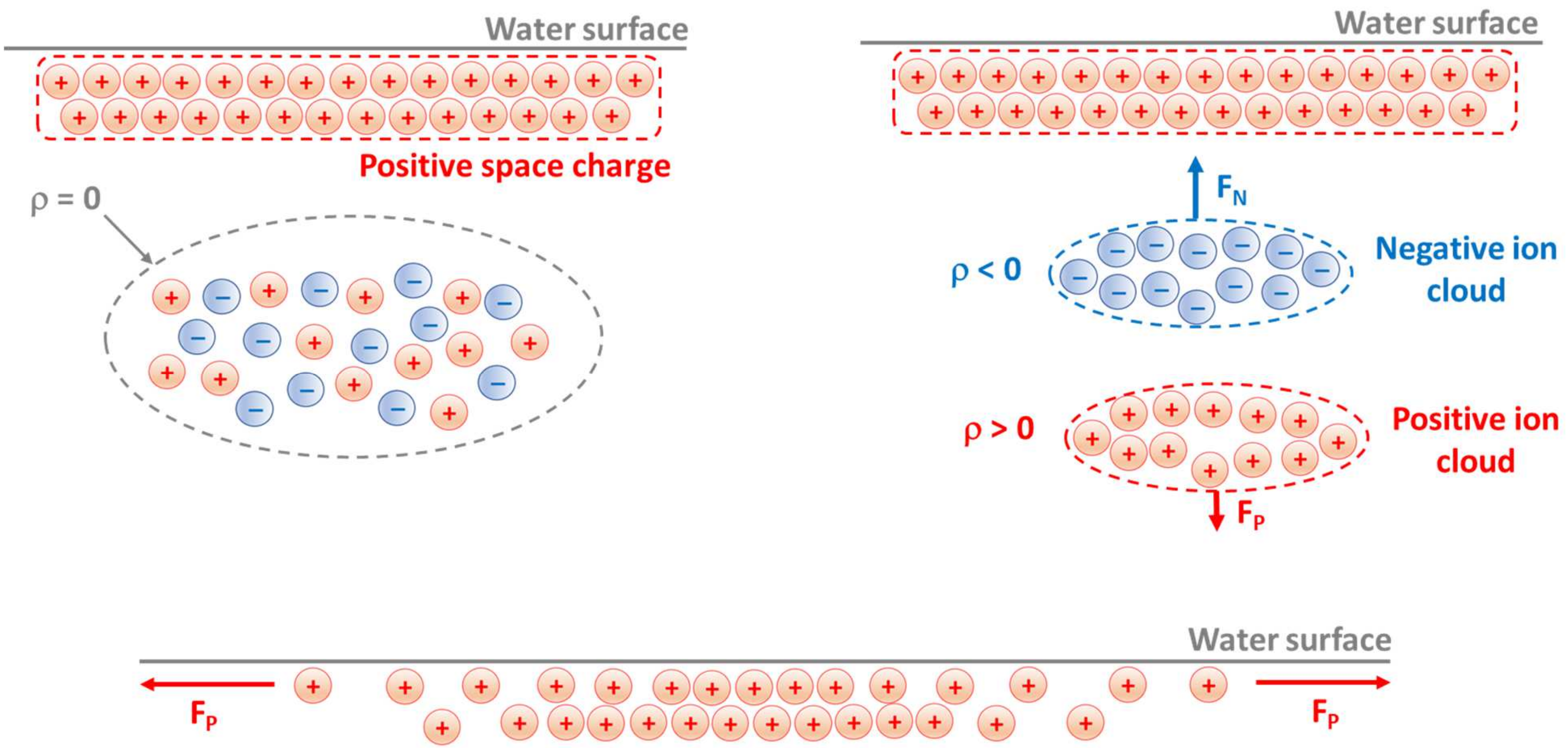


Discussion

- **EHD forces**

➪ $F_N > F_P \rightarrow$ **Upward EHD volume force**

➪ Positive charges repeal each other $\rightarrow$ **Outward EHD surface force**



Conclusion

▶ **Ionic wind for cooling systems**

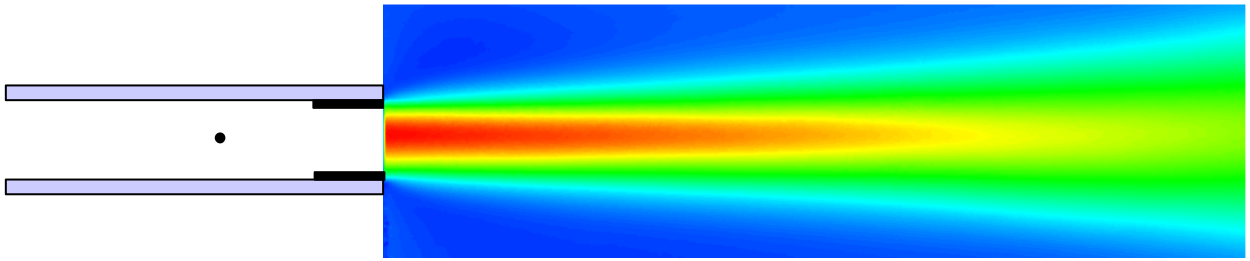
⇨ Lots of works on this topic with nice results but problem of high voltage …

⇨ I prefer to carry out fundamental experiments

⇨ Not for laptop

⇨ **Ionic wind at sub-millimeter scale** for nanometer-scale systems, with lower HV

⇨ We need to cancel the problem of measuring the ionic wind velocity at such low gaps



Conclusion

$$T = F_{EHD} - F_D \sim \frac{I \times d}{\mu}$$

- **Ionic wind for atmospheric propulsion**

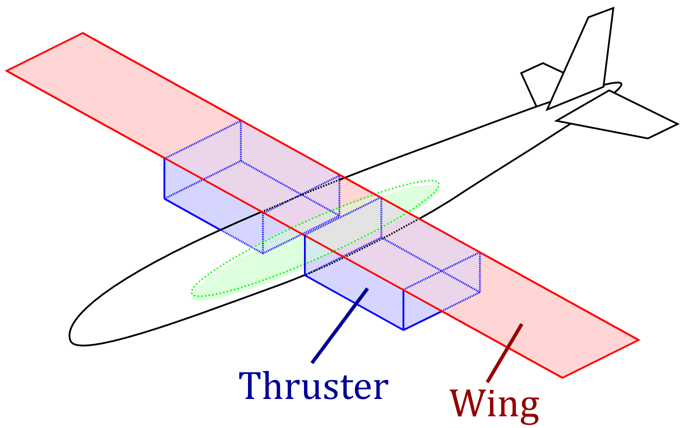
➪ **Propulsive system for small-size drone** (on-board batteries + corona discharge)

➪ Effectiveness a few times smaller than propeller propulsion with electric motor

➪ EHD thruster size must be high (low force density in N/m^2) → **thruster drag in flight !**

➪ 10 kg UAV, 300 m altitude, 20 km/h → flying duration of 4 hours

➪ **Lots of laboratories on this topic** (5 articles and I stopped) → numerical simulations !



Conclusion

▶ **Airflow control by plasma actuators**

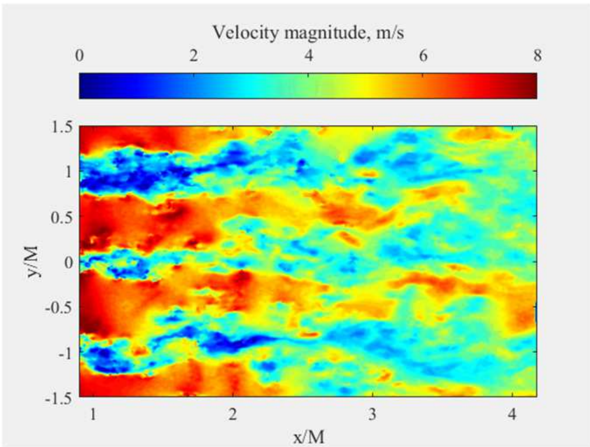
➪ Not for aeronautic applications …

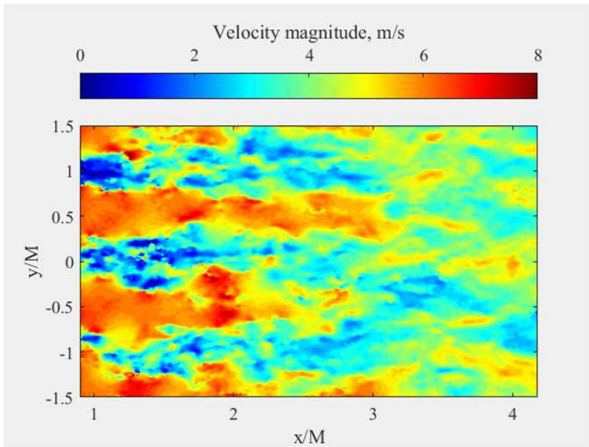
➪ Plasma-assisted grid for turbulence control (grid turbulence)

➪ Lots of applications in fluid mechanics → applications in mixing and fundamental research

➪ **Actuation results in the wake control and turbulence parameters**

➪ My colleague Nicolas BENARD





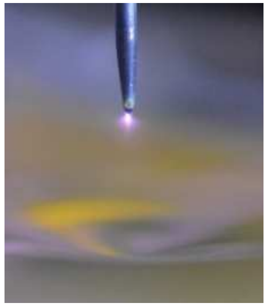
Conclusion

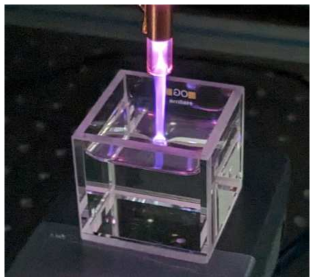
▶ **Plasma-assisted chemistry and biology**

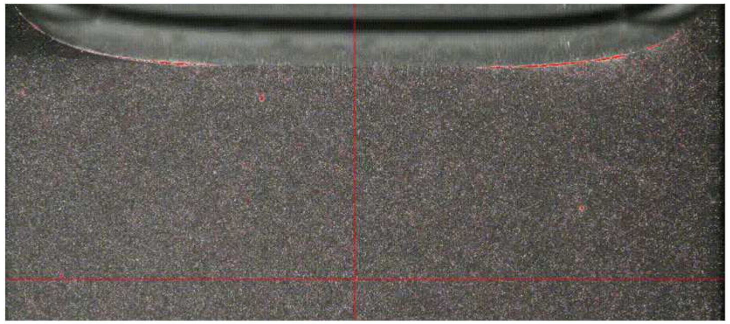
➪ **The link between the liquid flow and chemical effectiveness**

➪ Very exciting because :

- only ≈ 20 scientific articles on plasma-induced liquid flows
- nobody has a good explanation on the phenomena
- strongly improve effectiveness of reactors for chemistry and biology







Conclusion

▶ **Scientific collaborations ?**

➪ If you are interested in multi-metrology benches for your work :

- **PIV systems** (3D, frequency up to 100 kHz) → high level enginners
- **Schlieren visualizations** → velocity with a Canadian colleague ?
- ICCD cameras (PiMax 4 gen II et III, 500 ps)
- IR cameras
- **Spectroscopy** (OES, 1 µm, T. Orrière)
- Wind tunnels → to study the effect of an airflow on your cold plasmas !

➪ If you are interested in what I presented today

➪ **Two M2 internship positions and one PhD thesis position** (ANR with GREMI)

Thank you for your attention