Characterization of the electrothermal conversion mechanisms of a plasma actuator for icing control

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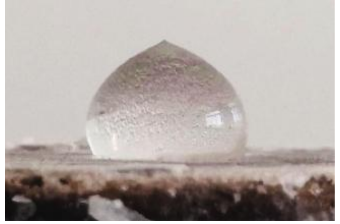
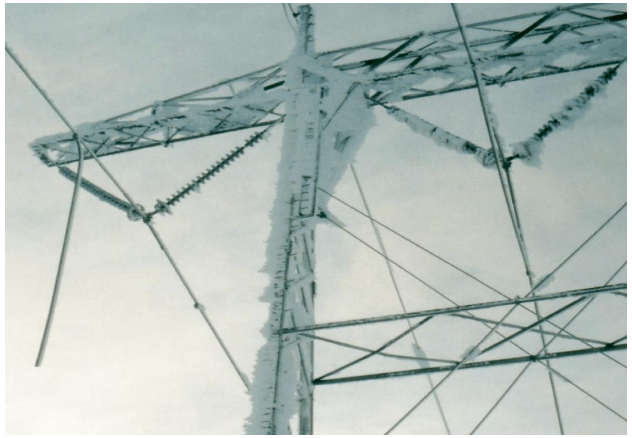
GdR TRANSINTER

Context : icing

Solidification of droplets impacting subcooled surfaces or deposition of water vapour





Potential fall

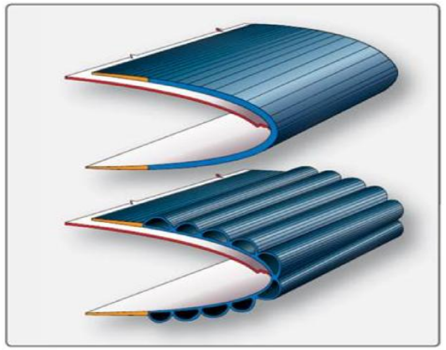
Performance limitation

Major malfunctions

Icing protection systems (IPS)

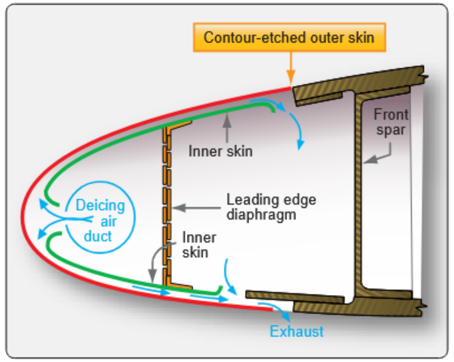
De-icing systems

De-icing and anti-icing systems



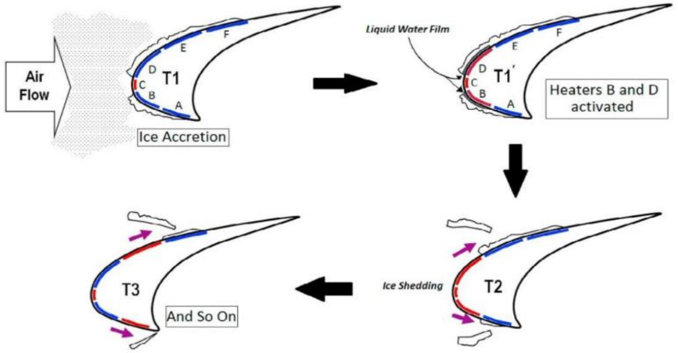
Pneumatic boots

- ✓ Low energy requirements
- × Frequent replacement



Hot air bleed

- × High energy consumption ($\approx 1\, kW.m^{-2}$)



Electrothermal Systems

- × High energy consumption ($\approx 10\, kW.m^{-2}$)

Limitation of certified IPS to medium and small aircrafts:

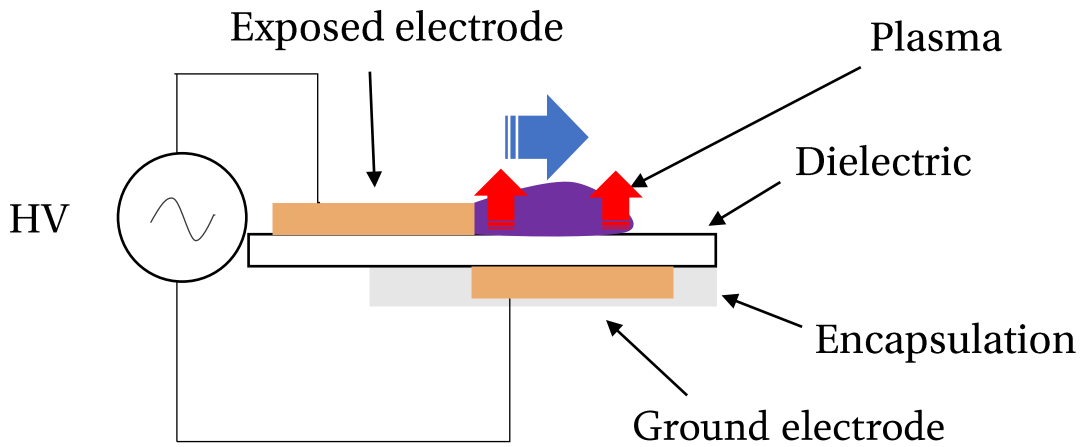
- High energy consumption
- Weight increase and limited durability

Need for IPS that can be transposed to smaller aircrafts such as drones or helicopters

Surface DBD plasma actuators

VERGLAS ANR project (dé**VE**loppement d'un système de p**R**otection contre le **G**ivrage des aéronerfs par p**LAS**ma)

→ Development of an icing protection system based on **<u>a surface Dielectric Barrier Discharge (DBD) plasma actuator</u>**



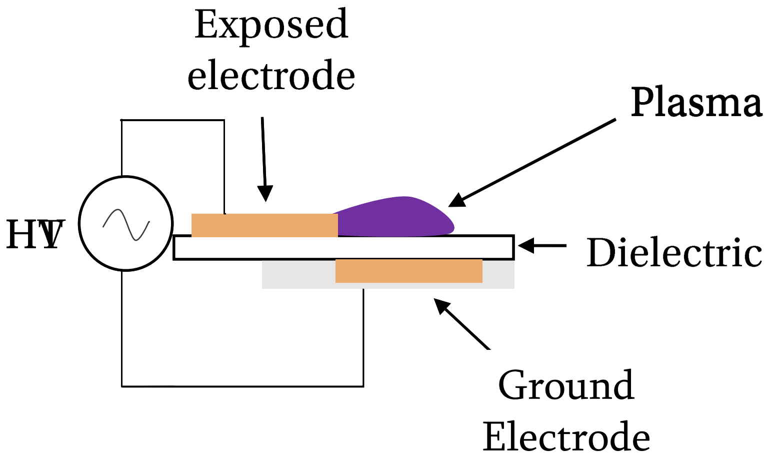
Standard linear configuration

<u>Induced effects:</u>

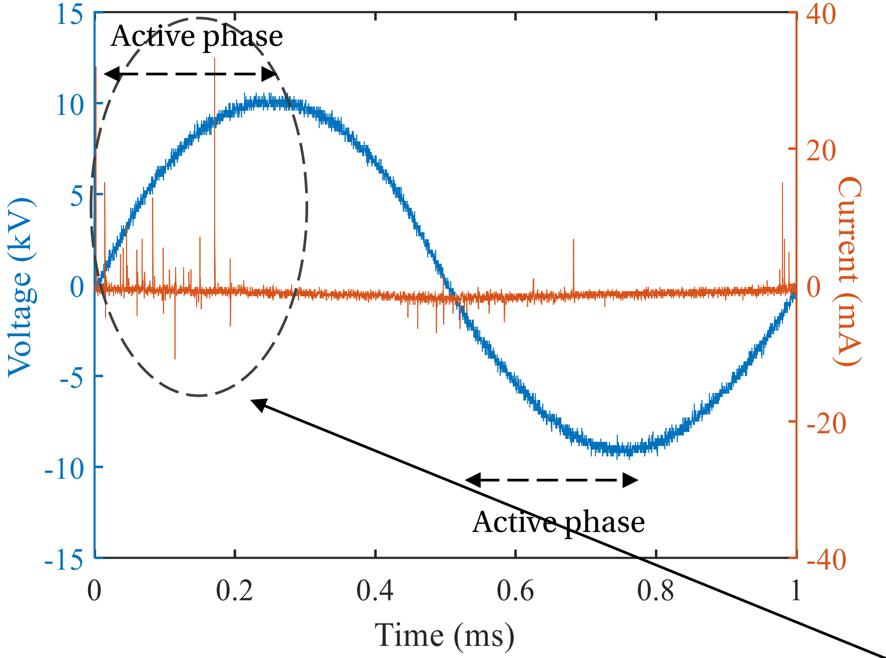
- Ionic wind - *electromechanical effect*
- Heating - *electrothermal effect*

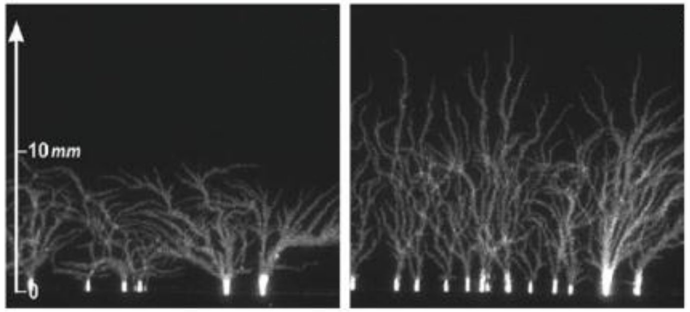
Surface DBD Plasma Actuators

Electrical parameters



Voltage and Current of a Surface DBD





(Benard and Moreau 2012)

Micro-discharges (streamers) on the surface of the dielectric

Plasma Actuators: Thermal Effects

Conversion Mechanisms – Drywall

☐ Heating in the plasma

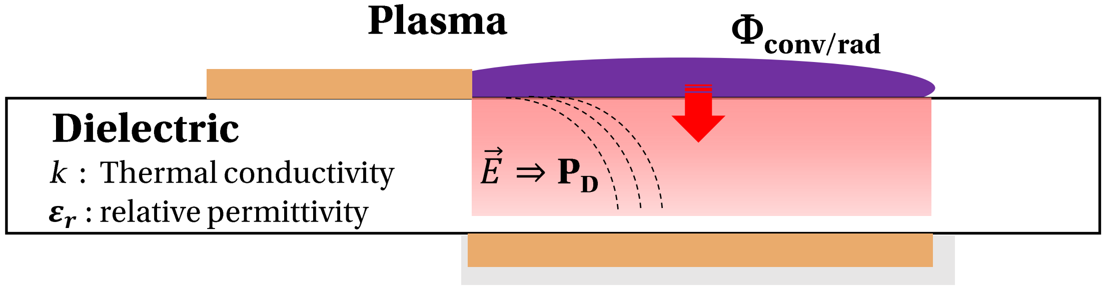
- **Electron heating :** particle collisions
- **Ionic Flux :** High current density of streamers

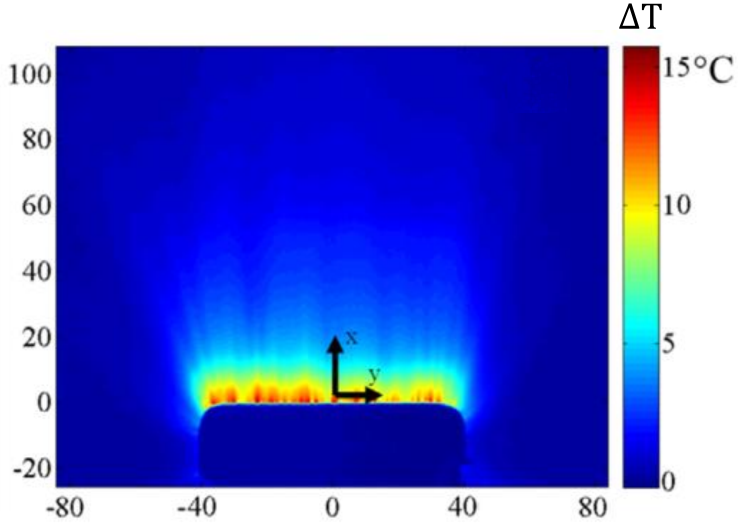
→ **Measurement of T_{plasma} by spectroscopic emission**

☐ Heating of the dielectric

- **Of the surface**: by convection and radiation $\Phi_{conv/rad}$ *depends on thermal conductivity k*
- **In the dielectric**: Dielectric Loss Dissipation *depends on the relative permittivity* $\varepsilon_r \Rightarrow P_D \propto \varepsilon_r$

→ **measurement of T_D by IR thermography**





(Tirumala et al. 2014)

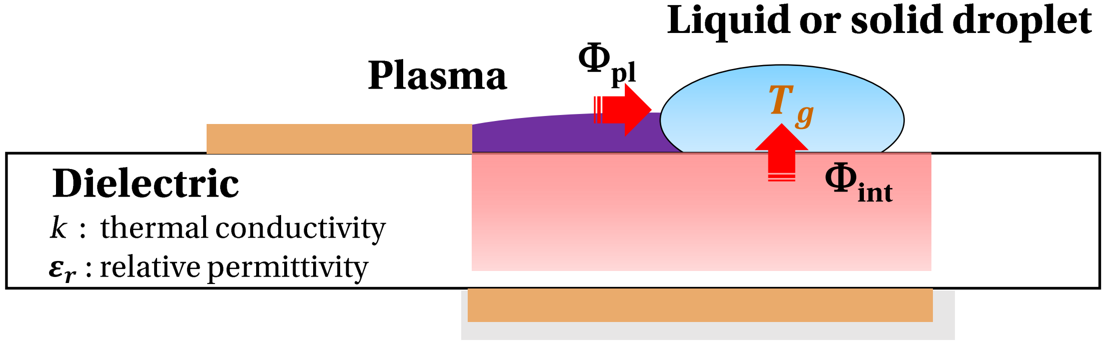
Plasma actuators: icing control

Interaction with a droplet

- The droplet receives a heat flux

  → **from the interface with the dielectric Φ_{int}**

  → **from the plasma Φ_{pl}**



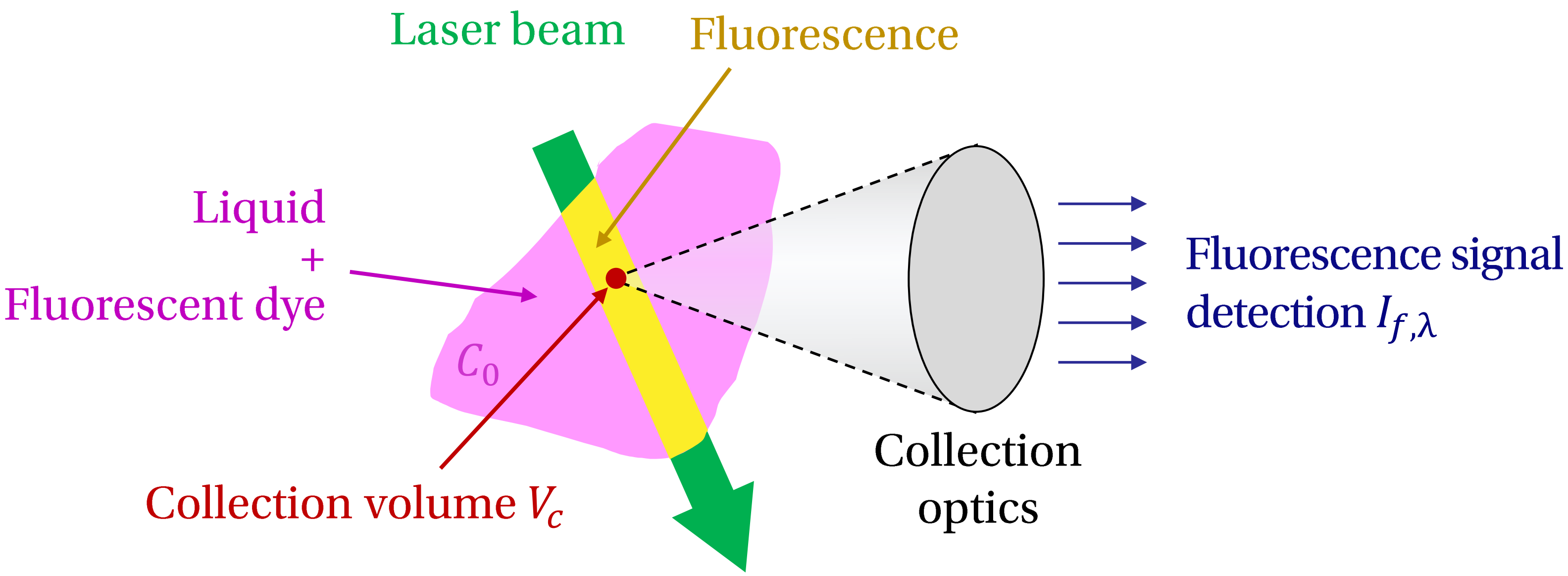
$$\Phi_{\mathrm{d}} = \Phi_{\mathrm{int}} + \Phi_{\mathrm{pl}}$$

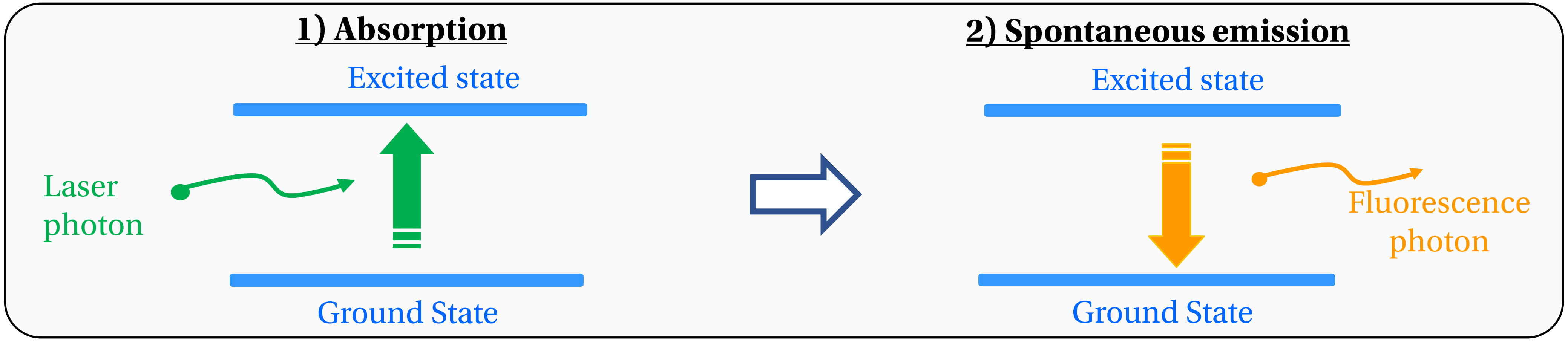
- Droplet temperature measurement

$$\Phi_{\mathrm{d}} = m_d\, c_p \frac{dT_g}{dt}$$

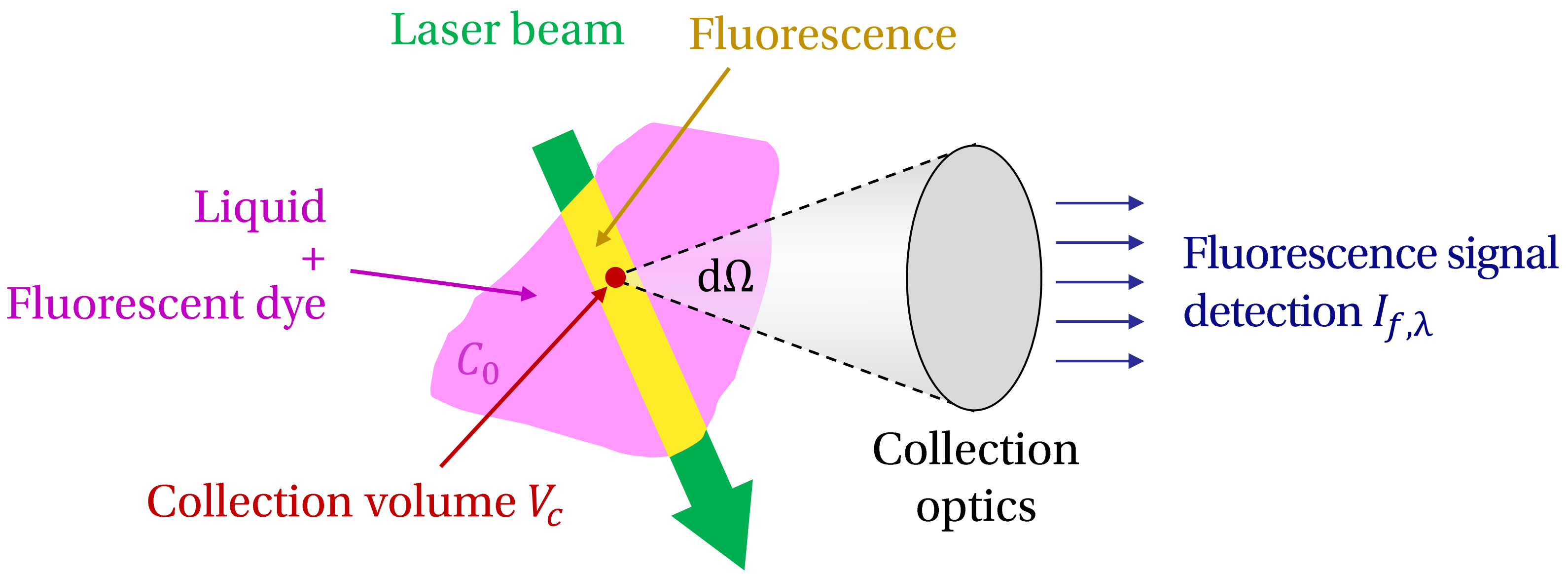
Need for **non-intrusive techniques→ Laser Induced Fluorescence (LIF)**

Principle of Laser-Induced Fluorescence





Principle of Laser-Induced Fluorescence



Laser beam

Fluorescence

Liquid
+
Fluorescent dye

C_0

$d\Omega$

Collection volume V_c

Collection
optics

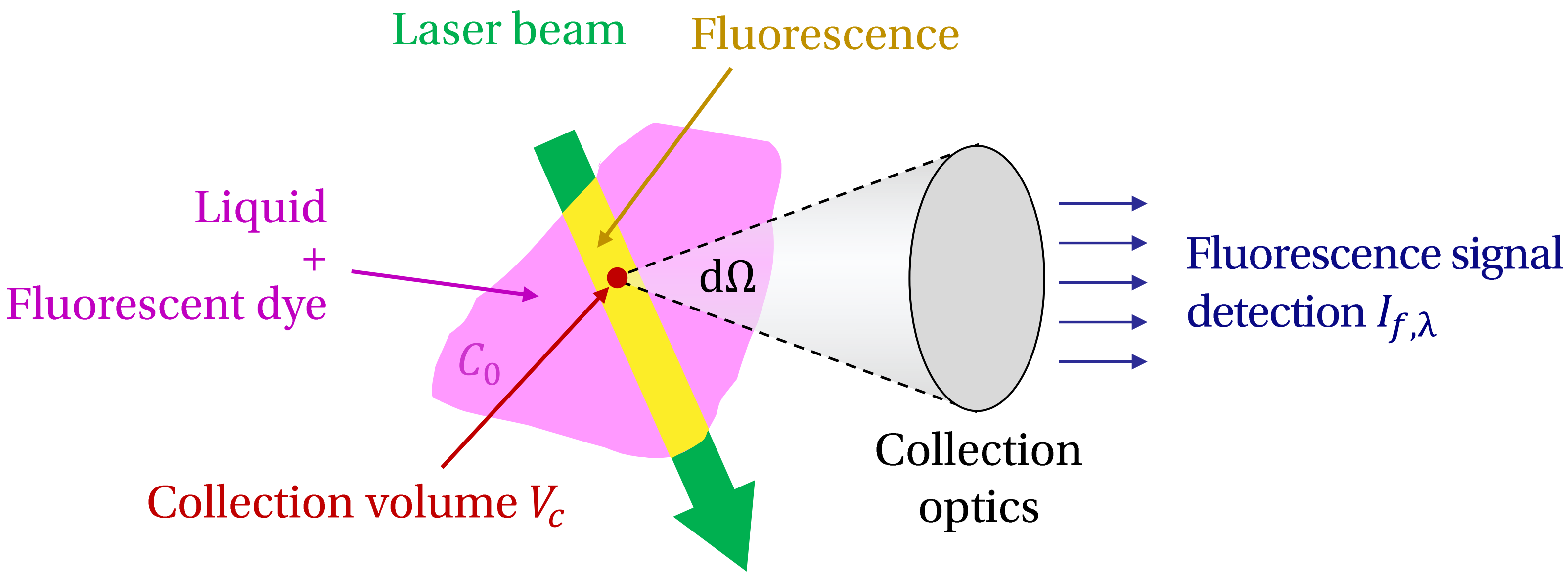
Fluorescence signal
detection $I_{f,\lambda}$

$$I_{f,\lambda} = \eta_\lambda \frac{d\Omega}{4\pi} \epsilon_0 \, \phi_\lambda \, I_0 \, C_0 \, V_c$$

η_λ	Transmission efficiency of the collection optics
C_0	Concentration of the dye molecules
I_0	Local intensity of the laser beam
ϕ_λ	Fluorescence quantum yield
ϵ_0	Absorption coefficient at laser wavelength

Temperature and **volumetric solid/liquid fraction** dependancy of $I_{f,\lambda}$

Principle of Laser-Induced Fluorescence



s_λ : *Temperature sensitivity [%/°C]*

$$I_{f,\lambda} = K_{opt} C_0 V_c I_0 e^{s_\lambda T}$$

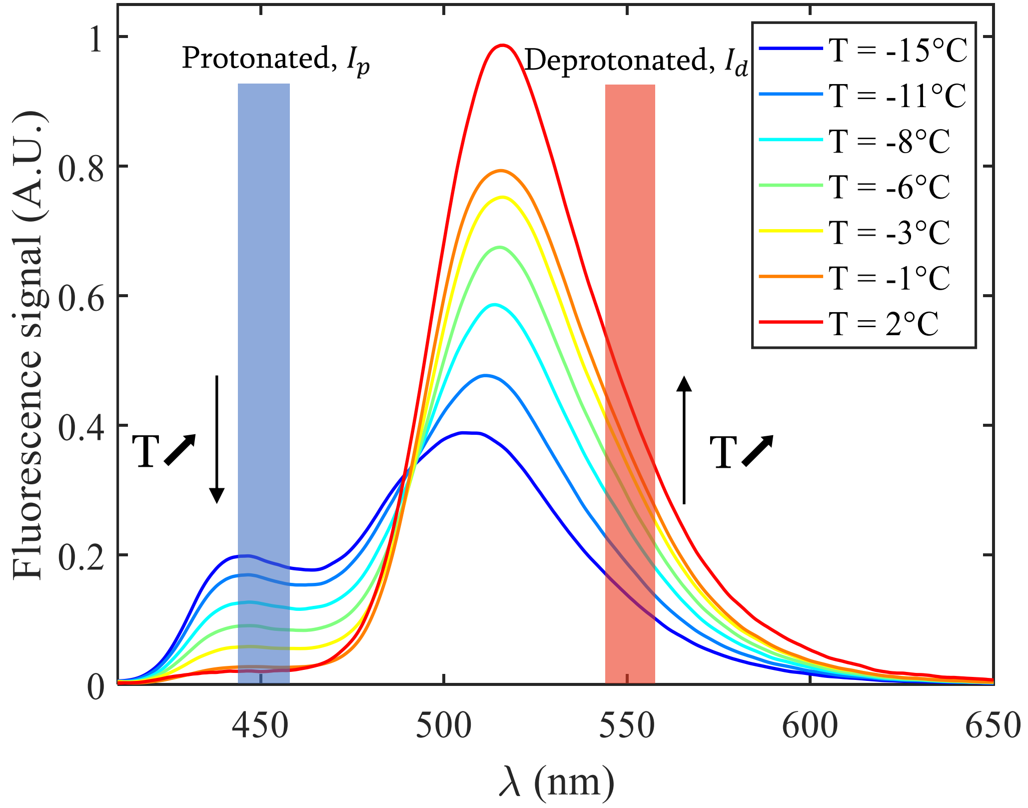
$$\phi_{\lambda,ice} < \phi_{\lambda,liquid}$$

Temperature and **volumetric solid/liquid fraction** dependancy of $I_{f,\lambda}$

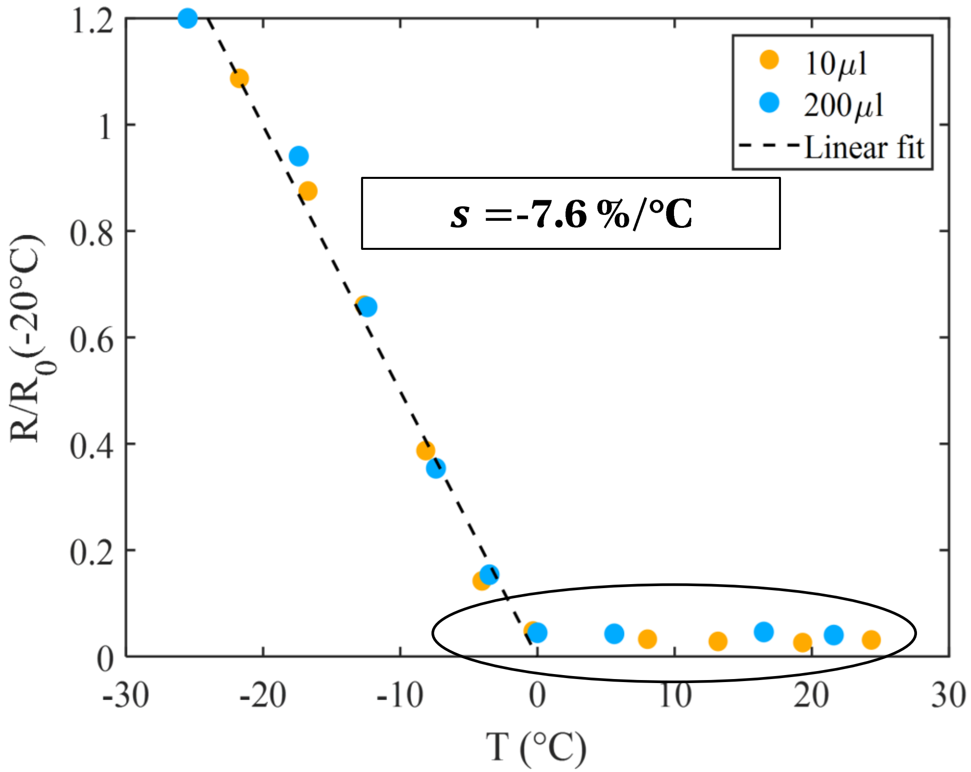
De-icing : Principle of ice temperature measurement

Fluorescent solution – temperature dependence

Pyranine ($C_{py} = 10^{-4}\ mol.L^{-1}$) + Sucrose ($C_{suc} = 0.5.10^{-4}\ mol.L^{-1}$)



$$R = \frac{I_d}{I_p} \propto T_{ice}$$



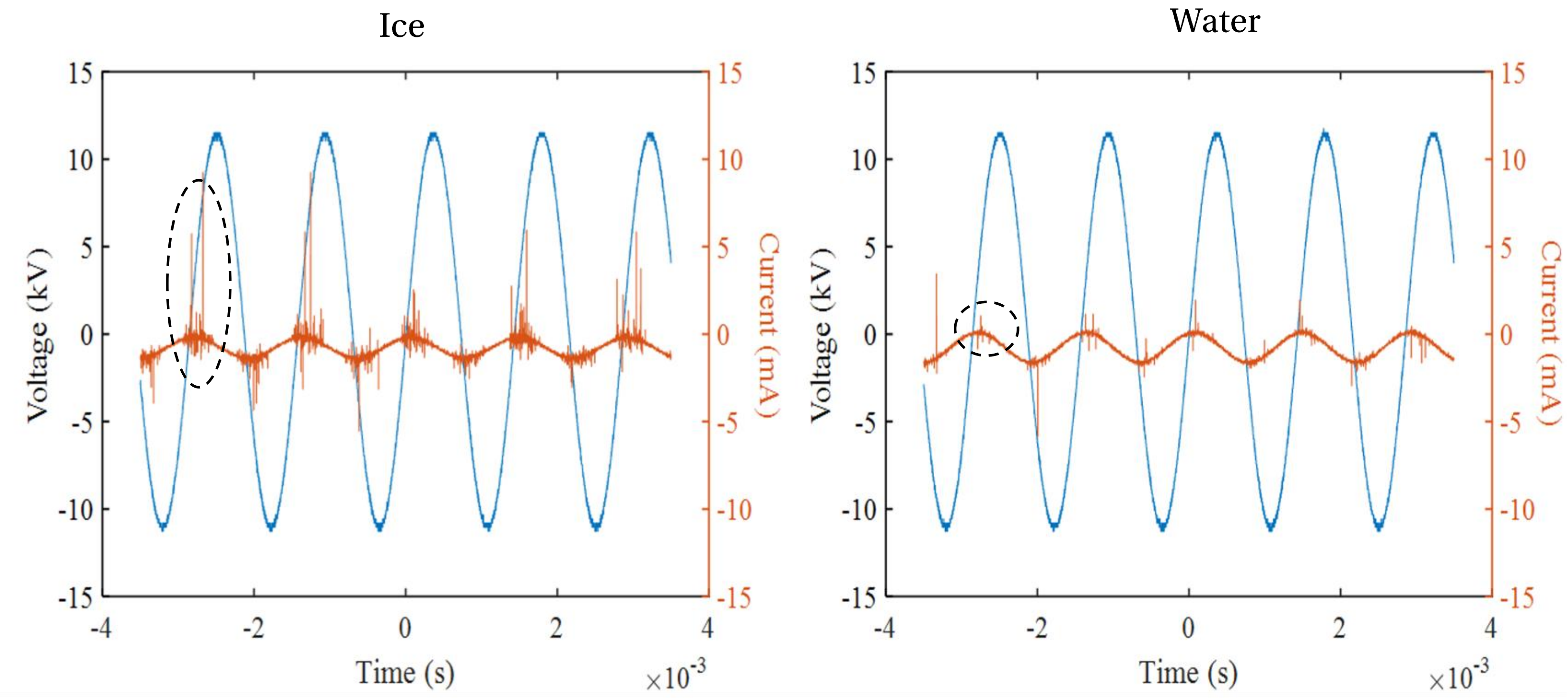
s =-7.6 %/°C

Necessity of a diagnostic for melting onset detection

Melting onset detection

Detection of the melting onset by streamer dynamics analysis : **electrical current**

U = 12kV ; f = 1kHz


Ice

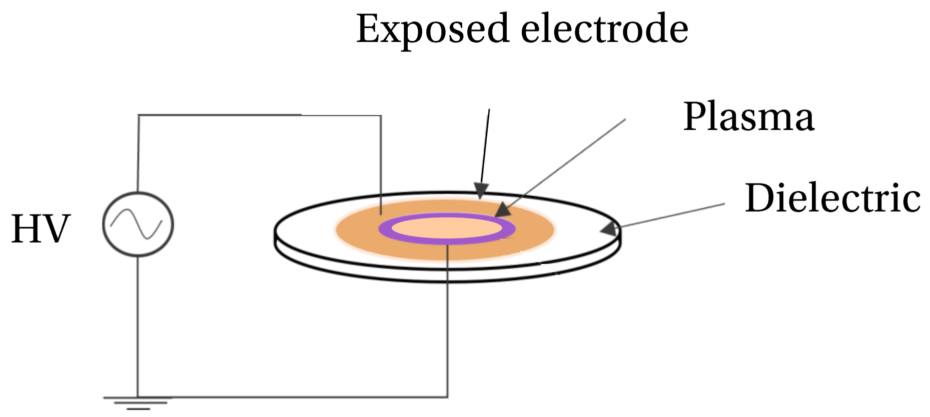
Water

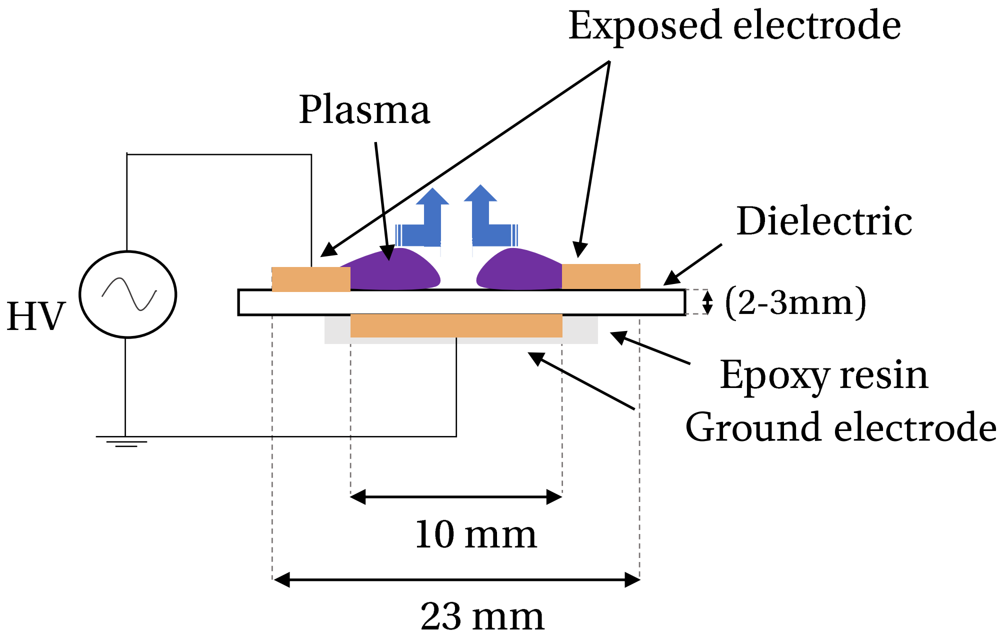
Decrease in the number and amplitude of current peaks

$$\varepsilon_{r,ice} \backsim 3.1 \neq \varepsilon_{r,water} \backsim 90$$

Actuator configuration

Annular geometry



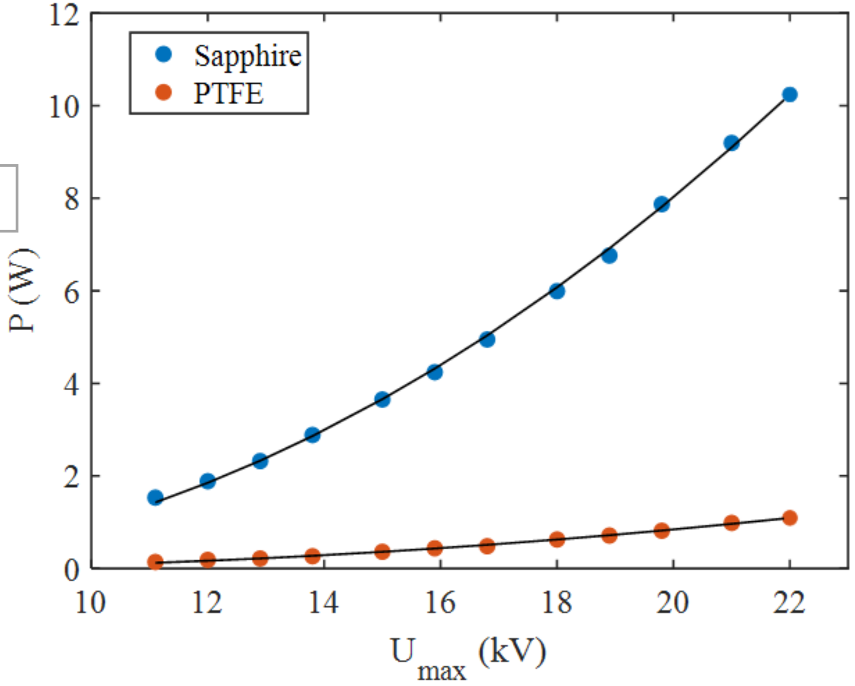


Dielectric	**Relative permittivity** ε_r	**Thermal conductivity** $k\ (W/m.\mathrm{K})$
Sapphire	9.4	30
PTFE	2	0.3

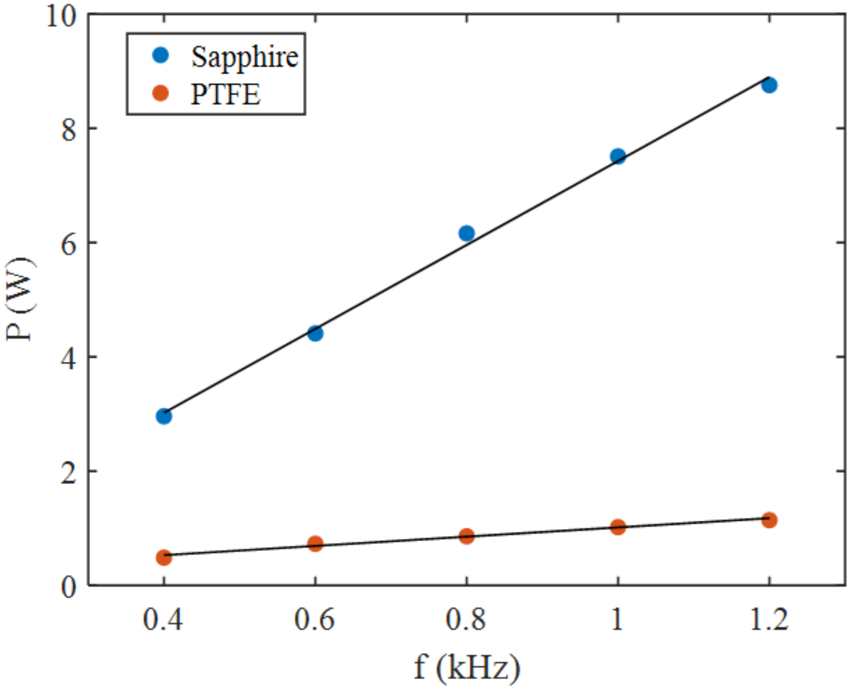
Actuator Configuration

Active power

$$P = Af(U - U_0)^2$$



f = 1kHz



U = 14 kV

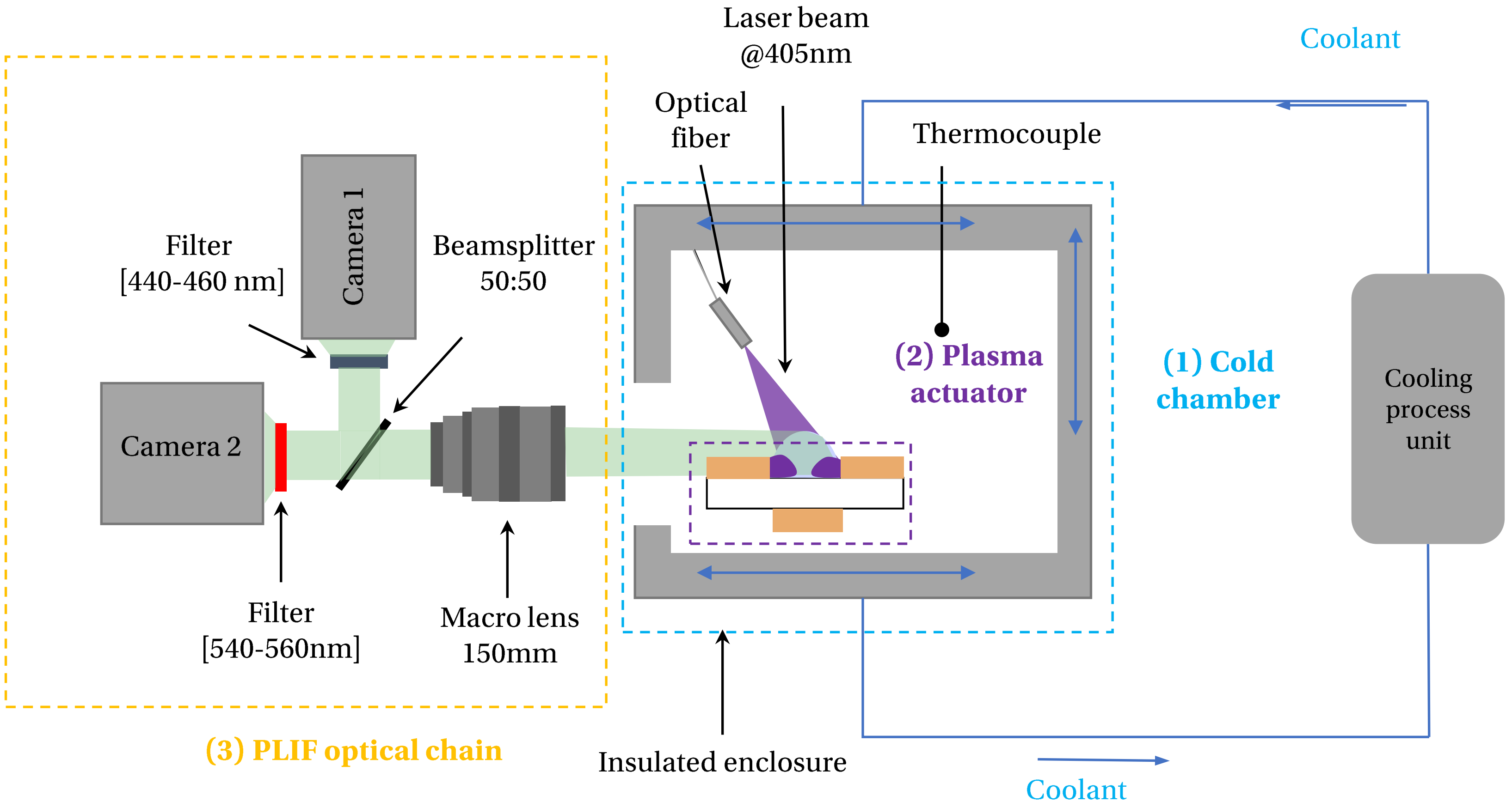
$$P = Bf$$

$\varepsilon_{r,\mathrm{saphir}} > \varepsilon_{r,PTFE}$ → Greater internal dissipation for the sapphire actuator

$$P_D \propto \varepsilon_r$$

PLIF2c1d chain for ice temperature measurement

Experimental set-up

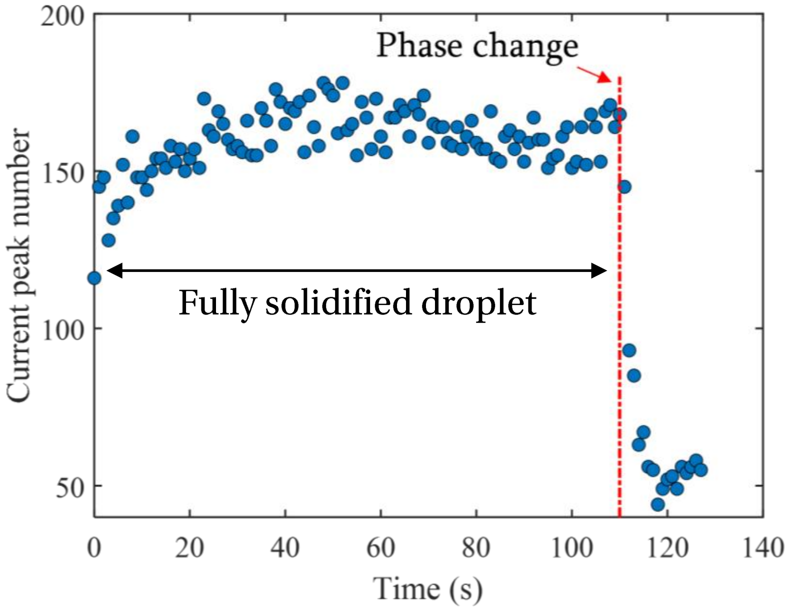


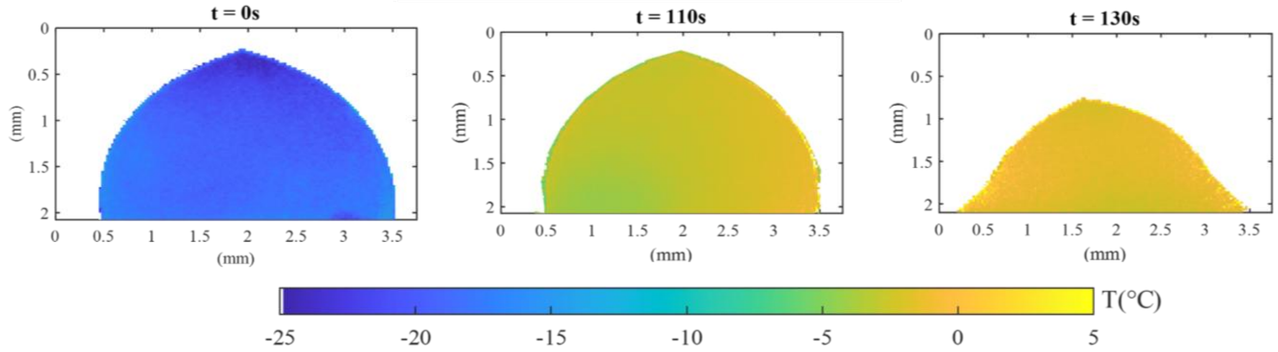
Principle of the measurement

- Coupling between PLIF measurements and monitoring of the evolution of electrical current peaks

Experimental protocol

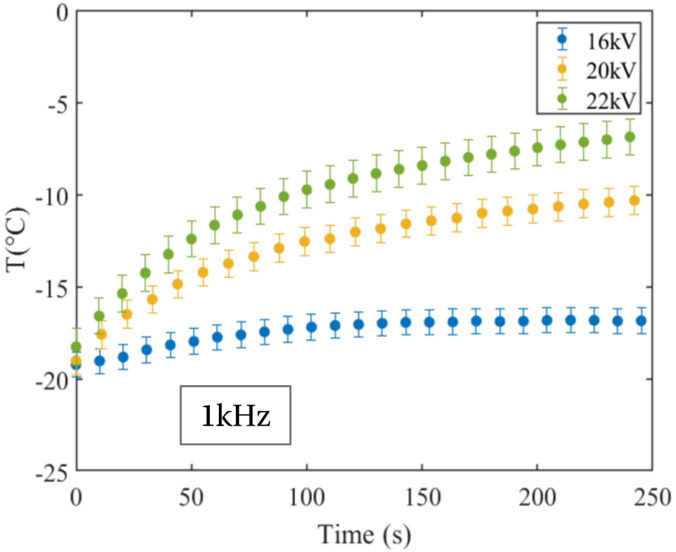
- ➢ 2mm droplet deposition on the actuator
- ➢ Solidification + thermal equilibrium with ambiant air
- ➢ Synchronization: discharge + start PLIF acquisition + current measurement

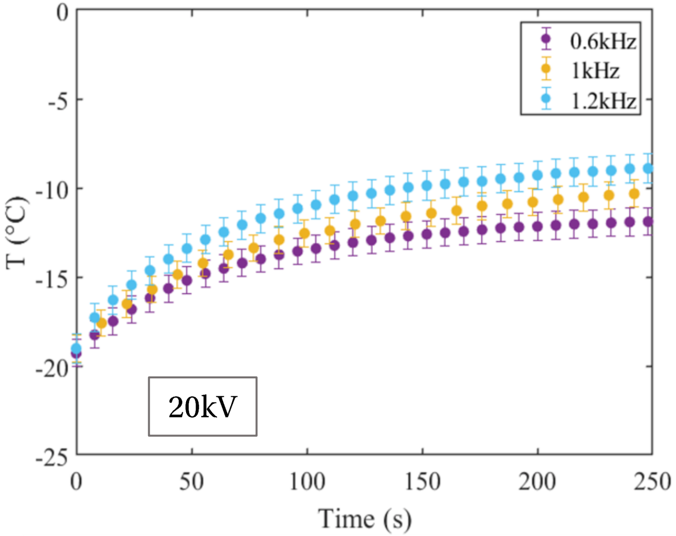




Results

PTFE





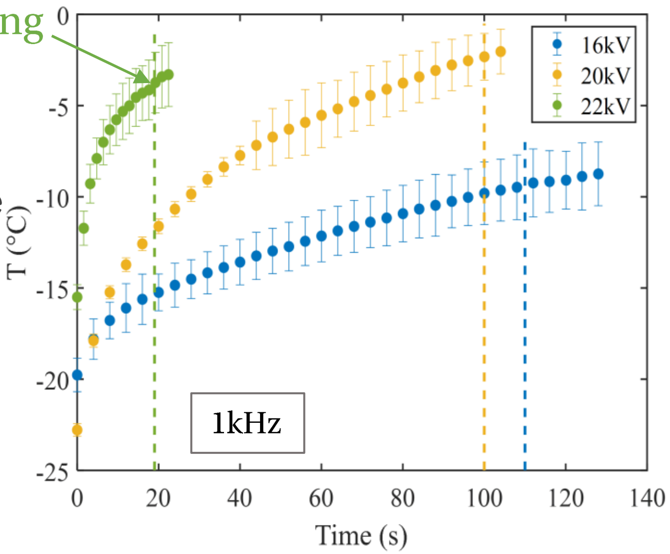
Influence of dielectric properties

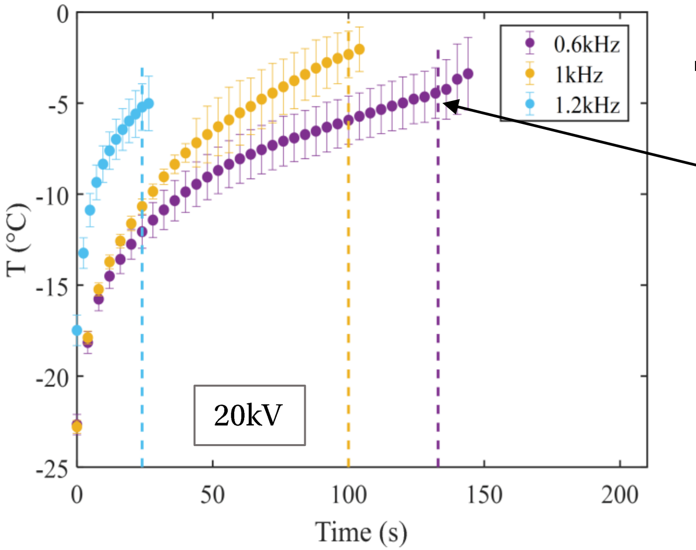
$\boldsymbol{\varepsilon_r(sapphire) > \varepsilon_r(PTFE)}$

$\boldsymbol{k(sapphire) > k(PTFE)}$

→ No droplet melting

Sapphire



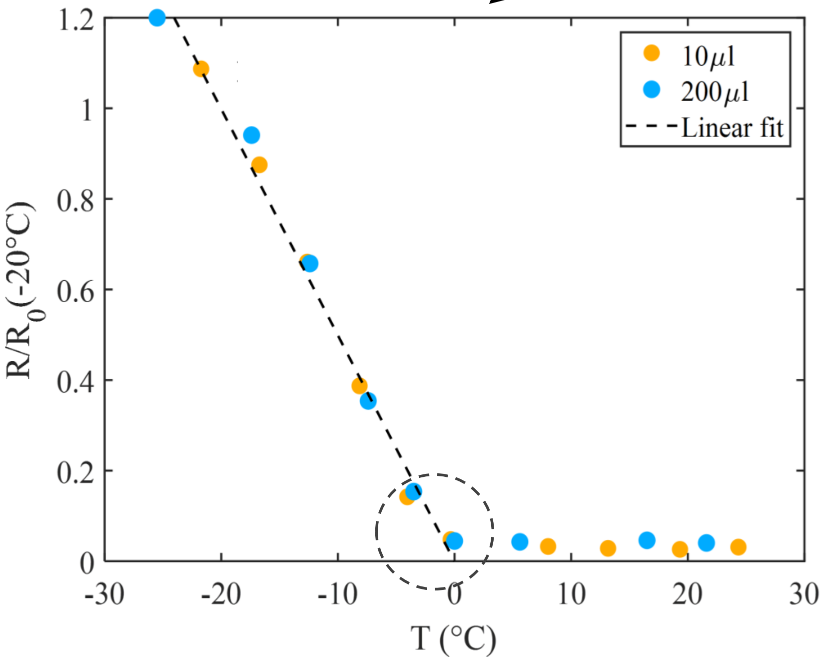


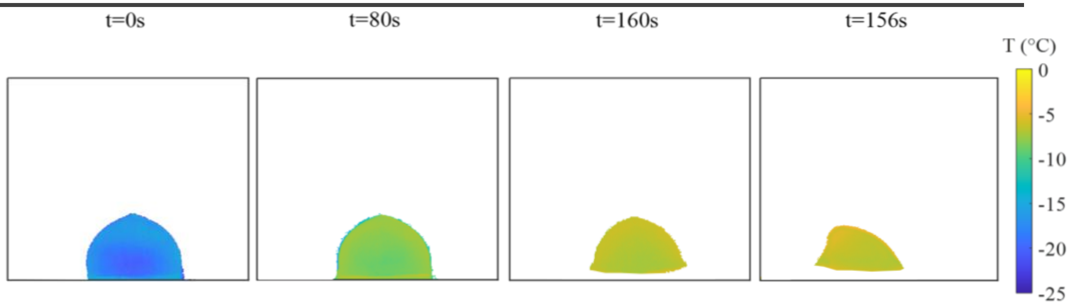
→ Melting

⚠ Melting at T<0°C → method does not allow for local temperature measurements

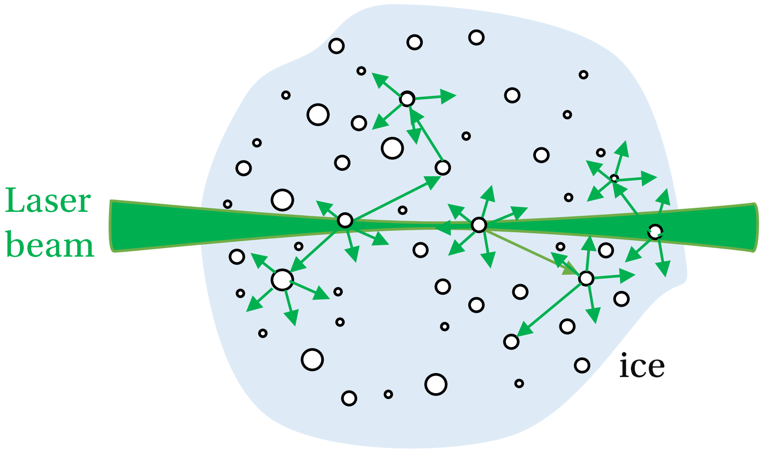
Results

⚠ Melting at T<0°C → method does not allow for local temperature measurements





Multiple scattering



Fluorescence induced by laser scattering

Technique allows the measurement of the average ice temperature

Anti-icing

Motivations

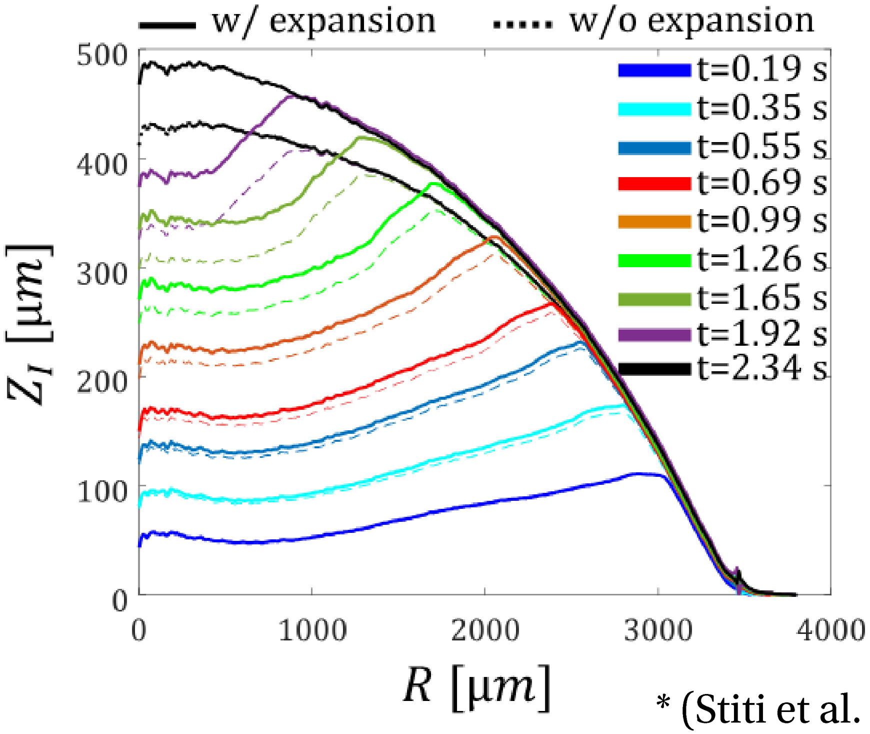
- Few studies on the impact of droplets on surface DBDs
- Characterizing the hydrodynamics of the impact

→ Single-color fast **PLIF metrology for phase change detection** *

- **Rhodamine 6G**

$\phi_{\lambda,ice} < \phi_{\lambda,liquid}$

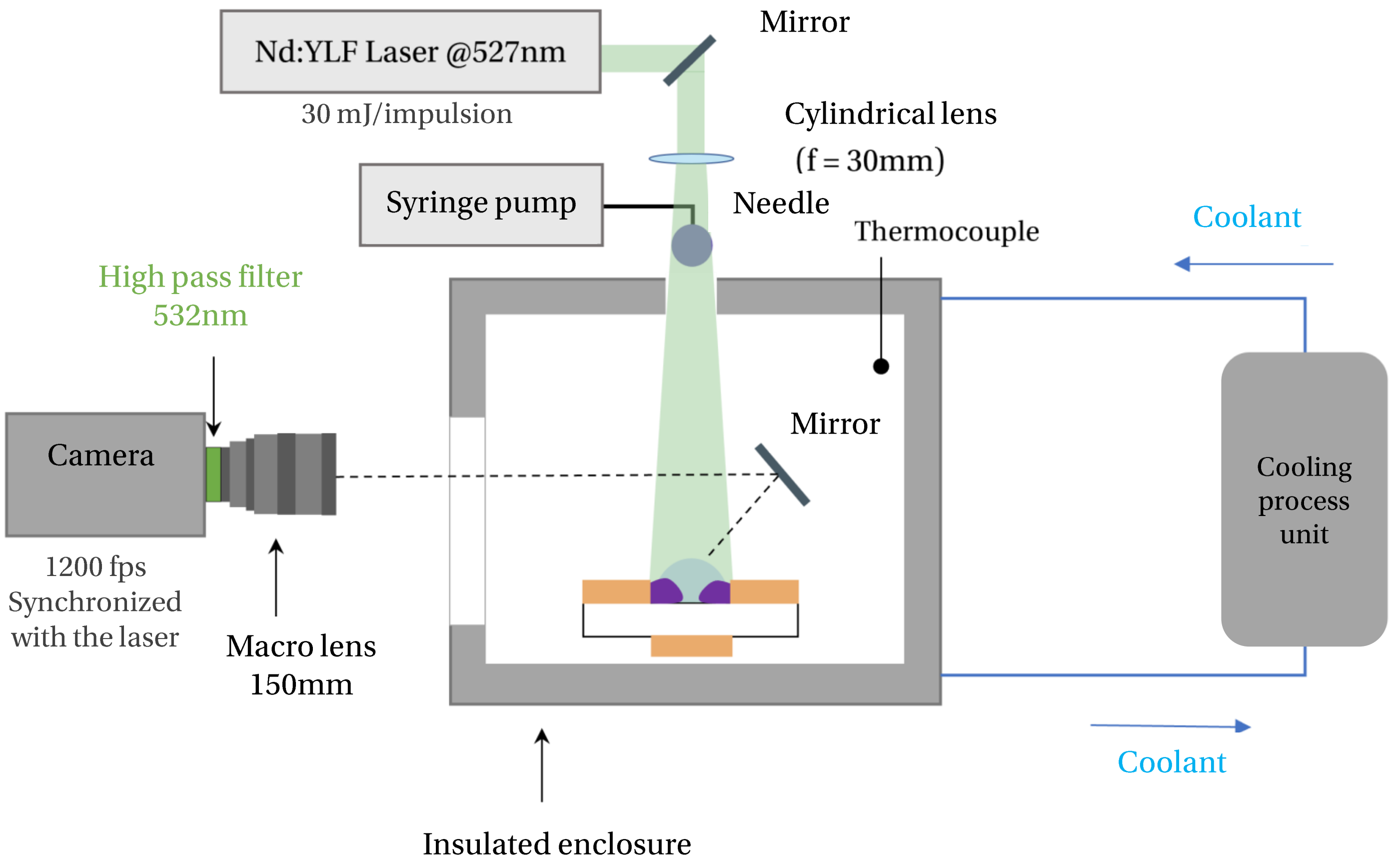
$I_{f,\lambda}$ is not temperature dependent



* (Stiti et al. 2020)

Droplet impact on a surface DBD

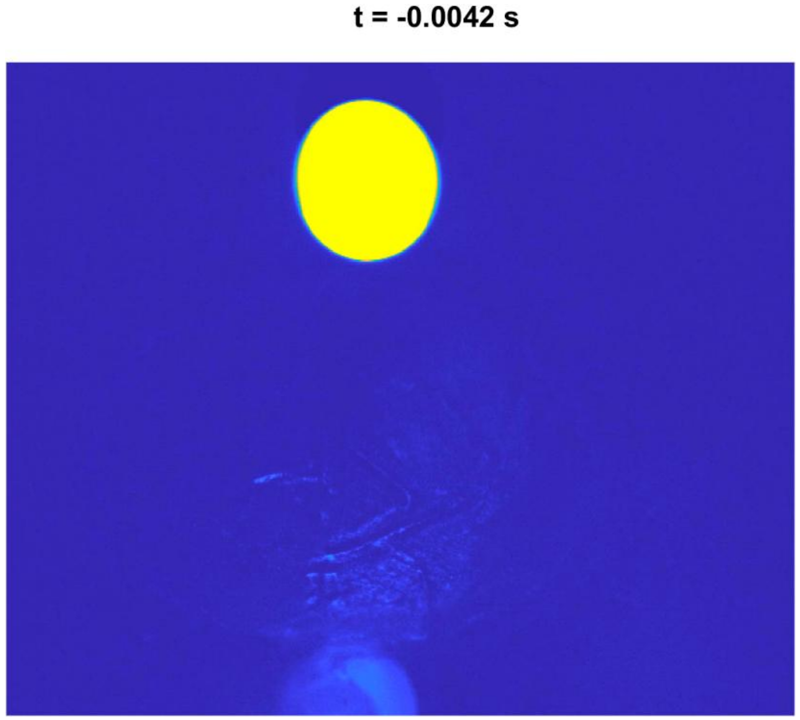
Experimental set-up



Droplet impact on a surface DBD

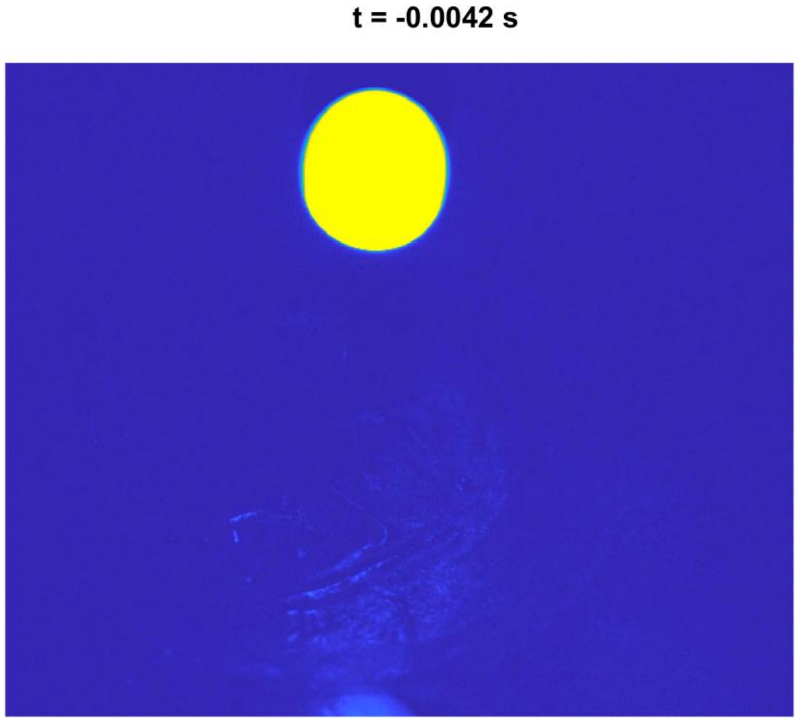
Impact at T > 0°C

Plasma OFF



Spreading → recoiling → equilibrium

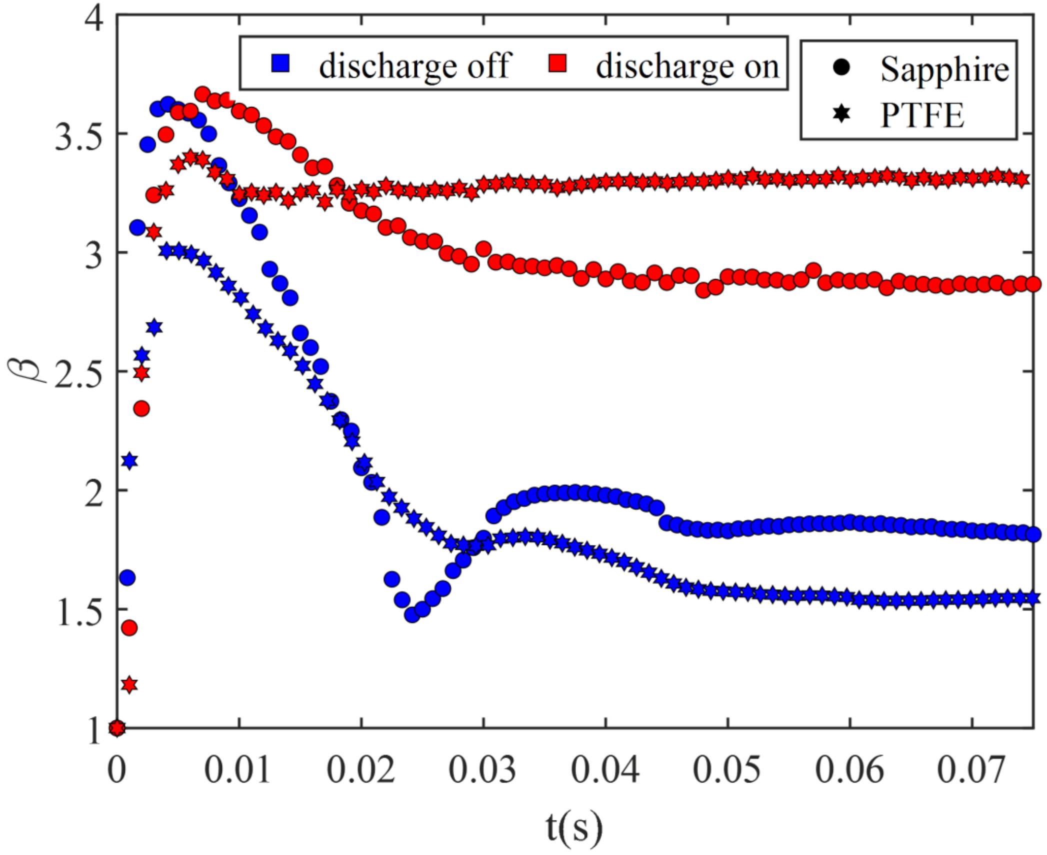
Plasma ON (12 kV/1kHz)



Spreading ↗ → no recoiling → equilibrium reached faster

Droplet impact on a surface DBD

Impact at T > 0°C



❑ Spreading factor

$$\beta = \frac{R}{R_0}$$

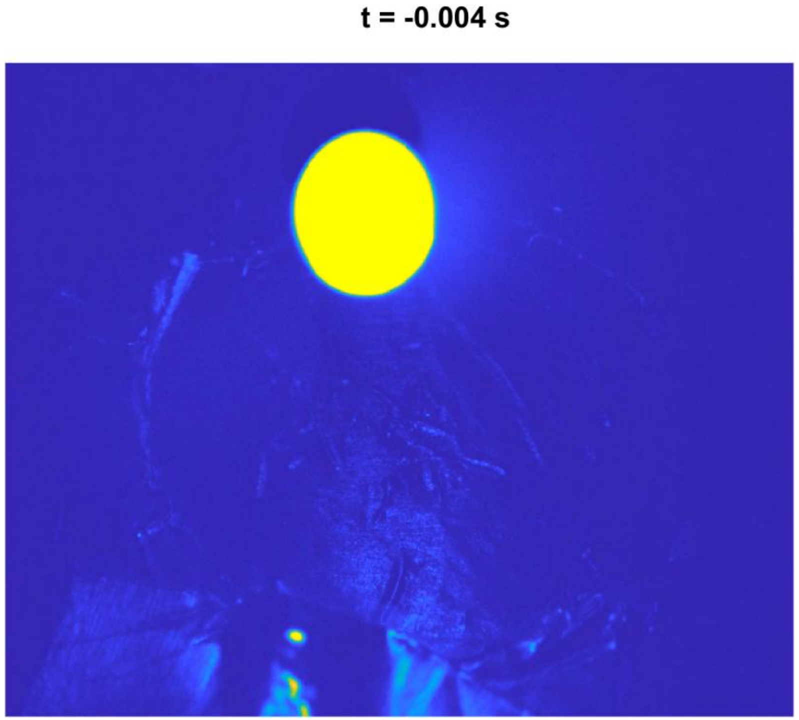
- Charge accumulation at the droplet surface

→Significant reduction in surface tension

Droplet impact on a surface DBD

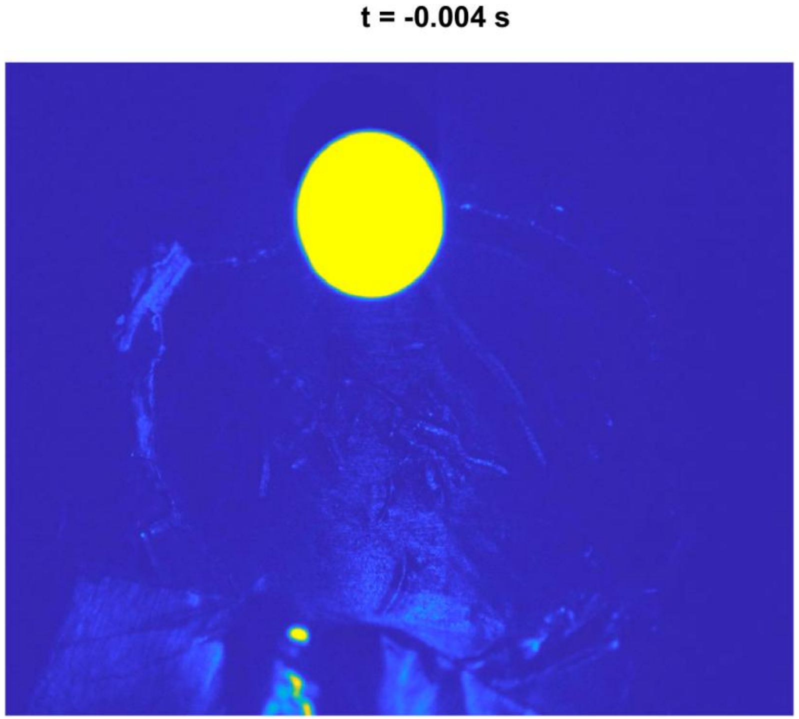
Impact at T < 0°C

12 kV/1kHz – 1 min



Solidification time→ 2.86s

22 kV/1kHz – 1 min



Solidification time→ 5.90 s

Droplet impact on a surface DBD

Impact at T < 0°C

Delay of solidification as a function of U

Dielectric	Amplitude and activation time				
	Plasma off	12kV - 1 min	12 kV - 5 min	22kV – 1 min	22kV – 5 min
Sapphire	2.86s	2.86s	6.18s	5.90s	x
PTFE	38.2s	38.2s	x	50.2s	x

$$e = \sqrt{k\rho c_p}\,;$$

$$T_c = \frac{T_w e_w + T_l e_l}{e_w + e_l}$$

$$e_{saphir} < e_{PTFE}$$

$$T_{c,saphir} < T_{c,PTFE}$$

Influence of pre-heating time

Different dynamics compared to de-icing (No melting on PTFE):
- Influence of thermal effusivity
- Streamer distribution change

Conclusions

- Development of a PLIF2c1d chain for ice temperature measurement
- Heating and melting of the droplet are mainly caused by power dissipation within the dielectric
- Spatio-temporal monitoring of the impact of a drop on a surface DBD by PLIF
- At T > 0 °C : Modification of the impact dynamics (max spreading, recoiling)
- At T < 0 °C : Influence of pre-heating and dielectric material

Perspectives

- Quantify the heat flux at the interface with the dielectric
  - Coupling with TIR measurements
- Modeling of fusion/solidification dynamics
  - Droplet size, We, DBD parameters

Thank you for your attention

(...and for any potential post-doc opportunity ☺)

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