Development and characterization of an atmospheric plasma source for non-thermal blood coagulation

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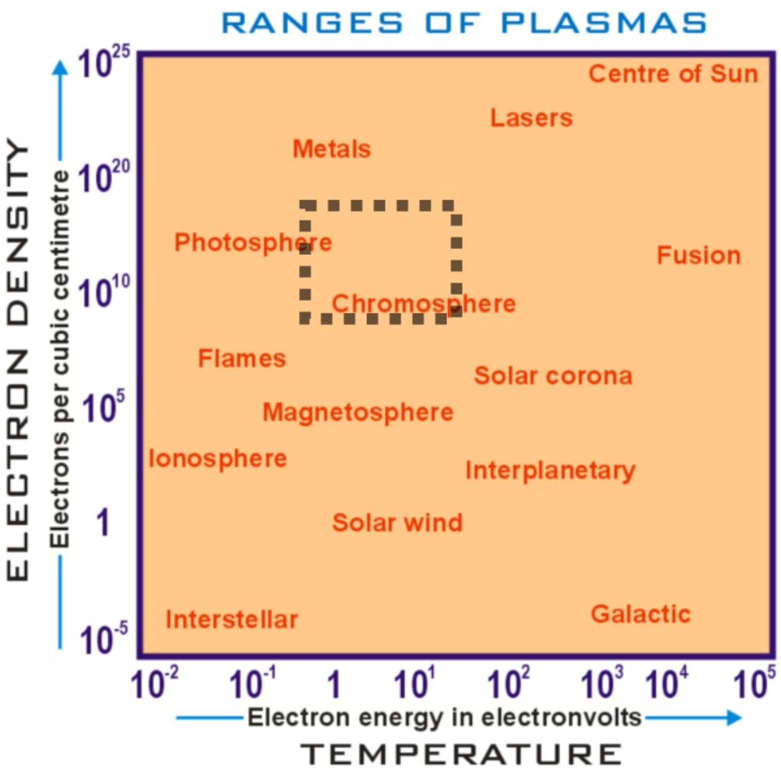
Cold Atmospheric Plasma for Plasma Medicine



$1 < \mathbf{T_e} < 10$ eV

$10^{17} < \mathbf{n_e} < 10^{22}$ m^{-3}

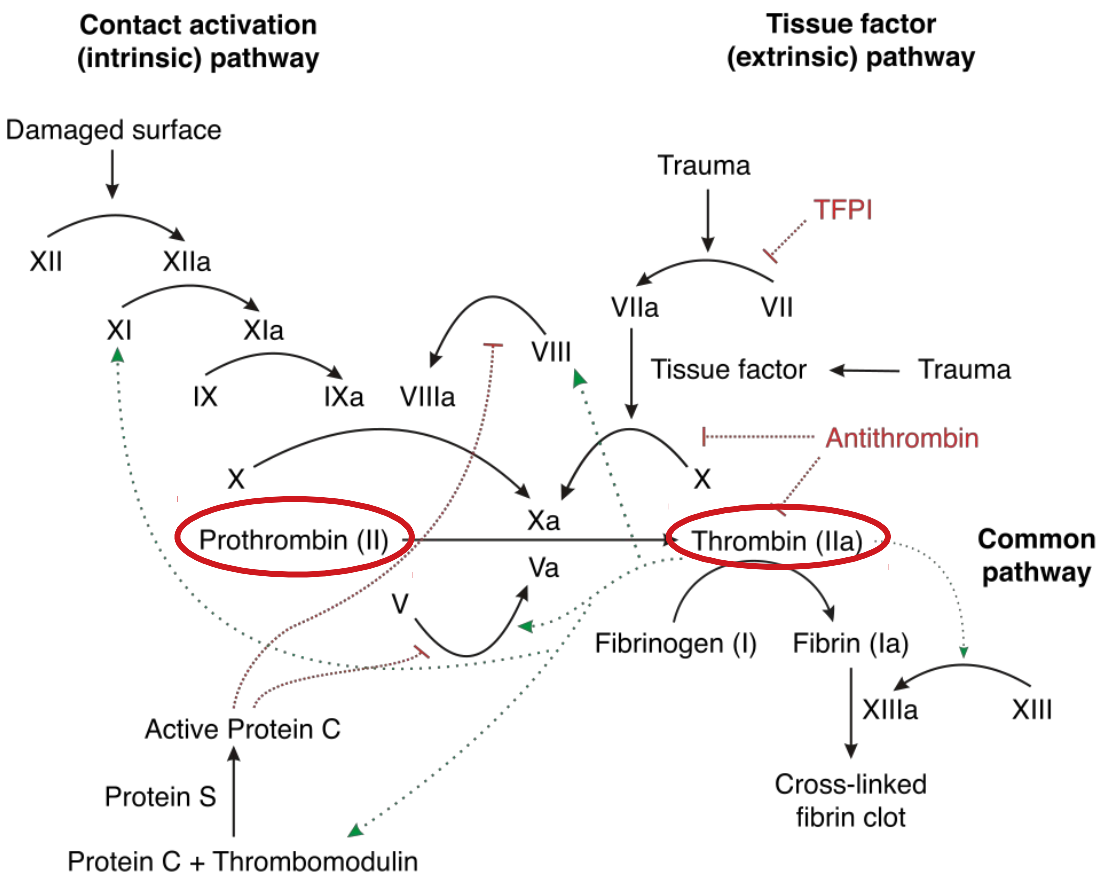
Cold = no thermodynamic equilibrium between electrons – ions
Atmospheric = mixed with air, many Reactive Species

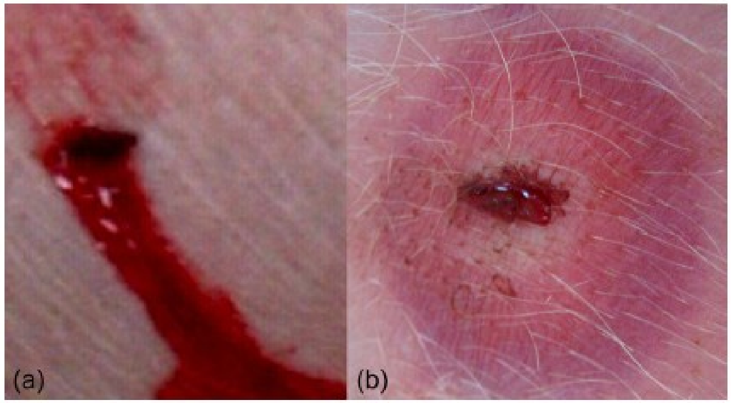
Plasma Medicine

- Sterilization and decontamination
- Wound disinfection and healing
- Cancer cell treatment
- Blood coagulation

Non thermal blood coagulation

Two pathways, many tissue factors and proteins involved. PCC improves *Prothtrombin* and *Thrombin* production.





Not treated
bleeding > 120s

Treated
Plasma = 18s

Plasma Coagulation Controller

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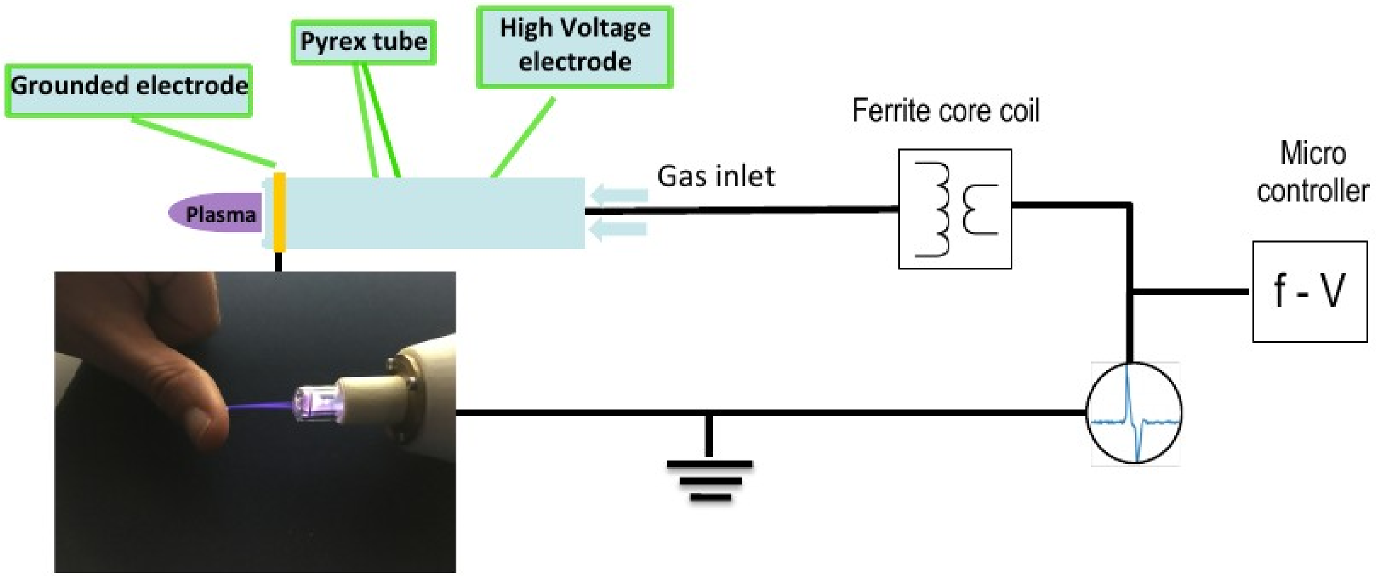
Voltage pulse on electrode covered in dielectric =
Dielectric Barrier Discharge

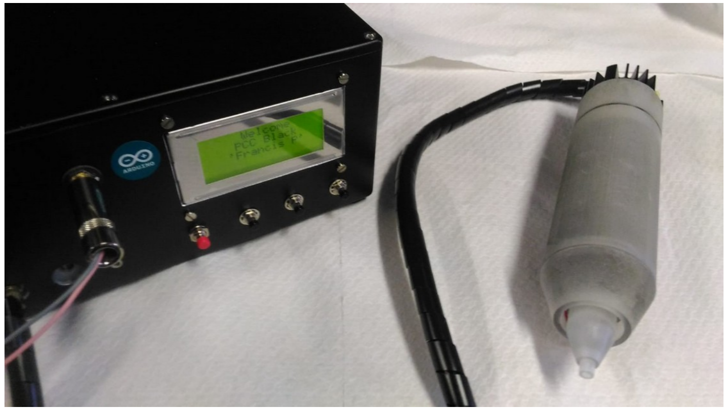


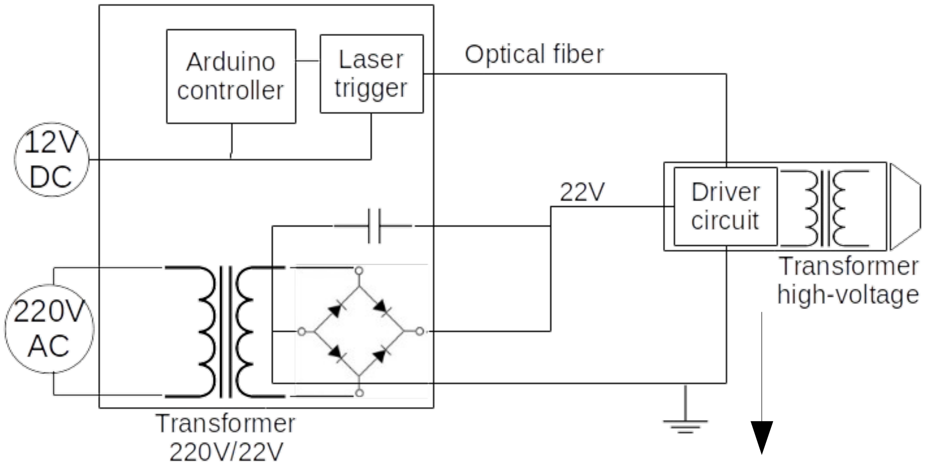
Neutral gas:
- Helium
- Neon
- Argon

Pulse Repetition Rate
1 kHz < f < 40 kHz

- Low current density = no risk of arc formation
- Low power deposition on target = low target temperature
- Presence of **Reactive Oxygen Species** and **Reactive Nitrogen Species** = therapeutic effects

Electric characterization



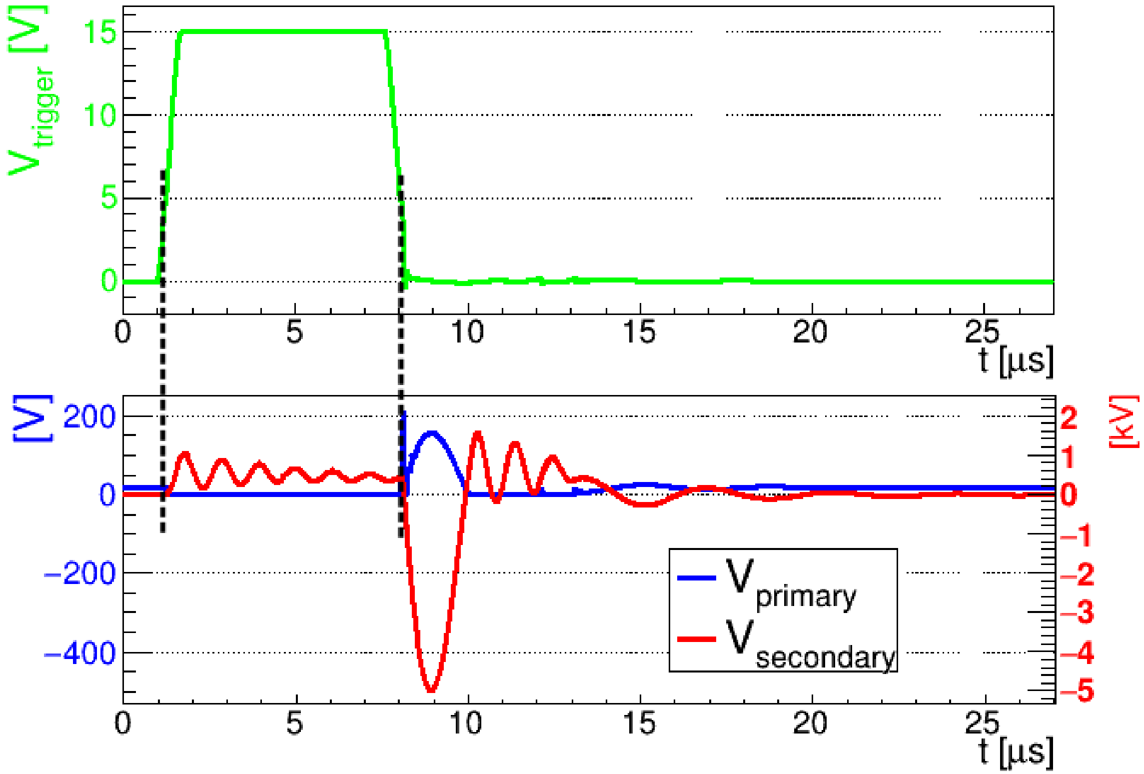


Controller module

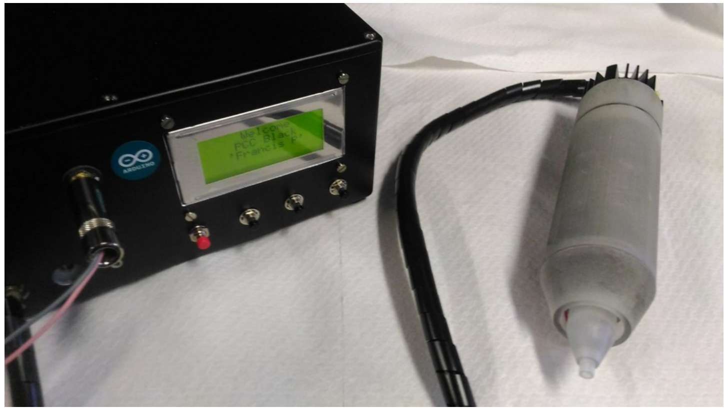
Discharge trigger

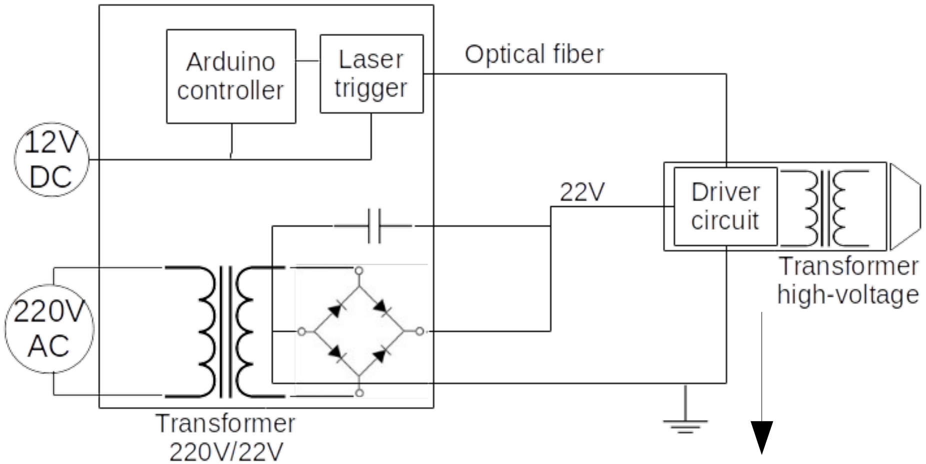
Head module

Plasma formation



Electric characterization





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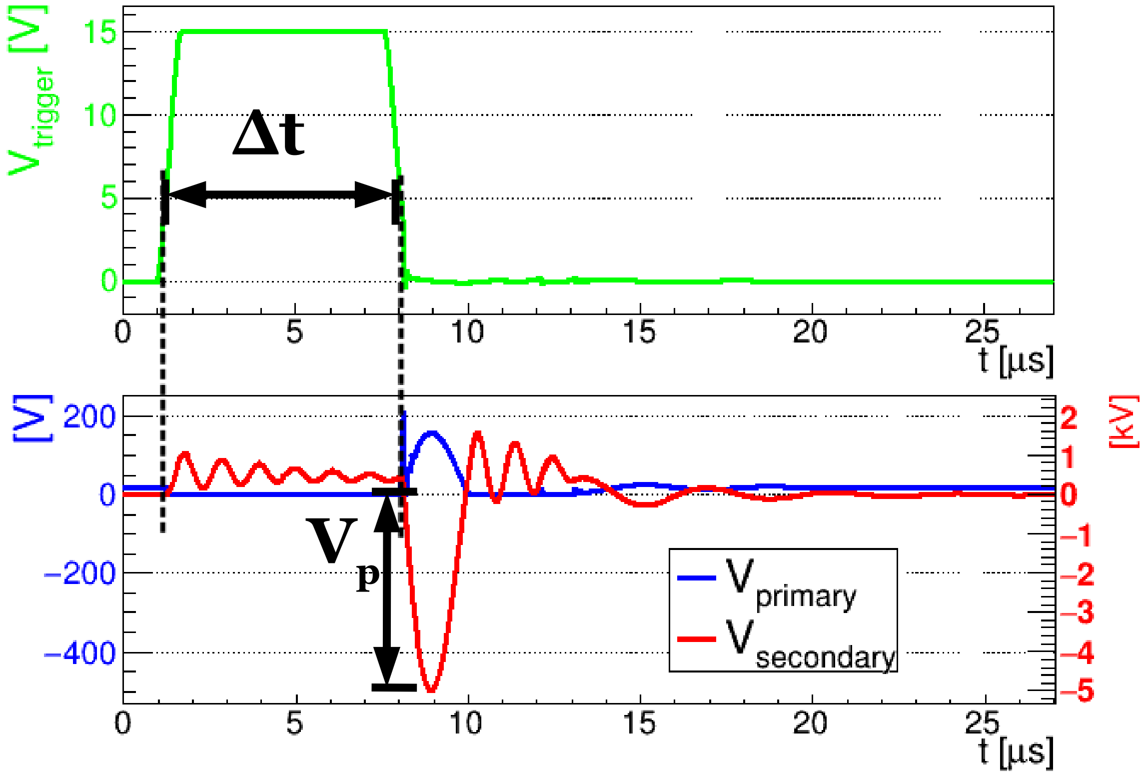
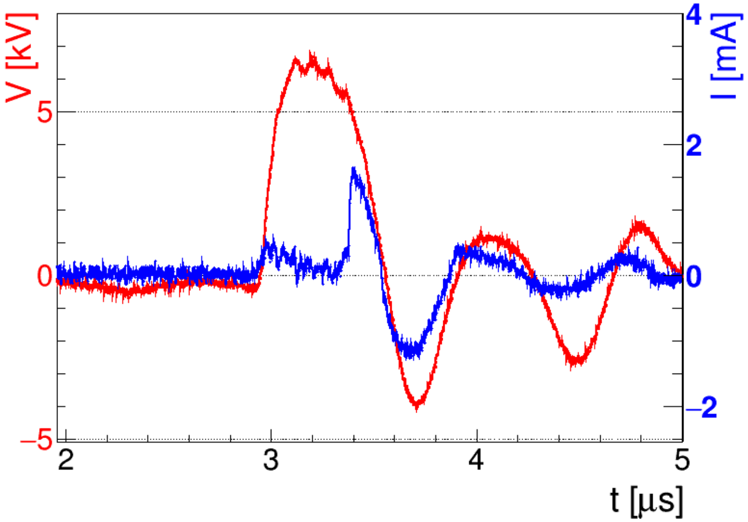
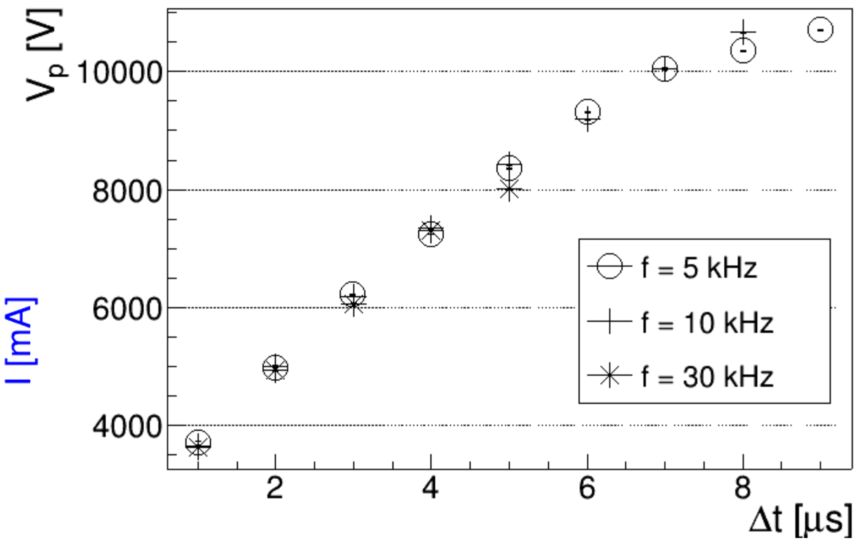


$$V_p \propto \Delta t$$

Electric characterization
Voltage and current measurements

Measurements of:
- Voltage pulse amplitude
- Current flowing in a copper target at 1cm from the nozzle



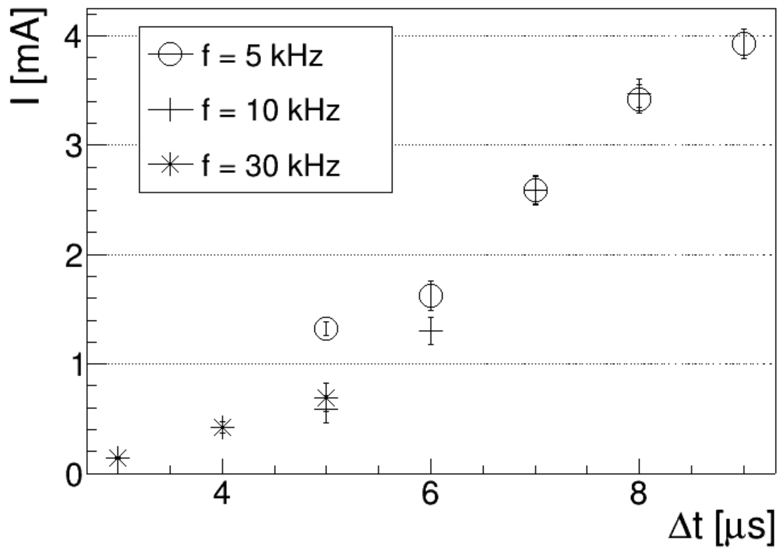


Voltage

Linearity $4 < V_p < 10$ kV

V_p independent from f

Pulse width ≈ 1 µs



Current

Always < 10 mA

Optical Emission Spectroscopy

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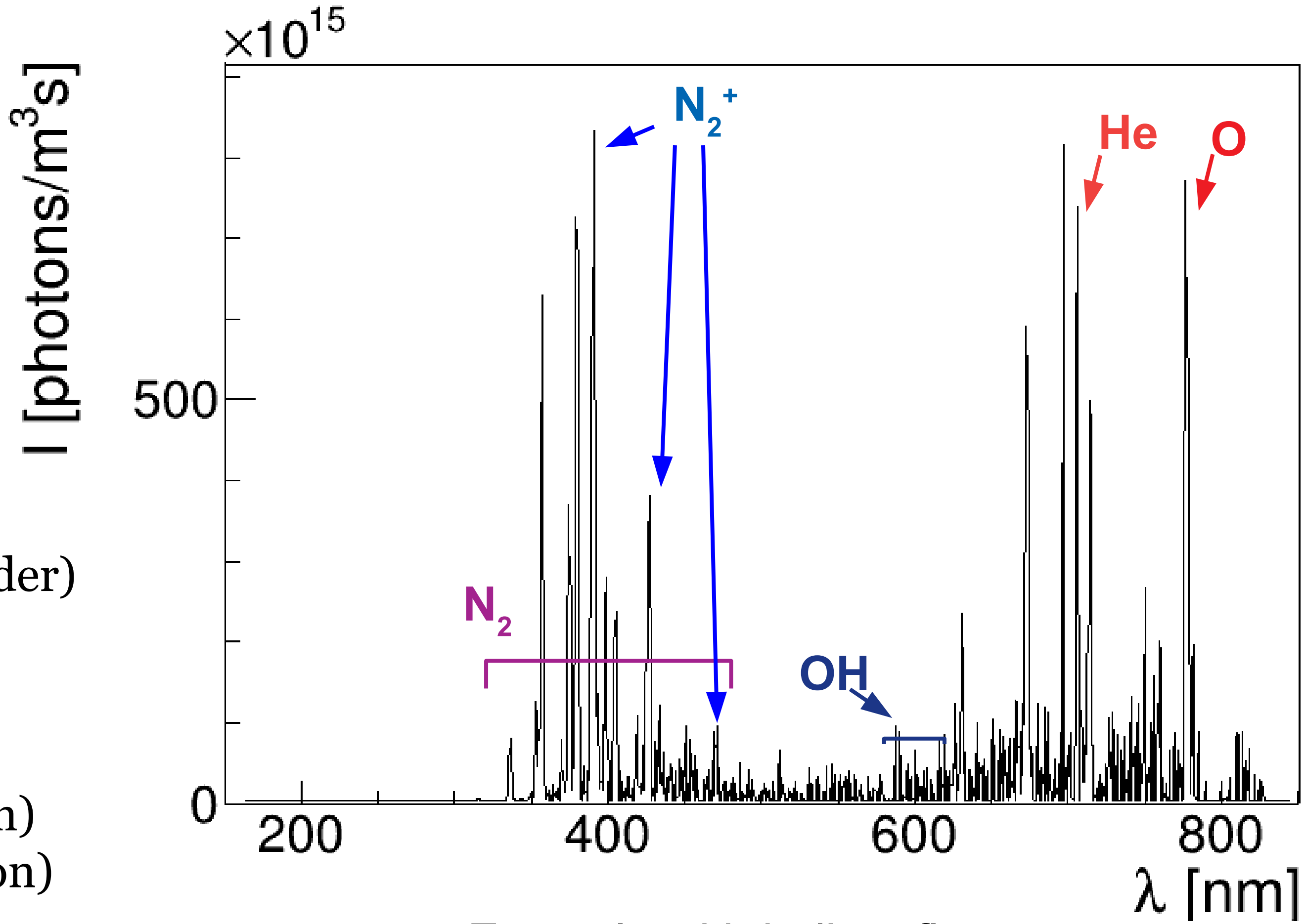
Spectrometer range 150-850 nm .

Emission spectrum of Helium, Neon, Argon or mixed flux.

Observed lines:

- **N_2 , N_2^+** 320-480 nm (1st, 2nd order)
- **OH** 300-310 nm (1st, 2nd order)
- **O** 777 nm
- **He** 706 nm (only with Helium)
- **Ne** 410-780 nm (only with Neon)
- **Ar** 660-850 nm (only with Argon)



Example with helium flux

Optical Emission Spectroscopy
temperature estimation

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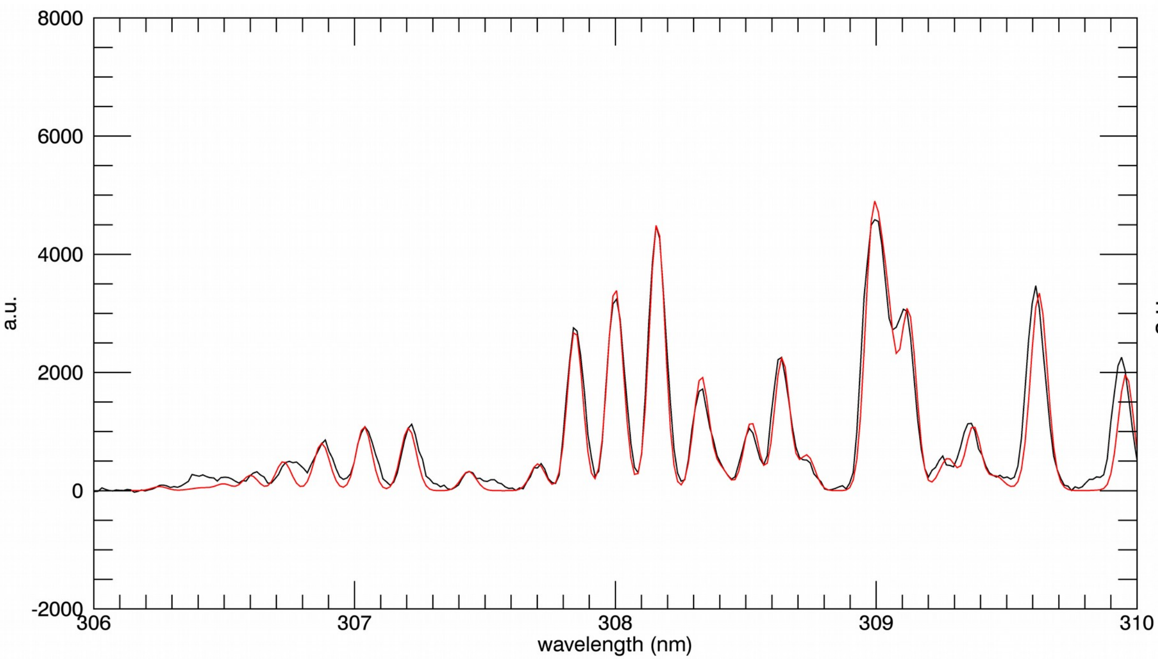
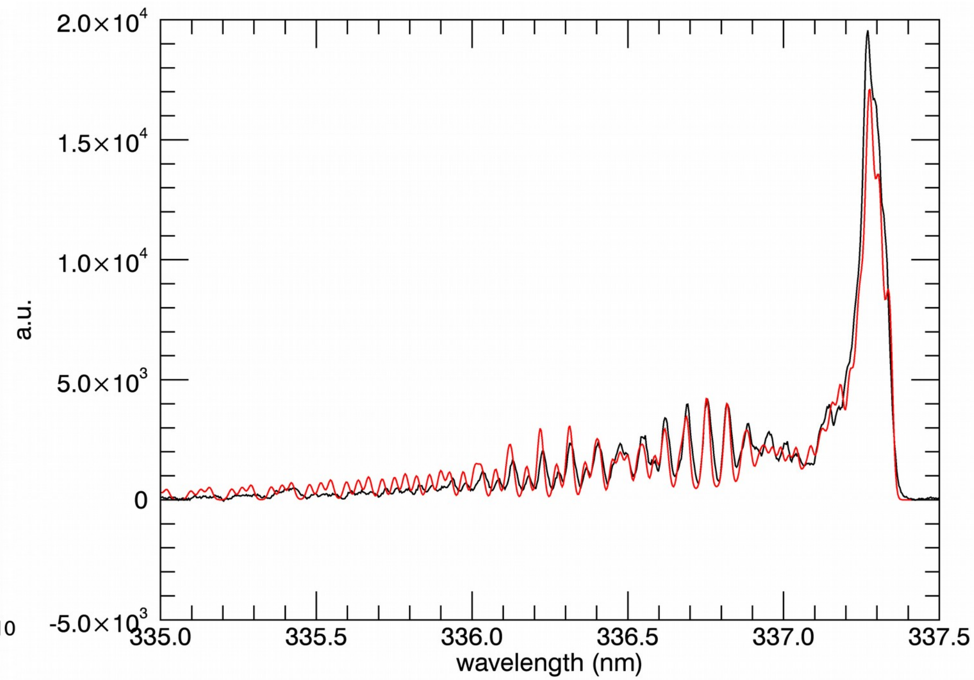
An high resolution spectrometer allows us to observe **OH** and **N_2** rotational bands.

Through a simulation of the rotational spectrum of the molecule it is possible to estimate its rotational temperature, which is approximately the temperature of the molecule itself. → $\mathbf{T_{rot} \approx T_{ion}}$

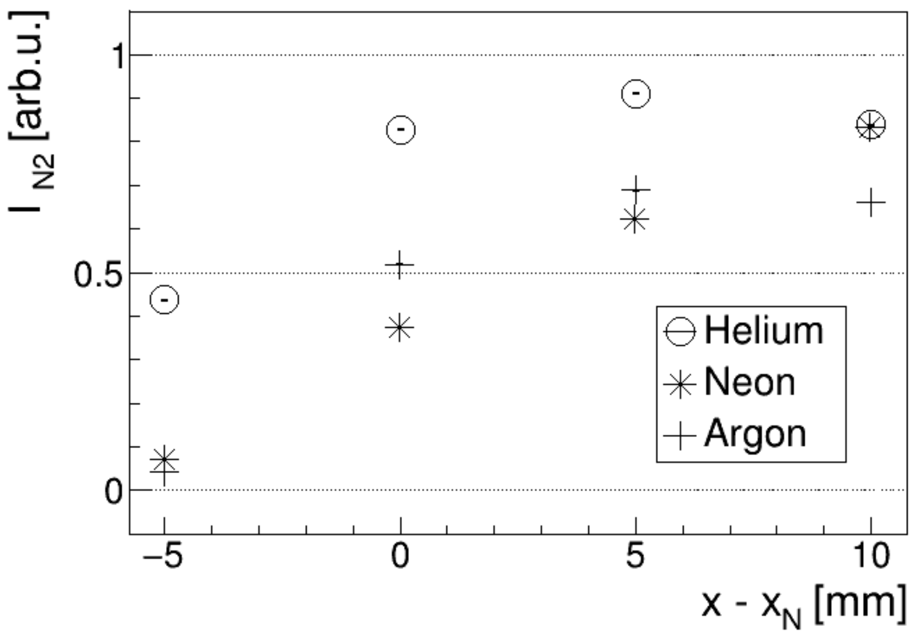


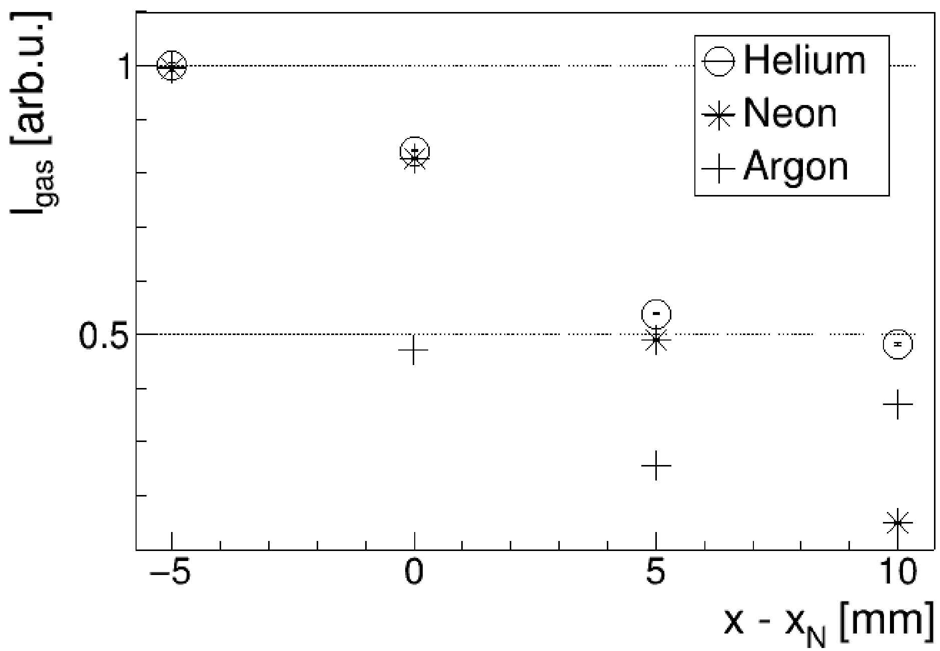
$\mathbf{T_{rot,\ OH} = 352 \pm 38}$



$\mathbf{T_{rot,\ N2} = 321 \pm 41}$

Optical Emission Spectroscopy
emission intensity





Spectrometer pointed:

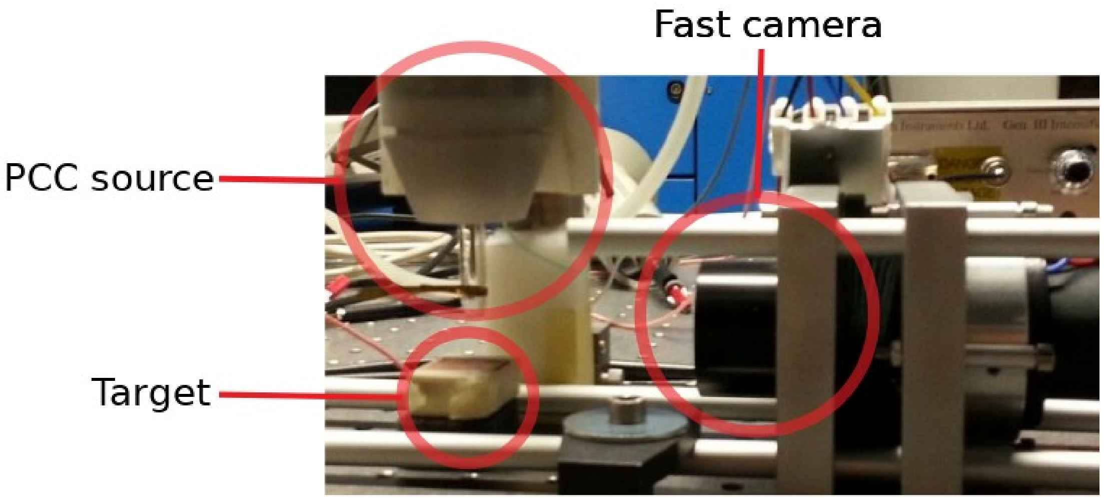
- 5mm inside the nozzle
- End of the nozzle
- 5mm outside
- 10mm outside

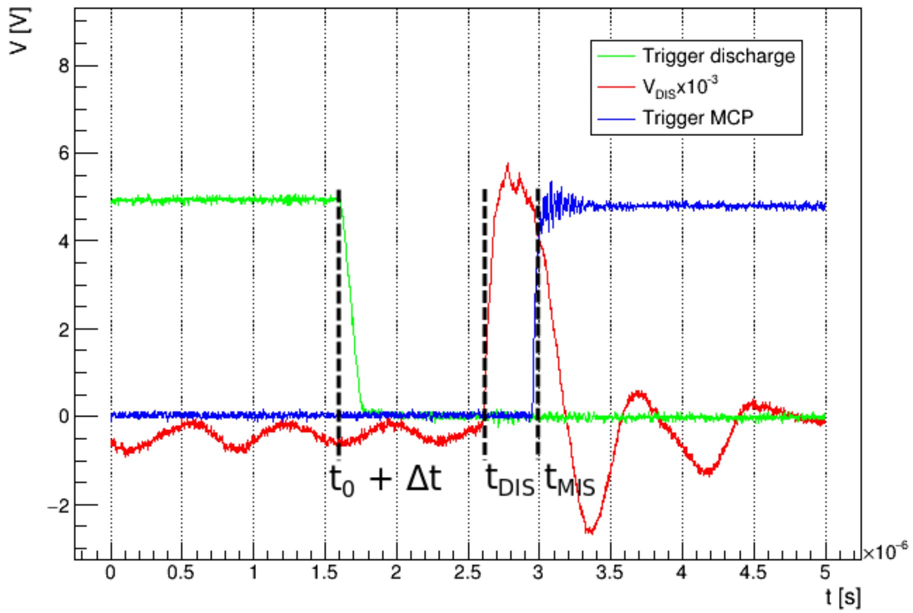
From inside the nozzle to the outside:

- N_2 emission increase
- Gas (He, Ne or Ar) emission decrease

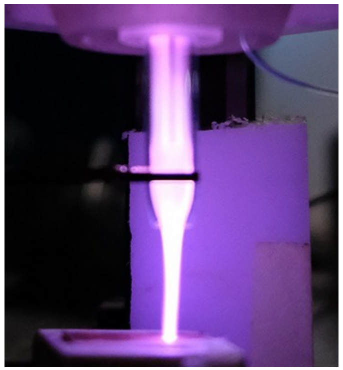
Fast camera measurements

Fast imaging allows us to see plasma formation and propagation.

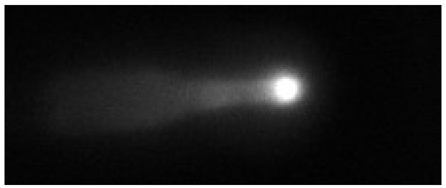




Synchronization between discharge and camera allows us to see the evolution of the discharge.

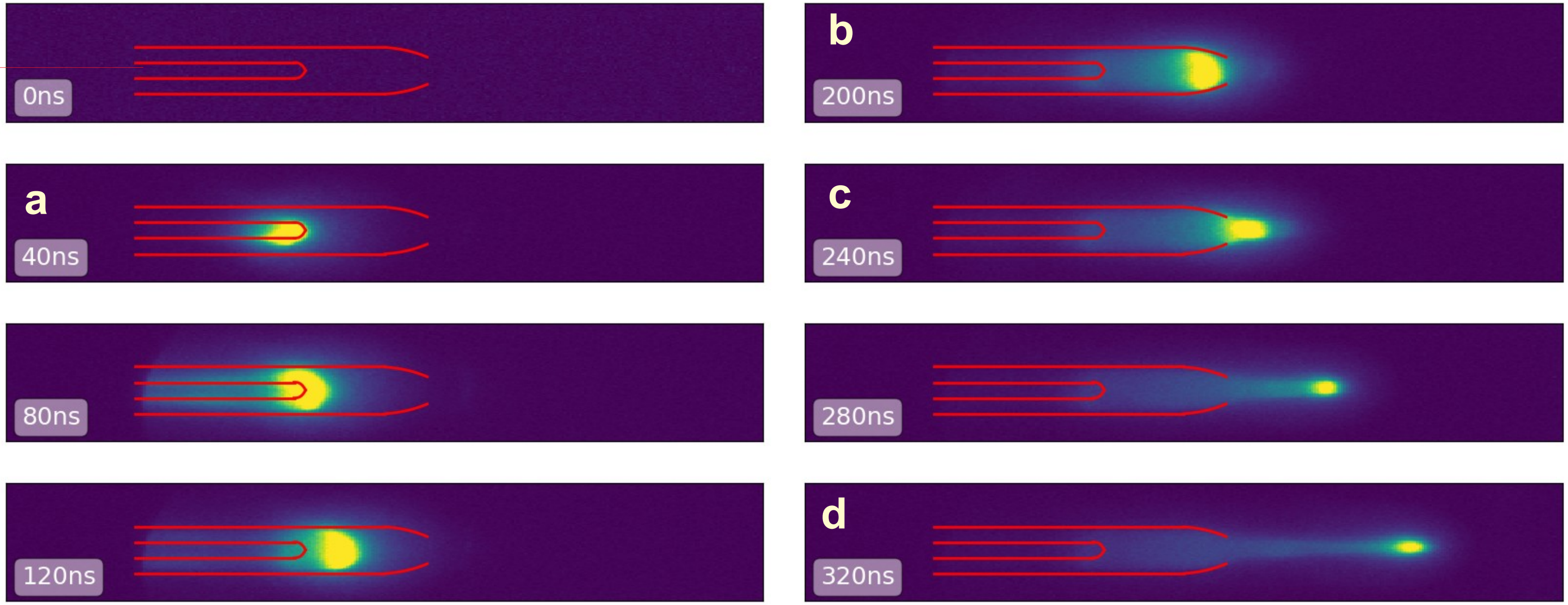


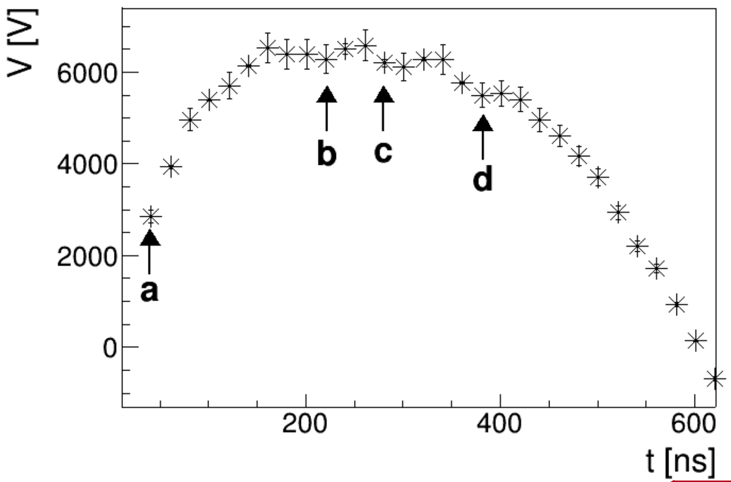
Standard camera integration time > 10ms



Fast camera integration time = 15ns

Helium and Neon plasma Bullets

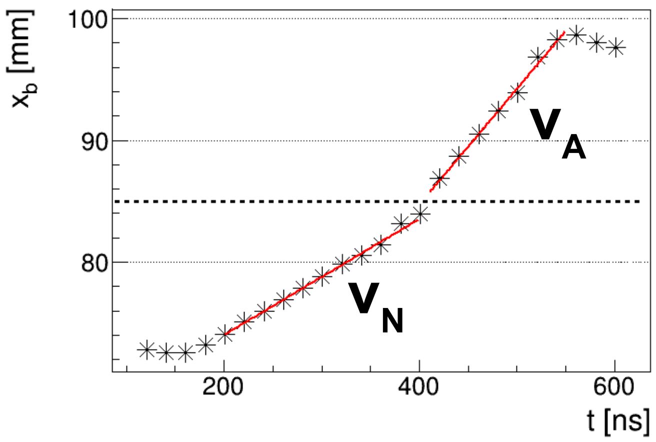




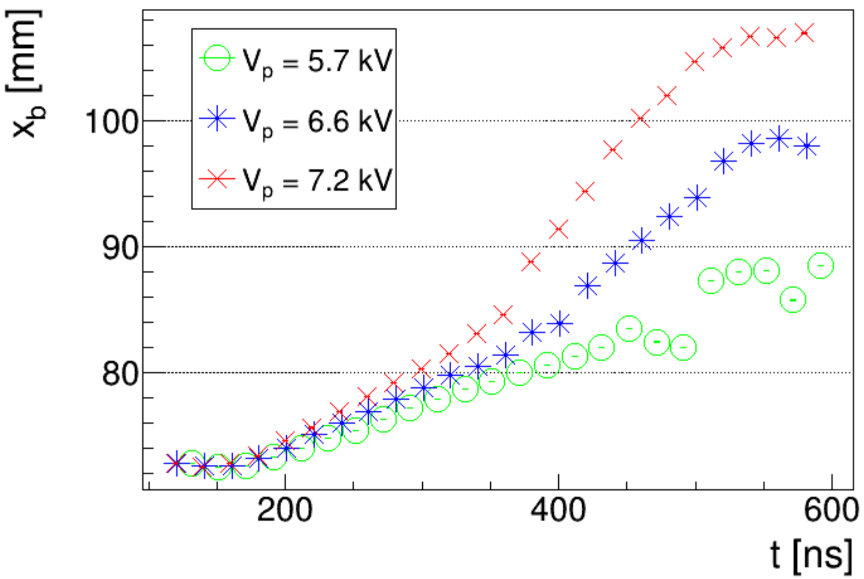
Plasma propagates as ***bullets*** : portion of gas moving from the electrode to the air outside.

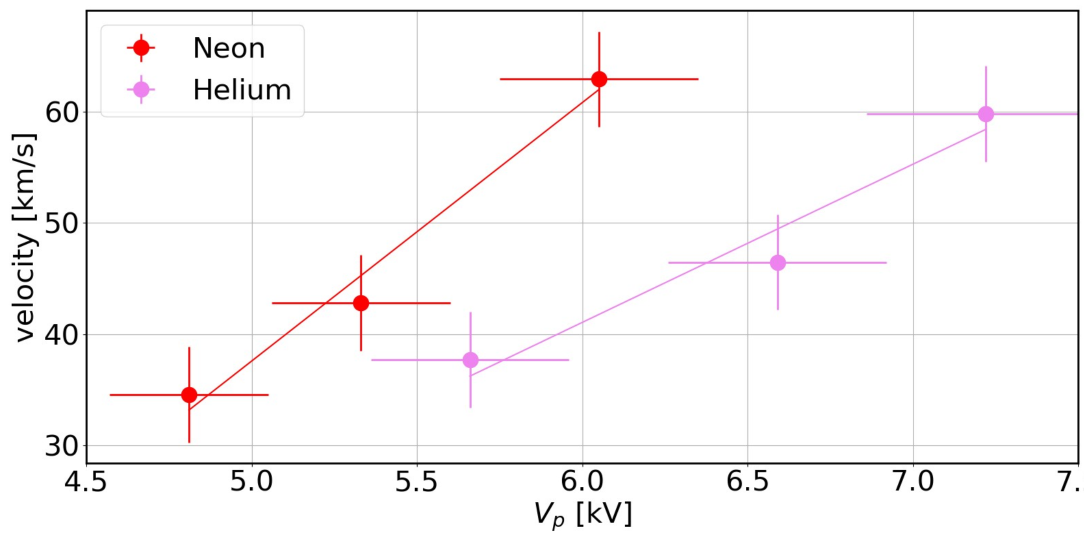
Plasma forms near the electrode (a) and propagates inside the nozzle covering its entire area(b), then it propagates in air with decreasing luminosity (c-d).

Bullet velocity



Gas	V_p [kV]	Δx_{MAX} [mm]	v_N [km/s]	v_A [km/s]
Helium	5.7 ± 0.3	16.0 ± 0.8	37.7 ± 3.2	-
	6.6 ± 0.3	26.1 ± 0.5	46.5 ± 4.0	95.2 ± 6.3
	7.2 ± 0.4	34.6 ± 0.5	59.8 ± 4.3	149.5 ± 11.9
Neon	4.8 ± 0.2	18.1 ± 0.9	34.6 ± 3.0	43.2 ± 7.2
	5.3 ± 0.3	22.4 ± 0.8	42.8 ± 4.6	61.2 ± 6.8
	6.1 ± 0.3	26.6 ± 0.9	62.9 ± 5.1	160.3 ± 15.7





Electronic motion equations

Electron energy distribution ***f*** in 6-dim phase space, without magnetic field :

$$\frac{\partial f}{\partial t} + v \cdot \nabla f - \frac{e}{m} E \cdot \nabla_v f = C[f]$$ **Boltzmann eq**

Where ***C[f]*** is given by collisions.

First two moments:

$$\frac{\partial n}{\partial t} + \nabla \Gamma = S$$ **Continuity eq**

$$\Gamma = -\mu E n - \nabla (D n)$$ **Drift diffusion eq**

Where:

- **n** is the electron density
- **S** is the source term given by reactions
- **Γ** is the electron flux
- **μ** is the electron mobility
- **D** is the electron diffusion coefficient

Electronic motion equations

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Related to bullet velocity

Where:

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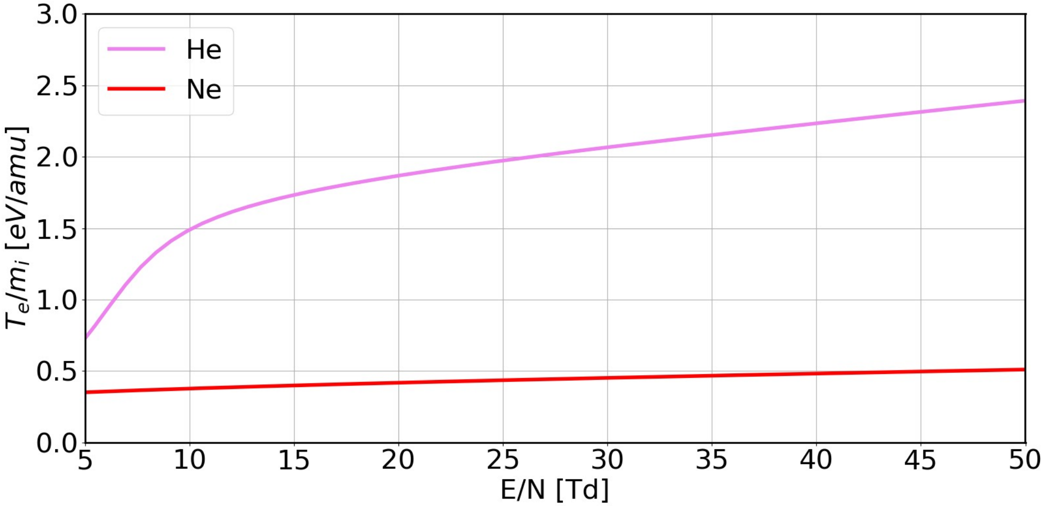
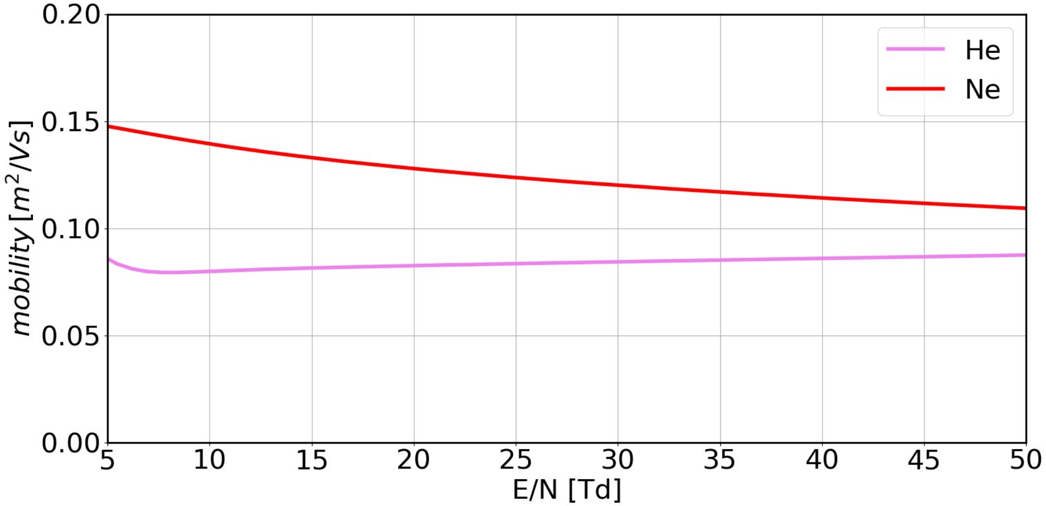
Electronic parameters

Previous equations can be solved by *Bolsig+*, a Boltzmann Equation solver for plasma with variable composition inside an electric field with variable intensity.

Helium and neon plasma at atmospheric pressure, electric fields from **130 V/mm** to **1.3 kV/mm** :





$$\left(\frac{T_e}{m}\right)_{He} > \left(\frac{T_e}{m}\right)_{Ne} \longrightarrow$$

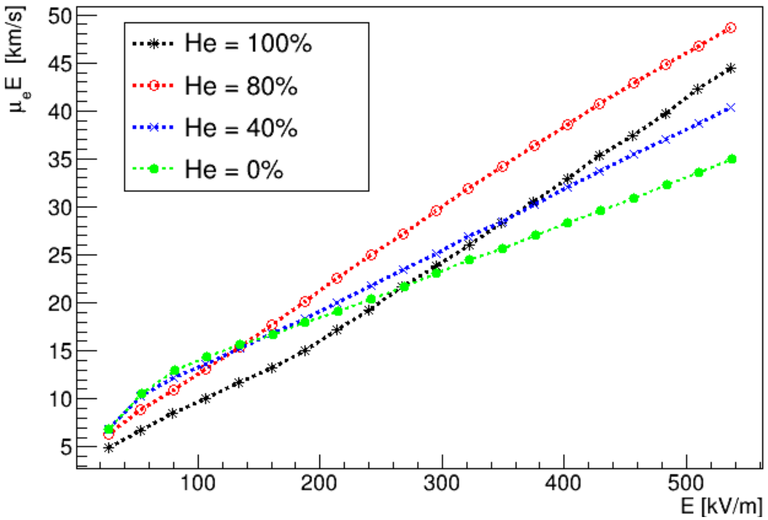
Bullet velocity not related to ion wave propagation

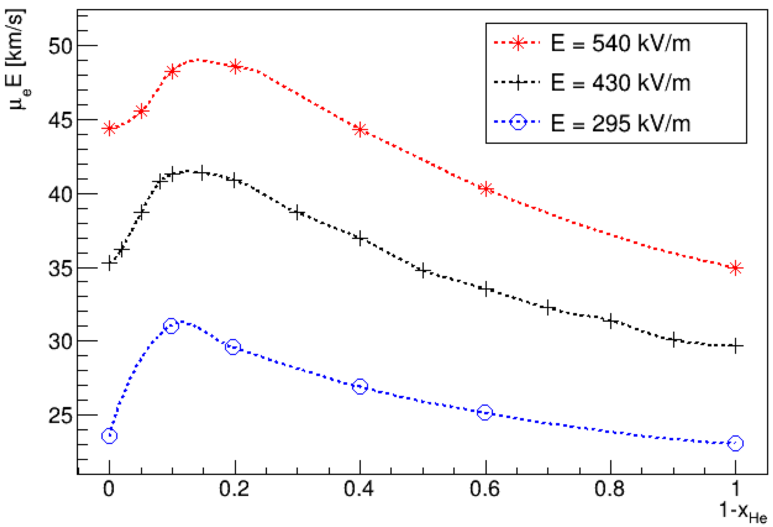
$$\mu_{He} < \mu_{Ne}$$

Bullet velocity related to electron mobility

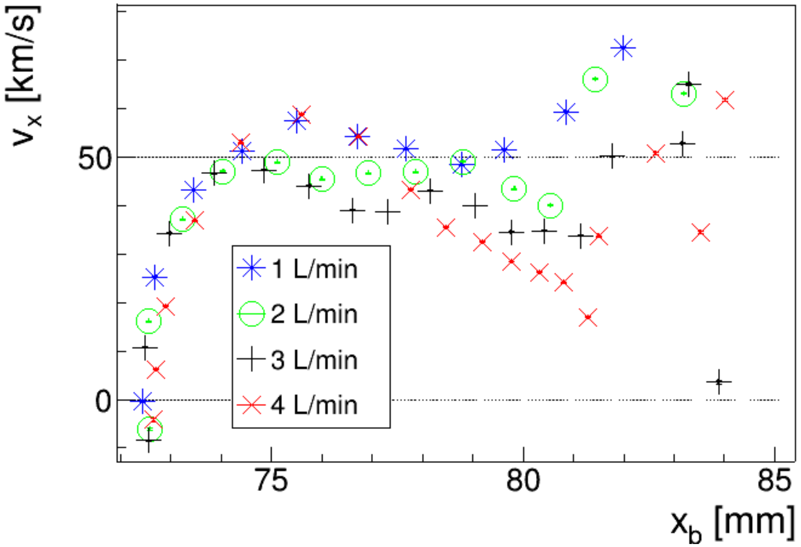
Electronic mobility and measured velocity

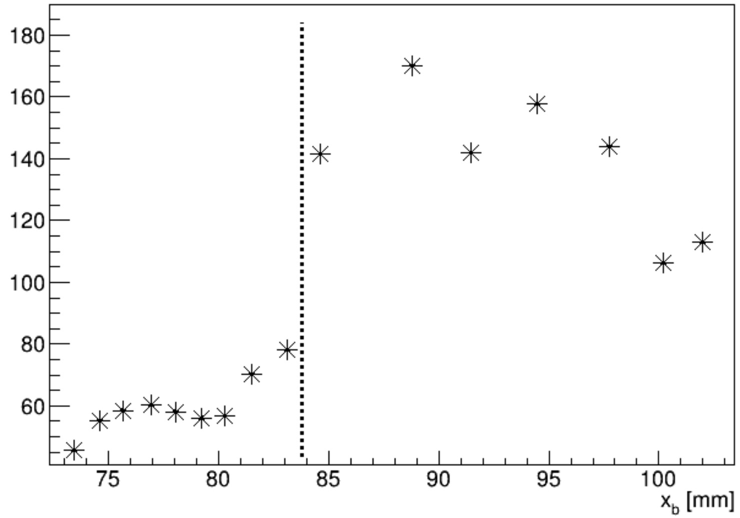
Drift velocity $\mathbf{v_D} = \boldsymbol{\mu}_e \mathbf{E}$





Measured velocity





Inside the nozzle: constant gas composition (near 100% helium) leads to linearity between **v** and **E**

Outside the nozzle: peak in **v** for increasing $\mathbf{N_2}$ concentration

Current measurements

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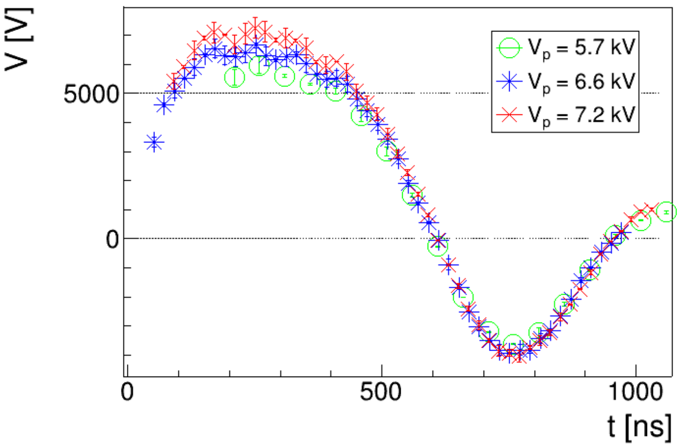
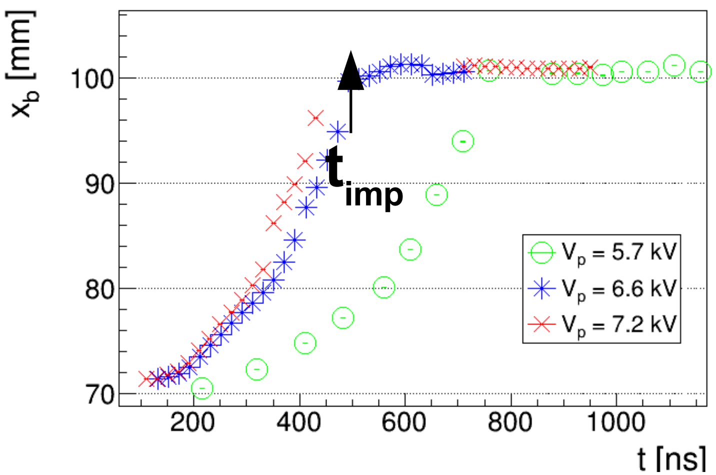
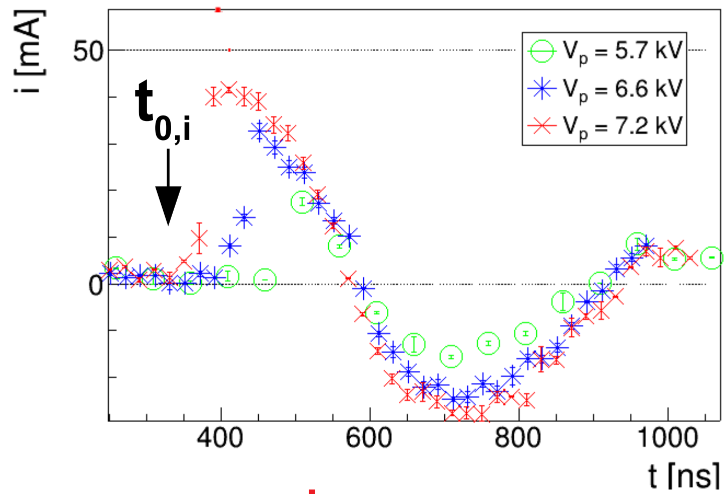
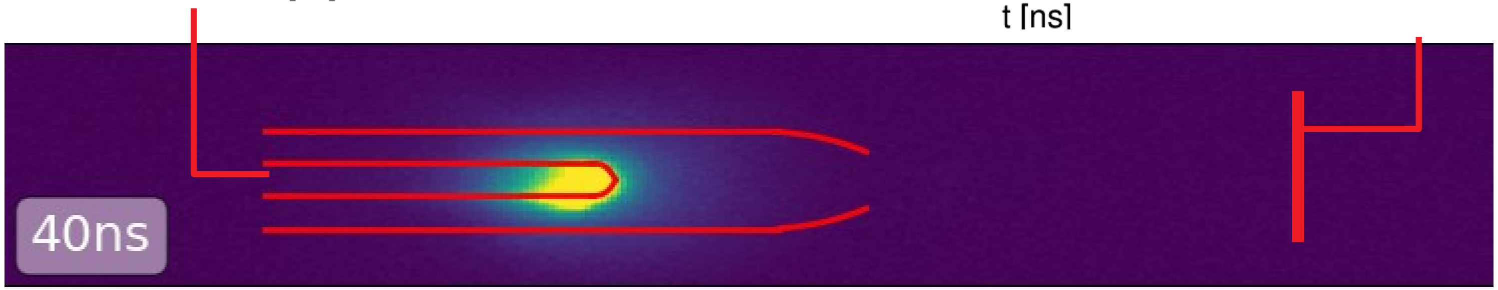
With a conductive target in front of the electrode: synchronization between voltage, fast camera and current measurements.









Current is measured before bullet impact
$t_{0,i} < t_{imp}$

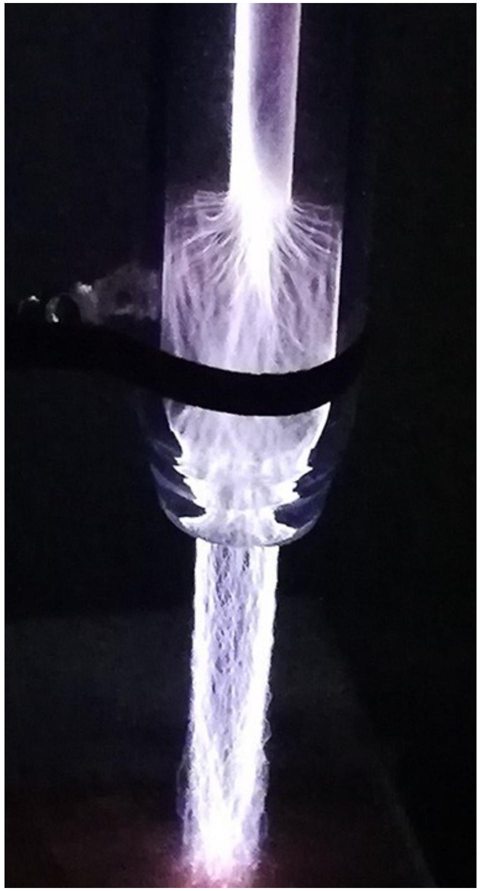
→

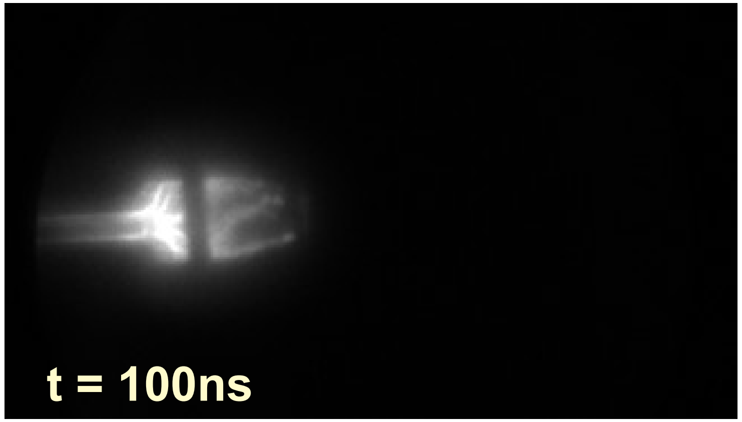
Hypothesis: there is a part of the bullet that does not emit at visible wavelength

Argon plasma

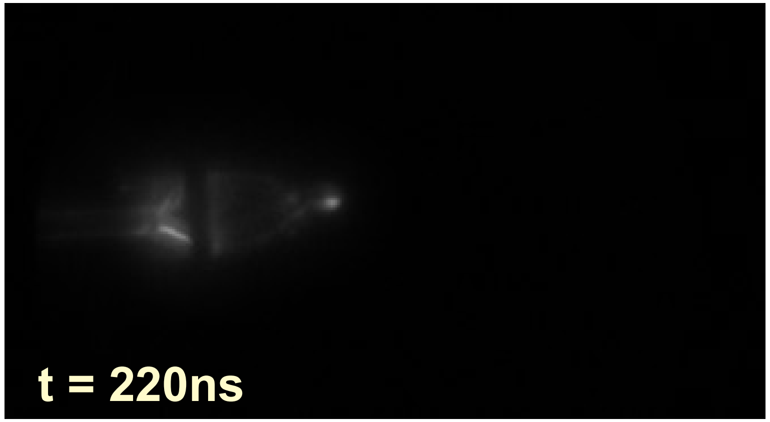
Argon plasma is hard to produce, a conductive grounded ring around the nozzle helps the process.

Once ionized, Argon produces filaments instead of bullets.





Argon filaments goes from the electrode to the end of the nozzle.



After a certain time there are tiny round shaped plasma formations going out from the nozzle.

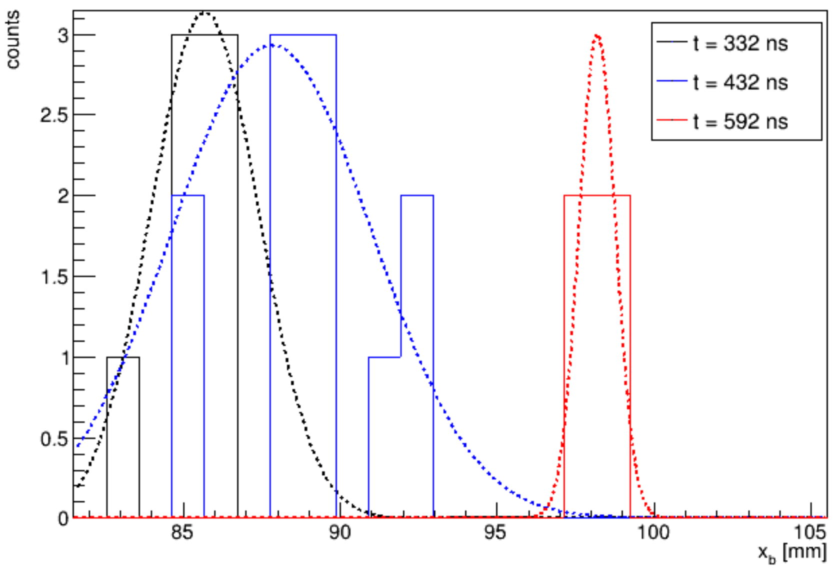
Is possible to study those formations as plasma bullets

Argon plasma
propagation

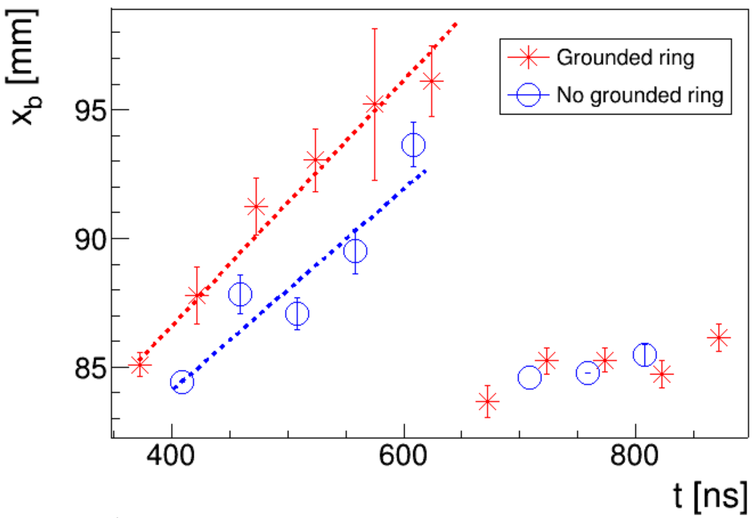
For each time, histogram for:

- <u>**positions**</u>
- **dimensions**

and are evaluated *average values*

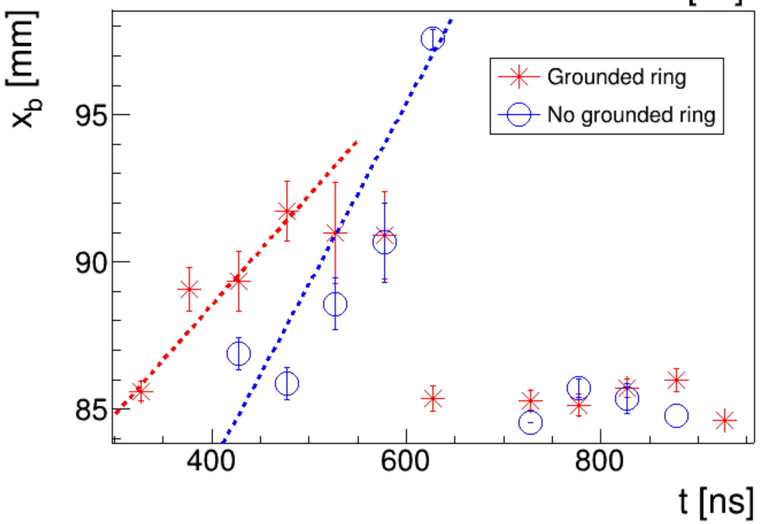


There is an average barycenter motion



Without target

$\mathbf{v_A = 47.9 \pm 4.9}$ **km/s**



With target

$\mathbf{v_A = 61.2 \pm 2.8}$ **km/s**

Conclusions and future development

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In conclusion in this work was:

- Developed the new PCC prototype.
- Guaranteed fine control over voltage output and low current intensities.
- Assured the presence of **ROS** and **RNS**, in different concentrations for different positions in plasma.
- Studied plasma propagation dynamics in different conditions: changing voltage peak value, neutral gas, neutral gas flow, distance from a target, typology of target.
- Plasma jet length, bullet velocity, current measurement are compared for Helium and Neon plasma, resulting that bullet velocity is correlated with electron mobility.

Future development

- Formulation of a model that could explain measurements and observations collected with this work.
- Further measurements, including the evaluation of the electric field around the electrode.

Thank you for your attention