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IONIZATION WAVE DYNAMICS OF A PLASMA JET IN CONTACT WITH A DIELECTRIC SURFACE

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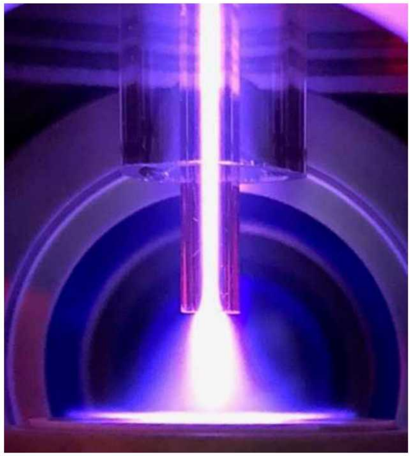
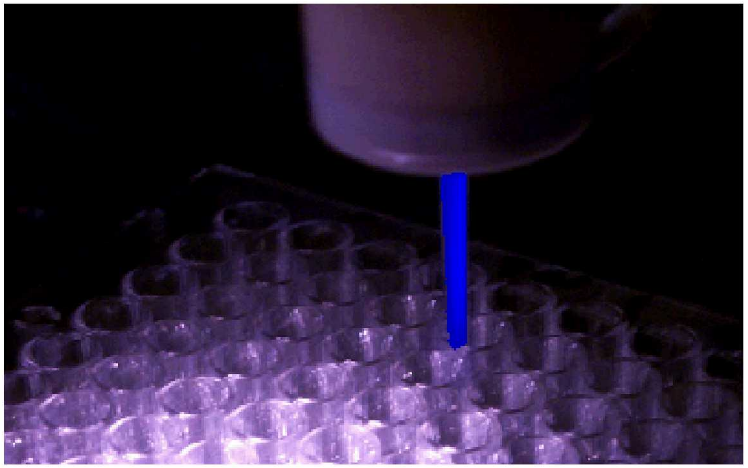
ATMOSPHERIC PRESSURE PLASMA JETS

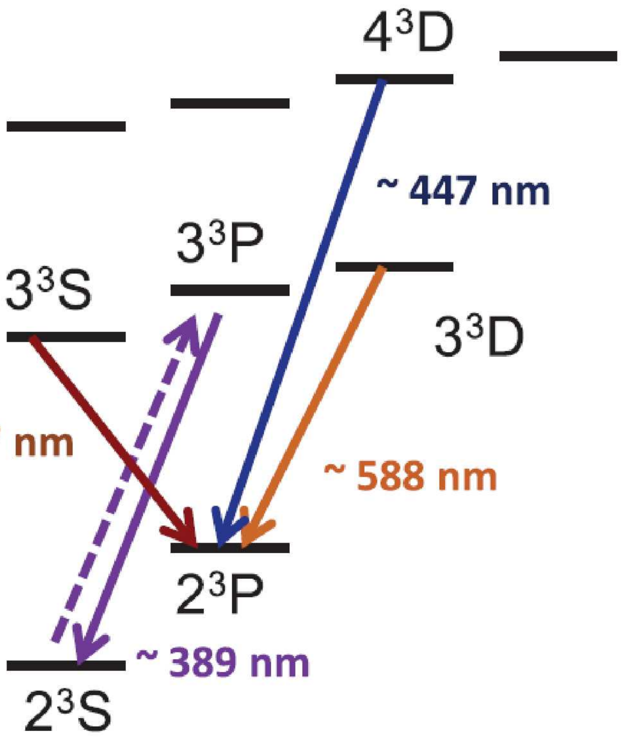
- **Atmospheric pressure plasma jets (APPJs) are a popular source of chemistry for biomedical applications.**
- **The plasma propagates as an ionization wave (IW) that is repetitively pulsed.**
- **The IW gives rise to reactive oxygen and nitrogen species (RONS) which produce the biological effect.**





S. Mohades, et al., Physics of Plasmas 22, 122001 (2015).

LASER COLLISIONAL INDUCED FLUORESCENCE (LCIF)



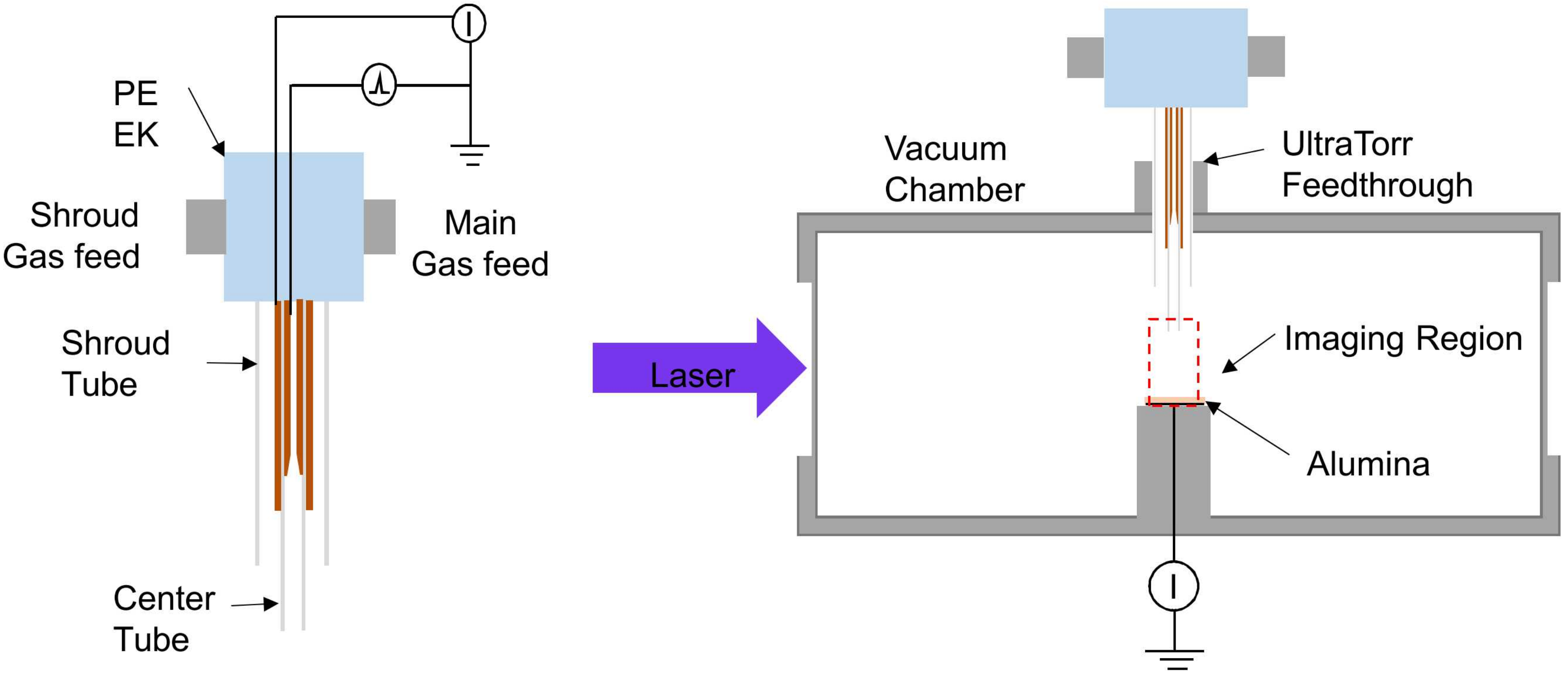
Barnat and Fierro, J. Phys. D: Appl. Phys., 50, 14LT01 (2017).

- **An ultrafast laser (<100 fs) is used to measure the electron density with a high time resolution.**
- **Electrons collide with laser excited He(3^3P)**

$$e + He(3^3P) \rightarrow He(3^3D) + e$$

- **n_e ~ 588 nm / 389 nm**
- **Sufficient He(2^3S) density is critical for accurate LCIF data.**
- **LCIF was developed for a pure He environment, but extending this diagnostic to mixtures is important for APPJs.**

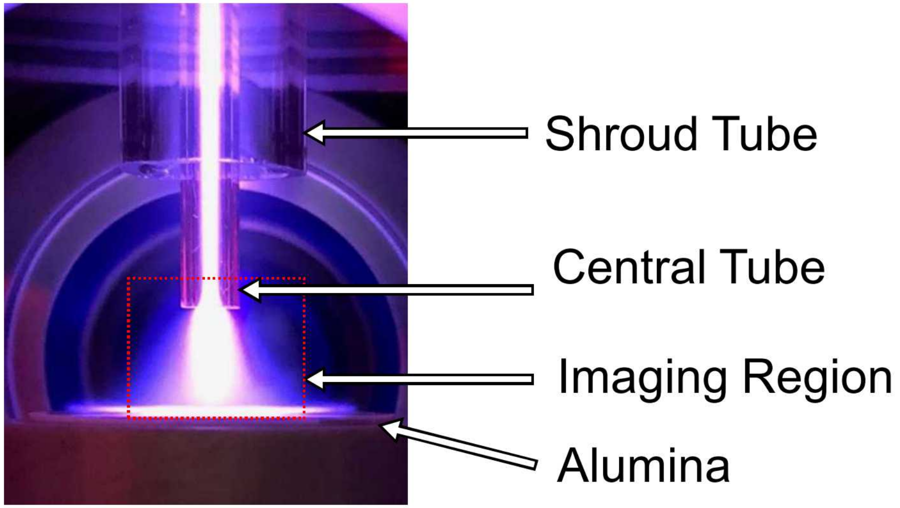
EXPERIMENTAL SETUP

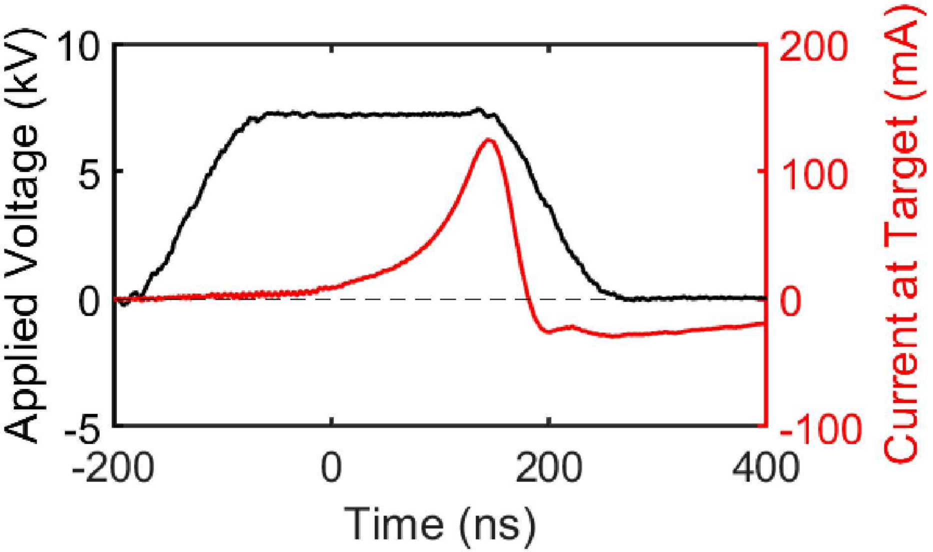


- **Annular powered electrode within the center tube**
- **Placing the APPJ in a vacuum chamber - consistent and controlled chemistry, ground planes, and gas flow.**
- **Coaxial tube allows a gas shroud – control environment independently of gas in main jet.**

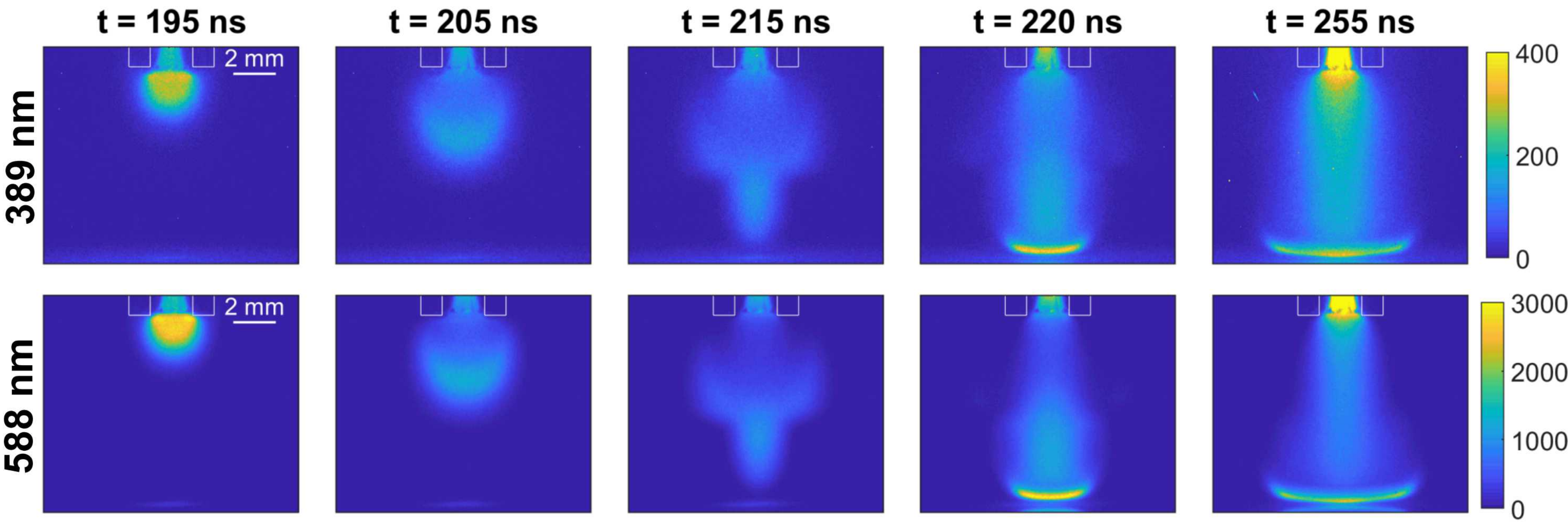
BASE CASE

- **+6 kV**
- **430 ns pulse, 100 ns rise**
- **200 Torr**
  - **Faster dynamics (for modeling)**
  - **Lower background LCIF signal (for experiment)**
- **500 sccm He in center tube**
- **Base pressure 20 mTorr**
- **Gap to target = 7.5 mm**
- **65 µm thick alumina disk**
- **Current measured at ground electrode under the alumina.**



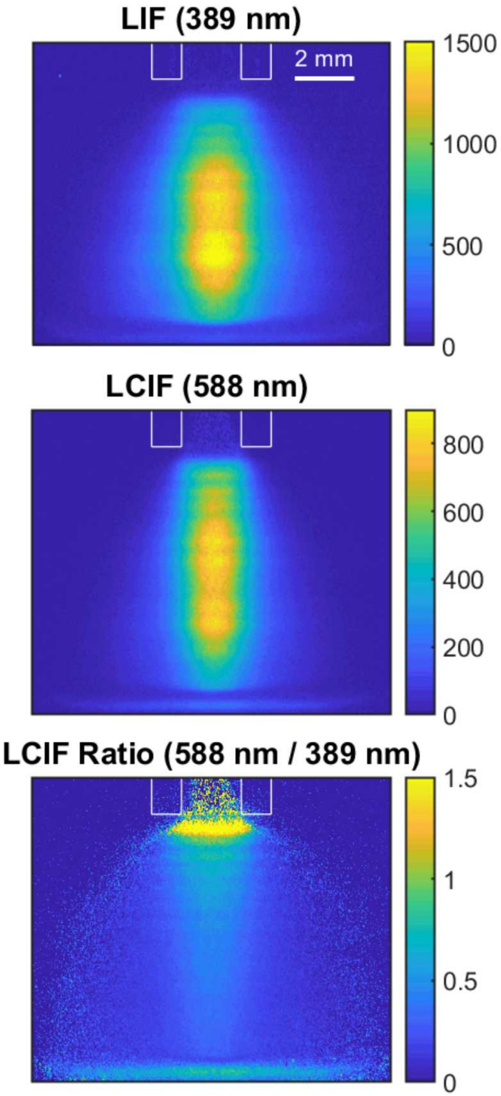


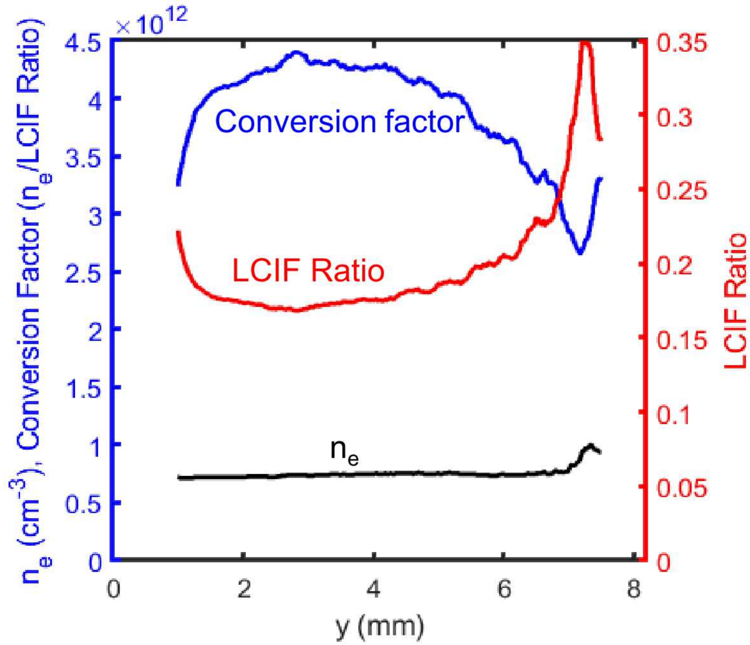
BASE CASE – PLASMA EMISSION



- 5 ns ICCD gate
- Ionization wave expands as it exits the tube.
- Approaching the alumina, it becomes more directed.
- Upon contacting the alumina, forms a surface IW (SIW) and spreads, charging the surface.
- As voltage falls, there a restrike occurs.

CONVERT LCIF TO n_e



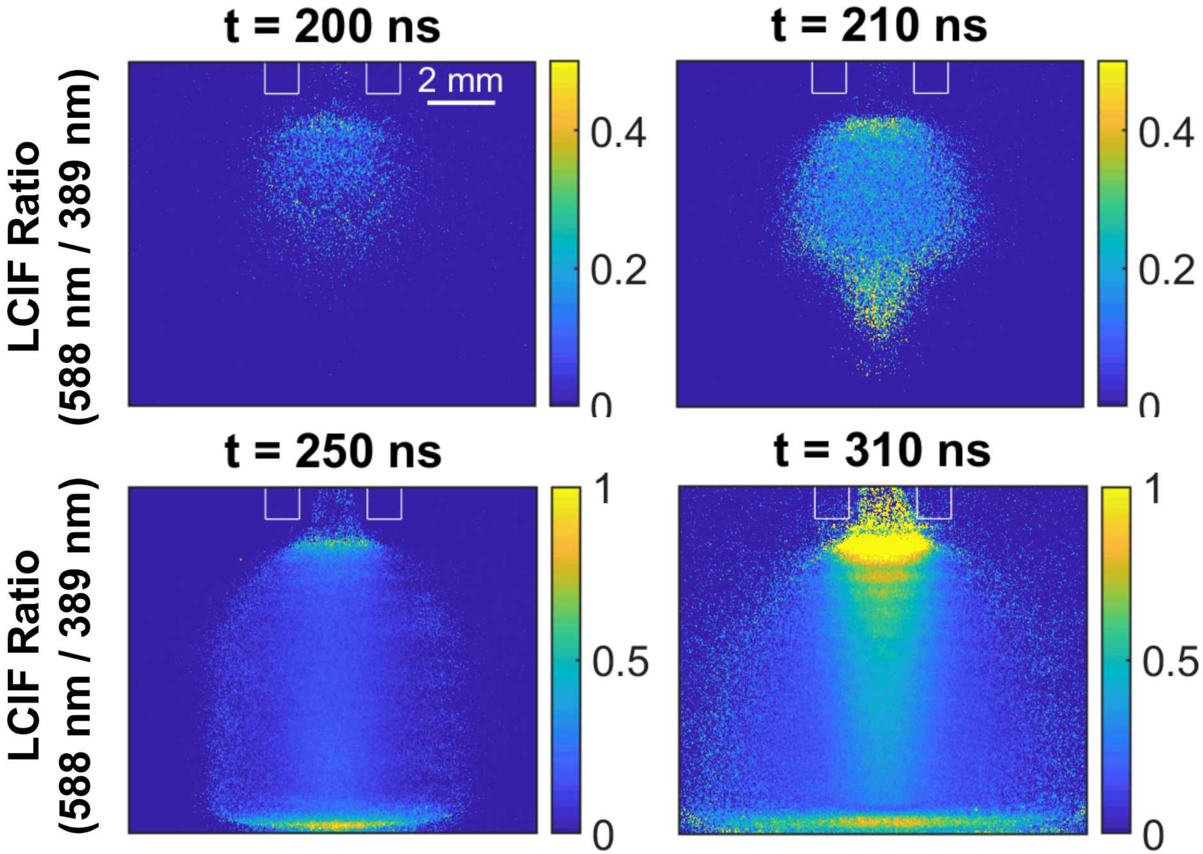


- **Calculate n_e using Ohm's law and measured E/N.**

$$I = \frac{e^2}{m_e}\frac{N}{\nu_m}\frac{E}{N}n_e A$$

- **An LCIF ratio of 1, is approximately 4 x 10^{12} cm^{-3} electrons.**
- **Previously, conversion factor estimated at 1.5 x 10^{13} cm^{-3}.**

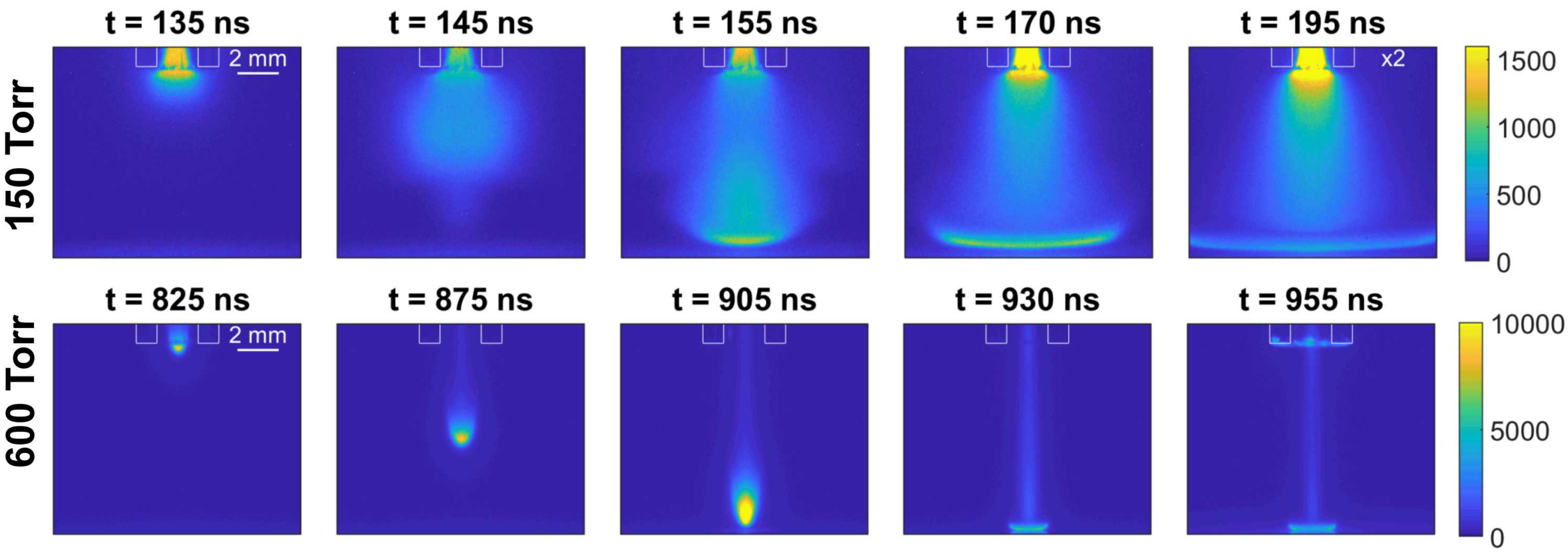
BASE CASE LCIF



- **+6 kV, 430 ns**
- **Pure He, 200 Torr**

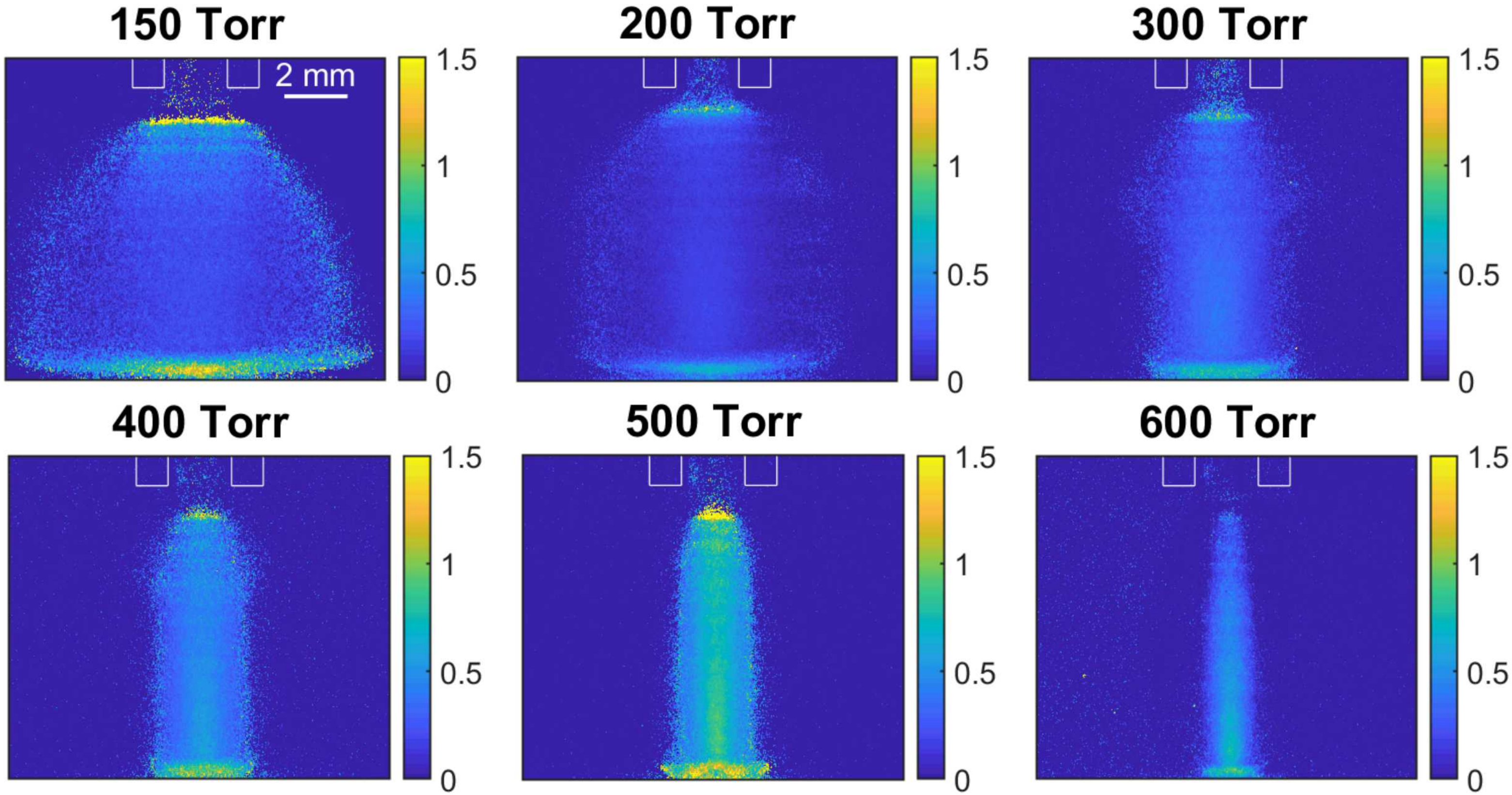
- **Before IW reaches the surface, He(2^3S) densities are low.**
- **n_e in the SIW is nearly double that of the bulk.**
- **Elevated n_e in IW front may be due to Stark mixing.**

VARY PRESSURE – EMISSION



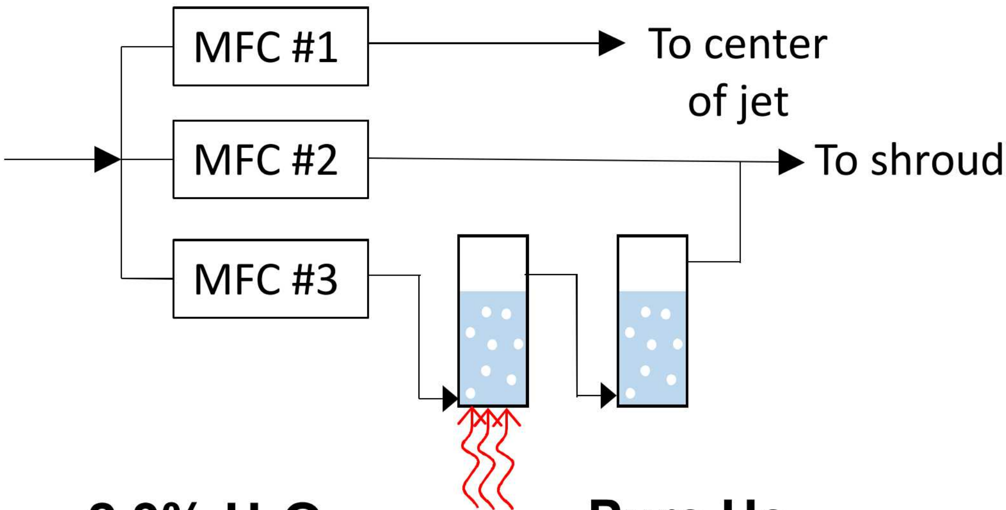
- 6 kV, 500 sccm He, 390 nm plasma emission
- Varied pulse duration so that voltage on for 80 ns after contact.
- Increasing pressure reduces electron mobility, preventing the IW from spreading as it exits the jet.
- IW propagates much slower for higher pressures.
- SIW becomes thinner at higher pressure.

VARY PRESSURE – n_e



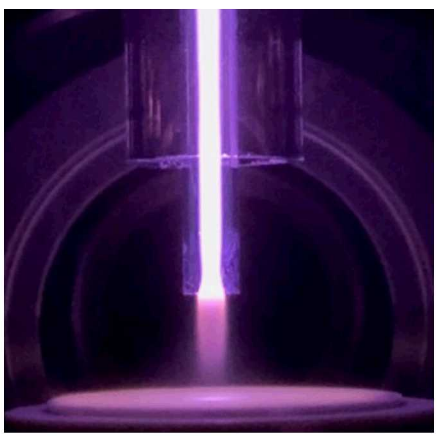
- 6 kV, 500 sccm He, 30 ns after IW contacts surface.
- Plasma is more confined at higher pressure, n_e increases.
- Current and energy deposition outside of the tube decrease with increasing pressure.
- Above 500 Torr, n_e is collisional enough that ionization rate drops.

HUMID He SHROUD

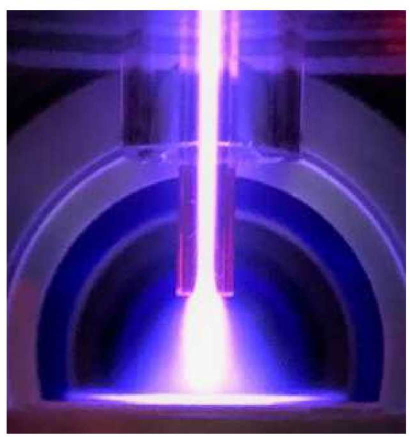


- **Humid He shroud allows an investigation of molecular gasses surrounding the jet, without interfering with LCIF measurements.**
- **First bubbler oversaturates water vapor, second bubbler removes excess.**
- **Temperature of second bubbler determines humidity of gas.**

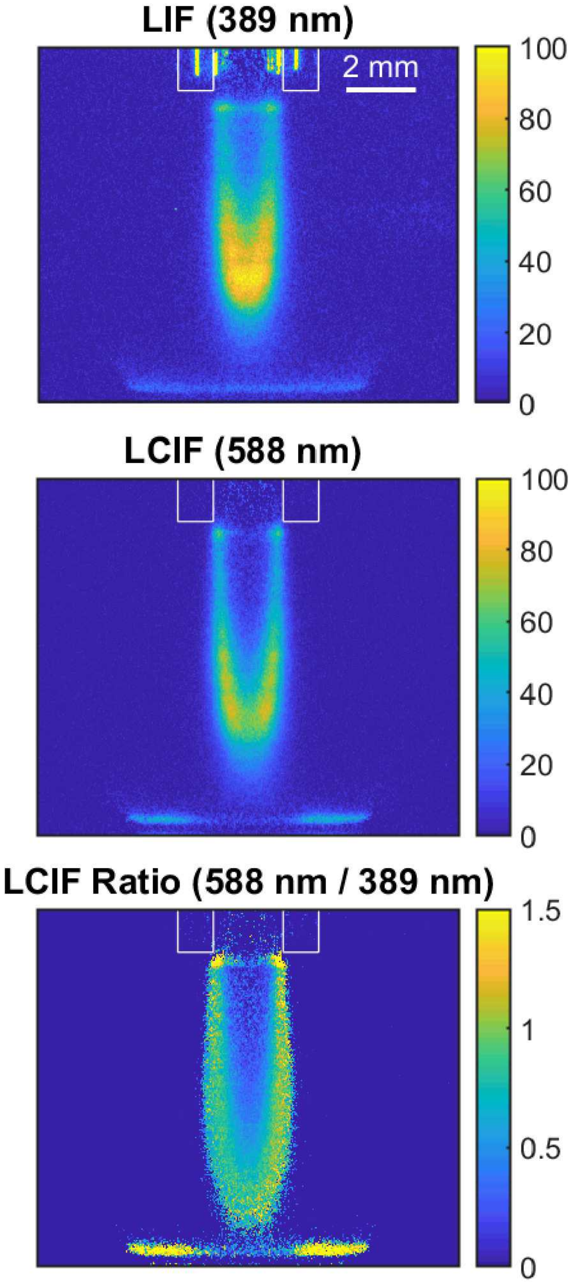
2.3% H_2O in shroud



Pure He (base case)



HUMID He SHROUD

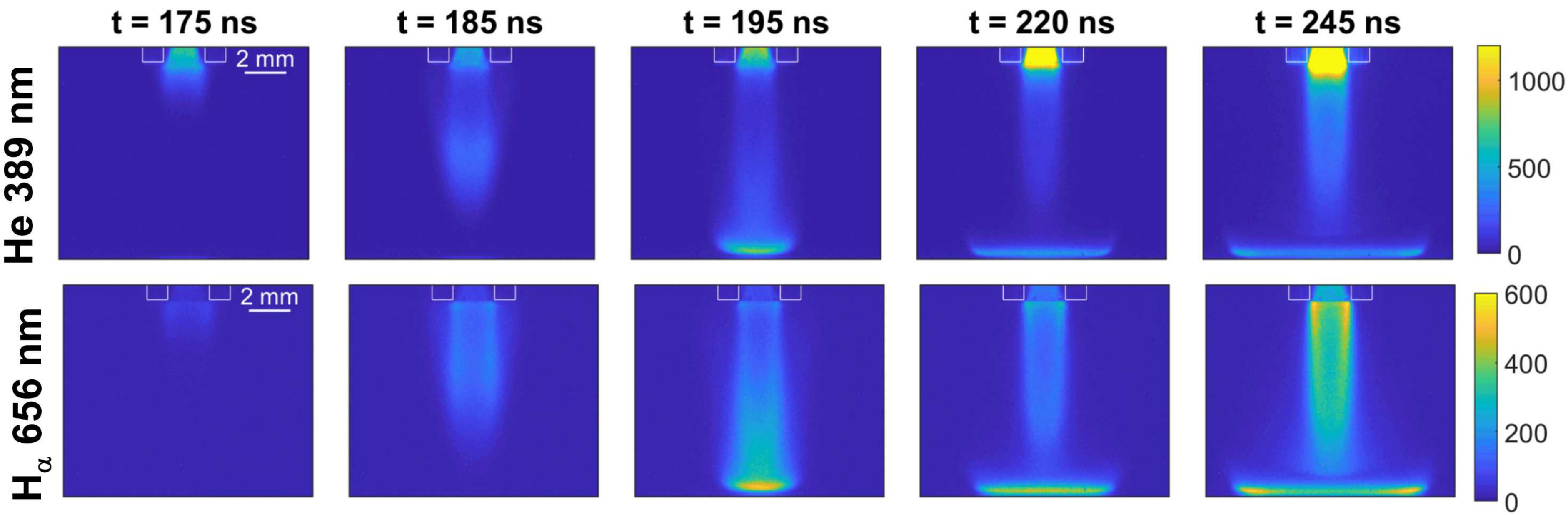


- 6 kV, 430 ns pulse
- Center: 500 sccm He
- Shroud: 500 sccm He/H_2O = 97.7/2.3
- t = 230 ns, 30 ns after IW contacts surface
- Moving away from He core, there are fewer He(2^3S), LIF signal decreases.

$$He(2^3S) + H_2O \rightarrow He + H_2O^+ + e$$

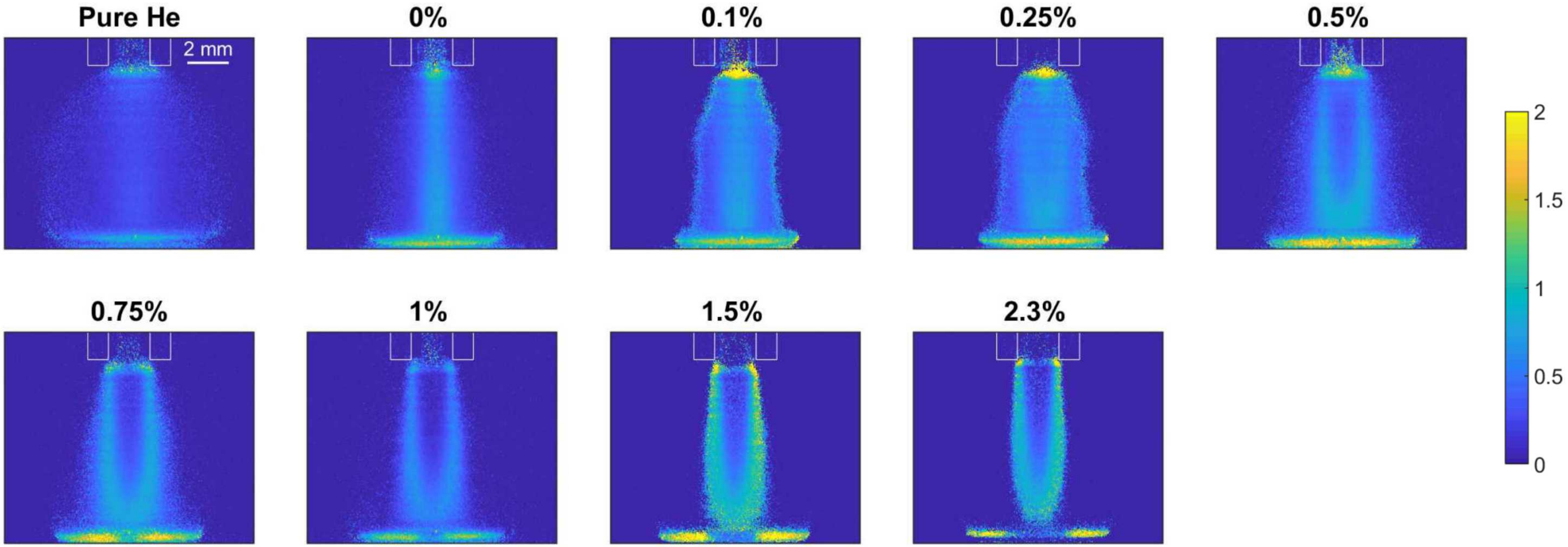
- In regions of high H_2O concentration, there may be significant ne which is not detectable due to low He(2^3S).

HUMID He SHROUD EMISSION



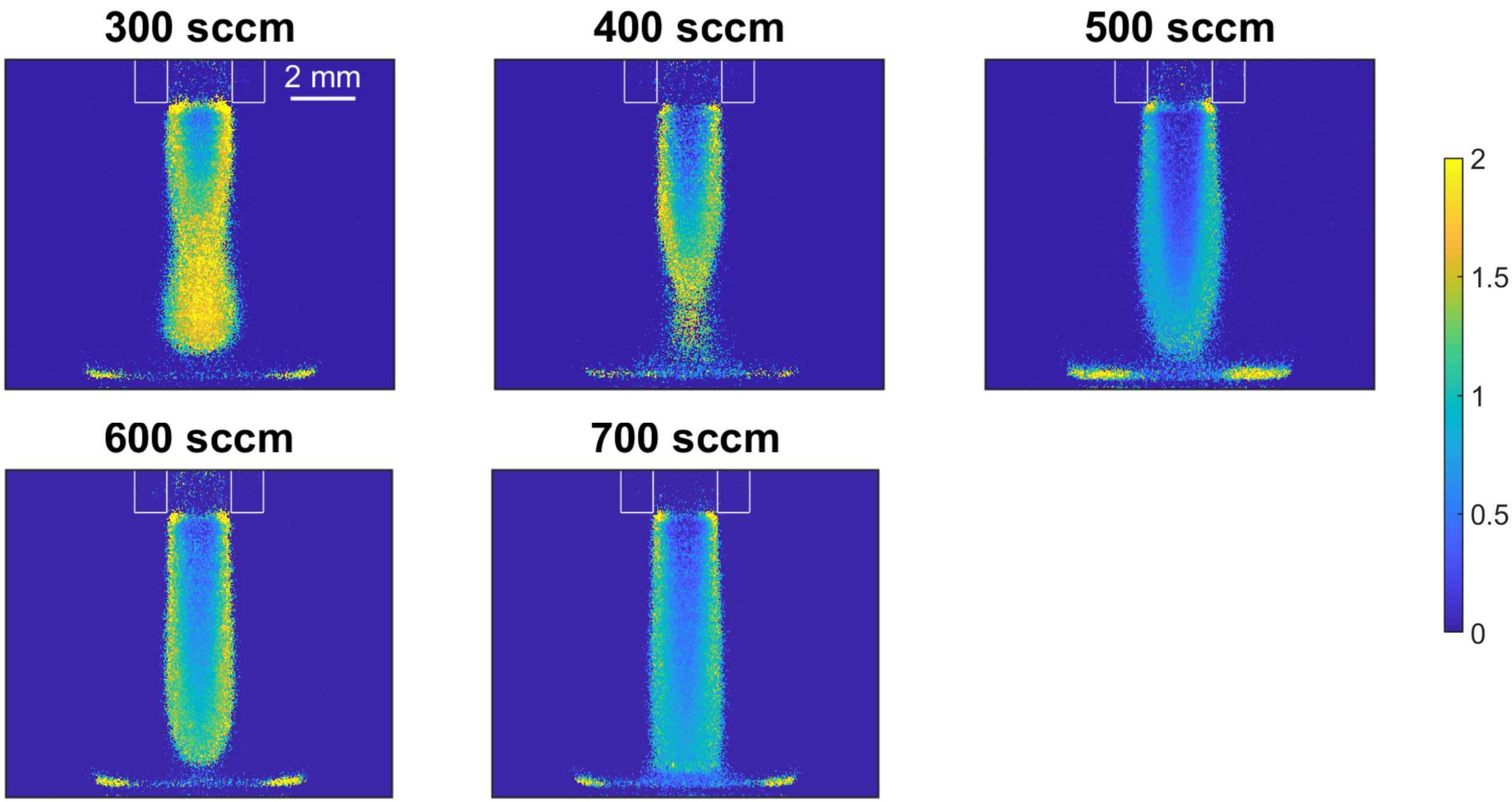
- 2.3% H_2O in shroud
- IW reaches outlet of the tube earlier than in base case – photoionization from He_2* causes non-local seed ionization.
- Photoionization and Penning ionization promote IW speed.
- H_α emission appears more annular – dominates at the interface of the center and shroud flow.

SHROUD HUMIDITY



- 30 ns after IW reaches surface.
- Transition from diffuse in pure helium case to confined by humid shroud.
- Higher electron energy loss rates with H_2O because of vibrational and rotational excitation.
- n_e increases with humidity due to Penning ionization.

VARY He FLOW RATE - n_e



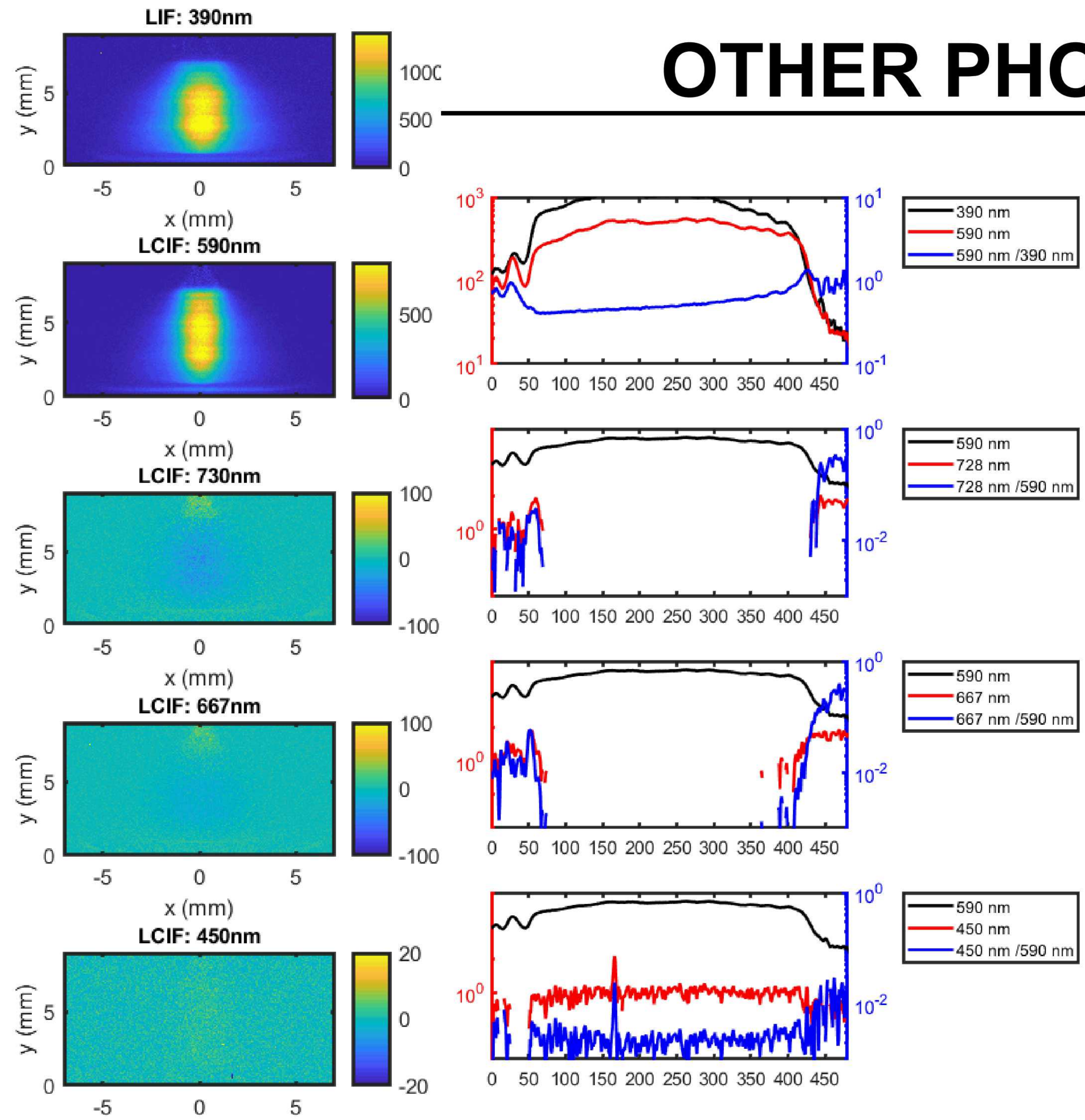
- Vary center flow rate. Shroud: 500 sccm, He/H_2O = 98.7/2.3
- Higher He flow rates more rapidly convect in-diffusing H_2O.

CONCLUDING REMARKS

- A plasma jet interacting with a dielectric surface produces a surface IW as it charges the dielectric.
- Molecular gases surrounding an APPJ confine the IW due to a lower electron mobility and higher electron energy loss rates.
- In the presence of H_2O, the IW speed increase, and the plasma and electron density become more annular.
- LCIF can be used in humid He, as long as the He(2^3S) density is sufficient.

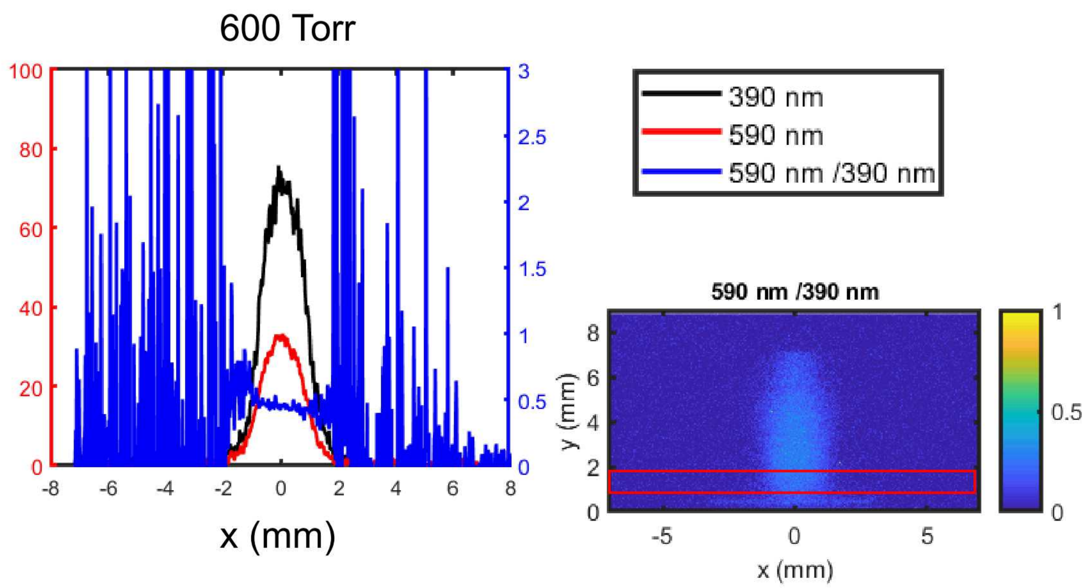
Appendix

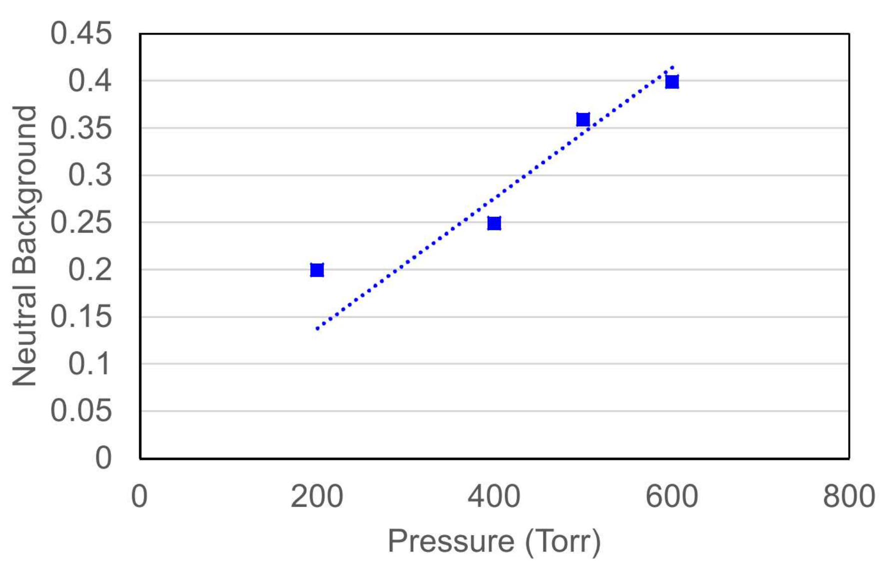
OTHER PHOTONS



- **t = 310 ns**
- **730 nm and 667 nm are consistently negative (depletion of He2^{3}S by laser?)**
- **Ratios indicate E/N ~ 2 Td**

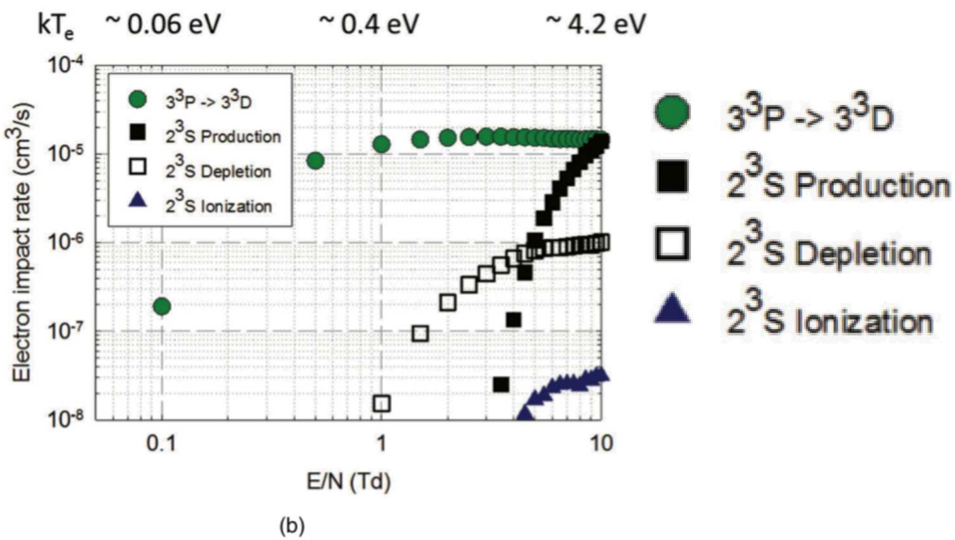
NEUTRAL BACKGROUND

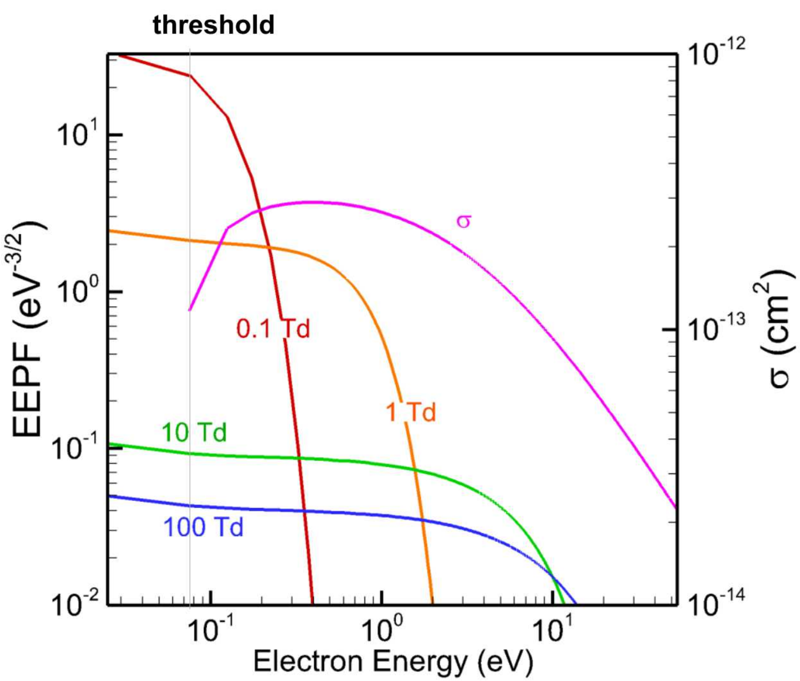




- **There is some portion of the LCIF signal which is caused by collisions with the background He gas.**
- **Should be proportional to pressure.**
- **Images take >4.5 μs after pulse ends.**
- **In the late afterglow electrons are thermalized and no longer contribute to LCIF.**

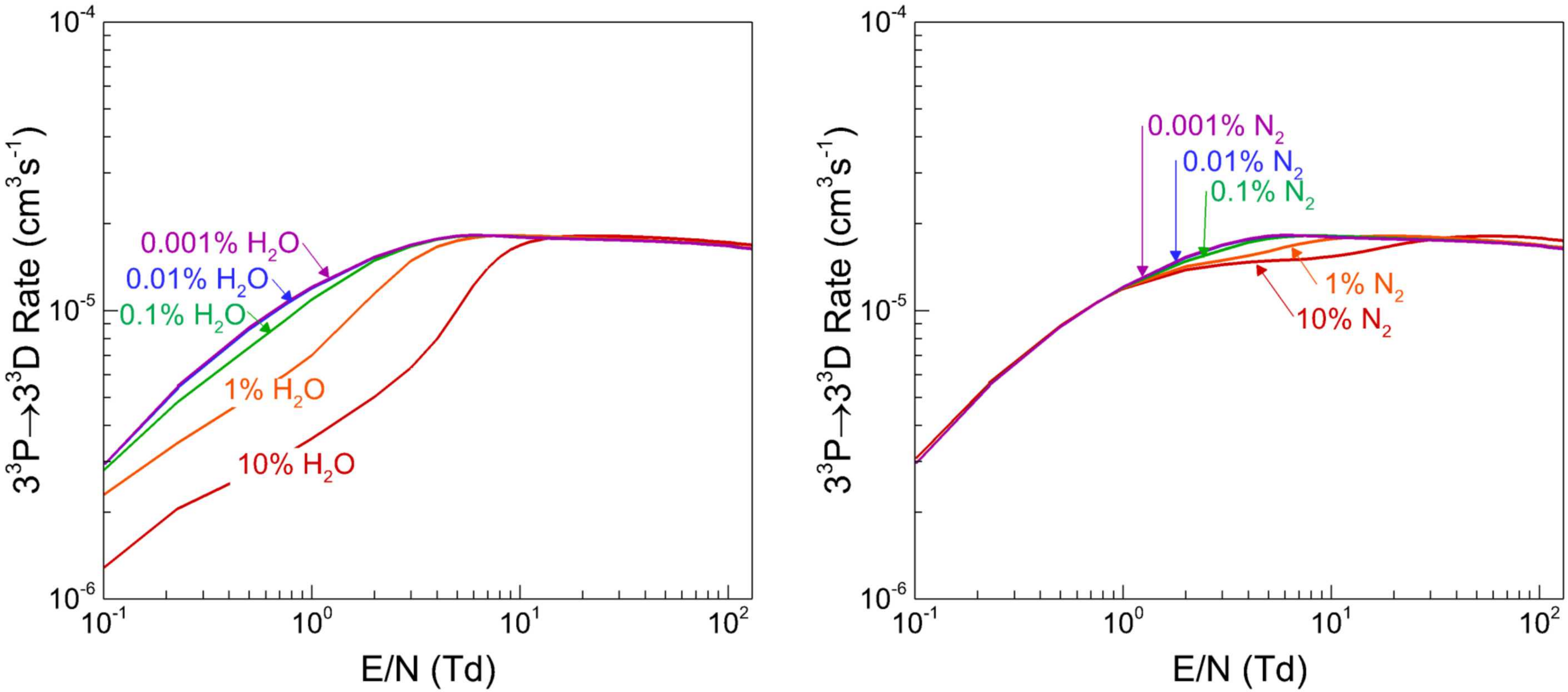
BOLTZMANN CALCULATIONS





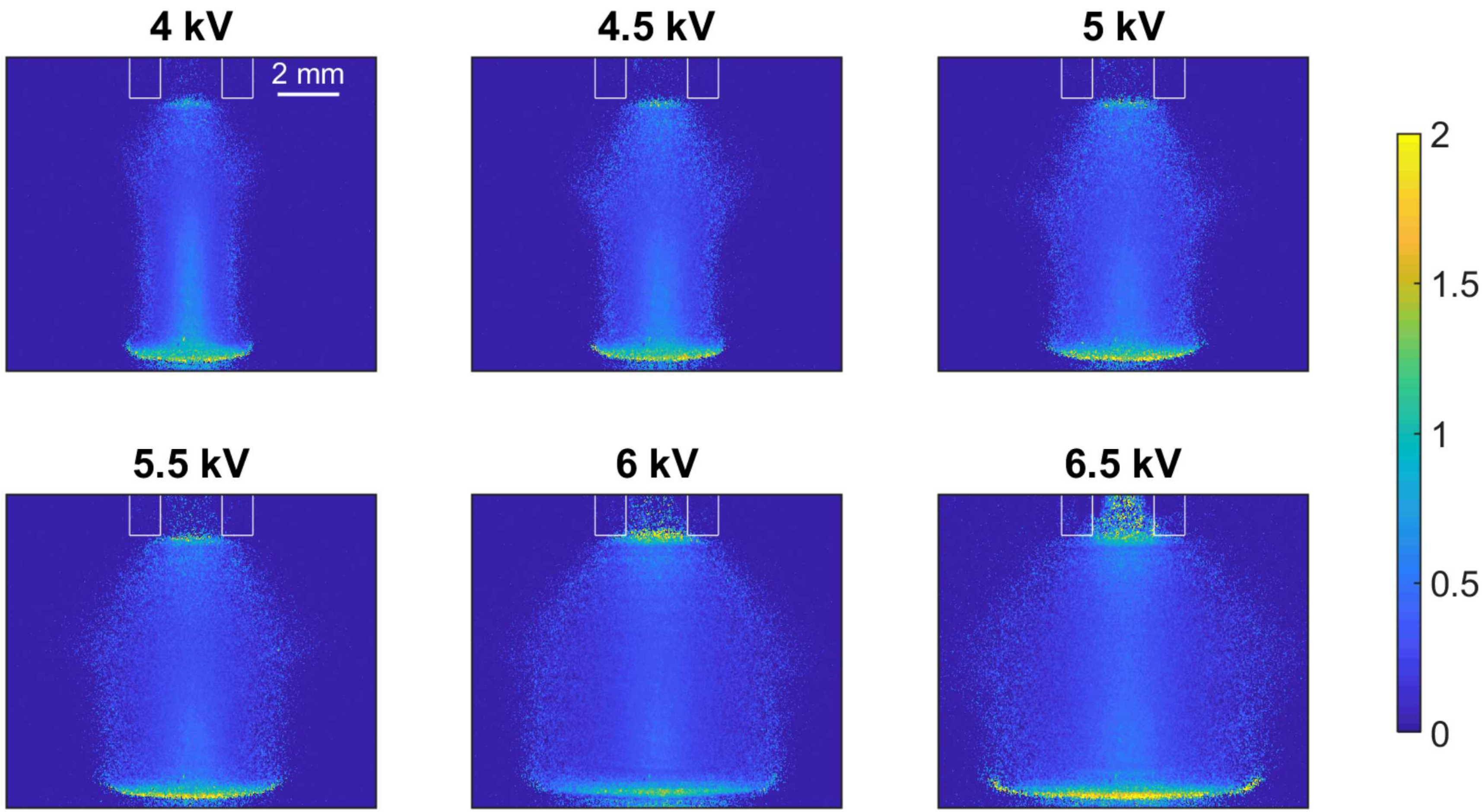
- **For LCIF measurement to be a linear representation of n_e, rate of $3^3P \rightarrow 3^3D$ must be independent of T_e.**
- **In pure He, this occurs when E/N > ~ 0.8 Td**
- **Threshold = 0.06 eV**

BOLTZMANN CALCULATIONS



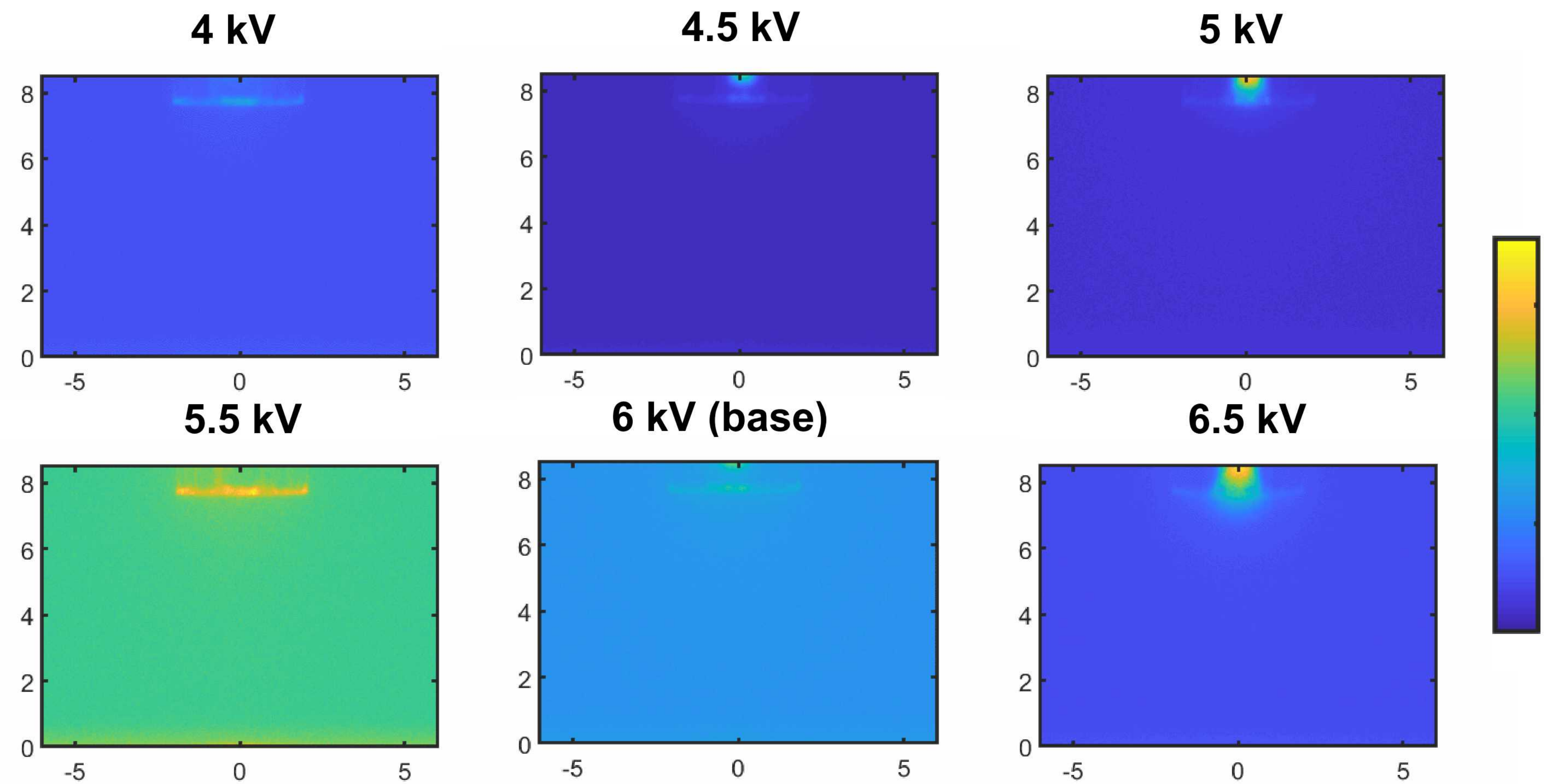
- **Cross section set to 0 for E < 0.15 eV**
- **For H_2O < 1%, LCIF is valid ~ 1 Td**
- **For all N_2 concentrations, LCIF is valid for > 0.8 Td**

VARY VOLTAGE – n_e



- LCIF ratio 30 ns after IW contacts surface.
- SIW spreads more rapidly for higher voltage, but n_e is only slightly higher.

VARY VOLTAGE – Emission

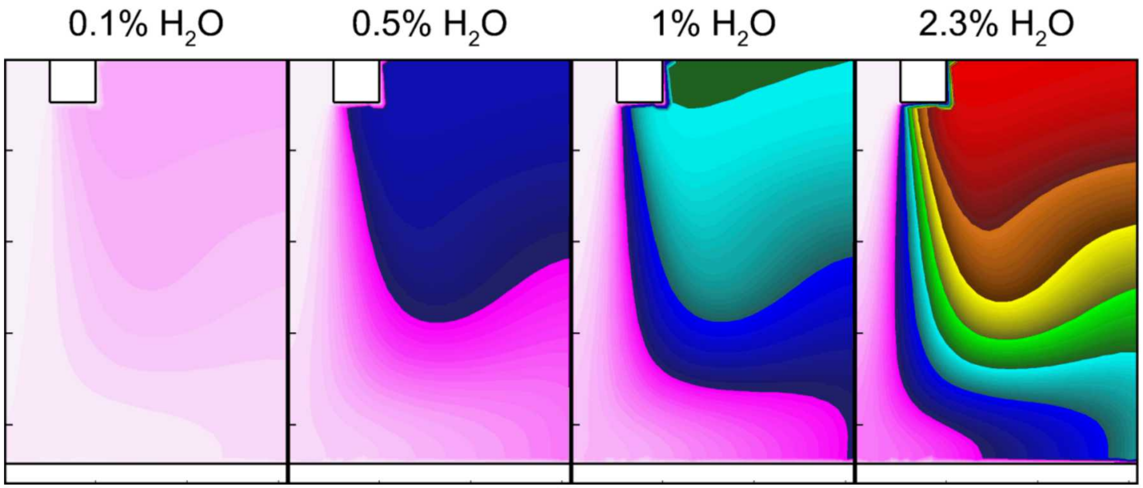


- **Pure He, 500 sccm**
- **Bubbler installed (leak rate slightly higher)**
- **250 ns animated**
- **390 nm emission**
- **20180410, 20180411, 6kV on 20180403**

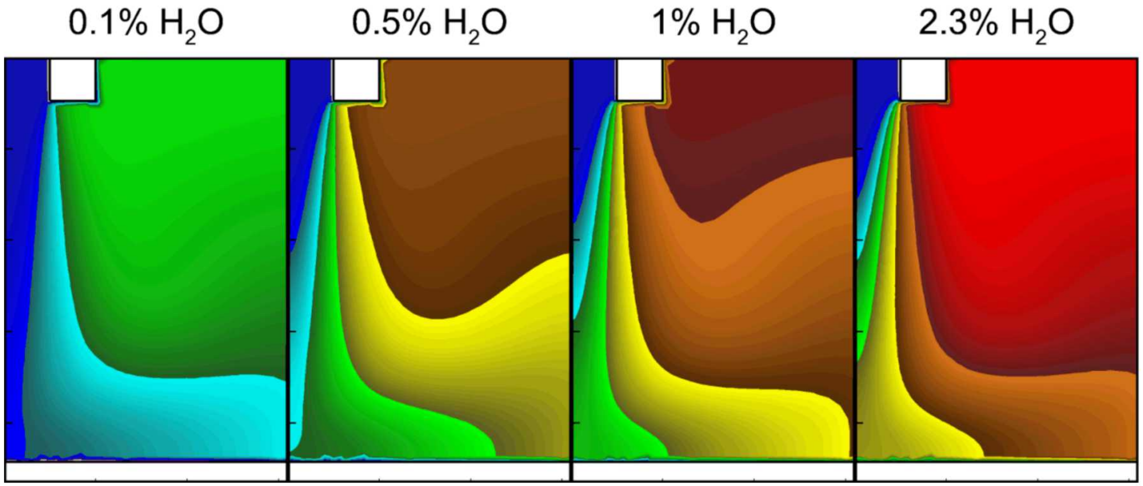
VARY SHROUD HUMIDITY

- **24 ms fluid simulation**
- **Region of high ne does not correspond to a particular % H_2O**
- **Chemistry and electron energy losses change with % H_2O, but mobility changes very little**

H_2O - 2.3% (linear)

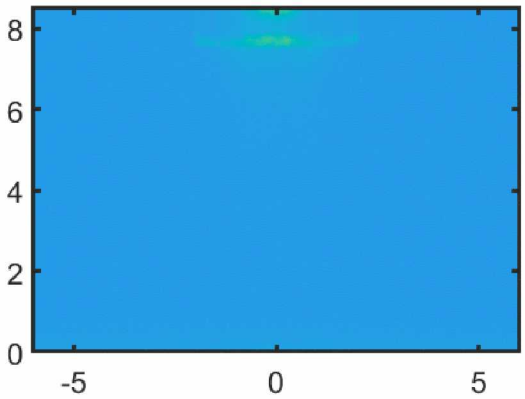


H_2O - 2.3% (3-dec)

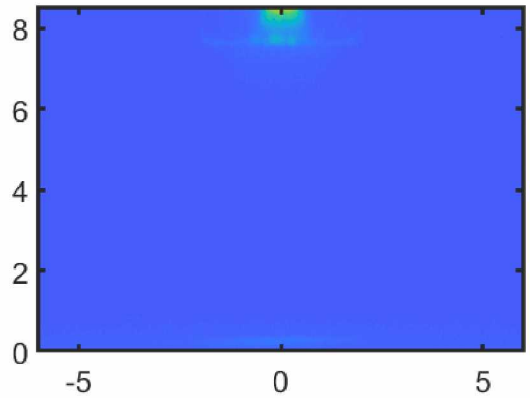


Emission - Vary Shroud Humidity

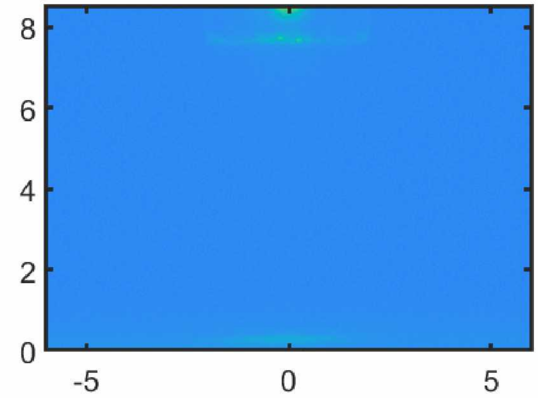
2.3% H_2O



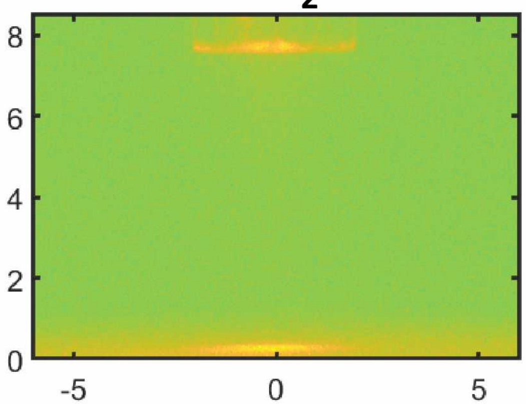
1% H_2O



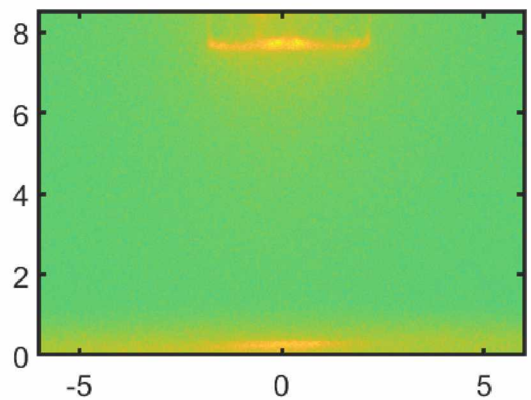
0.5% H_2O



0.1% H_2O

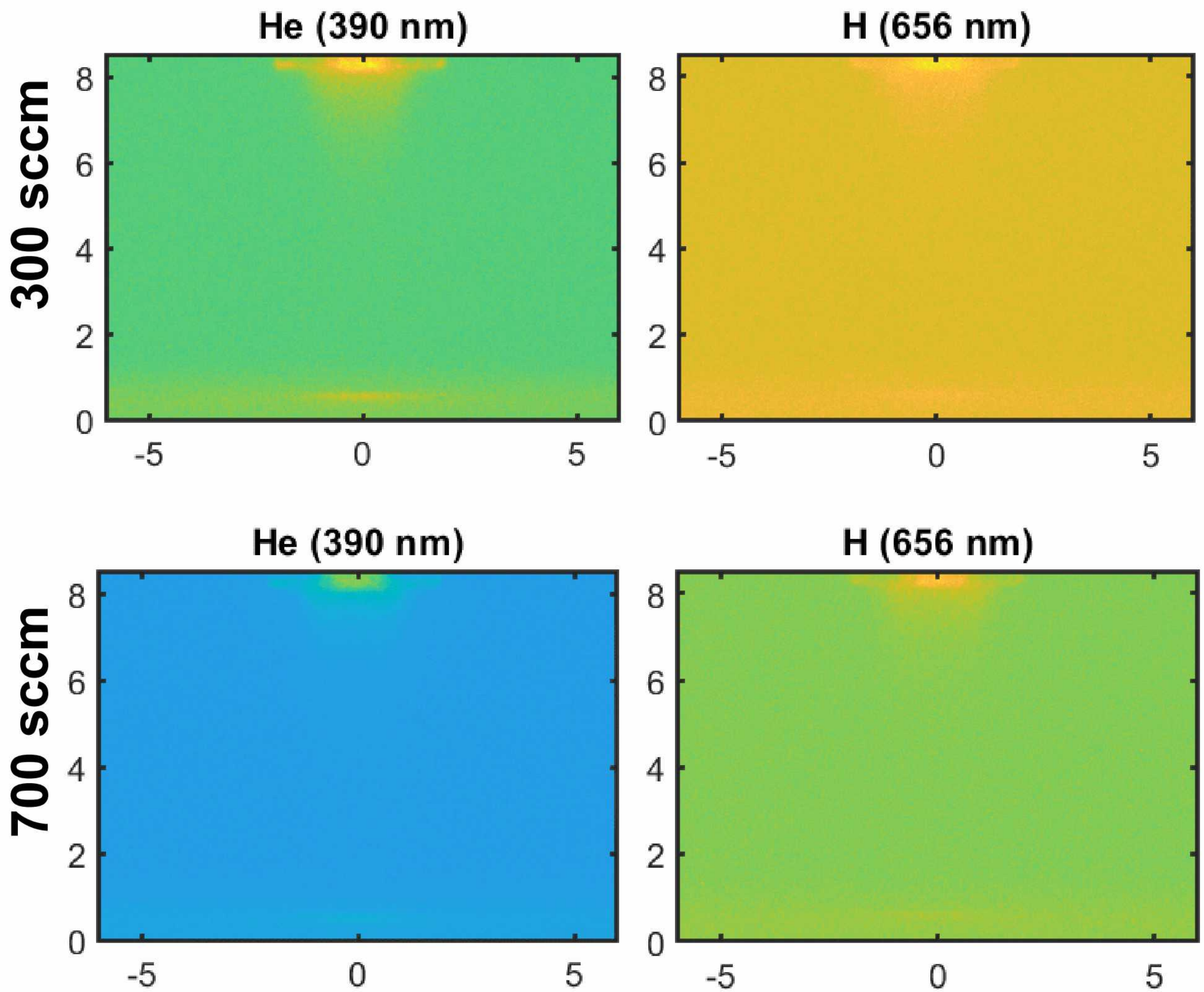


Pure He



- **390 nm emission, 250 ns animated**
- **IW propagates across the gap faster for higher H_2O – penning ionization, photoionization**
- **SIW spreads less rapidly for higher H_2O**
- **20180404 (2.3%), 20180327(1%,0.1%,pure He), 20180329 (0.5%)**

VARY He FLOW RATE – EMISSION



- 250 ns animated
- OH emission was not visible – UV filter has lower efficiency, camera is less sensitive
- H_α is much more accessible
- H_α emission is more annular at greater distances for 700 sccm