Calorimetry and Imaging of Plasma Produced by Nanosecond Discharges

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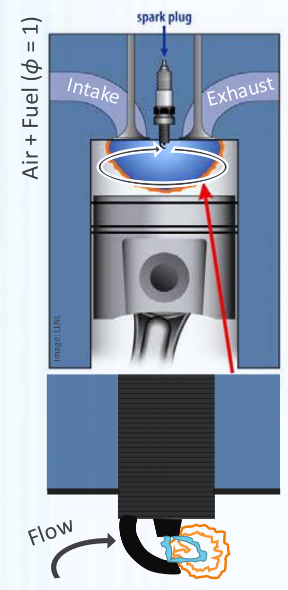
Establishing flame kernel is the key to stable engine operation in spark ignition engines



Dilution of the intake charge with **air** or **exhaust gas** (EGR) has many benefits:

↑ γ ($\eta_{Otto} = 1 - 1/CR^{\gamma-1}$) | ↓ T_{flame} (↓ NOx) | ↓ T_{bulk} (↓ Heat Loss) | ↑ η_{vol} (↓ Pumping Loss)

But dilution comes at the cost of: ↓ S_L (↓ Flame growth) | ↑ COV_{IMEP} (↓ Stability) | ↓ T_{ad} (↑ UHC)

Non-equilibrium plasma ignition systems aim to extend dilution tolerance: potential efficiency gain >15% + reduced emissions

Non-equilibrium plasma discharges lead to ultra-fast dissociation and gas heating due to high-energy electrons

Equilibrium plasma — **Low electron energies:** Elastic energy transfer leads to thermal-equilibrium gas heating. T(electron) ~ T(gas).

Non-equilibrium plasma — **High electron energies:** Energy transfer mechanism depends on electron energy (via E/N). T(electron) >> T(gas).

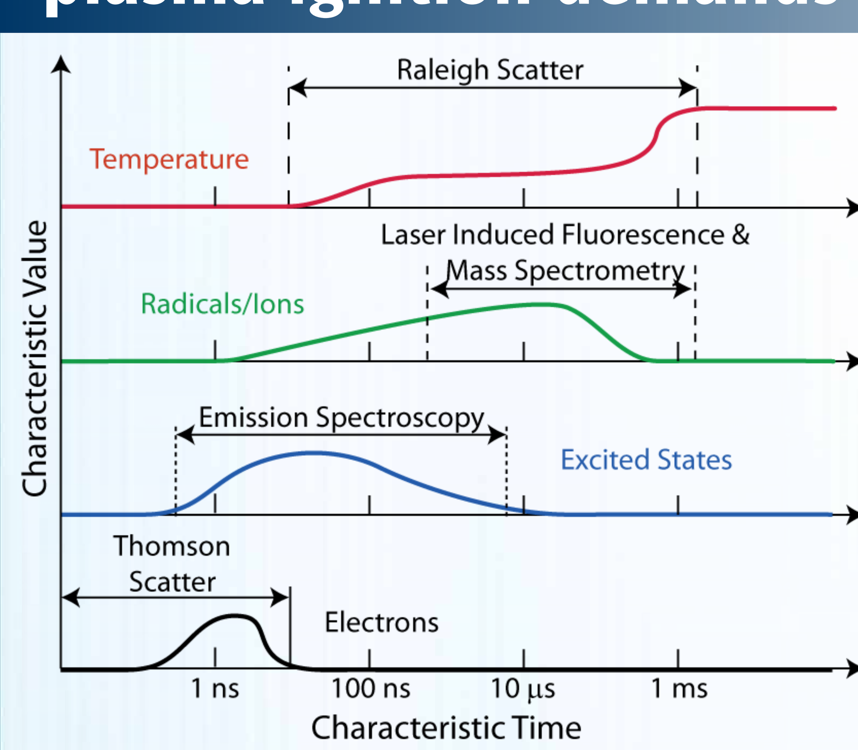
Discharge Energy → Ultrafast dissociation of species; Ultrafast gas heating; Ultrafast increase of vibrational energy → Slow gas heating

Ultrafast phenomena — T_{pulse} (ns) | Slow phenomena — T_{VT} (μs to ms)

V-T relaxation time depends on N (= P/k_BT)

Our focus: non-equilibrium plasma generated by high-voltage nanosecond discharges

Wide range of time scales in non-equilibrium plasma ignition demands suite of diagnostics



Schlieren: density gradients
Rayleigh scatter: temperature, density

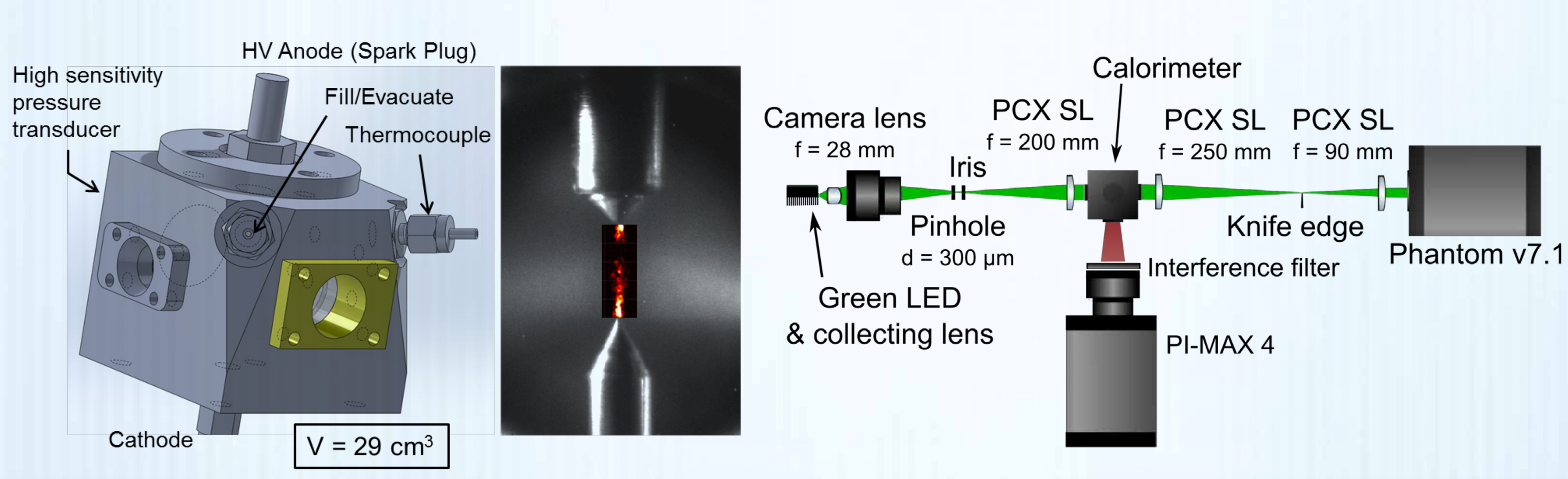
Laser-induced fluorescence: O-atom, OH, NO
Absorption: O_3

Emission spectroscopy: Vib./rot. temp. (N2)
Filtered imaging: *O*, N_2**

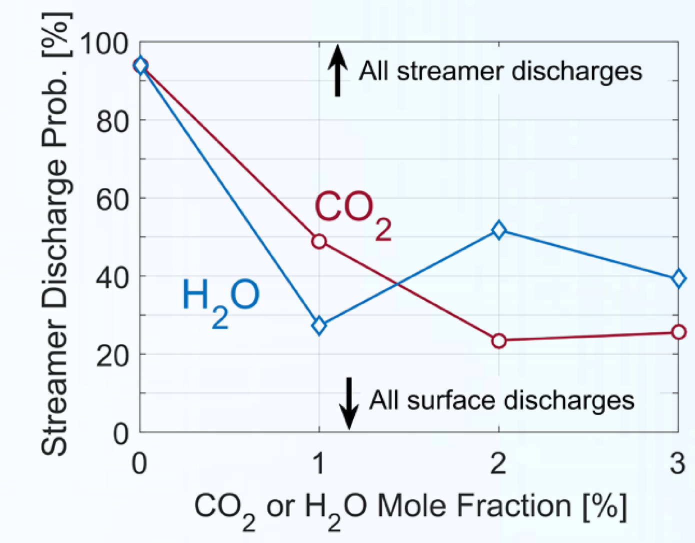
Thomson scattering: electron temp., number density
Interferometry: electron number density
Plasma modeling: BOLSIG+

Our recent work has focused on fundamental experiments at elevated densities

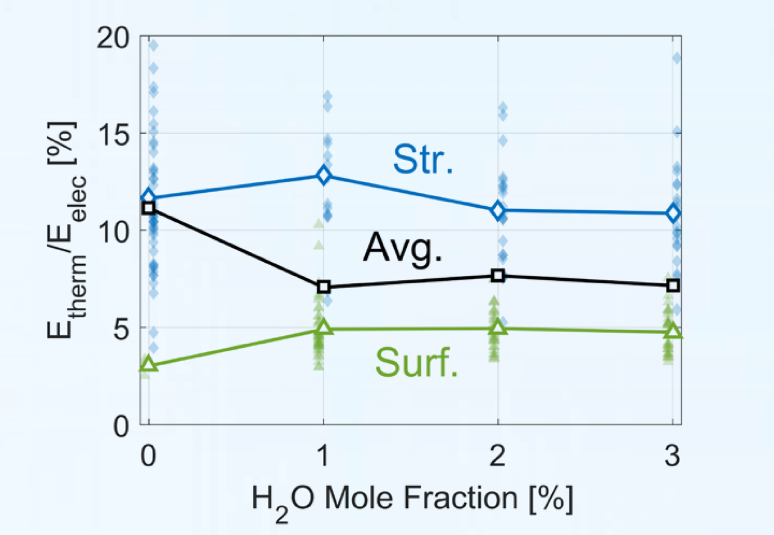
- 15.9% O_2 (held constant)
- Varied CO_2 and H_2O
- Major EGR constituents
- T = 70 °C
- P = 2.8 bar
- ρ = 2.9 kg/m³
- V_{peak} = 20 kV, I_{peak} = 185 A
- E_{pulse} ~ 5 mJ
- Rise time = 5 ns, FWHM = 12 ns



Increasing CO_2 or H_2O leads to increased propensity for surface discharge



Surface discharges along the ceramic insulator are undesirable: poor heating and radical production



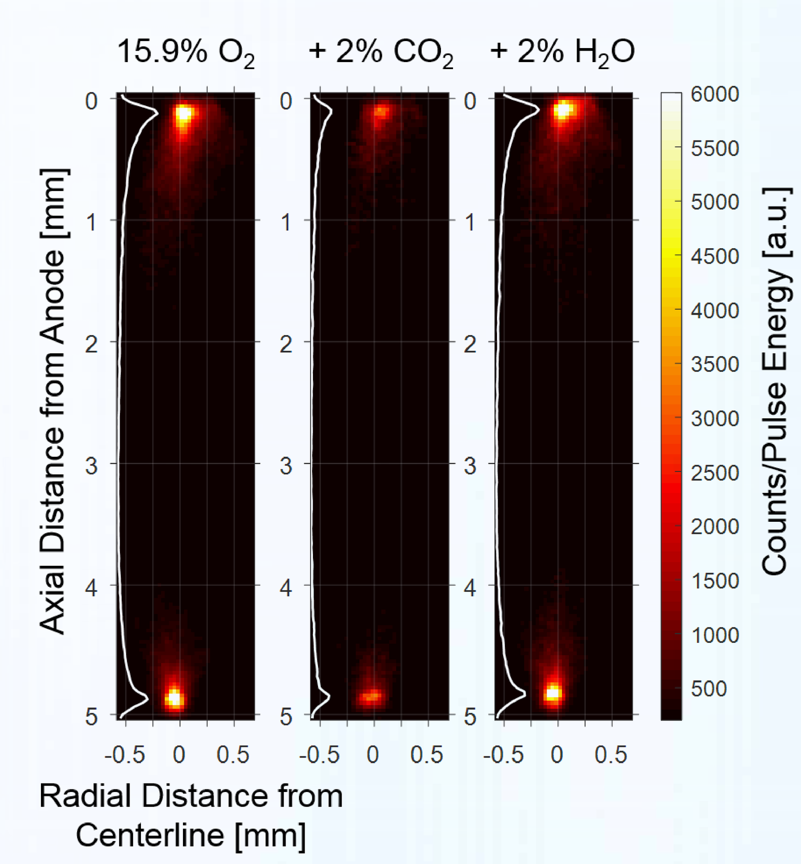
$$E_{elec} = \int_0^{t_p} W(t)dt = \int_0^{t_p} V(t)I(t)dt$$

$$E_{therm} = \int \delta u dV = \int \rho c_v \Delta T dV = \left(\frac{c_v}{R}\right) V_{cal}\Delta P = \frac{V_{cal}\Delta P}{\gamma - 1}$$

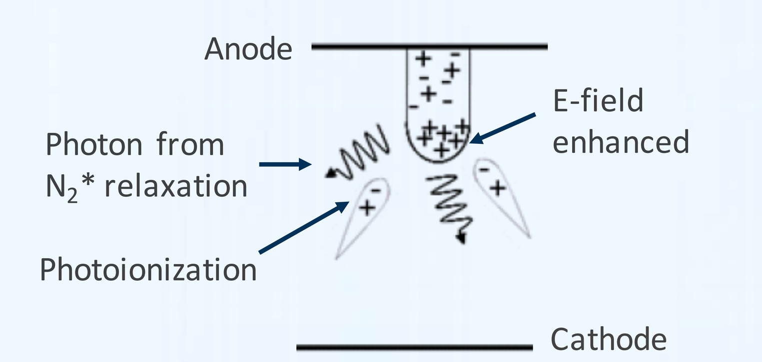
For CO_2: conversion efficiency decreased linearly to ~8% at 3% CO_2

CO_2 leads to decreased O* - interrupts photoionization?

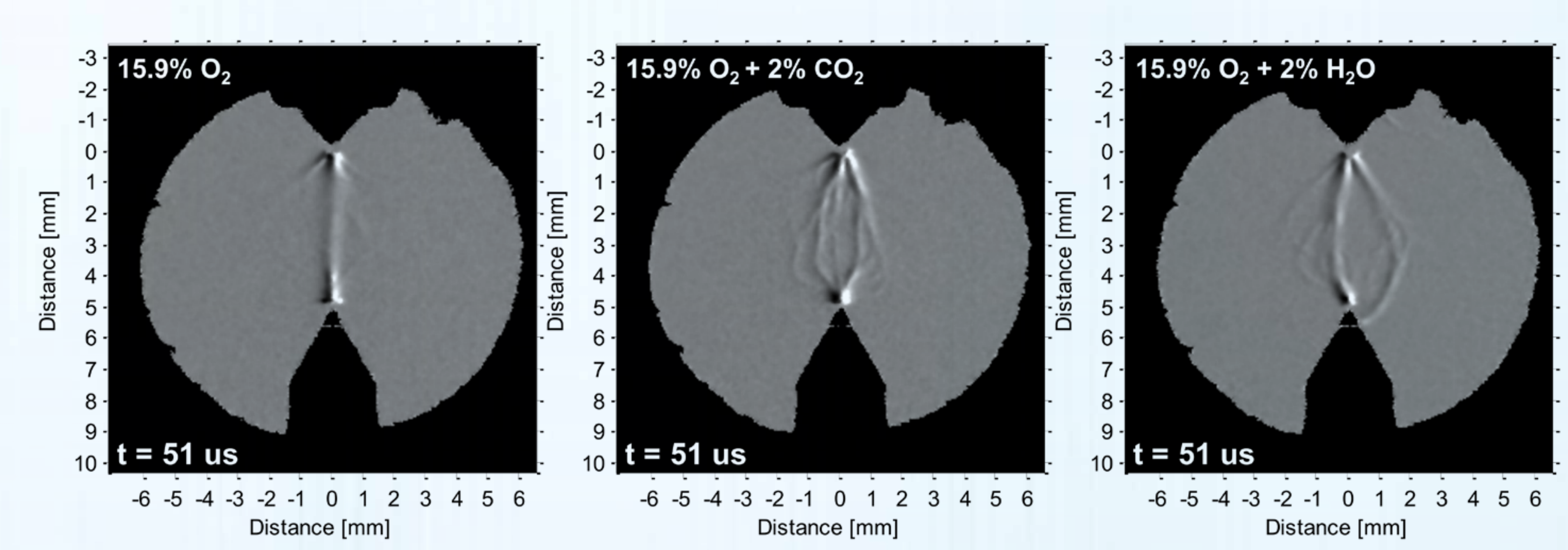
Mean O* Images:



- Quenching corrections have been made
- Modeling suggests that the electron energy distribution was relatively unchanged by CO_2 or H_2O
- CO_2 may have impacted photoionization processes near streamer head



Increased streamer branching observed with CO_2/H_2O addition



More branching → thinner streamers → faster cooling → faster V-T relaxation

Nanosecond discharges promising, more research needed

- Electrode designs must consider surface discharge propensity
- Pulsing strategy must consider decreased heating efficiency, radical production
- Continued research into nanosecond discharges needed:

  Elevated Density | *Pulsing Strategy*
  Gas Composition | *Electrode Design*

- Additional barriers to implementation in production automobiles: power consumption, cost, reliability, electrical noise

Publications
Wolk & Ekoto, SAE Int. J. Engines 10(3) (2017).
Wolk & Ekoto, 10th US National Combustion Meeting (2017).
Wolk & Ekoto, Ignition Systems for Gasoline Engines (2016).

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