Electric Field Measurements in Atmospheric Pressure Electric Discharges

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Motivation

- **High-pressure, low-temperature air plasmas: applications for plasma-assisted combustion, plasma flow control, plasma surface processing, biology and medicine**

- **Ns pulse discharges in air and fuel-air mixtures: stable at high pressures, efficient generation of excited species and reactive radicals**

- **Electric field in plasmas: controlled by ionization, electron and ion transport; electron emission from electrodes; surface charge accumulation on dielectrics**

- **Electric field controls energy partition in the plasma (vibrational and electronic excitation, dissociation, ionization), rate of gas temperature rise**

- **Need for non-intrusive, spatially resolved, time-resolved electric field measurements in transient reacting plasmas, near surfaces**

- **Insight into kinetics of ionization and charge transport, validation of kinetic models**
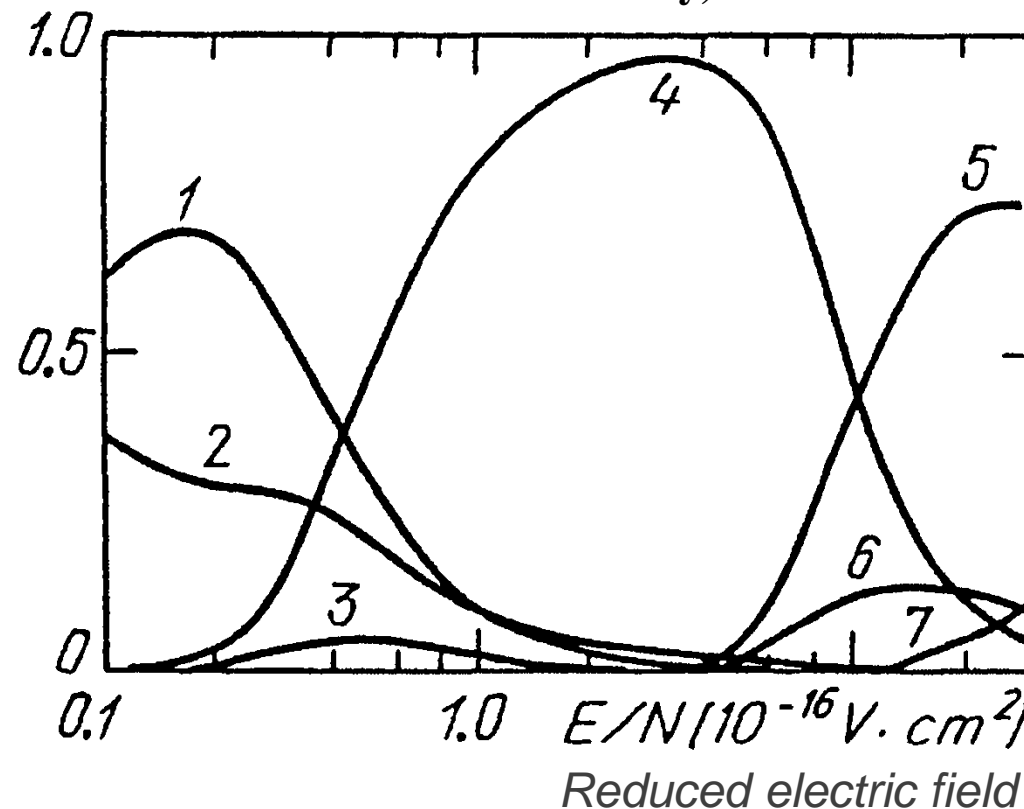
Energy Partition in Air Plasma vs. Electric Field

Yu. Raizer, Gas Discharge Physics, Springer, 1991

Quasi-steady-state discharges, low E/N:
(4) N_2 vibrational excitation:
Low reactivity, slow thermalization

Energy fraction

Reduced electric field

Pulsed discharges, high E/N
(5,6) electronic excitation, dissociation, (7) ionization
High reactivity, rapid thermalization

- **Reduced electric field, E/N, controls input energy partition in the discharge**

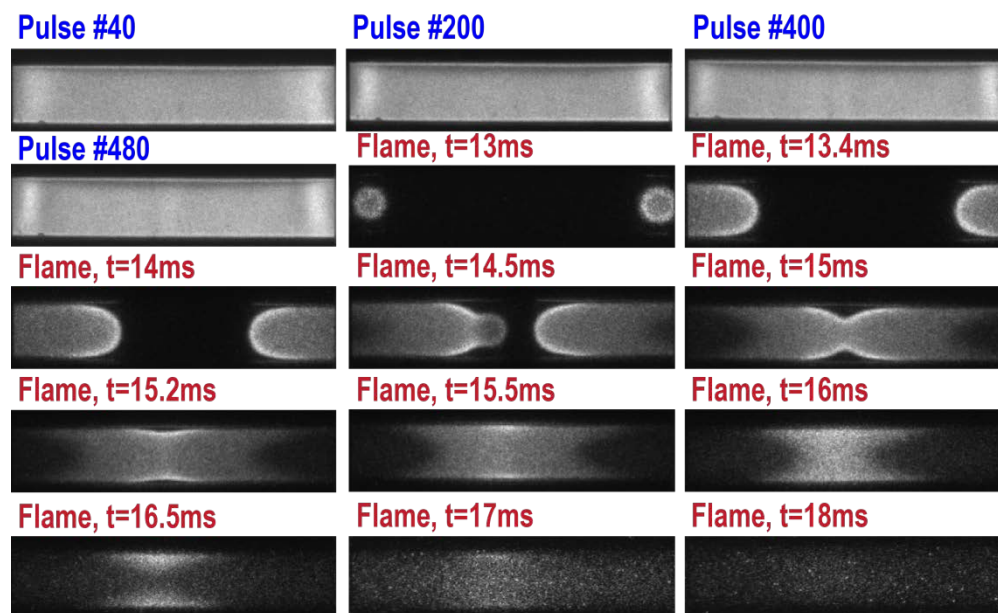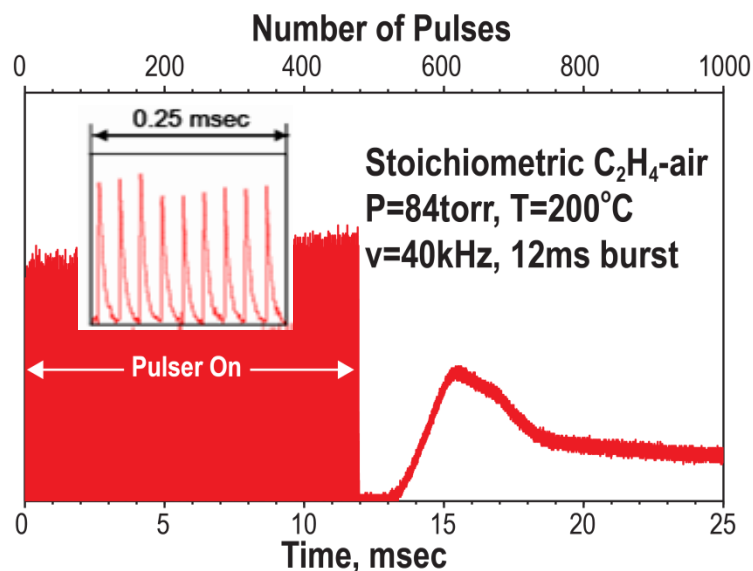- **Rates of electron impact processes: depend on E/N exponentially**

Ns Pulse Surface Plasma Actuators form spanwise vortices in flow over airfoil

45 m/sec

- Every ns discharge pulse produces a spanwise vortex

- Enhanced mixing with free stream → **boundary layer reattachment**

- Effect detected up to u=96 m/sec ($M=0.28$, $Re_x \sim 1.5 \cdot 10^6$)

Little et al, AIAA J., 2012
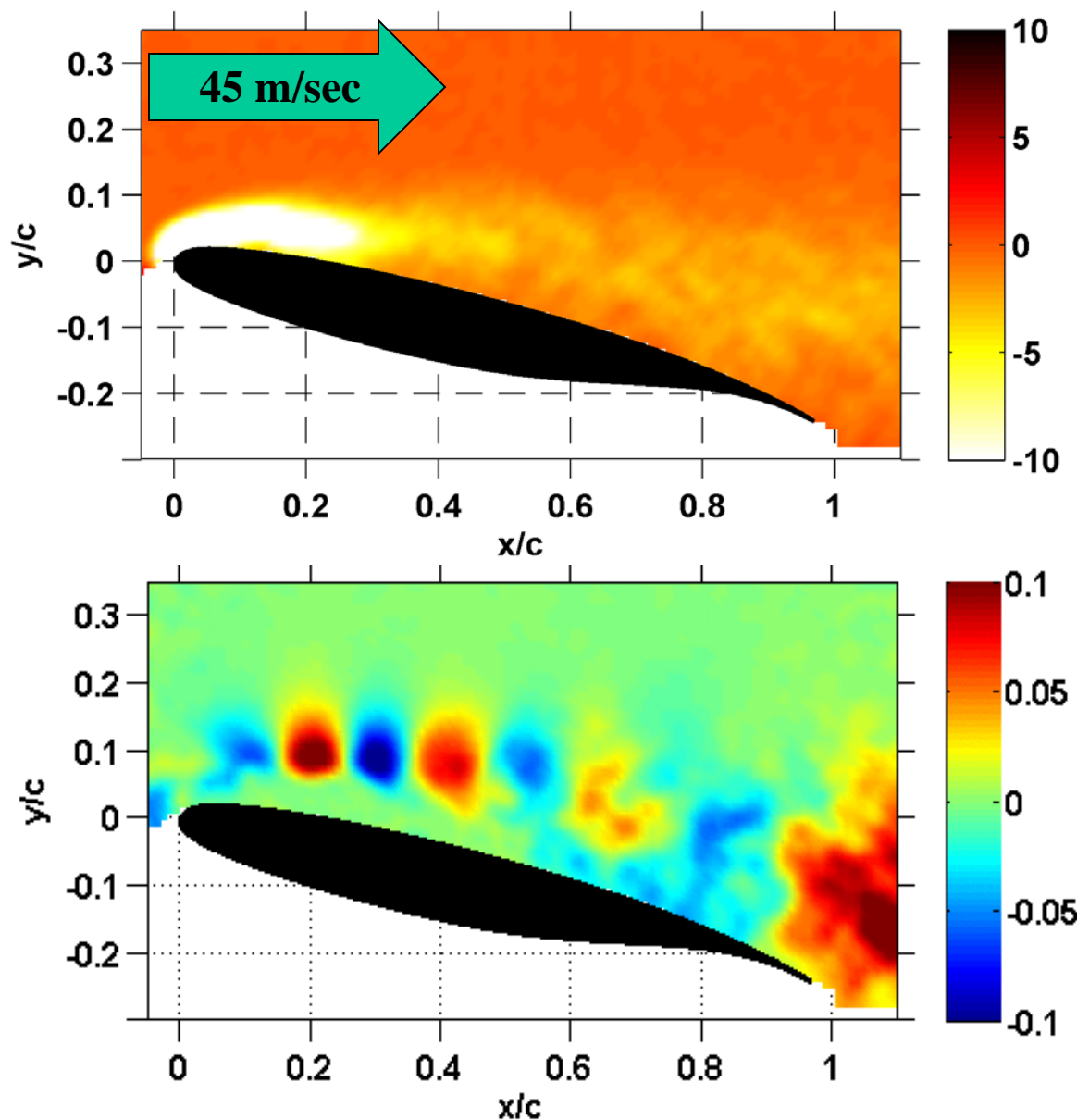
Pulse Burst Nanosecond Discharge: C₂H₄-ignition below autoignition temperature

Stoichiometric C₂H₄-air
P=84torr, T=200°C
v=40kHz, 12ms burst

OH emission from plasma and flame

- Ignition induced by radicals generated in the plasma (primarily O and H atoms)
- Ignition occurs at temperature ≈ 200 K below autoignition
- Ignition begins near edges of the plasma (higher energy loading)
- Flame propagates to the center of the plasma

Yin et al, IEEE Trans Plasma Sci. 2011

4-wave mixing: "CARS-like" process
(E-field acting as a "zero-frequency" probe beam)

$$I_{CARS} \sim \chi^2_{CARS} I^2_P I_{Stokes}$$

$$I_{IR} \sim \chi^2_{IR} I_P I_{Stokes} E^2_{Ext}$$
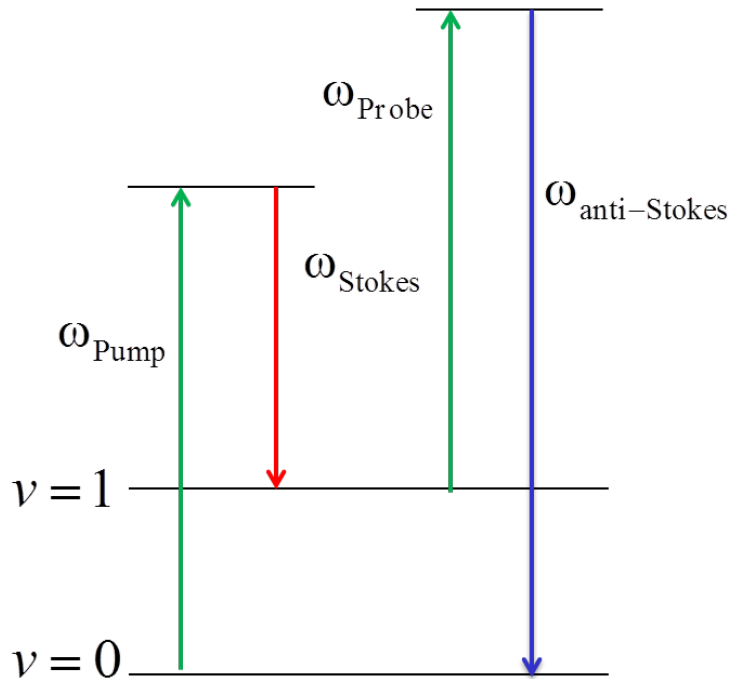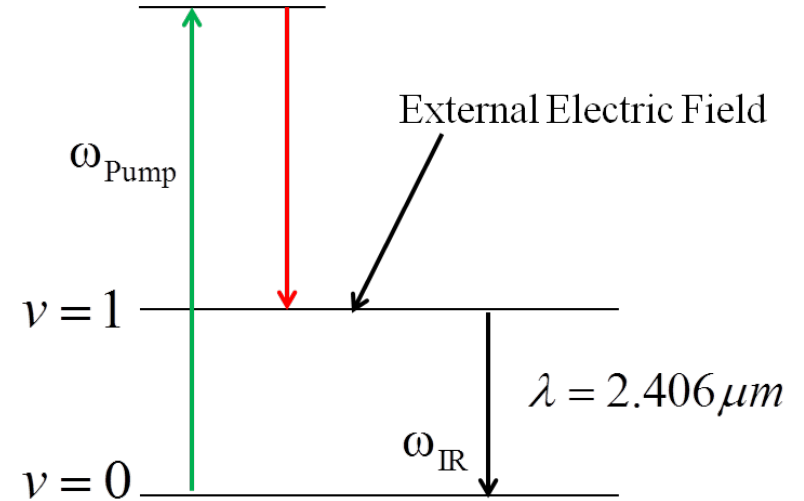
$$\left| E_{Ext} \right| \sim \sqrt{\frac{\chi^2_{CARS}}{\chi^2_{IR}} \frac{I_{IR} I_P}{I_{CARS}}}$$

- **Calibration using known electrostatic electric field**

- **Use of ps lasers: high peak laser intensity, higher 4-wave mixing signal**

# Ps 4-wave Mixing: Experimental Apparatus
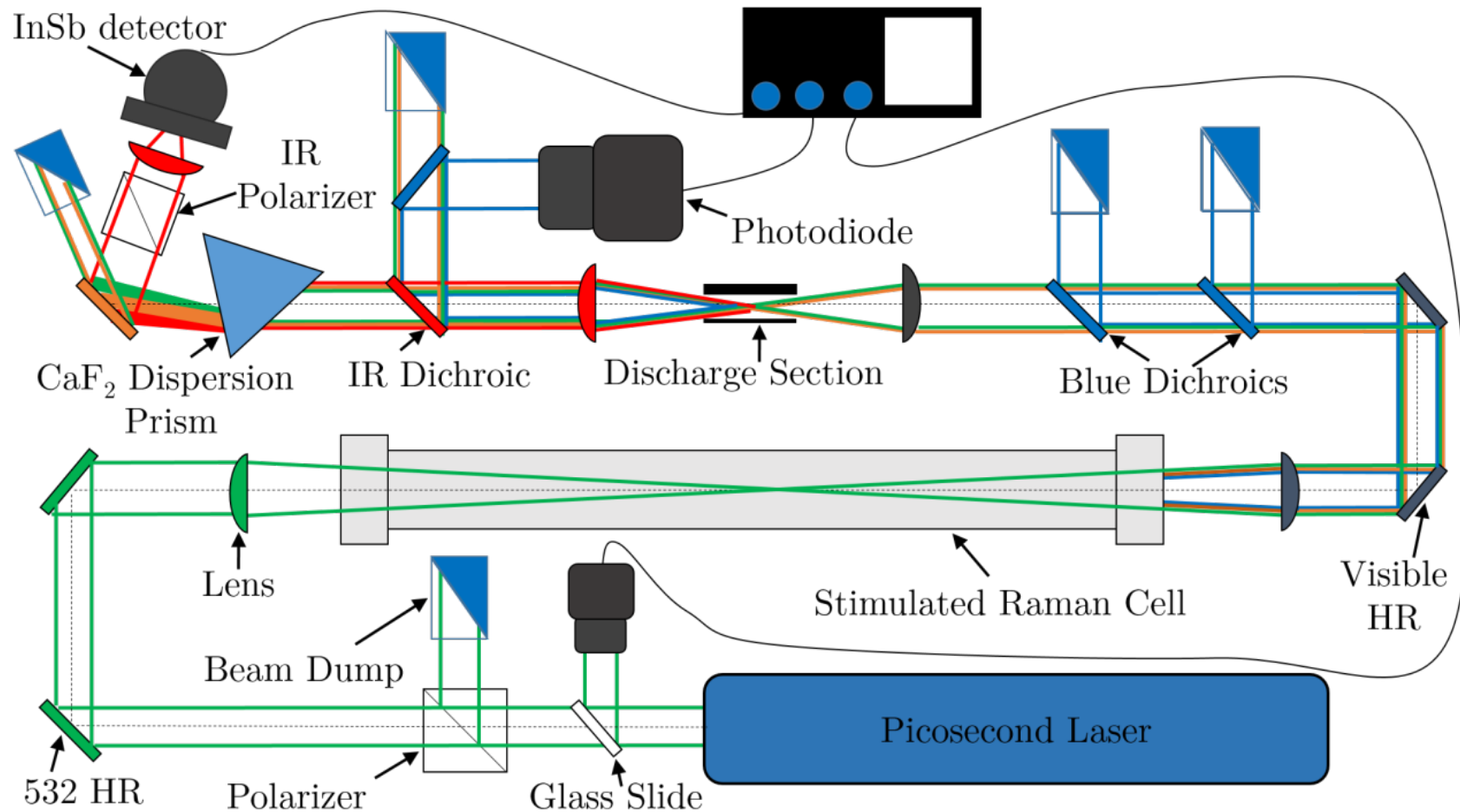
- **Key difference from previous work: use of stimulated Raman cell instead of a dye laser**

- **Raman cell filled with 15 bar N_2-He mixture**

- **Time resolution ~ 200 ps, spatial resolution (along laser beam) several cm**

Test Drive: Ns Pulse Discharge in Ambient Air Between Two Parallel Plate Electrodes
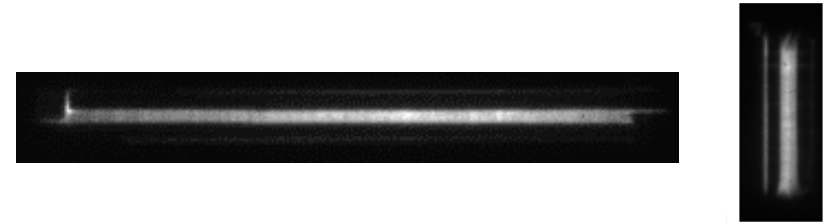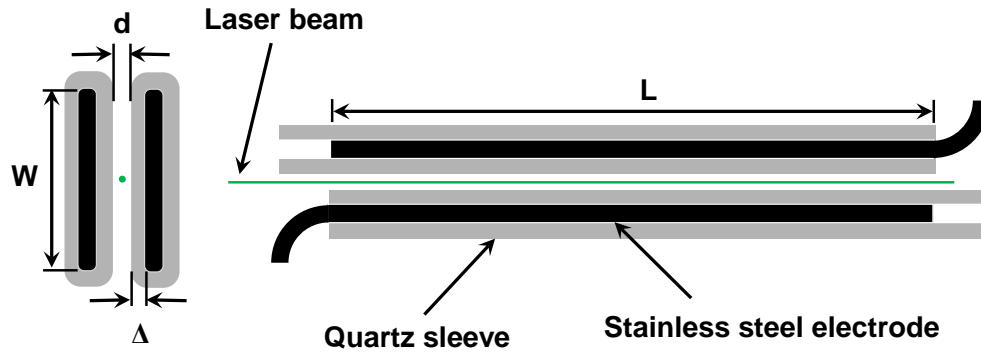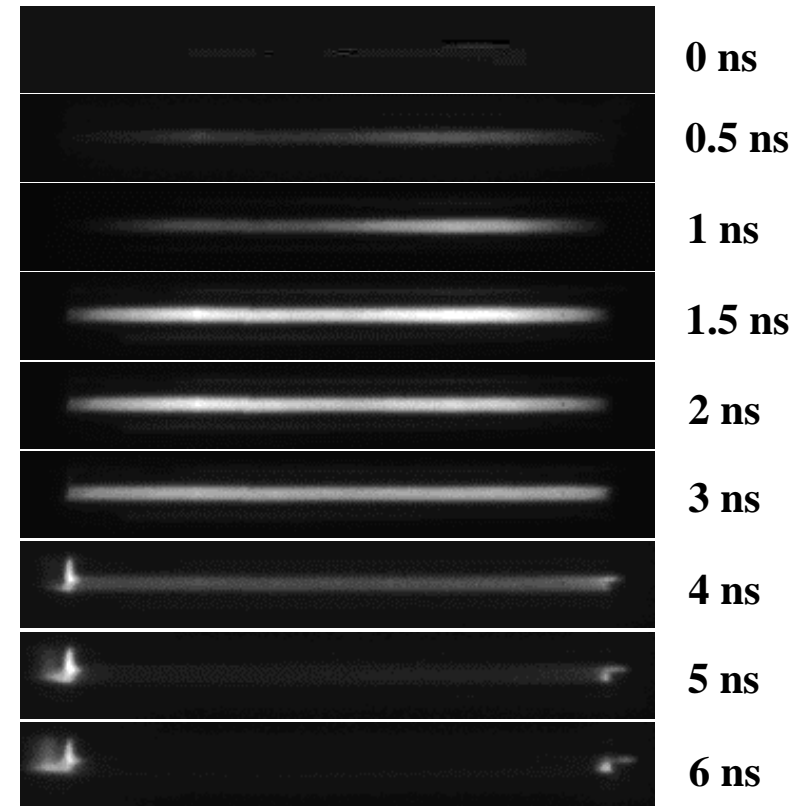

Camera gate 20 ns, single pulse

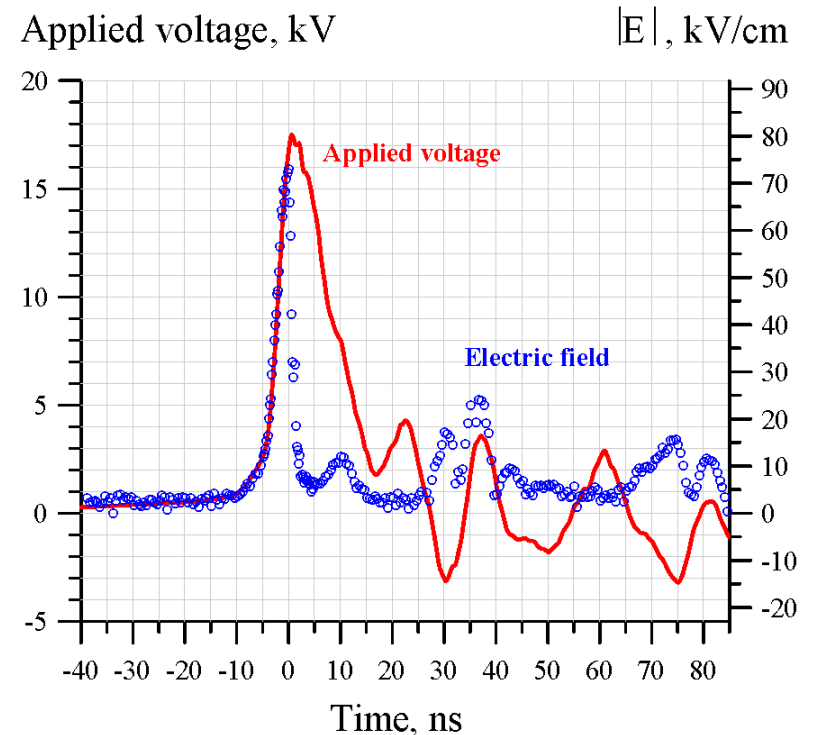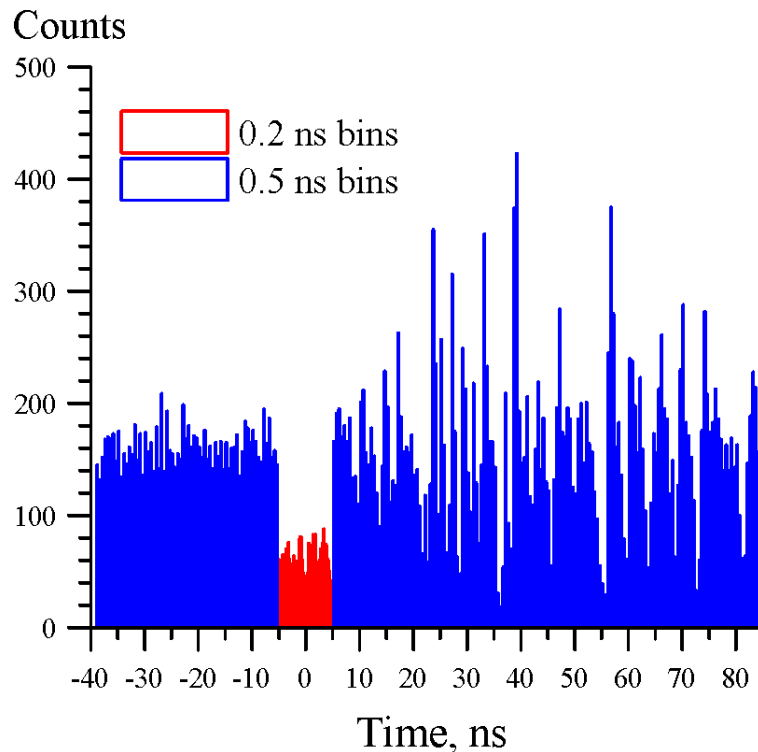**Two parallel plate electrodes encased in quartz sleeves**

Applied voltage, kV
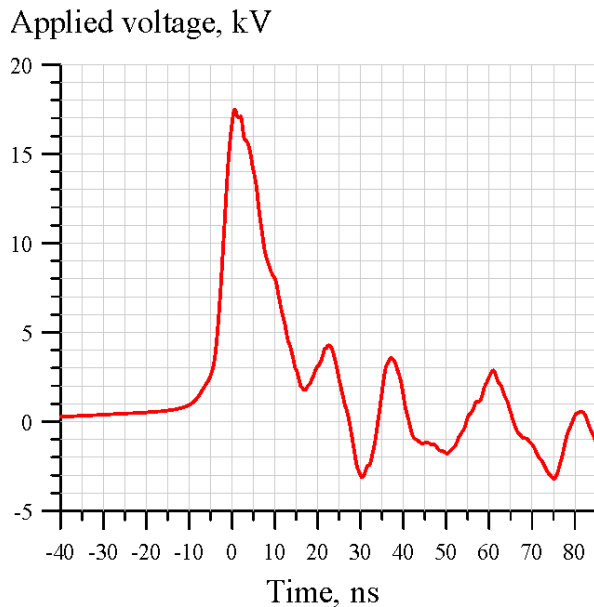
dU/dt ≈ 3 kV/ns, discharge gap 1.2 mm

Breakdown at t ≈ 0 ns, U ≈ 17 kV

	0 ns
	0.5 ns
	1 ns
	1.5 ns
	2 ns
	3 ns
	4 ns
	5 ns
	6 ns

Camera gate 1 ns, 50-pulse average

Time-Resolved Electric Field Measured with Sub-Ns Resolution (0.2-0.5 ns)

**Laser shots (150 ps duration) distributed randomly over 100 ns period**

Four-wave mixing (electric field) data points grouped into "time bins" 0.2-0.5 ns wide

- **Electric field follows applied voltage until breakdown at 75 kV/cm, then falls rapidly**

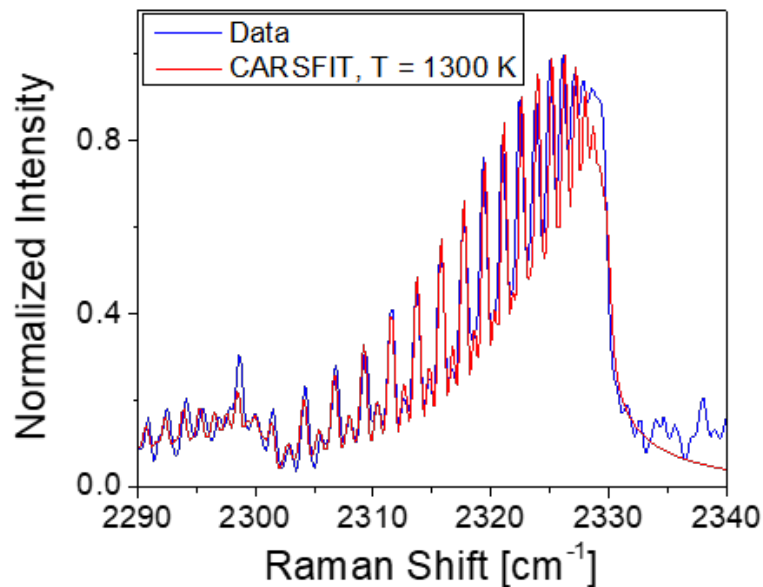- **Field after breakdown controlled by electron attachment, electron and ion transport**

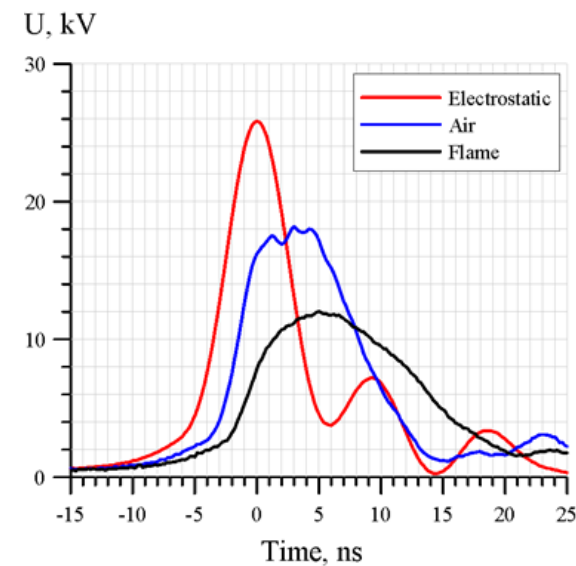# Hydrogen Diffusion Flame
Between Two Parallel Plate Electrodes

Hydrogen Diffusion Flame Setup
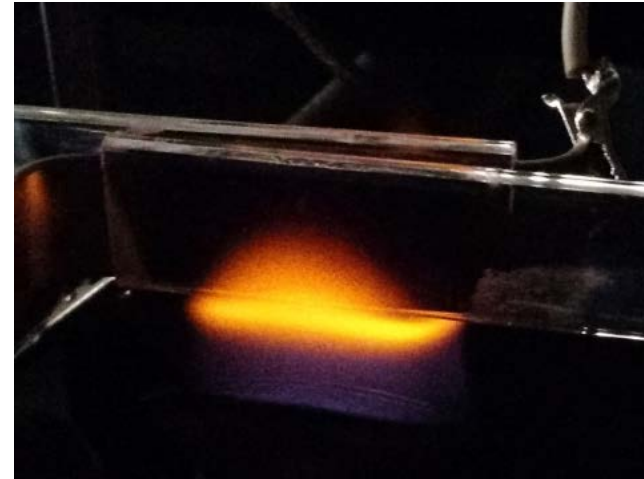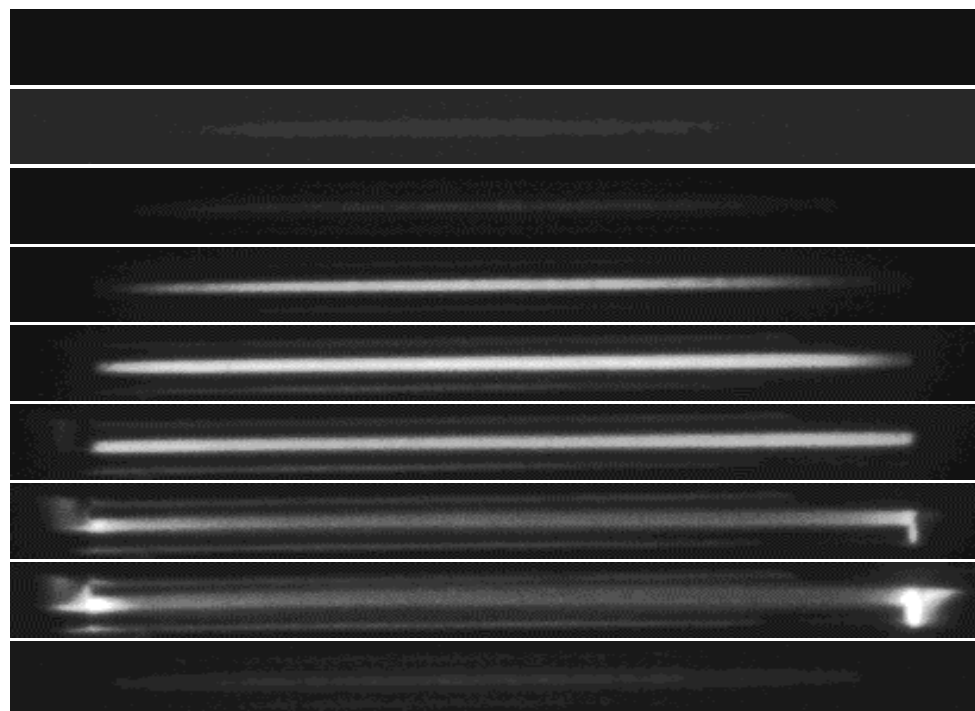

Hydrogen Flame

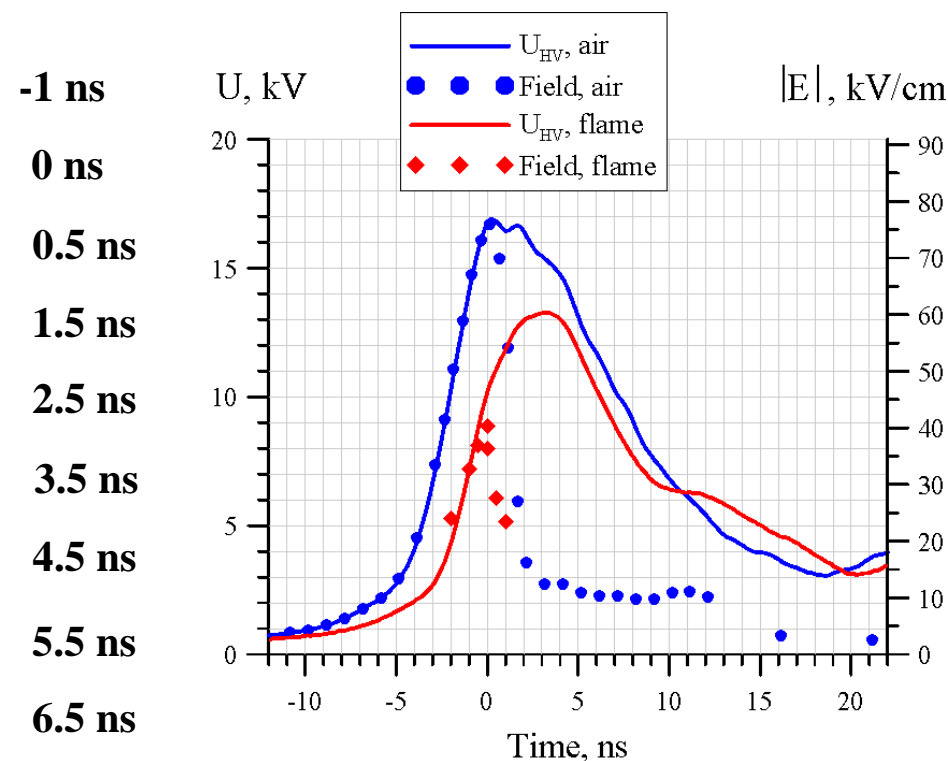**N$_2$ CARS spectrum: T=1300±50 K**

Voltage waveforms, discharge gap 1 mm

Comparison of Time-Resolved Electric Field in Ambient Air and in Hydrogen Flame
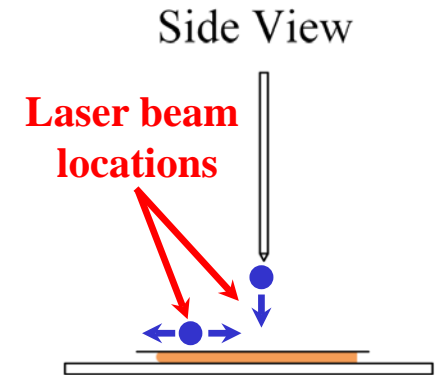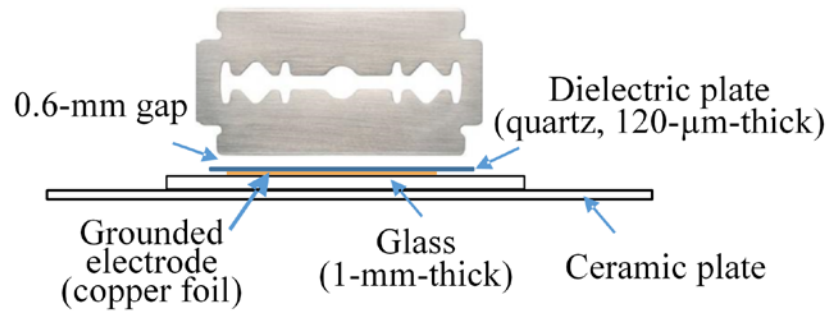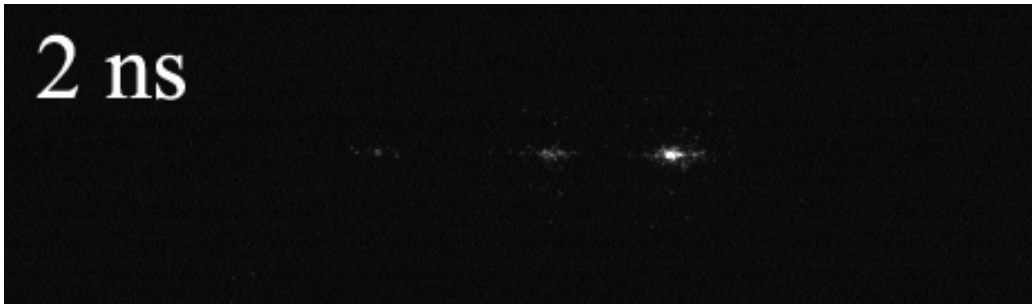

Top view, camera gate 1 ns, 50-pulse average

Discharge gap 1.3 mm

- **Four-wave mixing signal in flame is 2 orders of magnitude weaker than in air**

- **Higher temperature, lower N_2 fraction in mixture, signal spread over many rotational states**

- **Breakdown field in flame a factor of ~2 lower than in room temperature air**

- **In both cases, field is higher than DC breakdown field, $E_{DC} \approx 30$ kV/cm**
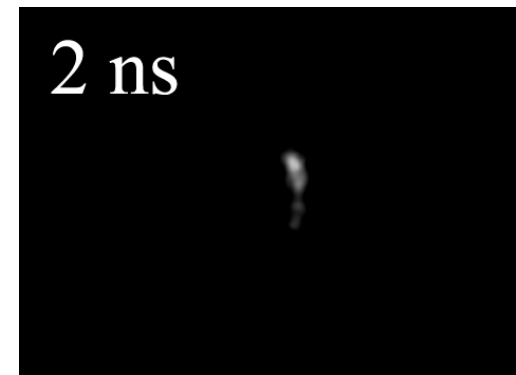
Negative Polarity Ns Pulse Discharge Over Quartz Surface

Side View

Laser beam locations

0.6-mm gap

Dielectric plate (quartz, 120-µm-thick)

Grounded electrode (copper foil)

Glass (1-mm-thick)

Ceramic plate

Top view, 2 ns gate

2 ns

Side view, 2 ns gate

2 ns

- Ns pulse discharge between a high-voltage electrode and a thin quartz plate

- Discharge gap 0.6 - 1.0 mm, diffuse surface ionization wave plasma ~ 200 µm thick

- Time-resolved electric field measured at multiple locations in the discharge gap

Electric Field Vector Components in a Surface Ionization Wave Discharge
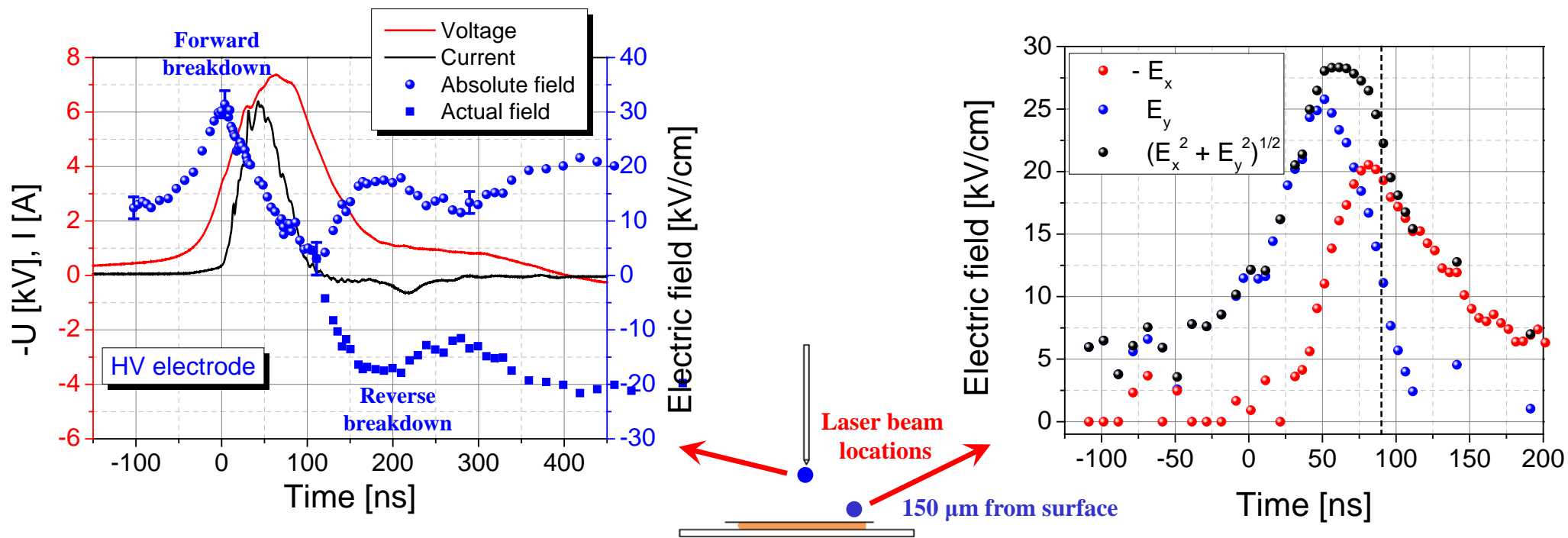
- **Initial field offset (at t < 0): charge accumulation on dielectric from previous pulse**

- **Breakdown field much lower than in "short" pulse discharge (dU/dt = 0.1 kV/ns vs. 3 kV/ns)**

- **After breakdown, field reduced due to charge accumulation on dielectric surface**

- **Field is reversed after applied voltage starts decreasing**

- **Away from HV electrode, field peaks later (E_y before E_x): surface ionization wave**
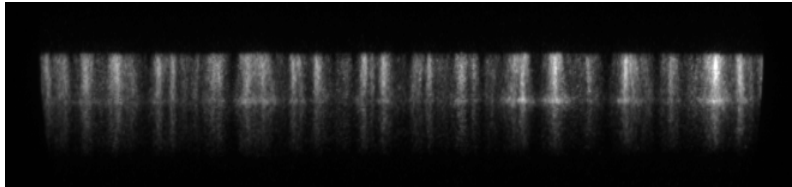
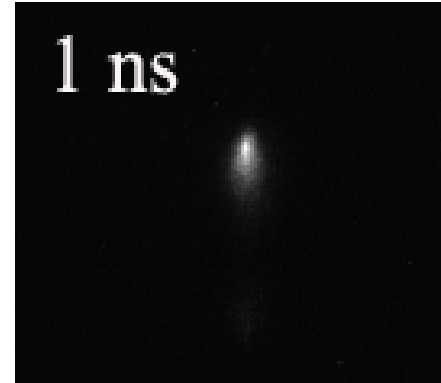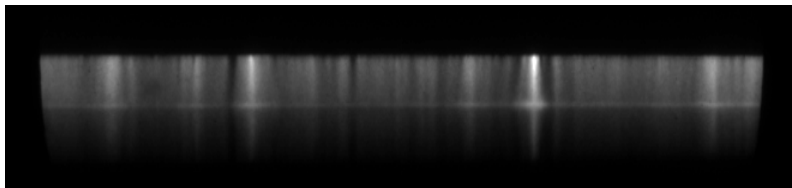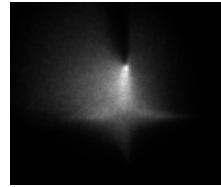# Negative Polarity Ns Pulse Discharge Over Liquid Water
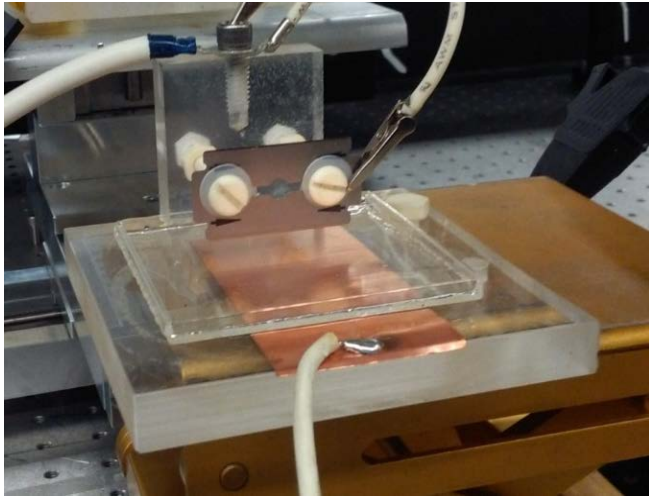
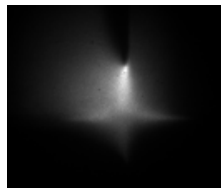**50-pulse accumulation movies**

1 ns
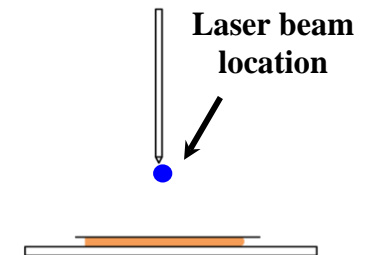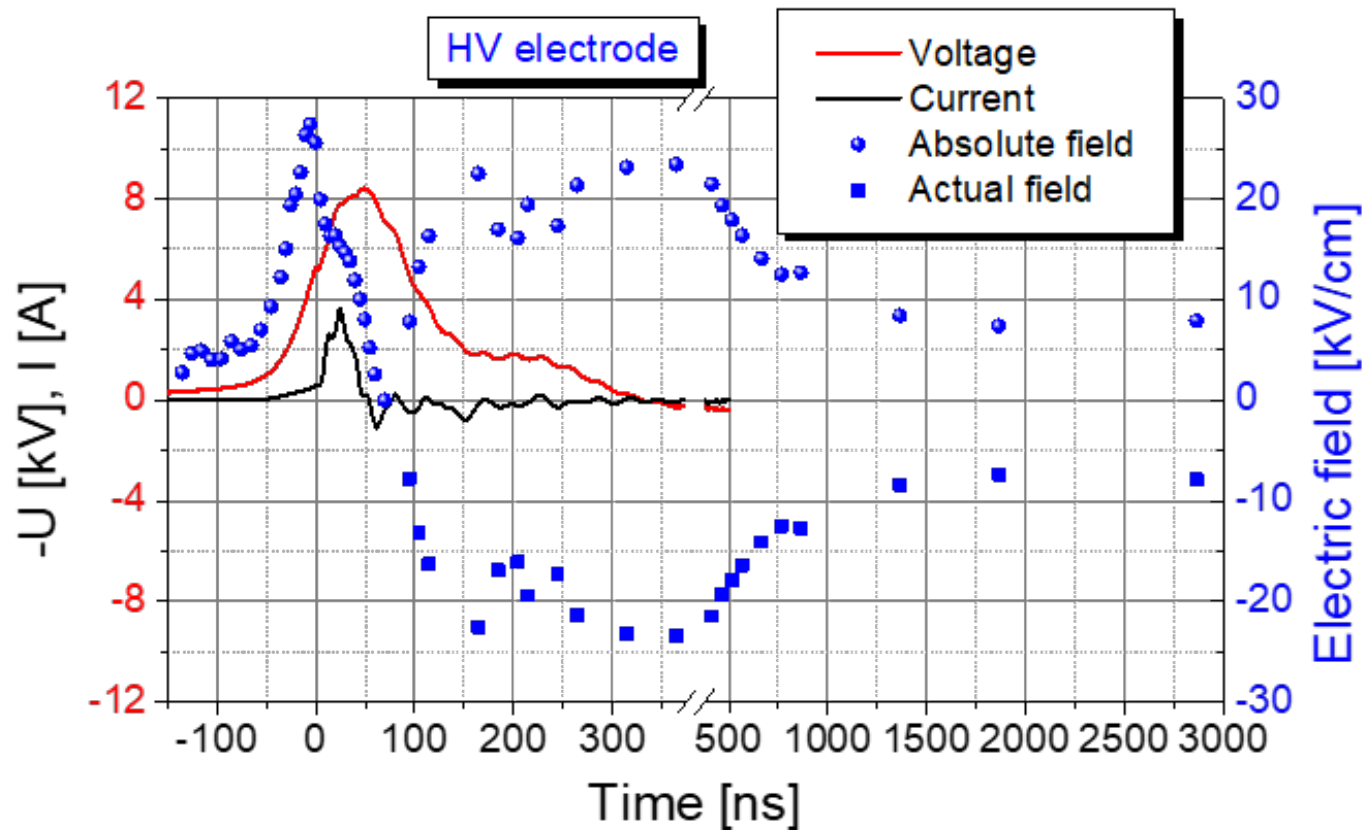
1 ns

Single-shot, 100 ns gate

100-pulse accumulation

**Positive polarity discharge plasma is strongly filamentary**

Electric Field in Discharge Over Liquid Water

- **Results similar to measurements over quartz surface**

- **Field reduction to near zero over tens of ns after breakdown: plasma self-shielding**

- **Field reversal during voltage decay: surface charge accumulation**

- **Field decay on microsecond time scale: surface charge neutralization by ion transport**

New Diagnostics for Electric Field Measurements: Femtosecond Second Harmonic Generation
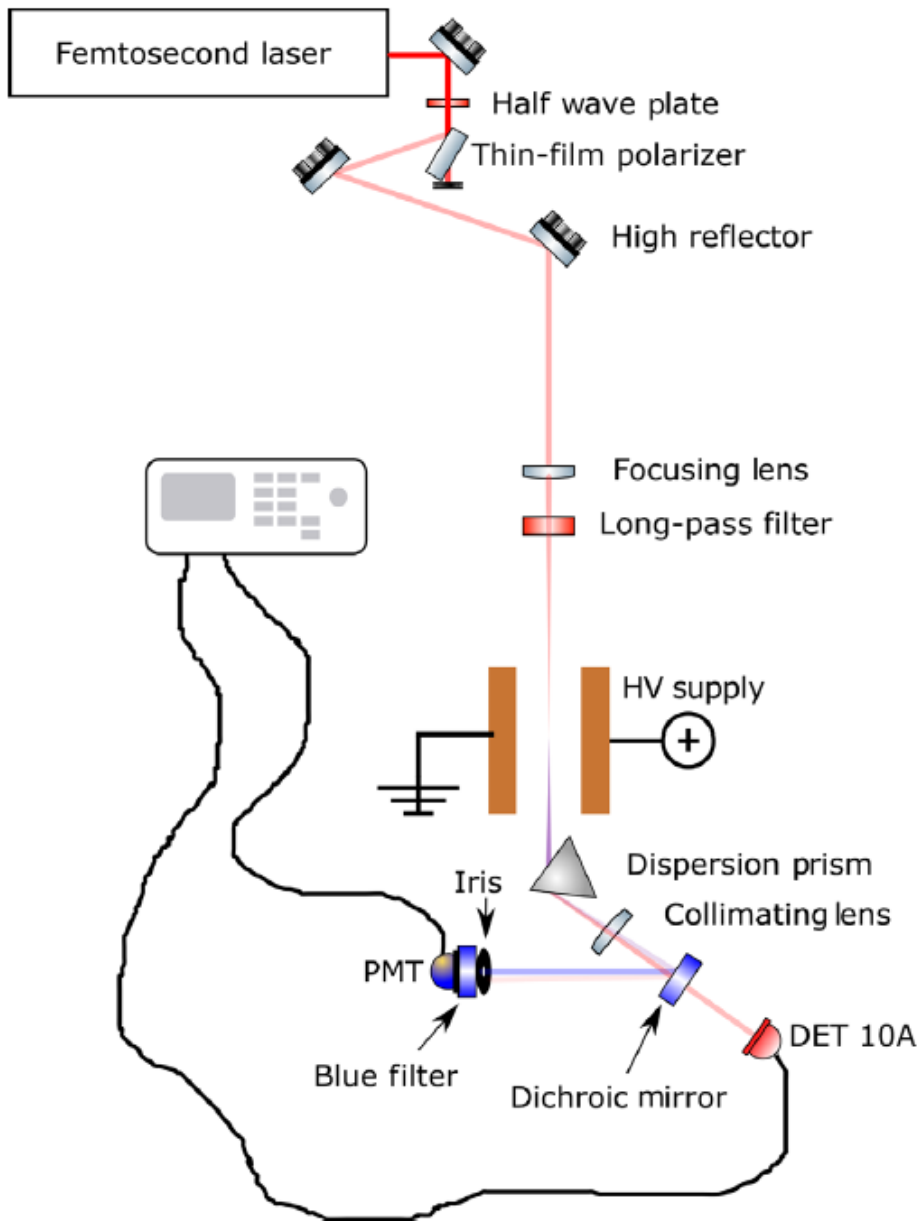
Polarization at **2ω** induced by applied electric field, $E^{(F)}$, in presence of laser field, $E^{(\omega)}$:
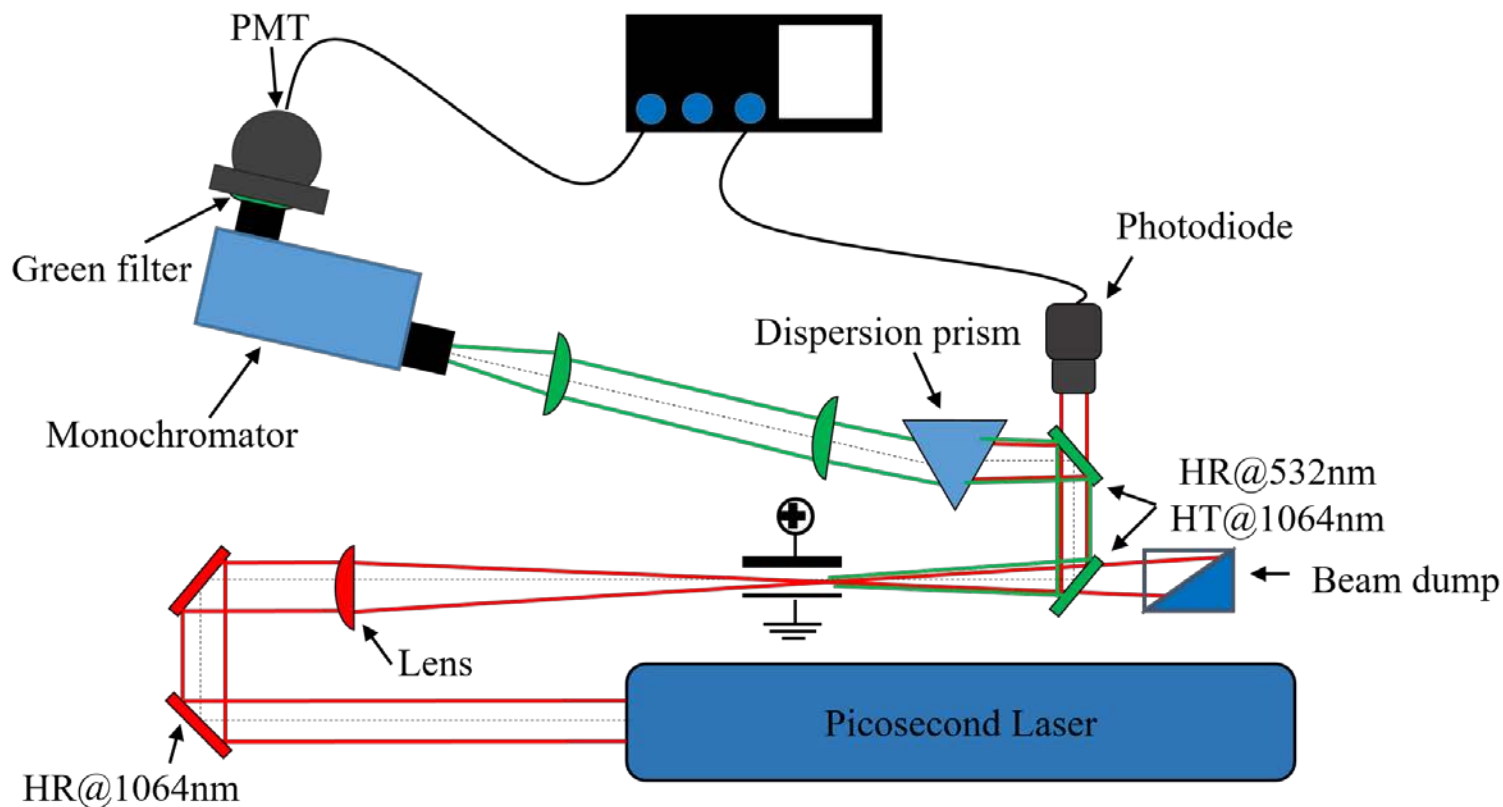
$$P_i^{(2\omega)} = \frac{3}{2} N \chi_{i,j,k,l}^{(3)}(-2\omega, 0, \omega, \omega) E_j^{(F)} E_k^{(\omega)} E_l^{(\omega)}$$

Signal proportional to laser intensity: need an ultra-short-pulse (ps or fs) laser

Field parallel or perpendicular to laser polarization plane can be measured

Critical advantage: non-species sensitive diagnostics, would work in reacting mixtures and flames

# Picosecond Second Harmonic Generation Experiment

- **Laser pulse 30 ps long, 2-4 mJ/pulse at 1064 nm, generating second harmonic at 532 nm**

- **SHG vs. compared to four-wave mixing: 10 times more signal at 10 times less laser power**

- **Goal: electric field measurements in fuel-air plasmas and atmospheric pressure plasma jets**

- **Test cases: AC Dielectric Barrier Discharge (DBD) plasmas**

Preliminary Results:
Electric Field in Plane-to-Plane AC DBD plasma
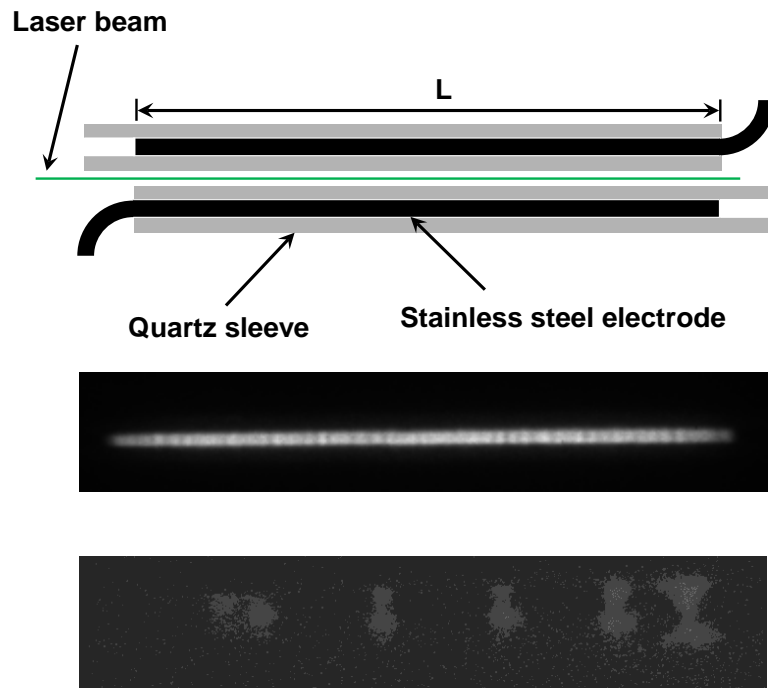

Microdischarges (not to scale)
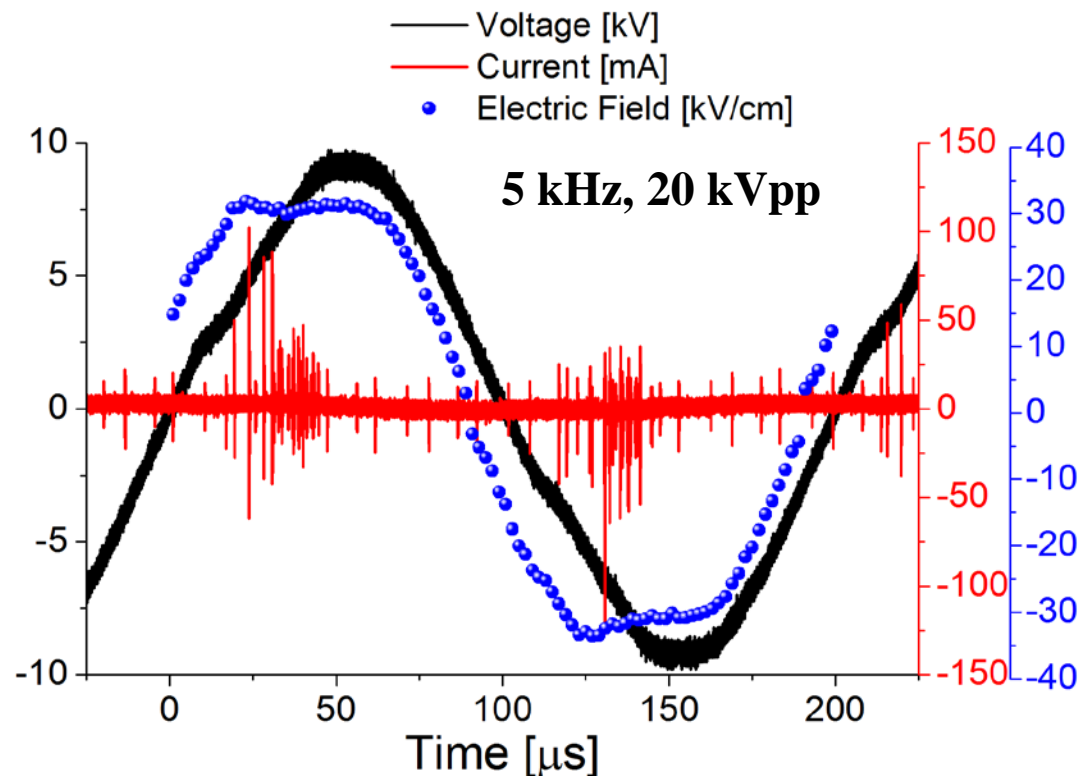
Test case I: AC DBD plasma in room air, two parallel plane electrodes 50 mm long, 5 kHz frequency, 20 kV peak-to-peak voltage, two dielectric barriers (quartz sleeves 1.5 mm thick), discharge gap 1.3 mm

Phase shift between applied voltage and electric field, due to surface charges

Micro-discharges keep electric field near breakdown threshold ($\approx$30 kV/cm)

Preliminary Results: Electric Field in AC Surface DBD Plasma Actuator
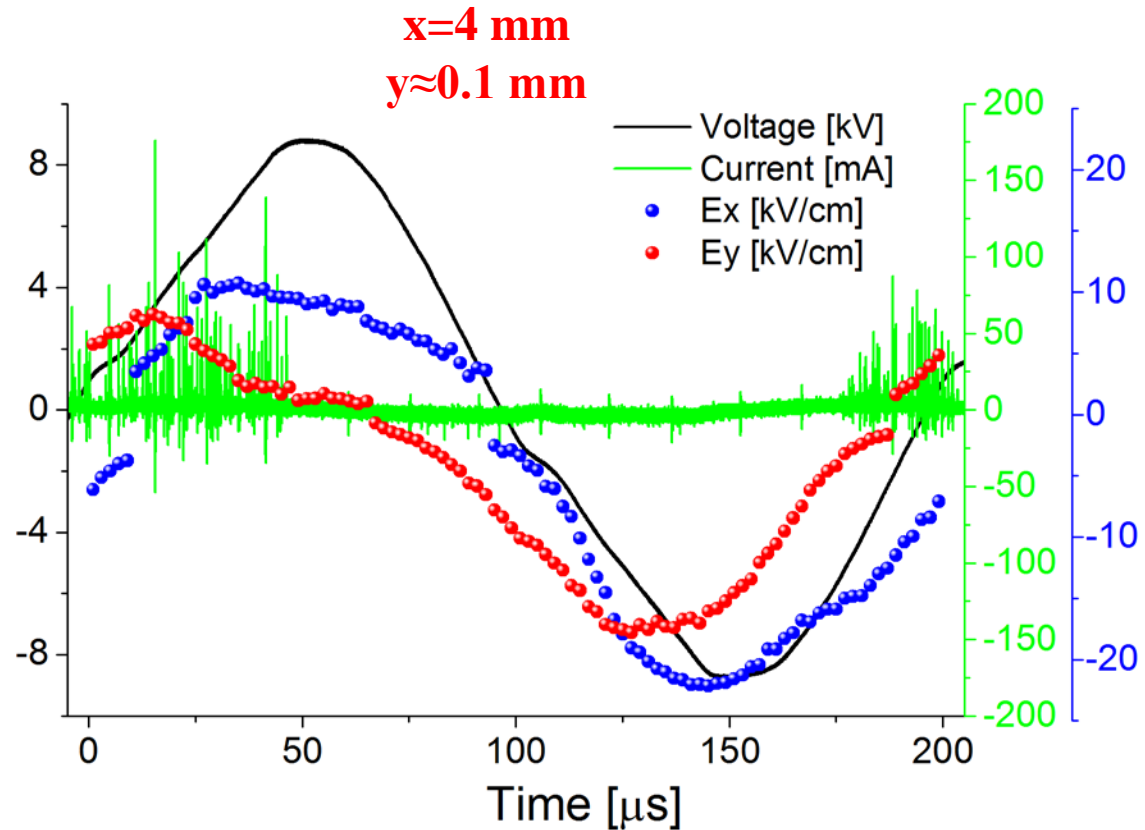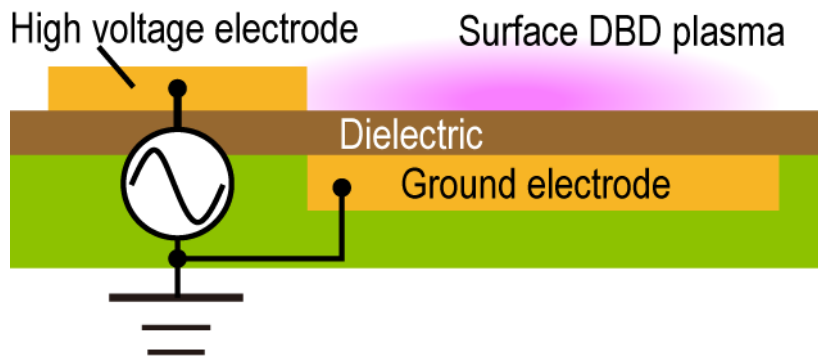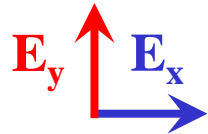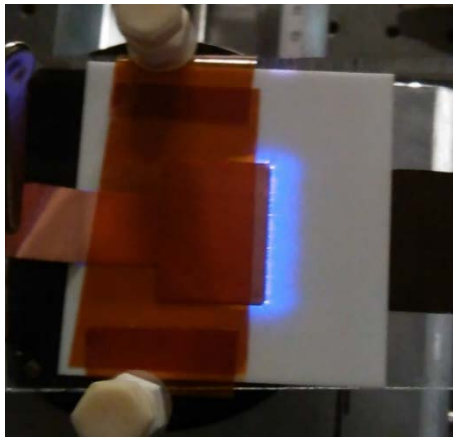
Test case II: AC DBD surface plasma actuator in room air, alumina dielectric plate 1.5 mm thick, electrodes 25 mm wide, 5 kHz frequency, 17 kV peak-to-peak voltage

Electric field vector components (E_x and E_y) measured at x=0-9 mm from high voltage electrode, y ≈ 100 μm above dielectric surface

Quantitative insight into mechanism of plasma actuator interaction with the flow?

Summary

- **Electric field vector is measured by ps 4-wave mixing in ns pulse discharges in ambient air and in H_2-air flame**

- **Demonstrated capability for sub-ns time resolution, measurements of individual electric field vector components**

- **Breakdown field in air and in flame considerably exceeds DC breakdown threshold, for pulse voltage rise time of ~ 5 ns**

- **Time-resolved, spatially resolved electric field (E_x and E_y) measured in ns pulse, surface ionization wave plasmas in ambient air, over quartz and water surfaces**

- **Ps second harmonic generation diagnostics for electric field measurements has been tested in AC DBD plasmas; further measurements underway**