Studies of Fast Ionization Wave Discharge Plasmas Using Optical Diagnostics with Sub-Nanosecond Time Resolution

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Objectives

• Generating controlled, reproducible nsec pulse duration discharges in plane-to-plane and axial (Fast Ionization Wave) geometries, in a discharge section with access for optical diagnostics

• Measurements of FIW speed in a wide range of pressures (P~1-100 torr), and voltage waveforms (peak voltage, rise time, pulse repetition rate)

• Development and testing of a new, portable psec CARS diagnostic system

• Time- and spatially resolved measurements of rapidly varying electric field in nsec pulse discharges (plane-to-plane and FIW) by IR (E-field) psec CARS

• Measurements of electron density in nsec pulse discharges by Thomson scattering*

*with luck
“Single pulse” nanosecond discharge in plane-to-plane geometry: spatially uniform?

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Voltage, kV

Air, P=60 torr, ν=40 kHz

Time, nsec

Single pulse

100 pulse average

Broadband ICCD camera images, gate 2 μsec
Air, P=60 torr, pulse repetition rate 10 Hz
Repetitive nanosecond pulse discharge: effect of residual ionization on spatial uniformity

Single pulse ICCD camera images in air from 40 msec “burst”
(P=60 torr, ν=40 kHz, 1000 pulses in a burst, 1 µsec camera gate)

Air plasma remains uniform during entire pulse burst at P=40-100 torr
(after first 1-2 pulses): effect of residual ionization

Same result for short camera gates (down to 4 nsec): justifies the use of a quasi-1-D approach
Effect of residual ionization: uniform plasma on nanosecond time scale

Air, P=60 torr, ν=40 kHz, pulse #100 in the burst

Same result for shorter camera gates (down to 4 nsec): justifies the use of a quasi-1-D approach
Nanosecond pulse discharge plasma / sheath model
(quasi-1-D drift-diffusion, time-dependent)

- Equations for electron and ion number density
- Poisson equation for the electric field
- Nitrogen, plane-to-plane discharge geometry
- Both electrodes covered with quartz plates
- Voltage pulse: Gaussian fit to experimental waveform
  \[
  E_{\text{app}}(t) = \frac{V_{\text{peak}}}{L + \frac{2l}{\varepsilon}} \exp \left\{ -\left( \frac{t - t_{\text{peak}}}{\tau} \right)^2 \right\}, \quad V_{\text{peak}} = 20 \text{kV}, \quad \tau = 15 \text{nsec}
  \]
- Townsend ionization coefficient vs. E/N: fit to experimental data; local kinetics only
- Dielectric plate charging / plasma shielding:
  \[
  \frac{dV_{\text{app}}(t)}{dt} = \left( 1 + \frac{2l}{\varepsilon L} \right) \frac{dV_{\text{gap}}(t)}{dt} + \frac{2le}{\varepsilon_0 \varepsilon L} \int_0^L \left[ \Gamma_+(x,t) - \Gamma_e(x,t) \right] dx
  \]

Numerical or analytic solution: time-dependent
electron density and electric field in the plasma and in
the sheath, coupled pulse energy
Nanosecond pulse discharge plasma / sheath model:
key processes and time scales

\[ E_{\text{app}}(t) - \text{applied electric field (Gaussian fit to experimental pulse shape)} \]

\[ E_{\text{app}}(t) = \frac{V_{\text{peak}}}{L + \frac{2l}{\varepsilon}} \exp \left[ -\left( \frac{t - t_{\text{peak}}}{\tau} \right)^2 \right] , \quad V_{\text{peak}} = 20 \, kV , \quad \tau = 15 \, n\text{sec} \]

\[ v_i - \text{electron impact ionization frequency} \]

\[ v_c + v_s - \text{frequency of dielectric charging / sheath formation} \]

\[ v_{\text{RC}} - \text{RC frequency of the load after breakdown (plasma / charged dielectrics / sheath)} \]

\[ v_i(E) = A_p \exp \left[ -\frac{B_p}{E} \right] , \quad v_c = \frac{2l e \mu_e n_0}{\varepsilon_0 \varepsilon_L \left( 1 + \frac{2l}{\varepsilon L} \right)} , \quad v_s = \frac{2l_s e \mu_e n_0}{\varepsilon_0 L} , \quad v_{\text{RC}} = \frac{1}{R_{\text{plasma}} C_{\text{load}}} = v_i^0 \frac{a - 1}{a \ln a} \]

\[ E_0 = E(t_0) - \text{breakdown field} \]

\[ E_0 = E_{\text{app}}(t_0) \quad , \quad \frac{t_0 - t_{\text{peak}}}{\tau} = \frac{v_i^0 \tau}{4 \ln(\gamma / 2)} \frac{E_0}{B_p} \]

\[ E^* = E(t^*) - \text{field in the plasma at the moment when coupled power peaks} \]

\[ v_i^0 = v_i(E_0) \quad , \quad \gamma = \frac{v_i^0}{v_c + v_s} , \quad a = \exp \left( \frac{3B_p}{2E_0} \right) , \quad \xi_1 = \frac{a - a^* / E_0}{a \ln a} , \quad \xi_2 = E^* \frac{a^{E^*/E_0}}{E_0} \frac{3a}{3a} \]
Nanosecond pulse discharge plasma / sheath model: key results

\( E(t) \): electric field in the plasma

\[
E_p(t) = \begin{cases} 
\frac{E_{app}(t)}{\frac{1}{\gamma} \exp(\nu_0^t t') + 1}, & t' \leq t^* \\
\frac{E^*}{E_0} \left(1 + \frac{\xi_2}{\xi_1}\right)E_{app}(t), & \frac{\xi_2}{\xi_1}, \ t' > t^*
\end{cases}
\]

\( E_p(t) \), \( E_s(t) \): electric field in the plasma and sheath

\[
E_s(t) = E_{app}(t) + \left[E_{app}(t) - E_p(t)\right] \cdot \frac{L - l_s^\infty}{l_s^\infty + \frac{2l}{\varepsilon}} \hspace{1cm} E_s^\infty = \frac{L + \frac{2l}{\varepsilon}}{l_s^\infty + \frac{2l}{\varepsilon}} E_{app}(t)
\]

\( n_e(t) \): electron density in the plasma

\[
n(t) = n_0 \left(1 + \gamma \frac{a - a^{E_p(t)/E_0}}{a \ln a}\right) \approx n_\infty \frac{a - a^{E_p(t)/E_0}}{a - 1}, \hspace{1cm} n_\infty = n_0 \left(1 + \gamma \frac{a - 1}{a \ln a}\right) \approx n_0 \gamma \frac{a - 1}{a \ln a}
\]

\( l_s^\infty \): steady state sheath thickness
Analytic and numerical solutions:
Electric field in the plasma and in the sheath

- Rapid field drop in the plasma after breakdown
- Dominant effect: plasma shielding by charging dielectric plates, sheath formation
- Steady-state electron density after shielding $n_e \sim 10^{12} \text{ cm}^{-3}$
- Steady-state sheath thickness / plasma thickness $\ll 1$
- Uniform field in the plasma
- Analytic and numerical solutions: excellent agreement
Analytic and numerical solutions: Electron density in the plasma and coupled power

- Most of the power coupled during breakdown pulse, $Q_{after} / Q_{break} \approx (\tau_{RC pulse})^{-1} \approx 0.1$
- Coupled pulse energy scales as the number density, can be increased by reducing $\tau_{pulse}$
- Pulse energies in N$_2$ and air are almost the same: attachment insignificant at short pulse durations
- Analytic and numerical solutions: excellent agreement
- Good agreement with pulse energy inferred from O atom measurements by Two-Photon LIF
Fast Ionization Wave (FIW) discharge
Test section schematic

Air, $P=10$ torr, $U_{\text{peak}} = 16$ kV
$\nu=10$ kHz, $L=20$ cm
Wave propagation velocity $\sim 4\text{ cm/nsec}$ (measured by capacitive probes)
Previous FIW discharge experiments
Moscow Institute of Physics and Technology (A. Starikovskii, S. Starikovskaya et al.)

Arrival time and amplitude of fast ionization wave in nitrogen, $P=24$ torr
Kinetic modeling of FIW propagation (quasi-1-D, long wavelength approximation)

- $E_y \ll E_x$
- Nitrogen, $P=10$ torr, $U_{\text{peak}}=25$ kV
- Channel height 1 cm, electrode gap 20 cm
- Both wave speed and peak electric field decrease along the length, $u=1-4$ cm/nsec
- Kinetic model needs to incorporate full Boltzmann equation, non-local kinetics effects. Collaboration with modeling experts welcome!
IR (E-Field) nsec CARS schematic and measurement region

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473nm Dichroic Mirrors

InSb

IR LP Filter

CaF₂ Lens

Beam Dump

IR Dichroic Mirror

476nm BP Filter

Focusing Lens

500mm CaF₂ Lens

Spectrometer

Camera

Delay Path

532 nm

Tunable Dye Laser

YAG

500mm Lens

Field Measurement Volume

CARS Energy Level Diagram

CARS Generated Along ~11 mm Line Segment (Determined using scanning microscope slide and NR background)

Non-Resonant CARS Signal vs Axial Location Relative to Nominal Waist
Preliminary raw IR nsec CARS data
(electric field measured between two plane electrodes
in atmospheric air, no breakdown)
Overview of new psec CARS system

Ekspla Nd:YAG laser
10 Hz, ~150 psec pulses
125 mJ per pulse max @ 532 nm

Modeless Psec Dye Laser
Broadband centered @ 607 nm
~ 6% conversion efficiency
Portable, broadband psec CARS diagnostic system
First sensitivity test of psec CARS:
Detecting N2 and CO in an optical absorption cell

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Most of CARS signal comes from inside the cell (20-30 shot signal accumulation)
Blue: 8 torr CO, 74 torr N2
Red: 9 torr CO, 120 torr Ar

Capable of detecting O2(a1Δ) generated in electric discharges (partial pressure ~1 torr)

Next sensitivity test: taking CARS spectra of N2-CO mixture vibrationally pumped by a c.w. CO laser
Here is what we expect to see (and more):
Spontaneous Raman Spectra in CO/N₂=4/96, P=400 torr (2001)

Laser power: 15 W, T≈500 K

5 vibrational levels of N₂, 40 vibrational levels of CO
(signal averaging over a few hundred pulses)
Work in Progress / Technical Issues

- New FIW discharge section still in glass shop
- Need an IR detector / 1-D detector array with short response time (~10 nsec)
- Need to determine sensitivity limit at low pressures and electric field
- Need to synchronize high voltage nsec pulses and CARS laser pulses and control pulse “jitter”
- Effect of EMI noise from the pulser on CARS system electronics yet to be determined