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Nanosecond pulse surface discharges for high-speed flow control

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Outline

I. Introduction: mechanisms of plasma flow control

II. Nsec pulse surface DBD discharges in quiescent air: effect on the flow, discharge characterization

III. Nsec pulse surface plasma actuators for separation control in subsonic flows

IV. Nsec pulse surface plasma actuators for shock wave control in supersonic flows

V. Modeling of nsec pulse, surface ionization wave discharges and coupling to compressible flow codes

Basic Plasma Flow Control Mechanisms and Challenges

I. EHD

- **Coulomb force interaction in AC DBD discharges: neutral flow entrainment by ions, boundary layer flow separation control, P ~ 1 atm, u_∞ ~ 10's m/s / M_∞ ~ 0.3-0.4**

II . "Brute Force" Localized Heating

- **High-power lasers, arc discharges: P ~ 1 atm, u_∞ ~ 500 m/s, high power budget. ~1 J/pulse at 100 kHz = ~100 kW**

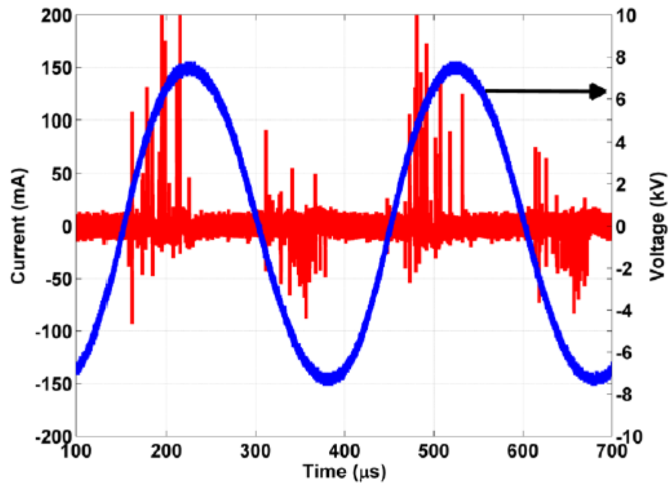
II(a). Repetitively Pulsed Heating

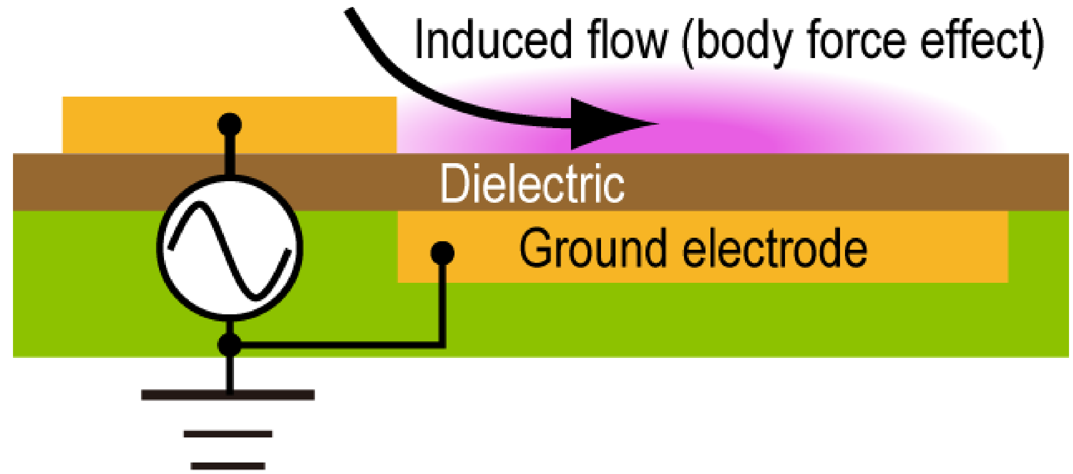
- **Targeting flow instabilities by localized arc filament plasma actuators (LAFPA): high amplitude heating / pushing at the right place, right frequency. Effective at low actuator powers (~10 W), P~1 atm, M=0.9-2.0**
- **Similar effect produced by low-T, nsec pulse plasmas (P=0.01-1 atm, M=0.1-5)**
- **Pulsed laser breakdown at low pulse energy, high rep rate (up to 100 kHz, U. Nagoya)**

Grand Challenge

High-speed flow control authority at low energy cost (boundary layer transition and separation, shock wave control, drag reduction, mixing enhancement)

EHD: Airfoil flow separation control by an AC DBD plasma actuator





Roth et al, AIAA Paper 2006-1203

Basic limitation: $\eta_{EHD} = \frac{\varepsilon_0 E^2}{\rho u_\infty^2} \cong \frac{e n_+ \Delta\varphi}{\rho u_\infty^2} \sim 1$ **(Coulomb force work / kinetic energy)**

Fundamental difference between AC DBD to NS DBD plasma actuators

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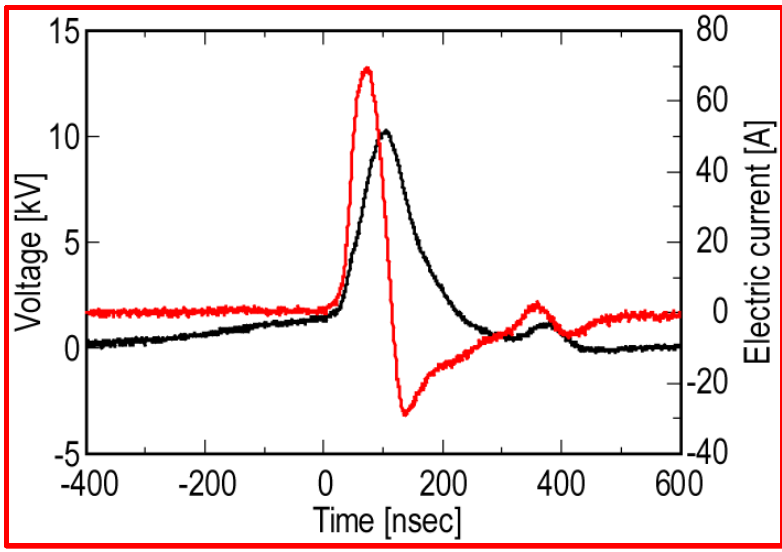
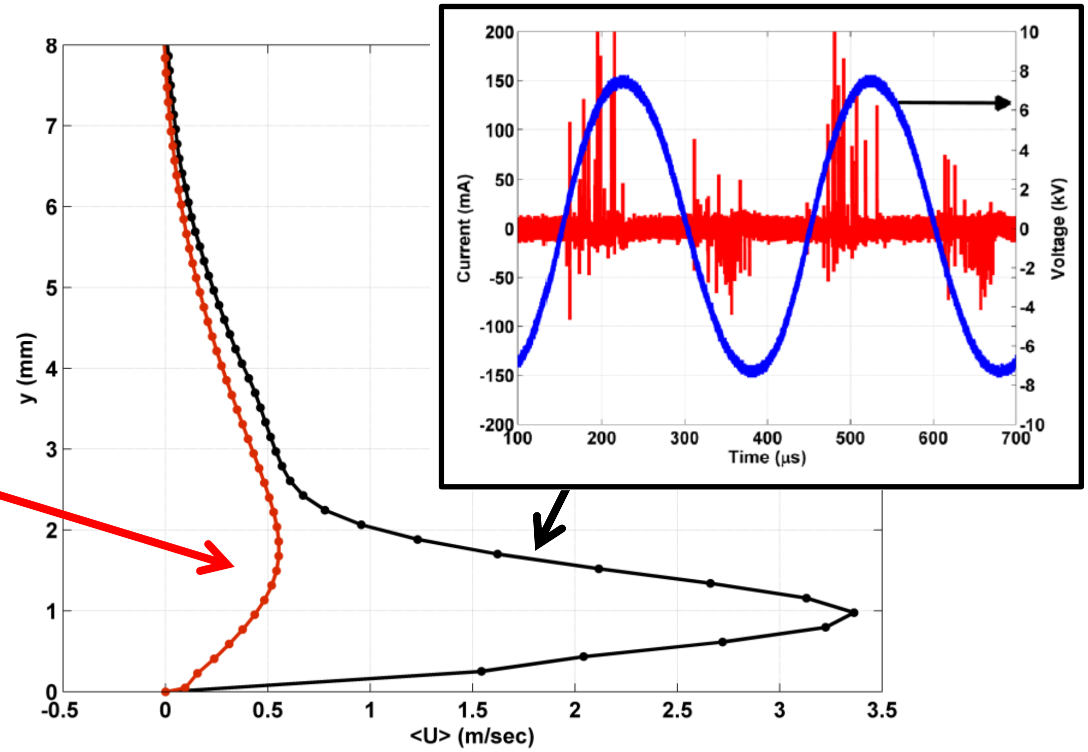
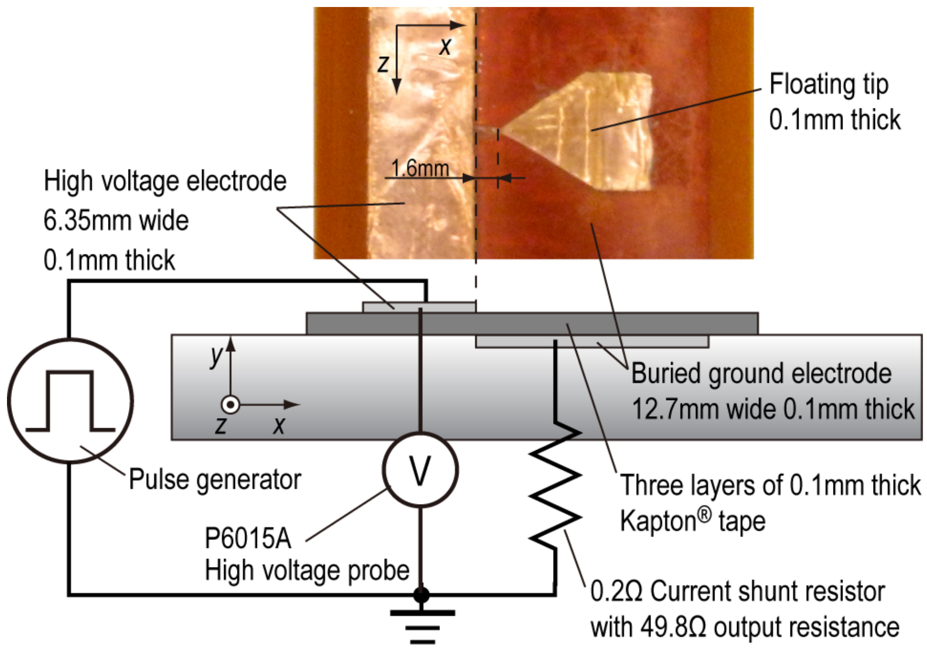
- **Previous work: airfoil flow separation control in transonic flows, M=0.74 (Roupassov et al. AIAA J., 2009)**
- **Recent work at Ohio State: pulse peak voltage 15 kV, FWHM 100 nsec, coupled pulse energy up to 50 mJ (up to 0.5 mJ/cm), rep rate up to 10 kHz**
- **How does this work? EHD force in NS DBD actuators is much weaker compared to AC DBD actuators**

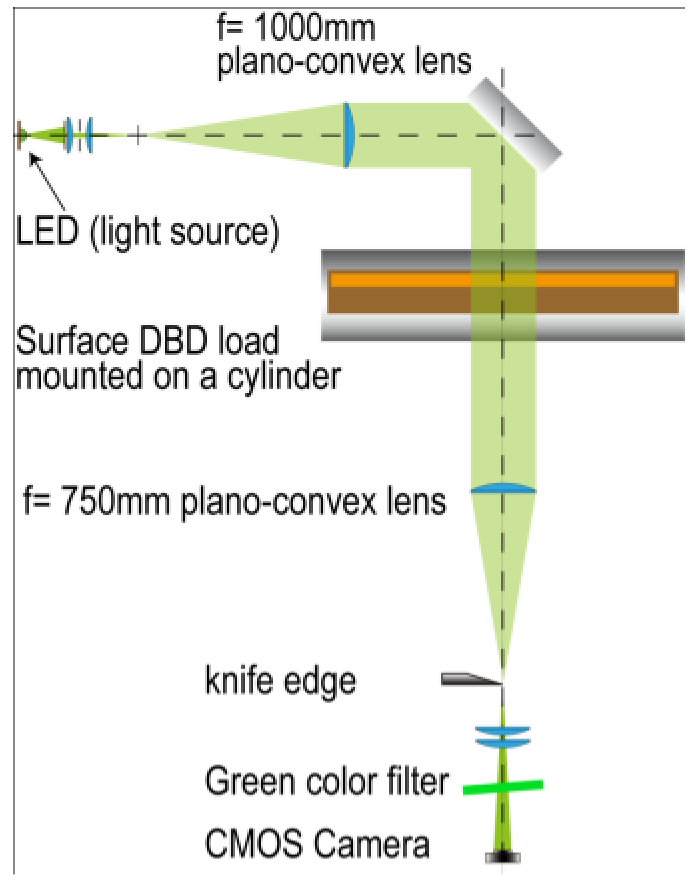


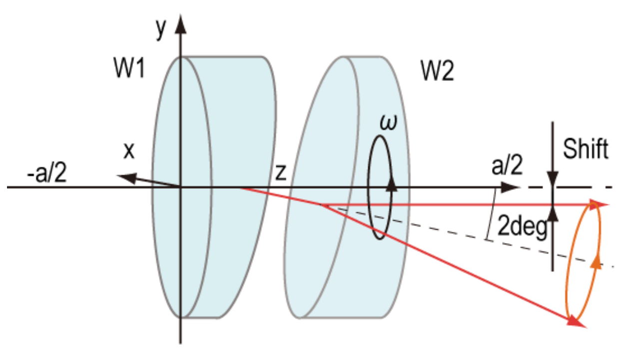


Little et al, AIAA J., 2012

NS DBD actuator operation and characterization in quiescent air







- **Coupled pulse energy (voltage and current waveforms)**
- **Compression wave formation, density gradient (calibrated, phase locked schlieren)**
- **Temperature (emission spectroscopy)**

NS DBD plasma actuator in quiescent air: Compression wave generation

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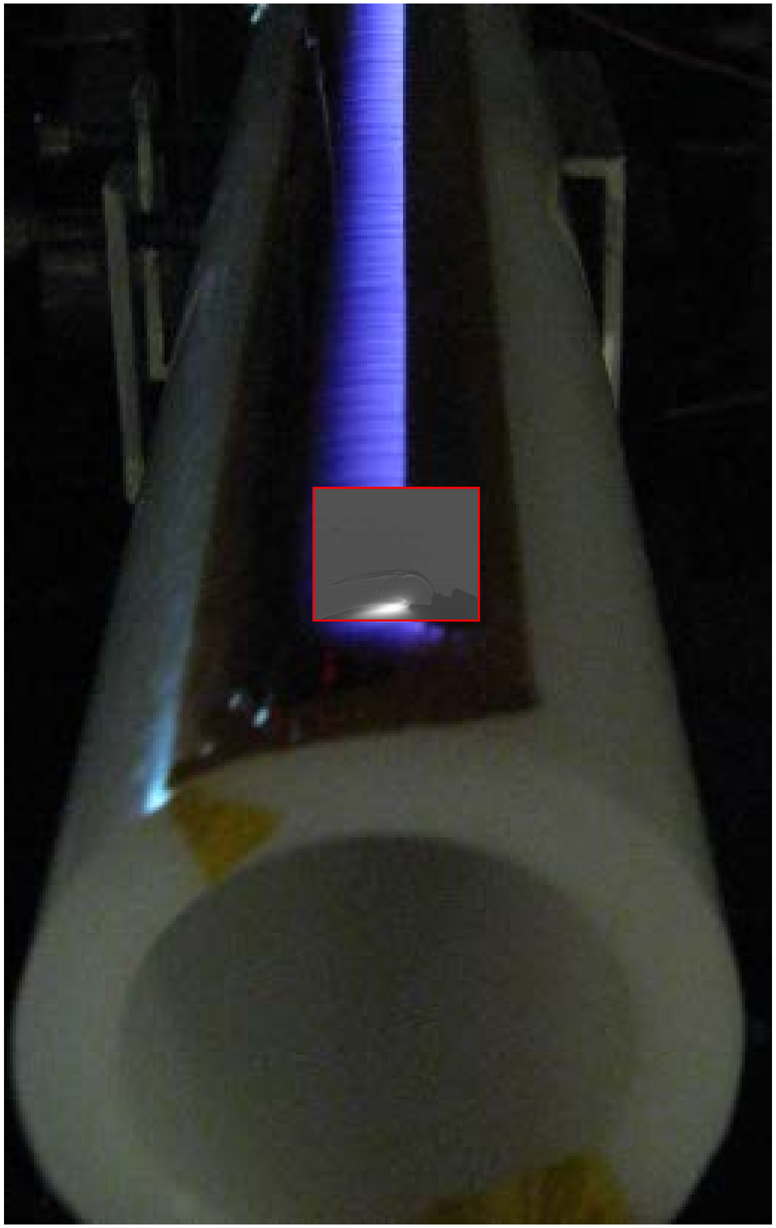
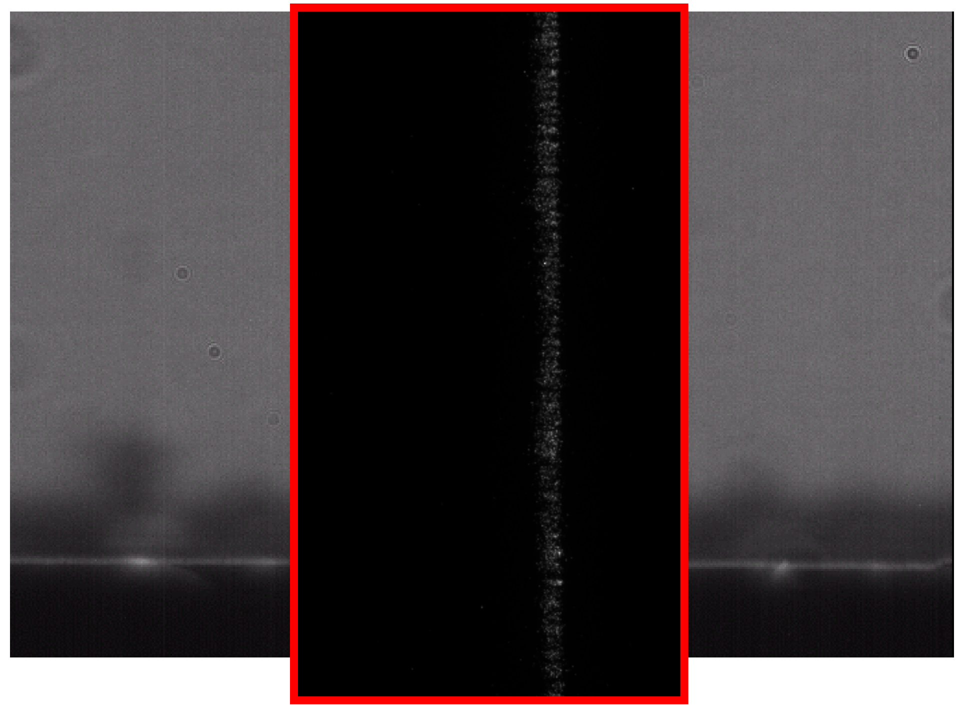
ν=1 kHz



ν=2 kHz



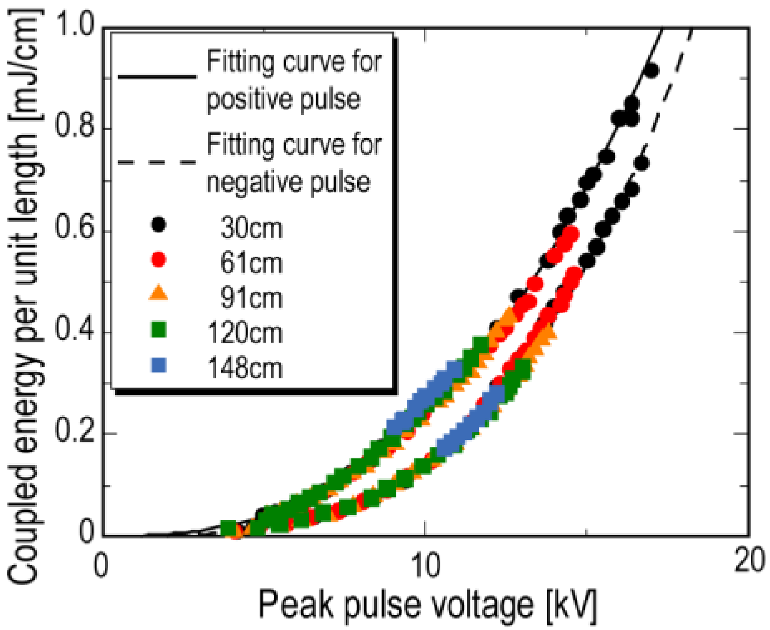
- Stronger waves generated by filaments
- Time delay between frames 5-10 ns
- Waves slightly supersonic near origin
- Surface ionization wave speed ~ 0.2 mm/nsec
- Thermalization time shorter than acoustic time:

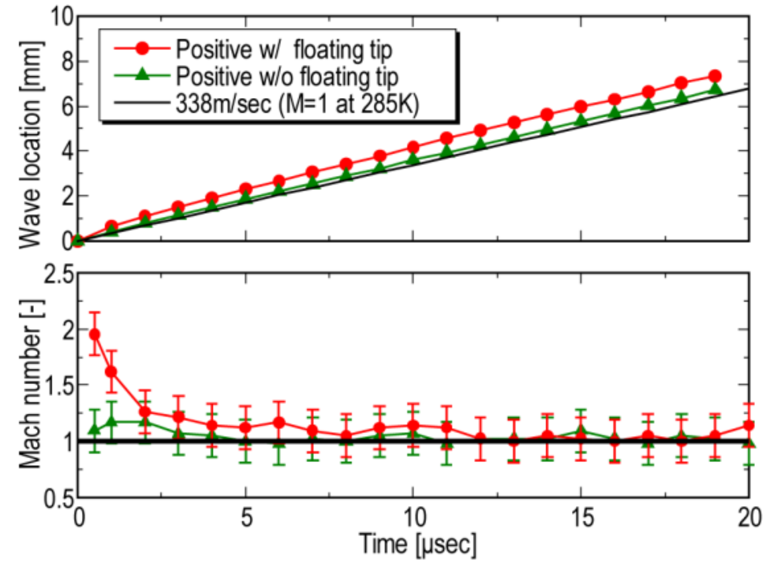
  τ_{acoust} ~ l/a ~ 0.1 mm / 300 m/s ~ 300 ns
- Complex structure near the surface
- Quasi-2-D structure in far field

Takashima et al, Plasma Sources Sci. Tech., 2011

OHIO STATE UNIVERSITY

Coupled pulse energy, compression wave speed, density gradient, and temperature



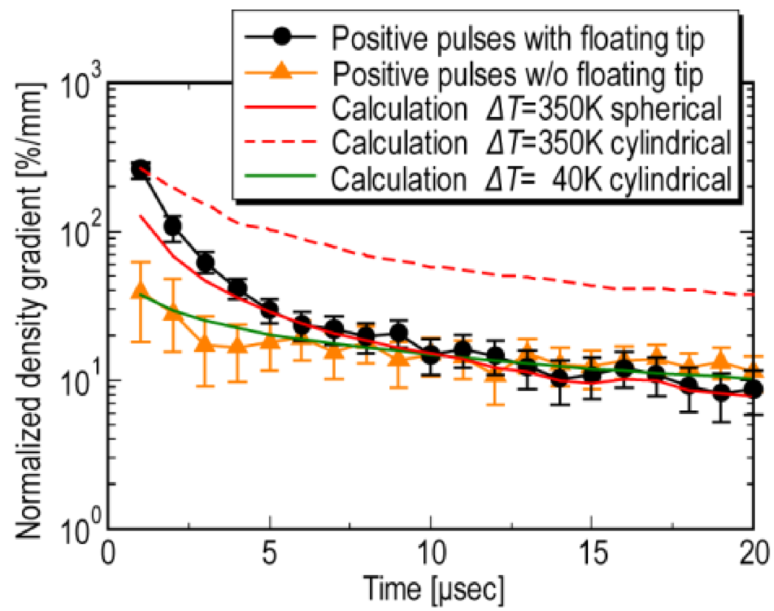


Energy coupled per unit actuator length controlled by pulse peak voltage, not by actuator length or voltage rise time

Compression wave Mach number: up to M=2 near the origin (with floating tip), decreases rapidly away from origin

Spatially averaged temperature from N_2* emission: T=380±50 K (pulse #1 in 50-pulse burst at 10 kHz), T=450±50 K (pulse #50)

Time-resolved , spatially-resolved temperature measurements:
<u>Essential but extremely challenging due to proximity of surface</u>



Takashima et al, Plasma Sources Sci. Tech., 2011

AIAA Paper 2012-3180, 10am Wed

T_{rot}, $T_v(N_2)$, and $N_2(v=0\text{-}9)$ measurements by psec CARS: energy thermalization in a nsec pulse discharge in N_2, air

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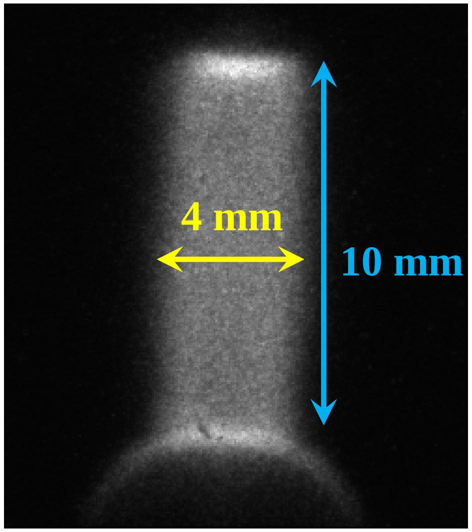

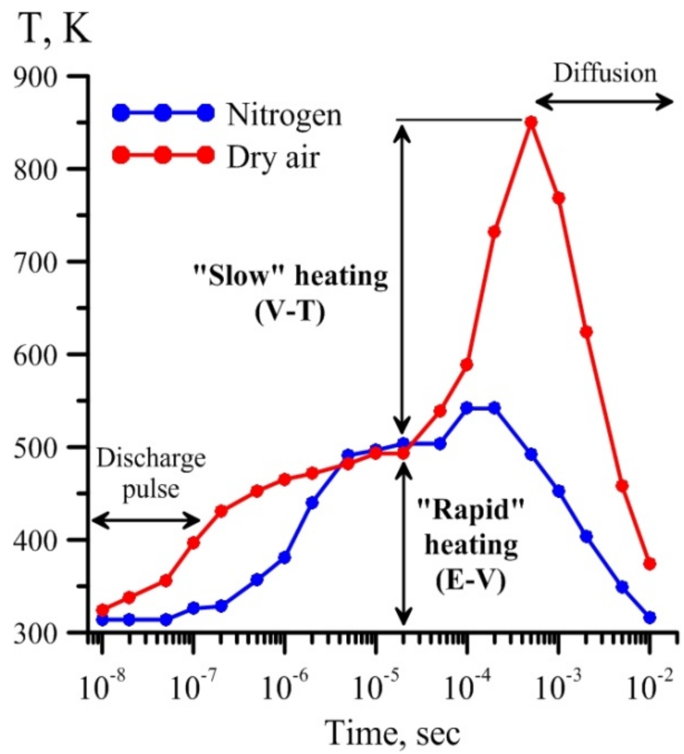

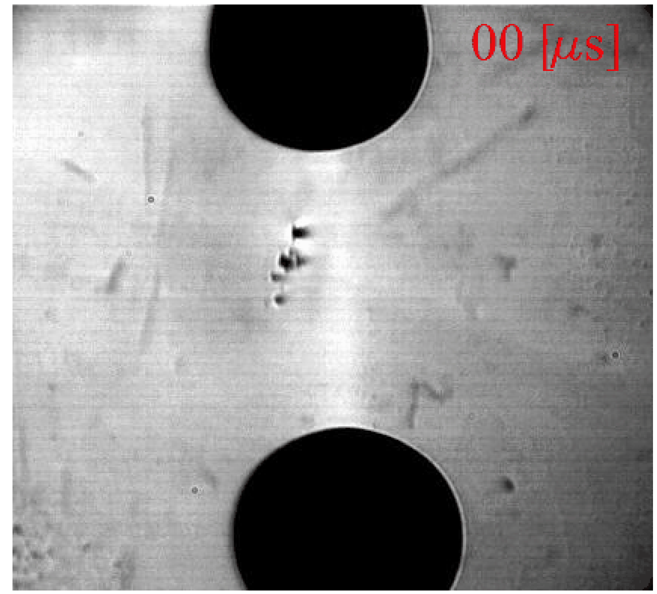

- **Point-to-point, nsec pulse, diffuse filament discharge in N_2 and air at 100 torr (not quite apples to apples). Coupled pulse energy 17 mJ/pulse (~0.3 eV/molecule/pulse).**
- **Note log scale on the time axis (6 orders of magnitude, 10 nsec to 10 msec)**
- **<u>"Rapid" heating:</u> quenching of electronically excited nitrogen, e.g. $N_2(A,B,C,a) + M \rightarrow N_2(X,v) + M$ (E-V processes). Acoustic time scale: ~3 μsec**
- **<u>"Slow" heating in air:</u> V-T relaxation by O atoms, $N_2(X,v) + O \rightarrow N_2(X,v\text{-}1) + O$. <u>Nearly completely absent</u> in N_2 where V-T relaxation is very slow.**

Effect of NS DBD perturbations on a subsonic flow

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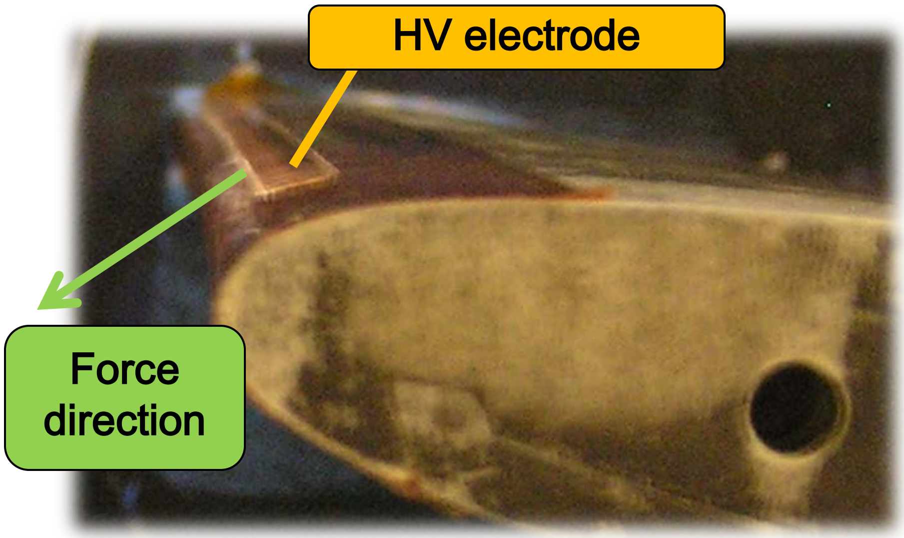

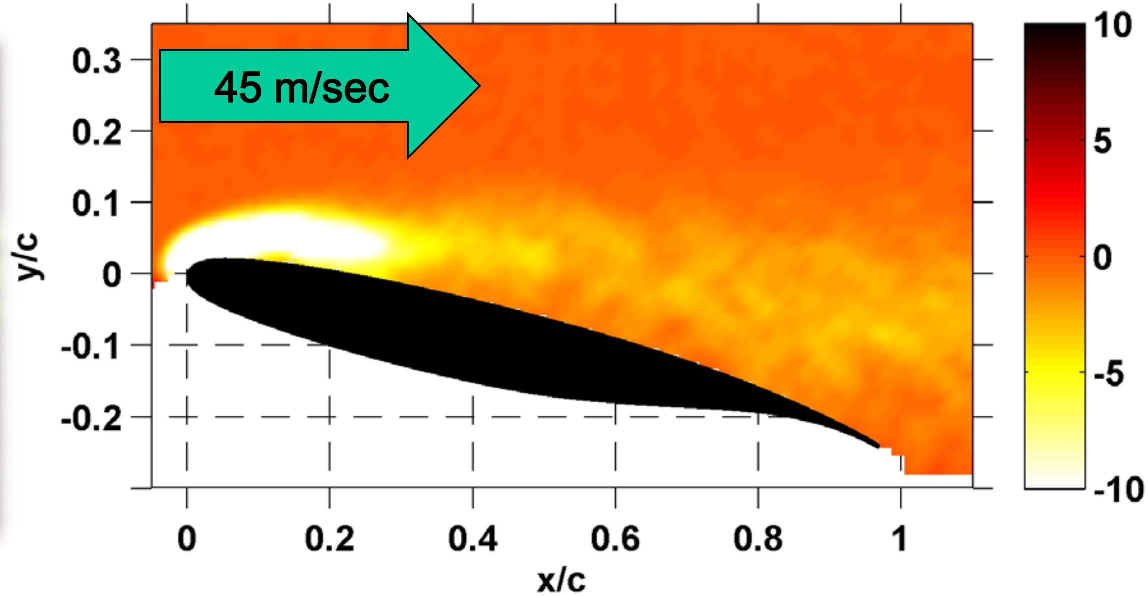

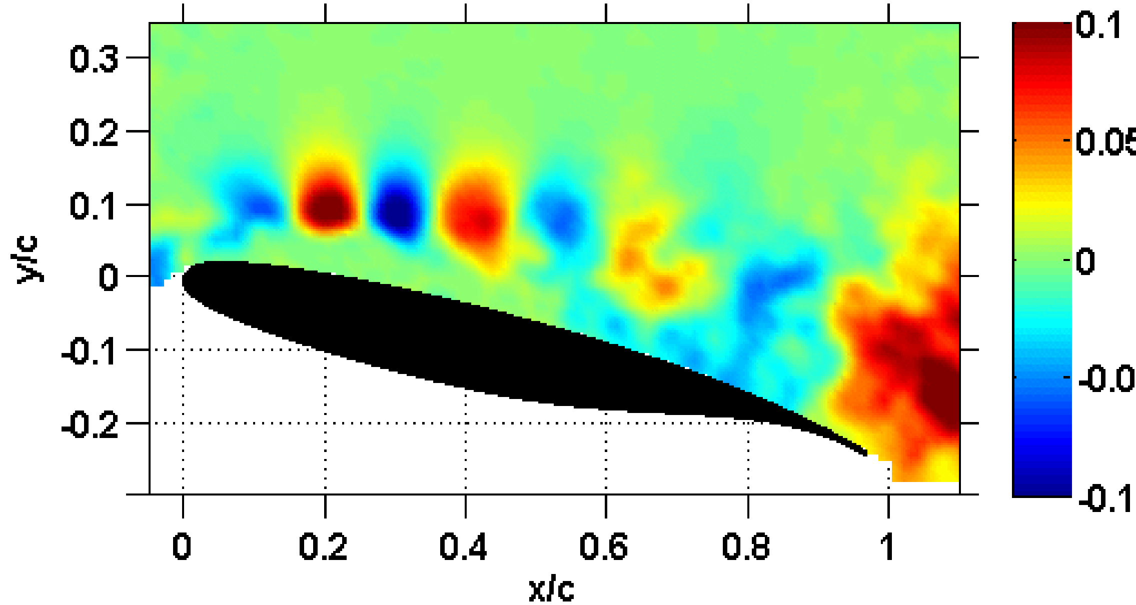

- Every nanosecond discharge pulse produces a robust spanwise vortex
- Enhanced mixing with free stream → boundary layer reattachment
- Same effect detected up to u=96 m/sec (M=0.28, Re_x~1.5 ·10^6)
- Consistently outperform AC DBD actuators at comparable power budget, ~0.1-0.3 W/cm

Little et al, AIAA J., 2012

Lift enhancement, separation control in flow over an airfoil

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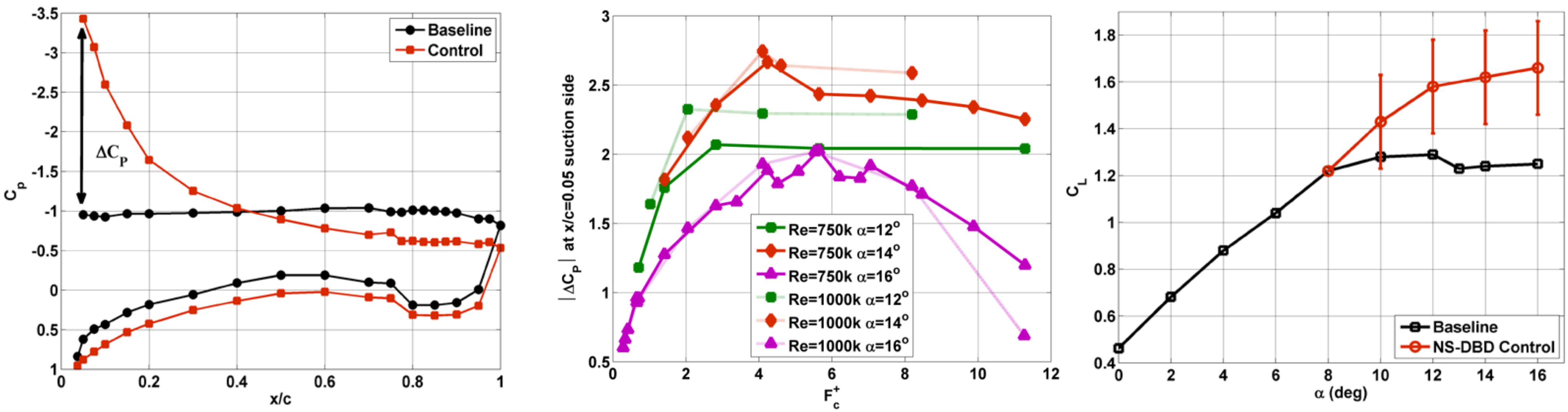

Little et al, AIAA J., 2012

- **Baseline and controlled C_P curves at Re=0.75·10^6, α=14°: significant C_P increase on suction side**
- **Effect of NS-DBD actuator forcing on ΔC_P on suction side at *x/c*=0.05: significant increase over a wide range of Strouhal numbers (forcing frequencies)**
- **Effect of NS-DBD actuator forcing on lift coefficient: significant C_L increase up to α=16°**
- **Similar results at Re=1.5·10^6, M=0.28**

Rethmel et al, AIAA Paper 2012-0487

Mach 5 bow shock control by a NS-DBD plasma actuator

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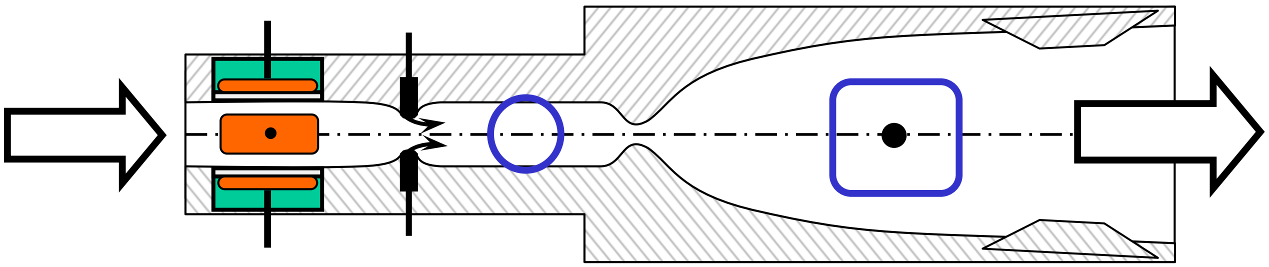
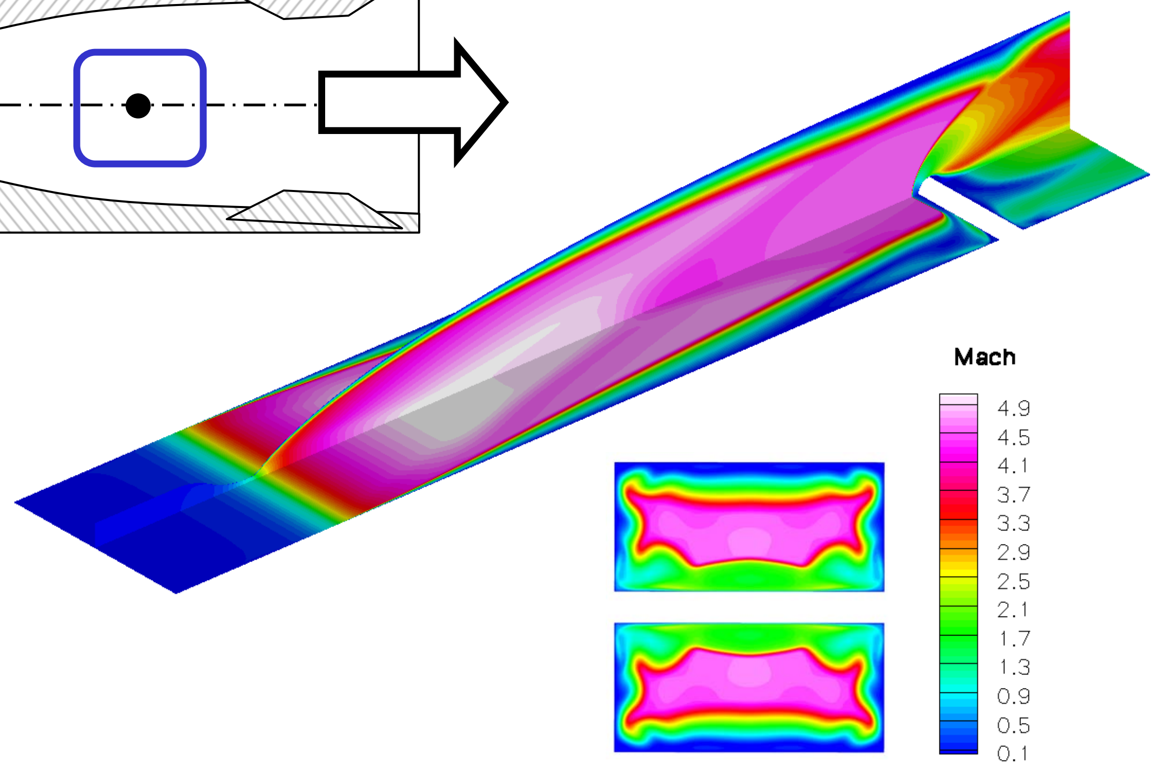
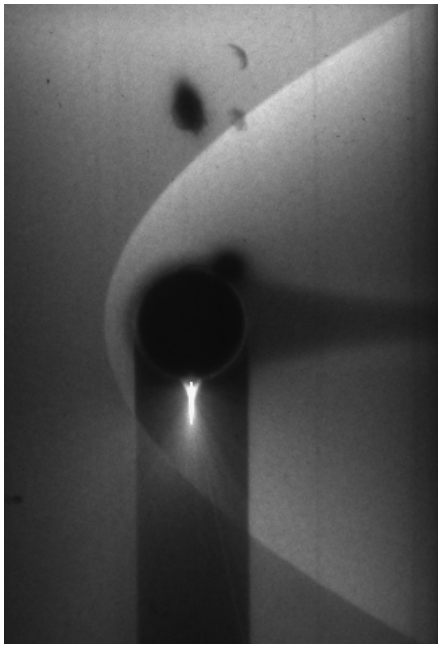




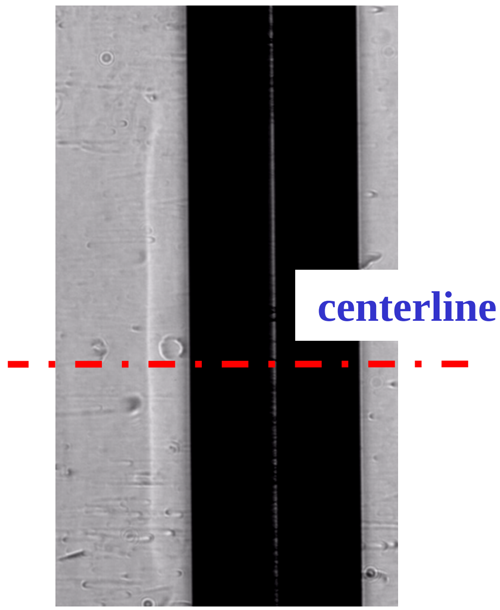
- Mach 5, steady state run time ~10 seconds, P_0=0.5-1.0 atm
- Test section cross section 4 cm x 4.6 cm, good flow quality (~50% inviscid core Mach 5 flow)
- Baseline operating conditions: dry air, P_0=370 torr, P_{TEST}=1.2 torr, M=4.6
- Quartz cylinder model in Mach 5 test section: 6 mm diameter, embedded in side wall windows
- Shock stand-off distance 1.2 mm, spanwise shock width 1 cm

Cylinder model / NS DBD actuator in a Mach 5 flow



NO PLIF image

Nitrogen, P_0=0.5 atm

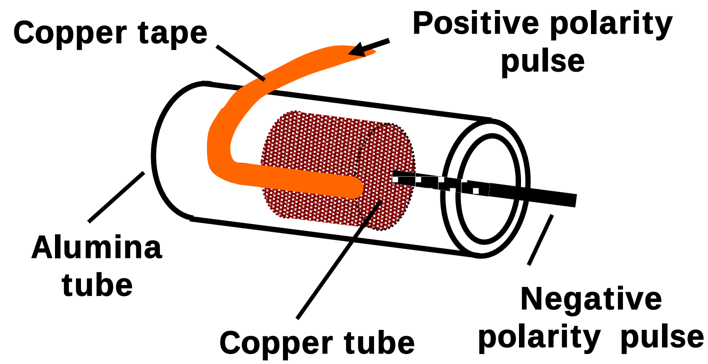


Schlieren image

Top view

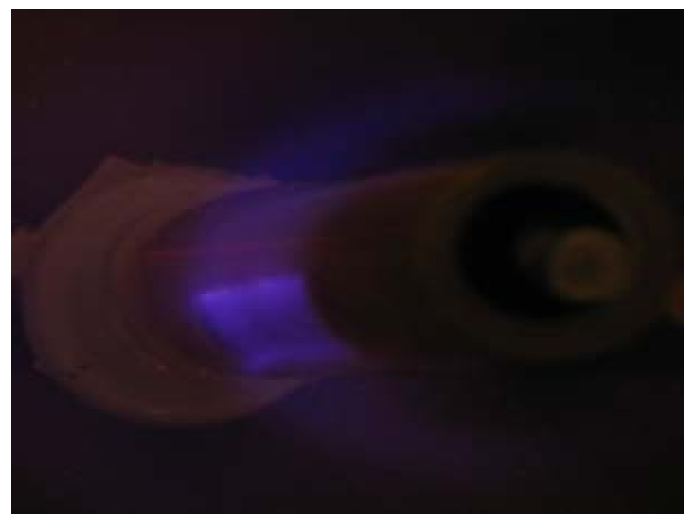
5 mm diameter model

Stand-off distance 1.2 mm



Cylinder model / NS DBD plasma actuator

- **Immersed electrode inside 6 mm quartz tube**
- **Exposed electrode: 1-3 mm wide copper strip**



Plasma span ~1 cm, test section width 4 cm

T_R=340±30 K, ΔT=50 K (N_2 emission spectra)

Nishihara et al, Phys. Fluids, 2011

Phase-locked schlieren

Air, P_0=370 torr, pulse repetition rate ν=200 Hz (“single pulse”)

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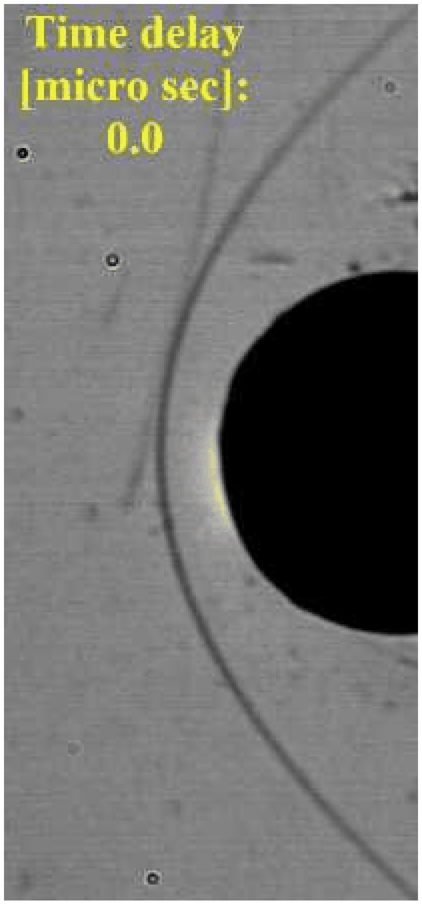

Phase-locked schlieren signal

Difference from baseline (taken at t=0)

- **Nsec discharge pulse: t=0 μs**
- **Compression wave formation: t=1 μs**
- **Wave propagation upstream: t=1.0-2.5 μs**
- **Compression wave reaches bow shock: t=3 μs**
- **Shock stand-off distance increase (up to 25%): t=3-5 μs**
- **Shock stand-off distance decreases: t=7-17 μs**

Nishihara et al, Phys. Fluids, 2011

Experiment and CFD

Pulse repetition rate ν=100 kHz (“quasi-continuous mode”)

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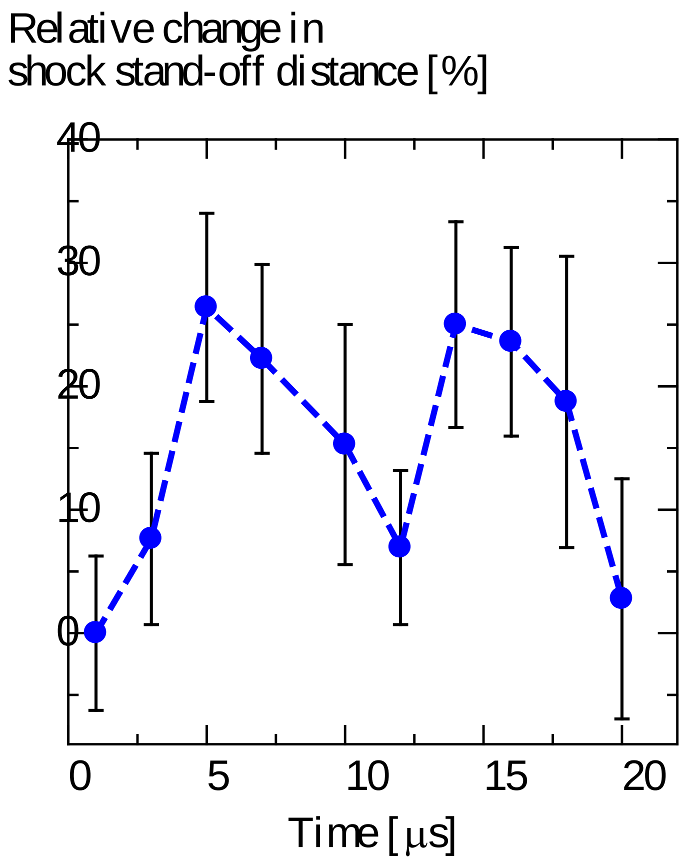
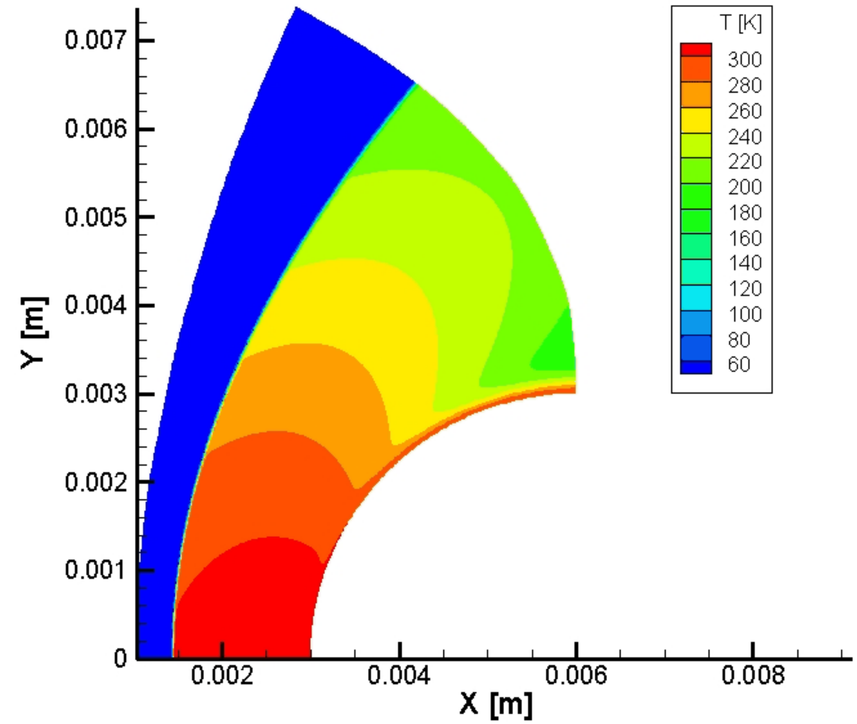


Experiment:

Discharge pulses fired at t=0 and 10 μs

7.3-7.8 mJ/pulse



CFD (LeMANS-MHD):

Best agreement with experiment for

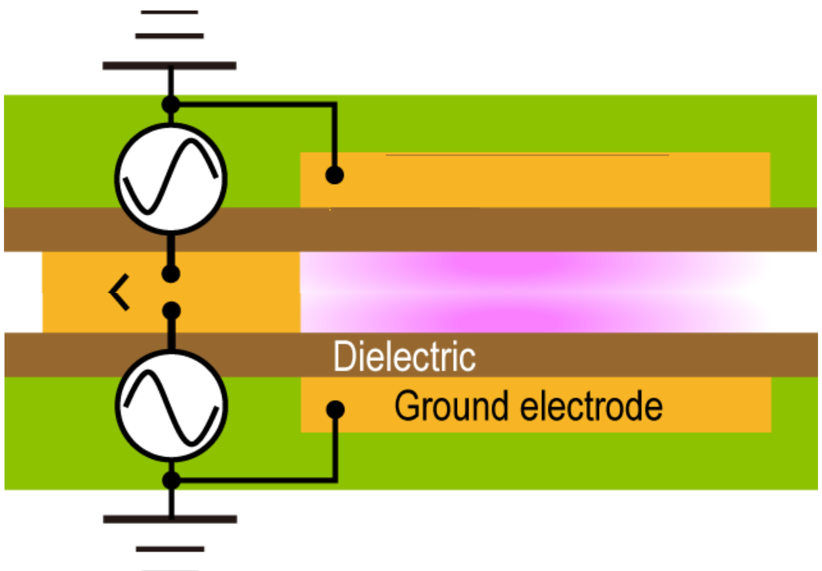
2.4 mJ/pulse dissipated over 800 nsec

(~30% of experimental value)

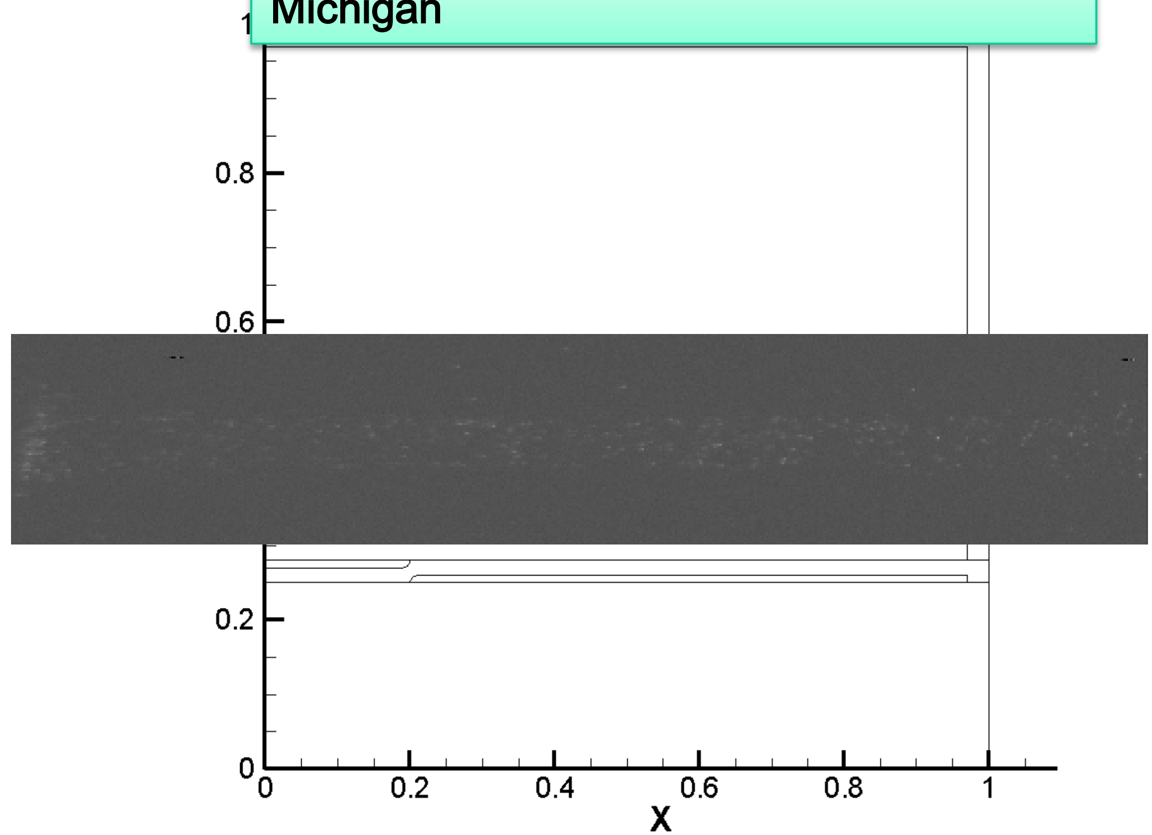
Nishihara et al, Phys. Fluids, 2011

Bisek et al, AIAA Paper 2012-0186

Challenge: surface ionization wave analysis in a nsec surface DBD plasma actuator (x,y,t problem)



Z. Andy Xiong and M. Kushner, U. Michigan



- Coupled surface DBD / Navier-Stokes numerical modeling: T. Unfer & J.-P. Boeuf, 2009
- Volumetric Fast Ionization Wave discharges in N_2 and air, P=10 torr, 10 kHz
- Coupling plasma kinetics (nsec scale) and flow (μsec to msec scale) is a formidable challenge
- 4 ns gate, 2 ns between frames, 1 cm channel height, 30 cm length, wave speed 0.5-1.0 cm/ns
- Looking for a self-simil ... nization wave

Takashima et al, Plasma Chem. Plasma Proc., 2012

AIAA Paper 2012-3093, 3:30pm Tue

Self-similar model of surface ionization wave discharge

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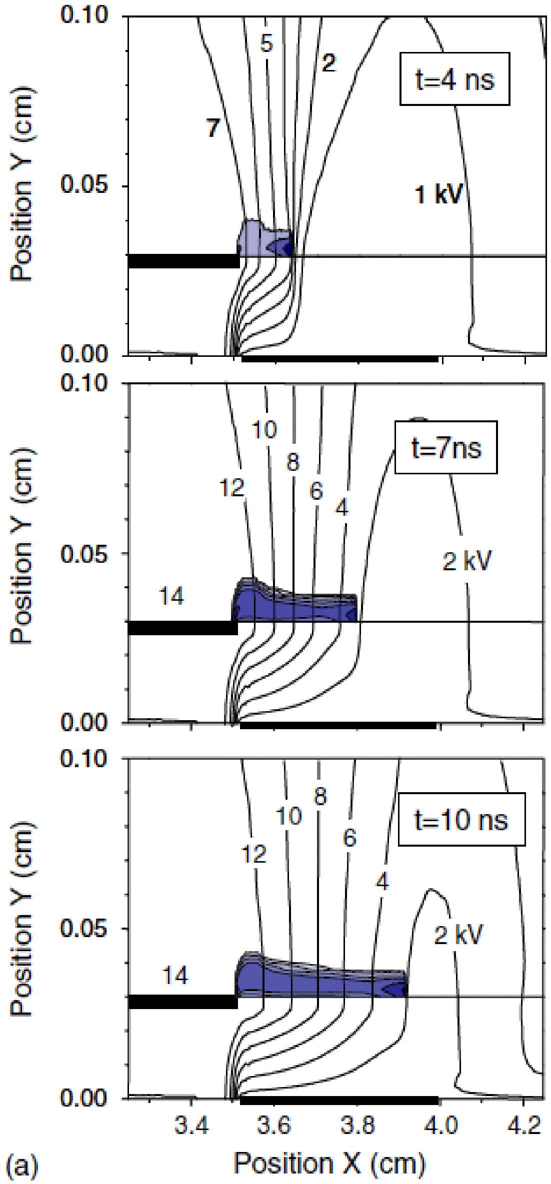
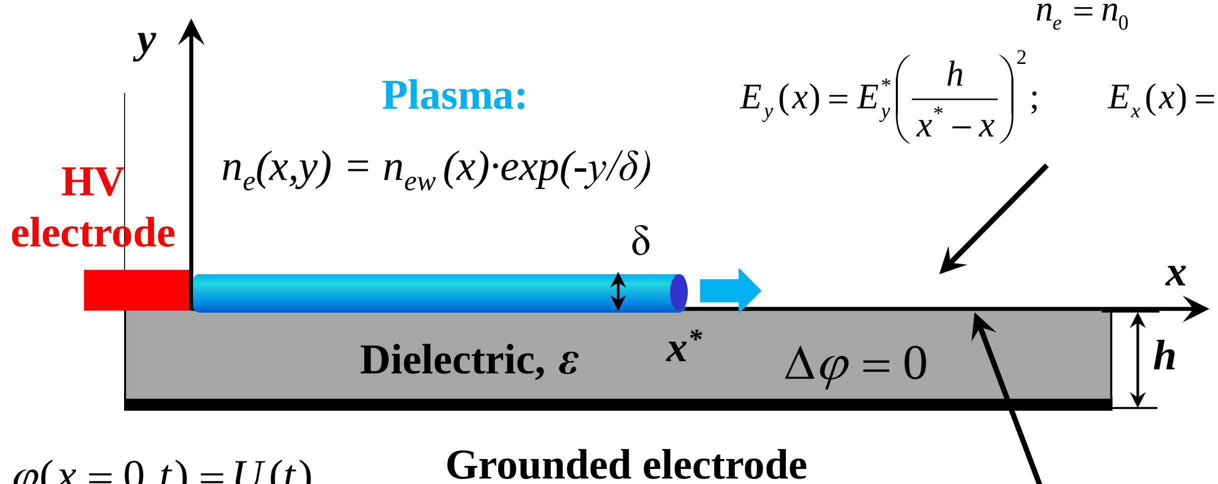


Unfer & Boeuf, J. Phys. D, 2009

Weakly pre-ionized region:

$n_e = n_0$

$E_y(x) = E_y^* \left(\frac{h}{x^* - x} \right)^2; \qquad E_x(x) = E_y^* \frac{2}{\varepsilon} \left(\frac{h}{x^* - x} \right)^3$



$n_e(x,y) = n_{ew}(x) \cdot exp(-y/\delta)$

$\varphi(x=0,t) = U(t)$

$j_{yw} = \varepsilon_o \frac{\partial}{\partial t} \left(\varepsilon E_{rw}^+ - E_{rw}^- \right)$

Field ahead of the wave created by space charge in the wave front

Ion motion, recombination insignificant on nsec time scale

ODE set: straightforward analytic solution possible

Wave speed (model input): related to voltage rise rate on HV electrode

$$\frac{dU}{dt} \approx E_{x\infty} V$$

Self-similar solution for surface ionization wave (top)
Comparison with 2-D numerical calculations (bottom)

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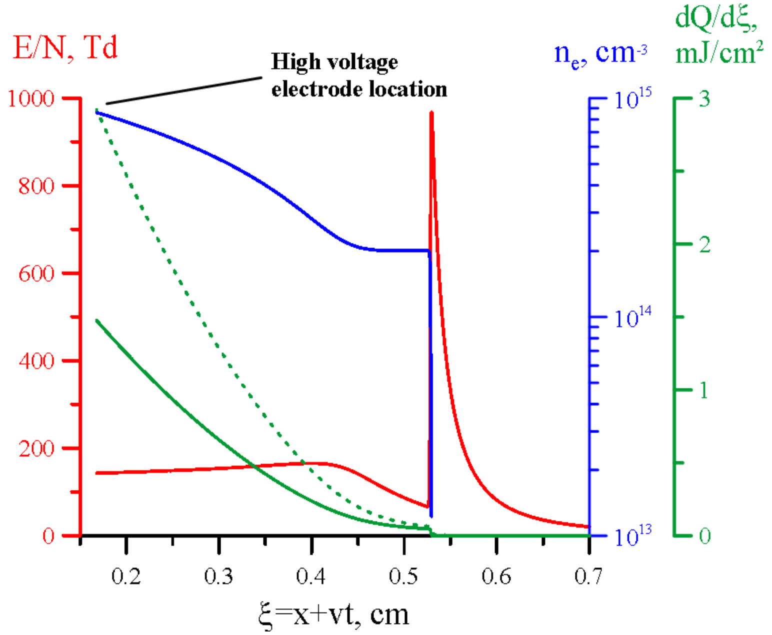
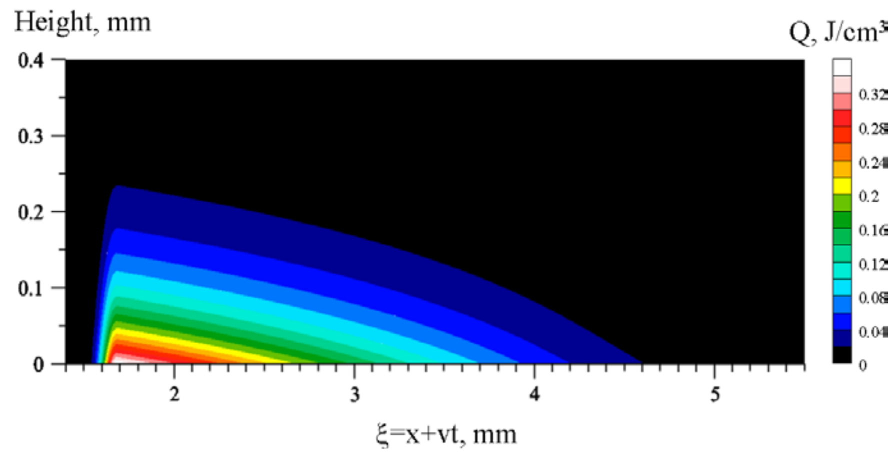
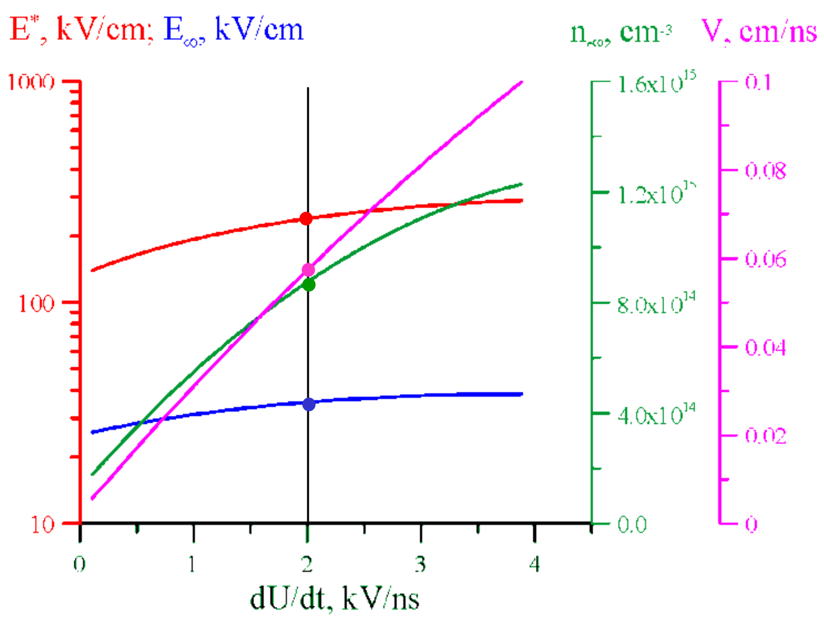
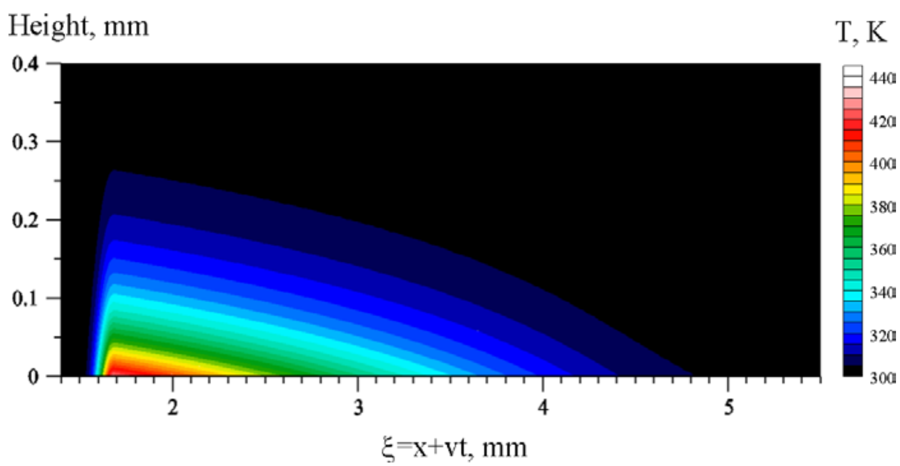






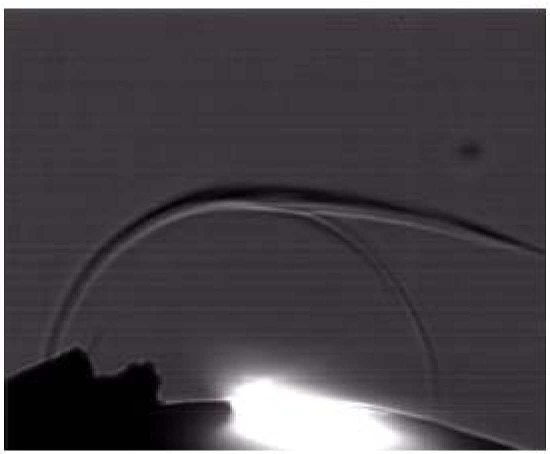
U_{peak}=14 kV dU/dt=2 kV/ns	2-D numerical	1-D self-similar
E_{peak}, kV/cm	≈200	230
E_∞, kV/cm	28	35
$n_{e,\infty}$, cm^{-3}	$1.1\cdot10^{15}$	$0.9\cdot10^{15}$
V, cm/nsec	0.05	0.057
I_{peak}, A	10	12
δ, μm	≈100	82
L, mm	3.0	3.6
Q, mJ/cm	0.48	0.38

Predicted 2-D temperature distribution: can be used to reproduce compression wave shape in quiescent air



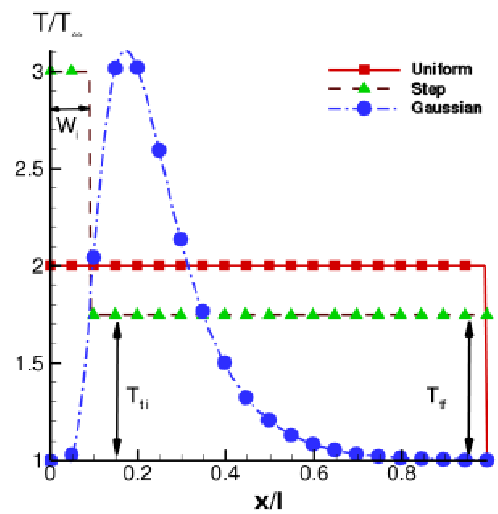
$$\Delta T(L) \approx \frac{2\eta}{\rho c_v \delta} \frac{dQ(\xi)}{d\xi}\bigg|_{\xi=L} \qquad \eta \approx 0.3$$

Present model prediction

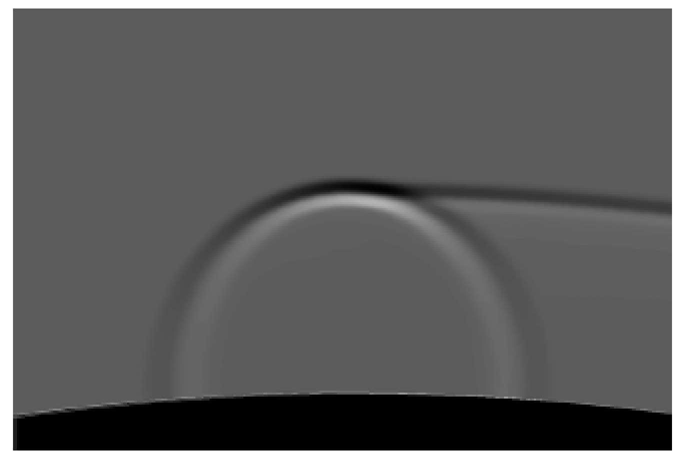


Experiment

Takashima et al, PSST, 2011



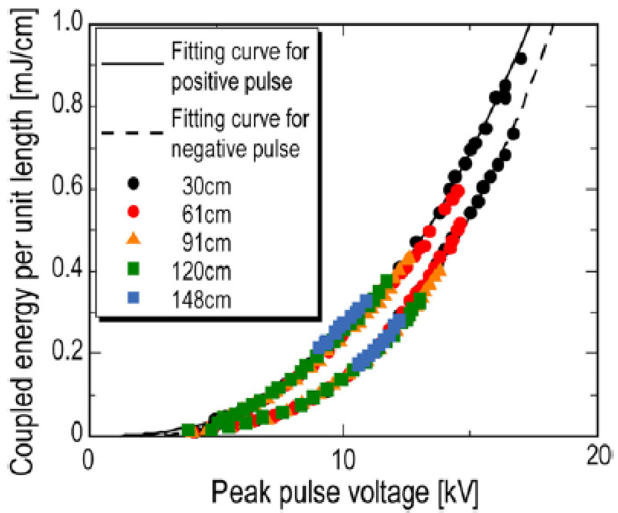
Surface temperature distributions tested



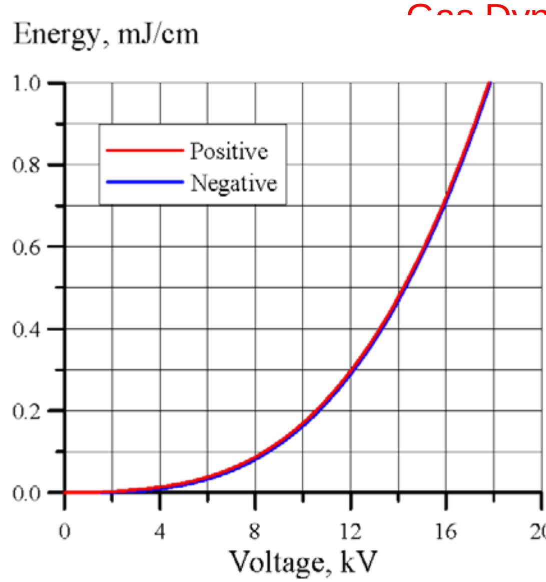
Code prediction for Gaussian distribution

Gaitonde, AIAA Paper 2012-0184

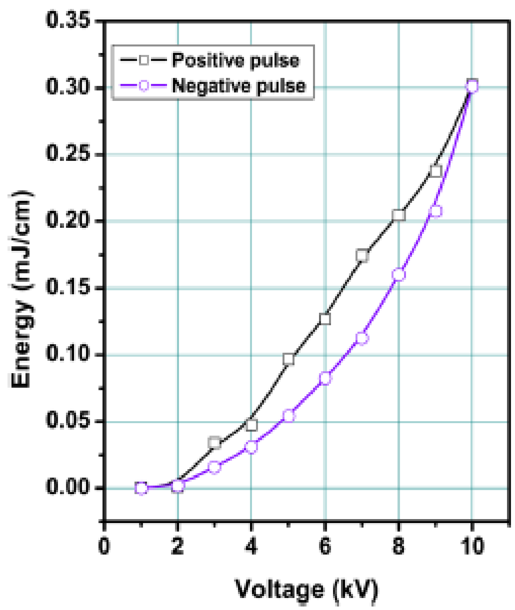
Comparison with experimental results: energy coupled per pulse



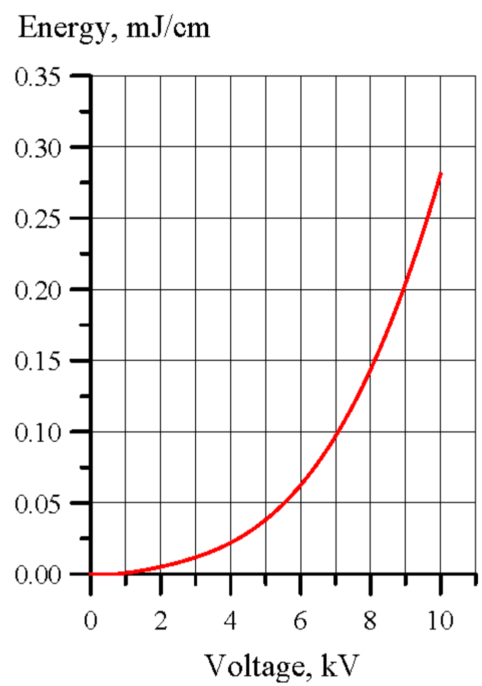
Takashima et al., PSST, 2011



***dU/dt*=0.32 kV/ns**
(*V*=0.12 mm/ns)

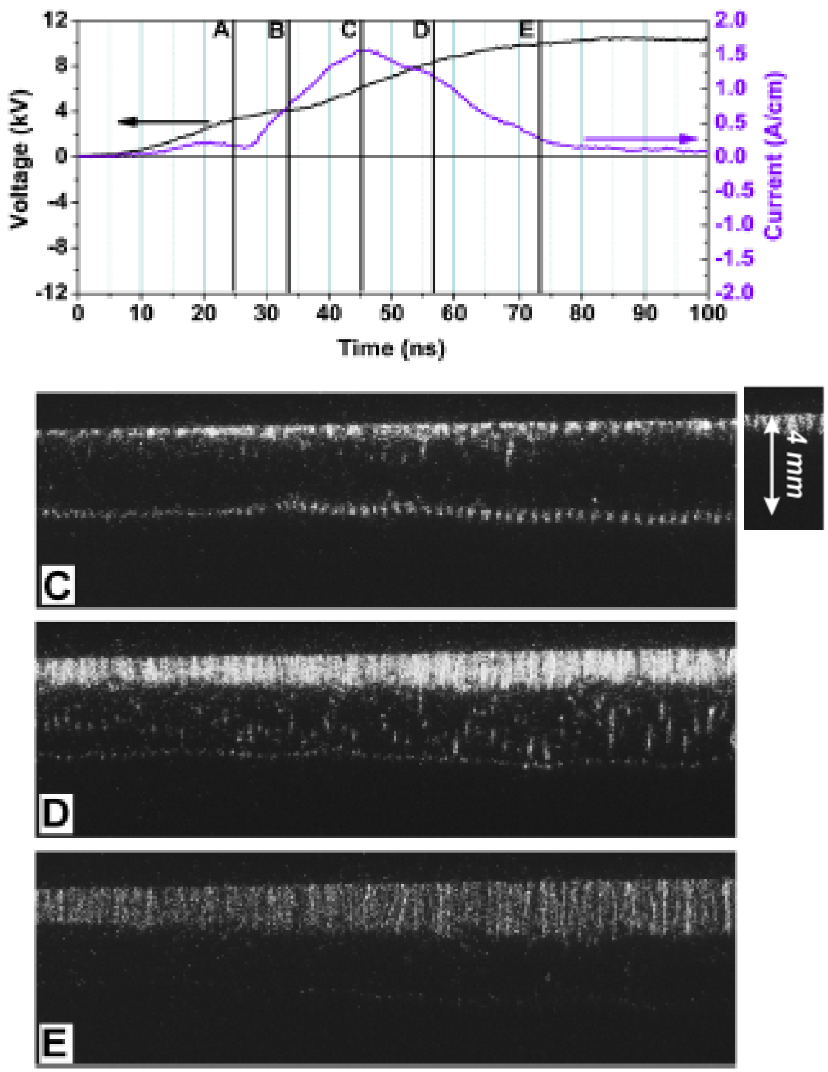


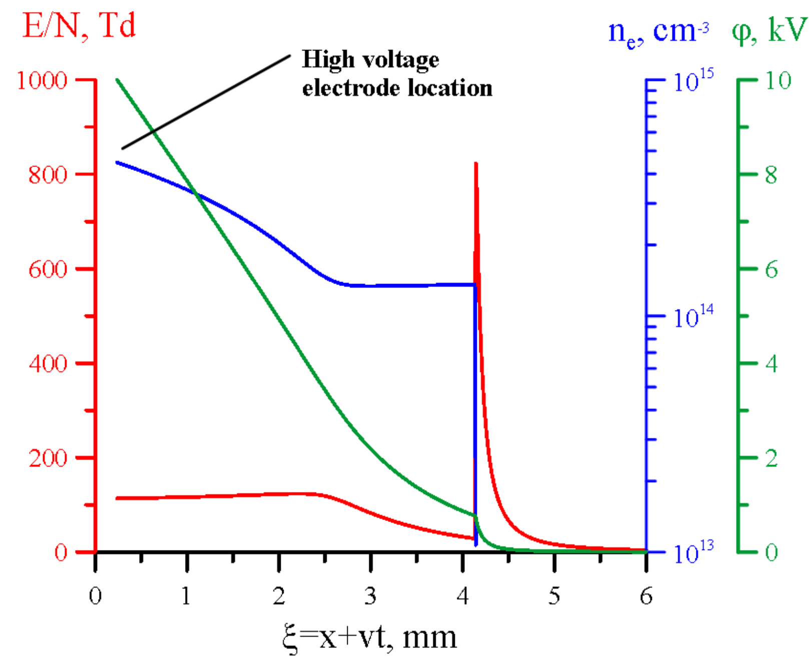
Benard et al., J. Appl. Phys., 2012



***dU/dt*=0.2 kV/ns**
(*V*=0.083 mm/ns)

Comparison with experimental results: “double” ionization front in a positive polarity wave





dU/dt=0.2 kV/ns
(V=0.083 mm/ns)

Benard et al., J. Appl. Phys., 2012

Summary / future outlook

- Surface nsec pulse discharges: evidence of energy thermalization on nsec time scale, high-amplitude pressure perturbations (compression wave generation)
- Formation of large-scale, coherent structures in the flow, significant flow control authority
- Nsec pulse DBD plasma actuators are effective at high flow Mach numbers & low actuator powers, scalable to large dimensions (~1 m)
- Reduced-order self-similar model of surface FIW discharge: good qualitative agreement with 2-D numerical calculations, experimental results
- Model allows closed-form analytic solution, coupling to existing time-accurate, compressible flow codes
- How is control authority affected by boundary layer thickness, boundary layer turbulence, free stream turbulence?
- Are NS DBD actuators effective in jet flows, shear layers, SWBLI flows?
- How does control authority scale with static pressure and temperature?
- How does control authority scale with pulse energy? What is the optimum pulse waveform?

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