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Thermal perturbations generated by near-surface electric discharges and mechanisms of their interaction with the airflow

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Outline

I. Background / Introduction

II. Kinetics of energy transfer and thermal perturbations in surface and volumetric ns pulse discharges

III. Effect of localized heating on formation of flow structures, implications for high-speed plasma flow control

IV. Effect of accelerated vibrational relaxation on nonequilibrium flow field, implications for high-speed flow control

V. Summary and future outlook

Plasma Flow Control Mechanisms and Challenges

I. EHD body force

- Coulomb force interaction in AC DBD discharges: neutral flow entrainment by ions. Low-speed boundary layer flow separation control.

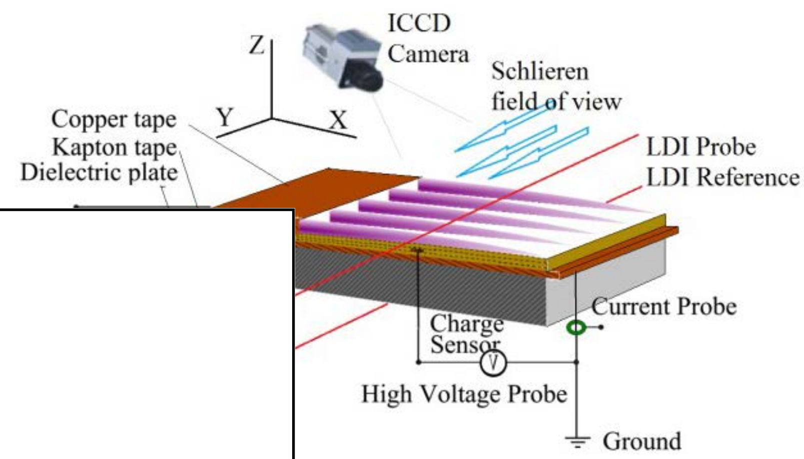
II. Repetitive Localized Heating

- Localized arc filament plasma actuators (LAFPA): inducing flow instabilities. Effective at low actuator powers, up to M=0.9-2.0
- Ns pulse surface plasma actuators (NS-DBD): coherent structures formation, boundary layer reattachment in low-temperature, ns pulse plasmas (up to M=0.3)

Goal

High-speed flow control at low energy cost, over a wide range of flow geometries, Mach and Re numbers: boundary layer transition and separation, shock wave control, drag reduction, mixing enhancement

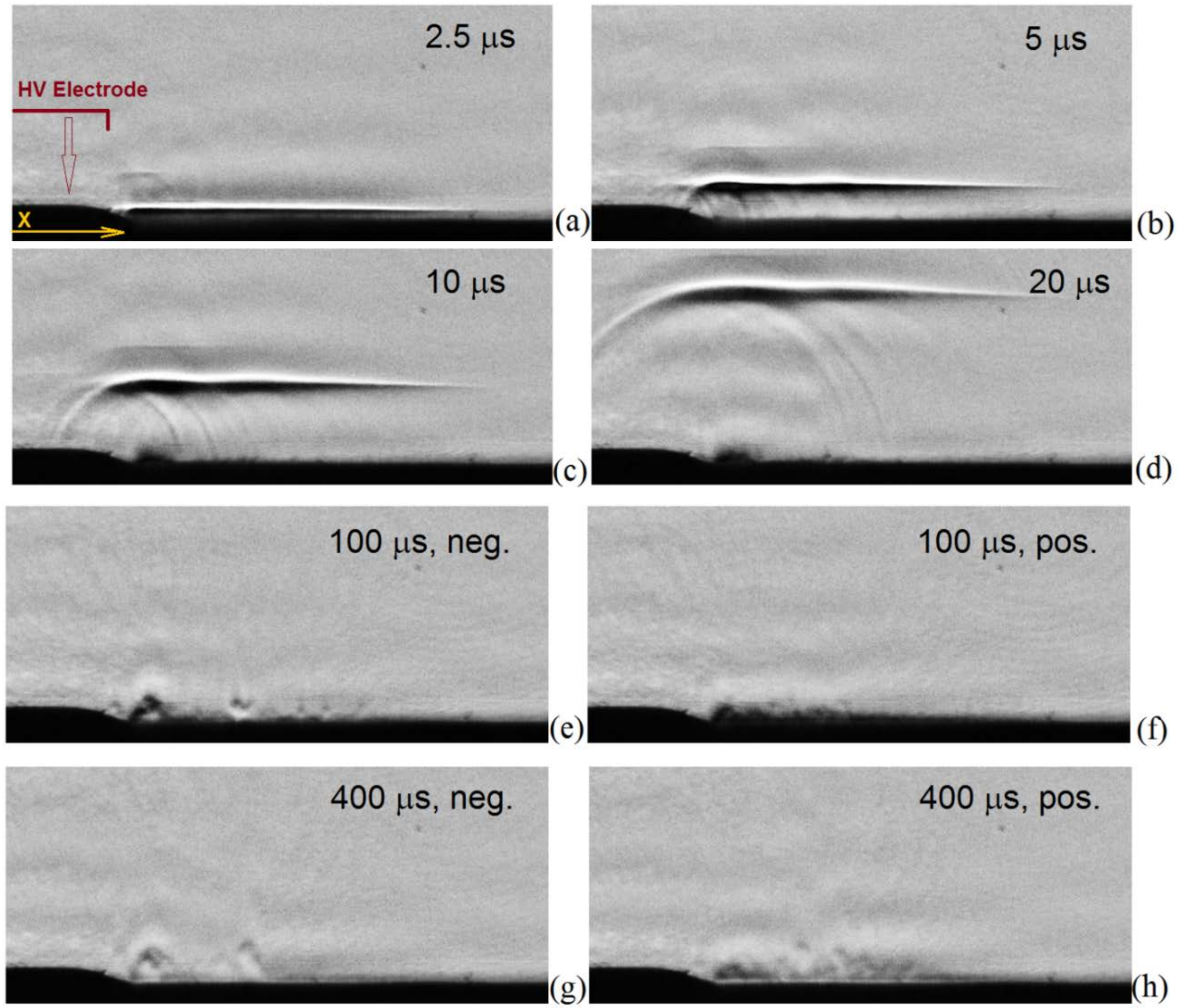
Schlieren visualization of a NS-DBD plasma actuator operated in quiescent air



Leonov et al, J. Phys. D: Appl. Phys., 2014

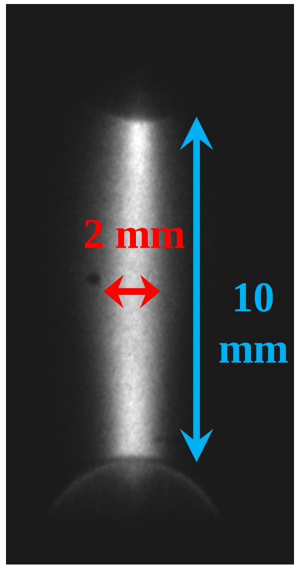
Schlieren visualization of a NS-DBD plasma actuator operated in quiescent air

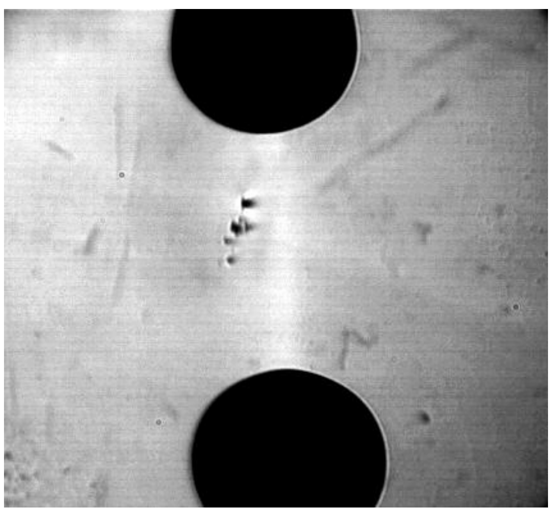
Leonov et al, J. Phys. D: Appl. Phys., 2014



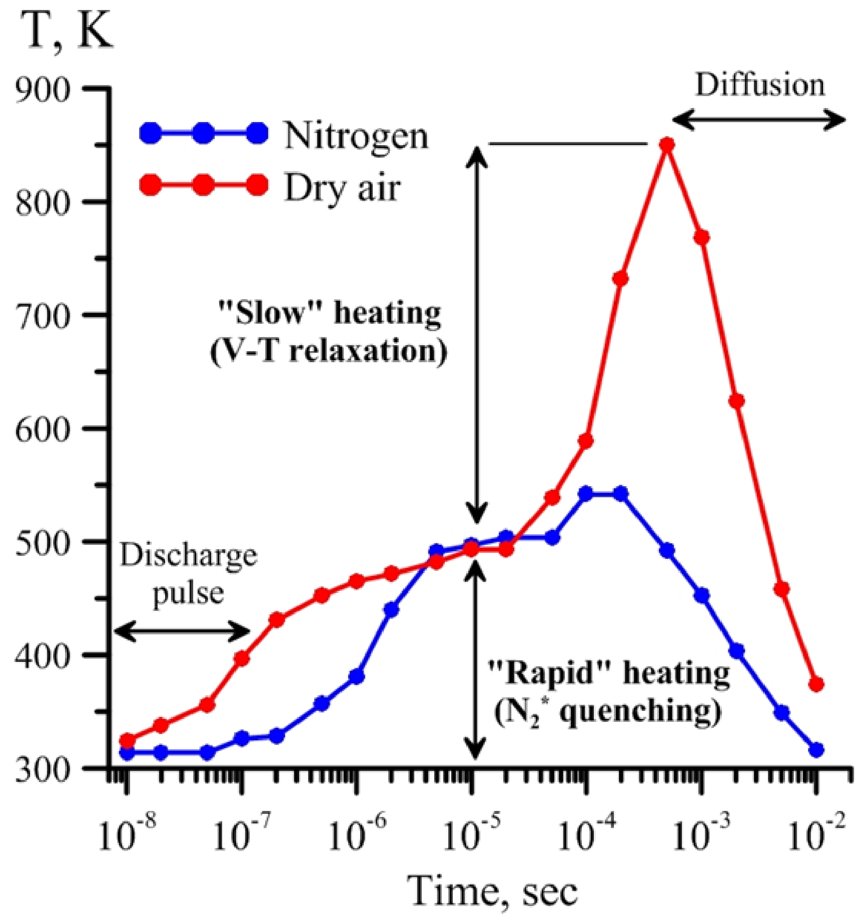
- Heating in the discharge: compression wave formation on μs time scale
- Residual heating: late small-scale random perturbations on ~ 0.1-1 ms time scale
- What are the kinetics involved? Which one is important for plasma flow control?

Temperature dynamics in volumetric ns pulse discharge filament in air (P=100 Torr)





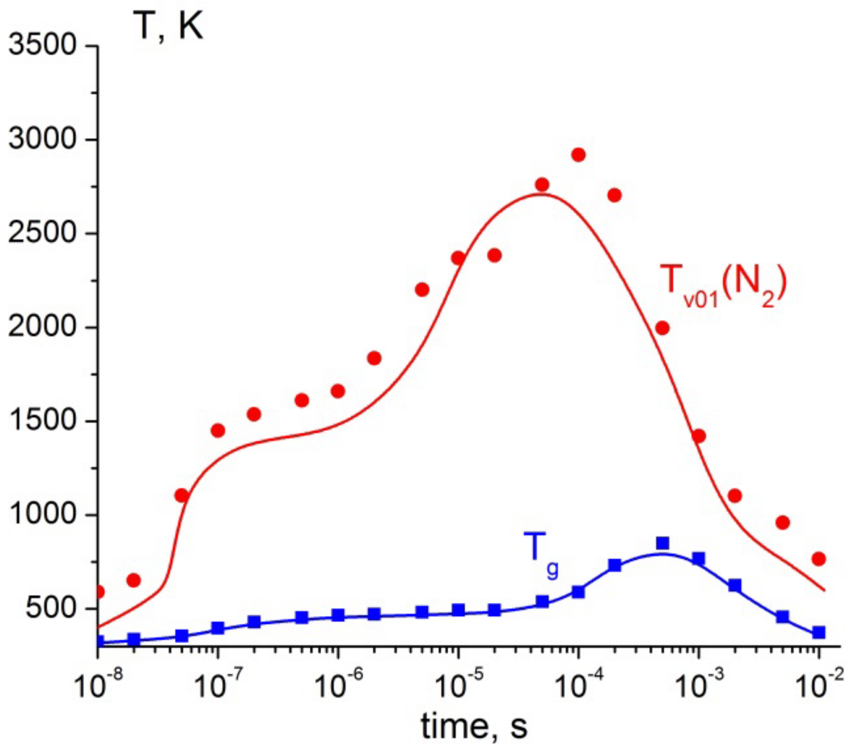
t= 1-10 μs (frames are 1 μs apart)

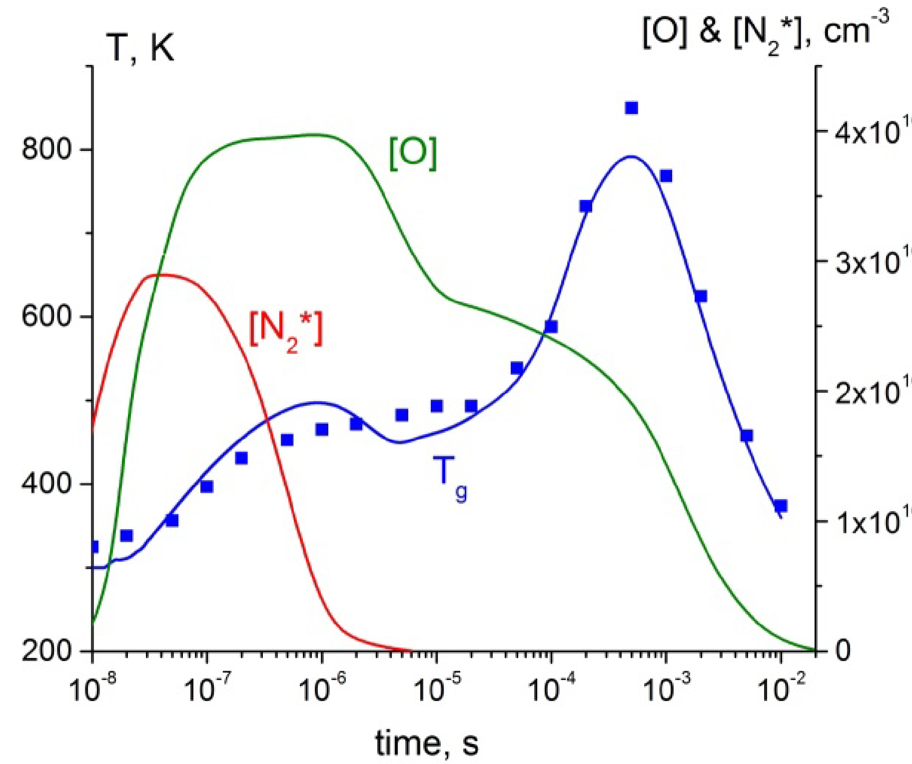


Montello et al, J. Phys. D: Appl. Phys., 2012

Montello et al, J. Fluid Science and Technol., 2013

Energy transfer and temperature dynamics in discharge and afterglow in air are well understood

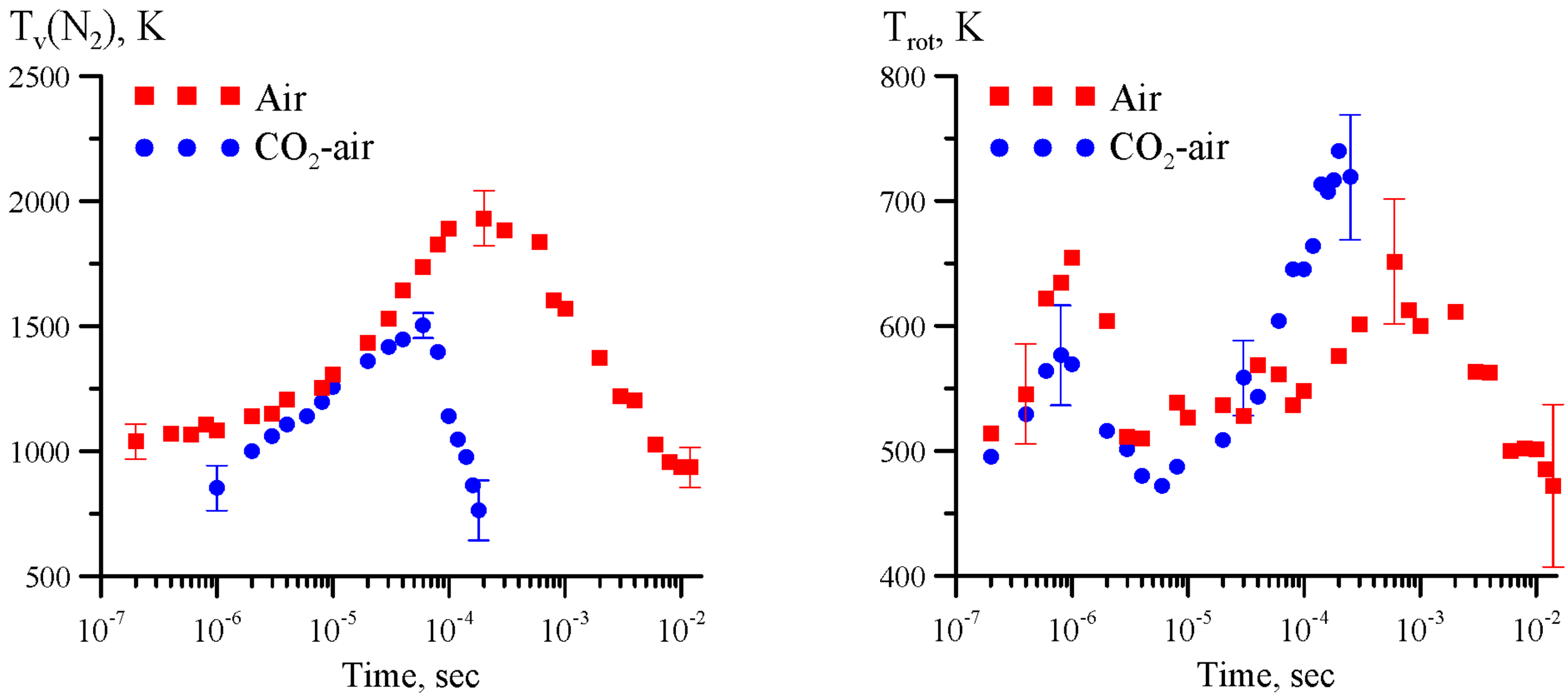




- T_v rise in early afterglow: V-V exchange, $N_2(v) + N_2(v=0) \rightarrow N_2(v-1) + N_2(v=1)$
- T_v decay in late afterglow: V-T relaxation, $N_2(v) + O \rightarrow N_2(v-1) + O$
- "Rapid" heating: quenching of N_2 excited electronic states, $N_2^* + O_2 \rightarrow N_2(X) + O + O$
- "Rapid" heating: pressure overshoot on centerline, compression wave formation
- "Slow" heating: V-T relaxation, $N_2(X,v) + O \rightarrow N_2(X,v-1) + O$
- "Slow" heating: affecting "late" random perturbations"?

Shkurenkov et al,
Plasma Sources Sci. Technol., 2016

Adding CO_2 (efficient V-T relaxer) to air: accelerating "slow" heating rate

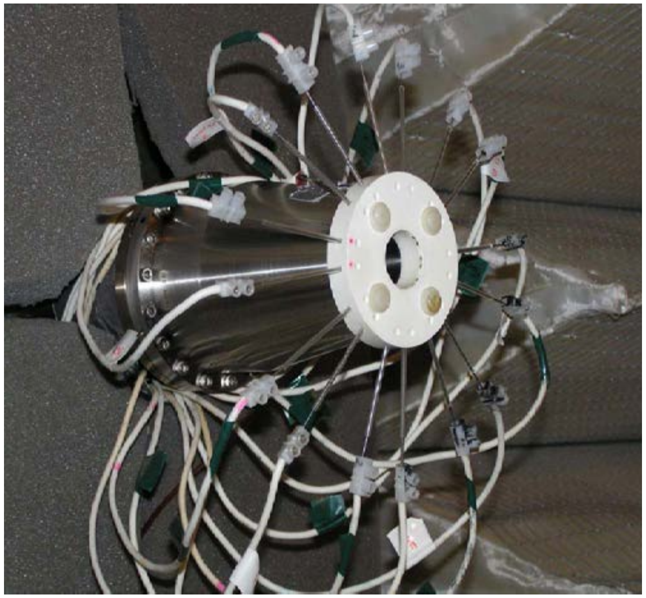


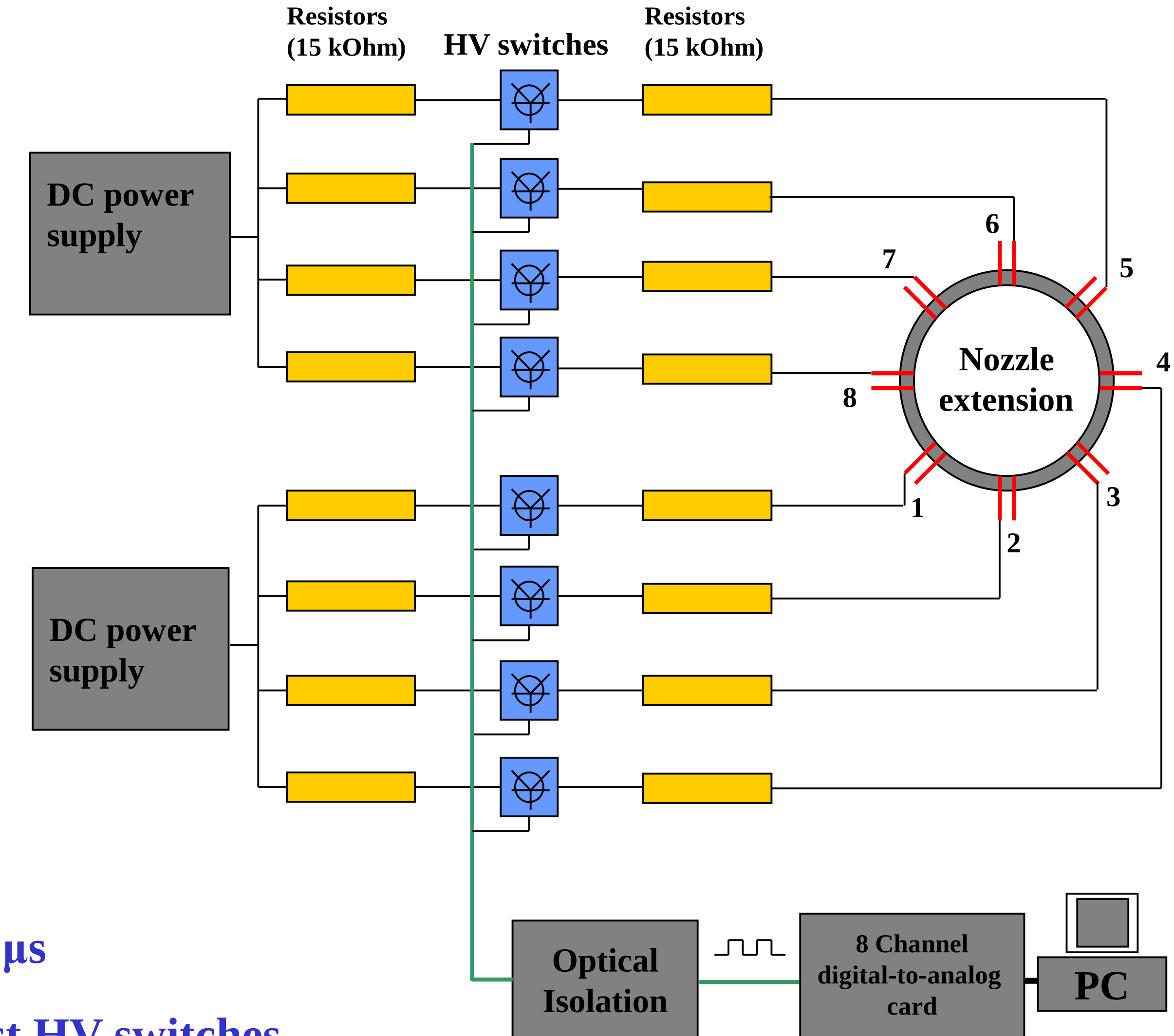
Mechanism of accelerated "slow" heating:

- **V-V energy exchange between N_2 and $CO_2(v_3)$ mode: $N_2(v=1) + CO_2(000) \leftrightarrow N_2(v=0) + CO_2(001)$**
- **CO_2 energy re-distribution among vibrational modes: $CO_2(001) + M \leftrightarrow CO_2(100,020,010) + M$**
- **V-T relaxation of bending mode: $CO_2(010) + M \rightarrow CO_2(100) + M$**
- **<u>Heating by accelerated vibrational relaxation may be used for nonequilibrium flow control</u>**

Frederickson et al, Plasma Sources Sci. Technol., 2017

Localized Arc Plasma Flow Actuators (LAPFA):
Exciting instabilities in transonic and supersonic flows (M=0.9-2.0)

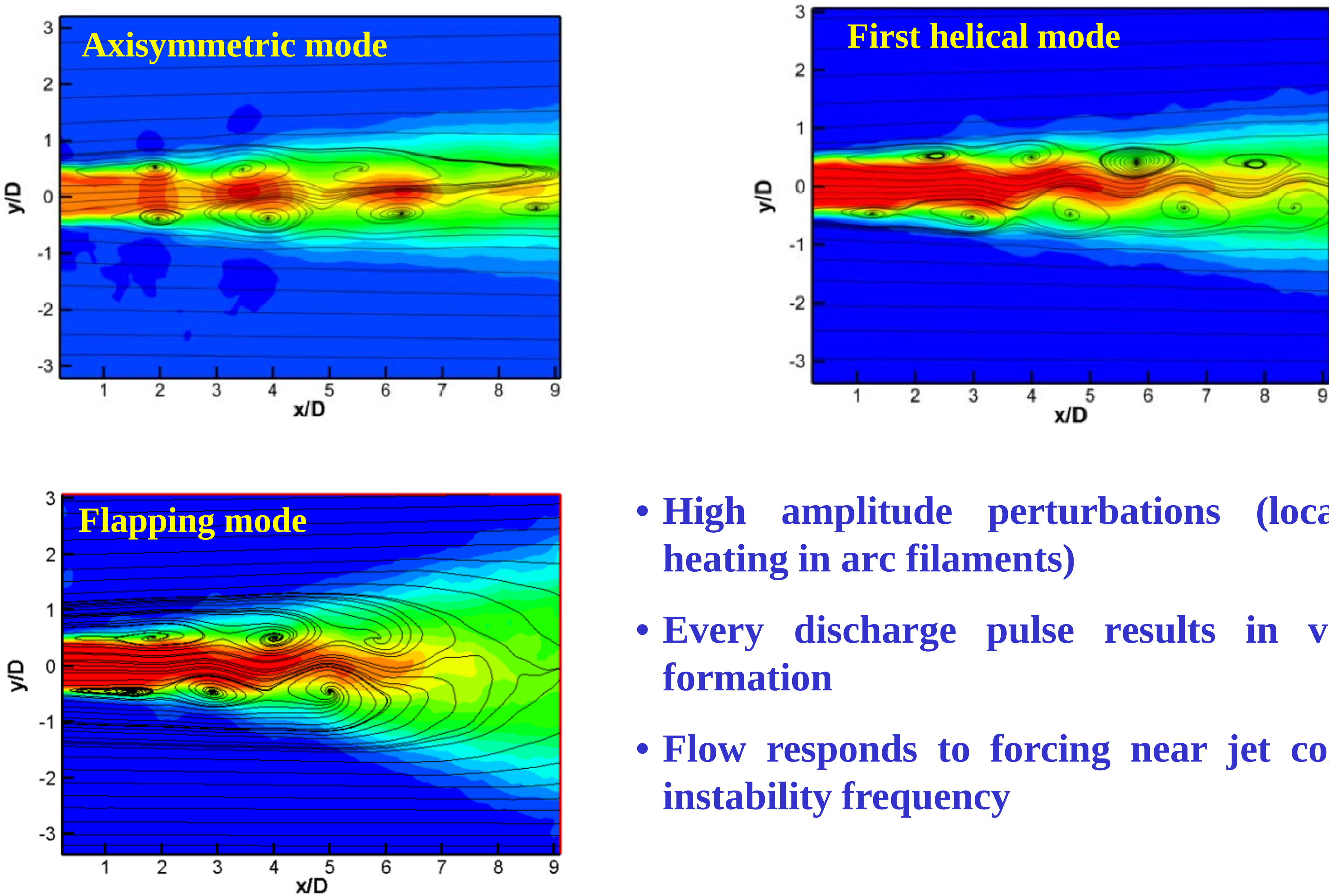




- Circular nozzle, 1 inch diameter
- Arc filament discharge pulses, ~10 μs
- Multiple channels controlled by fast HV switches
- Independent control of frequency, phase, and duty cycle → excitation of different instability modes

Samimy et al, AIAA J., 2007

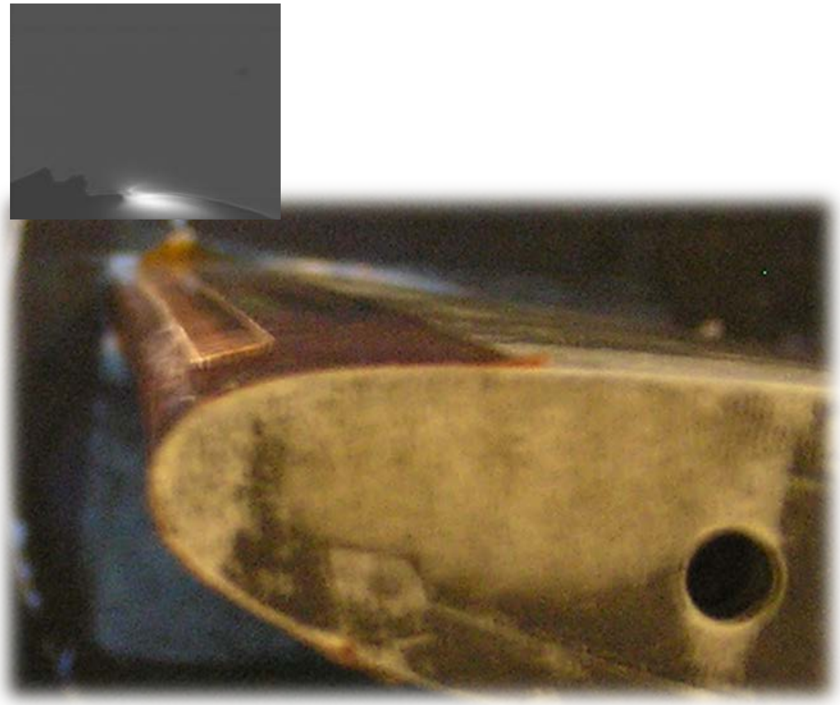
LAPFA: Formation of spanwise vortices in a M=0.9 circular jet

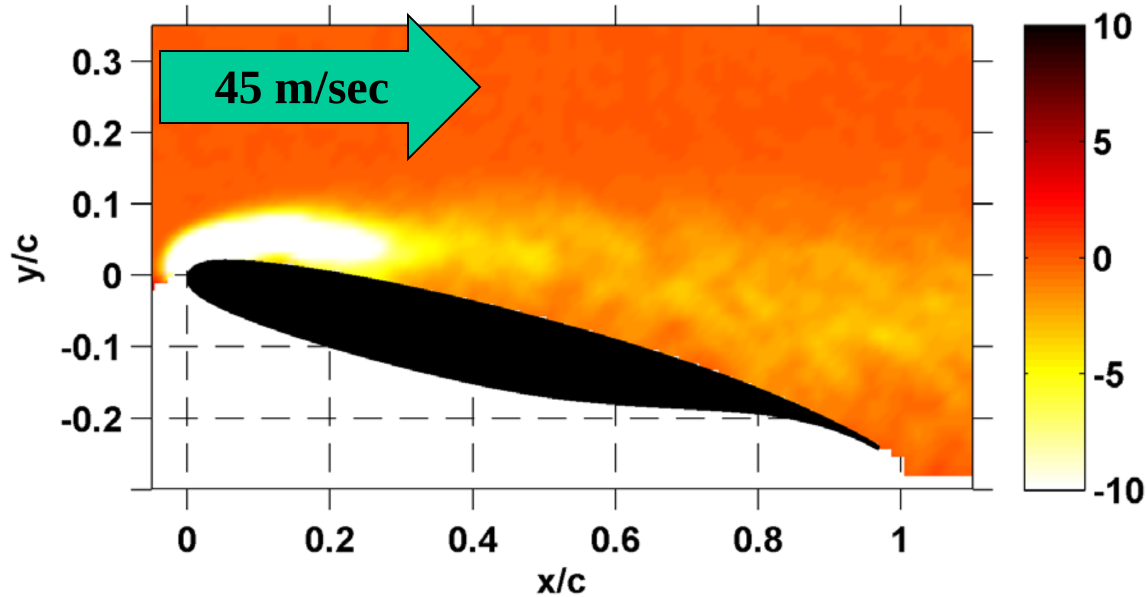


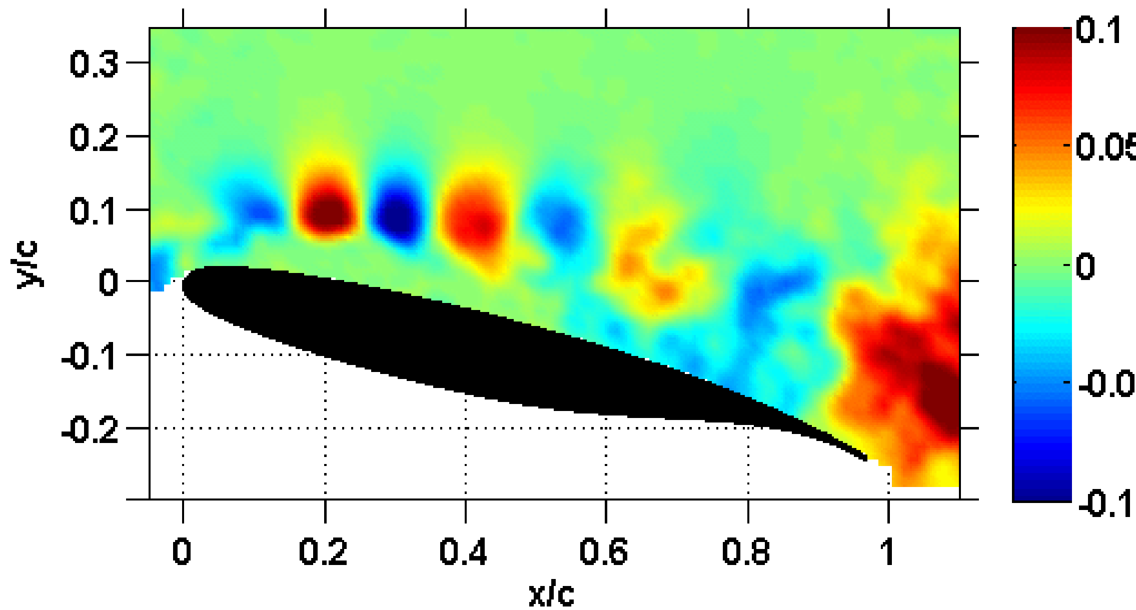
- High amplitude perturbations (localized heating in arc filaments)
- Every discharge pulse results in vortex formation
- Flow responds to forcing near jet column instability frequency

Kim et al, Expts. Fluids, 2010

Ns DBD plasma actuators: formation of coherent structures (spanwise vortices)



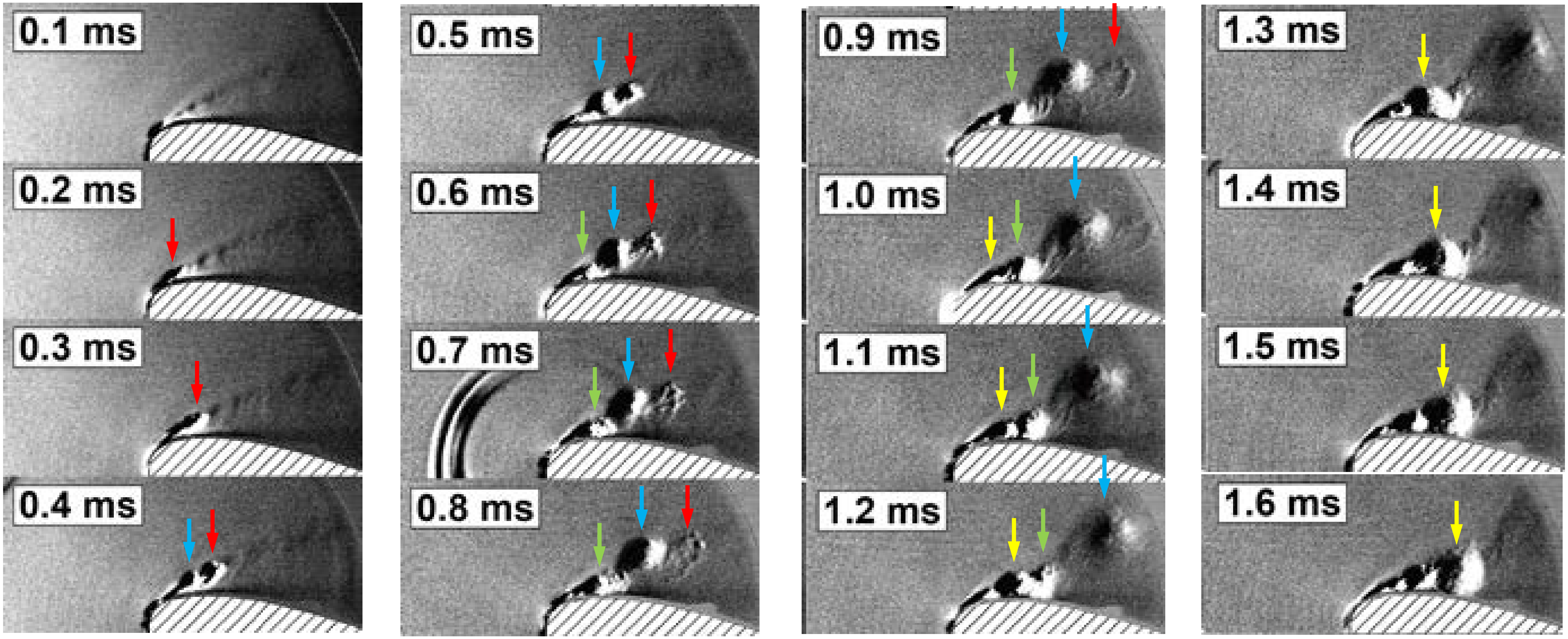




- Every nanosecond discharge pulse produces a spanwise vortex
- Qualitatively similar to LAFPA actuators
- Enhanced mixing with free stream → boundary layer reattachment
- Same effect detected up to u=96 m/sec (M=0.28, Re_x~1.5 ·10^6)

Little et al, AIAA J., 2012

Spanwise vortex dynamics: high-speed schlieren (Tohoku University, Japan)



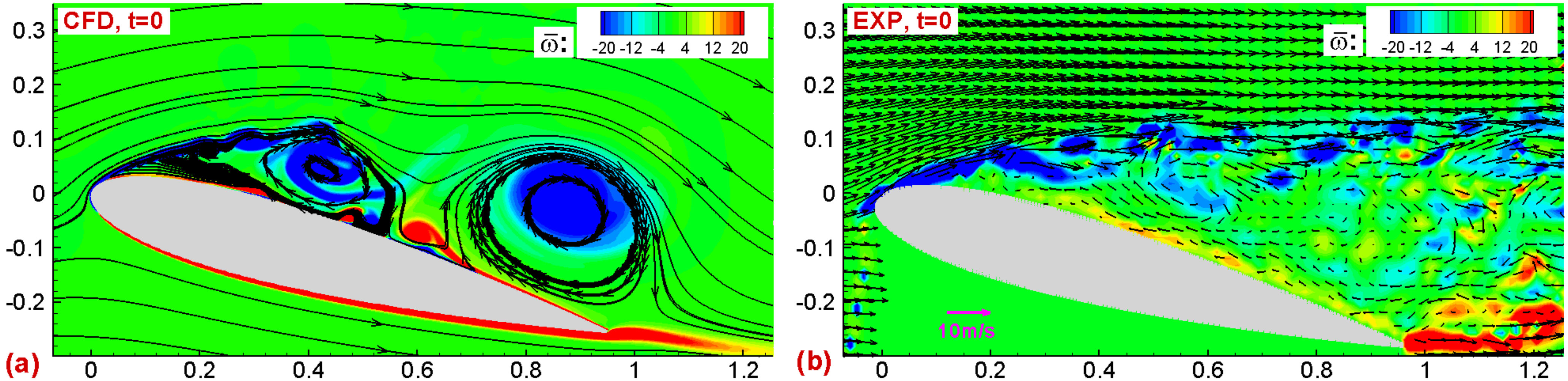
- U = 20 m/s, AoA = 22°, f = 3 kHz (τ = 0.33 ms)
- Compression waves are seen in 0.7 ms image only, others are "between the frames"
- No evidence of compression wave on flow structure (compare images at 0.6 ms and 0.7 ms)
- Every discharge pulse generates an individual vortex, all vortices appear to rotate clockwise
- Vortices #1 and #2 travel above the separation zone, all subsequent vortices follow the surface

Komuro et al, 68th GEC, 2015

PIV measurements and plasma / CFD modeling:

(National University of Singapore, AIAA Papers 2017-0712, 0715)

- **Objective: obtain quantitative insight into the mechanism of plasma flow control**



Baseline flow (without control): Re = $0.05 \cdot 10^6$ (U_∞ = 10 m/s), AoA = 15°

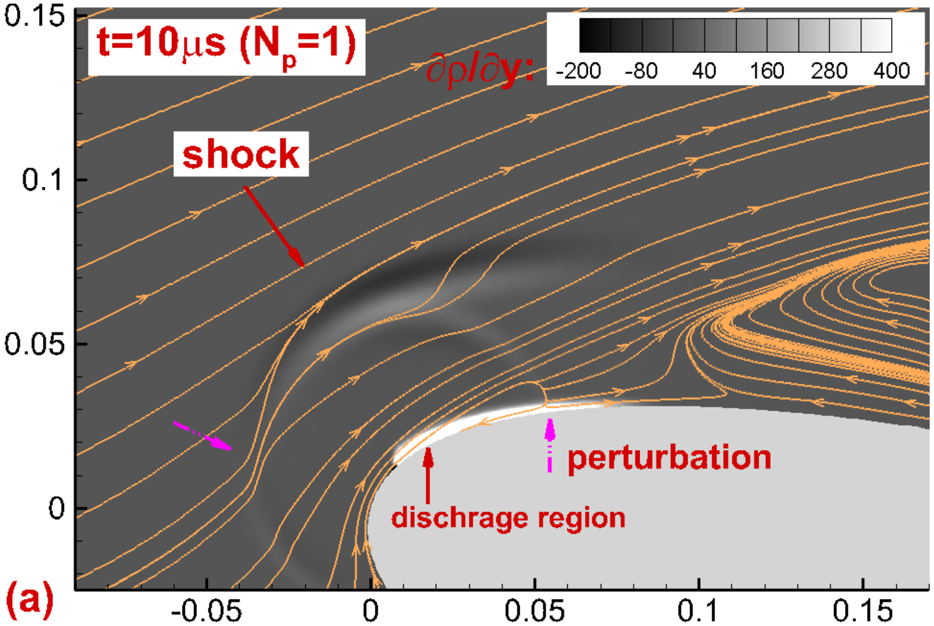
Ns pulse surface ionization wave plasma / volumetric residual heating model

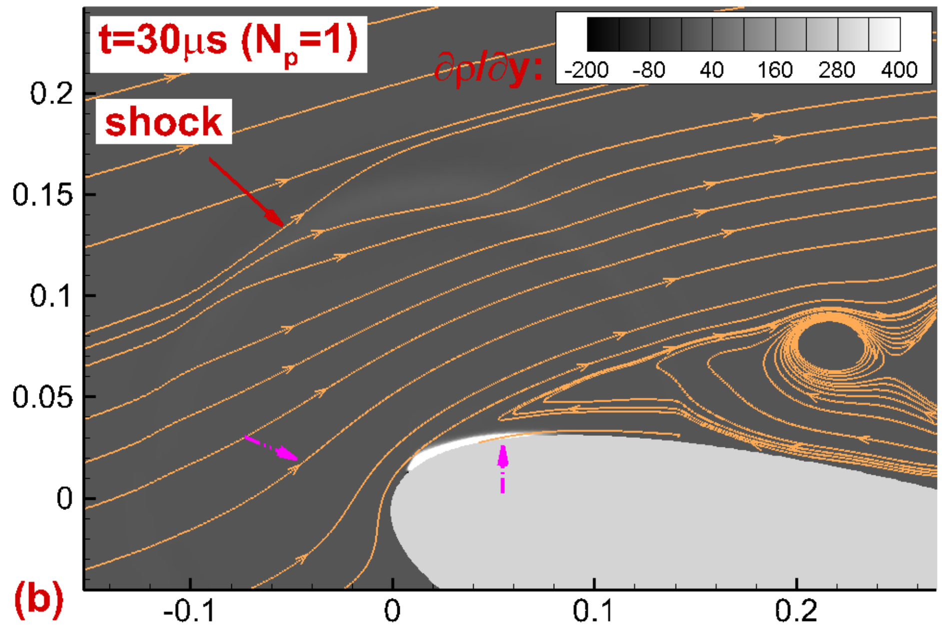
(Takashima et al., Plasma Sources Sci. Technol. 2013)

Coupled with 2-D compressible flow Navier-Stokes equations

Zheng et al, Phys. Rev. Fluids, 2016

Are spanwise vortices formed by compression waves?





Numerical schlieren images overlaid with streamlines:

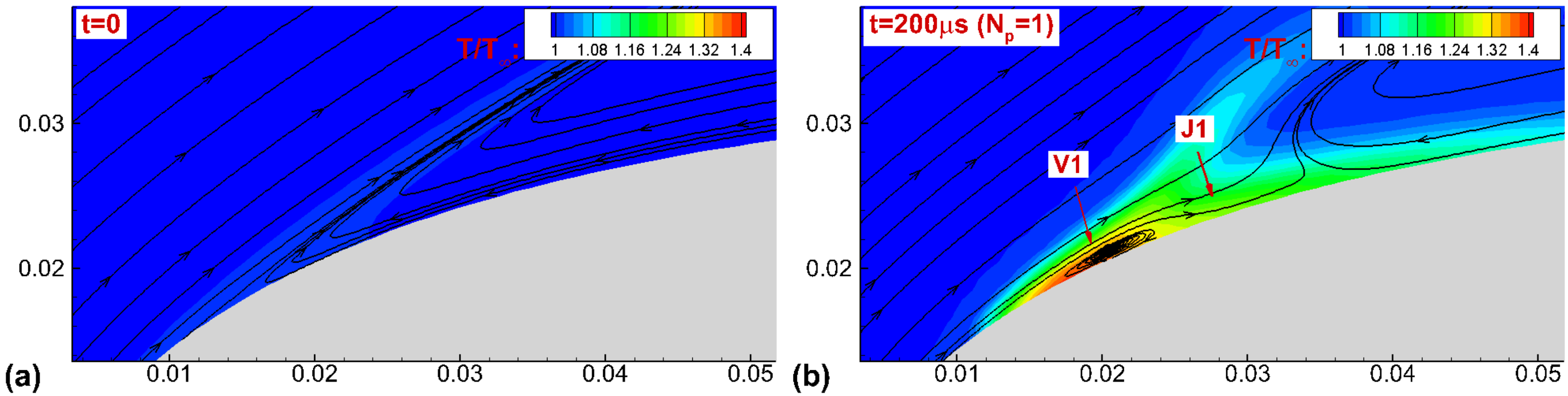
Compression wave propagation through the external flow

$Re = 0.05 \cdot 10^6$ (10 m/s), AoA = 15°, U_p = 20 kV, f = 0.15 kHz, f^+ = 1.2

Effect of compression wave on external flow is very weak

Zheng et al, Phys. Rev. Fluids, 2016

Are spanwise vortices formed by residual heating?



Numerical schlieren images overlaid with streamlines:

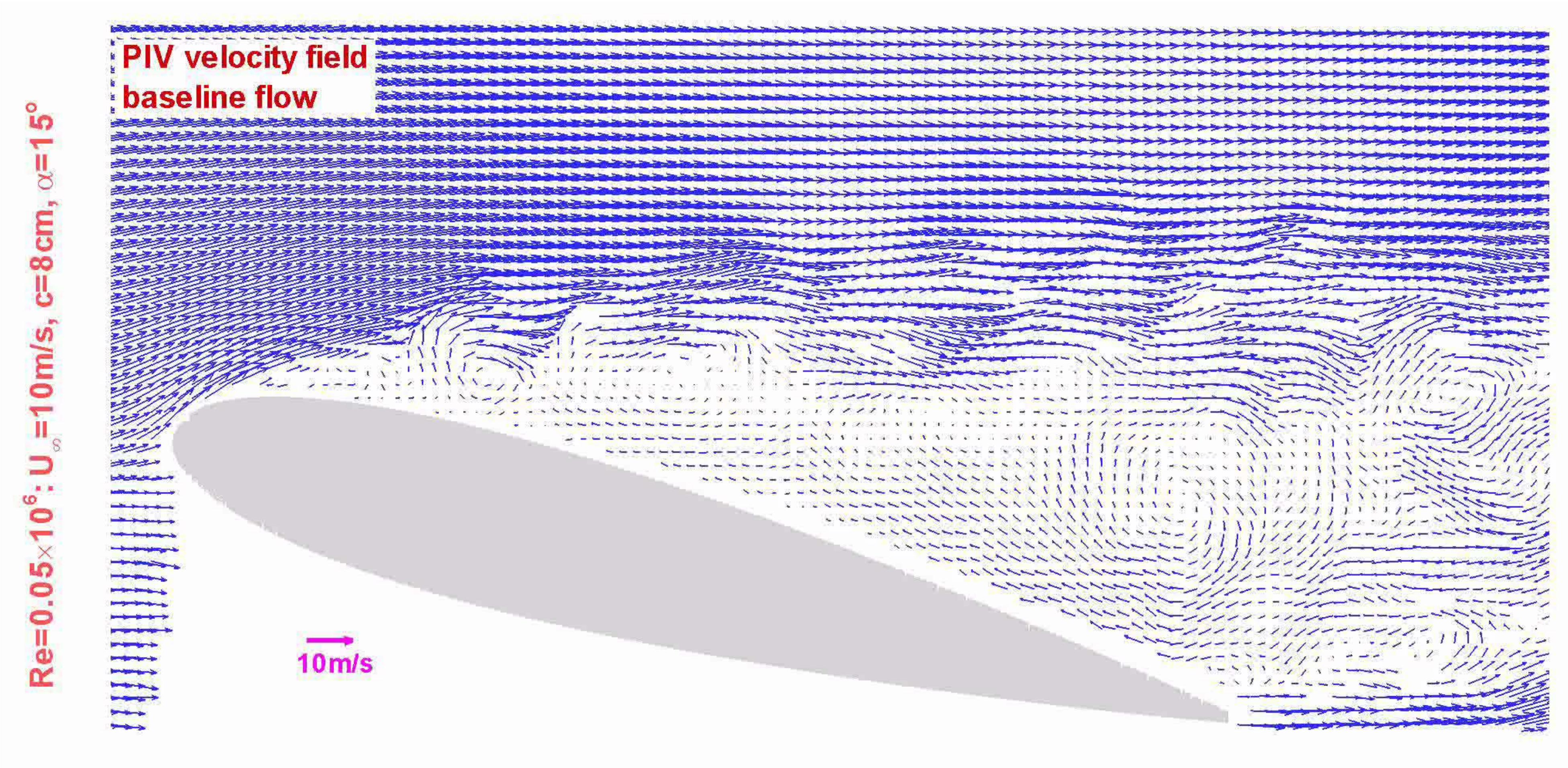
$Re = 0.05 \cdot 10^6$ (10 m/s), $AoA = 15^o$, U_p = 20 kV, f = 0.15 kHz, $f^+ = 1.2$

Generation of a spanwise vortex by residual heating

after the first discharge pulse (via inviscid instability)

Zheng et al, Phys. Rev. Fluids, 2016

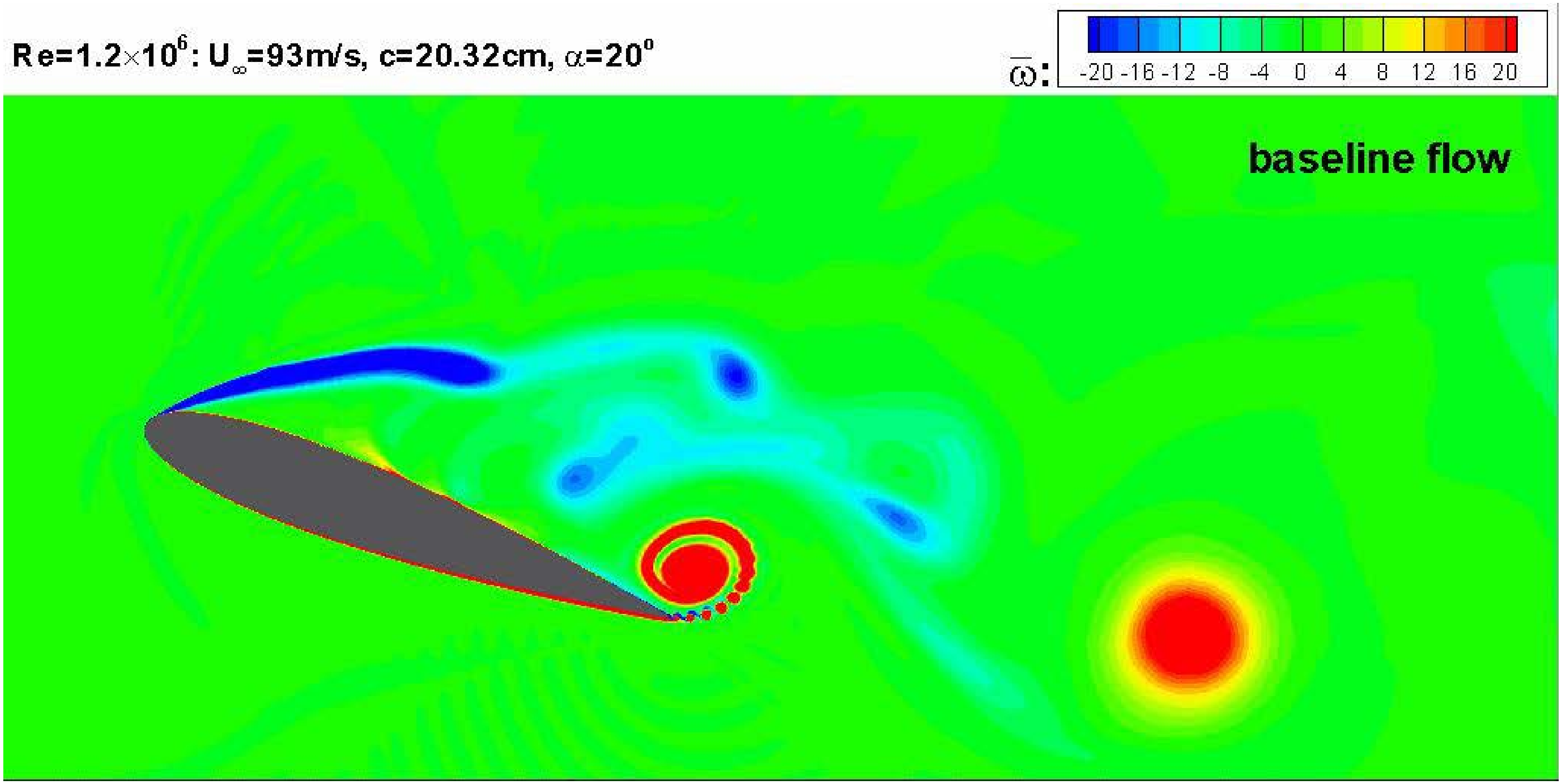
Experimental (PIV) data
Baseline and forced flows, Re = $0.05 \cdot 10^6$



Spanwise vortex formation, flow reattachment begins after the first discharge pulse

Zheng et al, Phys. Rev. Fluids, 2016

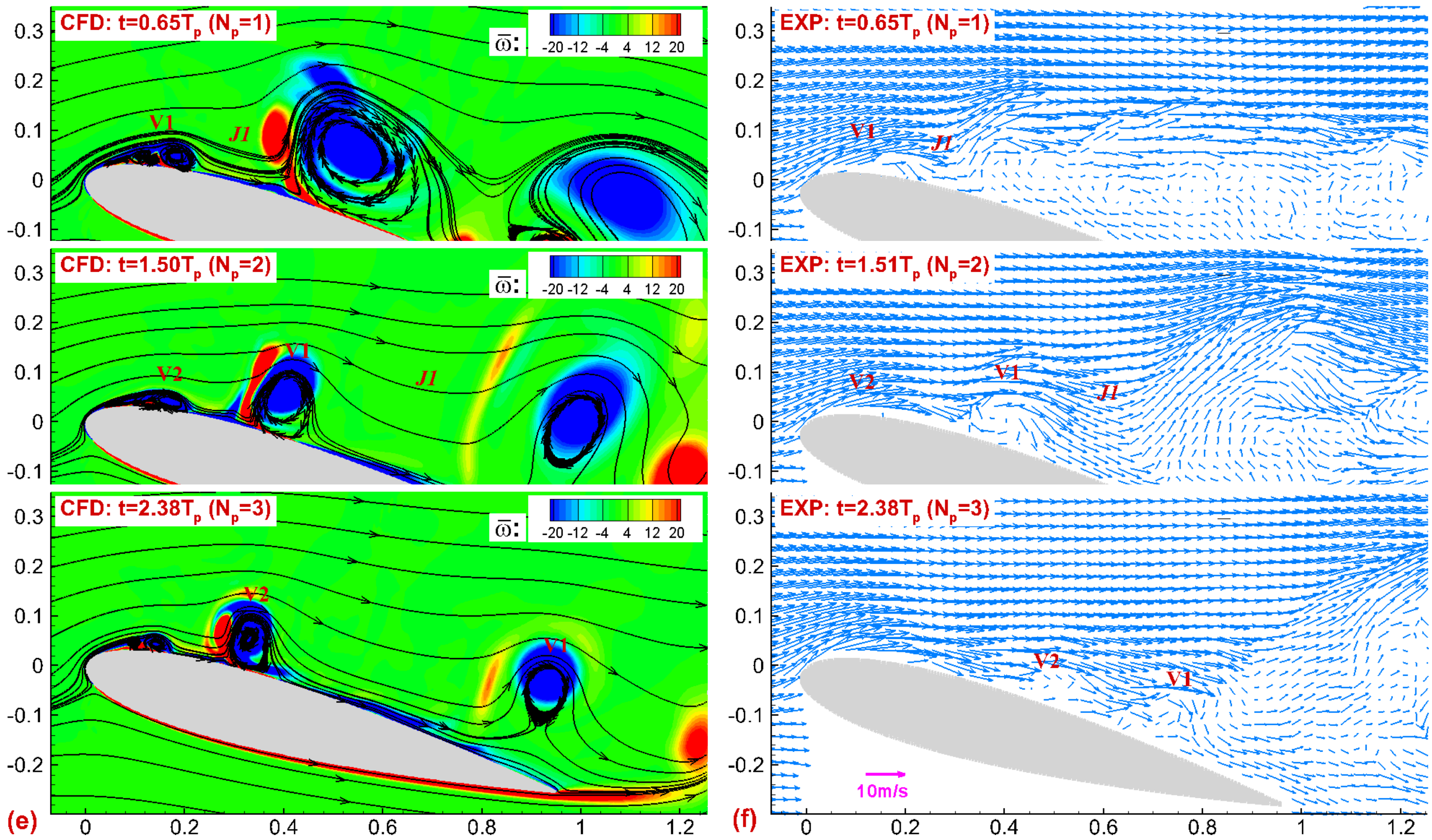
Plasma / CFD predictions
Baseline and forced flows, Re = $1.2 \cdot 10^6$



Residual heating after every discharge pulse results in a spanwise vortex formation

Zheng et al, Phys. Rev. Fluids, 2016

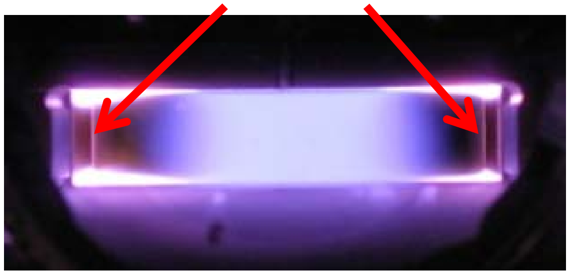
Comparison between PIV data and CFD predictions: $Re = 0.05 \cdot 10^6$



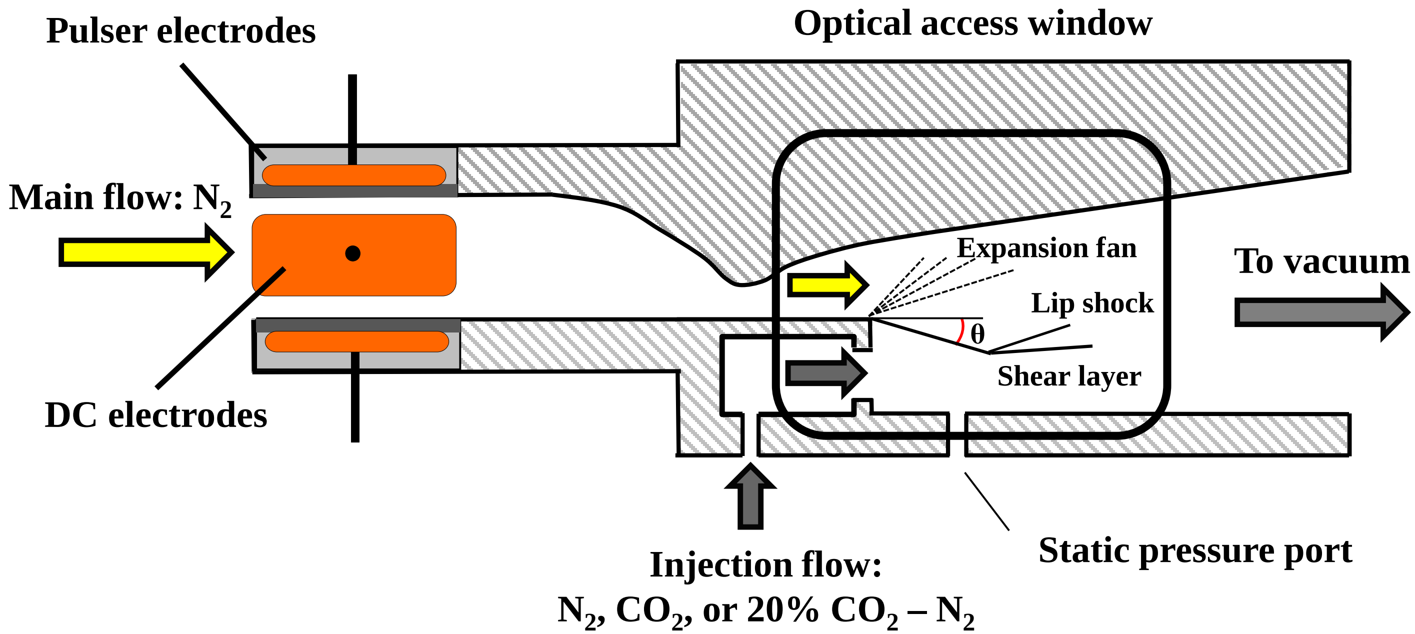
Results compared after N_p = 1, 2, and 3 discharge pulses: good qualitative agreement

Zheng et al, Phys. Rev. Fluids, 2016

Using accelerated relaxation of vibrational energy to control supersonic mixing / shear layer



Flow into the page

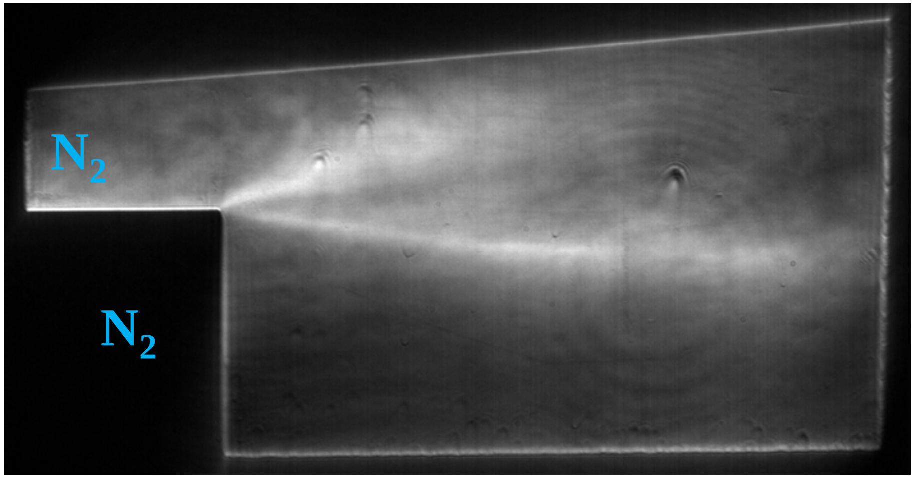


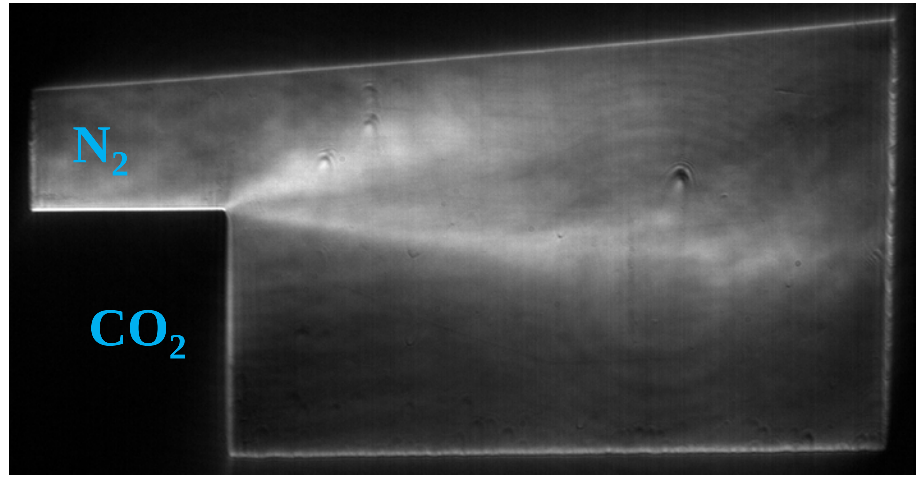
- Plenum: overlapped ns pulse / DC sustainer discharge for vibrational loading of N_2
- P_0 = 300 torr, T_V=2000, T=500 K, 2-D nozzle, top wall contoured, bottom wall plane
- Condition at nozzle exit : M = 2.5, P_{exit} = 15 torr
- Subsonic flow below expansion corner: injection of N_2 or CO_2
- Optical access for schlieren, CARS, and NO PLIF in subsonic and supersonic flows

Nishihara et al, AIAA Paper 2015-0577

Frederickson et al, Plasma Sources Sci. Technol., 2017

Effect of vibrational relaxation of shear layer: N_2 / N_2 (left) vs. N_2 / CO_2 (right)





N_2 "bleeding" through backstep

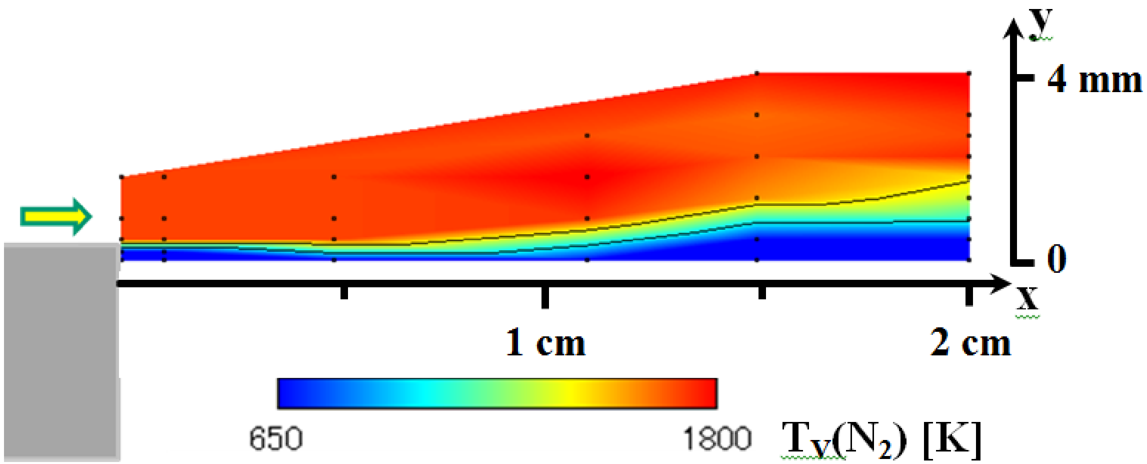
CO_2 "bleeding" through backstep

- Time delay between frames 5 ms, t = 0-80 ms
- Ns pulse / DC discharge (2.3 kW) is turned on at t = 10-45 ms, to excite main N_2 flow
- No perturbation of shear layer detected in N_2 / N_2 flow
- In N_2 / CO_2 flow, shear layer expansion angle decreases, approaching $\theta=0^\circ$
- No change observed if main N_2 flow is not excited

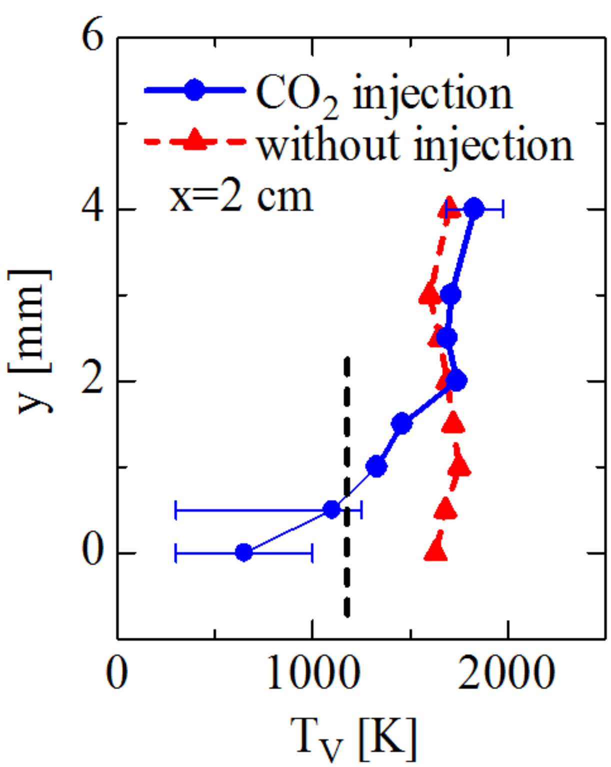
Nishihara et al, AIAA Paper 2015-0577

Frederickson et al, Plasma Sources Sci. Technol., 2017

N_2 Vibrational Temperature Distribution in Shear Layer



- Top flow: vibrationally excited N_2, T_V=1900 K, estimated T_{rot}=240 K
- Bottom flow: CO_2 bleeding through backstep, static pressure 7 torr



- CO_2 bleeding reduces $T_V(N_2)$, increases $T_{trans/rot}$ and static pressure
- Consistent with time-resolved measurements in ns pulse discharge in quiescent N_2-CO_2
- Static pressure increase pushes up shear / mixing layer

Nishihara et al, AIAA Paper 2016-1762

Frederickson et al, Plasma Sources Sci. Technol., 2017

Summary

- **Surface and volumetric ns pulse discharges:**
  - **Rapid energy thermalization on sub-acoustic time scale, high-amplitude compression wave generation**
  - **Residual heating affected by slow energy thermalization dominated by vibrational relaxation**
  - **Kinetics of energy thermalization ("rapid" and "slow" heating) is well understood**
  - **Dynamics of small-scale random perturbations, their potential for flow control remain uncertain**

- **NS-DBD surface plasma actuators**
  - **Compression waves have almost no effect on the external flow**
  - **Large-scale coherent flow structures (spanwise vortices) are formed by localized residual heating, via inviscid instability**
  - **Significant flow control authority in subsonic flows (up to M = 0.3), scalable to large dimensions (~1 m)**

Summary (cont.)

- **Flow control by accelerated vibrational relaxation:**
  - **Injection of “relaxer” species in nonequilibrium flow**
  - **Temperature and pressure rise due to accelerated relaxation**
  - **Strong effect on supersonic shear layer**

- **Outstanding issues:**
  - **Can “late” small-scale random perturbations be used for boundary layer flow tripping (e.g. see Yan and Gaitonde, Phys. Fluids 2010)?**
  - **Can accelerating vibrational relaxation (e.g. by CO_2 injection) enhance NS-DBD actuator flow control authority?**

Acknowledgments

AFOSR BRI "Nonequilibrium Molecular Energy Coupling and Conversion Mechanisms for Efficient Control of High-Speed Flow Fields"

US DOE Plasma Science Center "Predictive Control of Plasma Kinetics: Multi-Phase and Bounded Systems"

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