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Development and Application of Plasma Actuators for Active Control of High-speed and High Reynolds Number Flows

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Requirements for Actuators in High Reynolds Number and High-speed Flow Control

- Active flow control is often used to manipulate flow instabilities to achieve a desired goal (e.g. prevent separation, enhance mixing, reduce noise, …)
- Instability frequencies normally scale with flow velocity scale and inversely with flow length scale (U/ℓ)
- In a laboratory setting for such flow experiments, U is high, but ℓ is low, resulting in high instability frequency
- In addition, high momentum and high background noise & turbulence in the flow necessitate high amplitude actuation
- Developing a high amplitude and high frequency actuator is a major challenge
- Ironically, these requirements ease up in application (but other issues arise)

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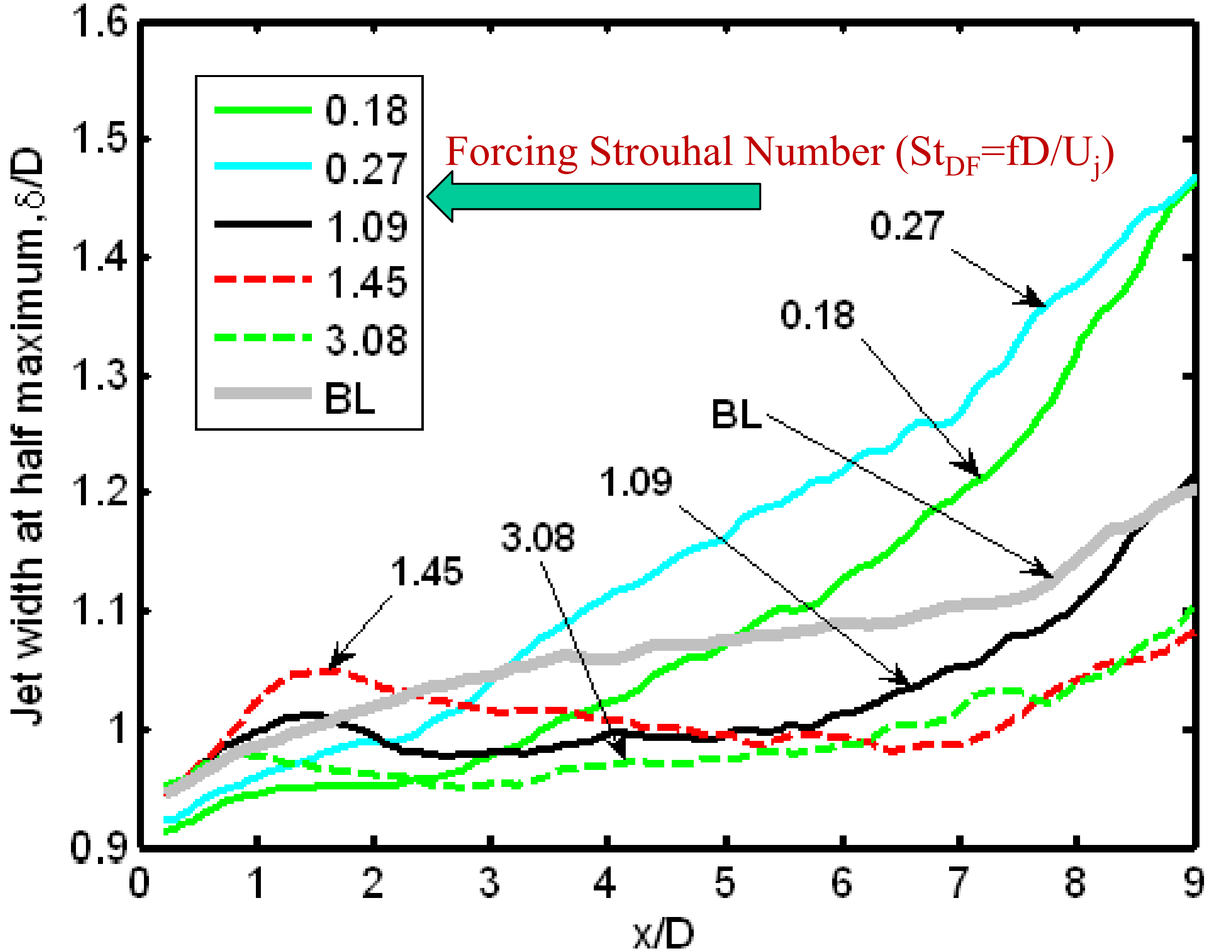
Some Applications of Interest

- Jet control for mixing enhancement or noise mitigation
- Shock wave – boundary layer interaction control (e.g. in supersonic inlets)
- Cavity flow control
- Mixing enhancement for combustion (e.g. in scramjet type applications)

High-speed Jet Control for Mixing Enhancement or Noise Suppression

- An axisymmetric jet has two length scales, jet diameter (D) and initial shear layer momentum thickness (θ), and three distinct instabilities
  - Initial shear layer instability with a $St_\theta = f\theta/U$~0.01 to 0.02 (e.g., Michalke 1965; Zaman and Hussain 1981; Ho and Huerre 1984) – ***f*~50,000 Hz**
  - Jet preferred mode instability with a $St_D = fD/U$~0.2 to 0.6 (e.g., Crow and Champagne 1971; Zaman and Hussain 1980; Ho and Huerre 1984) - ***f*~5,000 Hz**
  - Azimuthal mode instability with a primary parameter of D/θ (e.g., Michalke 1977; Cohen and Wygnanski 1987; Corke et al. 1991) – **require distributed actuators with individual control**

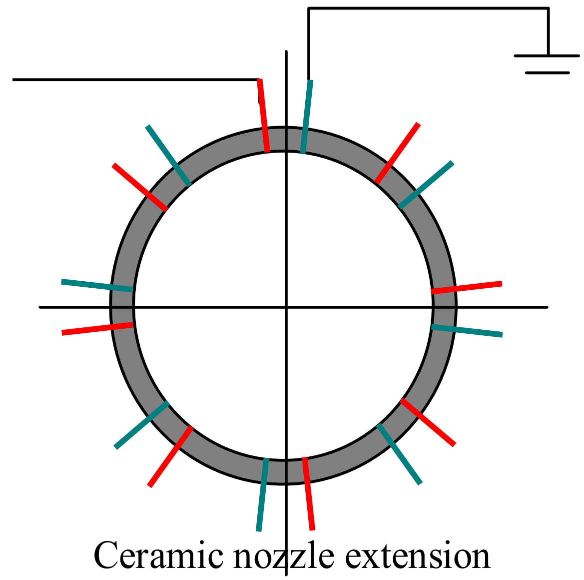
Initial Shear Layer & Jet Column Instabilities



PIV measurements - jet width at half centerline velocity for Mach 0.9 jet (Re_D=0.74x10^6) forced at m = 0 using 8 LAFPAs

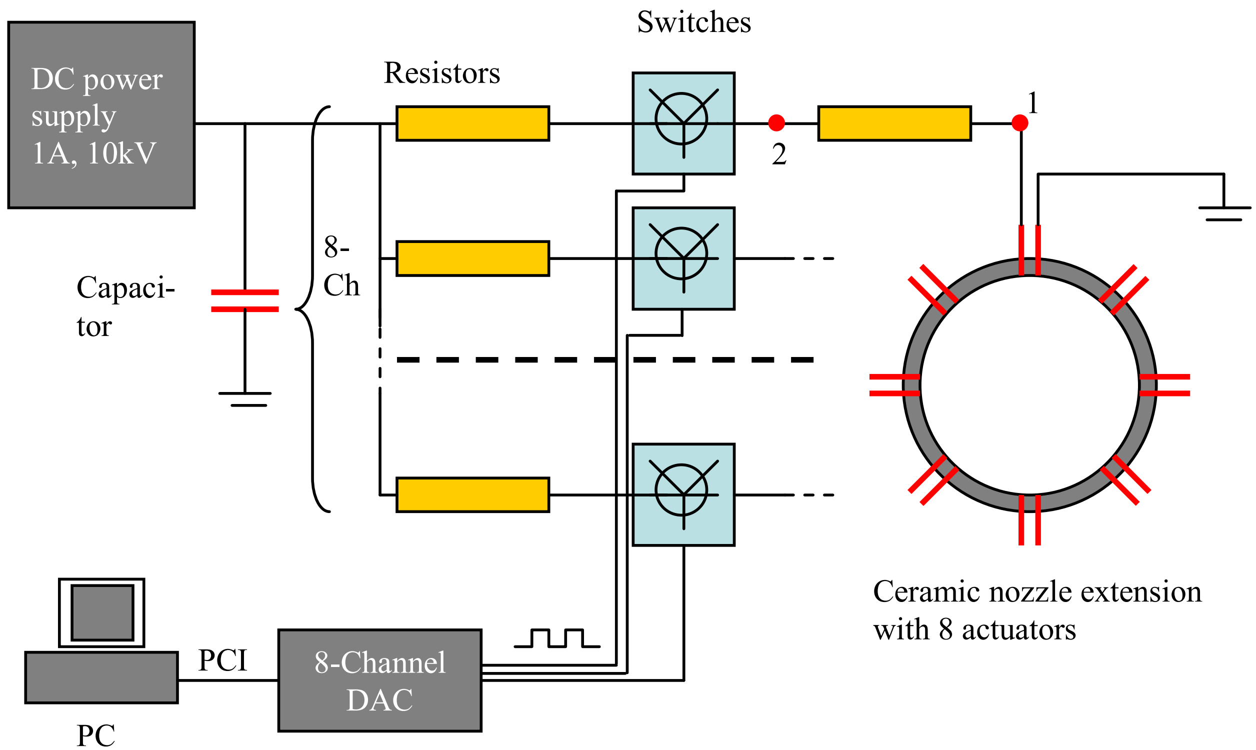
Localized Arc Filament Plasma Actuators (LAFPAs)

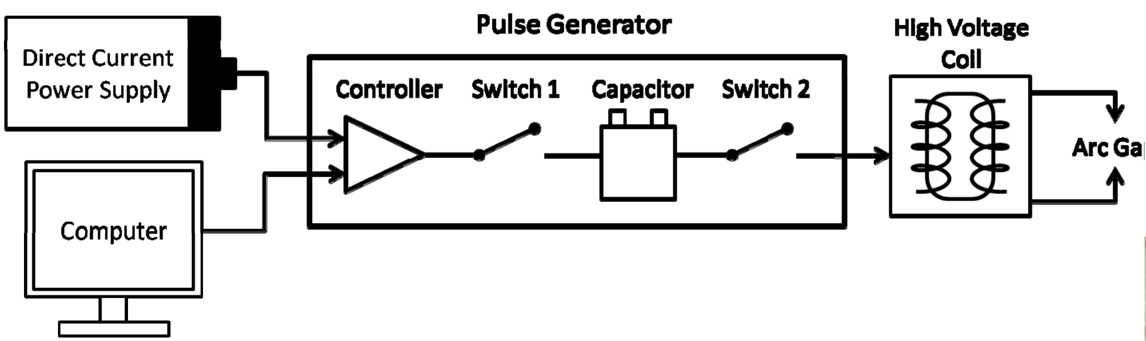
- A LAFPA constitutes a pair of electrodes (1 mm dia. tungsten) connected to a high voltage (~kV) or a low voltage & transformer power supply
- We have used 8 actuators with any prescribed frequency, phase, and duty cycle
  - Frequencies from 0 to 200 kHz
  - With 8 actuators could force azimuthal modes m = 0 to 3 & ±1, ±2, and ±4
- An actuator provides localized high amplitude heating (arc filament cross section is ~1-2 mm^2)

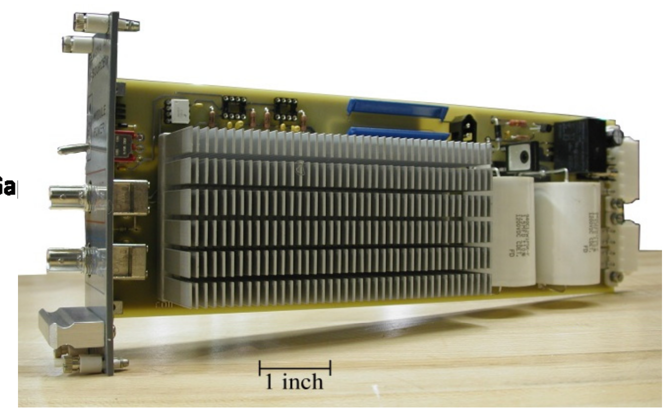


Ceramic nozzle extension with 8 pairs of electrodes

Power Supply and Control for Plasma Actuators

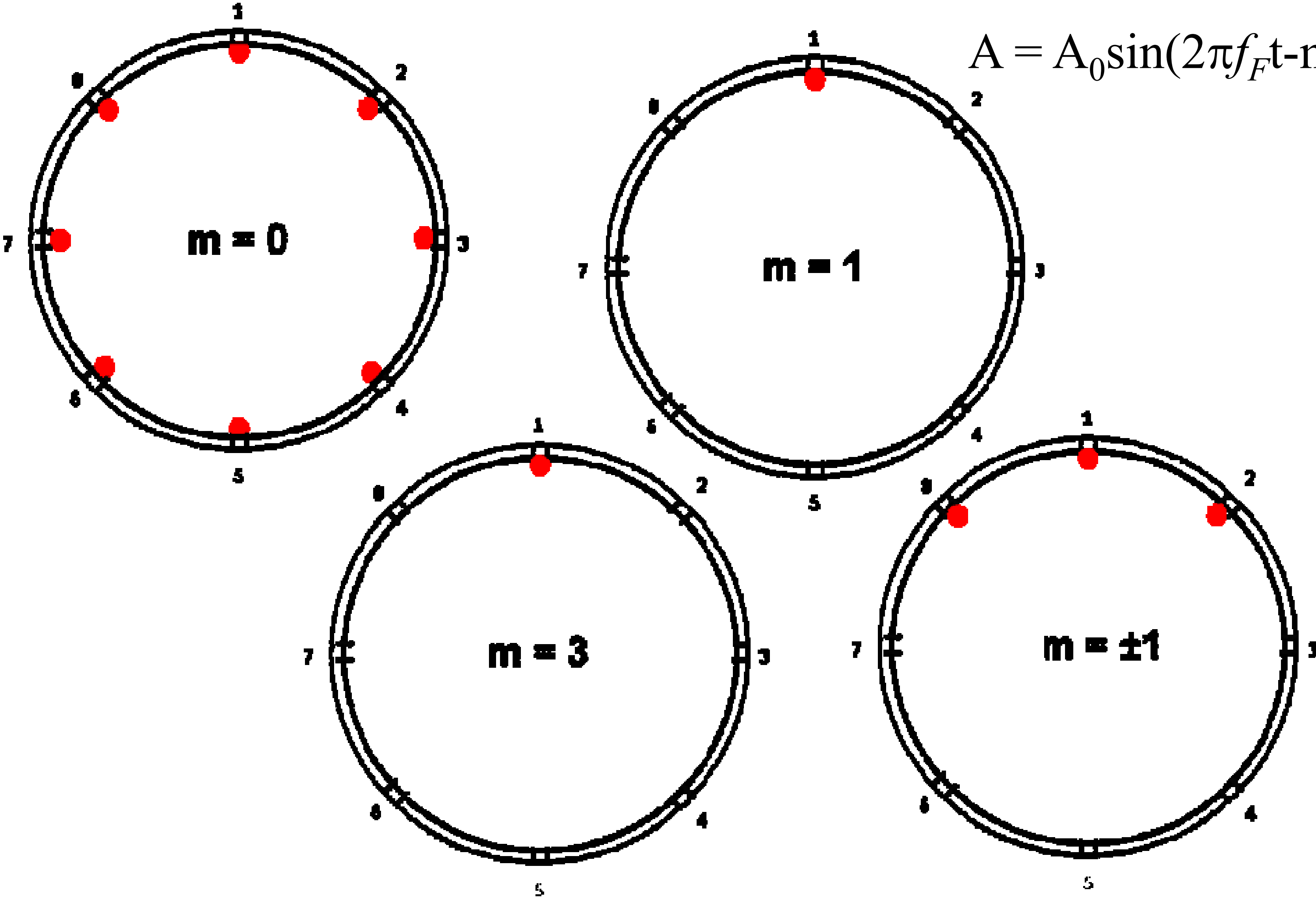






Excitation of Azimuthal Modes – 4 of 7

$$A = A_0 \sin(2\pi f_F t - m\phi)$$



Phase between successive actuation = m(360/8), m=0, 1, 2, or 3

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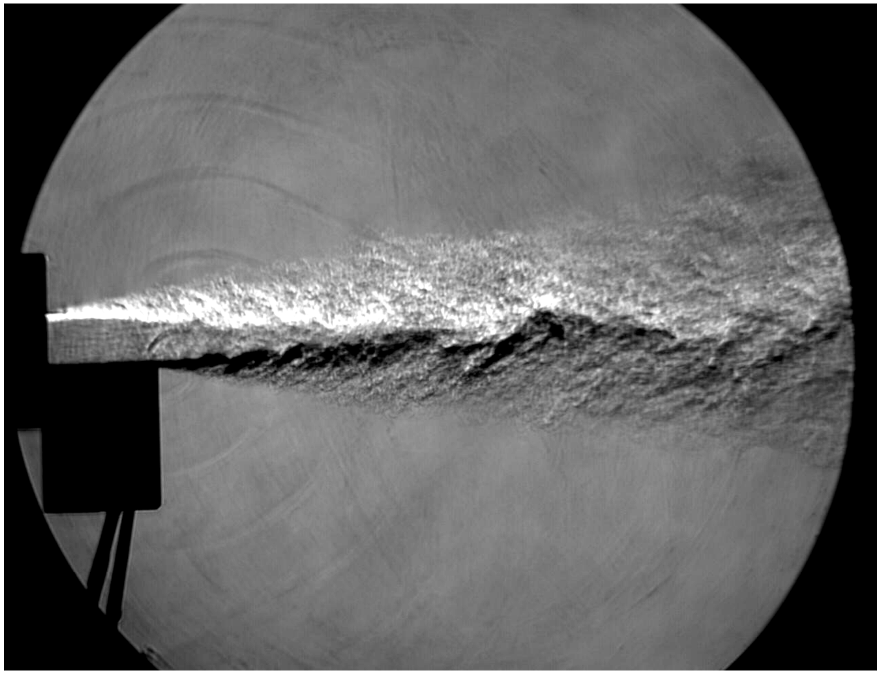
Jet Receptivity & Perturbation Generated by LAFPAs

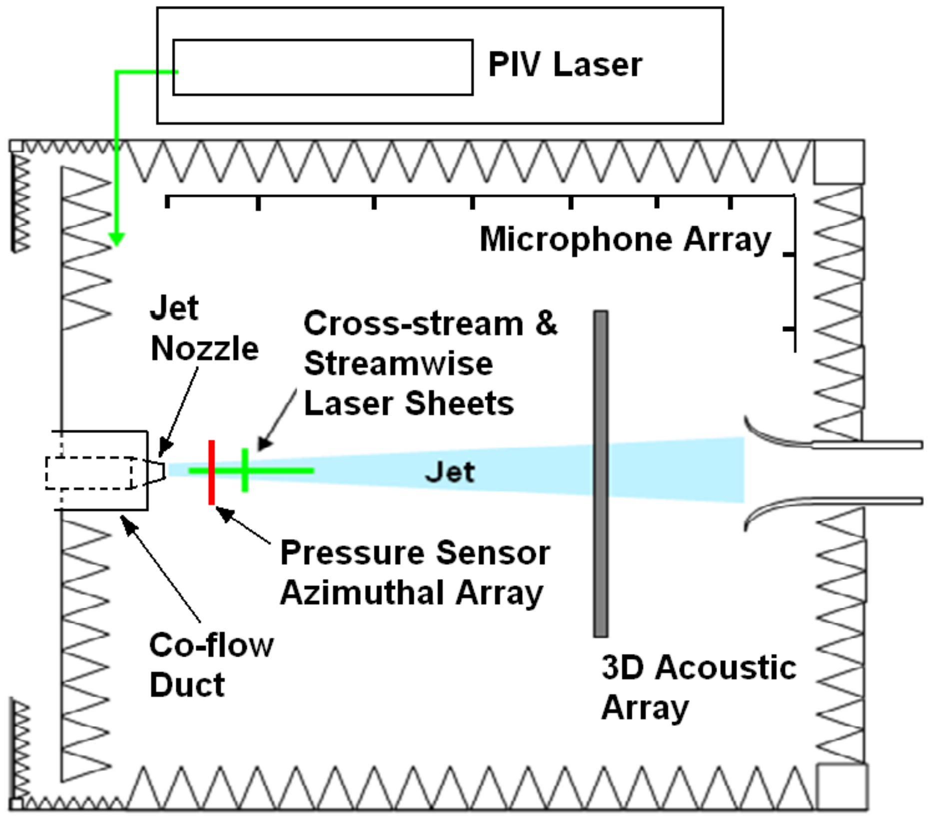
- Jets are known to be receptive to thermal, aerodynamic, or acoustic perturbations (Moore 1977)
- The most receptive location is just downstream of the nozzle
- LAFPAs impart temperature perturbation (~300 to 1200°C, depending upon the excitation frequency & duty cycle obtained by spectroscopy – temperature perturbation leads to pressure perturbation



- 2-D Mach 0.9 jet
- Frequency of 20 kHz
- Average temperature of 600°
- 4 actuators

Experimental Arrangement

- Mach 1.3, 1.65 (conical & contoured) and 2.0 axisymmetric jets
  - 1 inch nozzle exit diameter
  - Reynolds number 1.1×10^6 to 2.5×10^6
  - Can be heated to ~ 1000°F
- Flow measurements: instantaneous snapshots, ensemble/phase-averaged flow images, PIV measurements, real-time pressure measurements
- Far-field acoustic measurements: both in frequency and time domains



Not to scale

Experimental Arrangement

- Mach 1.3, 1.65 (conical & contoured) and 2.0 axisymmetric jets
  - 1 inch nozzle exit diameter
  - Reynolds number 1.1 x10⁶ to 2.5x10⁶
  - Can be heated to ~ 1000°F
- Flow measurements: instantaneous snapshots, ensemble/phase-averaged images, PIV measurement real-time pressure measurements
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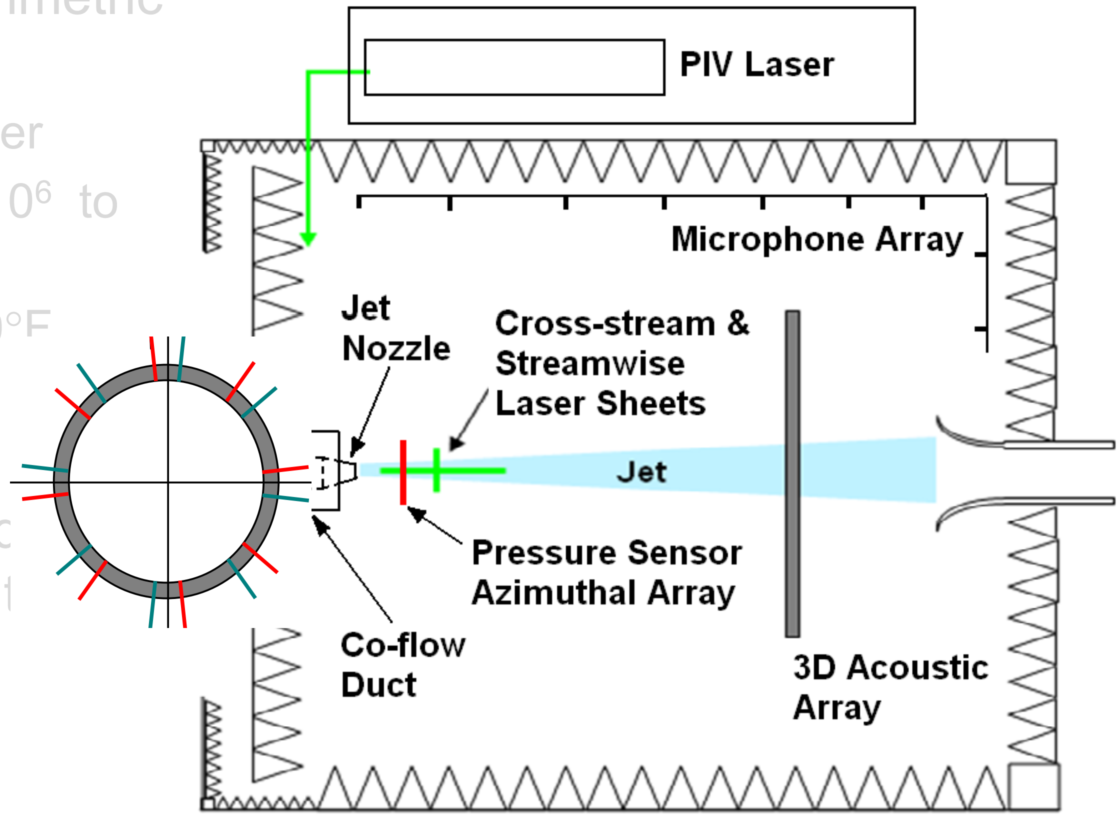

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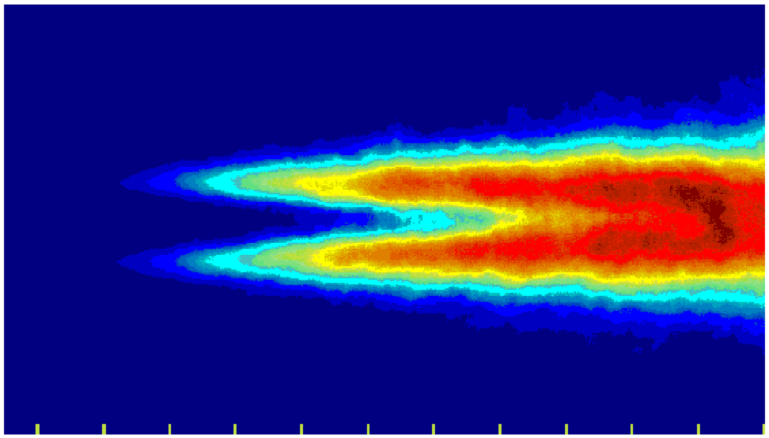
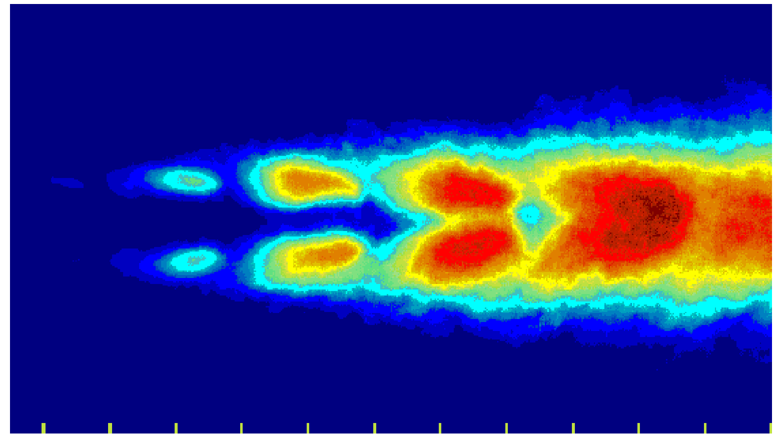
Phase-averaged Images in Mach 1.3 Axisymmetric Jet

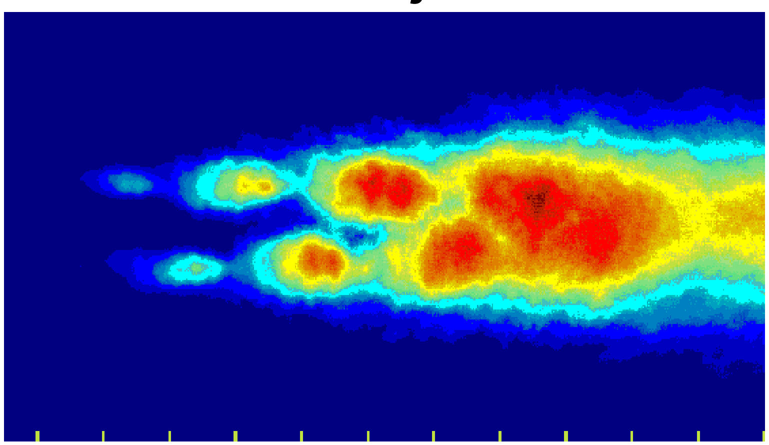
Forcing at $St_D = fD/U_j = 0.33$



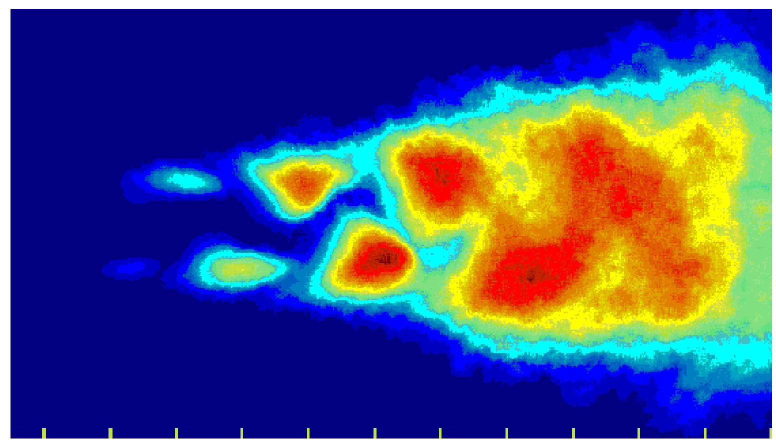
Baseline jet



Axisymmetric mode (m=0)



First helical mode (m=1)



Flapping mode (m=±1)

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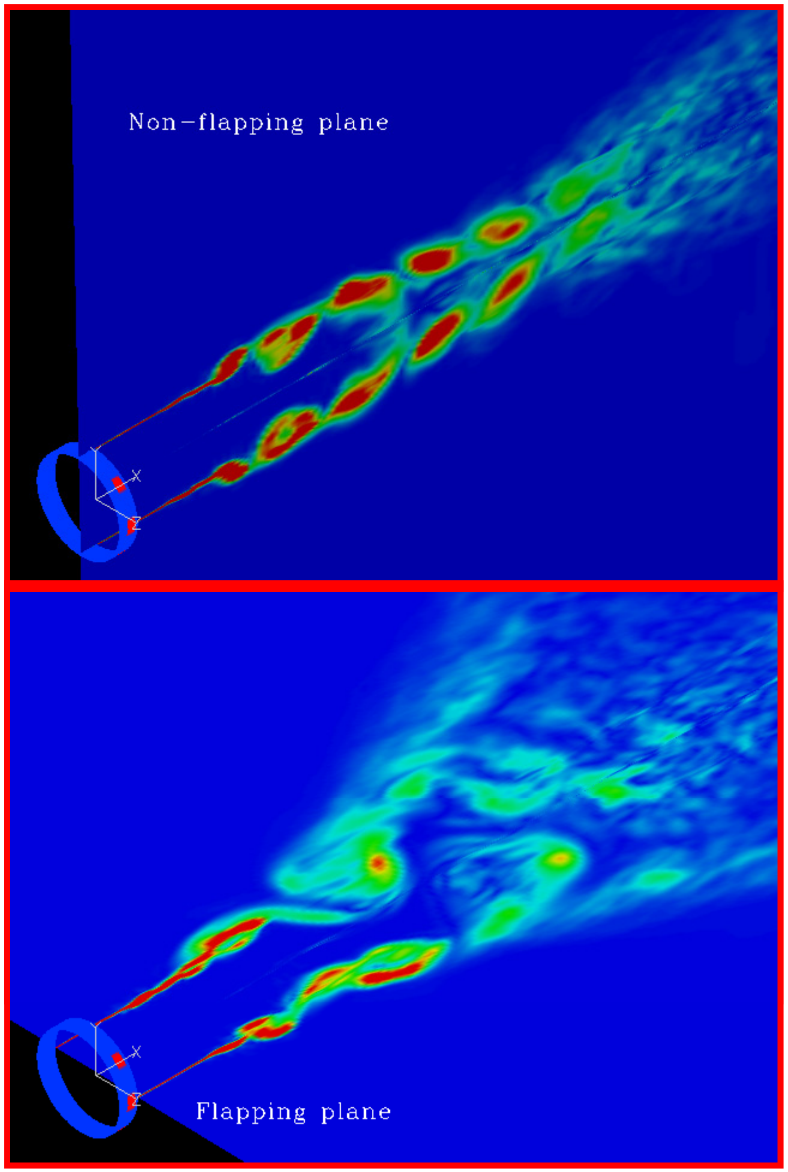
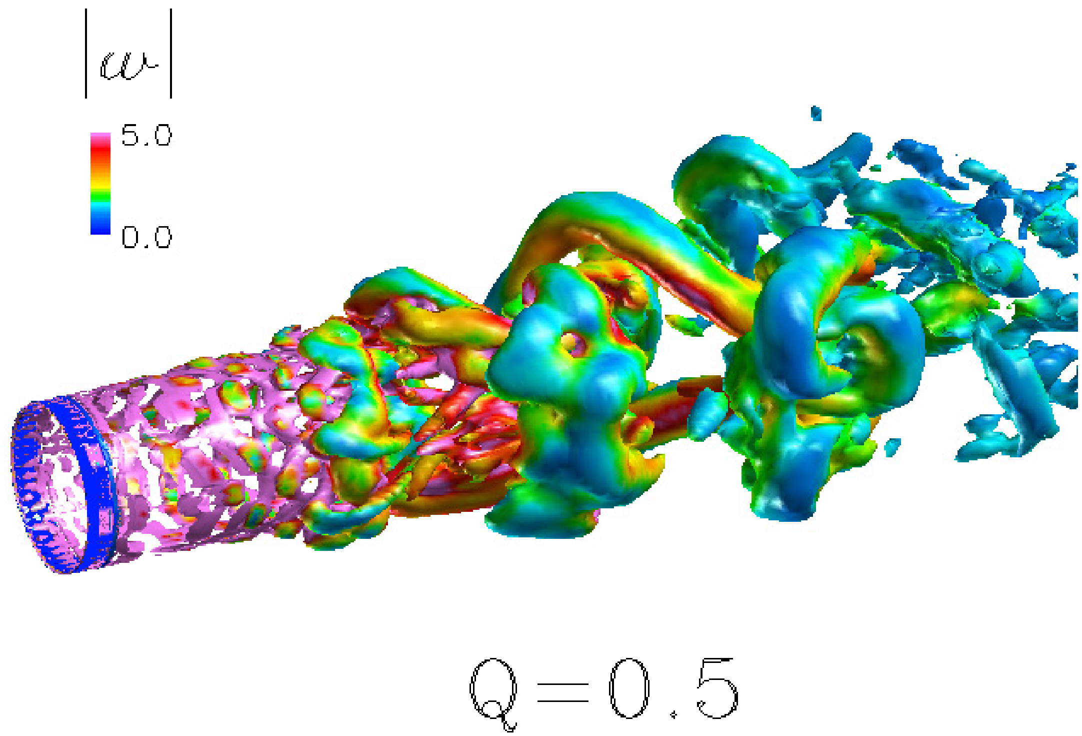
3-D Structure of Phase Averaged Flow: m=±1 (St_{DF}~0.3) – Datta Gaitonde (2009)



Rotating view at fixed phase angle

$$Q = \frac{1}{2}\left[|\Omega|^2 - |S|^2\right]$$

Ω & S: vorticity & rate of strain tensors
(Haller, JFM, Vol. 525,1985)



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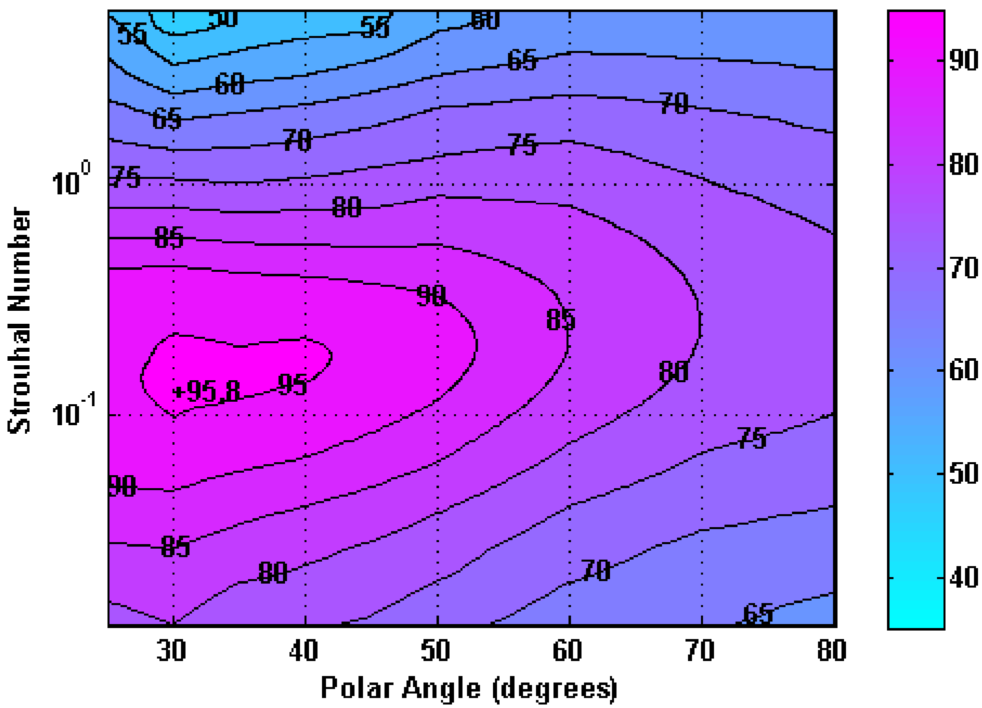
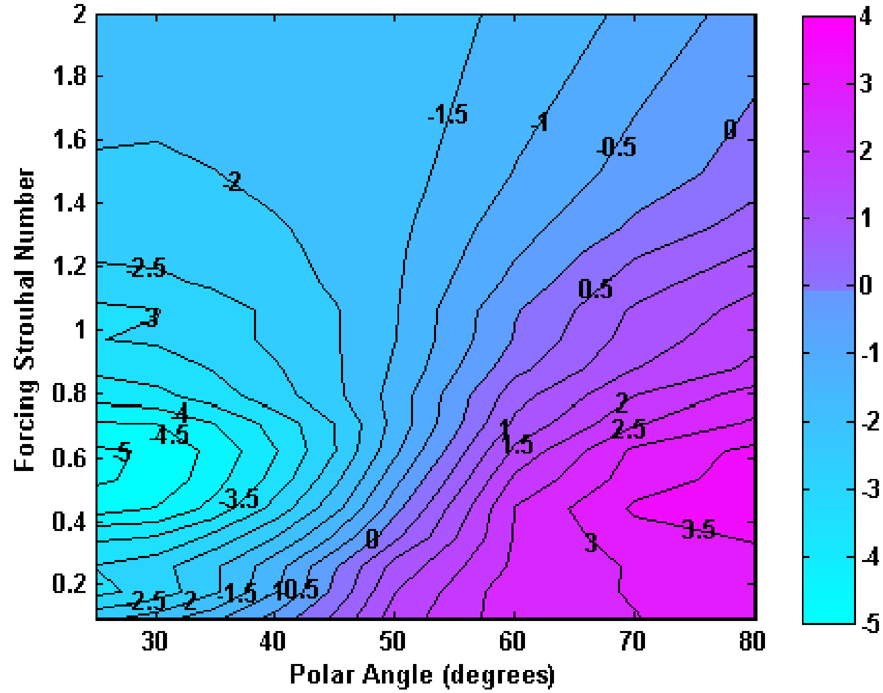
Noise Suppression – Mach 0.9 Heated Jet with Temperature Ratio of 2.5

Baseline jet far-field SPL



OASPL for controlled jet with azimuthal mode m = 3



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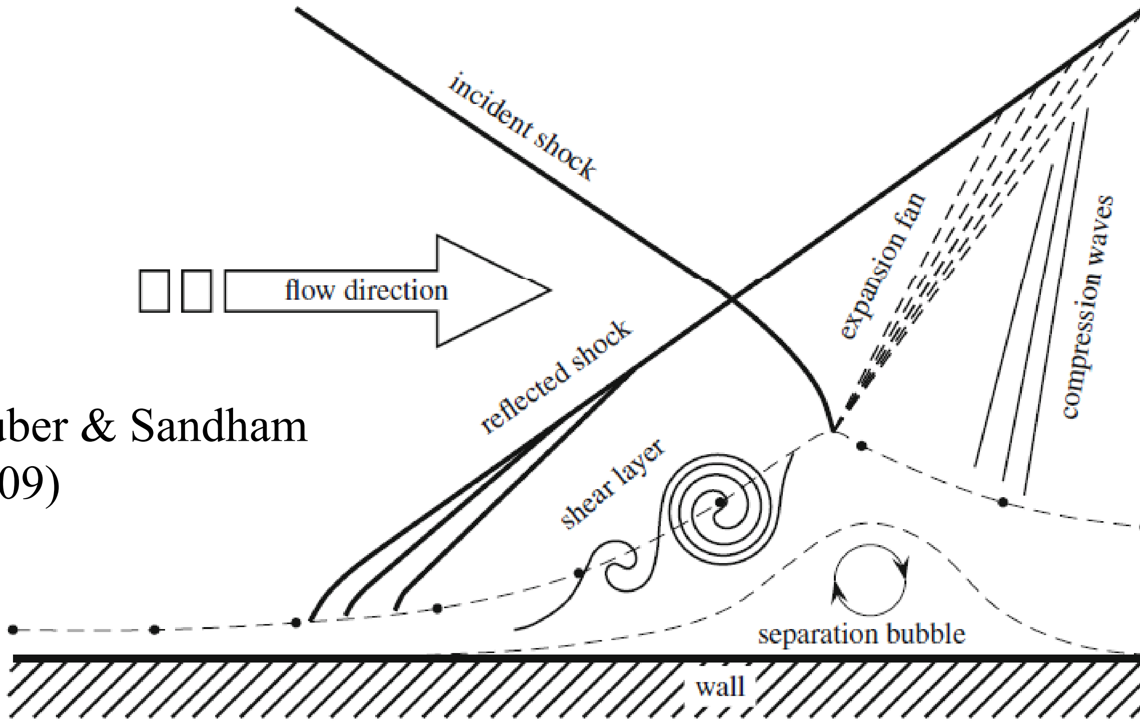
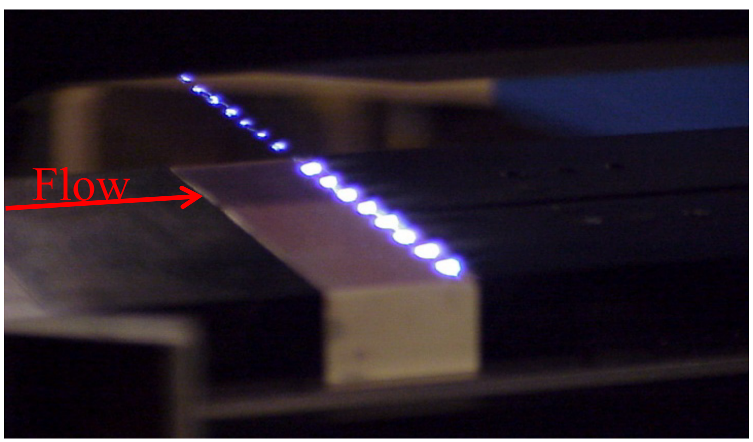
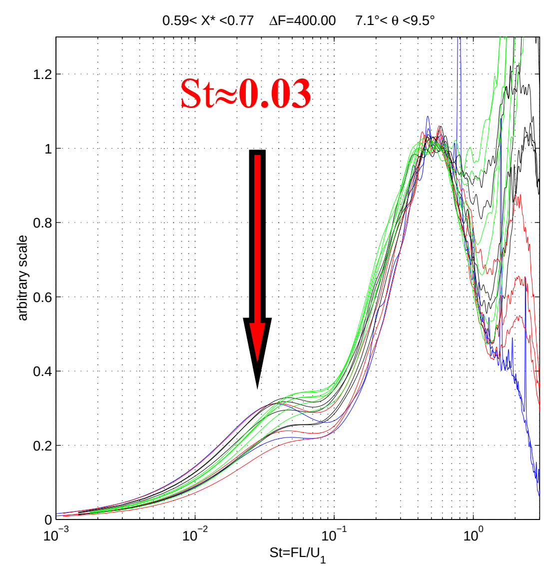
Shock Wave – Boundary Layer Interaction Control

Touber & Sandham (2009)



DuPont et al. (2008)





Normalized Streamwise Mean Velocity for Mach 1.9 Flow with α = 10°