Aerothermodynamics Overview and Prediction Assessment

Dr. James D. Heidmann
Aerothermodynamics API
Subsonic Fixed Wing Project

Fundamental Aeronautics Annual Meeting
New Orleans, LA
October 31, 2007

An overview of the Aerothermodynamics Discipline within NASA's Subsonic Fixed Wing Project is given. The primary focus of the presentation is on the research efforts conducted in fiscal year 2007. This year (2007), the work primarily consisted of efforts under level 1 (foundational research) and level 2 (tools and technology development). Examples of work under level 1 are large eddy simulation development, advanced turbine cooling concept development, and turbomachinery flow control development. Examples of level 2 research are the development of highly-loaded compressor and turbine test programs and advanced turbomachinery simulation development, including coupled inlet-fan simulations. An overview of the NRA research activity is also provided. This NRA focused on plasma and aspiration flow control for low pressure turbine application. Finally, a status report on the turbomachinery CFD code assessment activity is provided. This activity focuses on the use of several NASA in-house codes for the NASA rotor 37 and stage 35 test cases.

Aerothermodynamics Overview and Prediction Assessment

Dr. James D. Heidmann

Aerothermodynamics API

Subsonic Fixed Wing Project

Fundamental Aeronautics Annual Meeting

New Orleans, LA

October 31, 2007

Outline

- **Aerothermodynamics Overview**
- **In-House Research Progress**
- **Turbomachinery Code Assessment**
- **NRA Research Progress**
- **Summary**

Aerothermodynamics Research Objectives

- **Develop fundamental understanding and enabling technologies required for concepts such as ultra-high bypass engines, high power density cores, and embedded engines for hybrid wing vehicles.**

- **Dramatically improve engine thermal efficiency, reduce fuel burn and emissions, and reduce weight and complexity of engine systems.**

- **Improve understanding through experimental and analytical study of engine inlets, fans, compressors, turbines, and nozzles and their interactions.**

Aerothermodynamics Research Impact on Fuel Burn

- 162 pax, 2940 nm mission baseline
- Ultra high bypass ratio geared engines
- High power density engine cores
- Key Aerothermodynamics technology targets:

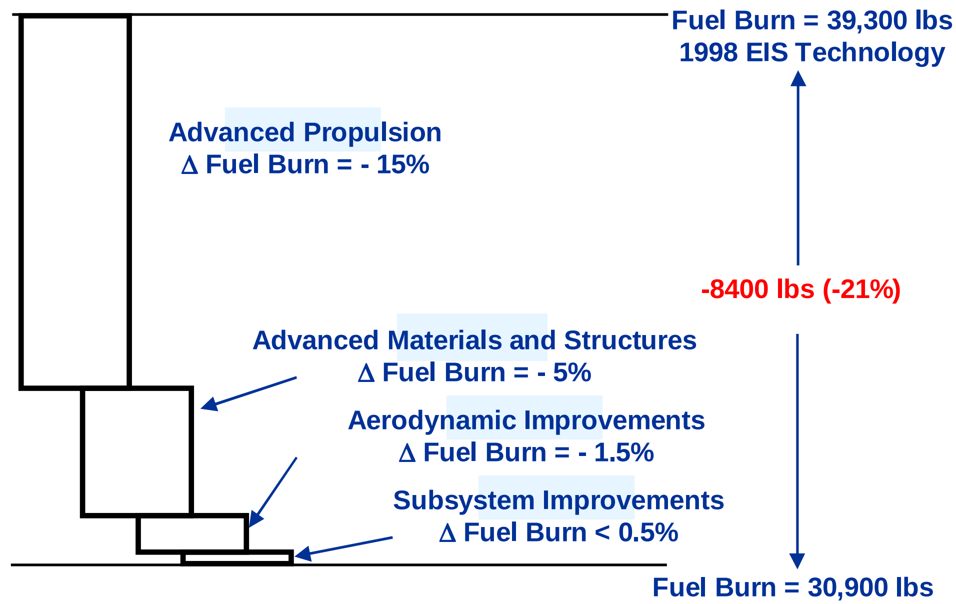
  +1 point increase in turbomachinery efficiencies

  -25% reduction in turbine cooling

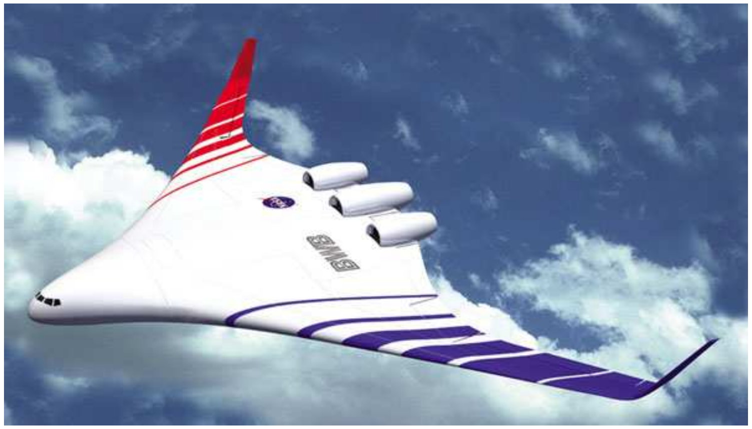
  +50 deg. F compressor temperatures (T3)

  +100 deg. F turbine rotor inlet temperatures

N+1 Conventional Small Twin

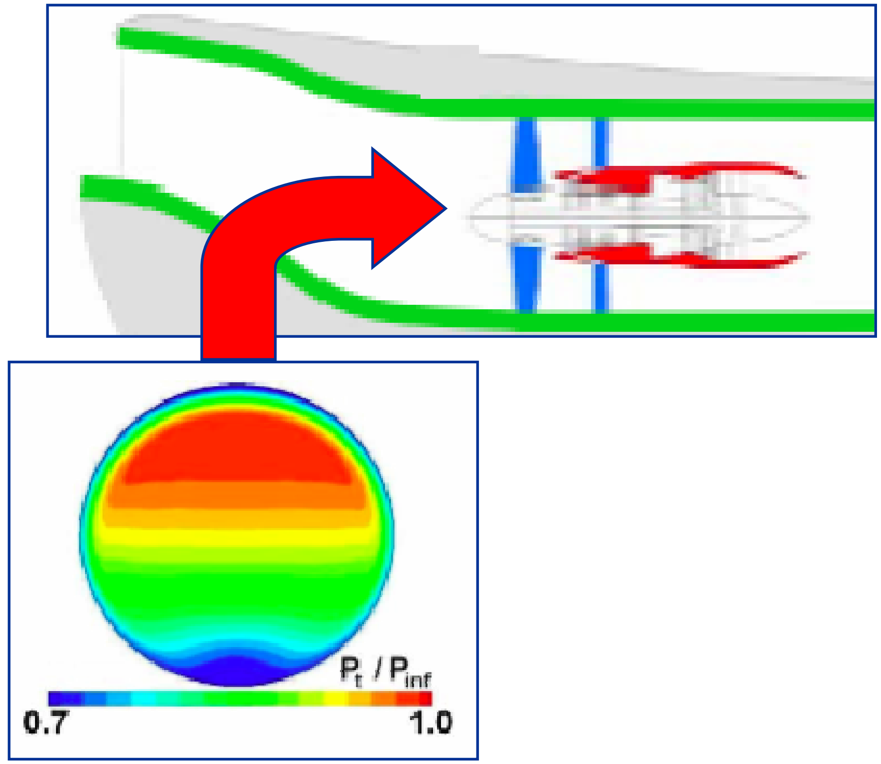


Integrated Embedded Propulsion Systems



N+2 Hybrid Wing/Body with Embedded Engines

Noise and fuel burn benefits to embedded engines



Distorted inlet flow propagated to fan-face for hybrid wing vehicle embedded engine, highlighting challenges in fan design and operation.

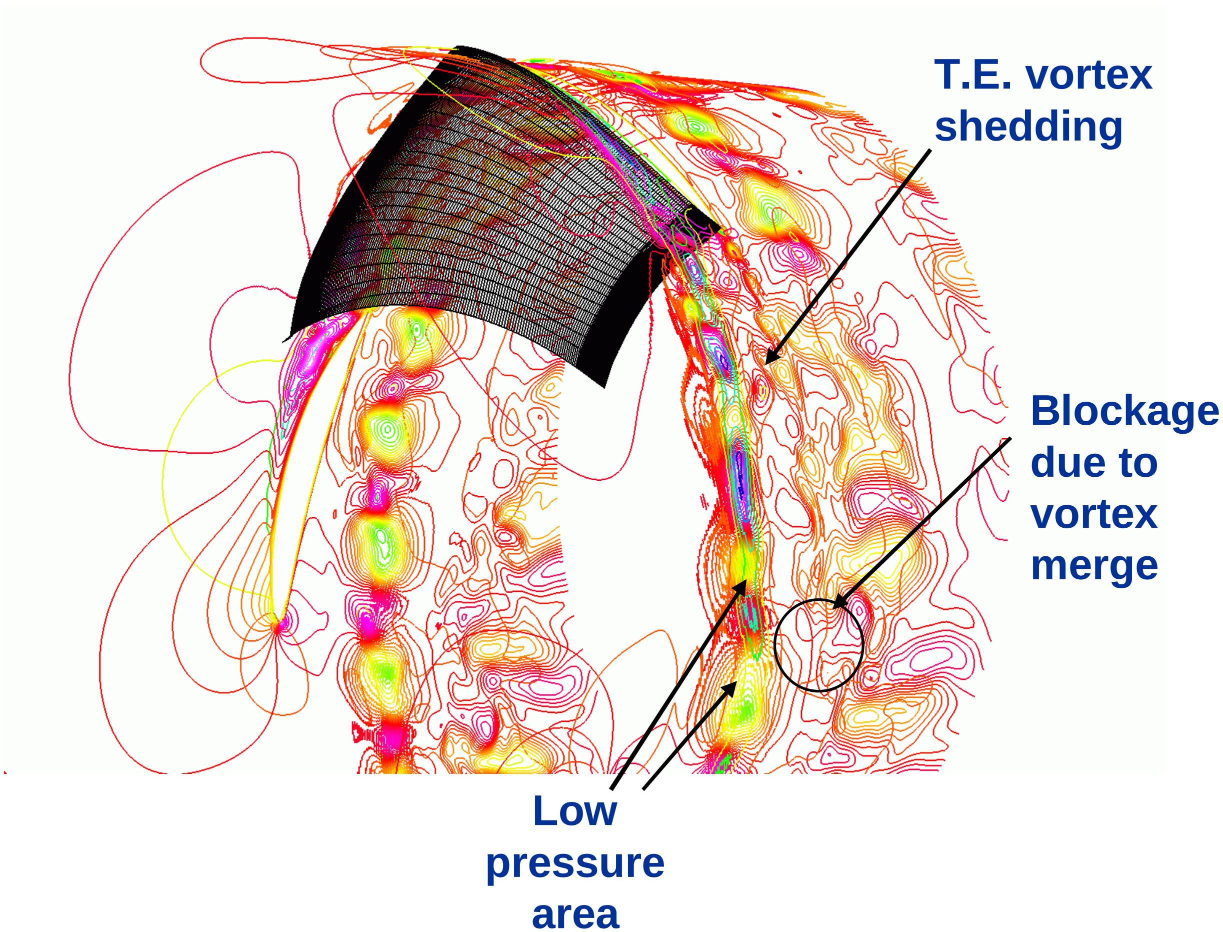
NRA Round 2 Addresses Embedded Propulsion Issues

Aerothermodynamics Research Areas:

- NRA Cooperative Agreements & Contracts
- Foundational Research:
  - Model and Method Development
  - Flow Control Development
  - Cooling Concept Development
- Technologies & Tool Development
  - Turbomachinery Simulation Development
  - Advanced Compression System Development
  - Advanced Cooled Turbine Development
  - Advanced Inlet and Nozzle Development
  - Turbomachinery Code Assessment

Foundational Research: Model and Method Development

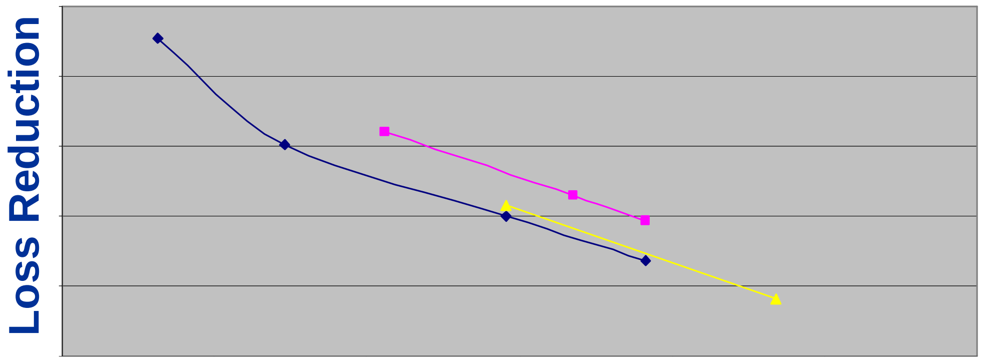
Large Eddy Simulation of Vortex Interactions at 95 % Span



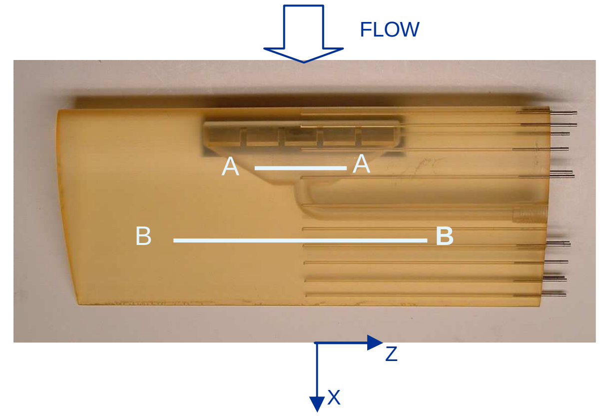
LES simulation of vortex interaction for a ducted propeller. Interactions between tip clearance vortex, shed vortex and tip vortex from the adjacent blade produce low pressure area. Tip gap size affects this phenomena.

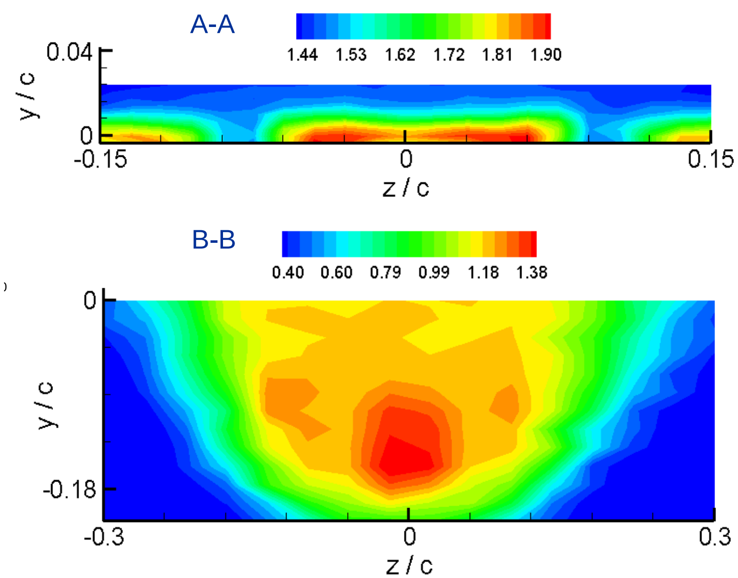
Foundational Research: Flow Control Development

Typical Stator Wake Loss Reduction As a Function of Increasing Momentum Coefficient for a Synthetic Jet in an Axial Compressor Stator Blade



10% to 20% reduction in aerodynamic loss achieved with zero net mass flow devices

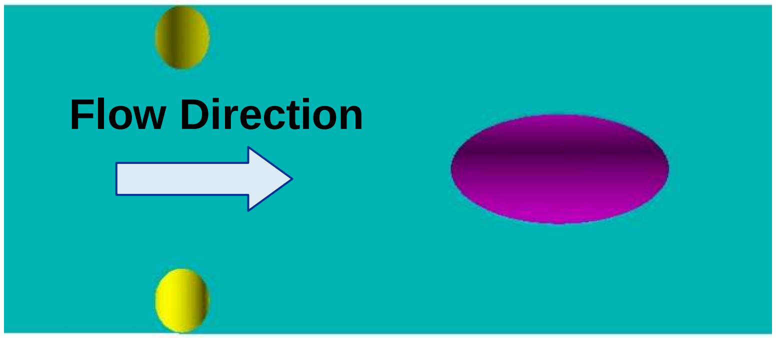




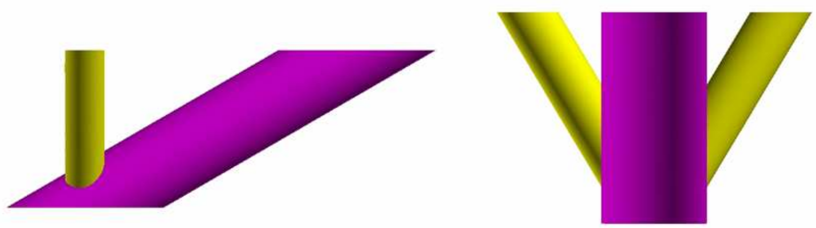
Experimental Study on Flow Control over a Blade by Acoustic Excitation (Synthetic Jets)

Foundational Research: Cooling Concept Development

"Anti-vortex" film cooling concept



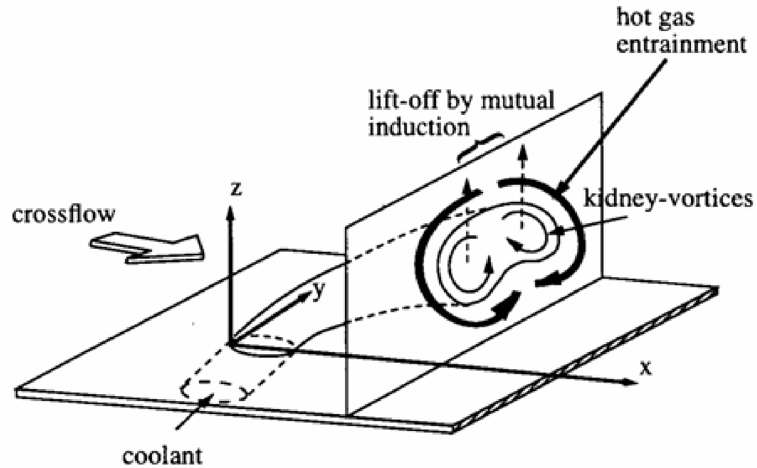
Top view



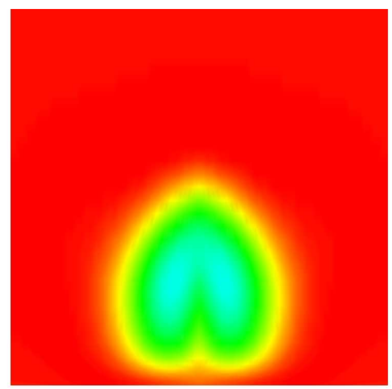
Side view

Front view

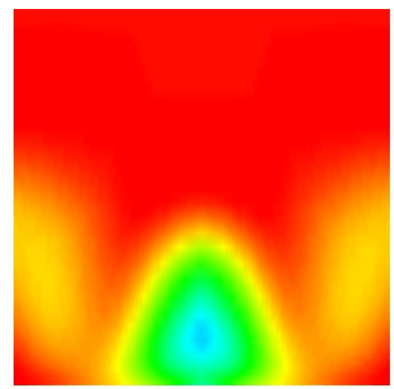
Typical film cooling jet lift-off behavior



Round hole



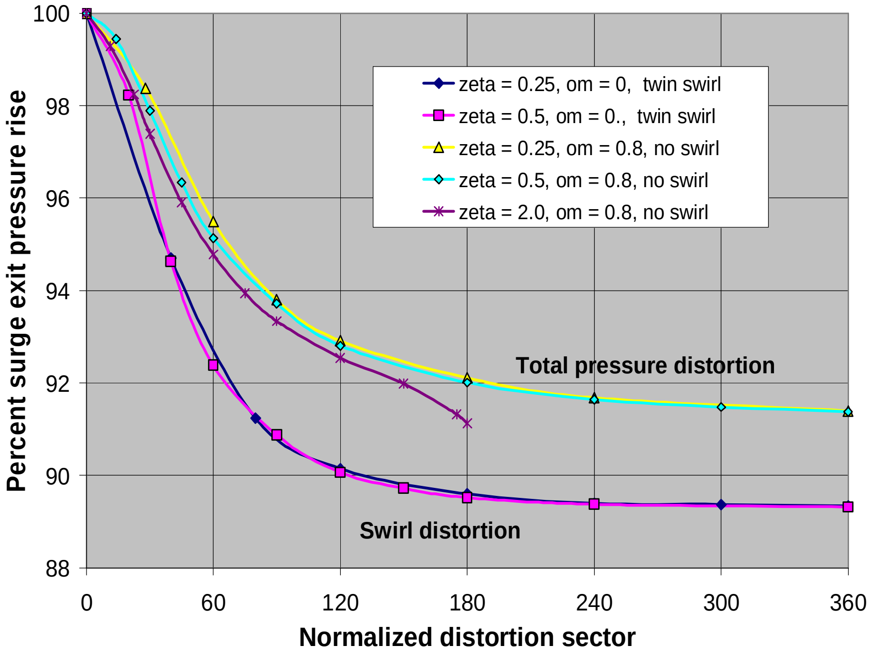
Anti-vortex hole



Comparison of round hole and "anti-vortex" turbine film cooling jet attachment

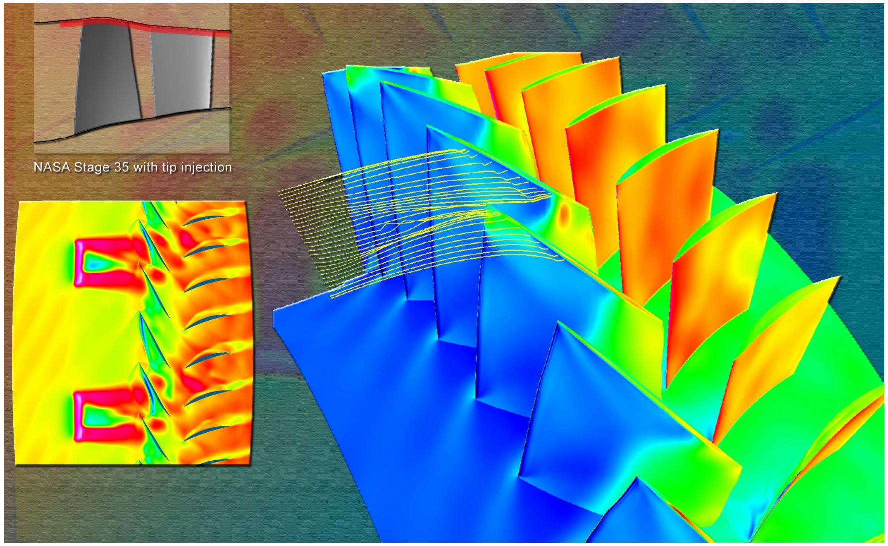
Technologies & Tool Development: Turbomachinery Simulation Development

Model for static & dynamic response of fans & compressors to inlet total pressure & swirl distortion developed using harmonic balance technique



Impact of twin-swirl and total-pressure circumferential distortions

Axial Compressor with discrete flow injection to mitigate rotating stall



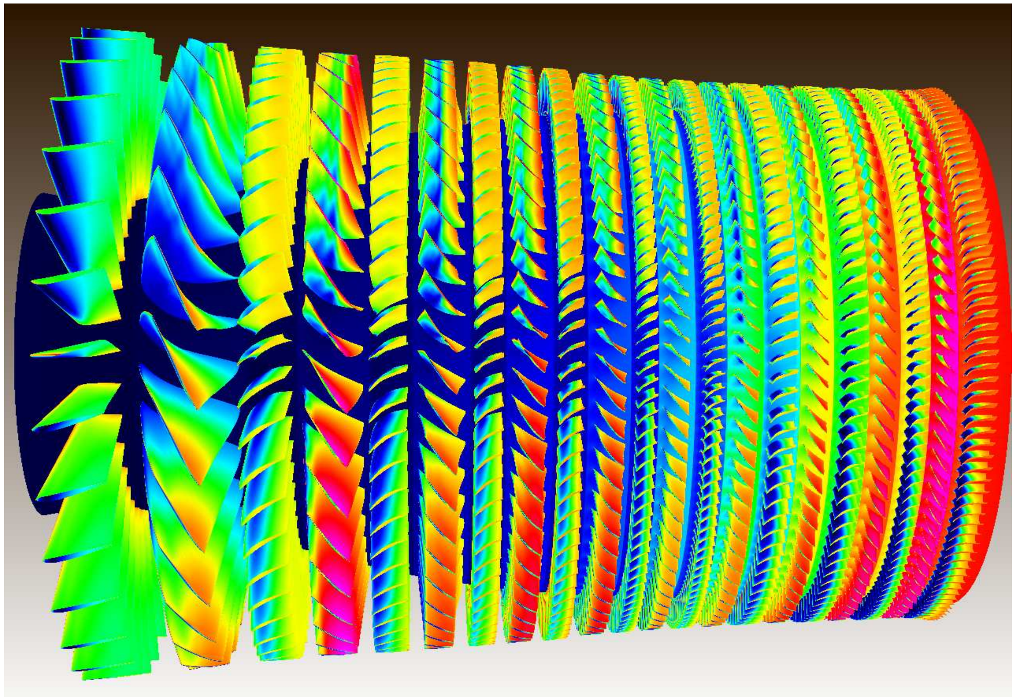
Integrated inlet/fan simulations with inlet flow distortion and flutter condition complete using TURBO.

Technologies & Tool Development:
Advanced Compression System Development

NASA Glenn W7 compressor facility currently being upgraded to full multistage testing capability

Initial test article is 76B 3-stage compressor

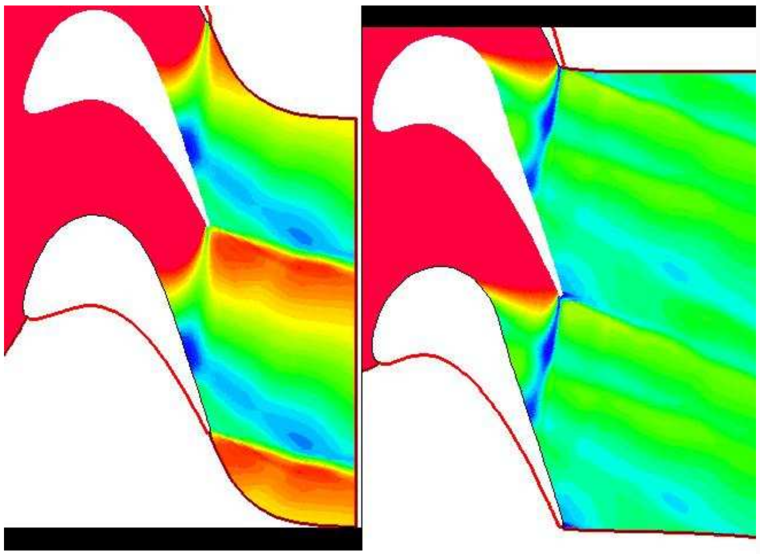
Advanced highly-loaded 3-stage compressor testing proposed



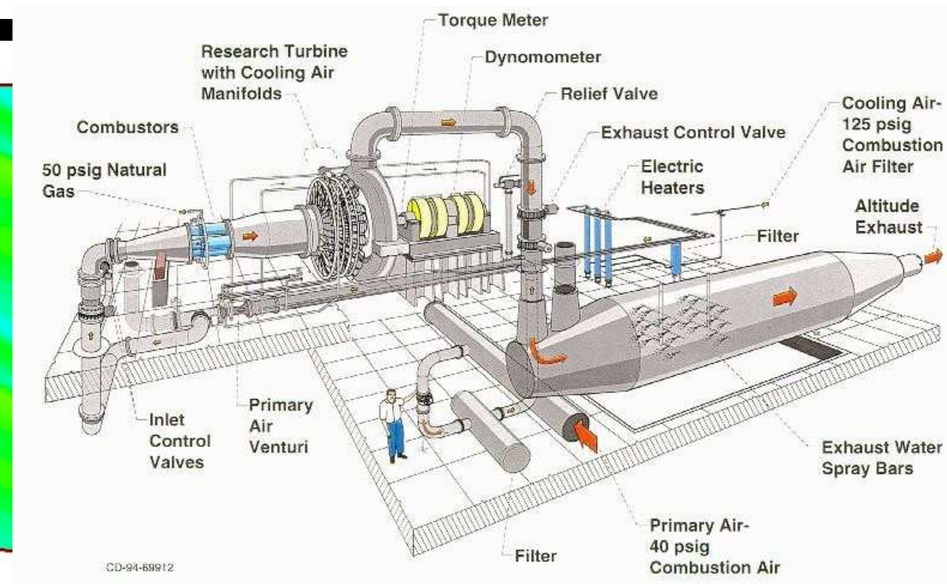
21 Blade Row High Pressure Compressor Analysis with APNASA Code

Technologies & Tool Development:
Advanced Cooled Turbine Development

General Electric Highly-Loaded High Pressure Turbine



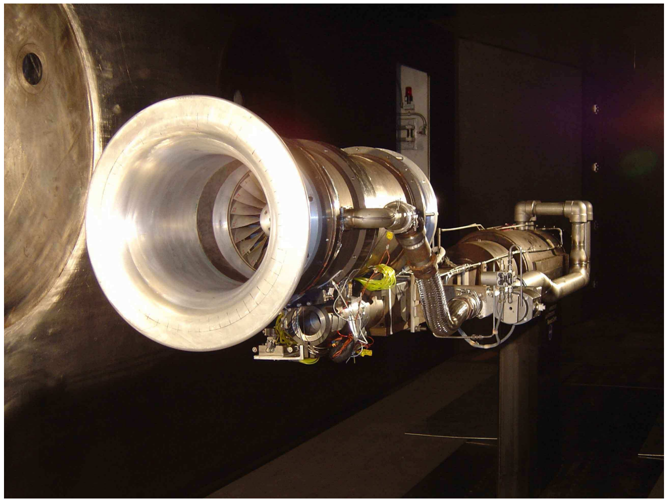
Conventional Reduced Shock Design

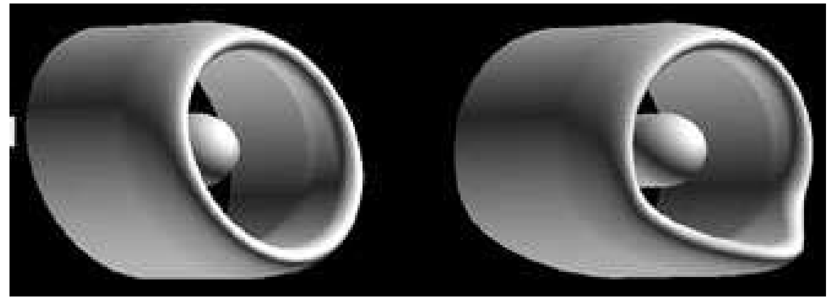


Pressure Ratio = 3.25

Both High and Low Pressure Turbines to be Tested in NASA Glenn Single Spool Turbine Facility (W6)

Technologies & Tool Development:
Advanced Inlet and Nozzle Development

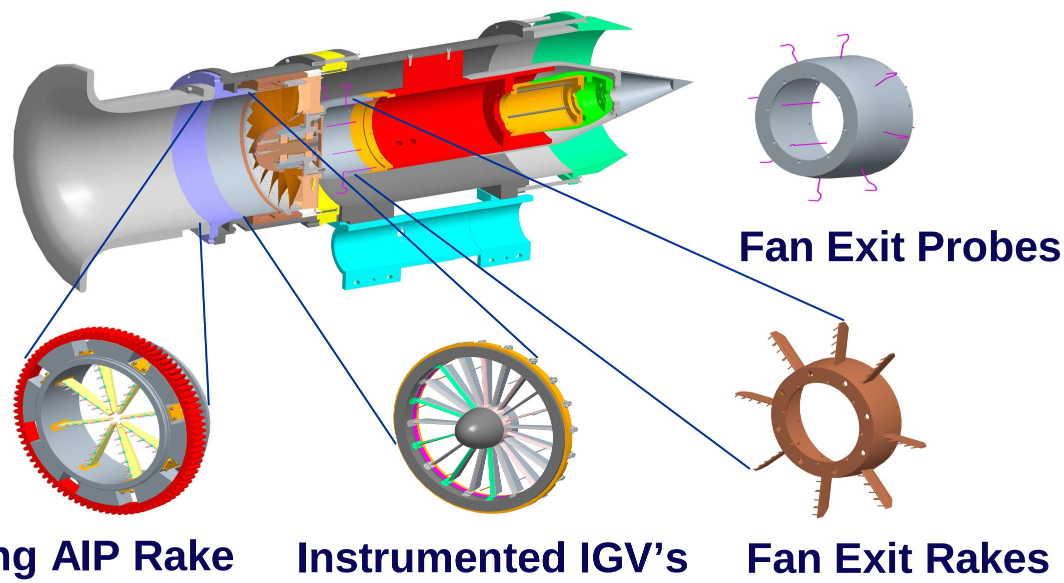




Subsonic scarf-inlet designs with inlet length transition angles of 180° and 67.5°.

Versatile Integrated Inlet Propulsion Aerodynamics Rig

Research focuses on inlet/fan interaction



Technologies & Tool Development: Turbomachinery Code Assessment

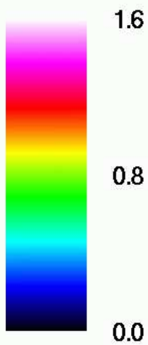
- **Code assessment conducted for 5 NASA turbomachinery Navier-Stokes CFD codes**
  - **Glenn-HT – Convective Heat Transfer Focus**
  - **H3D – Large Eddy Simulation Capability**
  - **Swift – Mixing Plane**
  - **APNASA – Average Passage Modeling**
  - **TURBO – Full Unsteady Simulation**

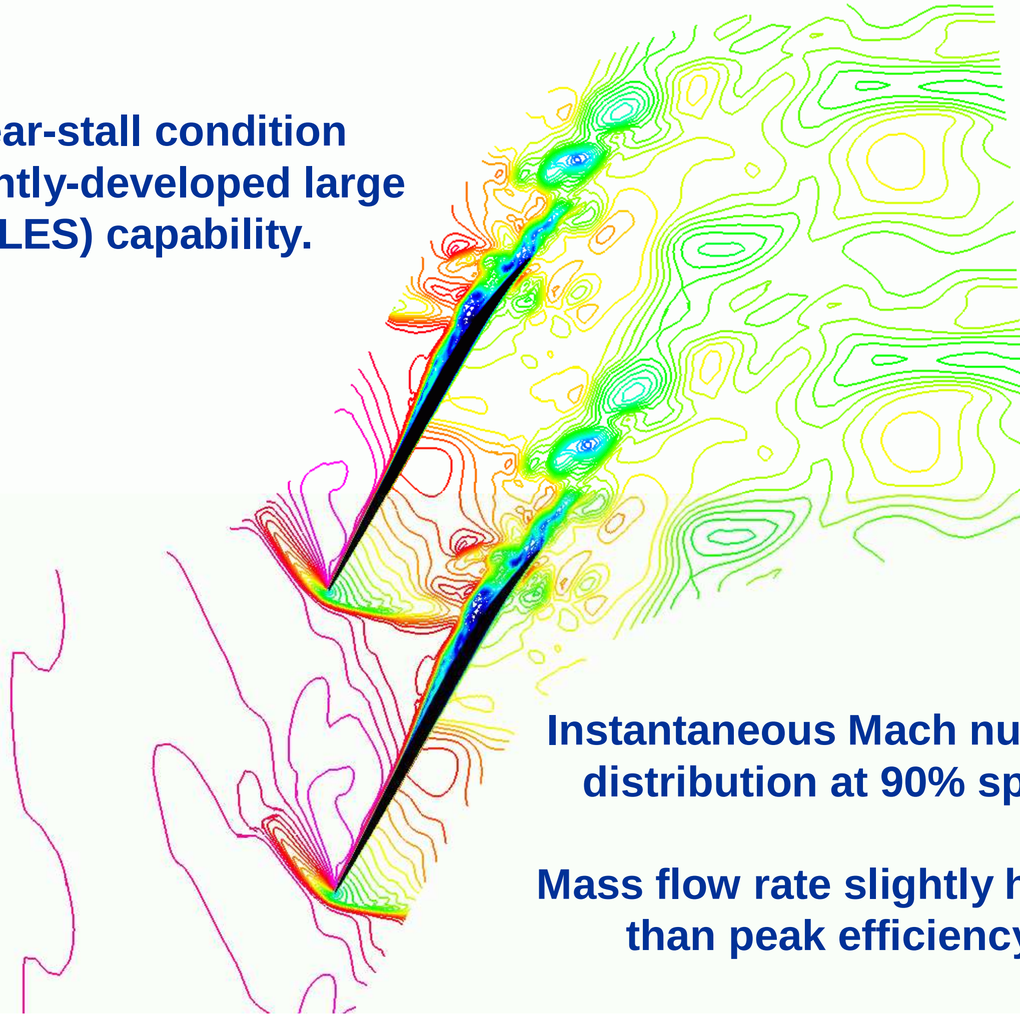
- **Test cases chosen based on previous benchmark activity, availability of high quality validation data, and relevance of case**
  - **NASA Rotor 37 – transonic compressor with very high quality data**
  - **NASA Stage 35 – transonic compressor stage for interaction effects**

H3D Analysis for NASA Rotor 37

New analyses at near-stall condition performed using recently-developed large eddy simulation (LES) capability.

Relative Mach Number

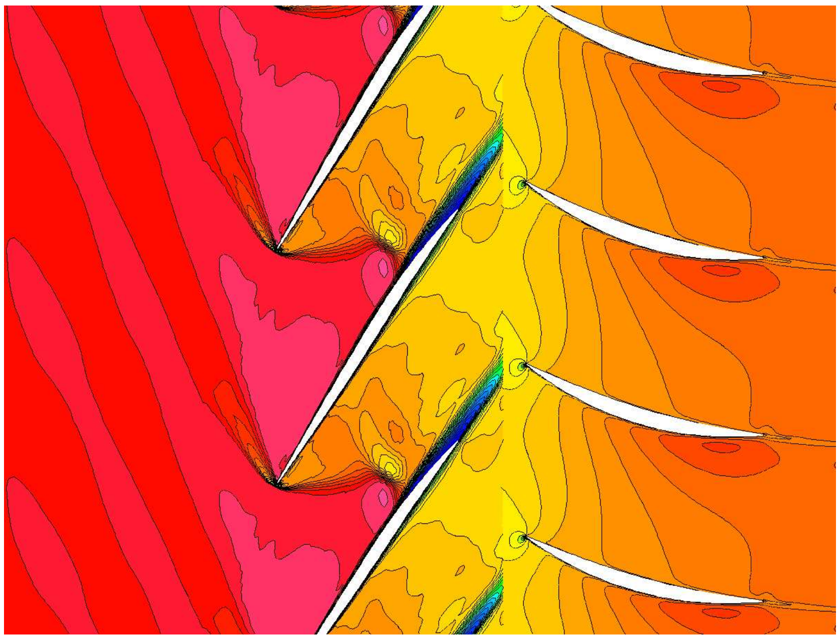




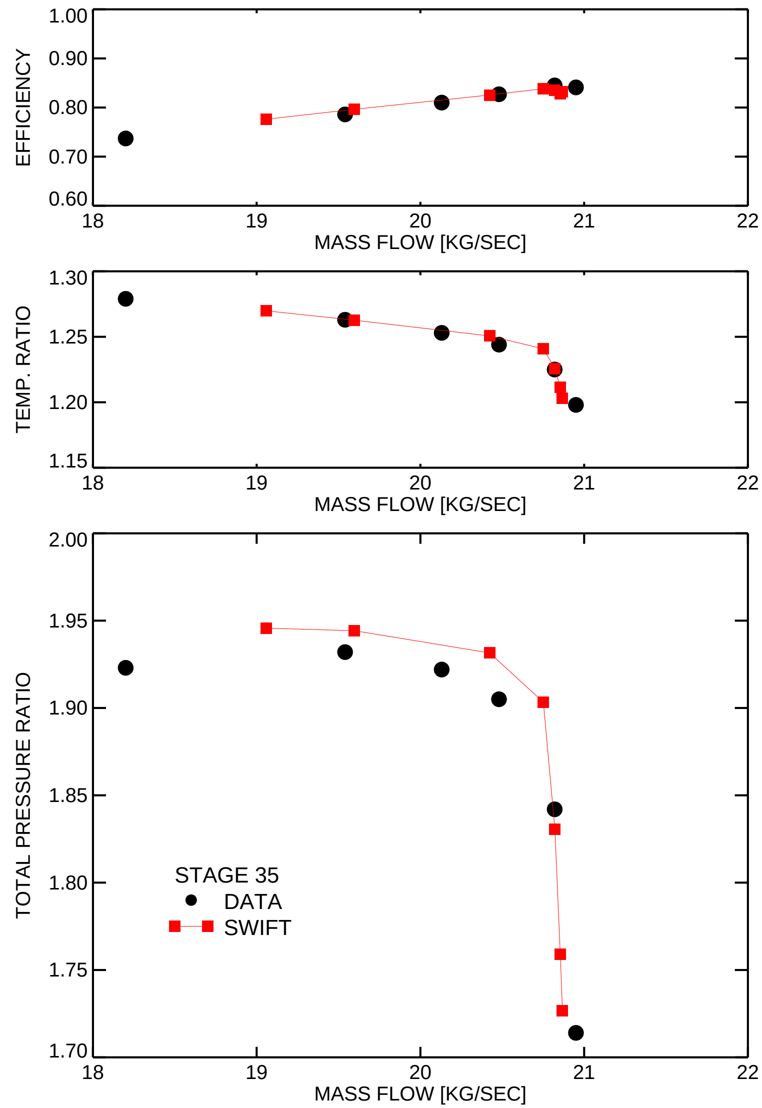
Instantaneous Mach number distribution at 90% span.

Mass flow rate slightly higher than peak efficiency.

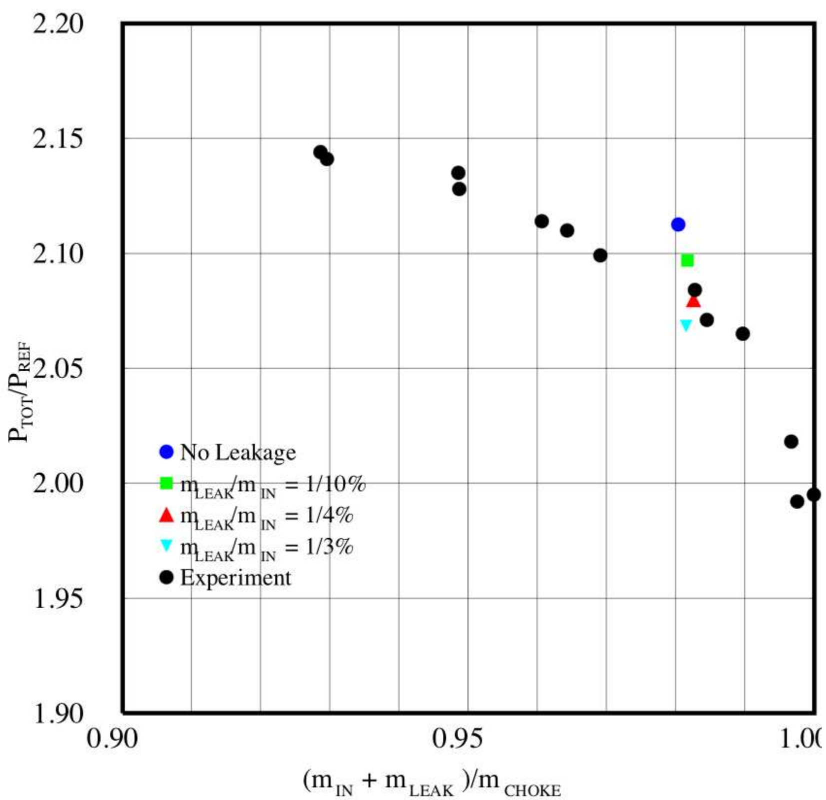
SWIFT Analysis for NASA Stage 35

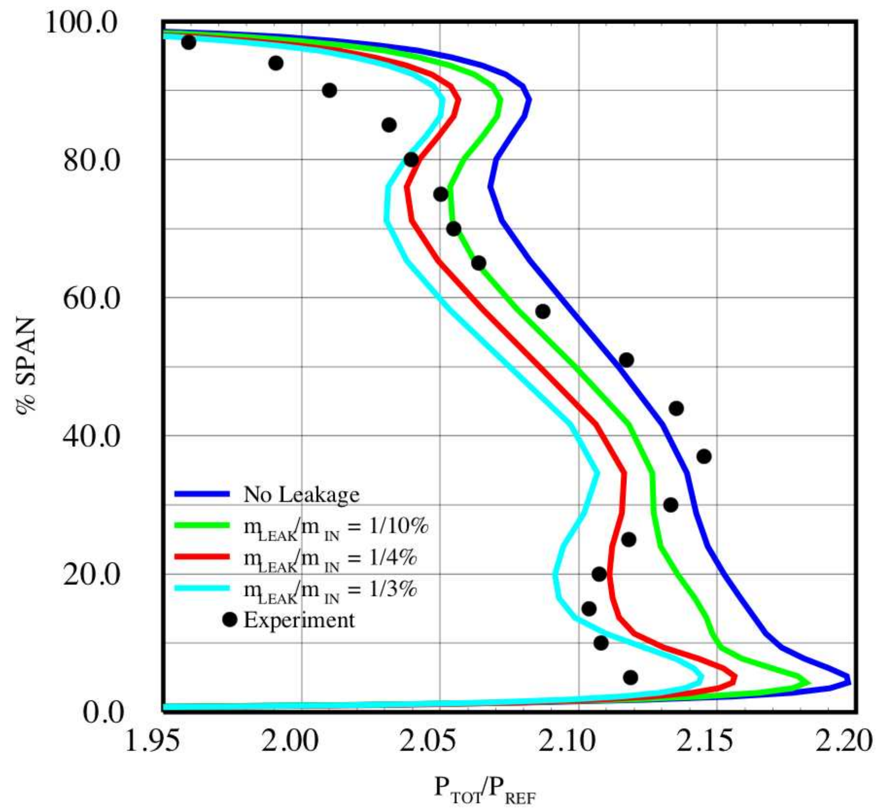


Relative Mach Number



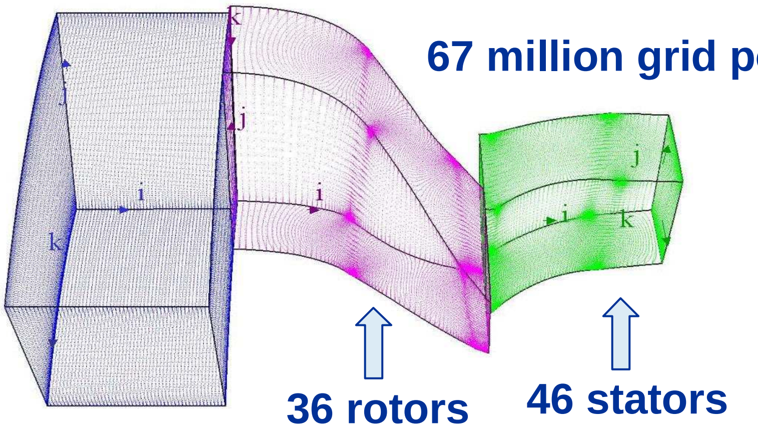
APNASA Analysis for Rotor 37

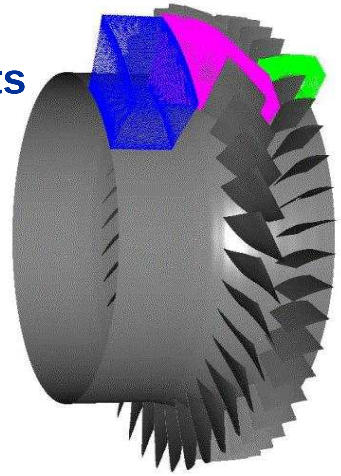


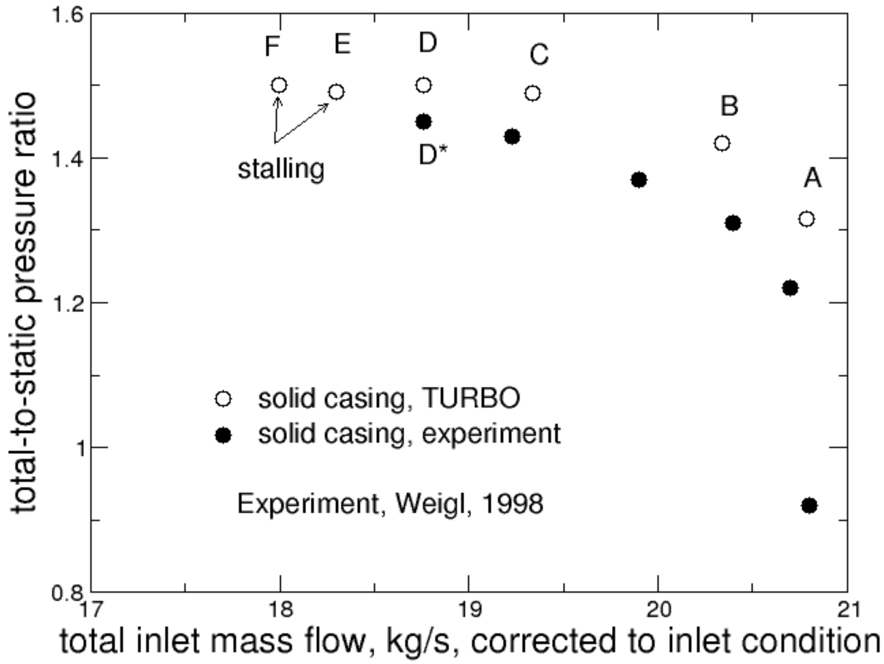


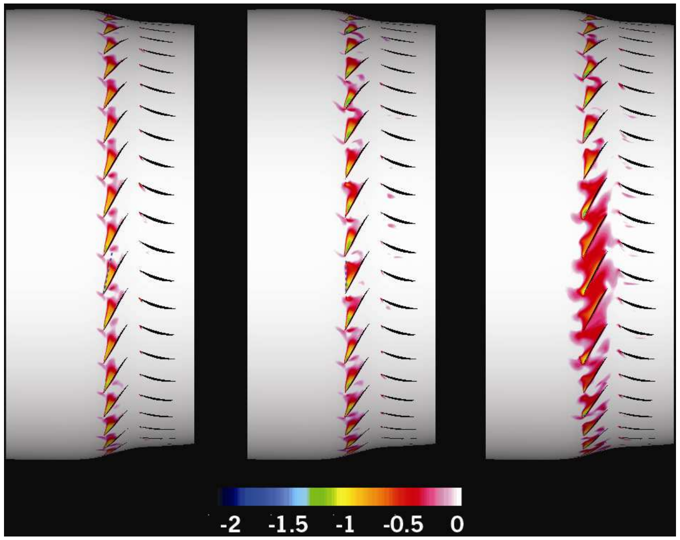
Effect of Hub Leakage on Total Pressure Profiles

TURBO Analysis for Stage 35



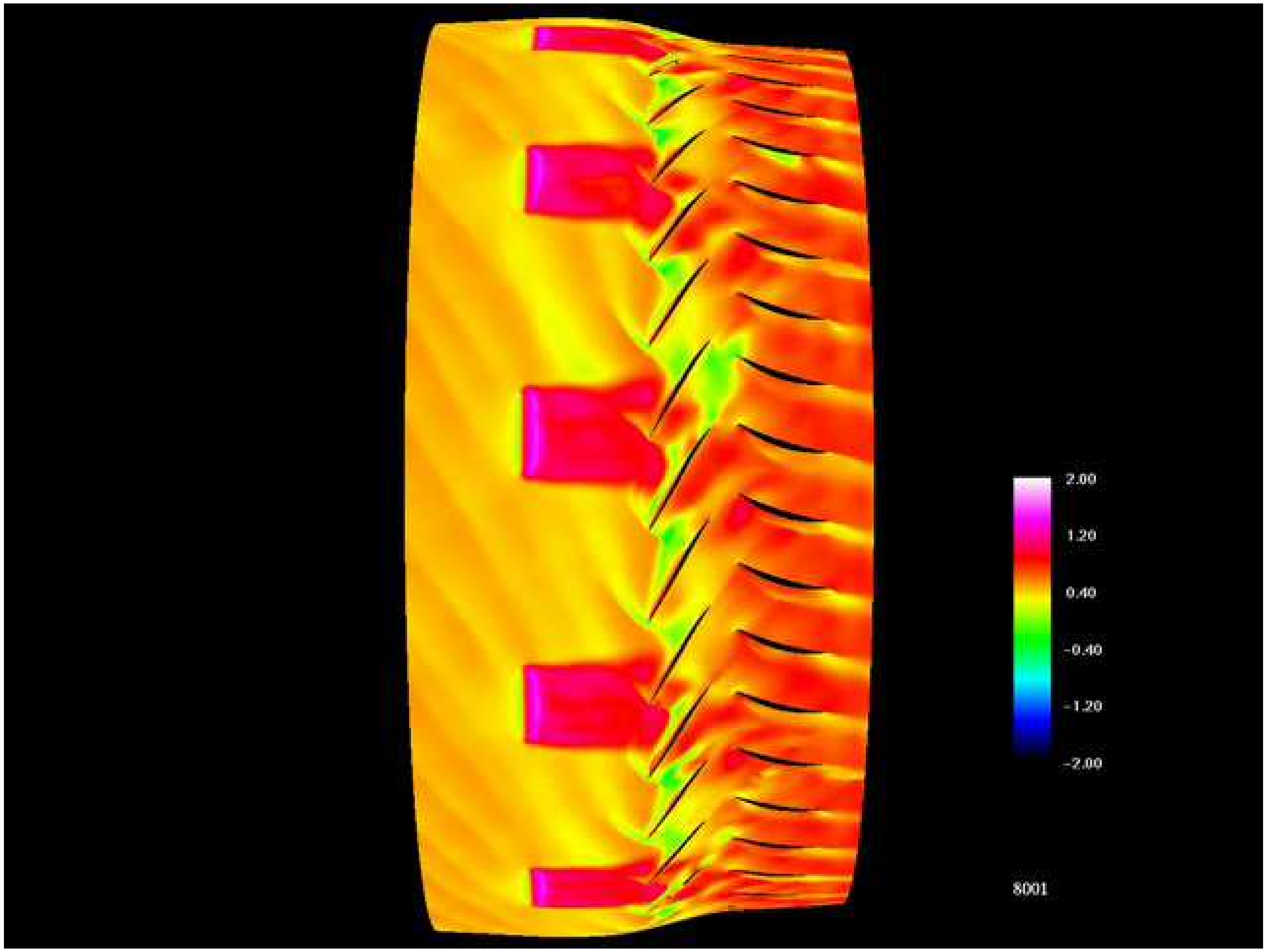






TURBO prediction of stall inception

TURBO Analysis for NASA Stage 35



Stage 35 with Tip Injection

Aerothermodynamics NRA Investment

6 Round 1 NRAs awarded – starting Jan 2007

University	PI	Topic Area	Tech. Monitor
Iowa State Univ.	Durbin	Turbulence Modeling	Hah
Naval Academy	Volino	LPT flow Control	Strasizar
Ohio State Univ.	Bons	LPT Flow Control	Strasizar
Princeton Univ.	Miles	Plasma Actuators	Ashpis
Univ. Minnesota	T. Simon	Plasma Flow Control	Poinsatte
Univ. Wisconsin	Hershkowitz	Plasma Actuators	Ashpis

Aerothermodynamics NRA Investment

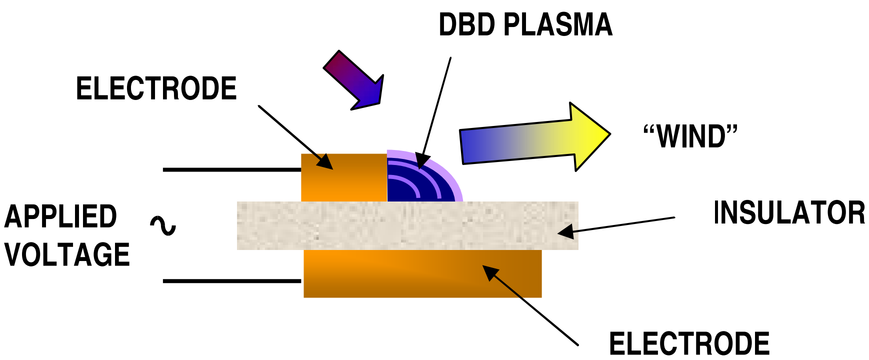
Integrated Embedded Propulsion Systems (N+2)

3 Round 2 NRAs awarded – starting October 2007

Performing Organization	PI	Topic Area	Tech. Monitor
U. of Tennessee-Chatt.	Whitfield	High Fidelity Modeling	Hathaway
The Boeing Company	Mace	Inlet Flow Control	Abbott
United Technologies	Florea	Inlet/Fan Interaction	Arend

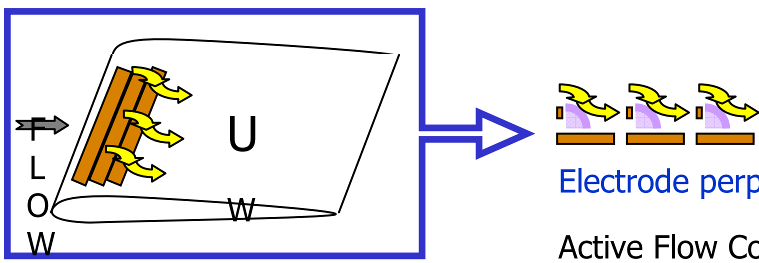
Background

Dielectric Barrier Discharge (DBD) Plasma Actuators



<u>Advantages of a GDP actuators</u>

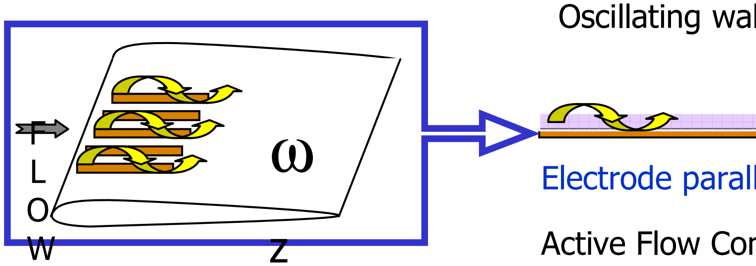
- Pure solid state device
- Simple, no moving parts
- Flexible operation, good for varying operating conditions
- Low power
- Heat resistance – w/ proper materials



Electrode perpendicular to flow

Active Flow Control via

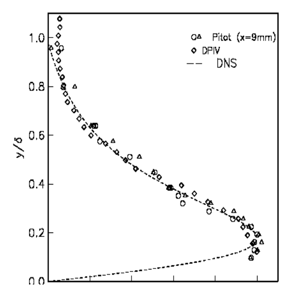
Oscillating wall jet



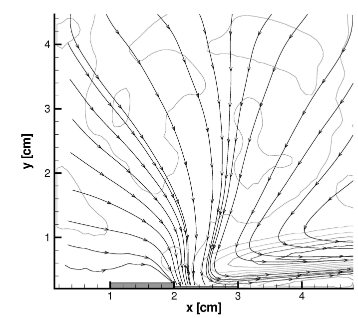
Electrode parallel to flow

Active Flow Control via

Streamwise vortices



Measured wall jet (Univ. Notre Dame)



Measured Streamlines (Univ. Kentucky)

The customary approach to DBD actuators:

- The applied voltage is in AC voltage 5-80 KV
- Signal shape: sine wave , saw-tooth, etc
- Frequency range 2-20 KHz.
- Generated “wind” peak velocities obtained 1-20 m/s

The Princeton novel approach to DBD actuators:

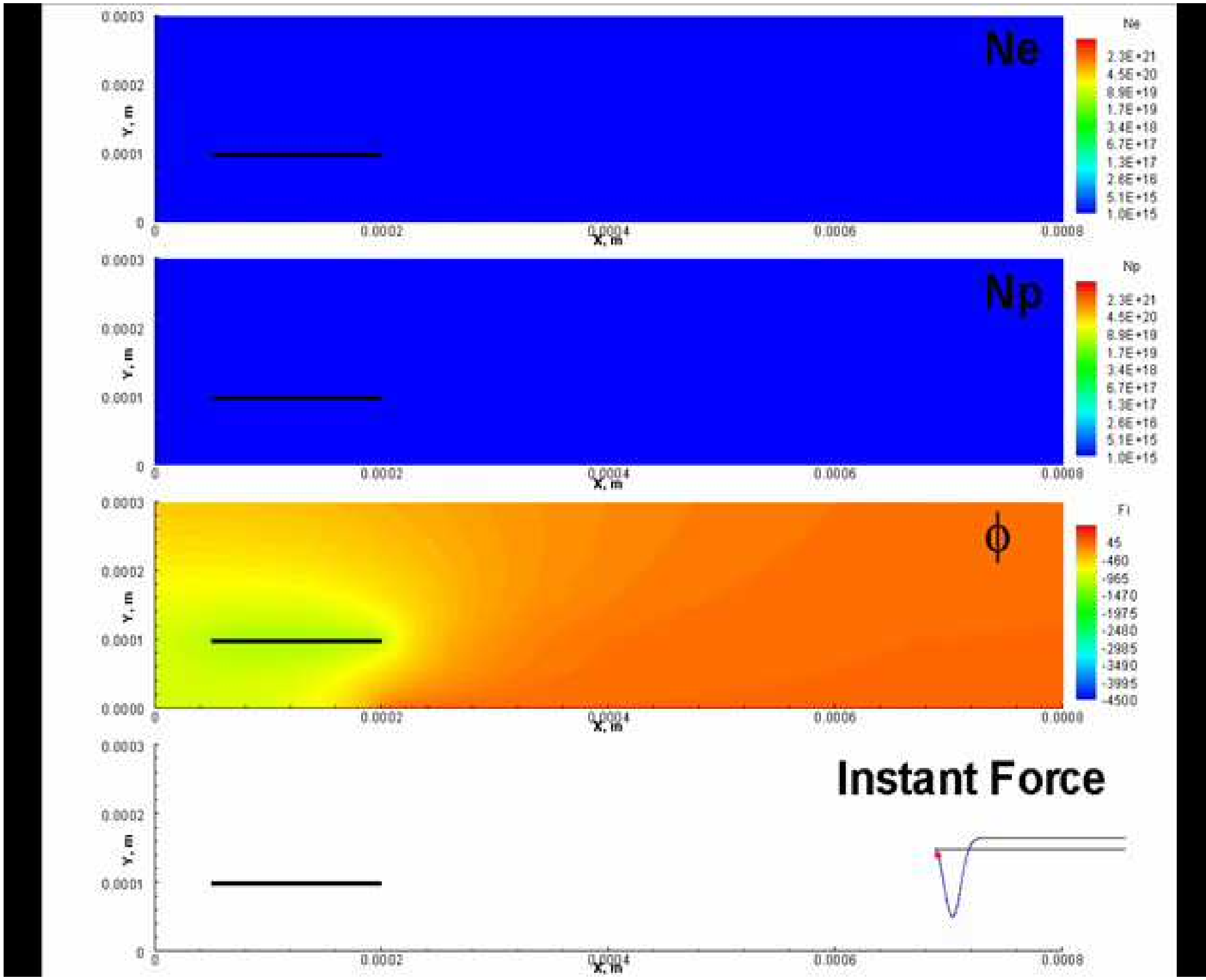
- Applied voltage: Ultra short pulses – nanoseconds
- Repetition rate > 100 KHz
- Bias Voltage
- Predicted two orders magnitude increase in “wind” peak velocities

Approach

- Computational
- Experimental

Example computational case: high voltage repetitive short negative Gaussian pulses and dc bias

•Peak voltage: -4.5 kV, FWHM: 4 ns, Bias: 0.5 kV, f=500kHz



electrons

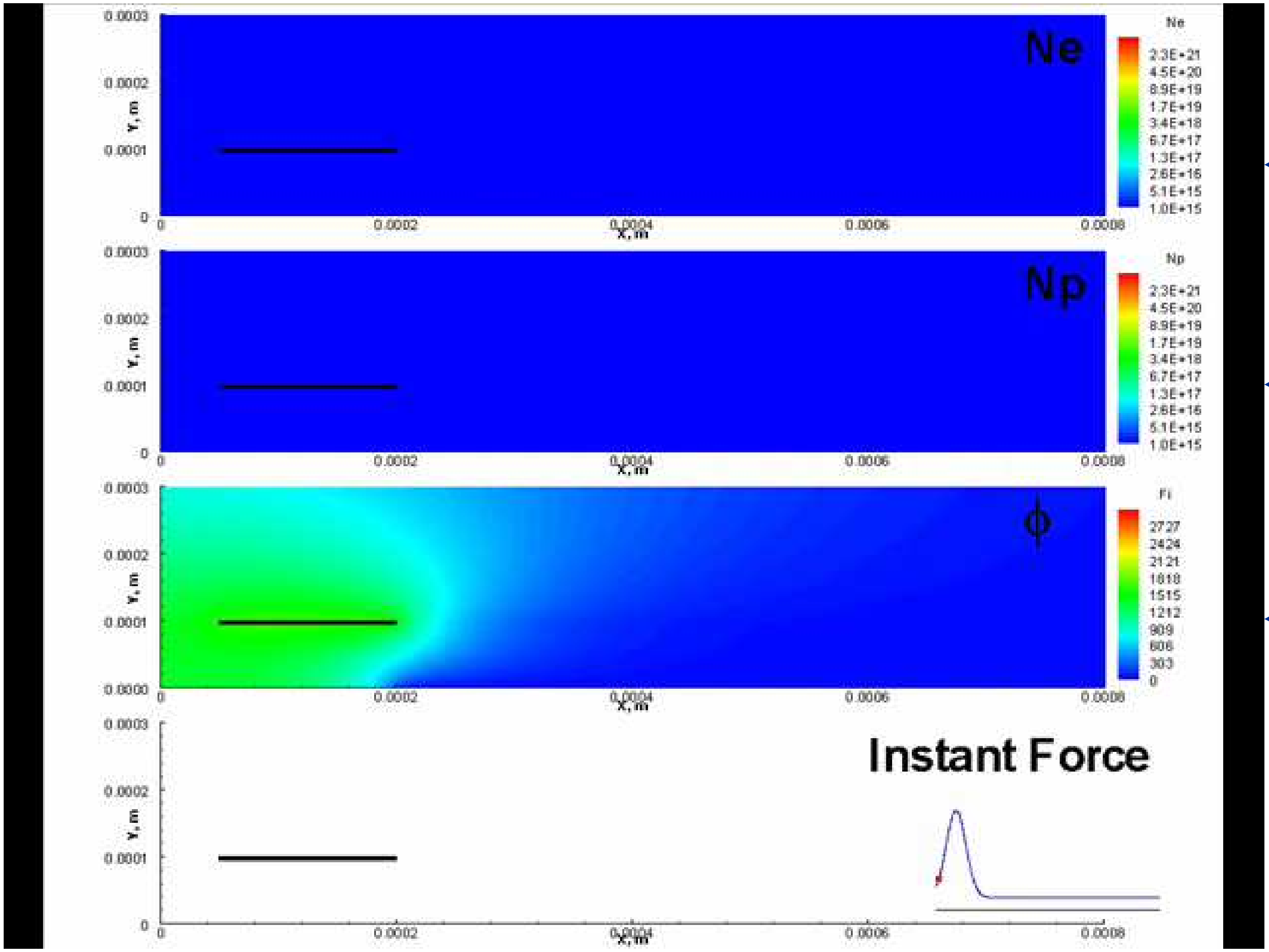
positive ions

electric potential

Applied Physics Group
Princeton University

Example computational case: high voltage repetitive short positive Gaussian pulses and dc bias

•Peak voltage: 3 kV, FWHM: 4 ns, Bias: 1 kV, f=500kHz



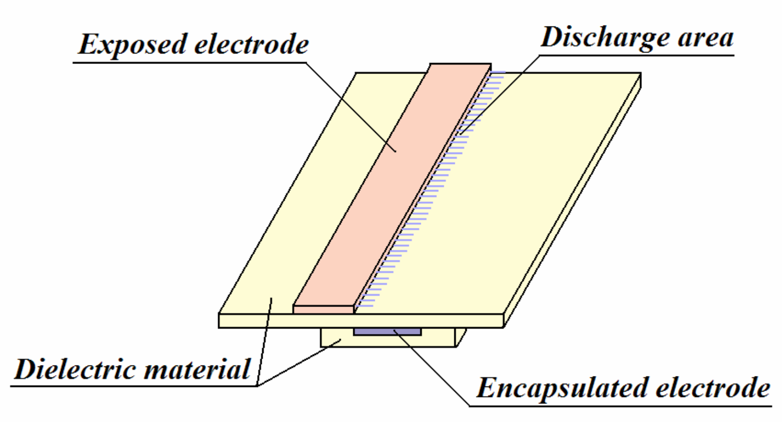
electrons

positive ions

electric potential

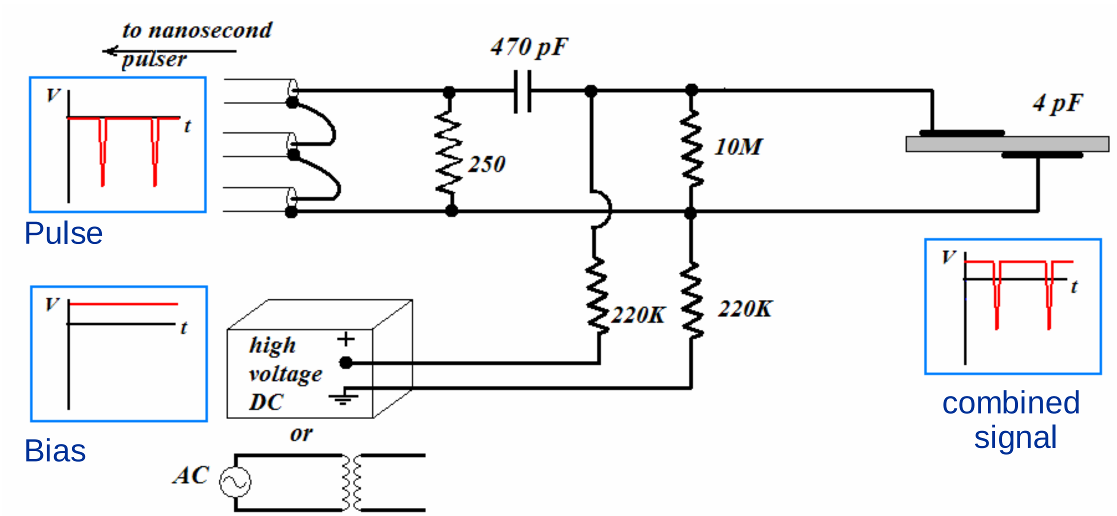
Applied Physics Group
Princeton University

Experimental setup



Dielectric material:
- kapton tape
- thickness 100 µm

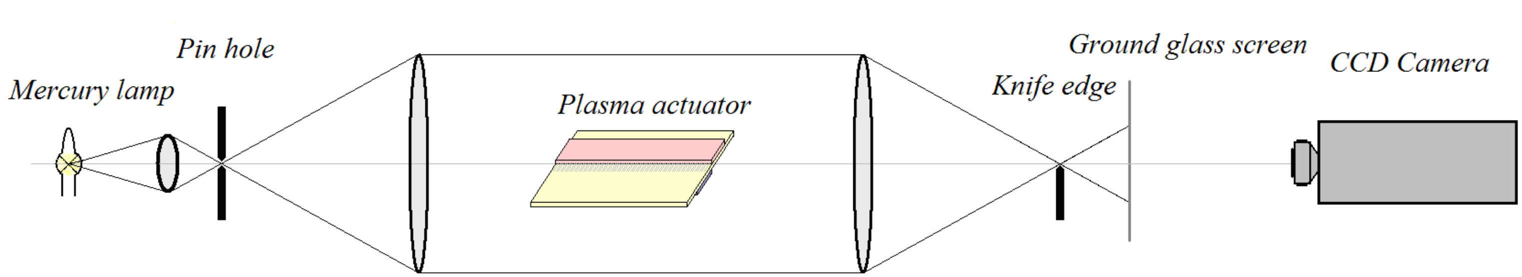
Electrodes:
- copper foil
- width 25 mm
- spanwise dim. 50 mm

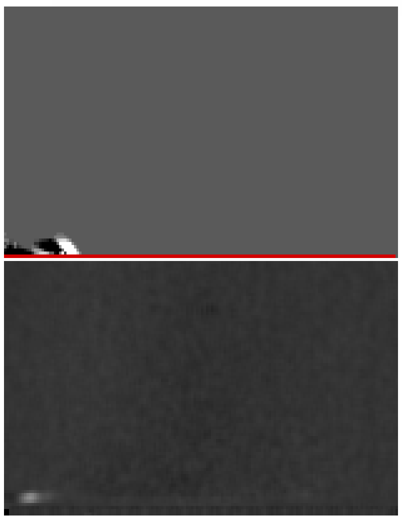


The circuit is designed so as to superimpose short pulses on a low frequency bias voltage without interference between the pulser and the low-frequency power supply. **The pulses and the bias voltage are controlled independently**

Schlieren technique

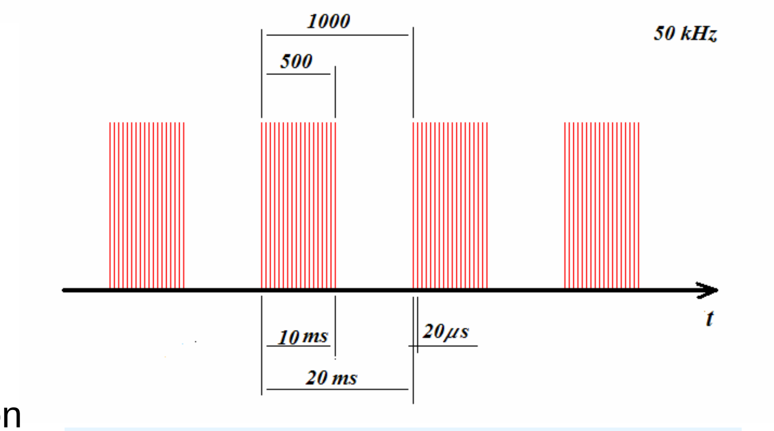
for the DBD plasma actuator induced flow





Numerical modeling

Schlieren visualization

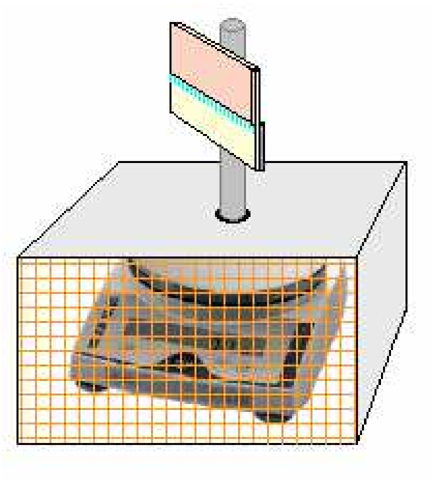


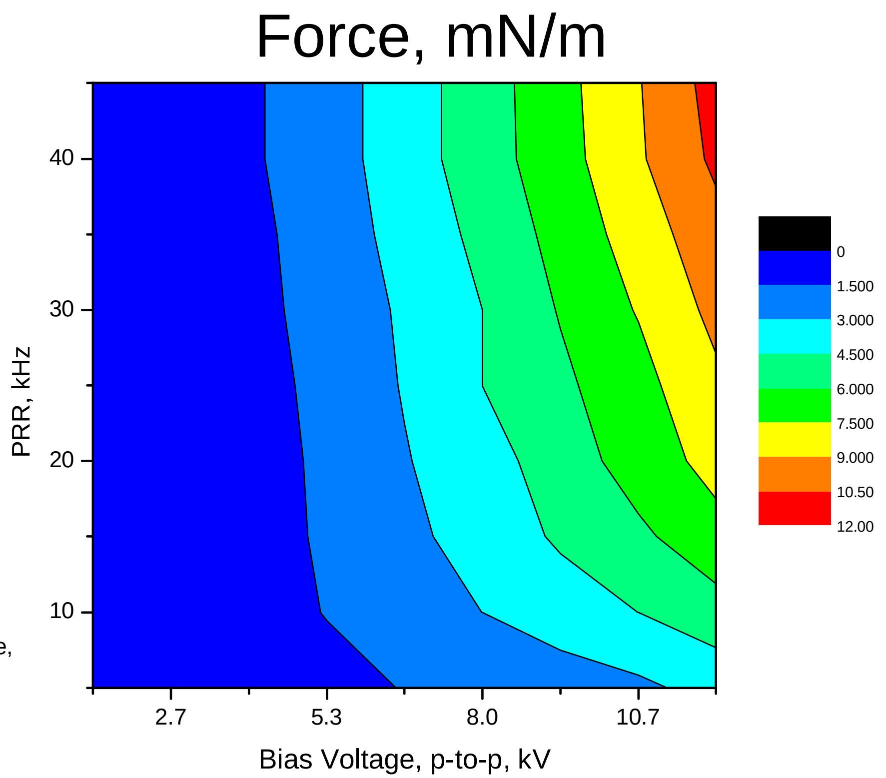
0.5 m/sec at 17 mm
7 m/sec in the plasma region!

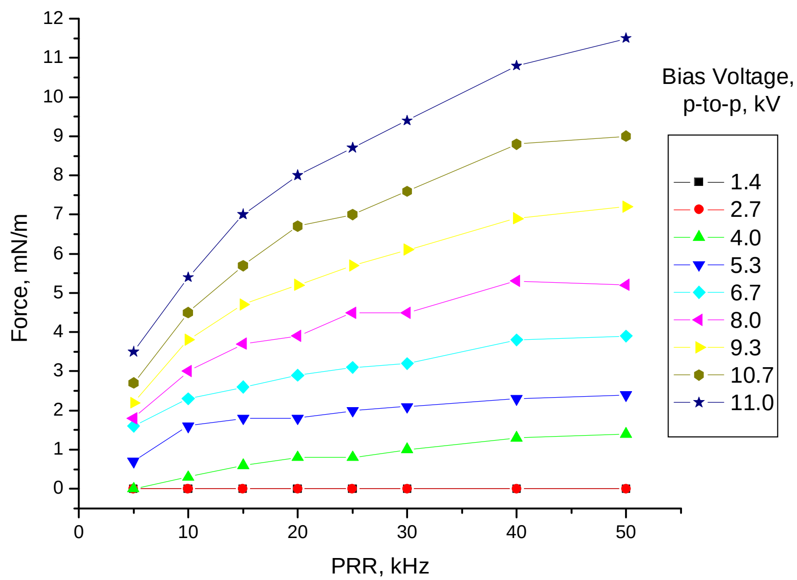
Schlieren technique, burst mode of plasma actuator operation, and 2-D fluid numerical model coupled together allow to restore the entire two-dimensional unsteady plasma induced flow pattern as well as the characteristics of the plasma induced force.

Applied Physics Group
Princeton University

Induced Momentum – via force measurements







MACOR 1/16''
Negative pulses 5kV

Princeton NRA Summary

- Progress has been made in deriving significant insights into the effect of the applied voltage and the role of the bias voltage.
    - The discharge is efficiently controlled by ultra-short pulsing,
    - Gas acceleration is controlled by the bias voltage
    - The effects can be controlled independently

- Progress has been made in further development of the numerical code – algorithm and parallelization
    - Numerical simulation already provided clear guidance for experiments.
    - Experiments point to needed code improvements

Aerothermodynamics Summary

- **Aerothermodynamics technologies play a critical role in the Subsonic Fixed Wing Project goals, particularly with respect to performance and fuel burn.**

- **NASA in-house efforts making progress in both foundational research and technology & tool development.**

- **Turbomachinery code assessment activity progressing with latest tools for NASA rotor 37 and stage 35.**

- **Significant investment in external research through NRA rounds 1 & 2**
  - **Round 1 focus on flow control**
  - **Round 2 focus on embedded engine issues**