Institute for Flow Physics and Control

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Institute for Flow Physics and Control

SIGNATURE RESEARCH AREAS

- Aero-acoustics
- Aero-optics
- Fluid-structure Interactions
- Gas-turbine Propulsion
- Wind Energy
- Multi-phase Flows
- Plasma Dynamics
- Sensors and Flow Control Actuators
- Hypersonic Aerodynamics

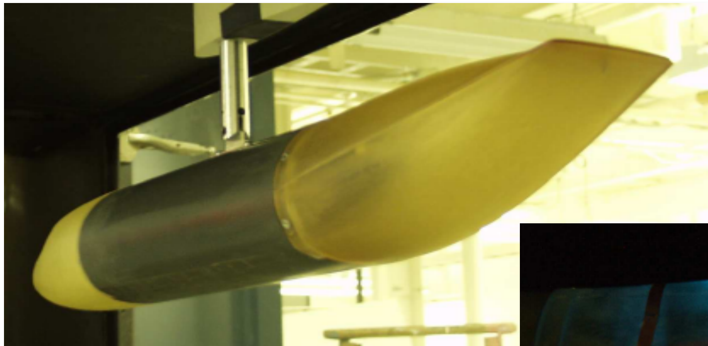
PARTICIPANTS

- 20 T&R Faculty
- 8 R Faculty
- 12 Technical Staff
- 75 Ph.D. Students (85% U.S. citizens)
- 11 U.S. Govt. Agencies
- 25 Companies

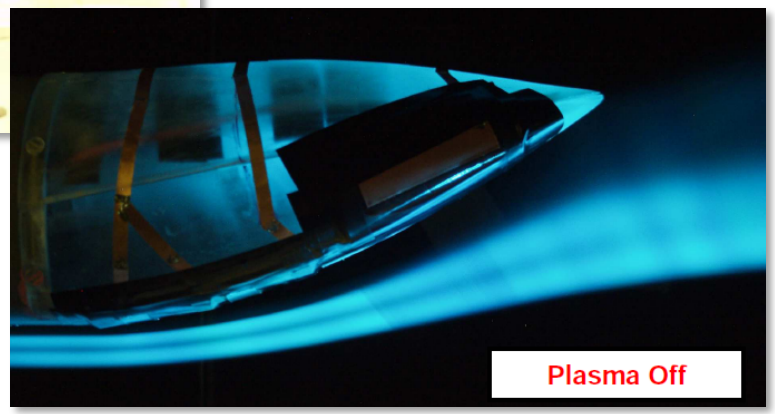
Hessert Laboratory

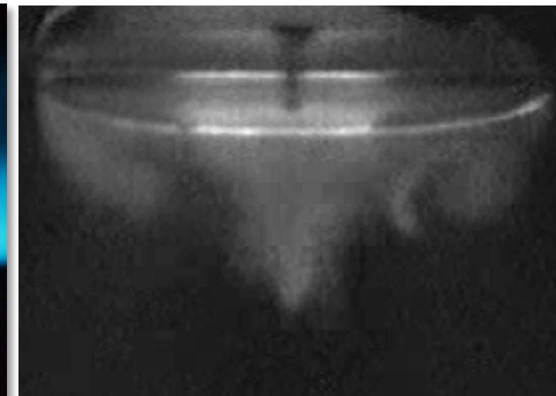
White Field Laboratory

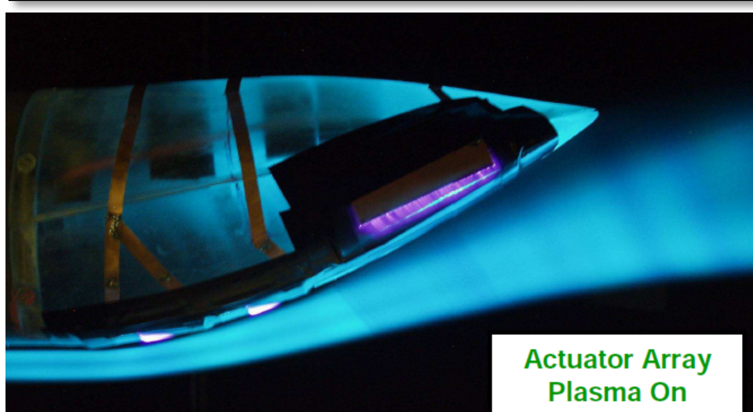
Low-Speed Wind Tunnels



Initial investigations utilizing flow visualization and other flow diagnostic tools (hot-wire, LDV, PIV, etc)

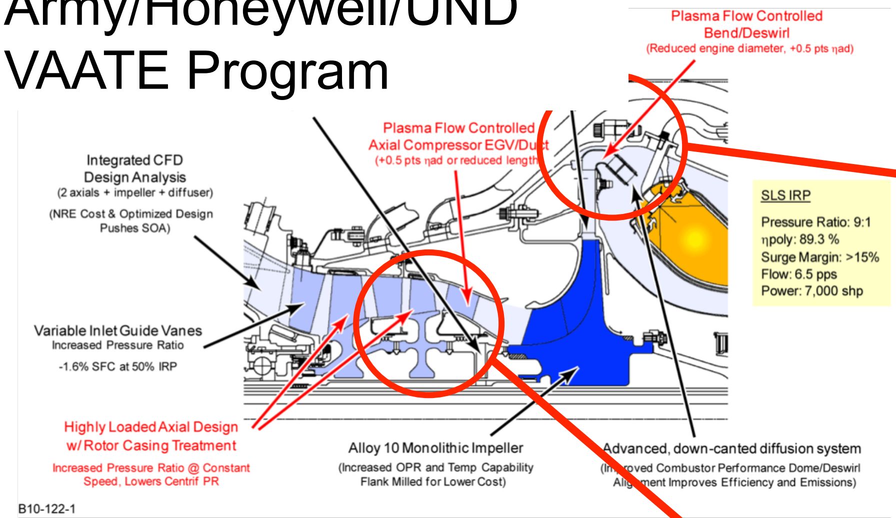




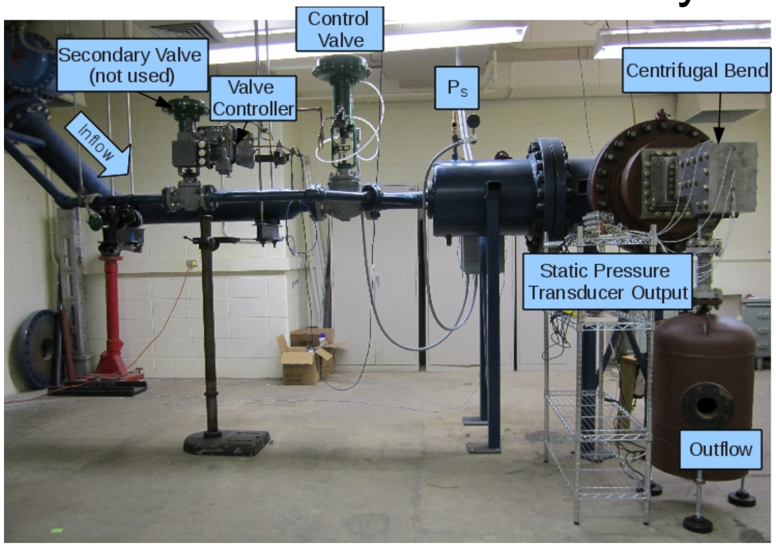


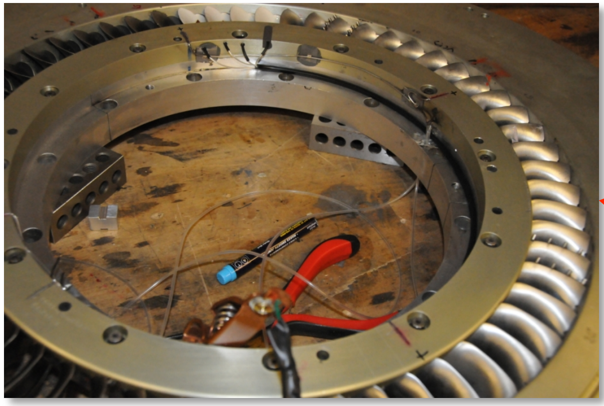
Component Facilities

Army/Honeywell/UND VAATE Program

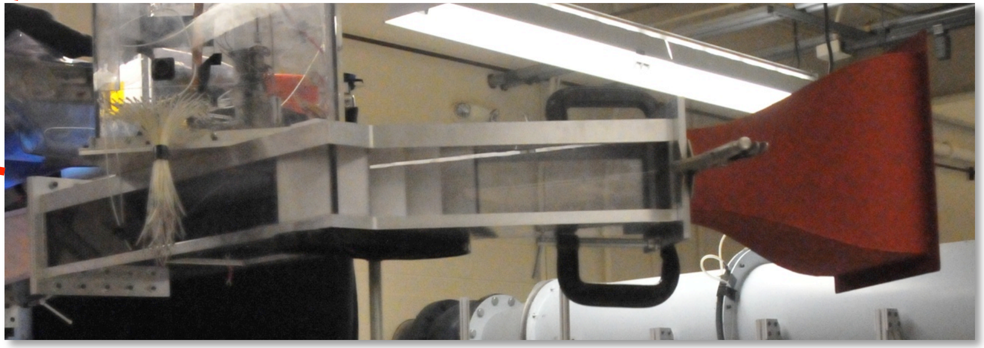


40Bar Blow-down Facility

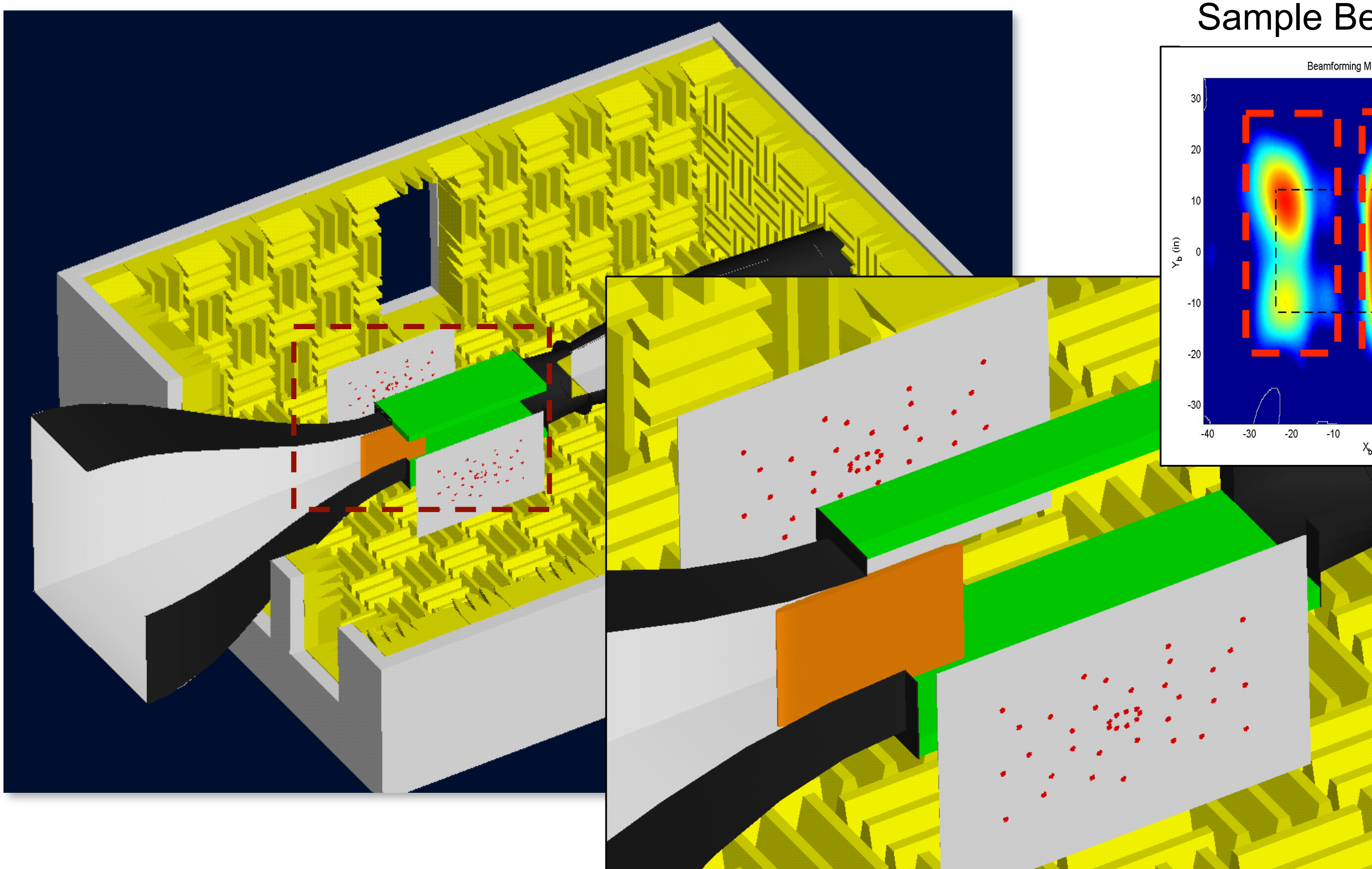




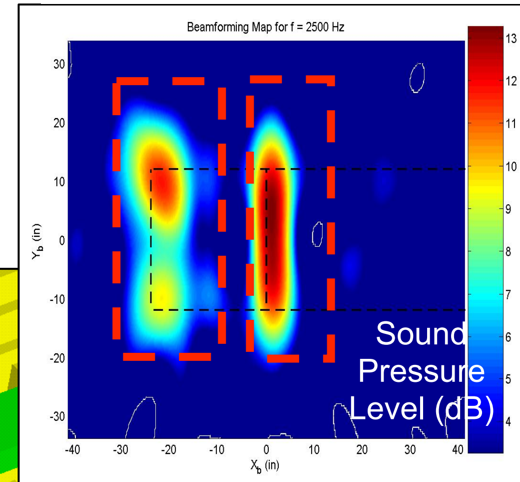
In-draft Tri-Sonic Facility



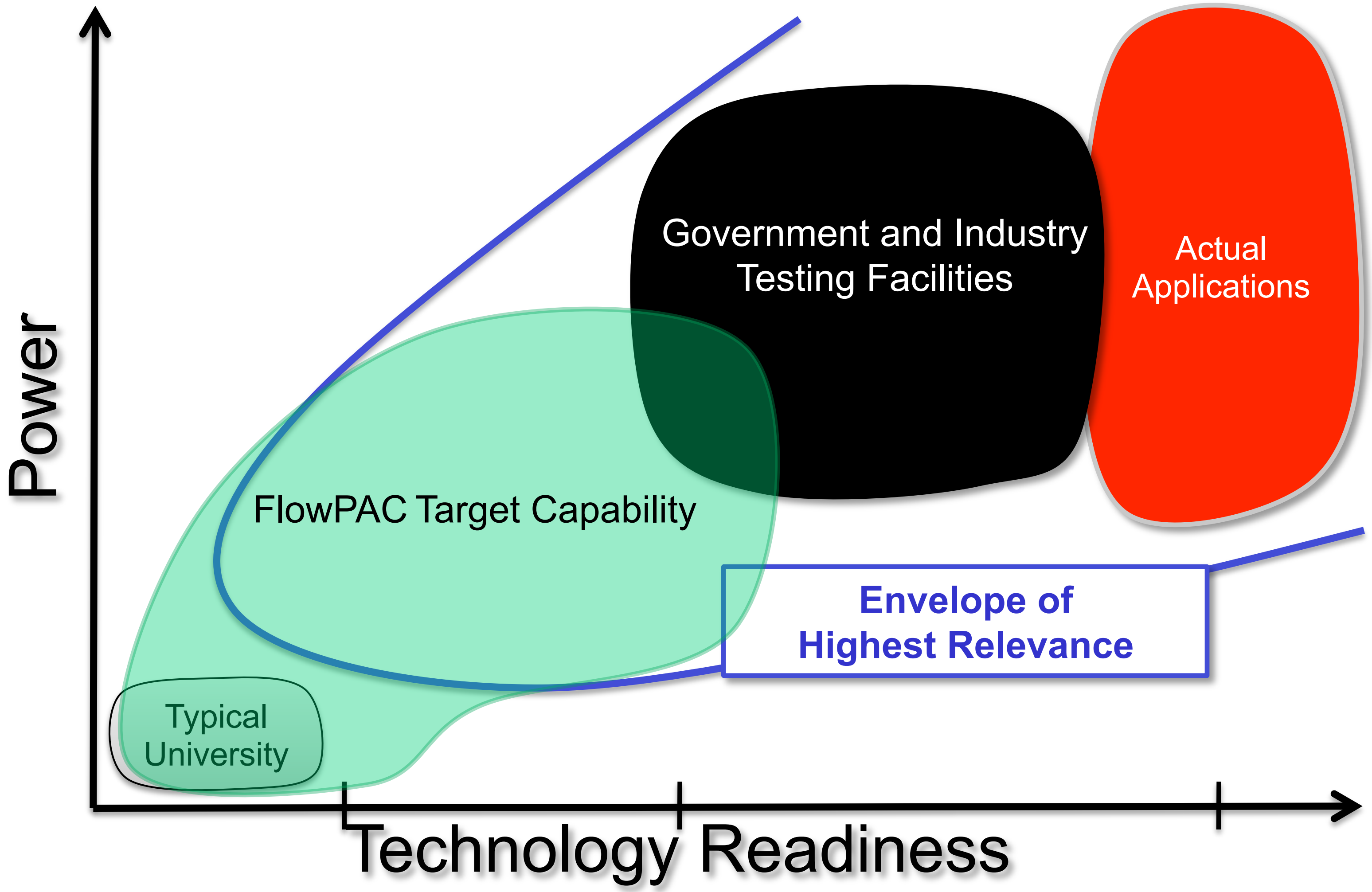
Anechoic Wind Tunnel



Sample Beam Forming



Experimental Facilities Vision

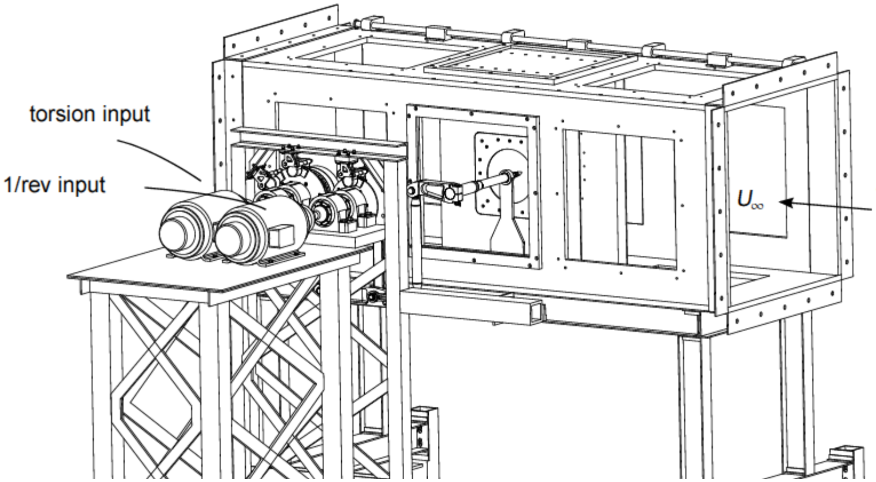


Mach 0.6 Wind Tunnel

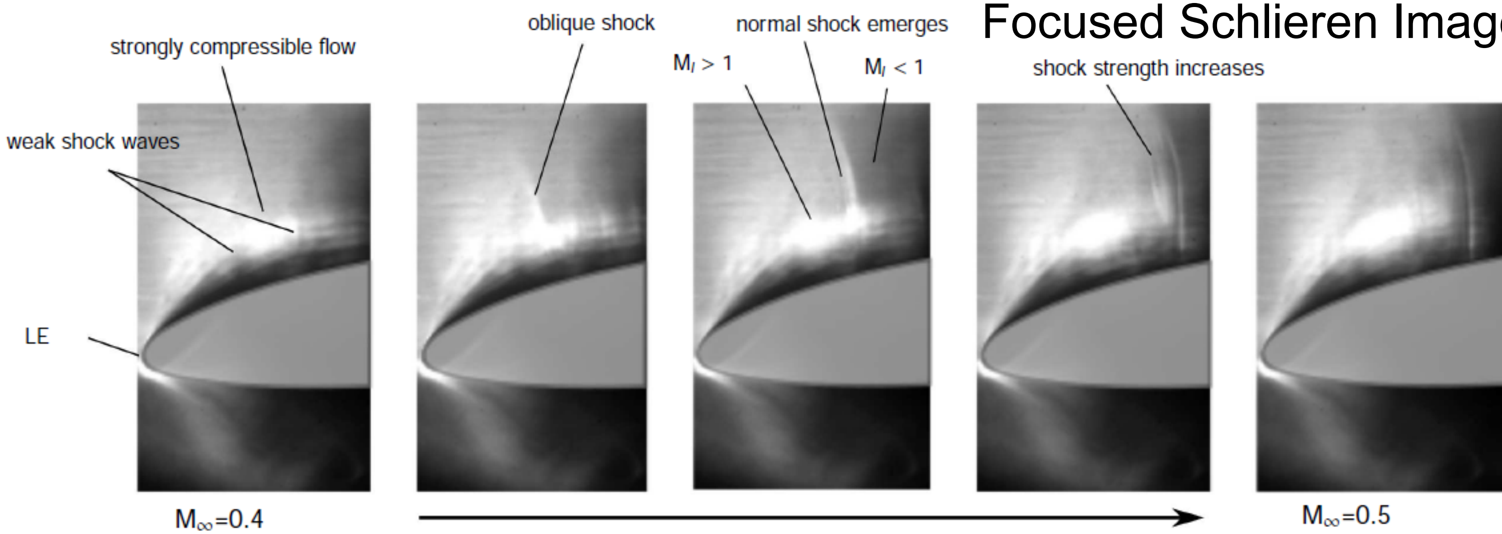
- 3’x3’x9’ test sections
- Large optical access
- Low turbulence
- Temperature controlled

- 1750 H.P. motor
- Variable R.P.M. AC
- 8’ diam., 2-stage fan
- 1000 ton-hr ice-storage chilled water cooling

Helicopter Dynamic Stall Facility

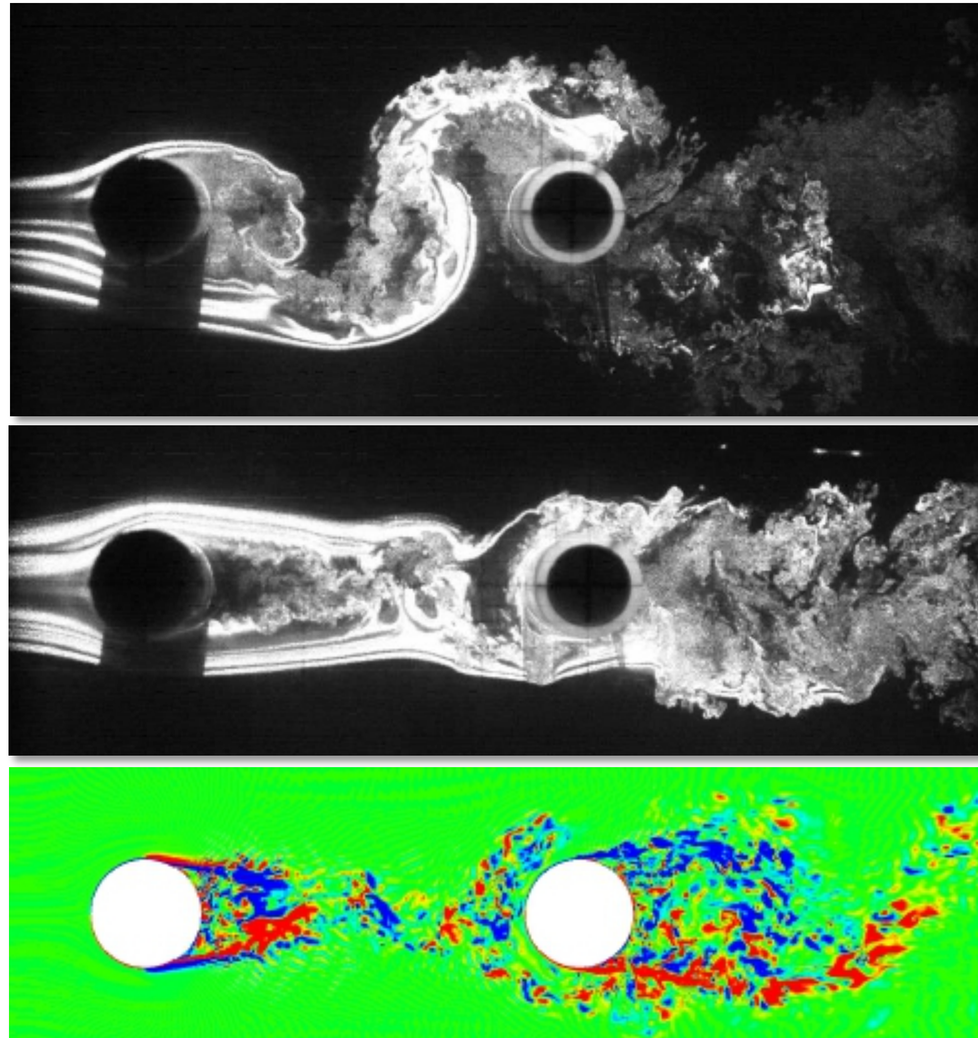


Focused Schlieren Images

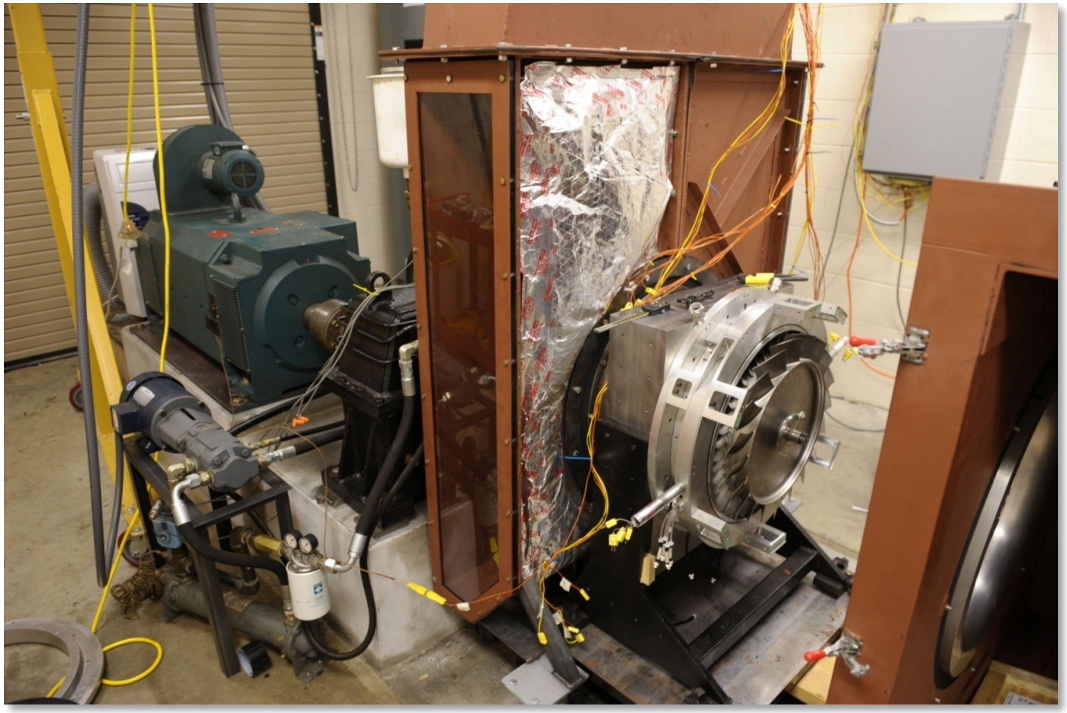


Airframe Noise

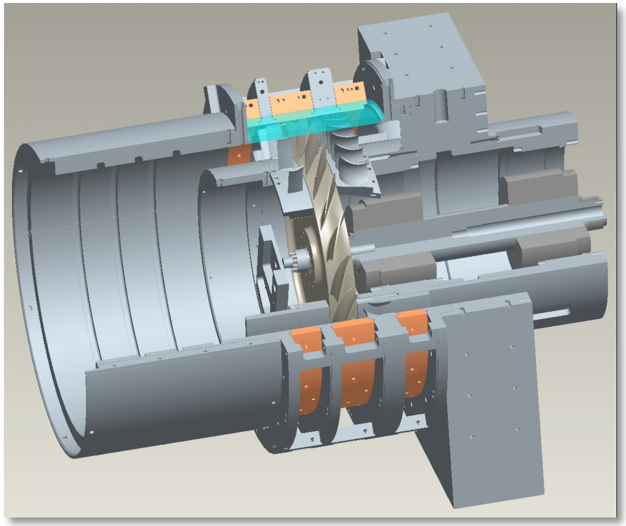
Gulfstream 550 Nose LG



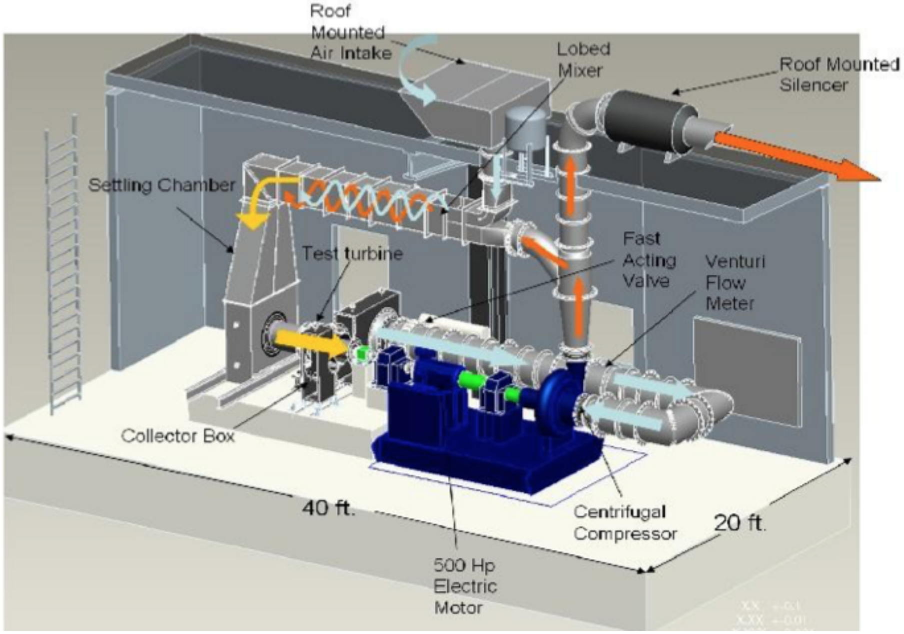
Transonic Compressor Facility



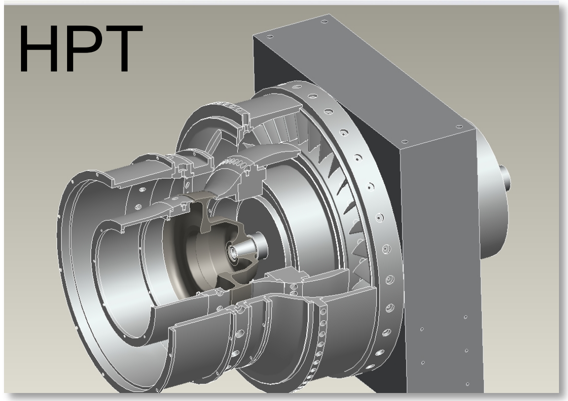
- 400 H.P.
- 15,000 R.P.M.
- Design tip-Mach: 1.2
- Magnetic levitation rotor bearings
- Rotor optical access

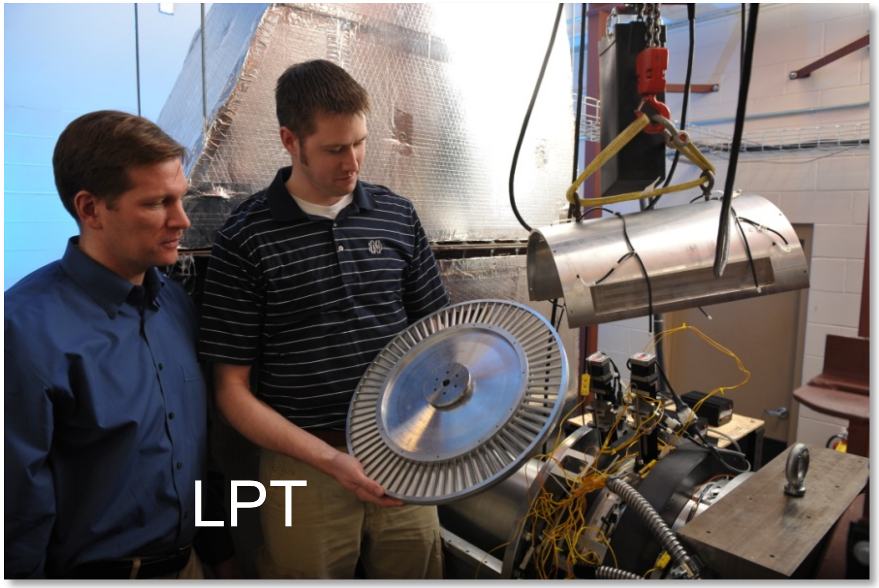


Transonic Turbine Facility: LPT & HPT Modules

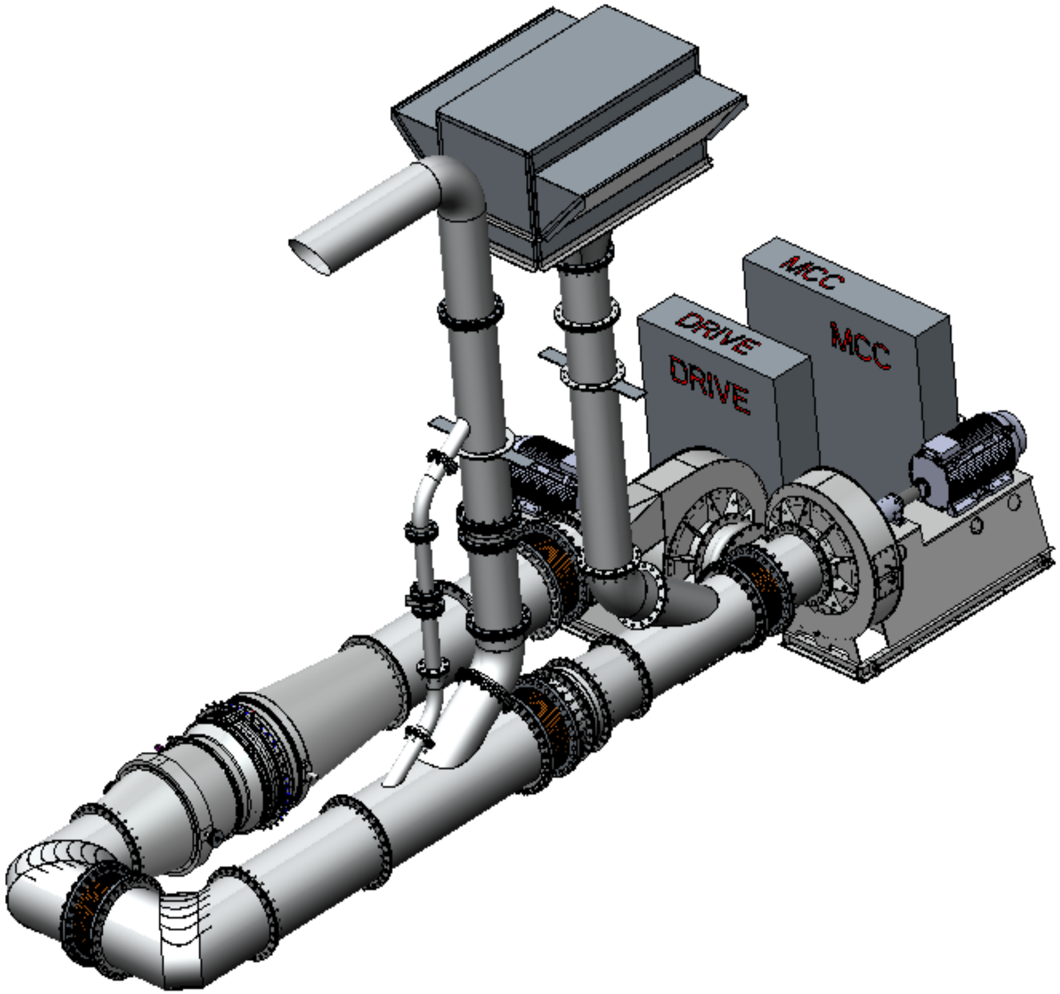


- 800 H.P. compressor
- 500 H.P. motor
- Design 300 H.P. turbine
- Magnetic levitation rotor bearings
- Highly-loading rotor design



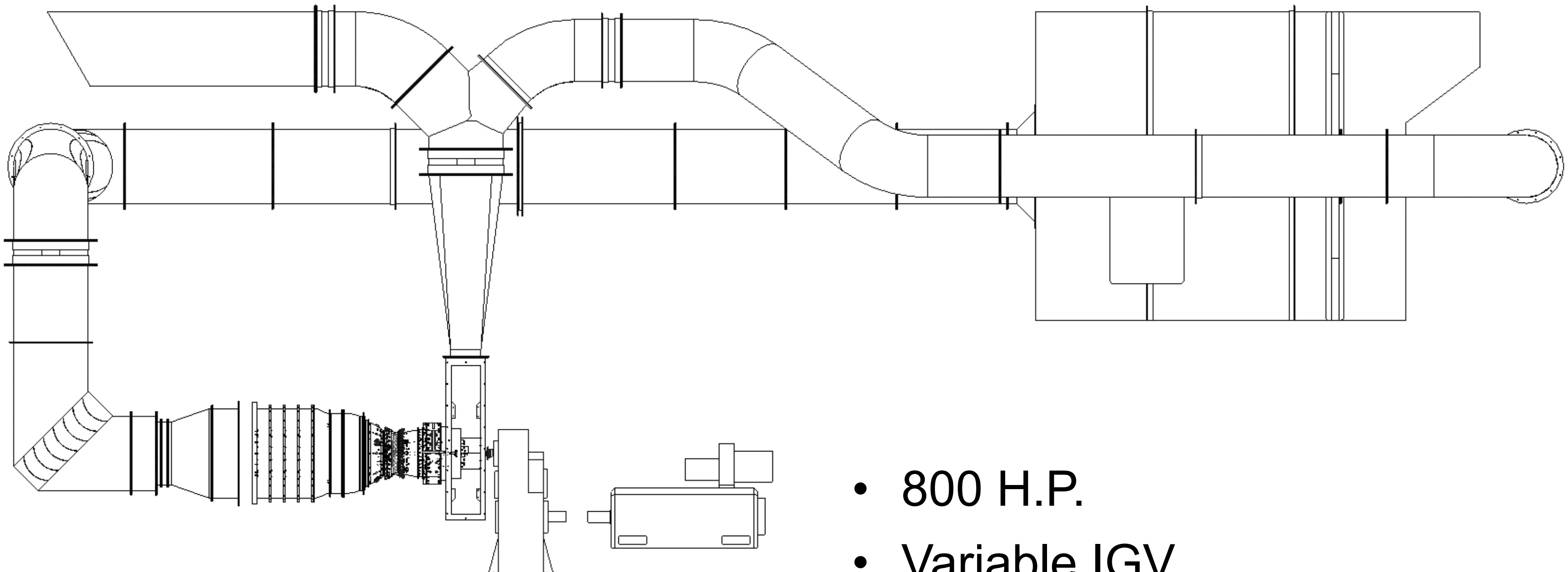


Hot Annular Nozzle Cascade (HANC)

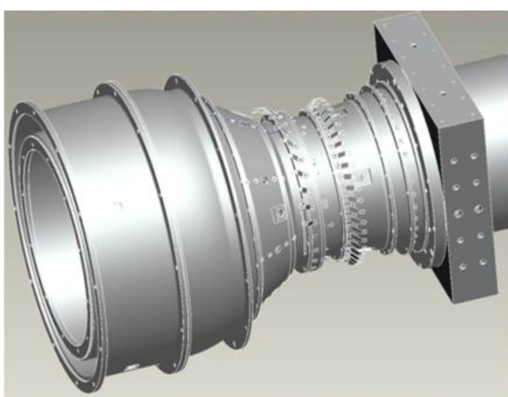


- 700°F primary flow
- Transonic nozzle Mach numbers
- Full secondary cooling systems
- 46 inch diameter
- Controlled inlet turbulence characteristics.
- Highly detailed aero/thermal measurements

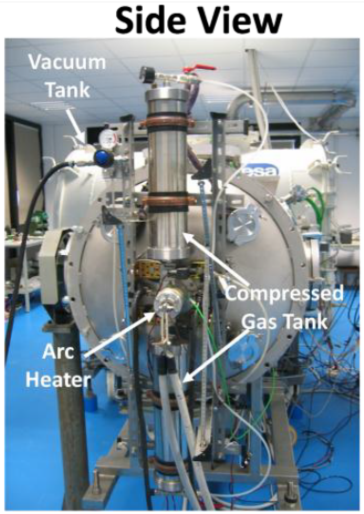
Front Stage Core Compressor (FSCC)

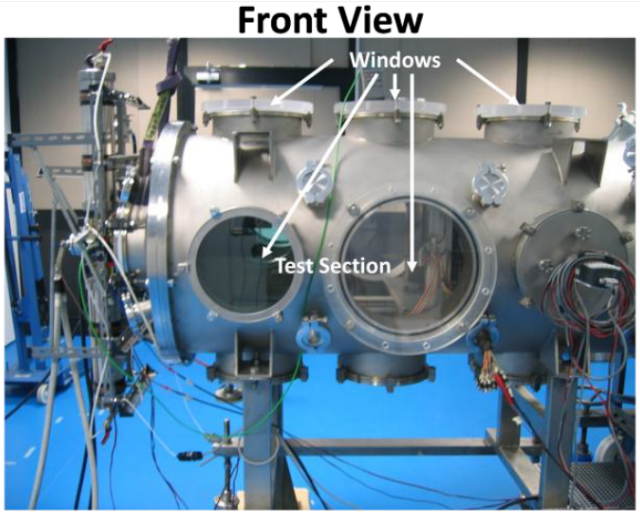


- 800 H.P.
- Variable IGV
- Transonic tip Mach number
- Magnetic levitation rotor bearings

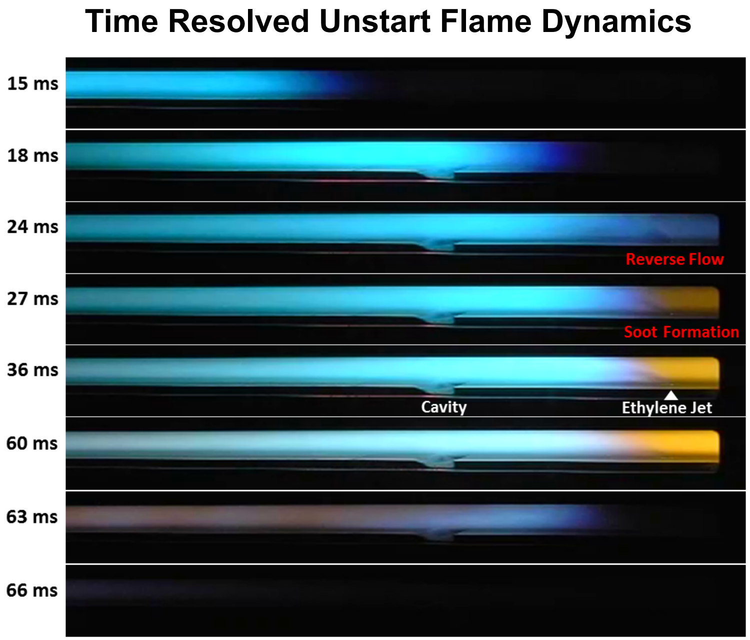


Arc Heated Hypersonic Wind Tunnel

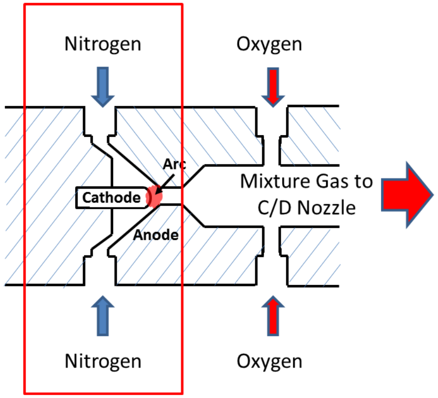




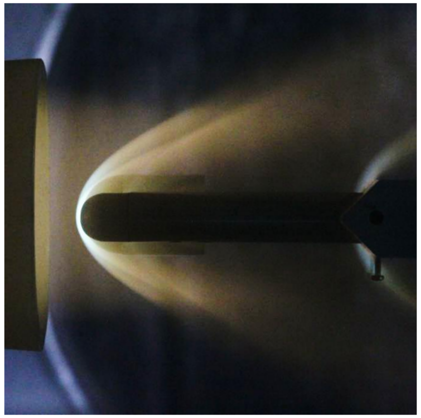
- $10m^3$ Internal Volume
- 500kW Maximum Power
- Mach Nos. 3, 4.5, 6 & 9
- Max. T_0 = 4200K
- Run Time ~ 1s



- **Minimizing test gas contamination: pure nitrogen arc-heating to prevent plasma induced chemical reactions in air, e.g., NOx production in plasma**



Previously, only two air inlets



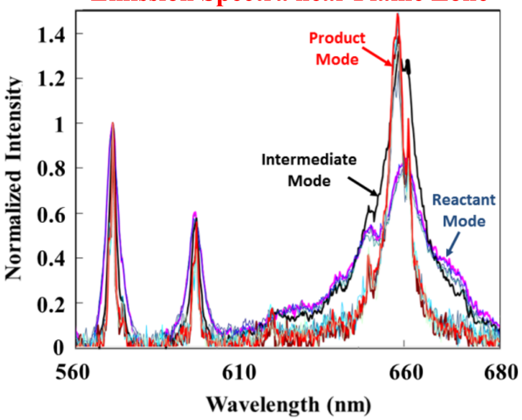
Notre Dame - AFRL/AFOSR Collaboration+

Non-intrusive Flow Property Measurements for Supersonic/Hypersonic Flows

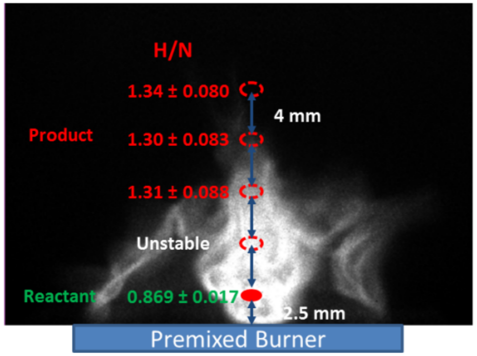
(2012/2013 Air Force Summer Faculty Fellowship Program)

Wright Patterson Air Force Base
(Dr. Campbell D. Carter)

Instantaneous Plasma Emission Spectra near Flame Zone



Locations of Plasma Probe in a Reacting Flow



*Do & Carter (2013)

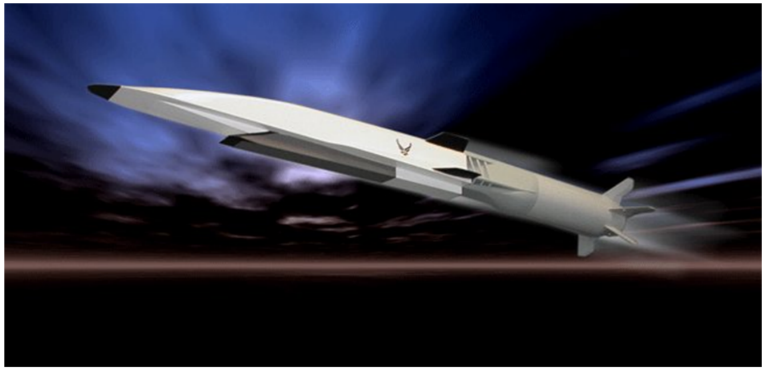
- A short-gated (35 ns measurement time) laser diagnostics method for fuel concentration/gas density measurement in high-speed unsteady reacting flows is proposed and tested.
- The new method will be used in RC-19 supersonic wind tunnel at Wright-Patterson Air Force Base to measure fuel concentration/temperature field in a scramjet combustor

Experimental Investigation of Turbulent Flames in Hypersonic Flows

(AFOSR Grant, FA9550-12-1-0161)

Air Force Office of Scientific Research
(Dr. Chiping Li & Dr. Campbell D. Carter)

Hypersonic Air-breathing Propulsion



X-51A, Waverider

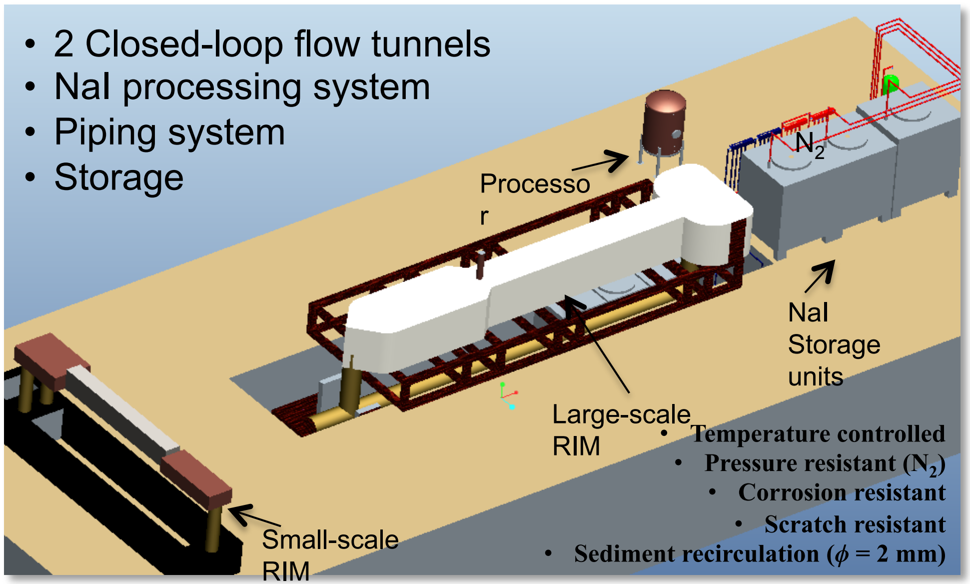
- Turbulent combustion enables hypersonic flights: turbulence property quantification & investigation of flame dynamics in supersonic/hypersonic flows.
- Optically resolved unsteady ethylene flame dynamics at Mach 4.5, 6 and 9 scramjet flight conditions.

*H. Do and C. D. Carter (2013) Combustion and Flame 160: 601–609

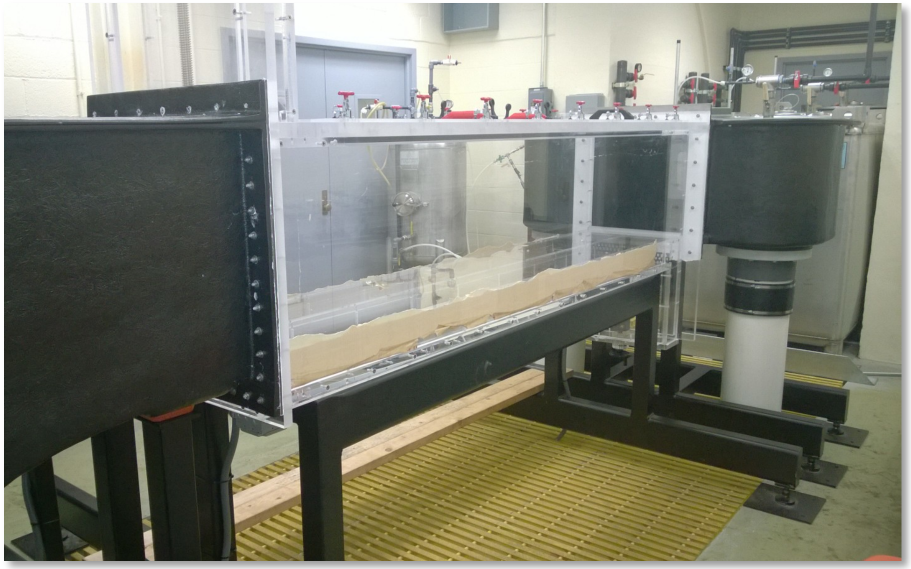
+Hyungrok Do, PI

Refractive-Index-Matched (RIM) Flow Facilities*

Laboratory overview

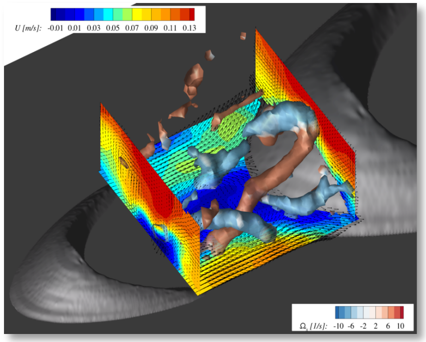


Large-scale RIM

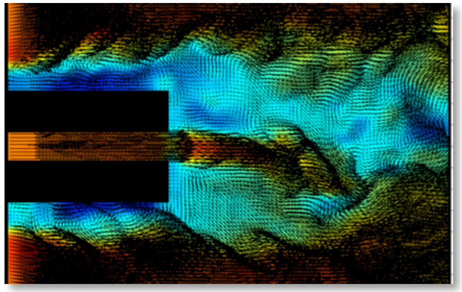


- Total volume: 4200 liters
- Velocity up to ~ 2 ms^{-1}
- Cross section: 0.45 m x 0.45 m
- Length: 2.5 m

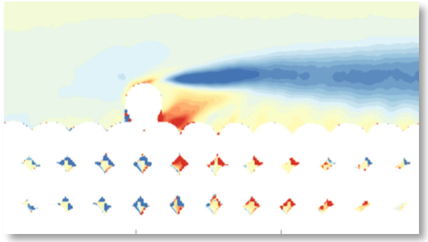
Complex 3D topography



Bluff Bodies



Permeable boundaries

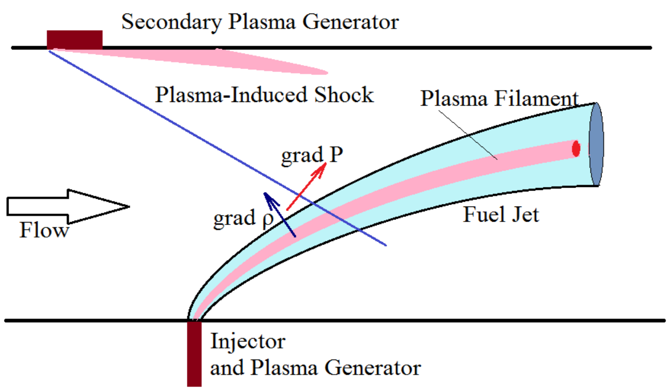


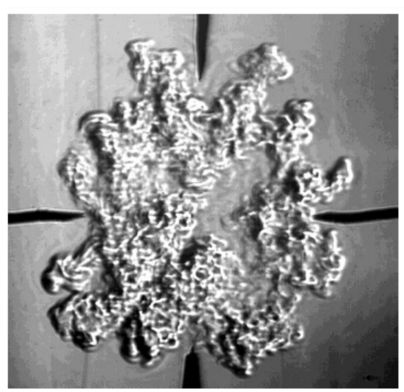
Applications

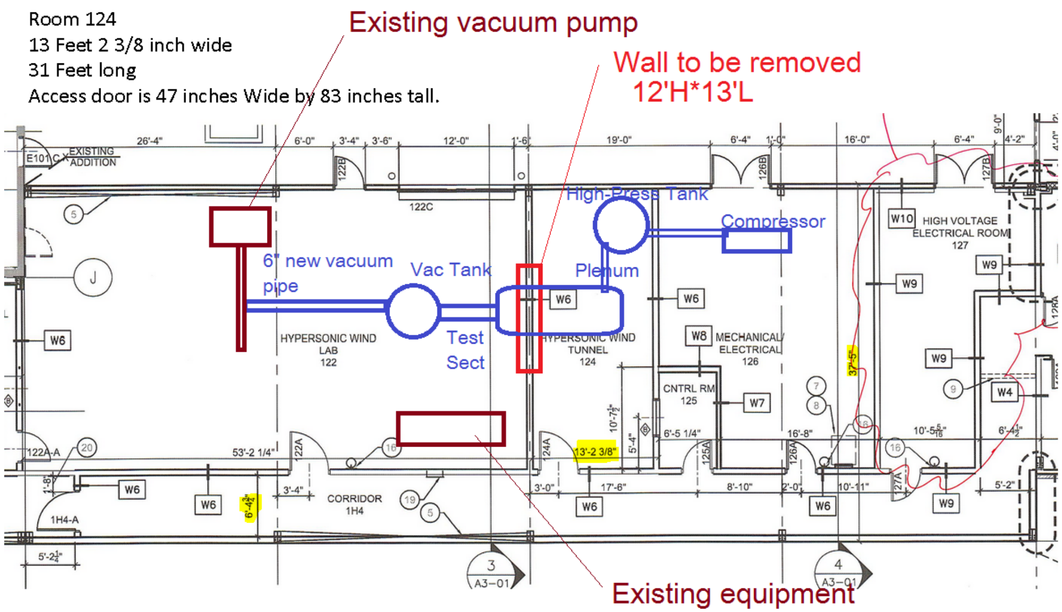
*AFOSR MURI, Ken Christensen PI

Supersonic Mixing Facility

Mixing Enhancement and Flame Stabilization in High-Speed Combustion Systems by Transient Plasma*







*Proposal by Sergey Leonov.
In review, Chiping Li (AFOSR)

Wind Energy Laboratory (eWiND)

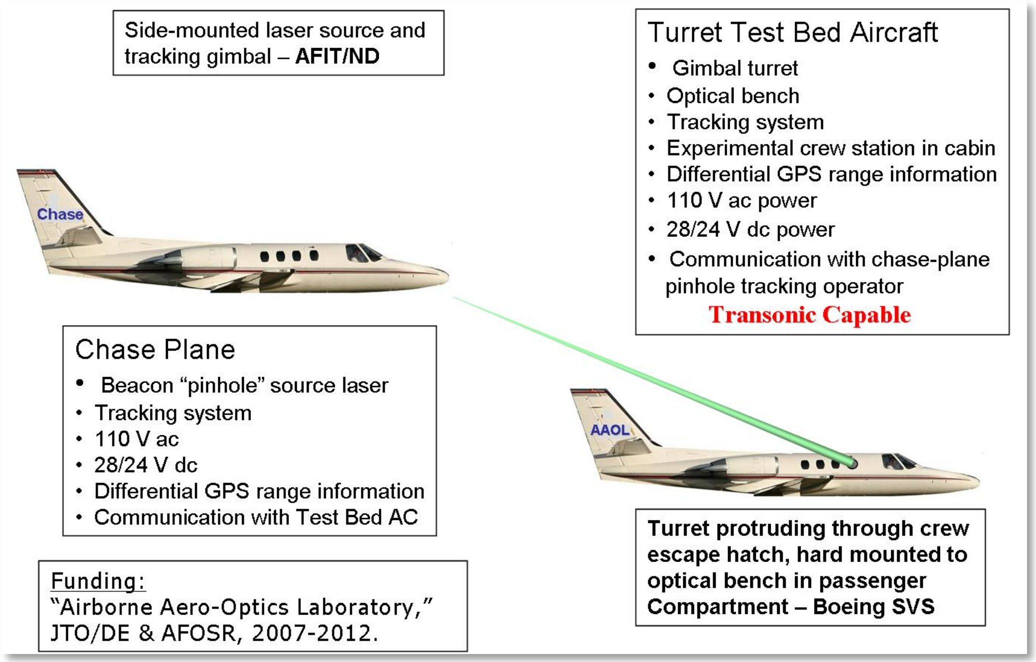
25kW Turbines:

- 30’ Diameter
- 59’ Hub Height
- Pitch Controlled

Meteorological Tower:

- 3-component, fast response ultrasonic anemometers
- Temperature
- Humidity
- Pressure

Airborne Aero-optics Laboratory



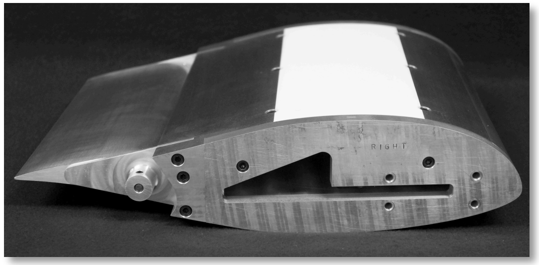
Dynamic correction of optical distortions produced by compressible flow structures

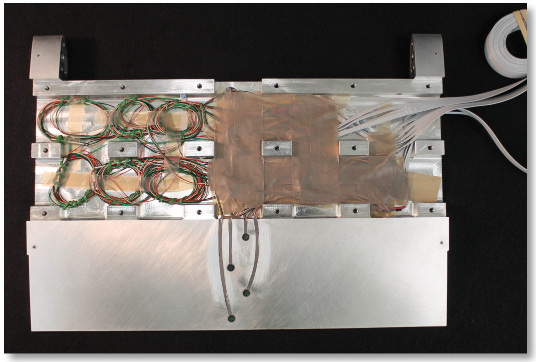
FlowPAC Fabrication Shop

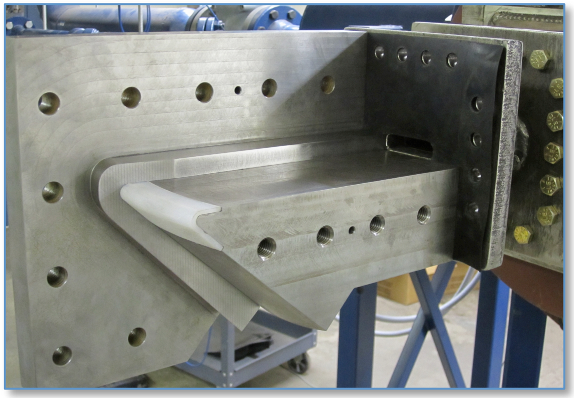
4 Axis Mill

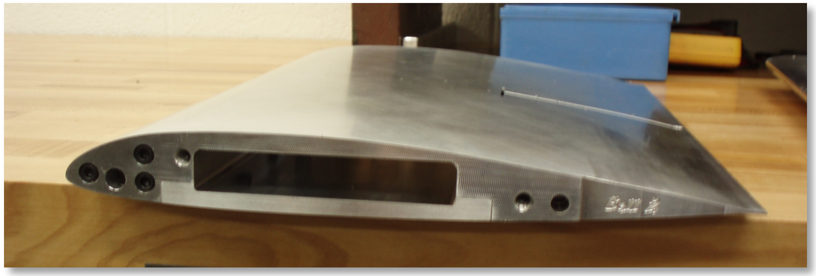
5 Axis Mill

Num. Lathe







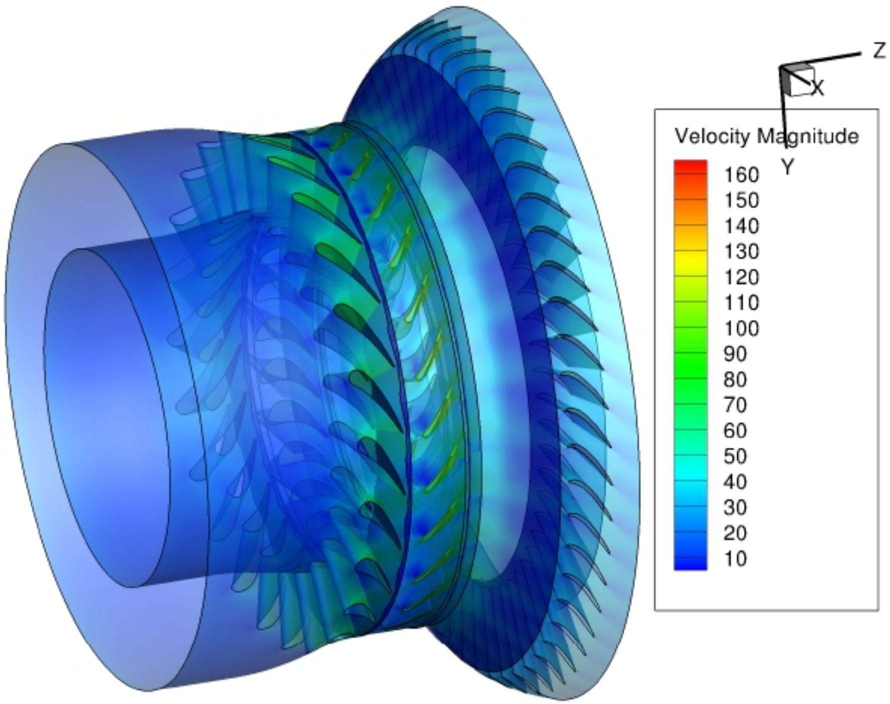


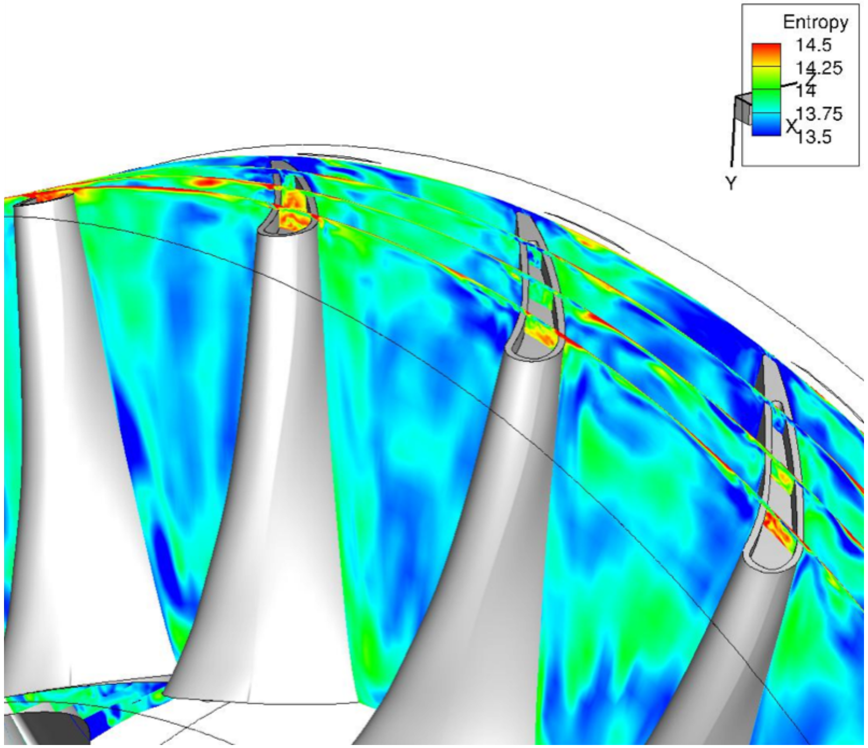
High Fidelity CFD

HPT Tip Clearance Analysis

Embedded Large Eddy Simulation (ELES)

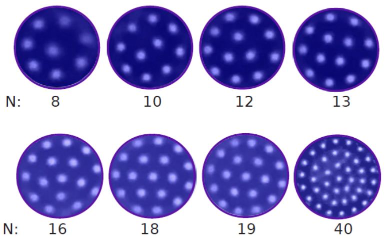
(375M Mesh Points, 512 Processor Cores)

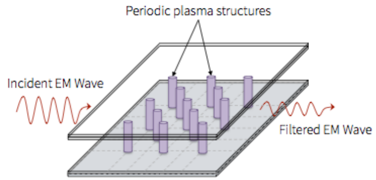


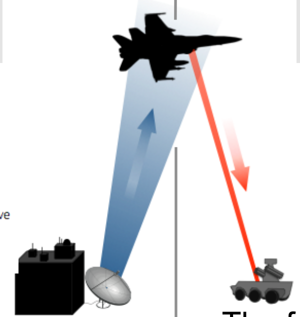


Tunable Plasma Metamaterials

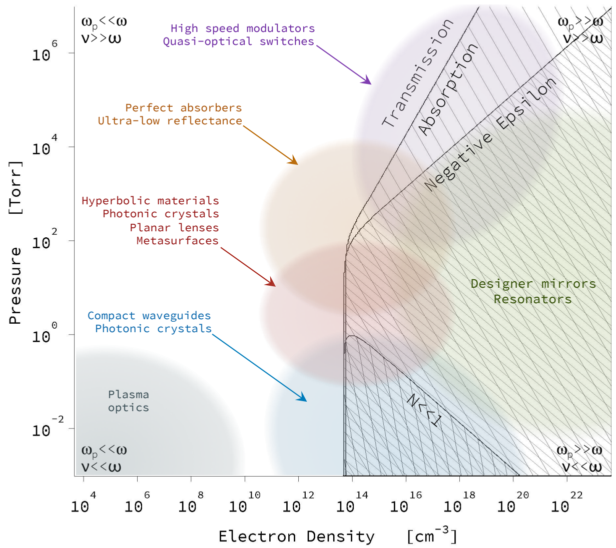
AFOSR MURI: Mitat Birkan







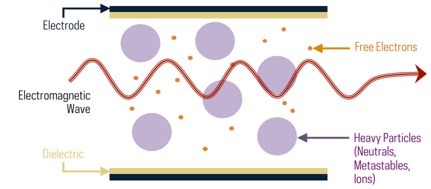
- Metamaterials are designed with a lattice structure of materials having two indices of refraction.
- Conventional metamaterials are designed for a single EM wavelength.
- Lattice tuning capability with a broad range of positive and negative plasma permittivity offers numerous applications.



60GHz

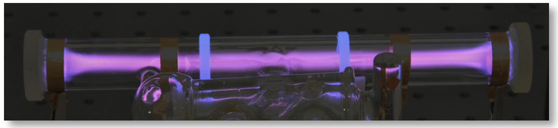
Plasma Adaptive Optics

DARPA DSO: Brian Holloway

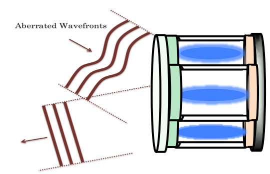


- The free electrons, neutrals, metastables, and ions in an ionized gas can affect the **permittivity to EM waves**.
- Change in the permittivity affects refractive index >>> Plasma Adaptive Optics (PAO). Technology Driver: Bandwidth

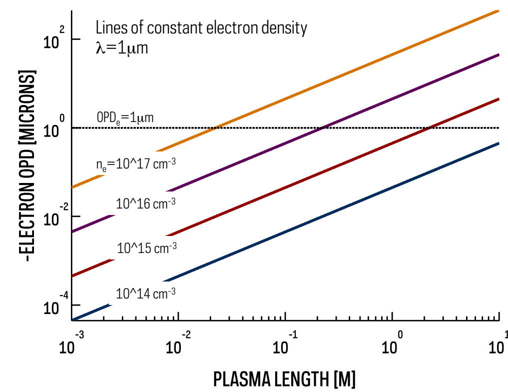
PAO



- Plasma optics OPD depends on the length of the plasma, electron density, EM wavelength, gas composition, and heavy particle density.



PAO Array

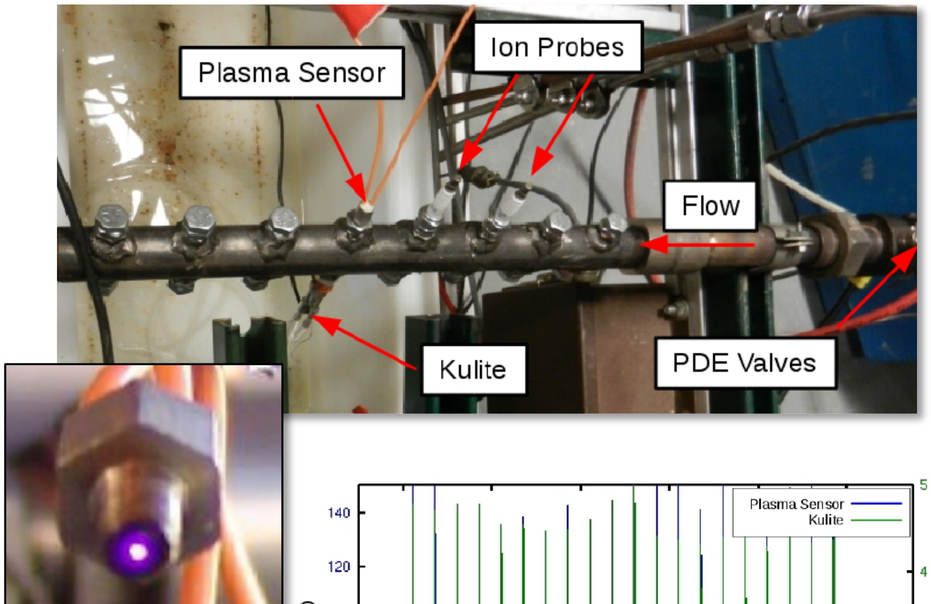


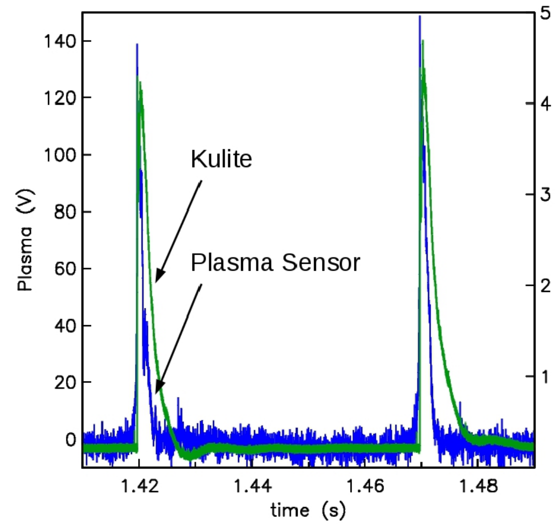
AIAA J., **50,** 1, 123-130 (2012); *AIAA J.*, **51**, 3, 657-664 (2013)

Patent: 8513583

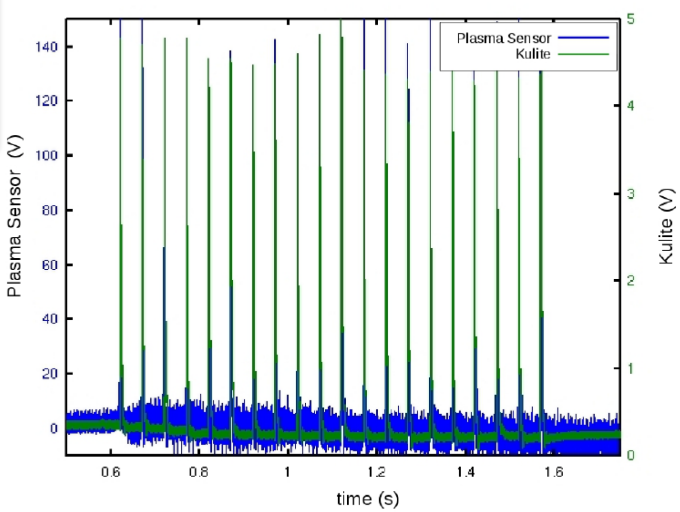
Plasma Temperature/Pressure Sensor

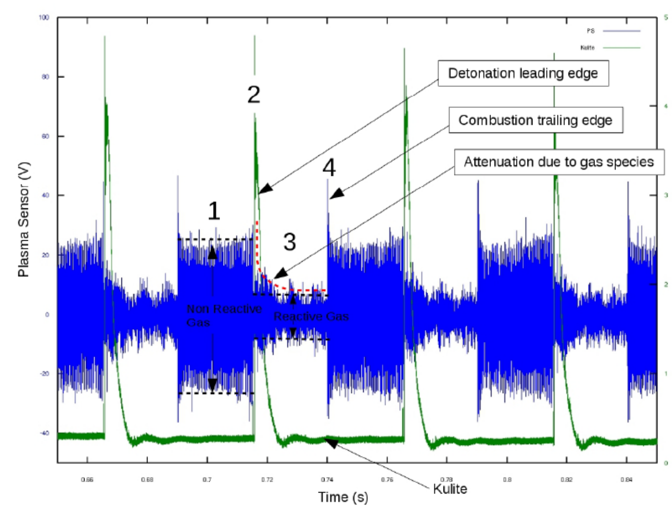
Pulse-detonation Engine





Temperature Mode

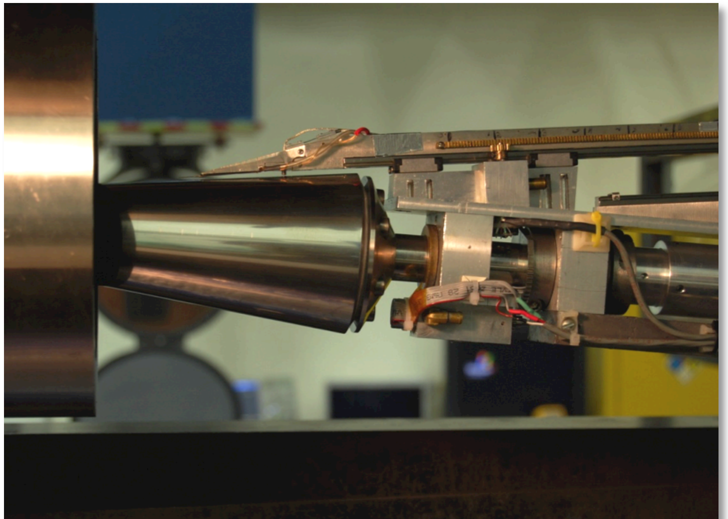


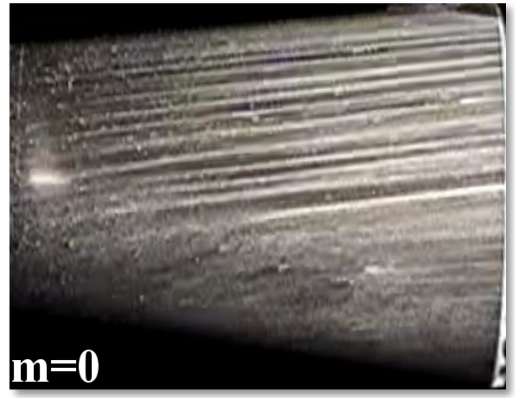


Pressure Mode

Patents: US7275013B1, US7908115

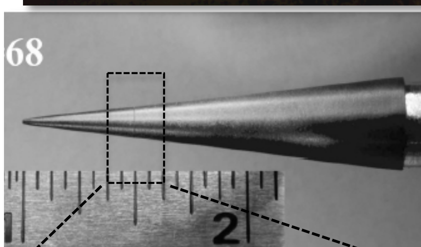
Boundary Layer Transition Control

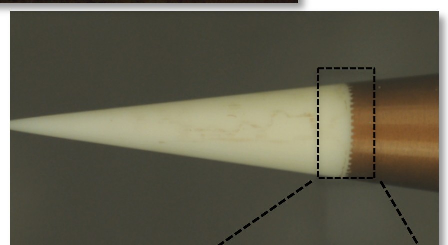


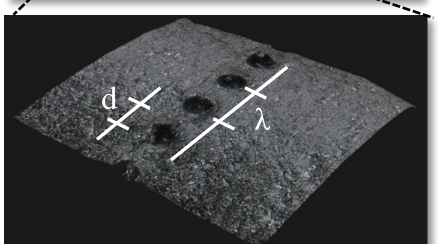


NASA Mach 3.5 0.5m Quiet Nozzle

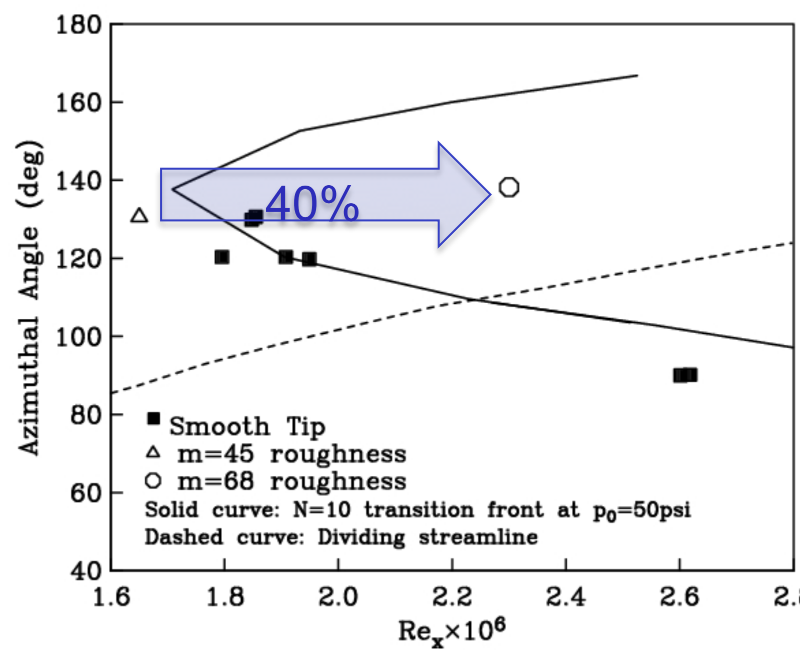
4° AoA 14° Cone Model



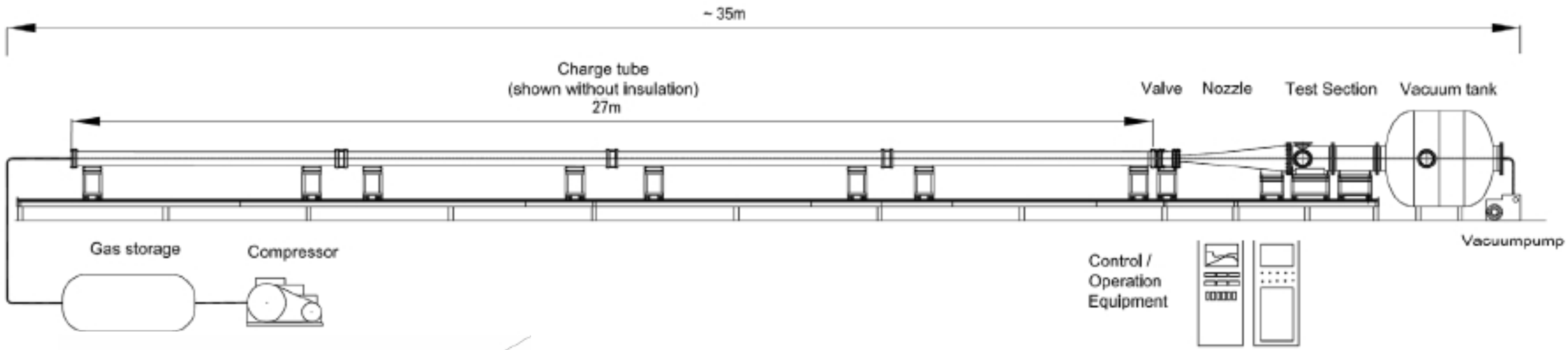


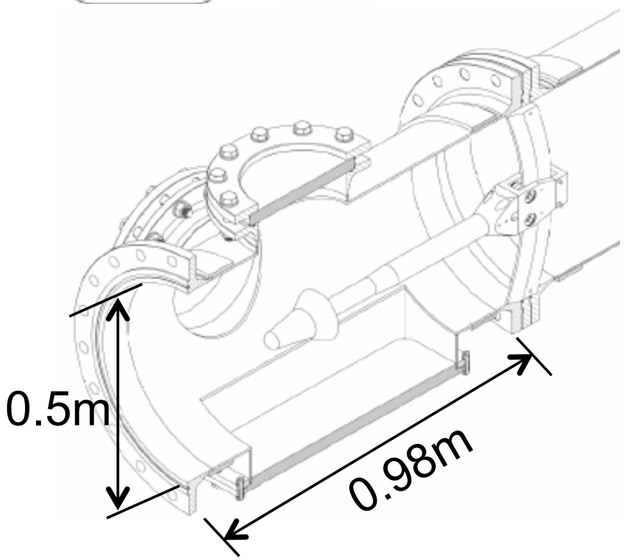


d=76μm
d/λ=0.43



AFOSR Proposal in AF Academy Mach 6 Facility*





- Same size test section, will accommodate existing model.
- Provides same Re_x range as previous NASA experiment.
- Intended to examine effect of higher Mach number and “noisy” environment on transition control.

*In review: Rengasamy (Pon) Ponnappan

Hypersonic High-Reynolds-Number Quiet Tunnel

Motivation

Schmisseur AIAA-2013-2606

15min. Range at Mach 6 & 9

DoD Hypersonic Vehicle Programs

- Advanced Hypersonic Weapon (AHW-2):
  - Army, Navy
- Tactical Boost Glide:
  - Air Force, Navy, DARPA
- Hypersonic Air-breathing Weapon Concept (HAWC)
  - AFRL High Speed Strike Weapon (HSSW)

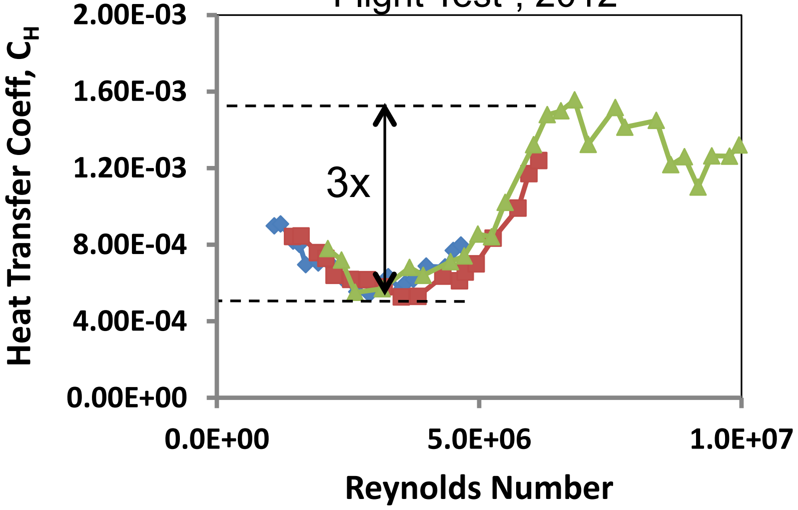
- Glide: Boeing, Raytheon, Lockheed Martin
- Air-breathing: Boeing, Raytheon
- $180M CRAD for technology maturation

- China reported to have had 3 hypersonic boost-glide flights in 2014.

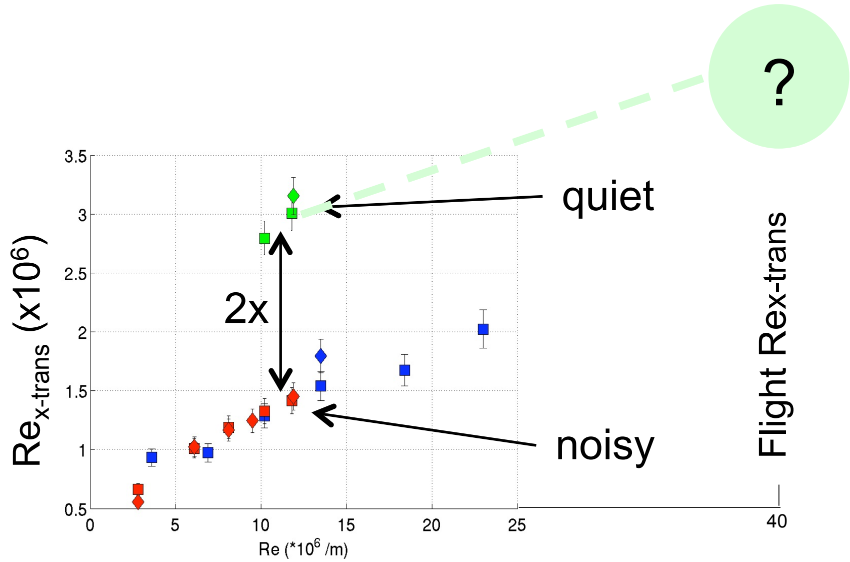
Hypersonic High-Reynolds-Number Quiet Tunnel

Motivation

Kimmel, "HIFiRE-1 Hypersonic Flight Test", 2012



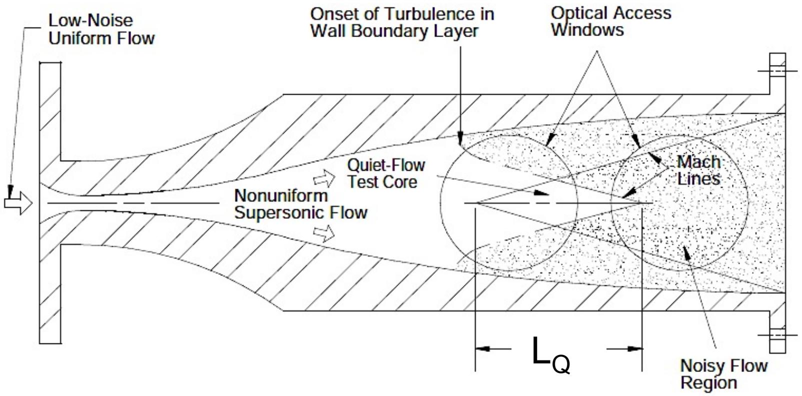
- Key issue is on the accurate prediction of if and where turbulent transition occurs.
- Determines the degree of heat transfer to the vehicle.



- Ground tests require hypersonic wind tunnels that can simulate flight conditions:
  - Low disturbances
  - Natural transition Reynolds numbers

High Reynolds Number Mach 6 & 10 Quiet Wind Tunnel

STATUS QUO



- Present "quiet" hypersonic wind tunnels are limited in quiet zone length, L_Q
  - TA&M Blow-down: Re_{LQ}=6M
  - Purdue 9" Ludwieg Tube: Re_{LQ}=13M
- Natural transition in these facilities only observed when instability growth is accelerated by geometry or disturbance generators.

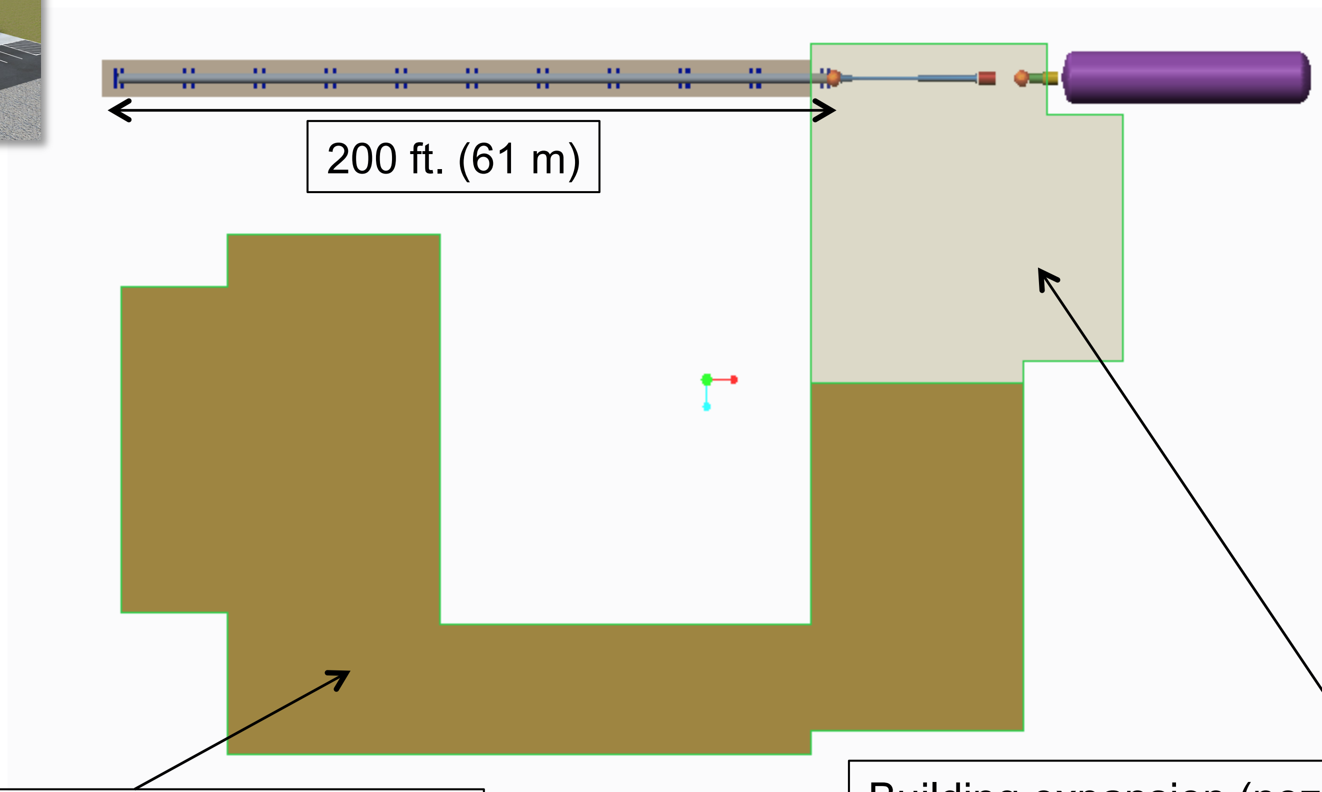
SOLUTION

- Ludwieg tubes with large diameter, long, slow expansion axisymmetric nozzles that suppress cross-flow and Görtler instabilities.
- Throat suction and heating to suppress TS.

UND DESIGN

- Mach 6 & 10 quiet zone to Re_x≥40M.
- 33' long nozzle, 2' I.D. test section.
- 200' long, 2.5' I.D. driver tube.
- 80,000 gal. vacuum tank.
- 2 sec. run time.
- 1 hr. run frequency.
- P_0 ≤ 10Bar > acceptable throat waviness ~1-2 mil./in. (NC lathe).
- Throat heated to ~670K (~750°F) to minimize TS growth.

High Reynolds Number Mach 6 & 10 Quiet Wind Tunnel



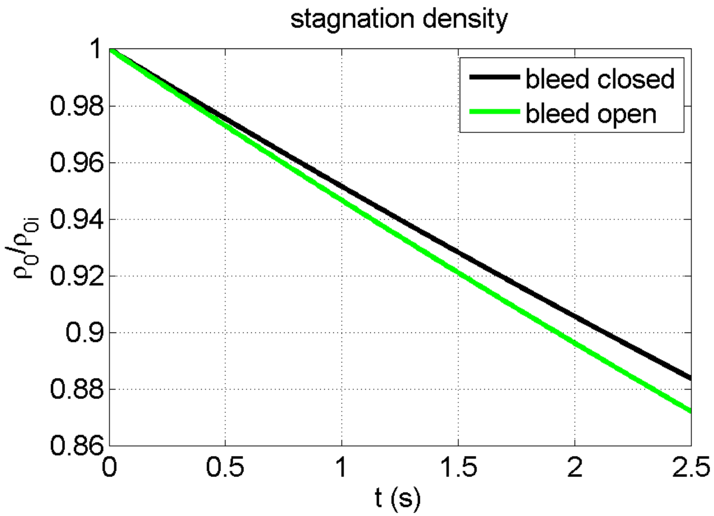
Existing White Field Laboratory (subsonic tunnel, turbomachinery test cells, etc.)

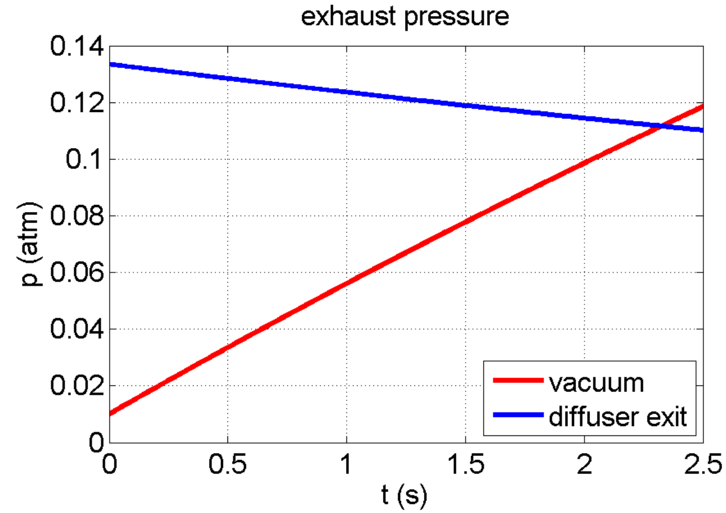
Building expansion (nozzle, test section, and diffuser plus labs and office space

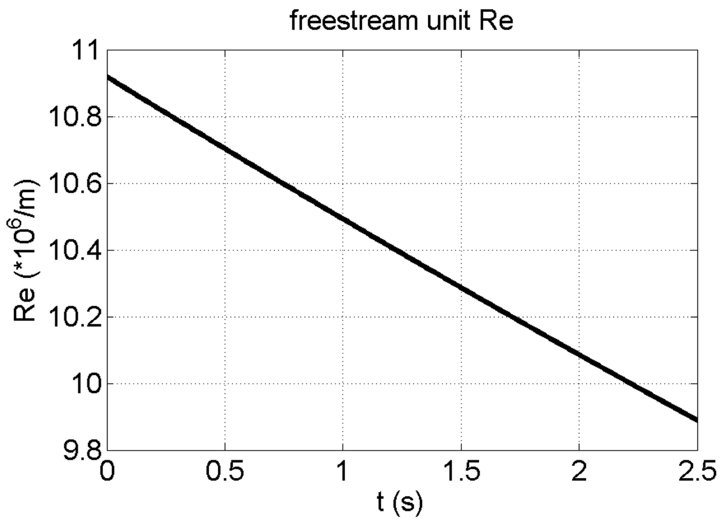
Vital Statistics

Tunnel configuration	Ludwieg tube	
Mach number	6.0	
Nozzle exit diameter	0.60 m	24 in.
Nozzle length	10 m (!)	33 ft.
Throat diameter	0.084 m	3.3 in.
Stagnation pressure (quiet flow)	1 MPa, 10 atm	150 psia
Stagnation temperature	430 K	310 ºF
Freestream unit Re (quiet flow)	11*10^6 /m	3.4*10^6 /ft.
Re_L (based on quiet-flow core length)	40*10^6	
Free jet test section length	0.9 m	3 ft.
Driver diameter	0.74 m ID	30 in. OD
Driver length	61 m	200 ft.
Vacuum capacity	300 m^3	80,000 gal
Run time	2 s	
Run frequency	Pending compressor & pumps, ~ 1 / hr	
Re variation during run	-9%	

Mach 6 Performance Estimates



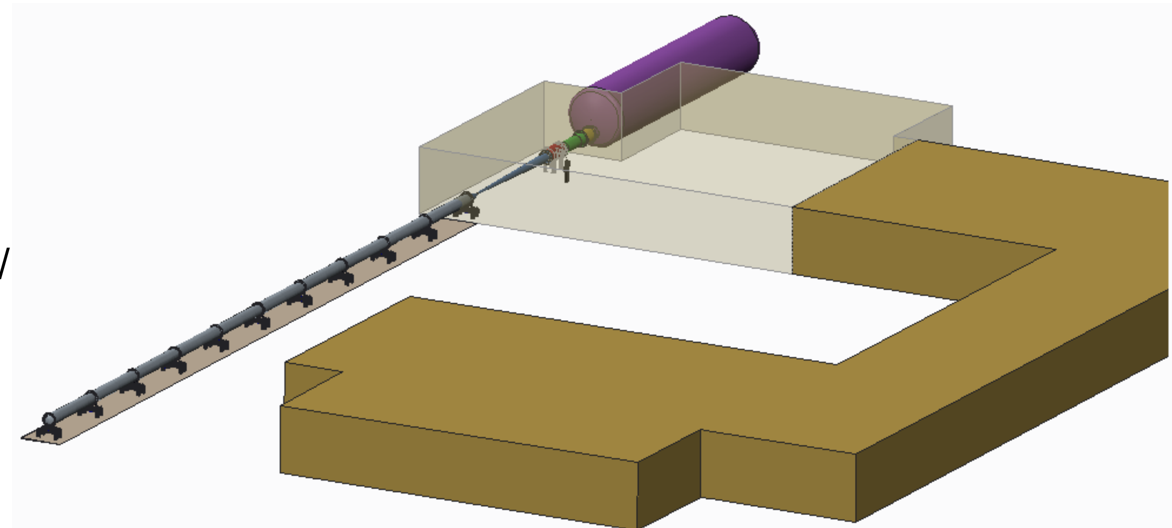




High Reynolds Number Mach 6 & 10 Quiet Wind Tunnel

SCHEDULE

- Boeing has committed FY15 funds to CFD design of Mach 6 nozzle.
- Pending DURIP submitted to ONR/ AFOSR).
- Seeking other corporate support.
- Seeking UND benefaction support.
- Estimated $3.1M Phase I.
- Mach 6 operation 24 mo. from funding start.
- Engineering design and major fabrication at UND.
- Phase II Mach 10 design starting in Year 3 from start of funding.



Mach 6&10 Quiet Tunnel Size Perspective