



Aerothermodynamics & Turbulence

8 March 2013

Dr. John D. Schmisser
Program Officer
AFOSR/RTE

Integrity ★ Service ★ Excellence

Air Force Research Laboratory

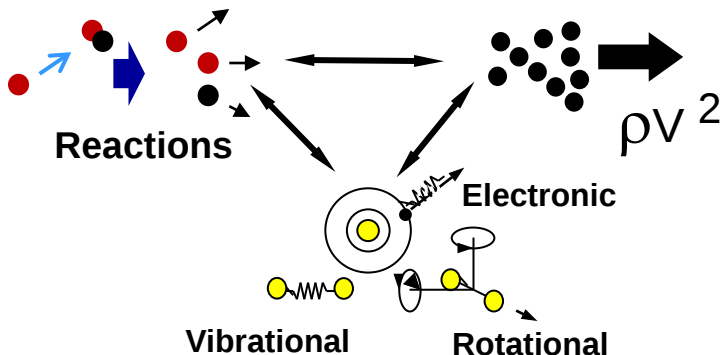
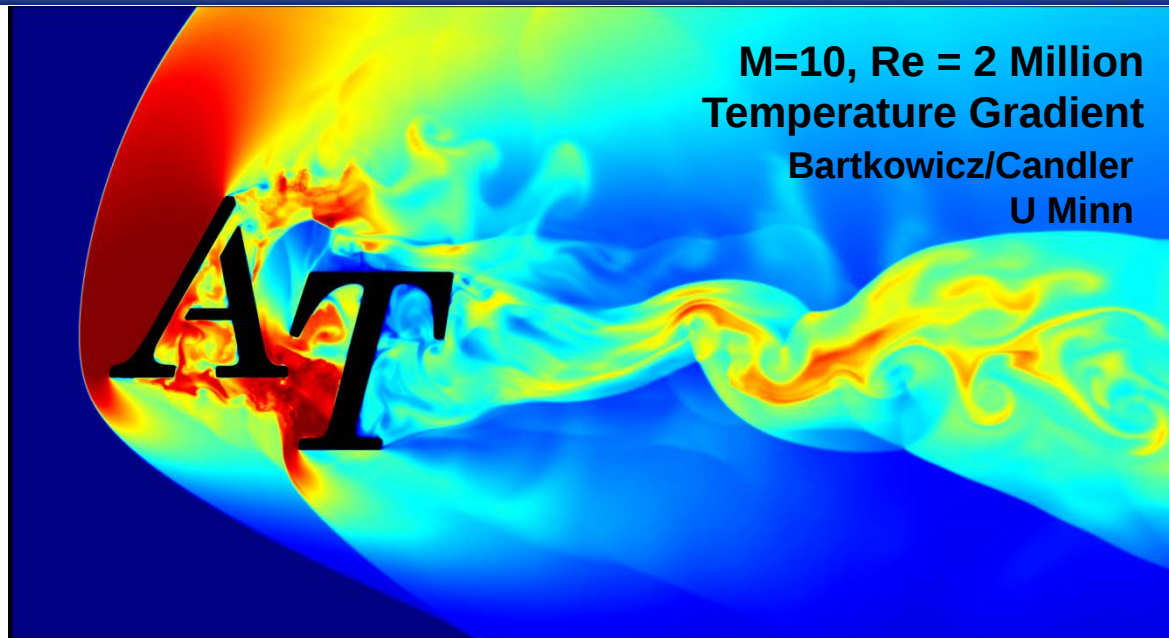
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Scientific Foundations of Aerothermodynamics & Turbulence



A&T portfolio exists
at the intersection of
gasdynamics,
thermophysics and
chemistry



Goal: *Understand and predict*
energy transfer between the kinetic,
internal and chemical modes
- *Exploit* this knowledge to shape
macroscopic flow behavior



Essential Science for Future High-Speed Capabilities



Strategic Priorities Require Efficient Area Coverage

“Pivot to the Pacific”

High-Speed Capabilities Are Potential Game-Changers in response to an Anti-Access/Area Denial threat

- Survivable
- Responsive
- **Efficient – greatly increased area coverage per asset**

23 min at Mach 6



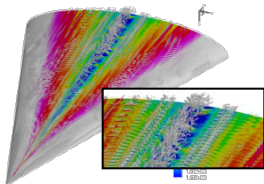
15 min at Mach 9
~120X area

15 min at Mach 6
~50X area

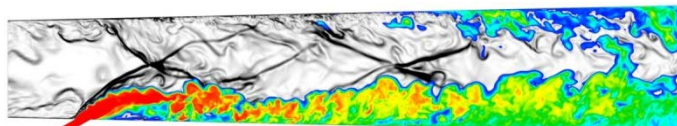
15 min at 500 nm/hr

Advanced Simulation Tools Provide Insight, Reduce Uncertainty

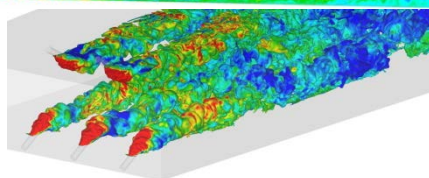
Reduced Uncertainty in Complex Flows



Surface Heat Transfer and Detailed Flow Structure



Fuel Injection in a Scramjet Combustor



Addressing Future Testing Challenges



NASA Langley High-Temp Tunnel

- Planned systems expected to be too large for ground test facilities
- Reliable simulations will help “connect the dots”



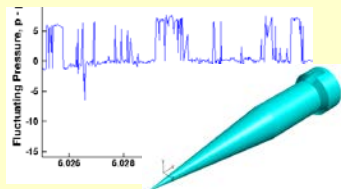
Leadership and Collaborations



Past



First hypersonic flight data to capture shock interaction unsteadiness



Sandia National Laboratories

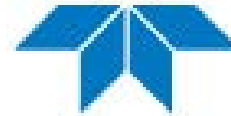


Ongoing

National Hypersonic Foundational Research Plan

Joint Technology Office – Hypersonics
Basic Science Roadmap

Jointly-Sponsored National Hypersonic Science Centers

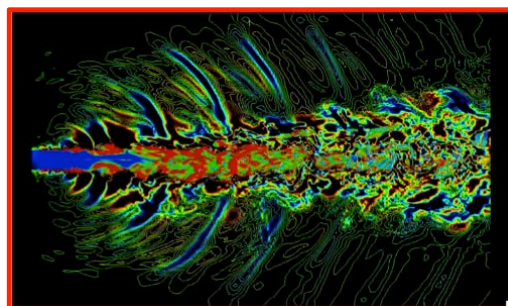


Assessment of SOA and Future Research Directions



ONR

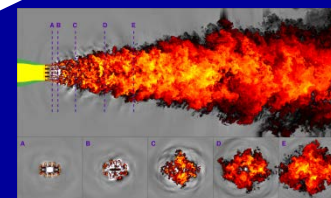
Office of Naval Research



Basic Research for Understanding and Controlling Noise from High-Speed Jets

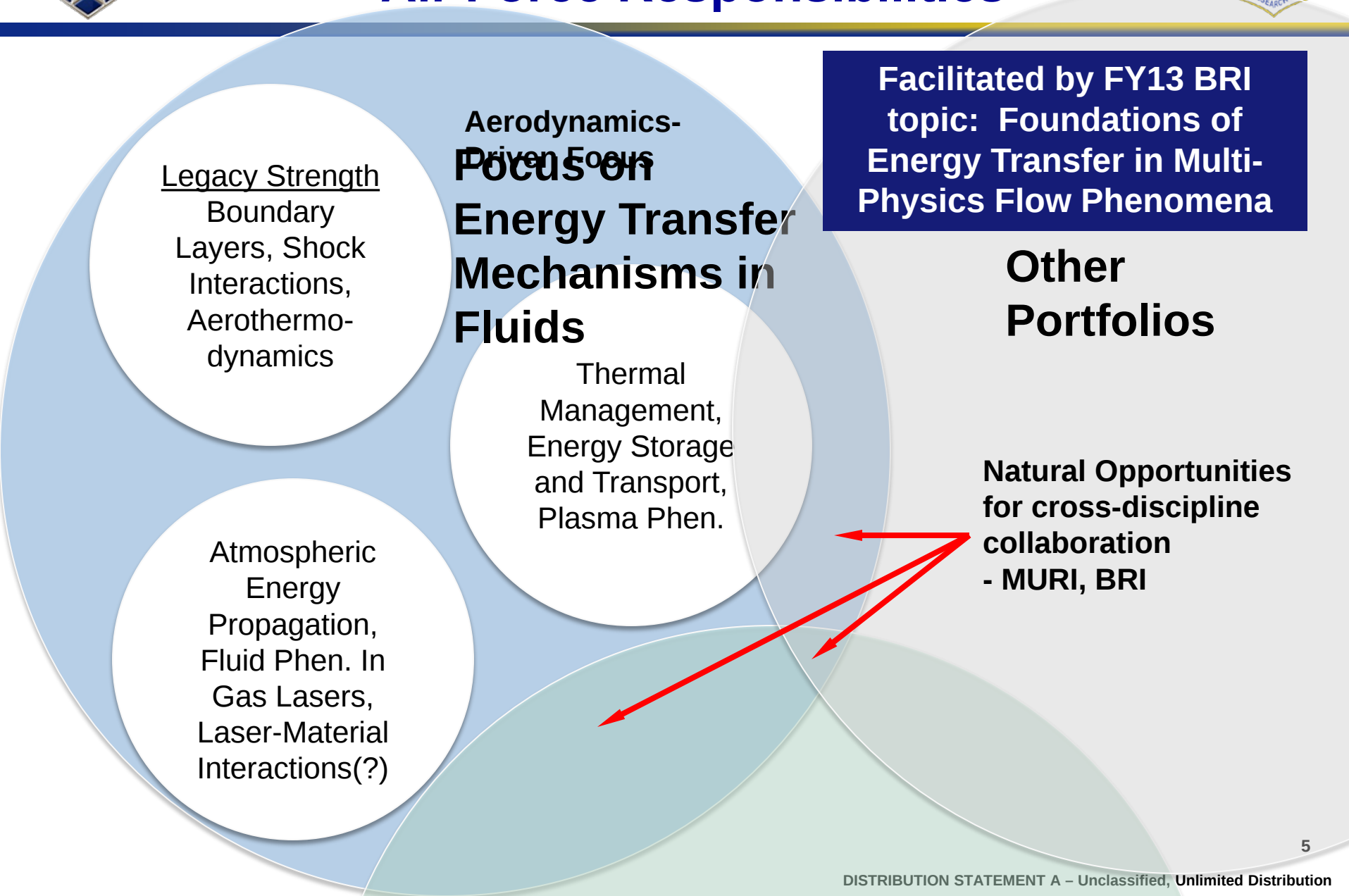
Driving a new scientific paradigm for high-speed flows

Future





Transforming Scope Reflective of Evolving Air Force Responsibilities

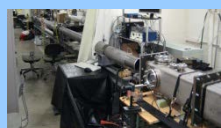




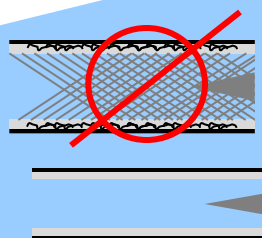
Strategic Vision

Innovation from other disciplines

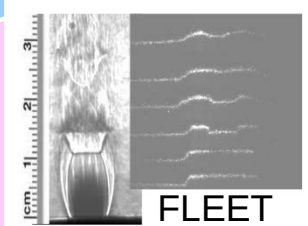
Facilities



Expansion Tubes – Study Noneq. Flows



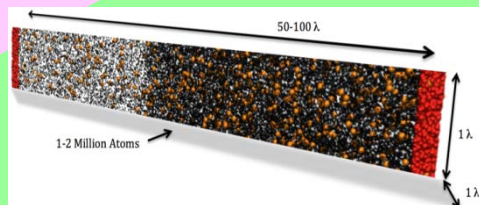
Quiet Tunnels



FLEET

Diagnostics

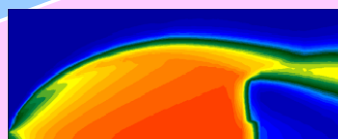
Accel. MD



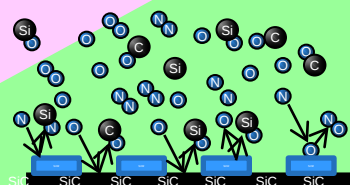
Simulations



Ludwig Tubes: Mach 6 at low cost



VENOM

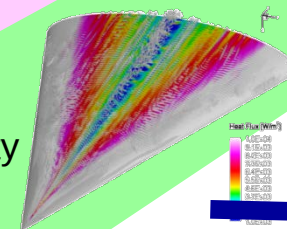


GSI

Sustainable Infrastructure for High Mach Science

New Insight Into Critical Fine-Scale Phenomena

High-Fidelity CFD



Goal: Understand, Predict & Exploit Energy Dynamics

Towards Model-Free Simulations

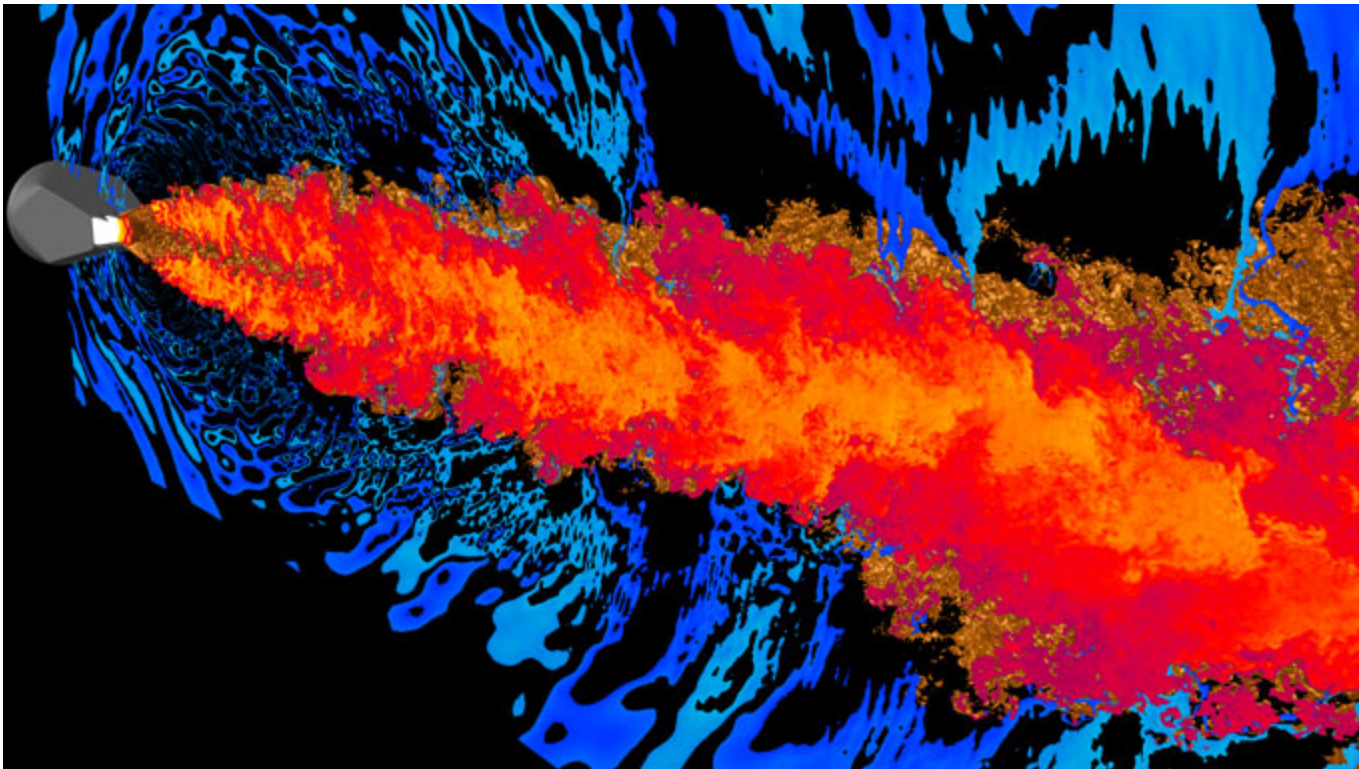
Tech Transition

Unprecedented Insight into Critical Molecular- and Micro-Scale Phenomena



Stanford Researchers Run First Million-Core Simulation at LLNL

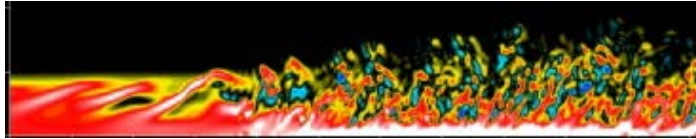
AFOSR project investigating jet noise hits milestone with breakthrough simulation



Parviz Moin and Joseph Nichols, Stanford – running CharLES on LLNL Sequoia

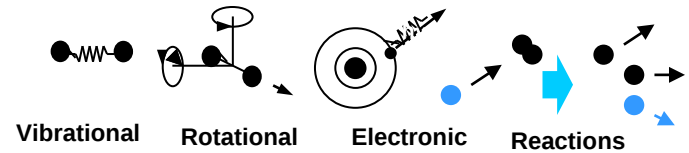


Portfolio Snapshot



Laminar-Turbulent Transition

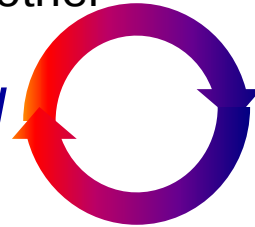
- Major investment area
- Significant progress as result
- Challenge to maintain momentum while balancing investment with other areas



Nonequilibrium Flows

- Emphasis on energy dynamics major new thrust area
- Significant portion of recent investments

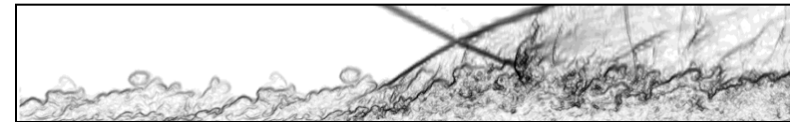
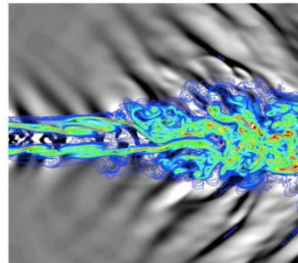
It's all connected



Progress in one area impacts others

Turbulent Physics:

- Roughness and Jet Noise
- Significant investment from other agencies
- OSR investment targets fundamental physics not emphasized elsewhere
- Kinetic energy dynamics is important here



Shock Interactions

- Critical to planned HS weapons
- Ripe for a hard challenge to inspire innovation
- Aspiring to push this community to the brink soon



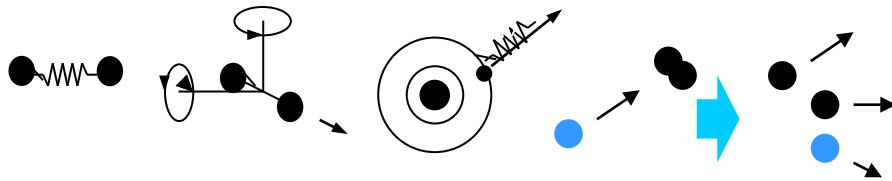
Future Portfolio Structure



Portfolio will be split as a result of the New AFOSR Organization

Aerothermodynamics

PO: J. Schmisser

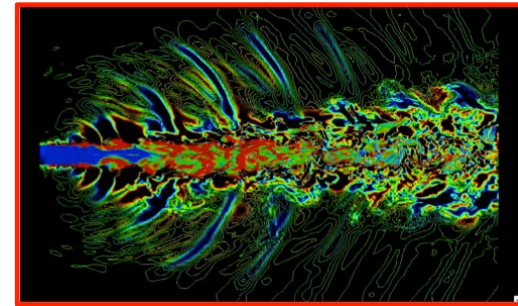


- Intermodal Energy dynamics
 - Kinetic, Internal, Chemical
 - Gas-Surface Interactions
- Excitation Mechanisms
 - Shock Interactions
 - Finite-Rate Processes

In Energy, Power & Propulsion

Turbulence & Transition

PO: TBD



- Kinetic Energy dynamics
 - Instability growth and competition
 - Physics of Turbulence
- Impact of Boundary and Initial Conditions
 - Surface Roughness
 - Inflow Disturbance Effects

In Dynamical Systems & Controls:



Accomplishments & Transitions



Current PI Accomplishments

- Members of the NAE (6)
- NSSEFF Fellow
- DoD Advisory Boards
 - AF SAB
 - JASON
 - Def. Studies Group
- PECASE (2)
- NSF CAREER (4)
- OSR Young Investigator (4)

Our Alumni

- AIAA Past President (2)
- AF Chief Scientists (2)
- Prior PM: Dr. S. Walker



Candler, Schneider and Miles
Recognized with AIAA Awards

Examples of Recent Tech Transitions

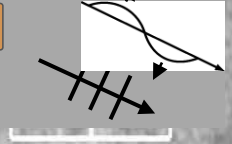
- 6 Students working at AFRL
- Purdue M6 Quiet Tunnel named critical national T&E resource
- *Lead* SME Consultants for HTV-2, CPGS
- Performed critical analysis for X-51 post-flight 2 investigation
- Transitioned STABL code to 25 org.
 - T&E version funded by TRMC
- Transitioned US3D CFD to 14 org.
 - AFRL, NASA, Boeing, LM, UTRC ...
- Provided algorithm for accelerated chemistry sims in CFD to AFRL/RV
- Supported DARPA, MDA, Sandia, ...



Outline



- Objectives, Challenges, Opportunities and Impact → Innovative approach to evolving AF needs
- Portfolio Description → Extensively coordinated with other agencies
- **Research Highlights** → Exciting Science
 - Laminar-Turbulent Transition
 - Energy Transfer Mechanisms
 - Leveraging advancements in numerics and diagnostics
 - Importing expertise from other disciplines
 - Unprecedented insight into fundamental processes
- Research Directions
- Summary



Freestream
Disturbances

Roughness

Laminar-Turbulent Transition

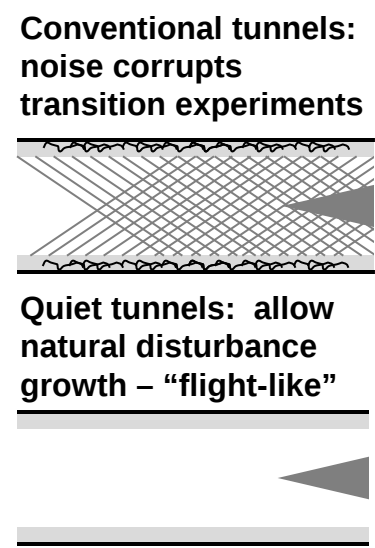
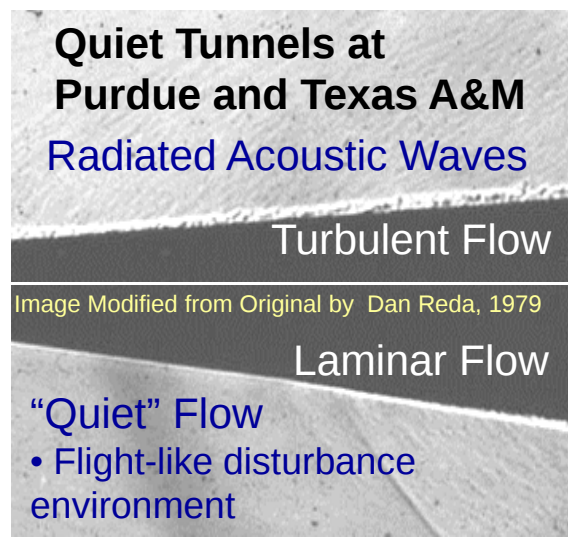
Disturbances trigger instabilities which drive breakdown to turbulent state

Image: Hornung,
Cal Tech

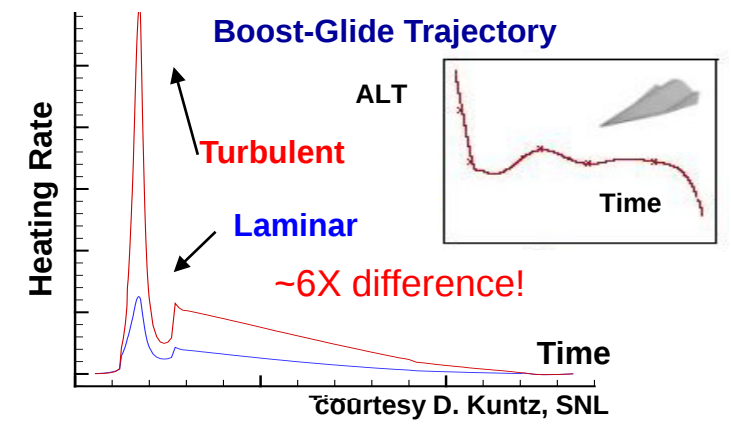
Challenges – understand K.E. Dynamics

- Dynamics occur at the microscale
 - Key instability dynamics occur at 10^{-6} of mean
- Process is a “race” between competing growing instabilities
- Nonlinear interactions play critical role

Key Capability Advancements

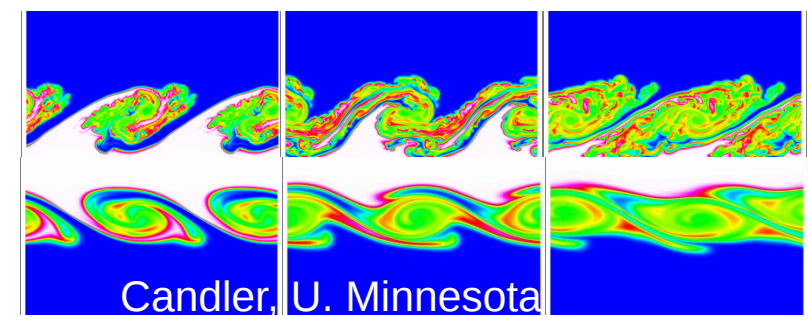


Design Driver for High-Speed Systems



Advanced Numerical Methods

- Stability analysis – Texas A&M, Minnesota
- High Resolution @ Scale - Minnesota

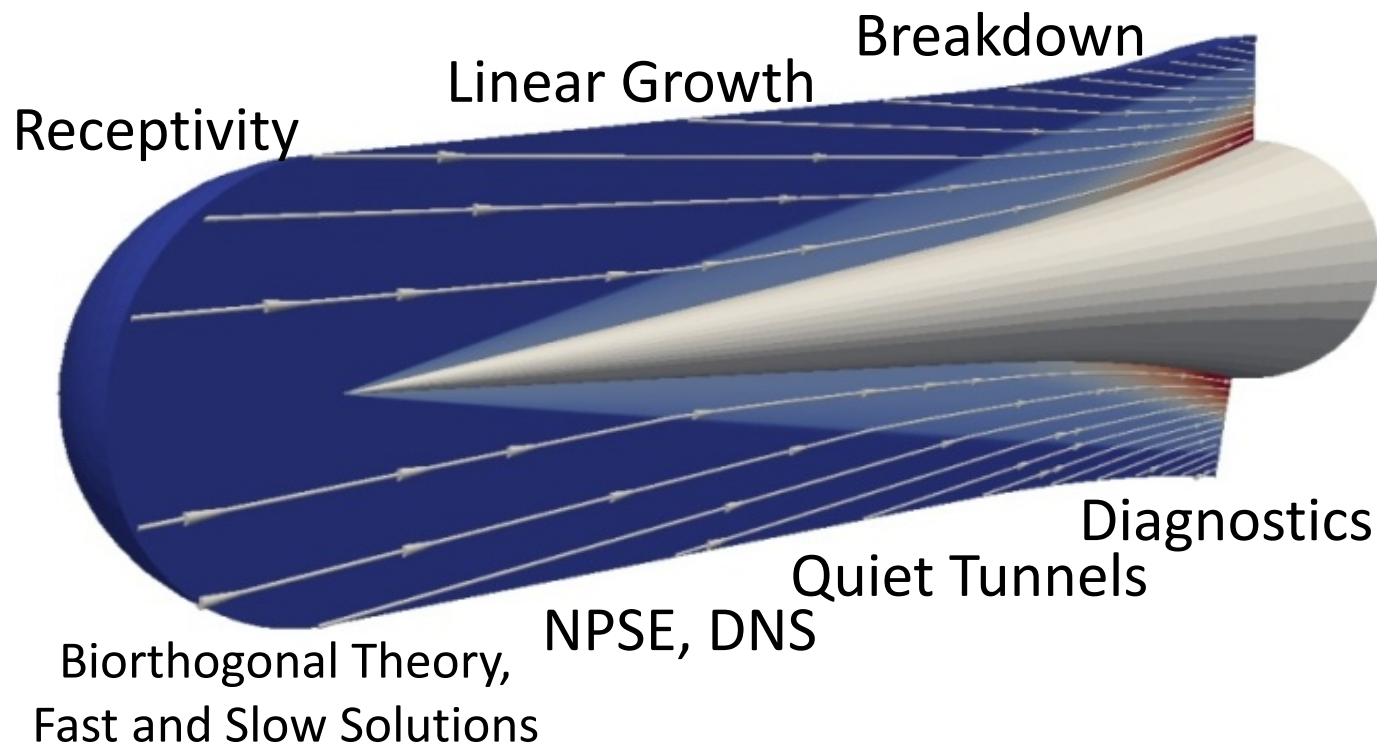




Driving Scientific Progress



National Hypersonic Science Center: *Integrating the best and brightest to enhance physics-based understanding and prediction of transition*



3 NAE Members
16 Fellows
2 NRC, 3 NATO
> 80 students
> 140 publications
2 Annual Review
Articles
Many external
meaningful
collaborations





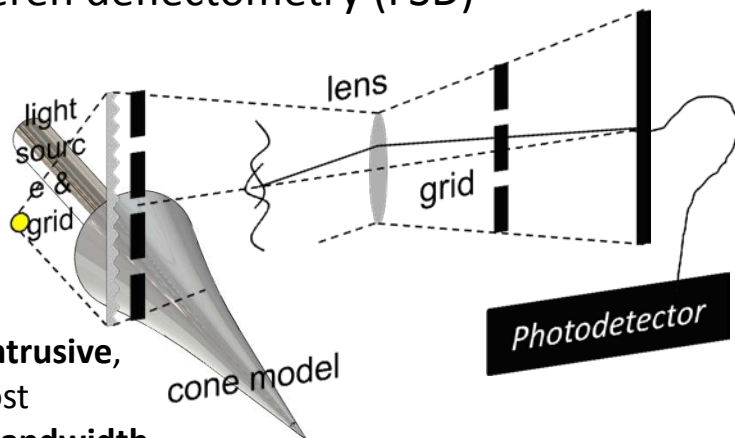
New Insight Into Critical Physics



Second-mode nonlinear interactions quantified

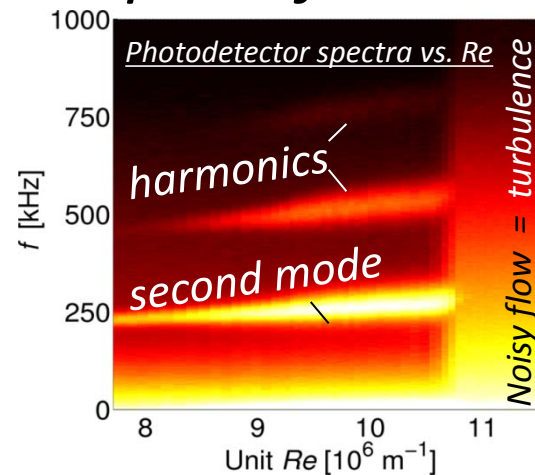
Texas A&M Mach 6 Quiet Tunnel

- New optical measurements via focused schlieren deflectometry (FSD)



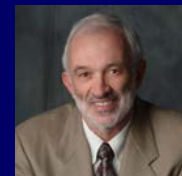
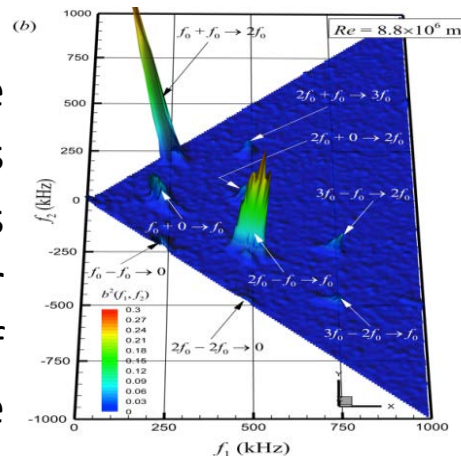
- **Non-intrusive,**
- **low-cost**
- **High bandwidth**
(1 MHz)

Quantified second-mode nonlinear interactions enable identification of critical modes in transition process



Sensitive FSD spectra reveal harmonics of second mode

Bicoherence analysis identifies nonlinear interactions of second mode and harmonics



W. Saric, NAE
Distinguished
Professor



Jerrod Hofferth
Ph.D. Candidate



Helen Reed
Professor
"NPSE Validation"

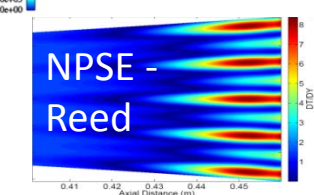
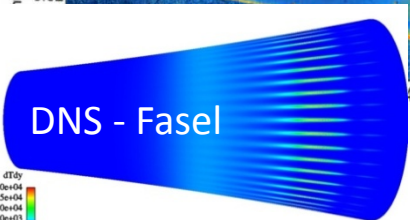
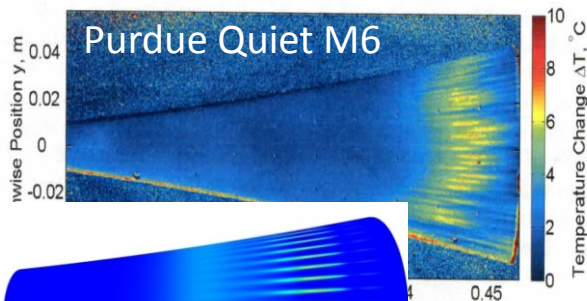


New Insight Into Critical Physics



Three-stage breakdown model provides new insight into hypersonic transition

Explains overshoot in skin friction and heat transfer



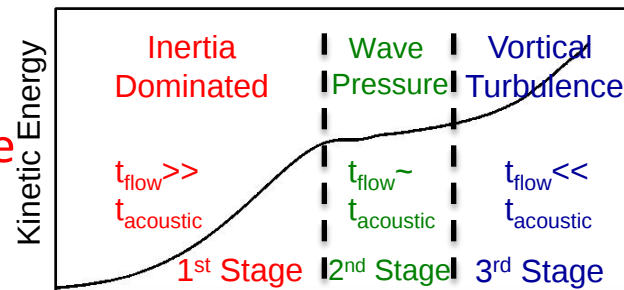
Initial rise in friction from large amplitude primary wave

Saturation of primary wave

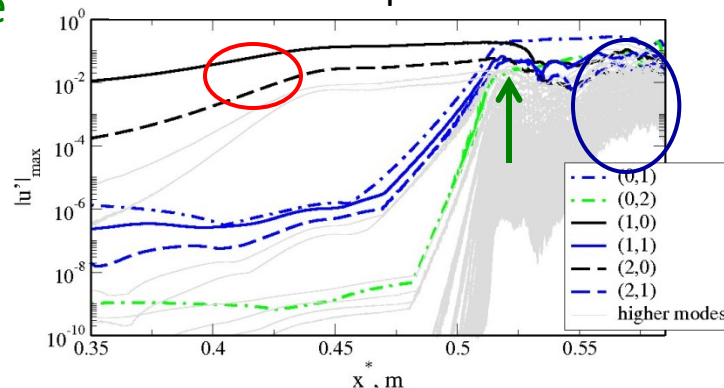
Steeper rise as all higher modes grow nonlinearly

Hot streaks of limited extent observed in DNS, experiment, NPSE for 3 different geometries

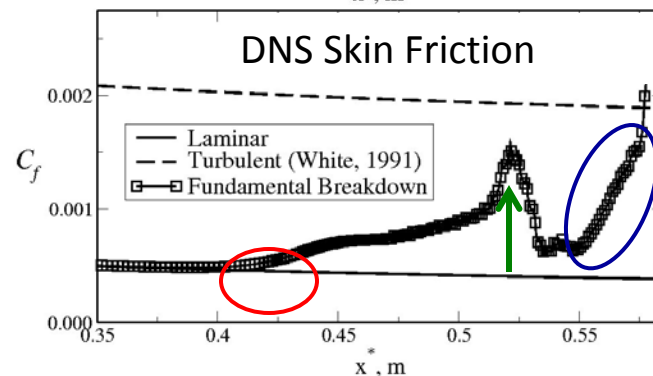
Theoretical Model



DNS Spectra



DNS Skin Friction



H. Fasel
Professor



S. Girimaji
Professor



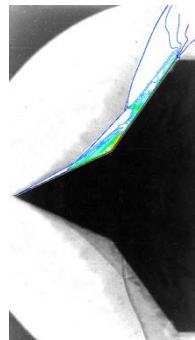
H. Reed
Professor



Establish and Exploit A Fundamental Understanding of Energy Transfer in Flows

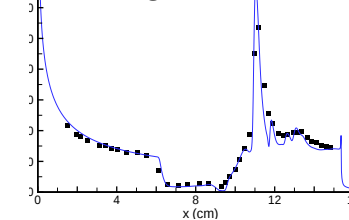


Predictions Fail as Chemical Complexity Increases

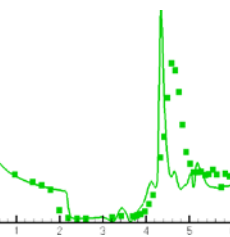


■ Experiment
— Numerical Simulation

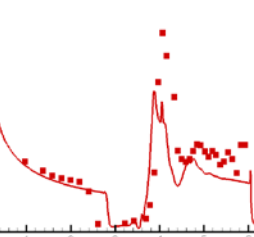
Nitrogen



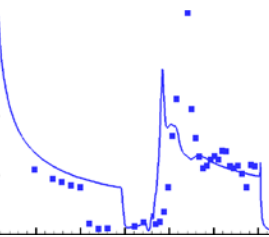
Air, 4.5 Mj/kg



Air, 10.4 Mj/kg

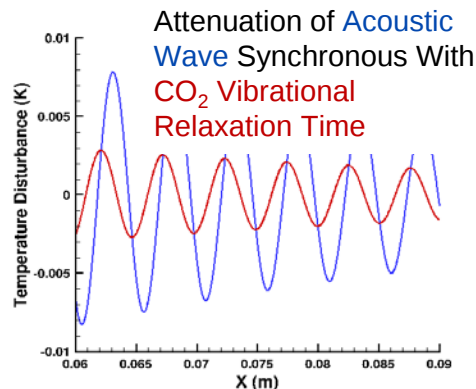


Air, 15.2 Mj/kg



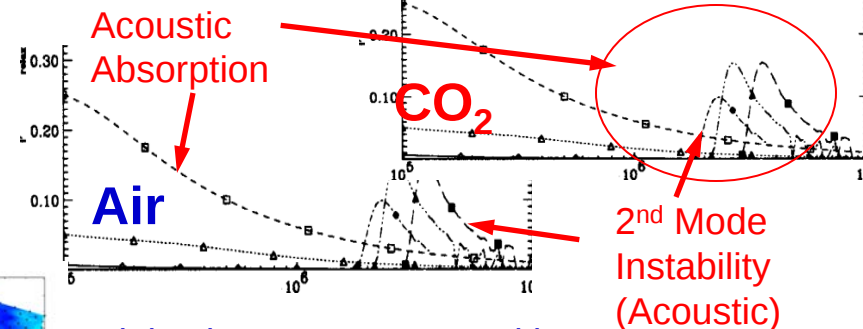
Increasing Energy/Chemistry G. Candler, U. Minn.

Control Energy Transfer to Tailor Macroscopic Flow

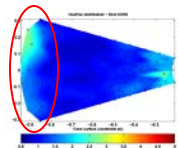


For CO₂ internal energy and acoustic instability modes overlap

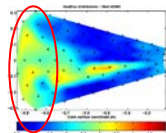
Curves for 3 total enthalpy values



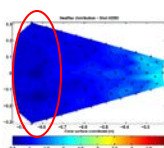
No Injection



Argon at 12 g/s



CO₂ at 12 g/s



Ar injection promotes transition, CO₂ inhibits transition

Key to Progress is the Understanding and Accurately Modeling the Rate-Dependent Energy Transfer Mechanisms



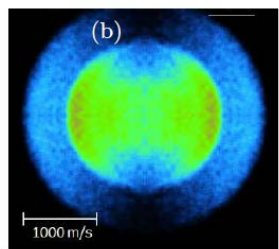
Foundations of Energy Transfer in Multi-Physics Flow Phenomena



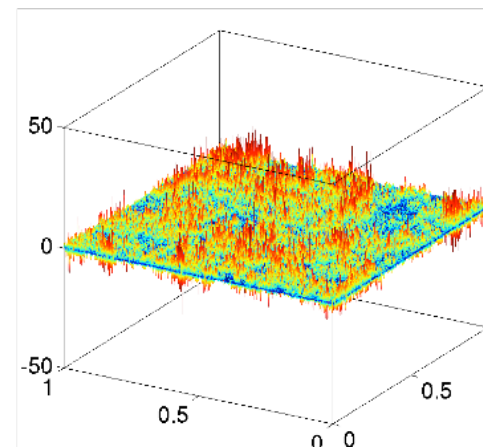
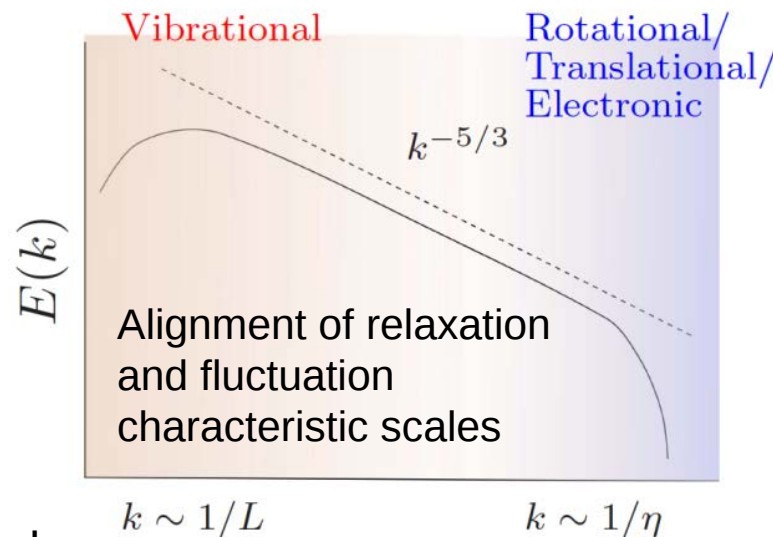
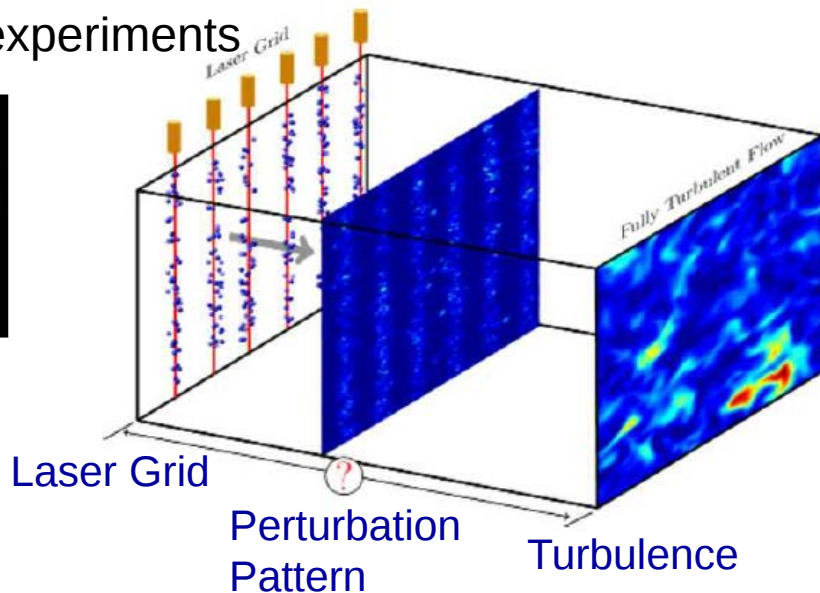
Non-equilibrium effects on turbulent flows:

Can turbulence be shaped via coupling with internal energy transitions?

Utilizing massively large-scale DNS, molecular dynamics simulations and novel laser based experiments



Laser-Generated Flow Perturbation



DNS: Velocity gradients from shock turbulence interactions



D. Donzis
Assist. Professor



R. Bowersox
Professor



S. North
Professor



W. Haze
Professor

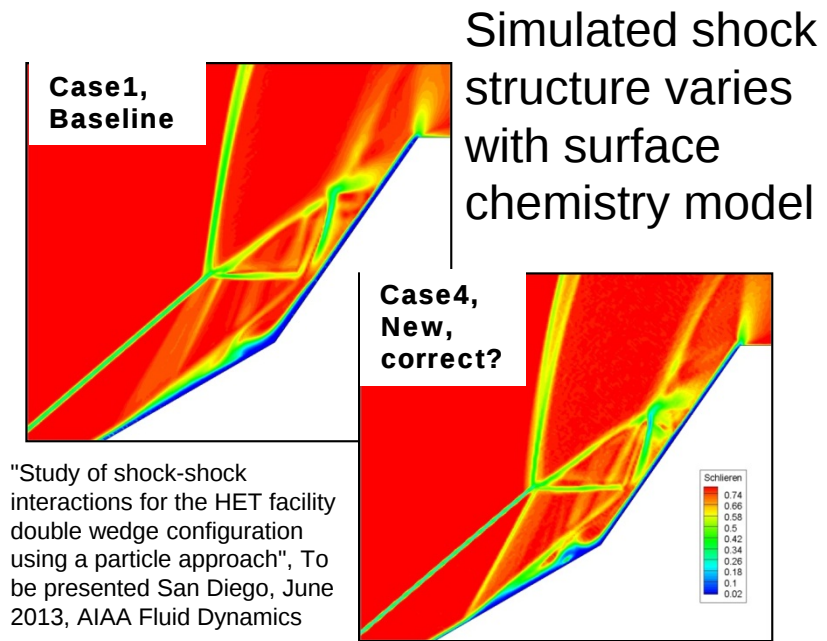
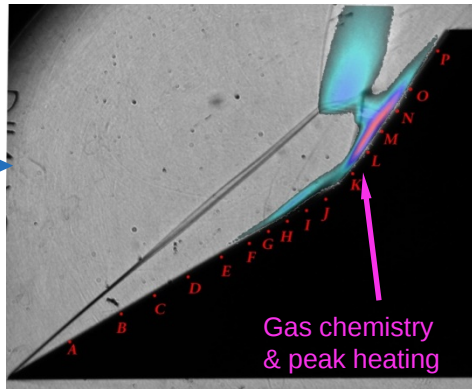
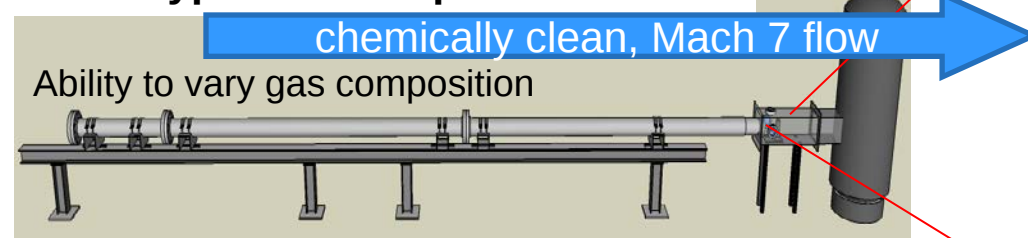


Establish and Exploit A Fundamental Understanding of Energy Transfer in Flows

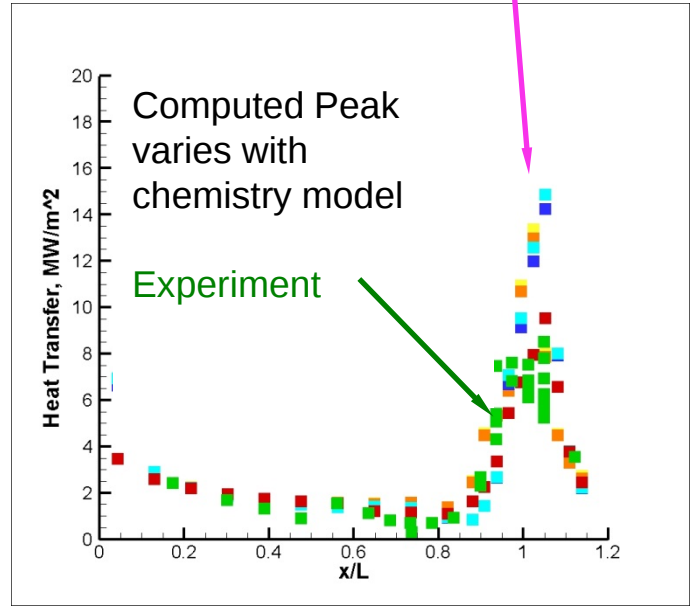


Joint experiments and simulations reveal new insight into gas chemistry effects

HET – Hypersonic Expansion Tube:



"Study of shock-shock interactions for the HET facility double wedge configuration using a particle approach", To be presented San Diego, June 2013, AIAA Fluid Dynamics



Joanna Austin
U. Illinois
• AFOSR YIP
• NSF CAREER



Deborah Levin
Penn State
• JHTT Assoc. Ed.

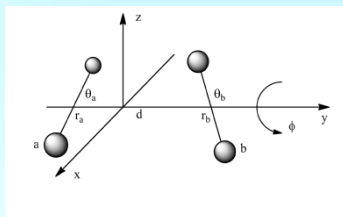
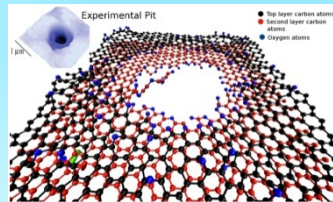
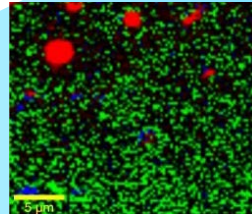
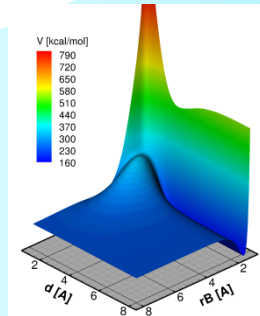


MURI: Fundamental Processes in High-Temperature Hypersonic Flows



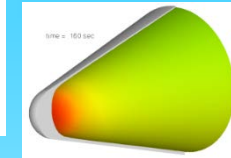
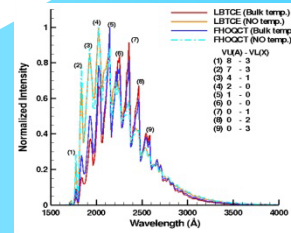
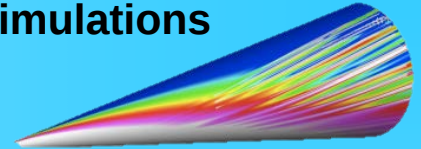
MURI addresses scale-up of knowledge from molecular potential to nonequilibrium flow over a full-scale body

- Integrates contributions from chemistry, material science, and aerothermodynamics
- Coordinated simulations and experiments



Quantum Chemistry

Accurate Hypersonic Simulations



PI - Graham Candler

Paul DesJardin,
Matt MacLean

Debbie Levin

Erica Corral

Tim Minton

Tom Schwartzentruber

Adri van Duin

Dan Kelley

Don Truhlar

- 14 grad students
- 10 post-docs
- 2 undergrad
- 18 articles
- 18 conference papers



Nanoscale: Quantum Chemistry / MD of Critical Processes



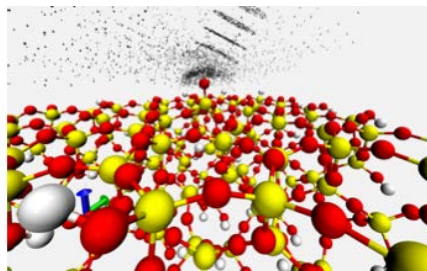
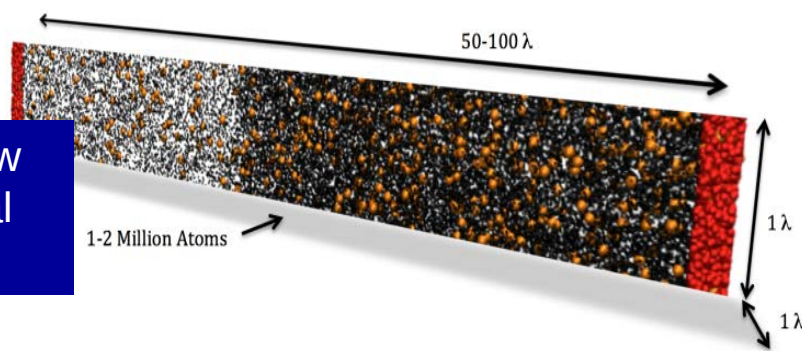
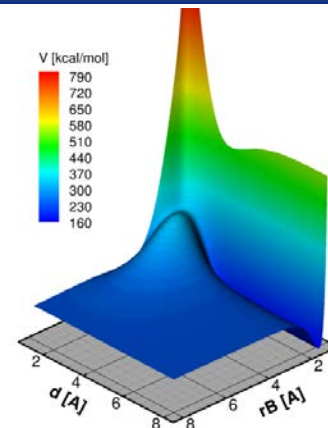
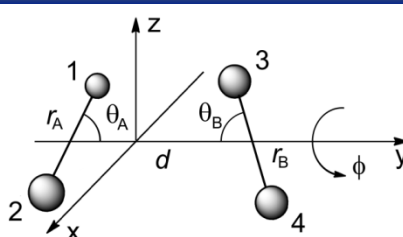
Quantum chemistry advances gas-phase and gas surface interaction simulations

Relevant N_4 , O_4 , N_2O_2 potential energy surfaces calculated from interatomic potential

First simulation of shock wave using only atomic potentials as model

MD + New Numerical Scheme

New gas-surface interaction model consistent with physical chemistry



Rate	Rate Equation	Rate constant (k_i)	units
r_1^f	$k_1^f [O][E_s]$	$(\bar{c}_O/4) \times (2\pi r_c^2) \times (A_1^f e^{-E_1^f/(K_B T)})$	m^3/s
r_1^r	$k_1^r [O_s]$	$A_1^r e^{-E_1^r/(K_B T)}$	$1/s$
r_2^f	$k_2^f [O][O_s]$	$(\bar{c}_O/4) \times (2\pi r_c^2) \times (A_2^f e^{-E_2^f/(K_B T)})$	m^3/s
r_2^r	$k_2^r [O_2][E_s]$	$(\bar{c}_{O_2}/4) \times (2\pi r_c^2) \times (A_2^r e^{-E_2^r/(K_B T)})$	m^3/s
r_3^f	$k_3^f [O][O_s]$	$(\bar{c}_O/4) \times (2\pi r_c^2) \times (A_3^f e^{-E_3^f/(K_B T)})$	m^3/s
r_3^r	$k_3^r [O_2s]$	$A_3^r e^{-E_3^r/(K_B T)}$	$1/s$
r_4^f	$k_4^f [O][O_2s]$	$(\bar{c}_O/4) \times (2\pi r_c^2) \times (A_4^f e^{-E_4^f/(K_B T)})$	m^3/s
r_4^r	$k_4^r [O_2][O_s]$	$(\bar{c}_{O_2}/4) \times (2\pi r_c^2) \times (A_4^r e^{-E_4^r/(K_B T)})$	m^3/s
r_5^f	$k_5^f [O_2][E_s]$	$(\bar{c}_{O_2}/4) \times (2\pi r_c^2) \times (A_5^f e^{-E_5^f/(K_B T)})$	m^3/s
r_5^r	$k_5^r [O_2s]$	$A_5^r e^{-E_5^r/(K_B T)}$	$1/s$

Table 4: Rate Constants and functional forms



Dr. Thomas Schwartzentruber
AFOSR Young Investigator Award (2009)



Dr. Adri van Duin

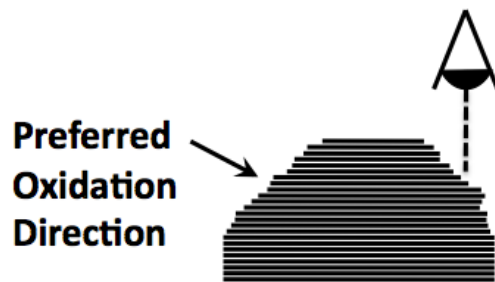


Microscale: Highly Oriented Pyrolytic Graphite Oxidation



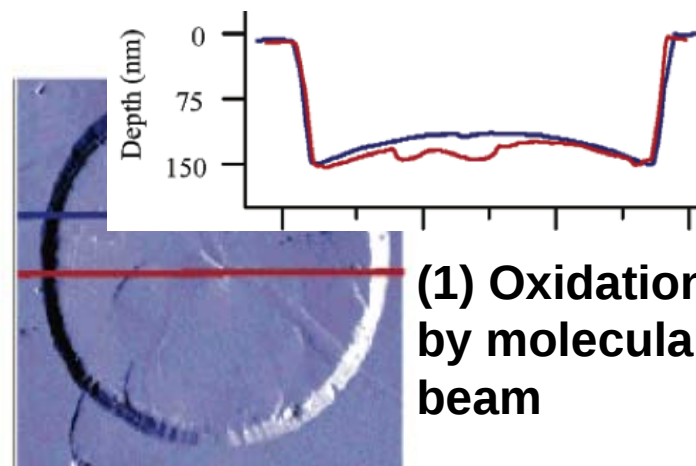
Coordinated experiments and simulations: bridging computational chemistry to macroscopic ablation experiments

(2) Oxidation in furnace
AFTER OXIDATION



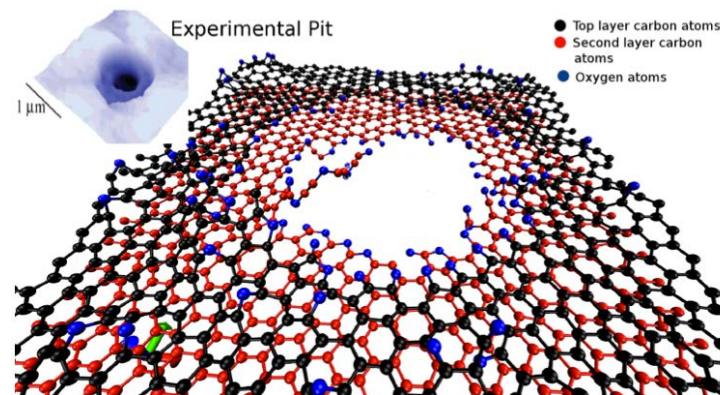
Graphitic layers preferentially oxidize at edges due to open bond sites

HOPG is a well-characterized form of carbon: planar



(1) Oxidation by molecular beam

(3) MD at molecular beam conditions



Prof. Thomas Schwartzentruber



Prof. Erica Corral



Prof. Tim Minton



Prof. Adri van Duin

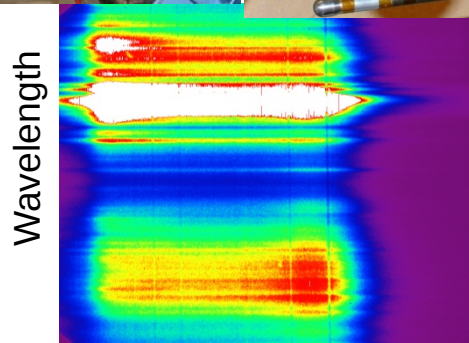
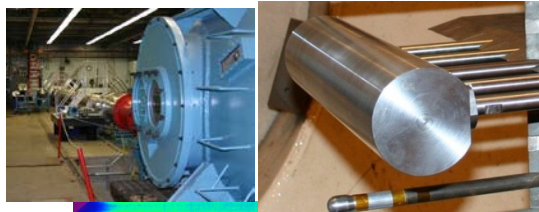


Macroscale: Spectral Measurements of Shocklayer Emission



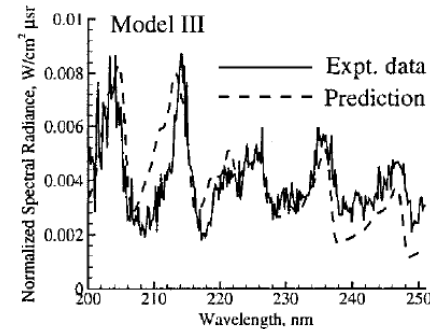
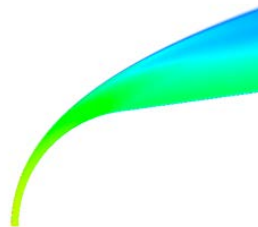
Integrated Flight and Ground Test Data Provide Unique, Detailed, and Unequivocal Data for Model Validation

UV Radiation Measured in LENS XX –Expansion Tunnel



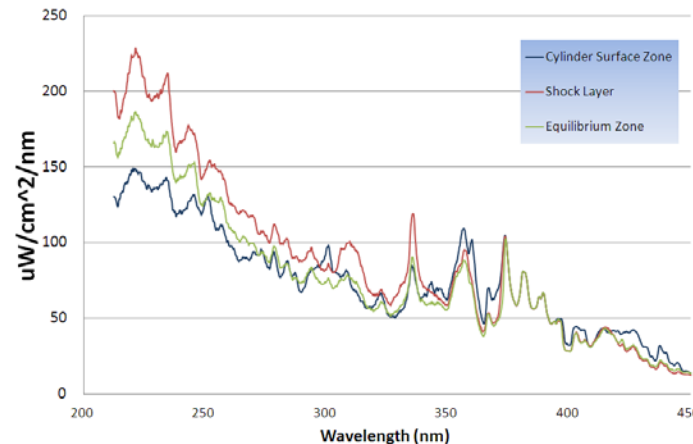
surface

shock



BSUV Flight Data: UV Emission from Sounding Rocket Nose:
Bose, Candler, Levin (1998)

Model effectiveness assessed from comparison of spectra from tunnel measurements, flight data, CFD and theory



Prof. Graham Candler
U. Minnesota



Prof. Paul Desjardin
U. Buffalo



Prof. Deborah Levin
Penn State



Outline



- Objectives, Challenges, Opportunities and Impact
- Portfolio Description
- Research Highlights
 - Laminar-Turbulent Transition
 - Energy Transfer Mechanisms
- **Research Directions** → • **Where we're going**
- Summary



Foundations of Energy Transfer in Multi-Physics Flow Phenomena



Establish the multidisciplinary scientific foundation for innovative approaches to *inherent* flow control

- Identify fundamental processes
- Exploit energy transfer in shaping macroscopic flow behavior

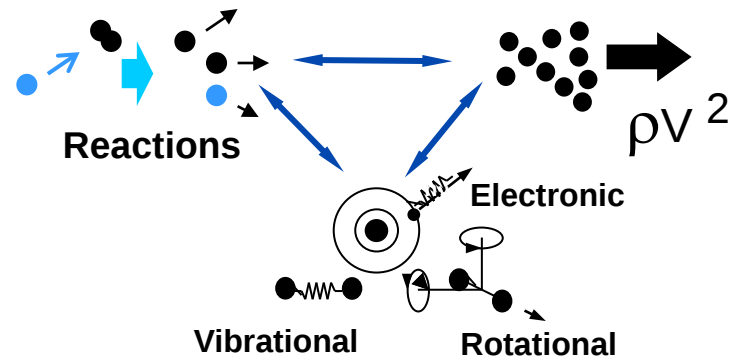
Bridging Multiple Portfolios

- Aerothermodynamics and Turbulence
- Energy Conversion and Combustion Sciences
- Molecular Dynamics and Theoretical Chemistry
- Flow Interactions and Control
- Plasma and Electroenergetic Physics

RTE

RTA

RTB



Emphasized projects that bridged interests of at least two of the participating portfolios

Opportunity to Pick Up New Ideas from Other Disciplines

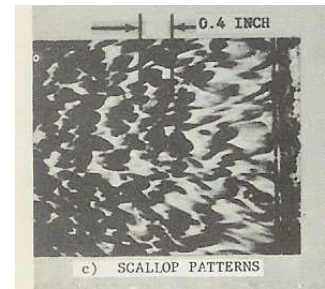
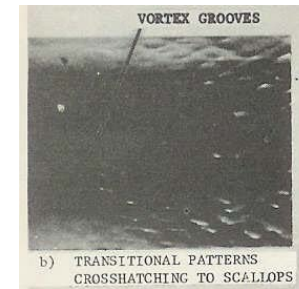
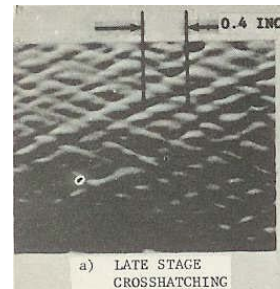


Upcoming Emphasis Area: Conjugate Gas-Surface Interactions

“...the crosshatch patterns degenerate to scallop patterns. For some materials, such as graphite, the degeneration process is so rapid that the initial crosshatch pattern is generally indiscernible.”

Grabow & White, AIAA J, 13, 5

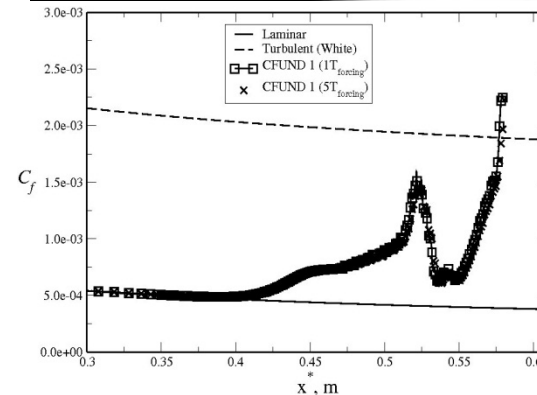
- Pattern is material-dependent
- Kinetic effect – occurs at low temp



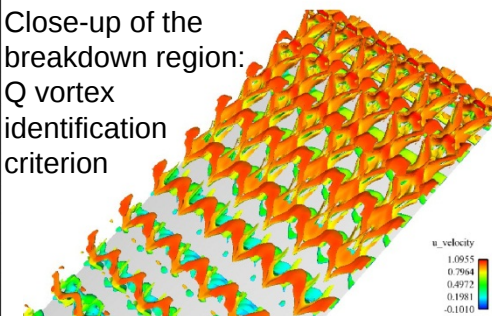
Larson and Nachtsheim, NASA Ames

Does the 3-Stage Breakdown Model Developed by the NHSC –Transition Team Contribute to the Ablation Pattern Above?

- How do the flow structure and material response couple?



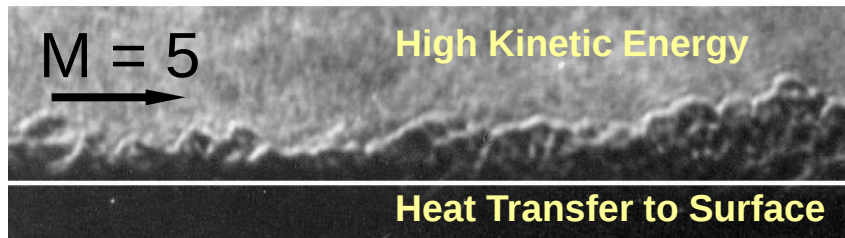
Close-up of the breakdown region:
Q vortex identification criterion



We now have the tools to take on the challenge of complex, coupled flow surface interactions



Upcoming Emphasis Area: Highly-Distorted Turbulence

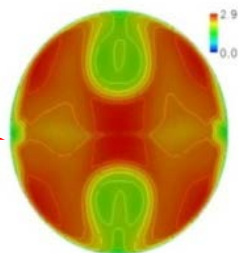
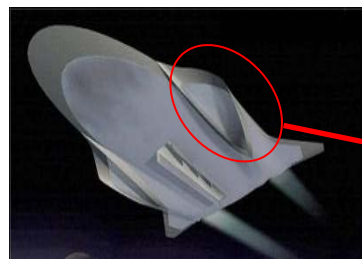
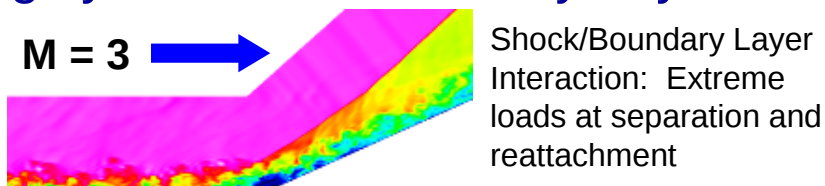
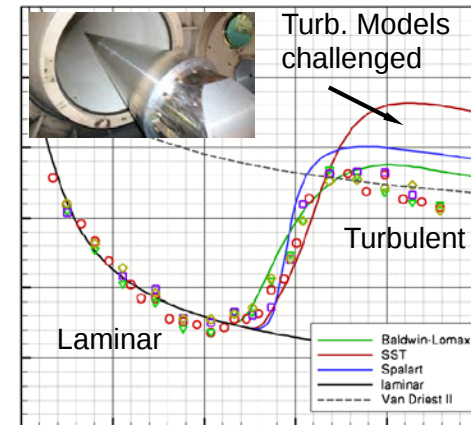


Boundary Layer: Viscous diffusion of kinetic energy into heat

Planned High-Speed Systems will have
Highly-Distorted Boundary Layers

If this is tough...

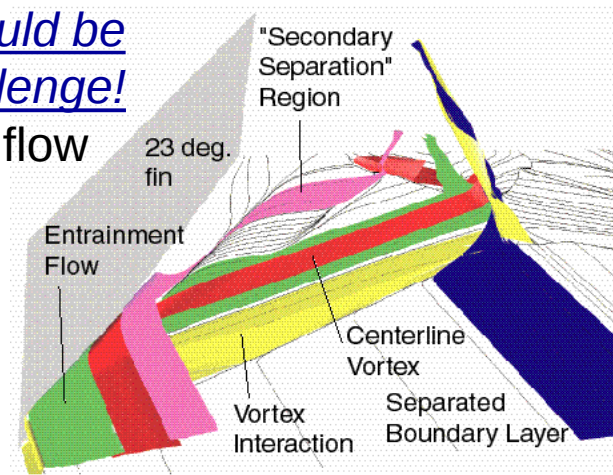
Heat transfer prediction remains a challenge for high-speed boundary layers



Inlet Distortion Effects Efficiency

... this should be a real challenge!

Significant flow distortion occurs in 3-D SBLIs



Utilize full-spectrum of diagnostic and simulation capabilities to explore energy dynamics in highly-distorted turbulent flows



Summary

- Objectives, Challenges, Opportunities and Impact
- Portfolio Description
- Research Highlights
 - Laminar-Turbulent Transition
 - Energy Transfer Mechanisms
- Research Directions
- Summary
- World-leading scientific research with game-changing impact
- Evolving with expanding AF areas of responsibility
- Leveraging contributions from other disciplines
- Unprecedented insight into fundamental processes
- Future directions are scientifically challenging while relevant



2013 AFOSR SPRING REVIEW

2307/A Aerothermodynamics and Turbulence



NAME: John D. Schmisser

Aerothermodynamics & Turbulence

BRIEF DESCRIPTION OF PORTFOLIO:

Identify, Model and Exploit critical physical phenomena in turbulent and high-speed flows

- emphasis on energy transfer

Sole US basic research program in this area

SUB-AREAS IN PORTFOLIO:

- Boundary Layer Physics
- Shock-Dominated Flows
- Gas Thermophysics
 - Gas-Surface Interactions
- Turbulence and Transition

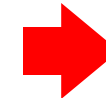
Partners



National Hypersonic Foundational Research Plan



Joint Technology Office - Hypersonics



Assessment of SOA and Future Research Directions



Jet Noise



Arnold Engineering Development Center



Tech Transition

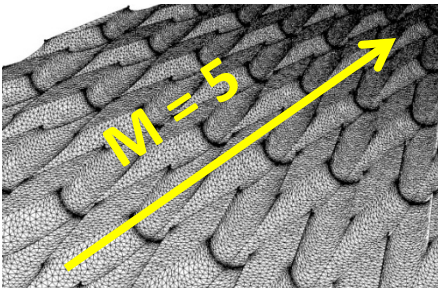


Exploring Nonequilibrium Turbulence



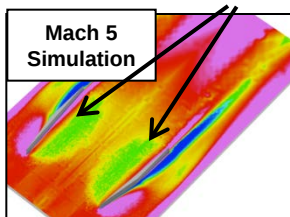
R. Bowersox
Professor

Roughness Pattern Reduces Turbulence Near Surface:
Unraveling energy redistribution improves understanding and control of hypersonic viscous heat transfer and drag

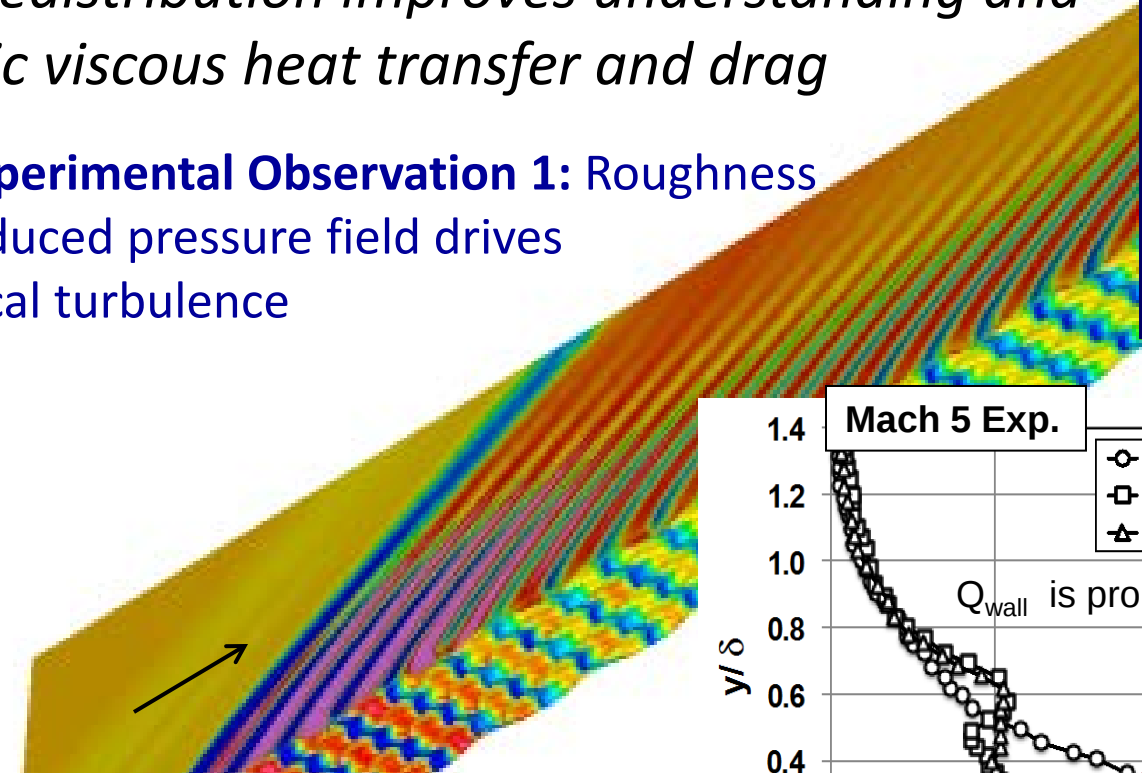


Cross-hatched roughness pattern similar to ablated surfaces

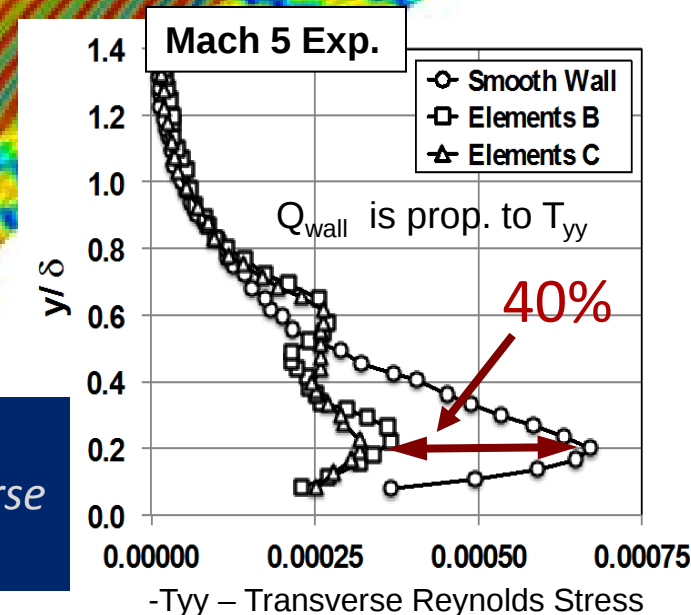
RANS Simulations: Tailored pressure gradient reduces local turbulence



Experimental Observation 1: Roughness induced pressure field drives local turbulence



Experimental Observation 2:
40% reduction in local transverse stresses → Reduced heat flux





Foundations of Energy Transfer in Multi-Physics Flow Phenomena

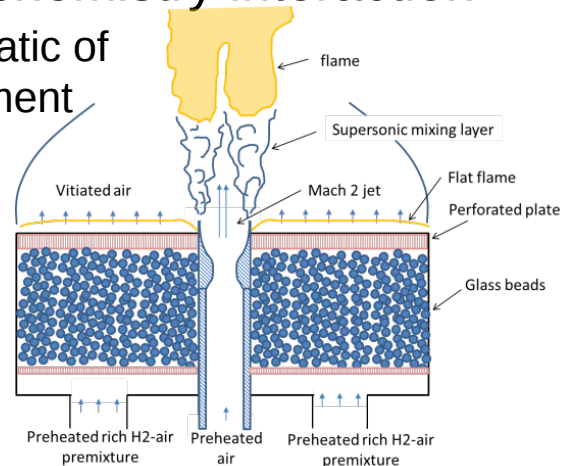


New Control Strategies for Supersonic Combustion

Non-equilibrium effects on turbulence chemistry interaction

Can ro-vibrational non-equilibrium effectively transfer energy from thermal to mechanical or chemical modes in high speed turbulent flow?

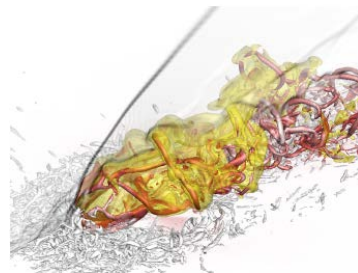
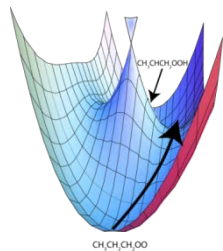
Schematic of experiment



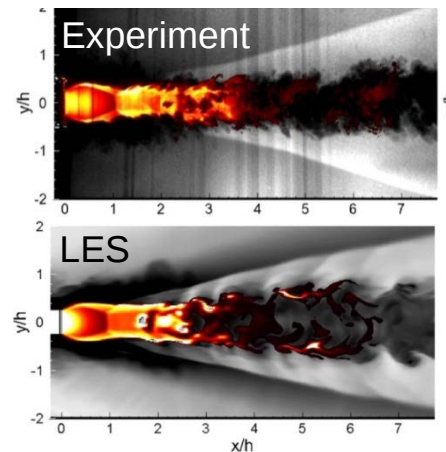
THE UNIVERSITY OF
TEXAS
— AT AUSTIN —

Profs. Philip Varghese, Noel Clemens, Venkat Raman – UT Austin
Prof. Wes Allen – U Georgia

Integrating advanced laser diagnostics with innovative computational chemistry



Potential Energy Surface – helps determine reaction rates
Detailed flow simulations of ethylene jet in cross flow using accurate rates



Kr PLIF + CO₂ Fog

S. Kim, P. Donde, V. Raman, K. Lin, C. Carter, AIAA paper 2012-482, 2012

R. Burns, H. Koo, N. Clemens, V. Raman, AIAA paper 2011-3936, 2011

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