

Overview of Hypersonic Airbreathing Propulsion Ground Testing and NASA's Enhanced Injection and Mixing Project

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Conceptual rendering of a hypersonic vehicle concept

[Source](#)



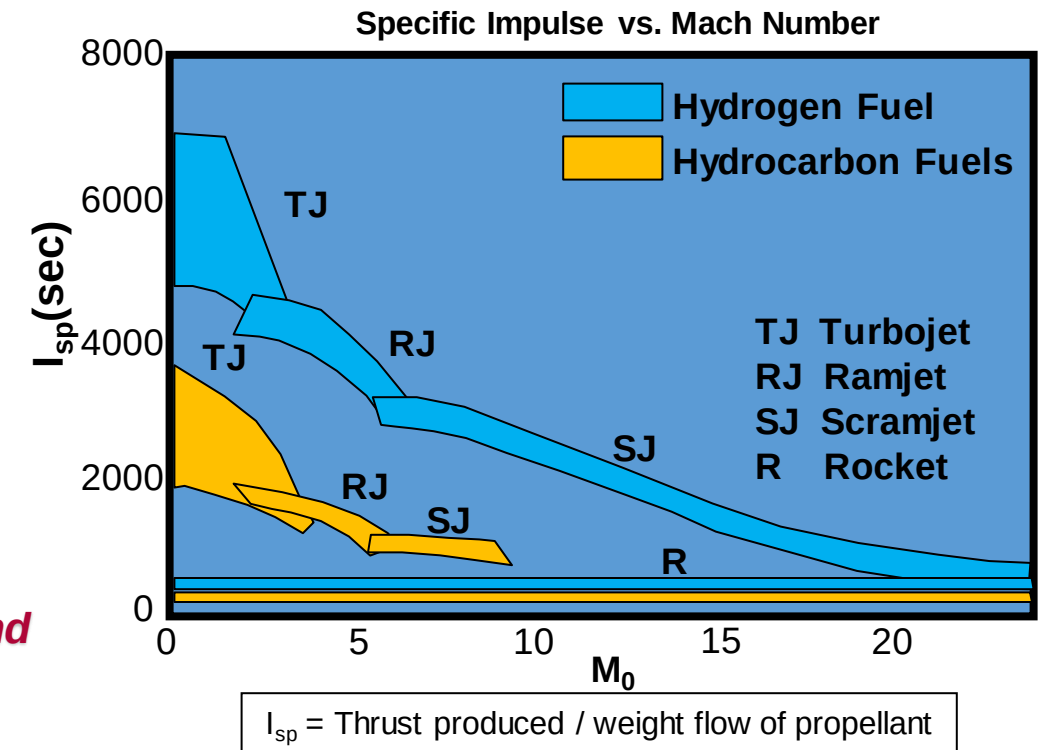
Part I: A Brief Introduction to Hypersonic Airbreathing Propulsion Systems and Ground Testing



What is Hypersonic Airbreathing Propulsion?



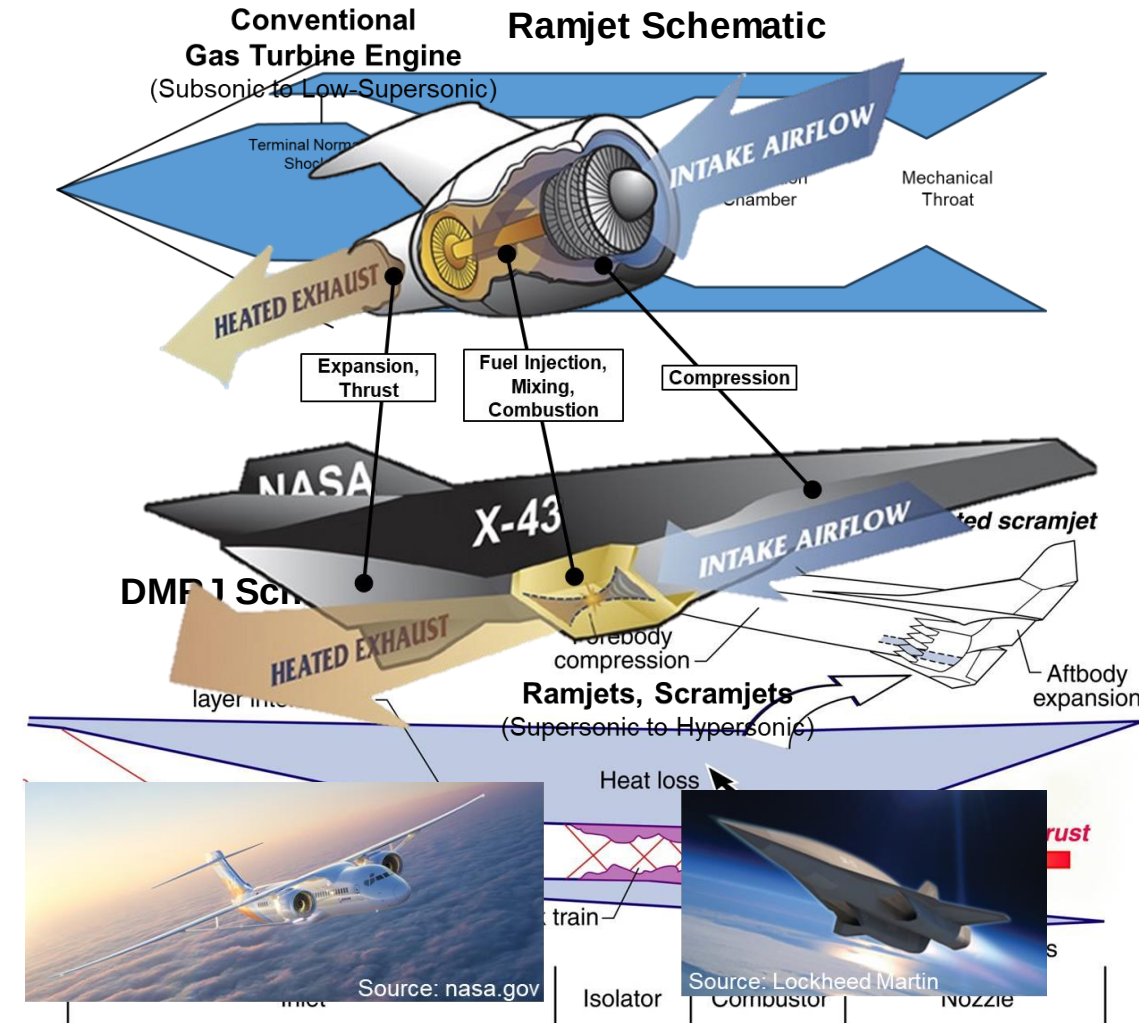
- “Hypersonic”
 - Hypersonic flow: speeds greater than Mach 5
 - Thin shock layers
 - Thick, high temperature boundary layers (viscous interaction)
 - High temperature → vibrationally excited, chemically reacting flow (γ is not constant!)
- “Airbreathing Propulsion”
 - Engines that obtain oxidizer from atmospheric air
 - Need to carry fuel onboard
 - In simpler terms: engines that utilize combustion and are not rockets
- ***Engines that generate thrust by combusting a mixture of fuel and atmospheric air and then expand the flow through a nozzle to propel a vehicle at speeds near to, or greater than, Mach 5.***
- Relevant engine types:
 - Ramjets (RJs)
 - Dual-mode ramjets (DMRJs)
 - Scramjets (SJs, supersonic combusting ramjets)



Hypersonic airbreathing propulsion systems

- 1) Can operate at Mach numbers above those of turbojets (limited by turbine inlet temperature)
- 2) Are more efficient at converting propellant to thrust than rockets since they only carry fuel

- **RJs, DMRJs, SJs:**
 - Utilize ram (i.e., shockwave) compression of the vehicle forebody and inlet to compress the flow in lieu of rotating machinery
 - Produce no static thrust, must be boosted to takeover speed
- **Ramjets:**
 - Terminal normal shock and subsonic diffuser
 - Subsonic combustion with mechanical throat
 - As Mach number increases, large total pressure losses and high static pressures/temperatures occur with a terminal normal shock. This makes pure RJs challenging for “true hypersonic” ($M > 5$) flight
- **Dual-Mode Ramjets:**
 - Oblique shocktrain and isolator
 - Subsonic combustion with thermal throat
 - Ideal for “low- to mid- hypersonic” Mach numbers (approximately, $4 < M < 7$)
- **Scramjets:**
 - Flow remains supersonic throughout
 - Minimal precombustion pressure rise, (i.e., much shorter shocktrain)
 - Ideal for Mach numbers greater than 7-8
- **DMRJ and SJs are highly airframe-integrated!**
- Recommended Reading:
 - “Hypersonic Airbreathing Propulsion” Heiser and Pratt, AIAA Education Series

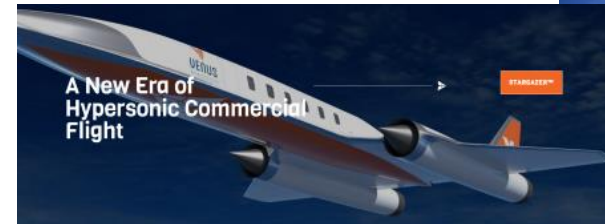


- **Civilian**

- *Access to space*
 - Two-stage to orbit (TSTO) systems utilizing combined cycle propulsion systems:
 - Increase launch flexibility and cadence (i.e., multiple launch windows per day, rapid response launch)
 - Higher efficiency
 - Increased safety of horizontal takeoff/landing
- *Point-to-point transport*
 - Potential passenger aircraft offer drastically decreased transatlantic/transpacific travel time. Startups playing in this arena



Source: nasa.gov



Source: venusaero.com



Source: hermeus.com

- **Defense**

- Near term: In the midst of a hypersonic arms race (USA, China, Russia)...news is full of articles
 - Multiple billions of dollars being spent on development of hypersonic weapons systems
- Further out: reusable hypersonic ISR/strike platforms

CNN

US tests hypersonic missile in Pacific as it aims to keep up with China and Russia

The US Air Force has tested a hypersonic cruise missile in the Pacific for the first time, in what analysts say is a signal to China that...

Mar 21, 2024

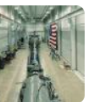


National Defense Magazine

Testing Top of Mind as U.S. Lags China In Hypersonics Race

A major reason for China surging to the lead in the hypersonics race is its "intense and focused investment" over the last 20 years in the necessary...

1 month ago

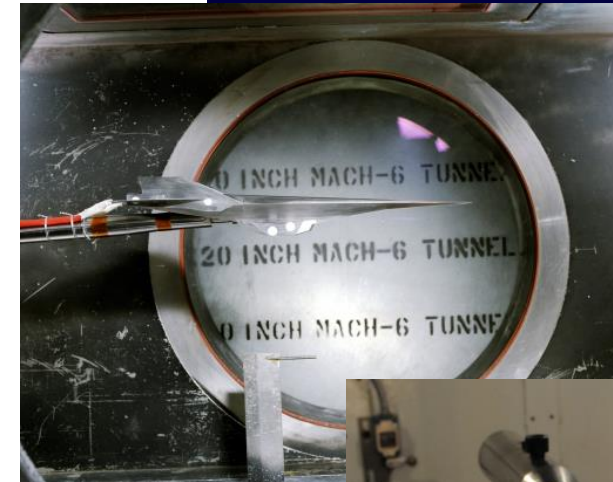
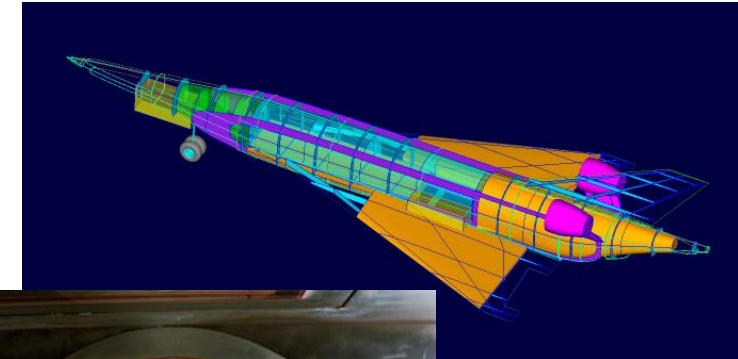




NASA's Hypersonic Technology Project



- **Goal:** *“to enable routine, reusable, airbreathing hypersonic flight by conducting fundamental and applied research to enable a broad spectrum of hypersonic systems and missions.”*
- Divided into four Research Topics (RTs) and three Technical Challenges (TCs)
 - **RT-1:** *System-Level Design and Analysis*
 - **RT-2:** *Propulsion Technologies*
 - **RT-3:** *Vehicle Technologies*
 - **RT-4:** *High Temperature Materials*
 - **TC-1:** *System-Level Uncertainty Quantification Methodology Development and Validation*
 - **TC-2:** *Turbine-Based Combined Cycle Mode Transition Technology Development*
 - **TC-3:** *Development of Improved Combustor Scaling Laws for Dual-Mode Ramjets*
- Research conducted across the agency at multiple NASA Centers



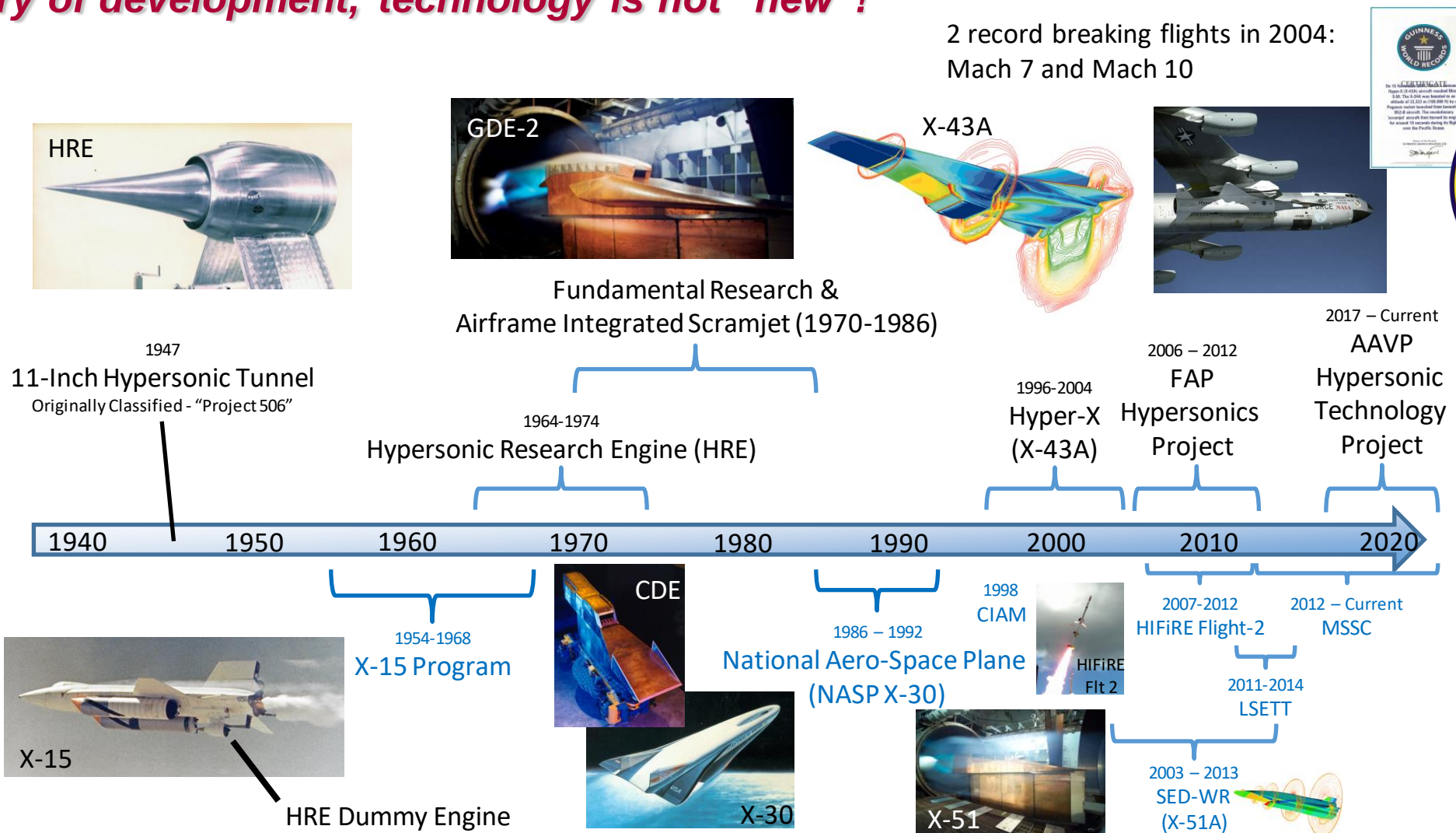
<https://www.nasa.gov/directorates/armd/aavp/hypersonic-technology-project/>



History of Hypersonic Airbreathing Propulsion at NASA Langley



Long history of development, technology is not “new”!

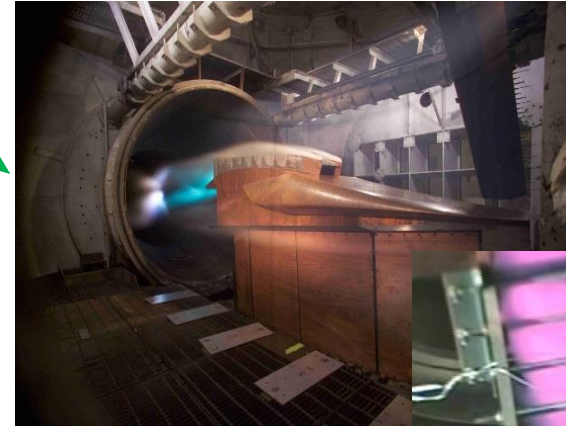


Modeling and
Simulation(\$)
100s/year

Ground Testing
(\$\$\$)
5-10/year per facility

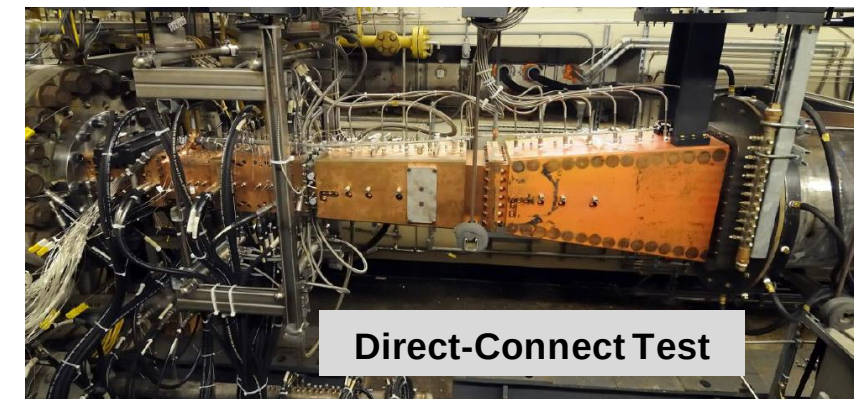
***“Three-Legged Stool”
of Hypersonic
Propulsion
Aeroscience***

Flight Testing (\$\$\$\$\$\$)
1-2/year per program



- **Types of ground tests**

- *Freejet*
 - Facility nozzle expands flow to flight Mach number
 - Flow completely envelops test article
 - Test article has full inlet compression system
 - Facility mass flow greatly exceeds mass swallowed by the engine
- *Semi-freejet*
 - Due to facility constraints, inlet compression system is truncated
 - Flow partially envelops test article
 - Facility nozzle expands flow to Mach number representative of some axial station downstream of vehicle leading edge, after some amount of compression ($M_{\text{nozzle}} < M_{\text{flight}}$)
- *Direct-connect*
 - Facility nozzle is “directly connected” to test article
 - Nozzle expands flow to isolator entrance Mach number
 - In a combustion test, the total enthalpy of the flow matches that of the freestream flight condition. Leads to an “enthalpy Mach number” in addition to the traditional aerodynamic Mach number
 - Inlet distortion is not simulated
- *Fundamental “unit” problem*
 - Some fundamental physical aspect of HAP is investigated, but is not part of an engine system
 - Some requirements of flow simulation are typically relaxed
- When scaling down a ground test article to fit in a facility, chemical timescales do not change, posing a challenge for combustion tests.
- ***A test program often contains multiple types of ground tests***





- Replicating hypersonic flight conditions in a ground test facility is extremely difficult
 - An ideal test facility would match freestream flight values of total pressure (P_0), total enthalpy (H_0), Mach number (M), and species composition for an unlimited duration.
 - ***No such facility exists for hypersonic flow!***
 - Why?....The “power” of hypersonic flow
 - In addition to being compressed, air must be heated to match total enthalpy of hypersonic flow
 - Most common heating methods (combustion air-heaters, electric arc-heaters) introduce *vitiates* into the air flow as a byproduct of the heating process
 - CO_2 , H_2O , NO_x for combustion heated facilities, NO (and copper slag) for arc-heated facilities. Species composition no longer matches freestream air composition!
 - Alternatives do exist:
 - “Clean air” at very high stagnation temperatures be generated by shock tunnels. But at high M it’s difficult for these facilities to match stagnation pressure, dissociation/non-equilibrium can also be issues. Burst diaphragms propagate downstream, can damage model. **Test times are only ms!**
 - Can also be achieved with “pebble bed heaters”. Ceramic bricks are heated, which then heat the test gas. However, the thermal capacity of the ceramics limits test time to a few minutes.

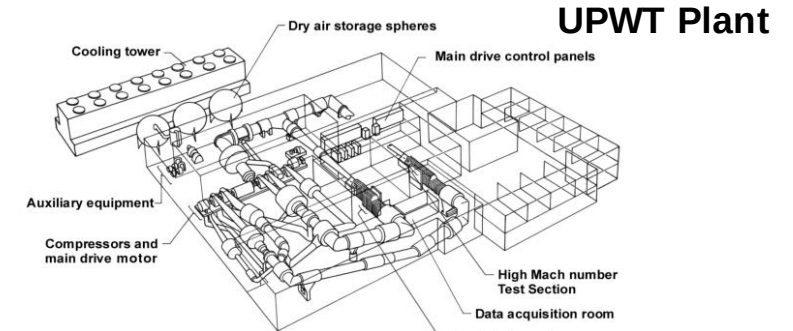
- **Types of wind tunnels used for hypersonic testing**

- *Continuous flow wind tunnels*

- Unlimited test time, can be open or closed loop
- Do not match enthalpy at high Mach numbers
- Used for aerodynamic testing (i.e., external aerodynamics or inlet testing)
- Ex: NASA Langley 4 ft. Supersonic Unitary Plan Wind Tunnel (UPWT)
 - Two legs using sliding block nozzles (TS1: M 1.5-2.9, TS2: M2.3-4.6, $T_0 \approx 150^\circ\text{F}$, 100,000 hp drive)

- *Blowdown wind tunnels*

- High-pressure compressed air is stored in a reservoir, expanded through a nozzle, flow processed through a diffuser and exhausts to atmosphere or a vacuum sphere
- Test time driven by storage capacity of high-pressure reservoir and vacuum sphere
- Test times from 10s of seconds to minutes
- Ex: NASA Langley Aerothermodynamic Lab
 - 3 blowdown to vacuum tunnels (31 in. M10, 20 in. M6, 15 in. M6). Used for hypersonic vehicle/reentry aerodynamic testing.



Mercury 7 (John Glenn, Alan Shepard, etc.) watch test in UPWT

- **Types of wind tunnels used for hypersonic testing**

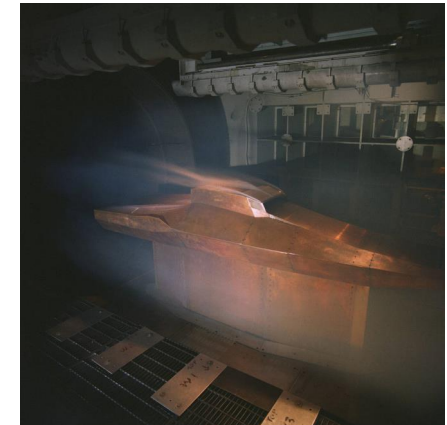
- *Combustion heated wind tunnels*

- High pressure air and fuel are combusted to reach desired total enthalpy, then expanded through facility nozzle.
 - O_2 replenishment makes sure test gas has required O_2 content
- Fuel can be H_2 , CH_4 , isobutane, etc.
 - At M5 ~10% of test gas is vitiate, usually used below M8
- Are blowdown tunnels, test time from 10s to several minutes
- Most large HAP wind tunnels are combustion heated
- Ex. NASA Langley 8' HTT
 - Nation's largest HAP test facility, M3, M4, M5, M6.5 nozzles

- *Arc-heated wind tunnels*

- Similar concept to combustion heated windtunnels, except electric arc is used to heat the test gas.
 - Still results in vitiates (NO , copper slag)
- Most commonly used for material testing, can also be used for propulsion testing (becoming more common)

8' HTT

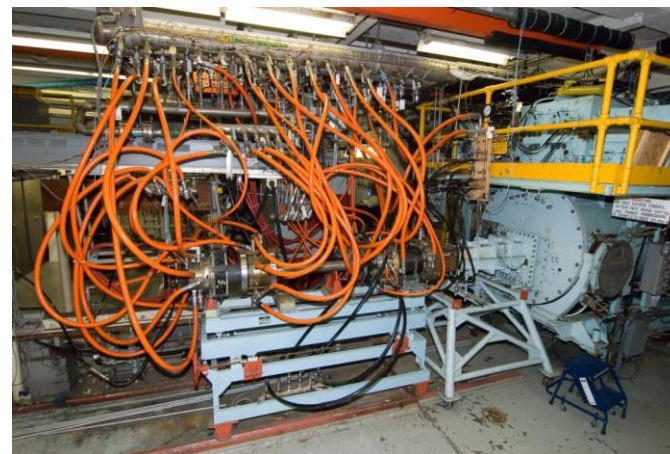


- **NASA Langley's Scramjet Test Complex**
- Two facilities:
 - *Direct-Connect Supersonic Combustion Test Facility (DCSCTF)*
 - Simulates isolator entrance flow at flight Mach enthalpies ranging from 2-7.5
 - Mostly used for combustor testing (heavy weight water cooled, copper heat sink, or flight weight fuel-cooled), but has also been used for materials testing
 - H₂-air combustion heater 8% H₂O at M4, 35% at M7.5
 - Up to 15-minute run duration
 - *Arc-Heated Scramjet Test Facility (AHSTF)*
 - Can accommodate semi-freejet, or direct-connect tests.
 - Used for subscale component and component integration tests
 - 20MW DC power supply
 - 200s run time
 - Simulated flight Mach enthalpy 4.7-8+
 - Max 675 psia total pressure
 - NO vitiate ~1% at M5, 3% at M8

DCSCTF



AHSTF



Part II: The Enhanced Injection and Mixing Project (EIMP)

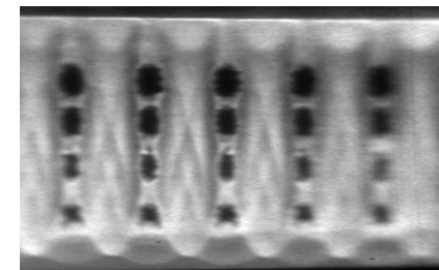
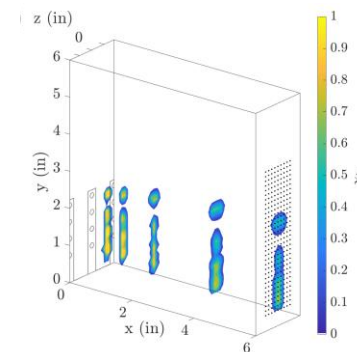
Motivation:

- Extending scramjet operation to higher Mach (8+) offers potential of lower cost/more efficient access to space by increasing the staging Mach number of TSTO systems.
- At M8+, fuel/air mixing is the rate-limiting step of the combustion process.
- Primary challenge is reducing combustor weight/thermal loads (i.e., shorten the combustor)
 - *Rapid fuel air mixing, without excessive drag, is key enabler*



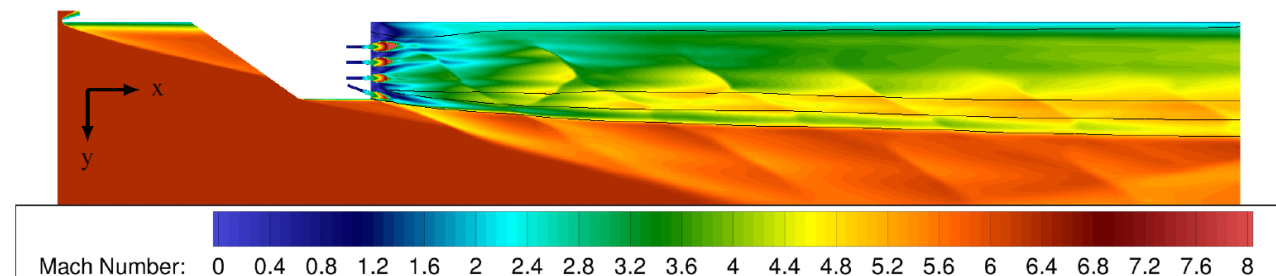
EIMP Objectives:

- Increase knowledge and understanding of the fundamental physics governing fuel-air mixing.
- Develop strategies for improving injector performance.
- Develop the functional relationships between mixing efficiency, losses and flowpath geometry.

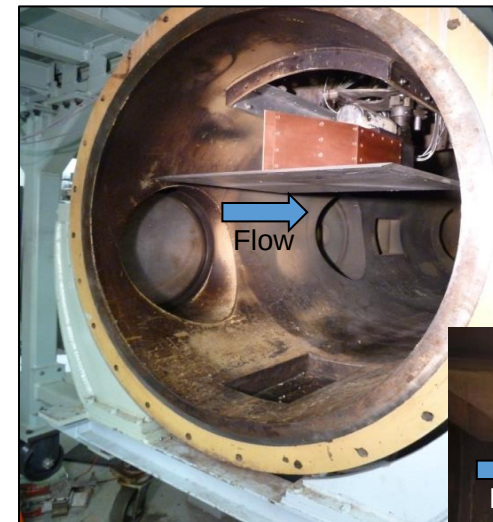
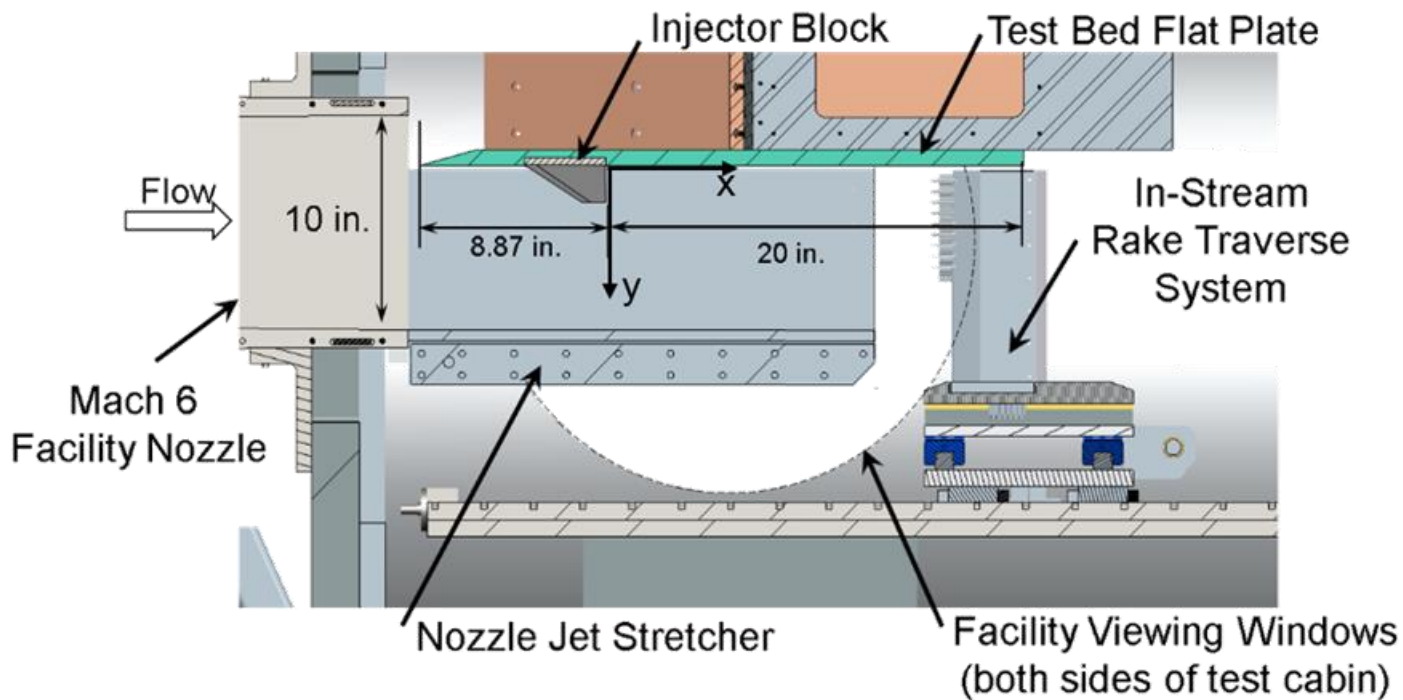


Approach:

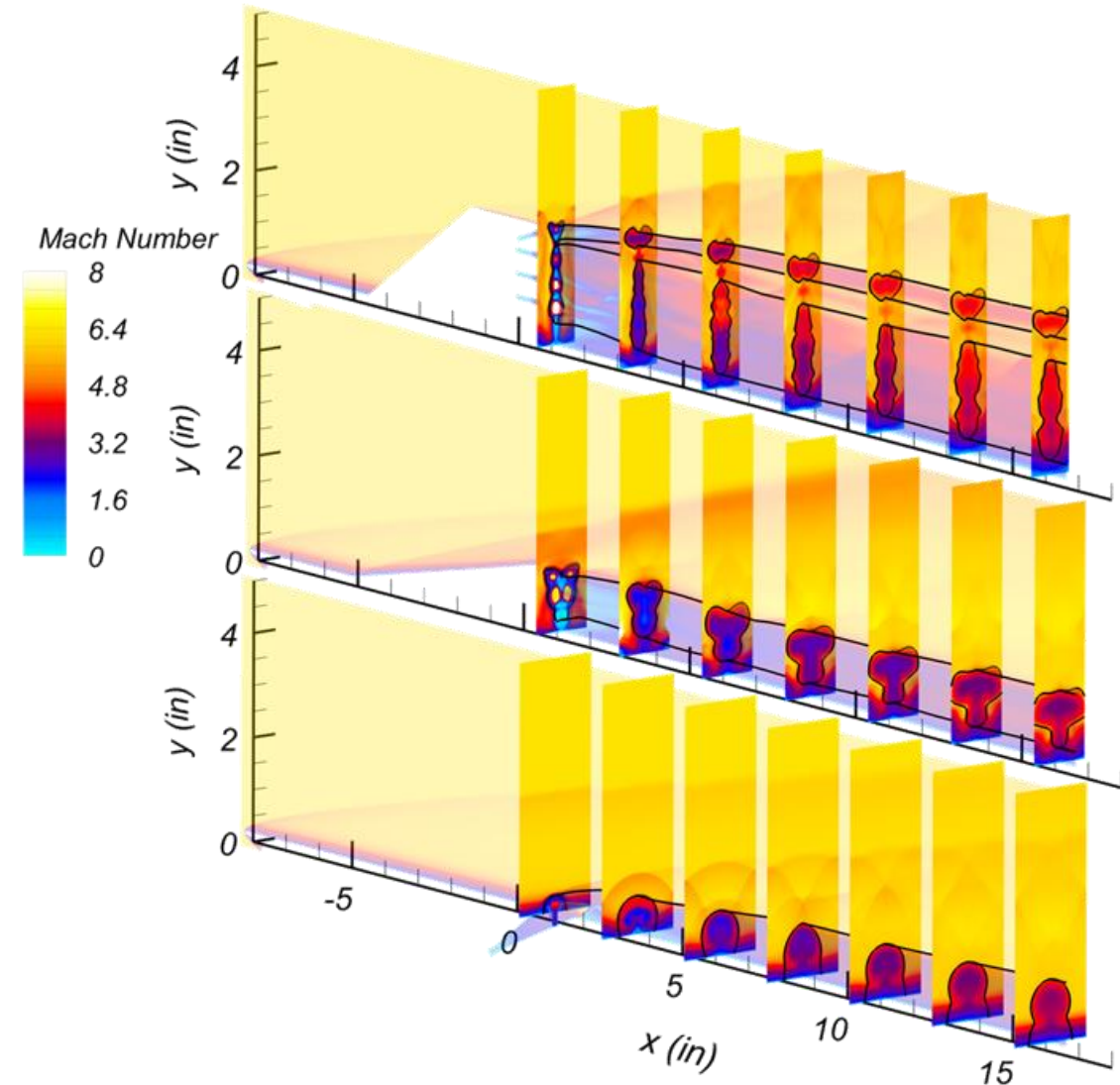
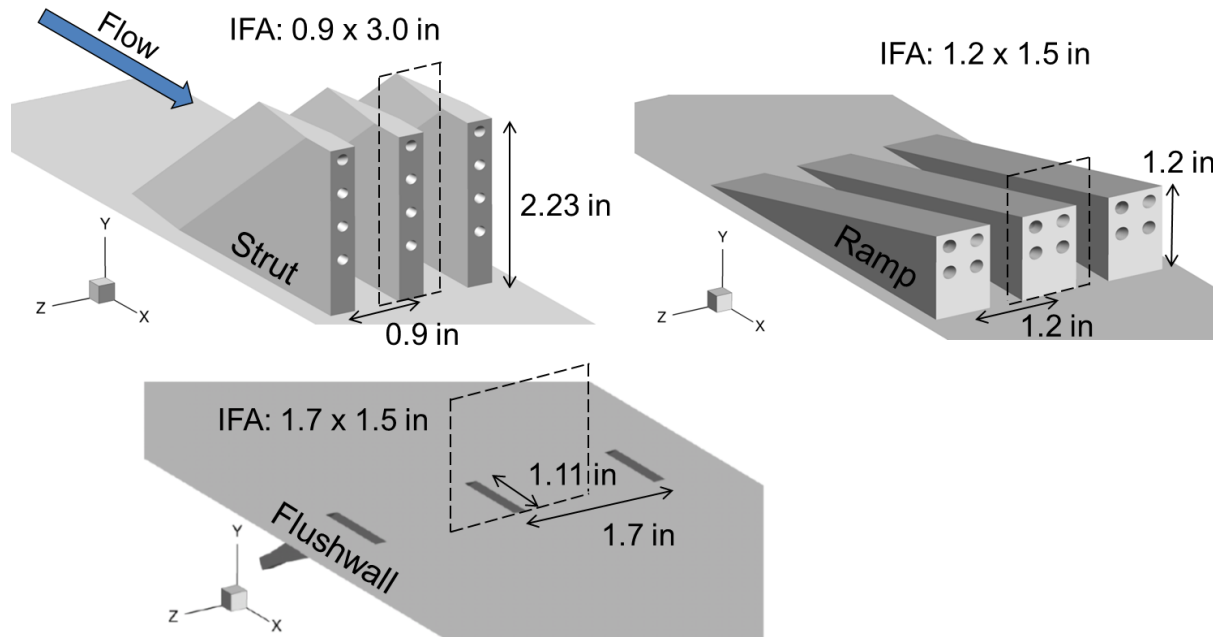
- Utilize Mach 6 mixing experiments of various injector configurations to anchor CFD simulations using VULCAN.



- EIMP experiments are conducted in the Arc-Heated Scramjet Test Facility (AHSTF) at NASA Langley
- Mach 6 Flow, T_0 : 1310-1760 °R, “Open” plate, Helium fuel, modular injector block (simulates Mach 15, 1500 psf combustor entrance conditions at reduced T_0)
- In-stream rakes are used for gas-sampling, pitot pressure, and total temperature measurements
- Nonintrusive measurements include schlieren and nitric oxide planar laser induced fluorescence (NO PLIF)

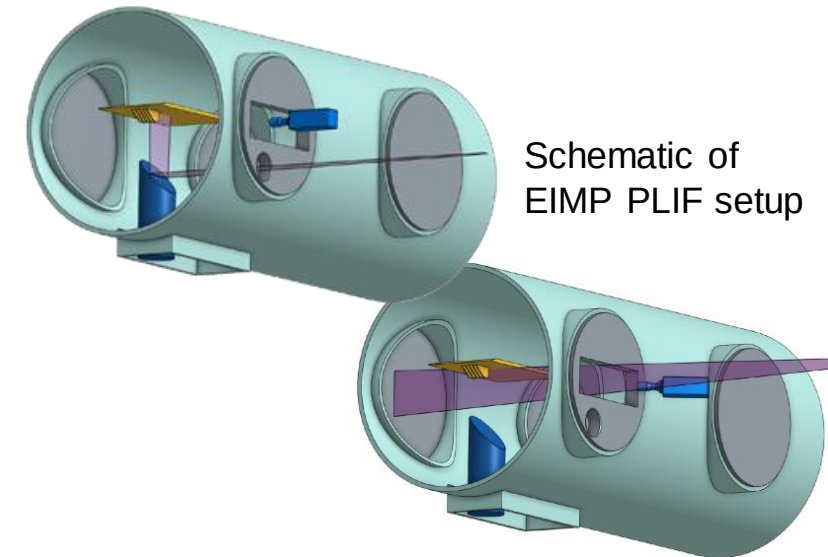


- Three different types of fuel injectors have been chosen as baselines for the EIMP study, representing the 3 basic classes of injectors commonly considered for high-speed propulsive flow paths.
 - Strut – fuel placement device
 - Ramp – vortical stirrer
 - Flushwall – interaction between jet and freestream creates multiple vortices that aid mixing



- NO PLIF is a nonintrusive laser diagnostic technique where a UV laser beam ($\lambda \approx 225.7\text{-}227\text{ nm}$) is formed into a sheet to excite fluorescence from the NO molecule, which is then imaged.
- NO PLIF can be used for qualitative flow imaging, but can also be used to measure temperature, velocity, or injectant mole fraction in controlled environments (with a “few” assumptions...)
- In EIMP:
 - Nitric oxide (NO) is produced in the AHSTF as a byproduct of the electric arc-heating process ($X_{\text{NO}} \approx 0.01 - 0.03$).
 - We take advantage of the NO vitiate and use it for NO planar laser induced fluorescence (NO PLIF).
 - Fluorescence is imaged with an intensified CCD camera at 10 Hz.
 - Since NO is present only in the facility air and not the fuel simulant, the absence of signal indicates pure helium.
 - Laser sheet and optics could be arranged to image either streamwise or cross-stream planes.
 - Gas cell is used for LIF signal verification.

Photo of EIMP PLIF setup





- In the weak excitation limit, the NO PLIF process can be described with a two-level fluorescence model.
 - In the most simple terms: NO molecule absorbs photon, moves from ground-state to excited-state. Can then emit a photon (at a red-shifted λ), upon relaxation to ground-state.
- Using the two-level model, a mathematical relation for the LIF signal can be derived:

$$S = C_{opt} E_p \frac{X_{NO} P}{k_B T} \phi(P, T, X_\alpha) \sum_i (f_B(T, J) B_{12}(J) g(\nu_0, \nu_l, \delta \nu_l, P, T, X_\alpha, u_{||}))_i$$

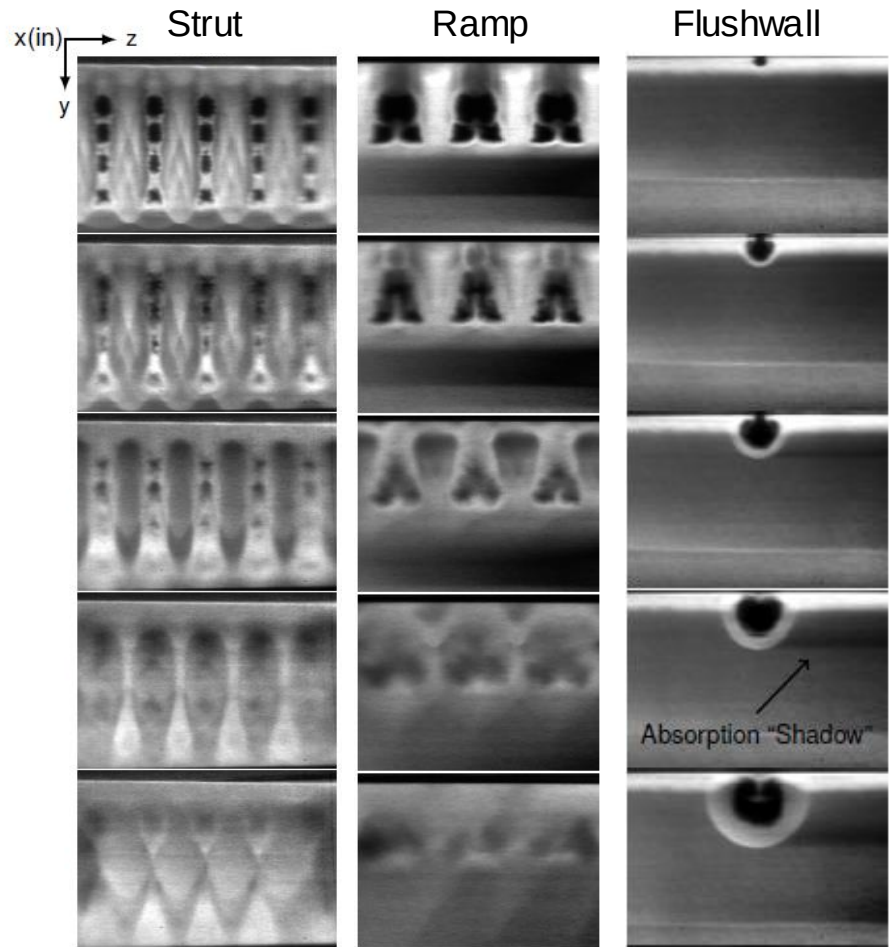
Where,

$$\text{Fluorescence Quantum Yield: } \phi = \frac{A}{A + Q(P, T, X_\alpha)} \quad \text{Collisional Quenching Rate: } Q = \sqrt{\frac{8k_B T}{\pi m_{NO}}} \frac{P}{k_B T} \sum_\alpha^{N_s} \left(X_\alpha \sqrt{1 + \frac{m_{NO}}{m_\alpha} \sigma_\alpha(T)} \right)$$

$$\text{Boltzmann Fraction: } f_B = \frac{hc}{k_B T} B_v (2J + 1) \exp \left(-B_v J(J + 1) \frac{hc}{k_B T} \right)$$

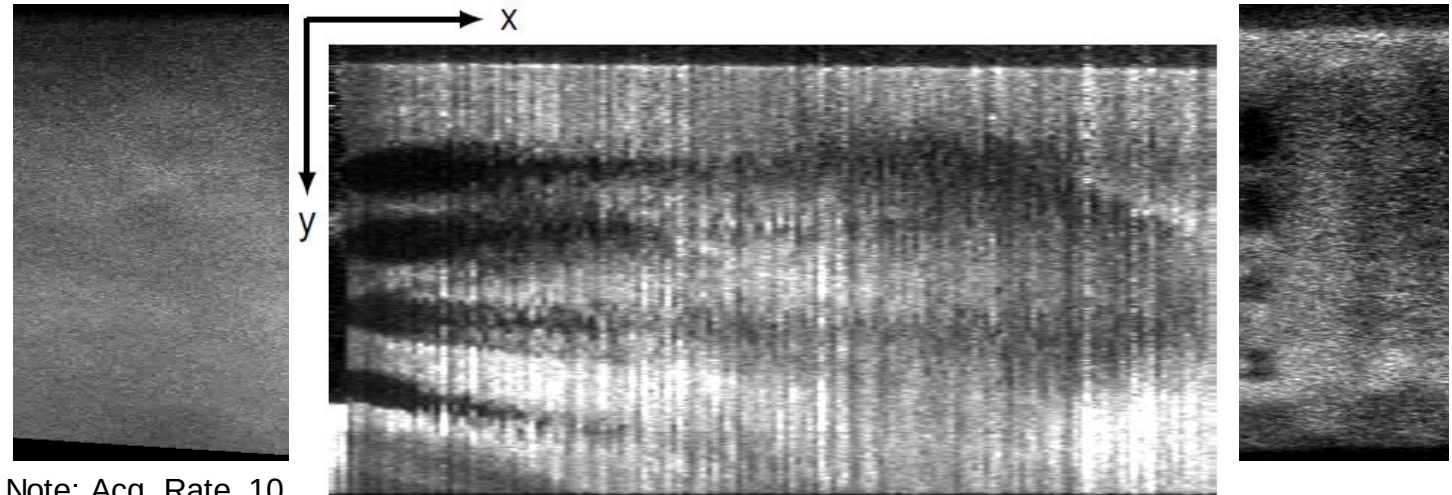
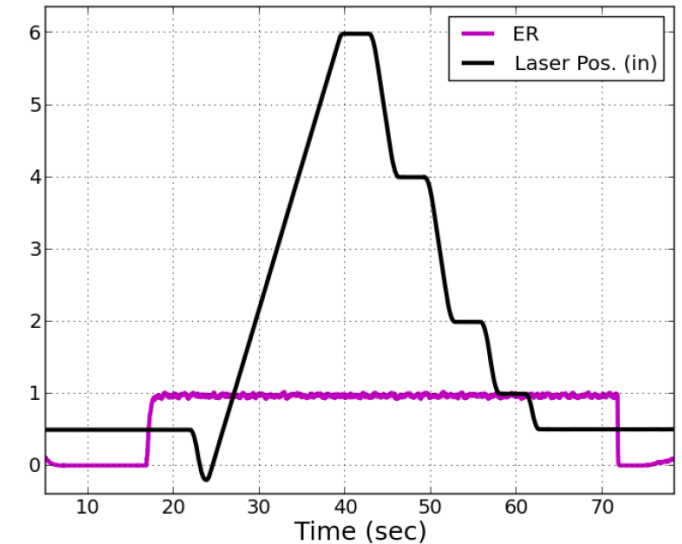
$$\text{Spectral Overlap Integral: } g = \int_{-\infty}^{\infty} g_l(\nu'; \nu_l, \Delta \nu_l) d\nu' \int_{-\infty}^{\infty} g_d(\nu'' - \nu'; \nu_0, T, u_{||}) g_c(\nu''; \nu_0, P, T, X_i) d\nu''$$

- Post-processed, time-averaged streamwise NO PLIF cross-sections of baseline injectors



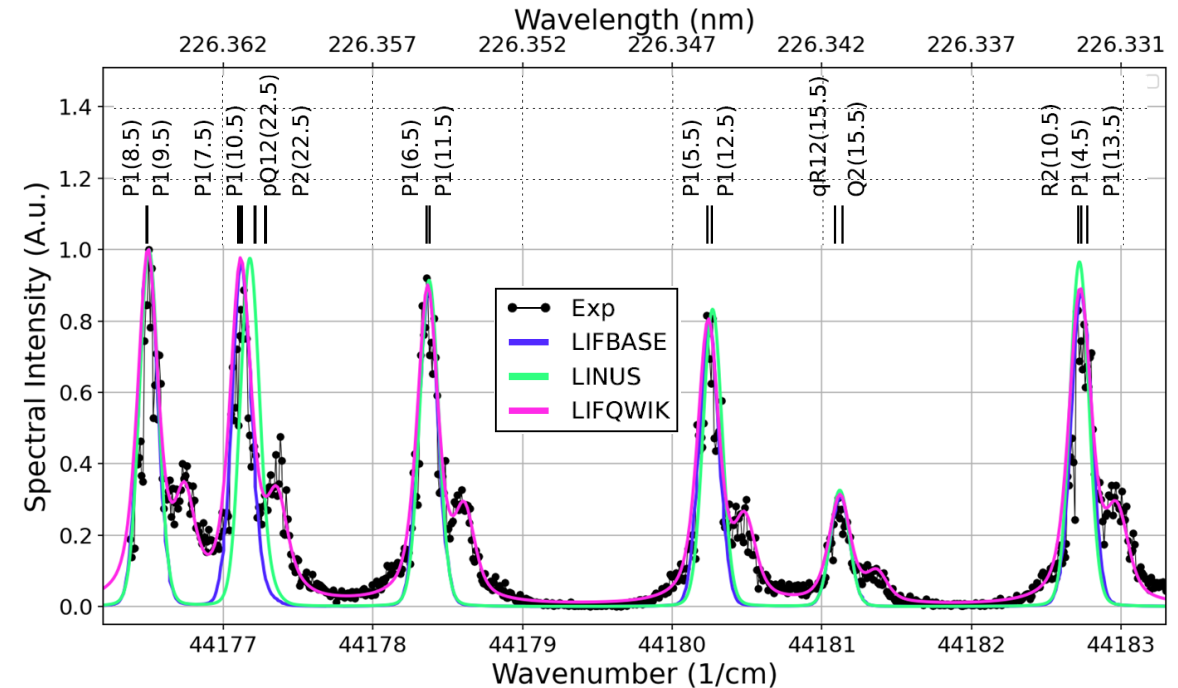
Note: x-stations for flushwall injector do not match those of the strut and ramp

- Light-sheet optics were on a translation stage, allowing for multiple downstream stations to be imaged in a single run.
- For the strut injector, instantaneous PLIF images highlight “lobular” fuel/air boundary.
- Slow translation from upstream to downstream allows for “reslicing” of flowfield, thus streamwise and spanwise structure revealed in a single run

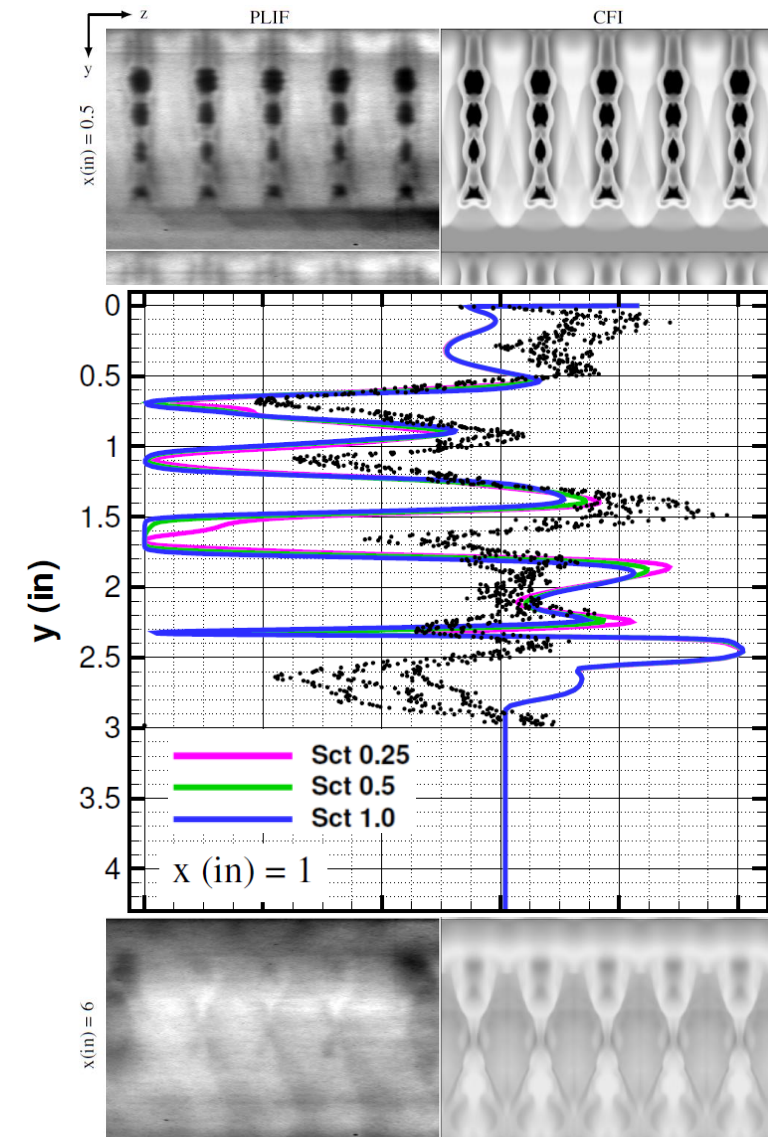


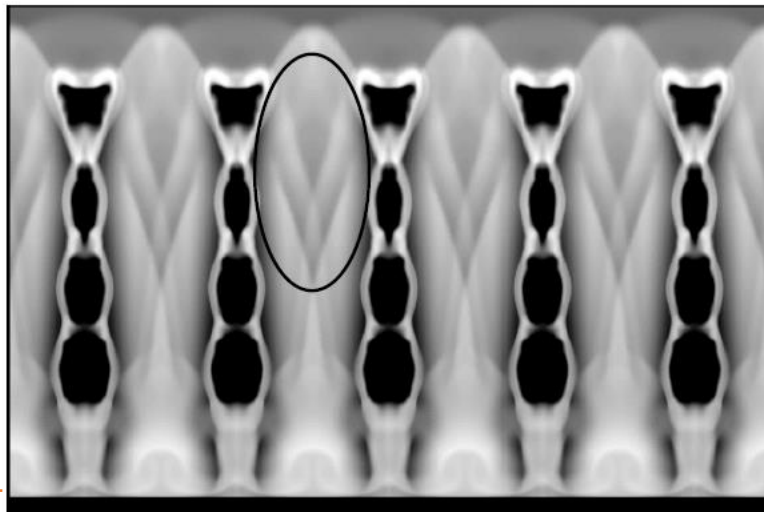
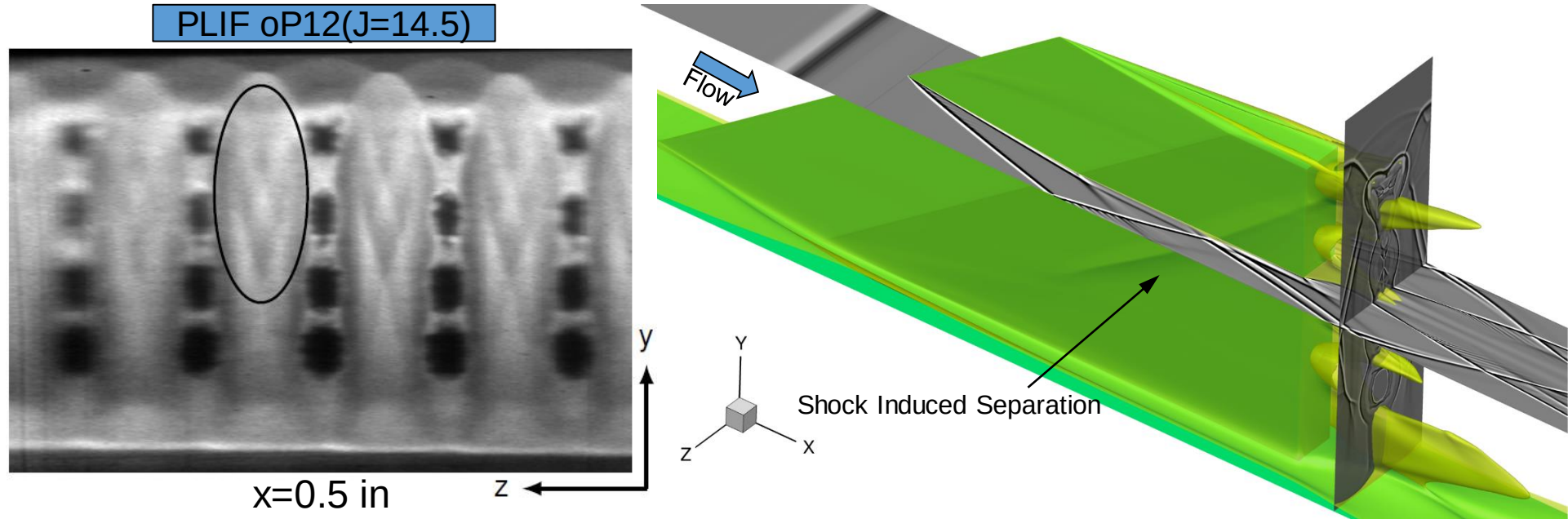
Note: Acq. Rate, 10

- In the absence of being able to directly measure a flow property with NO PLIF, how can we compare the NO PLIF results to our CFD simulations?
 - Answer: Computational Flow Imaging (CFI).
 - CFD has all the information necessary to compute a LIF signal, thus we can generate “NO PLIF images” from CFD solution
- First, a “new” NO PLIF model, LIFQWIK was created.
 - Based on previous NO PLIF models, but modifications were made to make it computationally efficient (primarily a numerical approximation of the Voigt profile)
- Model performs well compared to “physics-complete” models LIFBASE and LINUS, at a fraction of the computational cost

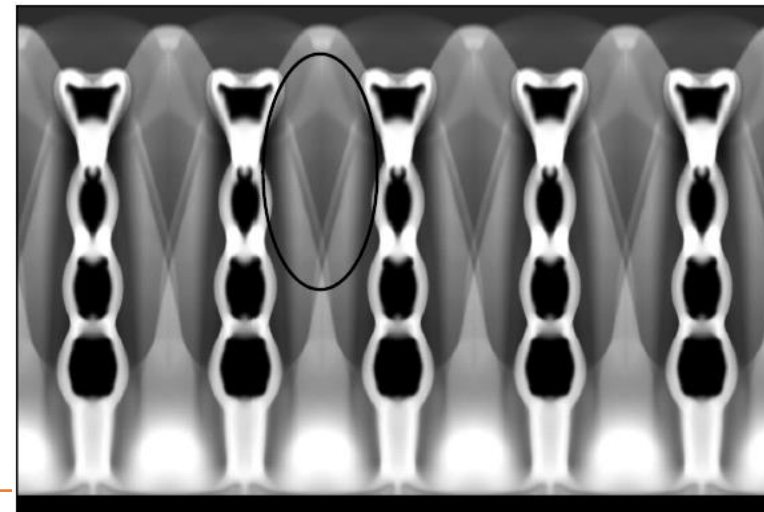


- The differences observed between the PLIF and CFI are due to:
 - flow unsteadiness (including facility air NO fluctuations),
 - as built geometric differences between adjacent injectors,
 - facility air flow distortion,
 - facility vibration,
 - quality of the experimental optics,
 - optical system resolution (CCD pixel size vs. lp/mm),
 - laser light absorption,
 - laser detuning (Doppler shift),
 - experimental image postprocessing,
 - and errors from turbulence modeling in the CFD.
- It is difficult to isolate the dominant source of the discrepancies, however, qualitative level of agreement is reasonable
 - Quantitative comparisons for CFD model verification remain elusive





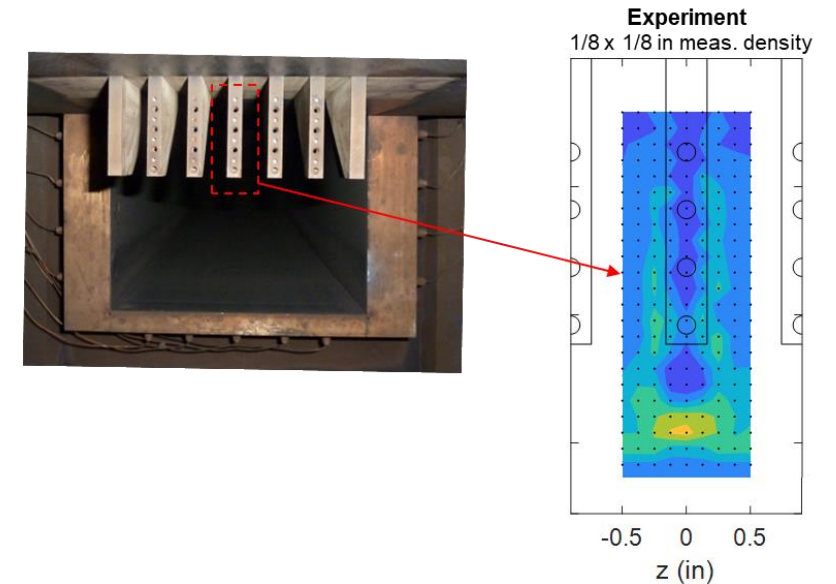
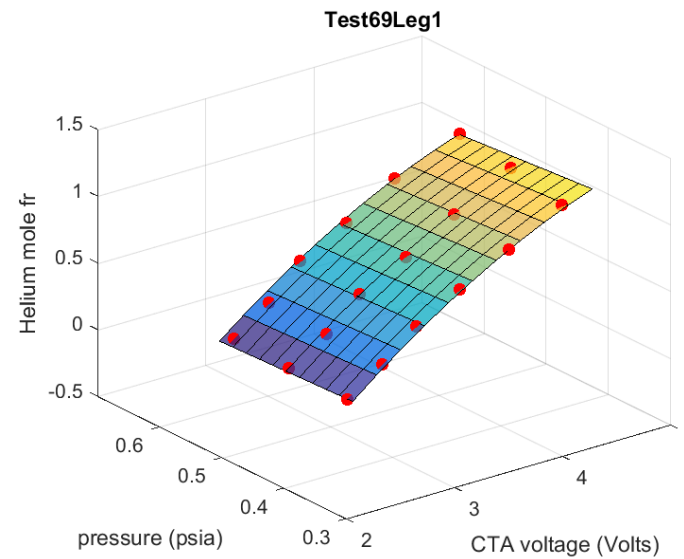
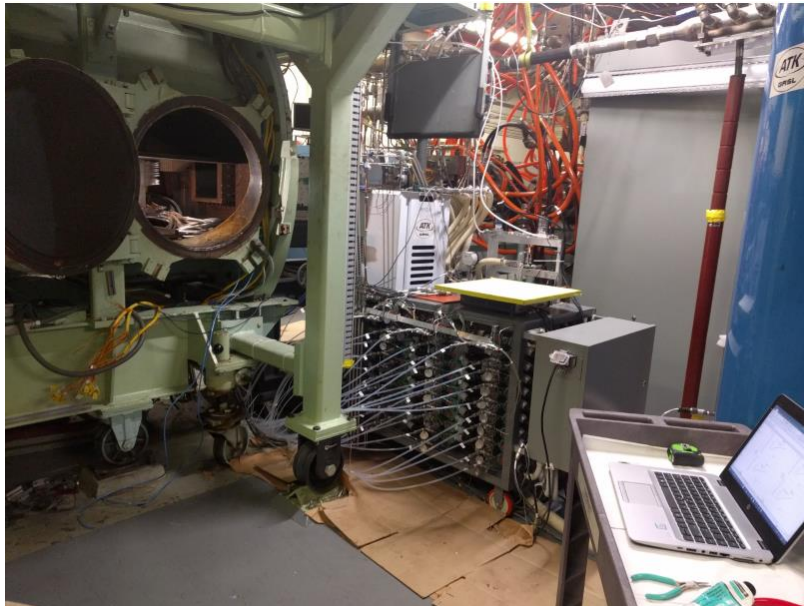
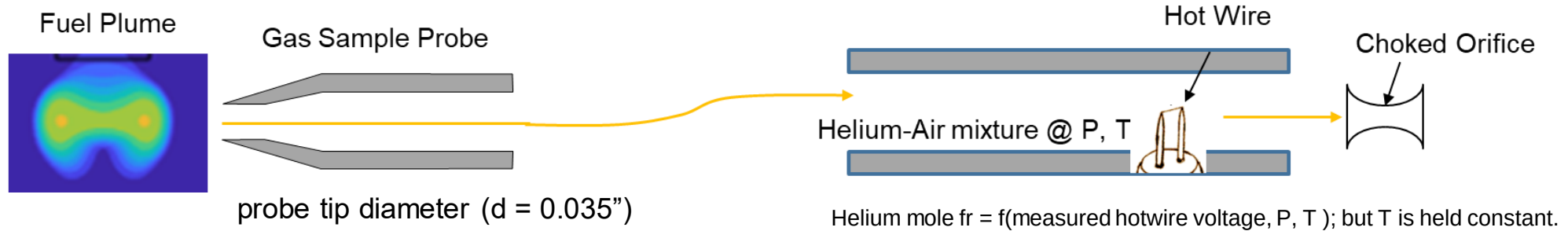
Laminar Simulation



Turbulent Simulation

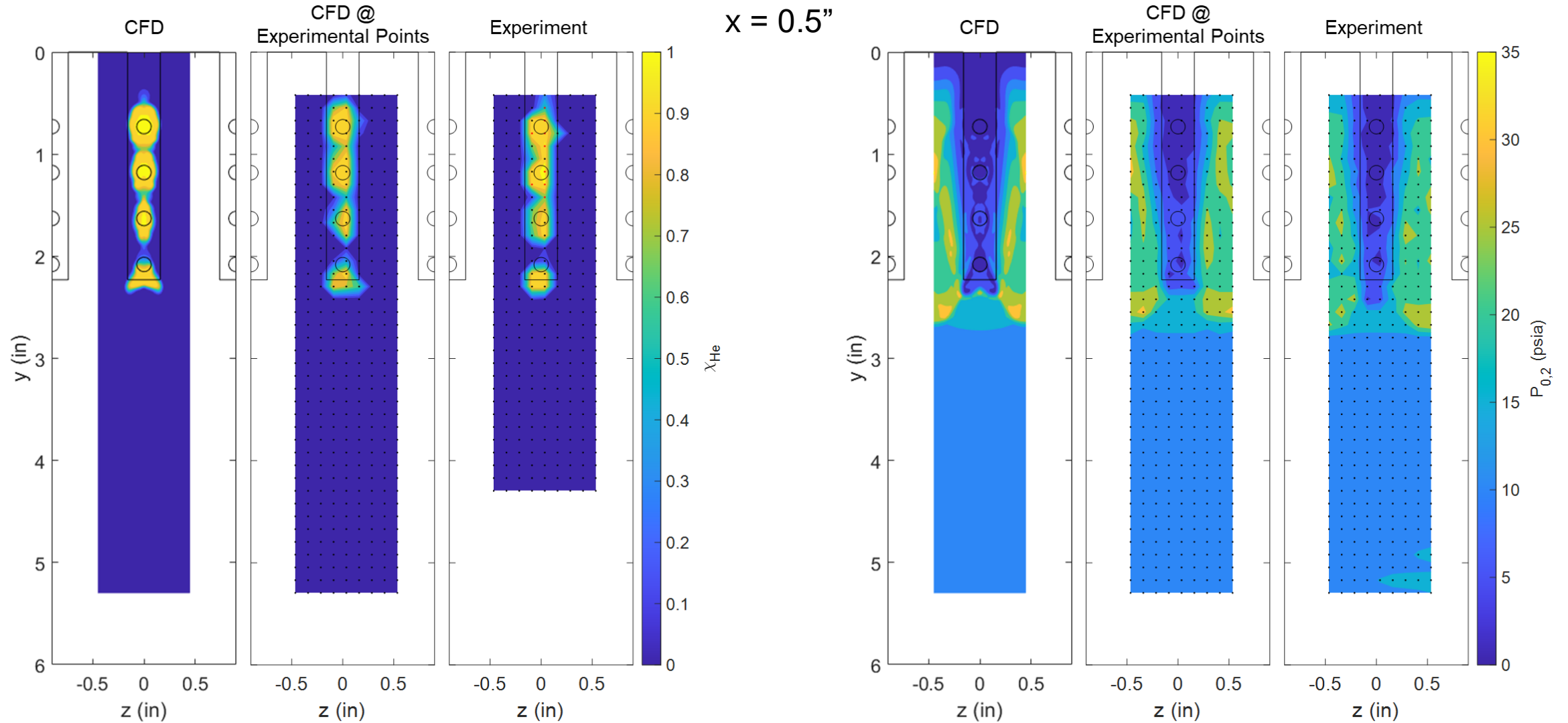
CFI helped identify laminar/transitional BL on strut.

- For quantitative comparison between CFD and experiments, a gas sampling system was used.



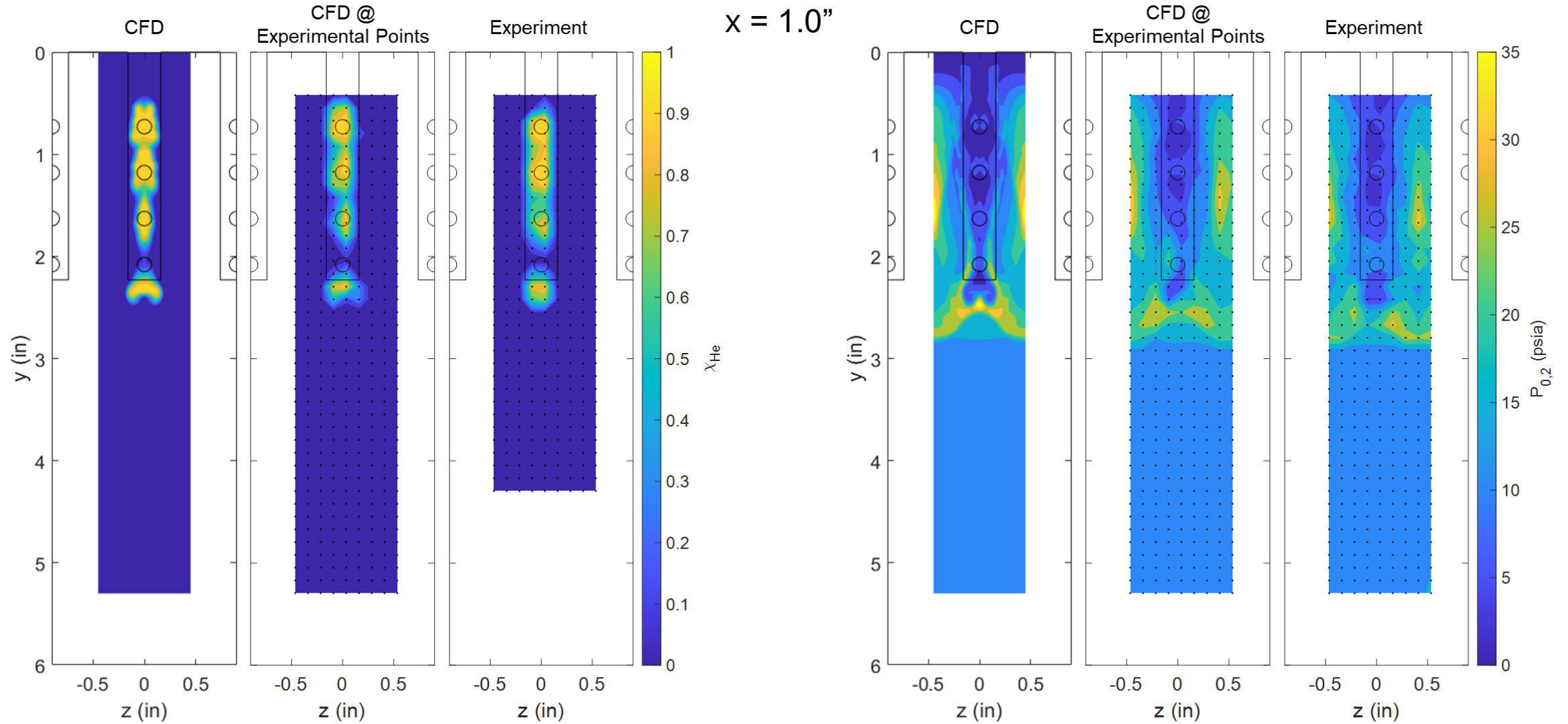


Gas Sampling and Analysis System (GSAS): Results



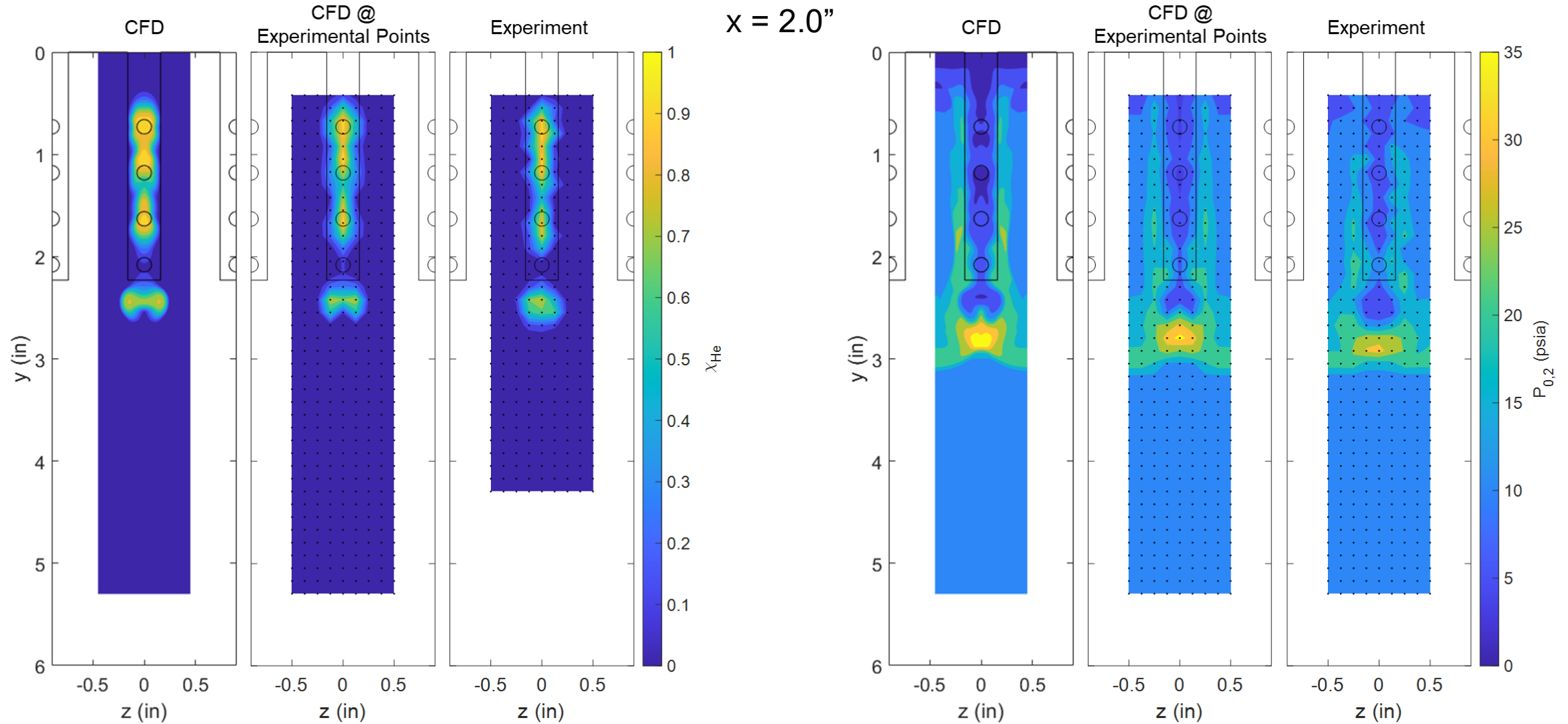


Gas Sampling and Analysis System (GSAS): Results



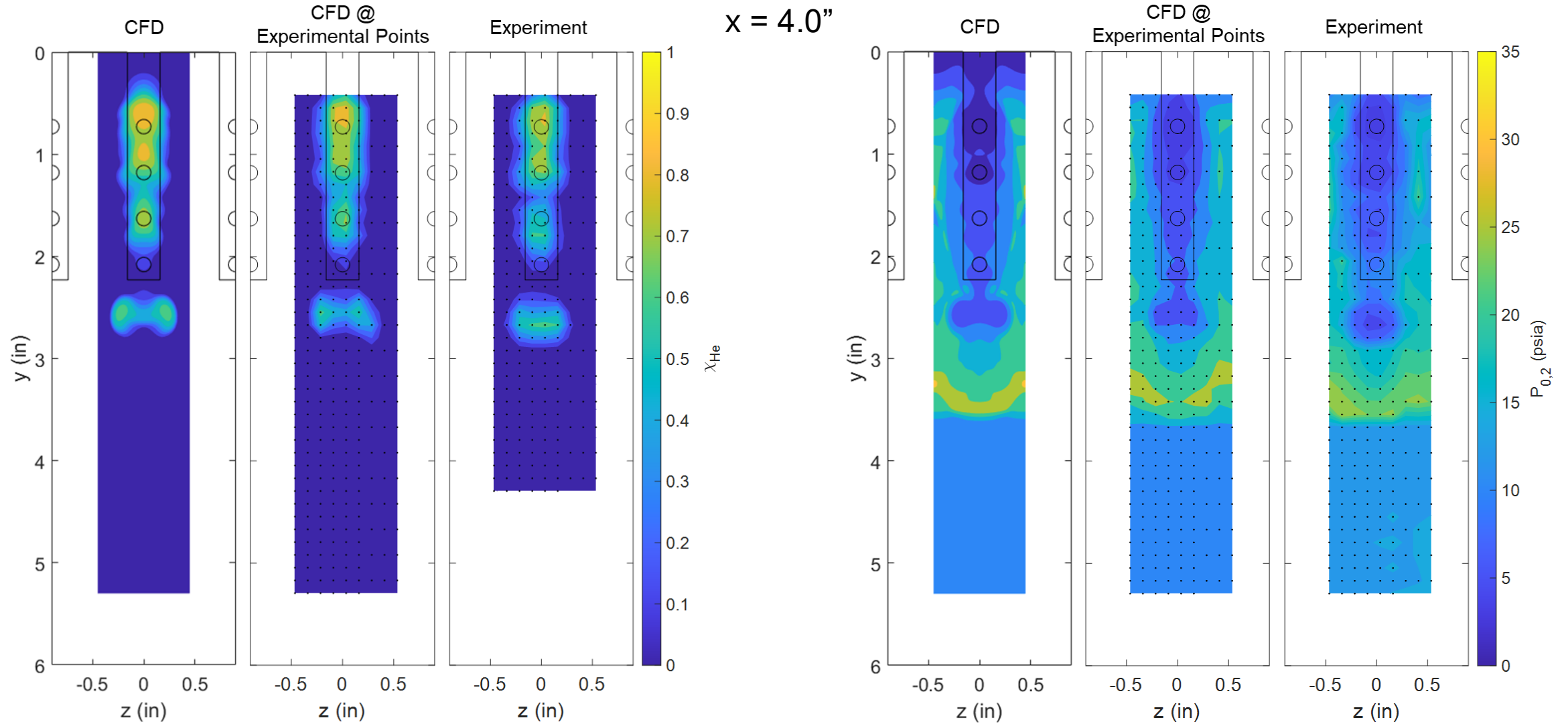


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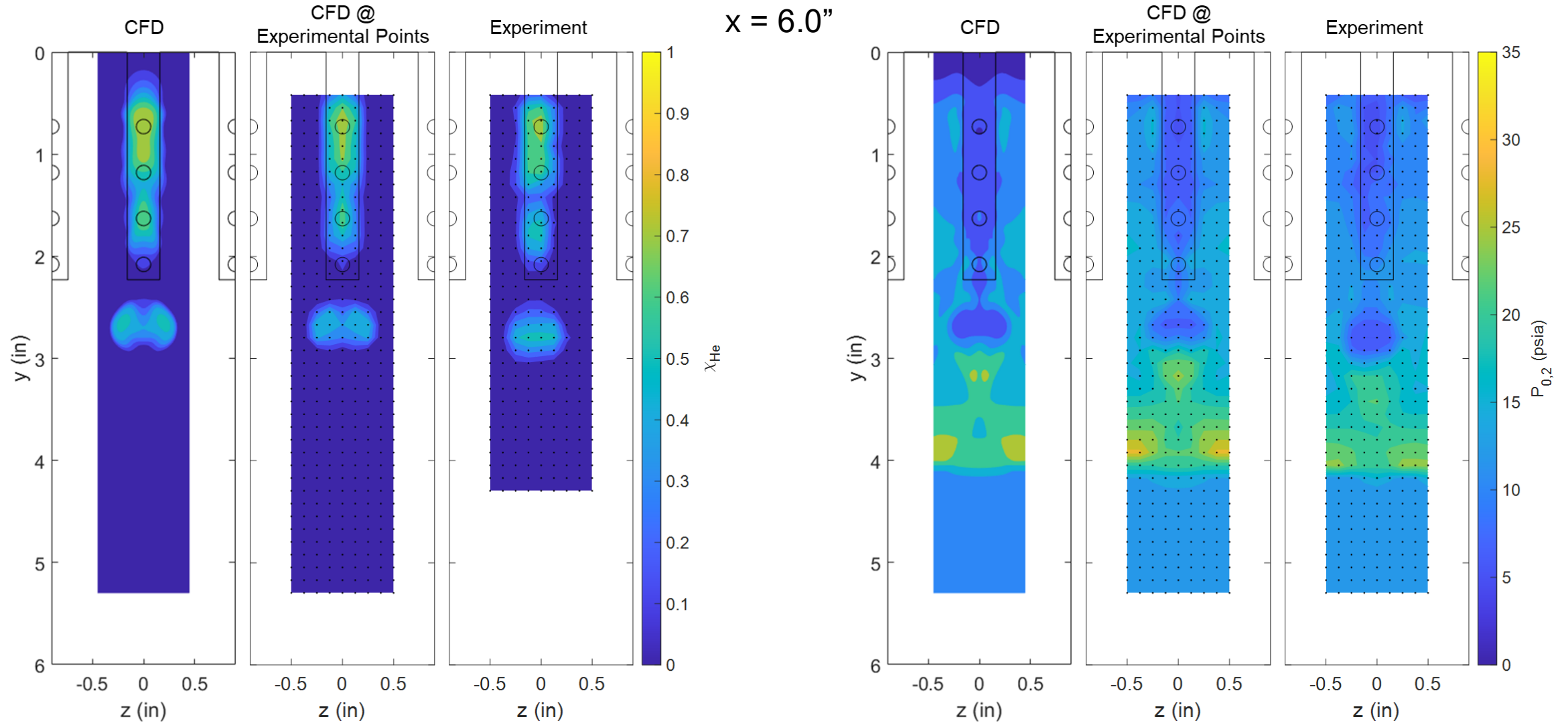


Gas Sampling and Analysis System (GSAS): Results





Gas Sampling and Analysis System (GSAS): Results

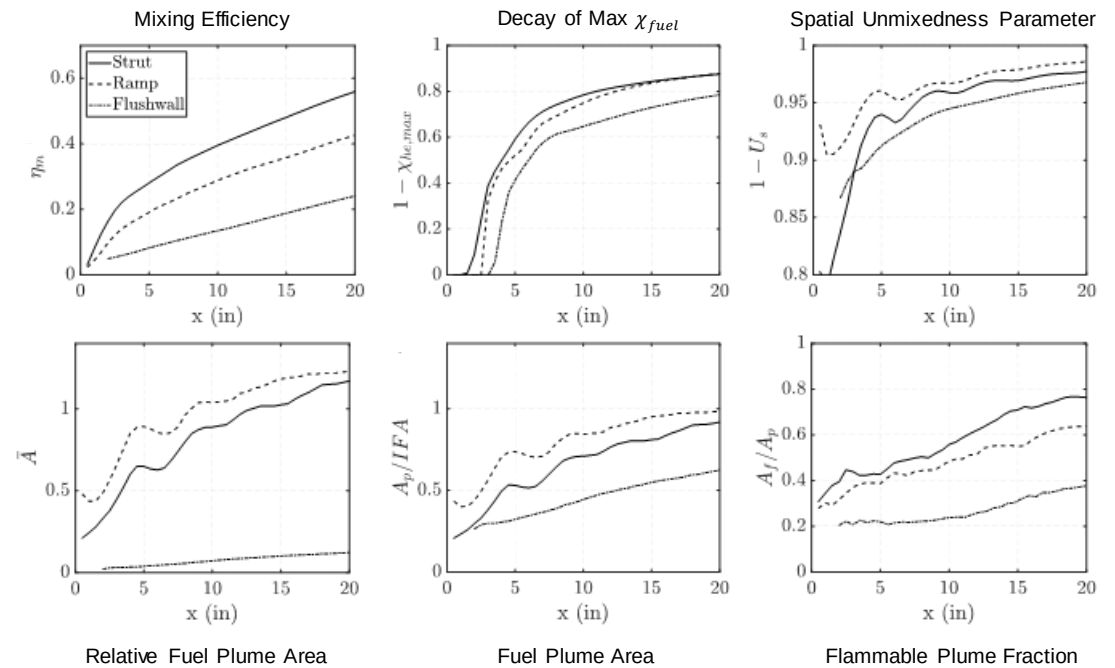


- To compare the mixing performance of different injector configurations, a global 1D metric is needed
- The metric best suited to compare mixing performance of different injector configurations is the mixing efficiency parameter, η_m
 - Mass flux distribution must be known, in addition to fuel distribution
 - Experimental determination requires the measurement of 3 independent aerothermodynamic variables in addition to fuel mole fraction**
- For simplicity, experiments commonly use metrics based on fuel distribution only as indicators of mixing performance with the implicit assumption that they correlate with η_m
 - Not always true!*

$$\eta_m = \frac{\dot{m}_{\alpha, mixed}}{\dot{m}_{\alpha, total}} = \frac{\int \alpha_R \rho u dA}{\int \alpha \rho u dA}$$

Mass flux
(difficult to measure)

Traditionally used fuel-distribution based alternatives do not correctly rank injector performance!





1D Mixing Metric: New Metrics

- We sought to find new mixing metrics to replace η_m
 - Criteria:**
 - Easier to determine than η_m (fewer measurements)
 - Better representation of mass flux-weighted mixing performance than traditionally used alternatives
- Two new metrics were found, both rely on substitutions for mass flux in mixing efficiency equation**
- We will use $\eta_m^{P_{0,2}}$ for CFD comparison because we already measure pitot pressure.
- However, there is great value to η_m^R , since it only requires the measurement of mixture composition
- Metrics also verified on data from older mixing experiment conducted at LaRC.
 - Direct experimental comparison between η_m and $\eta_m^{P_{0,2}}$ and η_m^R

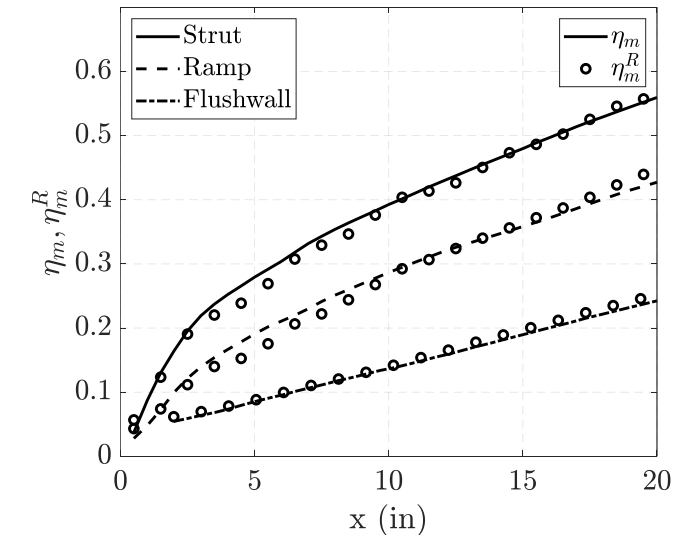
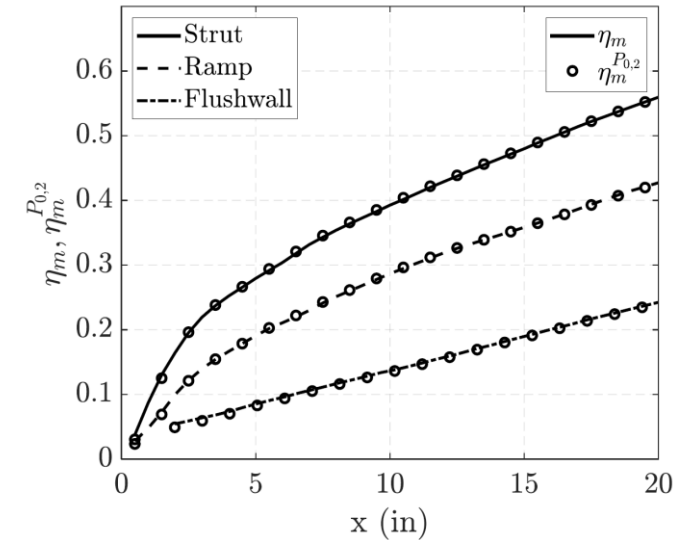
$$\eta_m = \frac{\dot{m}_{\alpha, \text{mixed}}}{\dot{m}_{\alpha, \text{total}}} = \frac{\int \alpha_R \rho u dA}{\int \alpha \rho u dA}$$

$$\rho u = \frac{P_{0,2}}{\sqrt{RT_0}} \left[\sqrt{\gamma} M_2 \left(1 + \frac{\gamma-1}{2} M_2^2 \right)^{\frac{-(\gamma+1)}{2(\gamma-1)}} \right]$$

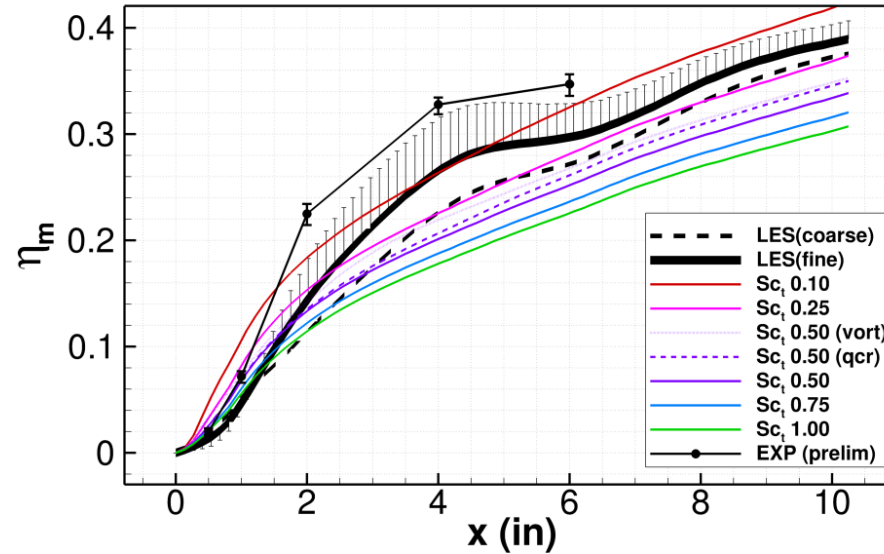
$$\rho u \propto \frac{P_{0,2}}{\sqrt{RT_0}}$$

$$\eta_m^{P_{0,2}} = \frac{\int \alpha_R P_{0,2} dA}{\int \alpha P_{0,2} dA}$$

$$\eta_m^R = \frac{\int \alpha_R \frac{1}{\sqrt{R}} dA}{\int \alpha \frac{1}{\sqrt{R}} dA}$$

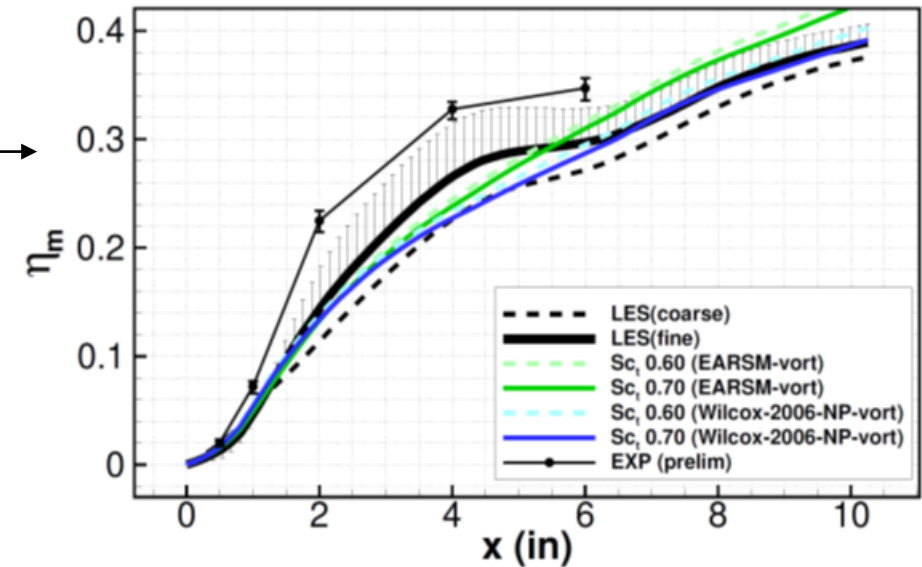


- Experimental measurements show faster mixing than all Reynolds-averaged simulations (RAS).
- Two different grid resolution large eddy simulations (LES) were also run.
 - LES better predicts shape of mixing curve.
 - “Unconventional” use of grid convergence index shows potential of finer resolution LES to approach experimental measurements
- LES appears to predict the region of suppressed mixing observed in the experiments.



← Sensitivity of Menter-BSL to turbulent Schmidt number

EARSM and Wilcox models →





Summary and Conclusions



- Renewed interest in hypersonic airbreathing propulsion in both the defense and civilian sectors has led to increased investment and the desire to rapidly mature these systems
 - NASA Langley is leveraging its historic legacy in this field to further advance the state-of-the-art
- Ground testing is crucial for the development of dual-mode ramjets and scramjets
 - Though computational tools are constantly evolving, ground testing is still needed to validate underlying models and overall vehicle performance
 - However, there is no “perfect” hypersonic wind tunnel due to the impossibility of identically matching hypersonic flight conditions on the ground
- Tightly coupled computational and experimental research approach is required in the development of hypersonic airbreathing propulsion systems
- If you’re interested in hypersonics (and the multiple exciting problems left to solve), there will be no shortage of work in the next 5-10 years



Acknowledgements



This work is supported by the Hypersonic Technology Project (HTP) in the Advanced Air Vehicles Program of the NASA Aeronautics Research Mission Directorate (ARMD).

Computational resources are provided by the NASA Langley Research Center and the NASA Advanced Supercomputing (NAS) Division.

Thanks to:

- **EIMP PIs:** Tom Drozda (CFD), Karen Cabell (Experiment)
- **CFD Team:** Robert Baurle, Rajiv Shenoy, Jake Lampenfield, Brad Passe
- **AHSTF Team:** Neal Hass, Austin Ziltz, Scramjet Test Complex Technicians
- **Advanced Diagnostics Team:** Paul Danehy, Jennifer Inman, Ross Burns, Brett Bathel, Steve Jones
- **Intern Support:** Rohan Deshmukh, Walker Knapp



Questions?



- **NASA Internships** www.nasa.gov/learning-resources/internship-programs/
 - For high school, undergraduate, and graduate school students
 - Various sessions over the course of the year (summer, fall, spring)
 - Stipend based on academic level and session length
 - Program tries to match student's and researcher's interests
- **NASA Fellowships** www.nasa.gov/stem/fellowships-scholarships/index.html
 - Support graduate-level projects and proposals which contribute to a NASA research topic
 - Applications accepted once a year
 - Fully funds tuition, stipend, health insurance, etc.
- **NASA Pathways Internship** www.nasa.gov/careers/pathways/
 - For current students and recent graduates
 - Co-op program with easy path to convert to full time civil servant position
 - Exposure to NASA research during time at sponsoring org
 - Vacancies are posted on www.USAJobs.gov



Backup

