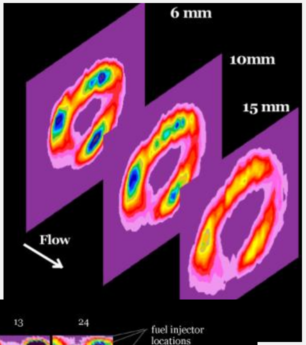
Applying Optical Diagnostics to Study Aircraft Gas Turbine Combustor Performance

Yolanda R Hicks
NASA Glenn Research Center
Senior Research Engineer
Combustion Branch

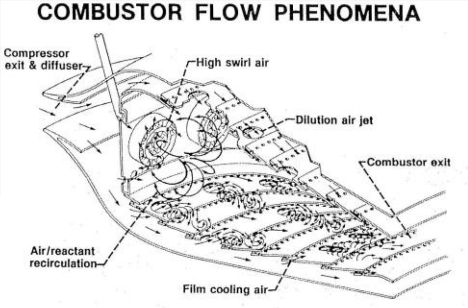
Diagnostics Objectives: Support efforts to produce next generation low emission combustor technology

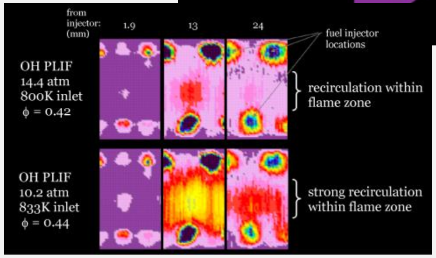
Use and develop tools to facilitate understanding of the fuel vaporization, turbulent mixing and combustion processes within aircraft combustors

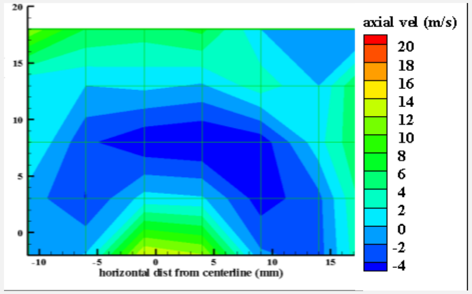


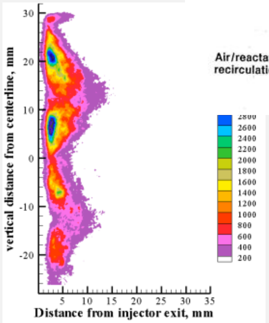
Describe overall performance:

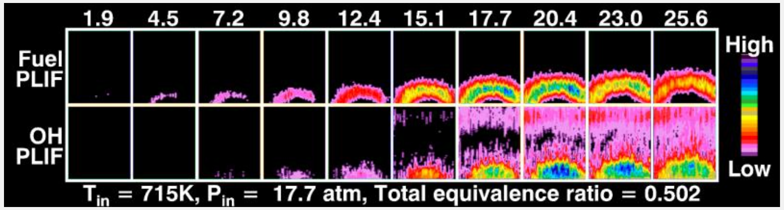
- *Characterize fuel injection-fuel/air mixing*
- *Characterize combustion*
- *Provide data to validate models*

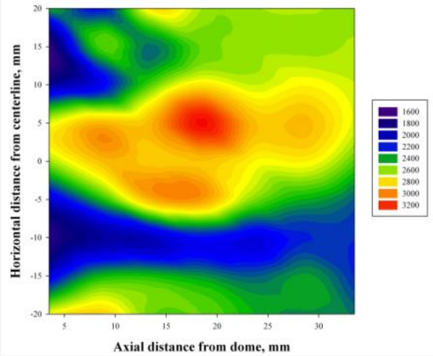








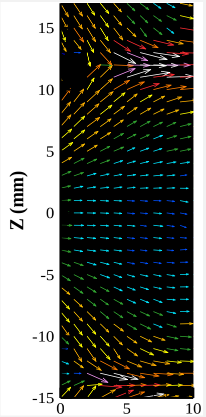




Example systems

- *Complex Swirl Mixers*
- *NASA Lean Direct Injector (**LDI**)*

low emissions technology research injector



Motivation and Goals

NASA has historically led the effort to reduce the environmental effects of aviation. In terms of aircraft gas turbine engines

- Reduce NO_x emissions from future aircraft engines
- NO_x emissions increase smog and ozone in the lower troposphere and decrease the protective ozone layer in the stratosphere.

NASA has sustained programs to develop technology that addresses the increasingly challenging regulations on NOx emissions. NASA Programs include Ultra Efficient Engine Technology, Environmentally Responsible Aviation, Fundamental Aeronautics, and currently Advanced Air Transportation Technology (AATT) and Commercial Supersonic Technology (CST).

- Most recently, we have added soot and particulate matter to the list of concerning species

Motivation and Goals

Throughout these programs, the combustion group at NASA Glenn has tested its own concepts for low emissions combustors **and** worked in collaboration with the engine companies, General Electric, Pratt & Whitney, and Rolls-Royce, among others, to test candidate low-emission concept fuel injection schemes.

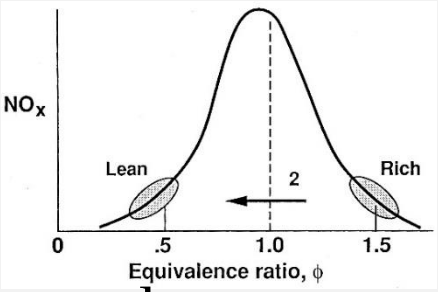
Many of these injectors were also tested using optical diagnostics for in situ measurements of

- *Fuel patternation and OH distribution*
- *Fuel droplet statistics—size and velocity*
- *Air Velocity*
- *Speciation*
- *Temperature*

First-try cases often cared most to verify fuel went where intended

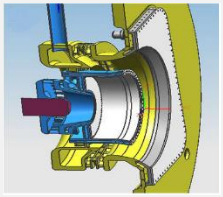
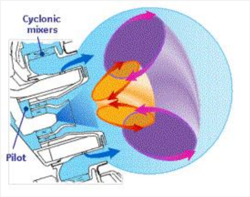
We also collaborate to compare a particular injector with modeling, e.g., NASA LDI, UTRC PICS, GE TAPS

Outline



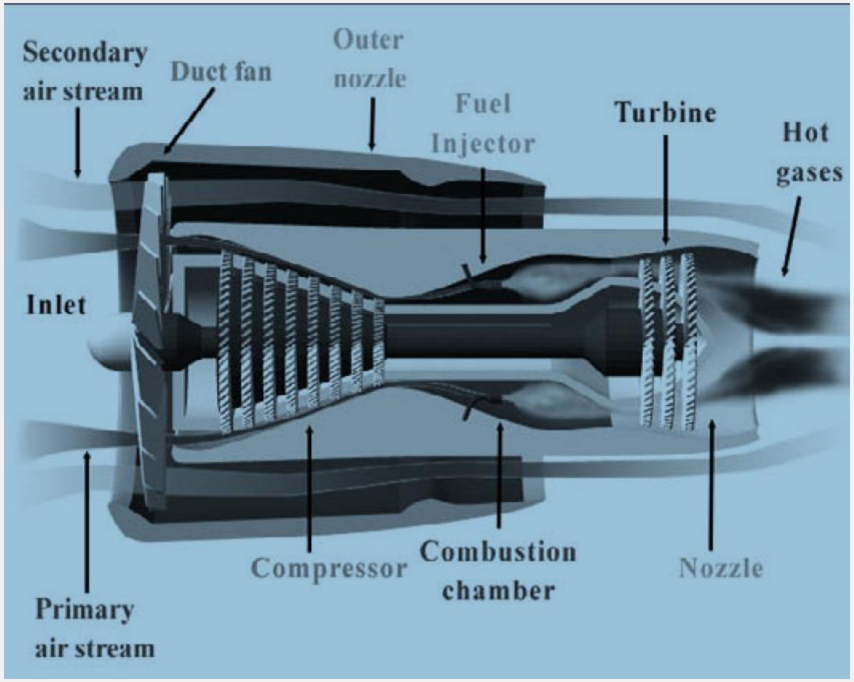
- <u>Brief</u> overview of modern gas turbine combustors
  - Emissions reduction strategies—it's all about fuel/air mixing and keeping the combustion temperature down

- Optical diagnostics typically used by Engine Combustion Group at NASA GRC and how they work

- Example Results—excerpts from previous papers/presentations
  - NASA Lean Direct Injection
    
    - *Particle Image Velocimetry (PIV)*
    - *Chemiluminescence (CL)*
  - PW/UTRC PICS
    
    - *Planar Laser-Induced Fluorescence (PLIF)*
    - *Planar Laser Scatter (PLS)*
  - GE TAPS
    

    - *Spontaneous Raman Scatter*
    - *PLIF, CL*

Cutaway view of a turbofan engine*



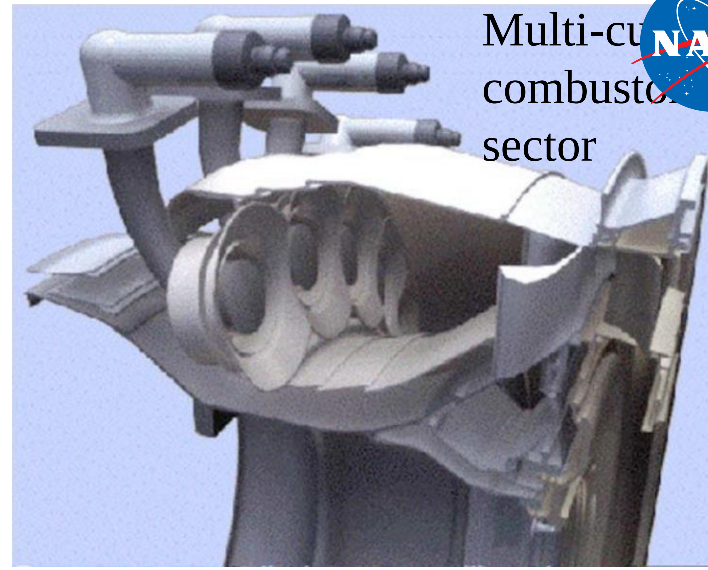
For more on aircraft engines, see

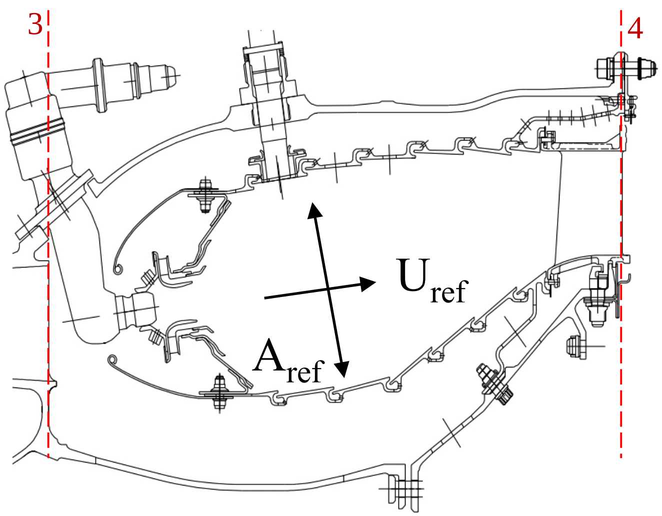
1. * "Pushing the Envelope: A NASA Guide to Engines" (2007). Publication EG-2007-04-013-GRC.
2. Mattingly (1996). *Elements of Gas Turbine Propulsion*, McGraw-Hill, Inc., New York.

A little bit on combustors: terminology


22-cup full-annular combustor case

There also are dual annular combustors





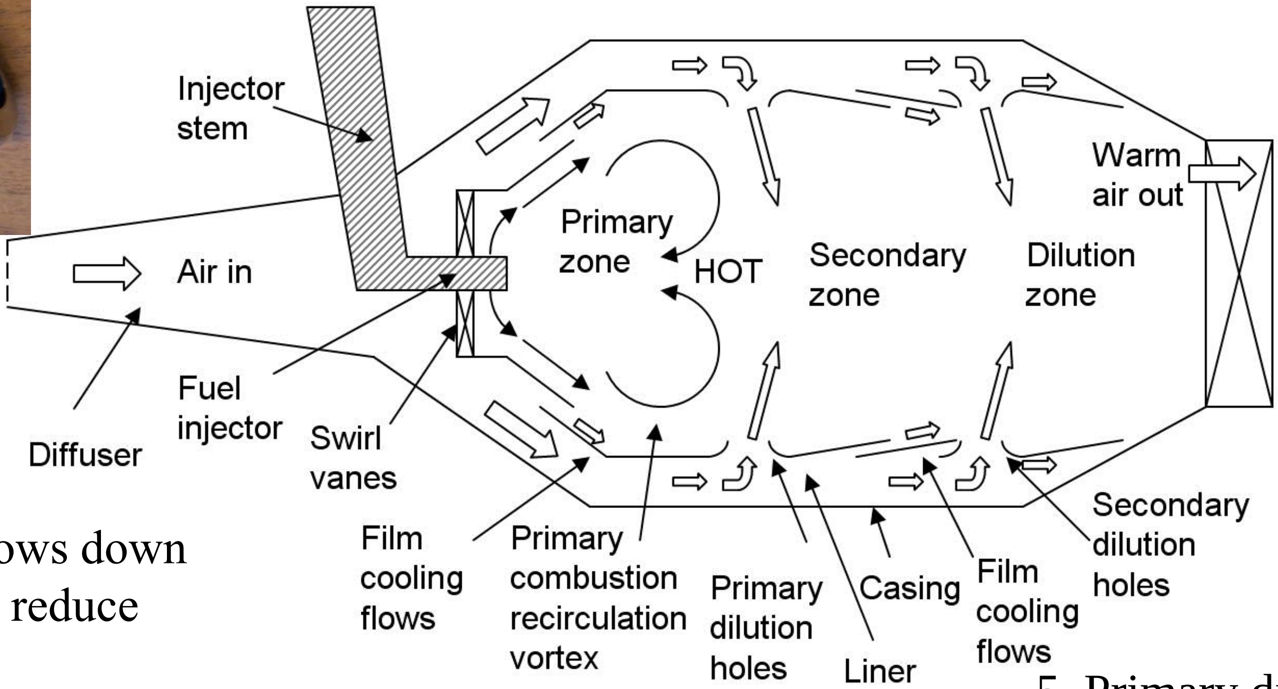

Single cup combustor: flame tube

Stations 3 (inlet) and 4 (exit) define the combustor control volume for mass, temperature, pressure

ΔP = combustor pressure drop = $P_3 - P_4$; % ΔP ~ 3 - 5

Cold flow (unfueled, non-combusting)Reference Velocity ~25-75 ft/s

Legacy Combustor Features



1. Diffuser slows down flow speed to reduce Rayleigh loss

2. Fuel-nozzle turbulence speeds up ***atomization*** by break up liquid into droplets

3. Liner film-cooling decouples thermal loading from pressure casing

4. Swirling flow forms recirculation vortex to provide ***flame-holding***

5. Primary dilution holes provide dilution and vortex anchor

6. Secondary dilution holes add more air to bring T4 down and shape T4 profile

We focus on fuel atomization/fuel-air mixing and primary zone combustion/flame holding

Stoichiometry

Stoichiometric combustion ($\Phi = 1$)

$$C_{12}H_{23} \text{ (~Jet-A*)} + 11.75\,(O_2 + 3.76N_2) \rightarrow 12\,CO_2 + 11.5\,H_2O + 66.74\,N_2$$

Non-Stoichiometric lean combustion ($\Phi < 1$)

$$\Phi\ C_{12}H_{23} + 11.75\,(O_2 + 3.76N_2) \rightarrow$$
$$\Phi\ 12\,CO_2 + \Phi\ 11.5\,H_2O + 66.74\,N_2 + (1-\Phi)\,11.75\,O_2$$

Equivalence Ratio, Φ

$$\Phi = (f/a)_{actual} \ / \ (f/a)_{\Phi = 1}$$

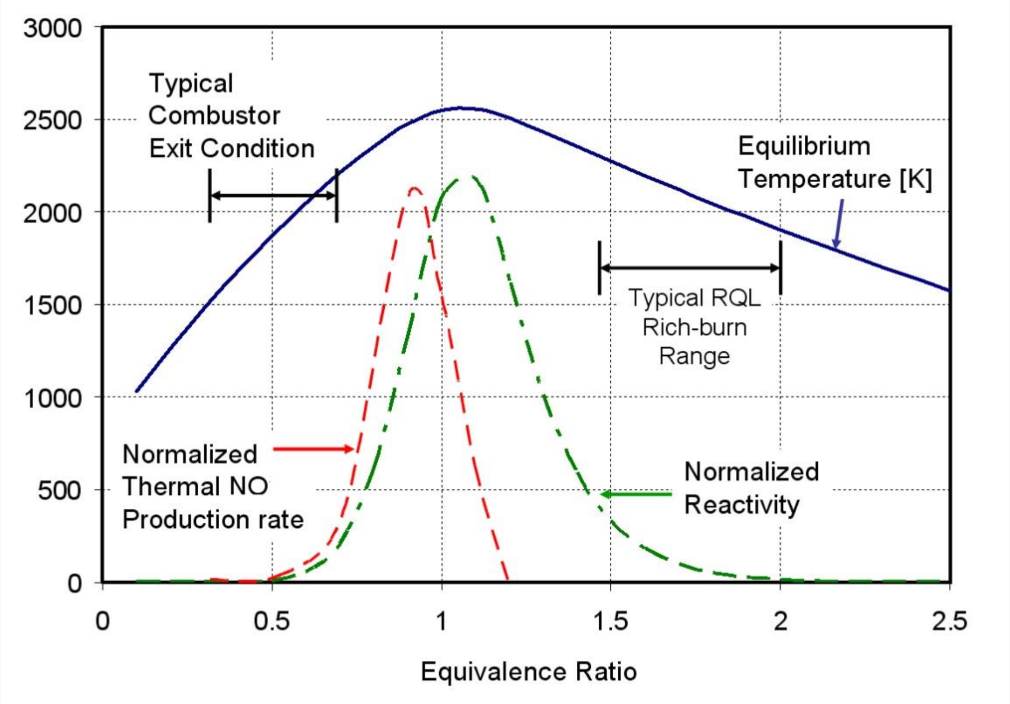
$\Phi = 1$ stoichiometric

$\Phi > 1$ fuel - rich

$\Phi < 1$ fuel - lean

* Jet fuels such as Jet-A and JP-8 are multicomponent, so this is an average formula

NOx Formation Concept and Avoidance Strategy

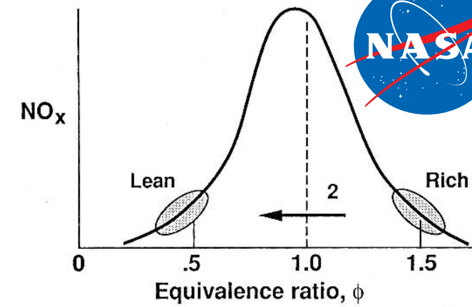


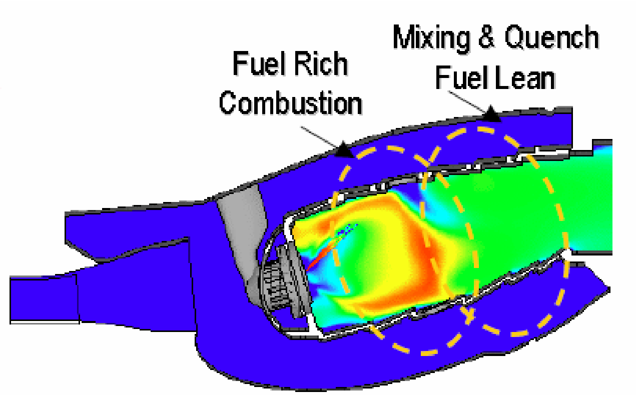
NOx Formation Rate (Highly Temperature Dependent) x Residence time = ObNOxious output

Key to Low-NOx:

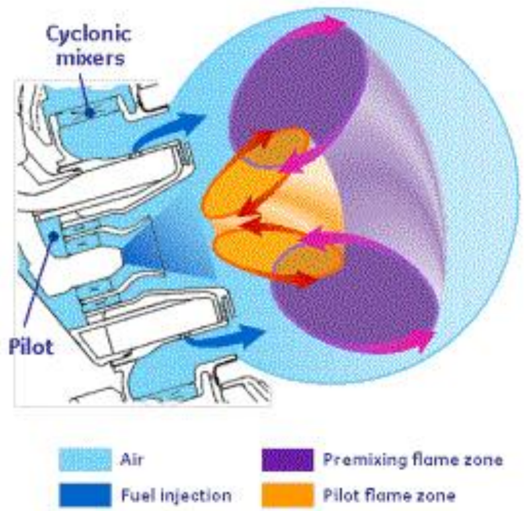
1. Avoid high temperature burning
2. Keep the exposure time short

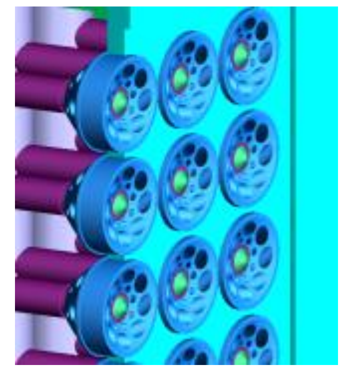
NOx Reduction Combustor Concepts





RQL[1]





Partially-Premixed hybrid[2]

Lean-Direct Injection

Rich-burn

- "inherently" more stable
- More likely to form soot and particulate matter
- Managing the dilution is key to lower NOx. How quickly do we pass through ϕ = 1 stoichiometric region?

Lean-burn

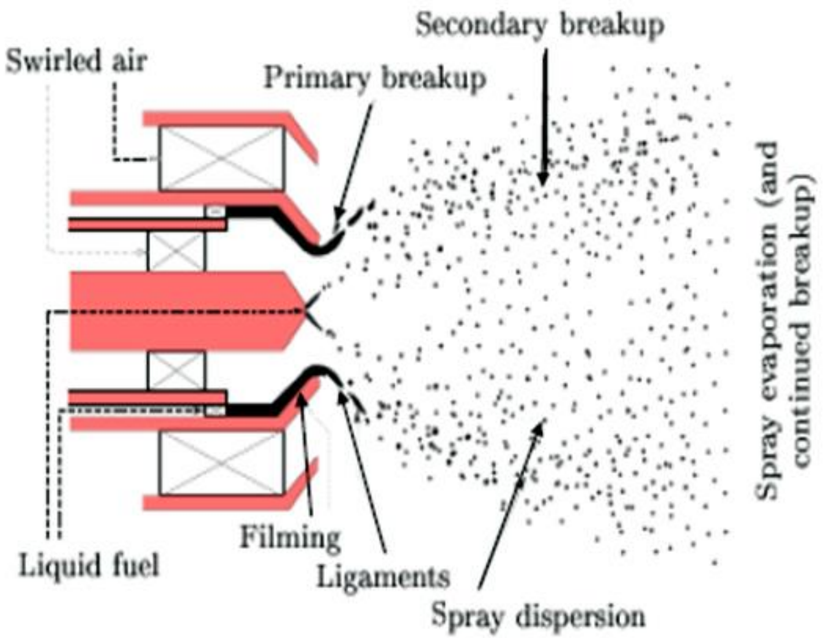
- More susceptible to flame instabilities and thermoacoustic coupling

1.McKinney et al. (2007). The Pratt & Whitney TALON X low emissions combustor: revolutionary results with evolutionary technology. AIAA-2007-386

2. Foust, M.J, et al.(2012). "Development of the GE Aviation Low Emissions TAPS Combustor for Next Generation Aircraft Engines," AIAA-2012-0936

Fuel Injection Processes

a.k.a. "How do you get the fuel to burn so quickly?"



- Atomize
- Vaporize
- Large-scale entrainment
- Small-scale mixing

For more on fuel injection and different types of fuel injectors, see

1. Lefebvre and McDonell, *Atomization and Sprays*, 2nd ed. (2017). CRC Press, Taylor & Francis Group, Boca Raton Fl.
2. Lefebvre and Ballal, *Gas Turbine Combustion*, 3rd ed. (2010). CRC Press, Taylor & Francis Group, Boca Raton Fl.

Optically-Accessible Combustor Facilities, 1
CE5 subcomponent test facility, intermediate pressure

	INLET CONDITIONS		MAX EXIT T	AIR FLOW	FLOW CROSS SECTION	WINDOWS		
	T, K	P, atm	K	kg/s	cm x cm	positions	thickness	C.A., cm
CE5b1 sector	450 – 866	18	2033	0.23 – 4.1	up to 21.6 x 21.6	up to 4 0°, 90°, 180°, 270°	1.27 cm	3.8 x 5.1
CE5b2 Flame tube	450 – 866	20	2033	0.23 – 1.4	7.6 x 7.6	up to 4 0°, 90°, 180°, 270°	1.27 cm	3.8 x 5.1

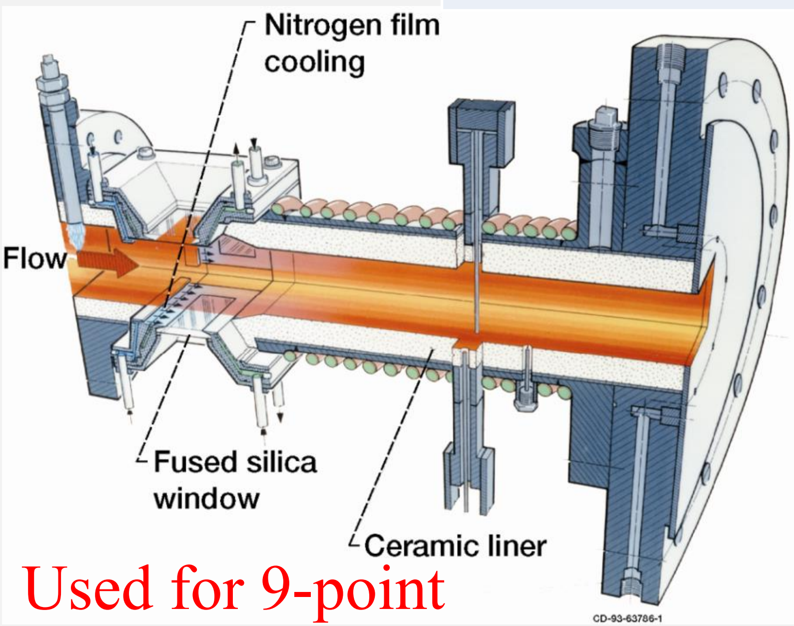
- Actual candidate aircraft fuel injectors are used
- The liners are formed from a castable ceramic, so these are adiabatic, uncooled, walls.
- The facility supports Jet-A, JP-8, or candidate alternatives. Three fuel circuit lines to each test stand provide the means for fuel staging and/or mixing.
- Both test stands can simulate supersonic and subsonic aircraft engine cycle conditions to study the combustor performance. We have also run a hypersonic application on stand 1.
- Windows (typically on three sides) provide access for optical diagnostics under operating conditions, thereby allowing for non-intrusive bench mark test testing within the primary combustion zone. Data are used for both performance validation and to validate reacting computational fluid dynamics (CFD) codes such as NASA's National Combustor Code (NCC).

Gaseous emissions, particle emissions, and dynamics pressure measurements are acquired for performance validation

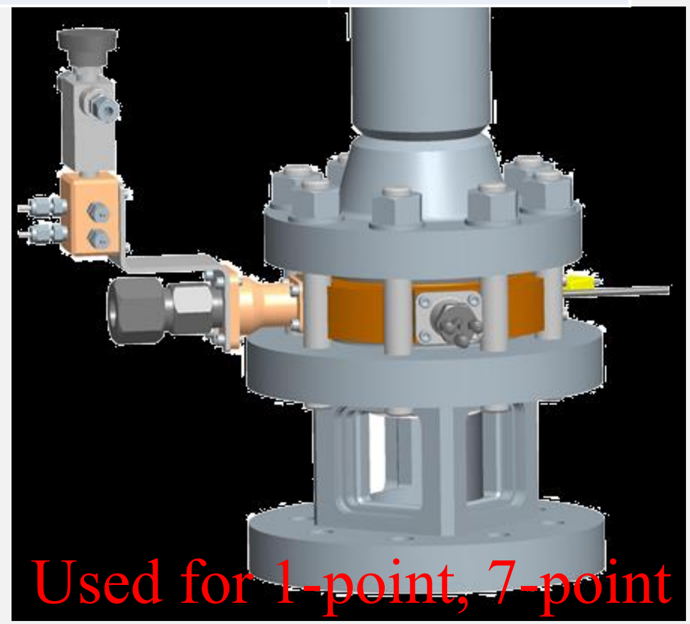
Optically Accessible Combustion Facilities, 2

Key differences:

	Combustor subcomponent	Combustion and Dynamics facility
Pressure range	4-17 atm (windows) 4 – 30 atm	1-5 atm
Air flow rates	0.4 – 0.78 kg/s	Up to 0.35 kg/s
Flow direction	Horizontal	vertical
purpose	Applied research focus	Basic research focus



- Three 1.5-in x 2.0-in windows
- 3-in **square** cross-section
- Flow horizontal

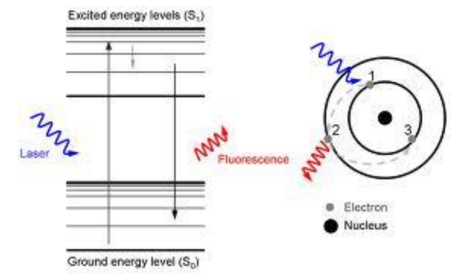


- Three 2.3-in x 2.4-in windows
- 3-in **diameter** cross-section
- Flow vertical, top to bottom
- T_3 typically 800°F (700K)

Optical Diagnostics Measurement Suite

Species, temp via PLIF, elastic scatter, Raman scatter

- *2D, 3D mapping of: OH, fuel liquid and vapor, profile and pattern factor*
- *1D mapping of major combustion species: CO_2, O_2, N_2, hydrocarbons, H_2O (+temperature)*

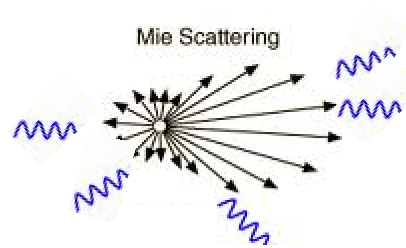


Global Chemiluminescence Imaging of C_2^*, CH, OH*, NO**

[**A**] + [**B**] → [◊] → [*Products*] + light

Velocity

- *2 component mapping via images—PIV*
- *3 component pointwise—LDV/PDI*

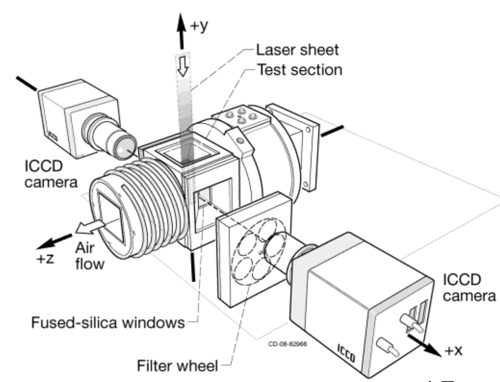


Drop Sizing

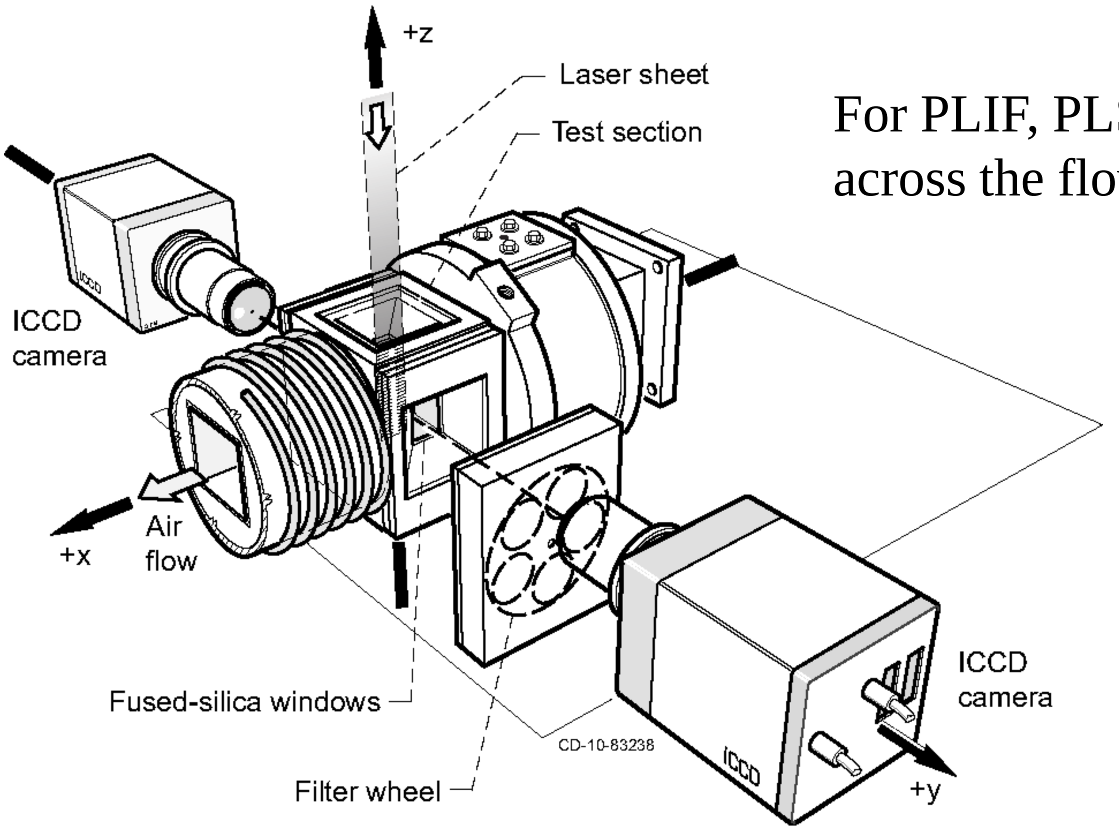
- *3 component pointwise—PDI*
- *shadowgraph-based, long range microscope*

Flow/flame visualizations

movies: video, high speed photography



Typical Imaging Setup—PLIF, PLS,PIV, Chemiluminescence

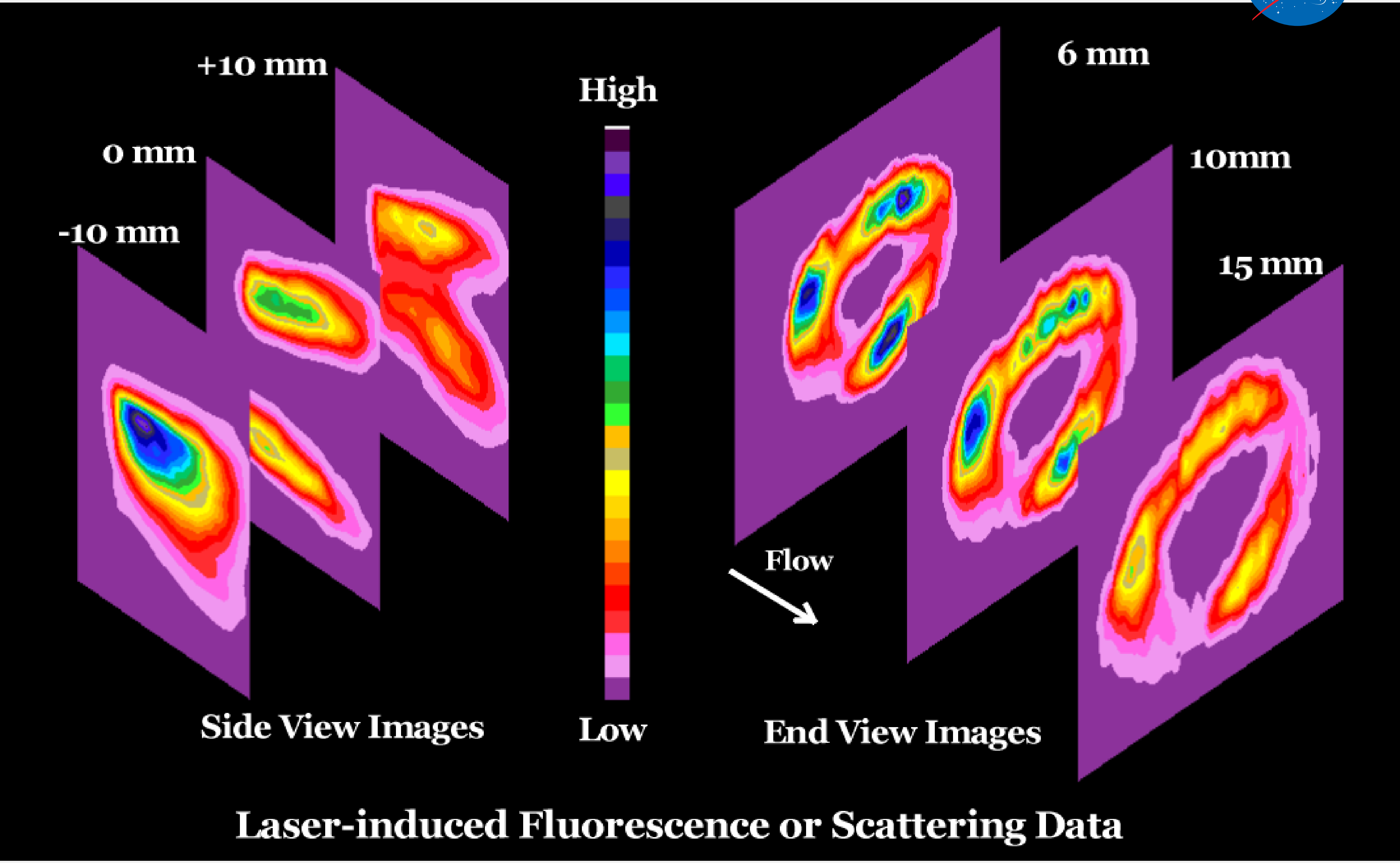


For PLIF, PLS, PIV, we usually traverse across the flow in 1-mm increments

PLIF Laser: 10-Hz Nd:YAG→ **dye** → **UV**: ~282-nm, ~ 9-ns pulse width
PIV Laser: 15-Hz, freq-doubled Dual Head Nd:YAG, ~5-ns pulse width

Cameras:
PLIF and chemiluminescence: Princeton Instruments PIMAX ICCD, 1k x 1k pixel, 200 on-chip avgs, 50-ns gate
Flame luminescence: Photron Fastcam SA1, 768 x768 px, 10000 frames/s
PIV: LaVision Imager Pro 2, 1600 x 1200 pixels , 500 image pairs collected

PLIF, PLS, PIV Results and Field of View Perspective:



Left: laser sheet oriented with flow, traversed across flow, side view images

Right: resulting traverse block sliced at fixed axial positions to produce End View images

Example results #1—NASA Lean Direct Injection

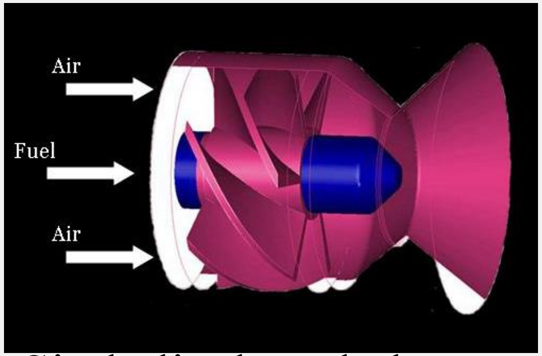
- Basic description of a single element
- Describe 9-point and 7-point
- Focus on PIV, non-reacting measurements (aka “cold flow”: Near field flow structure. Is there a recirculation zone to support flame stability?

Excerpted from:

- Hicks et al. [2019]. “Combustion and Emissions Study using a 7-point Lean Direct Injector Array—Focus on Flame Stability,” Paper ISABE-2019-24404.
- Hicks et al. [2011]. “Investigations of a Combustor Using a 9-Point Swirl-Venturi Fuel Injector: Recent Experimental Results,” Paper ISABE-2011-1106 , NASA/TM-2012-217245.

LDI Hardware Details

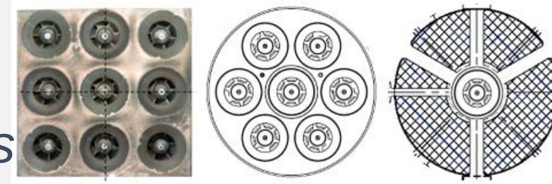
Baseline LDI element



- Six helical angled vanes
- Simplex atomizing nozzle
- Converging-Diverging Venturi

Swirlers: 45°, 52.5°, 60°
Swirl #s: 0.59, 0.77, 1.02

physical parameters



	9-pt	7-pt	1-pt
Combustor flow passage dimension	3-in x 3-in	3 inch diameter	3 inch diameter
Element size:		1-inch, nominal	
Axial	1	0.82	1
Radial	0.873	0.873	0.873
Diffuser diameter at dump plane	0.875	0.800	0.875
Diffuser length	0.215	0.172	0.215
spacing, center-to-center	**1 or 1.414**, position-dependent	**0.938**	n/a
Venturi throat D	0.512	0.512	0.512

Same for all configurations:

- **fuel nozzle outer envelope**
- **axial air swirlers**
- **venturi throat diameter**

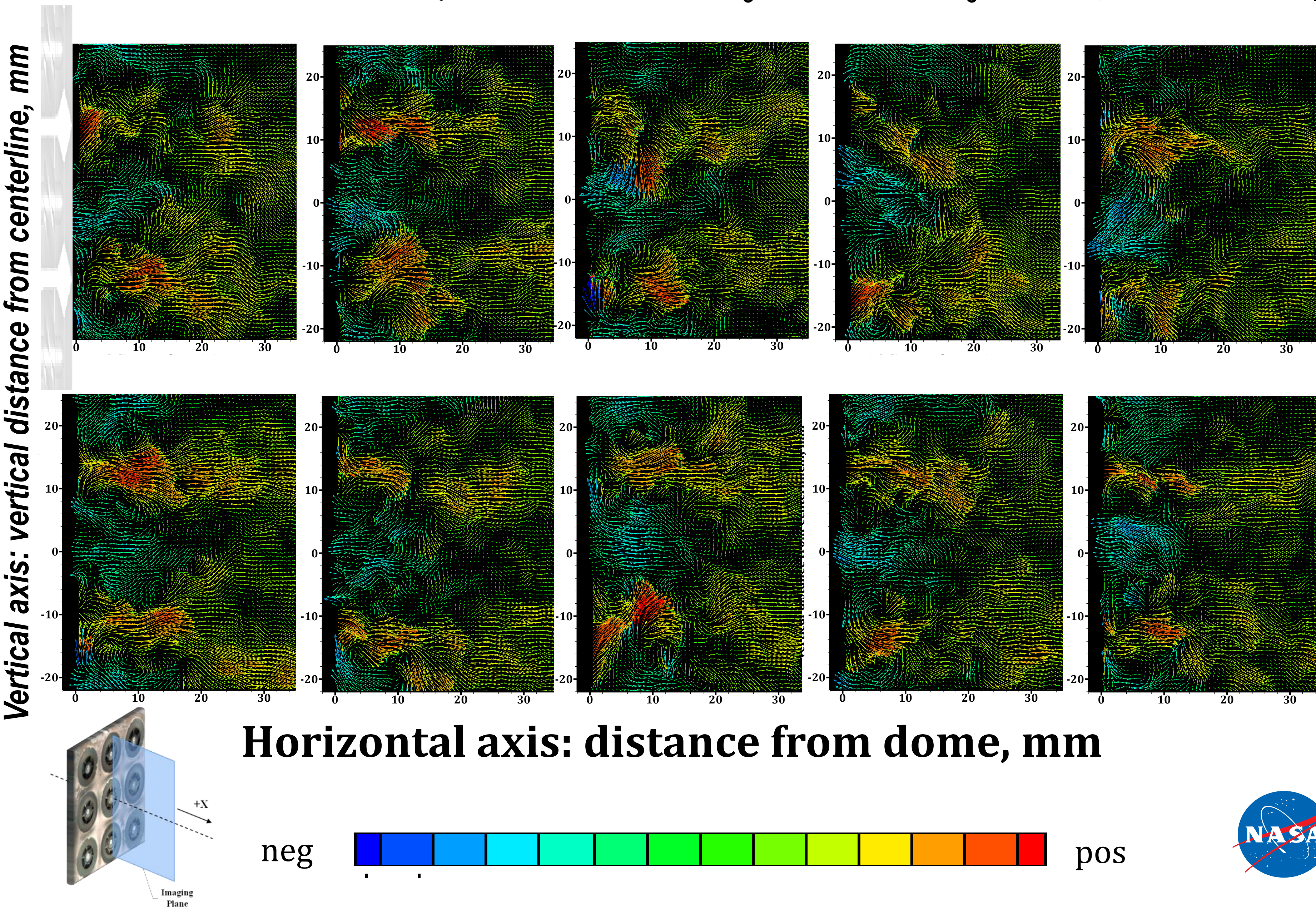
Different:

- **Flow passage shape/area**
- **Element spacing**

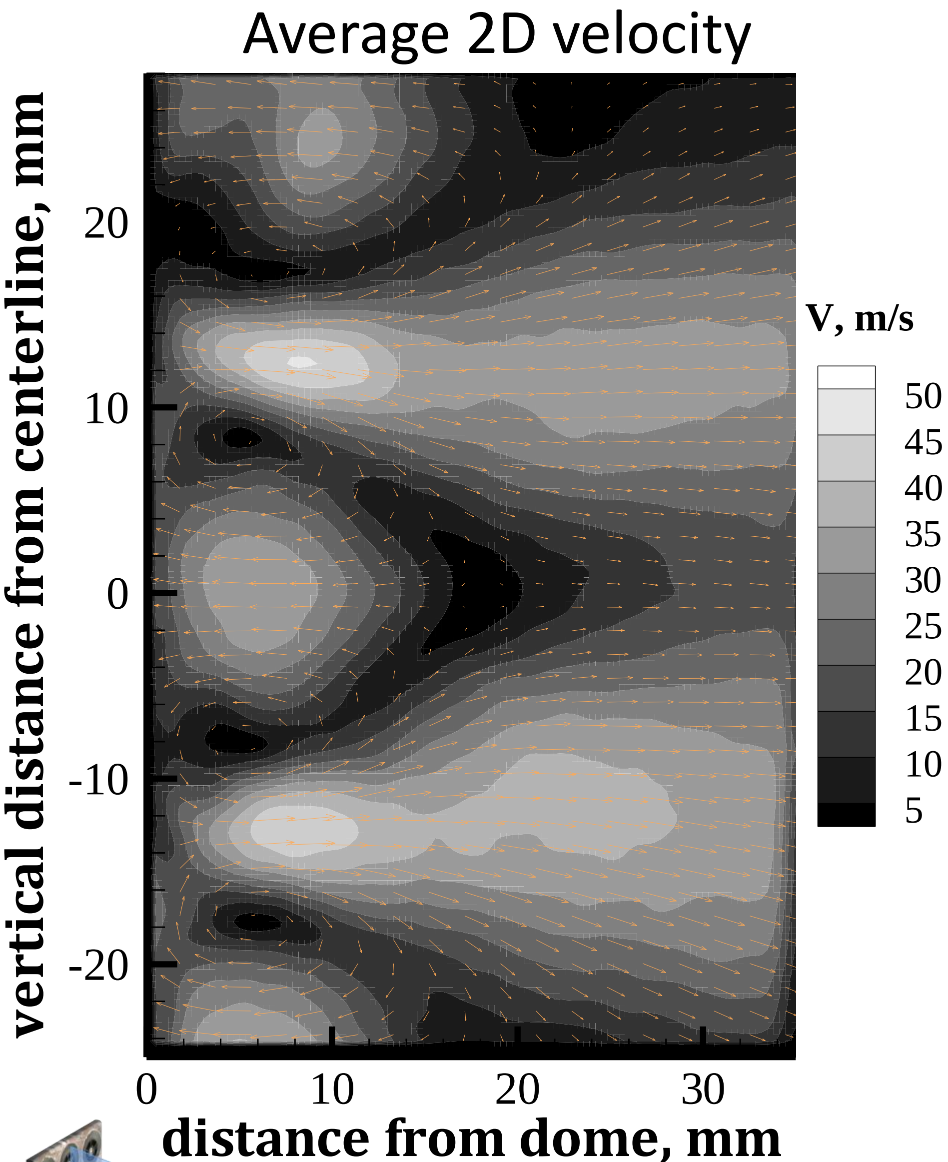
Packing the 7-point into the available space reduces the element spacing, compared to the 9-point.

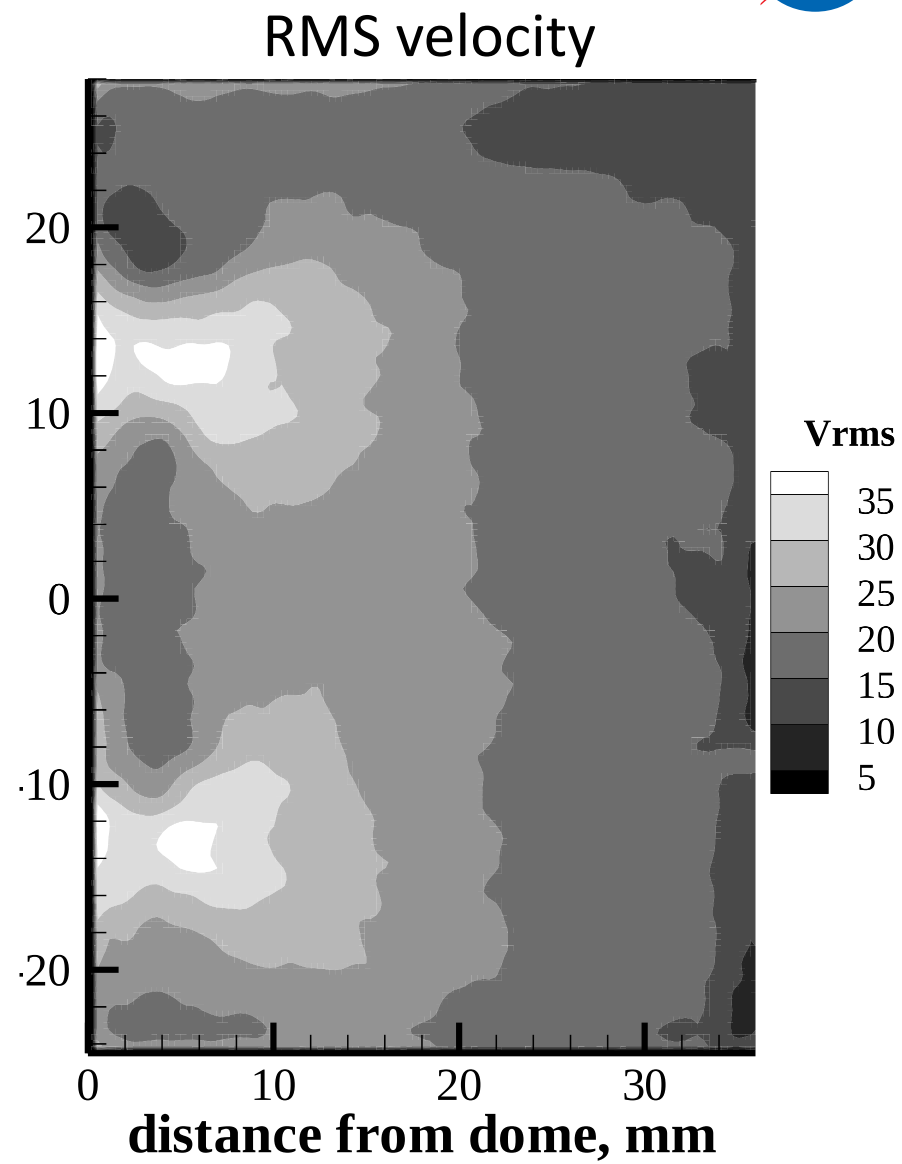
9-pt: Ten Consecutive Instantaneous PIV Axial-Vertical Velocity Fields

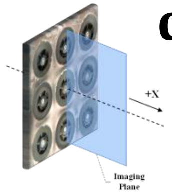
All RH 60° swirlers. Air only, alumina seed. T_3 = 1030°F, P_3 = 150 psia Δt = 5-μs



9-pt: Average PIV Axial-Vertical Velocity Fields ℄ slice







- *Recirc zones directly downstream of injectors*
- *Black bands—location of zero velocity*

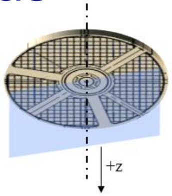
Average, 500 image pairs

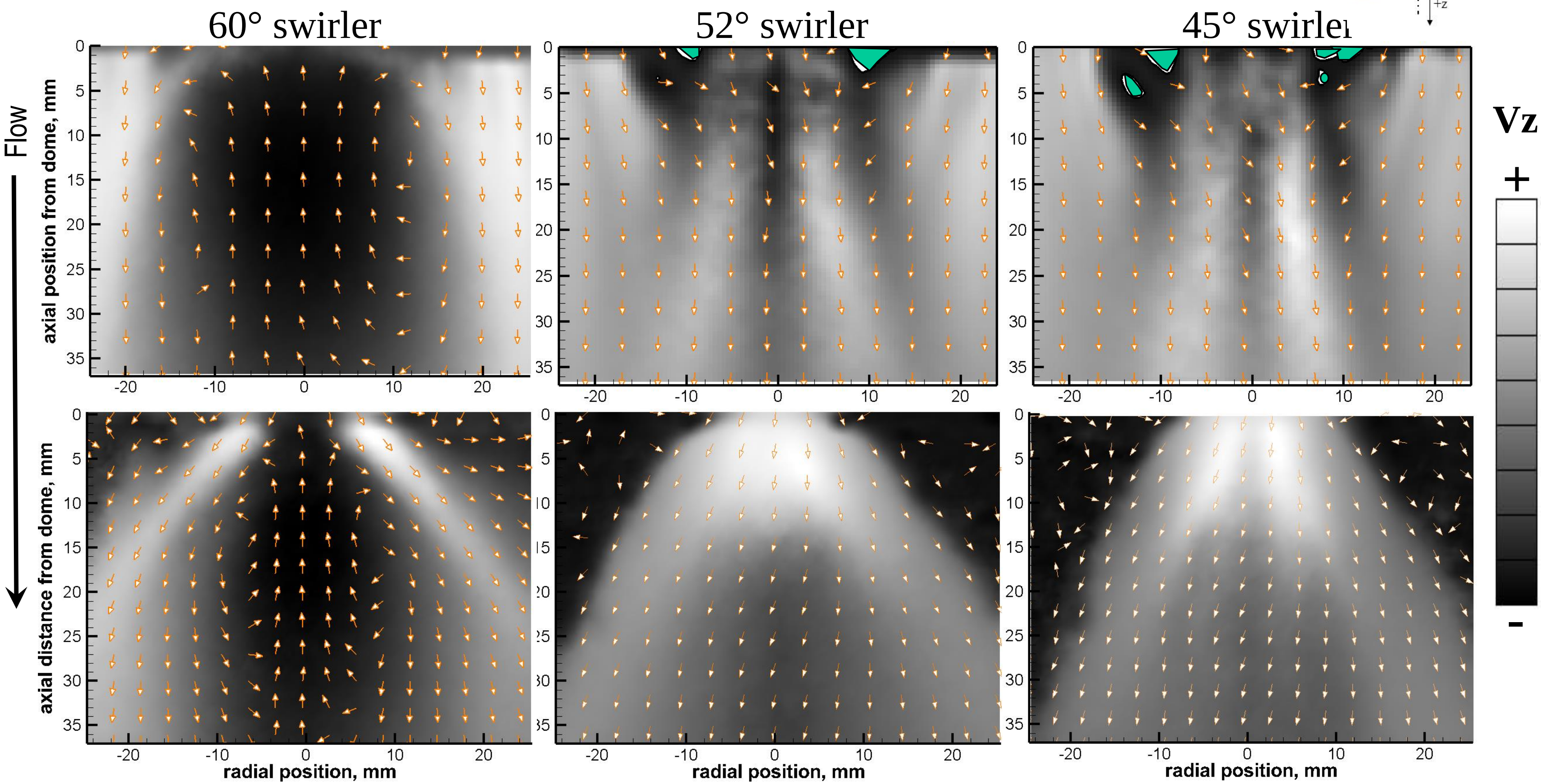
Reviewing Single Point LDI Cold Flow Results for Swirl Angle

On Central Recirculation Zone (CRZ) Development Avg Vel Fields

Top: oil-seeded air—50ft/s, 45psia, 300°F— (Vz ≤ 0 colored ◆ for 52°&45°)

Bottom: water seeding through fuel nozzle—50 ft/s, 75psia, 800°F



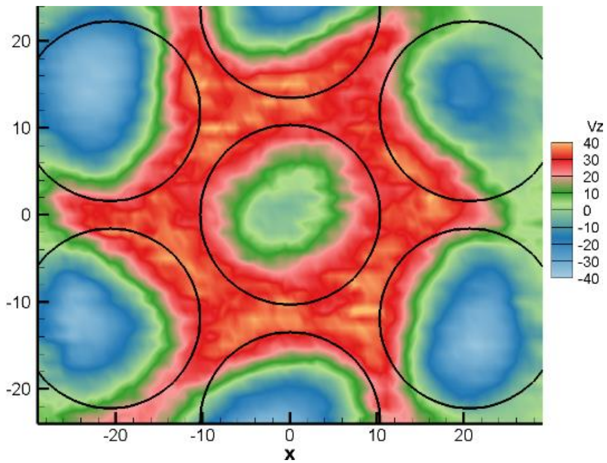


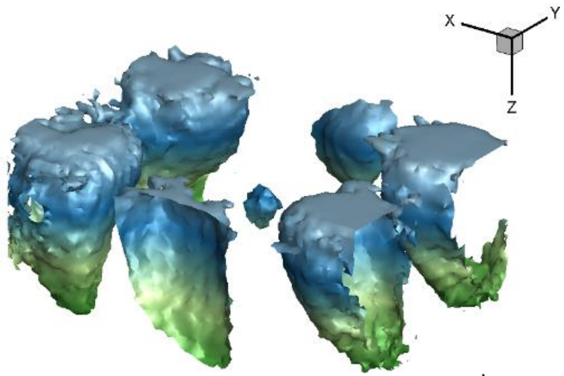
60°: wide angle ~90°, large CRZ
lowest downstream velocity

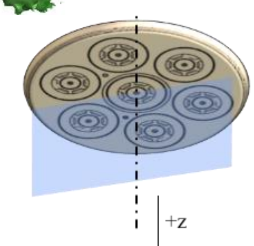
52°: small angle ~35°, no CRZ
high downstream velocity

45°: smallest angle~20°, no CRZ
highest downstream velocity

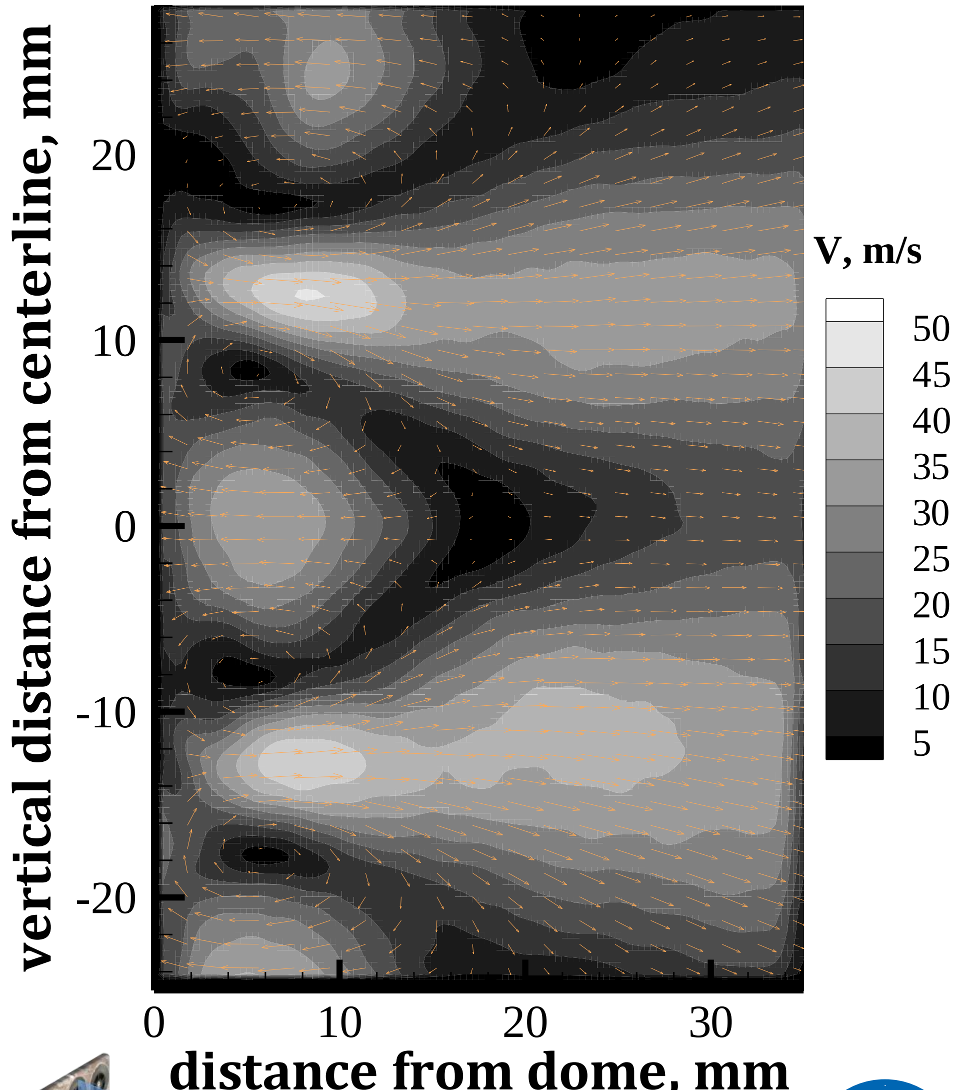
Comparing 7-point, 9-point LDI Cold Flow Results for CRZ "size"

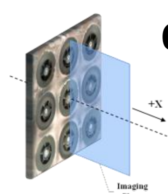






RH60all





7-pt Swirler spacing leads to interaction that reduces the center CRZ for the RH60all configuration

Example #2: Focus on comparing optical diagnostics and modeling results.
Diagnostics used: Fuel PLIF, Planar Laser Scatter from liquid fuel
Highlights what is done sometimes when facility conditions do not match actual engine conditions

NASA Numerical and Experimental Evaluation of UTRC Low Emissions Injector

Sarah Tedder

Yolanda Hicks, Robert Anderson, Anthony Iannetti

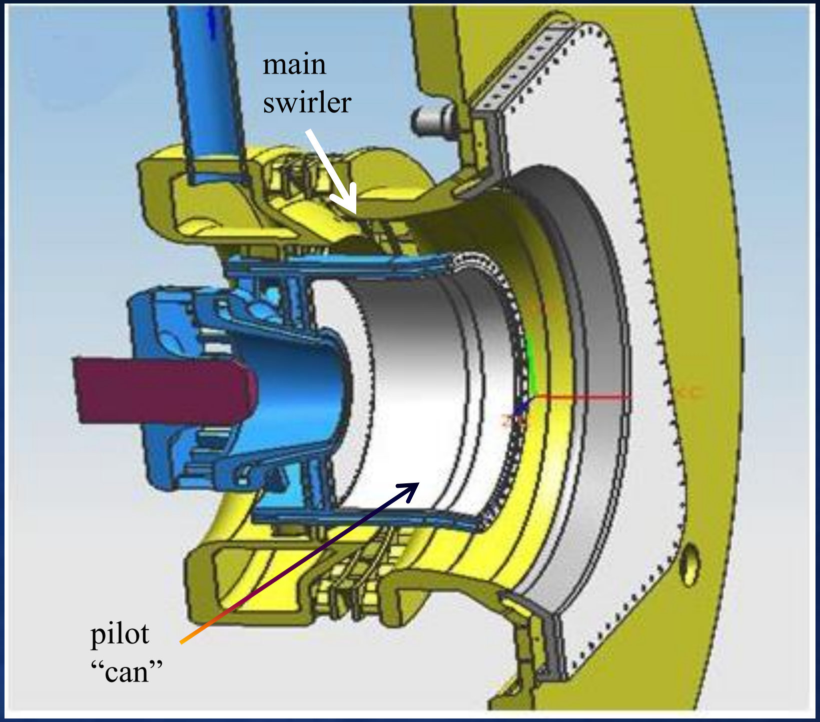
NASA Glenn Research Center

Lance Smith, Zhongtao Dai

United Technologies Research Center

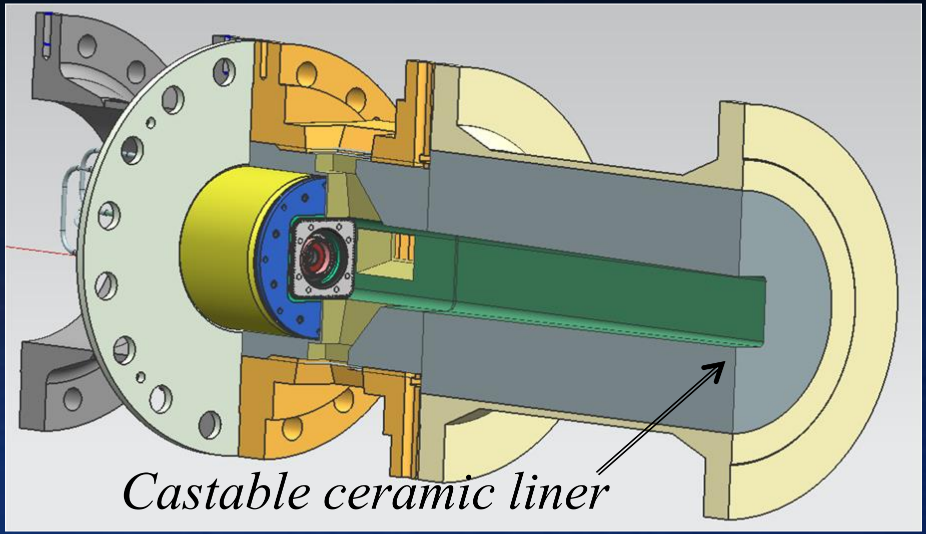
Paper AIAA—2014-3627, NASA/TM—2014-218493

UTRC Pilot in Can Swirler (PICS) injector concept



- Pilot
  - Low-power operation
  - Liquid fuel
  - Located in "can" inside the main swirler
  - can isolates pilot from main-stage flame
- Main-stage Supersonic flight
  - fuel used as heat sink
  - Flash vaporizes fuel for main swirler
  - low NOx emissions

PICS tests at NASA GRC



4-inch square castable ceramic combustor liner

Non-vitiated Facility Air (as configured):

Pressures: up to 250 psia

Inlet Temperature: 450°F – 1030°F

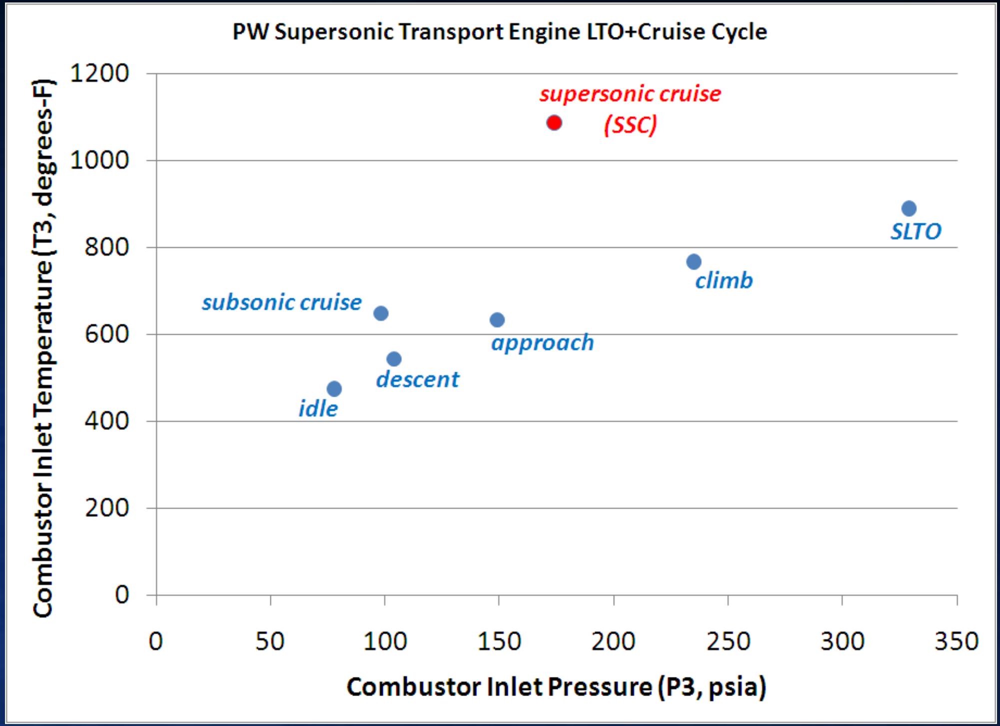
W_{air} : up to 10 pps

Differences between UTRC/NASA

- Supersonic cruise T3: 1087°F/ 975°F
- Subsonic cruise P3: 329/250 psia
- Fuel: *unheated* JP-5, ~ 70°F (UTRC used vaporized fuel)

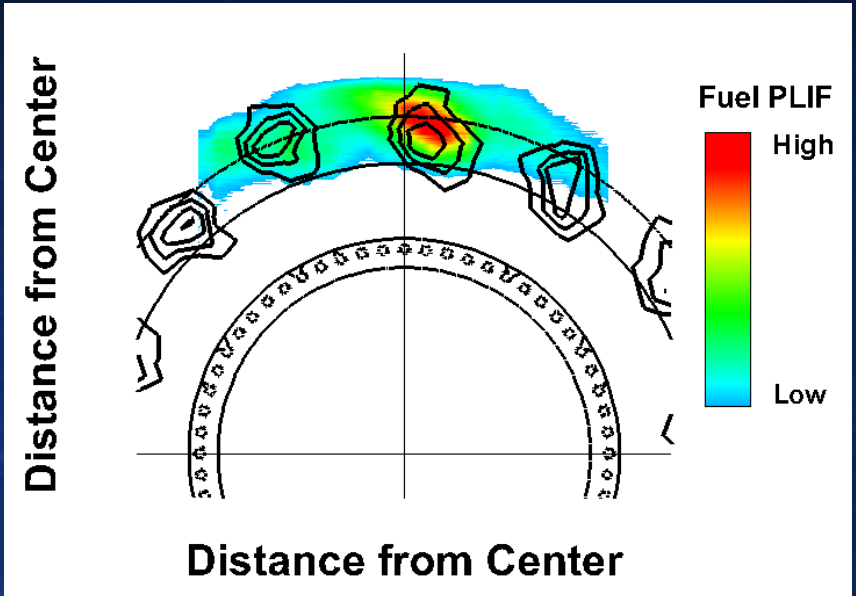
Nominal cycle	P3, psi	T3, °F	FAR/FAR$_{SLTO}$
Supersonic cruise, N+3	174	975* ↓	1.24
~ Subsonic cruise, N+2	250* ↓	1000	0.85
Approach, subsonic, N+2	205	716	0.75

Supersonic Cycle to address NASA N+3 goal

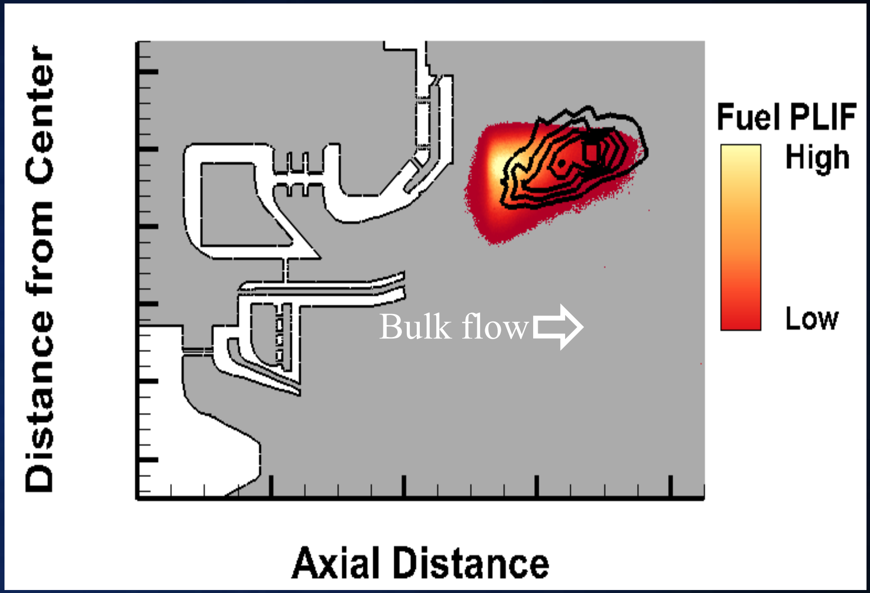


	P3-psi	T3-F	FAR / FAR_{SLTO}
supersonic cruise 50k / M1.8	174	1087	1.10
subsonic cruise 35k / M0.8	98	648	0.77
SLTO	329	890	1.00
climb-66%	235	767	0.82
appoach-32%	149	634	0.66
descent-15%	104	544	0.59
idle	78	475	0.57

Distribution of Fuel at N+3 Supersonic Cruise Condition
JP-8 enters as liquid at ~ 70°F, T3 = 975°F



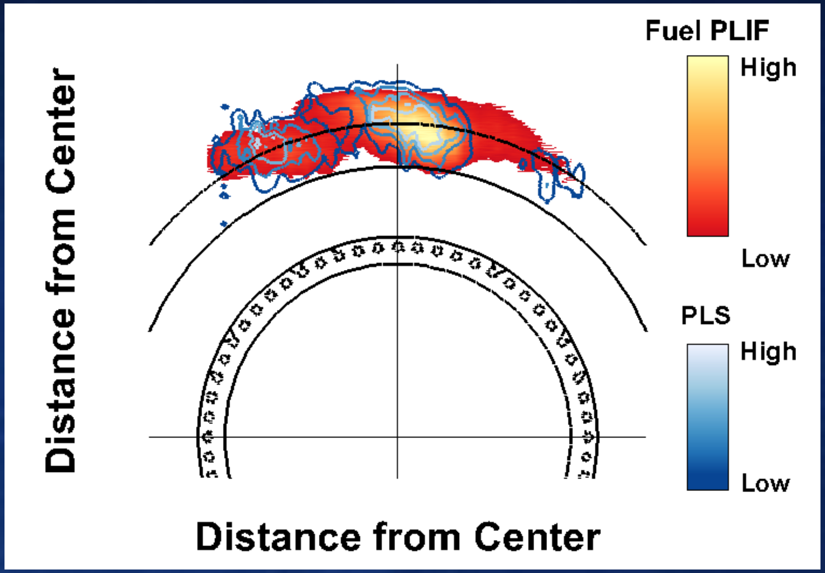
Fuel patternation—aft-looking-forward

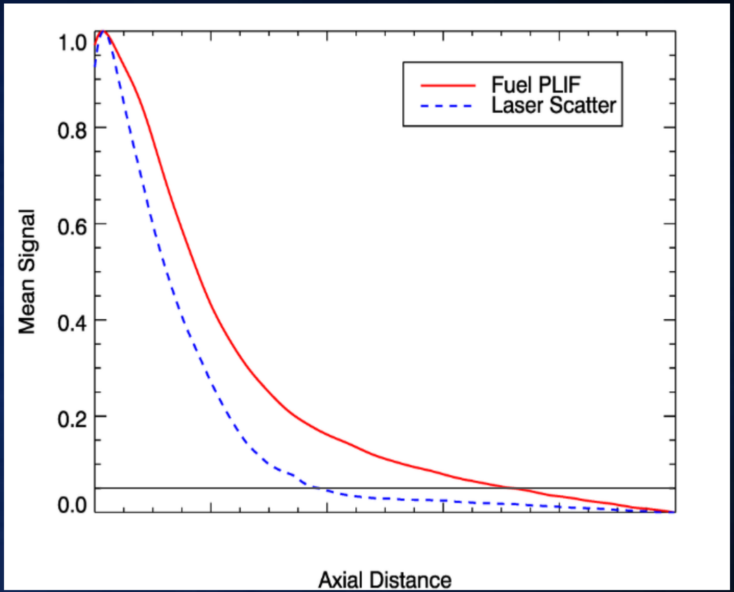


Side view, Y = 0

Fuel PLIF(color), CFD (lines)

Distribution of Fuel at N+3 Supersonic Cruise Condition
JP-8 enters as liquid at ~ 70°F, T3 = 975°F

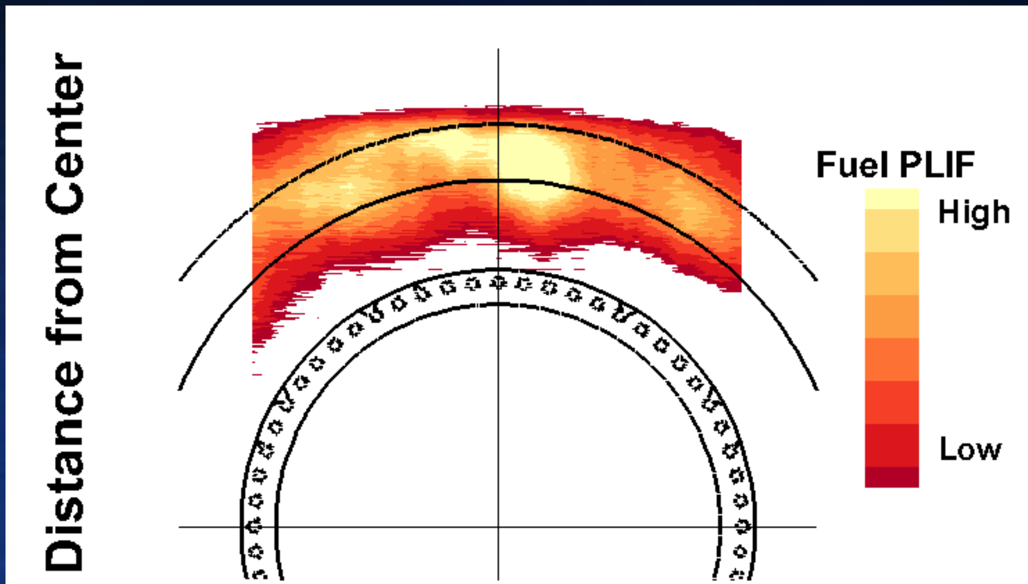


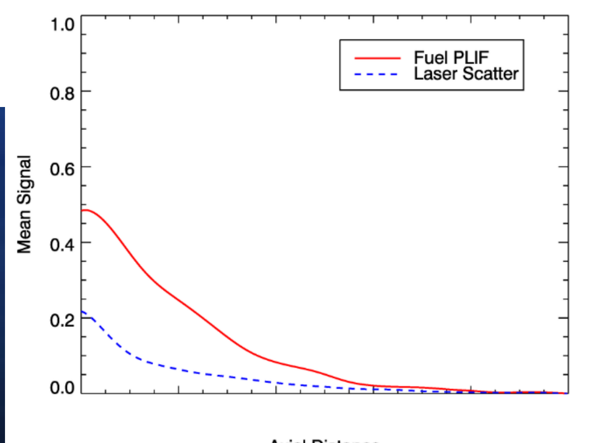


Liquid+vapor (red-yellow),
Liquid only(blue)

liquid fuel is evaporated an
axial distance approximately 60% of
the distance it takes the total remaining
fuel to be consumed

ERA: N+2 Subsonic Cruise Condition





Aft-looking forward view
Less stratified than N+3 sup cruise condition

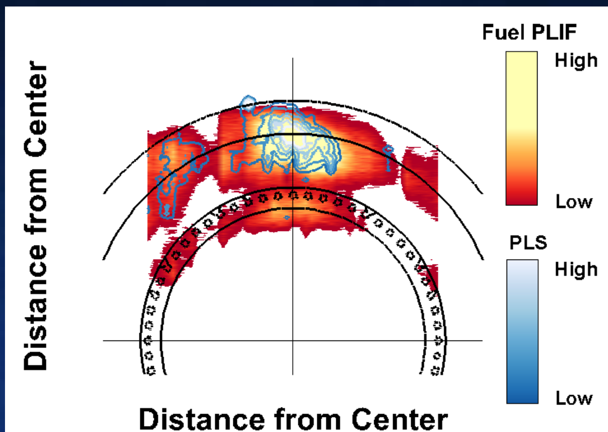
at most 10% of the total fuel signal from the liquid.

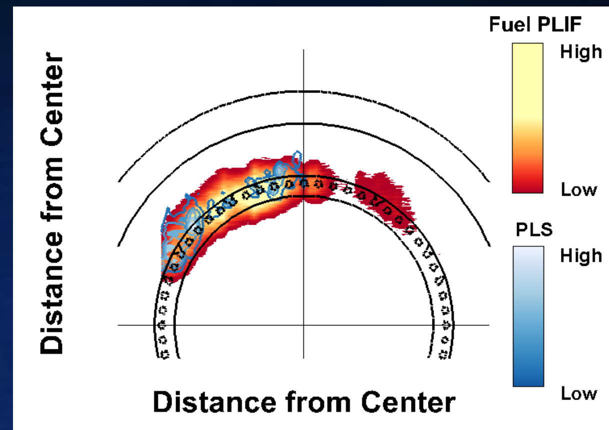
Total fuel and liquid fuel scaled relative to N+3 supersonic cruise:

- 50% less total fuel signal,
- 20% less liquid fuel signal

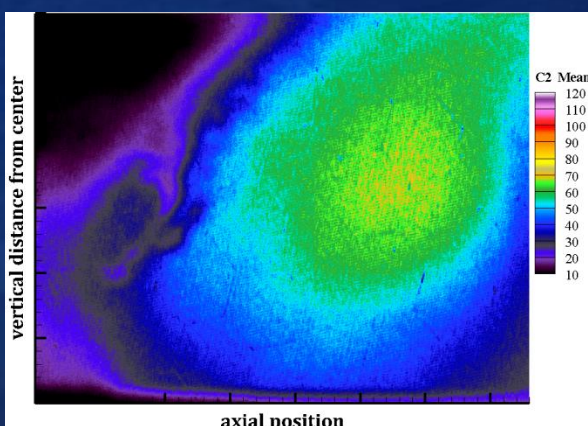
ERA: N+2 approach condition

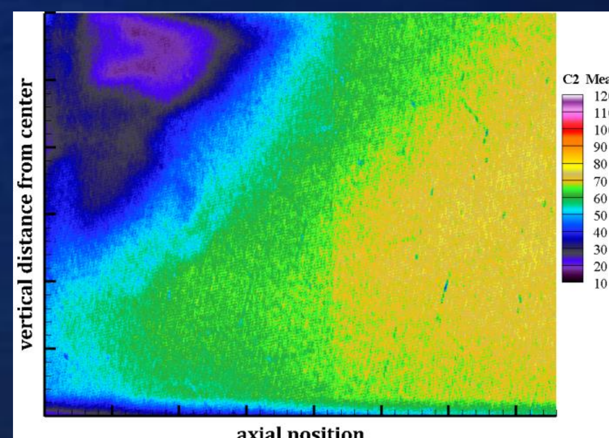
Approach-1—Pilot + Main | **Approach-2—Pilot Only**





Fuel signal





C_2* CL signal
(used as fuel surrogate)

- PLIF and PLS results show that condition with fuel staging between pilot and main is better mixed than condition that uses pilot only
- Fuel staging produced lower NOx emissions.

Example #3: Focus a) on comparing effect of fuel staging on minor species distributions.
Diagnostics used: Fuel & OH PLIF, CL from CH*, C_2*, OH*, NO*
Focus b) combustion temperature derived from N_2 Stokes/Anti-Stokes Raman Spectroscopy

Paper AIAA-2018-4476, NASA TM-2018-219984

Flame Tube Testing of a GEA TAPS Injector: Effects of fuel staging on combustor fuel spray patterns, flow structure, and speciation

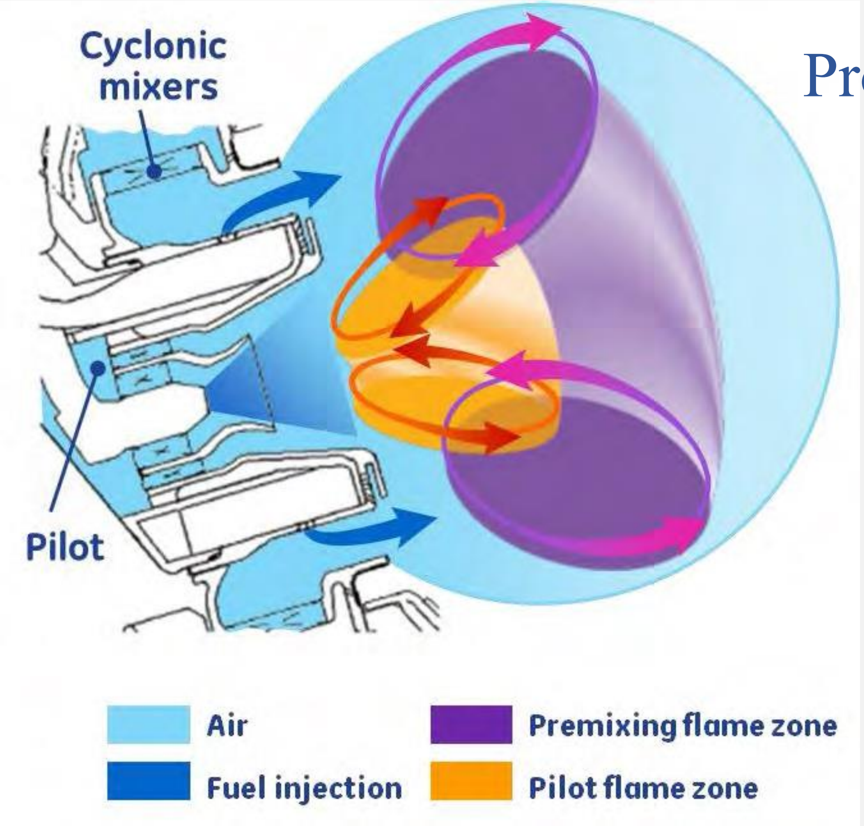
Yolanda R. Hicks

Tyler Capil, Robert Anderson

Glenn Research Center

9-11 July 2018 Cincinnati OH

GE Twin Annular Premixing Swirler (TAPS) injector concept for low NOx emissions



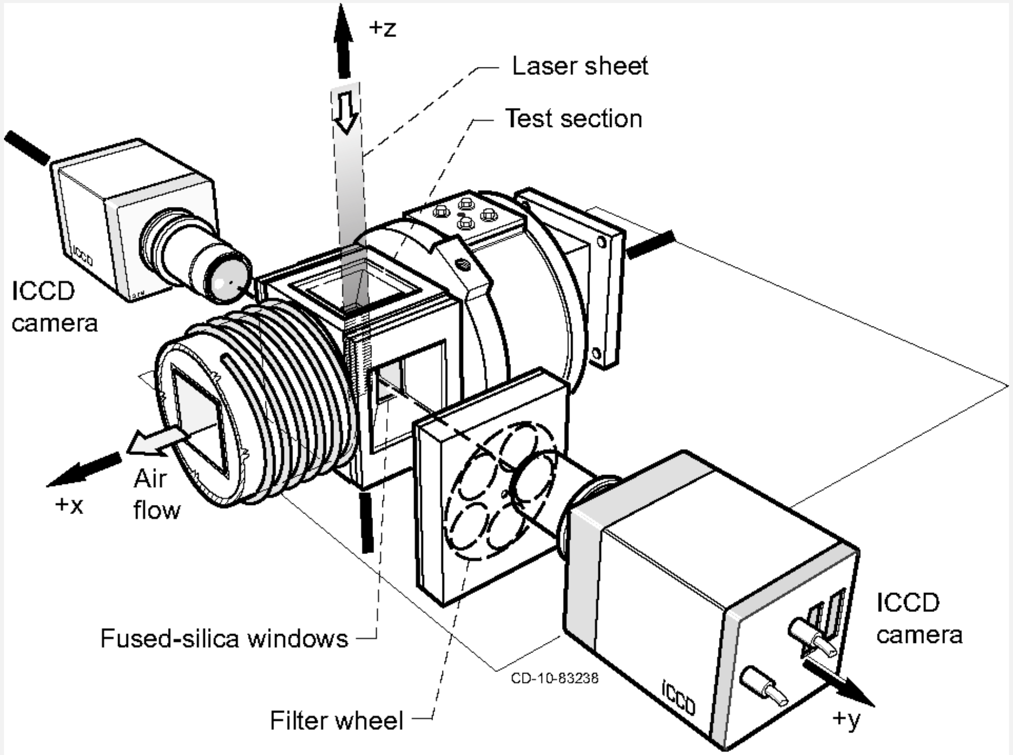
Provides independent control of:

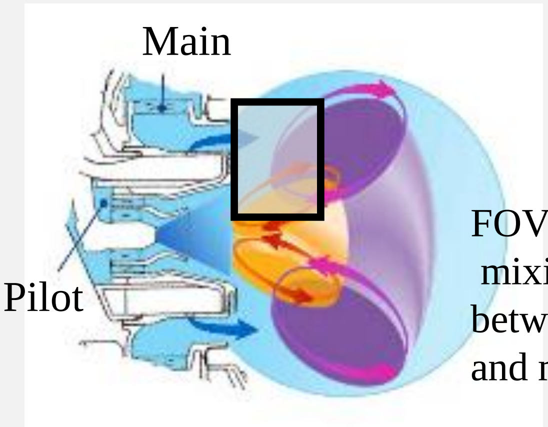
- Center pilot for low power operability, low CO, HC emissions
- Cyclone/main for high power operation, low NOx emissions

We'll look at fuel split, i.e. percent of total fuel going to pilot versus main

TAPS References:
Foust, Thomsen, Stickles, Cooper, Dodds—AIAA 2012-0936
Mongia—AIAA 2003-2657

Optical Diagnostics Setup and Testing—Imaging

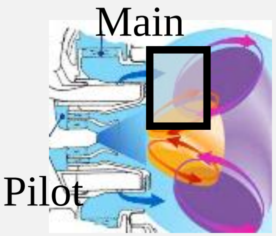




PLIF Laser: 10-Hz Nd:YAG→ **dye** → **UV**: ~282-nm, ~ 9-ns pulse width
PIV Laser: 15-Hz, frequency-doubled Dual Head Nd:YAG, ~5-ns pulse width

Cameras:
PLIF and chemiluminescence: Princeton Instruments PIMAX ICCD, 1k x 1k pixel, 200 on-chip avgs, 50-ns gate
Flame luminescence: Photron Fastcam SA1, 768 x768 px, 10000 frames/s
PIV: LaVision Imager Pro 2, 1600 x 1200 pixels , 500 image pairs collected

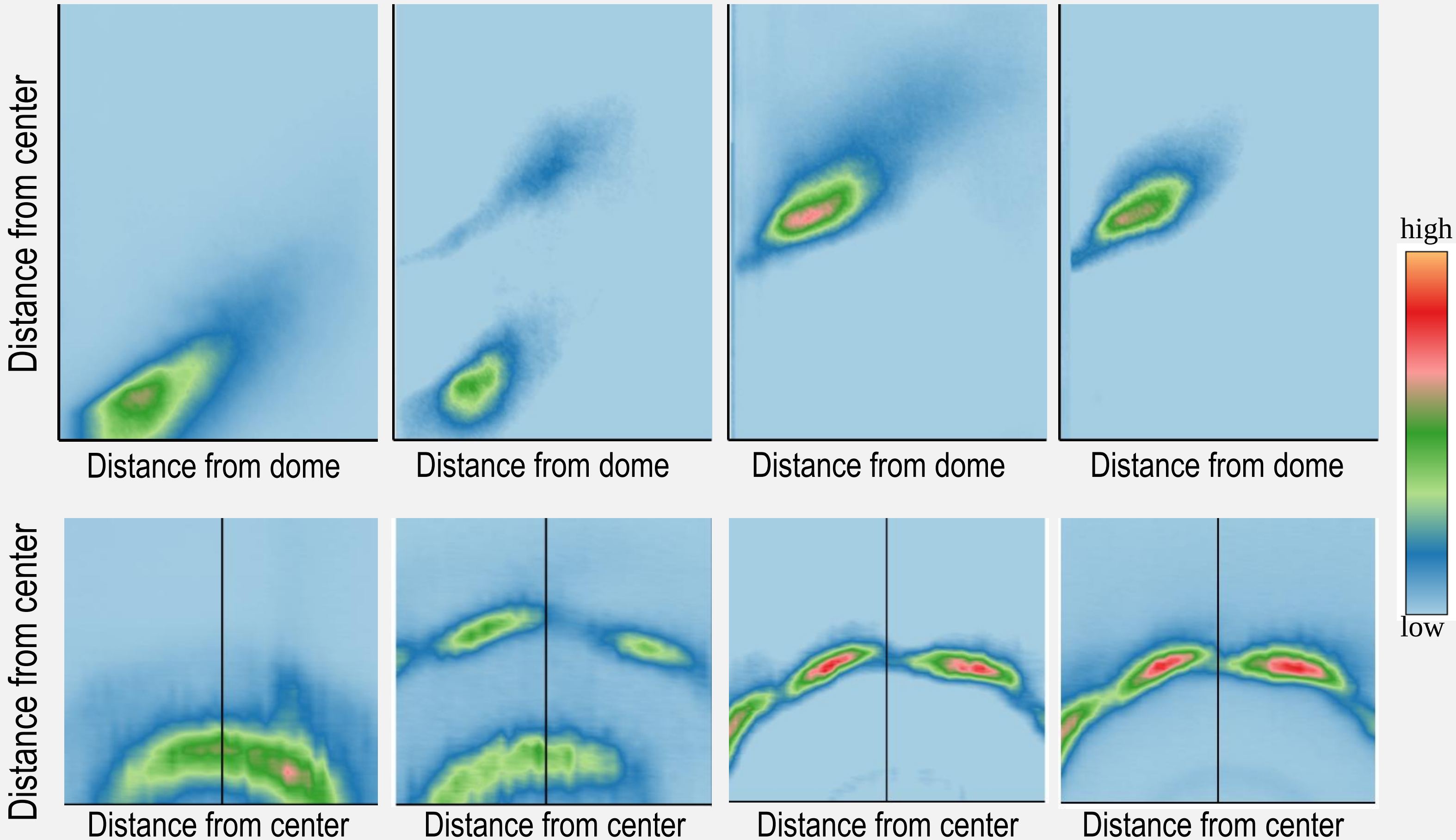
Fuel Split Effect— Fuel Patternation



Pilot/main split → **100/0** **60/40** **20/80** **10/90**

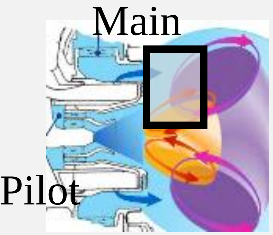
Side View
Y = 0

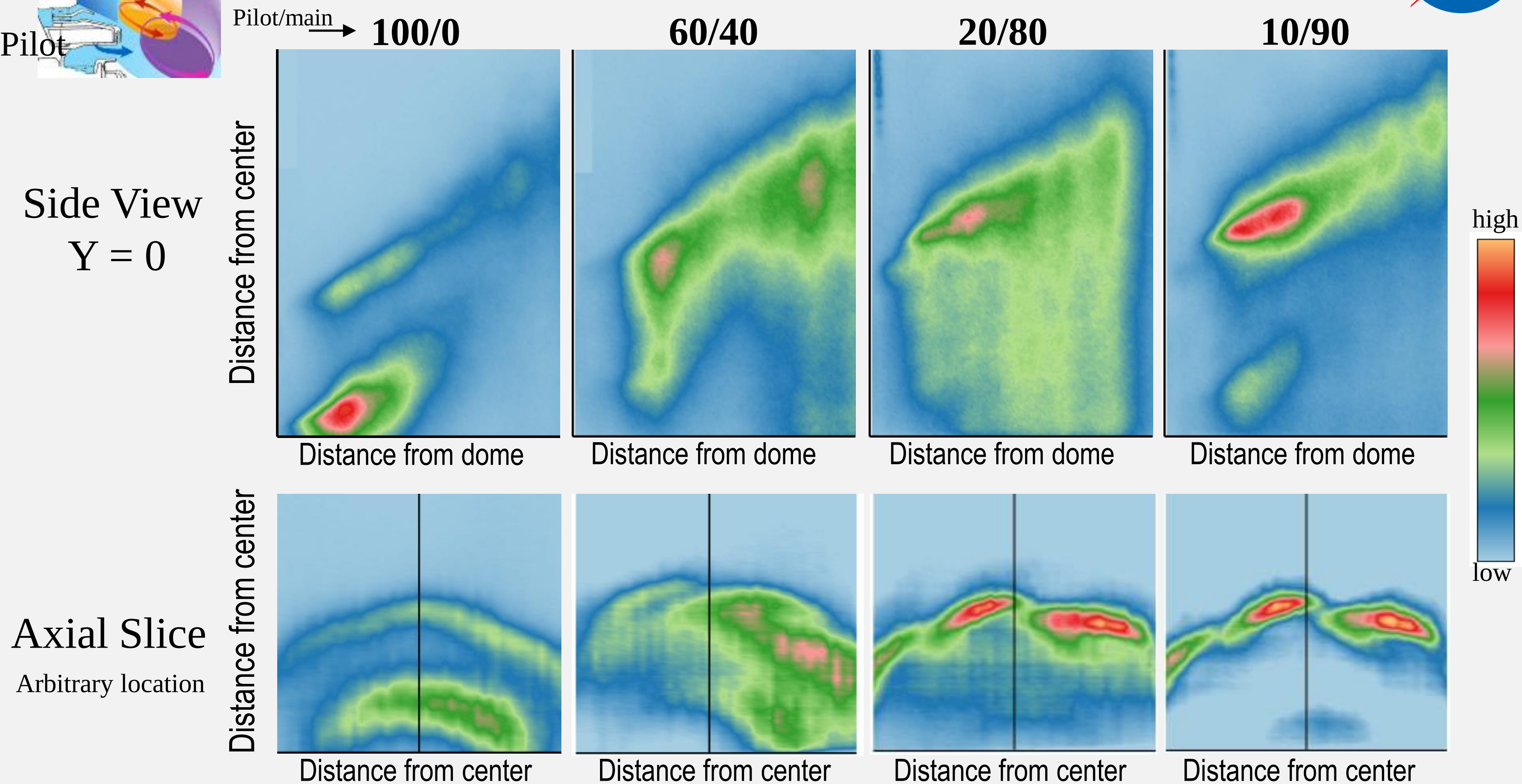
Axial Slice
Arbitrary location



- Symmetric spray pattern
- 20/80 & 10/90 splits more uniformly dispersed in from main than 60/40 split

Fuel Split Effect— OH distribution

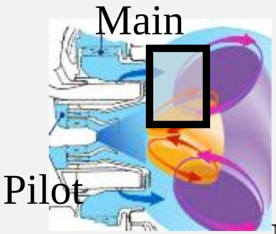


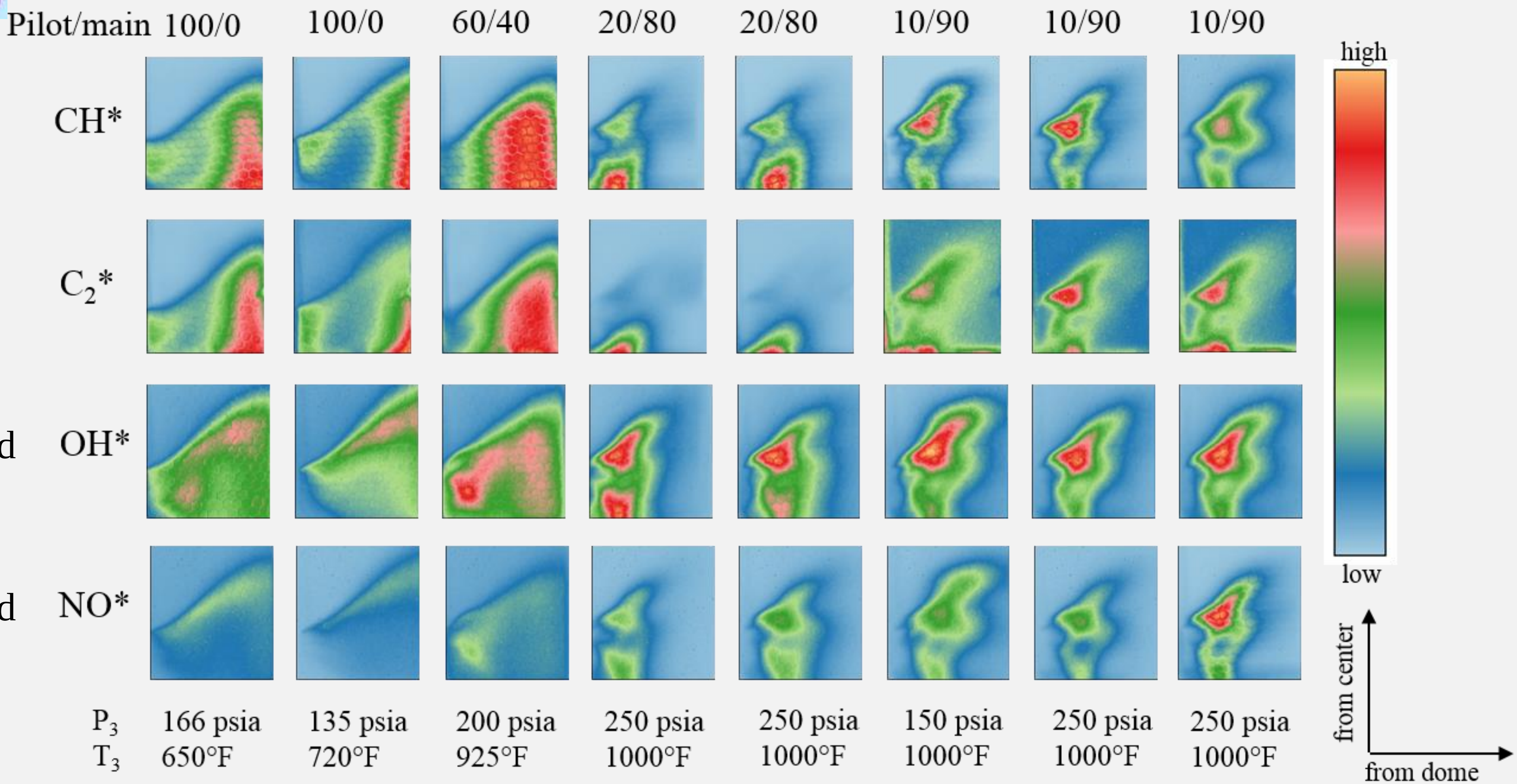


- OH along outer spray boundary—air side, e.g. pilot only
- 60/40 split shows bimodal distribution
- 60/40 & 20/80 have distribution within annular gap between pilot/main, 10/90 more discretized

Comparing CH, C_2*, OH*, NO* distributions*

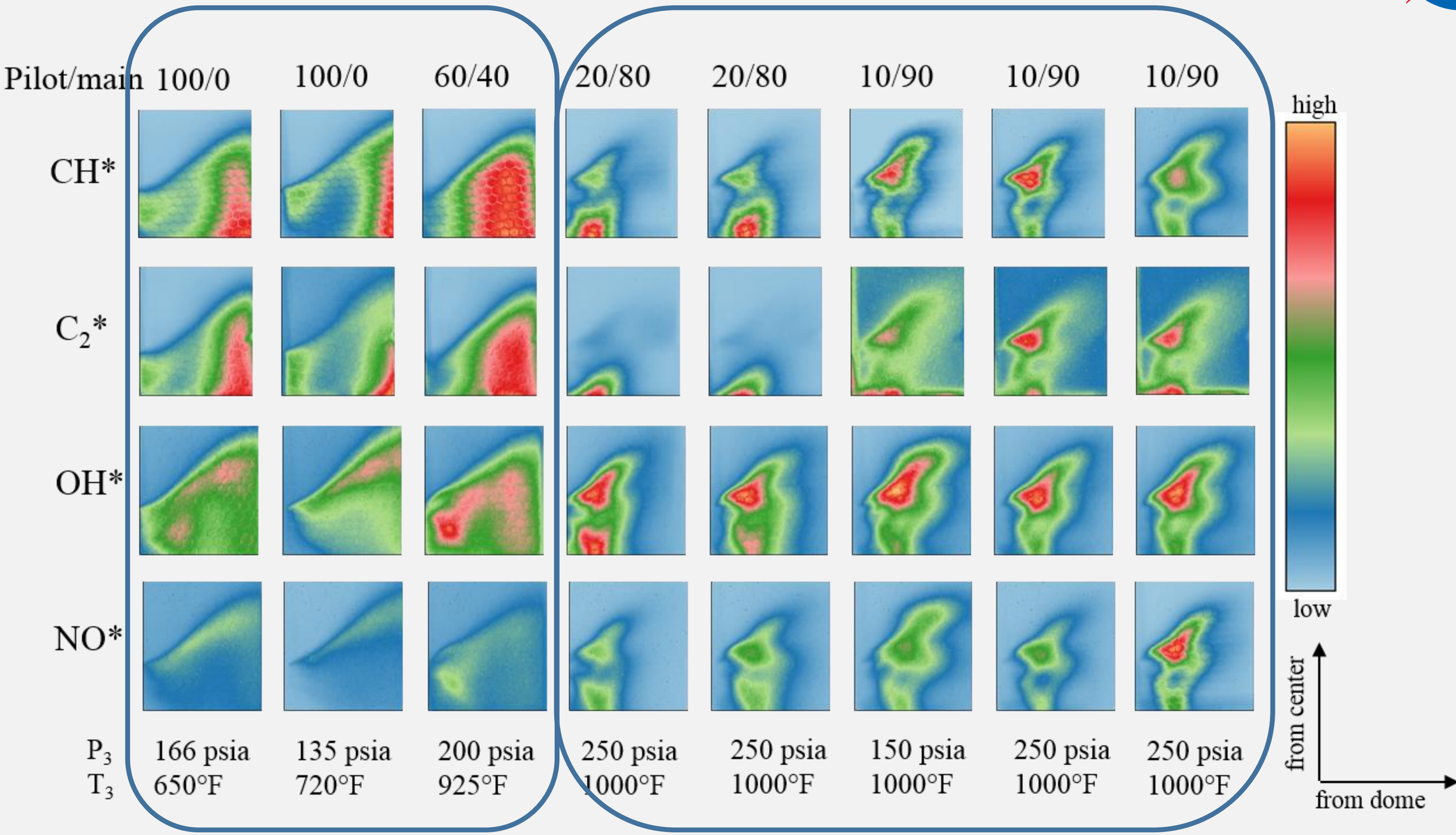
Line-of-sight through bulk volume





Three key points: ***(1) effect of %pilot***
(2) C_2* vs CH*
(3) NO* formation

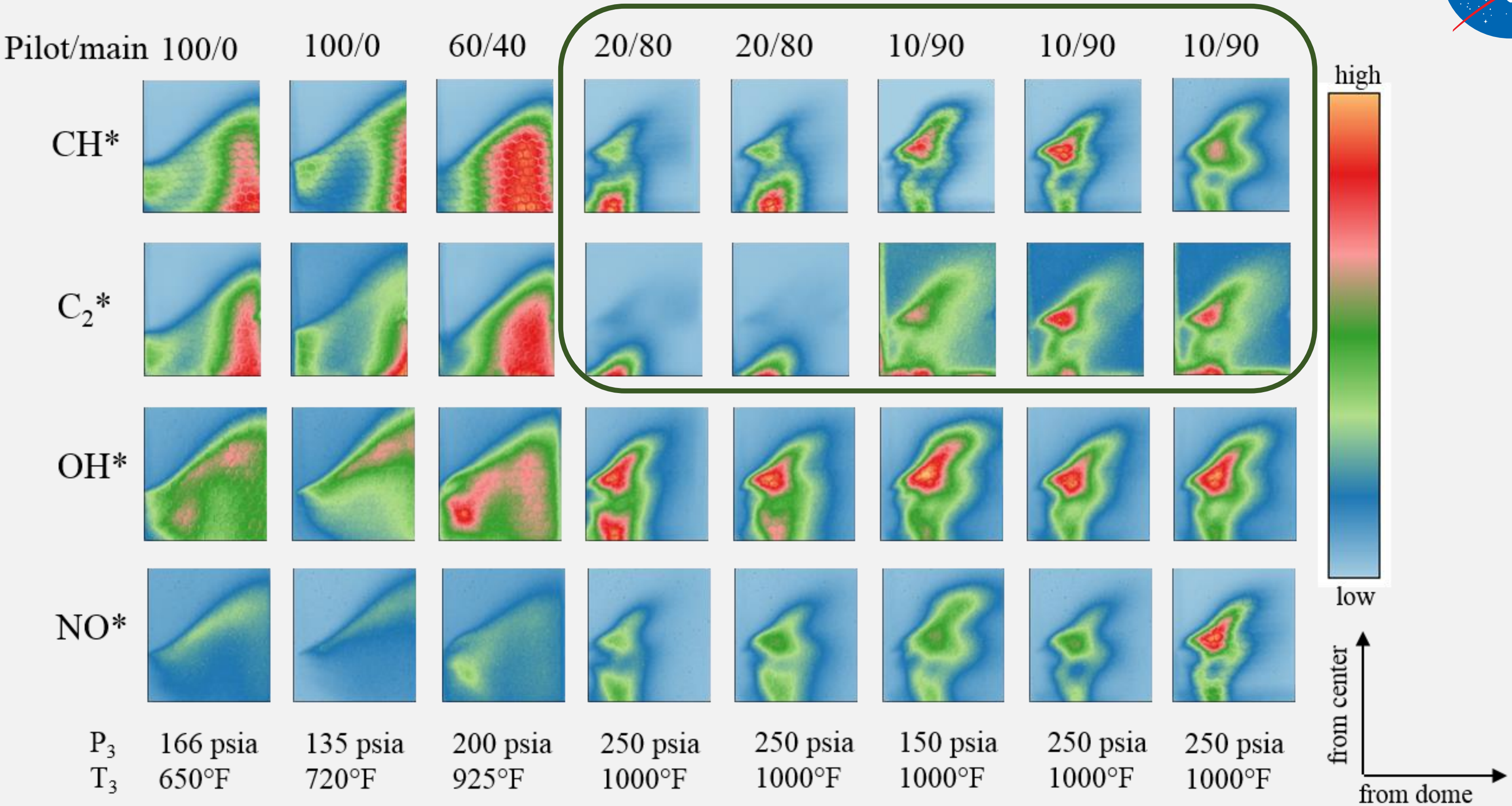
Comparing CH, C_2*, OH*, NO* distributions*



% pilot flow affects flame structure

- 100/0 and 60/40 splits have locally-rich pilots → high CH*, C2*, soot
- conical structure, longer flame
- 20/80, 10/90 splits have lower overall luminosity

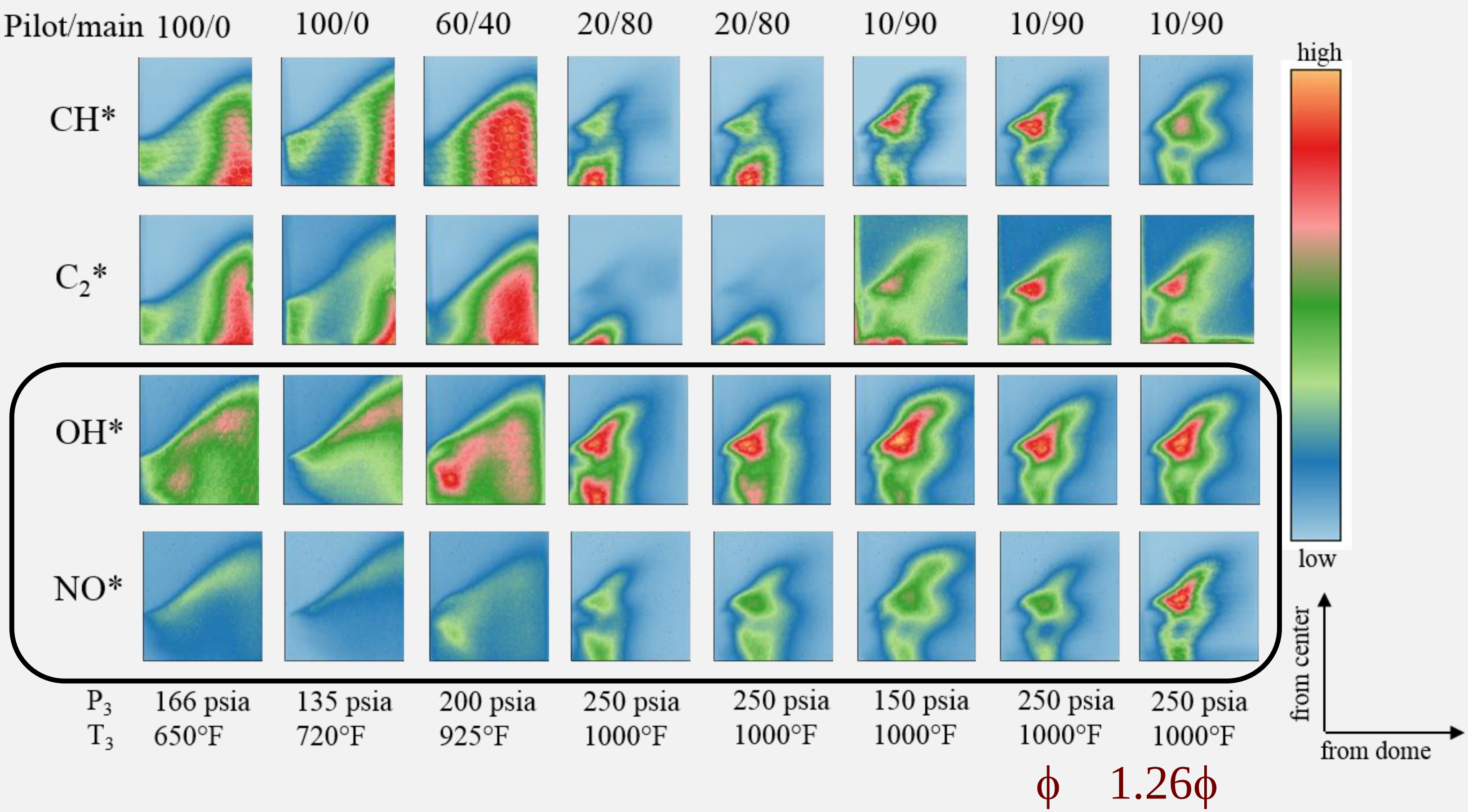
Comparing CH, C_2*, OH*, NO* distributions*



C_2^* vs CH^*

- 20/80: Both show weaker signal from main, but C_2^* much lower compared to pilot
- 10/90: Both show higher signal from main, but C_2^* pilot/main comparable
- Indicates different chemistry for these fuel splits—possible use for modeling using these chemiluminescent species

Comparing CH, C_2*, OH*, NO* distributions*

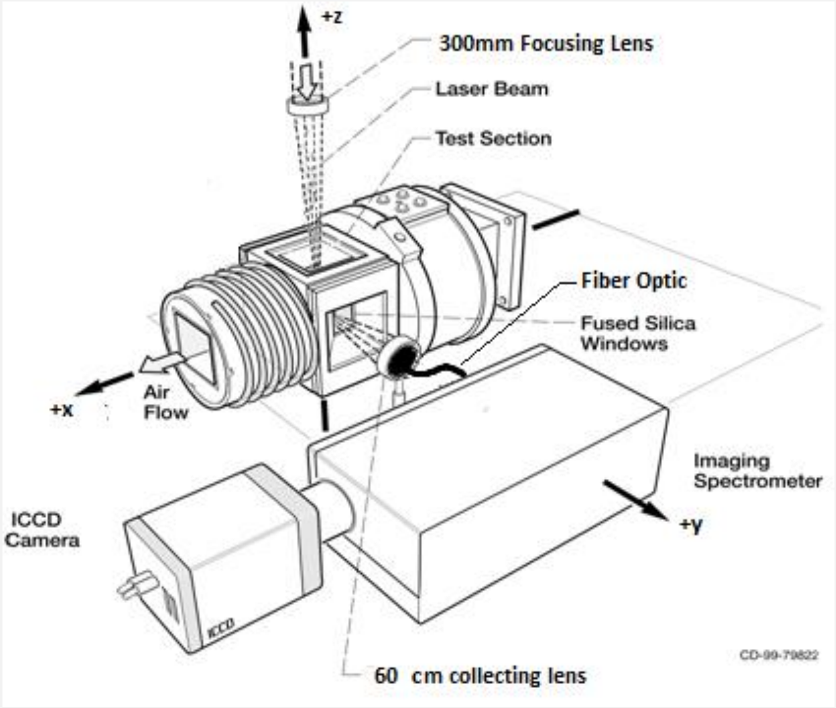


Regions with NO* closely follow regions of higher OH*

Highest NO occurs at highest overall equivalence ratio

Optical Diagnostics Setup and Testing—Pointwise

Spontaneous Raman Scattering

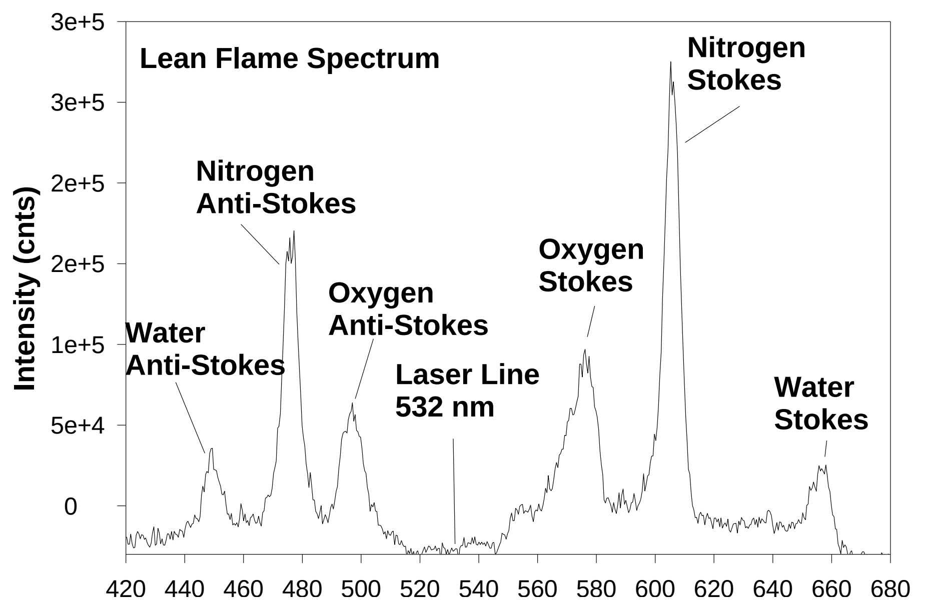


- Major Species
- Temperature via N_2 Stokes/anti-Stokes
- Probe volume imaged
  ~ 2-mm diameter x 5-mm

Raman Scattering

- Inelastic scatter from molecules
- Vibrational and rotational energy exchange
- Stokes: laser gives energy to molecule
- Anti-Stokes: molecule gives energy to laser

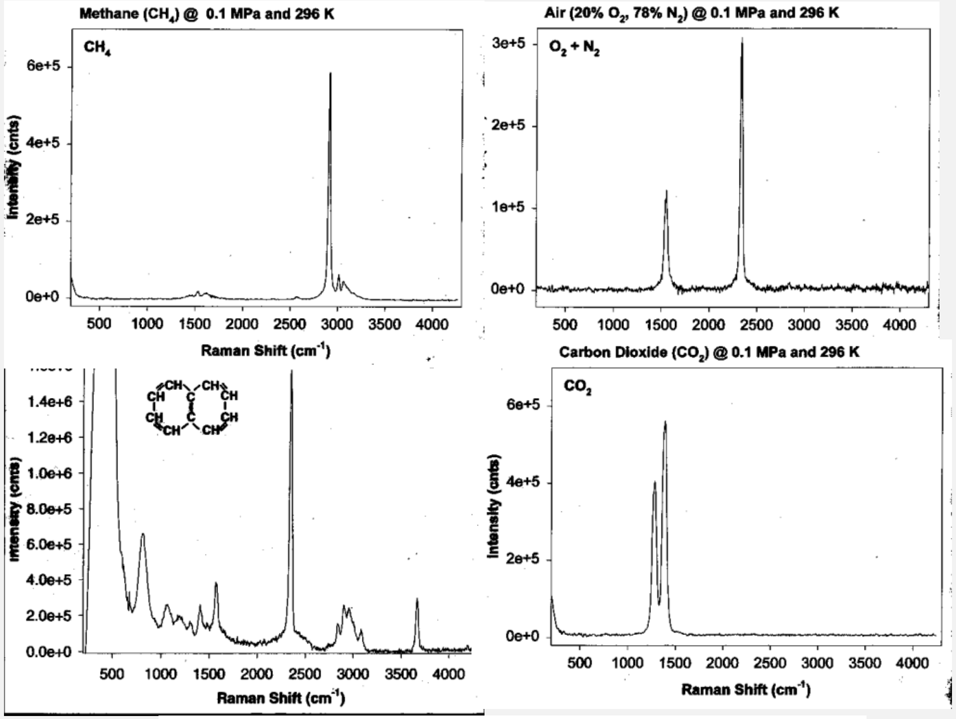
Example vibrational spectrum:
Hencken burner methane-air flame



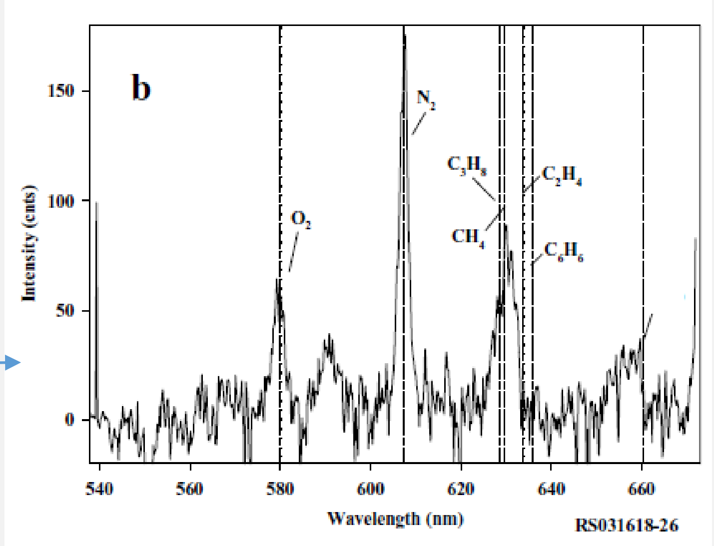
Raman Spectrum of post-reaction product mixture in a Hencken burner. The Stokes-to-Anti-Stokes ratio provides the temperature, and the integrated intensities under the Stokes curves of water, nitrogen, oxygen, and carbon dioxide provide the mole fractions. Note that the broad peak indicated as oxygen is actually a combination of oxygen and carbon dioxide.

Vibrational Raman: Some key combustion species and sample spectra

species	Raman freq cm^{-1}	relative cross-section incident 532	wavelength (nm) w/ 532nm scatter: Stokes	wavelength (nm) w/ 532nm scatter: AS
major species	**vibrational lines**			
H_2	4155.2	3.86	682.98	435.69
H_2	3796.19		666.63	442.61
water	3652	3.51	660.28	445.45
N_2	2331	1.00	607.31	473.31
CO	2143	0.93	600.46	477.56
O_2	1556	1.04	580.01	491.33
CO_2(n1)	1388	1.13	574.42	495.42
CO_2(2Sn2)	1285		571.04	497.96
fuels				
CH_4(n3)	3017	5.70	633.71	458.42
CH_4(n1)	2914	8.55	629.60	460.60
C_2H_2	1973	6.20	594.39	481.46
C_2H_4(n1)	3020	6.40	633.83	458.36
C_2H_4(n2)	1623	2.12	582.28	489.72
C_2H_4	1342	2.80	572.90	496.55
C_2H_6	993	1.72	561.67	505.31

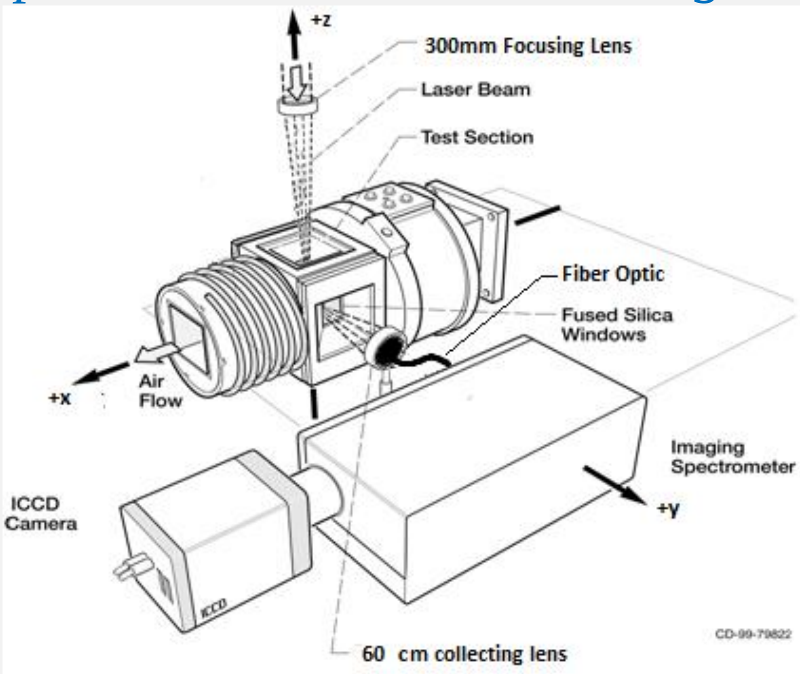


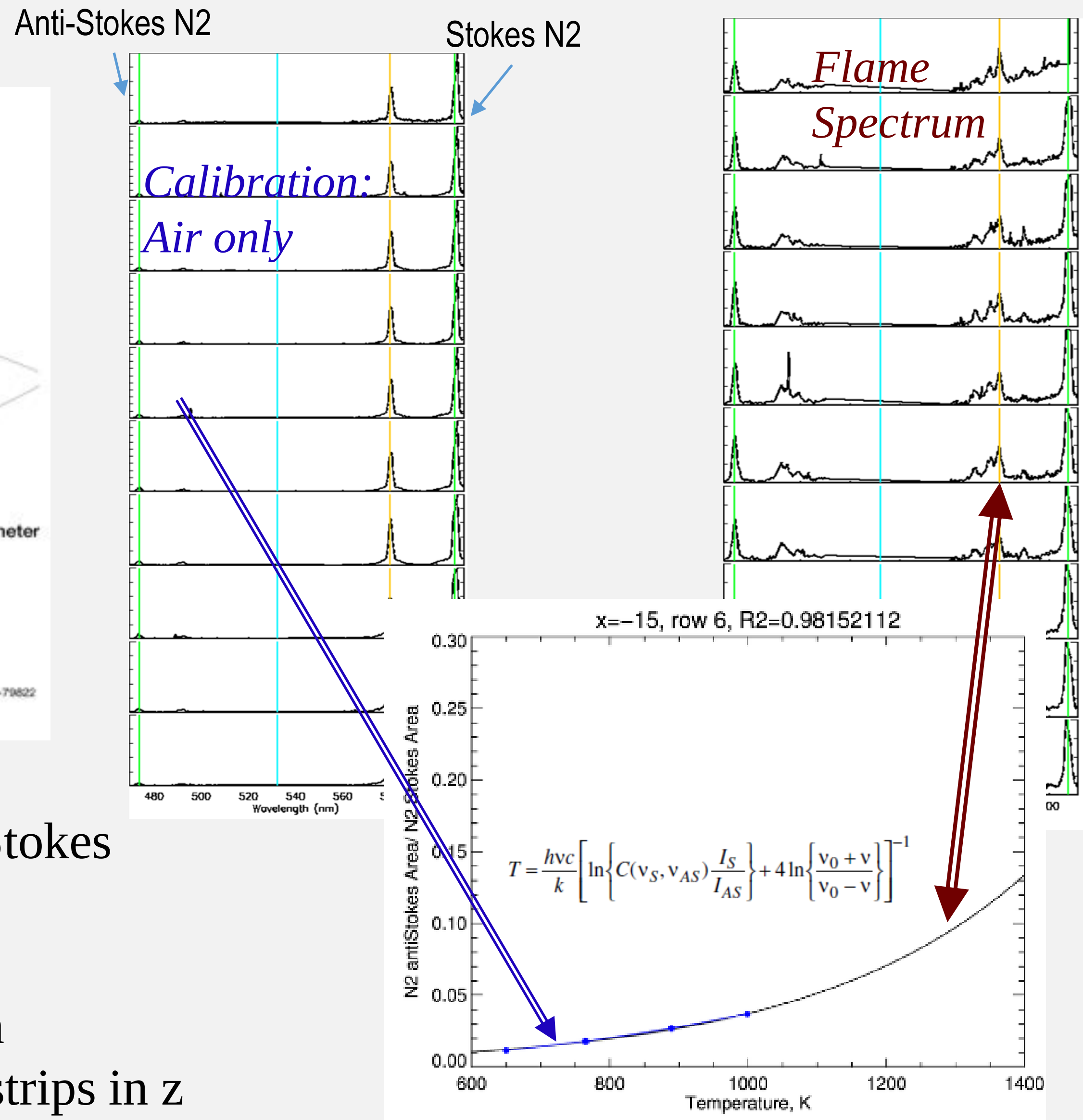
From 9-point LDI, CE5
T_3, P_3 = 900°F, 10 atm



Optical Diagnostics Setup and Testing—Pointwise

Spontaneous Raman Scattering



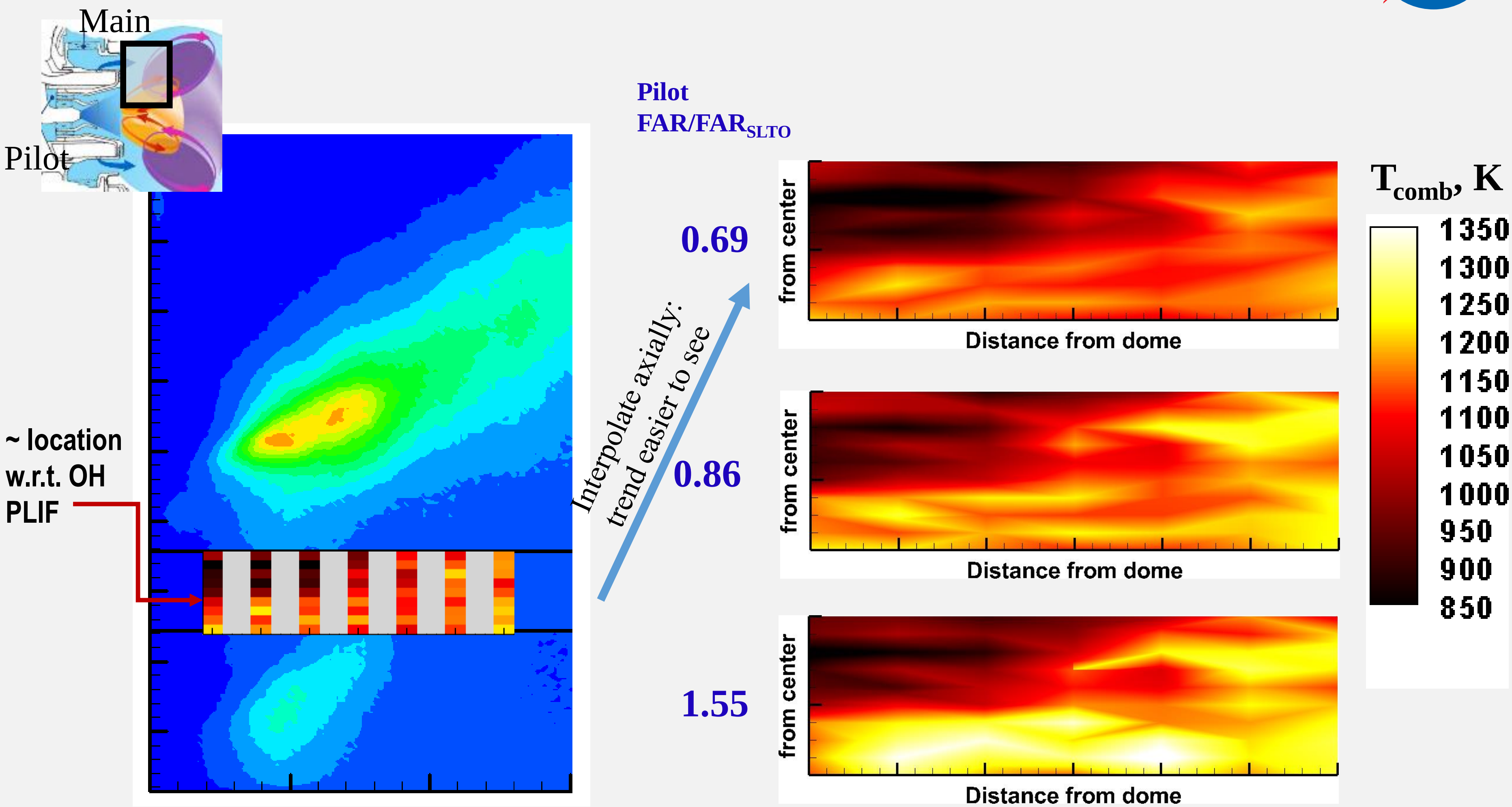


- Temperature via N_2 Stokes/anti-Stokes
- Limited speciation
- Probe volume imaged

  ~ 2-mm diameter x 5-mm high

  Camera: array binned into 10 strips in z
- Axial Traverse: 5-mm increments

Raman Scattering—relative local combustion Temperature



Stokes/Anti-Stokes method shows promise in this environment

- Temperature increases with radial and downstream location
- Highest temperatures correspond with highest local equivalence ratio

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11. Hicks, Y.R., T.G. Capil, and R. C. Anderson [2018]. "Flame Tube Testing of a GEA TAPS Injector: Effects of fuel staging on combustor fuel spray patterns, flow structure, and speciation," Paper AIAA-2018-4476, July 8-11. NASA TM-2018-219984
12. Hicks, Y.R., S.A. Tedder, R.C. Anderson, A.C. Iannetti, L.L. Smith, and Z. Dai [2014]. "UTRC Supersonic Low Emissions Combustion tests in NASA Combustor Subcomponent Test Facility—CFD and Test Results", Paper AIAA 2014-3627, NASA/TM—2014-218493.

Thanks for your attention!