

Nitric Oxide PLIF Visualization of Simulated Fuel-Air Mixing in a Dual-Mode Scramjet

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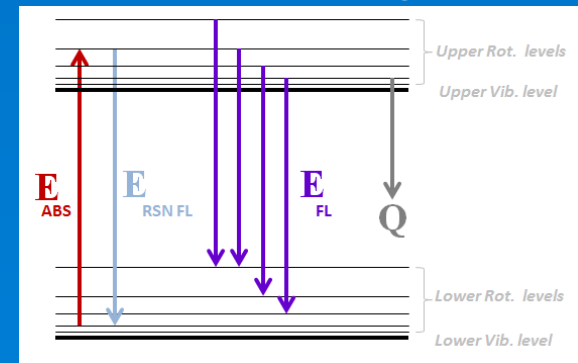


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Motivations



- Use Nitric Oxide (NO) Planar Laser Induced Fluorescence (PLIF) technique to evaluate fuel/air mixing in a dual mode scramjet
 - Pre-mix fuel and air to simplify the physics occurring in the combustor

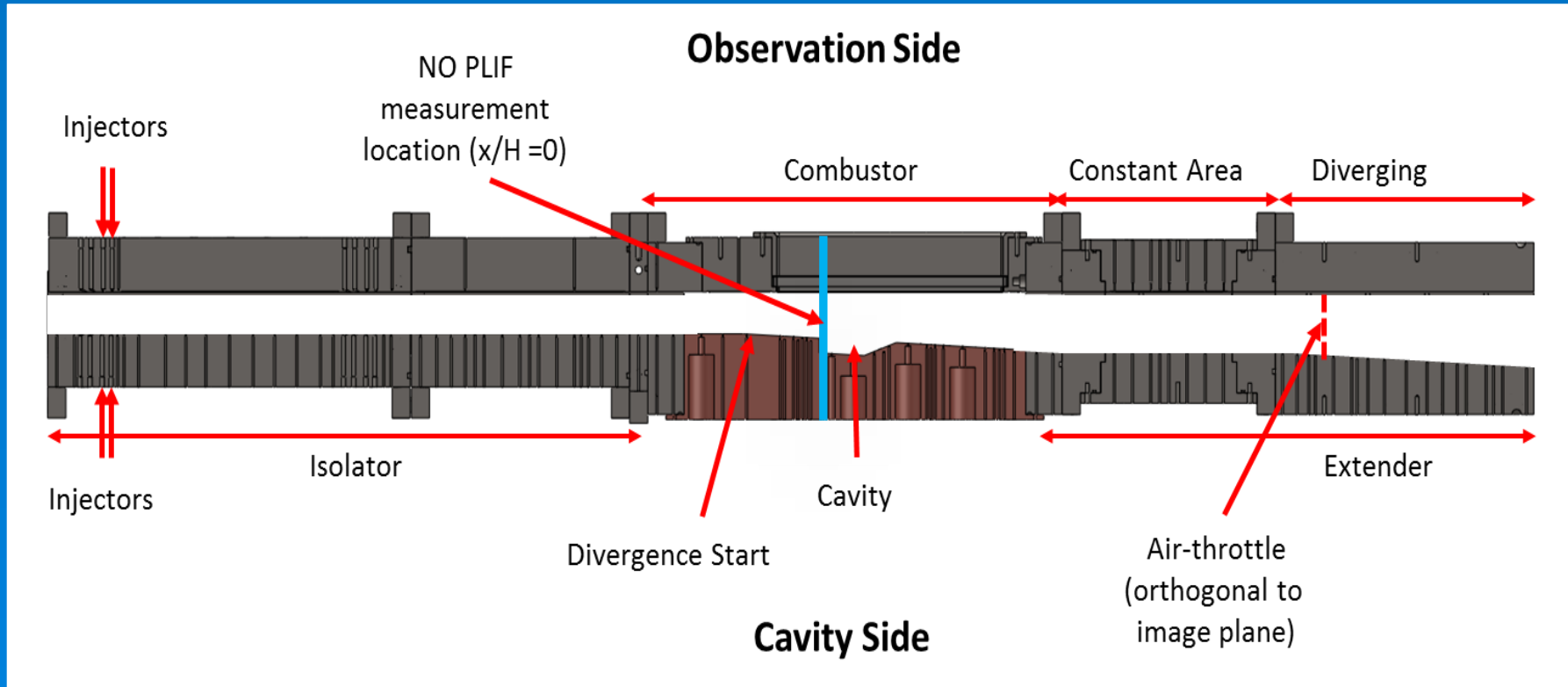


- Simulation of scramjet combustion using a cold mixture:
 - Fuel surrogate (N_2 -NO mixture) in place of ethylene (C_2H_4)
 - N_2 -NO mixture has similar molecular weight as C_2H_4
 - Combustion back-pressure effect simulated by air-throttle
- Different configurations tested to identify the best premixed case:
 - Variations in Equivalence Ratios (ER) tested
 - Variations in shock train locations tested

Experimental Setup



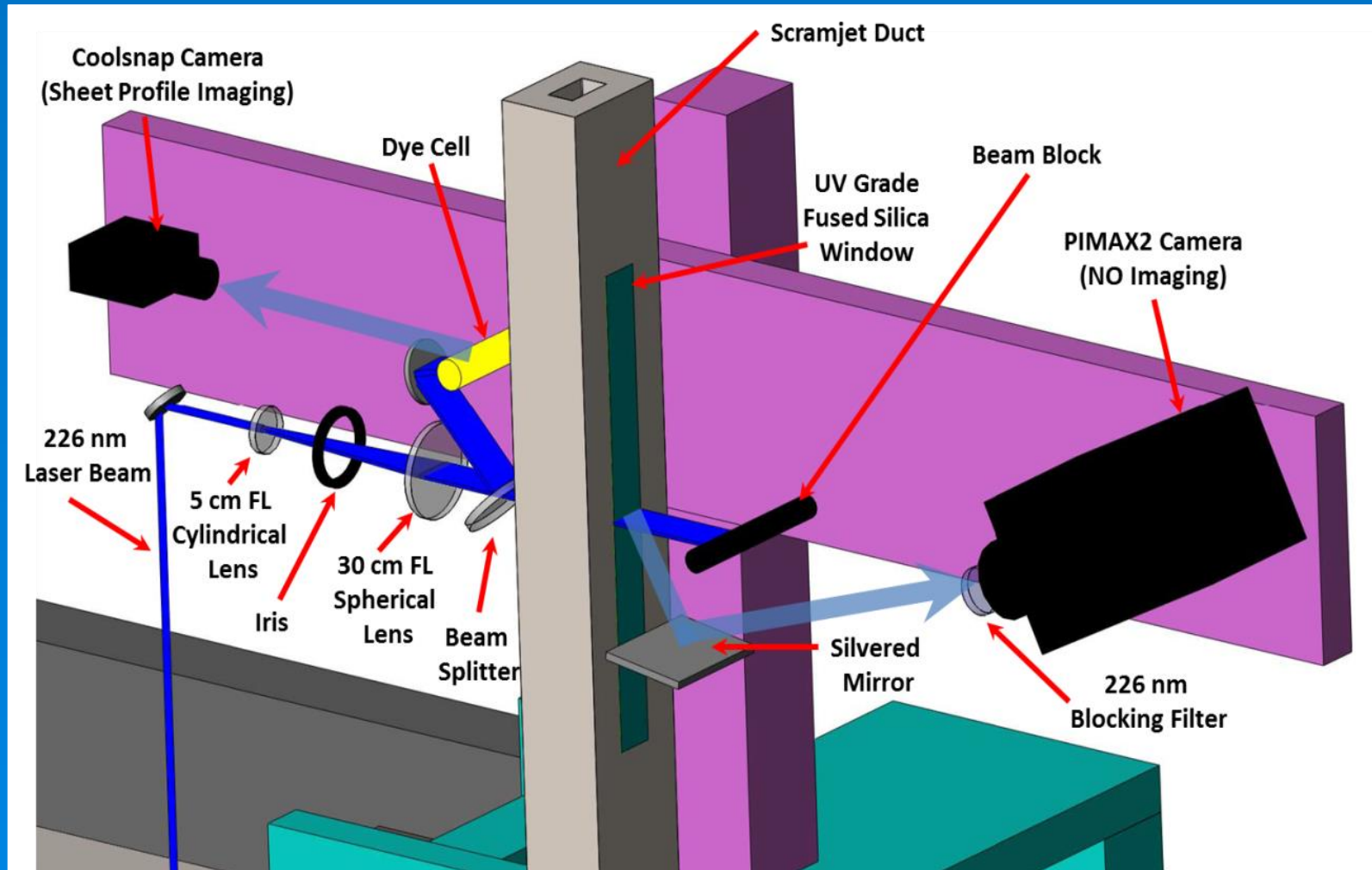
Facility Flow Path



- Two rows of upstream fuel injectors at 90 degree to the free stream
- Air-throttle mechanism to simulate combustion back-pressure
- Cavity for flame holding
- Vary equivalence ratio (ER) and shock train location

Experimental Setup

Laser and Optical Setup



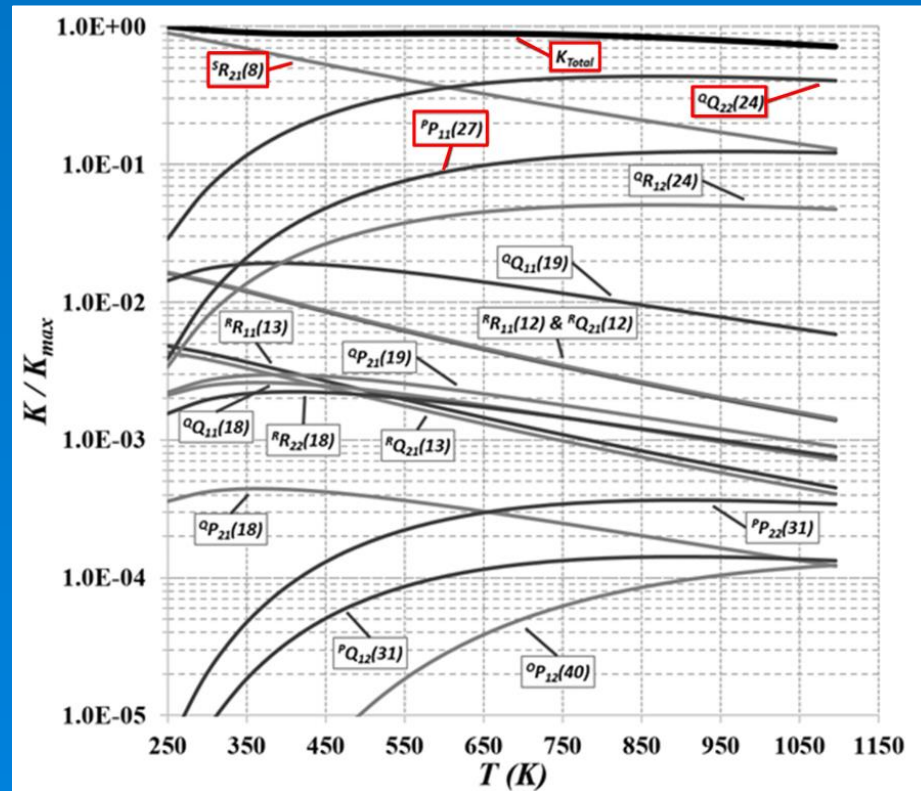
Experimental Method



Choosing the Laser Frequency

Laser frequency was chosen to make NO LIF signal (S_{LIF}) proportional only to NO mole fraction (χ_{NO}) and independent of temperature (T) and Pressure (P):

$$S_{LIF} \sim K \chi_{NO}$$



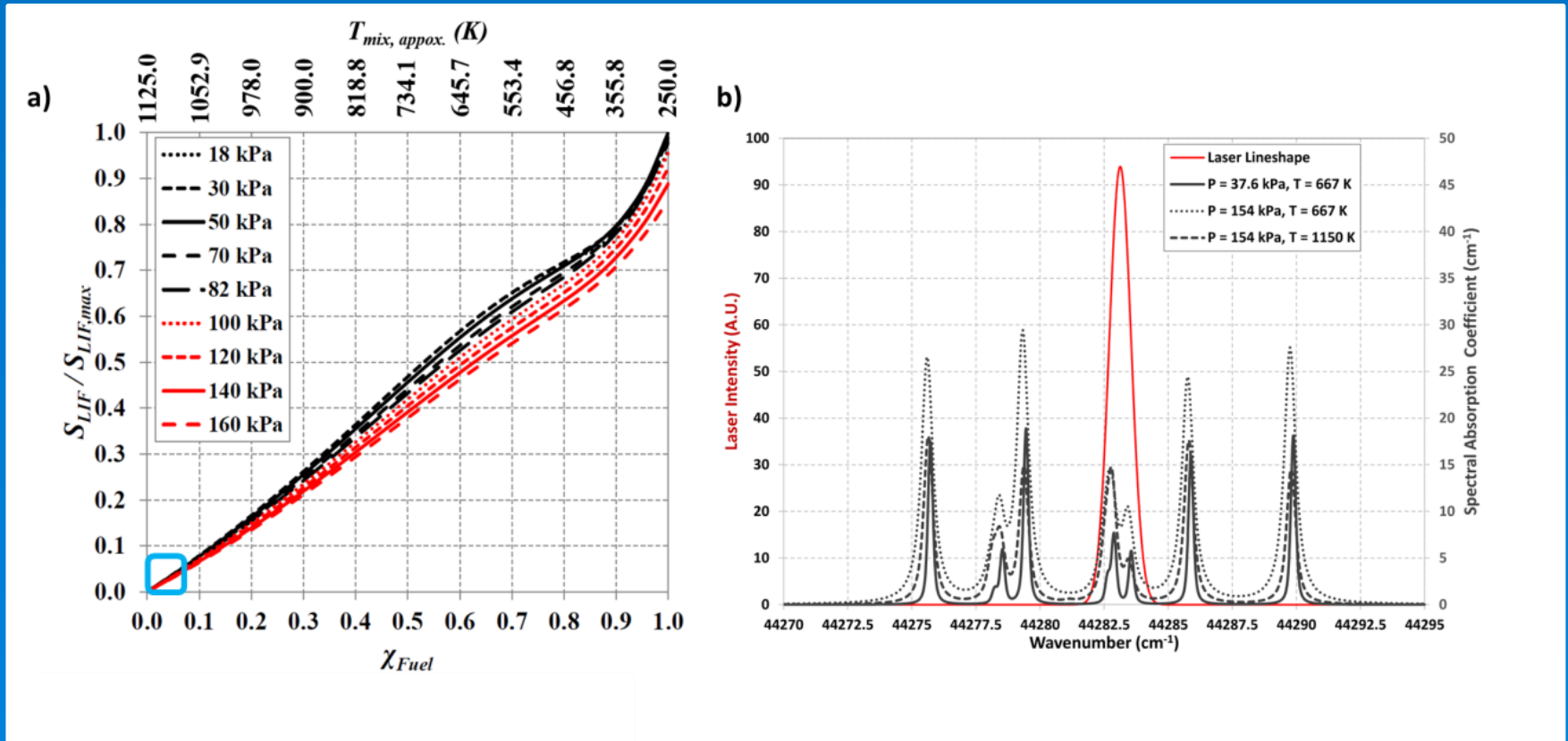
- Excitation of NO rotational transitions $P_{11}(27)$, $Q_{22}(24)$ and $S_{R_{21}}(8)$
- Line selected based on previous work* with extended range based on estimated test conditions ($T = 667-1100$ K, $p = 80-160$ kPa)

* J. S. Fox, A. F. P. Houwing, P. M. Danehy, M. J. Gaston, N. R. Mudford, S. L. Gai, "Mole-Fraction-Sensitive Imaging of Hypermixing Shear Layers", *Journal of Propulsion and Power*, Vol. 17, No. 2, 2001, pp. 284-292

Experimental Method



Sensitivity to Pressure

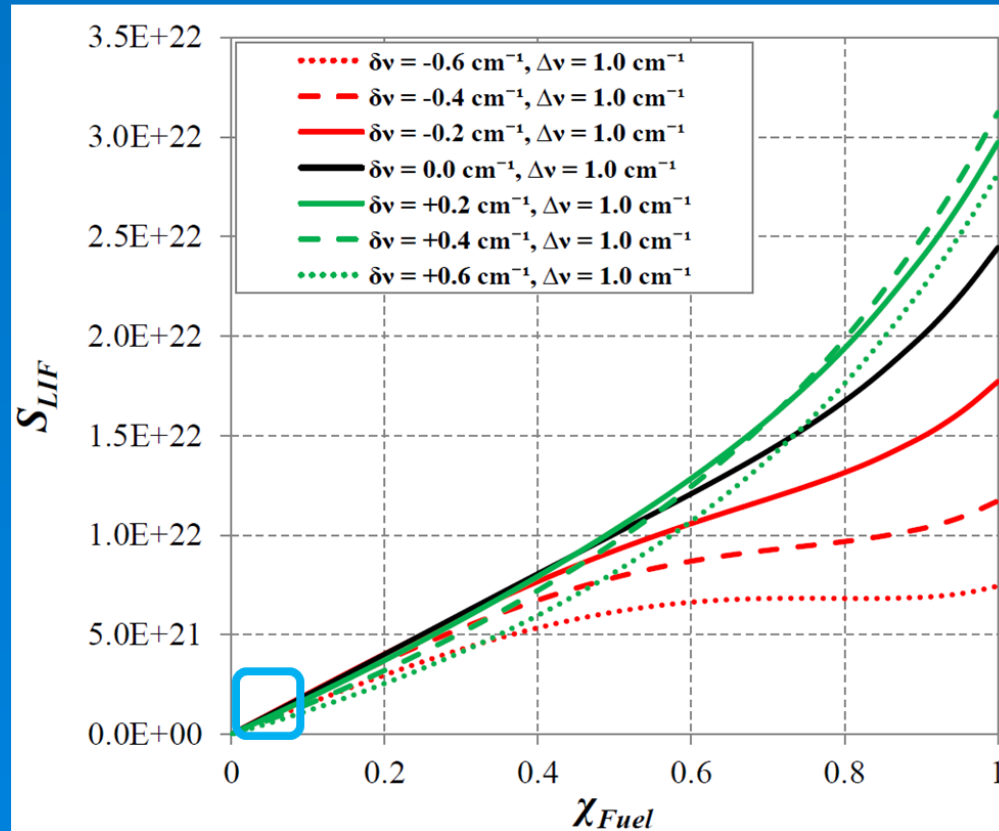


- LIF signal proportional to mole fraction
- LIF signal pressure-independent in measurement region (blue box)
- Laser profile always overlaps the selected NO transitions

Experimental Method



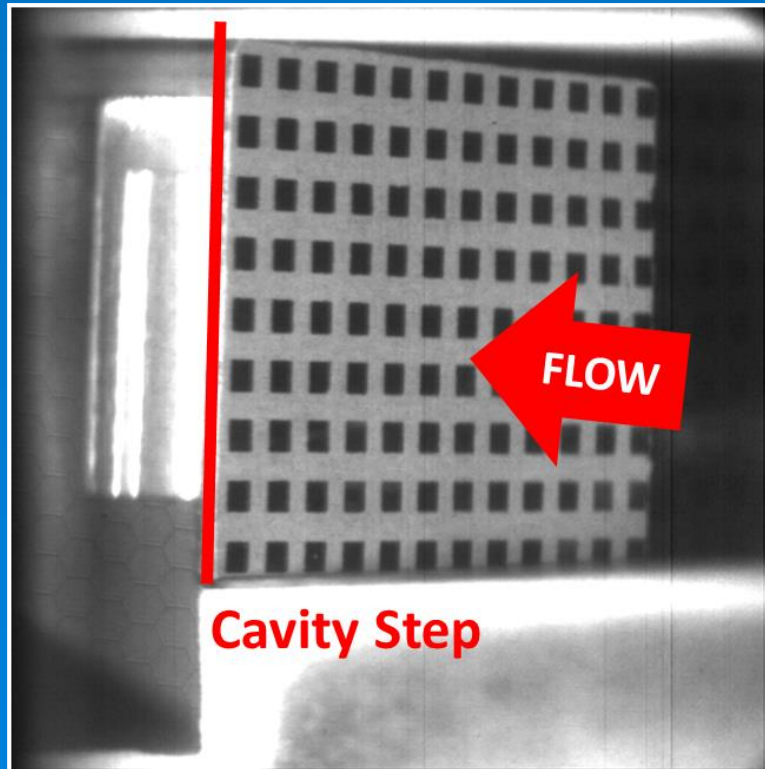
Sensitivity to Laser Detuning



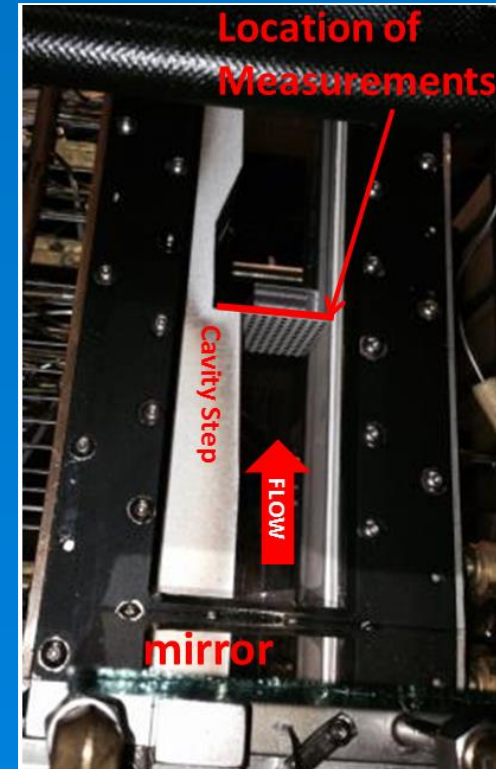
- LIF signal is proportional to mole fraction
- LIF signal not sensitive to small detuning in measurement region (blue box)

Experimental Method

Dotcard



PI Max (PLIF Camera) Image

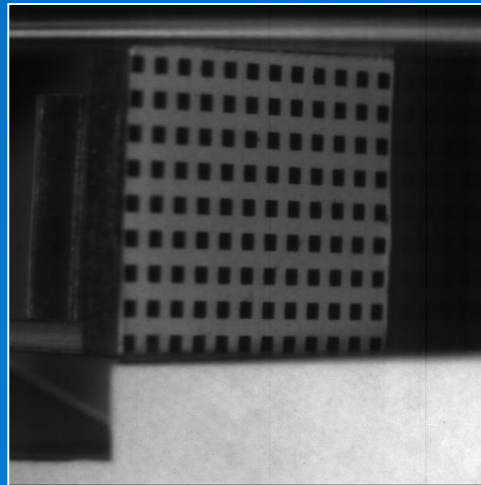


Photographic Camera Image

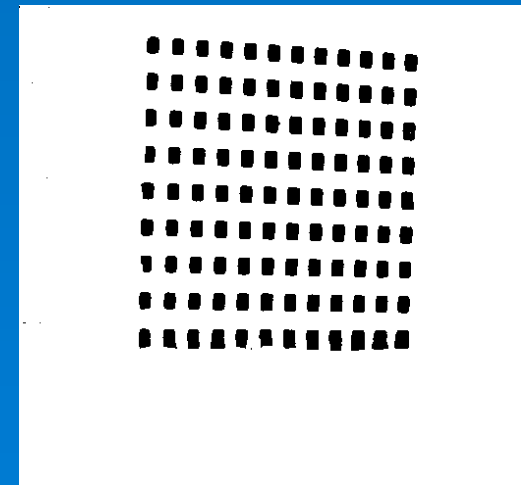
- Raw images (not cropped, not processed, not stretched, not rotated)
- X magnification: 7.75 pixel/mm, Y magnification: 12.5 pixel/mm
- Laser sheet passes right to left, skimming across the dotcard.

Experimental Method

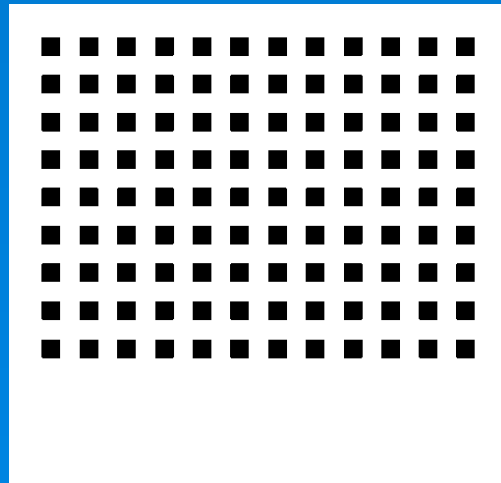
Dewarping



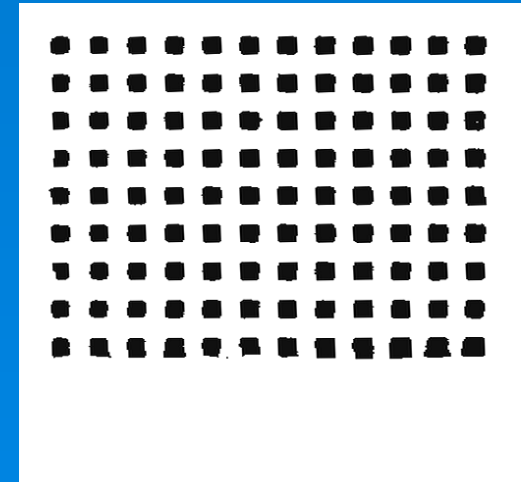
Original Dotcard



“Cleaned” Dotcard



Target Image



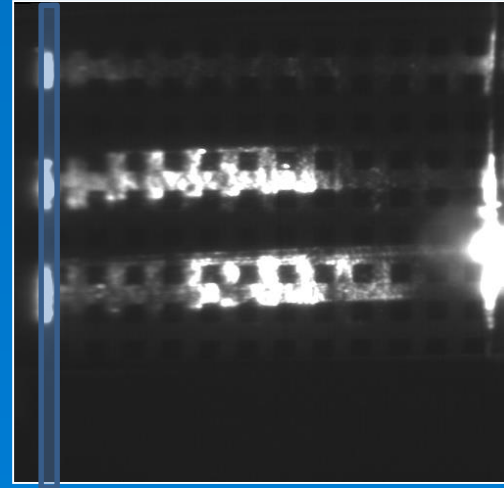
Dewarped Dotcard

Experimental Method

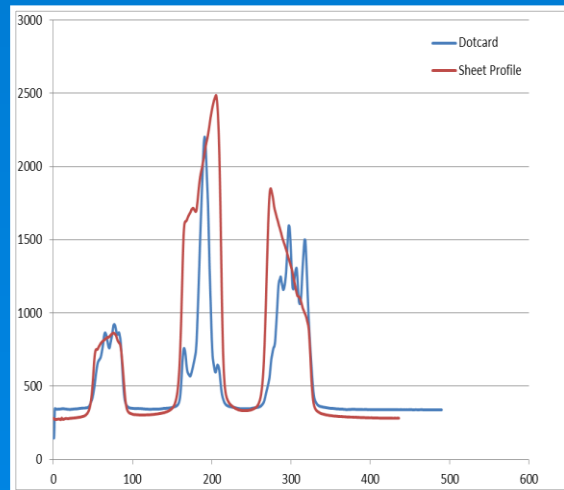
Laser Intensity Correction



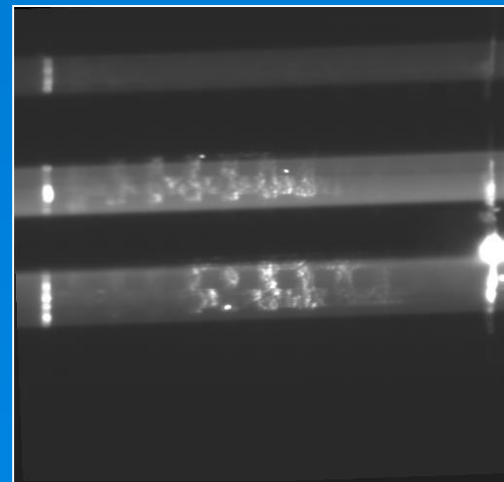
Laser Sheet with mask



Dewarped Dotcard with mask



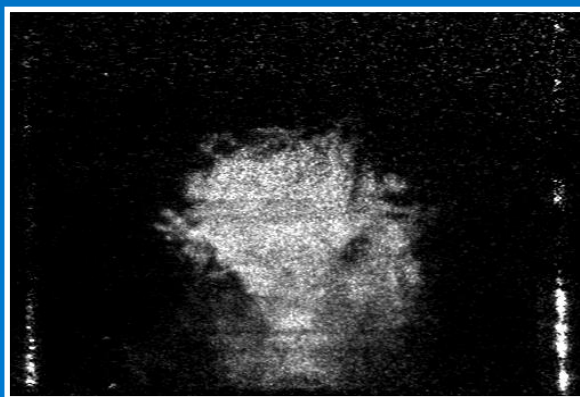
Plot profiles overlapped



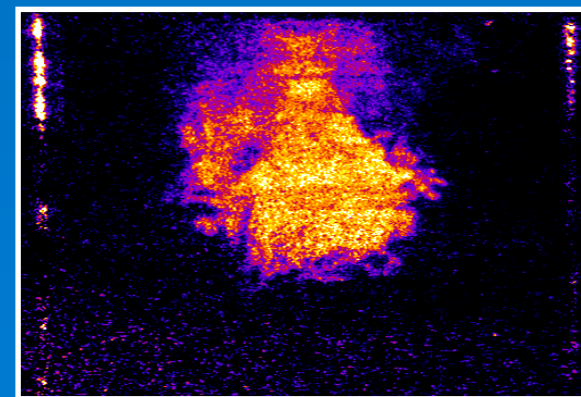
Dotcard and laser sheet overlapped

Experimental Method

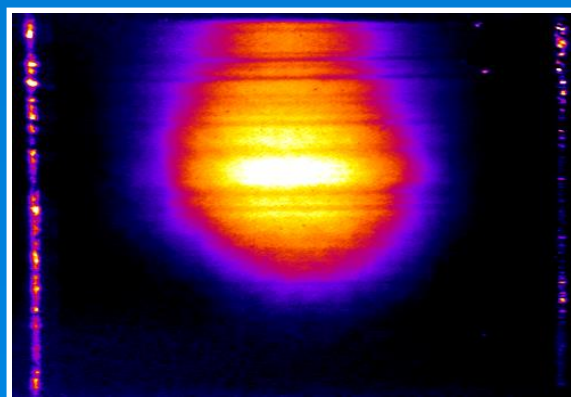
Image Processing



Dewarped and Laser
Intensity Corrected Image



180° Rotated Image and
False Colors Added



Average Image

Results



Cases Tested

Date	Run	NO conc.	E.R.	Injector split cav/obs	Shock train [x/H]	Mixing Goodness
Jun 13 th	3	10%	0.42	0.23/0.15	-45	81%
Jun 13 th	3b	10%	0.42	0.23/0.15	-45	75%
Jun 13 th	4	10%	0.31	0.31/0.00	-15	30%
Jun 13 th	5	10%	0.31	0.155/0.155	-15	80%
Jun 13 th	7	10%	0.31	0.155/0.156	off	69%
Aug 29 th	4	10%	0.44	0.22/0.22	-45	86%
Aug 29 th	5	10%	0.36	0.19/0.17	-45	87%
Aug 29 th	6	10%	0.35	0.18/0.17	-30	88%
Aug 29 th	7	5%	0.44	0.22/0.22	-45	90%
Aug 29 th	8a	10%	0.22	0.22/0.00	-45	81%
Aug 29 th	8c	10%	0.22	0.22/0.00	off	24%

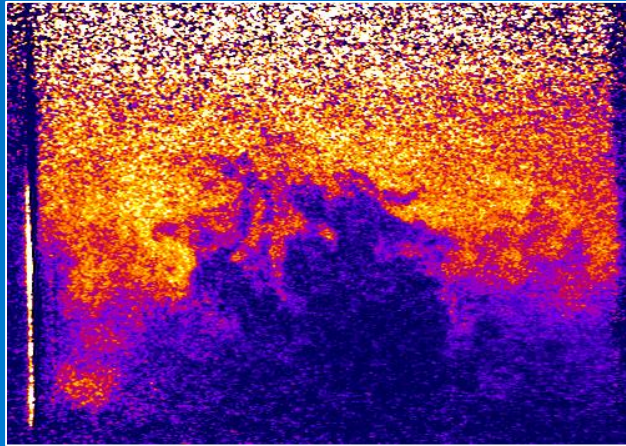
- Cases in green are presented herein
- Define “Mixing goodness”:

$$\text{Mixing goodness} = \left(1 - \frac{\text{Standard Deviation}}{\text{Mean}} \right) \times 100$$

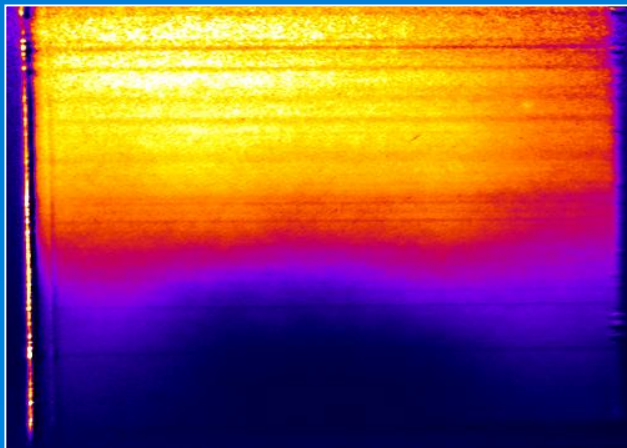
- Higher mixing goodness  more uniform image

Results

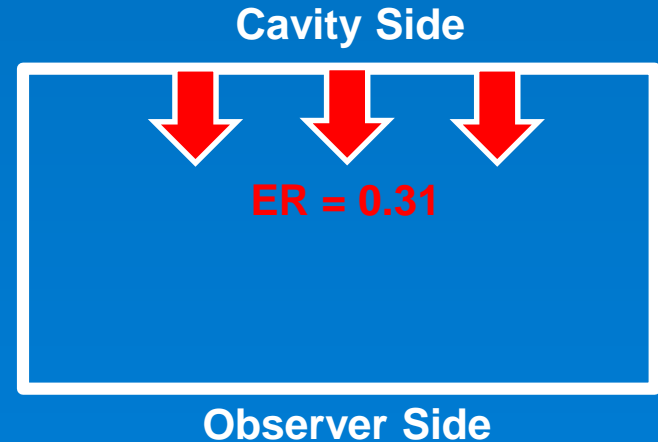
Run 4 June 13th



Selected single shots



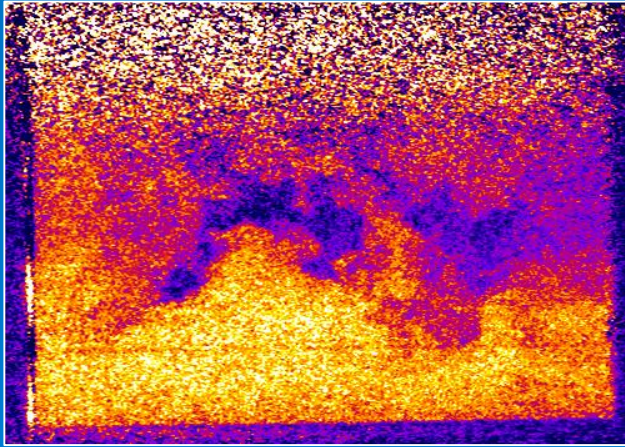
Average



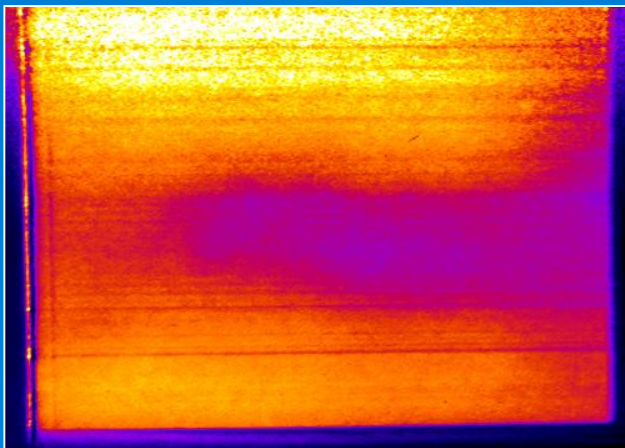
- ER = 0.31
- Shock Train $x/H = -15$
- Mixing goodness = 30%

Results

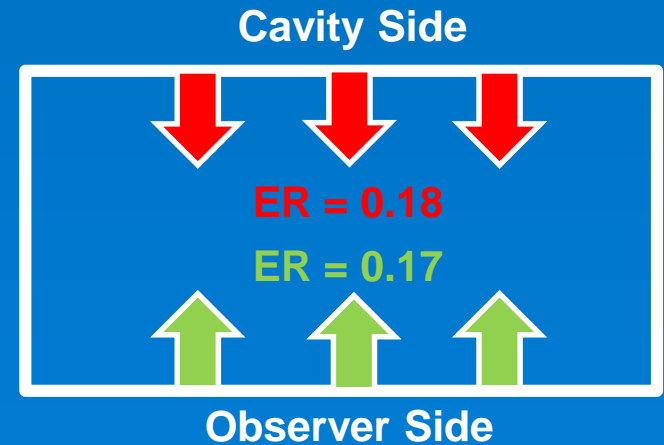
Run 7 June 13th



Selected single shots



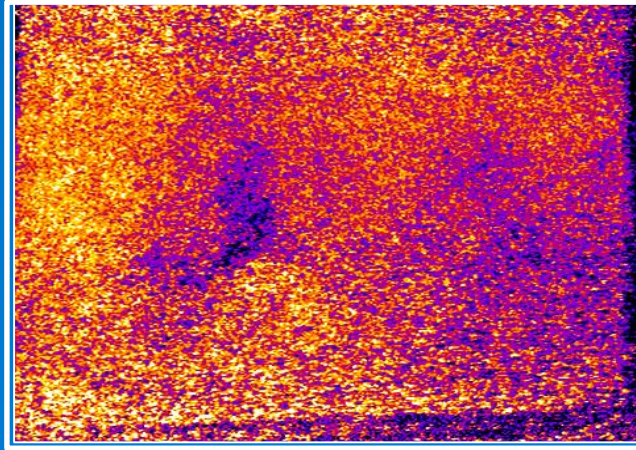
Average



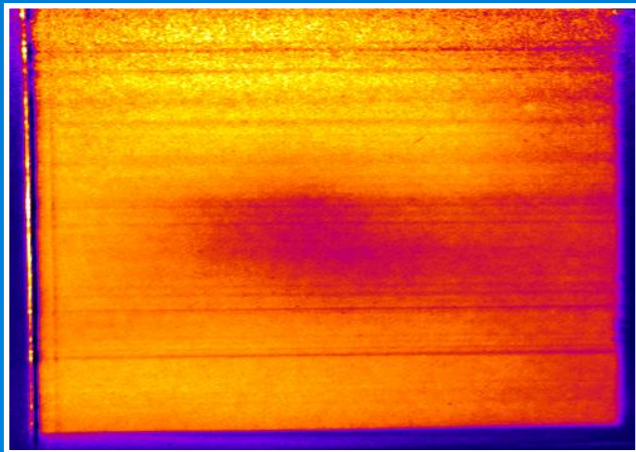
- ER = 0.35
- Shock Train off
- Mixing goodness = 69%

Results

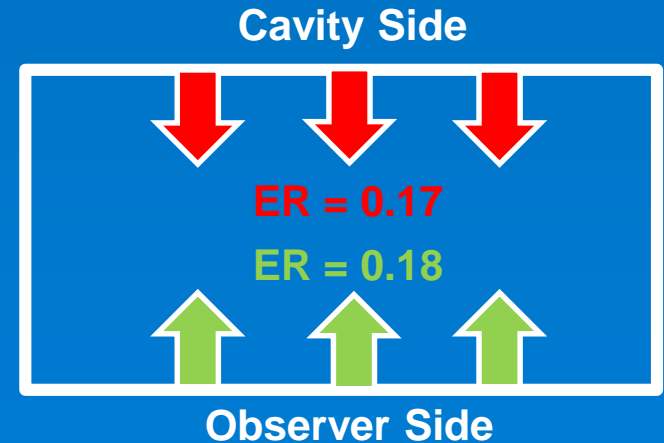
Run 6 August 29th



Selected single shots



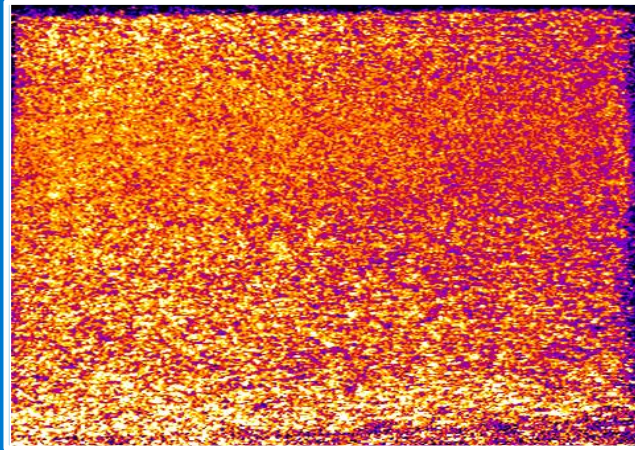
Average



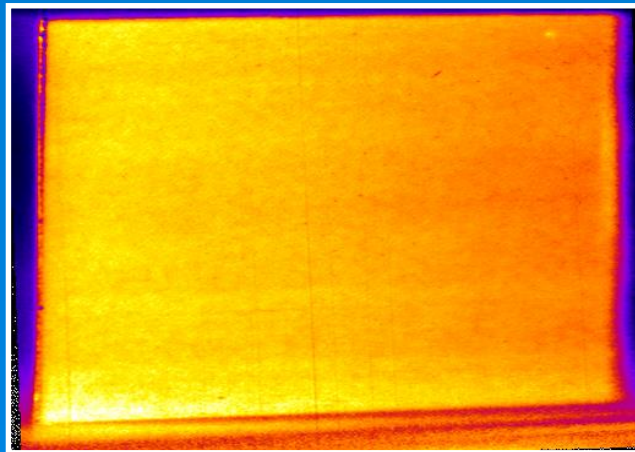
- ER = 0.35
- Shock Train $x/H = -30$
- Mixing goodness = 88%

Results

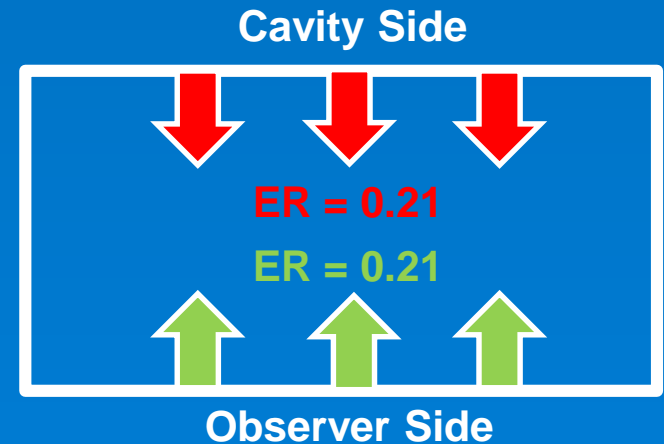
Run 7 August 29th



Selected single shots

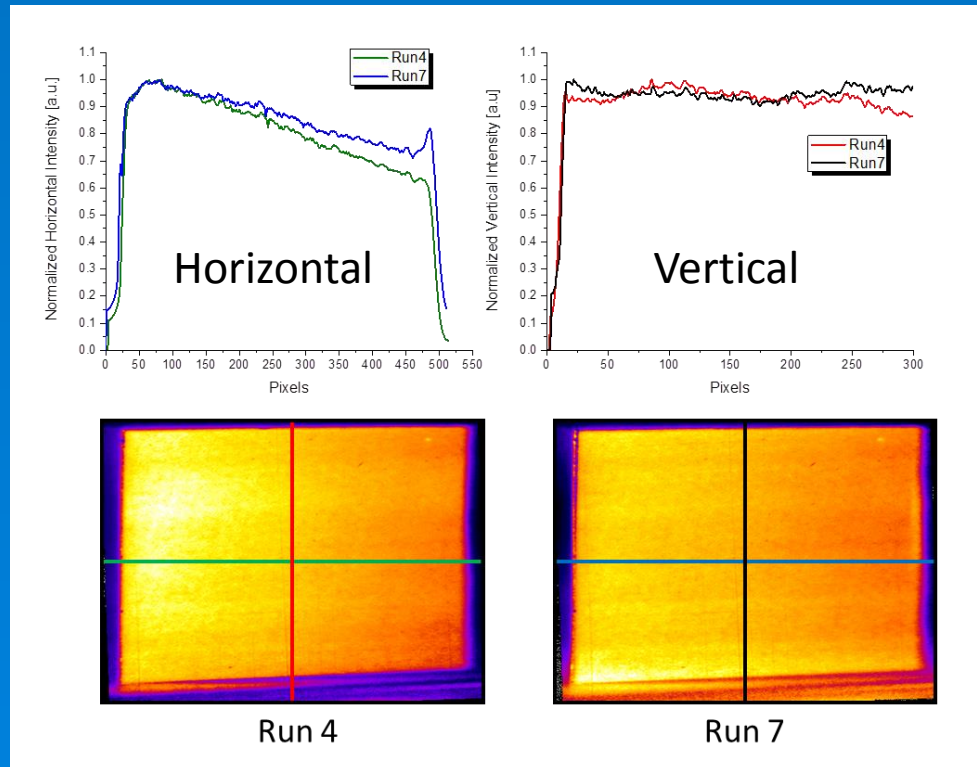


Average



- ER = 0.42
- Shock Train $x/H = -45$
- Mixing goodness = 90%

Laser Beam Attenuation from Absorption by NO



- Vertical uniformity is comparable ($\pm 5\%$)
- Horizontal uniformity is different for different amounts of NO:
 - More NO injected \Rightarrow more laser absorbed \Rightarrow less signal on right

- Observed left-to-right attenuation of PLIF signal in images: is it fuel distribution or an artifact of the experiment?
- Run 4 (August 29th):
 - Fuel: 10% NO – 90% N₂
 - Mixing goodness 86%
- Run 7 (August 29th):
 - Fuel: 5% NO – 95% N₂
 - Mixing goodness 90%

Conclusions



- NO PLIF system successfully integrated into existing laser cart:
 - NO PLIF, OH PLIF and WIDECARS on the same mobile system
- Excitation of NO rotational transitions ${}^P P_{11}(27)$, ${}^Q Q_{22}(24)$ and ${}^S R_{21}(8)$ provided:
 - LIF signal proportional to NO mole fraction
 - LIF signal pressure and temperature independent
 - LIF signal insensitive to laser detuning
- Theoretical calculations extended to test conditions:
 - Temperature range 667 – 1100 K
 - Pressure range 80 – 160 kPa
- NO PLIF images successfully acquired in scramjet combustor:
 - Mixing goodness parameter introduced to compare mixing uniformity
 - Runs 6 and 7 (Aug 29th) identified as best cases
 - Best cases used for subsequent tests using ethylene fuel

Thank you for your attention



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QUESTIONS ?