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

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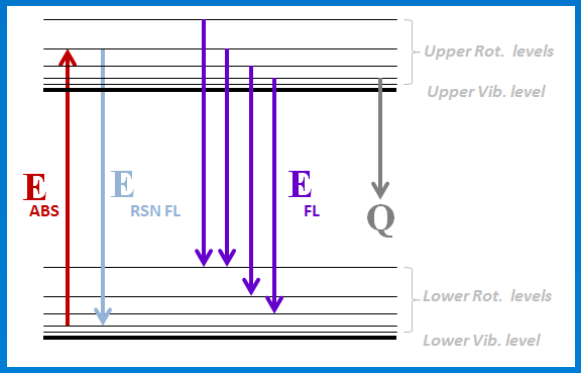
AIAA SciTech 2015, Orlando FL, Jan 5, 2015

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

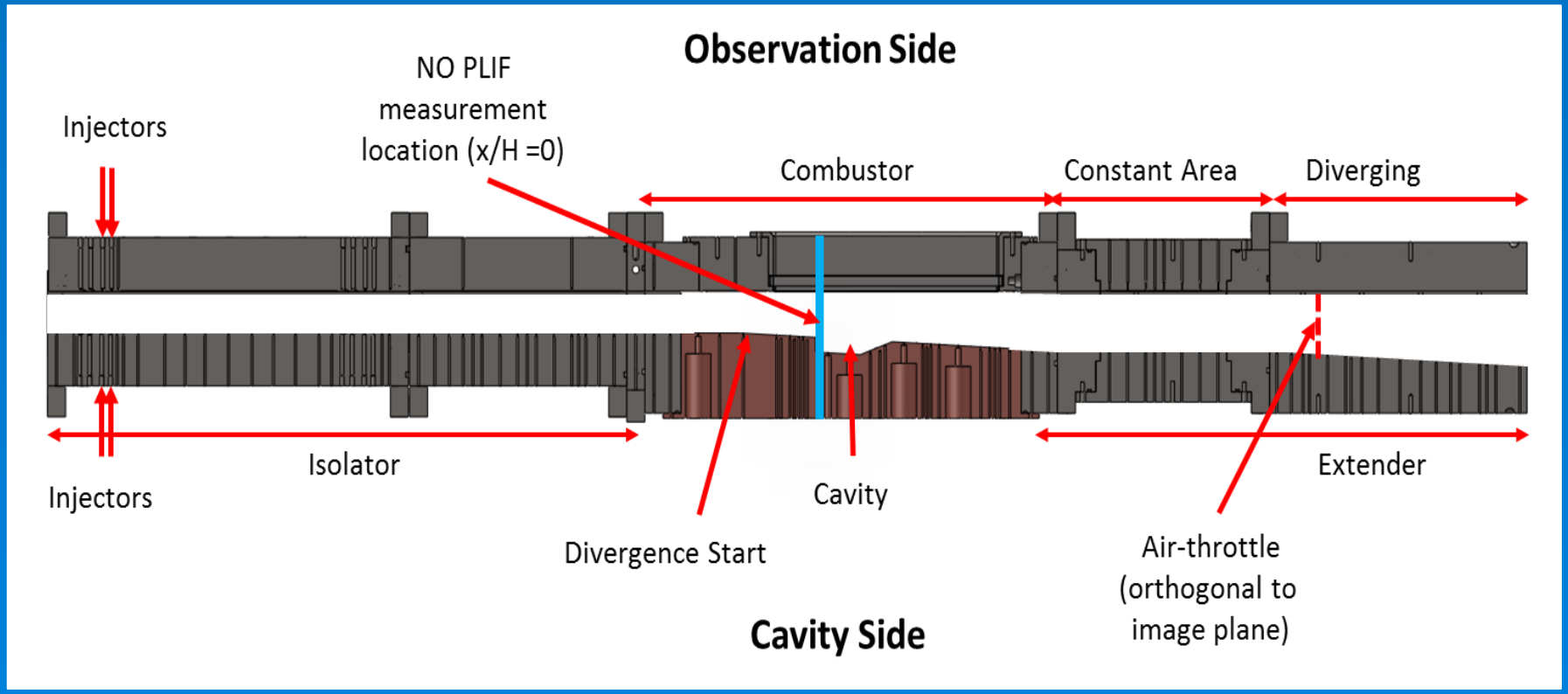


- Simulation of scramjet combustion using a cold mixture:
  - Fuel surrogate (N_2-NO mixture) in place of ethylene (C_2H_4)
    - N_2-NO mixture has similar molecular weight as C_2H_4
  - Combustion back-pressure effect simulated by air-throttle

- 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

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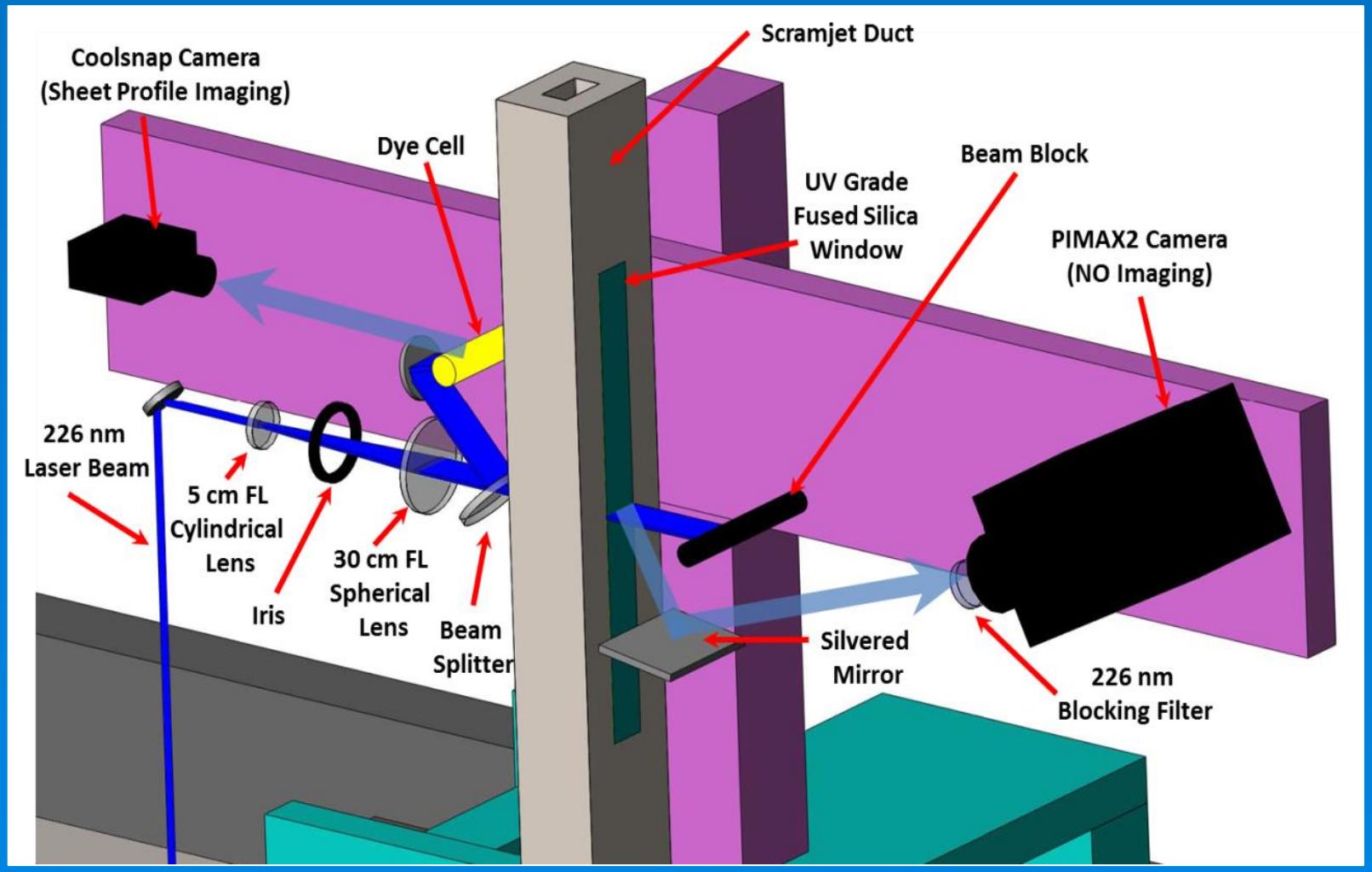
Experimental Setup

Laser and Optical Setup



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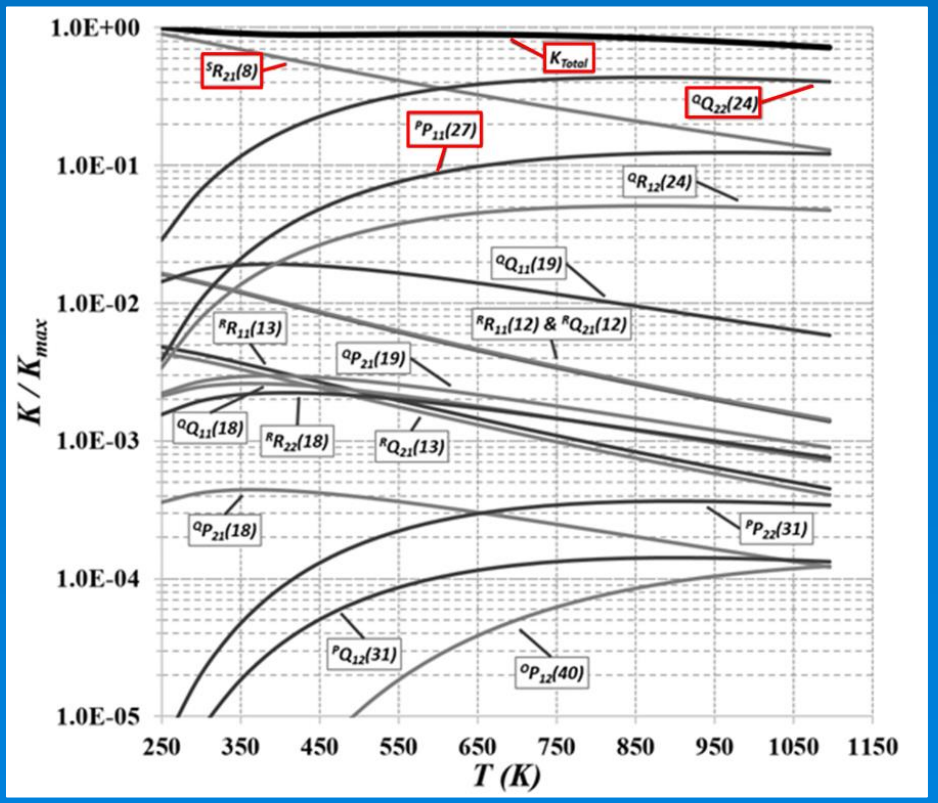
Experimental Method

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):

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

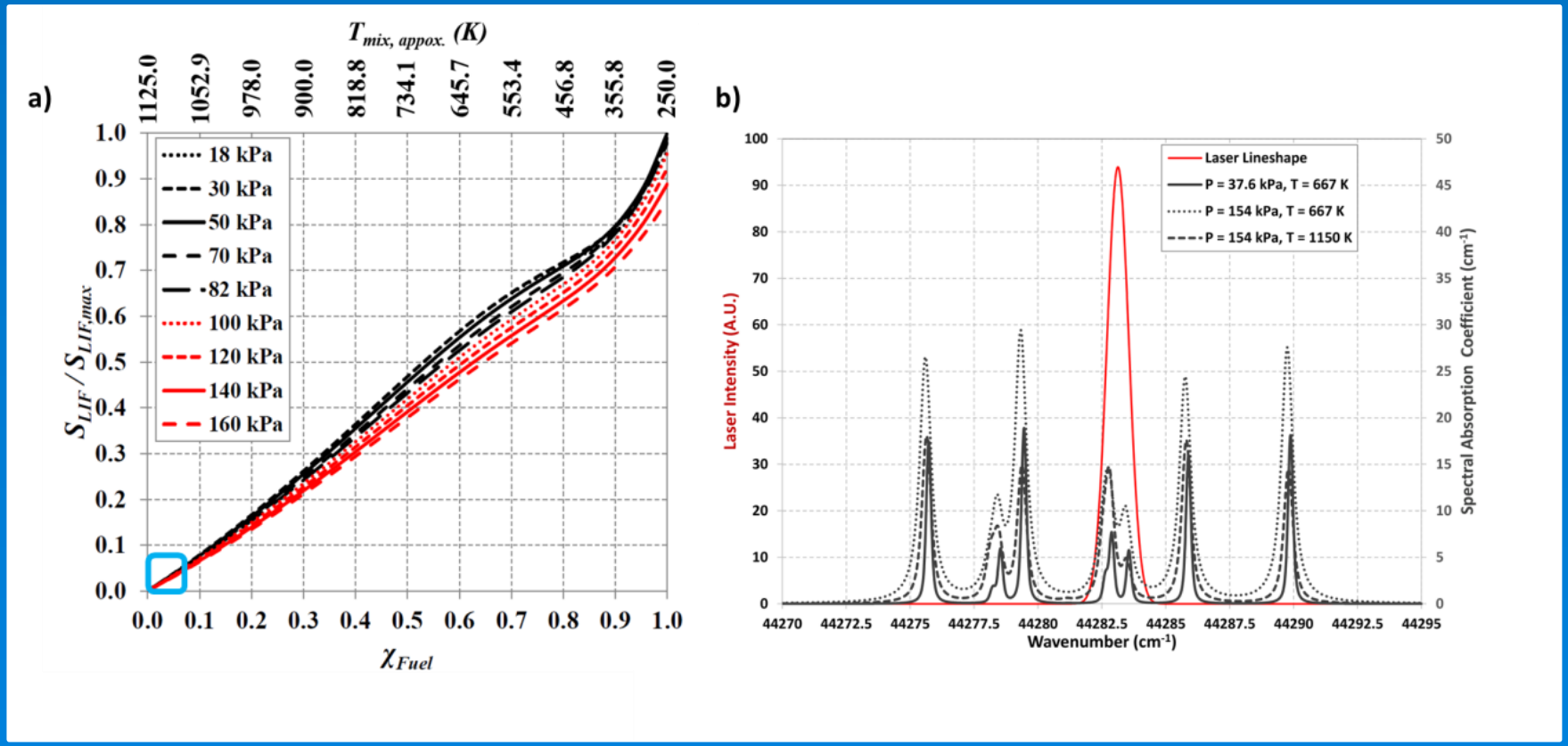


- Excitation of NO rotational transitions $^{P}P_{11}(27)$, $^{Q}Q_{22}(24)$ and $^{S}R_{21}(8)$
- Line selected base on previous work* with extended range based on estimated test conditions (T = 667-1100 K, p = 80-160 kPa)

* 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

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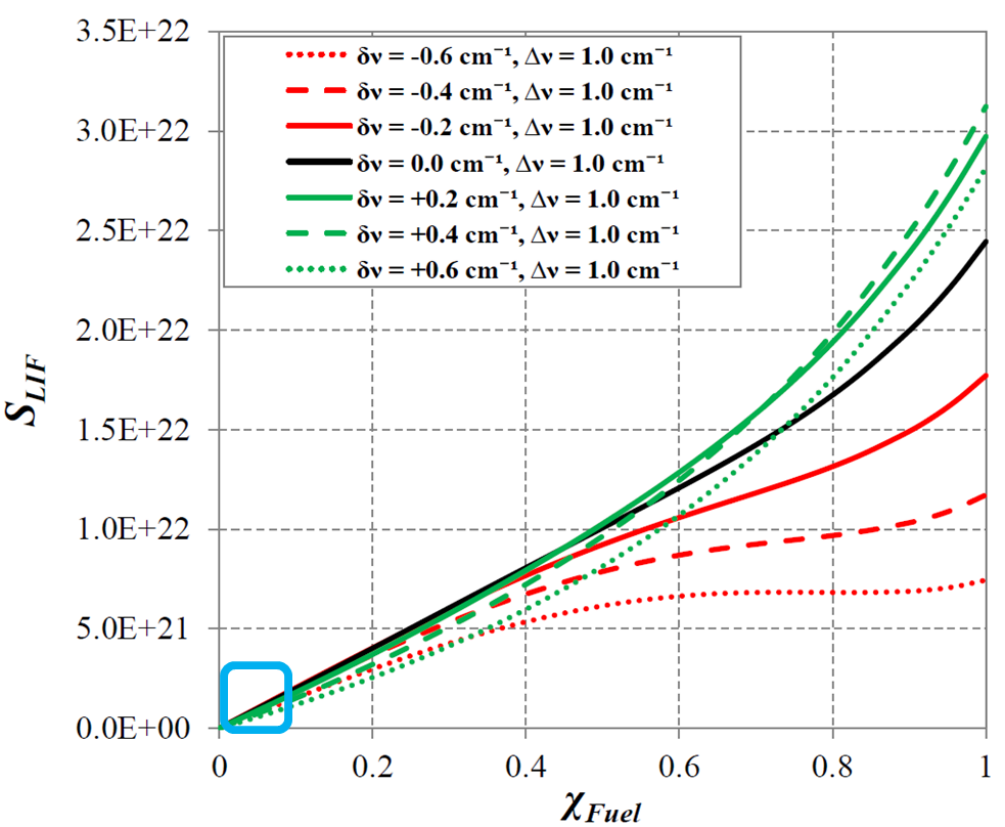
Experimental Method

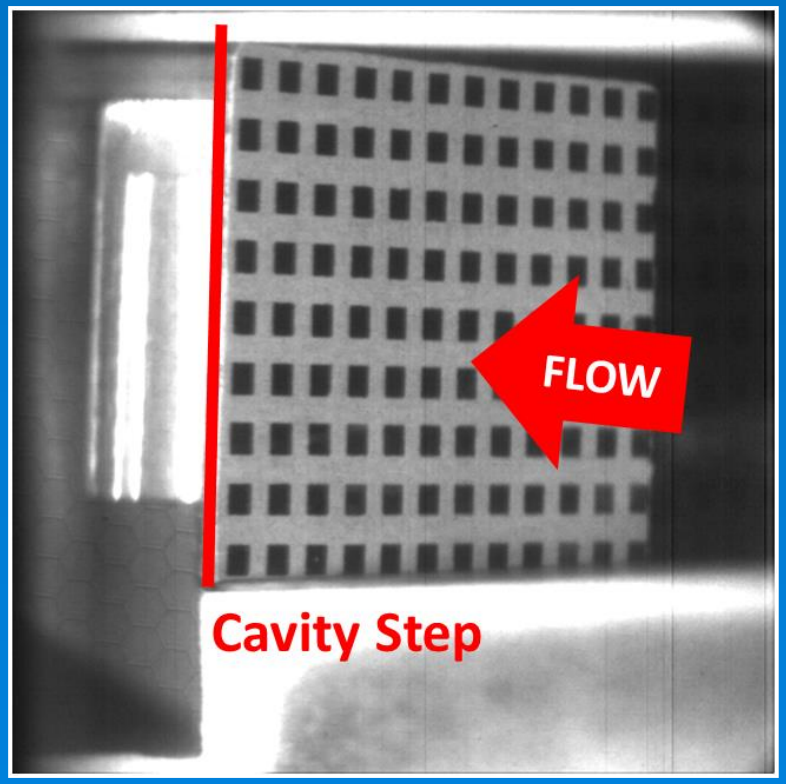
Sensitivity to Laser Detuning



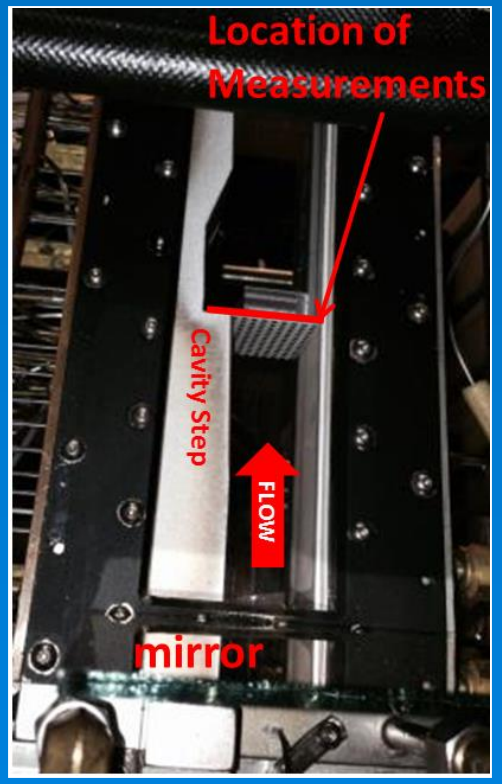
- LIF signal is proportional to mole fraction
- LIF signal not sensitive to small detuning in measurement region (blue box)

Experimental Method

Dotcard



PI Max (PLIF Camera) Image

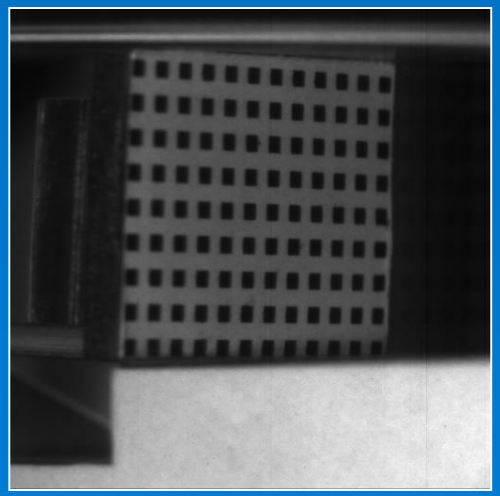


Photographic Camera Image

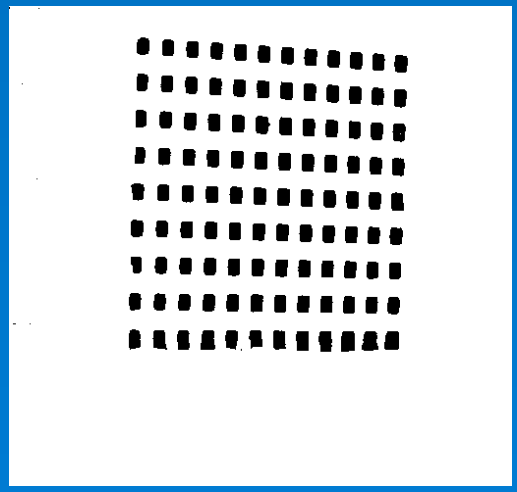
- Raw images (not cropped, not processed, not stretched, not rotated)
- X magnification: 7.75 pixel/mm, Y magnification: 12.5 pixel/mm
- Laser sheet passes right to left, skimming across the dotcard.

Experimental Method

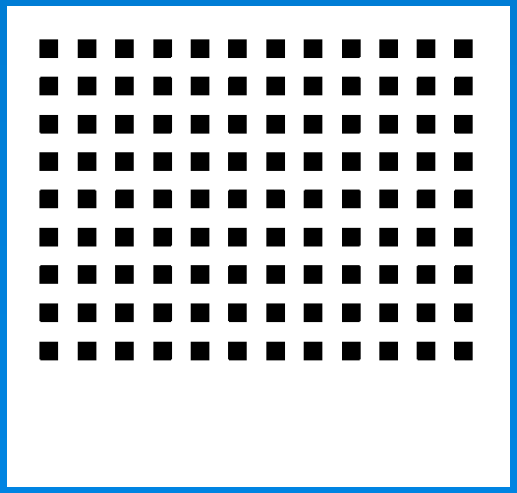
Dewarping



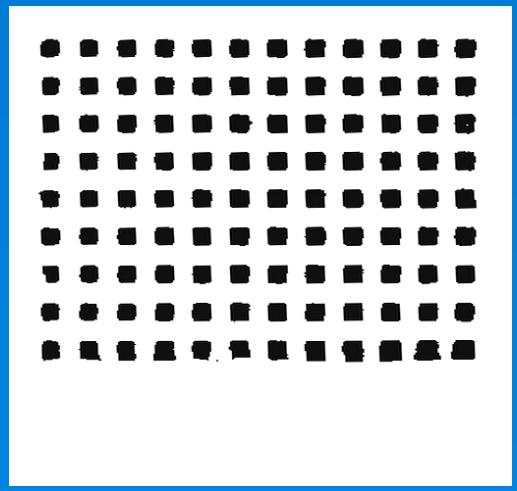
Original Dotcard



“Cleaned” Dotcard



Target Image



Dewarped Dotcard

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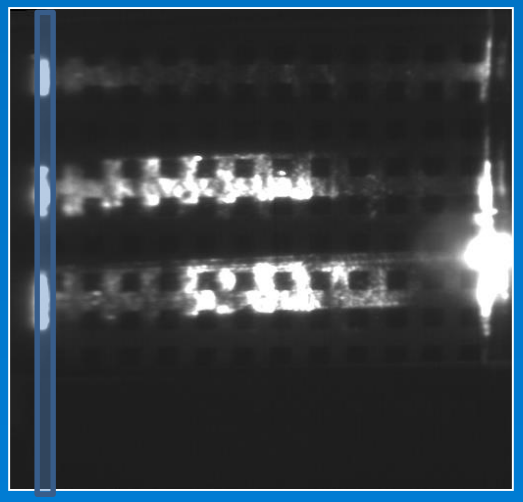
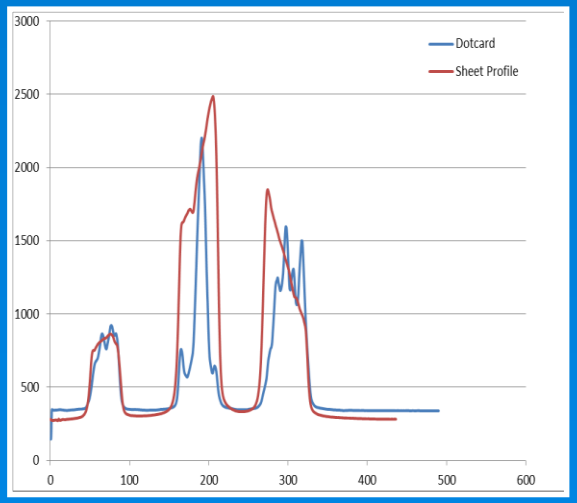
Experimental Method

Laser Intensity Correction

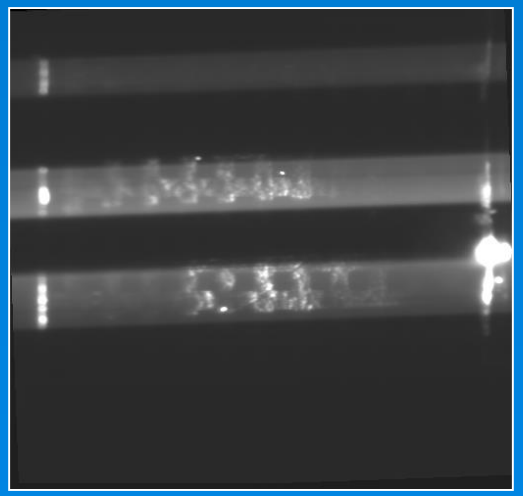
Laser Sheet with mask



Dewarped Dotcard with mask



Plot profiles overlapped



Dotcard and laser sheet overlapped

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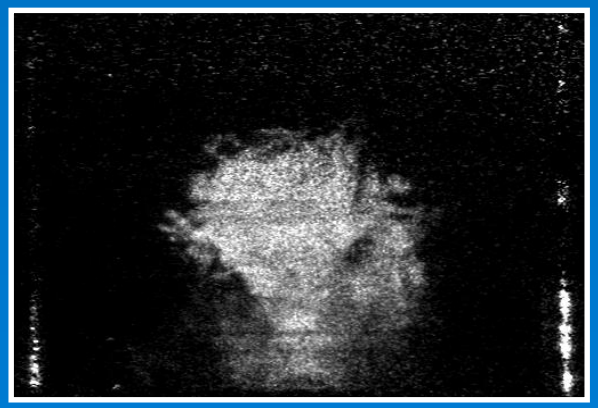
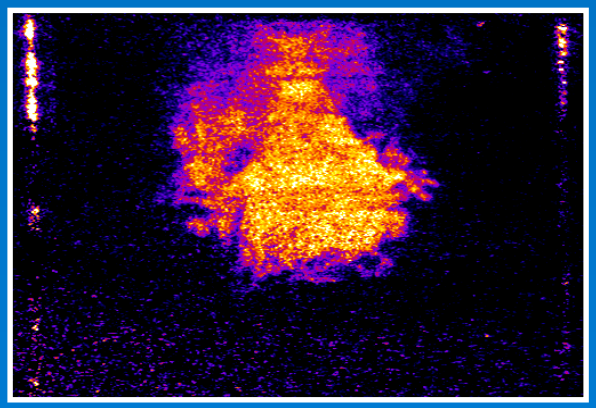
Experimental Method

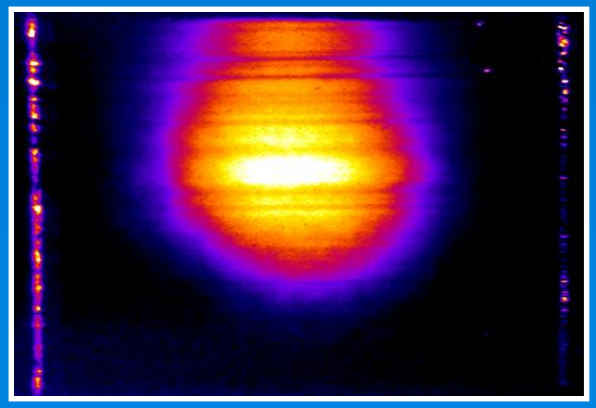
Image Processing



Dewarped and Laser Intensity Corrected Image



180° Rotated Image and False Colors Added



Average Image

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Results

Cases Tested

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

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

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

- Higher mixing goodness ➡ more uniform image

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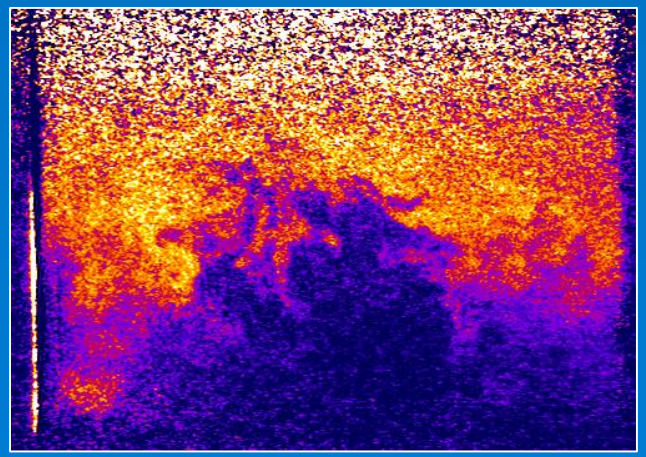
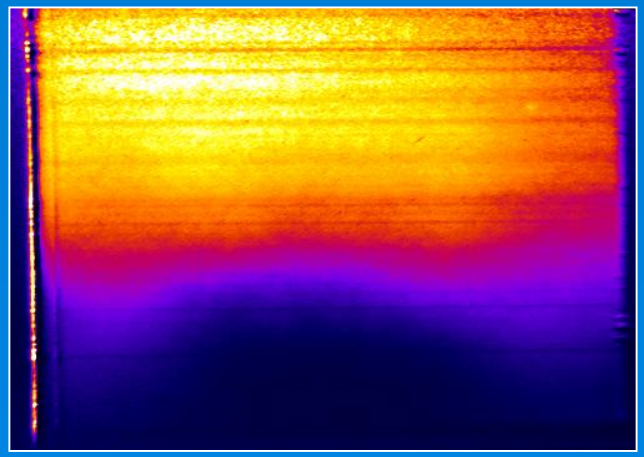
Results

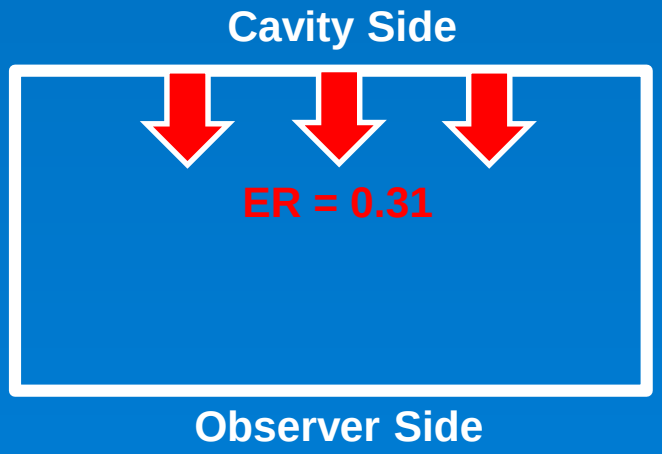
Run 4 June 13th



Selected single shots



Average



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

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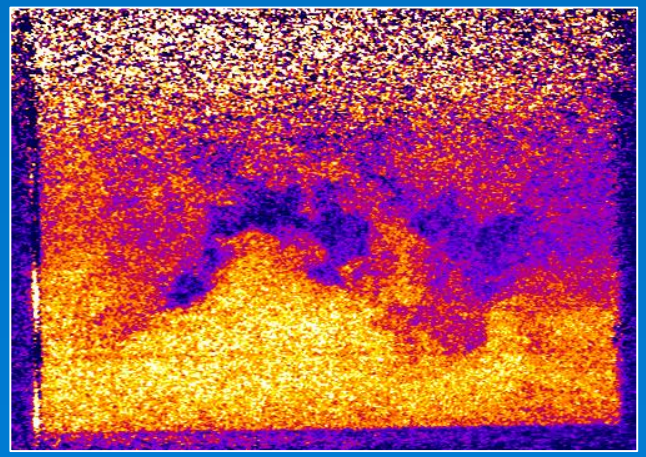
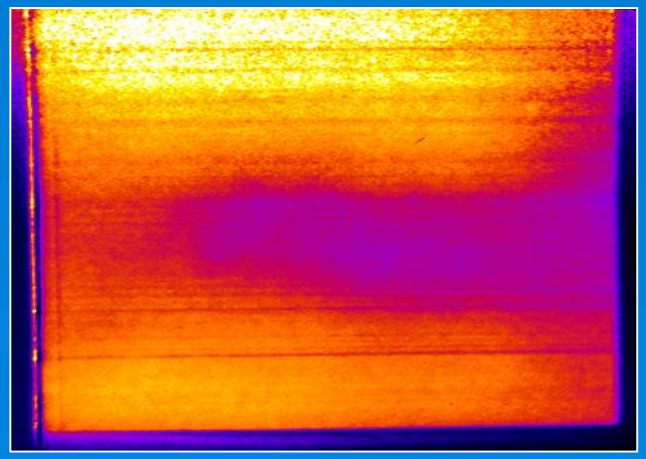
Results

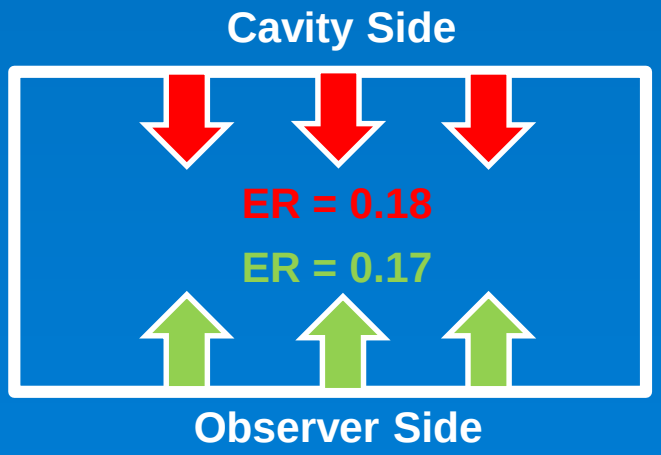
Run 7 June 13th



Selected single shots



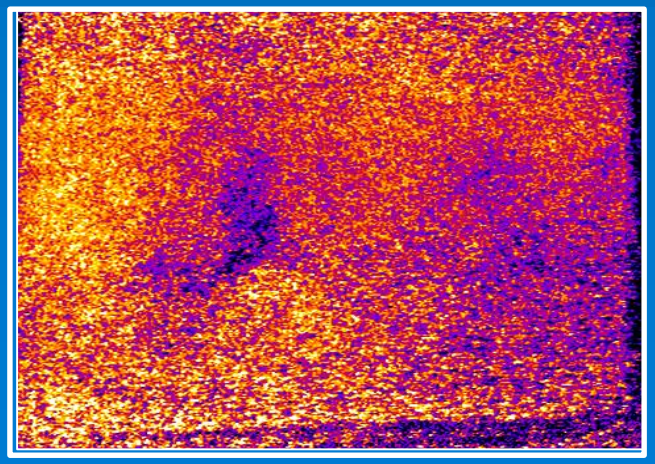
Average



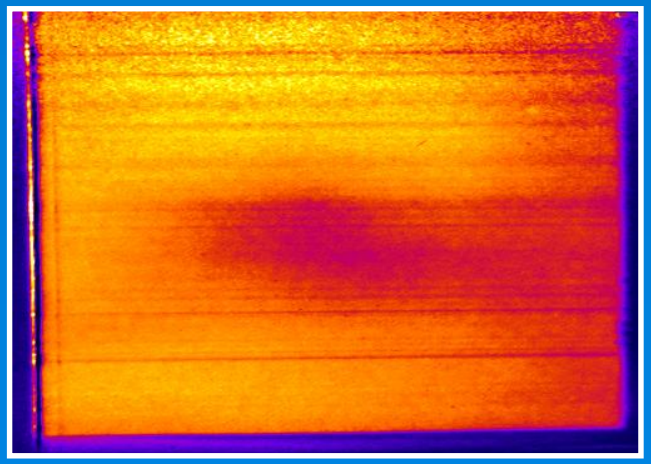
- ER = 0.35
- Shock Train off
- Mixing goodness = 69%

Results

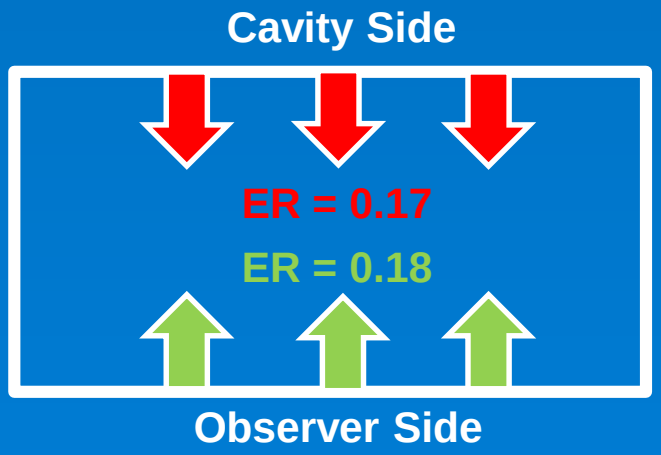
Run 6 August 29th



Selected single shots



Average



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

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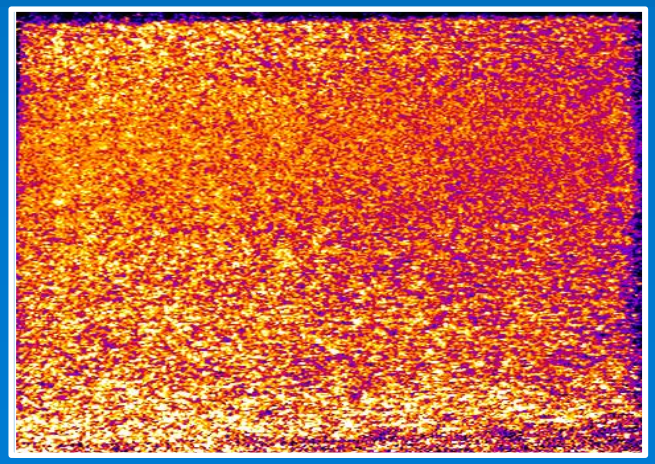
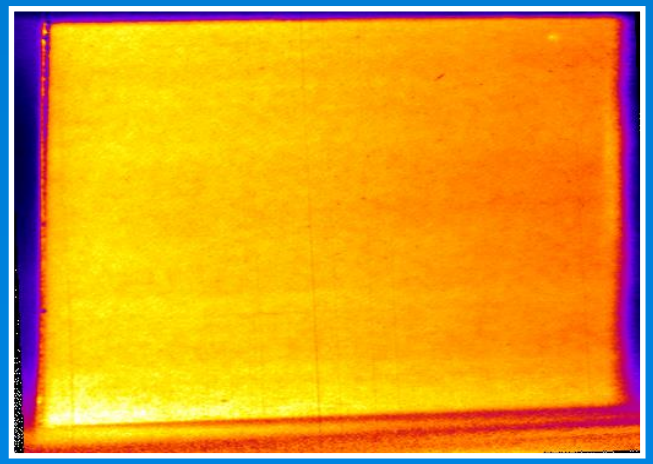
Results

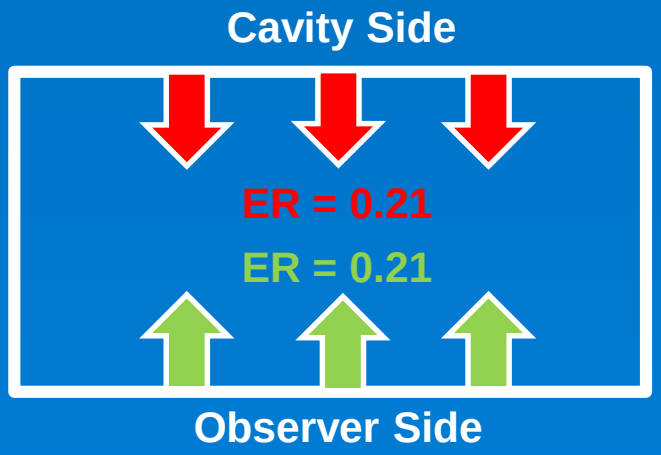
Run 7 August 29th



Selected single shots



Average



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

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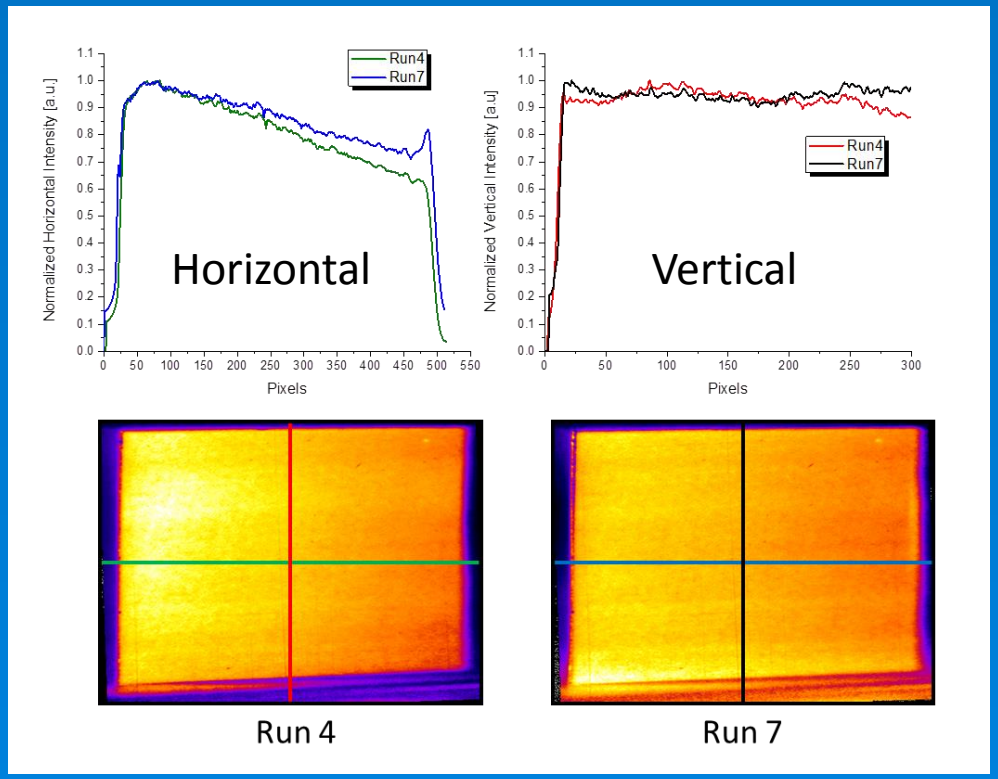
Results

Laser Beam Attenuation from Absorption by NO



- 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% N_2
  - Mixing goodness 86%
- Run 7 (August 29th):
  - Fuel: 5% NO – 95% N_2
  - Mixing goodness 90%

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

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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 ?