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Cryogenic hydrogen behavior and research priorities

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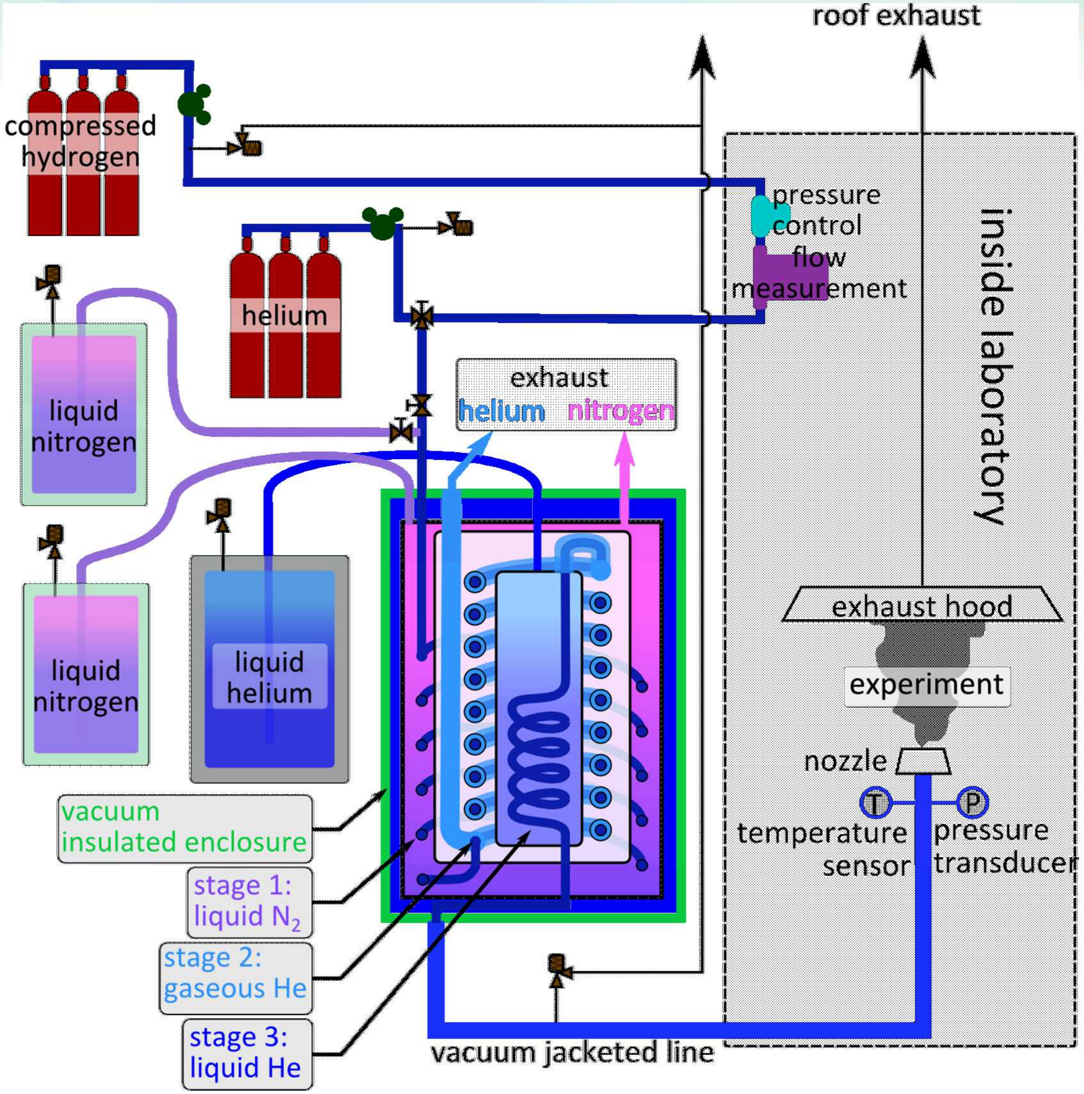
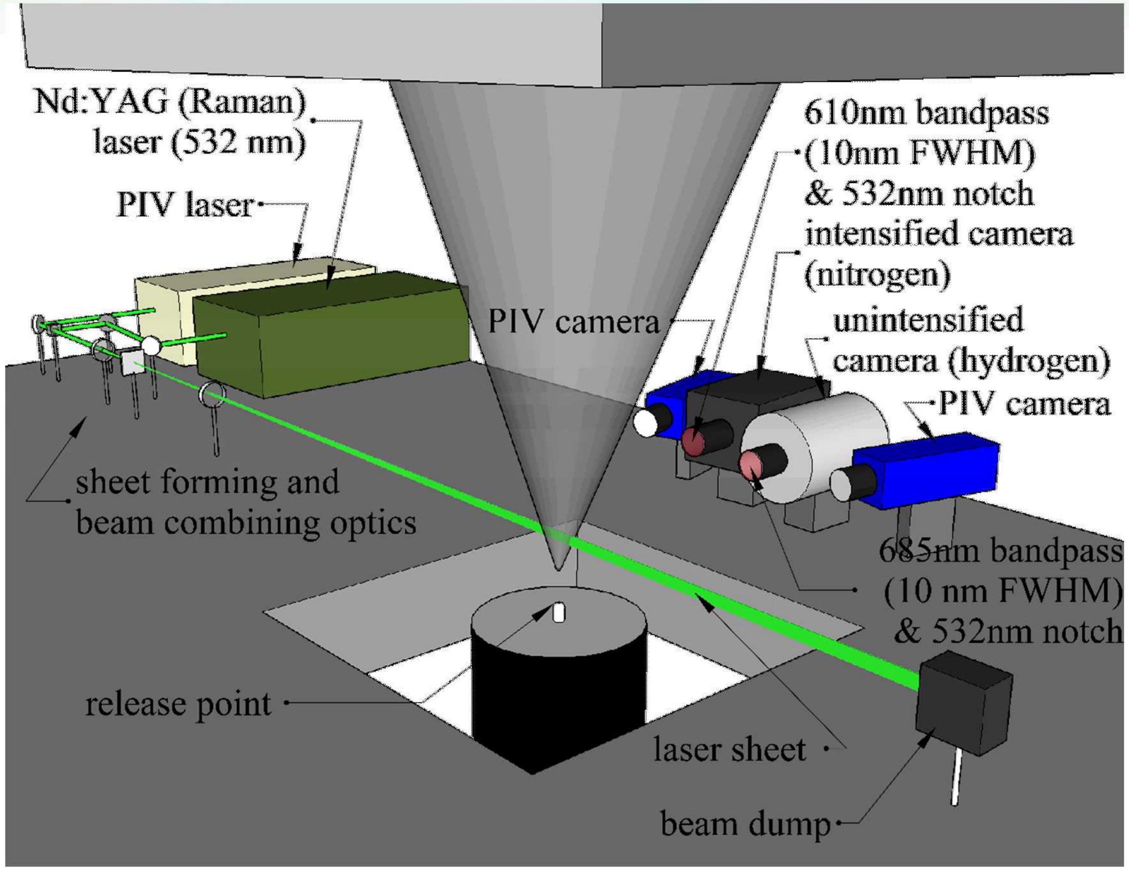
Where we left off (2016 Research Priorities Workshop)

- Experimental platform developed at Sandia to release cryogenic hydrogen through approximately 1 mm orifices at up to 10 bar
- Ignition and flame properties of cryogenic hydrogen measured
  - Cryogenic ignition distance collapses onto the same correlation for room temperature releases (scaled by effective diameter)
  - Flame length of cryogenic hydrogen scales the same as for room temperature hydrogen (square root of the Reynolds number)
  - Radiant fraction for cryogenic hydrogen flame also collapses when scaled appropriately (product of flame residence time, Plank-mean absorption coefficient, and adiabatic flame temperature to the 4th power)
- We were trying to determine a method for measuring cryogenic hydrogen concentration
  - Entrained moisture was scattering too much light for previously used Rayleigh scattering diagnostic
  - Wanted to maintain measurement in 2D of instantaneous concentration fields to measure statistical distribution of concentration (optical diagnostic)



Developed and implemented a planar Raman imaging diagnostic

- Large Raman shift enables higher optical density filters to remove unwanted Mie scatter (off of entrained moisture)
  - 10 nm FWHM bandpass filters at wavelengths of interest
  - OD of 12 @ all wavelengths
  - OD of 18 @ 532 nm
- Simultaneously imaged scatter off of moisture to perform particle imaging velocimetry (PIV)

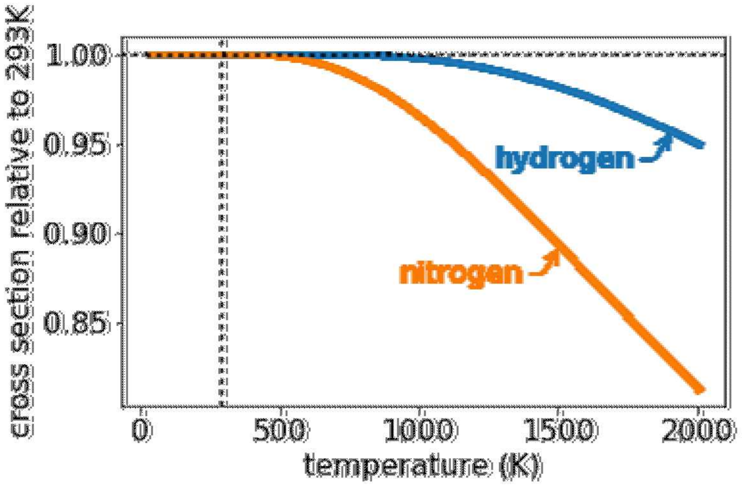


H_2: shift of 4161 cm^{-1} (532nm → 683 nm, 355nm → 416 nm)

N_2: shift of 2331 cm^{-1} (532nm → 607 nm, 355nm → 387 nm)

Quantification of Raman signals

- Signal is proportional to number density of molecules
- We use the ideal gas law to relate temperature and mole fraction to number density
  - $\frac{n_{total}\Sigma x}{V} = \frac{P_{total}\Sigma x}{RT}$
  - other equation of state could be used but may not have analytical solution
- Cross-section dependence matters for high-T (flames), but not low-T (cryogenic)



Eq. 1: $\frac{I_{H_2}}{I_0} = k_{H_2}\frac{x_{H_2}}{T}$ ← unknown 1, ← unknown 2

measured values

calibration constants

Eq. 2: $\frac{I_{N_2}}{I_0} = k_{N_2}\frac{x_{N_2}}{T}$ ← unknown 3

based on the composition of air

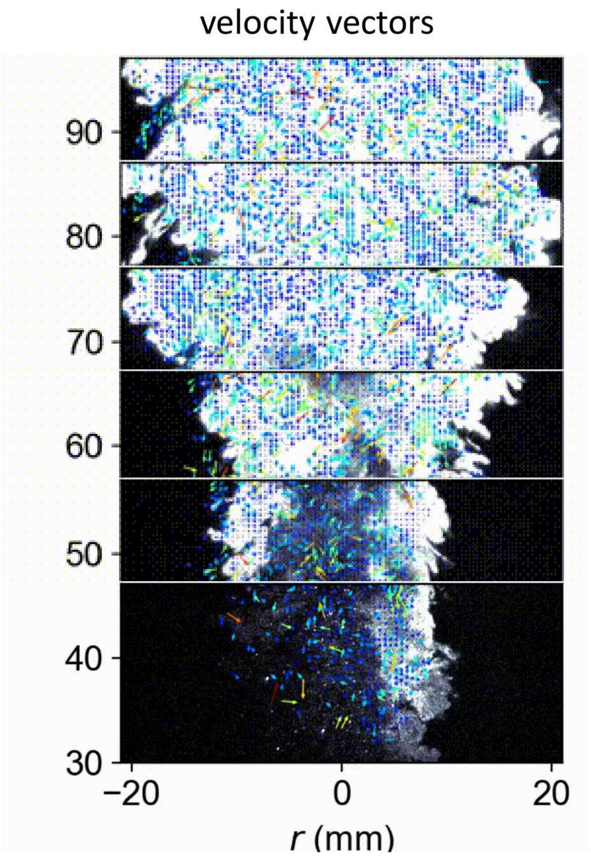
Eq. 3: $1 = x_{H_2} + 1.28x_{N_2}$

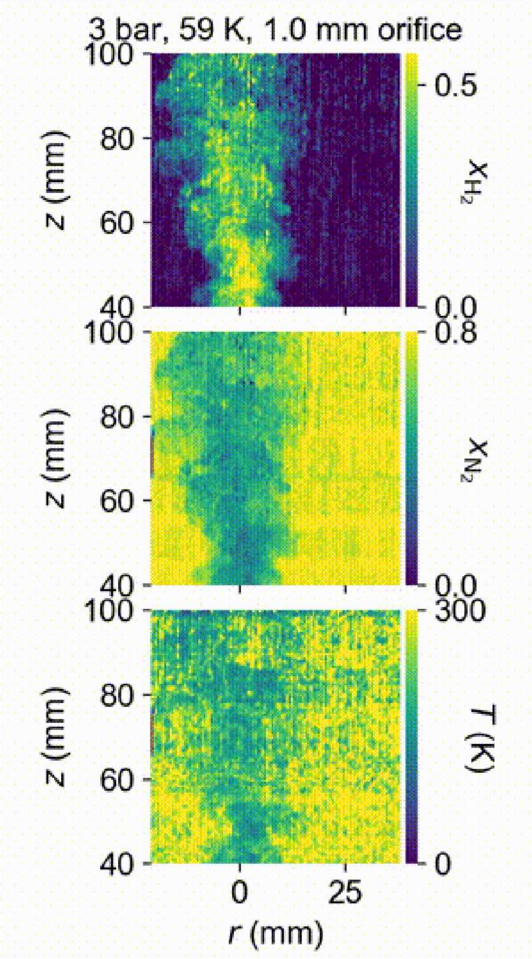
$$\begin{cases} x_{H_2} = \dfrac{\mathrm{I}_{\mathrm{H}_2}}{k_{H_2}\left(\dfrac{\mathrm{I}_{\mathrm{H}_2}}{k_{H_2}} + \dfrac{1.28\mathrm{I}_{\mathrm{N}_2}}{k_{N_2}}\right)} \\ x_{N_2} = \dfrac{\mathrm{I}_{\mathrm{N}_2}/\mathrm{I}_0}{k_{N_2}\left(\dfrac{\mathrm{I}_{\mathrm{H}_2}}{k_{H_2}} + \dfrac{1.28\mathrm{I}_{\mathrm{N}_2}}{k_{N_2}}\right)} \\ T = \dfrac{1}{\dfrac{\mathrm{I}_{\mathrm{H}_2}}{k_{H_2}} + \dfrac{1.28\mathrm{I}_{\mathrm{N}_2}}{k_{N_2}}} \end{cases}$$

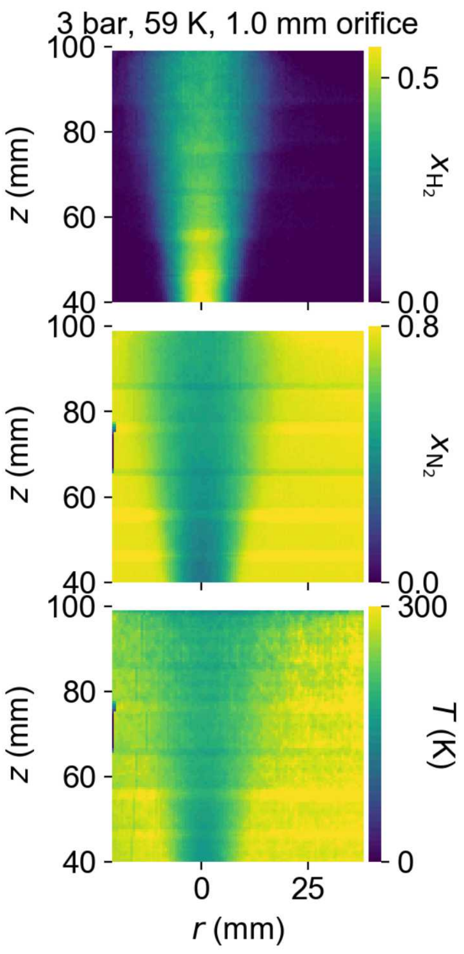
Raman has been used in a lab-scale campaign to measure releases from ≈1 mm orifices

T_{noz} [K]	P_{noz} [bar_{abs}]	d [mm]	T_{throat} [K]	n_{hts}
58	2	1	43.5	4
56	3	1	41.9	4
53	4	1	39.6	4
50	5	1	37.4	5
61	2	1.25	45.7	6
51	2.5	1.25	38.2	2
51	3	1.25	38.2	6
55	3.5	1.25	41.2	3
54	4	1.25	40.4	2
43	4	1	32.1	2
59	3	1	44.2	6
56	3.5	1	41.9	1
80	3	1	60.3	5

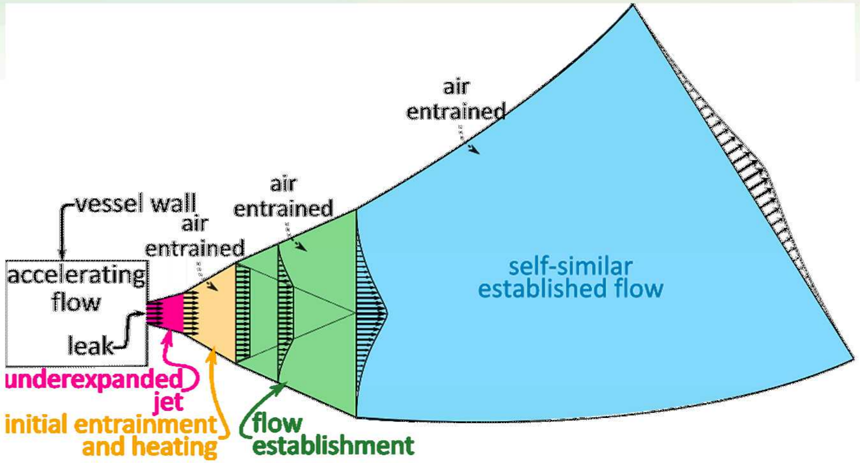
With PIV

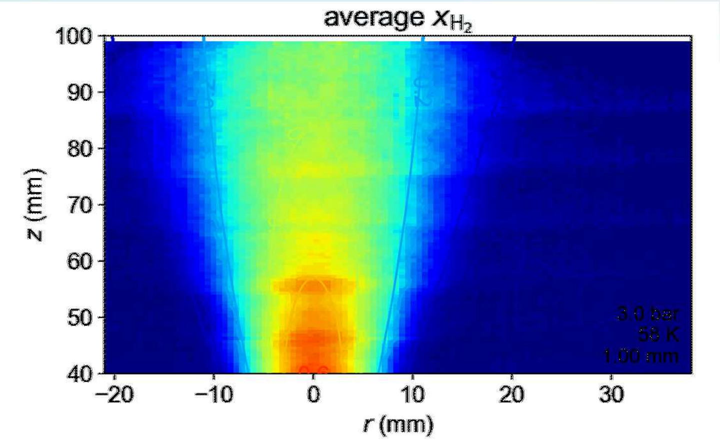




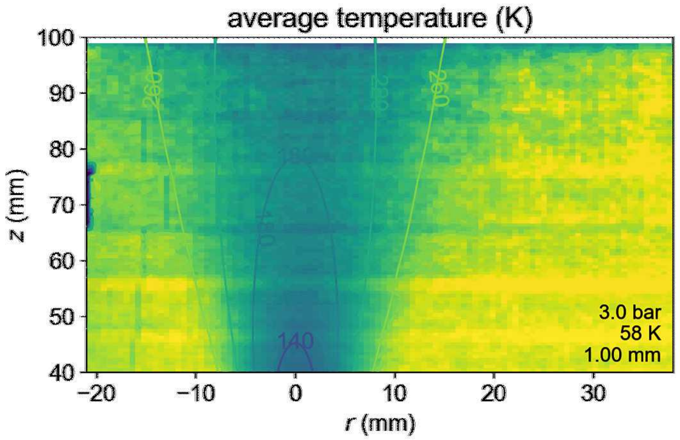


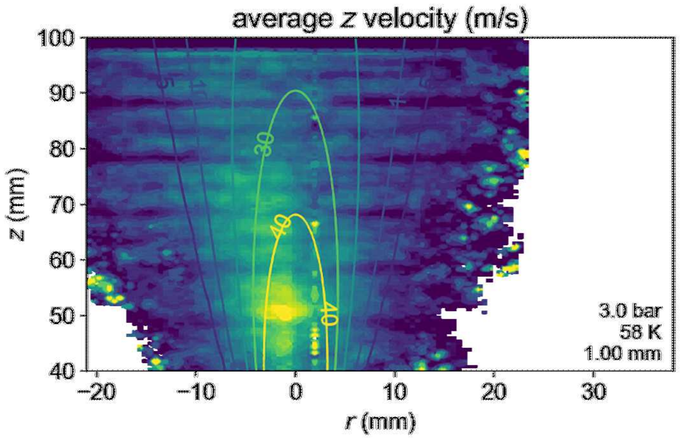
ColdPLUME model shows good agreement with the data





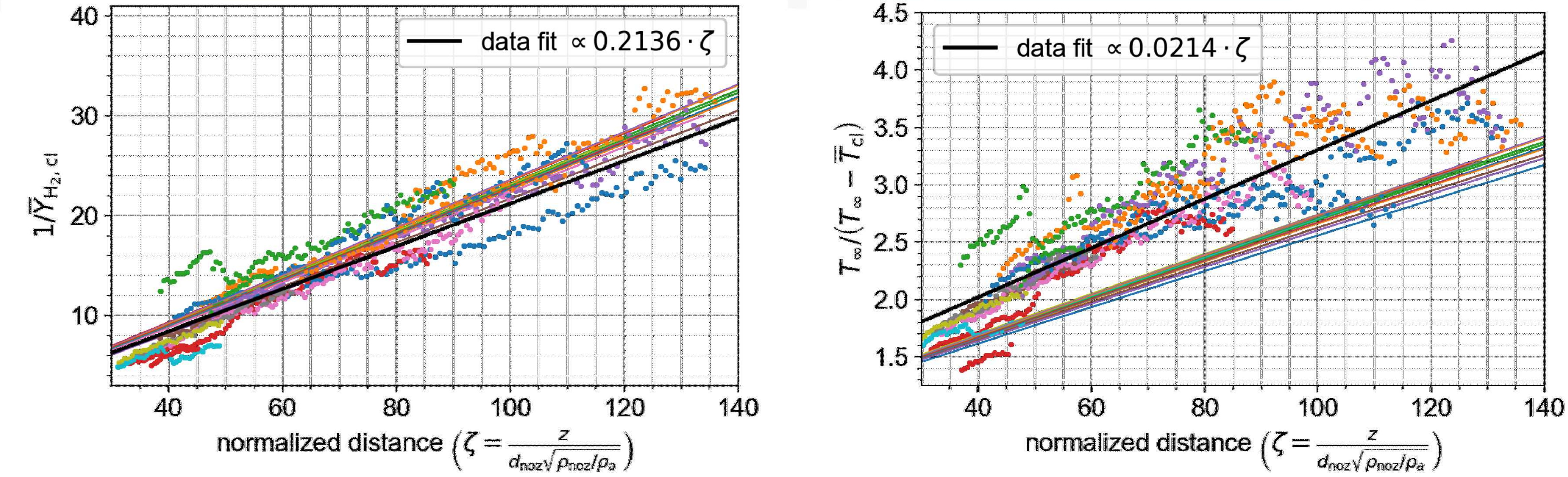
- Experimental results shown by shading and thick, dashed lines
- ColdPLUME model results are thin, solid lines





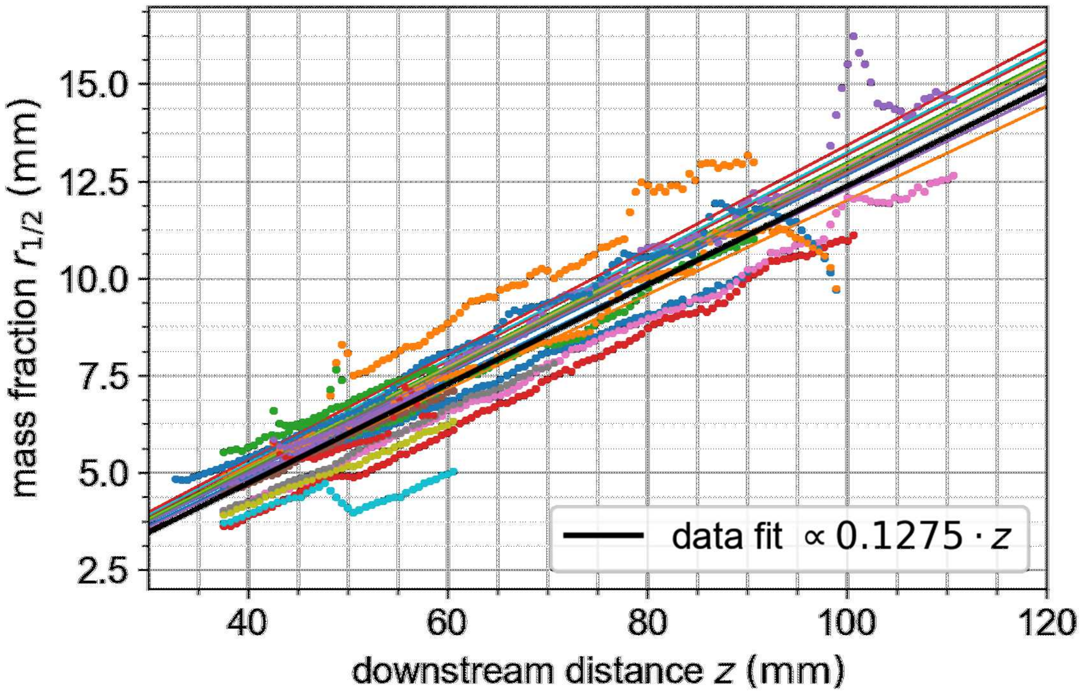
➢ Model accurately simulates mole fraction, temperature, and velocity -- can be used as a predictive tool

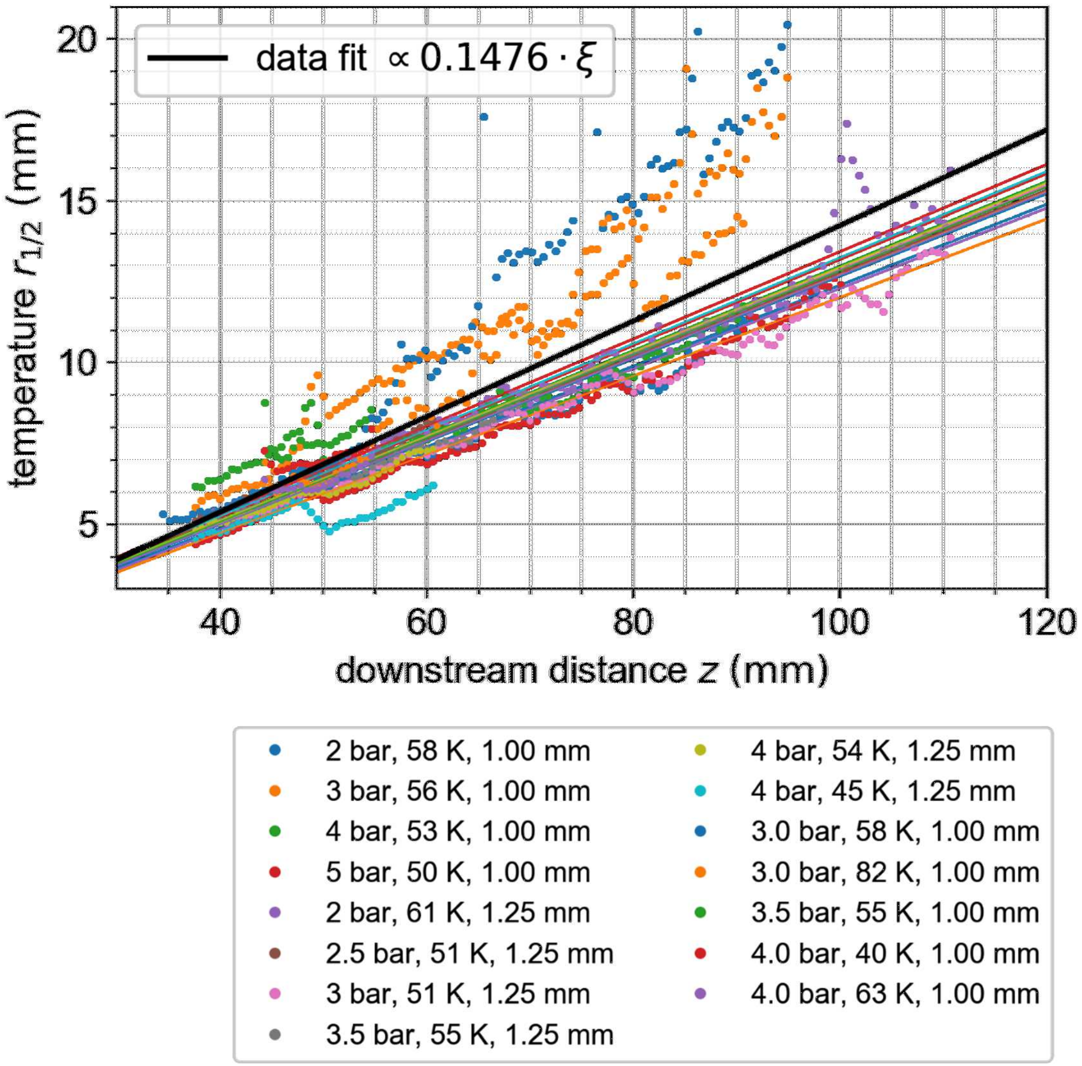
The centerline mass fraction and temperature decay linearly when plotted against the normalized distance



- Data shown by points, model by thin lines
- Literature inverse mass-fraction decay rate for warm releases: 0.21–0.271 – same as this data
- Model does not predict perfect collapse of the data

With two-dimensional images, we can also ensure that the widths of the jets are behaving as expected

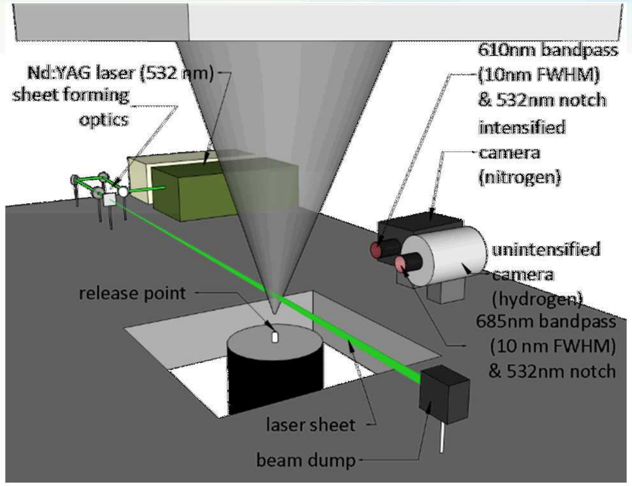


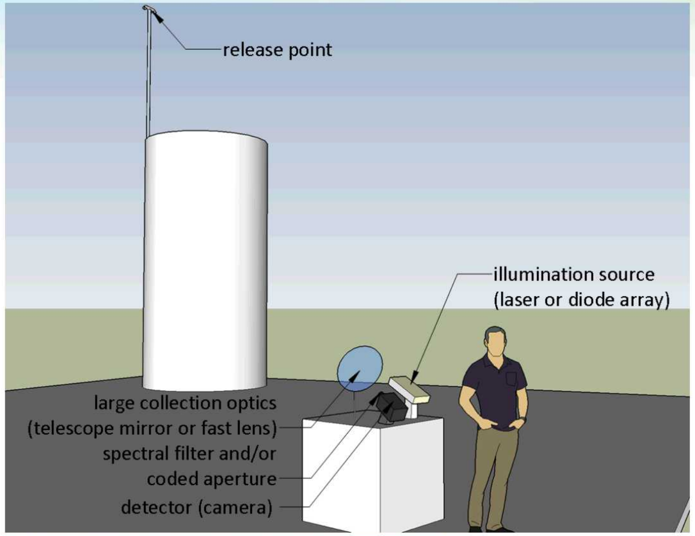


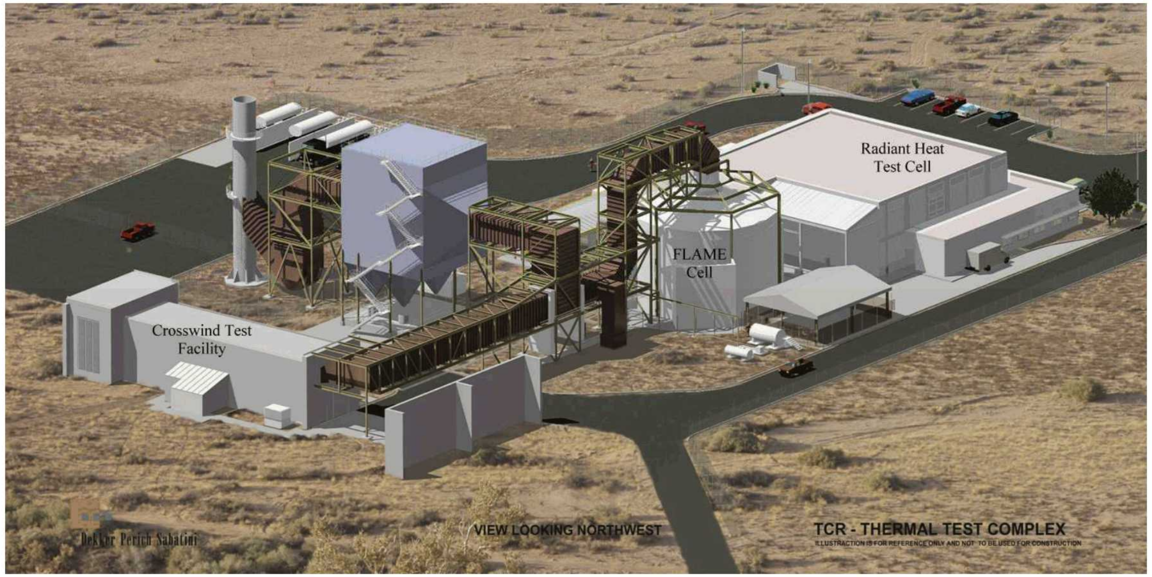
- Data shown by points, model by thin lines
- Literature mass-fraction half-width spreading rate (warm gases): 0.1–0.11 – similar to this data
- Both axes must have same units (some literature reports have incorrect axes definitions)

Lab scale data is great for model validation but we are working to scale-up our Raman imaging techniques

- **Remaining priorities for LH_2:**
  - Relate concentration data to ignition distance
  - Study non-circular orifices
  - Characterization and modeling of
    - Interactions with ambient (i.e. wind)
    - Pooling
    - Evaporation from LH_2 pools
- Currently developing an imaging diagnostic for outdoor and large-scale experiments
  - Quantitative concentration measurements
  - 2- or 3-dimensions
  - Video frame rates
  - Portable
- Will apply diagnostic to normally occurring outdoor releases (e.g., venting after LH_2 fill)
- Dedicated validation experiments (pooling, cross-wind) at well-controlled facilities next fiscal year (FY19-20)







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