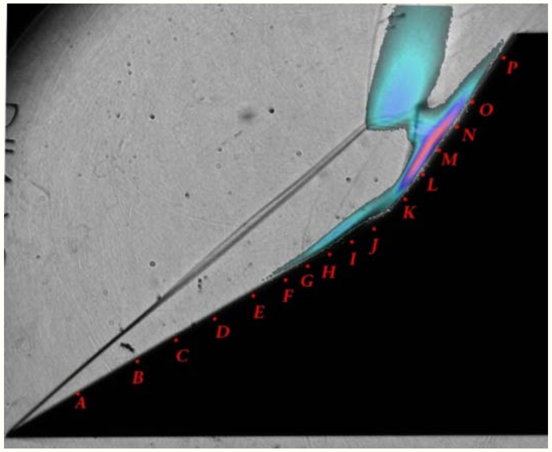
Shock Interactions in Nonequilibrium Hypersonic Flows



Joanna M Austin, Andrew Swantek, Andrew Kniseley

University of Illinois at Urbana-Champaign

Debbie Levin

The Pennsylvania State University

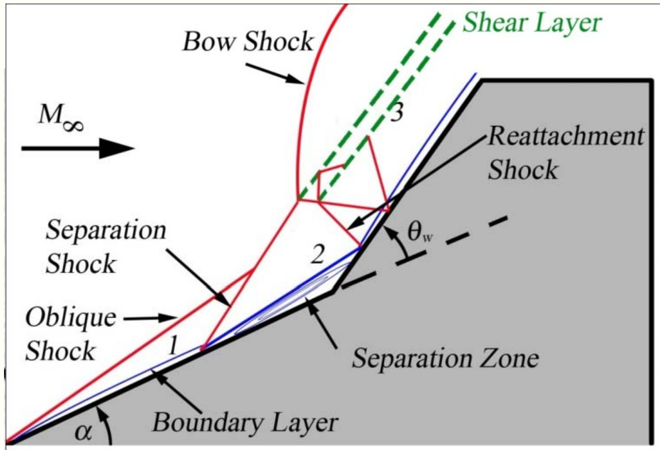
AFOSR Aerothermodynamics and Turbulence Portfolio Review

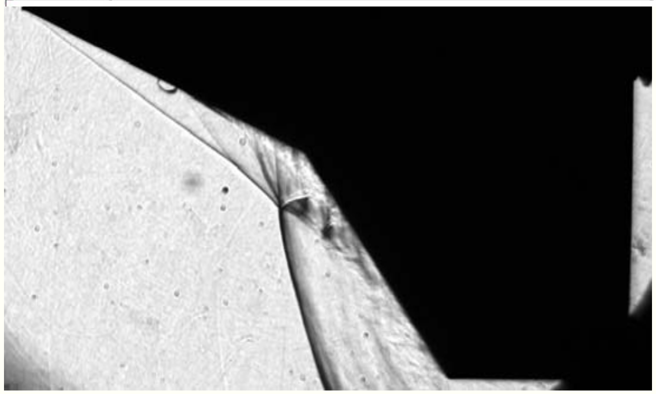
Arlington, VA, 15-18 July 2013

FA 9550-11-1-0129

Experiments with "Tunable" Freestream

- Double cone/wedge flows are a sensitive model problem for thermochemical modeling validation.
- Significant work both experimentally and computationally has been performed (Olejniczak *et al.* (1999); Wright *et al.* (2000); Nompelis *et al* (2003, 2005, 2010)).
- *State-of-the-art* simulations and experiments show poor agreement in high enthalpy (≥ 5MJ/kg) air flows, in spite of good agreement at lower enthalpies and in N_2
- Outstanding questions: freestream characterization, flow steadiness. thermochemistry.





A novel method of gas acceleration that minimizes free stream dissociation while producing a broad range of hypervelocity flows.

GOAL: Turn on/off the thermochemistry:

1) N2 to air while maintaining Mach and Ho

2) Low enthalpy to high.

Quantify the response of viscous and inviscid flow features

Previously:

- Heat transfer & single-shot schlieren data for eight test cases (varying freestream O_2 and H_o).
- Flow field establishment and possible unsteadiness examined experimentally.
  - Inviscid and viscous time scales measured using high speed schlieren and time-resolved heat transfer.
  - Comparisons with simulations (D. Levin) in progress; outstanding issues (challenges slide).

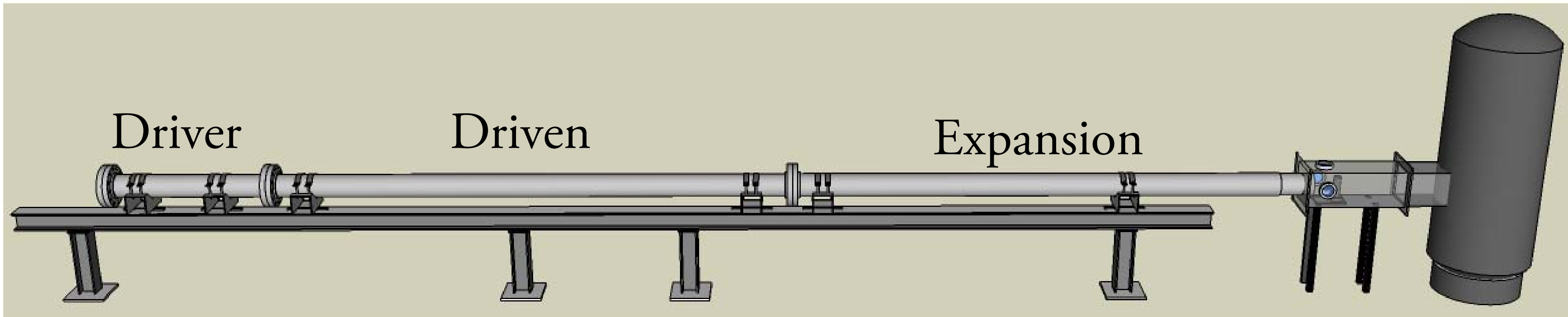
Currently:

- Which features of the flow are thermochemically activated & when? (Leading to why?!)
  - Direct measurements of chemical species and temperatures combined with flow feature visualization.

Hypervelocity Expansion Tube (HET)

- 152 mm ID, 9.14m length impulse facility
- Mach Numbers from 3-7.5
- Stagnation enthalpies from 2-9 MJ/kg
- Test times from 100 μs to 500 μs

Dufrene, Sharma, Austin 2007



- Diagnostic capabilities
  - Pressure Measurements
  - **Schlieren** (single frame & **high speed)**
  - **Heat transfer measurements**
    - Coaxial thermocouple
    - Platinum thin film gauges
  - **Emission spectroscopy**
  - Pressure Sensitive Paint

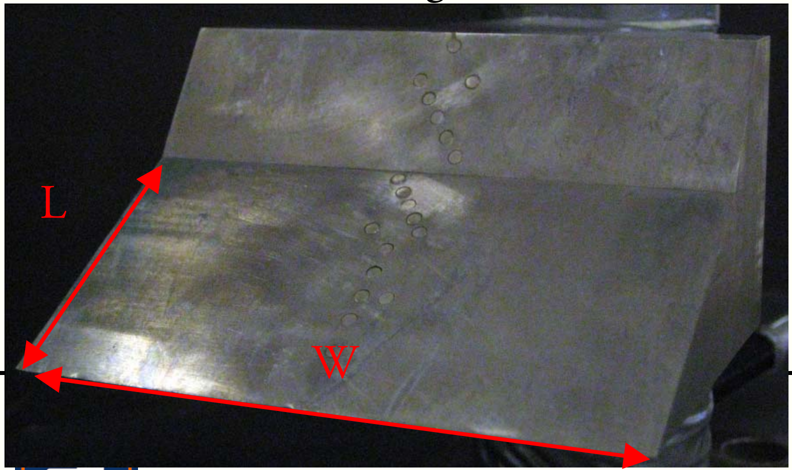
Test conditions and models

- Air can be replaced with N_2 and yields nearly the same freestream conditions.
- Two different model geometries are used.

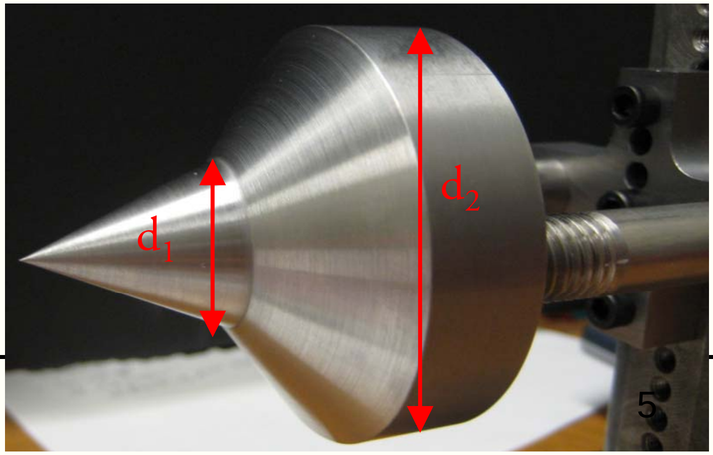
Run Condition	M	h_0 MJ/kg	T, K	P, kPa	ρ, kg/m^3	u, km/s	Re/m *10^{-6}
M7_8	7.14	**8.0**	710	0.78	0.0038	3.81	**0.44**
M5_4	5.12	**4.2**	676	8.2	0.042	2.67	**3.47**
M4_3.6	3.95	**3.6**	862	19	0.077	2.33	**4.73**
M7_2.2	7.11	**2.1**	191	0.39	0.0071	1.97	**1.10**

- 25º-55º cone
  - RTO studies
- 30º-55º wedge
  - Scale model of Davis and Sturtevant's wedge

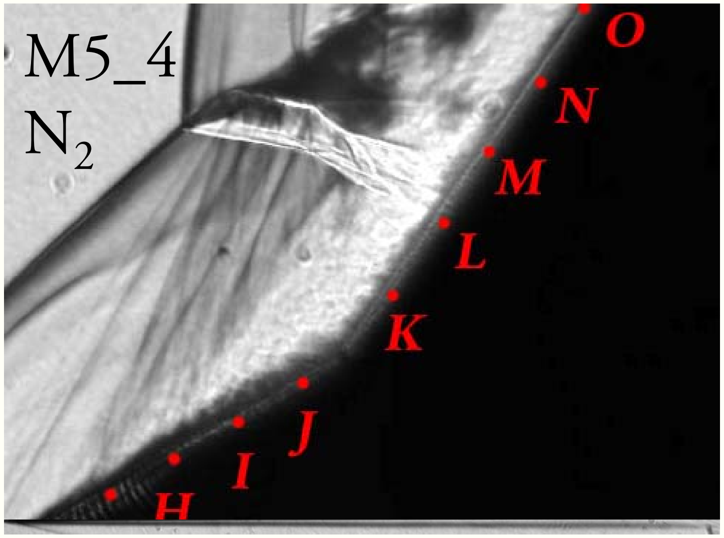
30-55 Double Wedge L=2", b=4"

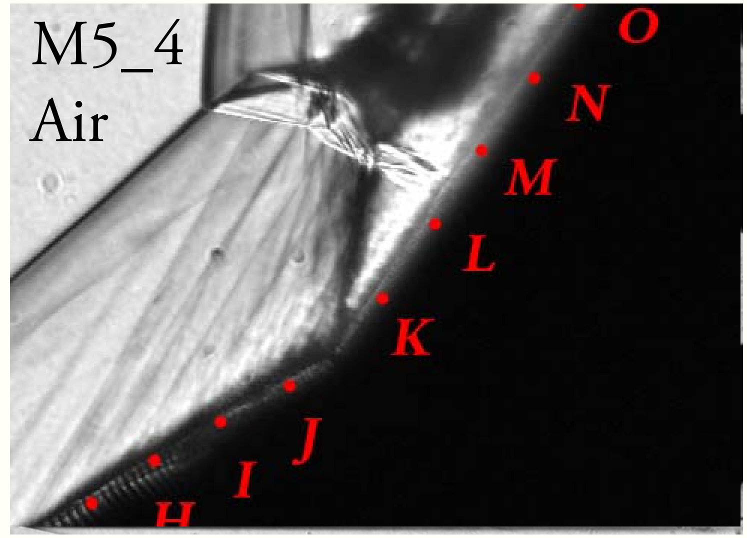


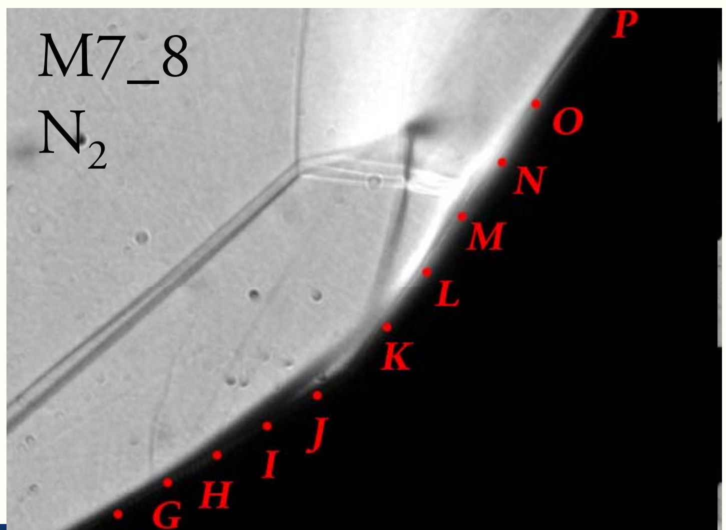
25-55 Double Cone d_1=0.984", d_2=2.5"

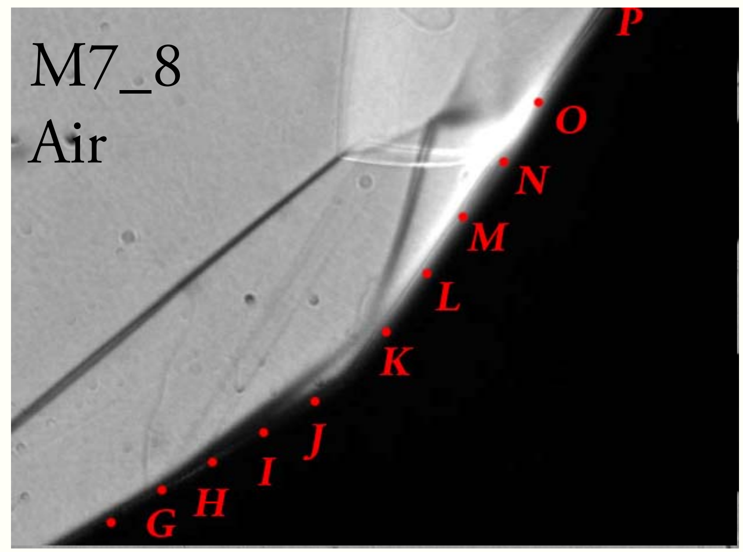


Sample cases showing differences between Air/N_2





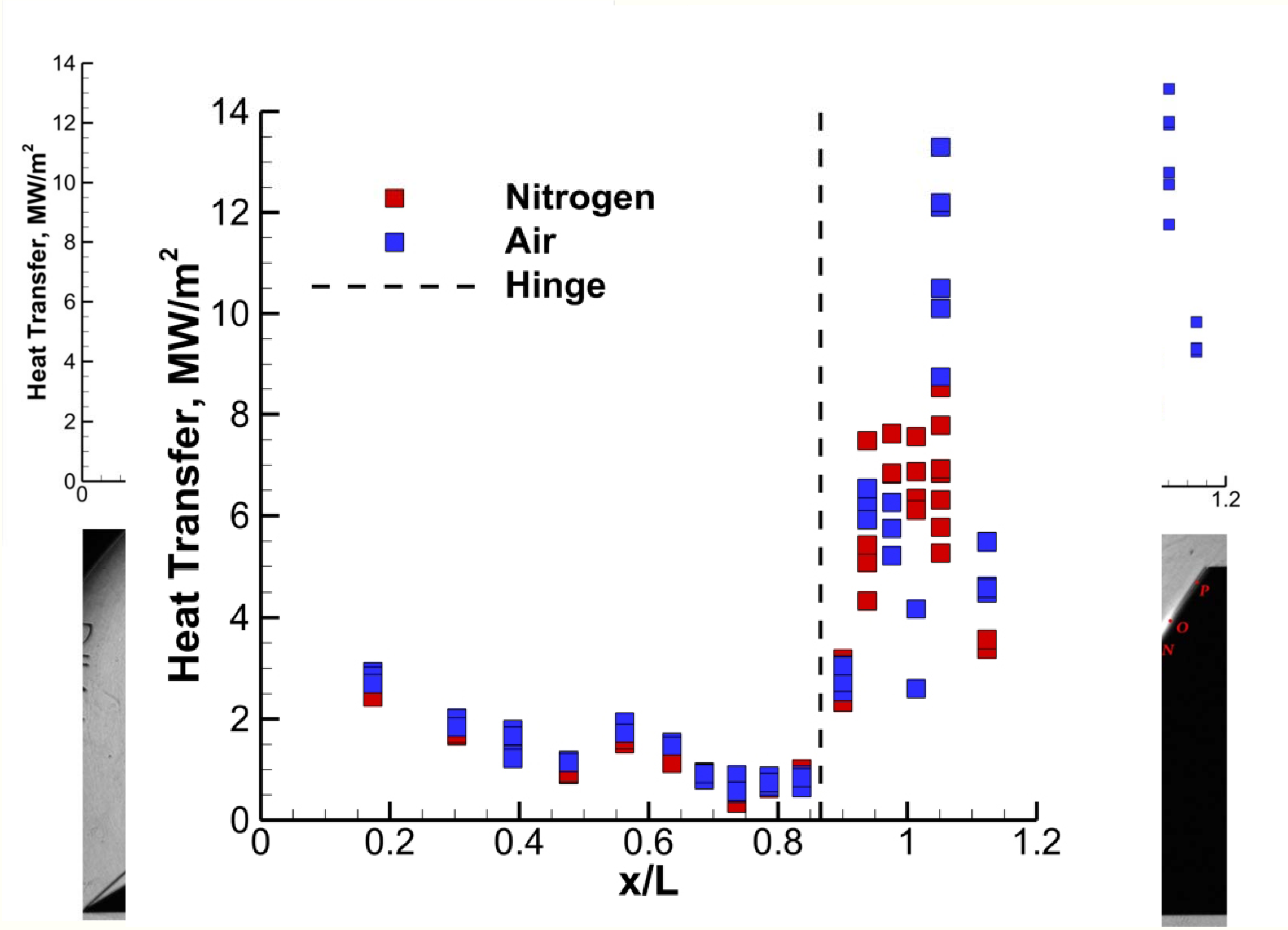




Mean Surface Heat Transfer – 8MJ/kg

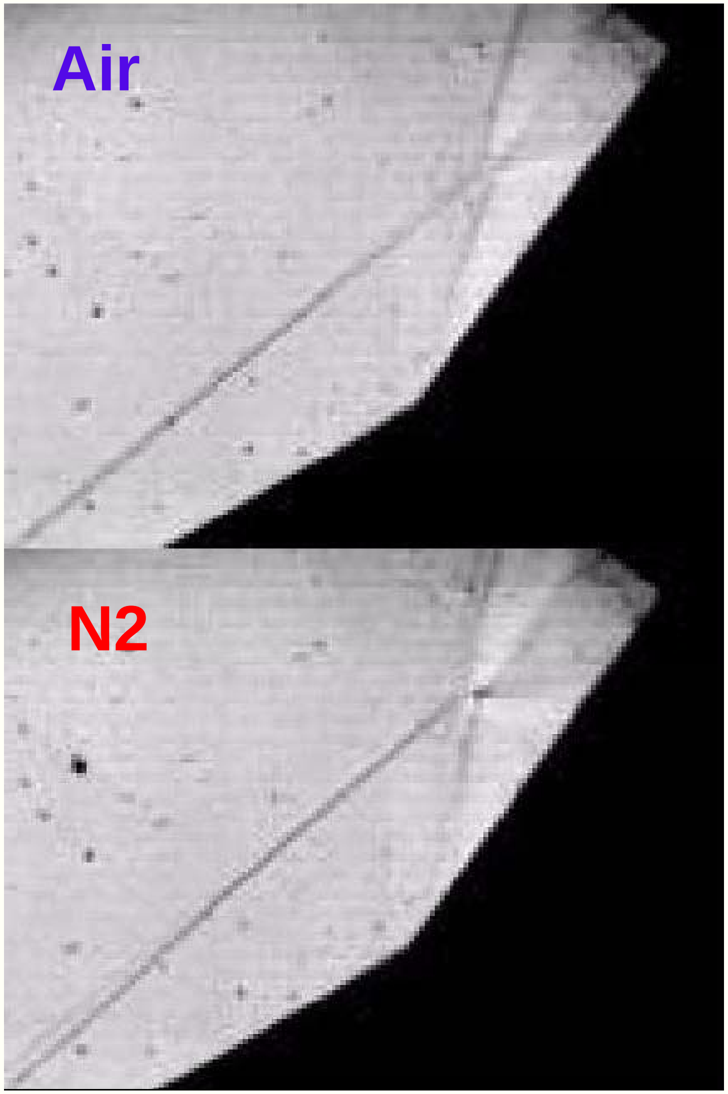
Mach 7

(M7_8)



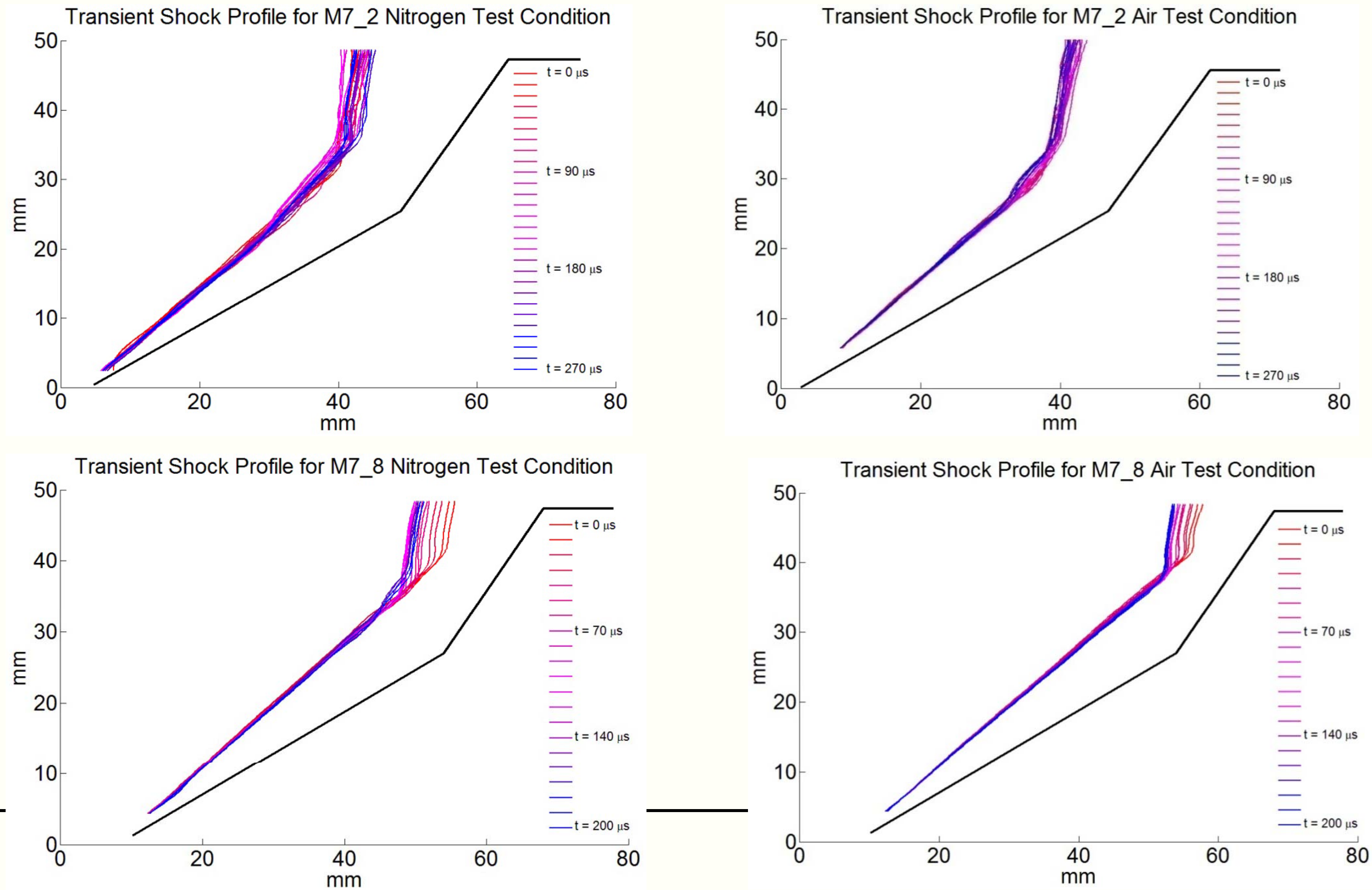
High Speed Schlieren: N2 and Air

Double Wedge
M7_8
Top: Air
Bottom: N_2
100,000 fps
7 fps playback
1μs exposure
200 μs test time



- Nitrogen exhibits a larger standoff distance = 2.29 mm
- Consequences for shock impingement, which occurs further downstream for air.
- Nitrogen shows more emission

Triple point establishment process: moving upstream



"Tuning" freestream from N2 to Air

Mach 7, Ho = 8MJ/kg

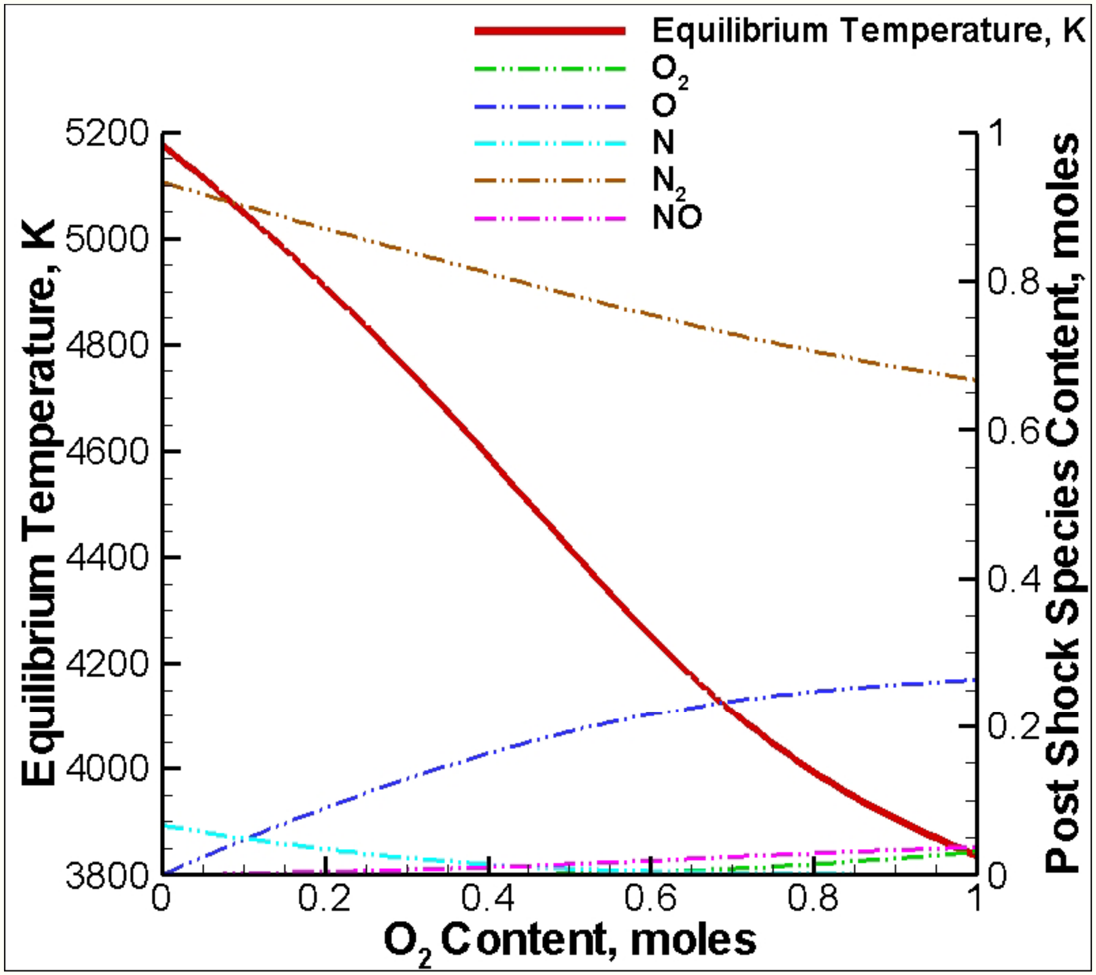
Percentages indicate the freestream oxygen percentage compared to atmospheric air. Compositions below.

	Freestream		Post Shock (Equilibrium)						
Mixture	N_2	O_2	N_2	N	O_2	O	NO	T, K
Nitrogen	1.000	0.000	9.330E-1	6.697E-2	-	-	-	5178
30%	0.926	0.074	8.404E-1	2.329E-2	3.250E-4	1.286E-1	7.343E-3	4754
50%	0.883	0.117	7.821E-1	8.755E-3	1.978E-3	1.924E-1	1.473E-2	4425
80%	0.825	0.175	7.057E-1	2.025E-3	1.474E-2	2.480E-1	2.949E-2	3990
Air	0.790	0.210	6.659E-1	1.082E-3	3.152E-2	2.639E-1	3.751E-2	3902

Mixture	f_{N_2}	f_{O_2}
Nitrogen	3.46	-
30%	1.79	99.5
50%	1.48	98.1
80%	2.18	90.4
Air	2.82	82.7

Dissociation Fraction (%) =
[dissociated molecules]/[initial concentration]

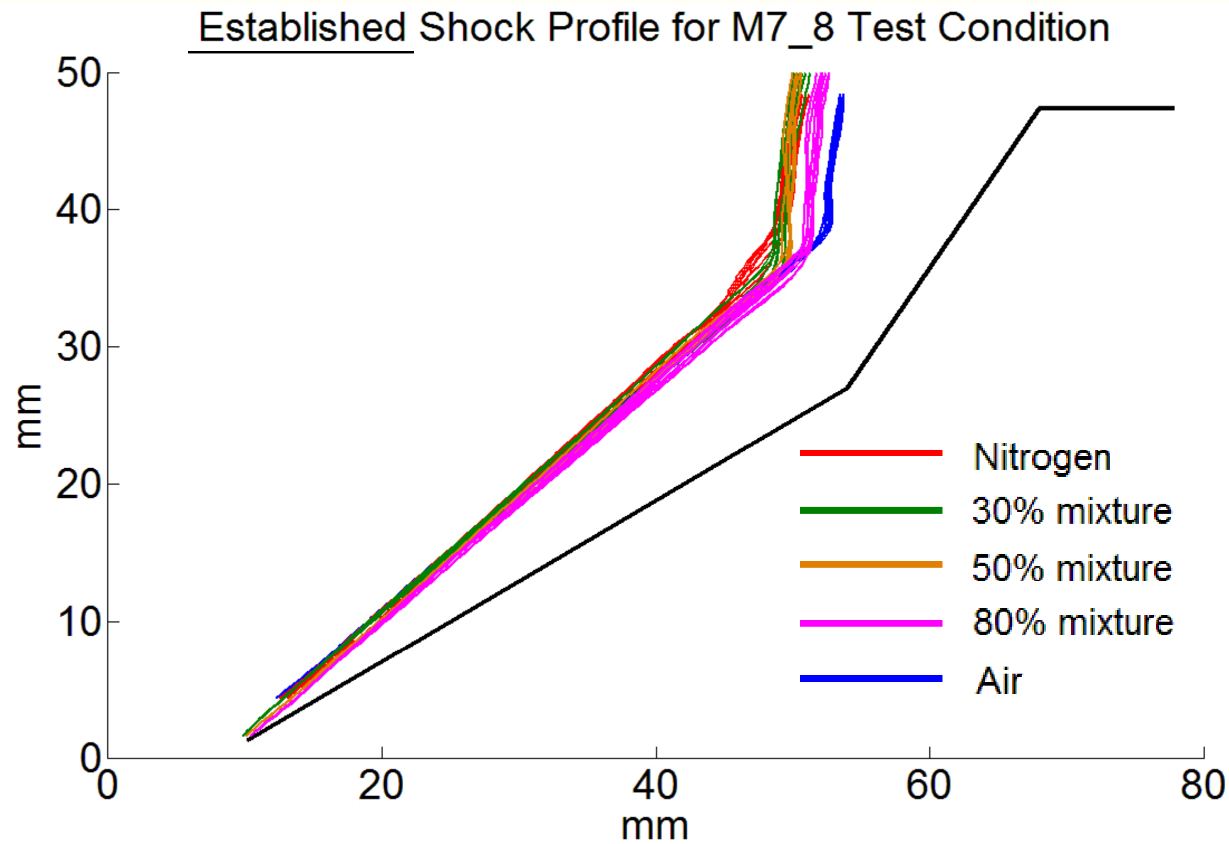
Sample post-shock quantities vs. freestream O_2



Lead shock location vs O_2 content

Edge tracking extracts shock surfaces from high speed images.

Percentages indicate the freestream oxygen percentage compared to atmospheric air. Compositions below.

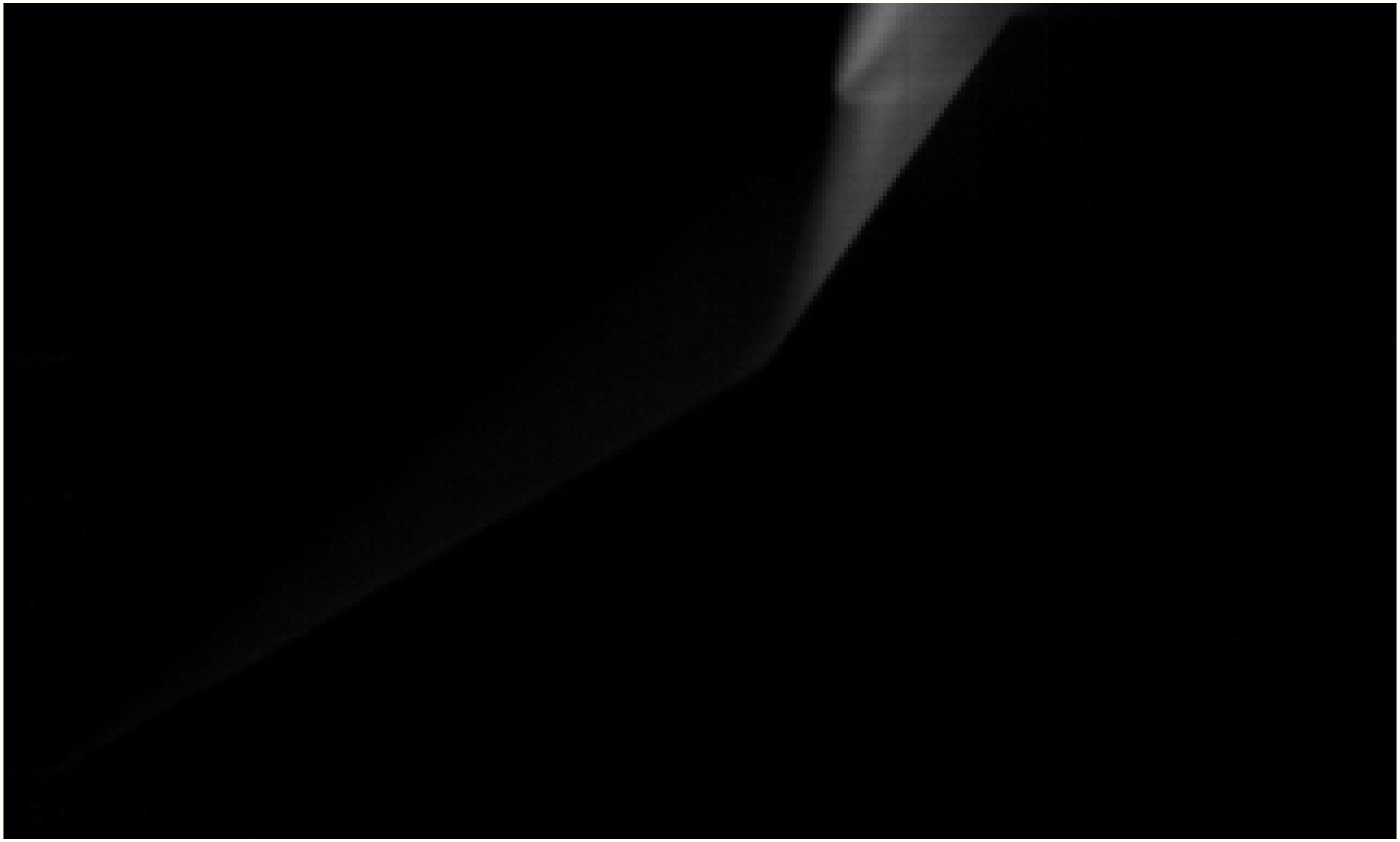


Mixture	Freestream N_2	Freestream O_2	Post Shock N_2	N	O_2	O	NO	T, K
Nitrogen	1.000	0.000	9.330E-1	6.697E-2	-	-	-	5178
30%	0.926	0.074	8.404E-1	2.329E-2	3.250E-4	1.286E-1	7.343E-3	4754
50%	0.883	0.117	7.821E-1	8.755E-3	1.978E-3	1.924E-1	1.473E-2	4425
80%	0.825	0.175	7.057E-1	2.025E-3	1.474E-2	2.480E-1	2.949E-2	3990
Air	0.790	0.210	6.659E-1	1.082E-3	3.152E-2	2.639E-1	3.751E-2	3902

High-Speed Chemiluminescence

Note: images taken during establishment process

N2

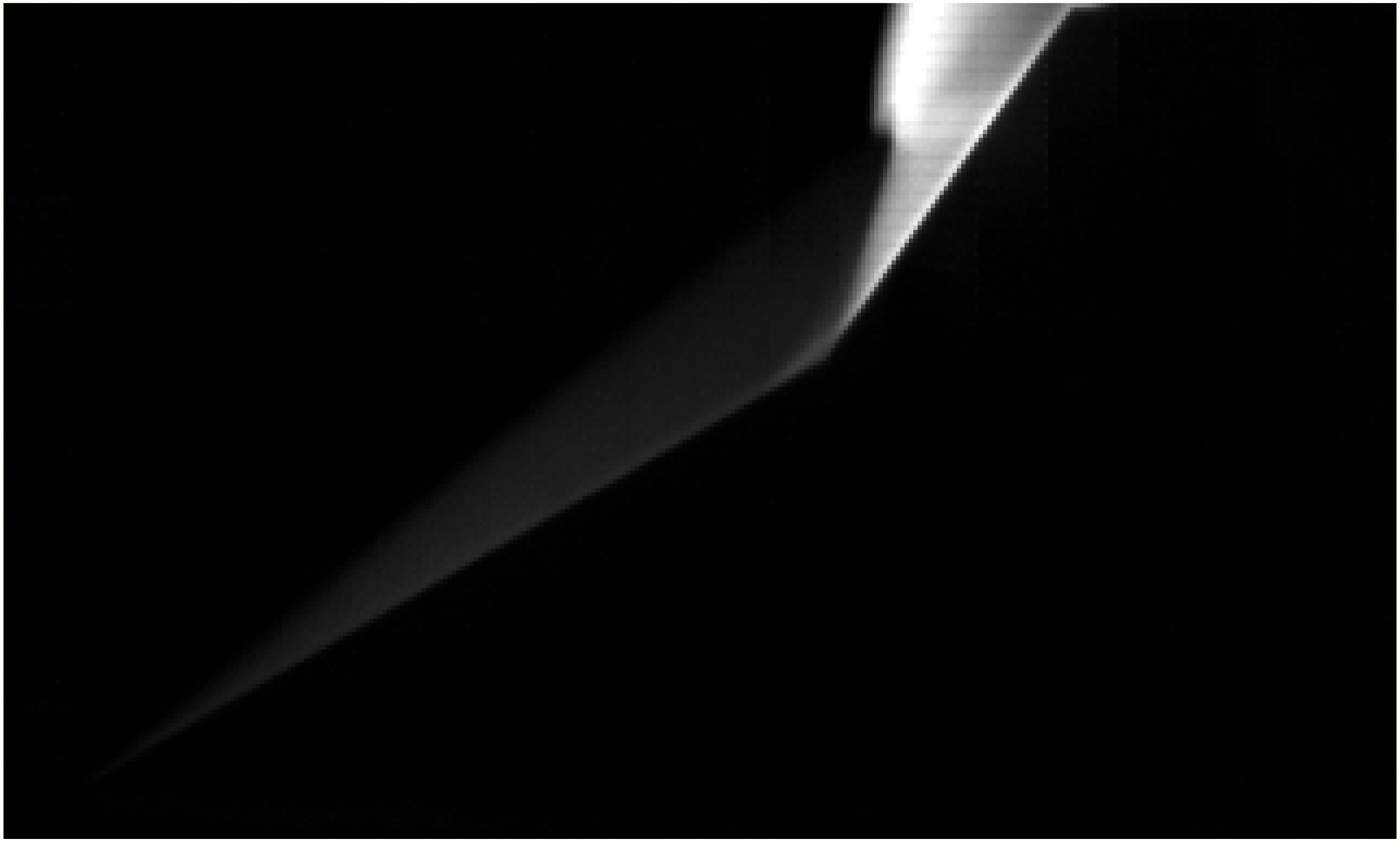


2μs, 100kHz

High-Speed Chemiluminescence

Note: images taken during establishment process

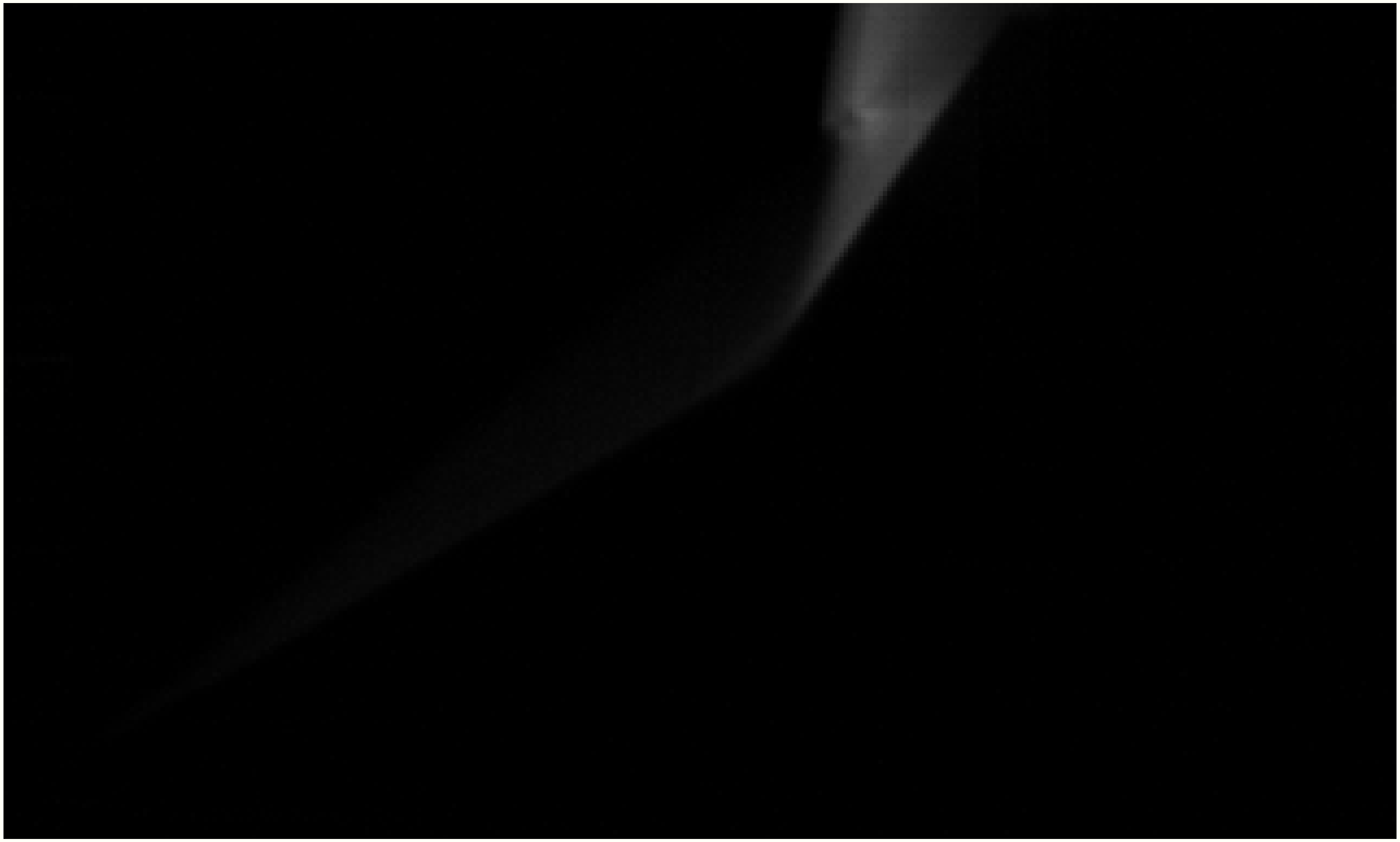
80% O2



High-Speed Chemiluminescence

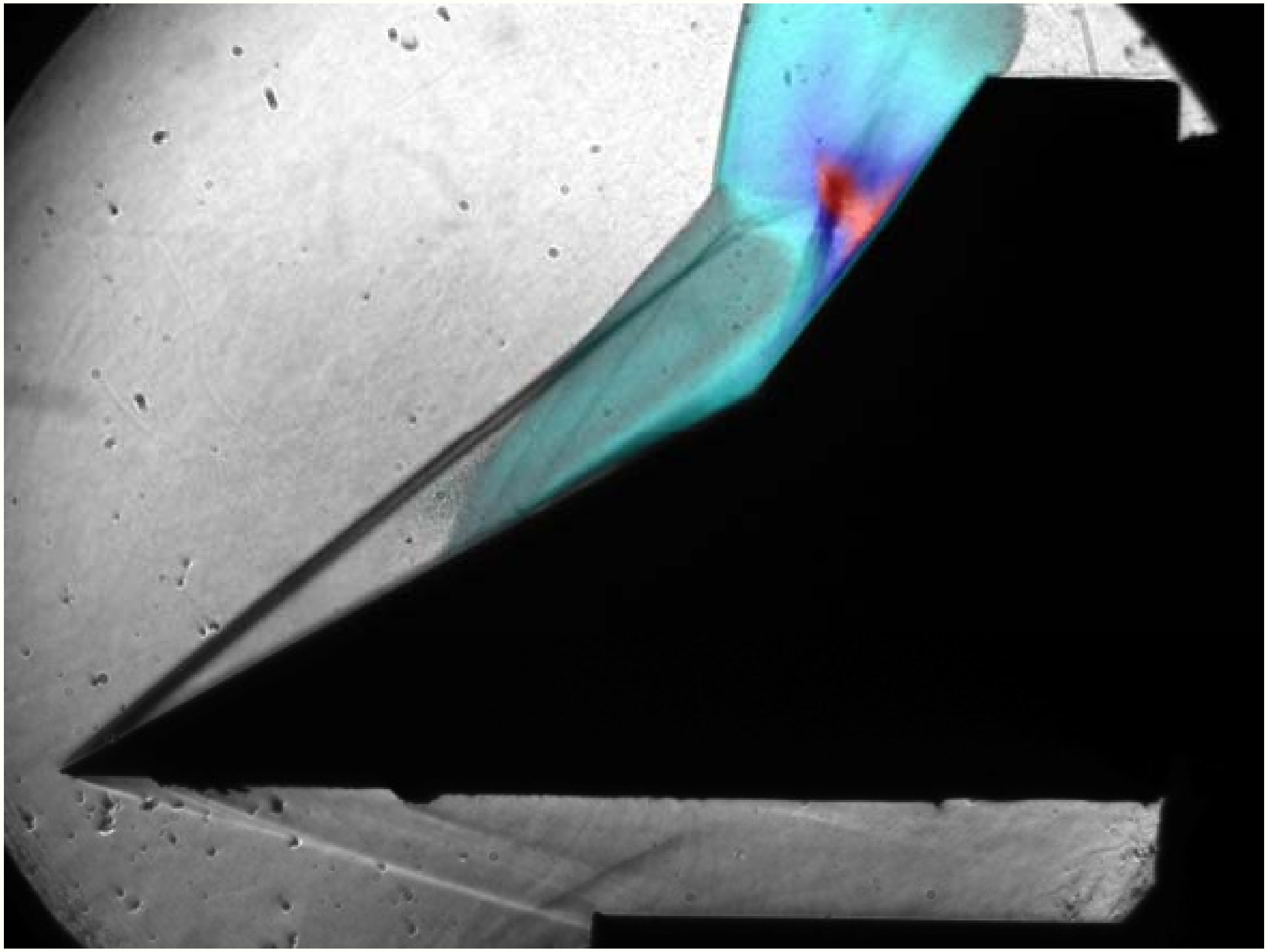
Note: images taken during establishment process

AIR



Schlieren & Chemiluminescence overlay

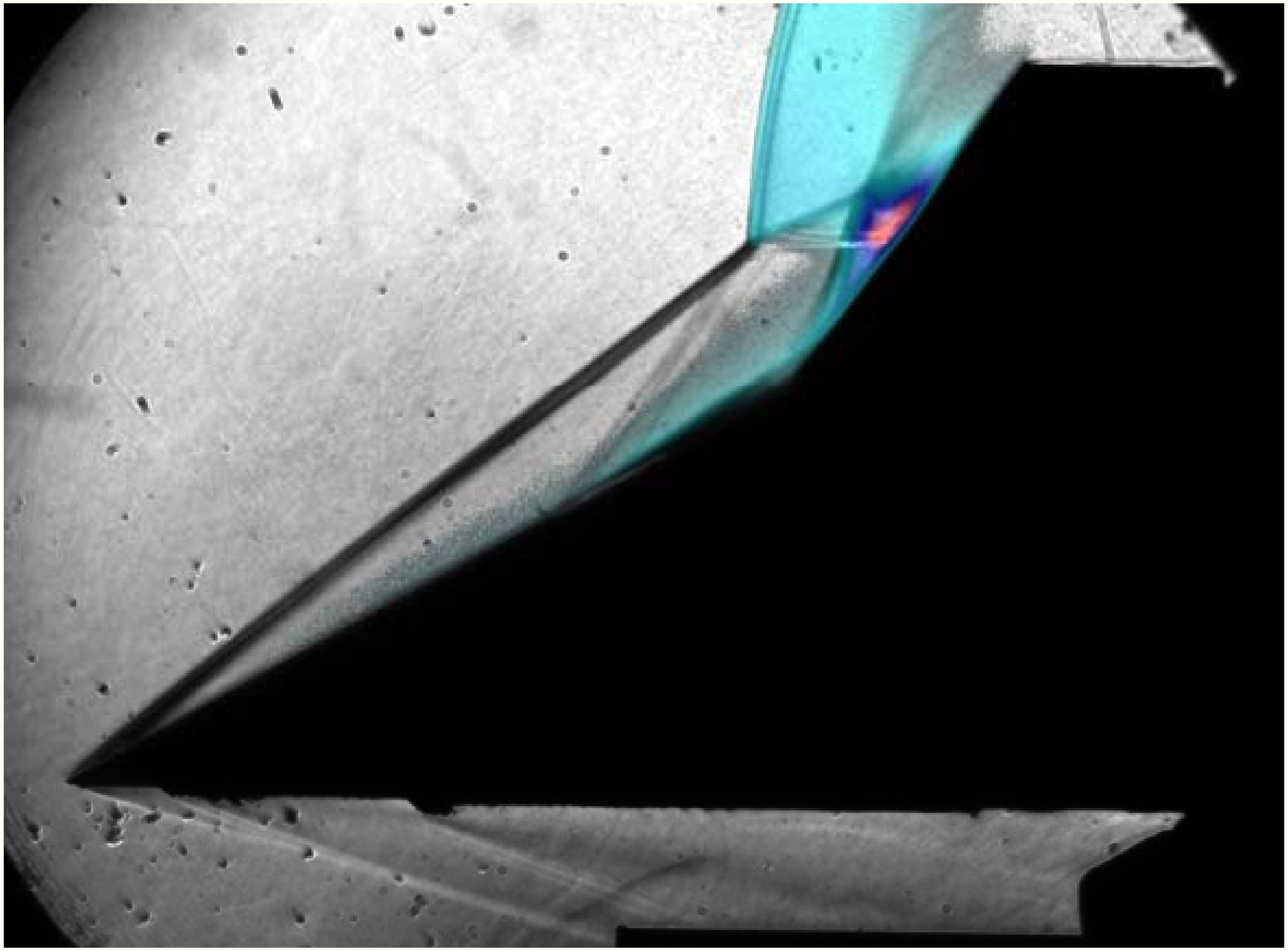
N2



Note: single shot images after flow established;
Separate experiments; false color chemiluminescence

Schlieren & Chemiluminescence overlay

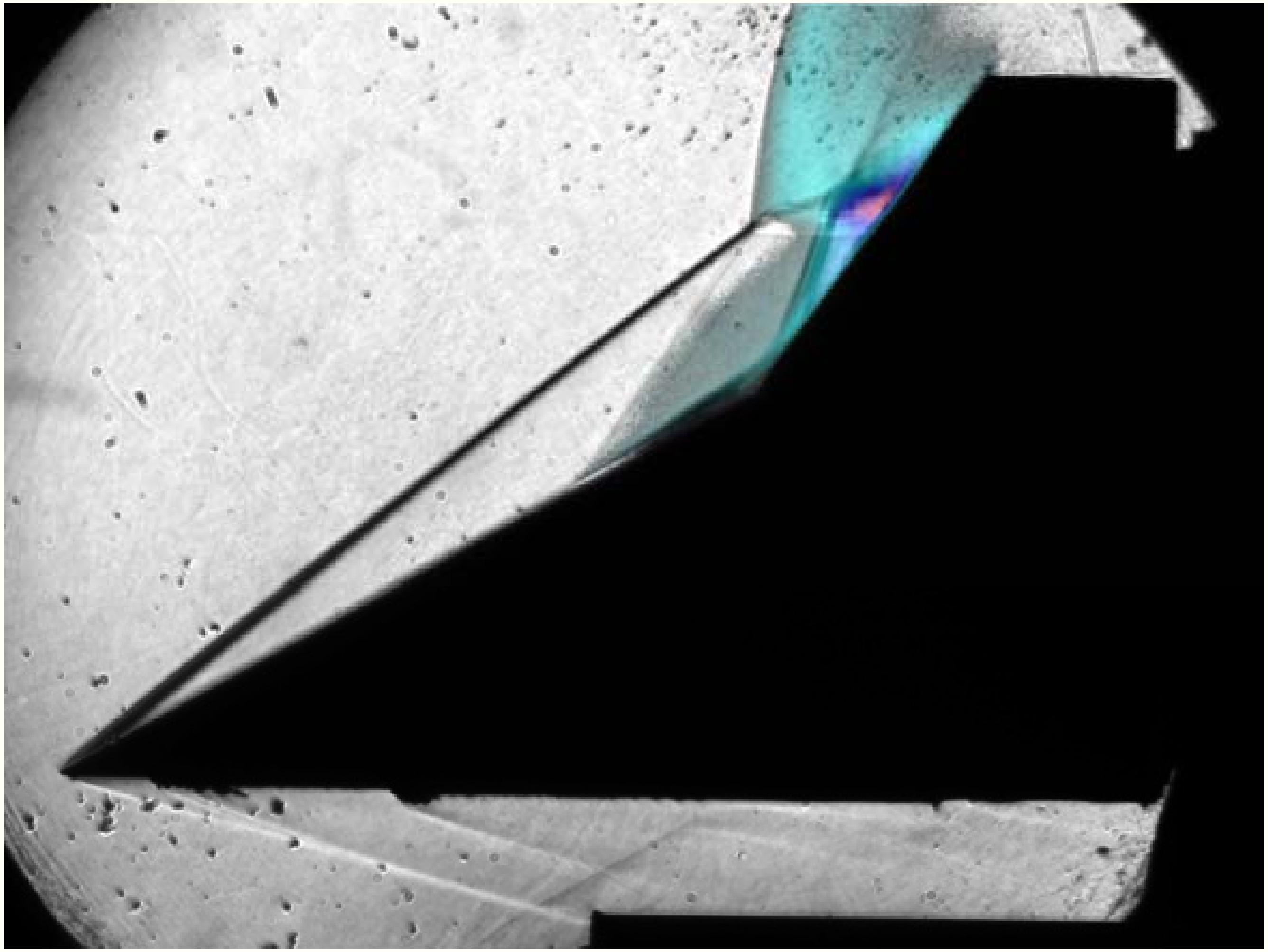
80% O_2



Note: single shot images after flow established; Separate experiments; false color chemiluminescence

Schlieren & Chemiluminescence overlay

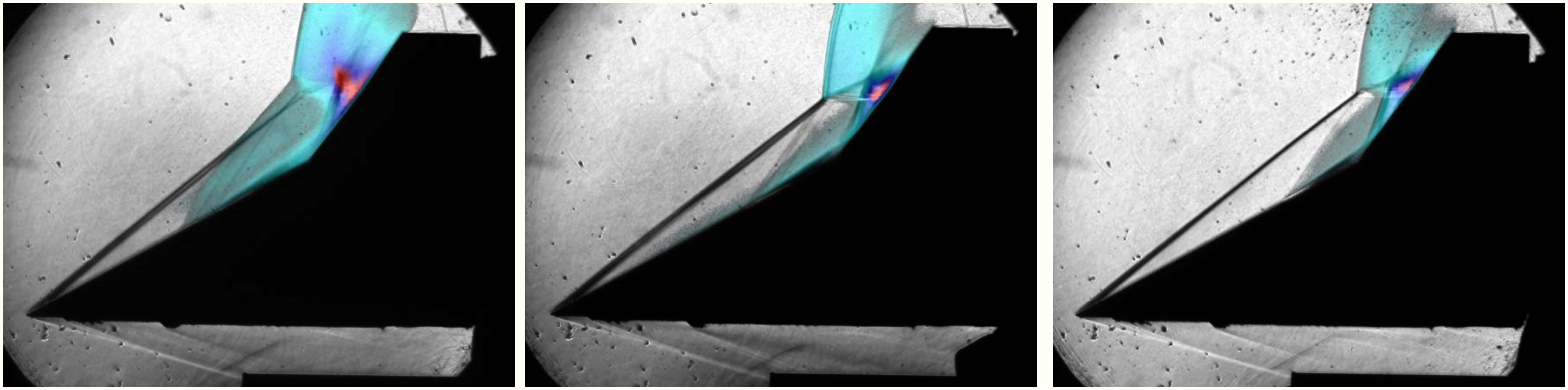
AIR



Note: single shot images after flow established;
Separate experiments; false color chemiluminescence

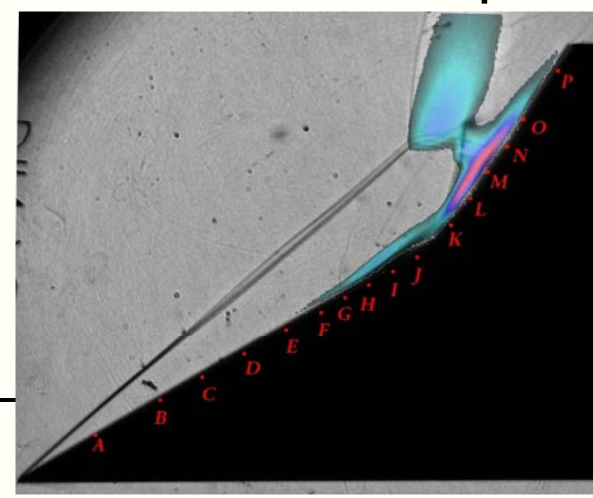
Quantifying response to increasing freestream O_2

170µs



N2 → AIR

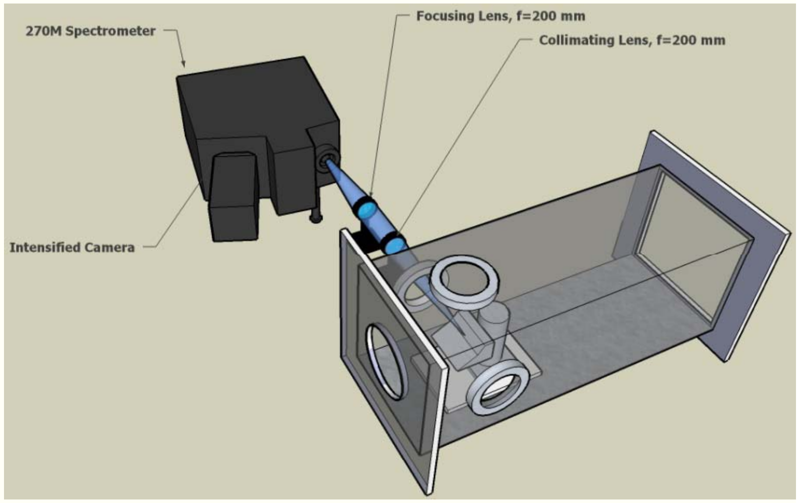
130µs



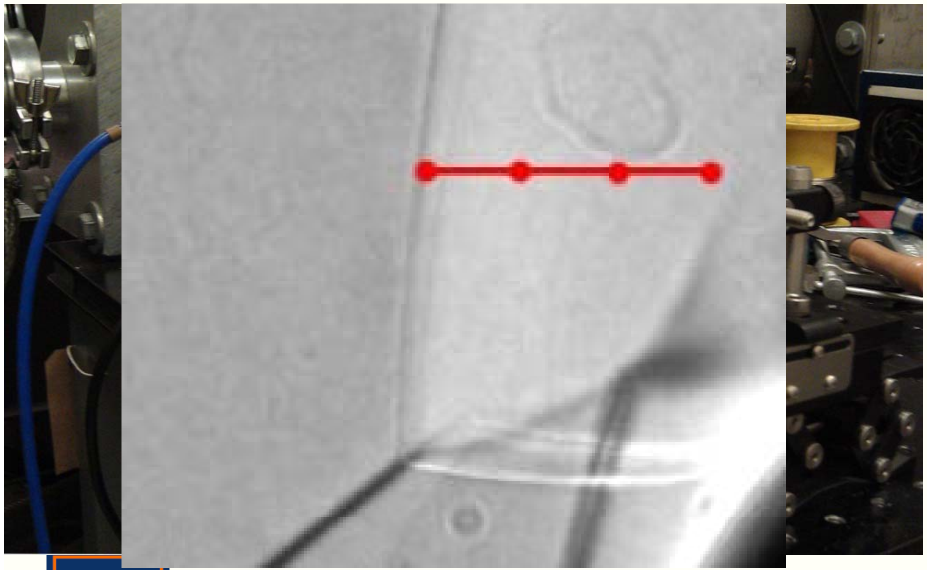
- Reflect observable differences in shock configurations and luminescence
- Activity behind reattachment shock affects L_{sep} (Davis & Sturtevant, N2)
- Activity behind separation shock
    - appears to initiate near boundary

Spectroscopic Setup

- Post bow shock NO emission spectroscopy.
  - NO γ band in the UV (220-255nm) is interrogated.
  - *f*/4 270M SPEX spectrometer: 43 μm slit, 1200 g/mm grating, 1.56 A resolution.
  - PI-Max 512 ICCD camera.
  - 110 μs exposure time in highest enthalpy condition on the double wedge.



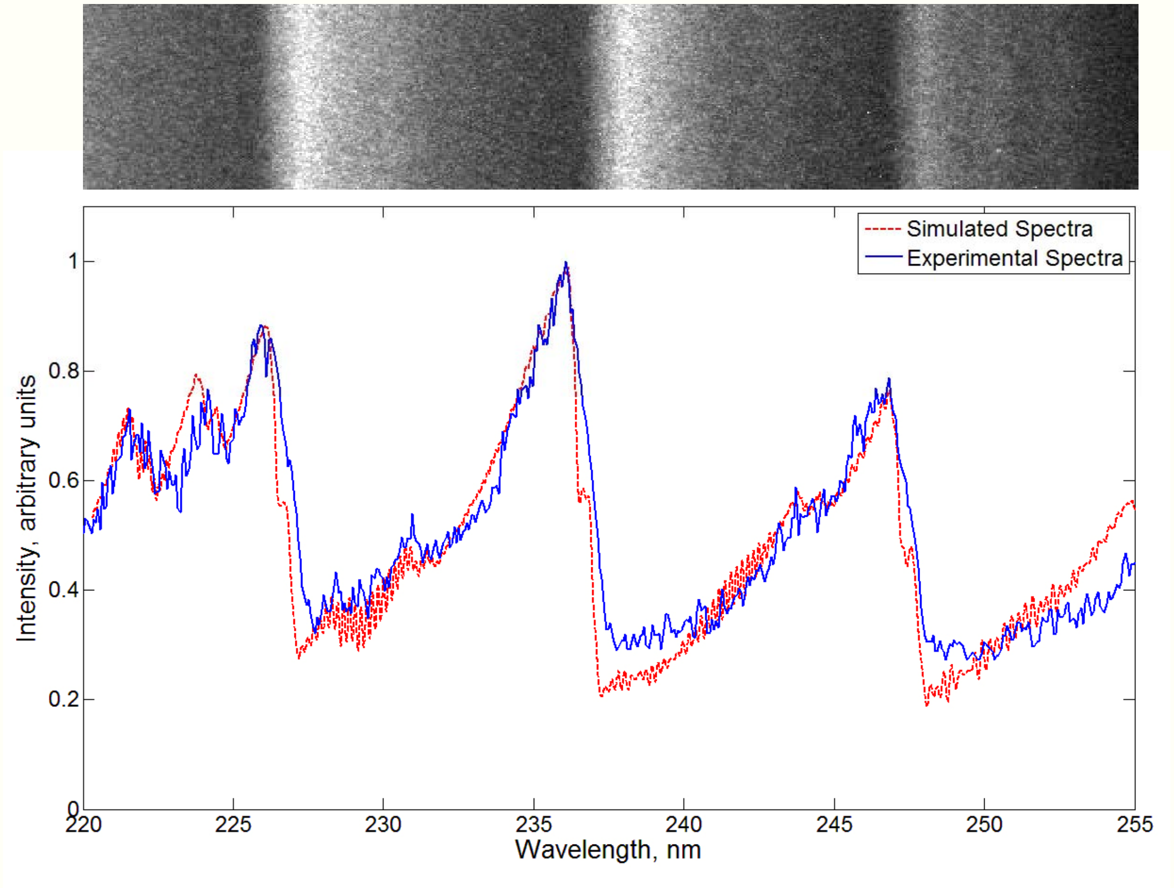
- Spectrometer calibration.
  - Fe hollow cathode used for wavelength.
  - Hamamatsu UV-VIS Deuterium lamp used for intensity.



- Optic fiber is used to transmit light.
  - Non-negligible losses through the fiber, therefore calibration of the fiber is performed.
- Guide plate is fabricated via wire EDM for spatial alignment of the optics
  - Four holes at 2 mm spacing are drilled 6.1 mm above the nominal triple point location

Temperature fitting

- Two codes are used for temperature fitting.
  - LIFBASE:
    - 5 vibrational levels.
    - 80 rotational levels.
  - In house code (Sharma 2010):
    - 20 vibrational levels
    - 250 rotational levels.
- Simulation wavelengths interpolated to match experimental data.
- Residual minimized to obtain vibrational temperature fit.

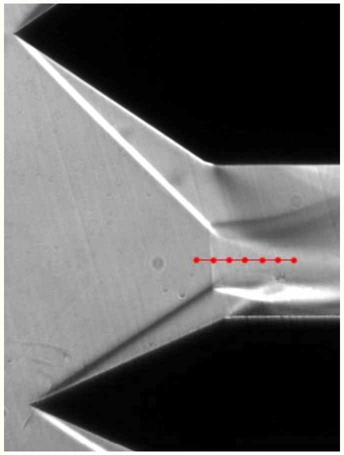


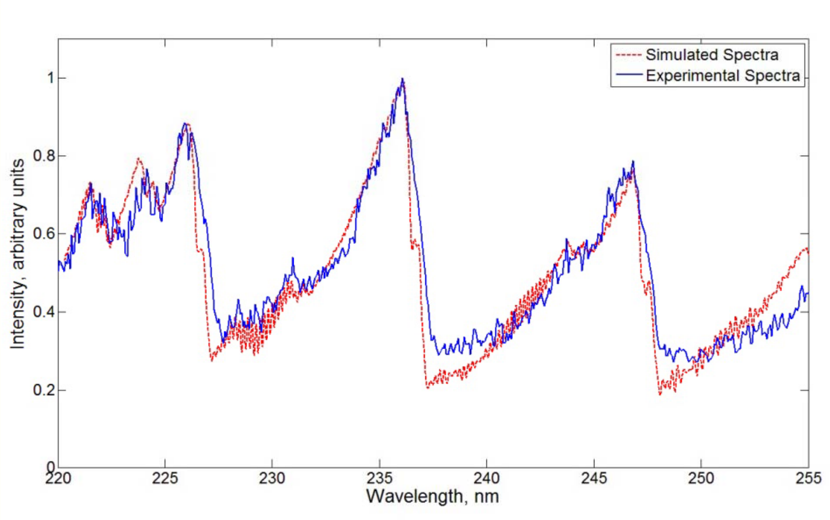
AIR

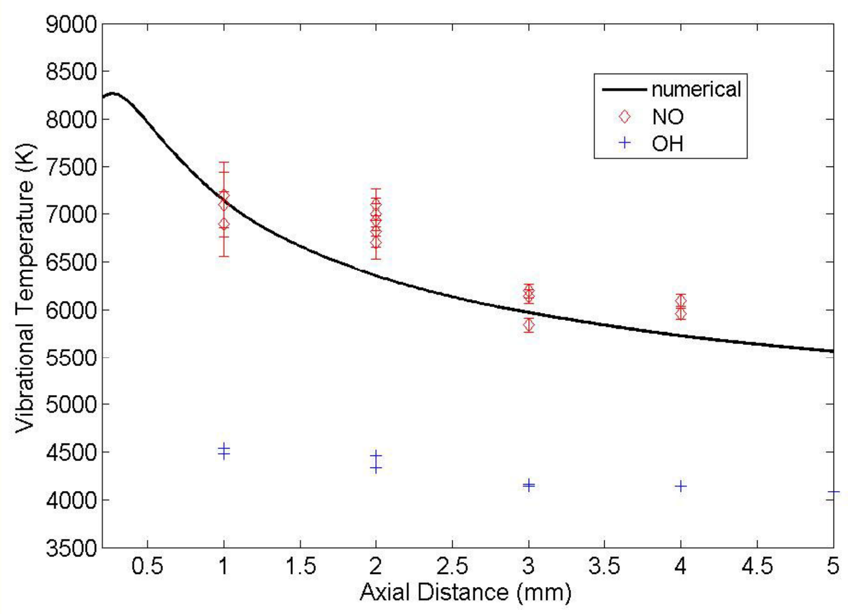
Shot 1197, 4mm position, in house simulation, T=7280K.

NO $A\ ^2\Sigma^+ \rightarrow X\ ^2\Pi$

Verification behind normal shock



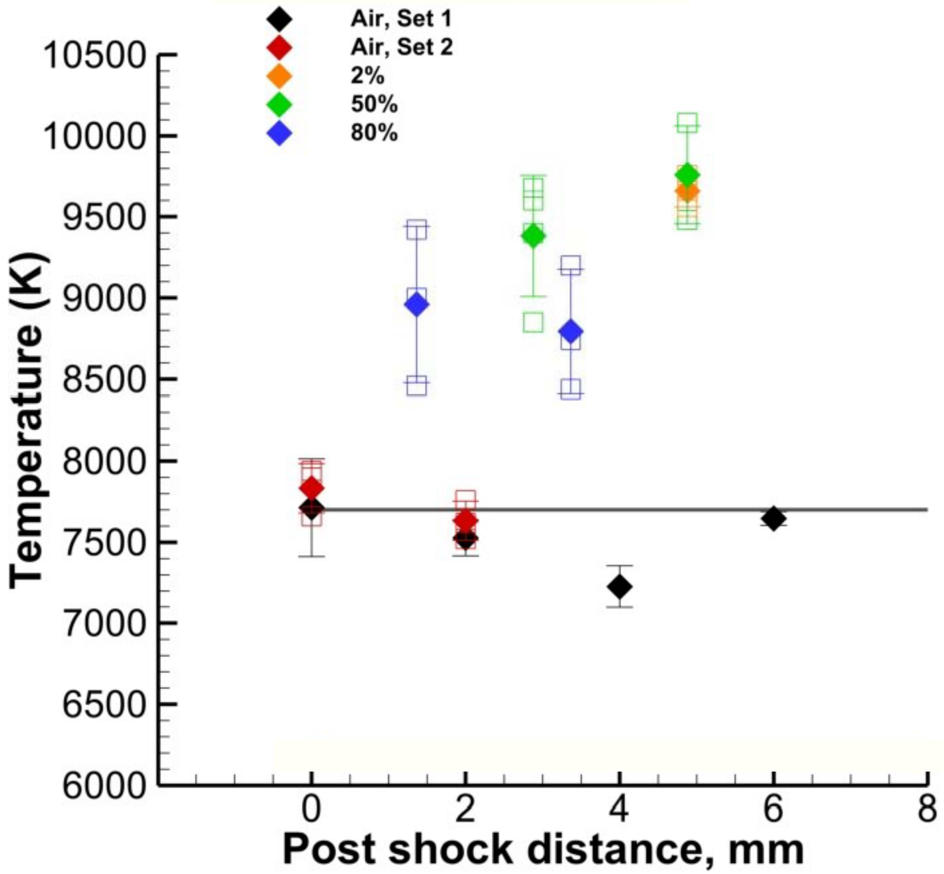


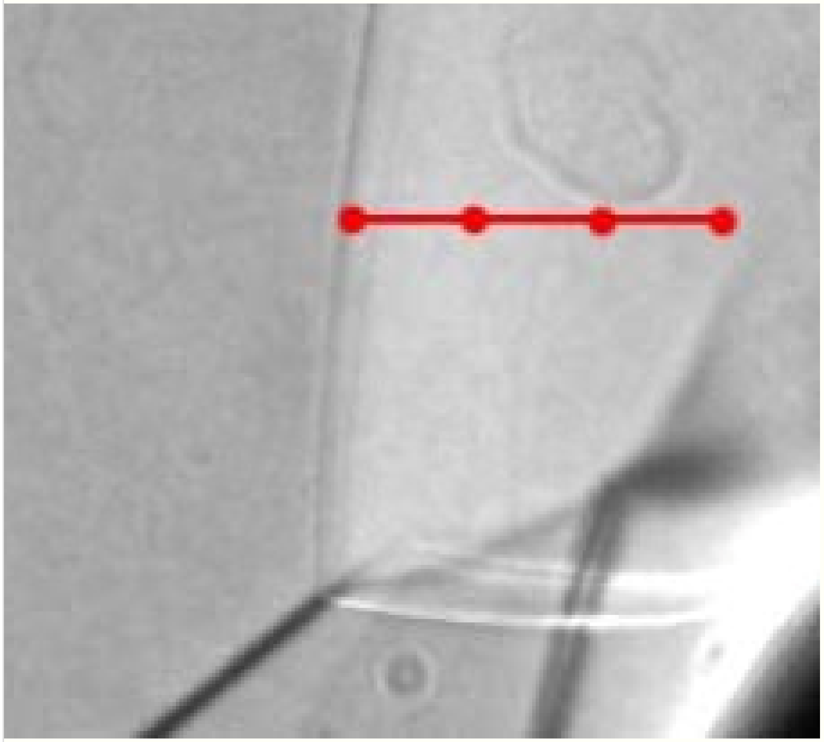


Calculation: 128 species model based on Adamovich

Sharma, Austin, Glumac, Massa, AIAA J, 2010

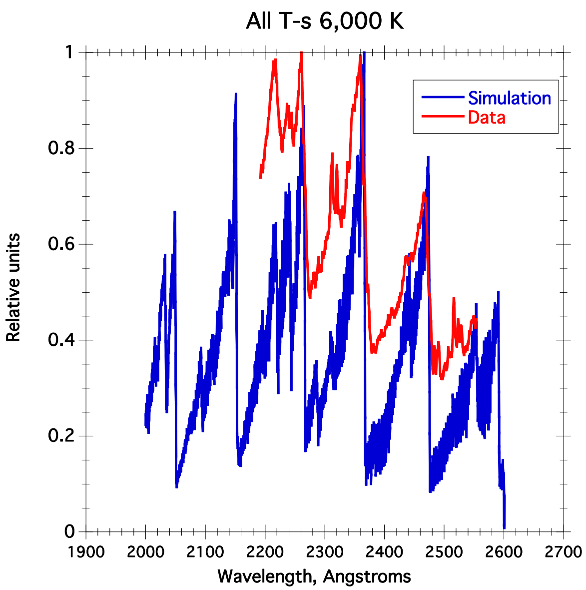
Temperature Profiles

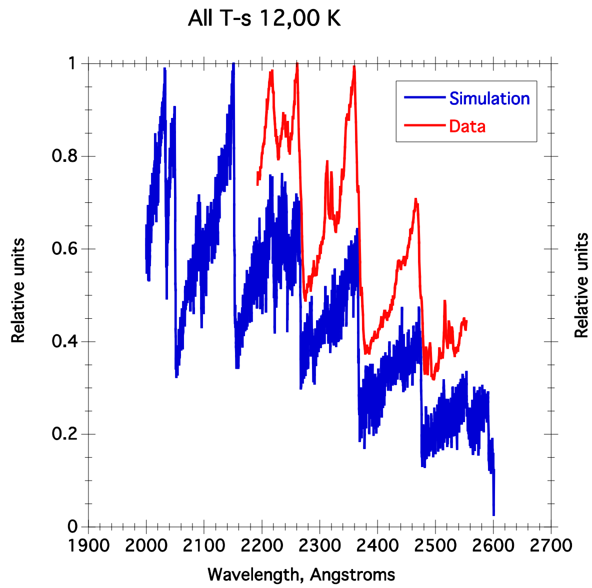


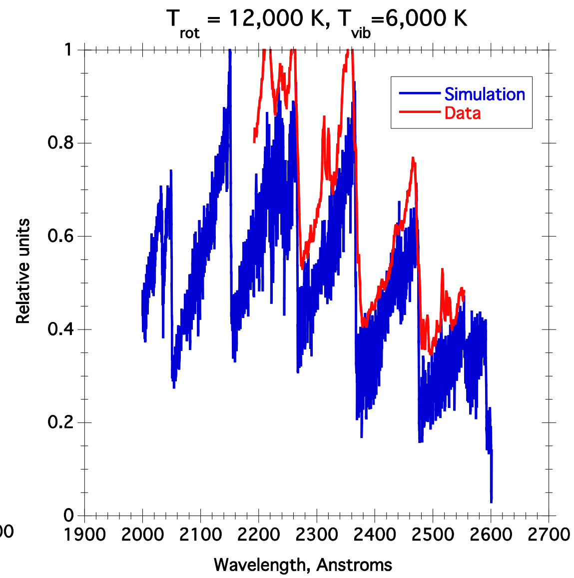


4 sampling positions
(kept relative to shock location)

Comparisons of HET spectral NO data with line-by-line spectral simulations







Assuming a single internal temperature

Simulations by Prof Levin

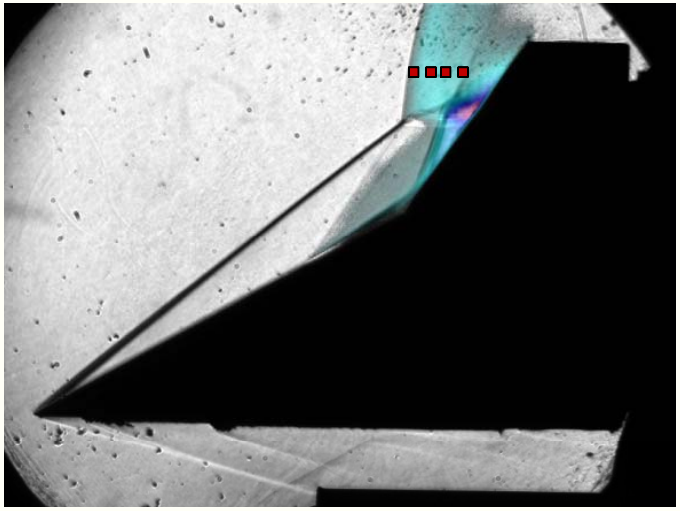
Significantly improved fit to data with **both rotational and vibrational temperatures included.**

Conclusions

- Data available: Heat transfer and single shot schlieren (AVT 205)
  Experimental viscous and inviscid establishment times
- Quantification of link between thermochemical activity and gas dynamic flow features

  Schlieren imaging overlaid with
  - chemiluminescence (global, qualitative)
  - spectroscopic temperature measurements (point, quantitative)

  as a function of freestream O2 content.



- Transition in shock configurations and temperature measurements identified at 80% O2.
- In air, NO vibrational temperatures well-captured by in-house spectral code (Sharma, Austin, Glumac, Massa)
- Additional spectral fits in collaboration with D. Levin in progress

Outstanding Challenges

- Installation and operation of Cordin camera for higher resolution imaging of separation zone – flow establishment and unsteadiness
- Additional off-centerline data (3D effects?)
- Spatial resolution of spectroscopic measurements

Acknowledgements

We gratefully acknowledge:

extensive collaborations with Prof Levin (PSU).

Prof. Hans Hornung, Drs. Eric Marineau, Simon Sanderson, Adam Rasheed, Ivett Leyva, Bahram Valiferdowsi (Caltech)

William Flaherty, Dr Manu Sharma, Prof Nick Glumac (Illinois)

FA9550-11-1-0129; Dr John Schmisseur