UNIVERSITY OF OXFORD

Emission Spectroscopy of Low Density Air Shock Tube Flows Above 10 km/s

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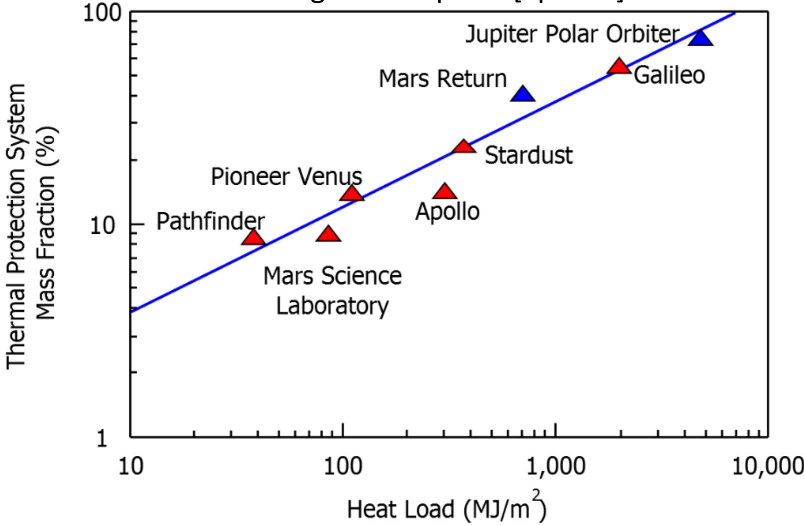
Atmospheric Re-entry and Heat Shields

- Large kinetic energy of flight transferred into internal energy of the gas in front of the capsule
  - Results in very high gas temperatures (>10.000 K)
  - Extreme re-entry conditions lead to large heat flux
- Protection by decomposing heat shield : Many missions are impossible due to too large heat shield mass
- Large uncertainties in the prediction of the flowfield
  - Non-equilibrium chemistry
  - Emission and absorption of radiation
  - Coupling between flow and heat shield
  - Convective heat flux (25% uncertainty)[1]
  - Radiative heat flux (80% uncertainty) [2]

Dragon V2 capsule [SpaceX].



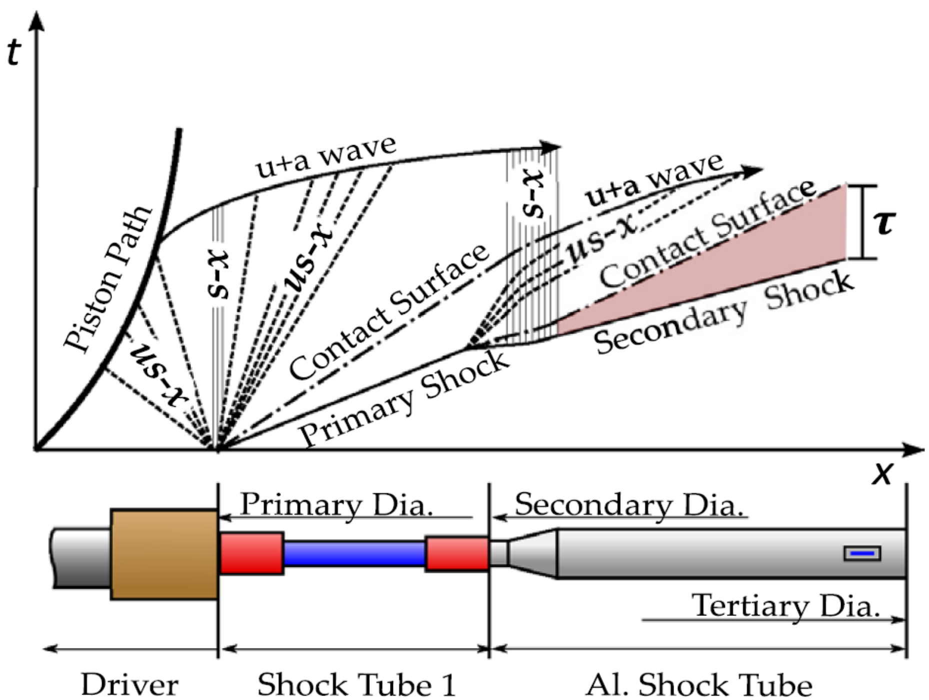
TPS mass fraction of exploration missions [M. McGilvray]

[1] Brandis and Johnston, AIAA Thermophysics conference, 2014.
[2] Johnston et al., JSR, 2013.

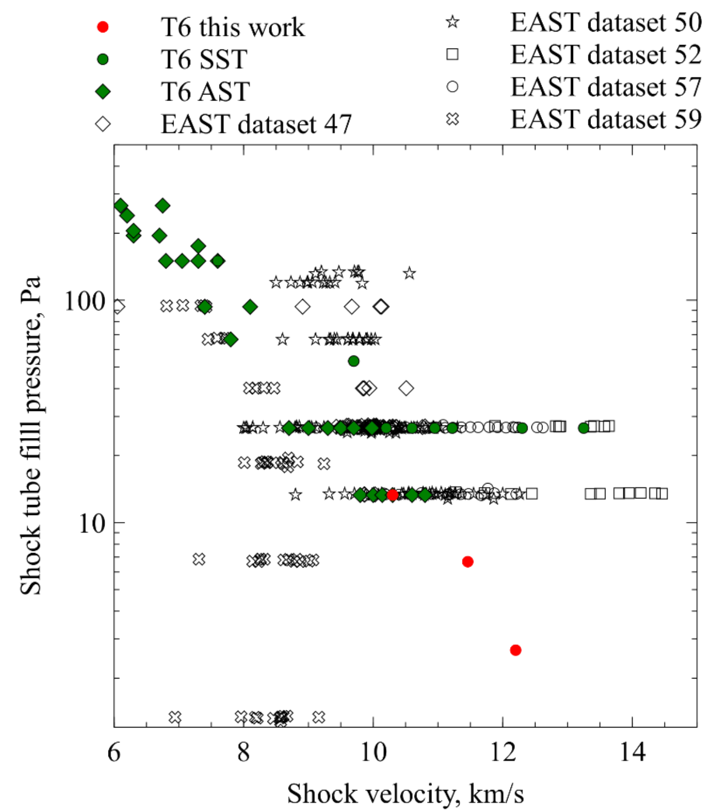
Shock Tube Testing and Flow Conditions

- Testing in T6 Aluminium shock tube mode
- Area change to achieve 225mm diameter at window location
- Use of secondary driver (10 kPa Helium)
- Synthetic air used as test gas

Shot number	Fill pressure, Pa	Shock velocity, km/s
221	13.3	10.30
229	6.67	11.26
231	2.67	12.31

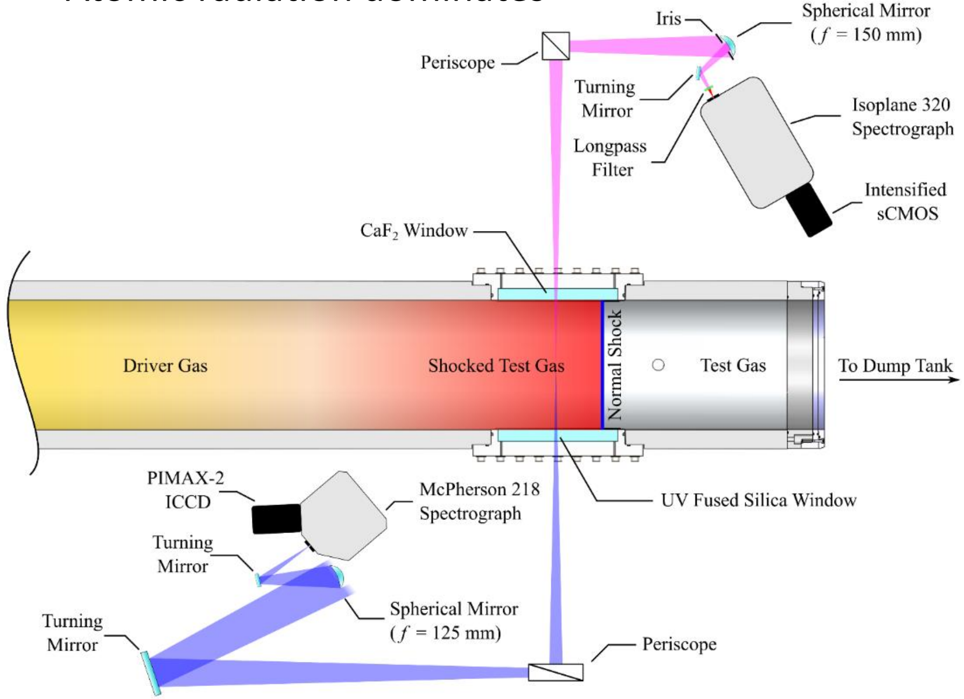


Collen et al. “Development and commissioning of the T6 Stalker Tunnel” ExiF 2021

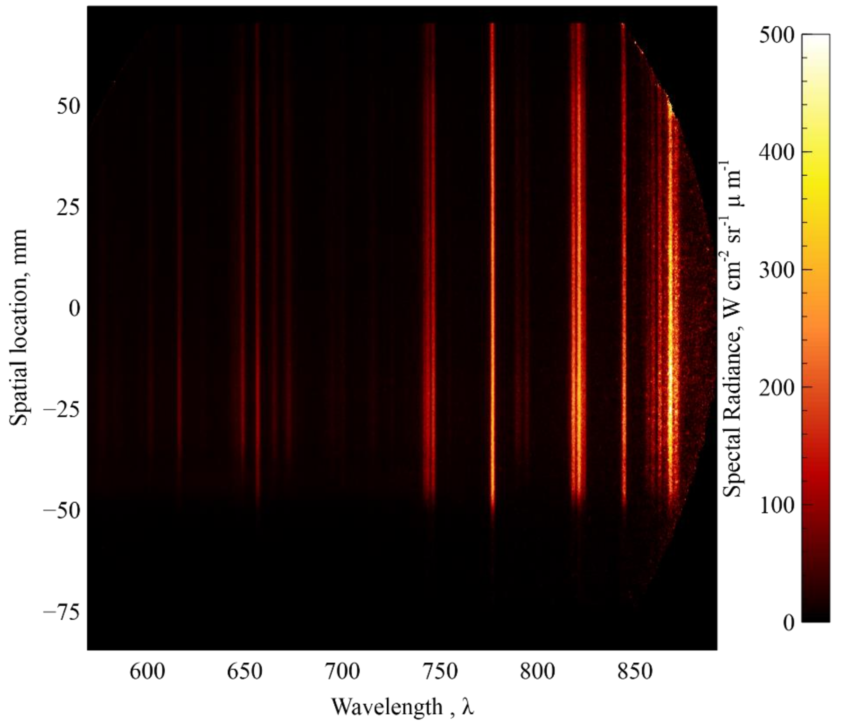


Emission Spectroscopic Setup

- Calibration for absolute radiance using integrating sphere
- Characterisation of instrument functions
  - Spatial: Derivative of integrating sphere edge ($FWHM_G$=0.7 mm, $FWHM_L$=0.5 mm)
  - Spectral: Mercury lamp with thin lines ($FWHM_G$=1.25 nm, $FWHM_L$=0.009 nm)
- Exposure time of 0.5 μs
- Atomic radiation dominates



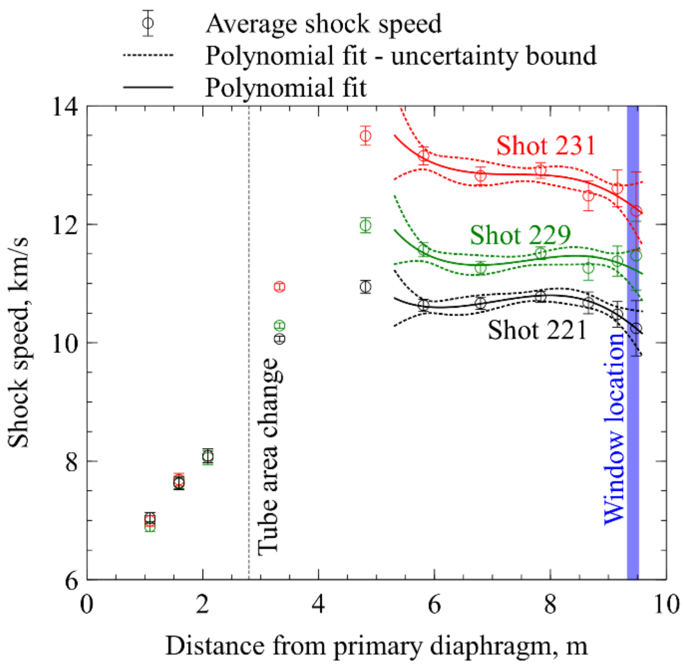
Glenn et al. "Comparison of Equilibrium Radiation between Shock Tube and Plasma Torch Spectroscopy for Atmospheric Pressure Air, RHTG 2022"

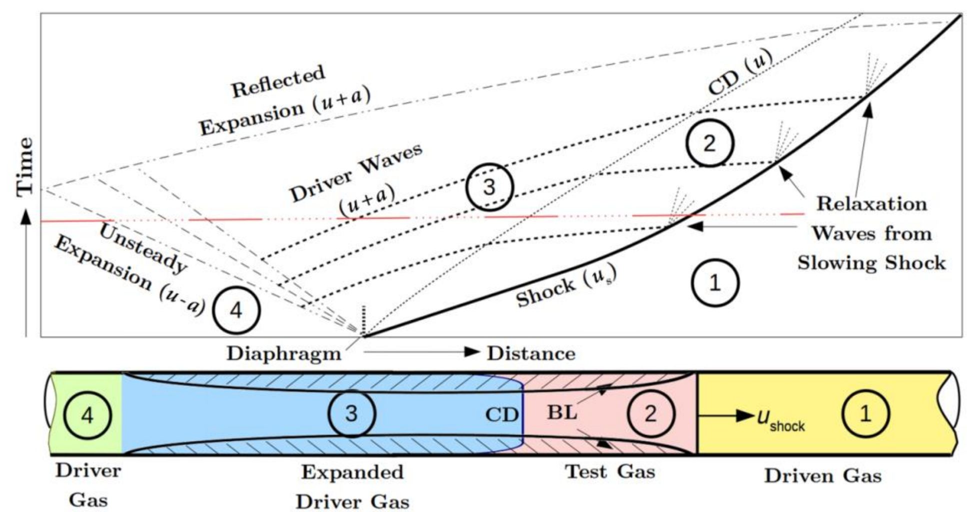


Calibrated spatially resolved spectrum of shot 221.

Analysis using Simulation Tools

- Shock speed analysis using Monte-Carlo approach with polynomial fit
- CEA equilibrium simulation using nominal shock speed at window location – shock speed uncertainty analysis for upper and lower boundary
- LASTA simulation using equilibrium gas composition: Spatial evolution behind shock
- Poshax simulation using nominal shock speed at window location (Park 93 rates): Non-eq. region
- NEQAIR 15.0 used with Boltzmann and flux limited QSS population distribution and spatial and spectral smearing functions
- Spectrum cumulated between 680 – 850 nm

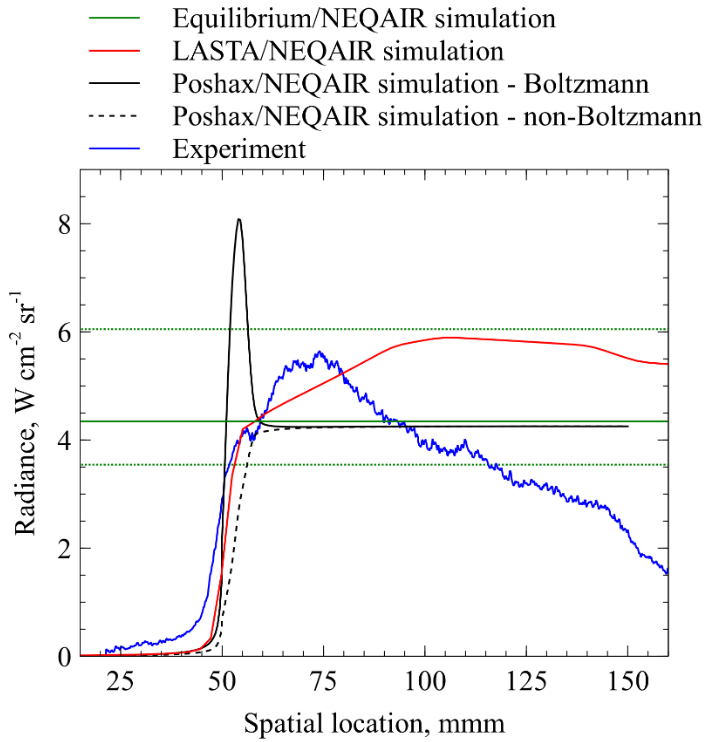


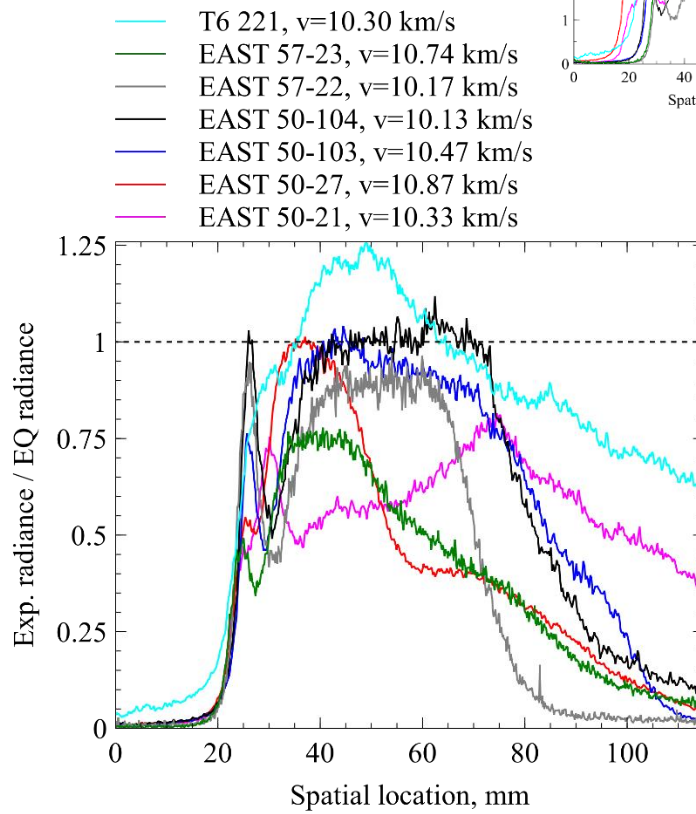


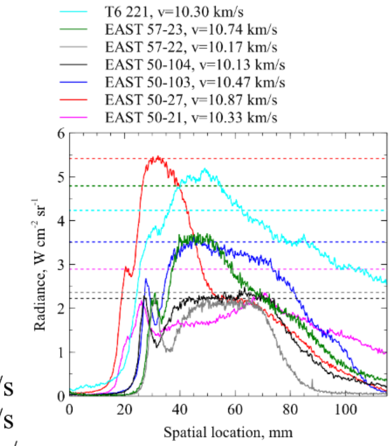
Satchell et al. "Analytical Method of Evaluating Nonuniformities in Shock Tube Flows: Theory and Development", AIAAJ 2022

Results – 13.3Pa, 10.30 km/s

- Comparison to simulations and to comparable EAST datasets (at 13.3 Pa)
- Reasonable agreement with LASTA – however, drop of radiation after 25mm
- Similar spatial features between T6 and EAST 57-23, 50-27
- Nonequilibrium region far from Boltzmann distribution
- Non-Boltzmann distribution does not adequately cover double peak
- No significant molecular radiation is observed in the non-eq. region

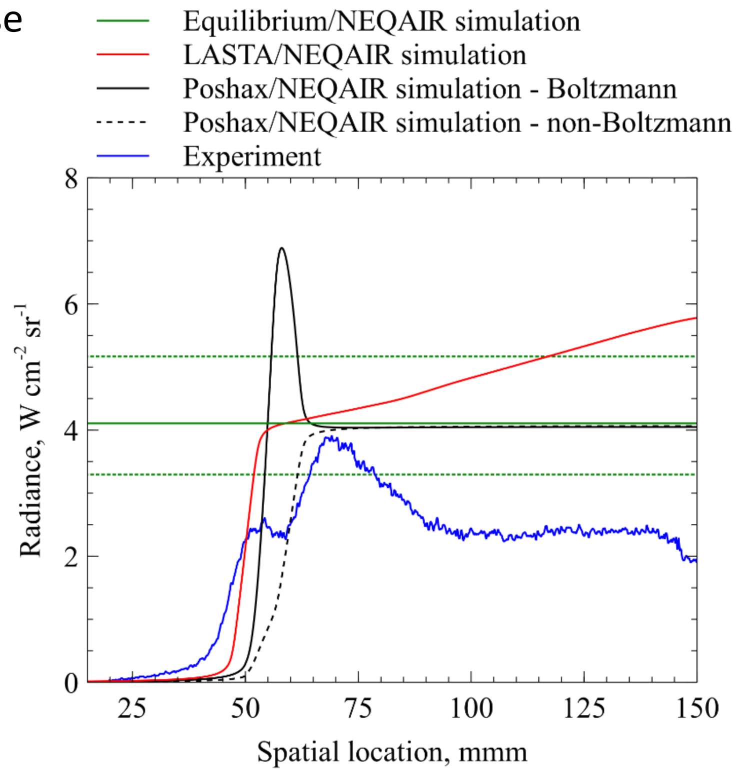


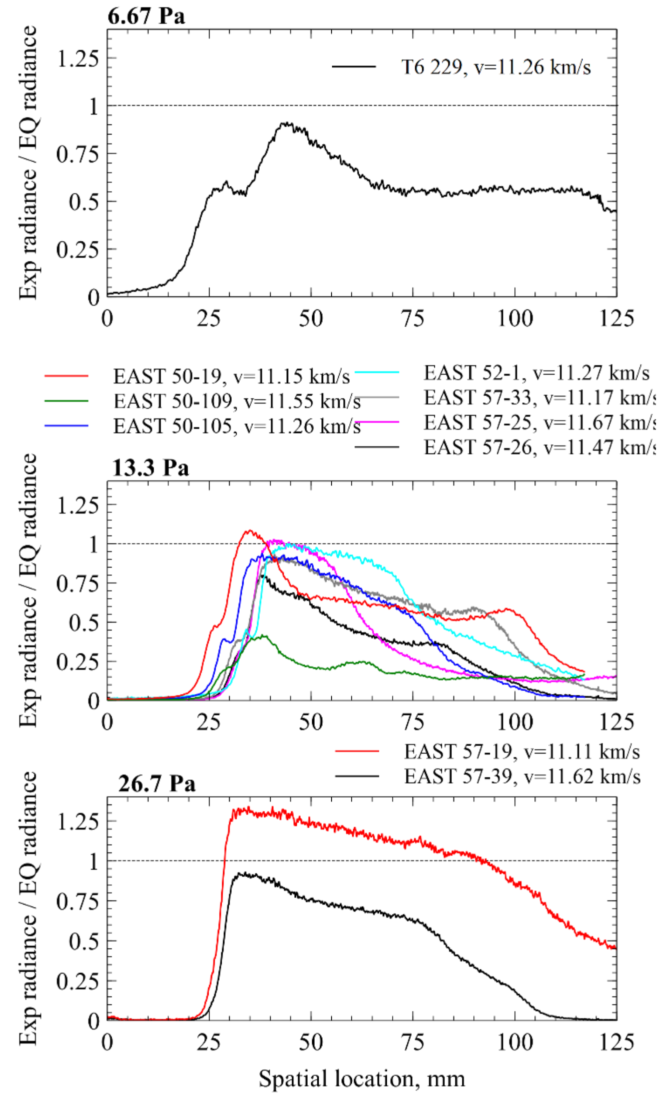




Results – 6.67 Pa, 11.26 km/s

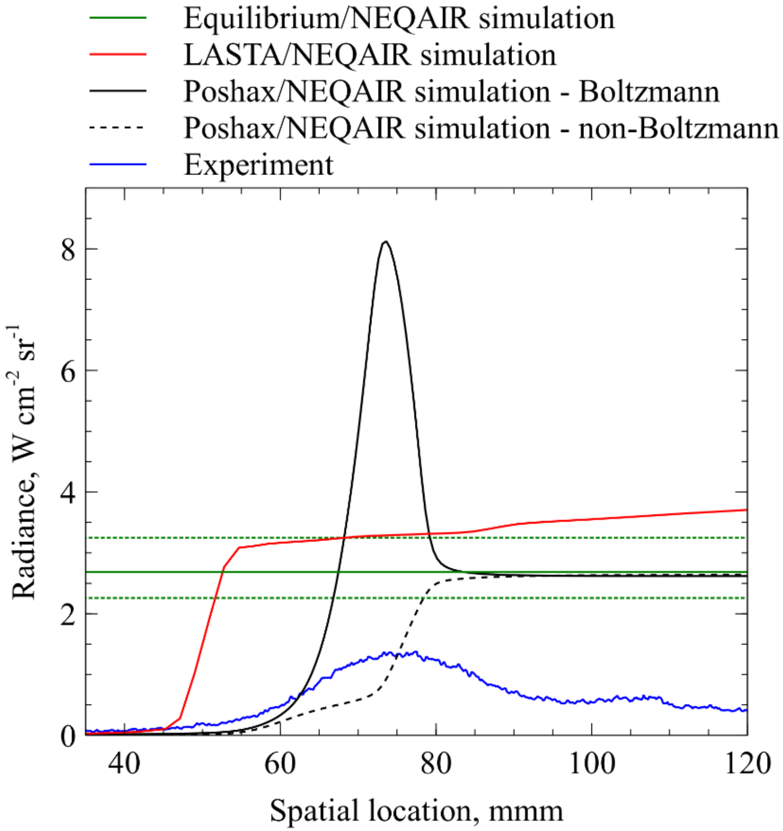
- Plateaued radiance region below equilibrium uncertainty
  - Potential mismatch due to large boundary layers or driver gas mixing
- Double peak non-equilibrium region more pronounced at lower pressure
- Neither Boltzmann nor non-Boltzmann models capture non-eq. rise

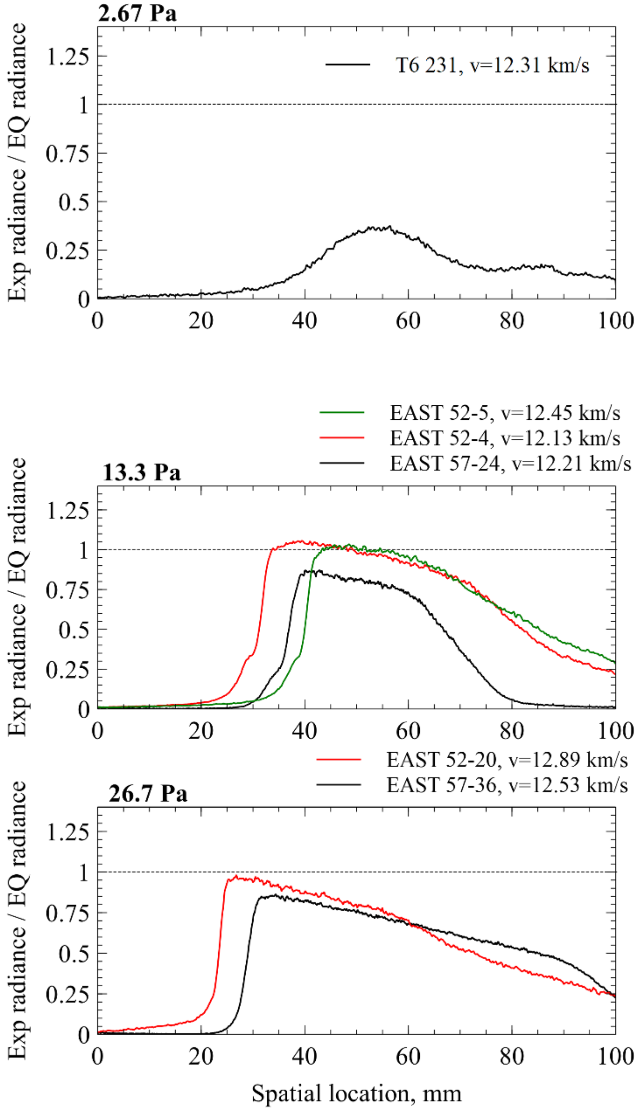




Results – 2.67 Pa, 12.31 km/s

- Non-equilibrium region strongly elongated at lower pressure
- Radiation intensity far below uncertainty boundary
- Both Poshax simulation fail to reproduce non-equilibrium





Conclusions

- Shock tube measurements carried out at low pressures in T6 Aluminium shock tube facility
  - Between 10.3 and 12.3 km/s
- Optical emission spectroscopy carried out in the VIS/NIR spectral regions
- Comparison to EAST data at similar shock velocities/pressures where possible
- Simulation using LASTA, Poshax, and CEA
- Agreement in absolute radiance for higher pressure experiments
- Mismatch in absolute radiance for low pressure conditions – possible boundary layer influence, premature mixing with driver gas
- Current simulation tools do not adequately reproduce measurement data
  - Spectral analysis methods needed to deduce thermochemical state from spectral data