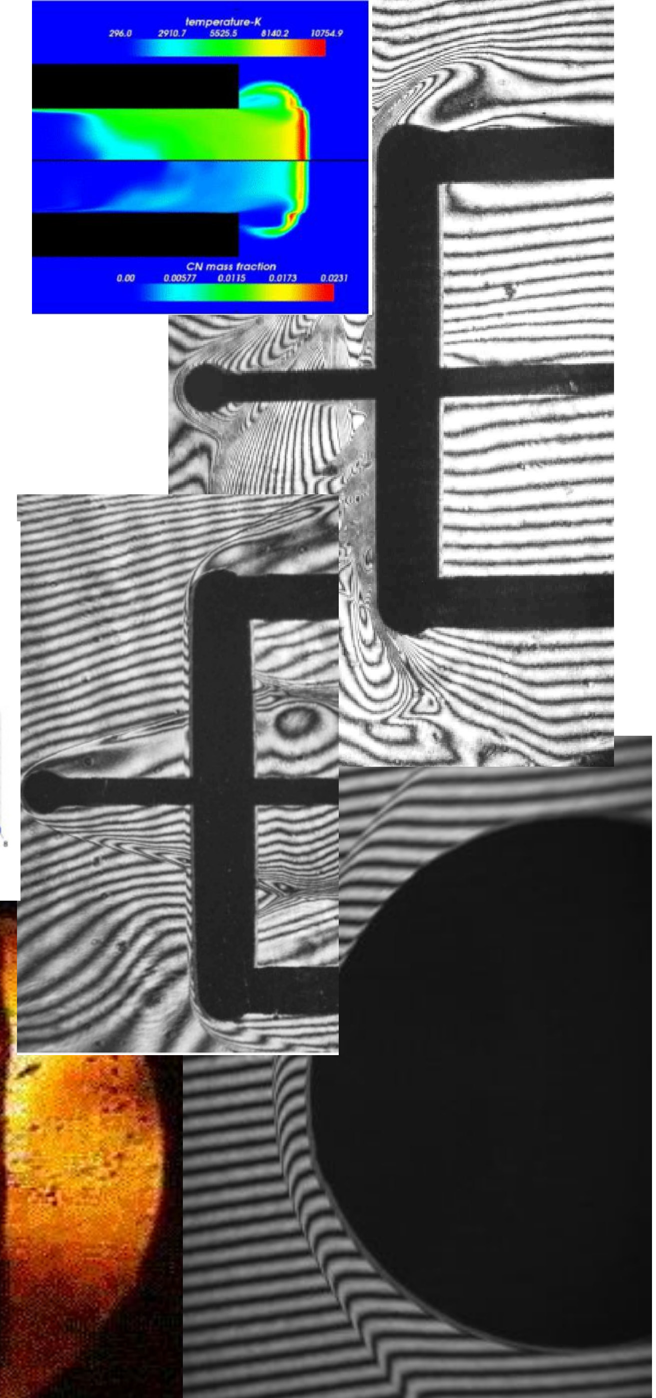
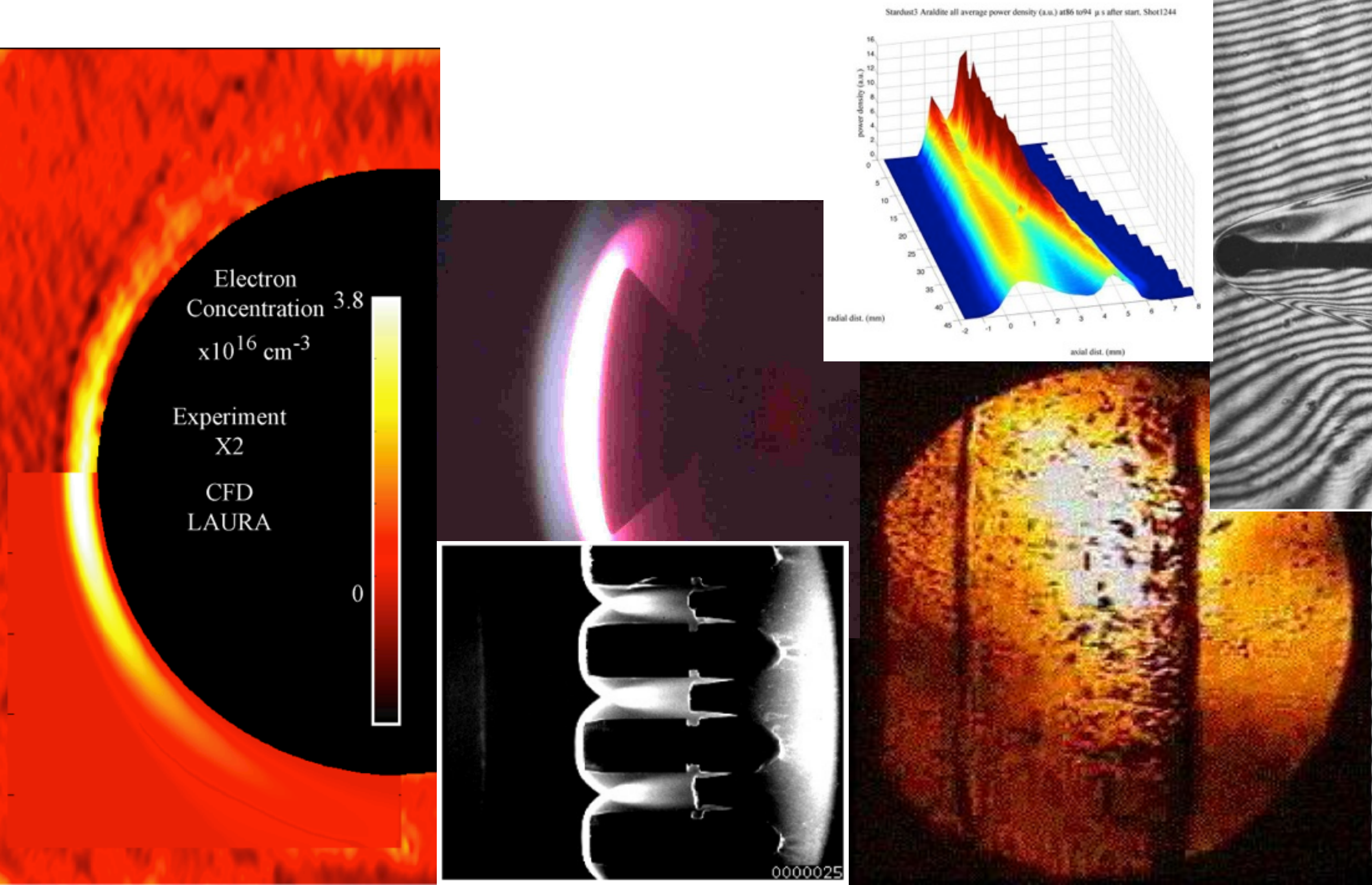
# Hypersonics Research at The University of Queensland

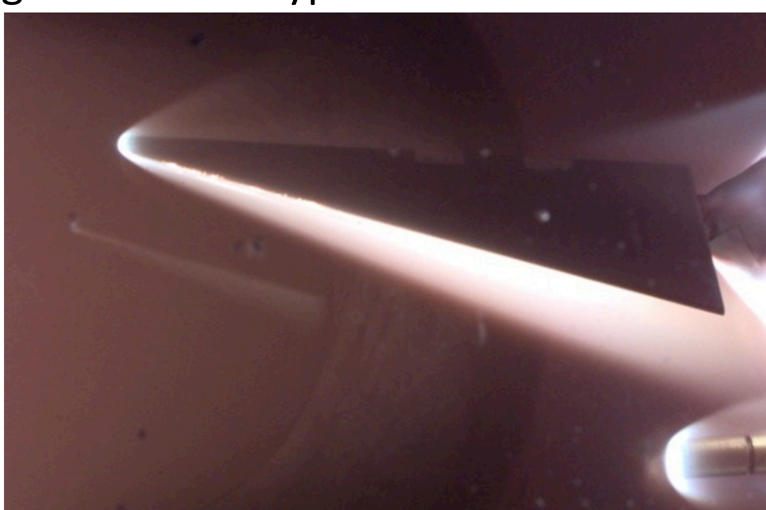
*Richard Morgan*
*Centre for Hypersonics*
*The University of Queensland*

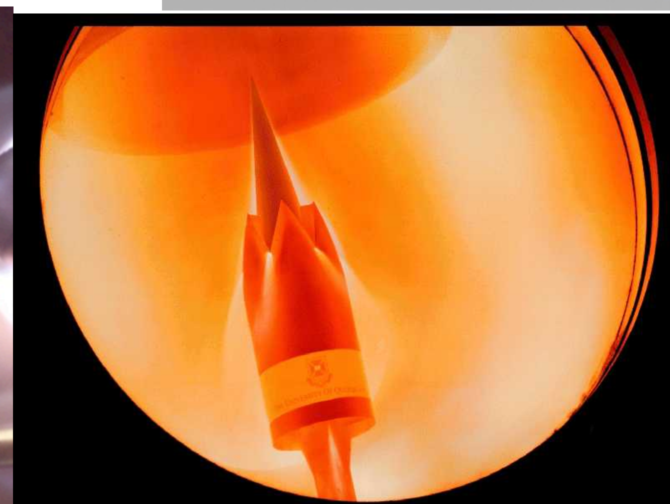


## *Current activities*

- All aspects of Scramjet propulsion
- Radiating flows
- Optical diagnostics
- Instrumentation
- Shock and expansion tube development
- CFD
- Flight testing
- Reentry flows and thermal protection
- Ablating flows
- Materials development
- High performance solid fuel rockets
- Hypervelocity aerothermo-dynamics
- Education. Over 100 higher degree students graduated in hypersonics



## *Personnel*

- 9 academic staff
- 8 research fellows
- 8 adjunct staff
- 40 research students
- 4 technical staff

## *Facilities*

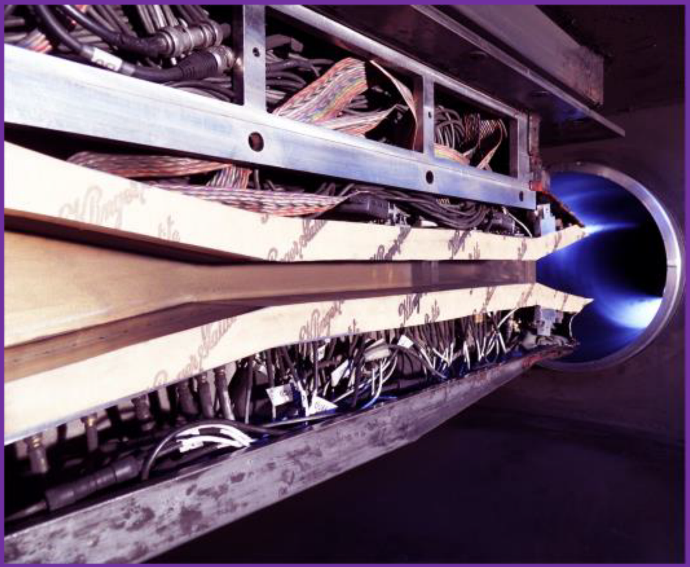
- T4 reflected shock tunnel
- X2 and X3 superorbital expansion tunnels
- ‘Griffin’ 25 mm light gas gun/reflected shock tunnel

## *Software*

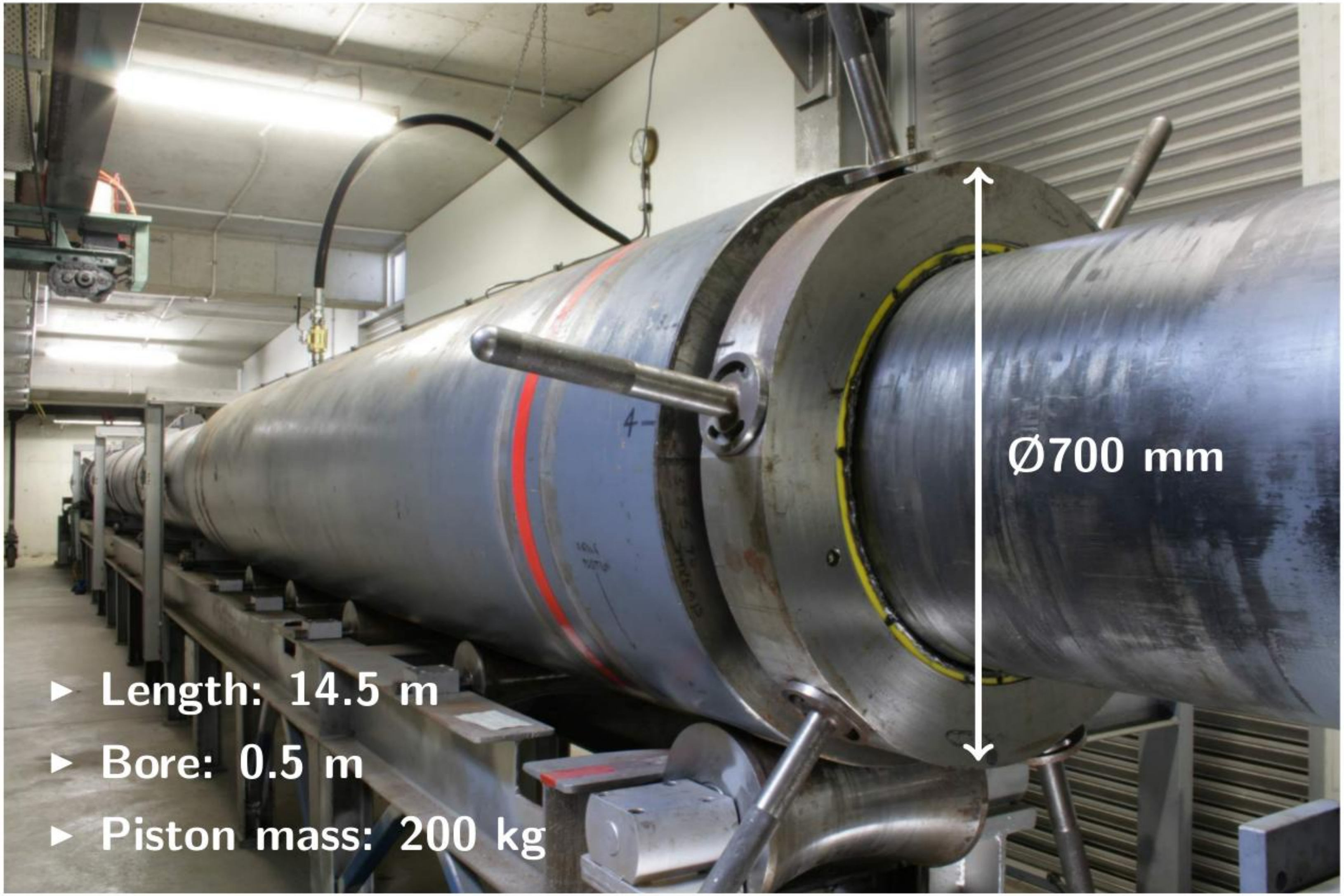
- L1D, EILMER, POSHAX (1D and 2D codes for facility analysis and general NEQ hypersonics computations)
- Photaura (line-by-line spectral model)

# *Flight testing*

HyShot,HiFIRE,HyCause,SCRAMSPACE`



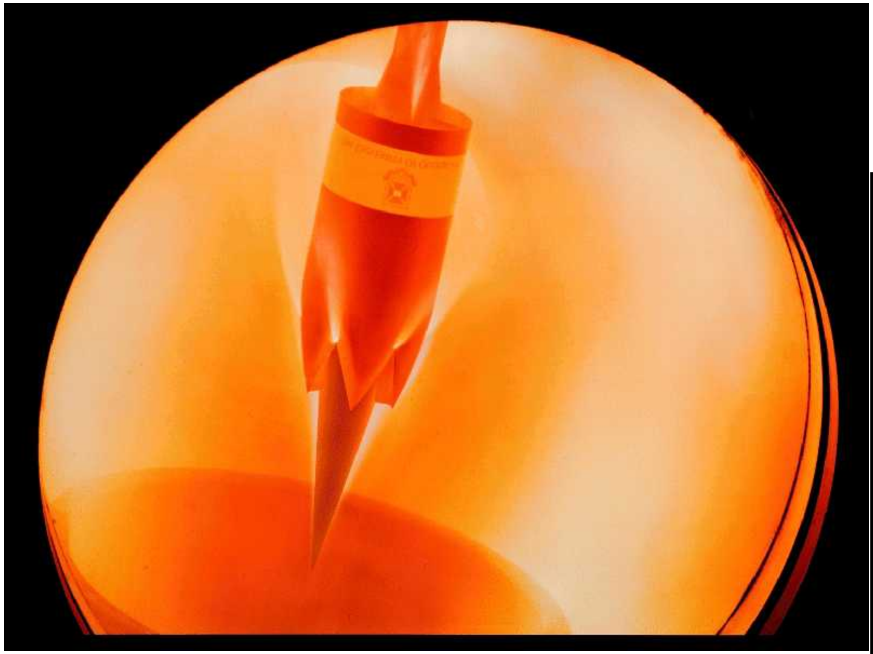
# X3 free-piston driver

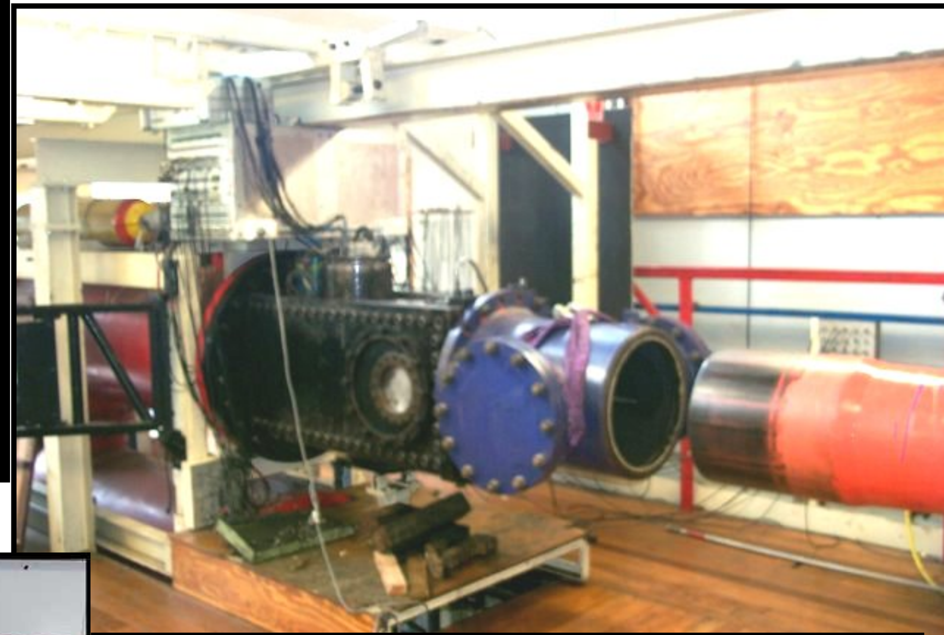


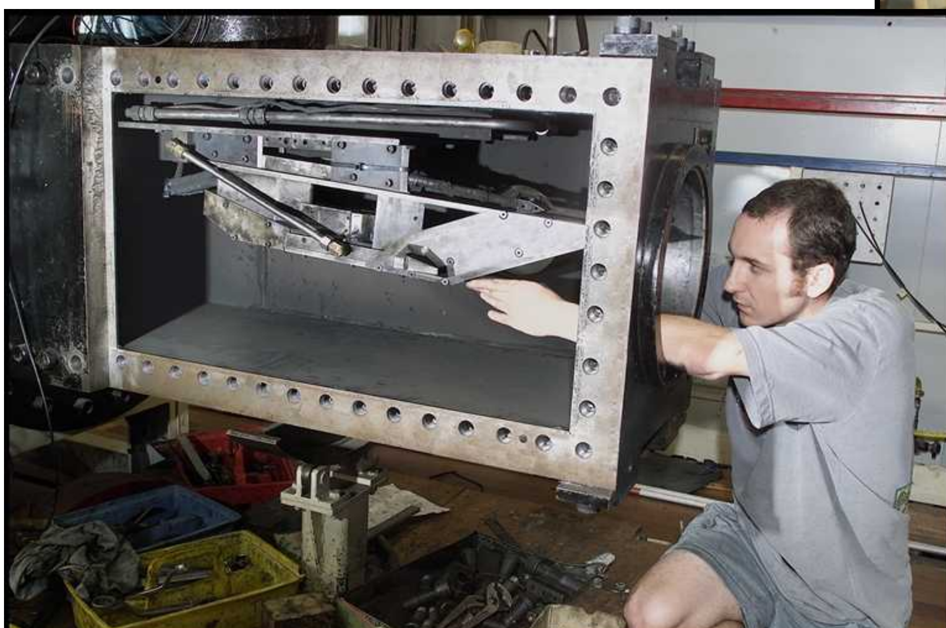
# X3 operating with Mach 10 nozzle

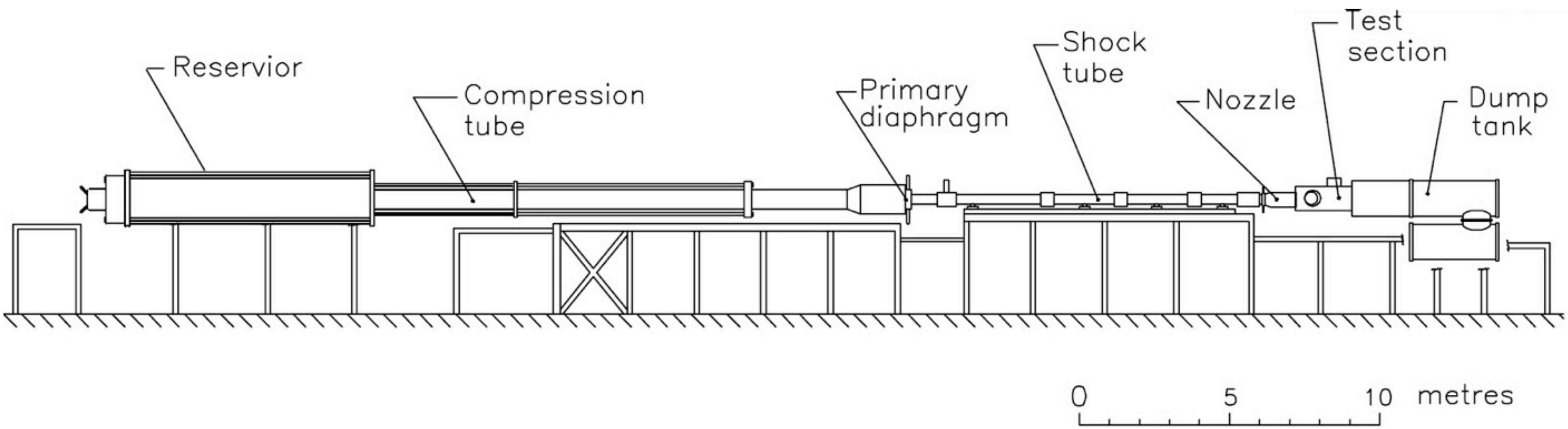

*Source: Fabian Zander*

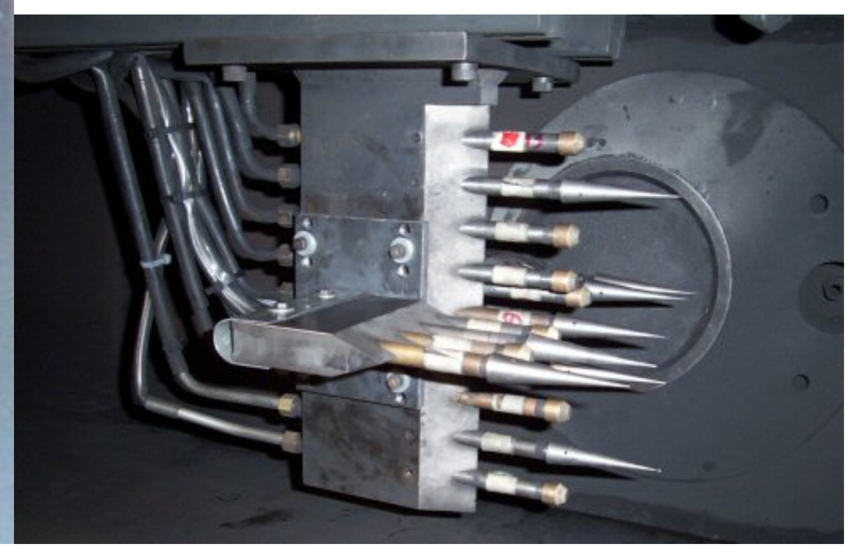
# T4 Shock Tunnel



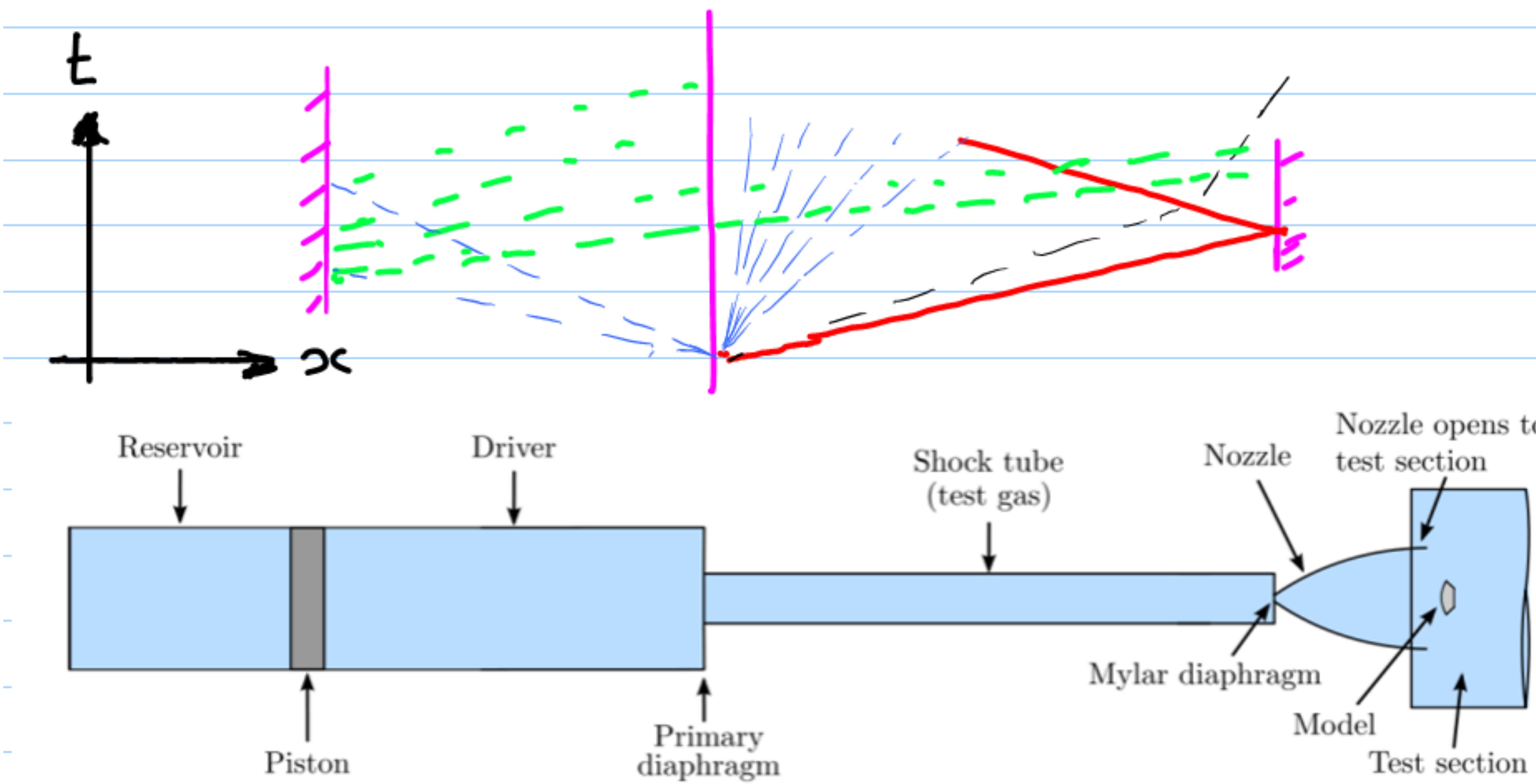




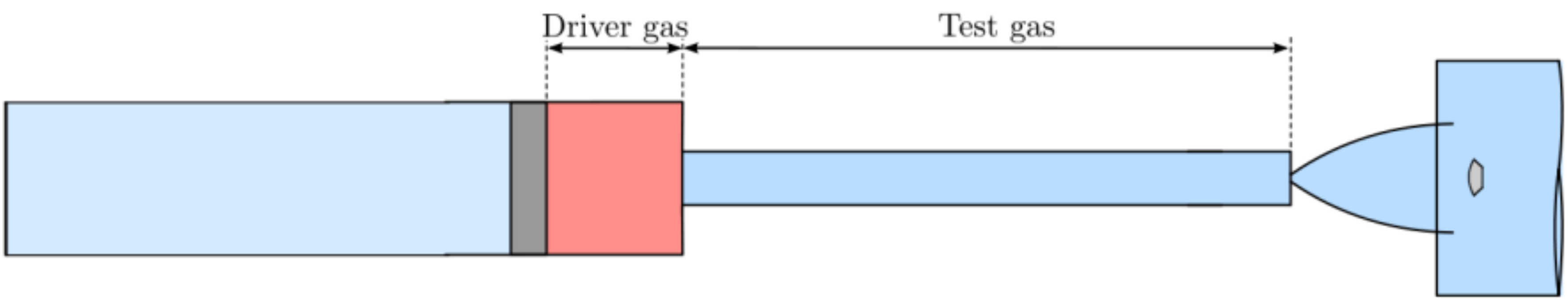

Reservior
Compression tube
Primary diaphragm
Shock tube
Nozzle
Test section
Dump tank
0
5
10
metres



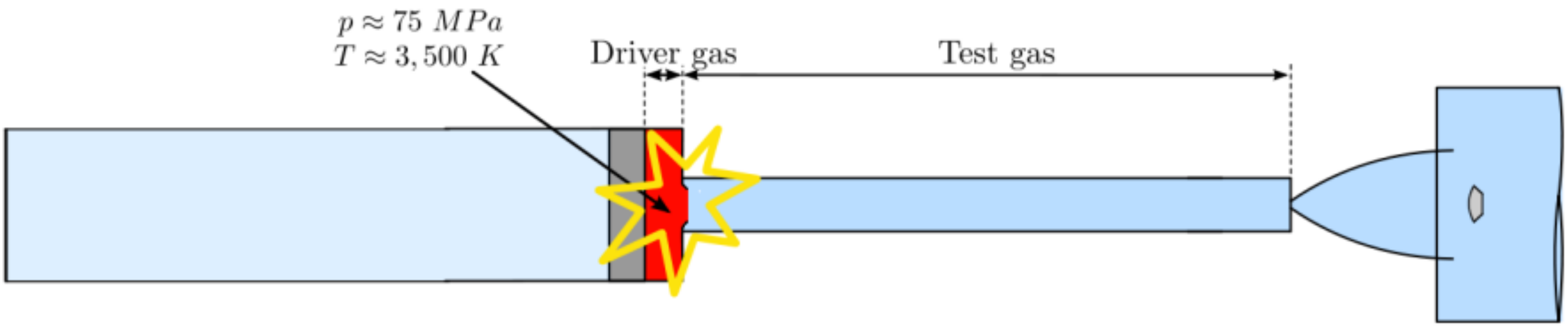
# Reflected Shock Tunnel Operation



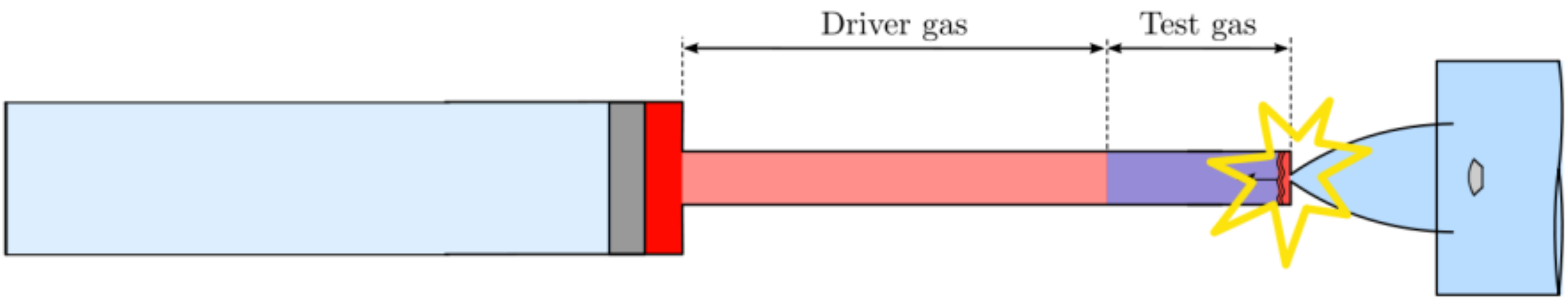
# Reflected Shock Tunnel Operation with free piston driver



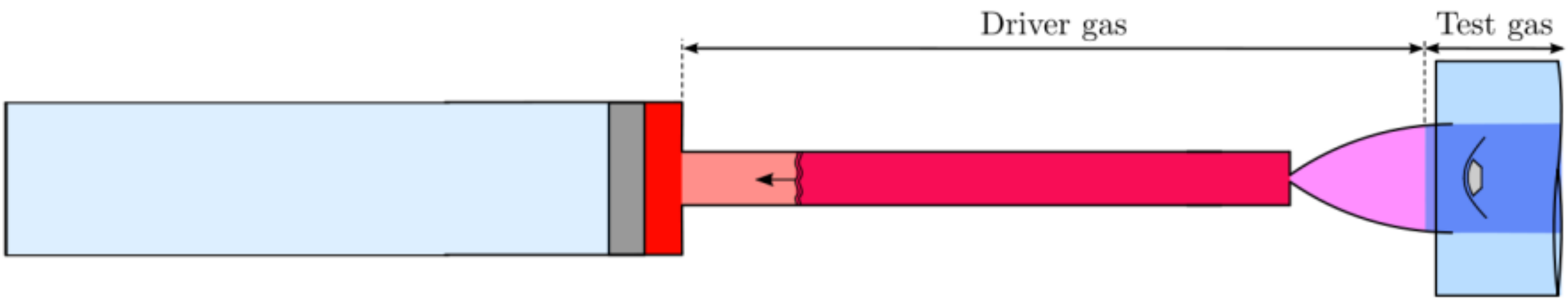
# Reflected Shock Tunnel Operation



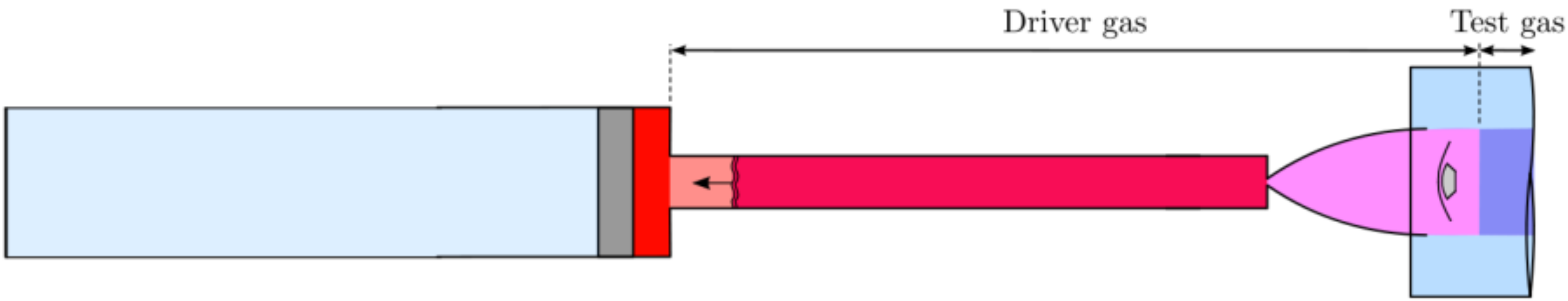
# Reflected Shock Tunnel Operation



# Reflected Shock Tunnel Operation

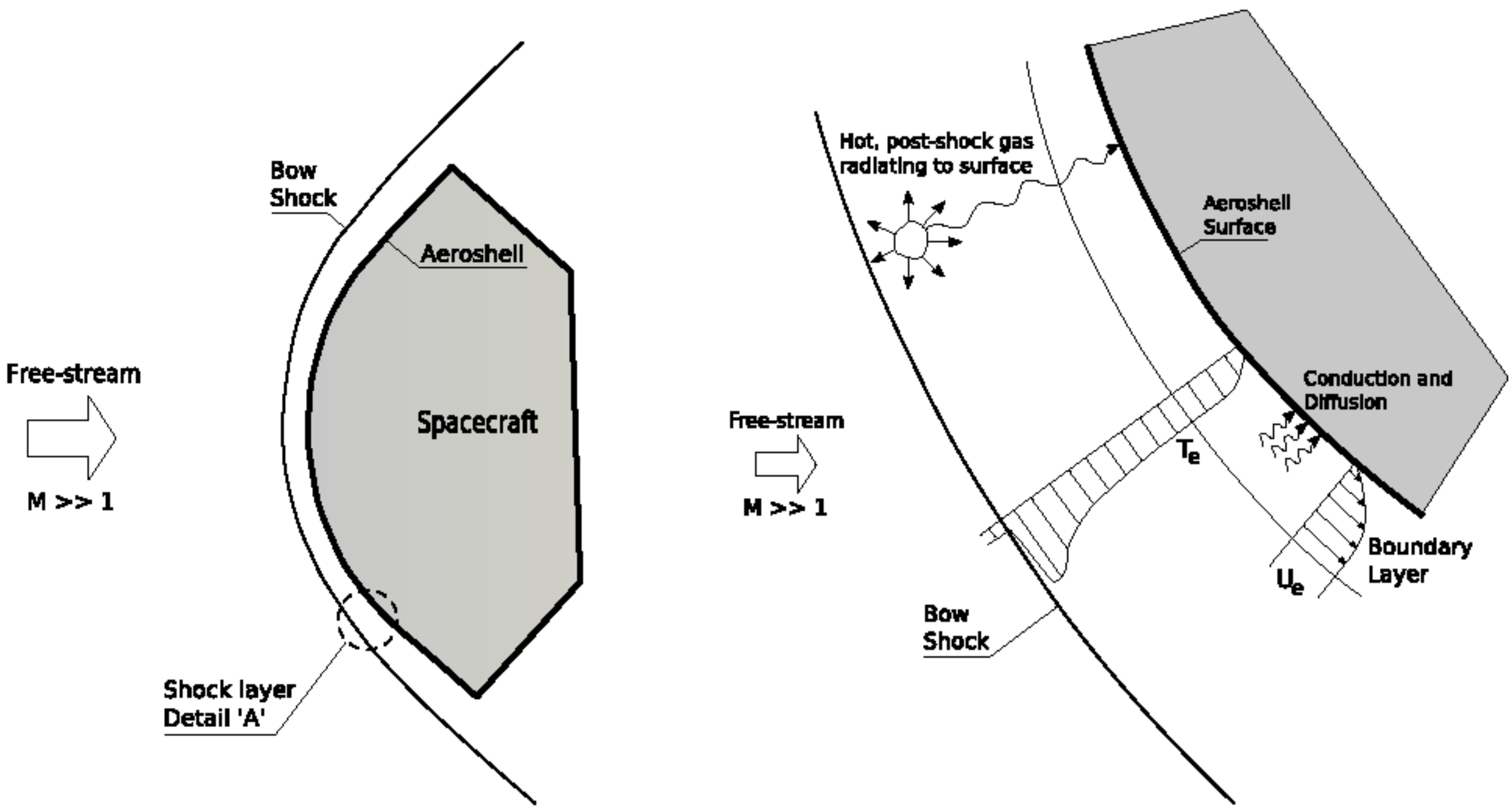


# Reflected Shock Tunnel Operation



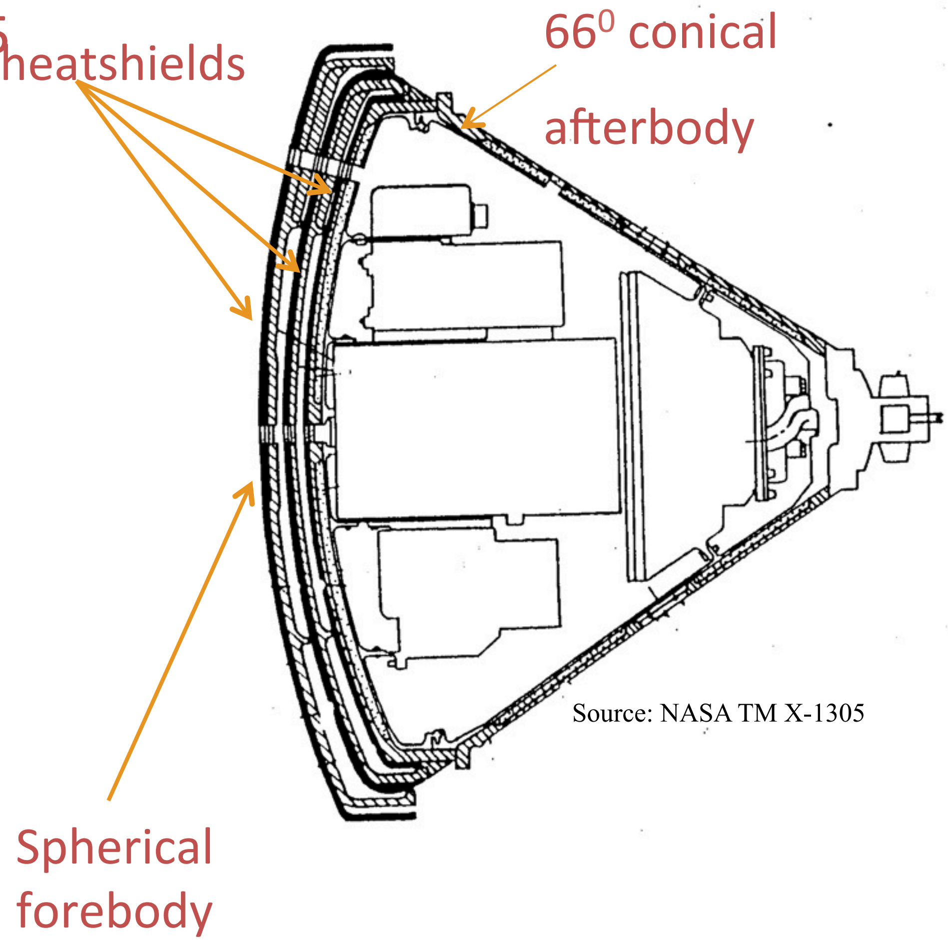

Test time ends

# *Radiation in reentry craft*

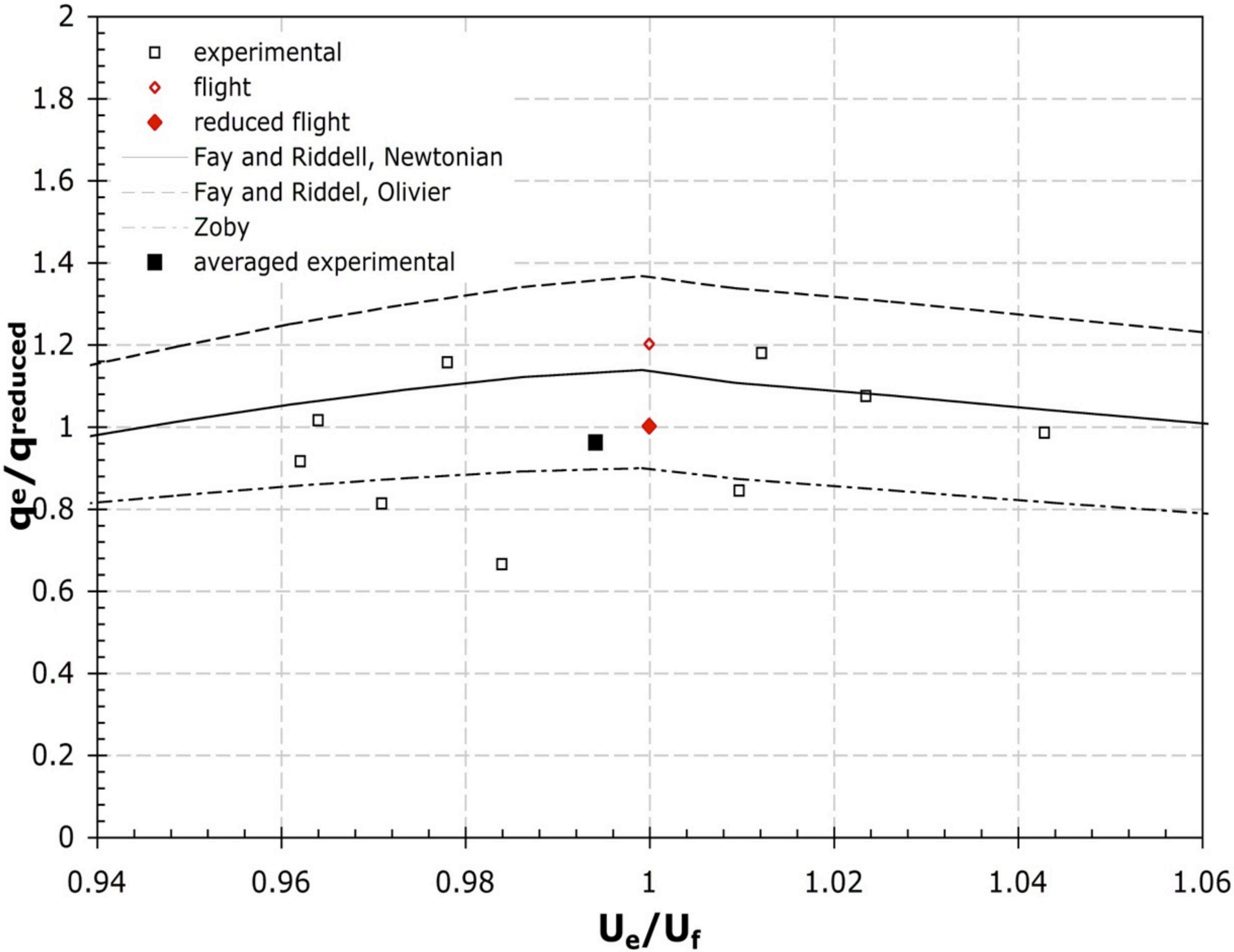


# *The FIRE (II) Project*

- Operational between 1962 - 1965
  - Part of the Apollo Program
- Flown on 22 May 1965
  - Reentered at
    Alt = 122km, $V_\infty$ = 11.35km/s
- Collected temperature information of the heating environment encountered on reentry to Earth
- Spherical heatshields attached to $66^0$ conical afterbody via a small corner radius

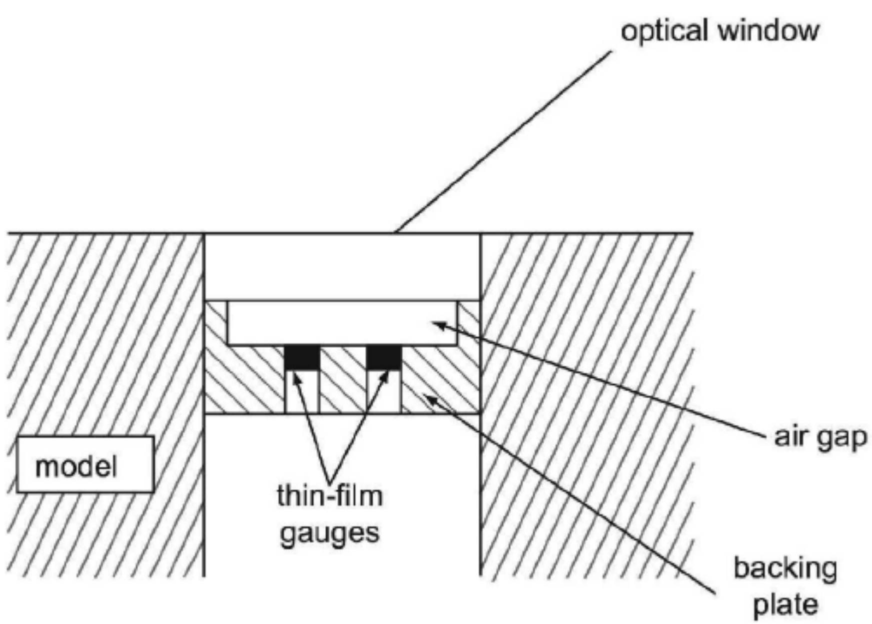


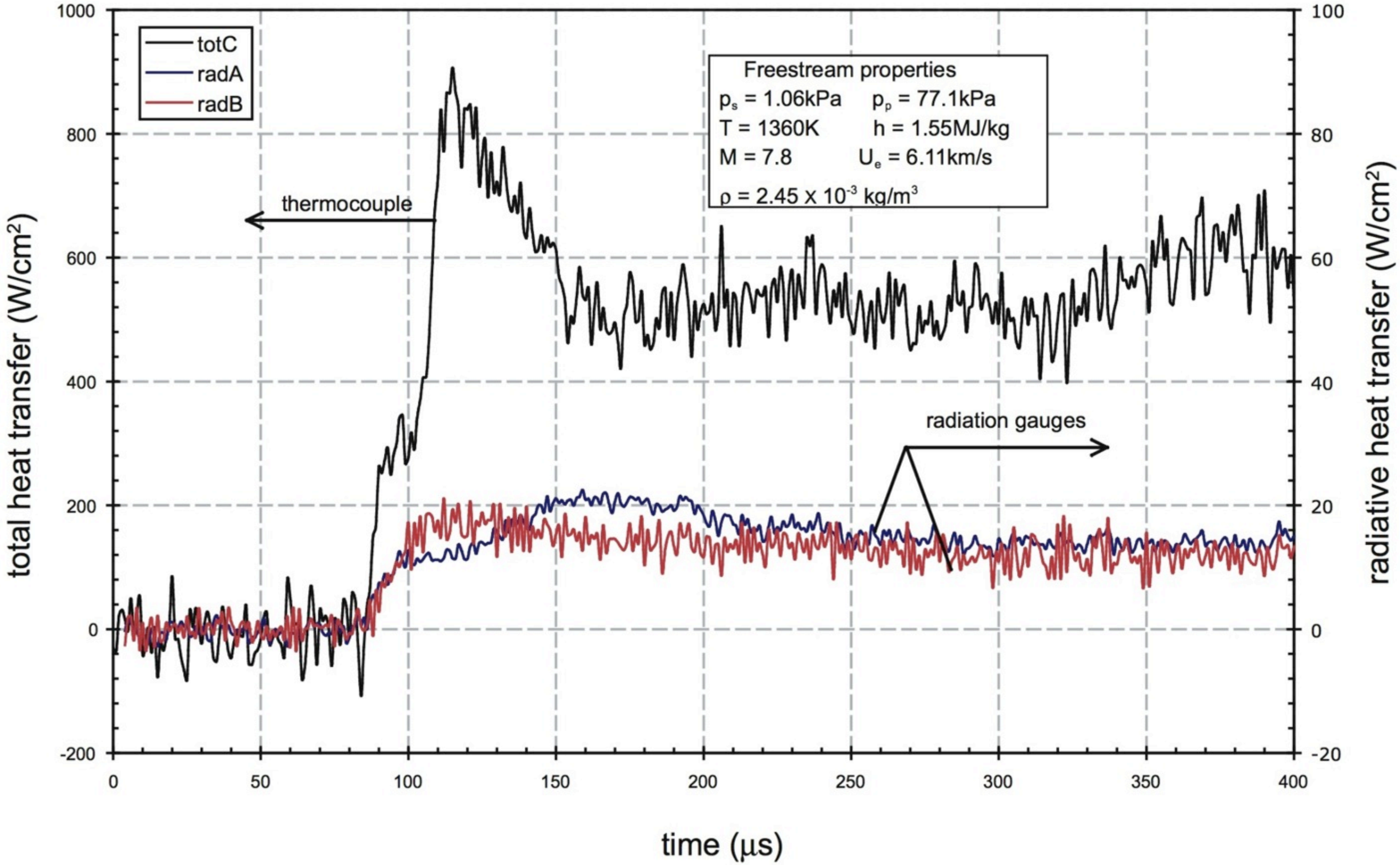
# *Stagnation point results (Capra et al)*



# Bulk Radiation Measurement

- Direct measurement of total heat transfer via surface junction thermocouples
- Separation of radiant component via thin-film gauges set behind glass window

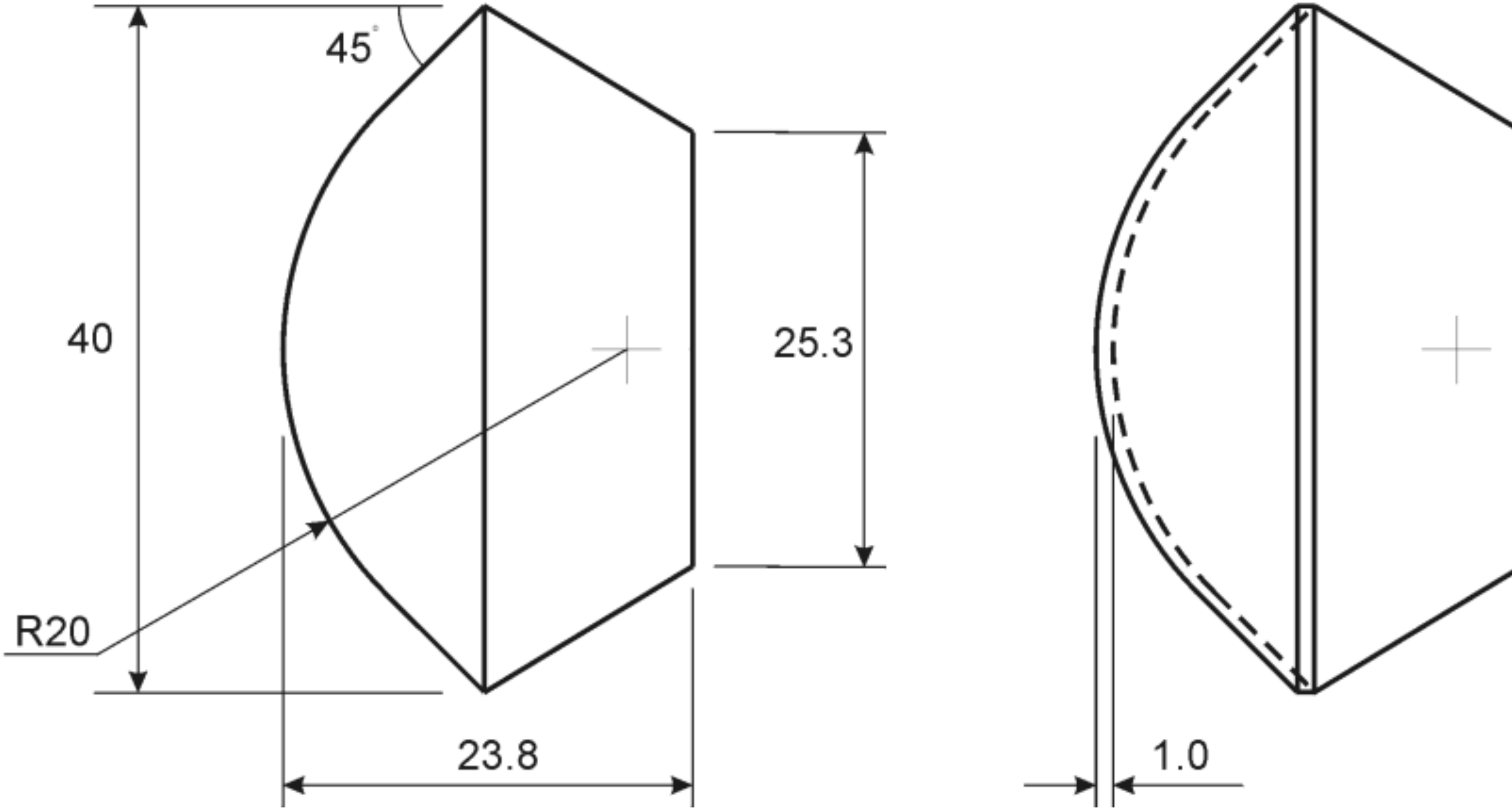




totC
radA
radB
Freestream properties
$p_s$ = 1.06kPa $p_p$ = 77.1kPa
T = 1360K h = 1.55MJ/kg
M = 7.8 $U_e$ = 6.11km/s
$\rho = 2.45 \times 10^{-3}$ kg/m$^3$
thermocouple
radiation gauges
total heat transfer (W/cm$^2$)
radiative heat transfer (W/cm$^2$)
time (μs)
1000
800
600
400
200
0
-200
100
80
60
40
20
0
-20
0
50
100
150
200
250
300
350
400

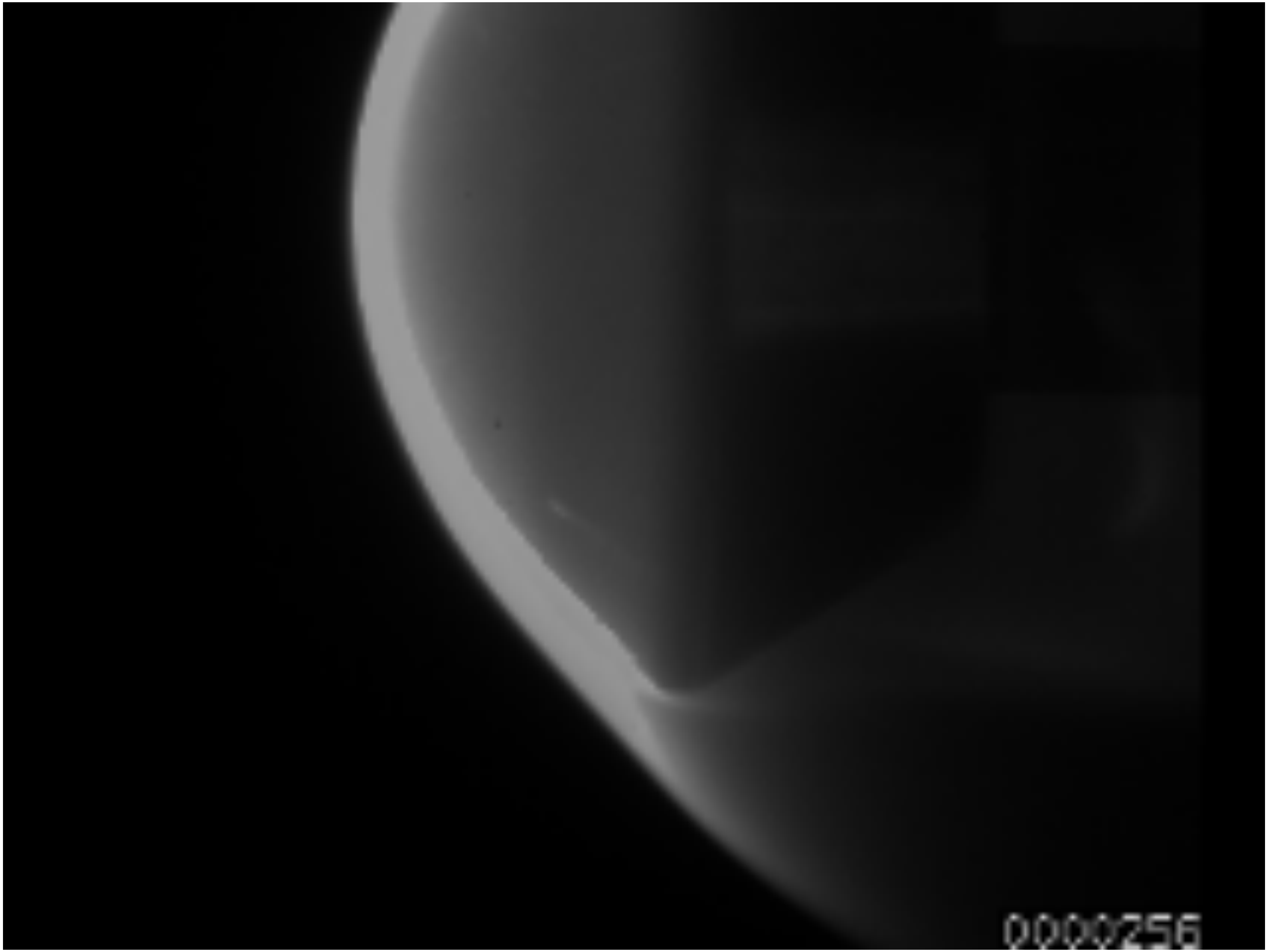

# Capra 2006

- *The short time scale of impulsive facilities make it impossible to accurately reproduce  the hot walls and 'quasi steady' thermal and mass flow balance that arises in flight with an ablating heat shield.*
- *Several features of the flow may be created by means of:*
- *Preheated walls*
- *Injection of simulated ablation products*
- *Transient aerodynamic heating of low density surface coatings*




- Epoxy coated ablation model

D'Souza 2009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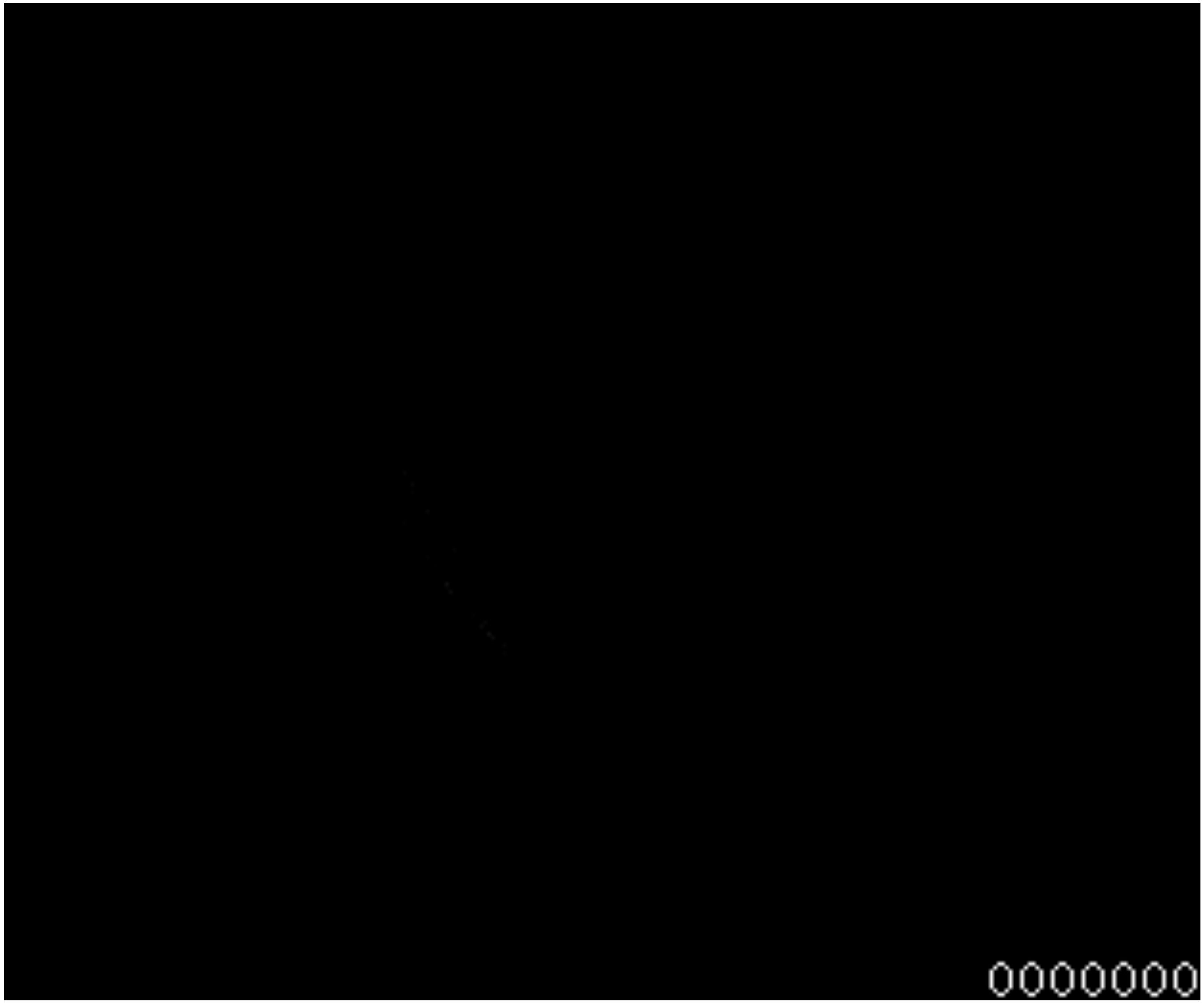
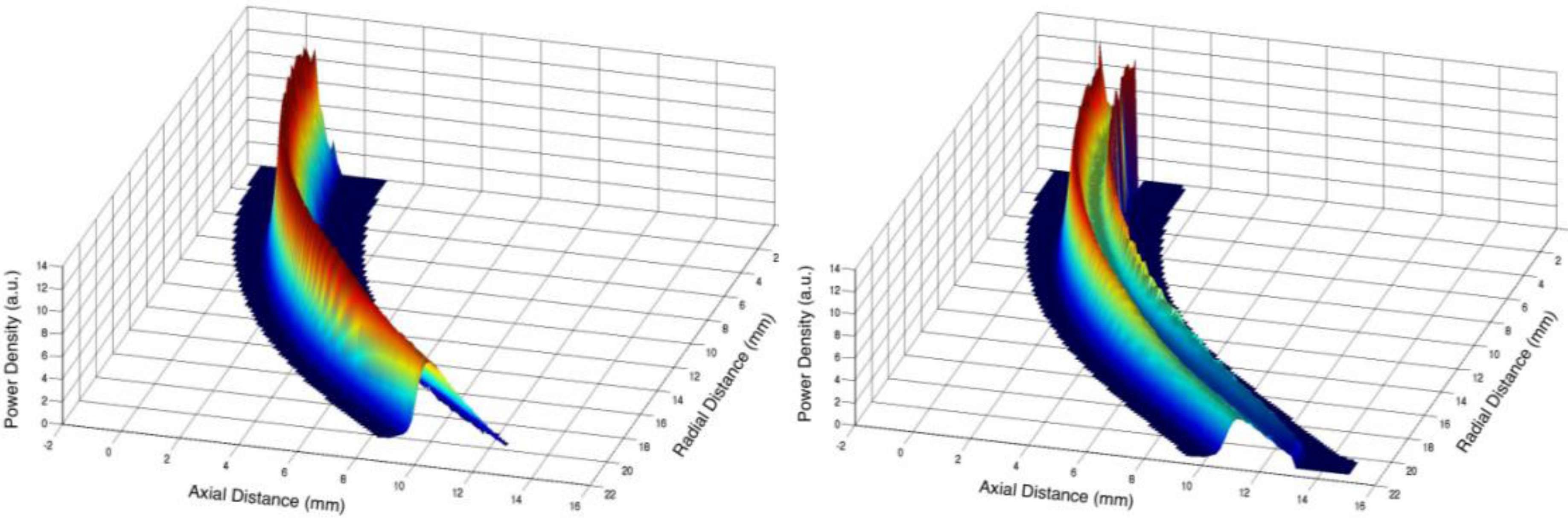
D’Souza 2010 ablative heat shields






- Radiation intensities with and without ablation (Mudford 2010)

# *Surface chemistry*

- Exposed char on ablative TPS eroded by reactions with energetic species
- Oxidation and nitridation are the most significant reactions
- Distinctive products CN and CO easy to identify from emission spectrometry
- Nitridation effects ablation rates but not heat transfer
- Oxidation increases heat transfer and ablation
- Catalytic recombination?
- sublimation

# Electrically heated RCC Zander 2012

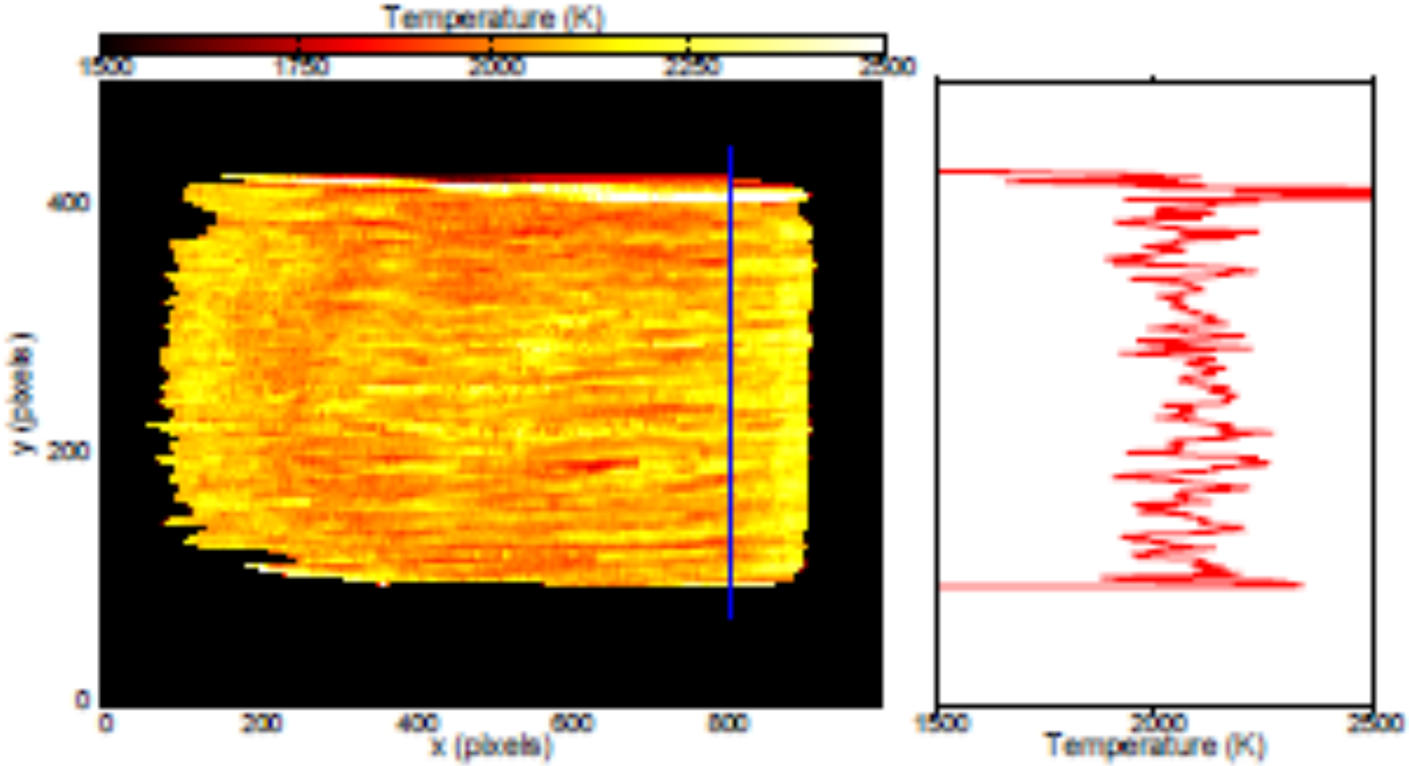
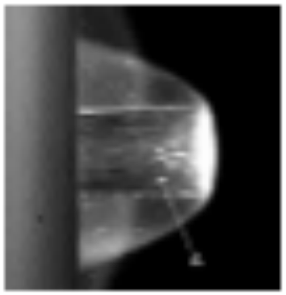
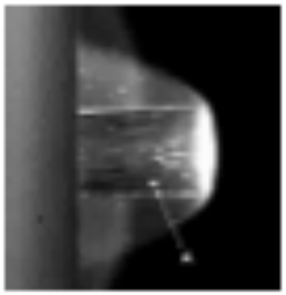



Fig. 10 Temperature derived from the DSLR photo of Figure 9 - profile extracted along dotted line

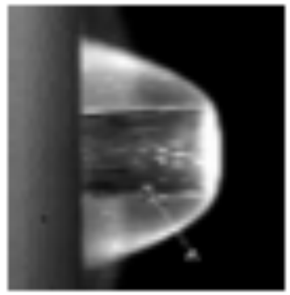
# Zander 2012



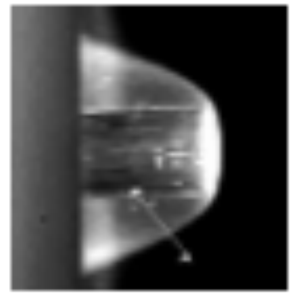
(a) 80μs



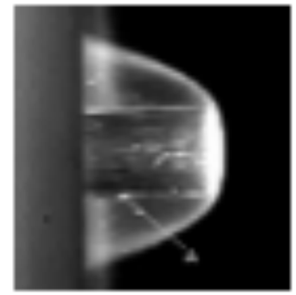
(b) 82μs



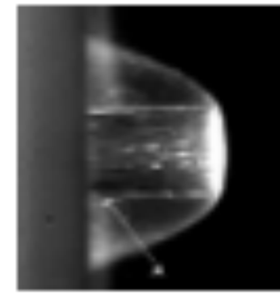
(c) 84μs



(d) 86μs

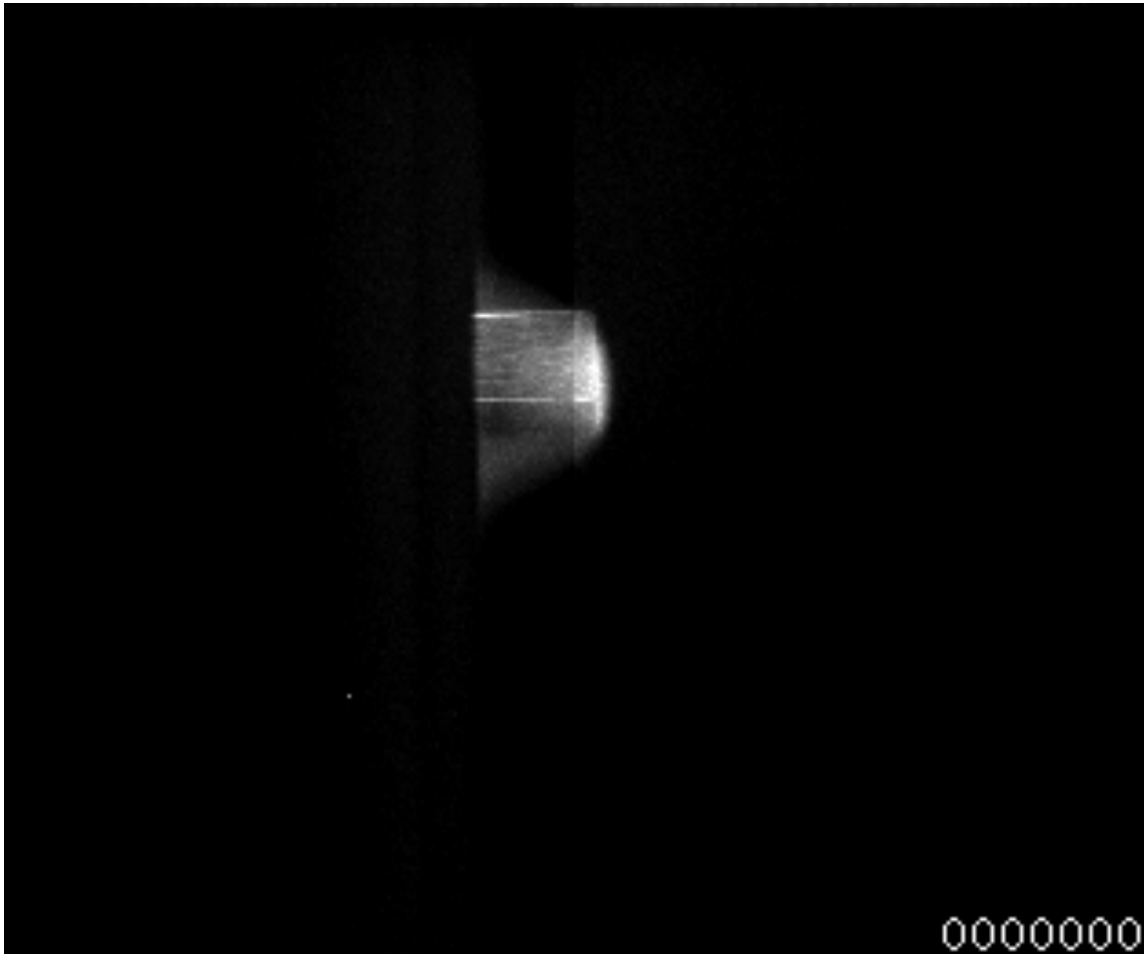


(e) 88μs



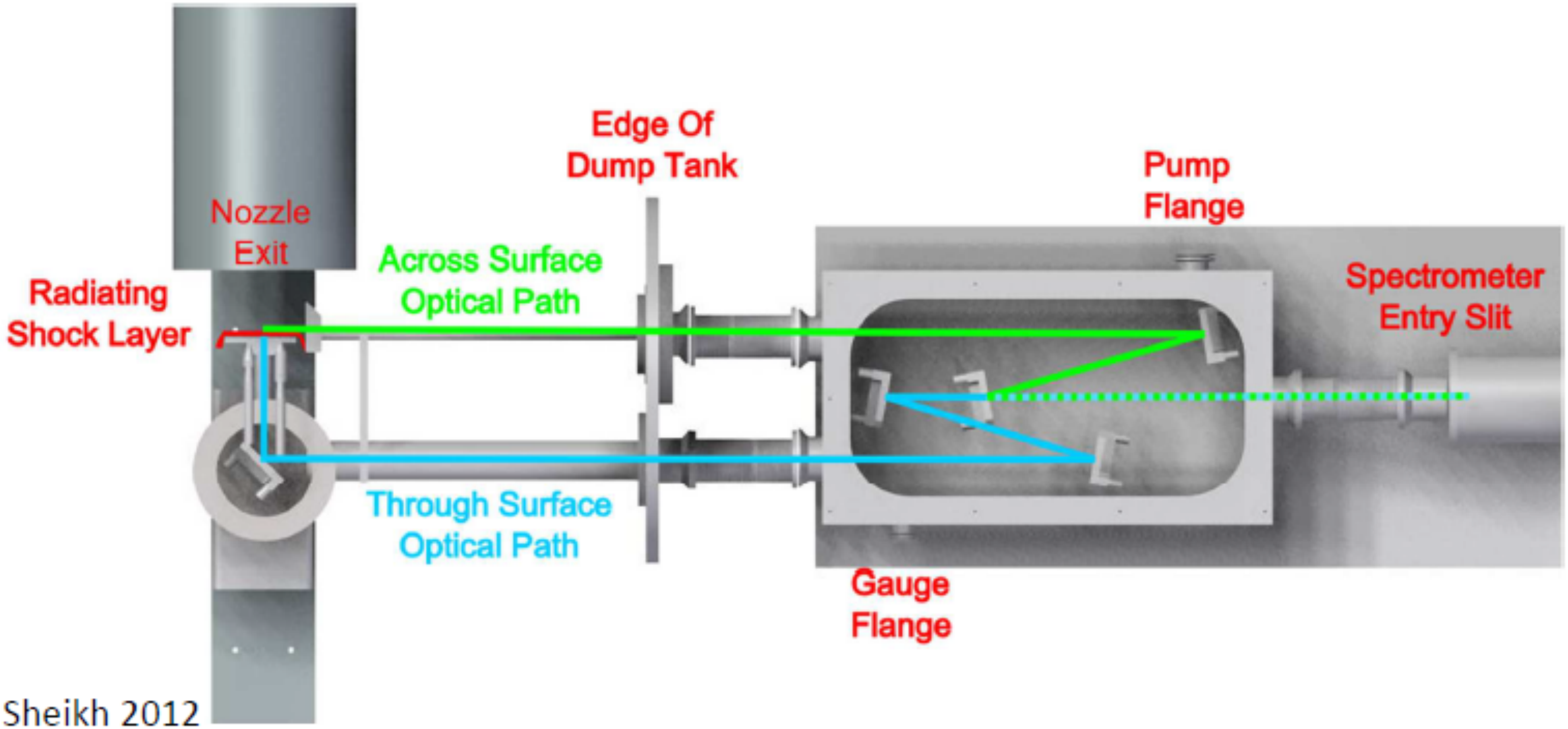
(f) 90μs

# Zander 2012



# *VUV Interferometry*

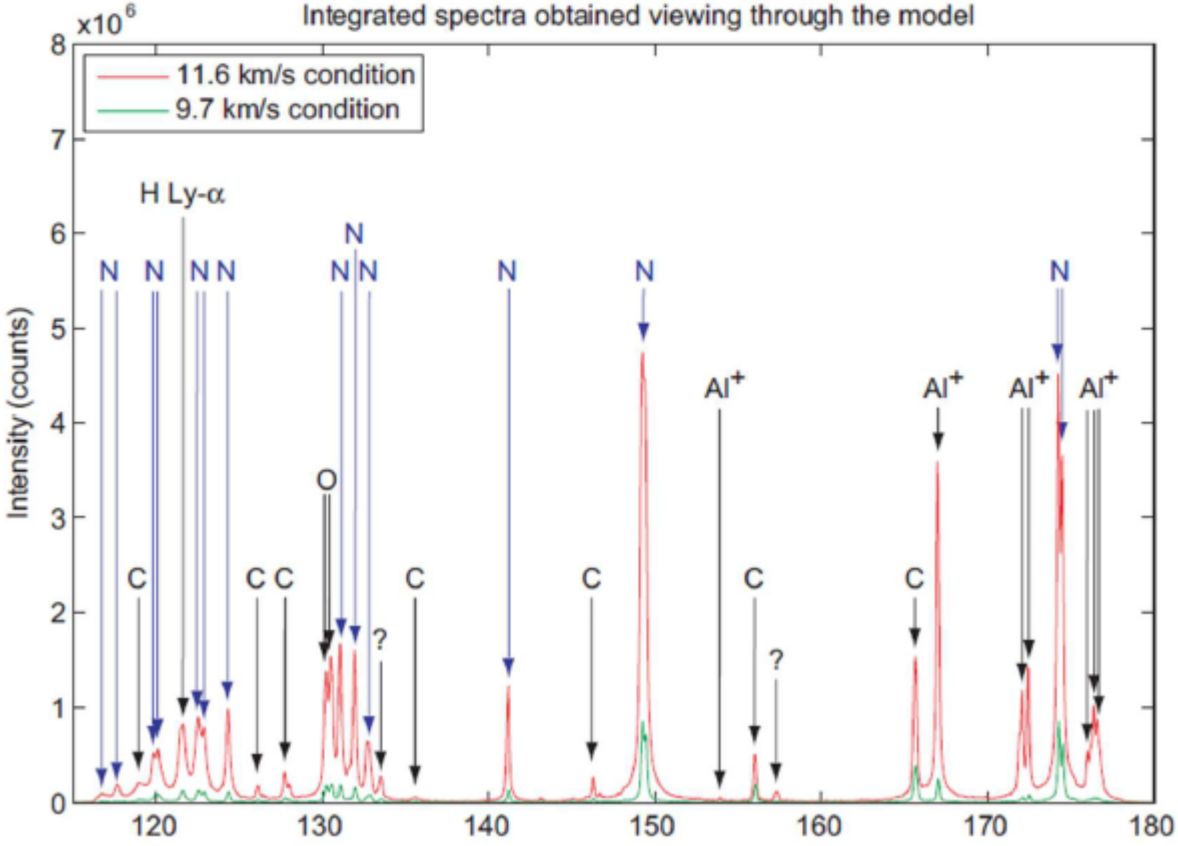
- f=500 mm focusing mirror
  - No chromatic aberration




Sheikh 2012

# VUV interferometry Sheikh 2012

- On Surface Spectral Data



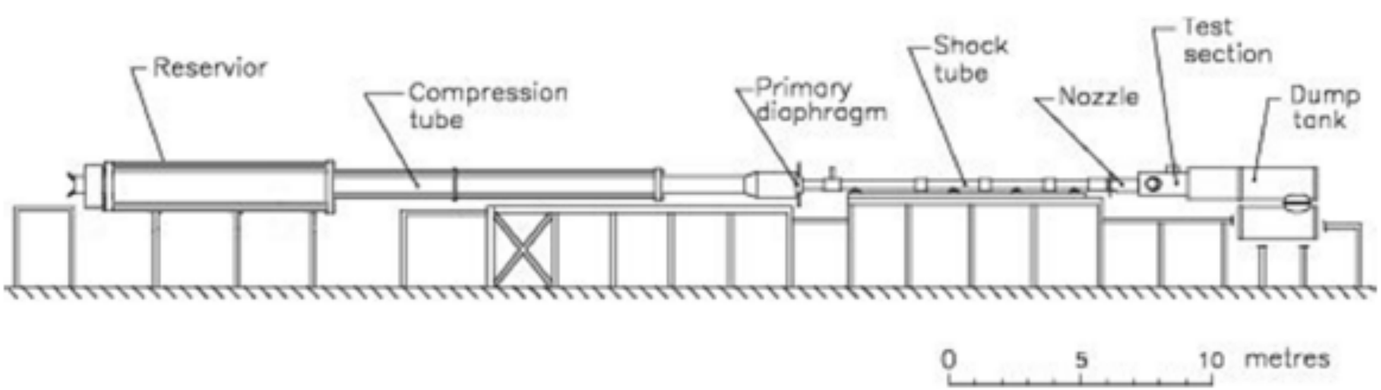
# UQ Scramjet Research Program

*Professor Michael K Smart*
**Centre for Hypersonics**
**The University of Queensland**

# UQ Scramjet Research Program Update – September 2013

TOPICS:

- Support of the HIFiRE Program
- Scramjet based access-to-space systems for small payloads (~500 lb)
- 3-D REST scramjet engine testing: Mach 10-12
- Fundamental studies of hypersonic mixing and combustion
- Defence Materials Technology Centre (DMTC)



# The HIFiRE FLEET

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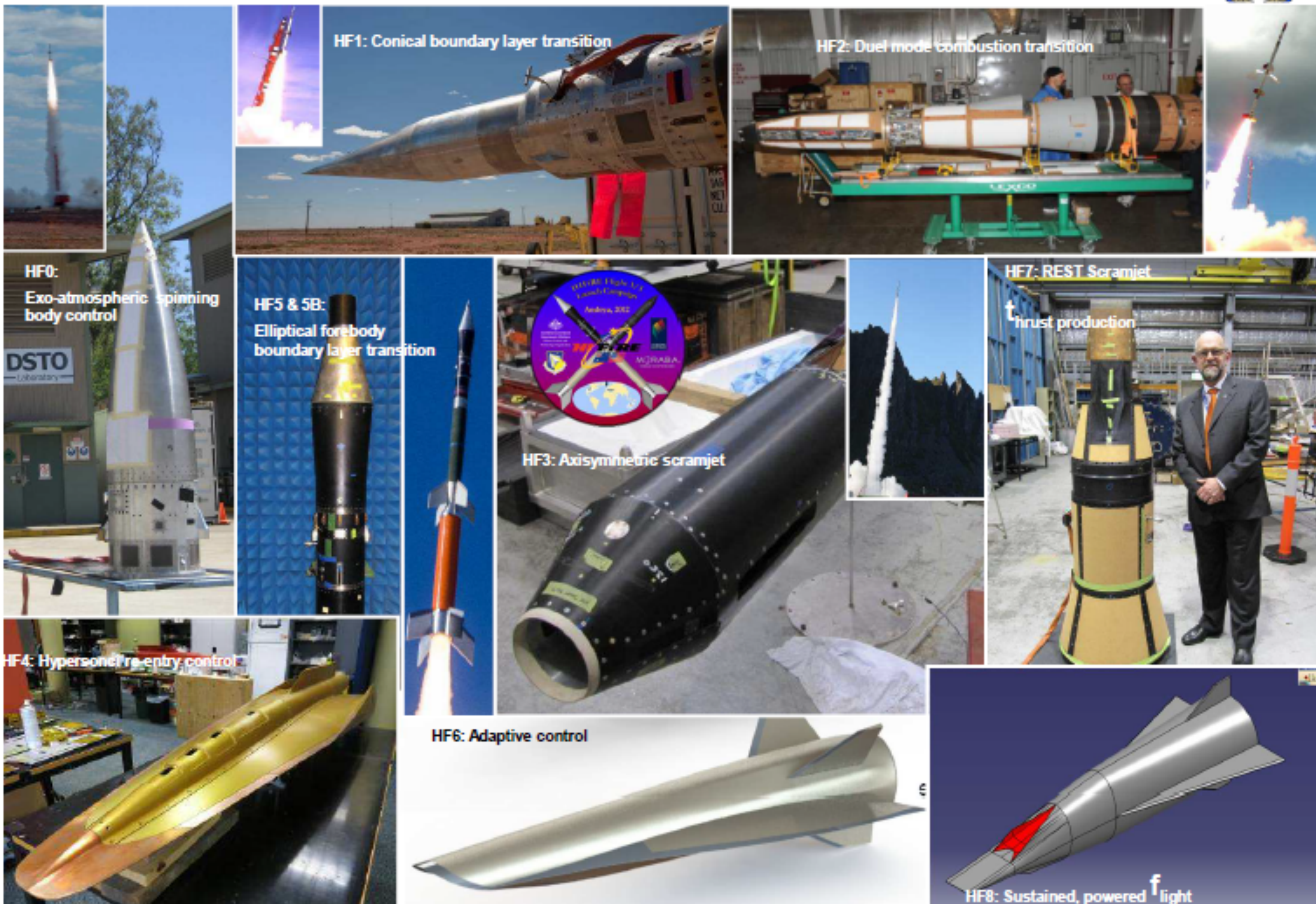
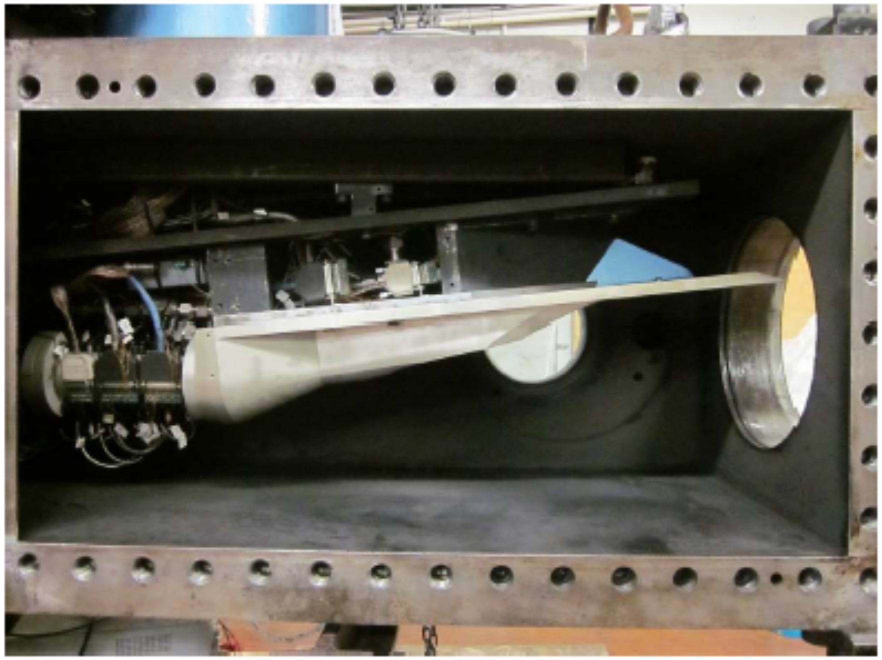
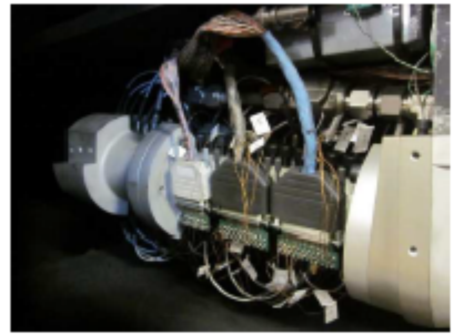
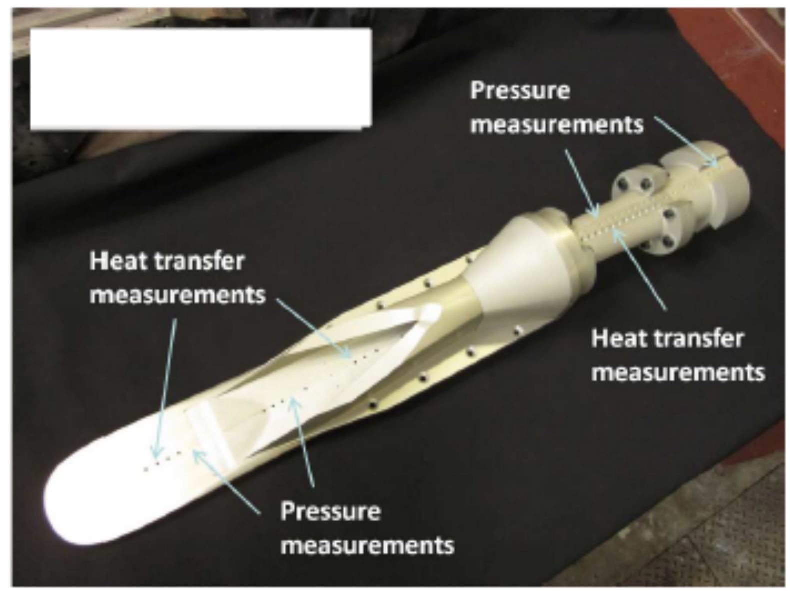


THE UNIVERSITY OF QUEENSLAND

# HIFiRE 7 Ground Testing








2013 Test matrix:

- Freejet Testing: Mach 7 – 8
- 0°, +2°, -2° AOA
- $H_2$ gaseous fuel
- flight altitude simulation: 25 - 30 km

# Rocket-SCRAMJET-Rocket Access-to-Space System

THE UNIVERSITY OF QUEENSLAND

Stage 1 – Rocket booster

Stage 2 - Hydrogen fuelled scramjet accelerator

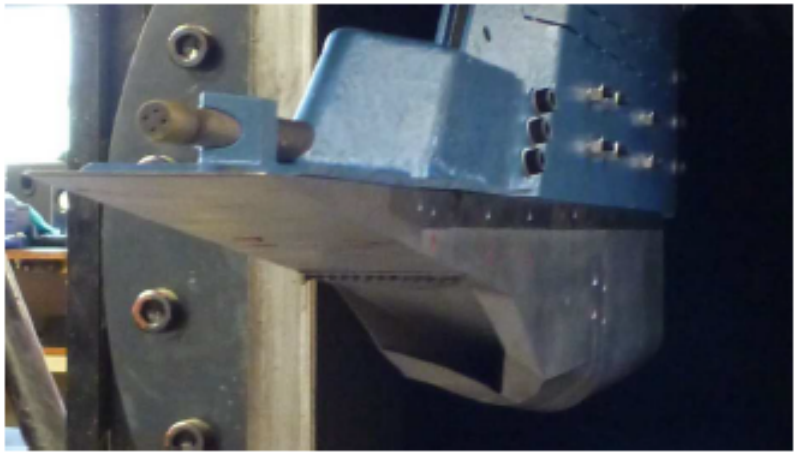
Stage 3- Rocket Boost payload into SSO (566km)

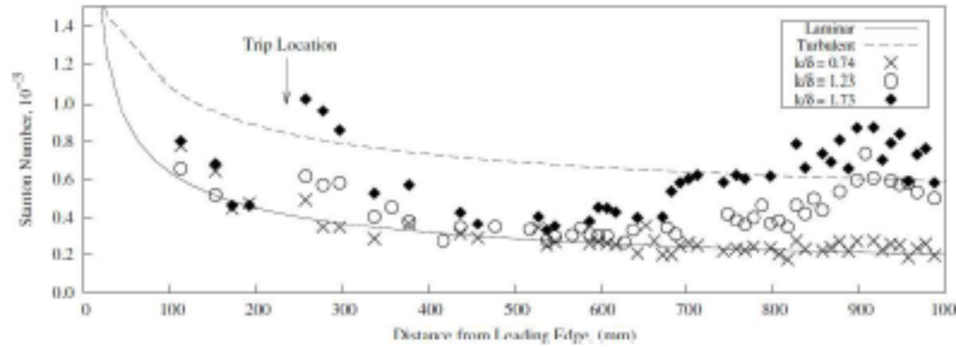
**Small scale payload delivery (300kg) with a reusable scramjet powered 2nd stage**

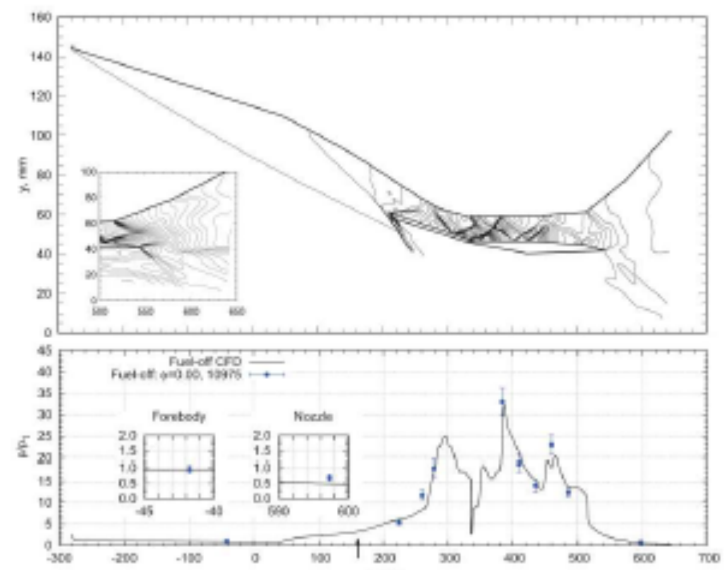
**Airbreather geometry optimized for minimum trim along a constant dynamic pressure trajectory**

**MANFRHAD – Geometry, Aerodynamics, Trajectory & Optimization package**

# 3-D REST Scramjet Testing – Mach 10-12





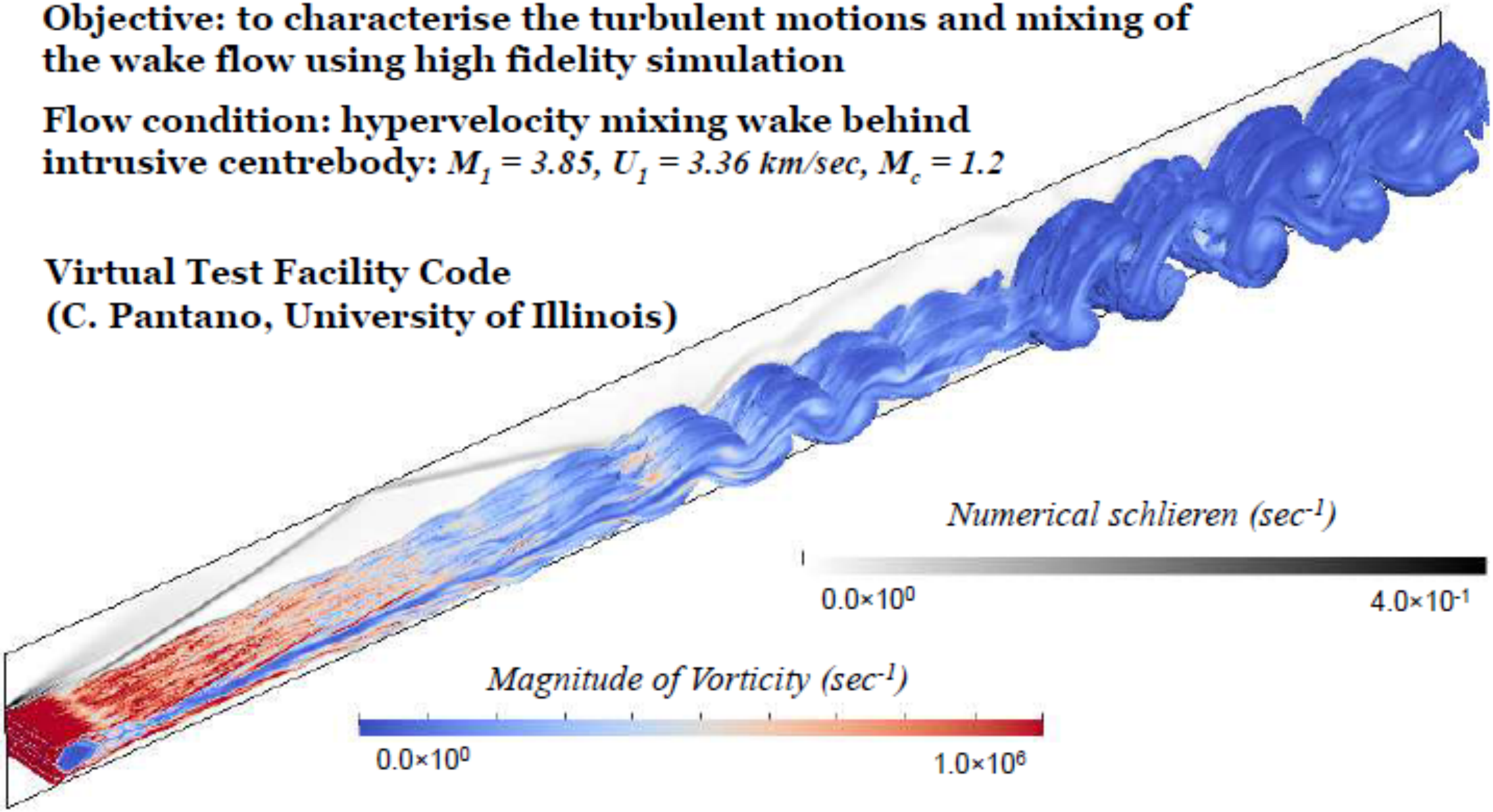

- Freejet Testing of Airframe Integrated flowpaths
- REST flowpath with Mach 12 design point
- H2 fuel for Access-to-Space
- Examining different fuel strategies to improve overall net thrust at Mach > 10

# Fundamental Studies of Hypersonic Mixing and Combustion: Compressible Large Eddy Simulation

**Objective: to characterise the turbulent motions and mixing of the wake flow using high fidelity simulation**

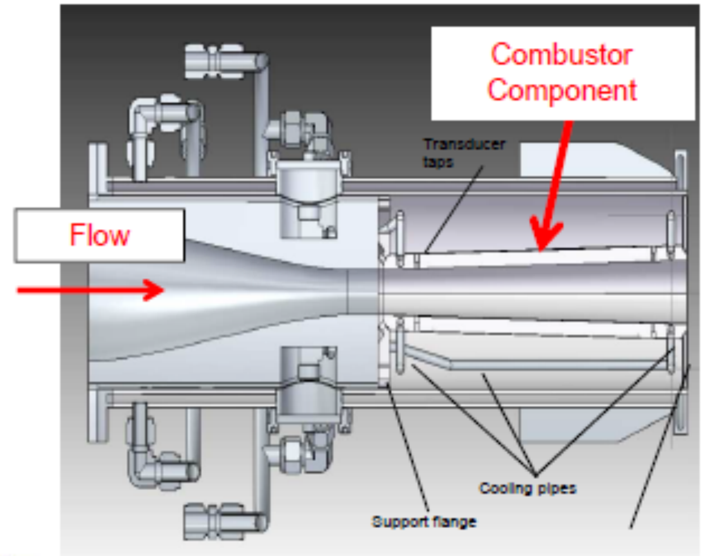
**Flow condition: hypervelocity mixing wake behind intrusive centrebody:** $M_1 = 3.85$, $U_1 = 3.36$ km/sec, $M_c = 1.2$

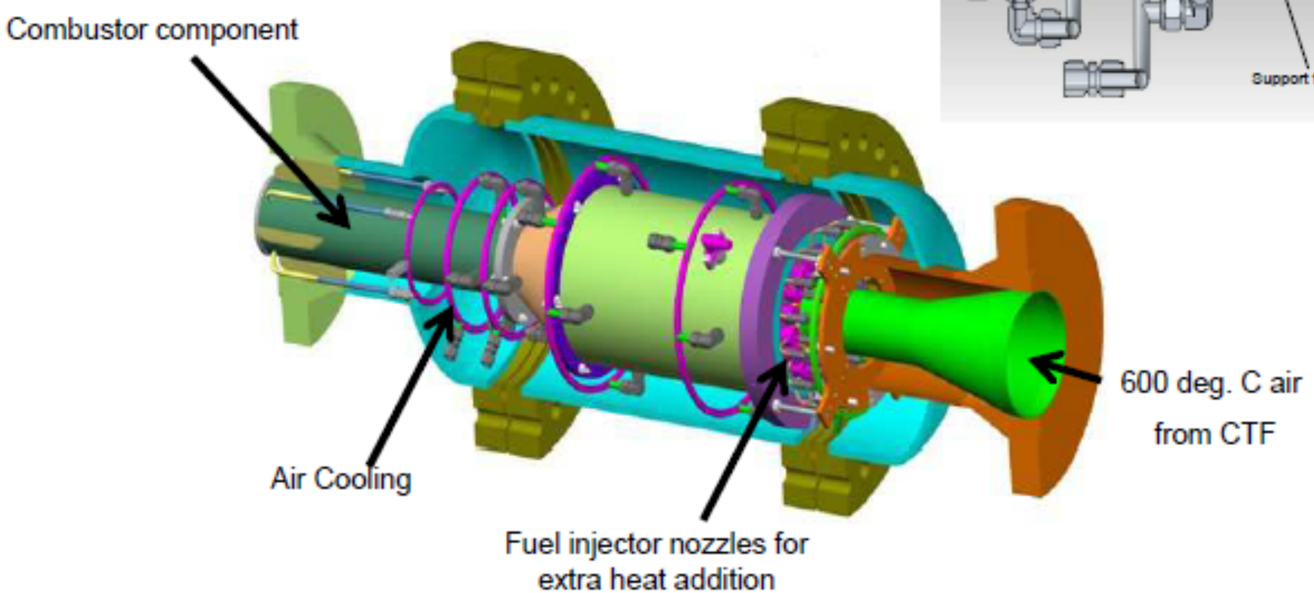
**Virtual Test Facility Code (C. Pantano, University of Illinois)**



# DMTC – Thermal Testing of Combustors

- Ground testing of combustor materials solutions required before transition to flight
- Vitiated heating added to existing electrically heated DSTO Combustion Test Facility (CTF)
- First test December 2014.



# HIFiRE MANIFEST

| Flight | Description | Launch Date |
|---|---|---|
| *HIFiRE 0* | Software Development (DSTO) | March 2009 (successful) |
| *HIFiRE 1* | Hypersonic Cone (USAF) | March 2010 (successful) |
| *HIFiRE 2* | Scramjet Combustor (USAF) | April 2012 (successful) |
| *HIFiRE 3* | Axisymmetric Scramjet (DSTO) | September 2012 (successful) |
| *HIFiRE 4* | Hypersonic Glider (DSTO-UQ-Boeing) | June 2015 |
| *HIFiRE 5* | Hypersonic Elliptical Cone (USAF) | April 2012 (2nd stage rocket failure) |
| *HIFiRE 5B* | Repeat of HIFiRE 5 (USAF) | February 2015 |
| *HIFiRE 6* | Adaptive Control (USAF) | 2016 |
| *HIFiRE 7* | Free flying 3-D Scramjet (DSTO-UQ-Boeing) | September 2014 |
| *HIFiRE 8* | Sustained 3-D Scramjet (DSTO-UQ-Boeing) | 2016 |

# Hypersonics Research
## at UNSW Canberra

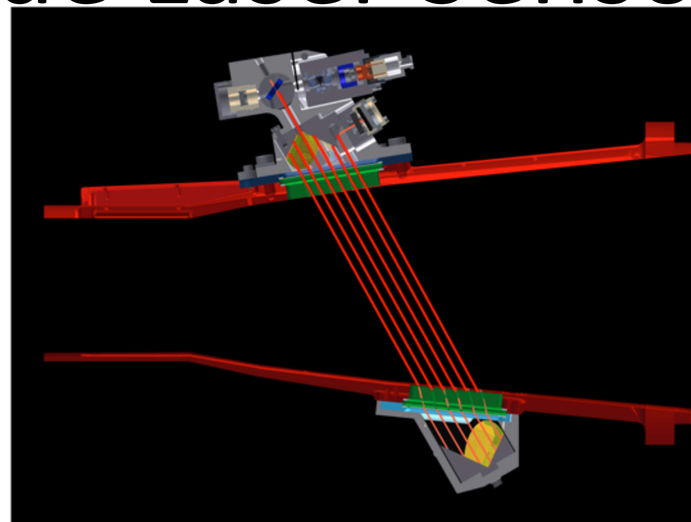
Never Stand Still

UNSW Canberra, School of Engineering and Information Technology

Sean O'Byrne, Sudhir Gai, Andrew Neely, Harald Kleine,
Paul Walsh, Joseph Kurtz, Mark Aizengendler, Deepak Ramanath
Yedhu Krishna, Tremayne Kaseman, Rishabh Choudhury, Arnab Dasgupta, Gaetano Currao

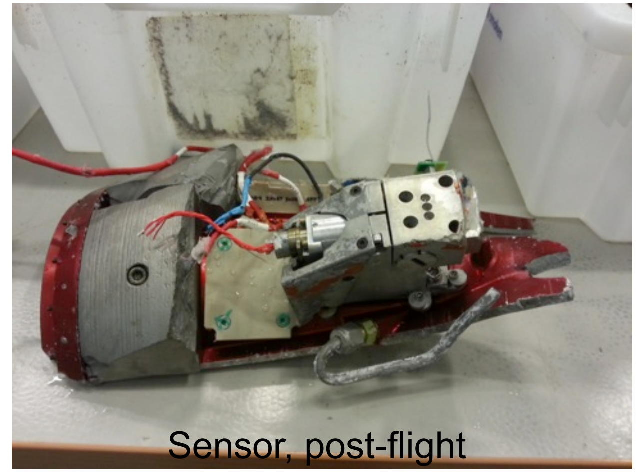
# SCRAMSPACE Diode Laser Sensor

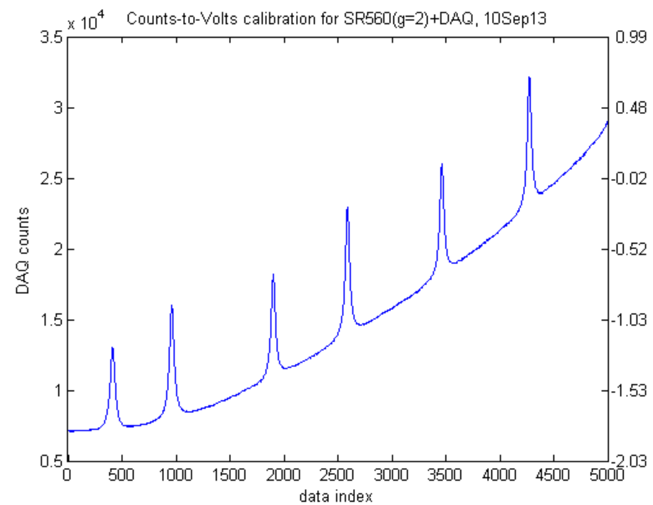
- Developed and flight-tested a hypersonic diode-laser inlet sensor
  - Designed to measure velocity and temperature
  - Simple, robust design using opposed retroreflector configuration and a single laser operating on oxygen lines at 760 nm
  - Log-ratio detection was used
  - All sensor mechanics and electronics were developed at built at UNSW Canberra



# SCRAMSPACE Diode Laser Sensor

- Flight test was not hypersonic, but diode laser sensor measured data throughout the flight, until the model hit the water. Data was used to measure pressure and temperature.
  - Too slow for hypersonic velocity measurement
- Measurements were obtained in spite of accelerations during flight in excess of 25 g.

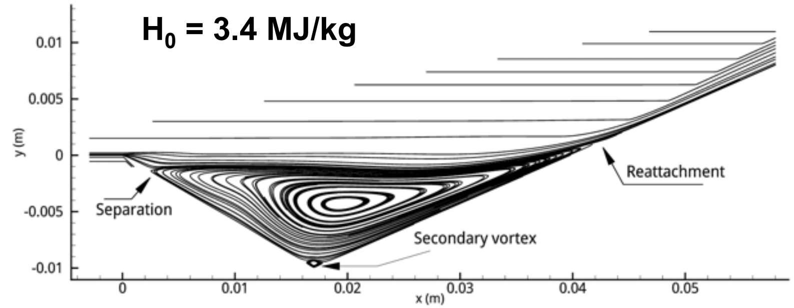

Sensor, post-flight

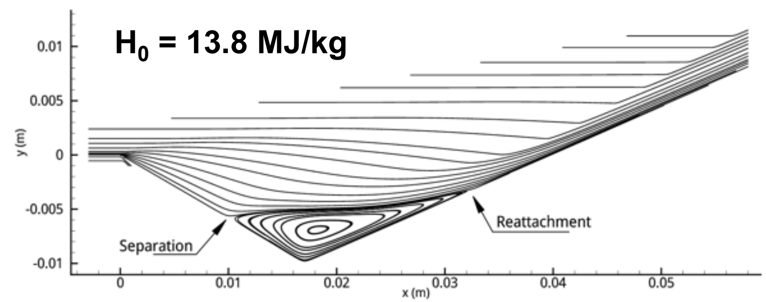



Absorption spectrum obtained in flight – raw data

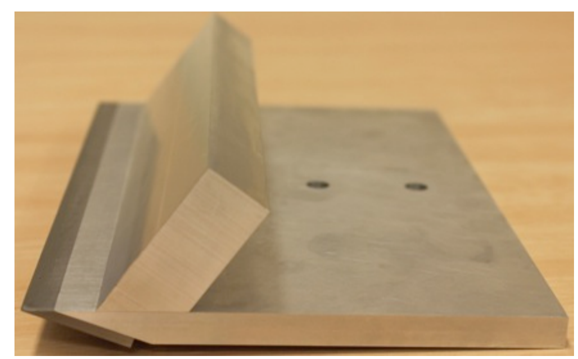
# Hypersonic Separated Flow

- Aims: to understand the fluid and thermal behaviour of nonequilibrium hypersonic separated flow in the transitional regime between continuum and rarefied flow using
  - DSMC and CFD computations
  - Time-resolved shearing interferometric imaging



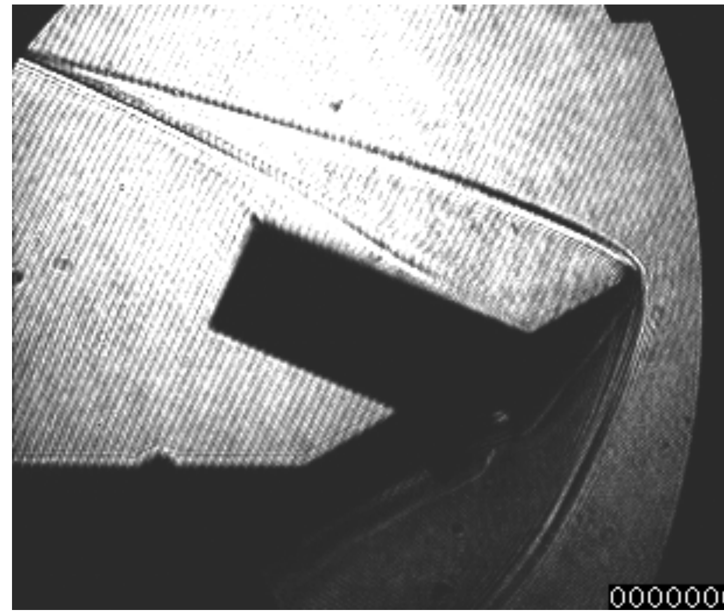




- Provides experimental data against which computations can be compared
  - Computations indicate significant decrease in size for higher-enthalpy condition, due to slip
  - International collaboration with 9 DSMC and CFD experts



# Resonantly Enhanced Shearing Interferometry

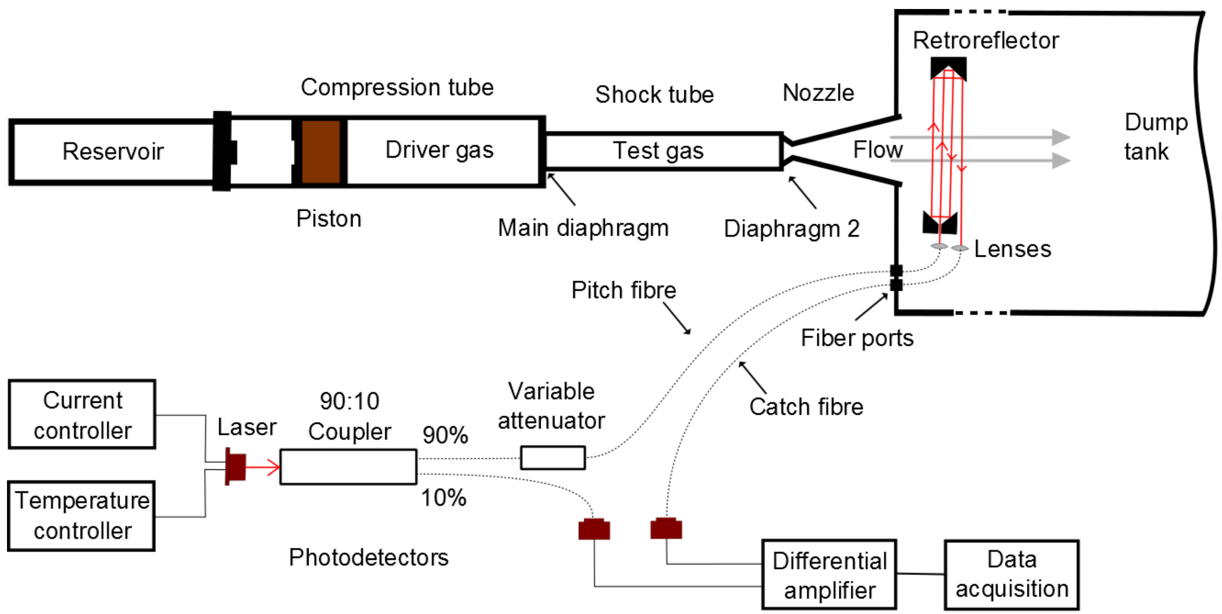
- Developed new method of highly sensitive flow visualization for low-density flows
  - Using RbCl seeding at 780 nm rather than Li metal seeding at 670 nm used in previous studies
    - Safer handling of salt
    - More uniform seeding (deposited in aqueous form rather than metal foil)
    - Laser is very narrow linewidth and single mode, so monochromatic
- Moderate resonant enhancement seen at low enthalpy (3.4 MJ/kg): stronger at higher stagnation enthalpy (13.8 MJ/kg)




**Video of RESI at 780 nm, time in microseconds after first frame, shown at lower right (3.4 MJ/kg condition)**

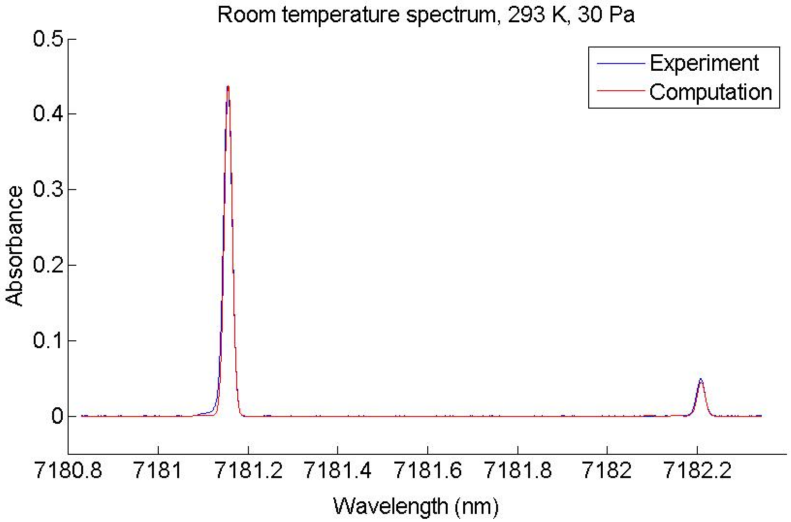
# Diode Laser Absorption Spectroscopy

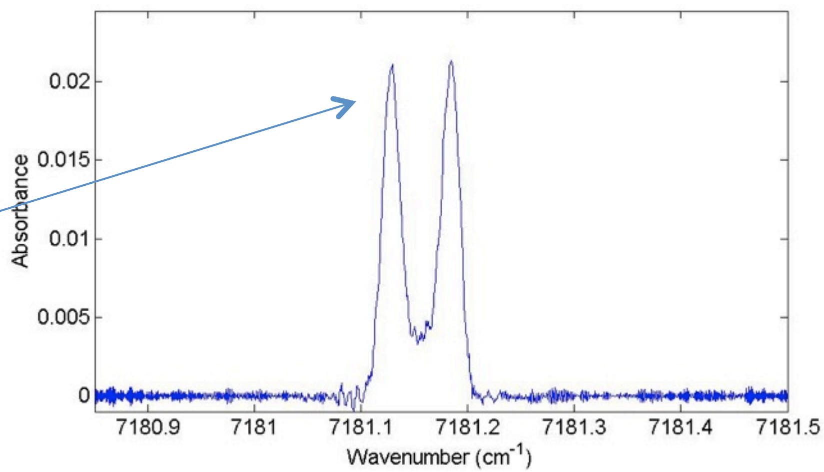
- Single vertical cavity surface emitting laser scans over 2 lines with differential amplification
- Scanning over two $H_2O$ transitions near 7181 and 7182 $cm^{-1}$
- Beams angled for velocity measurement
- Change in water vapour concentration over time indicates driver gas contamination



# Diode Laser Absorption Spectroscopy

- Measured temperature and velocity vs time at both conditions using ambient $H_2O$ absorption.
- Determined absorption outside the nozzle flow immediately before tunnel run and used that concentration to correct for non-flow absorption outside nozzle.
- Retroreflector produces beams in both directions: Doppler shift can be clearly seen on a single transition

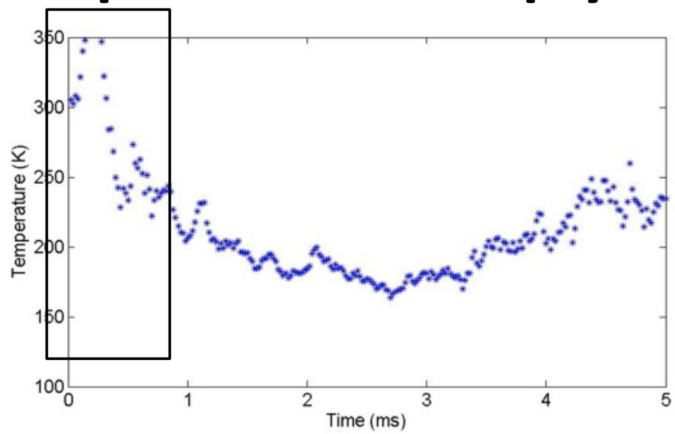


# Diode Laser Absorption Spectroscopy

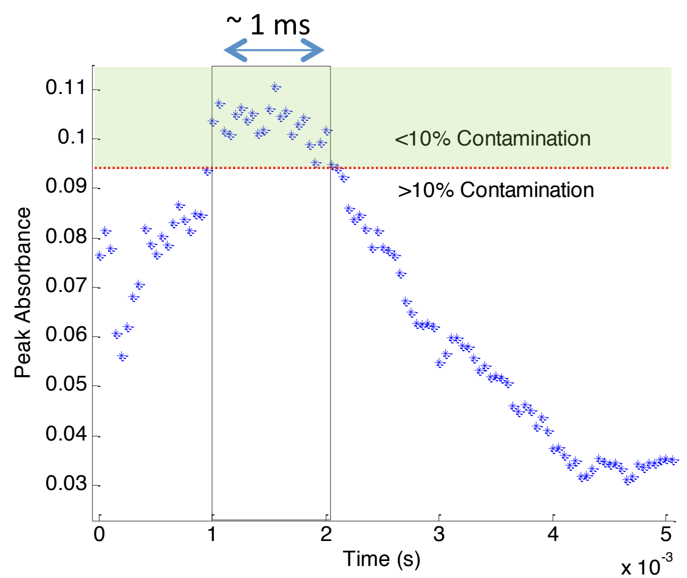
- Temperature vs time

(Condition E, single run)




- Driver gas contamination

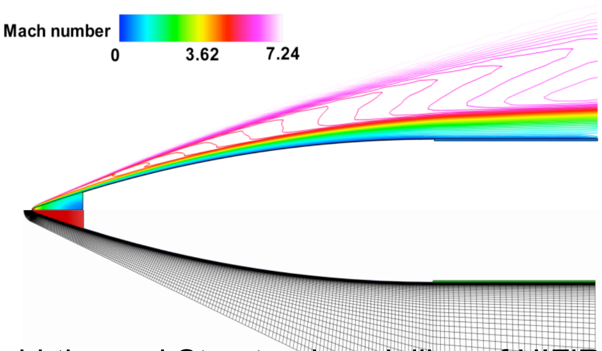
(Condition E, single run)



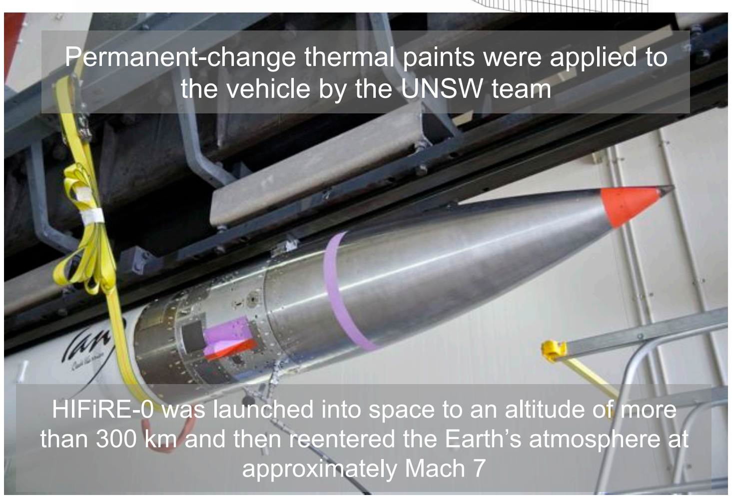
# Thermal-Structural Considerations for Hypersonic Flight

Development & implementation of methods to

- Numerically simulate fluid-thermal-structural interactions
- Measure distributions of in flight heating & associated aerothermodynamic phenomena
- Experimentally reproduce component transient heating on the ground
- Applied to HIFiRE, SCRAMSPACE & HEXAFLY-INT flight-test programs



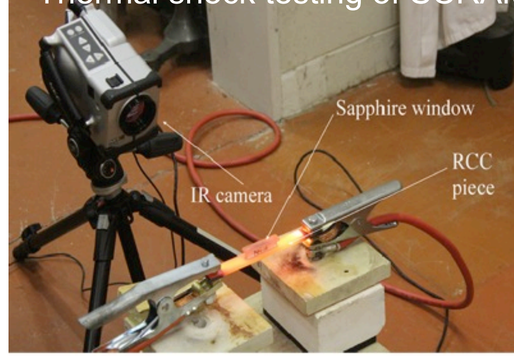

Fluid-thermal Structural modelling of HIFiRE-0

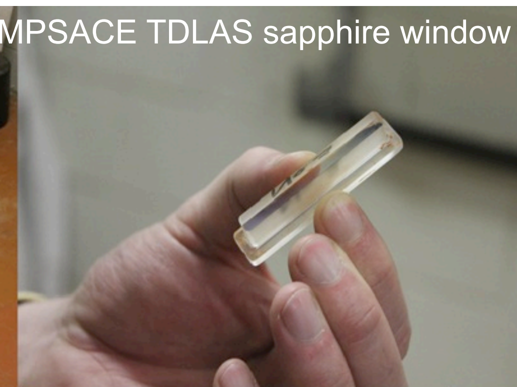


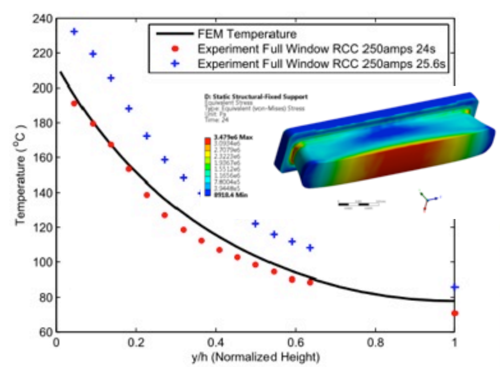
Permanent-change thermal paints were applied to the vehicle by the UNSW team

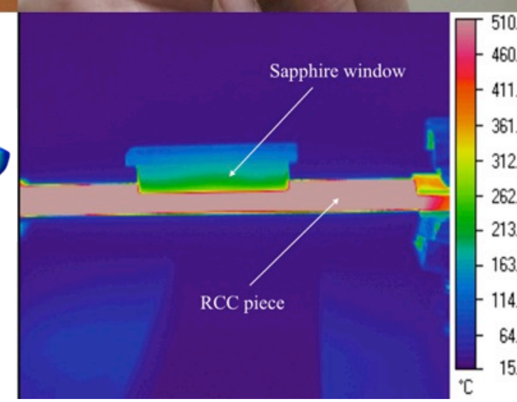
HIFiRE-0 was launched into space to an altitude of more than 300 km and then reentered the Earth's atmosphere at approximately Mach 7

Thermal shock testing of SCRAMPSACE TDLAS sapphire window





# *Summary*

- There are advanced ground based hypersonic testing facilities in Australia which cover a wide range of sub and super-orbital flow conditions.
- There is an active flight testing program to develop scramjet propulsion systems and the associated flight diagnostics
- Extensive expertise exists in facility development, instrumentation and flow diagnostics, hypervelocity aero-thermo-dynamics and the science of scramjet propulsion, the thermo-physical analysis of heated aerospace structures, and CFD
- Major research groups are based at The University of Queensland, UNSW at Canberra, The University of Southern Queensland and DSTO

# Back up slides

# *Reentry: some of the important issues*

- ***Macroscopic flow field definition***
- Vehicle stability and macroscopic aerodynamic coefficients for trajectory control
- ***Accurate predictions of surface heat transfer and ablation rates for TPS design***
- ***Substantial thermo-chemical changes occur in the shock layers, including dissociation and ionization, and non-Boltzmann thermal distributions.***
- ***Embedded regions of thermo-chemical non equilibrium, equilibrium and frozen flow.***
- ***Radiative heat transfer and flowfield coupling***
- ***Mass injection through ablation***
- ***Mechanisms of ablation***
    - ***Pyrolysis***
    - ***Surface reaction***
    - ***Sublimation and diffusion***
    - ***Spallation***
- ***Free stream entrainment and reaction of ablated products***
- ***Separated and recirculating flows, capsule leeward surface heating.***
- ***Transition, skin friction and convective heat transfer and the effects of catalycity***
- Dynamic Material response (heat conduction, internal chemical reactions (pyrolysis), radiative emission, gas flow and radiation through porous media, spallation, internal stress, etc.)
- ***Possible effects of radiative precursor photo chemistry at very high speeds***

# *Some ongoing projects*

- HiFIRE flight and laboratory program (Boeing, DLR, AFRL, DSTO….)

*NIRAP*

- *Australian Research Council* ablation and radiation project (UQ, ECP, AFIT, IRS, NASA Langley)
- *Australian Research Council Scramjet* science project
- *ESA* ablation-radiation coupling (EPFL, IRS, CIRA …)
- *Australian Research Council* The general Richtmyer-Meshkov instability in magnetohydrodynamics (DLR)
- *Australian Research Council* Flow physics of porous wall fuel injection for scramjet combustion and drag reduction (DLR)

# *Future plans*

- ***Non-equilibrium Radiation database.*** Obtain a comprehensive radiation data base of all the relevant atmospheres of the solar system, including Earth, Mars, Venus and the gas giants. Cover the full expected speed and altitude range. Test facility required, non reflected shock tube. Length scales to be such that equilibrium and the preceding regions of non equilibrium flow can be interrogated with advanced optical diagnostics.

***Equilibrium radiation database.*** Obtain complimentary data at the same post shock temperatures and pressures for steady flow equilibrium conditions as for the above shock tube data for all atmospheres of interest. Detailed diagnostics will be used to obtain high quality benchmark equilibrium data at critical conditions. Facility required, inductively heated plasma torch.

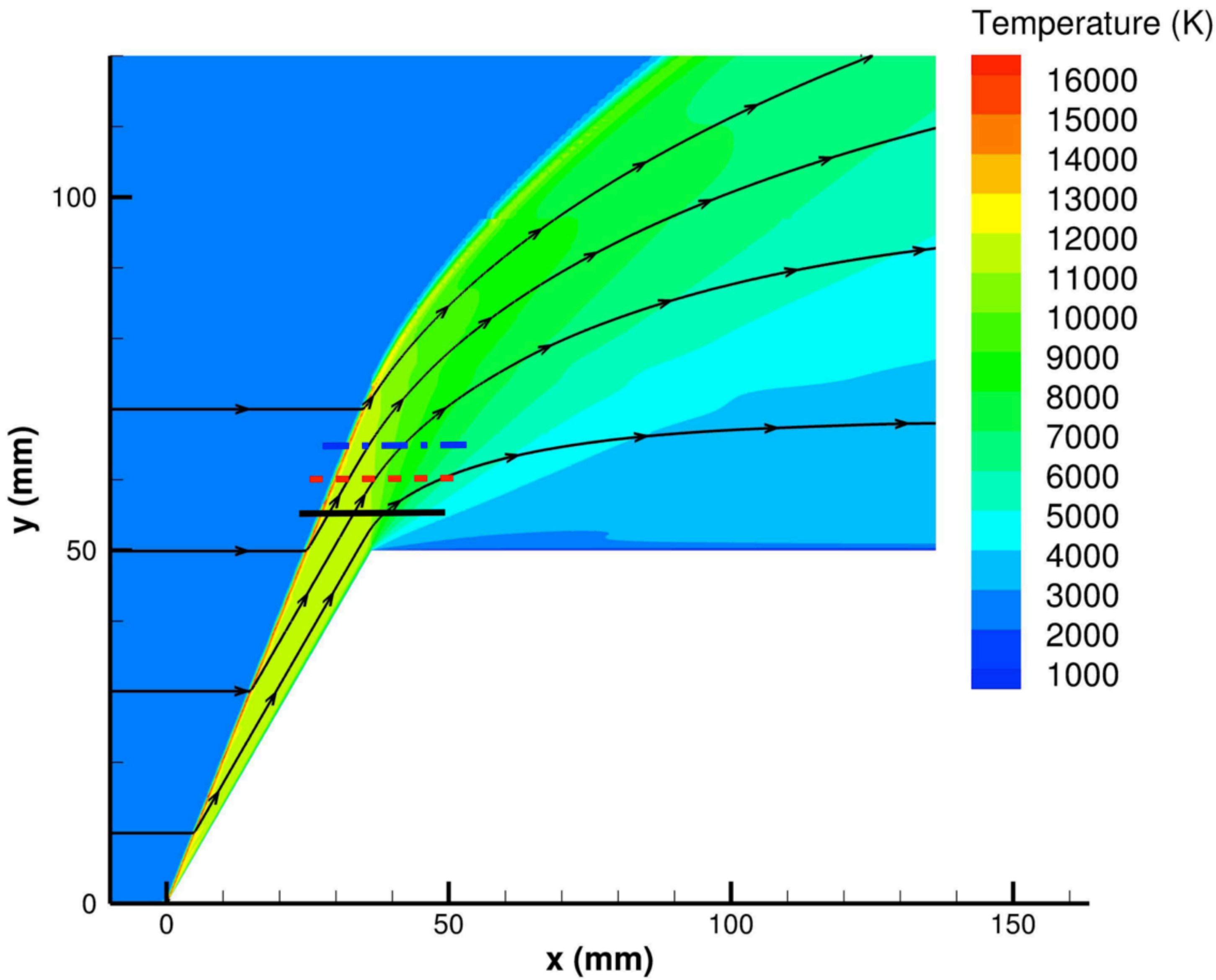
***Ablation-radiation coupling*.** The chemical interaction between shock layers and ablative surfaces is a critical area of study. Realistic simulation requires surface temperatures of the order of those in flight, and accurate measurements of species concentrations and radiation from the VUV to the infrared spectral ranges. A series of experiments measuring ablation rates, and surface temperature and heat transfer distributions would give very valuable  information for the study of the ablation process and its interaction with the radiative transport processes. Facilities required, plasma torch and superorbital expansion tunnel.

***Scaling experiments.*** Many complex processes are involved in forming the flow field around a hypervelocity flight vehicle. They do not all follow the same scaling laws, and direct scaling of flight vehicles by laboratory simulation is generally not possible with a high accuracy. Similarly, scaling of a proven design to a different length scale involves compromises to the parameters which can be conserved. Experimental studies of a family of generic re-entry shapes with different length scale and conservation of the primary flow parameters such as velocity and binary scaling parameter form a useful way to understand the interaction between the processes involved. It also provides a very powerful technique for validating complete analysis packages, which must include computation of the surrounding macroscopic flow field, and correct reproduction and coupling of the embedded regions of equilibrium and non equilibrium flows, and the ablating and viscous regions. Facility required, superorbital expansion tube.

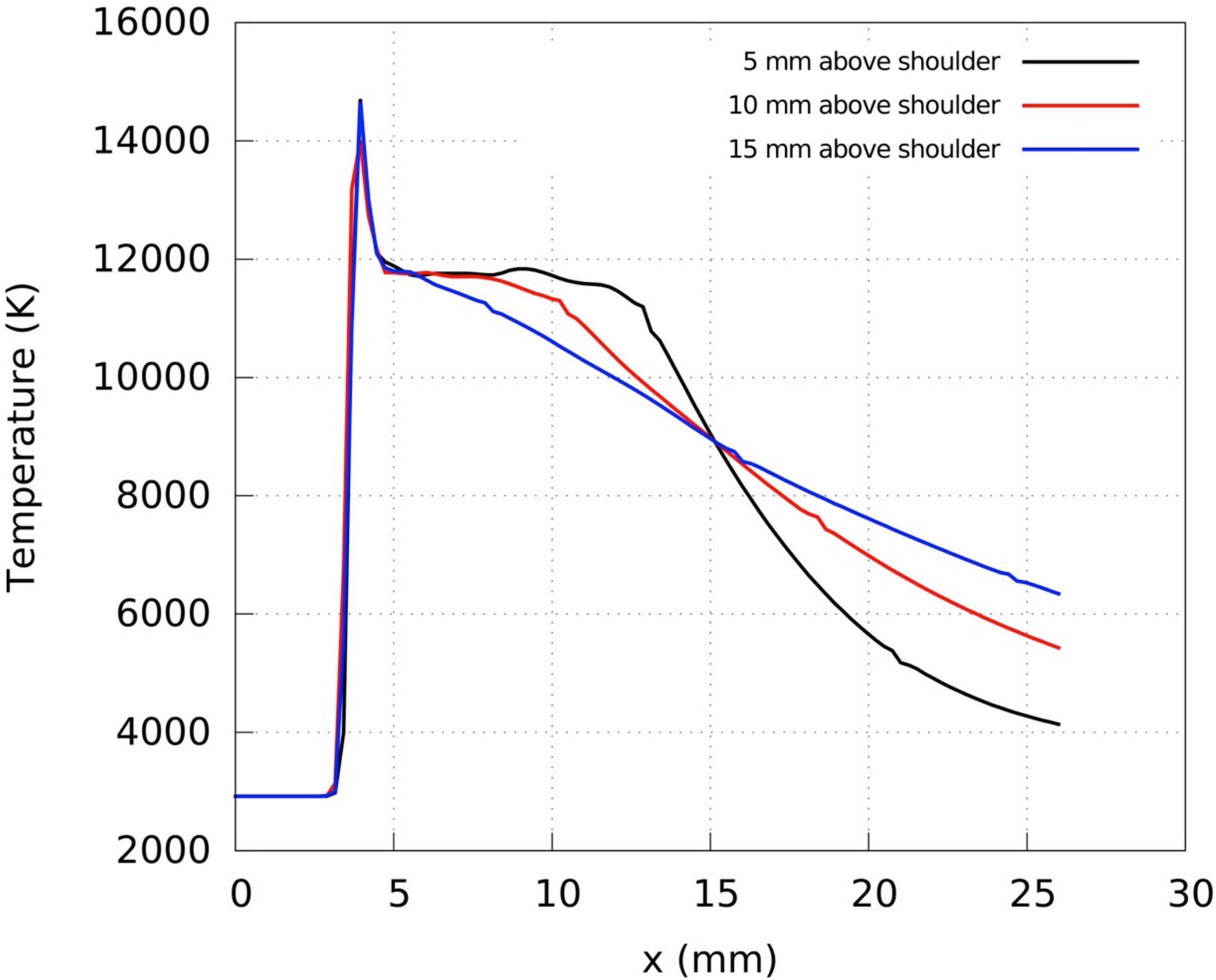
***Study of heat shield sublimation*. At very high speeds, characteristic for example of entry into the atmospheres of the gas giants, or a fast return to Earth from Mars, heat shield surface temperatures rise up to the levels where direct sublimation of carbon char becomes an important erosion and heat rejection mechanism. This is a poorly understood topic, with very little experimental data relating to the rate of species production, their entrainment into the flow and subsequent interaction with the shock layer. Well instrumented experiments are needed to help understand the phenomena. Suitable facilities, plasma torch and superorbital expansion tunnel.

# *Study of non equilibrium recombining flows*

- ***Study of radiating base flows***. Very high uncertainty exist concerning the levels of radiation in the base flow regions of reentry capsules, and if the presence of ablated products from the shock layer are important. Experiments involving heat transfer measurement and VUV to IR spectrometry in the base flow region wold be of high value.



Temperature (K)
16000
15000
14000
13000
12000
11000
10000
9000
8000
7000
6000
5000
4000
3000
2000
1000
100
50
0
y (mm)
0
50
100
150
x (mm)



16000
14000
12000
10000
8000
6000
4000
2000
Temperature (K)
0
5
10
15
20
25
30
x (mm)
5 mm above shoulder
10 mm above shoulder
15 mm above shoulder

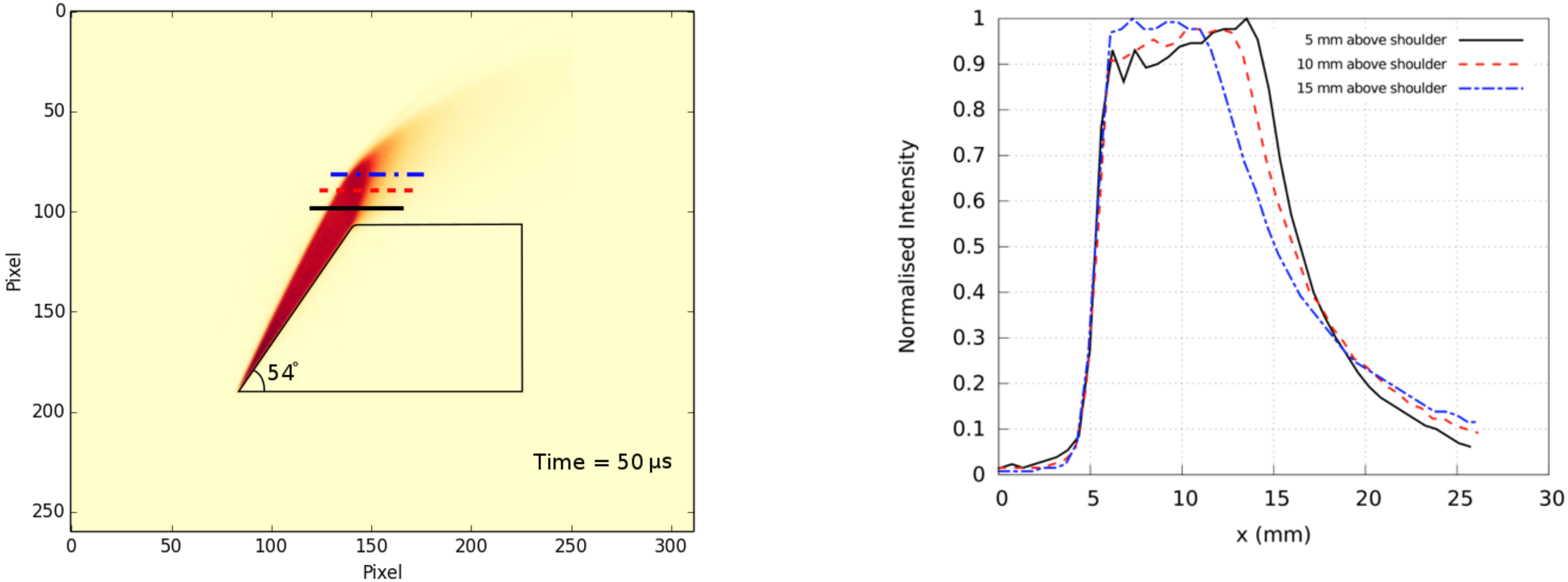



**Figure 3 - (Left) - Luminosity video from proof of concept experiment of proposed configuration (2 µs exposure time).**
**(Right) – Luminosity profiles extracted at varying heights above the model shoulder.**

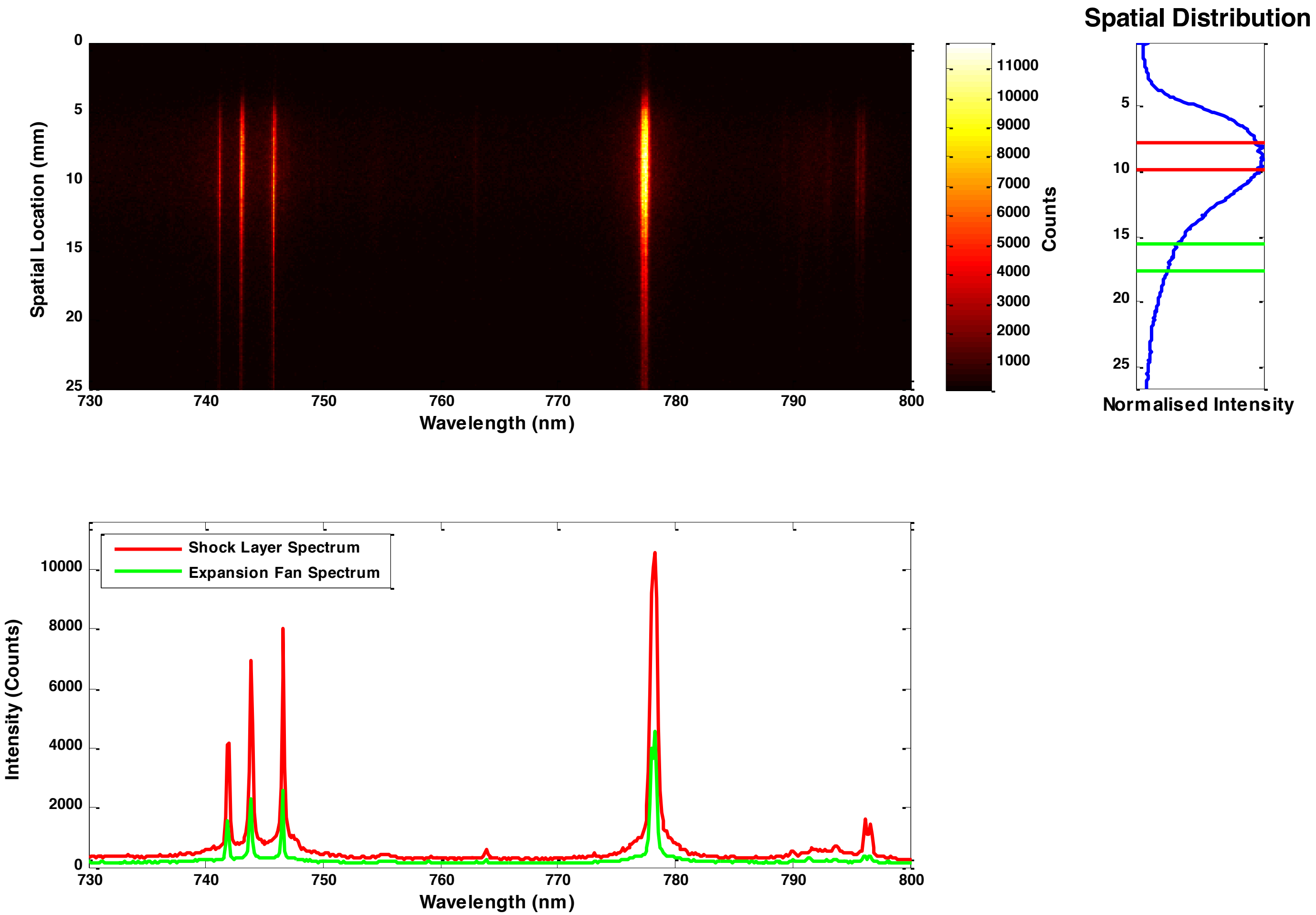
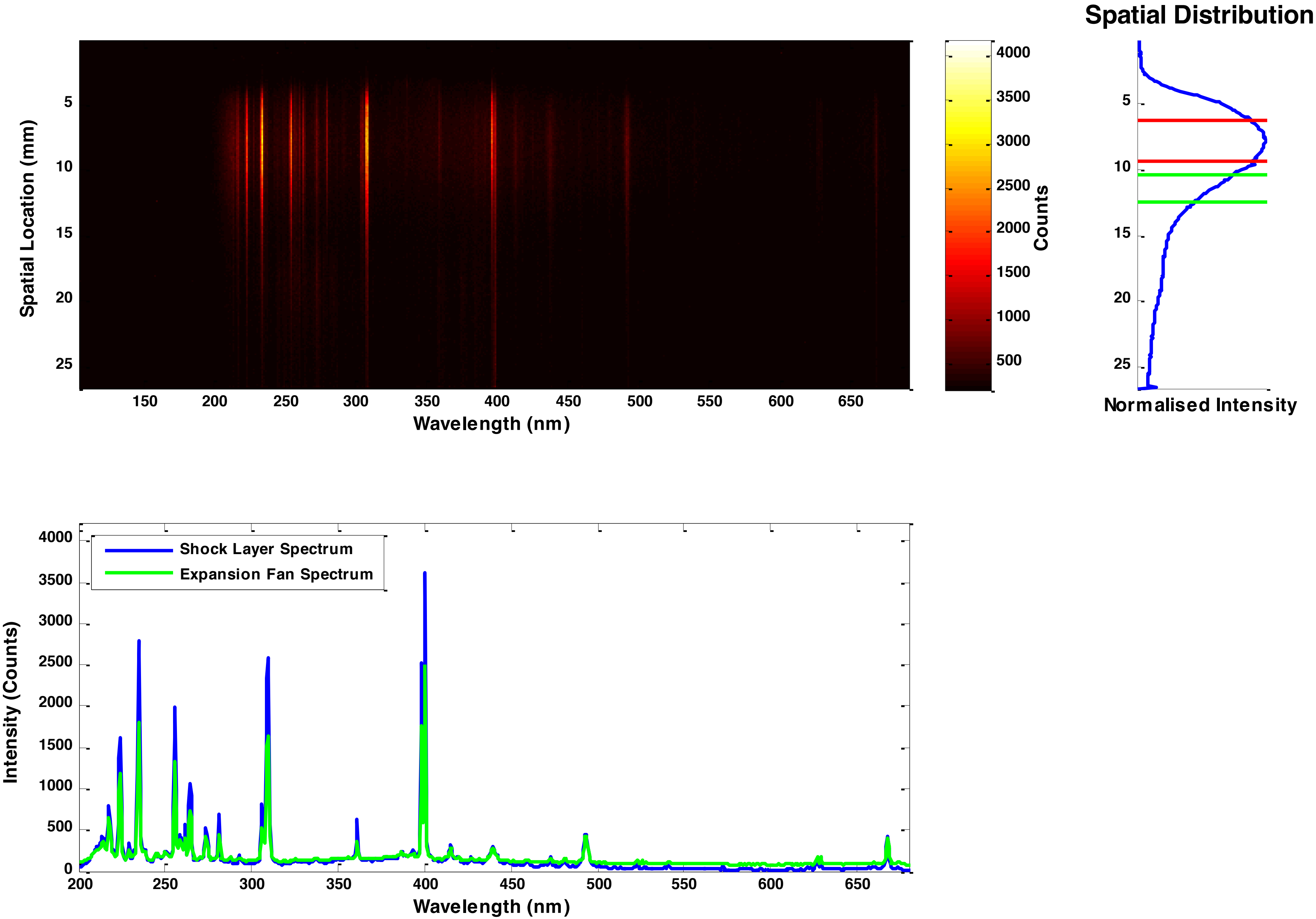



**Figure 4 – UV (top) and IR (bottom) spectra in X2 at 11.6 km/sec on a 54 degree wedge.**
**Images taken at 10 mm above the model shoulder, l**
**ocation as shown along dashed red lines in figures 2 and 3.**



Spatial Distribution
Spatial Location (mm)
Wavelength (nm)
Counts
Normalised Intensity
Shock Layer Spectrum
Expansion Fan Spectrum
Intensity (Counts)
Wavelength (nm)

# *Summary of radiating flow research*

- We have the option of modeling the whole flow field at reduced scale and high pressure, or encapsulated regions of the flow field at real flight conditions.
- The expansion tube mode is used for full flow field simulation.
- The non-reflected shock tube is used to create samples of gas at specific conditions.
- Flight vehicles of length scales like FIRE, Hayabusa and Stardust can potentially be reproduced full scale in expansion tubes.
- Electrically heated walls enable realistic thermal boundary conditions to be created