# Simulations of Electron Transpiration Cooling with Eilmer

Dr. Nick Gibbons,
*The University of Queensland, Brisbane, Queensland 4072, Australia*

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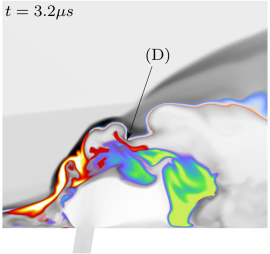
# About Me

- BE in Mech/Space Engineering, UQ (2010-2013),
- PhD in Hypersonics, UQ (2014-2019)
- Postdoctoral Research Fellow, UQ (2020-Present)

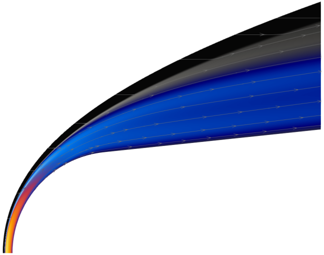
Things I do:

- The Gasdynamic Toolkit (github.com/gdtk-uq/gdtk)
- ceq: A lightweight Equilibrium Chemistry Calculator (github.com/uqngibbo/ceq)
- Simulations:

Supersonic Combustion



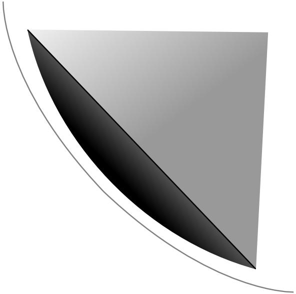

High-temperature Flows



# Background: Sharp-edged Hypersonic Flight

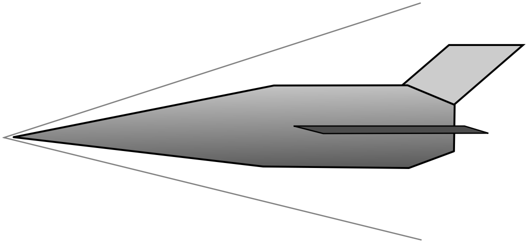
- Hypersonic aircraft come in two general types:

Re-entry capsule:



- High drag/low lift
- Large radius of curvature
- Generally sacrificial TPS

Hypersonic aeroplane:



- High lift/low drag
- Sharp leading edges
- Ideally reusable TPS

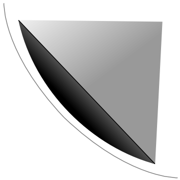
# Background: Sharp edged hypersonic flight

- Problem: Stagnation point heating scales with $\frac{1}{\sqrt{r}}$

$$q = 18.8\sqrt{\frac{\rho}{r}}\left(\frac{V}{1000}\right) \quad (1)$$

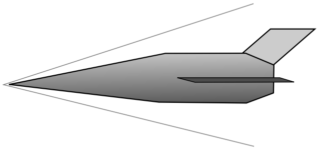
Apollo 4:

- r=4.6 m
- v=10.7 km/s
- q=483 W/cm$^2$



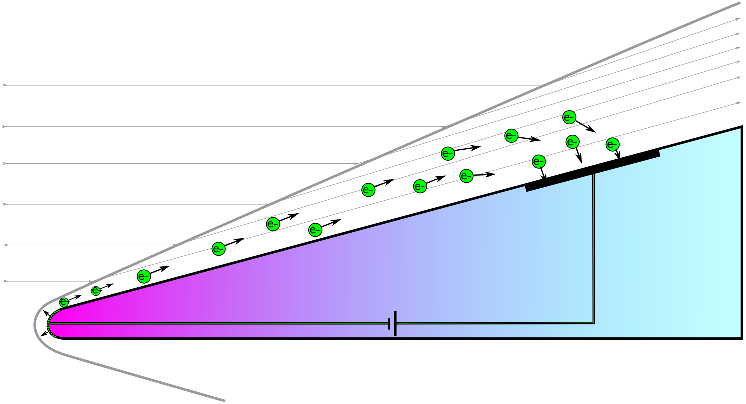
NASP:

- r=0.10m
- v=6 km/s
- q=800 W/cm$^2$



# Background: Electron Transpiration Cooling

- Use thermionic emission to carry energy away from hot leading edges
- Need temperature resistant materials with low electron work function $\phi$
- Linkage project with Lockheed Martin Australia to explore uses in hypersonics



# ARC Linkage Project with Lockheed Martin Australia

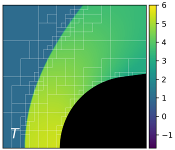
- Collaborative project with UQ, LMA, and DST Group
- Brad Wheatley is our liaison with LMA

Experiments in X2:

- Oliver Paxton
- Hadas Porat (DST)
- Ingo Jahn (USQ)
- Richard Morgan

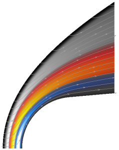
Two Fluid Plasma Modelling:

- Shazeb Imran
- Daryl Bond
- Vince Wheatley




CFD Modelling in Eilmer:

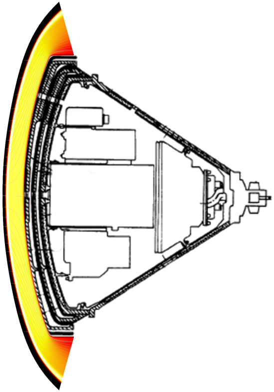
- Kyle Damm
- Rowan Gollan
- Peter Jacobs
- Robert Watt
- Myself



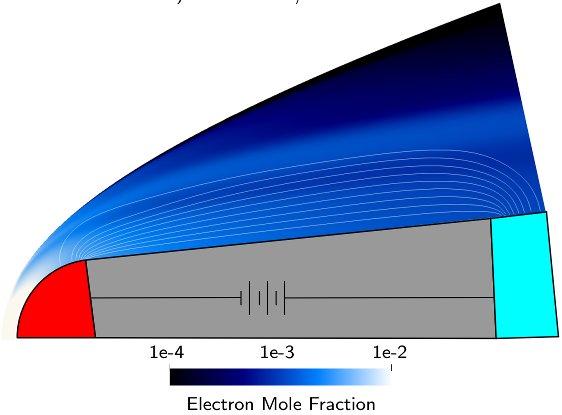
# ETC Simulations with Eilmer

- Eilmer is an Engineering-style flow simulation code
- As accurate as possible but still tractable for real-scale problems
- How to simulate ETC in Eilmer?

1.) High-temperature gas dynamics



2.) Electrostatic/fluid interactions



# High-temperature Gas Dynamics in Eilmer

2016: Eilmer 3 (written in C++) becomes an unmaintainable behemoth

- Peter Jacobs and Rowan Gollan begin investigating the D programming language
- Porting of key core routines to D begins, Eilmer 4 is born

July 2020: Eilmer 4 is taking over from Eilmer 3 in production use

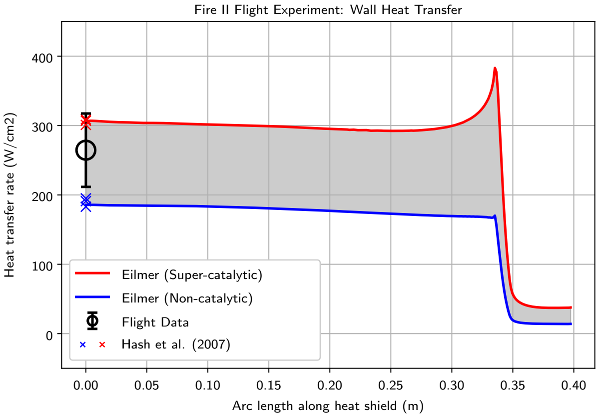
- New code has only a basic Two-Temperature model
- Good for inviscid flows with no ionisation
- Steady-state solver is in early testing: No chemistry or energy exchange terms

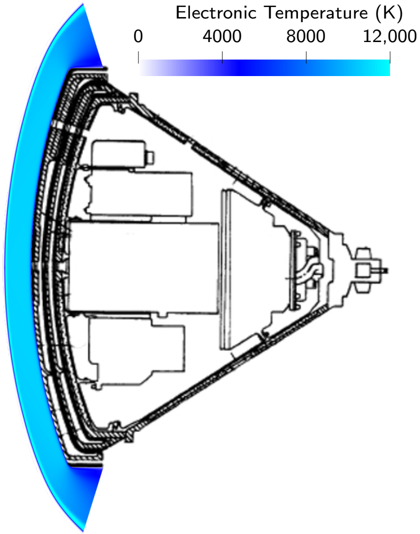
End of 2021: High temperature models are caught up to state-of-the-art

- Multi-species diffusion for heat transfer work
- Multi-mode energy exchange routines for super-orbital flow speeds
- Large number of bug-fixes, validation testing, numerical hardening
- Steady-state solver handles all of the available physics options
- Major optimisation and robustness improvements by Kyle Damm

# FIRE II Validation Exercise

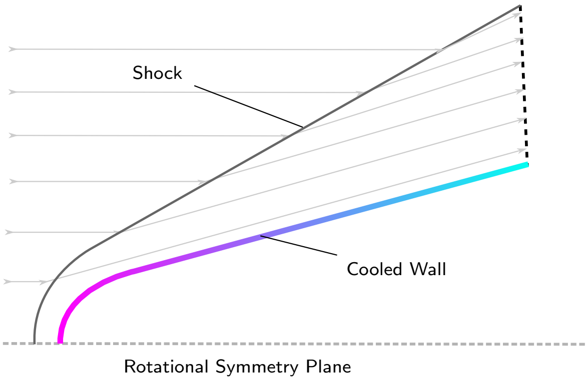
- Subscale ($\approx 1$ m) Apollo capsule model at 11 km/s, 71 km altitude
- 2-Temperature, 11 species air reactions by Kim and Jo, (2021)
- 100x257 cell mesh, $2\mu m$ first cell height, 75 minutes on 16 cores



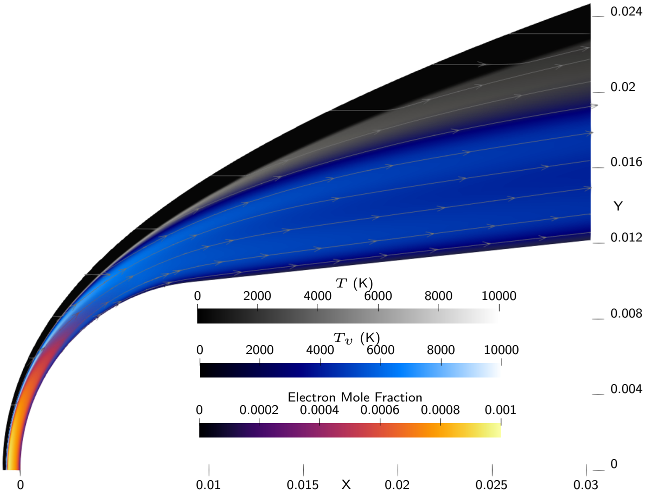
# Application: Where can we fly with ETC?

- AIAA Paper 2022-4141 (ASCEND/AIAA Spaceplanes conference 2021)
- 1cm radius conical leading edges, with 11 species 2T air
- Compute the steady wall temperature based on an energy balance
- One simulation with a radiatively cooled wall, one with radiation + ETC



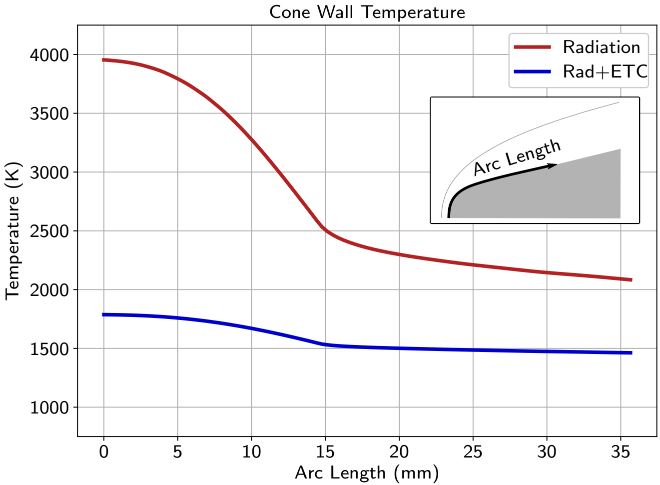
# Where can we fly with ETC?

- Solution at v=6 km/s, h=35 km, on 84x120 cell nominal grid



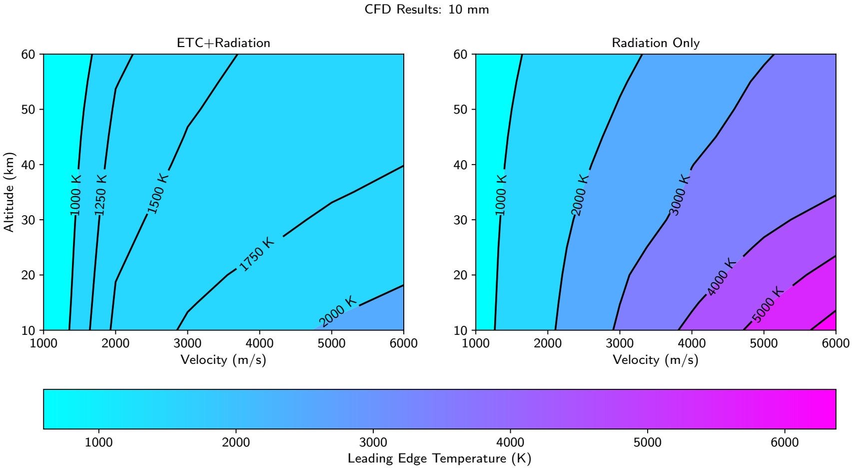
# Where can we fly with ETC?

- Computed wall temperatures for v=6 km/s, h=35 km case



# Where can we fly with ETC?

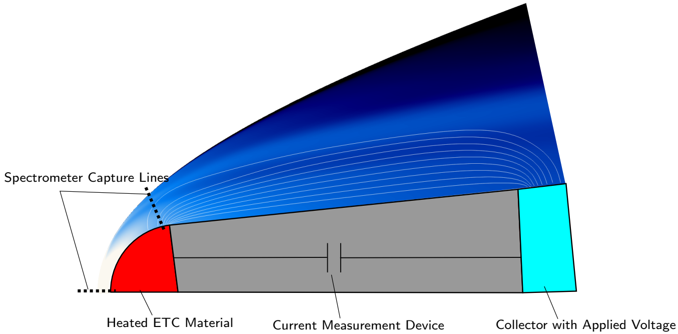
- Altitude/velocity plot showing leading edge temperatures



# Simulation of ETC Experiments

Oliver Paxton's experiments in the X2 expansion tube:

- Preheat the ETC material with an electric current
- Fire the expansion tube to create a brief instant of hypersonic flow
- Collect current using a capacitor bank and measure spectral lines in the shock layer



# Solving Electric Fields in Eilmer

- Finite volume based solution of the steady-state current continuity equation:

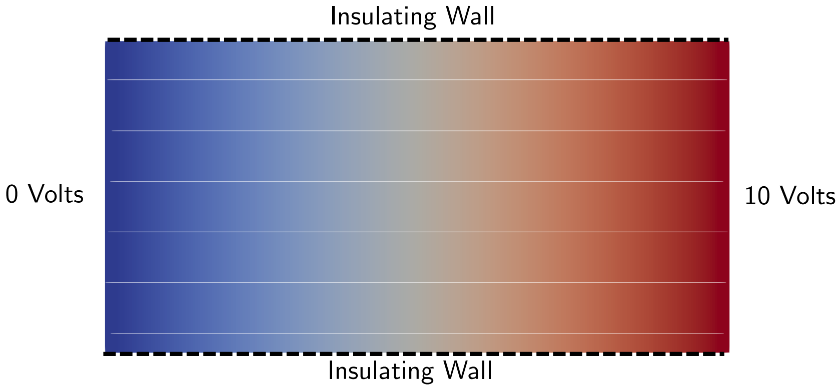
$$\nabla \cdot (\sigma \nabla \phi) = 0 \tag{2}$$

- $\sigma$ is the electrical conductivity of the plasma
- $\phi$ is the electric potential $E_j = \partial\phi/\partial x_j$

- Assumptions:
  - Very fast speed of light
  - No charge separation in the plasma
  - No magnetic fields affecting the conductivity

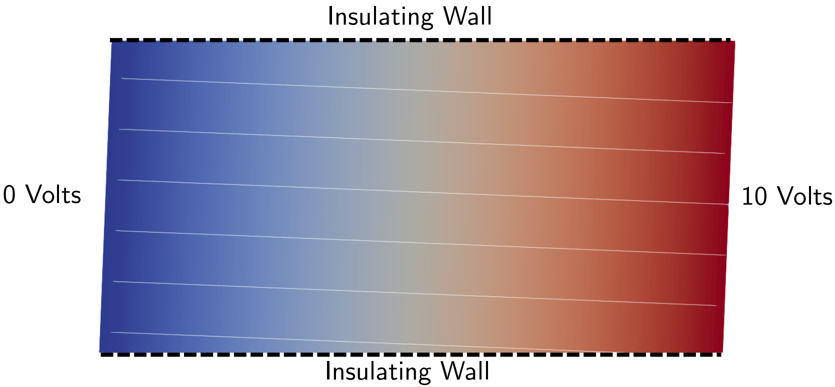
# Work in Progress: Insulating Boundary Conditions

- Insulators have no current, so $\nabla\phi \cdot \hat{n} = 0$



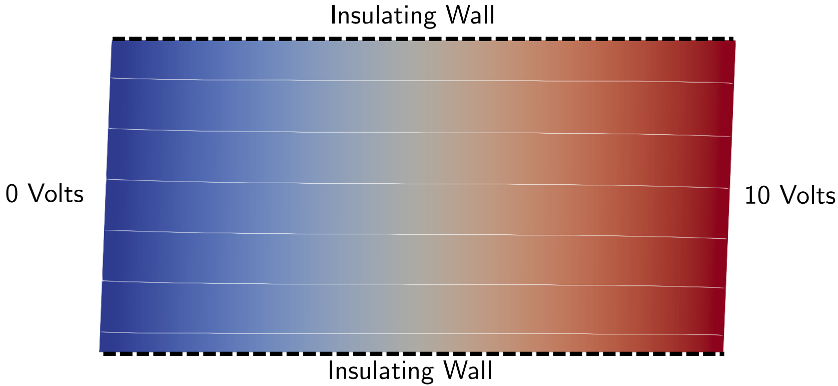
# Work in Progress: Insulating Boundary Conditions

- A slight skew in the cells introduces problems



# Work in Progress: Insulating Boundary Conditions

- New formulation couples in nearby cells at an insulating boundary
- Wall normal current is zero, but wall parallel current is whatever



# What's Next:

- Redoing spaceplanes calculations with catalytic walls (higher heat transfer)
- More work on the electric field solver: Aiming to simulate experiments soon
- Robert Watt investigating a 3 Temperature air model