Hollow cathodes – the need for the development of 2-D validated models and diagnostics

Stephen B Gabriel

Professor of Aeronautics and Astronautics

EPE Group

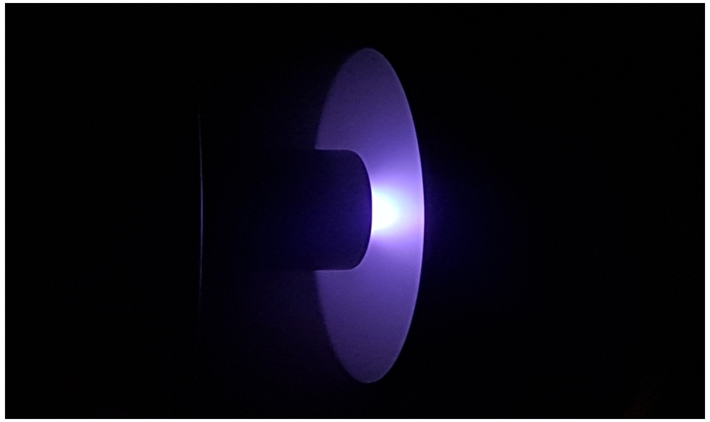
ECS

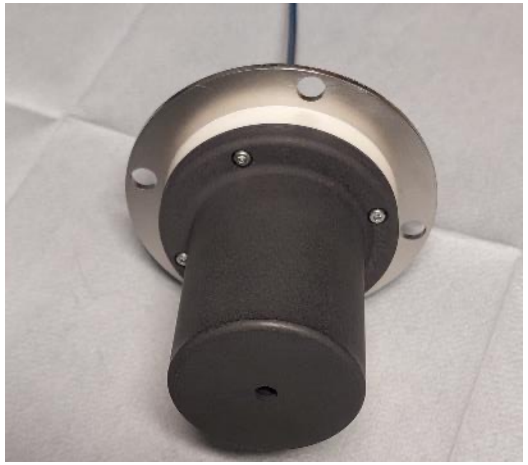
University of Southampton

England

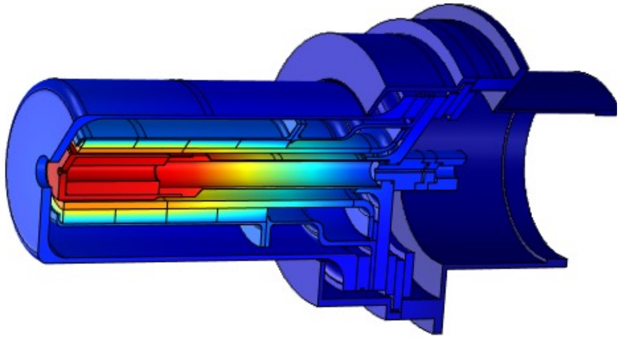
sbg2@soton.ac.uk

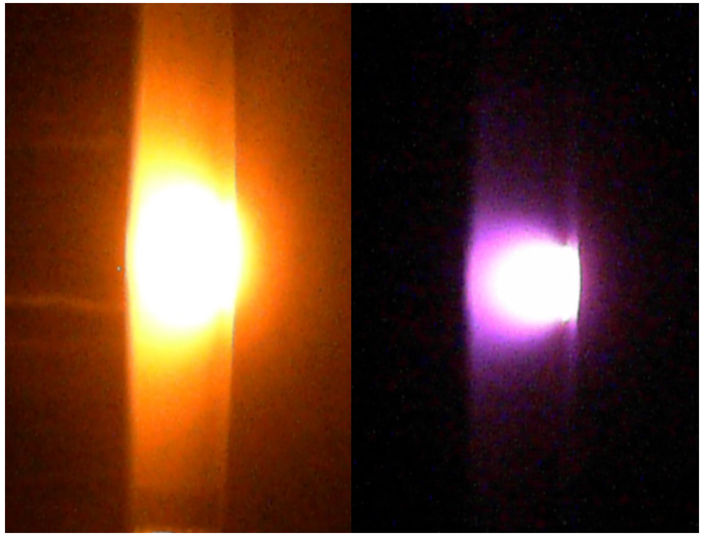
Outline





- Motivation
- State of the Art
- What's missing
- How we can fill these gaps





Motivation

- Why important :
  - Hollow cathodes are key components of electric propulsion devices, including HETs and GIEs, where they are used for both ionisation and neutralisation
  - Reliable and validated 2-D coupled thermal and plasma models needed for lifetime prediction(e.g. orifice erosion), design of new cathodes and full understanding of the underlying physics

State of the Art

- Currently there are only 2 or 3 validated, 2-D coupled plasma/thermal models for hollow cathodes worldwide

  - JPL: Orificed Cathode (OrCa2D), Ioannis G. Mikellides, Ira Katz, Dan M. Goebel, and James E. Polk "Hollow cathode theory and experiment. II. A two-dimensional theoretical model of the emitter region," Journal of Applied Physics **98**, 113303,2005

  - Gaétan Sary, Laurent Garrigues and Jean-Pierre Boeuf, "Hollow cathode modelling: I. A coupled plasma thermal two-dimensional model," Plasma Sources Sci. Technol. **26**, 055007, 2017

  - Stephen B. Gabriel , "Validation of a drift diffusion model for a hollow cathode" , IEPC-2019-914, *Presented at the 36th International Electric Propulsion Conference, University of Vienna, Vienna, Austria, September 15-20, 2019*

Validation

- JPL model: uses experimental measurements of plasma densities, electron temperatures and plasma potential taken with a Langmuir probe in all 3 regions of the cathode, the insert, orifice and plume on 2 cathodes : NSTAR and Nexus

- Sary model: uses JPL NSTAR measurements only

- Gabriel model: also uses JPL NSTAR measurements only

Measurements of insert region plasma parameters

- JPL measurements seem to be the only ones made and used a Langmuir probe(LP) (inserted and withdrawn rapidly using a pneumatic system to avoid probe damage)
- Only other measurements (known to author) are using fibre optic optical emission spectroscopy(OES)probes* and were not calibrated
- LP measurements are invasive(perturbing), perhaps only accurate to within a factor of 2 for the electron temperature
- No measurements of plasma parameters in Europe

* Pottinger, Sabrina (2005) Investigation of steady state characteristics of hollow cathode internal plasmas using optical emission spectroscopy. *University of Southampton, School of Engineering Sciences, Doctoral Thesis*, 238pp.

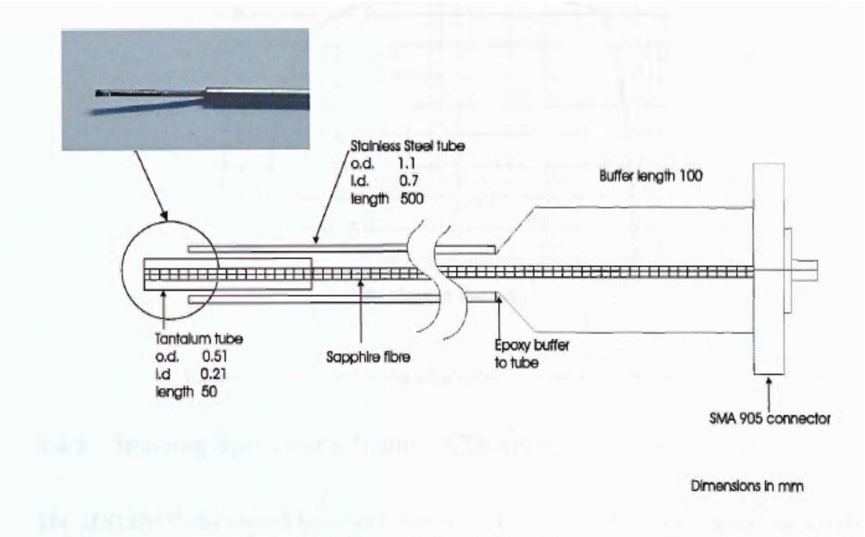


Figure 3.4: Optical Probe


Figure 3.2: Modified HC with probe access

Measurements of insert surface(inside) temperature profile

- Only some measurements using thermocouples on outside of insert on QinetiQ T cathodes and on a large (180A) cathode*
- Inside(emitting) surface measured only be JPL**
- Pottinger made some measurements using OES probes on T6 cathode but again uncalibrated

*Michele Coletti and Stephen Gabriel, “Insert Temperature Measurements of a 180A Hollow Cathode for the HiPER Project”, 48th AIAA/ASME/SAE/ASEE Joint Propulsion Conference & Exhibit, 30 July-01August 2012, Atlanta, Georgia

** J. E. Polk, C. M. Marrese-Reading, B. Thornbera, L. Dangb, L. K. Johnson and I. Katz, “Scanning optical pyrometer for measuring temperatures in hollow cathodes”, REVIEW OF SCIENTIFIC INSTRUMENTS 78, 093101 2007

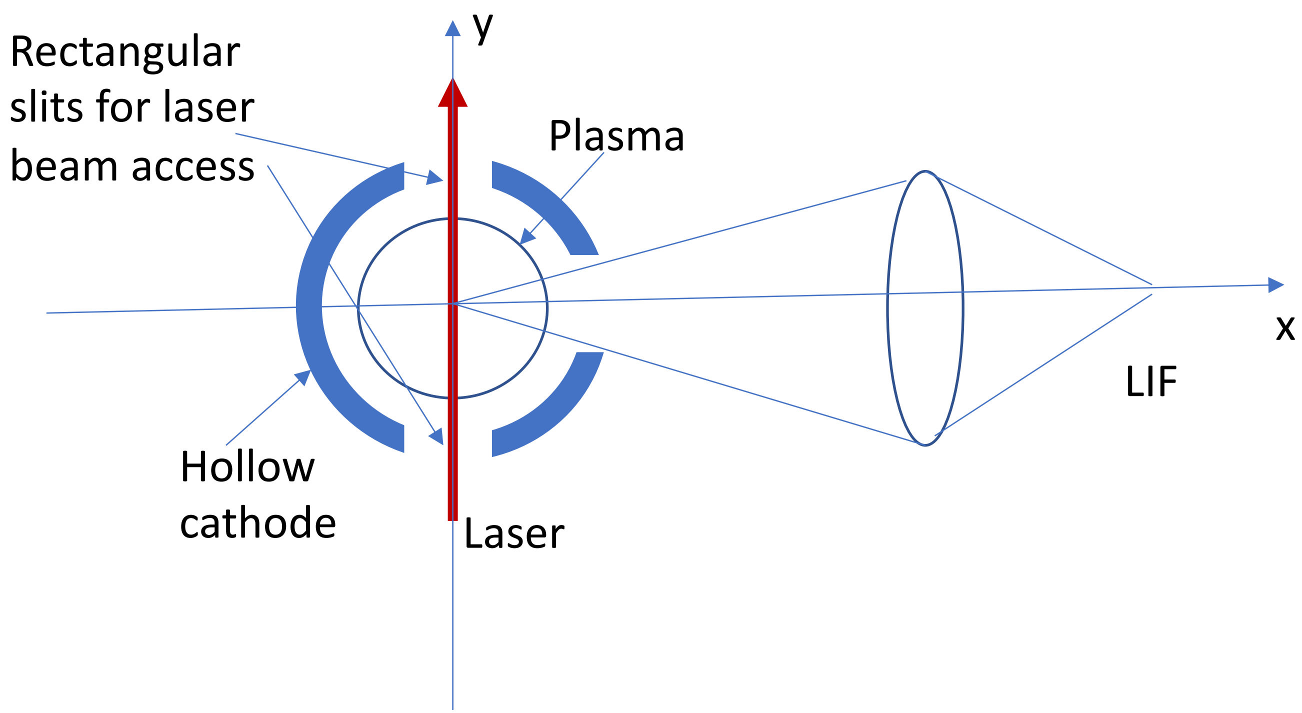
What’s missing

- Independent plasma parameter measurements in the insert and orifice regions of European hollow cathodes(QinetiQ T series and Mars Space cathodes) to validate models(Europe)
- Measurements (calibrated) of the insert temperature profile (taken with plasma measurements) (Europe)
- Measurements of the neutral densities(and temperatures) in all 3 regions
- Validated models for the neutral flow in the 3 regions
- Inclusion of plasma instabilities(e.g. ion acoustic, 2 stream) in the orifice region

How can these gaps be filled:

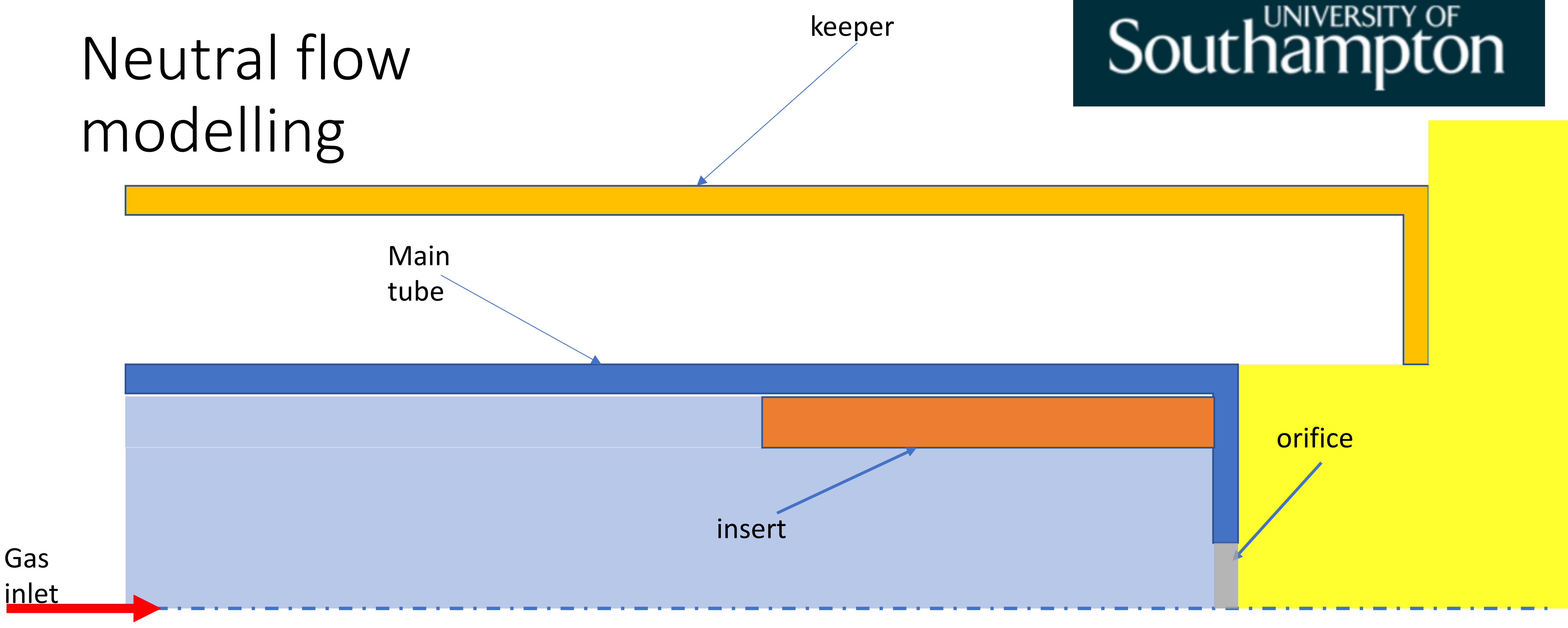
- Insert region plasma and surface temperature
  - Use JPL measurement methods for plasma parameters in insert region and orifice (LP) and scanning optical pyrometer for insert surface temperature measurements
- Neutral densities in all 3 regions
  - Experimental
    - Optical measurement techniques – Laser induced fluorescence(LIF) and Thomson Scattering
  - Modelling
    - Direct Simulation Monte Carlo (DMSC)
- Orifice region plasma
  - Full 2-D kinetic modelling to discover instabilities (source of anomalous resistivity)

Non-invasive optical diagnostics for neutral and plasma measurements



- Challenging:
  - Small volumes/dimensions
  - Optical access (fibres?)
  - Signal to noise ratio
  - Spatial scanning
  - But been done before in a larger HC

Neutral flow modelling



Laminar flow(collisional)

Transitional flow

Free molecular flow (collisionless)

NB –boundaries between 3 different regions are not known a priori

DMSC for flow of neutral gas

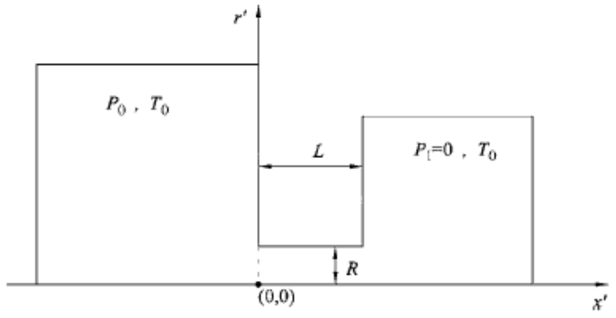
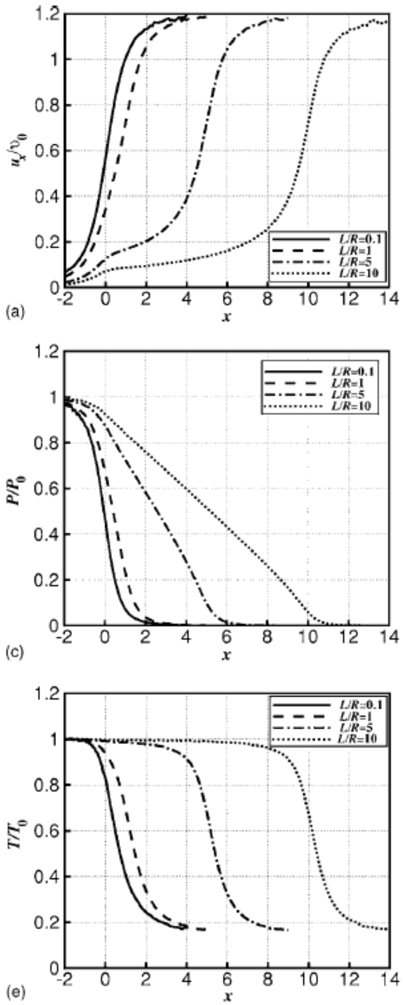


FIG. 1. Short tube geometry.

- Similar to S. Varoutis, D. Valougeorgis, O. Sazhin, and F. Sharipov, “Rarefied gas flow through short tubes into vacuum”, Journal of Vacuum Science & Technology A: Vacuum, Surfaces, and Films 26, 228 (2008) doi:10.1116/1.2830639
- But no plasma
- No heating in orifice, in fact temperature decreases

$\delta = \frac{RP_0}{\mu_0 v_0}$ = rarefaction parameter proportional to inverse Knudsen number



R is radius of tube(orifice)

P_0 reference pressure(pressure inside HC)

μ_0 gas viscosity at reference temperature T_0

$v_0 = \sqrt{2kT_0/m}$ = most probable atomic speed

k = Boltzmann constant

m = atomic mass

Conclusions

- Reliable and accurate prediction tools validated and verified by measurements of plasma and neutral gas parameters in all 3 regions of hollow cathodes as well as the insert surface temperature profile are needed to be independent of US models (which are used for example for orifice erosion and lifetime predictions and not generally available)
- Although very challenging, if feasible, non-invasive optical diagnostics for plasma and neutral gas measurements could improve accuracy of experimental data and hence models
- DMSC flow simulations of the neutral gas flow in all 3 regions should be developed and coupled with plasma models