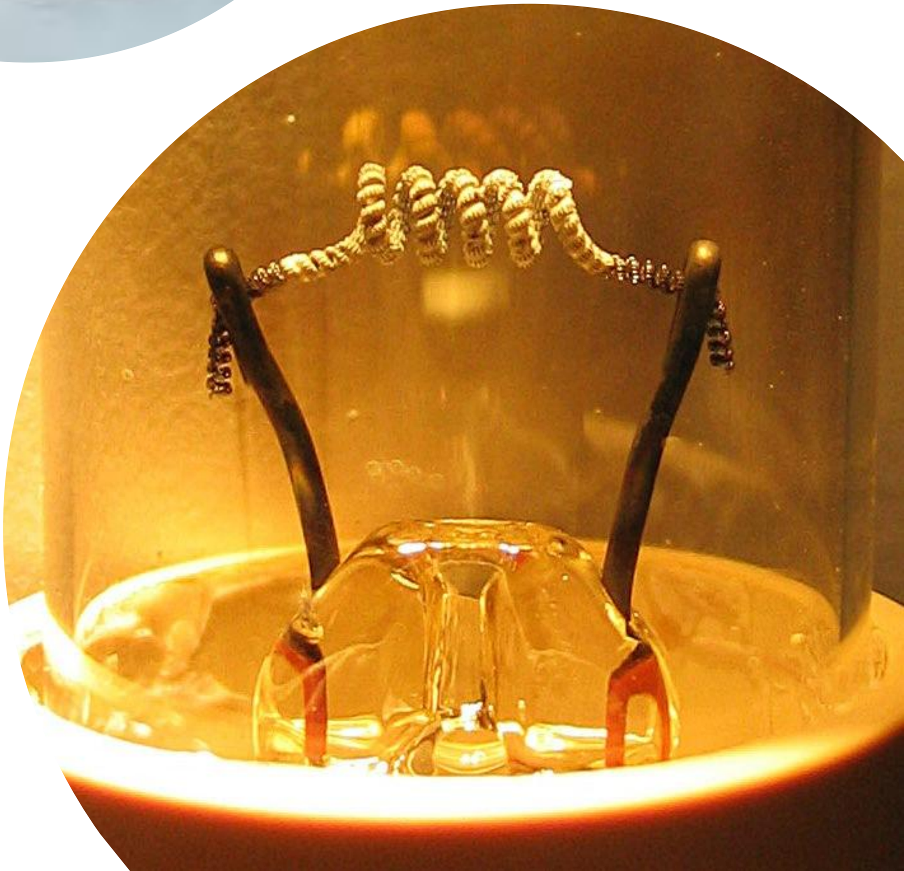
Cathodes

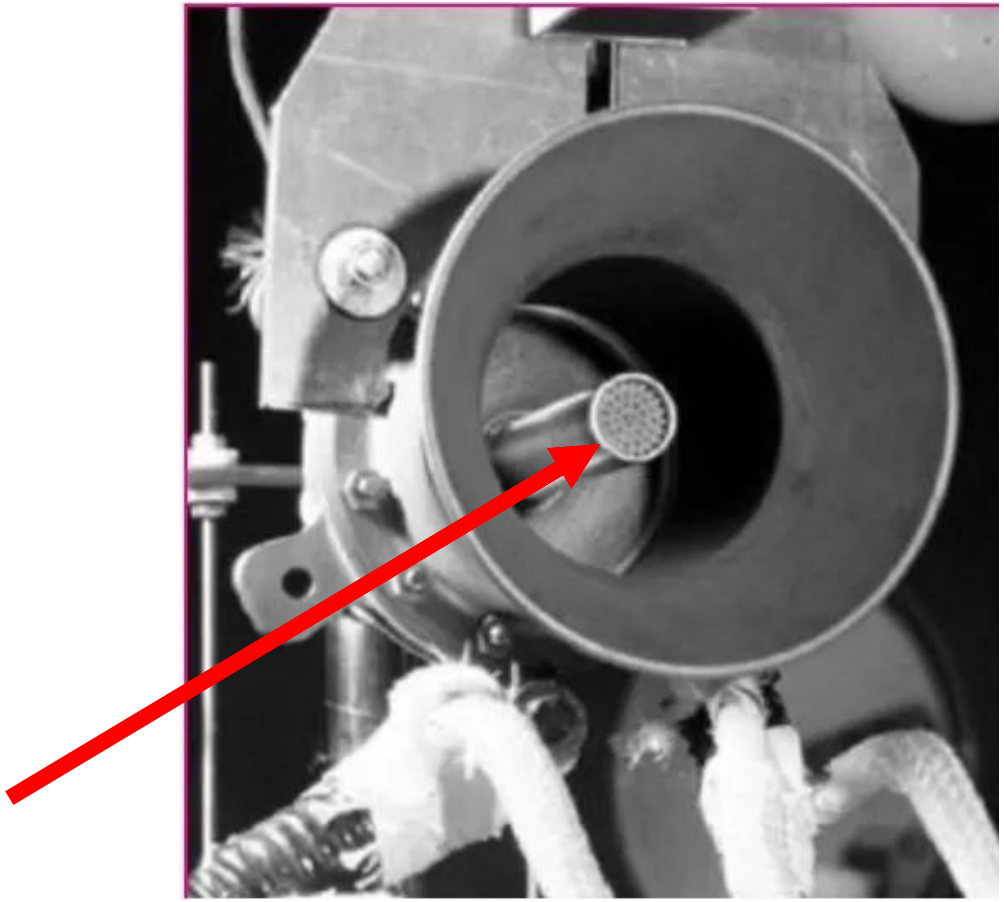
What are cathodes?

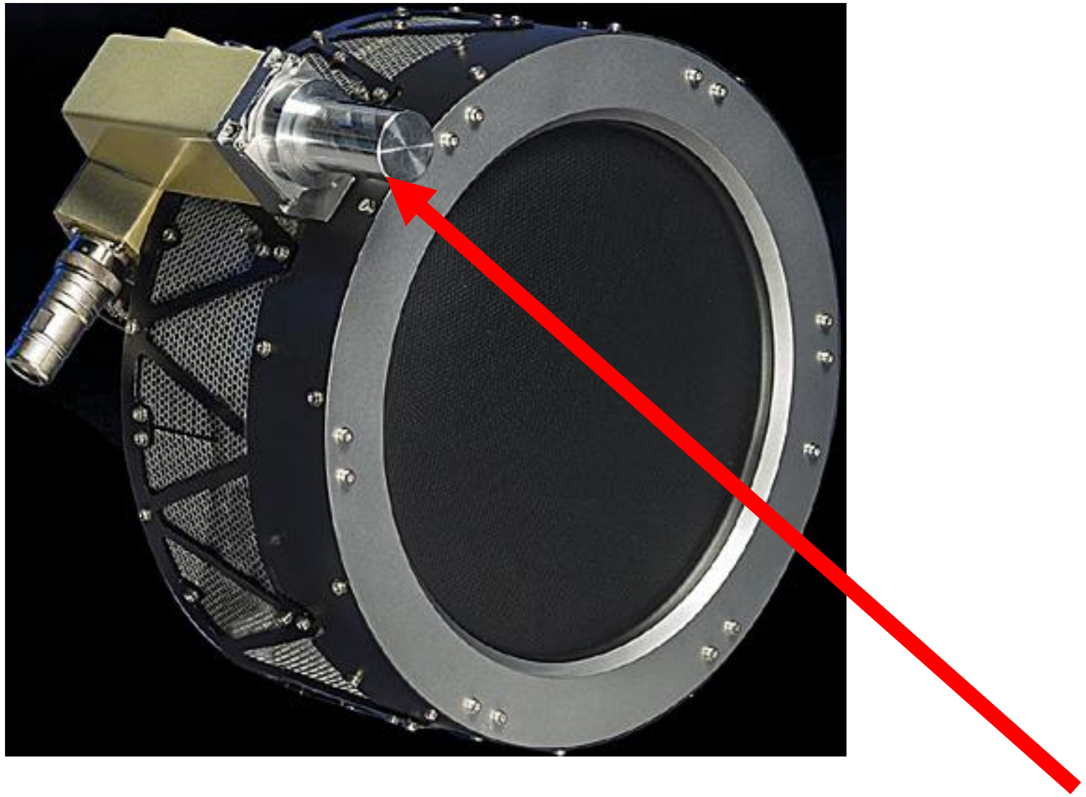
- Cathodes are an electrode with a net negative charge

- They are commonly used as electron sources for ionisation or neutralisation in electric propulsion

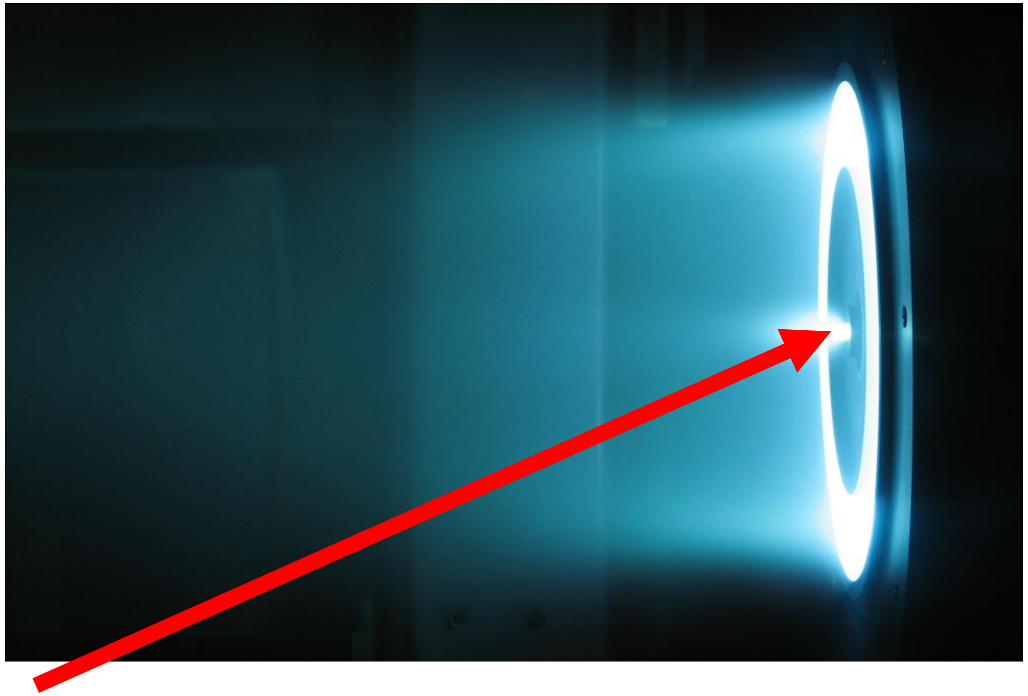


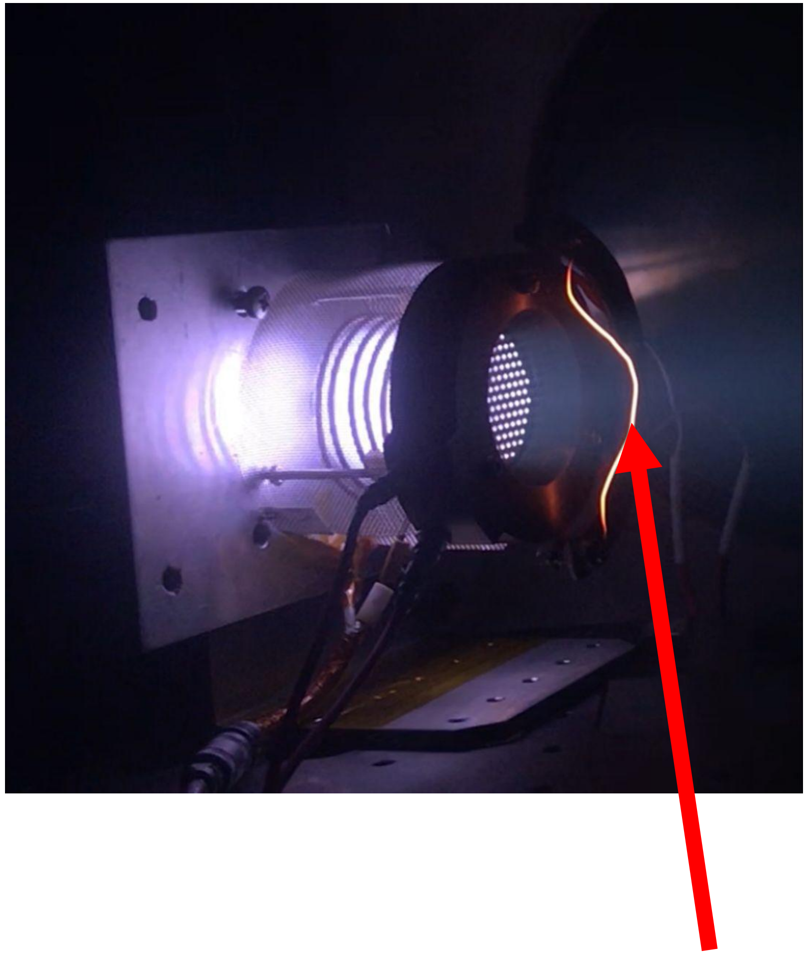
Examples





Examples

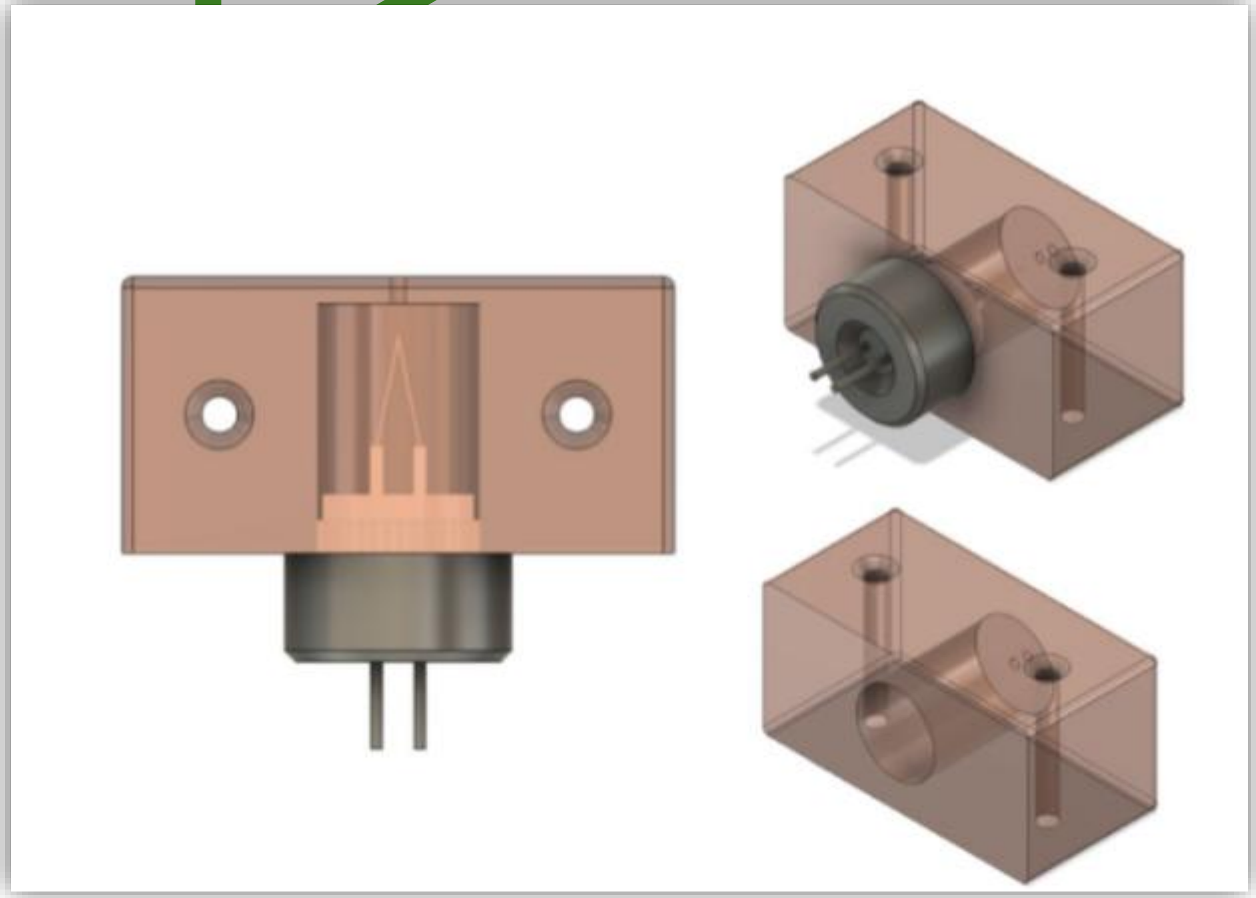




Filament Cathodes

Works by directly heating a wire (usually tungsten) to cause thermionic emission producing electrons.

- Very simple to build
- Can be cheap to build and maintain
- Short operational lifetime



B. Oh, A. Countryman, M. Regassa, A. Clowes, G. Miner, S. Kemp, S. C. "Mack" McAneney, M. Klein and C. Lee, "Design, fabrication, and testing of an undergraduate Hall effect thruster," J. Electric Propulsion, vol. 2, no. 6, 2023, doi: 10.1007/s44205-023-00040-3.

Filament Cathodes – Basic Emision

- Thermionic emission described by the Richardson-Dushman equation

$$J = A \cdot T^2 \cdot \exp\left(-\frac{e \cdot \phi}{k \cdot T}\right)$$

A is a constant somewhat hard to predict as it tends to deviate from theoretical values due to factors such as:

- Variation in crystal structures
- Variation in charge surface coverage
- Change in charge density at the surface

Filament Cathodes – Work Function Modification

To correct for these factors the work function can be assumed to be a linear function of temperature:

$$\phi = \phi_0 + \alpha T$$

This can be substituted into the original equation to acquire a more accurate version given by:

$$J = DT^2 exp\left(-\frac{e\phi_0}{kT}\right)$$

This can also be modified further to account for the presence of an electric field.

Filament Cathodes – Schottky Effect

If the surface of the cathode is subject to an electric field, then the required energy to emit an electron is decreased.

$$\Delta\phi = \sqrt{\frac{eE}{4\pi\epsilon_0}}$$

$$J = DT^2 exp\left(-\frac{e(\phi_0 - \Delta\phi)}{kT}\right) = DT^2 exp\left(-\frac{e\phi_0}{kT}\right)\exp\left(\frac{e}{kT}\sqrt{\frac{eE}{4\pi\epsilon_0}}\right)$$

The model above governs the relationship of discharge current as a function of temperature, E strength and material properties

Filament Cathodes – Power, Temperature Correlation

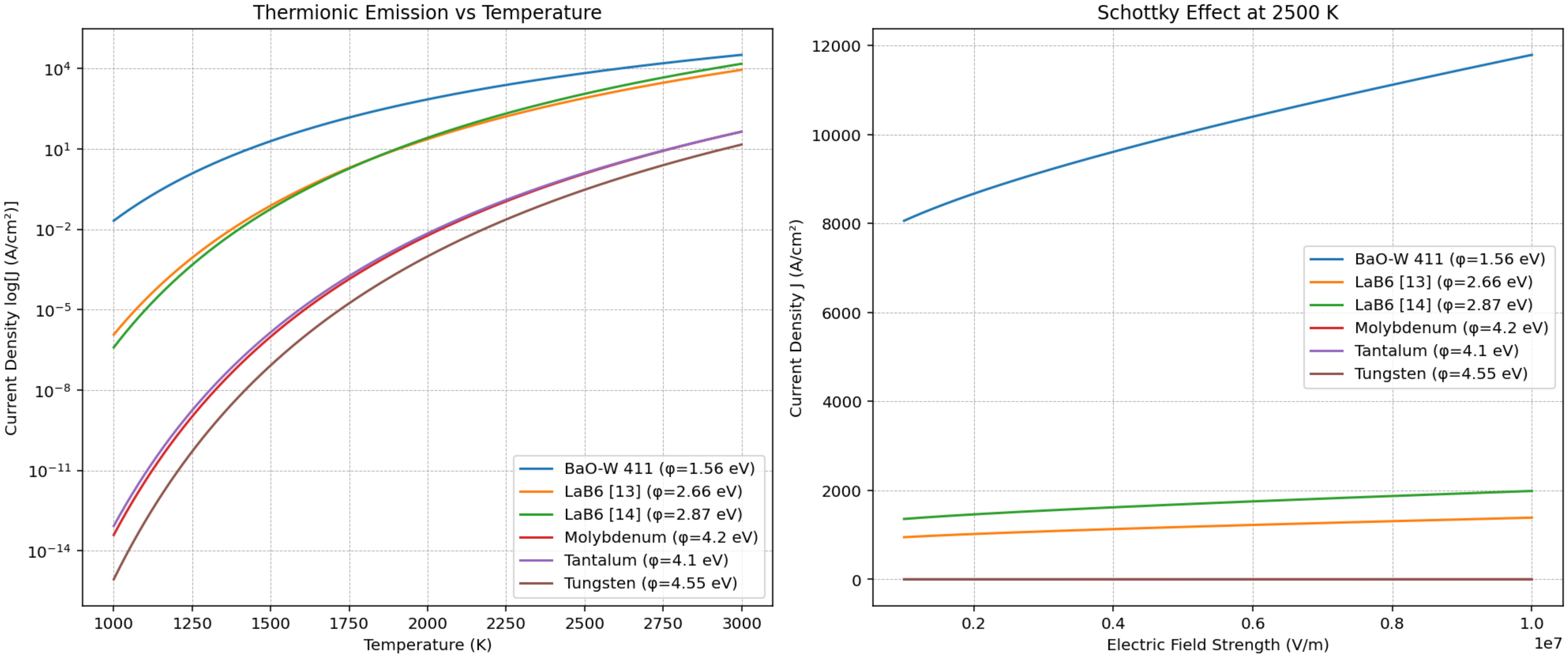
To determine the power required to heat up this filament cathode a combination of the Stefan Boltzmann equation and standard resistance for a wire equation can be used.

$$P = \varepsilon(T)\sigma A(T^4 - T_\infty^4)$$

$$R = \frac{\rho(T)L}{A}$$

Use these with traditional ohms law equations to determine the required voltage, current and power assuming 100% efficiency.

Filament Cathodes - Results



Let’s make a quick cathode for an EP device!

Hollow Cathodes

Cathode Tube:

- Holds other components together and acts as a common ground and a channel to let gas through

Cathode Insert:

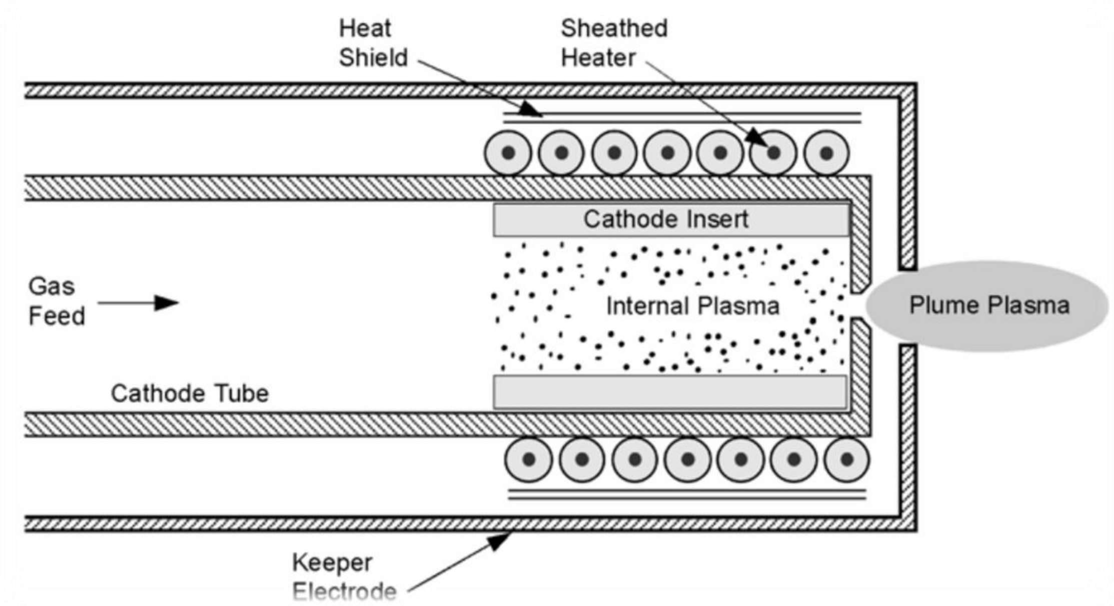
- Produced electrons through thermionic emission when heated
- Lowers overall work function making electron emission more efficient
- Enables long life by resisting sputtering

Sheathed Heater:

- Heating coil used to raise the cathode inserts temperature to start the process of thermionic emission
- Not necessarily needed after startup as the process becomes self sustaining

Keeper Electrode:

- Slightly positively charged to aid in initial electron discharge
- Protects other components from ion bombardment
- Maintains operating temperature



Hollow Cathodes – Key Points

Operation

- The cathode is initially heated to allow thermionic emission to occur.
- Propellant is then fed into the cathode and gets ionised .
- Ionised propellant then exits the cathode along with a stream of electrons.
- The keeper is used to fine tune the potential distribution outside the orifice of the cathode maintaining the discharge at lower particle densities.
- This allows electrons to attain higher kinetic energies ionising more neutral gas resulting in more efficient ionisation and electron production.
- Electrons eventually reach an anode and complete the circuit.

Design Considerations

- Efficiency (not going to be considered here)
- Heat
- Lifetime

Hollow Cathodes - Heat

Hollow cathodes produce plasmas inside them which can reach thousands of kelvin. Methodologies to minimise heat spread and damage must be employed to ensure operation.

<u>Key Factors</u>

- Material thermal conductivities
- Safe material operating temperatures
- Cathode operating current

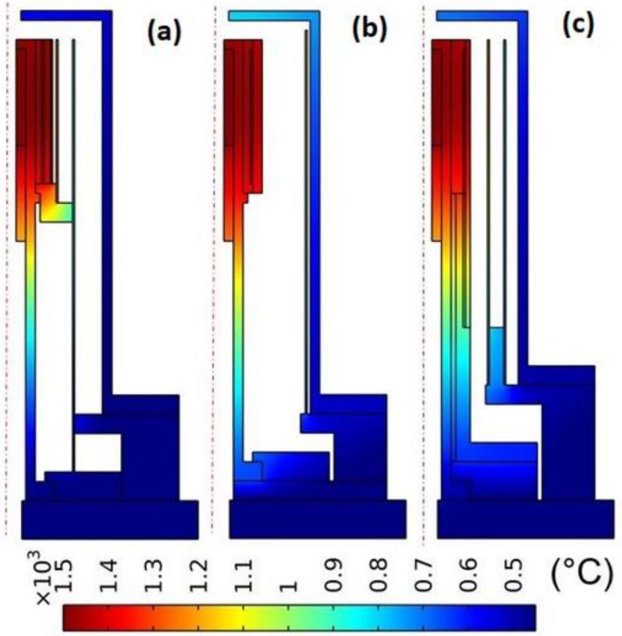
Identify desired operating current $T = AI_d^B$ A~1000 and B~0.1 are operating constants dependent on plasma conditions

↓

Create model and identify all material thermal conductivities and boundary conditions

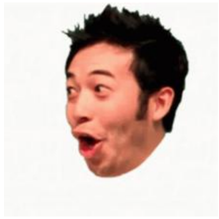
↓

Use results to estimate insert ablation rate and therefore cathode lifetime (the value of which taken from a operating requirement sheet)



U. Kokal, N. Turan, and M. Celik, "Thermal Analysis and Testing of Different Designs of LaB_6 Hollow Cathodes to Be Used in Electric Propulsion Applications," Aerospace, vol. 8, no. 8, art. no. 215, 2021, doi: 10.3390/aerospace8080215.

PRETTY COLOURS MAKE BRAIN GO BRRRRRR



Hollow Cathodes - Lifetime

Inserts inside a hollow cathode erode over time and will eventually be depleted.

<u>Key Factors:</u>

- Material work function
- Cathode tube and Keeper orifice geometry
- Operating conditions

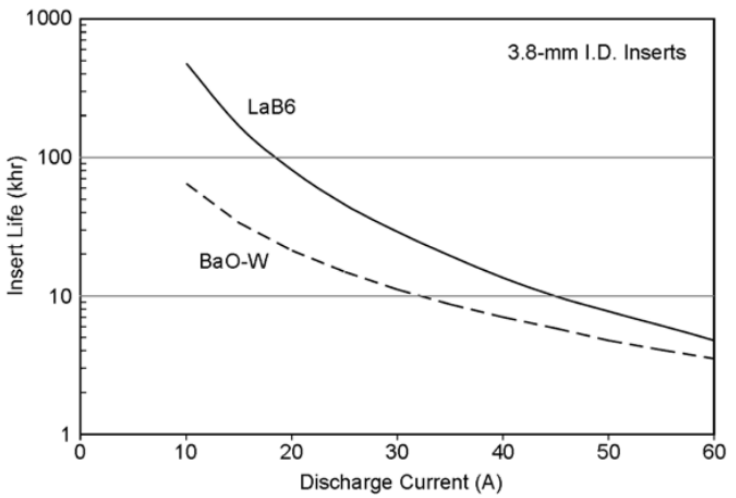


Fig. 6-48. Comparison of the calculated cathode lifetime versus the discharge current for the 0.8-cm outside diameter LaB6 cathode and the NSTAR dispenser cathode.

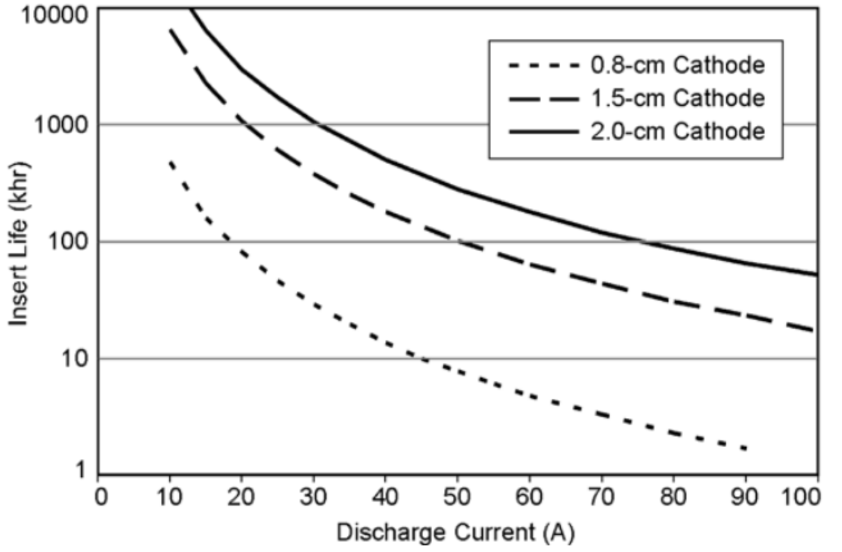


Fig. 6-47. Calculated lifetime in thousands of hours versus the discharge current for three different LaB_6 cathode diameters.

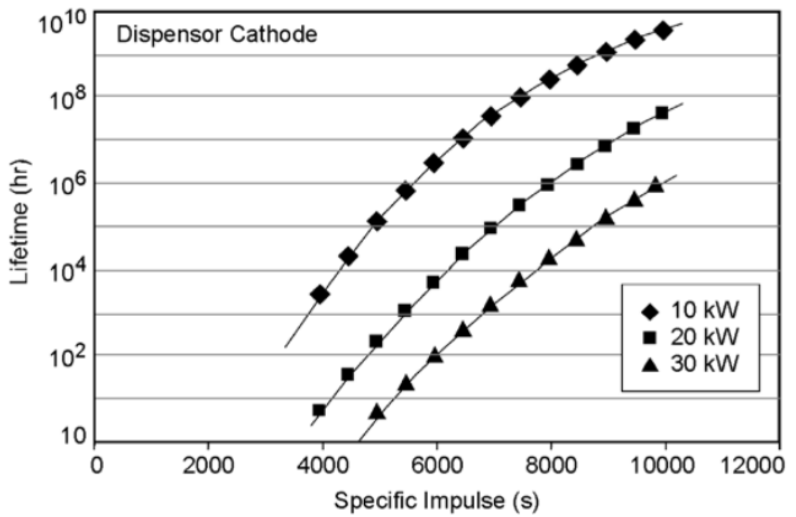
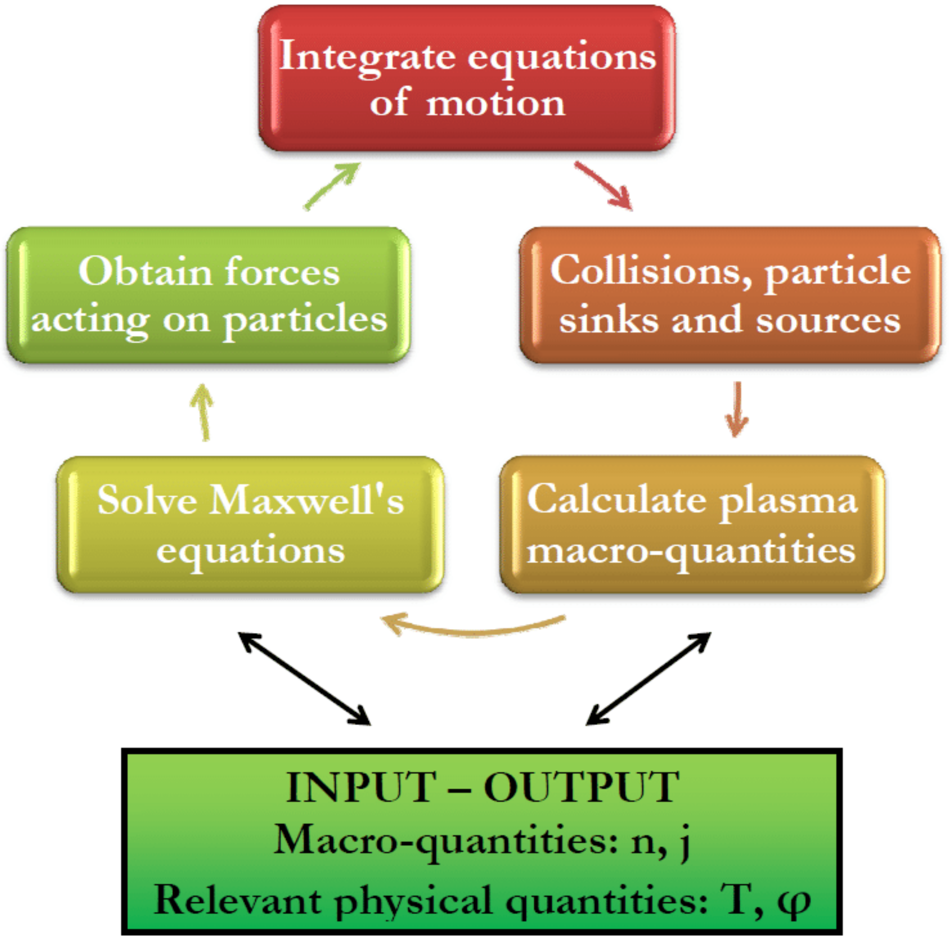


Fig. 6-46. Model prediction of NEXIS dispenser cathode life versus Isp for several thruster powers [47].

PIC Simulations

- Particle-in-cell simulations, a tool used to model plasmas by following the ions, electrons and how they interact with the E and B fields.
- To reduce computational overhead particles are represented in groups called **macroparticles**. Fields and macroparticles are computed on grids.
- These simulations are able to predict the general performance, erosion and hence lifetime of hollow cathodes



Further Readings:

1) Fundamentals of Electric Propulsion: Ion and Hall Thrusters, Dan M. Goebel and Ira Katz (Chapter 6 for Cathodes) [aka the EP Bible]

2) MIT OpenCourseWare Space Propulsion

3) Demo programs can be found on Sharepoint: Teaching\Demo Scripts

If there is something not explained in this lecture it is probably explained in further reading 1)