Electrons Unchained 1

Into the Wild Green Yonder

Idea Formation

Our initial idea was to try to build a particle accelerator. We looked at accelerating electrons as this would require lower energies. This led us to consider how we would produce the electrons. An initial idea was to use radioactive beta decay.

However, given the time constraints we could feasibly only make an electrostatic linear accelerator, we also need to figure out how to detect the electrons.

Eventually we decided to use thermionic emission to produce the electrons (granting us better control over beam intensity by changing temperature) and refocused our project to looking at the velocity distribution of the electron beam to better align with the project aims.

Electrons in metals

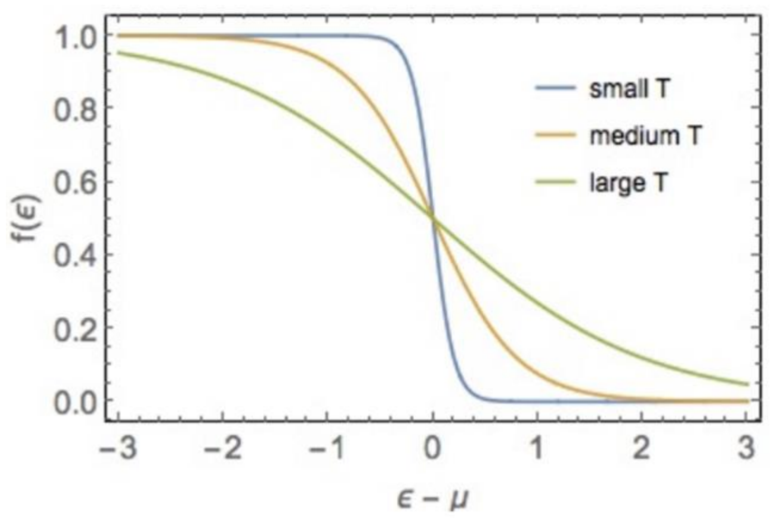
Electrons are a type of particle called fermions. Quantum theory predicts that no two fermions can be in the same quantum state. This is called Pauli's exclusion principle.

Electrons always want to occupy the lowest possible energy level, at absolute zero we call the highest possible energy an electron can have the *fermi energy*.

Due to these principles, electrons follow a *Fermi-Dirac distribution* of energies, which depends on temperature.

$$f(\varepsilon) = \frac{1}{e^{\frac{\varepsilon - E_F}{kT}} + 1}$$

As the temperature decreases, the distributions looks like a step function, with very few electrons having energy above the fermi energy. At higher temperatures there is a greater probability that electrons will have energy above the fermi energy.



Work Function

The work function (W) of a metal is the amount of energy it will take to move an electron from the surface of a metal to where the image charge is negligible. The work function is given by

$$W = -e\emptyset - E_F$$

Where ∅ is the electrostatic potential near the metal surface and E_F is the metal's fermi energy.

Copper has a fermi energy of roughly 7 eV. At 298 K, the thermal energy (kT) is approximately 0.026 eV. Using the Fermi-Dirac distribution we see that most electrons still have energy less than the fermi energy.

For an electron to escape a metal it's energy needs to be greater than $W + E_F$. Therefore, a metal with a lower work function will be a better emitter of electrons.

Thermionic Emission Theory

Richardson's law predicts the relationship between temperature (T) and current density due to thermionic emission (J) as follows:

$$\boxed{J = A_G T^2 e^{-\frac{W}{kT}}}$$

where W is the work function of the material, k is Boltzmann's constant and A_G is a constant, however there are multiple alternative theories about this value.

The accepted work function of thoriated tungsten is approximately 2.6eV.

Variable Resistance

The resistance (R) of a conductor will vary with temperature (T). It generally has the form:

$$R = R_0[1 + \alpha(T - T_0)]$$

where R_0 is the reference resistance at some temperature T_0 and α is the *temperature coefficient of resistance* at T_0. This can be rearranged into the form:

$$\boxed{T = T_0 + \frac{1}{\alpha}(\frac{R}{R_0} - 1)}$$

If we assume our 99% tungsten and 1% thorium has the same $\alpha = 0.0045\ ℃^{-1}$ and resistivity $\rho = 5.6 \cdot 10^{-8}\ \Omega\, m$ as pure tungsten at $T_0 = 20\ ℃$, then we find that $R_0 = 0.525 \pm 0.005\ \Omega$ at this reference temperature. We can use this information to estimate the temperature of the cathode at different resistance values.

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An Unexpected Journey

Cathode

The cathode was made using a 0.125mm wire composed of 99% tungsten and 1% thorium. This was purchased from an external supplier.

The cathode was suspended between two copper rods, and then the wire was bent to a sharp point.

The sharp point made the heating occur in that area. This meant most electrons were produced from that part of the cathode.

A current of between 1 and 2A was driven through the wire, causing it to glow red.

Wien Filter

A Wien filter is a velocity selector consisting of orthogonal electric and magnetic fields. By controlling the strength of the electric and magnetic fields we can tune the selector for specific velocities.

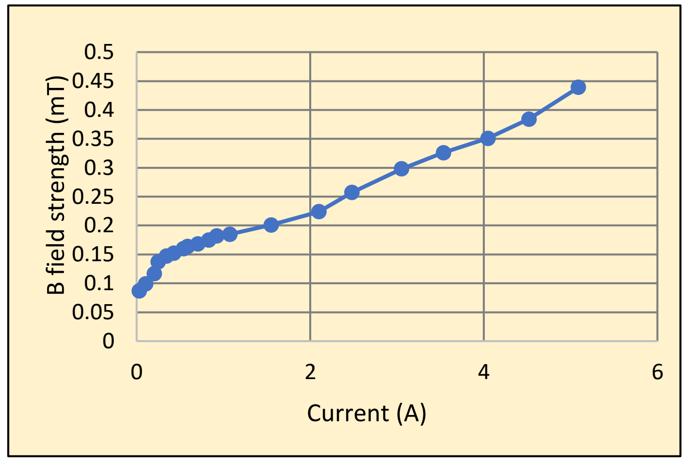
We used Helmholtz coils to create a pseudo-constant magnetic field and used a constant voltage on metal plates to create a uniform electric field.

Theory predicts that only electrons with velocity $v = \frac{E}{B}$ will continue in a straight line, with other electrons being deflected in the x direction, given by these equations:

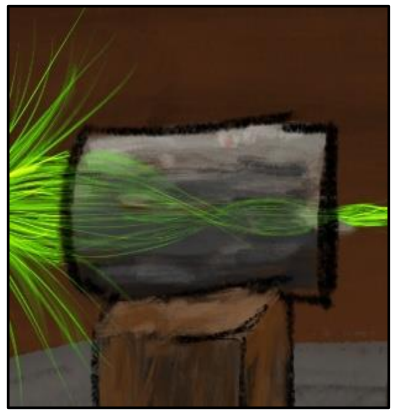
$$x(t) = \frac{vBm - Em}{qB^2}\left[\cos\left(\frac{qBt}{m}\right) - 1\right]$$

$$z(t) = vt + \frac{vBm - Em}{qB^2}\sin\left(\frac{qBt}{m}\right) + \frac{E - vB}{B}t$$

We can use this to find the range of velocities that will enter the Faraday cup.



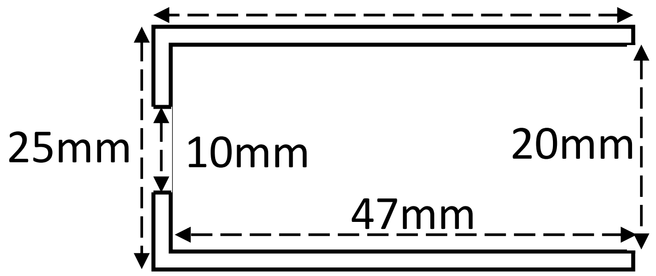
A calibration curve of the magnetic field produced by the Helmholtz coils



The Wehnelt Cylinder

The Wehnelt cylinder was made by the level one workshop. It was made from an aluminium rod with a diameter of 25mm.

We planned to negatively charge the cylinder. This would focus the beam of electrons produced by the cathode.



Cross-sectional design of the Wehnelt cylinder.

However due to issues with the anode we were unable to use this during lab time.

Anode

The anode was made from a 2mm thick sheet of copper. It was then laser cut into a circle with a 25mm diameter. We had four made with various sized holes in the centre.

A wire was soldered onto the copper disc, we then planned to use a 6kV power supply to accelerate the electrons.

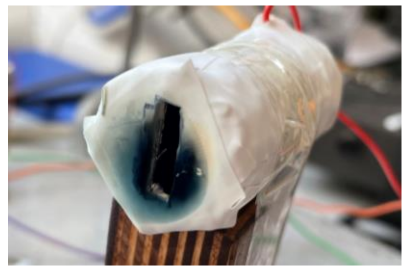
However, whenever we charged the anode to 6kV this caused background noise in the pico-ammeter. Therefore, we were unable to record any data when using the anode.

Faraday Cup

A faraday cup is a metal conductive cup designed to catch charged particles in a vacuum.
It was made from a copper tube that was wrapped in aluminum foil. Then it was wrapped using electrical tape. A rectangular aperture was cut into one end. A pico-ammeter was used to detect any current in the cup.

To reduce backscattering, the faraday cup was made so that the length was much greater than the width. This reduced the probability that electrons would bounce back out of the faraday cup.

As the cathode degraded, a blue substance was deposited onto the faraday cup. We believe this is a blue Tungsten Oxide.



The blue deposit on the faraday cup

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A New Hope

Data Collection and Analysis

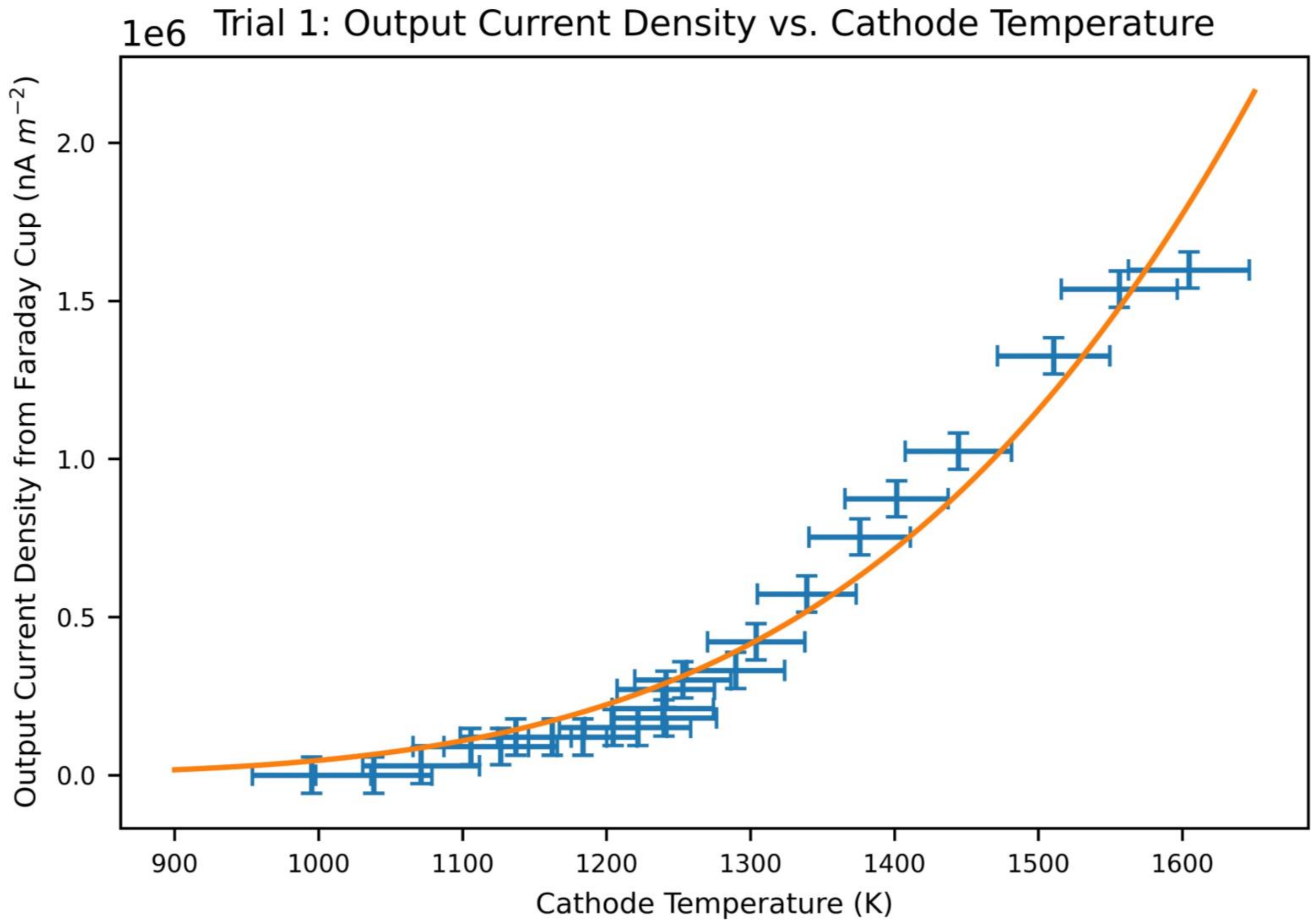
One set of results we were able to measure was when only using the cathode and faraday cup. We placed the faraday cup about 1mm from the cathode and got readings below 1nA.

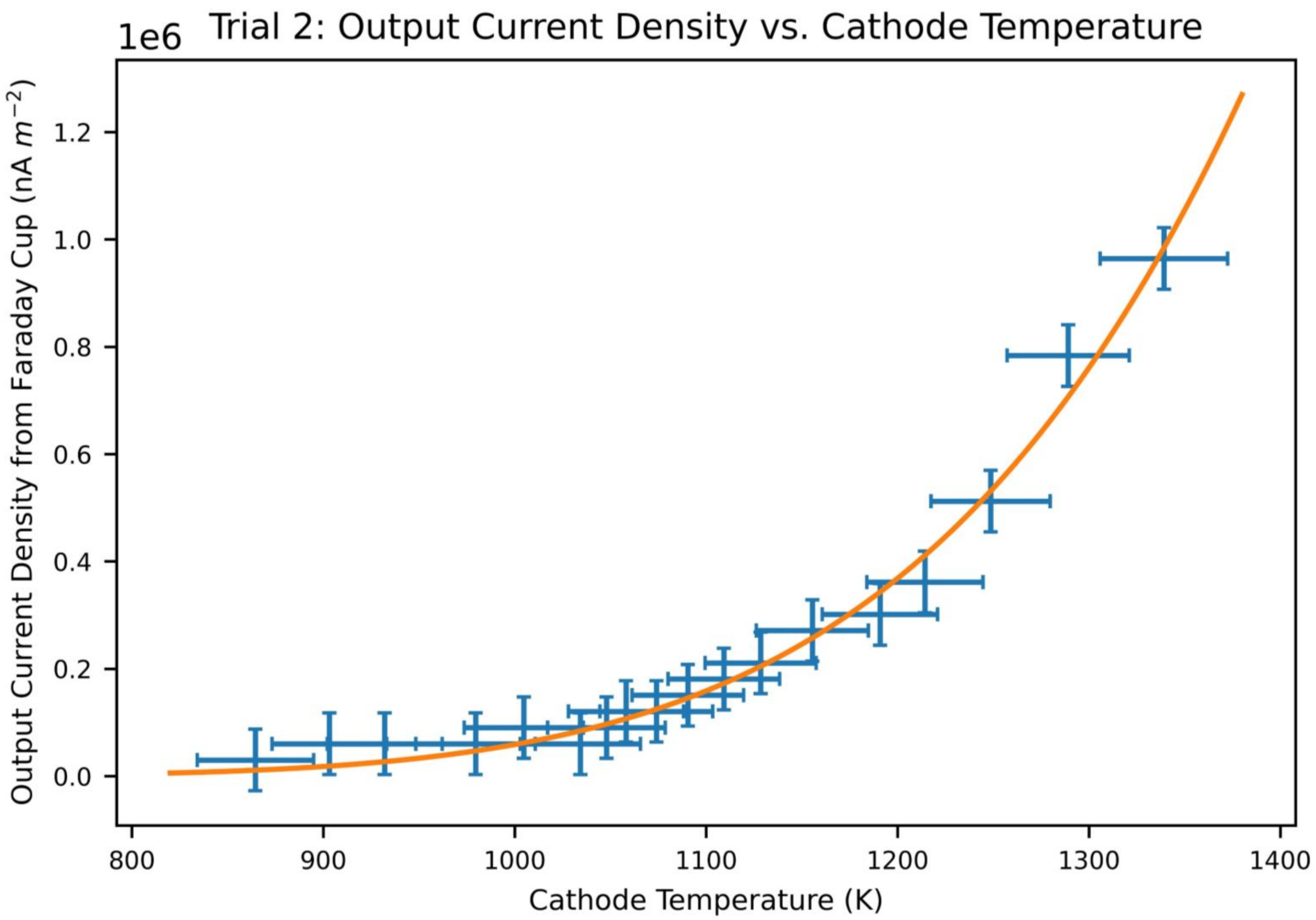
By measuring the cathode voltage and current we calculated its resistance, and from this the theoretical temperature of the cathode.

Each set of data was collected with a **different cathode** and the voltage was increased until the cathode burned out. Our power supply gave a constant voltage, over time the current dropped. We expect this due to the increase in temperature, which increases the resistance of the wire.

We plotted the emission current density (current per limiting area) detected at the Faraday cup against cathode temperature. We then curve fitted this against **Richardson's Law** to **interpolate experimental values of the scaling factor (A_G) and the cathode's work function (W).**

We used python to execute curve-fitting, which takes into account the measurement uncertainties.





Results and Conclusion

Quantities	Reference	Experimental 1	Experimental 2
$\boldsymbol{A_G}$ $(A\, m^{-2} K^{-2})$	$1.2 \cdot 10^6$	79 ± 17	$(5.1 \pm 3.1) \cdot 10^2$
$\boldsymbol{W}$ (J)	$4.17 \cdot 10^{-19}$	$(9.85 \pm 0.44) \cdot 10^{-20}$	$(1.21 \pm 0.11) \cdot 10^{-19}$

The experimental A_G value is roughly 4 orders of magnitude smaller than the reference, which was expected and caused mainly due to power loss in the circuit and limited coverage of the Faraday cup detector (most electrons went un-detected). The experimental mean work function values have **the same orders of magnitudes as the references** when rounded. Nevertheless, the reference work function values lies at approximately 7σ and 27σ from the experimental work function obtained from trial 1 and 2 respectively, indicating the existence of large systematic error(s). The random uncertainties in the experimental values propagate from the large fluctuations in the input and output current measurements, as well as minor fluctuations in the input voltage and uncertainties in the measurement of reference resistance at 20 °C.

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The Good, The Bad, & the Ugly

Issues with Our Experiment

One of the main set-backs in our experiment was the interaction between the electric fields produced by different components.

With only the cathode and faraday cup we measured emission currents of up to 1nA.
When we added the anode, we saw a new current of 20μA, this still appeared even when the cathode was off.

We later discovered that the connection of the 6kV line was sparking. This was solved by covering our connector in epoxy. Doing this reduced our background noise to about 20nA, however this still made our emission current undetectable.

During the experiment we designed multiple anodes in an attempt to reduce the noise. At first, we covered the anode in a dielectric material in order to hide the metallic surface of the anode (we used Blu-tac), this failed to reduce the noise. We then decided to use a negatively charged plate behind the cathode, which would 'push' the electrons away from it. This also failed. Another was to use two plates in a capacitor-like configuration, we hoped this would reduce the field strength near the faraday cup, to no avail.

Despite multiple attempts at solving this problem we were unable to find a way to reduce the noise to low enough levels and so we were unable to collect data while the anode was charged.

Improvements

One major way we could improve the experiment would be to reduce the variation of the cathode shape. As well as exploring different cathode geometries and better supporting structures.

We were never able to detect any emission current when using the anode. If given more time, we could try to get the experiment to work with the anode. Adding shielding between different components would reduce the effect of the electric field produced from nearby equipment.

Due to the time constraints, limited theoretical calculations were performed. During research we stumbled upon the SIM-ION software for predicting ion paths. This would allow us to determine the best sizes for components.

Our experiment was constructed very temporarily, ensuring proper alignment of the equipment would improve our experiment.

Using a better vacuum pump and chamber could reduce collisions during the electron flight path and would slow the speed of cathode degradation.

Looking Back

Looking back we believe that our group has worked together rather well, as we were already well acquainted before we began the project. This made working together much easier than usual.

One issue we faced was not getting into the lab early enough. This was because we left writing the risk assessment until later and so we missed some valuable lab time.

At the start of the project we planned to 3D print some holders for the equipment as well as a base. This turned out to be a waste of time and we ended up using wooden blocks, tape, Blu-tac, and hot glue to hold our experiment together. This allowed us much more freedom to change the dimensions of the experiment as we solved various problems.

Finally, our team would like to say a massive **Thank You!** to our project supervisor.