Investigating the Properties of an Electron Beam Produced from Thermionic Emission

Project Team Code: P3N

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Supervisor: Kenneth R. Long

***Abstract* – We attempted to generate a Maxwell-Boltzmann distribution of velocities of electrons produced by thermionic emission of thoriated tungsten. We planned to focus, accelerate, select velocities, and detect the electrons produced using a Wehnelt cylinder, anode, Wien filter, and a Faraday cup. Whilst we were unable to produce any data for the velocities due to the interaction between our components' electric fields, we were able to measure the relationship between cathode temperature and current density recorded, which followed Richardson's law.**

I. BACKGROUND

Our initial idea was to build a particle accelerator that can accelerate radiation from a radioactive source. We planned to produce electrons as this would require less energy compared to heavier substitutes such as the alpha particle. While researching about electron sources, we came across thermionic emission. We found that it would be both interesting and more in line with the practical spirit of our project to investigate the properties of this phenomenon (as thermionic emission allows us to better control electron intensity by varying the cathode temperature, providing a wider scope for collecting quantitative data). Therefore, we pivoted our aims to measuring the magnitude of an emission current produced from a 0.125mm Thoriated-Tungsten wire using devices made by ourselves.

During our first supervisor meeting with Prof. Kenneth Long, our discussion on the characterisation of electron beams led us to devise an extended goal of measuring the velocity distributions of electrons produced by thermionic emission of a heated conducting wire over a range of cathode temperatures. To enable this, we subsequently planned to build focusing, accelerating, and velocity filtering components.

To focus our beam, we created a Wehnelt cylinder, a negatively charged cylinder which would repel electrons into a beam. To accelerate the electrons, we adapted a positively charged metal disc with an aperture to allow electrons to pass through. A Wien filter, composed of Helmholtz coils and a set of parallel plates that create orthogonal electric and magnetic fields, was constructed to select different electron velocity ranges. A faraday cup was crafted to measure the current due to electrons produced in thermionic emission.

II. DESCRIPTION OF PROJECT WORK

A. Project start-up:

We began our project on 16/05/2022 and met our supervisor for the first time on the 19/05/2022 to put our accelerator idea against the test of professional insight, and to modify certain aspects of the project to plan a feasible yet practically challenging experiment. We met up an average of 3 times a week as a team and kept meeting our supervisor once a week. Each team-member kept a record of their research and contributions on a shared OneNote to track progress. We worked roughly 15-17 hours as a group each week with additional 1-2 hours each for individual research.

B. Splitting up the work within the group:

Once we had settled upon the basis of our experiment, we realised that the experiment consisted of four major parts: producing the electrons, focusing the electrons into a beam, filtering based on velocity and measuring the current. Each team member researched one of these parts (in the above order, HK, DSR, TSS, YS respectively).

C. Manufacturing Components:

At the start, DSR and TSS 3D printed mounts for all components. However, we quickly found that wood was much more flexible regarding changing distances and quicker to modify. Originally, we made our metal components (Wehnelt cylinder, anode, Faraday cup) out of aluminium, however we found it impractical to solder wires onto them. For the Wehnelt cylinder, HK and DSR were able to use a rivet gun to attach a wire. However, for the rest of the components, HK and YS re-made them with copper and used a heat gun to attach wires. TSS and HK constructed the Wien filter by wrapping copper wires around two aluminium parallel plates with a 3-D printed plastic structure (designed by DSR and TSS), which held the two parts apart and in place. We modified the vacuum chamber (with the assistance of lab technicians). Initially it had 5 wires capable of entering the chamber. We made another hole in the base of the chamber which we used to run six new wires to power all the aforementioned components.

D. Experimental Hurdles:

We encountered many setbacks during this project:

- We used the old connector to supply 6kV to the anode. However, the old connector had damaged wires and there was sparking between the wire and the metal base plate. We then used the new connector to supply the 6kV. However, there was no insulation between the metal pins so sparking occurred there. To solve this, DSR covered the pins in epoxy.
- When we charge to anode, its intense electric field would cause a large, unwanted current in the faraday cup. This was initially 10^6 greater than the signal we sought to detect. Many attempts were made to solve this, including TSS and YS replacing the anode with a set of parallel plates and HK and DSR insulating one side of the anode with blue tac to insulate its electric field, which together reduced the unwanted current by 10^4 times. However, we could not find an effective way of fixing this problem fully.
- We found that the current measured in the Faraday cup reduced drastically with its distance from the cathode, which made it unfeasible to mount the Wien filter in between the two components. We attempted to circumvent this issue by operating the cathode at its highest possible voltage of 8 V but failed to observe sufficient current.
- Over time, we saw degradation of the thoriated tungsten wire (cathode). A blue deposit was left on the Faraday cup and the Wehnelt cylinder. We believe this is a blue Tungsten pentoxide.
- Our cathode was held in position by suspending it between two horizontal copper rods. The wire was tied to each rod with a knot. We used a 3D printed triangular mould (made by DSR) to deform the cathode into a V shape in a repeatable fashion. However, the 0.125 mm diameter thoriated tungsten wires could not be bent fully to its ideal form. Furthermore, the cathode occasionally changed shape in the initial stages of heating, which meant that there were significant deviations in the cathode geometry.
- Another problem was ensuring the alignment of components. Alignment was done based on visual inspection. Given more time, a more rigorous method for alignment would improve the accuracy of results.
- During our research, TSS found a simulation program called SIMION, which would have helped better analyse these issues as well as anticipate. However, the cost of this program would have exceeded our limitations.

E. Adjusting the Objective:

Upon grappling with the above obstacles, we amended our main objective to testing the temperature dependence of the electron beam’s current density against cathode temperature. To do this, we aimed to interpolate the values of constants in Richardson´s law by fitting it to our data and comparing them to reference values (to evaluate our data´s validity and reliability). The new objective was chosen on the basis that the experiment could now be carried out without the anode and the Wien filter, which were the main contributors of unwanted background current and severe reduction in electron intensity.

F. Data Recording and Analysis

A pico-ammeter was employed to measure the current in the Faraday cup and two multi-meters were used to measure the voltage and current in the cathode (and thereby resistance). HK and DSR collected the data and HK carried out the data analysis in Python (numpy, scipy, matplotlib), which entailed calculating temperatures from variable cathode resistances, curve fitting, propagating uncertainty in quadrature, plotting graphs, and interpolating fit parameters.

G. Poster, Video, and Report

Every team member contributed roughly equal amounts to create the A1 poster, video, and this report (on a shared PowerPoint, iMovie, and a shared Word document respectively), where YS has contributed extensively by editing the video. As for the presentation, DSR finalised the theory section, TSS worked on the experimental set-up and calibration section, HK put together the data collection, analysis, and results section, and YS worked on the idea formation, issues, improvements, and acknowledgement sections. YS, using an iPad, also drew the component diagrams and pictures to go alongside them.

H. Purchased Equipment

The following items we purchased: (See page 9 for a full list of equipment)

- Thoriated Tungsten (Wire, W-14-WR-000300 [1]) - GBP 153.60:
  This was the material used to release the electrons that are then focused into an electron beam. We decided to use thoriated tungsten because it has a lower work function than tungsten, thus more electrons should theoretically be emitted through thermionic emission.

- A1 Poster - GBP 20.00:
  A visual A1 poster was professionally printed to assist with the exhibition days.

III. SUMMARY OF RESULTS

Due to the aforementioned issues with the anode, the only data we were able to collect was with the cathode and Faraday cup only. We placed the Faraday cup 1mm away from the cathode. We collected two sets of data, each from a different cathode. This was because, due to the poor vacuum, the cathode degraded and burnt out after approximately 5 minutes of operation. With these data, we aimed to verify the relationship between the current density due to the electron produced by thermionic emission and the cathode temperature. This was done by estimating the key parameters in Richardson's law by fitting curves to our data and comparing them against the reference values.

Our results are in agreement with Richardson's law, with one of the fitted parameters (work function of the cathode) lying within the same order of magnitude as the reference value. The measured scale-factor constant was significantly smaller than what theory predicts, which is in line with our expectation.

IV. CONCLUSION

We did not meet the main project goal of measuring the velocity distributions of an electron beam at varying temperatures. However, our initial objective of detecting current produced from the hot cathode, and the amended objective of verifying its temperature dependence (against theory) was met.

The currents produced by the cathode were very small (< 1 nA). The focusing, accelerating, and velocity-selecting components produced noise in the Faraday cup which was significantly greater than this value. This meant we were unable to collect any data whilst using these components.

There is significant scope for improvement with our project. Methods for isolating the electric field produced from various components shall be researched and implemented.

V. RISK ASSESSMENTS

Imperial College London

RISK ASSESSMENT AND STANDARD OPERATING PROCEDURE FOR FIRST YEAR UNDERGRADUATE PROJECTS

1. PERSON(S) CARRYING OUT THIS ASSESSMENT – The assessment should be carried out as a joint exercise between the student(s) and the supervisor.	
Name (Demonstrator/Supervisor)	Kenneth Long
Name (Student)	Hiroki Kozuki, Yaar Safra, Daniel Somerville Roberts, Thomas Stuart – Smith
Date	15/06/2022

2. PROJECT DETAILS – Delete building as applicable. You can fill in the room location once you know exactly where your project will be based.						
Project Name	Investigating the Properties of electrons from Thermionic emission				Project Code	P3N
Brief Description Of Project Outline	Initial aim: Investigate the velocity distribution of electrons produced via thermionic emission at varying temperatures/power. A cathode (thoriated tungsten) will be directly heated to trigger thermionic emission, and a positively charged anode will accelerate the electrons. A Wehnelt cylinder will be used to focus the electron beam. Electrons are emitted with a range of velocities and will be deflected by a Wien filter. A faraday cup will be used to measure current densities as different velocities will be separated by the Wien filter. From this, we aim to plot the velocity distribution of emitted electrons (velocity vs. current density). The distribution plot will be produced for varying input power and temperature of the cathode, and we aim to reach a conclusion that elaborates on their relationship. Modified aim: Determine the temperature dependence of the current density of electrons generated by thermionic emission from a hot thoriated tungsten cathode. Set-up will involve just the cathode and the faraday cup.					
Location	Campus	South Ken	Building	Blackett	Room	1st Year Labs

3. HAZARD SUMMARY – Think carefully about all aspects of your project and what your work could entail. Write down any potential hazards you can think of under each section – this will aid you in the next section. If a hazard does not apply then leave blank.			
Manual Handling	Careless handling of components when moving and calibrating may	Electrical	High voltage (~6 kV) AC/DC power supply used. May cause electric shocks if not properly isolated/insulated. High voltage

	cause them to break or inflict damage on the handler. These components include the vacuum chamber, high voltage power supply, chemical compounds in the cathode, and hot wires.		wires may cause sparking at the junction where wires enter the vacuum chamber. The probabilities of the accelerated electrons penetrating the glass chamber wall or producing secondary electrons are negligibly low due to the stopping power of the glass ($60 \sim 70\ MeV\ cm^2\ g^{-1}$) associated with its thickness ($5 \sim 10\ mm$ thickness with density of roughly $2.70\ g\ cm^{-3}$ giving $1.35 \sim 2.70\ g$ per $1\ cm^{-2}$ cross section. Hence stopping power across glass wall thickness is $81 \sim 189\ MeV$). This value is significantly greater than the expected energy of the emitted electrons ($\ll 1\ KeV$). Source: https://physics.nist.gov/PhysRefData/Star/Text/ESTAR.html
Mechanical	Hack saw will be used to cut copper cylinders to make the faraday cup and rods that supply current to the cathode. Uninformed use may lead to injuries (cuts) of the user and/or bystanders.	Hazardous Substances	Thoriated tungsten is mildly radioactive and carcinogenic when inhaled. May cause allergic skin reactions upon touching. Eating and drinking in the lab may cause poisoning.
Lasers	N/A]	Noise	Accidental implosion of the vacuum chamber would generate considerable sound. Vacuum pump produces low frequency noise when operating, which may cause minor inconveniences such as making voices hard to hear.
Extreme Temperature	Cathode (thoriated tungsten) will be heated to high temperature. May overheat and damage components, as well as inflict burns if not careful.	Pressure/Steam	Vacuum chamber with fractures may implode. May cause glass splinters and cuts. Severe damage may be dealt in the worst-case scenario.

	As a part of making our own equipment, we will need to **solder** metals together (soldering rod reaches roughly 400 °C and a heat gun 550 °C). For associated hazard risks and mitigations/solutions, refer to SOLDERING.pdf		
Trip Hazards	Potential risk of tripping over bags, as well as wires and cables connecting power supply to outlet.	Working At Height	Vacuum chamber may fall off the work-table if unstable or while carrying if there are any trip hazards.
Falling Objects	Vacuum chamber may fall off the work-table if unstable or while carrying if there are any trip hazards.	Accessibility	Vacuum chamber will be sealed off and any accidents that happen inside cannot be dealt with until chamber interior is pressurised to STP.
Other			

4. CONTROLS – List the multiple procedures which you may carry out during your project along with the controls/ precautions that you will use to minimise any risks. Remember to take into consideration who may be harmed and how – other people such as students, support staff, cleaners etc will be walking past your experimental setup even when you aren't around.	
Brief description of the procedure and the associated hazards	**Controls to reduce the risk as much as possible**
1. Setting up the vacuum chamber using a vacuum pump. Accidental fractures in the vacuum chamber may cause implosion due to pressure differential. Associated hazards are glass splinters (with risks of skin, eye, and respiratory damage) and exposure to harmful material inside the chamber (e.g., high voltage discharging plates, hot cathode, and carcinogenic Nickel/Barium oxides). Unstable positioning of the chamber may cause in to fall and break. People at risk are anyone within the range of flying glass.	1. Discuss with lab technicians whether the proposed experiment is viable to conduct inside the vacuum chamber. The glass container will be examined beforehand for small faults and fractures. The vacuum chamber and other lab equipment will be placed on a spacious and sturdy base. Metallic or plastic shield shall be placed around the chamber to block flying glass in case it implodes. Wear protective gears including safety goggles, lab coats, and gloves. Avoid wearing open shoes, short sleeves, and

2. Providing power to the cathode via high voltage AC supply (~6 kV). Unsecured connections and loose wires may cause electric shocks and sparks. Too high a voltage may also create plasma inside the vacuum chamber, which may damage components inside the chamber, as well as impose risk of accidents such as implosion. People at risk are anyone near the circuit where high voltage is set up. Overloading may melt the nickel oxide cathode, which may damage the set-up and potentially inflict burn on anyone who touches the cathode before letting it cool. 3. Thoriated tungsten is mildly radioactive and irritating to the skin. Will cause severe damage if it gets into the eye. Eating food with hands after touching the material may cause respiratory problems. They are also slightly carcinogenic. People at risk are anyone who touches the material. 4. Hack saws, when used without supervision and correct knowledge for operation, may inflict severe damage (cuts) on the users and/or bystanders in proximity. 5. Wires and cables will be used to provide current to heat the cathode. Disorganized wires may become trip hazards which could lead to more severe accidents such as dropping and breaking the vacuum chamber and getting electrocuted/burnt. People at risk are anyone passing nearby the experimental set-up. 6. Bags may become trip hazards if not properly put away under the table or if placed in the open. Tripping on bags could lead to broken instruments and injury. People at risk are anyone walking near the bags. 7. Fragile pieces of equipment may be damaged during transport and calibration and may result in injuries	short pants. Follow the lab protocol as instructed by lab technicians. 2. Current will be kept small such that accidental electrocution will not result in severe injury (we will decide on the range of operating current and voltage with the supervisor and lab technicians to keep them low enough to prevent plasma forming.) Voltage will be raised gradually to preserve the lifetime of the cathode as well as to avoid sudden surge in power input. Rubber gloves may be worn to diminish electric shock and prevent severe burns if anyone touches the hot cathode (we will generally not touch it until it cools down to roughly room temperature.). 3. We will thoroughly examine with our supervisor and lab technicians the feasibility of coating/doping the cathode with barium oxide safely. The substance will be stored in a well-sealed container with sufficient thickness to block small amounts of radiation emitted by barium oxide. Safety goggles, gloves, lab coats, and masks will be worn when dealing with barium oxide powder. We will ensure not to spill any of these chemicals during transportation and set-up. 4. Hack saws will always be used under the lab technicians' supervision. 5. Wires will be bundled and kept away from pathways. 6. Bags will generally be left in the lockers or safely put away under the worktable where they would not obstruct people traversing the lab. 7. General care will be taken in moving lab equipment and calibrating them gently. We will conduct the experiment under supervision by each other and the lab technicians.

from glass pieces, electric shocks, and implosion. 8. Soldering involved dealing with high temperature rods and melted metals, as well as harmful fumes. Consult SOLDERING.pdf for detailed risk assessment on soldering (including hazard risks and solutions).	

5. EMERGENCY ACTIONS – What to do in case of an emergency, for example, chemical spillages, pressure build up in a system, overheating in a system etc. Think ahead about what should be done in the worst case scenario.
In the case of emergency, turn off the power supply, undo the vacuum, and shut down the experiment. Evacuate the lab and call the lab technicians. If the situation is severe or a person is injured, call emergency service through Imperial's security office (4444 from internal phone or 020 7589 1000 form a mobile). More specifically, in the case of exposure to chemicals, rinse off the chemicals in the nearby sink or shower. If vacuum chamber is malfunctioning, pause the experiment and examine the container and the vacuum pump for faults. If an instrument brakes, call the lab technicians and order a replacement. Be ready to leave the lab anytime. Good communication among group members is essential.

6. TRAINING RECORD – As your project work evolves your experimental strategy/procedures may change. Therefore, it is important that you review this risk assessment on a weekly basis and update it as necessary. Please sign and date below to indicate that all person(s) have been trained in this risk assessment and associated procedures.		
Names (Supervisor + Students)	Sign	Date
Kenneth Long, Hiroki Kozuki, Yaar Safra, Daniel Somerville Roberts, Thomas Stuart-Smith.		15/06/2022

VI. EQUIPMENT LIST:

We purchased a roll of thoriated-tungsten wire, diameter 0.125 mm, length 5 m, to be used as the cathode from which electrons were produced.

Supplier: goodfellow.com (https://www.goodfellow.com/uk/en-gb/displayitemdetails/p/w-14-wr-000300/thoriated-tungsten-wire).

Price: GBP 153.60 (including 20% VAT)

Remaining pieces of equipment were made or readily available at the 1st year lab and workshop:

- Two copper rods, diameter 12 mm, length 120 mm
- Wooden Blocks, various sizes
- 25mm diameter aluminium rod, lathed into a cylinder
- Copper disc, 2 mm thick, 25 mm diameter with 4 mm diameter hole at centre
- Aluminium plates, 2 mm thick, 30 x 60 mm
- Copper wire, 1 mm diameter
- 3D printed base plate for Wien filter, made from PLA
- Faraday cup, made from copper pipe, aluminium foil, and electrical tape.
- Insulated 0.58 mm diameter copper wire
- Electrical connect, covered in epoxy
- Vacuum chamber and pump
- High current power supplies (10 A)
- High voltage power supply (6 kV)
- Bench power supply
- Pico-ammeter
- Multi-meter
- Gaussmeter
- Blu-tac, for holding components together and insulating the anode.

VII. BIBLIOGRAPHY:

[1] A. L. Reimann, Thermionic Emission, London: Chapman & Hall ltd., 1934.

A reference book which contains a good introduction to thermionic emission and derivations of Richardson's law.

[2] Kimball Physics Inc., "Tungsten Filaments: Hairpin Thermionic Emitters," [Online]. Available: https://www.kimballphysics.com/downloadable/download/sample/sample_id/1285/.

A datasheet of a commercially available hairpin tungsten filament, we based our cathode of this design.

[3] O. R. Battaglia, C. Fazio, I. Guastella and R. M. Sperandeo-Mineo, "An experiment on the velocity distribution of thermionic electrons," American Journal of Physics 78, pp. 1302-1308, 2010.

An undergrad experiment exploring thermionic emission. However, this uses a radial based design and retarding potentials. We didn't use either of these methods.

[4] *C. E. Sosolik, A. C. Lavery, E. B. Dahl and B. H. Cooper, "A technique for accurate measurements of ion beam current density using a Faraday cup," Review of Scientific Instruments 71, pp. 3326-3330, 2000.*

Publication elaborating the operation and calibration of Faraday cup to measure ion beam properties. From this paper, we obtained the inspiration to use a Faraday cup to measure the current from our electron beam.

[5] *S. D. Walck, "Poor Man's Faraday Cup," Microscopy Today Vol. 3 Issue 8, pp. 12-13, 1995.*

A short article which shows how to build a Faraday cup on a small budget. We based our Faraday cup design on this.

[6] *P. G. C. Valencia, "Electron Beam – Specimen Interaction," 24 August 2006. [Online]. Available: https://academic.uprm.edu/pcaceres/Courses/CHAMINA/HO5.pdf.*

Lecture slides which contain information of the penetrating ability of electrons. Due to the low depth, there is little risk of electrons leaving the vacuum chamber.

[7] *C. Ray, "Focusing Cathode Rays," Wireless World, pp. 133-137, 1954.*

An old article which explores the theorical methods of focusing cathode rays. We used this when designing our focusing equipment.

[8] *G. E. Smith, "J. J. Thomson and The Electron: 1897–1899 An Introduction," THE CHEMICAL EDUCATOR, 1997.*

A historical exploration of J. J. Thomson's 1997 paper on the discovery of the electron. There are significant overlaps between his experiment and what we would like to achieve. Although he only used a magnetic field whereas we used both electric and magnetic.

[9] *J. Lederer, "Electron Beam Dispersion Compensator Using a Wien Filter," University of Nebraska, 2021.*

Honour thesis elaborating on the theory, design, and calibration of a Wien filter, which utilises perpendicular magnetic and electric fields to focus an electron beam. Was consulted for Wien filter construction and equations of motion of electrons while in the filter.

[10] *R. Beiranvand, 2013. Analyzing the uniformity of the generated magnetic field by a practical one-dimensional Helmholtz coils system. Review of Scientific Instruments, 84(7), p.075109.*

Paper investigating the uniformity of magnetic field produced by a Helmholtz coil. We referred to this paper when designing and calibrating the Wien filter, which incorporates two Helmholtz coils.

[11] *Ipc.org. 2022. IPC-TM-650 TEST METHODS MANUAL. [online] Available at: <https://www.ipc.org/sites/default/files/test_methods_docs/2.5.4.1a.pdf> [Accessed 10 June 2022].*

Manual for characterising the properties of printed conductor materials, in particular, the temperature dependence of current flowing through the material. The variable resistance formula featured in this manual was used to calculate the temperature of the cathode at different resistance values.

[12] Engineeringtoolbox.com. 2003. Resistivity and Conductivity - Temperature Coefficients Common Materials. [online] Available at: <https://www.engineeringtoolbox.com/resistivity-conductivity-d_418.html> [Accessed 10 June 2022].

Website with a list of resistivities and temperature coefficients of resistance at 20°C for a range of materials. We referred to this website to determine the above values for pure tungsten, which were then used to determine the reference resistance of the thoriated tungsten cathode.

[13] P. Lulai, 2001. Determination of Filament Work Function in Vacuum. [online] Avs.org. Available at: <https://avs.org/AVS/media/Files/Education/SEW/vossenwinner01.pdf> [Accessed 20 May 2022].

A paper aimed at determining the work function of thoriated tungsten filament in a vacuum. We referenced the theoretical work function of thoriated tungsten (2.6 eV) alloy from this paper.

[14] L. van Dommelen, 2022. *6.15 Thermionic Emission*. [online] Web1.eng.famu.fsu.edu. Available at: <https://web1.eng.famu.fsu.edu/~dommelen/quantum/style_a/cboxte.html> [Accessed 15 June 2022].

Website detailing the physics of thermionic emission. We referenced the theoretical scale factor value in Richardson’s law from this website.