Scanning Electron Microscopy (SEM)

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Date of experiment: 23 and 24/11/2020
Date of submission: 30/11/2020

Abstract

The main conceptual goal of this experiment was to see how homogeneous magnetic field could focus a thermally generated electron beam in a teltron tube to a target. One quantitative application was to measure the specific charge of electron by recording current through a pair of Helmholtz coils versus voltage across the tube at different radii of the circular electron path. The result was $(1.769 \pm 0.022) \cdot 10^{11}$ C/kg, coinciding with the theoretical electron specific charge $1.759 \cdot 10^{11}$ C/kg. A more qualitative application was to focus an electron beam in a scanning electron microscopy (SEM) to record images of metal samples with magnification around 200-700. When the magnification got to a few thousands, the SEM gave blurry images.

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1 Introduction and Theoretical Background

As a hot tungsten filament is heated, it can thermally generate electrons to be accelerated and gain kinetic energy afterwards thanks to a potential difference in a Wehnelt cylinder. The voltage U across the tube will therefore dictate the electron beam velocity. An almost homogeneous magnetic field $\vec{B}$ which is aligned perpendicular to the electron velocity $\vec{v}$ will then generate a Lorentz force that balances the centrifugal force and bends the trajectory of the electrons into a circular path with radius r. The current I through the Helmhotz coils will govern the magnetic field magnitude generated by those coils. Finally, a quadratic relation can be established between the tube voltage U and the Helmhotz coils' current I:

$$U = \left[\frac{1}{2} \cdot \frac{e}{m_e} \cdot r^2 \cdot \left(\frac{4}{5}\right)^3 \cdot \frac{\mu_0^2 \cdot n^2}{R^2}\right] \cdot I^2 = k \cdot I^2 \tag{1}$$

where e is electron charge, m_e is the mass of one electron, r is the radius of the electrons' circularly bent orbit, $\mu_0 = 4\pi 10^{-7}$ H/m is the vacuum permeability, n is the number of Helmhotz coils, and R is the radius of those coils. Grouping together all the terms in the coefficient of I^2 as the slope k obtained from linear regression of U versus I^2, the specific charge of electron $\frac{e}{m_e}$ can be determined as

$$\frac{e}{m_e} = \frac{125}{32} \cdot \frac{R^2}{r^2 \cdot \mu_0^2 \cdot n^2} \cdot k \tag{2}$$

The literature value of electron specific charge is $\frac{e}{m_e} = 1.759 \cdot 10^{-11}$ C/kg.

When the principle of focusing an electron beam to a target distance by homogenous magnetic field is applied in scanning electron microscopy (SEM), a metal or metal-coated sample might be observed with a higher magnification factor than an optical microscope because electrons have a much shorter wavelength than visible lights and therefore gives a much higher resolution. Another advantage of SEM according to PVEducation is that although an electron beam cannot record color, it can show the depth and the inner structure of the sample whereas light in optical microscopes could only focus on a narrow part of the sample near the surface.

According to Goldstein et al. (2003), typical operations of an SEM include five stages. Firstly, the whole microscope column is evacuated with rotary and diffusion pumps connected to its bottom. Secondly, after sufficient vacuum is achieved, a filament is heated so that an electron gun can produce and accelerate electrons to energy levels of 0.1 - 30 keV. Thirdly, to sharpen the beam, the spot size is reduced to the sample spot size (around 10 nm) using electromagnetic electron lenses. At this stage, astigmatism (unequal focus in different directions and subsequent stretching of the image) due to local variation in magnetic field may occur and can be corrected by stigmator. Fourthly, two pairs of scan coils deflect the beam away from and then back to the perpendicular axis. By changing the deflection level (and therefore the length of the raster on the sample), the magnification factor can be adjusted. Fifthly, a detector with a positive bias grid attracts back-scattered and secondary electrons for signal analysis. A higher number of collected electrons will generate a brighter image. In some SEM devices, an additional X-ray detector collects released X-rays to study the characteristic of the sample material.

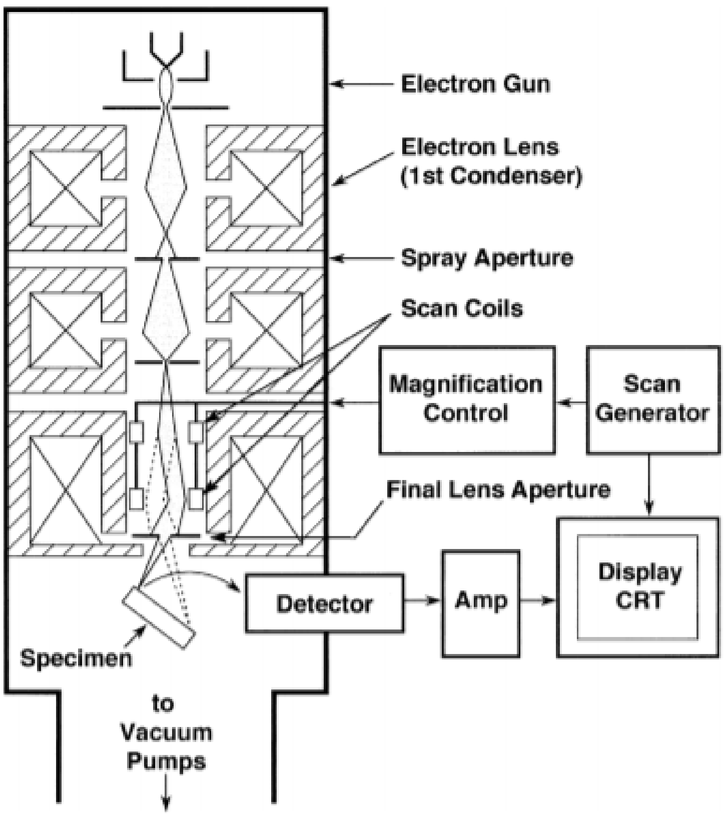

Figure 1: Sketch of typical components in SEM column (Goldstein et al., 2003)

2 Experimental Set-up and Procedure

2.1 Determination of specific charge of electron

The figure below showed the overall set-up for a teltron tube and a pair of $n = 154$ Helmholtz coils with radius $R = 0.2 \pm 0.005$ m appropriately connected to the power supplies and two digital multimeters for current and voltage measurement.

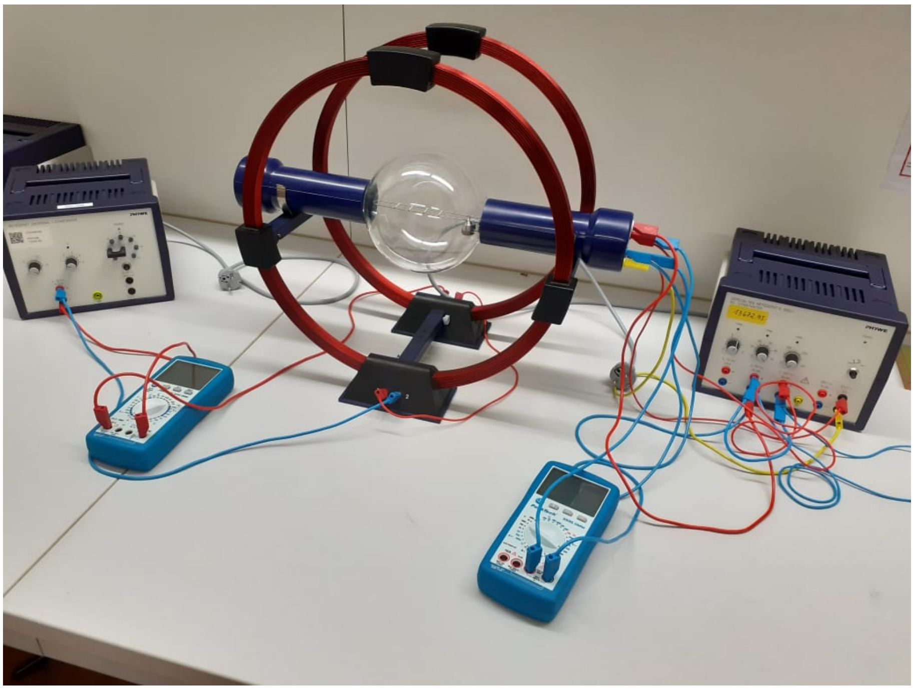

Figure 2: Overall Set-up for electron specific charge measurement

Particularly, wiring connection was showed separately for the Hemlholtz coils and the teltron tube in the two circuit diagrams put together into one figure below.

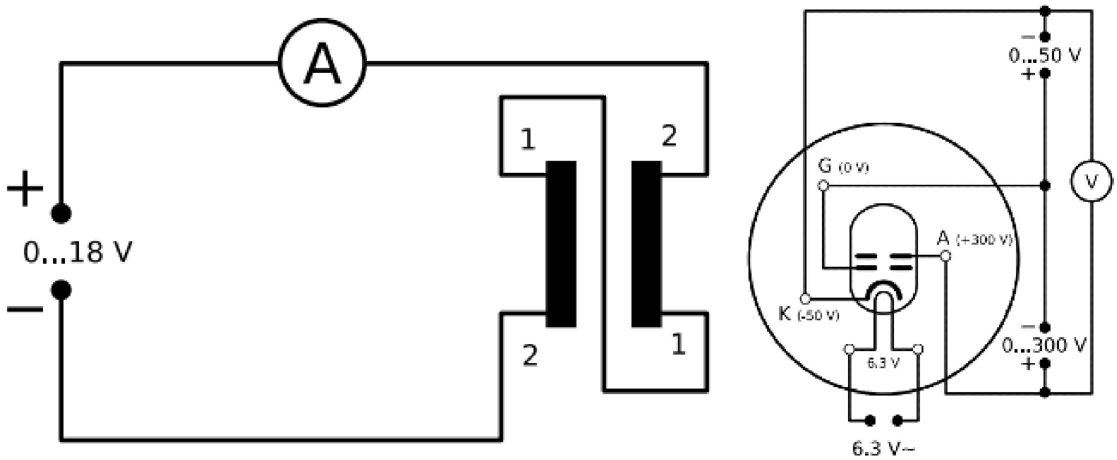

Figure 3: Circuit diagram for Helmholtz coils (left) and beam tube (right)

Once the circuits were completed, all other light sources in the room were turned off and measurements were conducted for a current range of 1-4 A and a voltage range of 156-356 V. Initially, the electron beam trajectory had a helix shape. By slightly rotating the tube around its horizontal axis, a circular path was achieved and maintained throughout all measurements. The strategy was to first fix a voltage across the tube, then vary the current through the Helmholtz coils and finally record the current and voltage values each time the circular trajectory coincided with one of the four luminous bars, which marked a radius value of 0.02, 0.03, 0.04 and 0.05 m. The same procedure was applied for several voltages. Lastly, all voltage versus squared current values were reorganized into data sets according to the trajectory radius at which they were recorded for later linear regression.

2.2 Investigation of samples with SEM

An overall outlook of the SEM used in this experiment was provided below.

Figure 4: Outlook of the SEM

First of all, water cooling was activated with a flow meter speed of 2 rounds per second. The rotary and diffusion pumps (RP and DP buttons) were then turned on until a vacuum level in the green region was achieved and the green lamp (V.L.) lighted up. The high voltage supply was then activated and the emission current control knob was slowly adjusted to the range where a clear image could be generated without overheating the filament. Further optimization was made regarding the spot size, the magnification, the X- or Y- positions of the object, and the rotation drive. For each sample exchange, the emission current was stopped and the chamber was evacuated again. Among observed samples, images of Sample 8 at magnification factors ranging from 100 to 3000 were included in this report.

3 Results and Error Analysis

3.1 Determination of specific charge of electron

The measured curves of voltage versus squared current at four different trajectory radii could be illustrated in the figure below. The fitted line for each curve was obtained from linear regression of the respective measured data set with the origin (0,0) since the theory implied that each curve should pass through the origin.

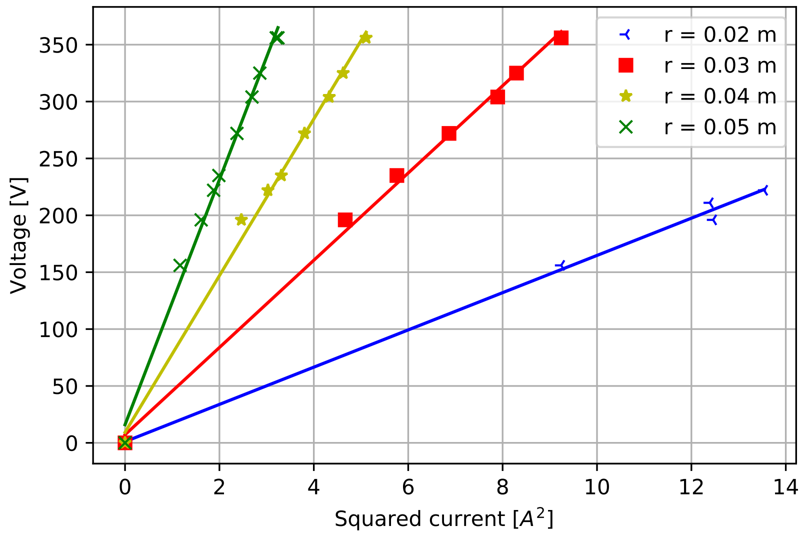

Figure 5: Voltage versus squared current for different trajectory radii

The specific charge value for electron obtained from the slope k of linear regression for each radius was summarized in the table below.

Table 1: Linear regression slope and specific charge for each trajectory radius

Radius r (m)	Slope k [V/A^2]	Specific charge e/m_e [C/kg]
0.02	16.4 ± 0.7	$(1.707 \pm 0.079) \cdot 10^{11}$
0.03	38.3 ± 1.0	$(1.777 \pm 0.063) \cdot 10^{11}$
0.04	68.9 ± 2.1	$(1.796 \pm 0.070) \cdot 10^{11}$
0.05	107.7 ± 3.0	$(1.798 \pm 0.068) \cdot 10^{11}$

Taking the average of those four specific charge values and the (statistical) error of the mean, the final electron specific charge value obtained from this experiment was $(1.769 \pm 0.022) \cdot 10^{11}$ C/kg, which coincided with the theoretical value $1.759 \cdot 10^{11}$ C/kg within its range of uncertainty.

3.2 Investigation of samples with SEM

Although a circular electron path was useful in determining the electron specific charge, in the second part, a helical electron path could be controlled by magnetic lenses in an SEM to hit different regions of a sample. Photos of Sample 8 were taken in front of the SEM screen for magnification factors between 100 and 3000.

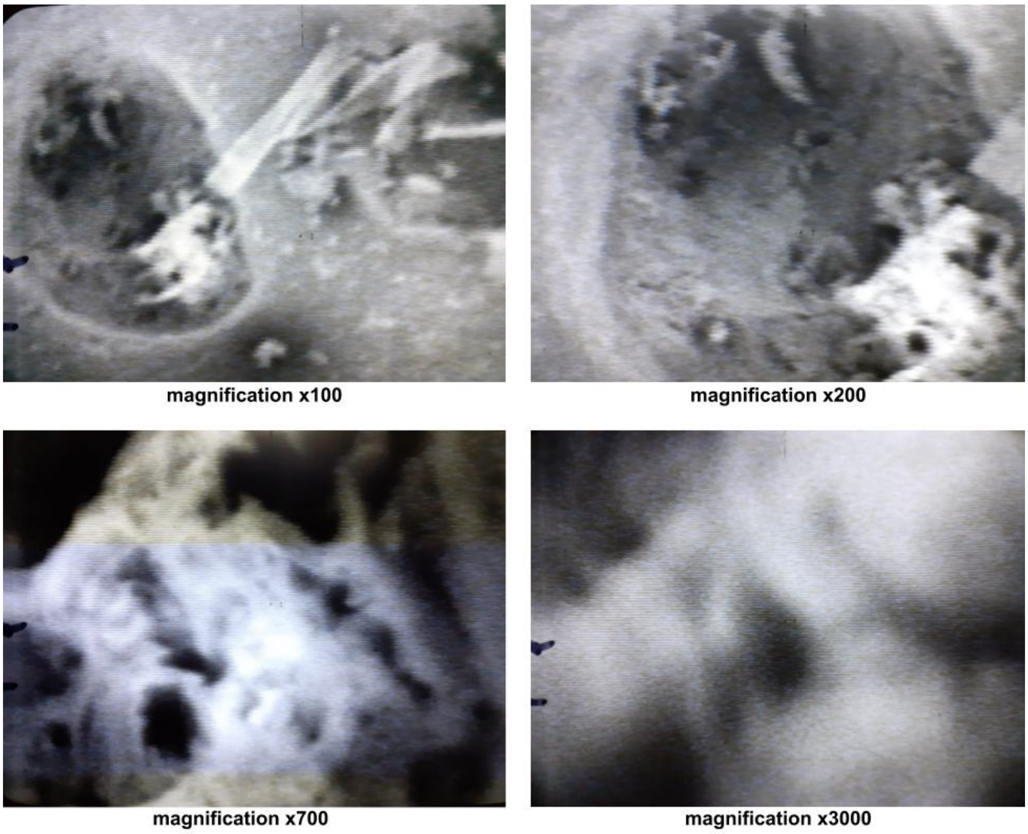

Figure 6: Sample 8 with SEM magnification factors between 100 and 3000

The figure showed that this SEM achieved the best resolution for Sample 8 at a magnification level between 200 and 700. When the magnification level got too high (around 3000), the image got much more blurry.

4 Discussion and Conclusion

The two main stages of this experiment were closely linked together as the first stage demonstrated how magnetic field could control the trajectory of an electron beam to hit a certain target while the second stage applied that principle with a helix electron beam in an SEM to observe real samples. Quantitatively, the experimentally measured specific charge of electron in the first stage was $(1.769 \pm 0.022) \cdot 10^{11}$ C/kg, agreeing with the literature value of $1.759 \cdot 10^{11}$ C/kg. The captured images of Sample 8 in the second stage showed that the SEM gave the best image quality at a magnification range around 200 and 700. Although the SEM produced images with more depth than a typical optic microscope thanks to the low electron wavelength compared to visible light wavelength, when the magnification factor went to the order of a few thousands, the image got too blurry. Maintenance of the SEM may improve the image quality in future experiments.

References

[1] Materny, A., Jovanov, V. (2020). Advanced Physics Lab I, CO-486-A.

[2] PVEducation. SEM and EBIC. Retrieved from https://www.pveducation.org/pvcdrom/characterisation/sem-and-ebic

[3] Goldstein, J. I., Newbury, D. E., Michael, J. R., Ritchie, N. W., Scott, J. H. J., Joy, D. C. (2003). Scanning electron microscopy and X-ray microanalysis.