
1 Total Current Spectroscopy

1.1 Description of Method

TODO: Put in "Experimental Methods" section

In Total Current Spectroscopy experiments, a current of primary electrons I_1 is directed at a target surface. Upon interacting with the surface, the primary electron beam is split into two components; the transmitted current I , and the secondary electron current I_2 . The current of secondary electrons includes all electrons emergent from the surface, regardless of origin. Generally I_2 includes components formed from elastically and inelastically scattered primary electrons, as well as electrons originating from bound states which have gained sufficient energy to leave the surface.

For any given mechanism behind the origin of an electron in I_2 , there is an associated "threshold" primary electron energy which must be exceeded before the process can occur. As a result, measurement of changes in I_2 as a function of primary electron energy E_1 provides a very sensitive means to characterise properties of the sample under bombardment. The energy E_1 of primary electrons is controlled by adjustment of the potential U .

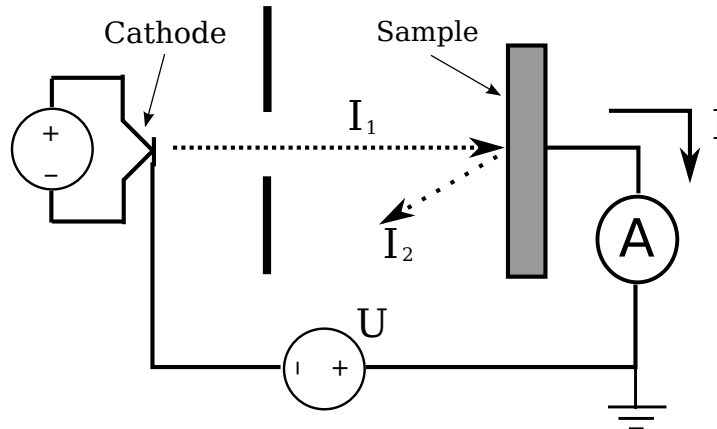


Figure 1: A simplified schematic of Total Current Spectroscopy Experiments

Figure 1 shows a simplified schematic for a Total Current Spectroscopy experiment ¹. When a current is passed through the cathode, electrons are thermionically emitted with a distribution in initial velocities. A series of electrodes (an electron gun) creates a potential which focuses the emitted electrons into a beam and accelerates them towards the target. The transmitted current I can be detected external to the vacuum chamber using a conventional DC ammeter².

The total current spectrum (TCS) is defined as:

$$S(E_1) = \frac{dI}{dE_1} = -\frac{dI_2}{dE_1}$$

This result assumes that the primary electron current I_1 is constant. Such an assumption is valid if the cathode has reached thermal equilibrium, and the potential due to the sample can be considered to have negligible effect on the focusing properties of the electron gun.

¹For a more detailed description of the experimental setup, refer to Appendix ??

²It is also possible to use lock-in amplifier techniques for noise reduction [1]. In this study, the DC ammeter has been used due to the relative simplicity of the measurement and control circuit.

The experimental goal of Total Current Spectroscopy is the measurement of $S(E_1) \propto \frac{dI_2}{dE_1}$. More information on the experimental setup and techniques are presented in Appendix ???. The remainder of this section will give an overview of concepts needed for relating $S(E_1)$ to properties of a sample.

1.1.1 Theory of Signal Formation in Total Current Spectroscopy Experiments

Here we will summarise the approach of Komolov [1] in constructing a theory relating $S(E_1)$ to scattering events within the target surface.

A single electron arriving at the sample has energy $E = eU + c$, where e is the electron charge, U is the potential applied between the cathode and sample, and c is a constant which includes the electron's energy relative to the sample when emitted. The minimum value for c is the contact potential of the cathode relative to the sample.

At the cathode, electrons are emitted with a distribution in energies about some mean value. A realistic model should take into account this distribution.

If the primary electrons are incident perpendicular to the surface, then we can write I as an integral over the whole distribution of energies:

$$I(E_1) = eA \int_0^\infty f(E - E_1) dE$$

where $f(E - E_1)$ is the distribution for an electron of energy E arriving at the surface. Generally $f(0)$ (ie: $E = E_1$) is the maximum of f .

TODO: Discuss angular distribution of incident electrons, due to focusing of electron gun?

To formulate a general expression for the secondary current, we introduce a cross section $\sigma(E)$, which gives the probability for a primary electron of energy E to give rise to a secondary electron (of any energy $E_2 \leq E$).

Then the total current of secondary electrons is:

$$I_2(E_1) = eA \int_0^\infty f(E - E_1) \sigma(E) dE$$

Using $I = I_1 - I_2$, and $S(E_1) = \frac{dI}{dE_1}$, it is straight forward to arrive at a general expression for the total current spectrum [1]:

$$S(E_1) = eA \left\{ [1 - \sigma(0)] f(-E_1) + \int_0^\infty f(E - E_1) \frac{d\sigma(E_1)}{dE_1} dE \right\}$$

All E_1 dependence in the first term is due solely to the distribution of primary electrons. It is clear that this term is maximised when $E_1 = 0$ with respect to the sample; ie: the contact potential between the cathode and sample is zero.

The second term contains dependence upon $\frac{d\sigma(E_1)}{dE_1}$. As E_1 is increased past the threshold for a particular interaction, $\sigma(E_1)$ will undergo a sharp change. This corresponds to a narrow maxima or minima in the derivative $\frac{d\sigma(E_1)}{dE_1}$. A corresponding maxima or minima will appear in $S(E_1)$, centred about the threshold for the interaction. The convolution with the primary electron distribution $f(E - E_1)$ has the effect of broadening and lowering these peaks; in other words, the resolution of Total Current Spectroscopy is limited by the distribution of primary electrons.

The (unphysical) case of a mono-energetic beam is equivalent to setting $f(E - E_1) = \delta(E - E_1)$. In this case, the integrals in the expressions for I and I_2 collapse, and the resulting total current spectrum is:

$$S(E_1) = \frac{dI}{dE_1} = eA \frac{d}{dE_1} (1 - \sigma(E_1)) = eA \frac{d\sigma(E_1)}{dE_1}$$

TODO: Include model for σ

1.2 Results

TODO: Put in "Results and Discussion" section

1.2.1 Data Analysis

NOTE: The below sections will be put into appendices. For now I have kept them with the other TCS information for completeness

1.3 Electron Optics

There are two goals of electron optics as applied to total current spectroscopy (and other forms of electron scattering experiments): firstly, to produce the narrowest possible distribution $f(E - E_1)$ of primary electron energies at the sample, and secondly, to ensure that

The electron gun used for this study contains a total of ten electrodes, with six independently adjustable groups. Figure 2 illustrates a cross section of the gun, using colour coding to indicate groups of electrodes which are kept at the same potential.

The important electrode groups are, in order from left to right:

1. Wenhalt Cylinder

The first electrode, which houses the cathode, providing a narrow aperture for electrons to exit. A positive potential (of the order of 10V applied to the Wenhalt causes electrons leaving the cathode to be accelerated into a narrow beam.

It is difficult to control the focusing properties of the gun using the Wenhalt alone; the main purpose of the Wenhalt is to create a high current, narrow beam of electrons, which can be focused by the other electrodes in the gun. If the potential applied to the Wenhalt is too high, electrons will be drawn into its surface. If the Wenhalt potential is too low, then the

2. Einzel Lens

The six central electrodes are an example of an Einzel lens, used for acceleration and focusing of the electron beam. The first and last pair of electrodes are held at a large positive potential, causing electrons to accelerate. A smaller potential (often negative, but not necessarily) applied to the central pair of electrodes has the effect of altering the angular dispersion of the beam.

3. Deflection Plates

Unequal potentials applied to the deflection plates can be used to bend the direction of the electron beam. To ensure the accelerating potential seen by the electrons is as uniform as possible, the deflection plates are biased at potentials of $\frac{V_d}{2} \pm V_a$, with V_d determined by the controlling power supply. When $V_d = 0$, the beam is undeflected.

4. Final Electrode

The electron gun was originally designed for use in a Cathode Ray Oscilloscope (CRO). This electrode is held just in front of a fluorescent screen, but is not electrically connected to the screen. When accelerated electrons strike the screen, they are

In the total current spectroscopy experiments, this electrode is typically at a much higher potential than the surface under bombardment. As a result, low energy primary electrons may be deflected or even turned back towards the gun, rather than striking the surface. This effect can be exploited to narrow the energy distribution of primary electrons at the surface, but also has the effect of greatly reducing the current of primary electrons reaching the surface.

In preparation for Total Current Spectroscopy experiments, the effect of each of the controllable potentials was investigated by focusing the electron gun on its original fluorescent screen. However, when repurposed for total current spectroscopy, the gun needed to be refocused several times (with changing sample holder design).

From 1.1.1, it is apparent that the electron gun should be focused to achieve the maximum possible resolution by producing the narrowest possible primary energy distribution at the target. In addition, to increase the energy range (relative to the target), it

The gun was focused using an iterative process, by which each potential was altered in turn to maximise the current.

1.3.1 A two dimensional electron gun simulation

The below figures 2 and 3 are the results of a simplistic electron gun simulation. The results of this simulation were not used to focus the actual electron gun; the images shown here are purely presented as a visual aid.

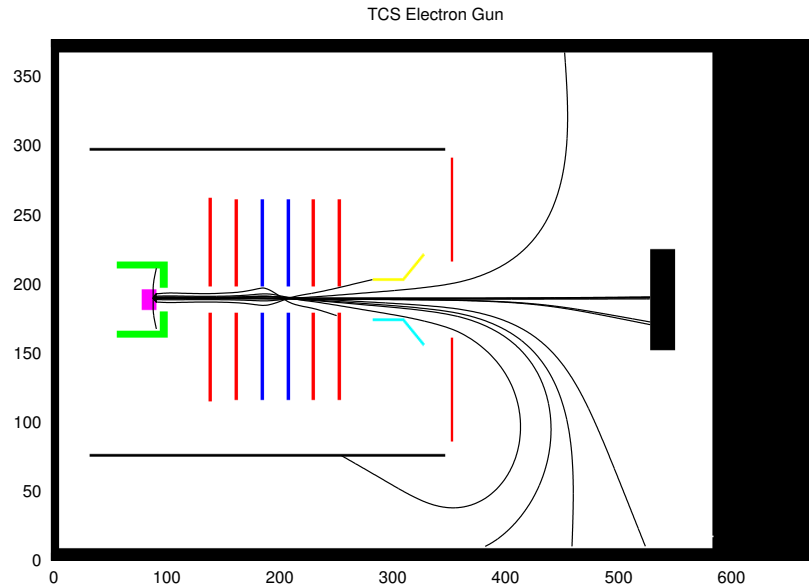


Figure 2: **2D Simulation of trajectories of electrons accelerated through an electron gun**

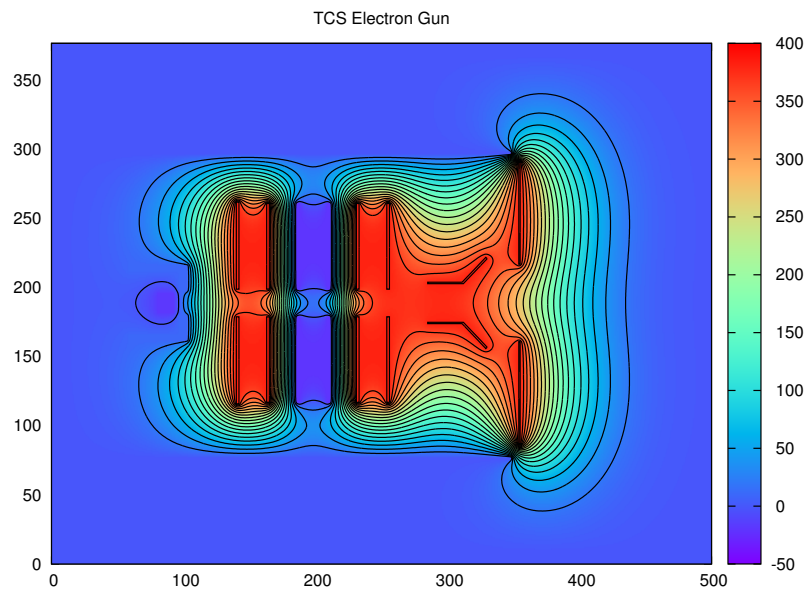


Figure 3: **2D Simulation of the electrostatic potential produced by the electron gun**

1.4 Electron Gun Control Circuit

The control circuit diagram for the electron gun is shown in Figure 4. The wiring of the circuit, including resistors and potentiometers, was incorporated into a single box, with external connections available for the power supplies, ammeters, electron gun, and sample holder. Both the components and operation of this circuit are straightforward; we will give a brief overview here for completeness.

- **Filament Heating** A constant current power supply is used to heat the filament. The inability to directly attach a wire to the filament leads to the requirement for biasing resistors in parallel with the filament. If the resistors are equal valued, assuming that each half of the filament has equal resistance, it is trivial to show that the potential of the emitting tip of the cathode is equal to that at the midpoint of the resistors.

NOTE: I suspect the periodically changing emission current may be due to temperature dependence of the resistance of the resistors, since the current through the parallel circuit is constant, but not necessarily the filament if R is not constant. However, I have not had time to test this.

- **Applied Potential** As discussed in Section 1.1.1, the energy of electrons arriving at the sample is proportional to U (plus a constant). For this experiment, the power supply for setting U has been chosen to allow for serial control using a Digital to Analogue Converter (DAC). Refer to Appendix ?? for more information.
- **Electrode Potentials** Separate power supplies have been used for each independent electrode potential. The power supplies are biased to the cathode, rather than the sample; this ensures that changes in U do not effect the optics of the gun.
 - **Deflection Plates** The deflection plates are referenced to the accelerating electrodes (connections not shown). By using a dual gang potentiometer, with one electrode wired in the opposite direction to the other, the deflection plates will always be at $\frac{V_d}{2} \pm V_a$.
- **Current Measurement** Three current measurement points are available:
 - **Sample Current** This is the current measured during Total Current Spectroscopy experiments (see 1). The ammeter used for this measurement provides an analogue output signal; Appendix ?? discusses the use of Analogue to Digital Conversion for automating the Total Current Spectroscopy experiments.
 - **Primary Electron Current** By applying Kirchoff's law, it can be seen that the sum of currents passing through a gun electrode or the sample is equal to the current flowing through this measurement point. This measurement point was used to verify that the primary current was constant, as assumed by Total Current Spectroscopy theory. Although some variation in primary electron current was observed, this occurred over an extremely long timescale compared to the timescales involved with sample current measurement.
 - **Leak Current** The third measurement point includes electrons which travel through the accelerating electrodes or deflection plates. Knowledge of the current lost through electrodes before the surface was useful for optimising the current incident on the surface.

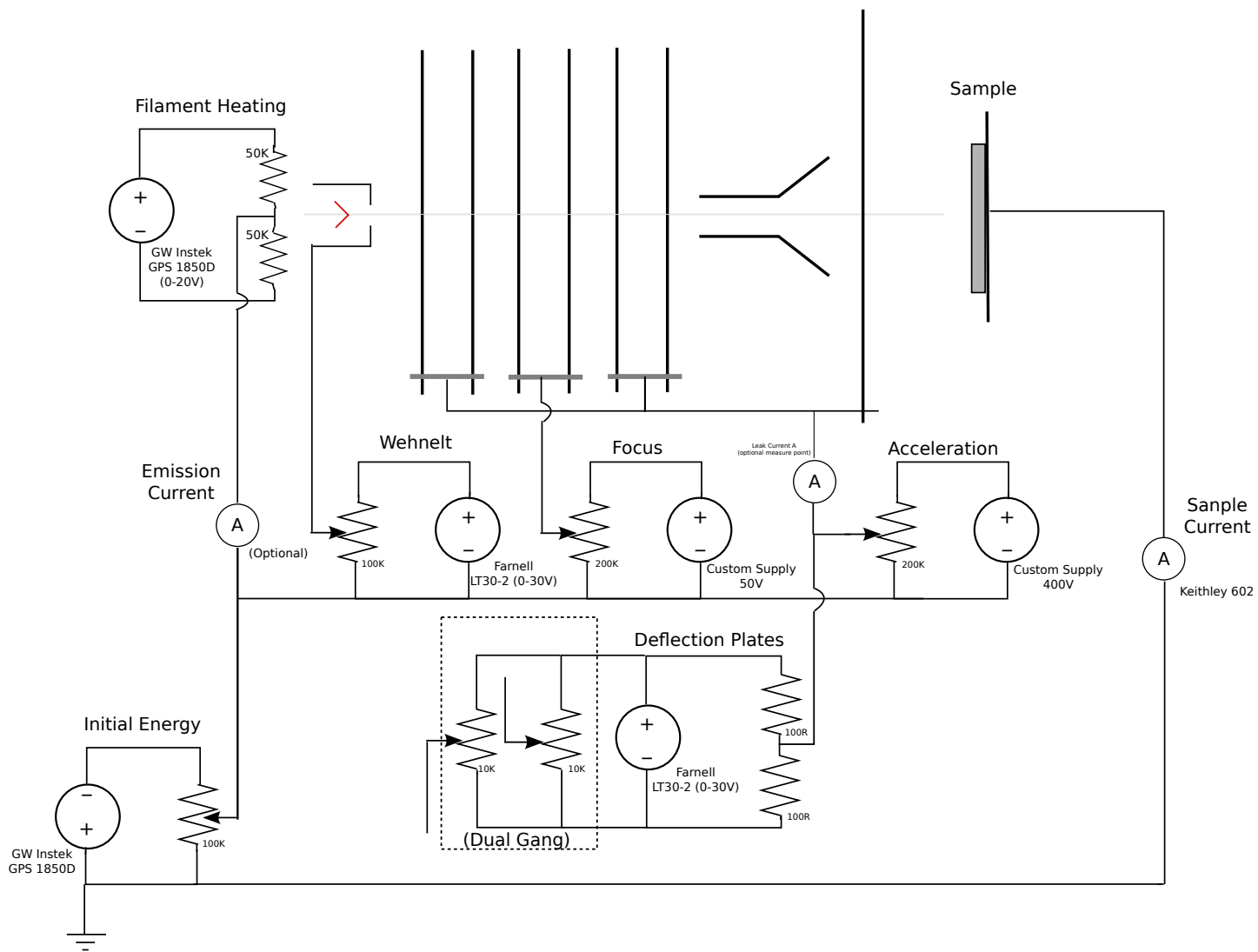


Figure 4: Circuit Diagram for Electron Gun Control

References

- [1] S.A. Komolov. *Total Current Spectroscopy of Surfaces*. Gordon and Breach Science Publishers S.A, 1992.