Design of a Cesium Vapour Pressure Gauge Based on Electronic Thermionic Emission

Enrico Fermi Institute, the University of Chicago, Chicago, IL
João Francisco Shida\(^1\), Fangjian Wu, Mesut Caliskan

Abstract

We describe the design and underlying principles of a tungsten-filament gauge for the partial vapor pressure of cesium. Operation is based on the temperature dependence of electronic thermionic emission from a tungsten filament with a thermally equilibrated partial coverage of cesium, which increases with vapor pressure and decreases with filament temperature. Due to the reduction of the work function of thermionic emission, the current from the filament is a measure of the coverage. By fitting the curve of emission versus filament temperature to a theoretical model, the cesium vapor pressure is obtained. We explain the physical principles behind the device, and describe the construction, operation, and calibration of a prototype built to test the performance of this concept. We document the construction, operation, and calibration of the gauge and analyse the differences between the predicted and experimentally measured data. Based on the analysis, we elaborate on how to design this gauge to obtain better data on desired thermionic emission.

1 Introduction

Cesium is used in the creation of the alkali photo cathodes for photo detectors called large area picosecond photo-detectors (LAPPDs). These are time sensitive photo-detectors with a time resolution in the scale of picoseconds. In order to create such a detector, cesium vapour is released on an antimony surface to create an efficient photo cathode, cesium antimonide. Therefore, it is paramount that the flow of cesium in the production pipeline is measurable to better control the reaction and to develop new ways to expedite and improve the LAPPD growth process. The proposed gauge would be used to measure how much cesium is moving between the source and the antimony-coated surface of a cathode.

The device we propose is based in the work of Taylor and Langmuir. In 1933 they described with great detail the effects of cesium vapour over tungsten surfaces [1], and have laid down the basis for two different kinds of cesium detectors based on hot tungsten filaments. One is based on the principle of alkali ion emission off the filament, while the other relies on the characteristic shape of the thermionic emission versus the temperature of the filament. The system described in this paper is based on the latter concept and therefore, when we mention thermionic emission in this paper, we refer to electronic thermionic emission.

The gauge consists of a tungsten filament parallel to two oppositely charged conducting plates and by varying the filament’s temperature, we can collect a current of thermionically emitted electrons. We fit this data to models experimentally determined by Taylor and Langmuir to find the partial pressure of cesium in the environment. Previous unpublished

\(^1\)Corresponding Author
work detailing the construction of the example gauge described in this paper can be found in the picosecond detector online library REFERENCE NEEDED.

The functioning of the detector is explained in section 2, the calibration procedure is described in section 4, and the performance of the prototype gauge, which we will refer to as the development system, are outlined in section 5. All software used in data analysis and plotting is available at the picosecond detector online library REFERENCE and GitHub page REFERENCE.

2 Working Principles

If cesium vapour is present around a tungsten filament, cesium atoms begins to condense on the exposed tungsten surface. The first atomic layer of cesium to form is of cesium ions in between the tungsten surface layer and the one below. As more ions deposit on the surface in this way, the work function of this structure diminishes. This goes on until two thirds of available spots cesium ions can condense in are occupied. After this point, cesium then begins to form a second layer above the tungsten surface (Fig. 1).

Figure 1: Scheme of how increasing coverage of cesium deposits on a tungsten surface, with coverage increasing from left to right. (A) is a pure tungsten surface, (B) is a stage with some coverage of cesium, the atoms that deposit are cesium ions and fit between tungsten atoms. (C) is the second layer of cesium that starts depositing at a coverage of about 0.67 of the surface by cesium. (D) represents a third layer of cesium deposited, where the surface presents the characteristic of pure cesium and the coverage is 1.

The cesium atoms of the second layer, however, are neutral, have a larger atomic radius and begin to form a cesium crystal over the tungsten surface with the incorporated cesium ions. This covers up the cesium ions and the work function of the surface begins to approach that of cesium. Therefore, the work function of the filament begins to increase. Because the magnitude of the electronic thermionic emission is inversely proportional to the surface's work function, as the fraction of the filament covered by cesium

The coverage of the filament by cesium is determined by both the cesium vapour pressure and the temperature of the filament. The relationship between these factors was experimentally determined by Taylor and Langmuir in 1932 REFERENCE. They measured the effect of cesium vapour on the work function of tungsten filaments and provided experimental curves on the emission of thermionic electrons from a tungsten filament as the pressure of cesium vapour and filament temperature vary (see solid lines in Fig. 2).

Because of this work, it is possible to discover the partial pressure of cesium by measuring the variation of the electronic thermionic emission as the temperature of a tungsten filament is changed. If directed by an electromagnetic field to conductors, the thermionic
electrons generate a measurable current. It is possible to convert this current to the magnitude of the thermionic emission, and we know the filament’s temperature by knowing the current that goes through it. By associating these two values, and by changing the temperature of the filament we can find a curve such as the one predicted by Taylor and Langmuir. From this curve, a fit to their model will yield the partial pressure of cesium.

Figure 2: Reproduction of the experimentally determined electronic thermionic emission by Taylor and Langmuir for three vapor pressures of cesium (Solid Lines) against curves corrected for a long filament with a temperature gradient at the same vapor pressures (dotted lines). The features of the curves such as the peaks and valleys become flattened with a filament that has a temperature gradient compared to one which has almost constant temperature.

2.1 Calculation of the temperature gradient of a filament given a current

To obtain the partial pressure of cesium, we must produce an experimental curve of thermionic emission versus temperature of the filament. To do so it is necessary to convert the two observable parameters, the current through the tungsten filament ($I_w$) and the current observed entering collecting conductors ($I_c$) to the temperature of the filament ($T_w$) and to the number of electrons leaving the filament ($\nu_e$) respectively.

The temperature of the filament is paramount to the characterization of the thermionic current. In their experiments, Taylor and Langmuir made use of guard rings to only measure thermionic electrons from the very center of their filaments so that they may safely assume its temperature is uniform in that region. However, without using guard rings, and instead
measuring electrons from the entire length of the filament, it is necessary to account for the filament’s temperature gradient.

Since the leads conduct away heat from the filament, there is a temperature gradient with a peak at the midpoint. The equation that represents the equilibrium (a steady temperature distribution) for a small part of the filament is:

\[ 0 = dP_e + dP_{ti} - dP_i - dP_{to} \]  \hspace{1cm} (1)

Where \( dP_e \) is the power lost by emission, \( dP_i \) is the power from the current through the filament, \( dP_{ti} \) is the power conducted in from the hotter end and \( dP_{to} \) is the power conducted out at the colder end (see Fig. 3). Each of these components can be written out as a function of the position in the filament as follows:

\[ dP_e = dA e(T(x)) BT^4 \]  \hspace{1cm} (2)

\[ dP_i = \frac{i^2 \rho(T(x))dx}{A_t} \]  \hspace{1cm} (3)

\[ dP_{ti} = A_t K(T_{(x_3)}) \frac{T_{(x_4)} - T_{(x)}}{dx} \]  \hspace{1cm} (4)

\[ dP_{to} = A_t K(T_{(x_2)}) \frac{T_{(x)} - T_{(x_1)}}{dx} \]  \hspace{1cm} (5)

Where \( l, w \) and \( d \) are the dimensions of the filament, with \( l \) being its long edge, \( A_e \) is the external area of the filament, \( A_t \) is the transverse area of the filament (in our case of a flat filament, \( A_e = 2l(w+d) \) and \( A_t = wd \) respectively); \( B \) is the Stefan-Boltzmann constant, \( T(x) \) is the temperature gradient; \( i \) is the current through the filament. Furthermore, \( \rho(T(x)) \) is the resistivity of tungsten as a function of temperature; \( e(T(x)) \) is the emissivity of tungsten as a function of temperature; and \( K(T_{(x)}) \) is the conductivity of tungsten as a function of temperature. These three tungsten properties were all fitted to 4th or 5th order polynomials as a function of \( T \).

Figure 3: Power transport scheme for a small piece of the filament, the different pieces are numbered as they are used in the equations 2 to 9. The Black arrows indicate power into the filament piece, and the grey arrows indicate power out. \( dP_{ti} \) is the power piece 3 conducts from piece 4 into the center piece, and \( dP_{to} \) is the power piece 2 conducts from the center piece to piece 1.

Note that equations 5 and 6 can be re-written as a function of the first derivative of \( T(x) \) at \( x_3 \) and \( x_2 \) respectively:

\[ dP_{ti} = A_t K(T_{(x_3)}) \frac{dT(x_3)}{dx} \]  \hspace{1cm} (6)
Substituting equations 3, 4, 7 and 8 back into equation 2 we have:

$$0 = dAe e(T_x) BT^4 + \frac{i^2 \rho(T_x) dx}{A_t} + (A_t K(T_{x_3}) \frac{dT(x_3)}{dx} - A_t K(T_{x_2}) \frac{dT(x_2)}{dx})$$

Which can also be re-written as a function of the second derivative of $T_x$:

$$0 = dAe e(T_x) BT^4 + \frac{i^2 \rho(T_x) dx}{A_t} + A_t \left( \frac{dT(x)}{dx} \right)^2 \frac{dK(T_x)}{dT_x} + K(T_x) \frac{dT^2_x}{dx^2} dx$$

This is a second order differential equation that can be solved numerically for $T_x$ with two boundary conditions. We assume knowledge of the temperature of the ends of the filament, which is valid if the leads it is connected to are heat-sunk enough. Furthermore, given that at high temperatures $K(T)$ is small, we assume that for the very center of the wire, where it is hottest, equation 2 has negligible conduction summands, and thus we can solve for the temperature at the midpoint given a current. Therefore, we have both $T(0)$ and $T(\frac{l}{2})$ as boundary conditions. Solving for $T_x$ we get for any current a temperature gradient in the filament.

Once we have $T(x)$, we can perform a numerical integration of how many thermonic electrons will be emitted by different parts of the filament based on Taylor and Langmuir’s experimentally determined curve. We do this to calculate the predicted thermonic emission from a filament with non uniform temperatures, and we can generate a curve analogous to Taylor and Langmuir’s but for a filament with a temperature gradient instead of an uniformly heated filament (See dotted lines in Fig. 2).

### 2.2 Required regime for thermonic ions and electrons

Because the work function fall in Taylor and Langmuir’s thermonic electron curve is due to the deposition of cesium ions in the tungsten surface, if any cesium ions leave the filament along with thermonic electrons, the work function will change in a different way as coverage increases. Instead of a continuous decrease, there will be a threshold where the work function of the surface will change between that of tungsten to that of cesium (Fig. 4). As a result, the experimental data from the detector will not match the model used to determine the pressure of cesium vapour.

This is likely because, given the expulsion of ions from the filament, they will not gradually form the ionic layer inside the tungsten surface (Item B in Fig. 1). Instead, once the temperature of the filament is low enough, the cesium will quickly form the ionic layer and begin to form the second cesium layer, thus making the work function suddenly change between that of tungsten to that of cesium.
Figure 4: The theoretical graph for the collected thermionic electrons if thermionic ions are also emitted for a given rate of arrival of cesium atoms on the filament's surface. This was calculated from Langmuir and Taylor’s experimental data. The two straight lines at both ends of the curve are from left to right the tungsten work function regime and the cesium work function regime, with a non-function-like connecting line which can be interpreted as a threshold. The coverage of cesium at the threshold is around 2/3, the same coverage as when, in the curve where only thermionic electrons leave the filament, the work function begins to approach that of pure cesium.

3 Gauge Design

The gauge consists of a cylindrical tungsten filament surrounded by conductor(s). The filament ends should be isolated and connected to a power source. The conductor should surround the filament and be biased at a positive voltage to direct thermionic electron into it. There should be a measurement device between the conductors and bias power supply that directly or indirectly measures current into the charged plates (e.g. a series ammeter or a resistor with a parallel voltmeter).

3.1 Guard rings

For best results, the conductors should be assembled so that there are guard rings and only the conductor surrounding the center of the filament should be used to measure thermionic electrons. This is because the wire’s temperature at the center of the filament can be well approximated without having to account for conduction factors like we have done in equation 1 and it would suffer very little effect from the cooling effect of the leads.

As a result, we obtain a portion of the filament that has a known uniform temperature, so we avoid the calculation in section 2.1 and obtain instead of a flattened curve (dashed lines in Fig. 2), the same curve Taylor and Langmuir present in their paper (solid lines in Fig. 2).

The guard rings should be of the same radius and be biased at the same voltage to guarantee an uniform field around the center of the filament and push to the non-collecting rings any edge effects that may interfere with the electric field (Fig. 5).
All three conductors would be biased at the same voltage and have the same shape. Around the center of the filament, the temperature can be considered almost constant. This means that instead of a flattened curve, we would measure the same curve Taylor and Langmuir predict.

3.2 The experimental gauge

The gauge built to demonstrate the working of the device consists of a tungsten ribbon inside a stainless steel manifold under vacuum. A tungsten filament is suspended between a ceramic plate coated with copper and a semi-cylindrical copper sheet, both of which we will refer to as charged plates (Fig. 6). The filament ends are wrapped around screws which in turn are connected to thick copper wires. The charged plates were tied by the same kind of copper wire and all terminals were connected to separate pins through a feedthrough and to independent wires which come out of the manifold. We did not use guard rings when assembling this system.

The vacuum manifold was assembled as follows: Using CF flanges and copper gaskets to achieve low pressures, we placed the gauge at one end of a CF cross. The system was then
put under vacuum and a cesium glass vial inside the manifold was broken using a magnetic system.

Careful thermal control of the manifold was necessary to achieve temperature uniformity and verify if the system behaved as predicted. Thermocouples were placed around the manifold and heaters were wrapped around it under an insulating layer of fiber-glass. This allowed us to control cold spots in the manifold where cesium would primarily condense in a small puddle. As a result we could control the temperature of the cesium source and the partial pressure of cesium so we could check the measurements from the detector.

The circuit used to measure thermionic emission is outlined in Fig. 7. The filament circuit consists of a power source with an ammeter and a voltmeter (NT-voltmeter and NT-ammeter in Fig. 7) connected to the ends of the tungsten filament, with the negative outlet tied to ground voltage. The bias circuit is made up of "open" connections that terminate in the charged plates through a 10k resistor. Across the resistor is a voltmeter. The elements in the bias circuit are all floating at a High-Voltage from a power supply that is set between +200V and +300V for measurements, and its other end is tied to ground.

![Figure 7: Circuitry of the detector. Thermionic electrons leave the filament at ground voltage and are pulled by an electric field towards the repeller and collector at a high voltage (greater than 200V above ground). They then pass through the series resistor and a voltage is detected in voltmeter 2 that can give us the current through the resistor.](image)

### 4 Measurements

A measurement with the detector consists of changing the current through the filament and measuring the voltage through the resistor for every filament current. These values can then be turned into the rate of emission and temperature of the filament, respectively. This data can then be fit to Taylor and Langmuir’s model (or the analogous model if no guard rings are used) and provide the partial pressure of cesium in the environment. However, to obtain reproducible results, certain precautions must be taken.
It is recommended by Taylor and Langmuir that before any measurement is done the filament undergoes what they call an aging process. This involves leaving the filament heated at 2400K for 10 hours, then at 2600K for an hour and finally conclude with a few brief flashes at 2900K. Prior to such aging, neither we nor Taylor and Langmuir could obtain reproducible results. Furthermore, we have determined that brief flashes to about 2500K before any measurement yields better reproducible results as well.

It is also necessary for the electric field to be generated by a high enough voltage so that all thermionic electrons are routed into the collectors. Taylor and Langmuir describe that as the bias voltage increases, so does the number of collected electrons until a certain voltage, which we will call critical voltage, after which the number of collected electrons plateaus. We measured this effect and determined the critical voltage for the present system to be about 200V (Fig. 8).

With voltages under the critical voltage, some electrons return to the filament or are not emitted. With higher voltages, the electric field manages to extract all possible thermionic electrons until a maximum of emitted electrons are extracted.

It is paramount that the system operate at a voltage in the plateau after the critical voltage so that the height and shape of the thermionic curve is accurate. Otherwise, the magnitude of the obtained curve will be diminished and there will be a maximum number of electrons collected that is under the predicted maximums. This results in a curve where clear ceiling can be seen in the thermionic current versus temperature curve where there should be a peak.

It is also necessary that the measurement not interfere appreciably with the temperature of the source of cesium. The filament heats up to high temperatures during the measurement (up to 2500K) and if the cesium source temperature changes mid-measurement, so will the pressure of cesium vapour. A fast measurement can solve this issue, as well as a source far away from the filament.

4.1 Leakage Current

Leakage currents between the charged plates and either ground or the filament terminals increase the background in the measurement of the currents collected from the plates. We assign the cause of this leakage current to condensed cesium on the ceramic tile connecting the ends of the filament, the plates and the manifold walls together.

There are two ways leakage currents interfere with the measurements. It makes it so that the signal measured across the series resistor does not only come from collected thermionic electrons, but also from ground electrons that arrive from leakage conductive paths. Furthermore, as one changes the temperature of the conductive paths, cesium evaporates or condenses, thus changing the resistance of the leakage pathways. This means that there is not a simple static current backround one might subtract from the measured signal.

It is possible to deal with such currents, however. By applying high voltages to the circuit elements any conductive cesium paths to ground will heat up and the cesium will evaporate off the surfaces. For the charged plates, half an hour at 300V took a 10kΩ short to up to tens of MΩ. Another effective counter to leakage currents was to keep the gauge much hotter than the source to avoid any cesium deposition. When both were left at the about the same temperature, all of the circuit elements were connected to each other and to ground by resistances under one kΩ. When left at a four times the temperature of the source, however, resistances went up to hundreds of kΩ.
Figure 8: Curve of observed current versus increased voltage. In this case the critical voltage observed was around 200V and after that the collected current started plateauing. If measurements were taken at a voltage before the plateau, not all electrons would be collected for some temperatures of the filament. The current was manipulated as the y-axis indicates to be in the same form as figure 21 in Taylor and Langmuir’s paper.

### 5 Performance

Because we did not use guard rings, we must put our data through the calculations in section 2.1, as well as fit the data to the flattened curves instead of the ones obtained by Taylor and Langmuir.

We have taken two measurements (A and B) at different source temperatures that can be seen in figure 9 plotted against each other. In figure 10a we plot measurement B against several curves calculated theoretically in the same way as in figure 15 in Taylor and Langmuir’s paper, and in figure 10b we plot measurement B against analogous flattened curves.
Figure 9: Curve of thermionic electrons versus 1000/Filament Temperature for two measurements at different partial pressures of cesium.
Figure 10: Curve of thermionic electrons versus 1000/Filament Temperature. The blue dots indicate the experimental data, and the solid lines correspond to three theoretical curves at different partial pressures (including the pressure given by the measurement, corresponding to a rate of arrival of cesium of $10^{15}\text{at}/\text{cm}^2/\text{s}$).

Furthermore, figure 11 is a plot of the predicted vapour pressure calculated from the temperature of the source against the pressures given by the gauge.
We could only take two useful measurements with this detector before it began to present un reproducible results. We attribute this failure to cesium deposition on the ceramic boards which shorted circuit elements and affected the measurement. Once the system had been opened to air, we verified a darkening of essentially all ceramic surfaces and between elements, lighter patches. This coloration pattern can be explained by cesium deposition, and the light tracks where cesium was "burned off" the ceramic with high currents as described in section 4.1.

Furthermore, upon closer inspection of the post-measurement detector, it was clear that very small movements and shocks would make the copper semi-cylinder touch the stainless steel manifold, further corrupting the measurement.

6 Conclusion

The data collected lacks accuracy, and does not fully agree qualitatively with the expected pattern. Nevertheless, the fact that the measured curve follows the predicted one up to low filament temperatures demonstrates that the proposed detector is a viable concept. Clearly it must be improved to achieve better accuracy.

A better fit and a greater accuracy could be obtained in a detector with guard rings around the filament, since the original theoretical curve has more distinctive elements and the curves for each pressure can be more easily set apart from each other (By position of the peaks, for example). Furthermore, we have described what precautions should be taken to ensure more precise and accurate results.

We believe this detector can be a valuable tool for scientific apparatus, and a second iteration of the experimental setup described will be used to measure cesium pressures in
the production manifold of a cesium-antimonide photo detector. This version will include guard rings and safeguards against leakage currents, which were the main issues with the experimental device.

7 Acknowledgements

Thank you Henry Andery Elagin, Eric Spieglan, Evan Angelico, Henry Frisch; and the undergraduates who worked on this before.

References
