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MEASUREMENTS OF FIELD EMISSION INDUCED OPTICAL SPECTRA

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Abstract

Field emission induced optical spectra in a DC electrode system have been measured using a spectrometer and digital camera system in order to gain insight into the nature of field emissions sites. Spectra were measured from between 2 ridged parallel copper electrodes with a gap ranging from 60 µm to 100 µm and a bias voltage of up to 8000 V under high vacuum conditions. A strong correlation between the light intensity of the spectra and the measured field emitted current was observed as a function of applied voltage. A characteristic broadband spectrum ranging from 550 nm and 850 nm wavelength was observed but there were important features which varied as a function of observation angle, polarity, and conditioning state and with time. Possible causes of the optical spectra being considered include black body radiation, optical transition radiation and cathode luminescence of copper. Further experiments are ongoing with an improved optical setup to increase optical alignment for measurements with different materials of electrodes, developing further understanding of the cause of the optical spectra, to provide understanding into characteristics and evolution of emission sites.

INTRODUCTION

Measurements of light spectra during field emission have been carried out in the Large Electrode System (LES) at CERN [1]. This is part of the research and development for high gradient test stands for CLIC [2-4]. Continuous light emission during the application of high voltage was originally seen in the previous DC system at CERN [5]. The emission mechanism and features of the spectra were not determined at the time. This investigation seeks to address these questions in order to gain insight into the nature of field emission sites. A significant correction, of a factor typically between 30 and 1000, is needed when comparing the Fowler-Norheim equation to field emission measurements from macroscopic high-field systems [6]. A better understanding of the origin of this correction factor would be important in developing high-field systems, like high-gradient accelerating structures.

There are several possible causes of light induced by field emitted currents; these include thermal radiation from heated emitter sites [7], optical transition radiation produced when the field emitted electrons strike the anode [8], and cathode luminescence from electrons captured in an excited state which subsequently decays, producing photons [9]. It is expected that the dependences on time, voltage, current and material will give experimental results for addressing important high-field questions such as the origin of the field enhancement factor, the nature of breakdown nucleation, the nature of the conditioning process and the evolution of high-field surfaces with pulses and time.

EXPERIMENTAL SETUP

For optical purposes, a ridged design of electrodes featuring a rectangular protrusion in the centre was used whilst measuring the spectrum [1, 10]. Figure 1 shows the shape of the copper electrodes and alignments used for the experiment described in this report. Due to the high field area where the light emission originates from, being of a reduced surface area, the optical alignment was simplified. Observing the high field area with a crossed alignment of the electrodes from different angles offers the possibility of reducing the optical restrictions and has a high probability of impacting the spectra measured. It is possible with the system used to observe the electrodes from perpendicular angles via different windows. The electrodes used for optical measurements have so far been made of copper, therefore any light reflected will be filtered by the reflection spectrum of copper.

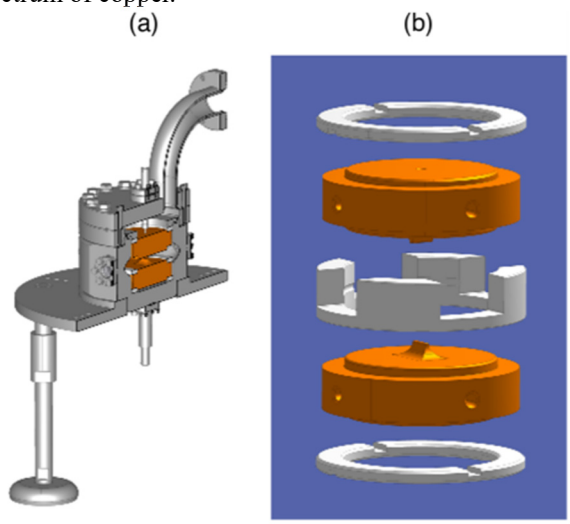

Figure 1: (a) CAD drawing of the LES vacuum chamber and (b) Exploded view of crossed ridged electrodes and ceramic spacers [10].

The LES is typically used with high-voltage pulses, however, for the following tests a constant power supply was used, making light emission more visible. These tests are limited to a maximum of 1 mA by the power supply and 8 kV by the cables used. From the power supply there is a 6.39 MΩ resistor (R1) in series with the system where the system acts electrically as a capacitor. R1 reduces the possibility of a breakdown from occurring by limiting the

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available current, as a result all spectra shown are without a breakdown.

Calculations of the field emission current in the gap were performed by measuring the voltage across the second resistor (R2). An oscilloscope and a multi-meter were placed in parallel to R2 to measure the voltage. For this, the resistance of both of these devices also needs to be included in the calculation. Equations for these calculations are given below.

$$U = V - IR \quad (1)$$

$$I = V^*/R^* \quad (2)$$

$$\frac{1}{R^*} = \frac{1}{R_{osc}} + \frac{1}{R_{multi}} + \frac{1}{R_2} \quad (3)$$

where U = gap voltage, V = supplied voltage, I = field emission current, V* = multi-meter voltage, R* = total resistance, R2 = 100 kΩ, Rosc = 1 MΩ, Rmulti = 10 MΩ, therefore R*≈ 90.1 kΩ.

Use of these equations allowed for the field emitted current and voltage in the electrode gap to be calculated. This was then used to analyse the relationship between these values and to generate Fowler Nordheim plots to determine the field enhancement factor. Similar analysis was also possible using the spectra results for a comparison to the field emission.

SPECTROMETER SETUP

Light from the system was collected by a collimator attached to one of the 4 windows. All light external to the system was blocked using various shields due to the low light intensity of field emission. Light was measured while no field was applied to verify that there was no background light. An optical fibre was screwed onto the output of the collimator and transmitted the light to the spectrograph. The spectrograph used was a Shamrock 303i, which contained several components that impacted the light measured.

An iDus CCD camera is a specially resolved light intensity sensor that is connected to the direct output of the spectrograph, used to capture the spectrum. The camera pixels were integrated vertically for statistics, with each row providing intensities for different wavelengths, used to form the following graphs. The grating used for the following measurements had a range of 570 nm in wavelength with 1024 values across this range. The speed of the camera used was relatively slow in the millisecond range and for a sufficient amount of light to be measured a large exposure time of 5 seconds was used. Therefore it was not possible to take high speed captures using this setup.

Control of the different aspects of the spectrometer was done from the computer using the Andor Solis software. The software contained the settings for the spectrometer to change the different parameters or capturing spectra. A background measurement was taken with no applied voltage and this was removed from subsequent measurements, labelled 'background corrected'. This removed the light measured as a result of dark current in the CCD camera.

OBSERVATION ANGLE AND POLARITY

Several measurements were taken at each step in voltage and averaged together to give the values used in the following plots. Parameters for the measurement were set to measure a sufficient amount of light, including an exposure time of 5 seconds and an input slit width of 2500 µm. Wavelengths observed were between 500 nm and 900 nm, to view the majority of wavelengths generated, therefore a UV fibre was used.

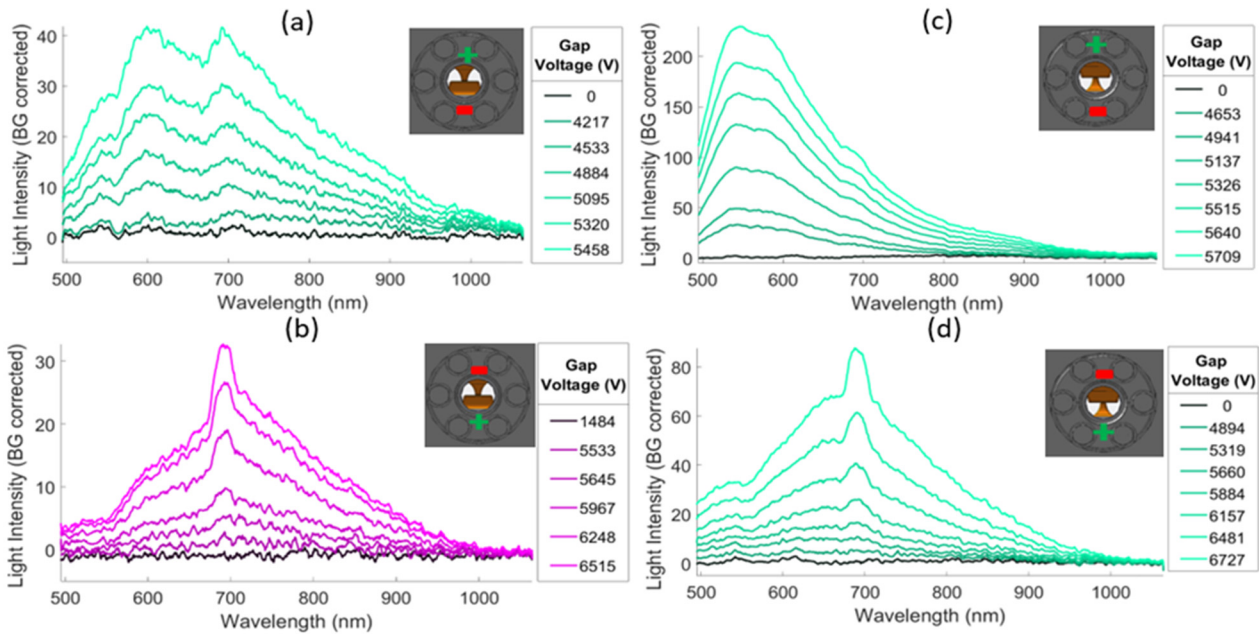

Figure 2: Spectra measurements from each perpendicular angle and both polarities. (a) Conditioning polarity transverse anode, (b) Negative polarity longitudinal anode minus noise, (c) Conditioning polarity longitudinal anode, (d) Negative polarity transverse anode.

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Measurements displayed relatively broad band spectra with a drop off on either side.

The aim of the following tests was to increase the amount of light measured during field emission. As a crossed alignment of electrodes provided a higher light intensity, this was chosen for the continuation of measurements. The following measurements were completed in both polarities. This was done to determine whether the spectra observed was a result of the optical alignment with the presumed emitting electrode. The expected result was that the spectra measured from each angle would be the same as the opposite for the different polarities. An image of the view through the windows and the polarity are shown in the diagrams in the corner of each measurement. These measurements were done consecutively with no breaks between and in the order given from a-d in Fig. 2.

Figures 2 (a) and (c) show the same polarity as conditioning, with a clear difference in the light between 500 nm and 600 nm as it was more intense during Fig. 2 (c) measurements and therefore more dominant. The dependence on angle had a large impact on the amount of light measured. With a peak at 700 nm on both plots, but clearer in Fig. 2 (a) due to the reduced intensity of the other peaks.

Figures 2 (b) and (d) show the measurement with the polarity reversed to the polarity in which all previous tests and conditioning were done. Figure 2 (b) had some residual noise when no voltage was applied, therefore the results shown (in purple) had the noise removed during analysis. The result of these measurements gave a prominent narrow peak at 700 nm that was different to all previous measurements. There was still a visibly larger amount of light from the same angle as previously, indicating this is not a result of alignment with the emitting surface.

A significant result from these measurements is the result from the reverse polarity. The difference in spectra suggests that the conditioning of the electrodes plays a role in the field emission and spectra. Currently it is unknown what is causing the peak in spectra or exactly why it is different in the reverse polarity, but it does lead to possible further tests to analyse this.

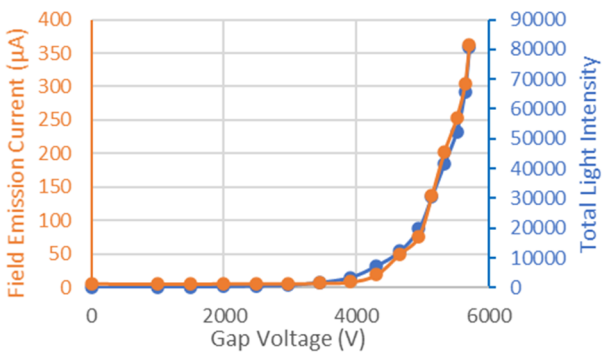

Figure 3: Field emission current and total light intensity vs. gap voltage from the measurement in Fig. 2 (c).

The current was measured in parallel with all results as the supply voltage was increased. Figure 3 shows a clear correlation between the current and spectra light intensity at all wavelengths given. The gap power given as the gap voltage multiplied by the current measured, also had a linear correlation with light intensity; therefore, it is not possible to specify which is directly related to the cause of the light.

OPTICAL SPECTRA FLUCTUATIONS WITH TIME

The following measurements observe fluctuation in optical spectra with time. For this test, the supply voltage was kept at 7 kV and the current and spectra were measured every 30s, displayed in Fig. 4. It is clear from this plot that the fluctuations in spectra were between 650 nm and 850 nm, with the largest fluctuations between 800 nm and 850 nm. This measurement verified that there was a characteristic fluctuation in the spectra was not always observed during measurements, suggesting it is a feature that is not always present. The fluctuations were also more prominent at higher voltages and clearer due to the higher intensity of light.

"Total light intensity" is the light intensity at every measured wavelength summed together. These results did give a clear relationship between the light intensity and current measured with respect to time. As the current fluctuated the light intensity appeared to follow the same changes in terms of increasing and decreasing by similar proportions.

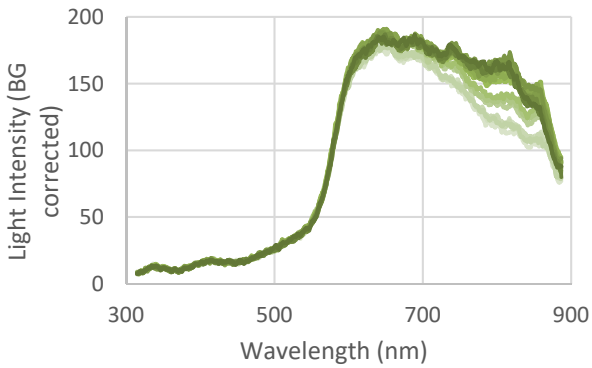

Figure 4: Spectra measurements every 30 seconds with a constant DC voltage of 7 kV applied, where the colour becomes darker with time.

CONCLUSION

In conclusion measurements of light spectra during field emission displayed a clear increase with increased supply voltage and gives a linear correlation with light. Currently the source of light is unknown, as the results shown did not differentiate between the possible causes. Properties of the spectra that are known include a dependence of observation angle and optical restrictions that could distort results. Also, applying a potential negative to the polarity in which the electrodes are conditioned provided a prominent spike in the spectra at 700 nm in wavelength. There was also a fluctuating component of the spectra that changes with time and correlated with the field emitted current. Further analysis of such features is expected to help constrain the mechanisms producing the optical spectra.

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