Measurement of electron number per pulse in UED set up

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1.Introduction

Ultrafast Electron Diffraction (UED) is a powerful tool for probing time-resolved structural dynamics of molecules (Fig.2) [2]. The effectiveness of this technique relies on the brightness of the electron beam (i.e. number of electrons) and the pulse duration per electron bunch. Quantifying the number of electrons per pulse of the beam is important because it determines the quality of the diffraction image. For accurate assessment of the electron number, three methods were used and compared amongst each other:

1. Faraday Cup electron current measurement,
2. Princeton Instrument CCD camera
3. Simulations from General Particle Tracer.

1.1 Faraday Cup

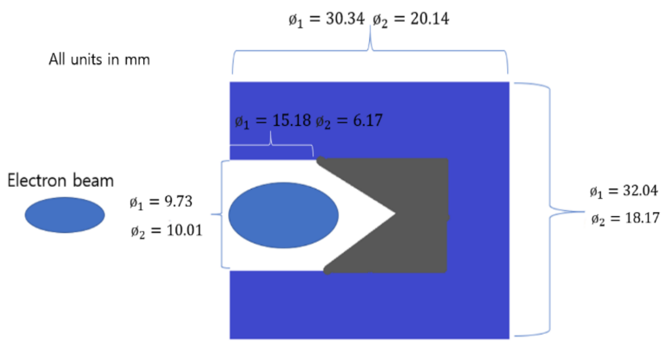

Fig.1. Sketch of a Faraday Cup. An electron beam strikes and collects on a cup which is connected to an electrometer. The size of the cup must be large enough to capture all the electrons. Two different Faraday Cup were used: $\emptyset_1, \emptyset_2$ are dimensions for the two different Faraday Cups.

Faraday Cup is the device to measure the beam current in experiments using electrons or ion beams. The Faraday Cup has the shape of cylinder with an inner cavity and consists of conducting materials (Fig.1). The incoming electron beam strikes the Faraday Cup and absorbed, and electrons flow out to the Electrometer which is electrically connected to the Faraday Cup.

To measure the beam current with good precision, the size of the Faraday cup should be big enough to capture all the electrons from the beam and thick enough so all captured electrons can flow to ground through the electrometer. There are three factors which decrease the accuracy of the measurement for

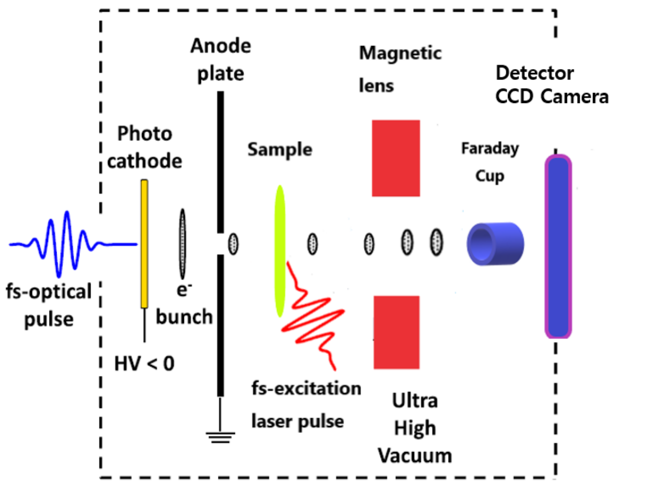

Fig.2. Ultrafast Electron Diffraction layout [2]. A fs-optical pulse (blue) generates, via the photoelectric effect, a fs-electron pulse. The photocathode is held at negative potential controlled by the high voltage supply ranging from 0 to -125kV with respect to ground. Electrons are therefore accelerated through the cathode-anode potential drop. The aperture in the anode plate is 100µm in diameter. A magnetic lens is used to improve the sharpness of the diffraction pattern at the screen. When CCD camera is used, Faraday Cup is moved out of the electron beam path.

a low current on a high intensity pulsed electron beam. First is measurement position and angle of the Faraday Cup. Second is the electrons back-scattering out of the cup. Third is the loss of current due to the leakage to ground, bypassing the electrometer [1].

Usually, Faraday Cups are made with low-Z material (graphite) on the surface to reduce the amount of backscattering and increase the absorption by adding more dense material (Stainless Steel) behind. Also, a magnetic field in front of the Faraday cup can be used to reduce the amount of backscattering even further [1]. The Faraday cup is connected to a Keithley 6514 electrometer which can make current measurement range from 20pA to 20mA [3].

1.2 CCD Camera

When accelerated electrons hit phosphor screen in the surface of CCD camera (Fig.2), phosphor screen emits photons via scintillation. The conversion factor of the phosphor screen depends on the phosphor type and the kinetic energy of the electrons and typical used phosphor screen has conversion factor between 20 and 200 photons per electron [4]. These emitted

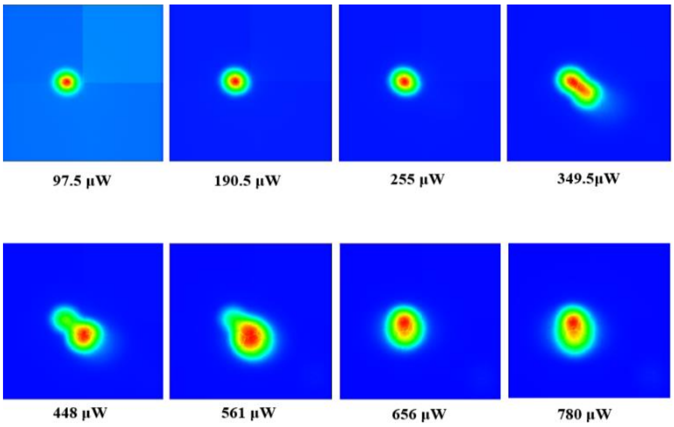

Fig.3. Picture of electron beam in the region of interest with different laser powers with -110kV at photocathode. To use the CCD camera, Faraday Cup is moved out of the way from Fig.2. Each image was taken by exposing the CCD camera for 0.2 second and the average of 10 frames.

photons are detected by CCD camera and converted into digital values. Then, the data is transferred to the computer and analyzed with software *LightField* (Fig.3). *LightField* can set the region of interest (ROI) in the camera and the sum intensity of the ROI is used to estimate the number of electrons per pulse since sum intensity is proportional to the number of electrons that strike the phosphor screen.

1.3 General Particle Simulation

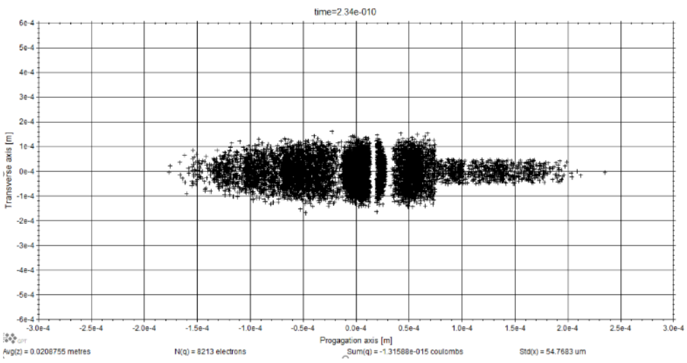

Fig.4. Simulation of the moment when part of an electron beam passes through the aperture at anode plate. Fraction of electrons are cut off due to the limited size (100μm) of aperture (Fig.3) and expansion of the beam from space charge effect. Initial electrons per pulse is set to 10000 and the voltage at photocathode is held at -100kV.

General Particle Tracer simulates the behavior of an electron beam as it travels from the photocathode through aperture at anode and all the way to the CCD camera. The effect of space charge and relativistic correction on propagation of electron pulse, which is considered as Gaussian beam, was investigated with simulation. The dependence of these effects on the number of electrons, beam radius, initial pulse duration, and propagation time was analyzed. Space charge effect explains the electron pulse broadening as it travels due to the repulsive forces between electrons, especially significant in the case of dense electron bunches [5]. Relativistic correction can calculate the travel time for accelerated electrons from photocathode to CCD camera and this time can help to calculate how much the electron bunch expands with the space charge effect (Fig.4). For instance, if V=-100kV and photocathode-to-anode distance is 22mm and anode-to-CCD Camera distance is 591mm, the electron pulse spends ~3ns in this region. However, simulation is only used for confirming the trends of the data from CCD Camera and Faraday Cup measurements, because not only the simulation is the result of the ideal conditions such as perfect vacuum inside the chamber but also, simulation uses approximation due to the limited computing power of a desktop computer.

2. Discussion and Results

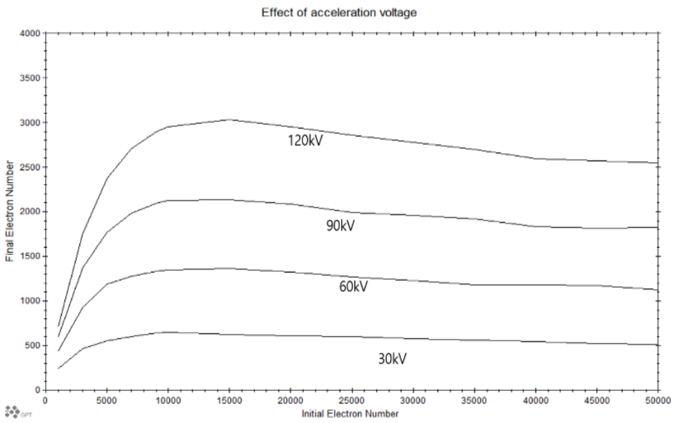

Fig.5. Estimated number of electrons detected at the CCD camera position from General Particle Tracer simulation. Four different values of voltage at photocathode were simulated. Initial electron number in the horizontal axis is proportional to the incoming laser power to photocathode.

To observe the effect of laser power and number of electrons per pulse, the voltage at the photocathode was fixed and laser power (Fs-optical pulse in Fig.2) was varied with full range.

As simulation shows the expected number of electrons detected at the CCD camera position in Fig.5, all the final number of electrons for each different voltage reaches plateau but have different maximum values. The reason for the plateau is due to the aperture in the anode plate limiting the number of electrons passing through aperture as shown in Fig.4 and the lower voltage forces larger acceleration on the electron beam and gives less time for expansion when it reaches at aperture so more electrons per beam passes through the aperture. Each curve has the hump shape near 10000 initial electrons, because too much electrons in the constant beam size results in too much expansion due to space-charge before it reaches to the aperture in anode and less electrons end up passing through it as discussed in detail in [5].

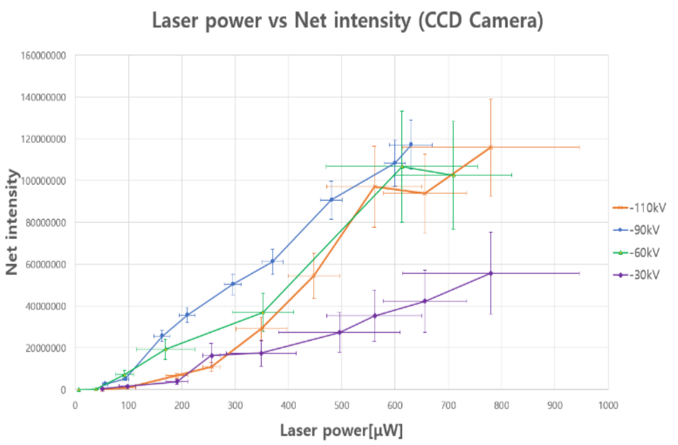

Fig.6. Intensity profile with CCD camera. Net intensity is calculated by subtracting background intensity from sum intensity in the region of interest. The exposure time is 0.2 second and the intensity is the average of 10 frames.

The result from CCD camera can be seen in Fig.6 The intensities corresponding to different values of laser are monotonically increasing for -90kV and -30kV, but it reaches plateau with -60kV near the maximum laser power. The biggest uncertainties came from the instability of the laser power, the fluctuation of laser power was especially significant at high power. Maximum laser power fluctuation was about $\pm 150 \mu W$ at the max laser power: $780 \mu W$. Comparing with simulation, the maximum intensities for -60kV, -90kV and -110kV were close to each other unlike the simulation. Besides the instability of the laser, the imperfect alignment of the laser beam to aperture in anode plate (Fig.2) can deformed the electron beam as shown in Fig.3, and it prevents the optimal number of electrons from reaching to CCD camera. There is a possibility of higher laser power produces plateau behavior as shown in Fig.5, but we have to wait until the laser instability is fixed.

Data from first Faraday Cups $\emptyset_1$ is shown in Fig.7. Each data point is the average of the 200 counts for ~150 second exposure of Faraday Cup to electron beam as shown in Fig.2. One of data point from Fig.7 is illustrated in Fig.8. The conversion from current to number of electrons per pulse is given by

$$\frac{(Current\ - Background\ current)}{(1000Hz\ ) \times (Charge\ of\ an\ electron)} \tag{1}$$

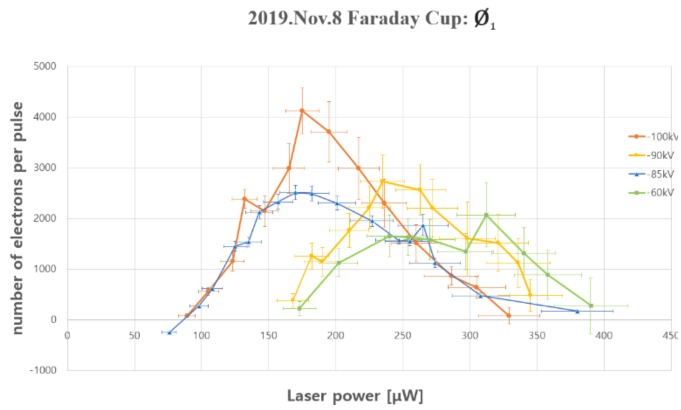

Fig.7. Laser power versus number of electrons per pulse detected through the Faraday Cup $\emptyset_1$ (Fig.1). Laser power was measured directly in front of the photocathode.

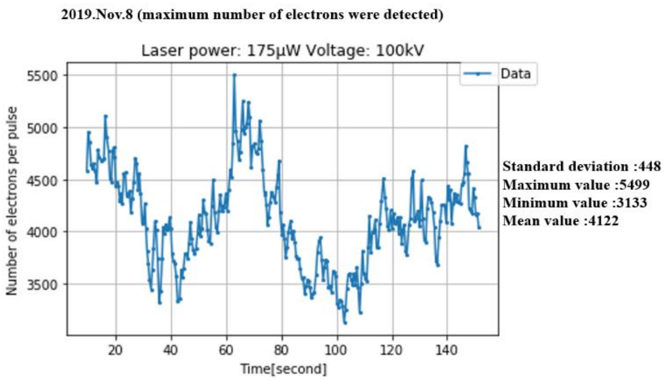

Fig.8. Current measurement from Faraday Cup for fixed laser power and voltage at photocathode. The computer was connected to the electrometer and recorded the data and python program was used to convert the current to number of electrons per pulse using Eq 1.

The Faraday Cup $\emptyset_1$ could not detect electrons when laser power close to the maximum. This inverted U-shaped curve always occurred regardless of temperature, humidity and time of measurement which are conditions affecting the stability of laser. One of speculations for this unexpected result was that size of the electron beam is too big to be detected in graphite of Faraday Cup due to the expansion from space charge effect. Therefore, the beam size was simulated and measured with CCD Camera as shown in Fig.9 and Fig.10.

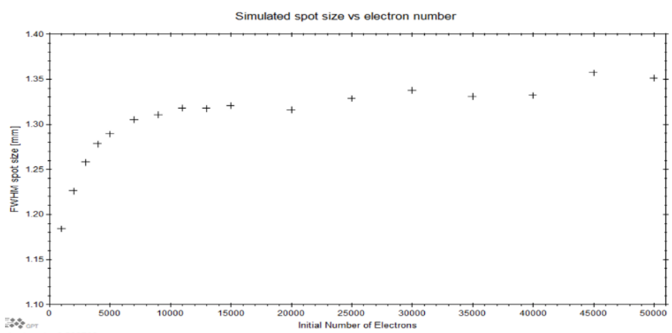

Fig.9. Initial number of electrons versus beam spot size estimation at CCD camera position from General Particle Tracer Simulation. Photocathode is held at -100kV.

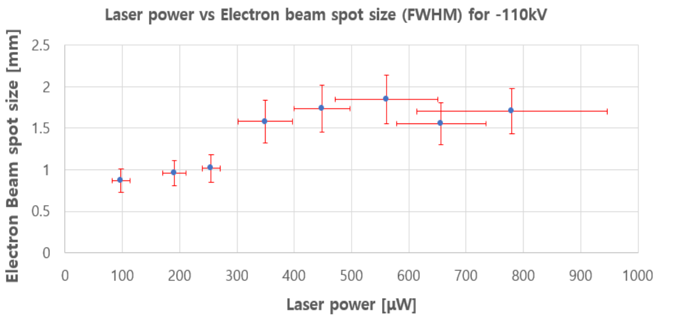

Fig.10. Laser power versus Beam spot size (FWHM) from *LightField* using CCD camera. Photocathode is held at --110kV.

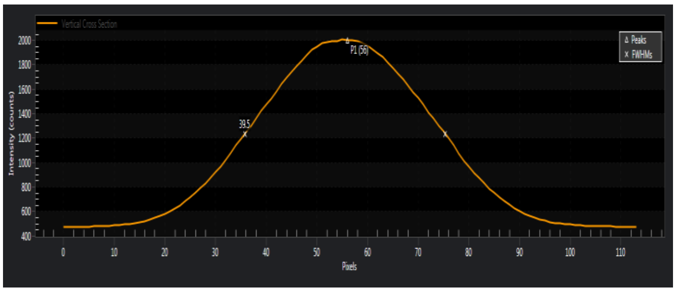

Fig.11. Vertical intensity profile of the electron beam from *LightField* for 190.5µW in Fig.3. The size of one pixel is 24 µm. Each data point in Fig.10 is the average value of the FWHM of vertical and horizontal intensity curves.

Full width at half maximum was used for the beam spot size. *LightField* has the function which finds the FWHM of Gaussian-like intensity profile of electron beam spot as shown in Fig.11. The maximum beam spot size with -110kV is 1.8456mm in diameter and simulation estimate less than 1.35mm. In both cases, the beam spot size is less than 18% of the diameter of graphite which cannot be the reason for Faraday Cup not detecting electrons at the maximum laser power. However, as Fig.3 shows, the shape of the beam changes for different laser powers due to the imperfect alignment of laser beam and the intensity curve does not always have Gaussian shape. Nevertheless, the beam spot size is small enough so that the graphite area in Faraday Cup can capture all the electrons and beam size cannot be the factor for the Faraday Cup $\emptyset_1$ not detecting electrons at high laser power.

The design of second Faraday Cup $\emptyset_2$ has larger surface area of graphite and the depth of the cup is shorter compared to the first Faraday Cup which is more accessible for electrons to enter. The second Faraday Cup $\emptyset_2$ detected electrons at the maximum laser power unlike the first Faraday Cup $\emptyset_1$.

Two different methods were performed with Faraday Cup $\emptyset_2$. First method was the measurement with fixed alignment of laser beam for all voltages

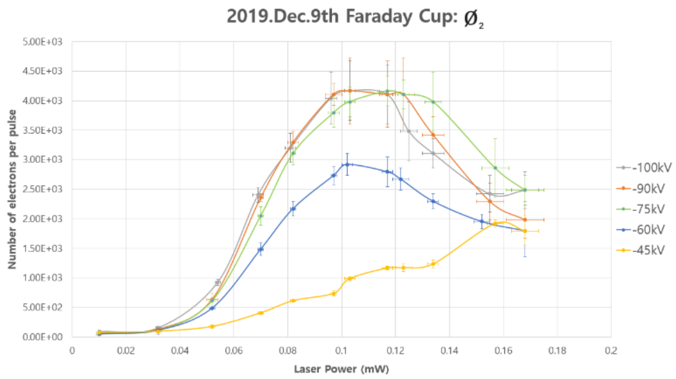

Fig.12. Laser power versus number of electrons per pulse detected through the Faraday Cup $\emptyset_2$. This measurement was performed without adjusting the alignment of laser to maximize the sum intensity from *LightField* for each voltage. Laser power was measured in an indirect manner reflected off the mirror (≈35% of laser power from Fig.7).

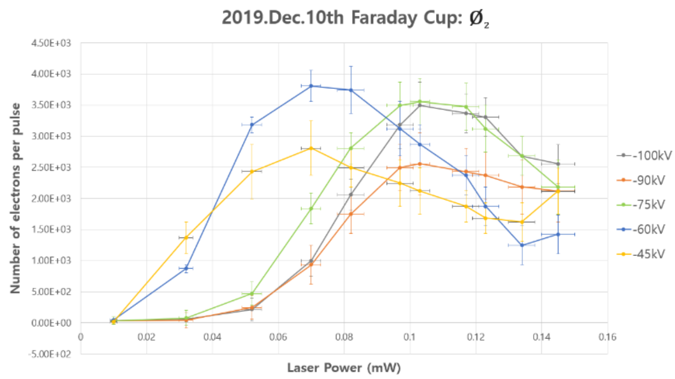

Fig.13. Laser power versus number of electrons per pulse detected through the Faraday Cup $\emptyset_2$. This measurement was performed by adjusting the alignment of laser to maximize the sum intensity from *LightField* for each voltage.

(Fig.12) and the second method was performed by adjusting the alignment of laser beam to obtain the maximum intensity of the electron beam at the CCD camera (Fig.13) because different voltages change the position of the electron beam proximately hundreds of micrometer. In both cases, most of the curves have hump but did not show clear plateau as simulation predicted in Fig.5, or monotonic increase from CCD camera in Fig.6

Adjustment of laser beam is supposed to optimize the number of electrons but surprisingly measurement without adjustment detected more electrons for -100kV, -90kV and -75kV than one with adjustment. Since two measurements were performed in different days, this unexpected result could come from the instability of laser, but as shown in Fig.13, -60kV, -45kV and -75kV has higher maximum values than -90kV cannot be explained.

3. Conclusion

The purpose of this project is to develop a method for accurately measuring the electron number per pulse generating by our UED machine. The Faraday Cup provides a direct measurement of beam current, but have large fluctuations and is very susceptible to small environmental changes. Also, measurements from the Faraday Cup are hard to replicate, meaning we don't get the same beam current reading given the same voltage, laser power, and other initial conditions. The sum intensity of pixels measurement with the CCD camera is the most stable, but is not a direct measurement of electron number, therefore it must be calibrated. Simulations with General Particle Tracer simulation can give an approximation of the electron number, but cannot be a completely true representation of experimental conditions. However, the simulations are very useful for confirming trends and behavior of the UED system, thus giving us insight on the results of our measurements with the other two methods.

Another finding of this project is that Faraday Cup $\varnothing_2$ is much better for detecting electrons than Faraday Cup $\varnothing_1$, since Faraday Cup $\varnothing_1$ fails to detect electrons with high laser power as well as the size and geometry of Faraday Cup $\varnothing_2$ allows more electrons to be captured. This shows that the physical design of the Faraday Cup plays an important role and should be carefully considered for all future Faraday Cup designs.

To help investigate problem of Faraday Cup and CCD camera more accurately, the stabilization of laser must be fixed in the future since laser instability contribute the largest fluctuations to all measurements.

Reference

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