FLUENCE UNIFORMITY MEASUREMENTS IN AN ELECTRON ACCELERATOR USED FOR IRRADIATION OF EXTENDED AREA SOLAR CELLS AND ELECTRONIC CIRCUITS FOR SPACE APPLICATIONS

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INTRODUCTION

It is common to have liquid crystal displays and electronic circuit boards with area sizes of the order of 20x20 cm^2 on board of satellites and space vehicles. Usually irradiating them at different fluence values assesses the radiation damage in these types of devices. As a result, there is a need for a radiation source with large spatial fluence uniformity for the study of the damage by radiation from space in those devices.

Kent State University's Program on Electron Beam Technology has access to an electron accelerator used for both research and industrial applications. The electron accelerator produces electrons with energies in the interval from 1 to 5 MeV and a maximum beam power of 150 kW. At such high power levels, the electron beam is continuously scanned back and forth in one dimension in order to provide uniform irradiation and to prevent damage to the sample. This allows for the uniform irradiation of samples with an area of up to 1.32 m^2. This accelerator has been used in the past for the study of radiation damage in solar cells (1). However in order to irradiate extended area solar cells there was a need to measure the uniformity of the irradiation zone in terms of fluence. In this paper the methodology to measure the fluence uniformity on a sample handling system (linear motion system), used for the irradiation of research samples, along the irradiation zone of the above-mentioned facility is described and the results presented. We also illustrate the use of the electron accelerator for the irradiation of large area solar cells (of the order of 156 cm^2) and include in this paper the electrical characterization of these types of solar cells irradiated with 5 MeV electrons to a total fluence of 2.6×10^{15} e/cm^2.

EXPERIMENTAL

Fluence Measurements

The electron accelerator facility and associated instrumentation to irradiate research samples have been described elsewhere (1). The moving platform to irradiate research samples consists of an aluminum frame 198 cm long and 35.2 cm wide. For the irradiation of solar cells of small area a Faraday Cup (FC) specifically designed to be used with electrons with initial energies as high as 5 MeV, is fitted in the center of this platform and on top of it an aluminum plate is attached, serving as a sample holder for the solar cells. The aluminum plate has a hole in its center, which is aligned with the entrance of the FC, so the fluence is measured at the center of the aluminum plate, Figure 1 shows a photograph of this experimental setup. However, to determine the fluence uniformity on the moving platform the FC is not very useful, since it is not easy to move to different locations and its spatial resolution is not very high (its collimator is 1.7 cm in diameter). In order to determine the fluence uniformity in this case, cellulose triacetate (CTA) film was selected because of its property to give high spatial resolution (of the order of 3 mm) in radiation dose and its ease of use. This film comes in reels 125 μm thick, 8 mm wide and several tens of meters long. The film can be cut to the specific length needed for a particular application. Upon irradiation the CTA develops an optical absorption band in the ultraviolet region (with a peak at 280 nm), which increases with the fluence. This system is extensively used as a radiation dosimeter in radiation processing applications and as such its response, that is its net change of absorbance per unit thickness, is usually calibrated in terms of the radiation dose (2). To determine the fluence uniformity in the irradiation zone, though, a calibration of the CTA film in terms of fluence was needed. To do this a calibration between the response of irradiated CTA films and actual fluence measured with the FC was performed for fluence values ranging from 1 x 10^{13} to 1 x 10^{15} e/cm^2. Five CTA films (1 cm^2 in area) were sealed in an aluminum pouch and placed on top of the 25 cm x 40 cm aluminum plate attached to the top of the FC which was already mounted in the center of the moving platform. The aluminum pouch was located next to the opening of the Faraday Cup. The FC and CTA films were then irradiated with 5 MeV electrons. The beam current absorbed in the FC was integrated using an ORTEC counting system (3) and from there the fluence was determined. Particular fluence values were obtained by allowing the samples to traverse through the irradiation zone several times at constant speed (usually 2.54 cm/s) (4).

Absorbance values of CTA films were measured in a Genesys 5 spectrophotometer two hours after irradiation to allow for the absorbance value of the film to stabilize. The process was repeated for each of the fluence values in the above-mentioned range. A calibration curve correlating absorbance values to fluence values was then created.

Fluence uniformity measurements

The fluence uniformity was determined for two different situations. First for the moving platform, and secondly on top of irradiated solar cells. The fluence uniformity on the moving platform was determined by using two CTA film strips, one 198 cm long positioned along the length of the platform and perpendicular to the direction in which the platform moves, and the other one 35 cm long along the width of the platform and parallel to the direction in which the platform moves. The film was irradiated to a target fluence value of 5 x 10^{14} e/cm^2 with 5 MeV electrons. Figure 2 shows a schematic diagram of the irradiation setup. After the irradiation the CTA film absorbance was measured using the same procedure as described before for the calibration of the CTA films, but using a driving mechanism in the spectrophotometer that allows the continuous measurement of long filmstrips. The fluence values were determined from the calibration curve obtained before and graphed in terms of the length of the CTA film strip.

For the determination of the fluence uniformity on top of solar cells, six 12.5 cm x 12.5 cm silicon solar cells (3 monocrystalline and 3 polycrystalline) provided by BP Solar[1] were placed on the aluminum plate positioned on top of the FC (see Figure 3). Two strips of CTA film were placed on top of three cells located along the length of the aluminum plate and another strip on top of two cells located along the width of the aluminum plate and irradiated to a fluence value equal to 9 x 10^{13} e/cm^2 with 5 MeV electrons.

Solar Cell Characterization

The six silicon based solar cells (monocrystalline, and polycrystalline), described above were characterized before irradiation by developing corresponding I-V (current/voltage) curves under illuminated conditions using a Keithley 2400 SourceMeter connected via an IEEE-488 interface bus to a personal computer running Keithley's LabTracer component characterization software. A four-wire connection was used to connect the cell under test to the SourceMeter. Cells were illuminated by a 500 W halogen lamp positioned to a height of 85.1 cm above the top surface of the cell. This height was selected to minimize the heating effect on the cell under test and control the short circuit current to a level that would not overload the range capability of the 2400 SourceMeter. Surface temperatures of the cells averaged 27.5 °C during these illuminated conditions.

[1] The mention of any commercial product is for clarification purposes only and does not imply any type of endorsement from the authors or Kent State University

After the initial characterization of the cells, they were irradiated with 5 MeV electrons to the following accumulated fluence values, 1 x 10^{13}, 1 x 10^{14}, 1 x10^{15}, and 2.6 x 10^{15} e/cm^2, and measured after each subsequent irradiation as explained above.

RESULTS

Figure 4 shows the results of the calibration of the CTA film in terms of fluence. The figure shows a useful range of operation of the dosimeter from 4 x 10^{13} to 8 x 10^{14} e/cm^2. Fluence values can be determined with this calibration curve with a maximum uncertainty of 5 % at one standard deviation.

The calibrated CTA films were used then to measure the fluence uniformity in two different experiments. First, on top of the moving platform of the linear motion system, and then on top of extended area solar cells (156 cm^2). Figures 5, and 6 show the results of the fluence uniformity for those experiments, respectively. As can be seen from these figures the fluence is fairly uniform in each instance. In the case of the platform the fluence did not change by more than 1.2% (1 standard deviation, see Figure 5a and 5b) over and area of 0.38 m^2 (1.25 m by 0.30 m). In the case of the solar cells irradiation, the fluence changed by no more than 1.2% (1 std. dev, see Figure 6a) along the long side of the aluminum plate, and no more than 0.9% (Figure 6b) along the short side of the aluminum plate.

The results presented in Figure 6 also allow us to compare the fluence measurements made with the CTA film, with those made by the FC. According to the graphs in Figure 6 the average fluence measurements with CTA film for the irradiation of solar cells experiment was 9.8 x 10^{13} e/cm^2 with an uncertainty of 1.2 % (one standard deviation), whilst the FC measurement gave a total fluence of 8.8 x 10^{13} e/cm^2. This gives an overall difference of 11 % with respect to the FC measurement. The fact that the CTA film is giving a higher fluence value can be due to the effect of backscatter electrons from the solar cells going back into the film, this effect contributing to the added absorbance value observed in the films, and not present in the case of the FC measurements. However further confirmation of this will be made with some Monte Carlo simulations.

Electrical measurement data for four cells (two monocrystalline and two polycrystalline) with similar initial characteristics were selected for analysis. Prior to irradiation the average maximum power measured was 159 mW for the monocrystalline solar cells and 158.5 mW for the polycrystalline cells. Average maximum power degraded to 56.5 mW for the monocrystalline cells and 52.5 mW for polycrystalline cells after they were subjected to a cumulative irradiation fluence of 2.6 x 10^{15} e/cm^2 (see Table 1). This represents an overall average change of 64.7% for monocrystalline and 66.9% for polycrystalline cells in maximum power degradation (see Table 2). The small variation between maximum power measurements at each fluence level with an overall standard deviation of 0.3 correlates with similar fluence uniformity as obtained from the CTA film measurements.

Short circuit current (I_{sc}) degraded an average of 63.8% for the monocrystalline solar cells and 64.1% for polycrystalline solar cells. Open circuit voltage (V_{oc}) degraded an average of 27.3% for both types of cells after irradiation to an accumulated fluence of 2.6 x 10^{15} e/cm^2 (see Table 3).

ACKNOWLEDGEMENTS

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REFERENCES

1. C. Vargas-Aburto and R. M. Uribe, “Electron Irradiation Facility for the Study of Radiation Damage in Large Solar Cell Arrays in the Energy Range 0.5 < E ≤ 5 MeV” Sol. En. Matls. Sol. Cells. **87**, 1-4, 629-36 (2005).

2. W. L. McLaughlin, A. W. Boyd, K. H. Chadwick, J. C. McDonald, and A. Miller, “Dosimetry for Radiation Processing”, Taylor and Francis (1989), p. 162

3. D. M. Korwin, C. Vargas-Aburto, R. M. Uribe, and K. J. Hudson “Design and construction of a Faraday Cup for electron fluence measurements in the energy range from 1 to 5 MeV.” Presented at the annual meeting of the American Physical Society, Austin TX, March 3-7, 2003.

4. D.M. Korwin, C. Vargas-Aburto, R.M. Uribe and D. Gentile “Development of a Third-Generation Material Handling System for Electron Beam Irradiation”, Presented at the annual meeting of the American Physical Society, Austin TX, March 3-7, 2003.

Table 1. Maximum Power (mW) Measurements in the irradiated solar cells discussed in this paper in the fluence range from 1 x 10^{13} to 2.6 x 10^{15} e/cm^2 with 5 MeV electrons.

Fluence |----------| Cells	0	1E13	1E14	1E15	2.6E15	Avg
M2	156	128	100	68	56	
M3	162	126	102	68	57	
Avg	159	127	101	68	56.5	
Std. Dev.	3	1	1	0	0.5	**1.1**
P1	156	128	97	64	52	
P2	161	128	101	66	53	
Avg	158.5	128	99	65	52.5	
Std. Dev.	2.5	0	2	1	0.5	**1.2**

Table 2. Percent Cumulative Change in Maximum Power Measurements for irradiated solar cells in the fluence range from 1 x 10^{13} to 2.6 x 10^{15} e/cm^2 with 5 MeV electrons.

	1E13	1E14	1E15	2.6E15
M2	-18.2	-36.3	-56.7	-64.4
M3	-21.0	-37.0	-58.1	-64.9
Avg	-19.6	-36.7	-57.4	-64.7
Std. Dev	1.4	0.4	0.7	0.3
P1	-19.5	-38.0	-58.9	-66.6
P2	-20.1	-37.3	-58.7	-67.2
Avg	-19.8	-37.7	-58.8	-66.9
Std. Dev	0.3	0.4	0.1	0.3

Table 3. Change in open circuit voltage (Voc) and short circuit current (Isc) for the irradiated solar cells described in this experiment, in the fluence range from 1 x 10^{13} to 2.6 x 10^{15} e/cm^2 with 5 MeV electrons.

	0		**2.6E15**	
	Voc	**Isc (ma)**	**Voc**	**Isc (ma)**
M2	0.55	755	0.40	269
M3	0.55	755	0.40	278
P1	0.55	657	0.40	242
P2	0.55	686	0.40	240

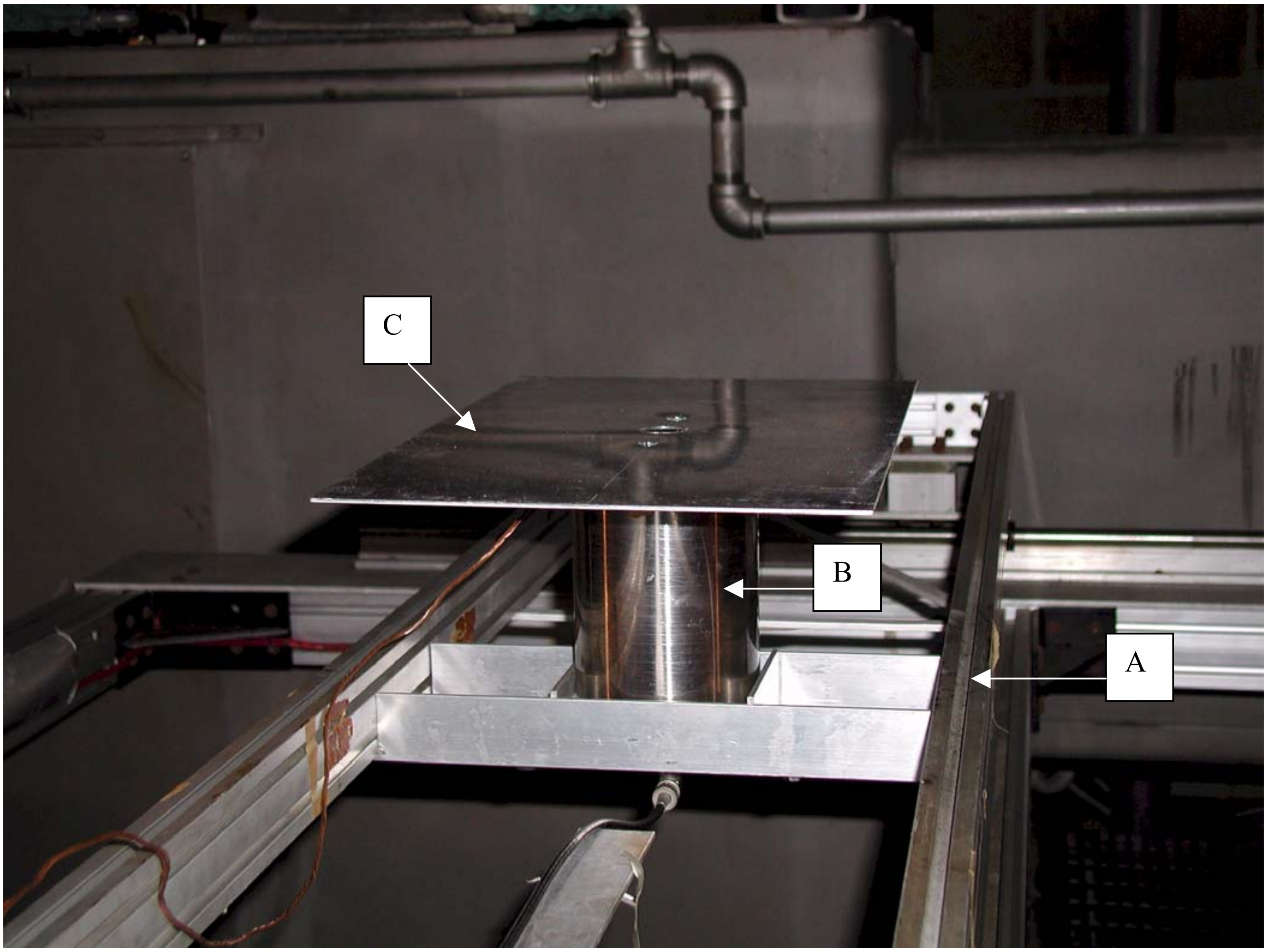

Figure 1. Photograph of the experimental setup to irradiate solar cells. The photograph shows the moving platform (A), the Faraday Cup (B), and the aluminum plate that serves as samples holder. The platform moves from left to right and back.

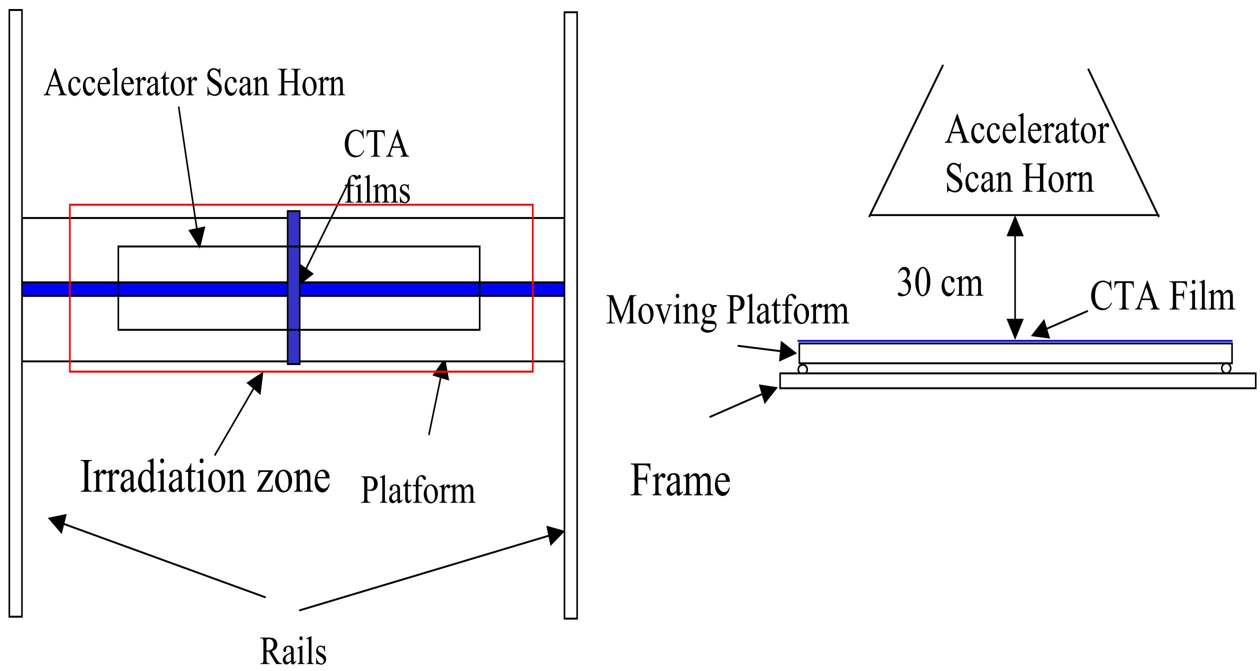

Figure 2. Schematic diagram of the irradiation setup used to determine the fluence uniformity on the moving platform used to irradiate solar cells. The diagram on the left shows a top view of the setup and the one on the right a side view in front of the scanner of the electron accelerator.

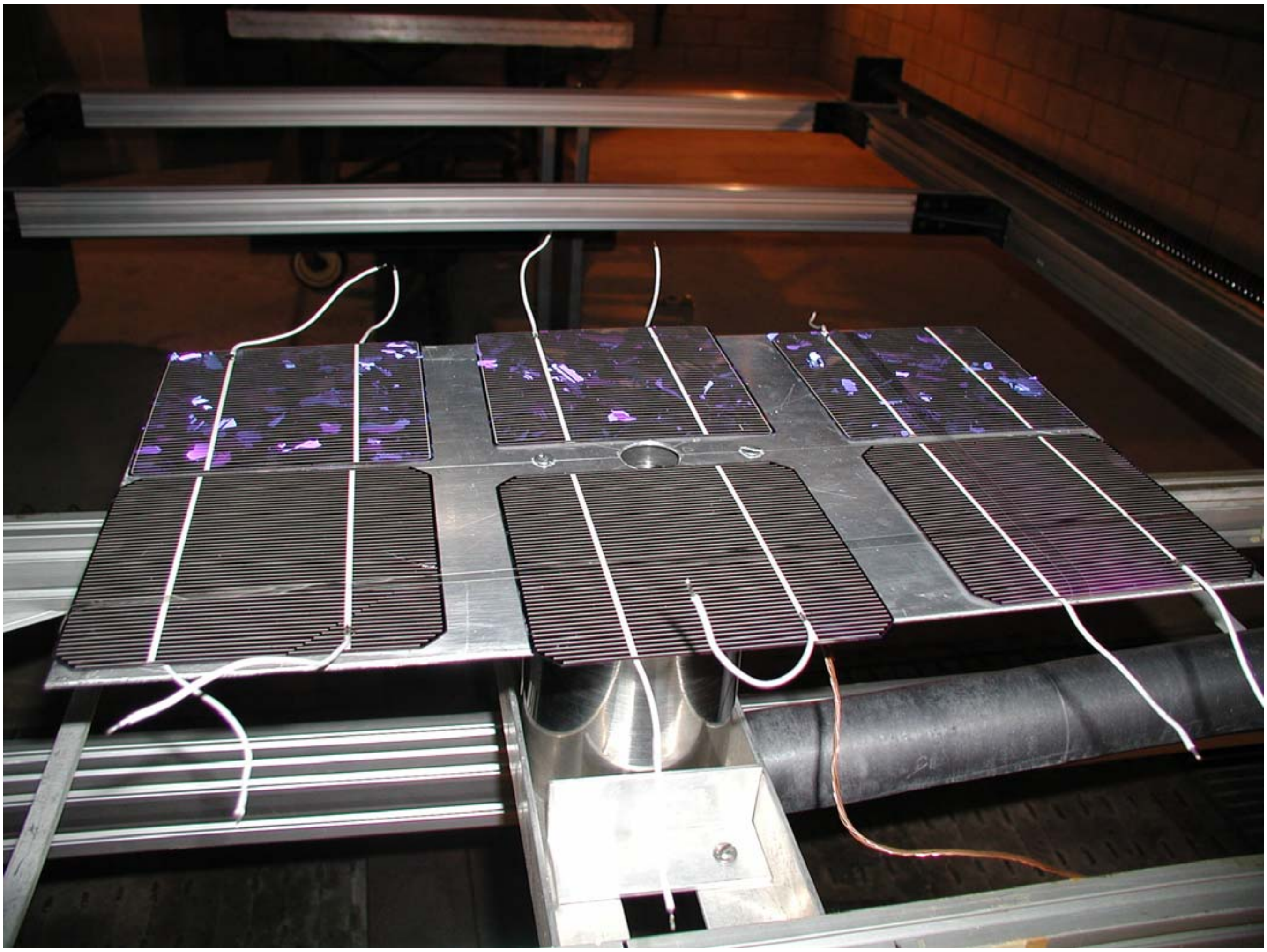

Figure 3. Solar cell irradiation using the FC setup. The solar cells were mounted on the aluminum plate on top of the FC. Three solar cells are monocrystalline Si, on the back; the other three are polycrystalline Si. BP Solar donated both types of cells. CTA film strips were placed on top of the solar cell array, one along the long side of the aluminum plate and the other one along the width of the aluminum plate. The solar cells were irradiated with 5 MeV electrons to a fluence value of 9×10^{13} e/cm^2 to determine the fluence uniformity with the CTA film.

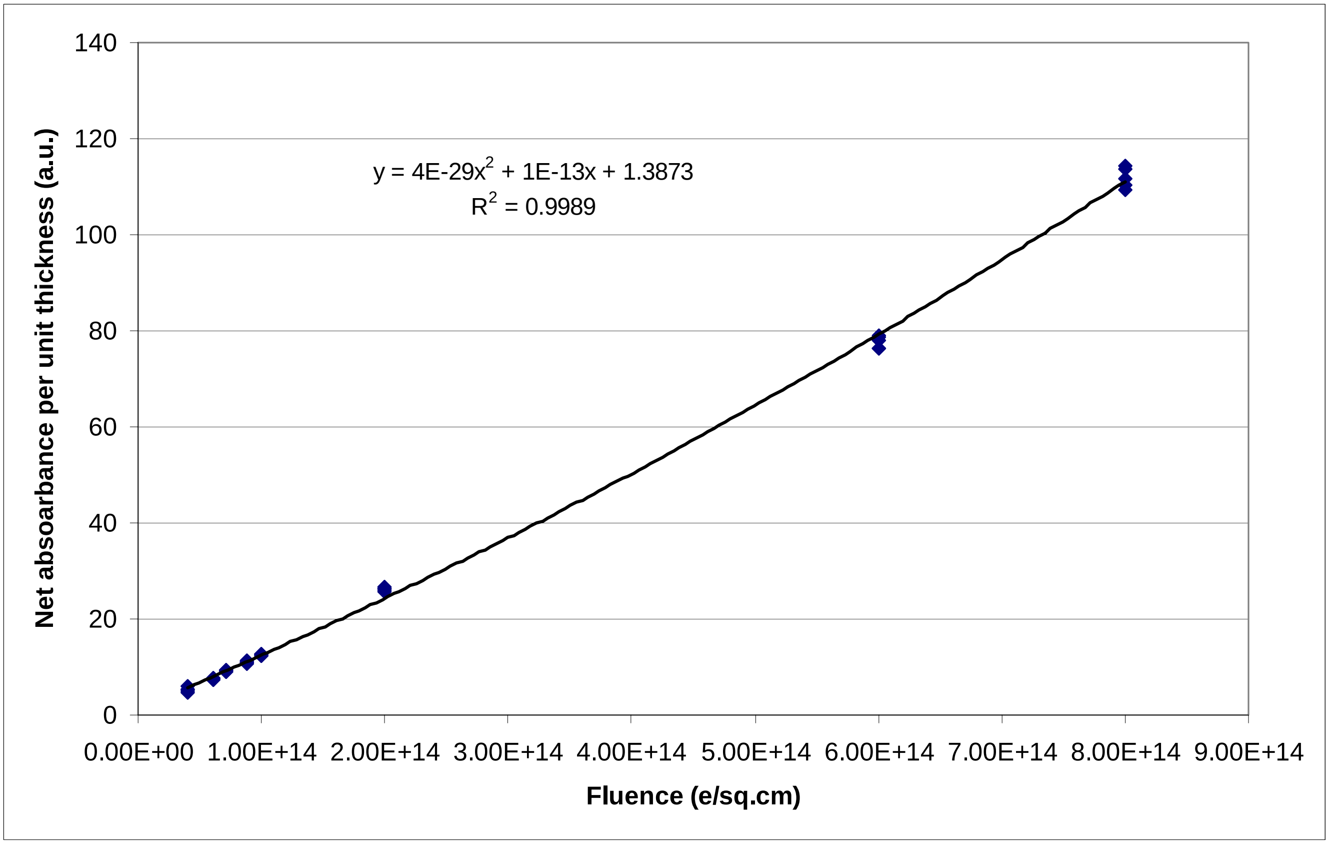

Figure 4. Calibration curve of the response of the CTA film in terms of fluence values. The films were irradiated with 5 MeV electrons and constant dose rate.

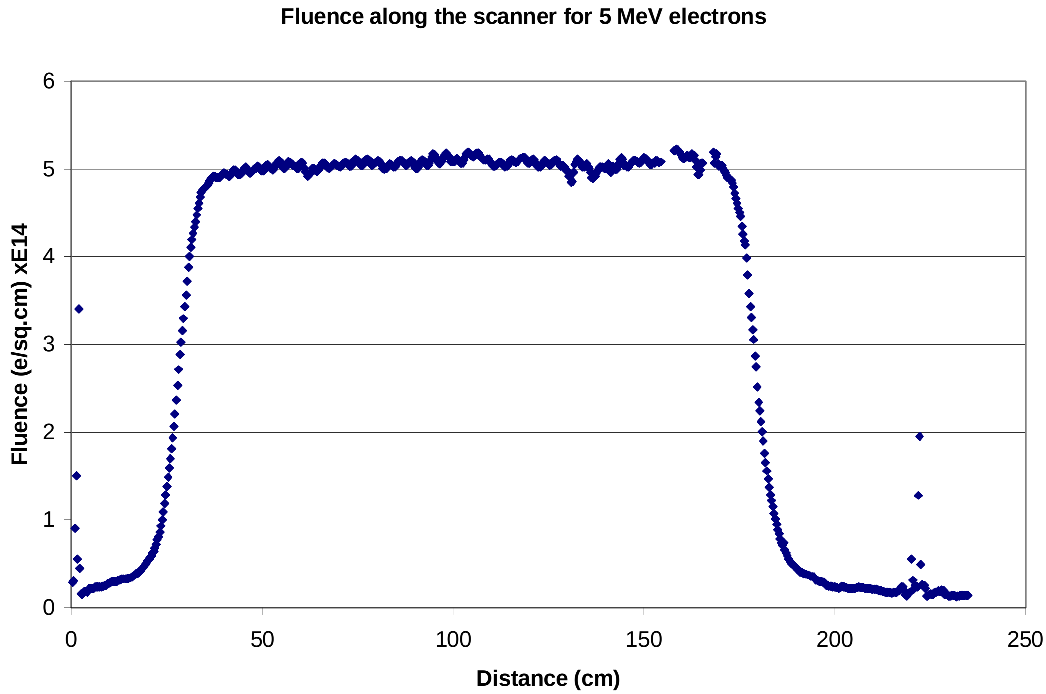

Figure 5a. Fluence uniformity along the moving platform of the linear motion system used to irradiate solar cells. The CTA film was irradiated with 5 MeV electrons to a total fluence value of 5 x 10^{14} e/cm^2

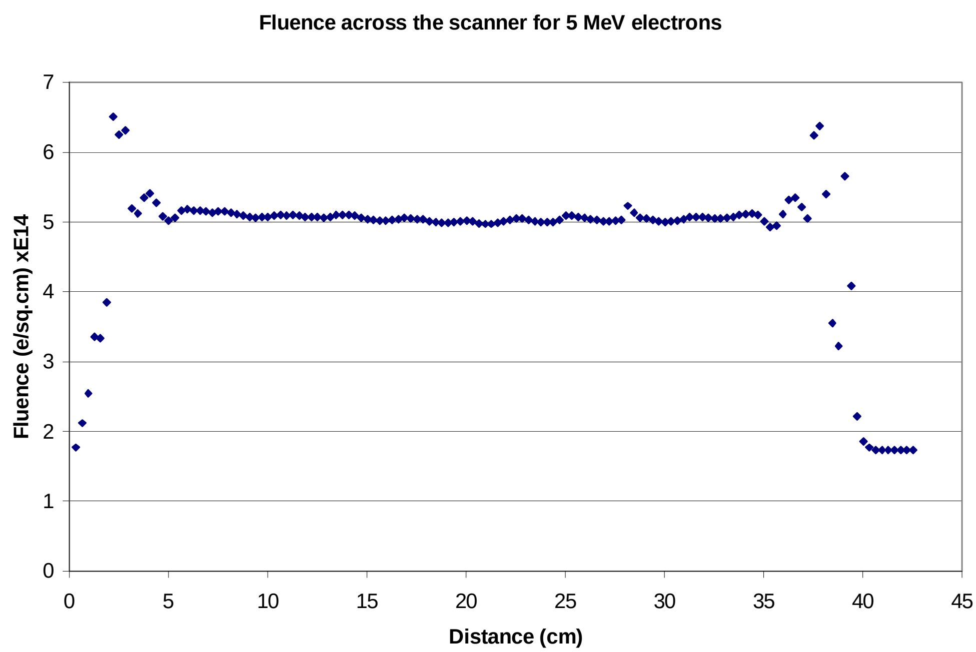

Figure 5b. Fluence uniformity across the moving platform of the linear motion system used to irradiate solar cells. The CTA film was irradiated with 5 MeV electrons to a total fluence value of 5 x 10^{14} e/cm^2

Long side of aluminum plate

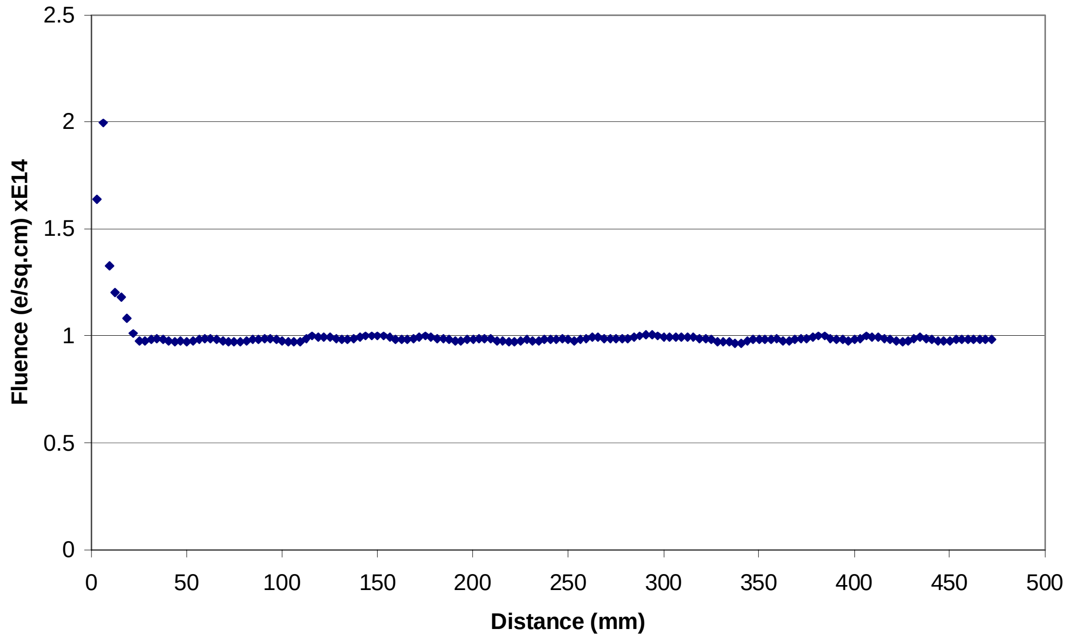

Figure 6a. Fluence uniformity on solar cells irradiated on top of the aluminum plate placed on top of the FC, along the long side of the aluminum plate. The CTA film strip was irradiated with 5 MeV electrons to a total fluence value of 9 x 10^{13} e/cm^2.

Short side of aluminum plate

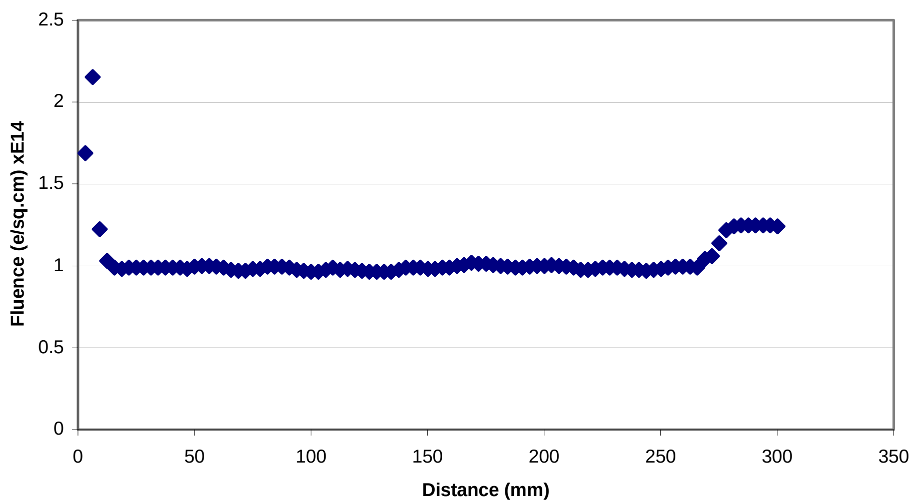

Figure 6b. Fluence uniformity on solar cells irradiated on top of the aluminum plate placed on top of the FC, along the short side of the aluminum plate. The CTA film strip was irradiated with 5 MeV electrons to a total fluence value of 9 x 10^{13} e/cm^2