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Abstract

We measured the absolute response of image plate (Fuji BAS SR2040) for electrons at energies between 100 keV to 4 MeV using an electron spectrometer. The electron source was produced from a short pulse laser irradiated on the solid density targets. This paper presents the calibration results of image plate Photon Stimulated Luminescence PSL per electrons at this energy range. The Monte Carlo radiation transport code MCNPX results are also presented for three representative incident angles onto the image plates and corresponding electron energies depositions at these angles. These provide a complete set of tools that allows extraction of our absolute calibration to other spectrometer setting at this electron energy range.

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I. INTRODUCTION

Energetic electrons are commonly produced from ultra-intense (10^{19} W/cm^2) laser-solid interactions. Diagnosing these hot electrons with energies up to MeV is of a fundamental importance to understanding the detailed laser plasma interactions, as well as in potential applications such as the fast ignition concept of inertial confined fusion research [1]. Previously we built an scintillator array coupled to a CCD based electron spectrometer which was calibrated using an electron gun [2]. Recently, we built a new set of electron spectrometers that uses image plates as the detector. Image plates (IP) were developed at first as an alternative to X-ray film [3], but later, it was found that as an effective measuring tools for energetic particles. For an electron spectrometer, using IP has multiple advantages compared to using a scintillator array coupled to CCD detector. First, with its scanning size being as small as 50 μm per pixel, IP allows much higher electron energy resolution than that of scintillator array, which is typically has more than 500 μm diameter in each fiber. Secondly, IP is not sensitive to the electric and magnetic pulses from the ultra-intense laser-solid interactions, which presents a harsh environment for CCD usage. Thirdly, comparing to CCD, IP is reusable and significantly more cost-effective. Lastly, using IP has no complex mechanical requirements such as vacuum electrical feedthroughs and cooling system as needed for a CCD in a spectrometer. Due to these compelling reasons, IPs have been chosen as detectors in electron spectrometers to study laser produced hot electrons for various short pulse laser physics experiments [4, 5].

To infer an absolute number of electrons from the dose collected by IP exposed to the source, we need the IP to be absolutely calibrated for the electron energy range of interest. A couple of groups have tried to address this issue. In 2002, Gonzalez et al. [6] reported the energy response of IP to different beta-sources. They showed that the response of IP is higher for lower beta energies (225 keV) than that of higher beta energies (up to 2 MeV). In 2005, Tanaka et al. [5] made the first measurement of the absolute IP response for three electron energies of 11.5, 30 and 100 MeV using a LINAC accelerator source. In addition, they also made a comprehensive study of the fading effect of IP dosage as time after exposure, and the effect of electron oblique incidence into the IP. So far, there are no measurements available on the absolute calibration of IP to energetic particles at energies less than 10 MeV. However, short pulse laser produced hot electrons at energies between 100 keV to a few MeV are of critical importance to fast ignition research which makes electron measurements at this energy range an important issue.

In this paper, we present measurements of the IP absolute response for hot electrons at energy range between 100 keV to 4 MeV produced on a short pulse laser plasma interaction experiment.

II. THE PRINCIPLE OF THE MEASUREMENT

We calibrated the photostimulated luminescence (PSL) of the image plate against the dose of a set of absolutely calibrated ultra-thin thermoluminescence dosimeters (TLD) by exposing both to the same electron source. Both IP and TLDs were placed on our electron spectrometers and the spectrometer was fielded in a short pulse laser experimental chamber. The principle of the calibration using the spectrometer is illustrated in Fig. 1. Energetic electrons entered the spectrometer through a slit into an uniform magnetic field of 750 Gauss where they experience Lorentz force and are bent to the side of the spectrometer with their relativistic Larmor radius. They were collected by the image plate that was at the side of the spectrometer.

During the calibration process, we placed the TLDs on the cut holes on the IP strip, as illustrated in Fig. 1. The electron source had good evenness across the detection plane perpendicular to the energy direction. The intensity variations in most cases were within 5%, therefore, we can assume that the TLDs and IP were exposed to the same intensity of electron source simultaneously. Once the exposure is made, the TLD and IP data was processed separately, as illustrated in the flow-chart in Fig. 2.

A. Image plate data process

The image plate in our calibration is Fuji BAS-SR 2040. Its manufacture composition is listed in Table I [7]. The IP was read out by the FLA-7000 image plate scanner [7] and recorded in unit of PSL.

The IP scanning pixel size was set to be 100 μm which corresponded to a much higher electron energy power than that of the TLDs, which have a diameter of 4.763 mm and were spaced along the IP every 12 mm. The corresponding electron energy grid for TLD

TABLE I: Image plate composition

Type	Layer	Depth (μm)	BaFBrI
BAS-SR 2040	Back	160	
	Base	190	
	Undercoat	12	
	Phosphor	121	BaFBr0.85I0.15
	Protective Coat	7	
	Total	490	

was therefore averaged over the range covered by the IP. Due to the non-linear dispersion of electron energy on the detection plate, we averaged the IP dose across the TLD by the weight. This procedure modifies the simple linear averaged value by at most 10%.

To account for the background noise of the measurement, we used the part of IP that was not exposed to the electron source but exposed to the same x-ray and γ-rays that affect the whole spectrometer. We found some variation of the noise value along the plate which could be real, but since the exact nature of the background noise is not known, we took the averaged value along the plate as background while the range of variation was taken as the uncertainty of the background measurement.

Another important factor to be taken into account is the fading effect which has been thoroughly studied by Tanaka et al. [5]. We took care to scan every image plate for 35 $\pm$ 5 minutes after exposure, which resulted in a signal level at about 65% relative to the original dose using equation given by Tanaka et al [5]:

$$f(t) = 0.16exp(-ln2 \times t/0.56) + 0.21exp(-ln2 \times t/11) + 0.63exp(-ln2 \times t/1991) \qquad (1)$$

This effect (as list in Table II) has been taken into account in our data analysis.

B. TLD data process

The ultra-thin TLD [8] has a diameter of 4.763 mm and was composed of LiF (with 0.07% Li6) doped with Mg (0.2 mol%), P(2.0 mol%) and Cu (0.035 mol%). The TLD and its readout were calibrated with a standard NIST traceable source, and the error in the calibration is about 5% [10]. The absolute dose (in rad) recorded by the TLD can be converted to energy (in J) per unit of area. We estimated the area in the TLD to be accurate to better than 5%.

To deduce the number of electrons from the TLD measurement, we used the calculation from a Monte Carlo radiation transport code MCNPX. The MCNPX code [9] was developed by Los Alamos National Laboratory. It is a three dimensional general purpose Monte Carlo radiation transport code that tracks neutrons, photons, protons, and electrons over a wide range of energy. For this study, we calculated fraction of electron energy absorbed by the TLD and IP material for each incident electron energy and incident angle defined by the spectrometer geometry. To account for all possible scattering effect, the calculation used a multileveled model to simulate the TLD and IP inside the spectrometer. For example, a three dimensional MCNPX image plate model includes a 9-micron thick polyethyleneterephthalate (PET) front layer followed by a 120-micron thick BaFBrI image plate. A 500 μm PET and 3175 μm Al plates were also included at the back side of the image plate to simulate the housing of the spectrometer. The calculations were performed with various incident energy and angle beam sources (see TABLE II) located at 10 cm from the image plate.

We found from the MCNPX calculations that the environment of either IP or TLD can affect the deposited electron energy. This is shown in Table II, where we listed the calculation results for TLD material only, and for TLD backed with 50 μ m poly and 3.175 mm thick Al, as in the actual spectrometer setting. The difference in the deposited energy for the latter case is overall larger than the TLD only case. This is likely caused by the back scattering of electrons from the back layers of material. Also in Table II, we listed the MCNPX calculation for the actual IP (composition listed in Table I) in the spectrometer. We also studied the deposited electron energy on the IP related to the electron incident angles (θ), with θ being the angle between the electron trajectory entering the image plate and the normal of image plate. We found that for high electron energy (20 MeV), the effect of angular incident can be simply scaled with $1/\cos(\theta)$, which is an extended interaction length between electrons and IP. For electron energy less than 20 MeV, the angular incident effect is however more complicated. The details are described in Section IV.

Finally, the number of electrons per unit of area derived from TLD is then compared to the PSL per unit of area measured by the image plate, which results in the number of electron per PSL for each electron energy and electron incident angle, as will be discussed

TABLE II: MNCPX TLD electron stopping energy results

Electron energy (MeV)	Incident angle θ (degree)	Deposited energy (MeV)		
		TLD only	TLD-poly-Al	IP
0.12	68	7.31E-02	7.41E-02	4.54E-02
0.20	30	3.75E-02	4.43E-02	1.27E-01
0.35	0	1.81E-02	2.12E-02	1.35E-01
0.60	16	1.66E-02	2.18E-02	9.64E-02
1.00	30	1.69E-02	2.27E-02	8.59E-02
1.60	38	1.80E-02	2.36E-02	8.60E-02
2.00	44	1.96E-02	2.61E-02	8.84E-02
3.00	52	2.30E-02	3.06E-02	1.02E-01
4.00	56	2.57E-02	3.40E-02	1.10E-01
5.00	60	2.92E-02	3.87E-02	1.28E-01

in the Results and Discussion section.

III. EXPERIMENTS

It has been known that ultra intense short pulse laser pulses incident on solid targets can generate energetic electrons either from direct laser electric field acceleration or the ponderomotive force associated with the gradient of the field. These electrons can then generate energetic protons due to the target normal sheath acceleration mechanism [11]. For our purpose, we used these energetic electrons produced from short pulse laser as our source.

Our experiments were performed at Titan short pulse laser facility [12] at Lawrence Livermore National Laboratory. The overall peak laser intensity measured from 16 bit focal spot images of the OPCPA to be about 10^{20} W/cm^2. The target variation was for other experimental purposes, not critical to these measurements. We took 15 measurements. The conditions of these measurements are listed in Table III. Each set of data was analyzed independently.

TABLE III: Laser shot conditions

Shot	Laser E (J)	Pulse (fs)	Target	IP Scan) (mins)	IP Fading (f(t)/f(0))
1	141	700	10um A/25um Cu/1mm Al foil	32	0.65
2	141	700	10um Al/25um Cu/1mm Al foil	32	0.65
3	130	700	Cu cone	29	0.66
4	130	700	Cu cone	29	0.66
5	60	700	Cu cone	30	0.66
6	60	700	Cu cone	30	0.66
7	140	700	25um thick Cu foil	35	0.65
8	140	700	25um thick Cu foil	35	0.65
9	151	700	25um thick Cu foil	39	0.64
10	35.5	700	25um thick Cu foil	33	0.65
11	134	700	25um thick Cu foil	35	0.65
12	146	700	25um thick Cu foil	40	0.64
13	146	700	25um thick Cu foil	40	0.64
14	117	700	Cu cone	31	0.65
15	117	700	Cu cone	31	0.65

IV. RESULTS AND DISCUSSION

Each measurement resulted in a set of IP calibration data together with its own error assessment. The error of the measurements was estimated including the uncertainty in the IP and TLD background subtraction, TLD readout error (about 5%) and error in the TLD area measurement (up to 5%). All the data was then averaged to produce the final calibration of the image plate, as shown in Fig. 3. Also plotted in Fig. 3 are the absolute calibration results from Tanaka et al. [5] for higher electron energies.

To extend this IP calibration to any other instrument setting, one needs to consider their specific geometry setting which likely leads to different electron incident angle. We have performed MCNP calculations for three incident angles of 30, 60 and 90 degree. The results are shown in Fig. 4. In the upper panel of Fig. 4, we plotted the actual electron deposited energies on IP for electron energy up to 100 MeV at the three angles, while at the lower panel, we plotted the ratio between the actual deposited energy and that scaled with $1/\cos\theta$. As mentioned before, the scaling of $1/\cos\theta$ does not appear to be accurate to account for electrons at energies less than 20 MeV. This is because high energy electrons have forward dominant scattering behavior which results in the deposited electron energy being proportional to its path length.For low energy electrons, we do not see those trends due to energy leakage/loss by low energy electron isotropic scattering (or none-forward scattering).

With the angular scaling (Fig. 4) and the calibration results (Fig. 3), one should be able to extract calibration that is unique to individual electron spectrometer.

V. SUMMARY

We presented the results from measurements of the image plate absolute response (Fuji BAS SR2040) for electrons at energy between 100 keV to 4.5 MeV, and the MCNPX calculation results of electron energies deposition for three incident angles. These provide a complete set of tools that allows extraction of our absolute calibration to any other spectrometer setting at this electron energy range.

Acknowledgments

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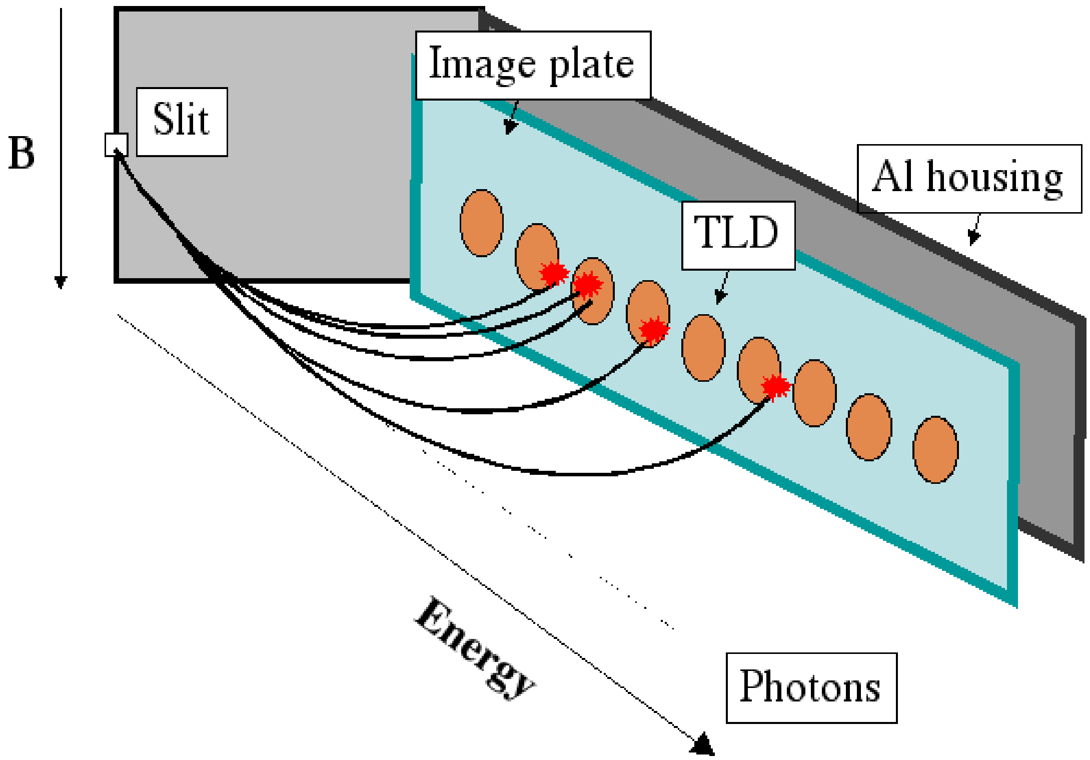

FIG. 1: Illustration of the electron spectrometer and calibration setup.

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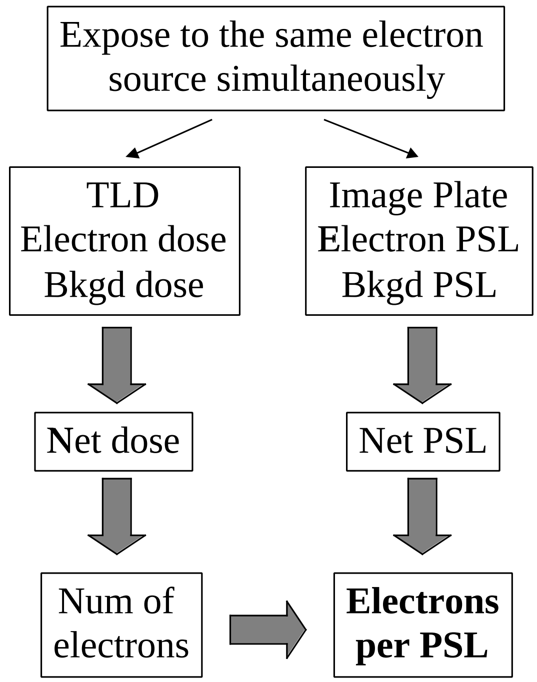

FIG. 2: A flow-chart on the calibration method.

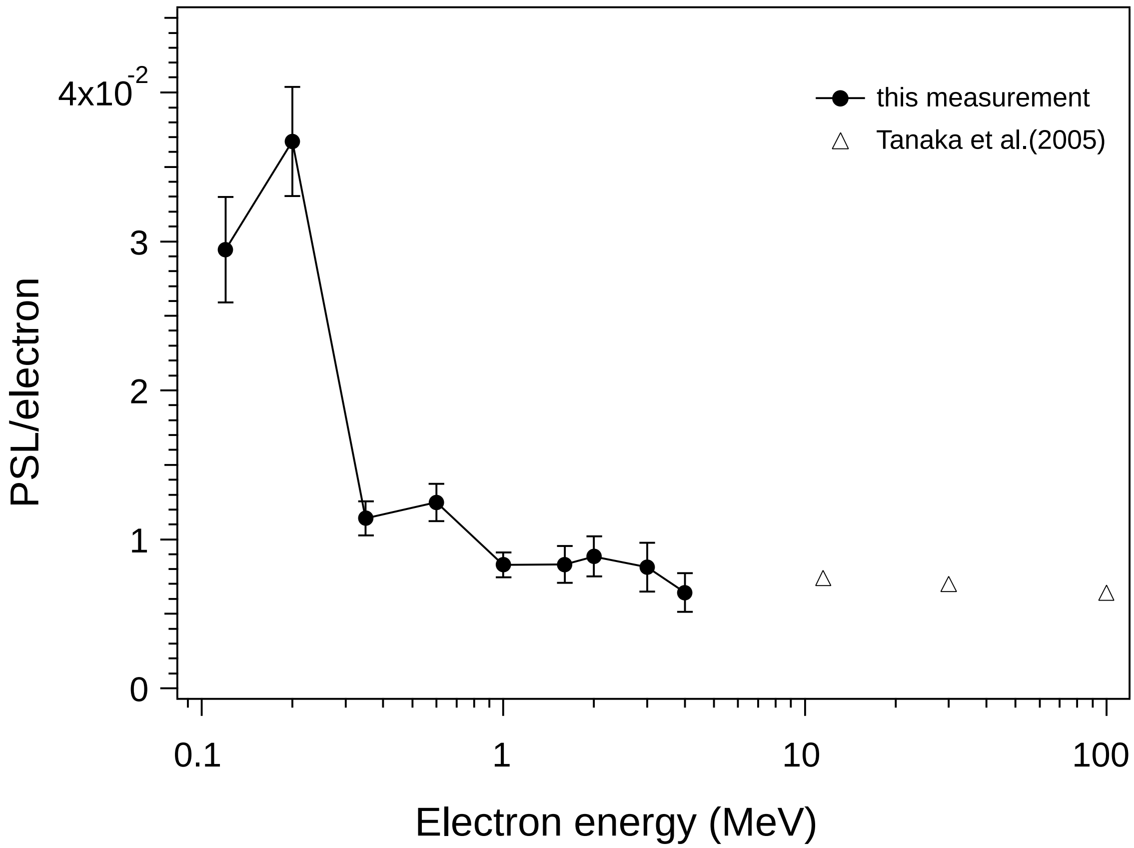

FIG. 3: Absolute response of the IP to electrons at energy between 100 keV and 4 MeV (Solid dots and error bar). Also shown are the calibration at higher energy by Tanaka et al. [5] (trangles).

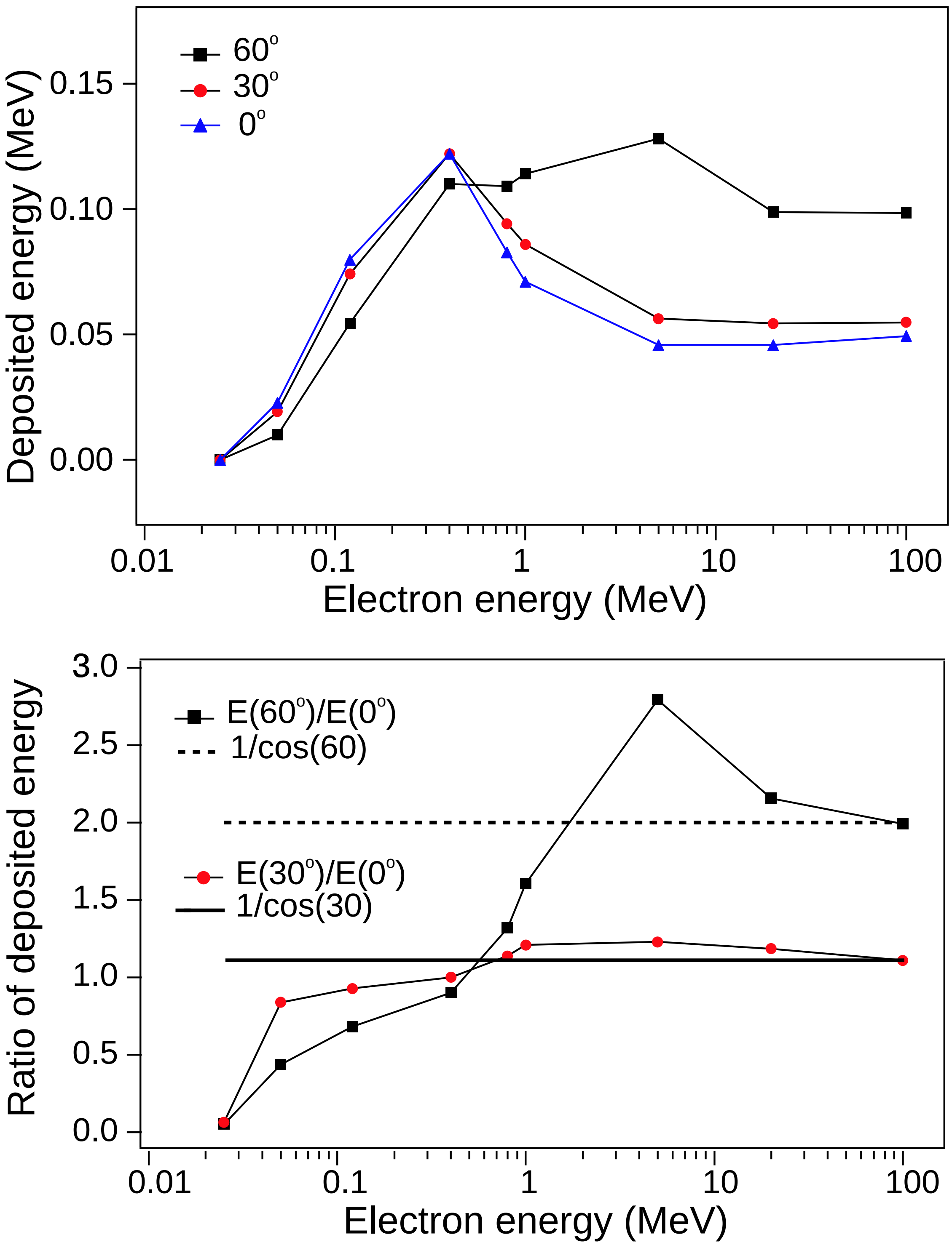

FIG. 4: MCNP calculation of electron scattering in IP at three incident angles of 30. 60. and 90 degrees for energy between 100 keV and 100 MeV (Upper panel), and the ratio between the calculated scattering raltive to the ones scalled with the $1/\cos\theta$ (Lower panel).