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ENERGY DEPENDENCE OF SECONDARY EMISSION MONITORS BETWEEN 10 MEV AND 5 GEV

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Abstract

It is shown that the energy dependence of secondary emission monitors built of thin aluminum foils is in agreement with the theoretical treatment of Aggson[1)] in the energy range from about 10 MeV to 5 GeV. The secondary emission yield increases logarithmically with energy up to about 1 GeV. Beyond 1 GeV the increase with energy depends on the distance between the foils and, for a foil distance of 1 cm, becomes nearly constant above 2 GeV. For energies beyond 5 GeV (e.g. SLAC), a stable and practically energy independent SEM, built of gold plated aluminum foils with a spacing of 0,5 cm, is recommended.

Introduction

The secondary emission monitor (SEM) developed by Tautfest and Fechter[2] is widely used for monitoring high energy electron beams. The SEM is constructed of two sets of thin metal foils - usually aluminum of about 10^{-3} cm thickness - which are alternately connected to a bias voltage and a charge measuring device. The foil assembly is placed into a high vacuum of 10^{-5} to 10^{-7} Torr. Thin windows for beam entrance and exit reduce the scattering of the beam to a tolerable level. The efficiency of the SEM - the ratio of the secondary current to the primary current - is about 50 % with 20 aluminum foils.

The main advantage of the SEM over the ionization chamber is its linear response over a wide range of beam intensities.

The stability of the SEM with aluminum foils is about 1 % over several days, but may change by several per cent during the first hour of a run and for long periods of time. The secondary emission coefficient of the foils depends on the surface condition and on the sign and value of the bias voltage. It may, therefore, greatly vary between different laboratories.

The experimental evidence on the energy dependence of the secondary emission yield is quite complex. Earlier measurements show a constant response[2-5], but during the last years significant variations with energy have been found[6-10].

Several attempts have been made[1,2,11,12] to explain the general behaviour of the energy dependence. According to Aggson[1] the secondary emission coefficient should become constant beyond a characteristic energy of about 1 GeV, which depends on the distance between the foils. Recently,

de Pagter and Fotino[13] and Ladage and Pingel[14] have measured the secondary emission yield in the range from 1,5 GeV to 5 GeV. Their data indicate a remarkable agreement with Aggsons' prediction, as will be shown in the following sections.

Theory

Aggson[1] has treated the secondary emission by comparison with the energy loss due to ionization. In fig. 1 the secondary emission coefficient δ of several experiments[9,10,15,16] is plotted against energy according to Aggson. The data have been completed by the measurements of de Pagter and Fotino[13] and of Ladage and Pingel[14]. The general behaviour of this curve is similar to the well known energy loss by ionization. One should expect that the secondary emission can be described by the same theoretical formalism as the energy loss, if one neglects multiple scattering of the primaries and other effects which play a role at low energies only. In order to do this, Aggson assumes a constant maximum energy transferred of η = 10 KeV only, since the secondary electrons have energies of the order of 10 eV and emerge from a thin surface layer of about 100 Å thickness[17]. Inserting this constant value into the theory of ionization loss, one obtains a constant energy loss above 1 MeV, if one takes into account the so-called density effect due to the polarization of the material. This disagrees with the experimental data, as shown in fig. 1.

On the other hand, if one neglects the density effect, the expected energy loss at relativistic energies increases with increasing energy: the electromagnetic field of the particle contracts in the direction of motion, but expands

transversally and hence causes more ionization loss and secondary electron emission in surface elements farther away.

This behaviour of the ionization loss without density effect is given by the well known Bethe-Bloch formula:

$$\frac{dE}{dx} = \frac{const}{\beta^2} \left[\ln \{ \frac{2m_o c^2 \cdot \eta \cdot \beta^2}{I^2(1-\beta^2)} - \beta^2 \right] \qquad (1),$$

where $\beta = v/c$, η = maximum energy transferred, and I = average ionization potential of the medium. The expression increases logarithmically with energy but, for constant η, yields a rise which is twice as high as found experimentally between 50 MeV and 500 MeV. This suggests that the energy dependence of the SEM is given by the sum of the energy losses with and without density effect, which can be understood by the following arguments of Aggson.

In order to include the density effect in equation (1) he replaces the $(1-\beta^2)$-term by a term $(1-\beta^2+\beta^2 \cdot \frac{4\pi n Z \hbar^2 c^2 r_o}{I^2})$ where $r_o = \frac{e^2}{m_o c^2}$ is the classical electron radius and $n \cdot Z$ is the number of electrons per cm^3 of the medium, obtaining

$$\frac{dE}{dx} = \frac{const}{\beta^2} \left[\ln \{ \frac{2m_o c^2 \cdot \eta \cdot \beta^2}{I^2(1-\beta^2+\beta^2 \frac{4\pi n Z \hbar^2 c^2 r_o}{I^2})} \} - \beta^2 \right] \qquad (2),$$

which indeed becomes constant beyond about 1 MeV.

The argument for combining equation (1) and (2) comes from the so-called "field forming distance" parallel to the particle's trajectory. This is the minimum length of trajectory necessary to produce ionization at the maximum possible distance from the trajectory. At the entrance

side of the foils of the SEM, the field forming distance is large compared to the maximum depth of secondary production (100 Å), and the electromagnetic field of the incident particle was "formed" while the particle was still in the vacuum. Thus, for the energy loss at the entrance side of the foils no density effect should occur. At the exit side of the foils, however, the energy loss including the density effect is expected, since the field forming distance in the aluminum is smaller than the foil thickness of 10^{-3} cm. The secondary emission coefficient therefore should be proportional to the sum of equation (1) and (2):

$$\delta = \frac{\text{Const}}{\beta^2}\left[\ln\left\{\frac{2m_o c^2 \cdot \eta \cdot \beta^2}{I^2(1-\beta^2)(1-\beta^2+\beta^2\,\frac{4\pi n Z \hbar^2 c^2 r_o}{I^2})}\right\} - \beta^2\right] \qquad (3)$$

The energy dependence of this formula in the relativistic region has one half the relativistic rise of the case with no density effect (eq. 1). Aggson compared this equation with the measurements of Richter et al[10] and found excellent agreement between 70 MeV and 400 MeV.

The field forming distance increases with energy and can become comparable to the distance t between the foils of the SEM. From there on the electromagnetic field at the entrance side of the foils no further is formed in the vacuum, but in the foils upstream. For a foil spacing of t = 1 cm the secondary emission of the SEM should thus become constant beyond about 1 GeV. Aggson accounts for this effect by replacing the $(1-\beta^2)$-term by a term $(1-\beta^2+\frac{\hbar c}{tI})$ and obtains for the energy dependence of the secondary emission coefficient of the SEM, i.e. the secondary yield devided by the number of electron emitting surfaces,

$$\delta = \frac{\text{Const}}{\beta^2}\left[\ln\left\{\frac{2m_0c^2\cdot n\cdot\beta^2}{I^2(1-\beta^2+\frac{\hbar c}{tI})(1-\beta^2+\beta^2\frac{4\pi nZ\hbar^2c^2r_0}{I^2})}\right\}-\beta^2\right] \quad (4)$$

Equation (4) is expected to be valid for primary energies above 10 MeV.

Comparison with experiments

As mentioned in the introduction, the absolute value of the secondary emission coefficient δ depends on the condition of the surfaces of the aluminum foils. The absolute value of δ for a given energy may therefore vary by about 20 % between different experiments. Comparing with Aggson's formula, we can only expect that the energy dependence is correctly described.

In fig. 2 the experiments of Richter et al[10] between 20 MeV and 600 MeV and the experiments of de Pagter and Fotino[13] and of Ladage and Pingel[14] between 1,5 GeV and 5 GeV are compared with the calculated data. The value of the constant in Aggson's equation has been chosen to yield $\delta = 3{,}20 \cdot 10^{-2}$ at 5 GeV. A foil distance t = 1 cm as in the SEM of Ladage and Pingel has been used for calculating the solid curve. The rise of this curve between 1,8 GeV and 5 GeV is 1 %. This is in good agreement with the measurements of Ladage and Pingel, who found a constant $\delta = (3{,}20 \pm 0{,}03)\cdot 10^{-2}$ in this energy interval. These authors controlled the response of their Faraday cup, in addition to the usual procedure of applying bias voltages to the cup, by applying potentials to a grid surrounding the absorber. Furthermore, they compared the cup with a calorimeter and found excellent agreement. The charge loss of the Faraday cup was only 0,3 % up to 5 GeV.

Between 20 MeV and 600 MeV, the solid curve is about 7 % higher than the measurements of Richter et al[10]. Its slope, however, agrees very well with the measurements, as can be seen from the dotted curve which has been drawn parallel to the solid curve.

The dashed curve between 1 GeV and 5 GeV has been calculated for a foil distance of 1,4 cm, which is close to the distance used by de Pagter and Fotino (as estimated from a photograph of the SEM in their report[13]). The rise of the curve between 1,5 GeV and 5 GeV is 2 %, while de Pagter and Fotino found about 4 %. However, if one corrects for the energy dependence of their Faraday cup, which is about 1 %, the increase with energy reduces to 3 %. Within experimental errors, this is in good agreement with the calculated 2 %, as shown by the dash-dotted curve of fig. 2, which has been drawn parallel to the dashed curve.

Fig. 3 shows the comparison between theory and measurements in the energy interval between 1 GeV and 5 GeV at a larger scale.

For computation of δ, the following data have been used:

maximum transferred energy $\eta = 10^4$ eV
average ionization potential $I = 10^2$ eV
number of electrons per unit volume $n \cdot Z = 2{,}25 \cdot 10^{23}$ cm^{-3}

The data for I and $n \cdot Z$ are calculated for Al_2O_3 rather than for aluminum. This was thought to be more reliable, since the maximum depth of secondary emission is only 100 Å[17], and the saturation thickness of the Al_2O_3 has been measured by electron diffraction to be higher than 50 Å [18]. With the data for aluminum the slope of the curve would nearly be doubled between 1,5 GeV and 5 GeV, and the agreement with experiments would be poorer.

Conclusions

Aggson's theory for the secondary emission coefficient δ is found to be in excellent agreement with experiments; in particular, the prediction that δ becomes constant beyond about 1 GeV seems to be verified. For future electron accelerators with energies up to 40 GeV (SLAC), the SEM with thin aluminum foils and a foil distance of 0,5 cm should show a constant energy response above about 1 GeV and, instead of a Faraday cup, may be used for beam monitoring. The long term stability of the SEM with aluminum foils may be improved by plating the foils with gold[19]. This will shift the constant energy response towards higher energies due to the increase of the average ionization potential I ($I_{Al_2O_3}$ = 100 eV; I_{Au}=870 eV). In the energy interval between 1 GeV and 5 GeV, the secondary emission will then increase by app. 6 % for a foil distance of 0,5 cm, which may be achieved without mechanical difficulties. For absolute monitoring in this region, this energy dependence partly compensates the advantage of stability. Above 5 GeV, however, the efficiency of the SEM will change by less than 1 % only, and the gold plated SEM, therefore, is recommended as a useful beam monitor for SLAC.

Following Aggson's suggestion, one may change the secondary emission efficiency of the foil surfaces by coating with special materials. MgO_2, for instance, would give about 6 times more secondary electrons than aluminum[20].

Since the beam exit side of the foil has no energy dependence, this surface should be of a material with high secondary emission, while the beam entrance side should have low efficiency, because this side accounts for the energy dependence. However, it might not be easy to find appropriate coating materials of stable response.

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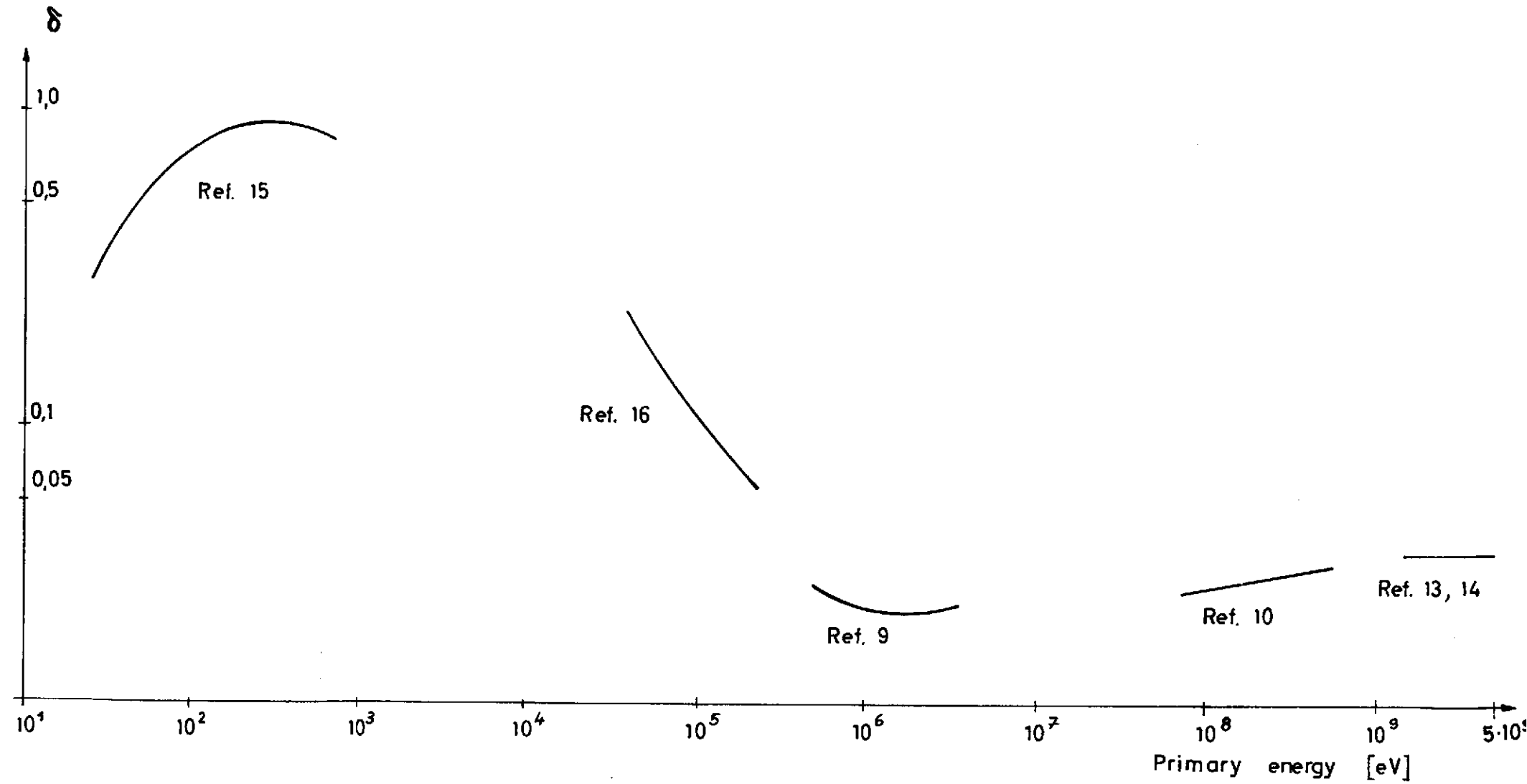

Fig. 1: Secondary emission coefficient for aluminum between 50 eV and $5 \cdot 10^9$ eV.

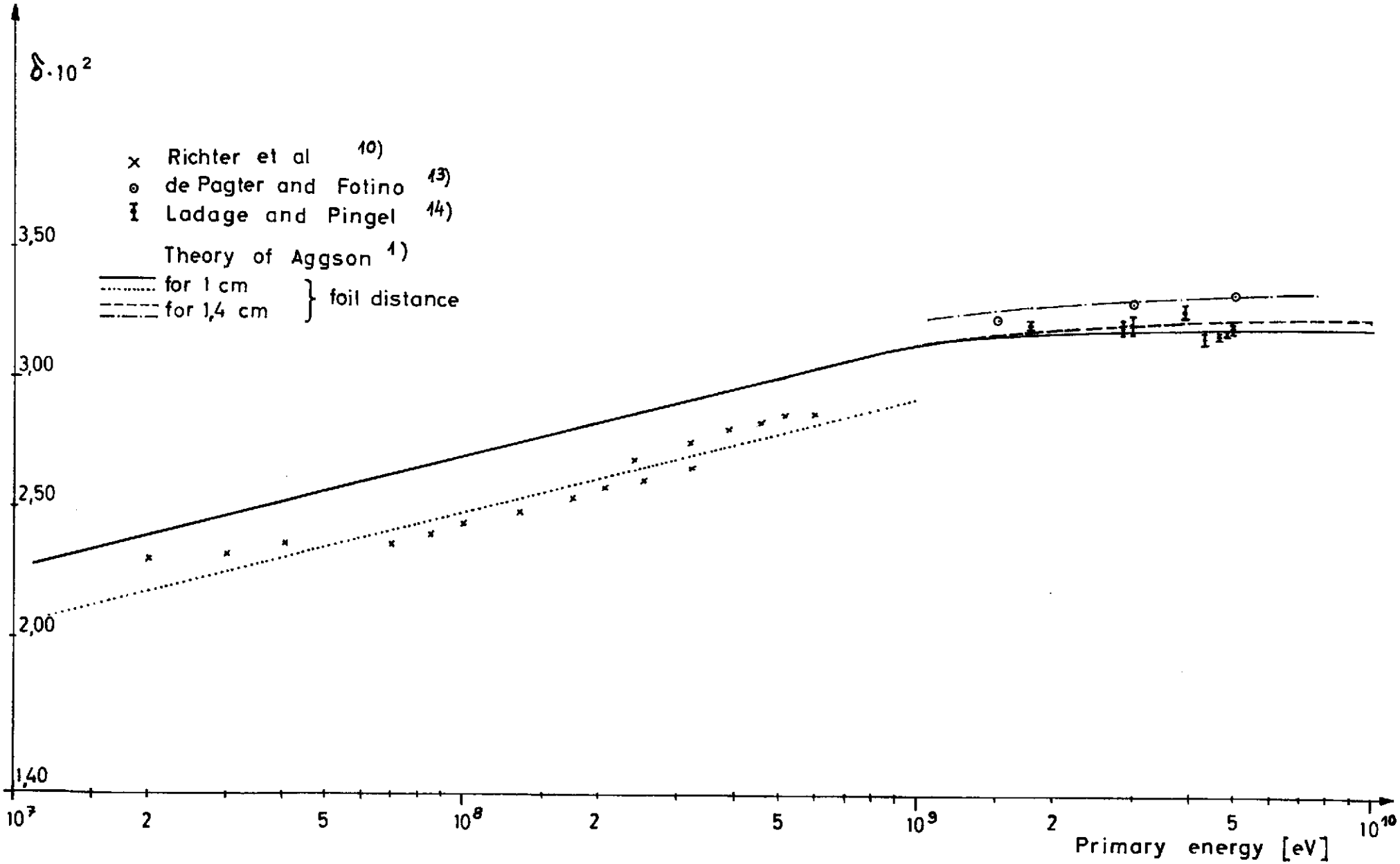

Fig. 2: Energy dependence of secondary emission coefficient δ.

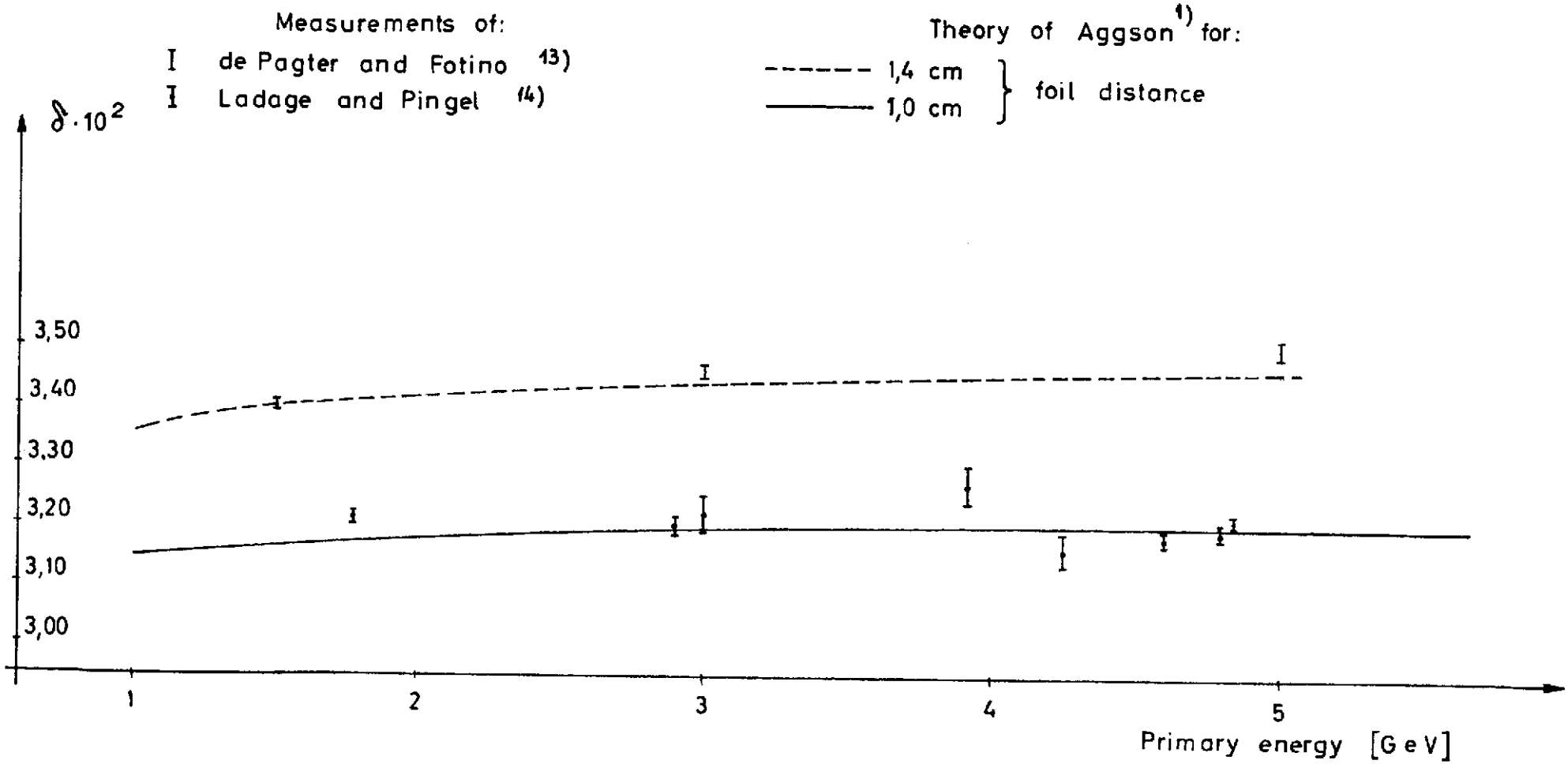

Fig. 3: Energy dependence of secondary emission coefficient δ.