Study of low multiplicity electron source LEETECH with diamond detector

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ABSTRACT: In this paper, we present experimental and numerical studies of the calibration of low-multiplicity electron source using signals from electrons incident on a diamond detector. The experiments were performed at the newly commissioned versatile LEETECH platform at the PHIL photoinjector facility at LAL. We show that with a single crystal CVD diamonds of 500 micrometers thickness, the energy losses from the first three electrons of 2.5–3 MeV are clearly resolved. The described technique can be used as a complementary approach for calibration of diamond detectors as well as for diagnostics of accelerated beam halos in a regime down to a few particles.

KEYWORDS: Beam-line instrumentation (beam position and profile monitors; beam-intensity monitors; bunch length monitors); Diamond Detectors; Instrumentation for particle accelerators and storage rings - low energy (linear accelerators, cyclotrons, electrostatic accelerators)

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## 1 Introduction

LEETECH (Low Energy Electron TECHnique) is a versatile source of electrons with adjustable sample intensity and energy [1]. LEETECH is based on the beam from the PHIL photoinjector at LAL [2]. The energy and direction of the PHIL electrons are smeared using an aluminum attenuator. Sample energy is defined by the magnetic field of the spectrometer ensuring a half-turn of the selected electrons and collimator systems define sample content and its energy spread.

Conceptually the principle of obtaining electron samples with adjustable characteristics has been developed using a powerful radioactive source in 1970 [3]. In addition, close approaches are used for material studies employing electrons of eV to keV energy scale issued from the cathodes in electron energy loss spectrometry as e.g. in ref. [4]. For the commissioning and calibration of LEP calorimeter a source of a few electrons in a single bunch was built based on the LEP pre-injector [5]. The ELBE facility in Germany, by using a different approach, in which the scattering of electron bunch occurs in the middle of the two accelerating sections, demonstrated the test beams of single electrons of energies up to 40 MeV [6]. At higher energies between 50 and 800 MeV, BTF provides a versatile test beam facility, having also demonstrated a feasibility of low-multiplicity operation mode, including signals from a single electron [7]. While inheriting a basic principle from ref. [3], LEETECH platform employs the PHIL electron beam to produce adjustable electron samples and covers energy range between few hundreds keV and 3.5 MeV.
LEETECH provides a compact low-energy electron source for characterisation and quality control of a wide range of detector techniques, including semiconductor detectors, scintillating materials, and gaseous tracking detectors. One of the key goals of LEETECH is to ensure low-multiplicity operation mode with a capability to deliver calibrated samples of a few electrons with energy spread at the level of a few percent.

An important demonstration of providing few-electron samples, including samples with a single electron, is performed using a Diamond Sensor (DS). Physics properties and the ability to detect single electrons with diamonds are discussed e.g. in refs. [8–11]. Recently S. Liu and co-authors [12], using the in-vacuum DS successfully demonstrated a dynamic range of $10^6$ by simultaneous beam core ($10^9$ electrons) and beam halo ($10^3$ electrons) measurements at ATF2. In this paper we investigate a capability of diamond sensors to distinguish between signals from 1, 2, and 3 electrons. Systematic studies of DS sensitivity to a few electrons require electron sources operating in low-multiplicity mode. The knowledge of DS operation in this regime is crucial, for several applications, and in particular for the experiments at high energies, where the detector is located near a beam pipe (beam loss monitors), where showers from high-energy particles are almost completely absorbed leading to only a few particles intercepted by the DS [13].

This paper is organized as follows. In section 2 we discuss the relevant characteristics of the PHIL accelerator and a operation principle of the LEETECH platform. Simulation of the experimental setup is also addressed. Section 3 is dedicated to the low-multiplicity operation mode, explaining both the correspondingly required LEETECH settings and approaches used to determine the number of electrons in the sample. Diamond detector design and calibration is described in section 4. Experimental measurements of the LEETECH electrons using diamond detector are addressed in section 5. The results are discussed in section 6, followed by a summary in section 7.

## 2 LEETECH spectrometer at the PHIL photoinjector

### 2.1 Principle of operation

The LEETECH operation is initiated by the bunches of few $10^8$ electrons which are generated and accelerated to 3.5 MeV by PHIL. The principal parameters of PHIL and LEETECH are presented in table 1. LEETECH spectrometer is installed at the extremity of the PHIL direct beam line (figure 1). The beam is degraded by the aluminum attenuator introducing large momentum and angular distribution spreads. The collimator system selects a direction of electrons sent to the spectrometer also adjusting the intensity. The obtained narrow secondary beam passes the magnetic field region inside the vacuum chamber. At the exit the electrons are again filtered by a collimator system and pass through a thin (100 µm) aluminium exit window before reaching the detector.

Depending on the desired energy of the delivered sample different attenuator thickness is preferred. Several aluminum attenuators 100 µm to 6 mm thick have been manufactured. A detailed study of LEETECH parameters, such as the role of the attenuator thickness, the magnetic field and the optimization of the vacuum chamber shielding is presented in [1].

Low multiplicity mode is an important function of LEETECH, in which the facility delivers a few electrons per sample. An optimized set of LEETECH parameters ensures such a regime, in which a Poisson-like distributed low average number of particles is delivered and can be registered by a diamond sensor.
Figure 1. Schematic view of LEETECH facility. The PHIL beam pipe (1), attenuator (2), vacuum chamber with magnetic field (4), entrance and exit collimators systems (3, 5) are shown. Red (green) curves corresponds to the electron (photon) trajectories.

Table 1. Main operation parameters of PHIL and LEETECH.

|                  | PHIL       | LEETECH          |
|------------------|------------|------------------|
| Number of electrons | up to $10^9$ |                  |
| Beam energy      | 3.5 MeV   |                  |
| Emittance FWHM   | $4\pi$ mm-mrad |                  |
| Bunch length rms | 7–10 ps   |                  |
| Repetition frequency | 5 Hz          |                  |
| Attenuator thickness | 100 $\mu$m–8 mm |                  |
| Input collimator openings | up to $20 \times 20$ mm |                  |
| Output collimator openings | up to $20 \times 20$ mm |                  |
| Magnetic field   | 200–2000 G |                  |

2.2 Simulation model and sample characteristics

A complete realistic Geant4 [14] model of the LEETECH facility is developed. The flexible simulation framework provides a possibility to perform Monte Carlo simulation of particular experiments and estimate the expected results.

Simulation and experimental results addressed throughout the paper are obtained using PHIL beam energy 3.5 MeV, beam intensity of few $10^8$ electrons, LEETECH aluminum attenuator of 2 mm thickness, and 2.7 MeV energy of test samples corresponding to the dipole magnetic field of 400 G. For the sake of simplicity the photoinjector is modelled as unidirectional point source.

Entrance collimator. For the 2 mm thick attenuator, a typical angular and energy distribution of the electrons before (figure 2a) and after the entrance collimator is shown (figure 2b). Clear peaks in energy and polar angle can be observed which proves the efficiency of the collimator system. In figure 2c the transversal 2D position of electrons leaving the entrance collimators is illustrated. The dense region in the center corresponds to the electrons which, taking in account small angular spread, enters the magnetic field region. One can also observe a clear shadow from the rectangular
shape of horizontal collimators. Electrons of accepted momenta from the dark square region in figure 2c make a half-turn in the magnetic field, propagate to the exit of the vacuum chamber and further to the exit collimator system, which limits the beam multiplicity complementary to the entrance collimator system, also reducing the energy spread.

**Exit collimator.** Simulated spectra before and after the exit collimator system are shown in figure 3. One can see that the low energy tail, which corresponds to electrons scattered on the inner surface of the vacuum chamber and collimator box, is significantly reduced by the collimator system. The RMS of the spectrum becomes 1.6 times lower. At the same time the peak width is reduced to 86% of that upstream of the exit collimator. From figure 3, the energy spread of electrons delivered by LEETECH is about 53 keV for a mean value of 2.7 MeV, using 7 × 7 mm entrance and 5 × 5 mm exit collimator openings.

**Figure 3.** Typical electrons spectra upstream (a) and downstream (b) of the exit collimator system. Entrance (Exit) collimator opening 7 × 7 mm (5 × 5 mm), magnetic field 400 G.
Sample quality control. The energy spread was studied for different exit collimator openings. Figure 4a shows energy spread depending on the entrance collimator opening, while the exit collimator was 20×20 mm open. While the energy spread increases with opening collimators and accepting more electron directions, starting from a 10×10 mm opening, all the electrons, defined by the target characteristics and the exit collimator openings are accepted and the energy spread curve is saturated.

The energy spread can be improved by better defining the electron direction using entrance and exit collimators. This is illustrated by figure 4b for the entrance collimator opening between 1 and 7 mm, exit collimator opening between 2 and 20 mm. For small collimator openings a very low energy spread of 10 keV can be achieved. Starting from 7×7 mm entrance collimator energy spread curve becomes saturated and the sample quality can not be further improved.

2.3 Parametric scans and computational time

The full Geant4 simulation of one bunch of 10^8–10^9 primary particles passing through LEETECH is computationally challenging. Simulation with a sample acquired in a typical experiment (thousands of bunches) is not realistic in terms of computational power. On average it takes 12 hours using one CPU, and approximately 1.5 hours in configuration with 8 threads. For the optimization studies the computing time increases proportionally to the number of simulation parameters and becomes resource consuming.

Therefore the simulation is splitted in several steps — data from artificial detectors were recorded at each stage and used as a source for the following simulation stages.

Firstly, from the distribution after the entrance collimators (figure 1) we constructed a new particle source with generalised parameters representing the particles arising from bunches at that location. It includes normal distributions of energy, angle, and position of the electrons (discussed in section 2.2). With this new General Particle Source (GPS) we obtain the same results after the exit collimators as with the initial electron bunch. For different configurations of the entrance collimator this procedure has been repeated. In such a way the Geant4 tracking in section upstream the vacuum chamber (PHIL, attenuator, entrance collimator) and downstream the entrance collimator (vacuum chamber, magnetic field, exit collimator) can be treated separately, thereby significantly decreasing the modelling time.
3 Low-multiplicity operation mode

In the previous section we have discussed the simulation model of LEETECH and the electron energy spread in a single sample. In this section we describe how the number of the electrons varies from sample to sample in the low-multiplicity mode. We introduced a detector in the test area at a distance of 6 cm downstream the LEETECH exit window (figure 1) in the simulation model. The experimental studies described in section 5 are performed with the diamond sensor with lateral dimensions of $4 \times 4 \text{ mm}$ and $0.5 \text{ mm}$ thick, which is implemented in the simulation.

3.1 Expected distribution of electrons at the exit

For a discrete set of $N \gg 1$ trials with normal random variable $T$, mean $\mu$ and dispersion $\sigma$, the number of entries $\lambda$ in the interval $(T_0 - \delta T, T_0 + \delta T)$ follows the Poisson distribution. The corresponding probability $\Pi$ is:

$$\Pi = \frac{\lambda}{N} = \frac{1}{\sqrt{2\pi\sigma^2}} \int_{T_0-\delta T}^{T_0+\delta T} \exp\left(-\frac{(T-\mu)^2}{2\sigma^2}\right) dT.$$

LEETECH low-multiplicity operation mode with a small range of energies and directions assumes similar process where a number of delivered electrons is approximated by the Poisson distribution. The sensitivity of the rate parameter to the variation of number of incident particles $N$ is $\frac{\Delta \lambda}{\lambda} = \frac{\Delta N}{N}$.

![Figure 5. Probability to observe 0,1,2,3 electrons in a single sample as a function of Poisson parameter $\lambda$.](image)

We describe the obtained number of electrons with by the Poisson distribution:

$$P(\lambda, k) = \frac{\lambda^k e^{-\lambda}}{k!},$$

where $\lambda$ is the Poisson parameter, the average rate parameter, and $k$ is the actual number of electrons passing the exit collimators for each event. The probability of observing 0, 1, 2, 3 electrons as a function of $\lambda$ is presented in figure 5. From eq. (3.2) the ratio of the probabilities of $k + 1$ and $k$ events is

$$\frac{P(\lambda, k + 1)}{P(\lambda, k)} = \frac{\lambda}{k + 1},$$

yielding the probability ratio between one and no electrons in the sample of $\frac{P(\lambda, 1)}{P(\lambda, 0)} = \lambda$, two and one electrons in the sample of $\frac{P(\lambda, 2)}{P(\lambda, 1)} = \lambda/2$, etc. (curves’ intersections in figure 5). Therefore, the single electron mode can unambiguously be achieved by choosing $\lambda \ll 1$, while the number of
empty samples \(( \approx 1 - \lambda )\) will dominate. Note, that this way of selecting signal samples containing single electrons does not require any instrumental control. Figure 5 shows that simultaneous studies of low-multiplicity samples containing one, two and three electrons require \( \lambda \) setting between about 0.5 and 5.

### 3.2 Modelling of the operation in the low-multiplicity mode

To simulate thousands of bunches from PHIL accelerator the GPS was constructed as described in section 2.3. To obtain the GPS data one bunch of \( 2 \cdot 10^8 \) electrons was used with entrance collimator opening of \( 2.6 \times 1.8 \) mm, giving \( 10^4 \) detector hits. Using the constructed GPS we randomly generate the samples each containing \( N_{e-} = 10^4 \) electrons. Then the electrons are propagated, and the energy deposition in the DS is recorded.

![Graphs showing energy deposition](image)

Figure 6. Energy deposition in the DS by the LEETECH electrons. a, b) Energy deposition distribution for different exit collimator apertures. Entrance collimator opening \( 2.6 \times 1.8 \) mm.

Figure 6 shows the energy deposition in the diamond sensor for the exit collimator openings of \( 1 \times 1 \) mm and \( 1.4 \times 1.4 \) mm respectively.

One can discriminate clear peaks in figure 6a and figure 6b. These peaks represent contributions from one, two, three and four electrons, respectively, traversing the diamond simultaneously. For figure 6a, and 6b the numbers of empty samples are 15% and 1.4%, respectively. Thus, comparing figure 6a and figure 6b one can see the role of exit collimators.

### 3.3 Average number of electrons in the sample

In order to demonstrate that the distributions in figure 6 are consistent with those expected from small number of electrons according to Poisson statistics, we generate the energy depositions in the DS, \( E_{\text{dep}}(N_{e-}) \), from a given number of electrons \( N_{e-} = 1, 2, \ldots, 100 \). The \( E_{\text{dep}}(N_{e-}) \) is normalized to the total number of events \( N_{\text{samples}} = 10000 \), which is the same as in figure 6. Therefore \( E_{\text{dep}}(N_{e-}) \) can be used as a basis for describing the simulated LEETECH distributions (figure 6). In order to
find \( \lambda \) the minimisation of the following single parameter cost function is performed:

\[
f(\lambda) = \ln \left( \sum_{E} E_{\text{dep}}^\text{LEETECH}(E) - \sum_{N_{e}^- = 1}^{100} P(\lambda, N_{e}^-) E_{\text{dep}}(N_{e}^-) \right)^2, \tag{3.4}
\]

where \( E_{\text{dep}}^\text{LEETECH}(E) \) is the result of our Geant4 simulation of LEETECH (blue curves in figure 6a, 6b), \( P(\lambda, N_{e}^-) \) — Poisson weights and \( E_{\text{dep}}(N_{e}^-) \) is the energy deposition in the DS for \( N_{e}^- = 1, 2, \ldots, 100 \) electrons.

### Table 2. Estimation of the Poisson parameter \( \lambda \).

| \( \lambda \) | empty samples | mean  | variance | fit   |
|--------------|---------------|-------|----------|-------|
| figure 6a    | 2.08          | 2.02  | 2.31     | 2.00  |
| figure 6b    | 4.08          | 4.08  | 4.76     | 4.13  |

The results of the minimisation of \( f(\lambda) \) are shown in figure 6a and 6b in red. One can see a good agreement between the fit and the simulation data. In these numerical experiments LEETECH provided the Poisson distributions of electrons with rate parameter of 2.0 and 4.13 for figure 6a and 6b, respectively. The Poisson parameter estimated from empty samples as \( \lambda = -\ln(N_{0}/N_{\text{samples}}) \), from the mean value and from the variance is presented in table 2. The value of Poisson parameter obtained from the variance is overestimated, due to the long tails in \( E_{\text{dep}}(N_{e}^-) \), which contribute to the neighbouring peaks. However since the resolution of 0-electrons peak (noise) and 1-electron peak is good, the estimation of \( \lambda \) from the number of empty samples gives a reasonable result, which we use as the starting point during the minimisation of eq. (3.4).

### 3.4 Control of the rate parameter

In figure 7 the Poisson parameter obtained by minimisation according to eq. (3.4) as the function of the exit collimator opening is presented. For the openings smaller than the size of the detector the dependence can be expressed as a linear function:

\[
\lambda(x) = \alpha \Delta x \Delta y = \alpha S, \tag{3.5}
\]

where \( \Delta x \) and \( \Delta y \) are the exit collimator openings along the horizontal and vertical axes measured in mm. The linear fit in the mentioned range gives the value of non-dimensional parameter \( \alpha \) of \( 2.3 \pm 0.1 \). This form of dependence confirms that the number of electrons passing through the exit increases linearly with the opening of the collimators.

Thus the quantity \( \alpha \) describes the **efficiency** of the reduction of the initial sample population down to the delivered low multiplicity of the sample. For exit collimator opening of \( S = 1 \text{ mm}^2 \) Poisson parameter \( \lambda \) coincides with the efficiency parameter \( \alpha \). For fixed values of the magnetic field the parameter \( \alpha \) is a function of the sample charge entered LEETECH, determined by PHIL bunch charge and entrance collimator openings. Decreasing the entrance collimator openings leads to smaller values of \( \alpha \) which allows to control the Poisson parameter in accurate manner.
3.5 Beam size effect

In the results presented in figure 7 the PHIL electron beam was simulated as a unidirectional point source. Taking into account realistic beam size greatly reduces effective number of electrons entering the spectrometer.

Figure 7. Poisson parameter \( \lambda \) as a function of the exit collimator opening.

Figure 8. Correction factor as a function of beam size. Blue cross represents the unidirectional point source, red cross corresponds to the PHIL beam size during the experiment.

The simulation of LEETECH with realistic PHIL beam size containing the same number of primary electrons as in case of unidirectional point source was performed. The ratio between numbers of detected electrons in both cases is defined as a beam size correction factor. The correction factor rapidly decreases with the beam size growth as shown in figure 8. The unidirectional point-like source is represented by the blue cross.

Using the LANEX scintillating screen installed at the LEETECH entrance the beam size was estimated to be \( 2.7 \pm 0.3 \) mm. Only \( 0.094 \pm 0.020 \) (red cross in figure 8) of electrons reached the detector compared to the unidirectional point source, while the rest of electrons after scattering on the attenuator were filtered by the collimator system. The error in this factor was estimated from simulation by varying beam size within the uncertainty. As a result of this correction the efficiency \( \alpha \) becomes \( 0.21 \pm 0.05 \). The results presented in figure 8 can be also used to estimate the expected electron multiplicity at the exit of LEETECH depending on the PHIL beam focalization.
The effect of beam alignment was also extracted from the fit of LANEX scintillating screen image. The estimated values of horizontal and vertical displacement are $2.0 \pm 0.2$ mm and $1.5 \pm 0.2$ mm respectively. The simulation including the beam size effect and alignment effect yields the overall correction factor of $k_{\text{corr}} = 0.050 \pm 0.015$, and the corrected efficiency is obtained as $\alpha_{\text{corr}} = \alpha k_{\text{corr}} = 0.12 \pm 0.04$.

4 Diamond detector

Low-multiplicity operation mode of LEETECH is studied below using DS. The DS used in the experiment (figure 9) was prototyped and fabricated at LAL. A single crystal Chemical vapour Deposition (CVD) diamond from Element Six,\(^1\) with TiPtAu metallisation on the top and bottom surfaces, is glued with the conducting glue on the PCB. The top surface of the diamond is connected to the signal line on the PCB by four bonding wires. Such a design allows to reduce electron scattering before they reach the active area of the diamond. High voltage is applied through the conductive area on the PCB underneath the diamond.

Proper calibration of the diamond detector requires a MIP source. One of possible candidates for such calibration can be atmospheric muons. However, taking into account a small surface of DS the rate of such events will be low, on average ten events in one hour. Electrons with energies above 1.8 MeV can be also used for calibration. For calibration of the DS we use a $^{90}$Sr radioactive source. To avoid the contribution of non-MIP electrons from the $^{90}$Sr spectrum we trigger on a scintillator placed behind the DS. This allows filtering the low-energetic part of the $^{90}$Sr spectrum and detecting only the electrons possessing sufficient energy to traverse the “sandwich” diamond — PCB. The signal from DS is amplified by charge sensitive amplifier (CIVIDEC C6) with gain factor of 4mV/fC and the noise RMS of 0.7 mV.\(^2\) On average the ionisation of diamond yields 36 electron hole pairs in 1 micrometer. The Most Probable Value (MPV) of the collected charge for a single crystal CVD of 0.5 mm thickness is 2.88 fC, which corresponds to an energy of 225 keV deposited in the diamond.

![Diamond sensor.](image1)

![DS response to the single MIP electrons. The MPV of the energy deposition is 12 mV.](image2)

**Figure 9.** Calibration of the DS with radioactive source $^{90}$Sr.

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\(^1\)Element Six is a synthetic diamond supermaterials company: [http://www.e6.com](http://www.e6.com).

\(^2\)Solutions for beam diagnostics based on CVD diamond technology: [http://www.cividec.at](http://www.cividec.at).
The mean value and the standard deviation of the Landau distribution are not well determined due to the long tails towards high energies. Instead, we use the MPV and FWHM of the distribution. From figure 9a, the MPV of the signal amplitude and the FWHM are 12.0 ± 0.5 mV and 4.0 ± 0.5 mV, respectively. Note that the histogram in figure 9b is a convolution of the Landau distribution and Gaussian function to account for the amplifier noise.

5 Measurements

![Figure 10. Photo of the experimental setup. The diamond sensor (1), charge sensitive amplifier (2), translation stage (3), LEETECH dipole magnet (4), PHIL photoinjector (5) and lead shielding around the detector area (6) are shown.](image)

In the experimental setup the DS and the low noise charge amplifier are fixed on a remotely controlled XZ translation stage (figure 10). The signal acquisition consists of a 12-bit 500-MHz bandwidth digitiser, sampling between 400 MS/s and 3.2 GS/s (USB-Wavecatcher [15]), which was installed near the LEETECH setup and protected from radiation. The event triggering/synchronisation was done using the photo-injector laser pulses. A sample of 10000 events corresponds to the data acquisition of approximately half an hour.

The mutual alignment of the electron beam, LEETECH spectrometer, and DS is important to control the test sample characteristics. The absolute positions of the collimator box were aligned at the fabrication stage with a precision of 0.05 mm in such way that the centres of the collimators coincided with the centre of the vacuum chamber.

The PHIL beam position at the attenuator is visualised using the LANEX scintillator screen and controlled using the DS signal. Synchronous vertical scan of entrance and exit collimator positions reduces the effect of the stray field outside the dipole. Using the DS as a sensitive device positioned at the geometrical centre of the exit collimator, the magnetic field of 400 G is selected to maximise the number of electrons in the delivered sample. Complementary scan of the DS position aligns the DS with respect to the electrons coming from the spectrometer.

The working opening of the entrance collimator is selected to be $2.6 \times 1.8 \text{ mm}^2$. The opening of the exit collimator is varied in the measurements outlined below.
Figure 11. Histogram of measured energy deposition in the DS. Vertical lines are separated by 12mV and indicate the expected positions for different electron multiplicities. The first peak corresponds to the empty electron samples.

6 Results and discussion

Characteristics of the samples delivered by LEETECH can be adjusted by varying the PHIL bunch intensity, beam position and other machine parameters, attenuator material and thickness, position and opening of entrance and exit collimators. LEETECH platform should be calibrated depending on the above parameters. Alternatively electron multiplicity can be measured on a sample by sample basis via non-destructive technique.

In figure 11 we present the measurement of several electrons by DS at the LEETECH spectrometer. The first peak (below 5 mV) in each sub-figure corresponds to the empty electron samples. The width of this peak reflects the noise of the charge amplifier. The percentage of the empty samples can be used to estimate the Poisson parameter. The vertical dashed lines are shown as indications of the expected signal positions from the samples containing different number of electrons. One can discriminate the peaks corresponding to the electrons multiplicity of 1, 2 and 3. The skewness in the distribution in figure 11 is the natural property of the Poisson distribution for small $\lambda$.

The increase of the opening of the exit collimator leads to the increase of the $\lambda$. The Poisson parameters for the experimental results in figure 11 are presented in the summary table 3.
errors in the experimental results were calculated by averaging the difference of estimations from mean and empty samples.

The simulation parameters (discussed in section 3) were taken to be the same as in the experiment. In order to compare the simulation and the experimental results (table 3) the beam size and beam alignment were taken into account in section 3.5. The efficiency parameter $\alpha_{\text{corr}} = 0.12 \pm 0.04$ obtained in the simulation is close to the experimental result of $\alpha_{\text{experiment}} = 0.11 \pm 0.02$.

**Table 3.** Comparison of experimental data and simulation results.

| Exit collimator | $\lambda$ experimental (figure 11) | $\lambda$ simulation | $\lambda$ simulation, beam size correction | $\lambda$ simulation, beam size and alignment corrections |
|-----------------|---------------------------------|----------------------|-------------------------------------------|--------------------------------------------------------|
|                 | $1.2 \times 3.1$                | $6.9 \times 3.1$     | $9.9 \times 3.1$                         | $19.9 \times 20.6$                                     |
| $\lambda$       | $0.7 \pm 0.1$                   | $2.2 \pm 0.2$        | $2.8 \pm 0.1$                            | $8.7 \pm 0.9$                                         |
| Efficiency $\alpha$ |                              |                      |                                           |                                                        |
|                 | $0.11 \pm 0.02$                 | $2.3 \pm 0.1$        | $0.21 \pm 0.05$                          | $0.12 \pm 0.04$                                       |

7 Summary

We report the calibration of the low-multiplicity mode of the LEETECH spectrometer using a diamond detector. Using a complete description of the LEETECH spectrometer a low-multiplicity operation is fully understood. A single efficiency parameter $\alpha$ selects an optimal LEETECH operation mode for detector measurements. We demonstrate LEETECH electron samples to follow the Poisson distribution with the parameter $\lambda$ measured with the diamond detector. The estimate of the expected diamond detector response to a single electron passage is obtained. Measurement of the Poisson parameter in the wide range with a compact diamond detector is presented. Simulation results reproduce all the effects observed experimentally. Although diamond detector resolution of low-multiplicity peaks obtained is worse than that predicted by the simulation, one can discriminate the peaks corresponding to empty samples and to the samples containing 1, 2, 3 electrons. The origin of limited diamond detector resolution is caused by the Landau distribution of energy deposition in thin detectors. The use of the low-noise charge amplifier is expected to further improve the peak resolution. A capability of diamond detector to discriminate low-multiplicity electrons in the vicinity of a beam line is demonstrated experimentally. Moreover, observation of the temporal evolution of the collected charge allows to follow variations of the parameters of the accelerator machine, providing a promising tool for the beam loss monitoring.

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