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Radiation hardness and linearity studies for a diamond luminosity calorimeter

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Abstract

We describe the current design elements of a diamond luminosity calorimeter for TESLA. We report on the detector simulation that has been performed to estimate the energy deposited on the LCAL per bunch crossing and the constraints it has on the choice of detector material. The recent results of diamond detector studies done at DESY are also described.

1 Introduction

The high luminosity and the small beam size of the TESLA accelerator will cause the electrons and positrons in the beams to feel each other's electromagnetic field and to radiate photons. This *beamstrahlung* effect [1] will produce a large amount of photons and electrons at low angle which could hit beam elements and create a large background in the detector if they are not shielded. For this reason, a tungsten mask has been designed on both sides of the detector to absorb both the photons and electrons from the beamstrahlung and potential background particles created along the beam line. Figure 1 shows a sketch of the mask region, which is described in detail in the TESLA TDR [2].

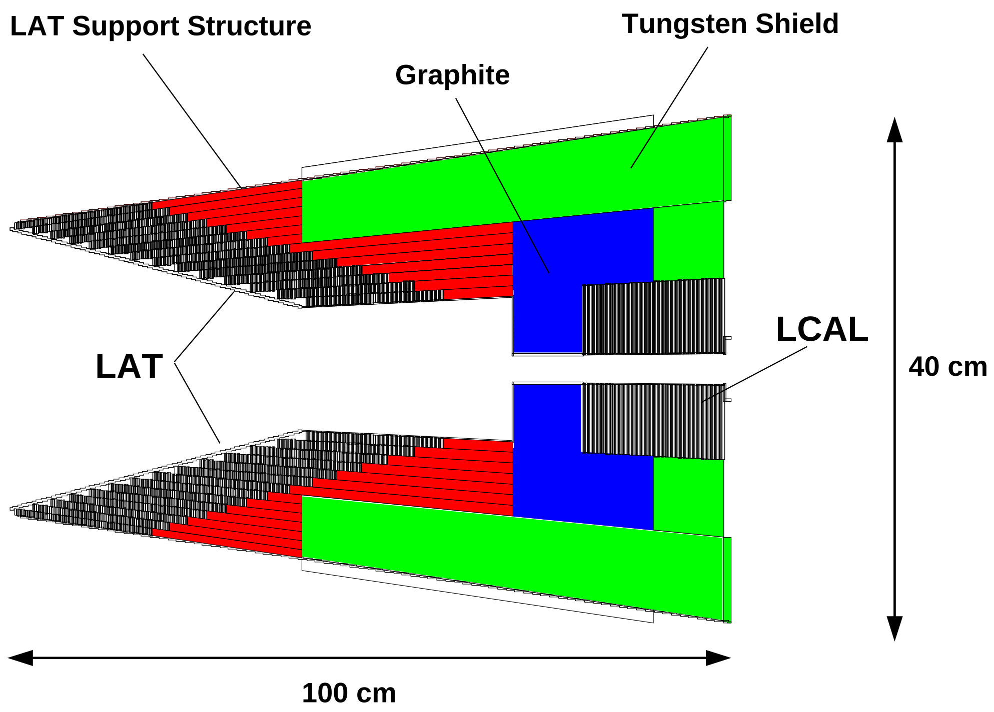

Figure 1: Schematic view of the TESLA mask region.

The tungsten shield will be instrumented by two calorimeters. A first calorimeter, the Low-Angle Tagger (LAT), is a silicon/tungsten detector which covers the angular range between 27 mrad and 83 mrad. It is subdivided in 63 planes of silicon diodes interleaved with 2.6 mm of tungsten (0.74 X_0). Each plane is subdivided in 7 layers in r and 24 sectors in ϕ. The individual cells have a surface of about 1 cm^2. This surface varies according to the location of each cell. The thickness of the detectors was assumed to be 500 μm.

The second calorimeter, the Luminosity Calorimeter (LCAL), covers the angular range between 5.5 mrad and 28 mrad, with a structure similar to the LAT. A sketch of the structure of the LCAL is shown in figure 2.

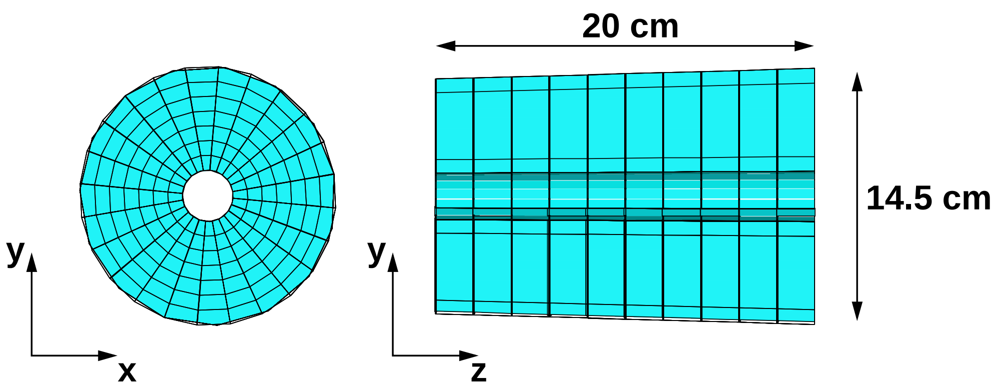

Figure 2: Sketch of the structure of the LCAL.

This detector will be used to measure the relative luminosity between bunches and for calorimetric measurements. By measuring the signal from the beamstrahlung background, this detector will be part of a fast-feedback system of the accelerator [3]. Due to the very large electromagnetic radiation near the beam, a diamond/tungsten detector is considered. Placed only 1.2 cm from the beam, this detector could received as much as a few MGy of electromagnetic radiation per year. Diamond detectors have been extensively studied in the past years for applications at the LHC [4], and more recently for applications at TESLA [5].

Another important aspect of the choice of the active material for the LCAL is the response of the detector to large energy depositions. The detector should provide a good response over the complete range of energies needed to provide a precise relative measurement of the luminosity. Although a linear response is in principle not necessary, avoiding saturation effects would maximize the luminosity resolution.

Section 2 describes the simulation that was performed to estimate the amount of energy deposited on the LCAL. The results of this simulation were used to determine the dose up to which diamond detectors must be tested and the energy density up to which their response must be evaluated. The results concerning the radiation hardness of diamond, which were already published [5], are summarized in section 3. The recent results of the linearity tests of diamond detectors are described in section 4.

2 Detector simulation

The e^+e^- pair background production from beamstrahlung was simulated using the Guinea-Pig program [6]. These electrons have an energy in the GeV range. The resulting pairs were fed in the TESLA detector simulation program Brahms [7], which incorporated the LCAL design described in the Technical Design Report [2].

For each bunch crossing, an average of 17000 electrons per side hit the LCAL, depositing an average of about 19 TeV. Figure 3a shows the energy deposited per plane for one bunch crossing. The seven overlayed distributions correspond to the seven r layers. One sees that most of the shower is absorbed in the 47 radiation lengths of the calorimeter, although a very small fraction escapes the detector. Figure 3b shows the corresponding yearly electromagnetic dose on each plane and each layer. At the peak of the shower development, the inner cells of the detector can receive as much as 2 MGy of electromagnetic radiation per year.

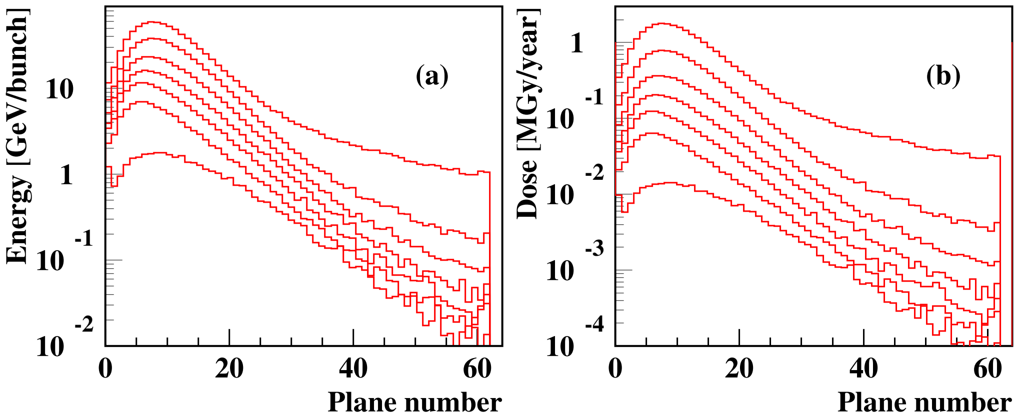

Figure 3: Energy deposited on the LCAL per bunch crossing for the different detector planes and layers (a) and the corresponding yearly electromagnetic radiation dose (b). The seven histograms on each plot represent the seven radial layers of detectors. The histogram with the largest energy deposition corresponds to the inner layer.

Figure 4 shows the distribution of the energy deposited per bunch crossing in all the detector cells. Certain inner cells can receive up to about 4 GeV per bunch crossing. An energy deposition of 1 GeV is equivalent to the energy deposition from about 4000 minimum ionizing particles (MIP).

In the light of the detector simulation, two important questions were identified and were the subject of R&D activities at DESY:

1. **Radiation hardness:**
   Some of the inner cells of the LCAL can receive up to 2 MGy of electromagnetic

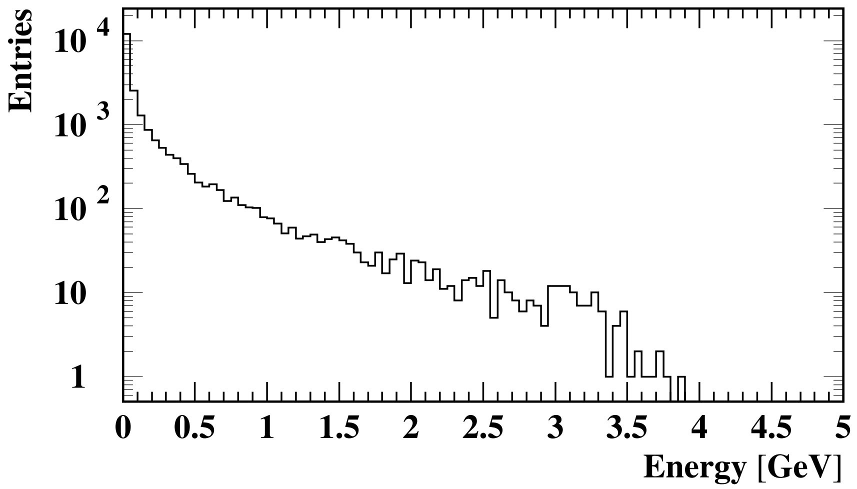

Figure 4: Distribution of the energy deposited per bunch crossing in all the detector cells.

radiation per year. Diamond samples must be tested for radiation hardness at least to that level.

2. **Response linearity:**
   The signal from the LCAL will be used in the fast-feedback system of the accelerator. For this purpose, the relative luminosity needs to be measured to a precision of about 1 %. The number of electrons hitting the first plane of the detector during a bunch crossing ($N \simeq 17000$) gives an estimate of the minimal charge to which the detector must be sensitive. For $N = 17000$ electrons, $\sqrt{N}/N \simeq 0.8\%$, which is close to the precision goal of 1%, so that the minimal detectable charge should correspond approximately to the charge of a minimum ionizing particle (MIP).

   The maximum charge to which the detector must be sensitive is given by the charge corresponding to the maximum energy deposition for a given cell. Depending on the position of each cell, this could correspond to the equivalent of about 10^4 MIPs. Depending on the expected luminosity variations and on the position of each cell, the detector would have to work over a range of charges up to this value while keeping a precision of about 1 MIP. Although the dynamic range of the detector will depend on the details of the electronics, it is important to test the response of diamond detectors for such large energy depositions. The response of the detector need not be linear, but any saturation effect will worsen the resolution.

3 Radiation hardness

Diamond detectors have recently been tested for radiation hardness at DESY. The experimental setups and the results are described in detail in another publication [5]. Diamond samples have been submitted to doses of about 6.8 MGy at the Hasylab synchrotron radiation facility and to doses of about 10 MGy from a Co^{60} source. In both cases the response of the samples to minimum ionizing electrons was found to remain constant after a series of irradiation periods. These results were established by measuring the charge collection efficiency, which is defined as the ratio of the charge induced on the contacts to the total charge deposited in the sample $\epsilon = Q_{\mathrm{induced}}/Q_{\mathrm{deposit}}$. The charge collection efficiency for diamond is relatively low (usually below 50%) because of defects in the material which can trap charge carriers. In this respect, the charge collection efficiency is a quality factor of diamond samples. Experimentally, one often measures the collection distance, which is defined as $\mathrm{d} = \epsilon \mathrm{D}$, where D is the thickness of the diamond sample. Figure 5 shows the ratio of the collection distance measured after irradiation to the collection distance measured before irradiation for different diamonds submitted to increasing doses of electromagnetic radiation. The collection distance is seen to remain constant for each diamond for different doses.

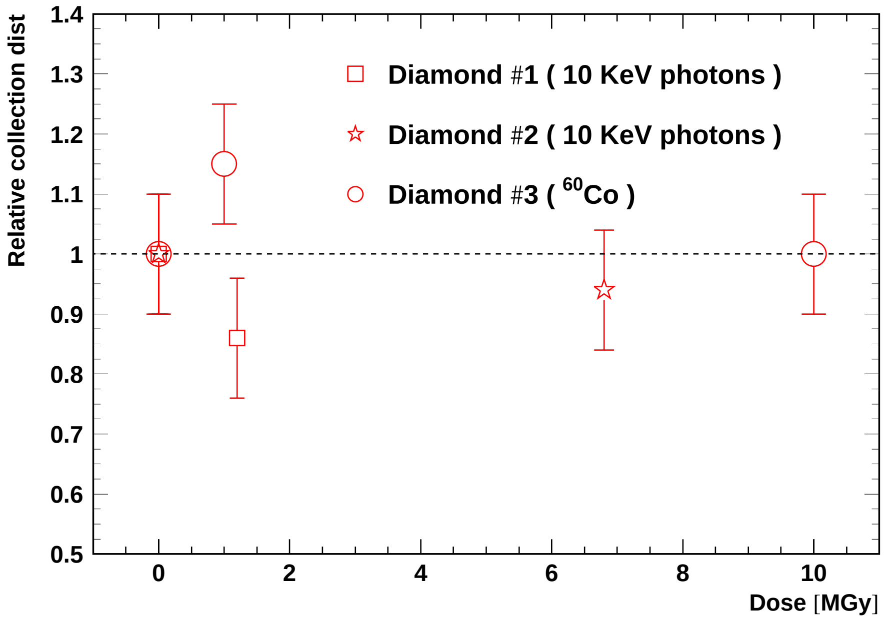

Figure 5: The ratio of the collection distance measured after irradiation to the collection distance measured before irradiation for each diamond and each irradiation period (from reference [5]).

A set of Thermally Stimulated Current (TSC) measurements [5, 8] were also performed to establish the radiation hardness properties of diamond. TSC scans of the surface of diamond samples were done using the Hasylab facility to study the local variations of the defect density of the material. The defect density has been found to remain unchanged after large doses of electromagnetic radiation.

The conclusion of the radiation hardness tests of diamond [5] is that the properties of diamond were found to remain unchanged after radiation doses of up to 6.8 MGy of 10 keV photons and of up to 10 MGy of photons with 1.17 MeV and 1.33 MeV. Such a resistance to electromagnetic radiation justifies the use of diamond as material for future detectors such as the TESLA LCAL. In comparison, silicon detectors have been successfully tested for electromagnetic radiation doses of up to 4 MGy. In this respect, silicon detectors could also be used for the TESLA LCAL.

4 Response linearity

The linearity of the response of a diamond detector was tested using the Hasylab synchrotron radiation facility at DESY. A diamond detector was placed in a 10 KeV photon beam [10] which was intense enough to provide an energy density comparable to that seen by the inner cells of the TESLA LCAL. The beam intensity was about 2000 photons per bunch on a 300×300 μm^2 area. The beam was shone on a diamond surface of about 1 mm^2, defined by a copper mask.

The photon flux on the detector for the maximum DORIS beam current (about 80 mA) corresponds to a deposited energy density in the diamond of about 7.5 GeV/cm^2 for a 300 μm thick diamond. This energy density is about twice the maximum expected value for the TESLA LCAL. The beam current minimum (about 50 mA) corresponds to a deposited energy density in the diamond of about 4.5 GeV/cm^2 for the same thickness.

The flux variation of the DORIS accelerator during a given fill was used to test the linearity of the detector. As the electron current in the accelerator diminishes, the photon flux from the undulator diminishes as well. By measuring the variation of the signal induced on the diamond as a function of the beam current, the response of the detector as a function of the energy density can be tested. A scintillator detector was used to monitor the photon beam by measuring the number of electrons from photon-air interactions a few centimeters away from the photon beam. The measured number of electrons was found to vary linearly with the DORIS beam current, so that the latter could directly be used to test the linearity of the detector. Figure 6 shows an example of the DORIS current variation as a function of time. Each fill lasted about 8 hours, during which the beam current dropped by about 40%.

In order to study the response of the detector over a wider range of energy depo-

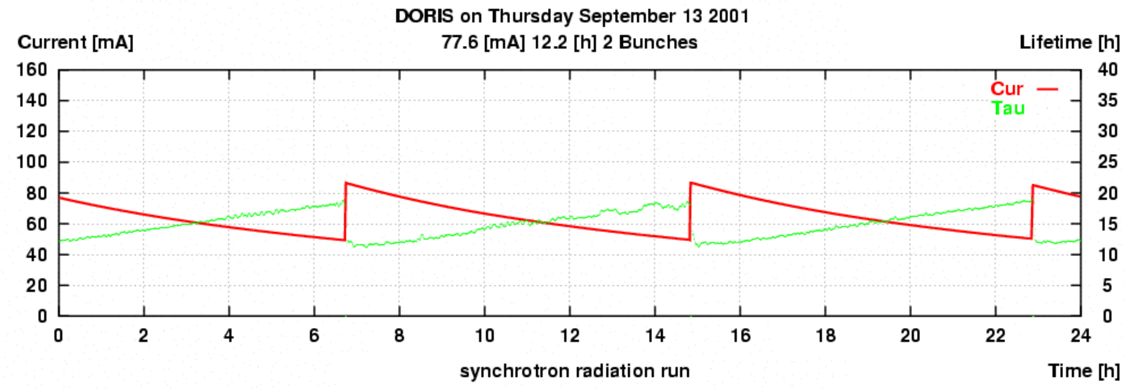

Figure 6: Example of the variation of the DORIS electron beam current as a function of time. Taken from the Hasylab internet site (`www-hasylab.desy.de`).

sitions than possible with the current variation of the DORIS accelerator, Aluminum foils were used to attenuate the photon beam. Each foil was (50 ± 5) μm thick, which provided an attenuation of about 27%. With up to seven Aluminum foils, an attenuation of about 90% could be reached, corresponding to an energy deposition of 0.5 GeV/cm^2/300 μm.

The diamond detector was read out using an Amptek A250 [1] pre-amplifier, that was followed by an Ortec amplifier/shaper with a 50 ns shaping time. The output signal of the amplifier/shaper was sent to a Lecroy 1182 ADC. Although the repetition rate of the beam was 2 MHz, a data taking rate of about 50 Hz was sufficient to accumulate enough data.

Figure 7 shows the variation of the measured signal as a function of the energy density in the diamond. The open points are those taken without attenuation of the photon beam. The filled points are taken with different numbers of Aluminum foils. The data shown are pedestal subtracted. The data taken without attenuation and with one and two Aluminum foils were fitted together to a straight line to extract the attenuation factor of a single foil. The fitted value is $27.2 \pm 0.5\%$, which agrees with the attenuation calculated using the Bethe-Bloch equation. This value was then used to estimate the attenuation factor for the other data sets with a larger number of foils and signals smaller than 1000 ADC counts. As can be seen on figure 7, these data sets do not have a linear response. The reason for the non-linear behavior at lower energy density is ascribed to the pedestal, which extends beyond 500 ADC counts. Above this region, the response of the detector was found to be linear over almost an order of magnitude of energy density.

The bottom plot on figure 7 shows the relative difference Δ(ADC counts)/(ADC counts) between the data and the linear fit to these data. The statistical errors on the points

[1] AmpTek Electronics (`http://www.amptek.com`)

are small compared to observed variations, which we attribute to systematic errors from the measurement procedure. These errors correspond to a standard variation of about 20 ADC counts, which means between 0.7% and 2.0% of the ADC counts depending on signal size. We conclude from these measurements that our diamond detector is linear to better than 2% up to 7.5 GeV/cm^2 for a detector thickness of 300 μm.

5 Conclusions

The Luminosity Calorimeter of TESLA is designed to evaluate the relative luminosity between bunches by measuring the signal from beamstrahlung electrons. The beamstrahlung particles will produce very large signals in the inner cells of the LCAL at each bunch crossing. Over a period of a year, the electromagnetic radiation received by these cells can accumulate to a dose of up to 2 MGy. Two initial questions were identified to establish the feasibility of a diamond LCAL: the radiation hardness of diamond and the response of the detector to large energy depositions. Both aspects have been recently tested at DESY. The radiation hardness of diamond has been tested up to 10 MGy and the results have already been the subject of a publication. A study of the response of a diamond detector to energy depositions of up to 7.5 GeV/cm^2 for a detector thickness of 300 μm is reported in this note. The diamond detector studied has been found to be linear to better than 2% over almost an order of magnitude in the energy range interesting for the TESLA LCAL.

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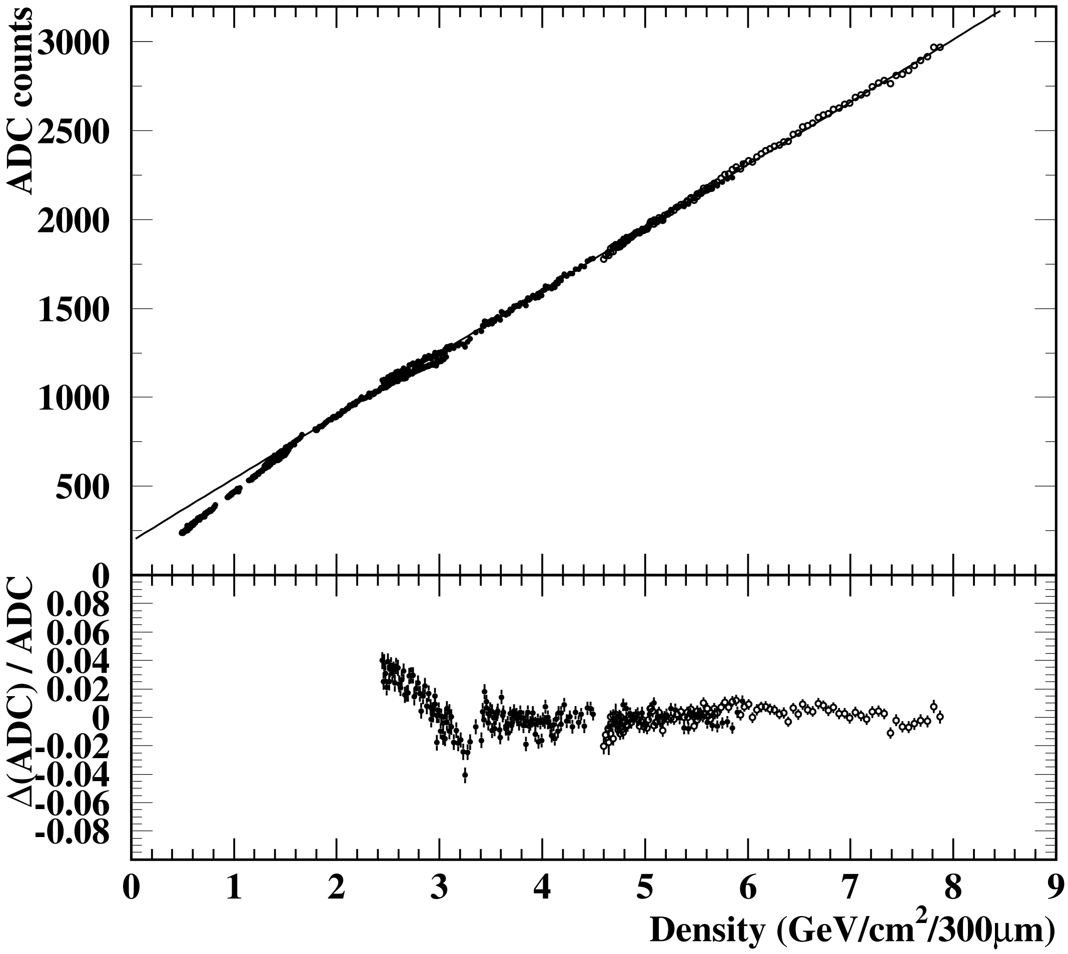

Figure 7: Diamond signal (ADC counts) as a function of the deposited energy density. The open points represent data taken without attenuation of the photon beam, while the filled points represent data taken with different numbers of Aluminum foils. The line shows the fit result. The bottom plot shows the relative difference Δ(ADC)/ADC between the measurement and the linear fit. Only the points used in the fit are shown on the bottom plot.