MDT gamma response

I.Boyko, G.Chelkov, V.Dodonov,
M.Ignatenko, M.Nikolenko, V.Zhuravlev

JINR, Dubna, Russia

Abstract

The response of the aluminum drift tubes to the photons of different energies in the 0.6T magnetic field has been studied. A Monte-Carlo model for the simulation of the photon detection in the drift tube has been developed. The results of the model calculation are compared with the measured amplitude spectra from radioactive sources. For gamma energies above 100 keV a significant reduction of the measured response with respect to the calculated value is observed. This effect can originate from the avalanche saturation for very large proportional signals. The resultant tube response is equal to the initial gamma energy for photons softer than 30 keV and varies between 35 and 40 keV for the photon energy between 50 and 1000 keV.

Introduction

One of the important questions from the ageing point of view for Monitored Drift Tubes (MDT) is the average tube response to the background particles. Since the main contribution to the MDT occupancy comes from the gamma background [1] it is vital to study carefully the MDT response to photons. The background photons near the ATLAS muon system are produced mainly by neutron absorption in the detector (ATLAS) elements. The photon energy ranges from few keV up to few MeV [1,2].

Recently the MDT efficiency to photons has been studied in the energy range from 6 to 1300 keV [3]. It has been shown that the lower energy limit is defined by absorption of photons in the tube wall. In the energy range from 10 to 200 keV the photon interactions in the gas gives an essential part in the tube efficiency. Above 200 keV Compton scattering in the tube wall is the main mechanism responsible for photon registration. Similar results have been obtained for aluminum tubes of slightly lower diameter filled with C_4H_{10} and CF_4 gases at 1 atm [4]. On the contrary for cathode strip chambers which have much thicker walls the gamma efficiency is completely defined by photon interactions in the walls [5].

Although the MDT gamma efficiency have been studied carefully there is no exhaustive information on the photon energy deposition yet. Since MDT are planned to work in a magnetic field of about 0.6 T oriented along tube axes one can expect some influence of the magnetic field on the MDT response. It is well known from the first experience with proportional counters that the magnetic field has no noticeable effect on the gas gain at least for counters of moderate diameters [6]. At the same time an escape of secondary electrons through the side wall of a counter is substantially reduced, since the track is coiled around the axis parallel to the field direction. It leads to increase in the energy deposition for an electron produced in the gas volume and to decrease of the average energy deposition for an electron produced in the cylindrical wall and is rapidly bent back into the wall by the magnetic field.

In this paper we describe the measurement of an aluminum drift tube response to photons from radioactive sources in a magnetic field of 0.6 T. Since only a limited set of radioactive isotopes is available for the gamma response studies and they can not cover the full energy range of photon spectrum, the calculations of the tube response in the full photon energy range were performed for better understanding of the experimental results.

Experimental technique

In the measurements we used the 40 cm long, 3 cm in diameter aluminum drift tube (DT) with 400 μm thick wall. The 50 μm gold plated tungsten wire was used as an anode. The DT was filled with $Ar/CH_4/N_2$ (91/5/4) gas mixture at 3 atm pressure. If other is not stated explicitly, the positive high voltage applied to the wire was 3285 V that corresponds to the gas gain 20,000. The DT was placed along the field lines of the magnet which provided a magnetic field up to 1.5 T.

The measurements were performed with two positions of radioactive gamma sources: on the tube wall and 5 cm away from the tube. In the last case the collimated photons irradiated 5 cm of the DT length. No significant difference in results was observed between these options. The following table summarizes all the isotopes and their lines used in this study.

Table 1. Gamma sources and line energies (in keV).

^{55}Fe	^{57}Co	^{57}Co	^{241}Am	^{241}Am	^{241}Am	^{133}Ba	^{241}Am	^{133}Ba	^{57}Co	^{60}Co
6.0	6.5	14.4	14.4	17.8	26	30.5	59.5	80	122	1252

The ^{60}Co isotope has two close lines and in this paper they are considered as a single line with the average energy of 1252 keV.

In all measurements the DT was working in a self-triggering mode. The discrimination threshold corresponded to about 1÷2 keV of the DT response. The amplitude spectra were measured by the LeCroy 2249W ADC. The ADC gate was 600 ns long to cover completely the full collection time of the primary ionization.

The Monte-Carlo Model

As one can see from table 1, there is a large gap in the gamma energy between 10^2 and 10^3 keV. To obtain information about the DT response in the full interesting energy range one needs a reliable theoretical model based on main processes of the photon interaction in MDT. The model we developed in this work is an extension of the model used for the study of the MDT gamma sensitivity [3].

In the energy region being studied two mechanisms of gamma absorption are significant: Compton scattering and photoabsorption. A recoil electron can be produced either in the tube wall or in the gas volume. In the former case the electron is registered by the DT only if it reaches the gas volume. Two simulated trajectories of 250 keV electrons within the gas are illustrated in fig.1 which displays a part of the DT cross-section. In the case 1 the electron was produced near the tube wall (or within the wall) and after the rotation clockwise in the magnetic field it was absorbed in the aluminum. It is interesting that the electron track length in this case is almost independent of the angle between the tube axis and the electron direction. In another case (2) the electron was produced far enough from the wall to rotate until it lost all its initial energy.

In the simulation the type of the photon interaction (Compton or photoabsorption) is generated randomly according to the total photon cross-sections in aluminum and argon [7]. The direction of the recoil electron is generated according to the differential cross-section of the appropriate process. If the electron is produced in the tube wall it is traced taking into account energy loss, bending in the magnetic field and multiple scattering until it loses its full energy or until it reaches the gas volume. Once an electron appears in the gas volume, its motion is integrated over 50 μm steps until one of three following conditions is satisfied: the electron reaches the tube wall, the electron energy is zero, or the total bending angle of the electron exceeds 2π. In the first two cases the energy deposition is the difference between initial and final energies of the electron. In the last case to speed up the calculation we neglect the possibility for electron to escape from the tube due to multiple scattering and assume that the energy deposition is the whole initial energy. The electron dE/dx losses were taken from [8] and the multiple scattering on each step was calculated according to [9].

To compare the simulated and measured spectra of the DT response the calculated energy deposition was smeared by a Gaussian with the energy resolution obtained from measurements.

Results

The main mechanism of the soft (below 30 keV) X-rays detection in MDT is photoabsorption on argon atoms. The produced recoil electron in this case has too short range to escape from the tube even without the magnetic field. The DT response in this energy range is exactly equal to the energy of the primary photon. The experimental results for this energy region are presented in fig.2. The positions of peaks from different X-ray lines in ADC spectra are shown versus the line energy. The dependence shows an excellent linearity in agreement with the model prediction. These data were used in the further study for calibration of the ADC scale. The peak positions were the same with the magnetic field on and off.

For the photon energies larger than 30 keV we observed a disagreement between the model and the experimental results. In fig. 3 and 4 the measured spectra for photons of 60 keV (^{241}Am) and 122 keV (^{57}Co) are compared with the calculations. The simulated spectra were scaled to fit the maxima of the photoabsorption peaks. Soft X-rays of these isotopes were suppressed by a filter. At these energies photons still interact mainly in the gas. The signals from Compton scattering are well seen at the low-energy parts of the spectra but the photoabsorption peaks are still significant. The model predicts almost no signals in the gap between these two regions, but such signals are observed in the data and their abundance increases with the gamma energy.

With the increase of the photon energy the disagreement between the calculations and the results increases as well. Fig.5 shows the model prediction for spectra of energy deposition by 1252 keV photons. At this energy the main mechanism of gamma registration is Compton scattering in the wall. Out of the magnetic field the calculated distribution has a maximum near 20÷25 keV and then falls exponentially. This "high-energy" tail is produced by recoil electrons with the initial direction "almost parallel" to the tube axis. But with 0.6 T magnetic field the model predicts a very specific shape of distribution. Most of the signals are concentrated below 20 keV response because the electrons produced in the wall are bent by the magnetic field back to the wall (case 1 in fig.1) and pass only few millimeters in the gas volume. However, about 10% of all signals originating from the Compton scattering in the gas (case 2 in fig.1) deposit their whole energy in the sensitive volume producing a flat response spectrum from 0 to about 1040 keV (the maximum allowed energy of recoil electrons).

The results of measurement with ^{60}Co source are presented in fig.6. The spectrum measured in absence of the magnetic field is in a qualitative agreement with the model. But with the 0.6 T field the measured spectrum again falls exponentially showing a disagreement with the predicted flat shape and no signals in excess of 650 keV are observed.

We checked the linearity of our electronic in a large dynamic range with a pulse generator and observed a linear response over the whole range of studied amplitudes. So, the only reason which might reduce the MDT signals is an avalanche saturation effect. To check this the high voltage on the DT was reduced to 3120 V that corresponds to the gas gain of about 8,000. The results of the measurement with the ^{60}Co source are presented in fig.7. The shape of the distribution out of the magnetic field remained almost unchanged, but when the field is on, the large signals appeared with amplitudes up to the expected value of 1100 keV. The shape of the distribution still does not match the simulated one, but we consider these results as a strongest indication of the presence of the saturation effect.

This effect is well known since the invention of proportional counters. It manifests itself as a loss of proportionality between primary ionization and total collected charge [10]. The so-called limited proportionality appears when the total avalanche charge exceeds some critical value which depends on the gas mixture, the incident angle of the ionizing particle and the density of the energy loss [11]. This critical value ranges between $1.4 \cdot 10^7$ and 10^8 electron charges that corresponds to 20÷120 keV energy loss at $2 \cdot 10^4$ gas gain. In our measurement the first evidence of non-linearity (filling of gap between the signals from Compton scattering and photoabsorption) is observed at 60 keV energy that is in a good agreement with the quoted results.

An interesting feature of the measured spectra for 60÷120 keV photons is that the photoabsorption peaks are found at the positions where they are expected. The saturation manifests itself not in shifting of the whole peak to lower amplitudes as one could naively expect, but in reduction of the amplitude for only a part of the signals. Apparently the similar effect is observed in many MDT aging studies [12], where the ^{55}Fe peak stays on the initial position, but a new peak appears at lower energy.

It should be emphasized that since the avalanche from large primary ionization does not reach the expected amplitude, the contribution of such signals to the DT current and to the aging rate is reduced with respect to the values calculated from the gamma energy deposition. Therefore any theoretical calculation of the MDT gamma response should be corrected for the saturation effect to obtain the correct result. A precise measurement of the ratio of the signal amplitude to the primary ionization, which we call "response ratio", requires a special careful study which was not done yet. In this paper we make only a rough estimate using the spectra measured in the magnetic field. This estimation was performed as follows.

For the gamma energies from 59.5 to 122 keV the Compton parts of the spectra were removed the response ratio was calculated dividing the average amplitude of remaining signals to the energy of the primary photon. For the ^{60}Co we made a qualitative assumption that 5% of signals with largest primary ionization will produce 5% signals with largest amplitude. The model predicts average ionization of 780 keV for the 1252 keV photons and in the spectrum measured at 20,000 gas gain the average response was 250 keV for the tail of 5% signals. This gives the response ratio at average primary ionization of 780 keV. The choice of the cutoff value of 5% is absolutely arbitrary, but the result was stable against its variation from 2% to 10%.

The estimated values of the response ratio is shown in the fig.8 versus the gamma energy. The model predictions of the MDT response were corrected for this factor and the results of the calculations are presented in the fig.9 together with the experimental results. We can not extrapolate the model prediction to energies above 1300 keV because the saturation effect in that region is unknown. However it does not affect the result because only a negligible part of background photons have so large energies.

To obtain the average response per one photon detected by the ATLAS muon system one should convolve the energy dependence of the gamma response with the MDT spectral gamma efficiency and with the gamma energy spectrum expected in ATLAS. The MDT gamma efficiency without magnetic field was calculated in [3]. The introduction of the magnetic field did not change the results significantly. The gamma energy spectrum was taken from [13]. The convolution of the dependence shown in fig.9 with these functions has given the average MDT gamma response: 36 keV per photon detected by MDT.

Summary

We have studied the DT response to photons with energies from 6 to 1250 keV in a magnetic field of 0.6 T along the tube axis. We have also developed a theoretical model to extrapolate experimental results to the energy regions where no gamma lines are available. The main results are the following:

1. For the gamma energies below 30 keV the measured DT response is equal to the primary photon energy in an agreement with the model.
2. At higher gamma energies the effect avalanche saturation was observed. It manifests itself in reduction of the amplitude for only a part of the signals. This part increases with the increase of the energy deposition and is almost 100% for energies near 1 MeV.
3. The theoretical model corrected for this saturation effect predicts the average DT response in the energy region from 50 to 1000 keV ranging between 35 and 40 keV.
4. The convolution of the energy dependence of the gamma response with the MDT spectral gamma efficiency and with the energy spectrum of photons near the ATLAS muon system gives the average MDT gamma response value of 36 keV.

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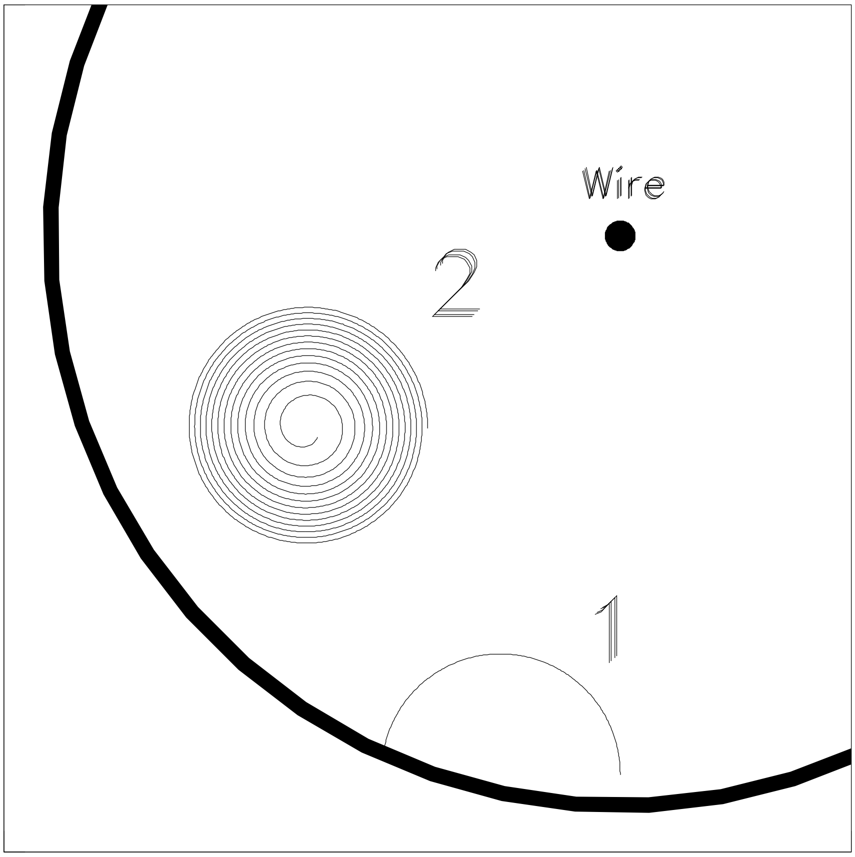

Figure 1: Schematic view of the DT cross-section with simulated trajectories of 250 keV electrons in 0.6T magnetic field.

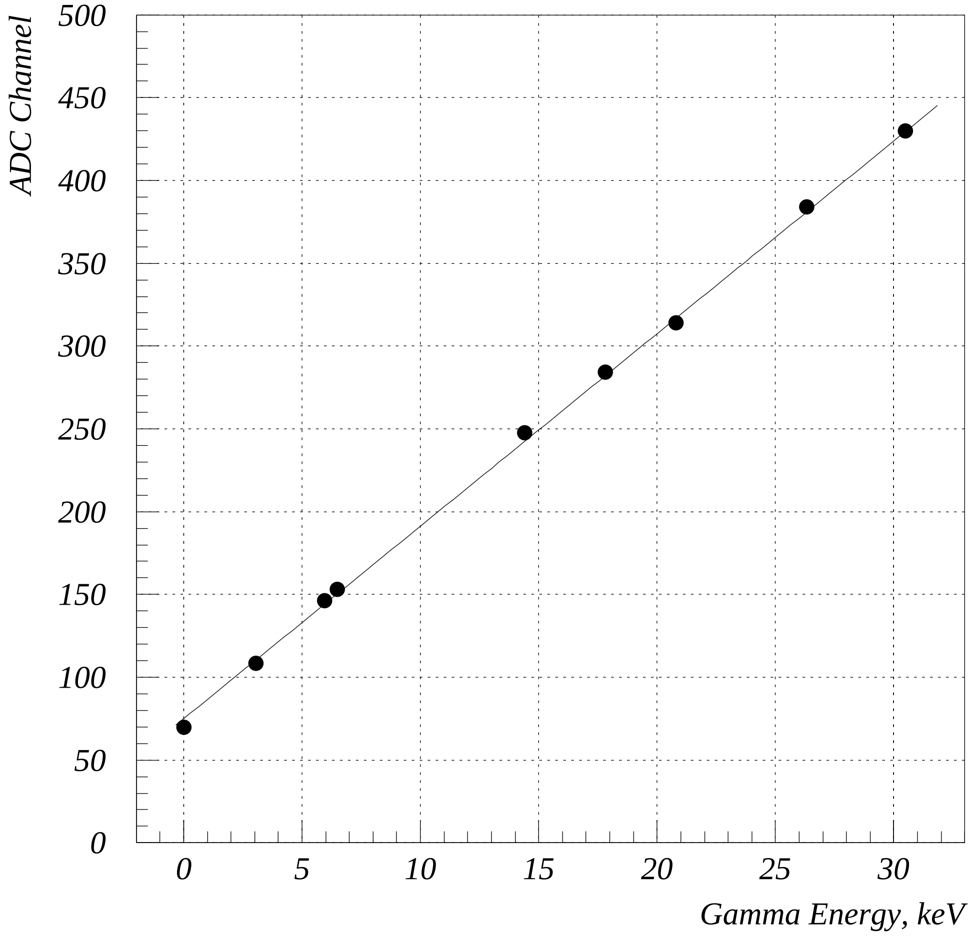

Figure 2: The peak position of the DT signals as a function of the gamma line energy.

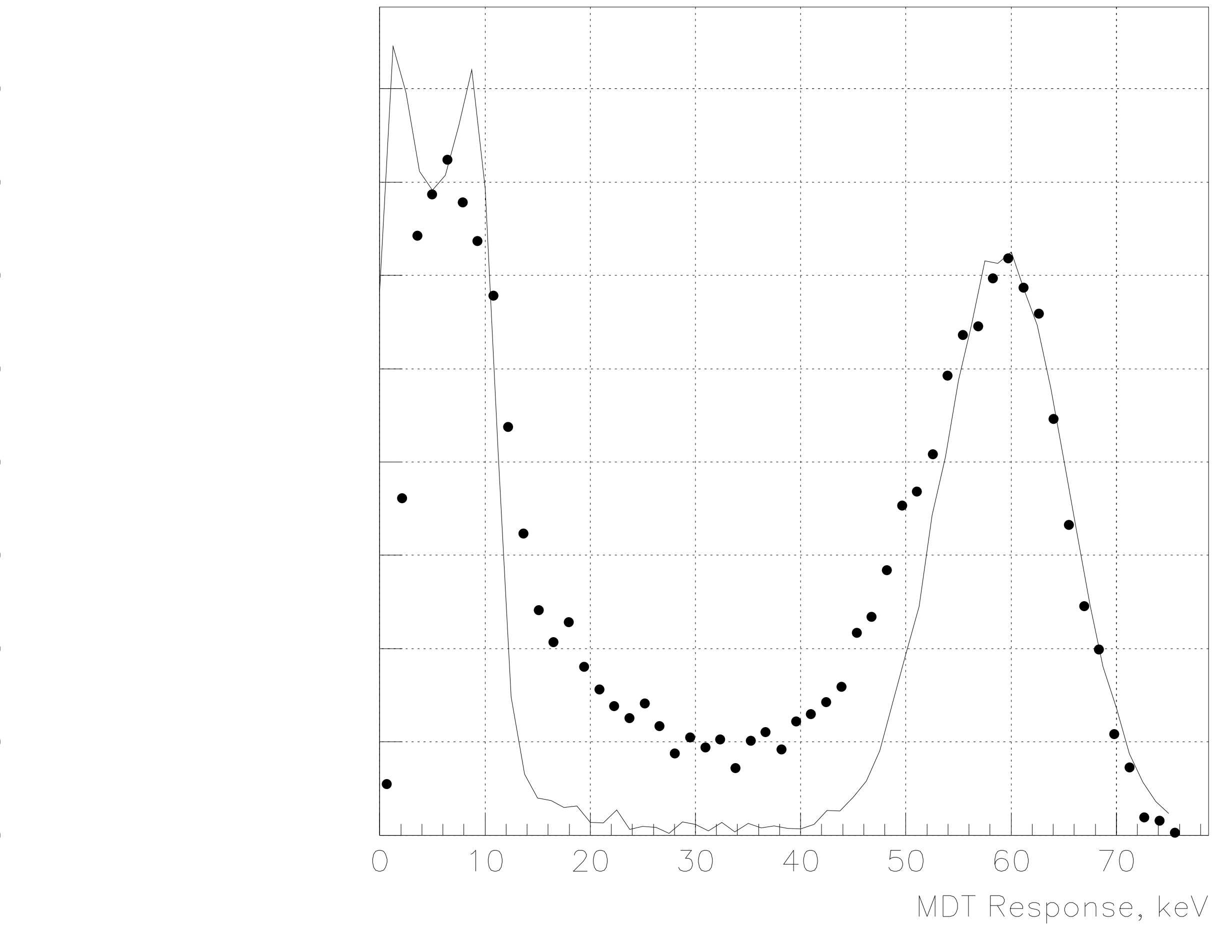

Figure 3: Spectrum of MDT response to 60 keV photons. The circles are data, the line is the model prediction.

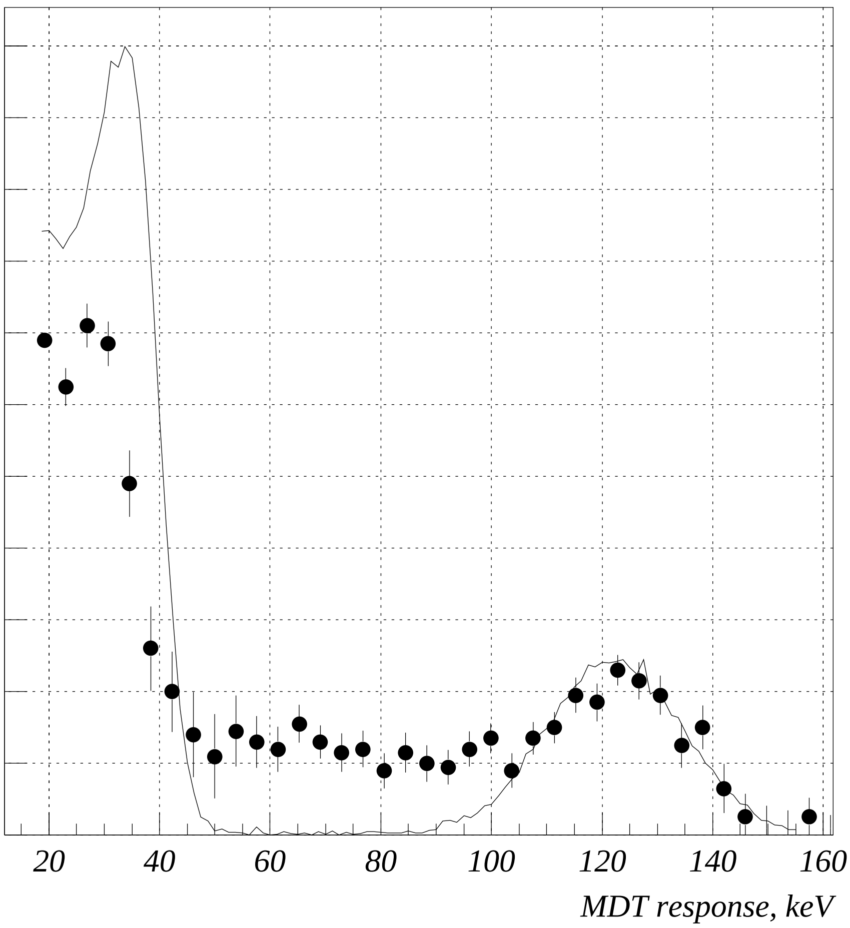

Figure 4: Spectrum of MDT response to 122 keV photons. The circles are data, the line is the model prediction.

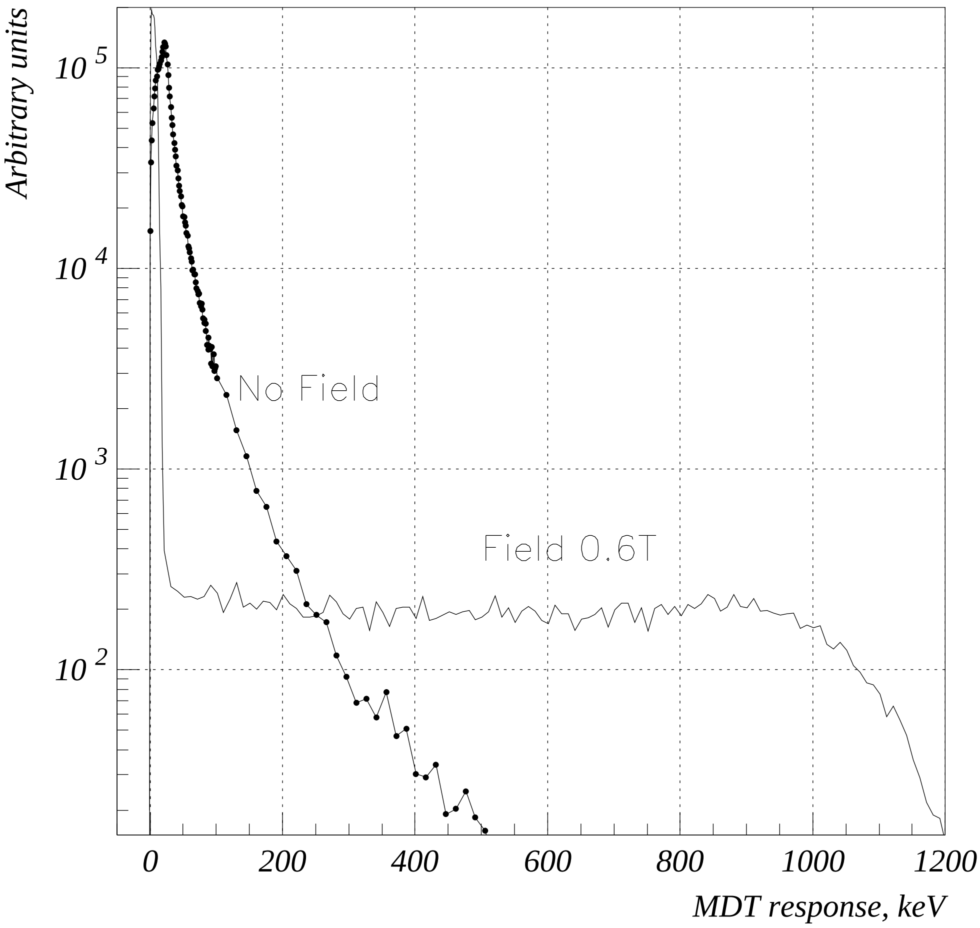

Figure 5: The simulated spectra of the MDT response to 1252 keV photons in and out of the magnetic field.

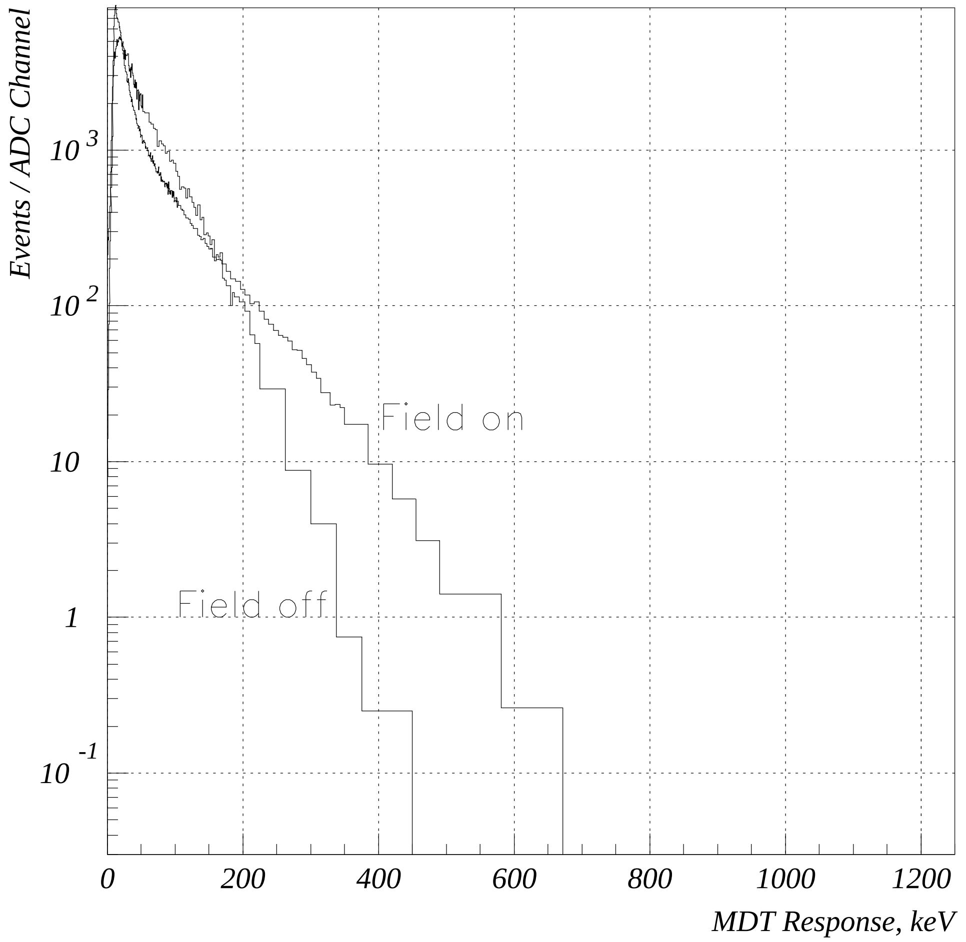

Figure 6: The measured spectra of the MDT response to photons from ^{60}Co (1252 keV) in and out of the 0.6T magnetic field. Gas gain value is 20,000.

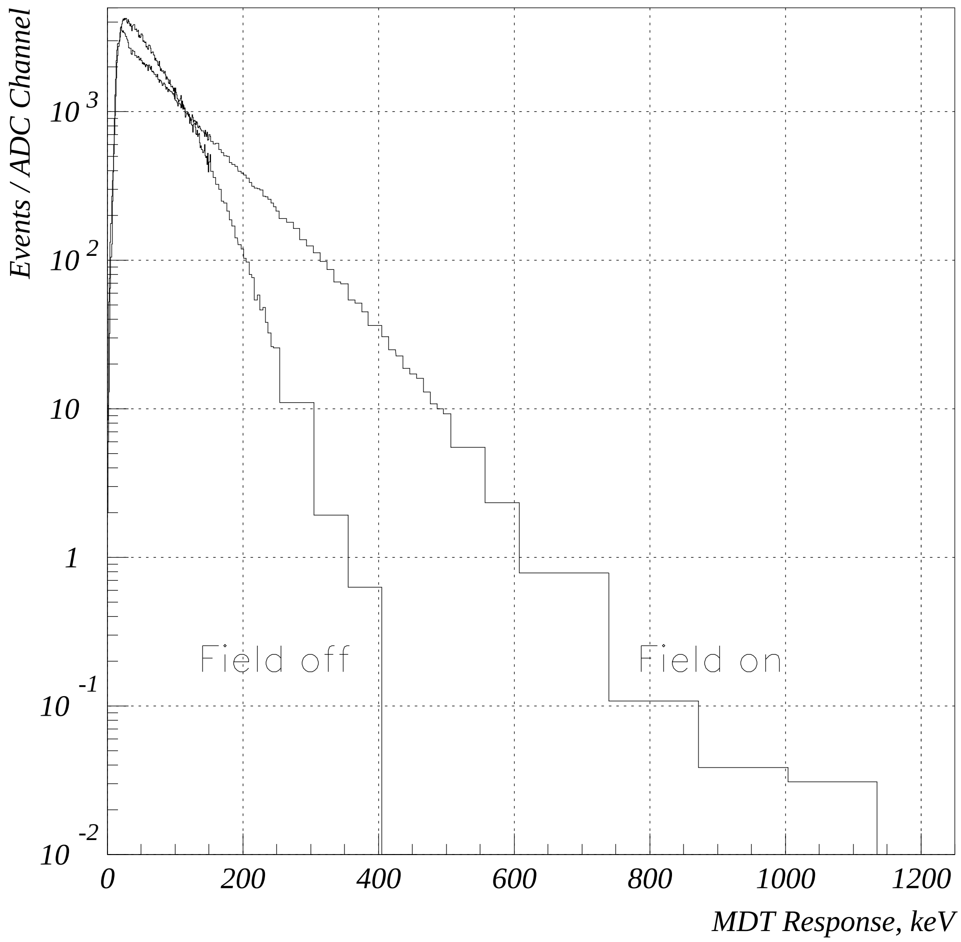

Figure 7: The measured spectra of the MDT response to photons from ^{60}Co (1252 keV) in and out of the 0.6T magnetic field. Gas gain value is 8,000.

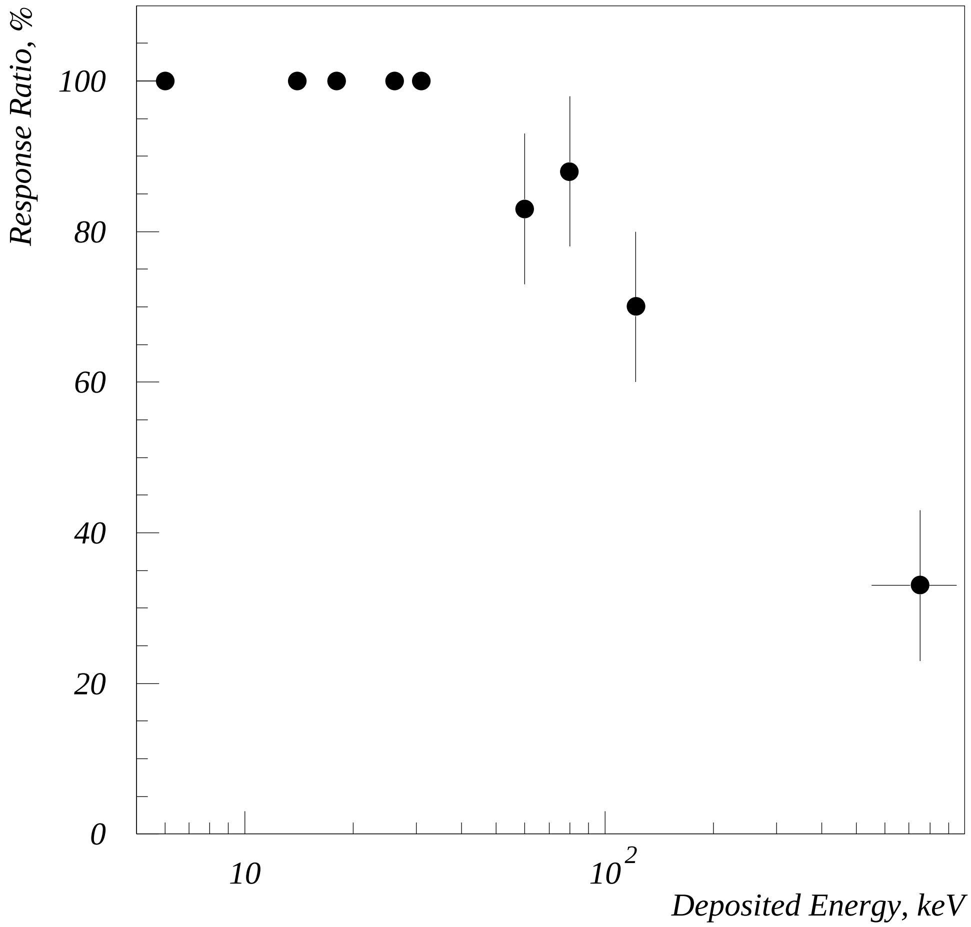

Figure 8: The "response ratio" (see text for details) versus the energy deposition.

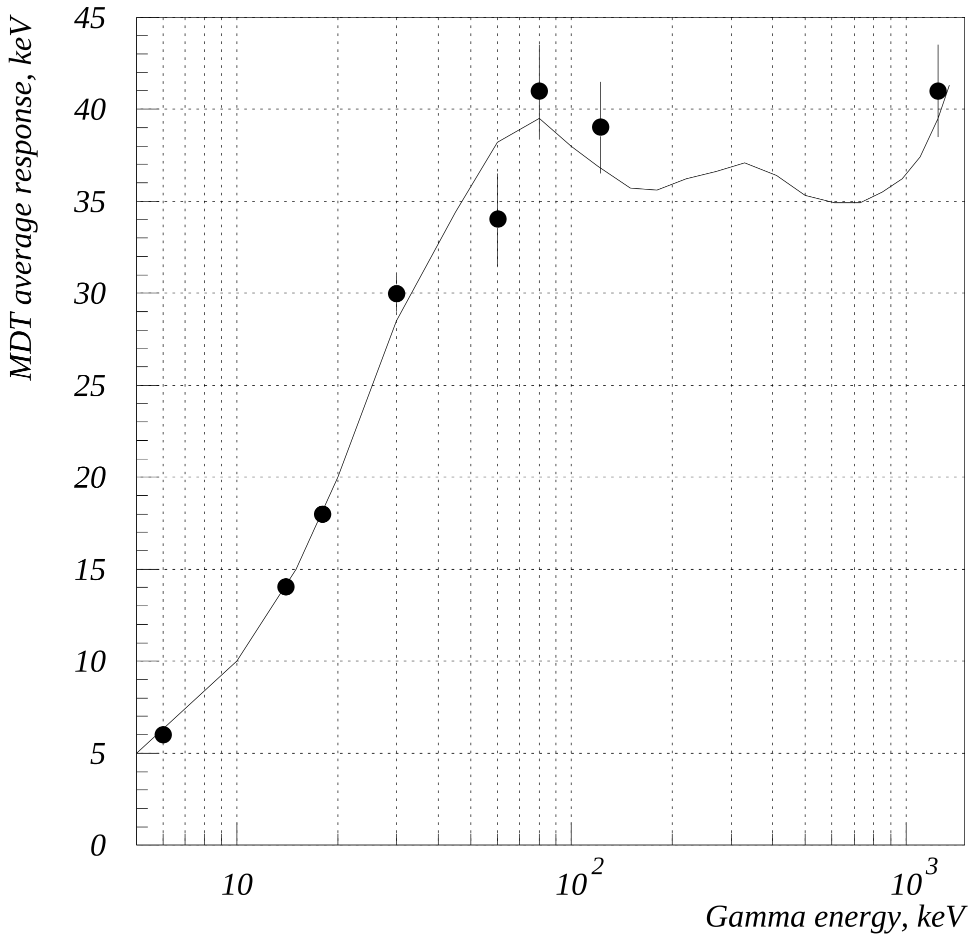

Figure 9: The average MDT response as a function of the gamma energy. The circles are data, the line is the model prediction.