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Background identification system in MEG II experiment based on high-rate scintillation detector with SiPM readout

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Abstract: The MEG experiment has been searching for the lepton flavor violating process, $\mu^+ \rightarrow e^+\gamma$, which is a clear evidence of new physics models beyond the Standard Model. The upgrade experiment (MEG II) is currently being prepared to obtain one order higher branching ratio sensitivity $\mathscr{B} < 5.0 \times 10^{-14}$ by using the world's most intense muon beam up to $\sim 10^8 \mu^+/s$ and upgraded detectors with considerably improved performance. One of the keys for the upgrade is to suppress the background rate which is significantly increased with the higher muon decay rate. In the MEG II experiment, the Radiative Decay Counter (RDC) will be newly introduced for active background identification. The RDC is able to identify the most dominant background due to photons from Radiative Muon Decay and improve the sensitivity by 22%. In this paper, the concept of the RDC and its development are described.

Keywords: Detector design and construction technologies and materials; Calorimeters; Timing detectors

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1 Introduction

$\mu^+ \to e^+\gamma$ decay is one of the lepton flavor violating processes which is predicted to occur at a sizable rate by many of new physics models beyond the Standard Model. The best upper limit on the branching ratio is $\mathscr{B} < 4.2 \times 10^{-13}$ (90% confidence level), which was set by the MEG experiment in 2016 [1]. Currently, the preparation for the upgrade experiment (MEG II experiment) is in progress. The MEG II experiment aims to achieve one order higher sensitivity [2] by using the world's most intense muon beam ($\sim 10^8 \mu/s$), which is provided at the πE5 beam line at the Paul Scherrer Institut (PSI). This maximum beam intensity was not used in the previous experiment because the background rate would be significantly increased. To avoid this problem, excellent resolutions of photon and positron detectors are required in the MEG II experiment.

For further improvement of the sensitivity, a new active background identification system, called Radiative Decay Counter (RDC) is under development. Two detectors will be installed on the muon beam axis, upstream and downstream the muon stopping target. RDC is able to improve the sensitivity by identifying a high energy photon from Radiative Muon Decay which is the dominant source of the background events.

2 Accidental background

A signature of the $\mu^+ \to e^+\gamma$ signal is a simple 2-body decay in the rest frame. A positron and a photon are emitted back-to-back ($\Theta_{e\gamma} = 180^\circ$) and coincident in time ($t_{e\gamma} = 0$). The energy of the emitted photon and positron are equal to half of muon mass ($E_\gamma = E_e = m_\mu/2 = 52.8\,\text{MeV}$).

Therefore, precise measurements of timing, energy and emission angle are important for the positron and photon detectors.

There are two types of background events for the $\mu^+ \to e^+\gamma$ signal. One is the Radiative Muon Decay (RMD; $\mu^+ \to e^+\overline{\nu}_\mu \nu_e \gamma$) where both photon and positron carry away large energy. In MEG II, the fraction of this background is relatively small thanks to improved energy resolution of the photon detectors.

Another background is the accidental coincidence of an energetic positron from Michel decay ($\mu^+ \to e^+\overline{\nu}_\mu \nu_e$) and an overlapping photon. This background rate is proportional to the square of the muon decay rate, and thereby it is the dominant source of background. The source of the photon is either RMD or Annihilation In Flight (AIF) of a positron. The fraction of the two sources in the analysis region ($E_\gamma > 48\,\mathrm{MeV}$) were almost the same in the previous experiment. On the other hand, the fraction of AIF becomes much smaller in MEG II. This is mainly due to the new positron spectrometer which has less material. In addition to this, further identification of the AIF is possible with analysis. Therefore, accidental pileup of RMD and Michel decay (figure 1) is the dominant background event in the MEG II experiment.

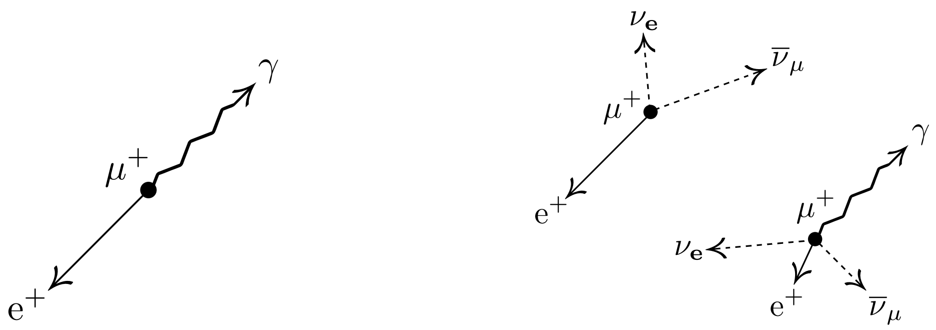

Figure 1. Left: $\mu^+ \to e^+\gamma$ signal. Right: accidental background (positron from Michel decay and photon from RMD).

3 Radiative Decay Counter

The concept of the RDC is illustrated in figure 2. In the MEG II experiment, muons are transported to a thin stopping target and decay at rest. The positron emitted from the target follows a trajectory at constant bending radius due to a gradient magnetic field, which is produced by a special superconducting magnet (COBRA). When a high energy photon is emitted from RMD, a low momentum positron of typically 2–5 MeV is also emitted. This positron does not enter the positron spectrometer but it is swept away along the beam axis along the magnetic field lines. The bending radius of these positrons are smaller than 9 cm. Therefore, the background photons from RMD can be identified by detecting the time-coincident low momentum positrons. On the beam axis, the detectors can be installed both upstream and downstream of the muon stopping target. According to the simulation results, RDC is able to identify 41% of total background photons and thus improve the sensitivity by 22%.

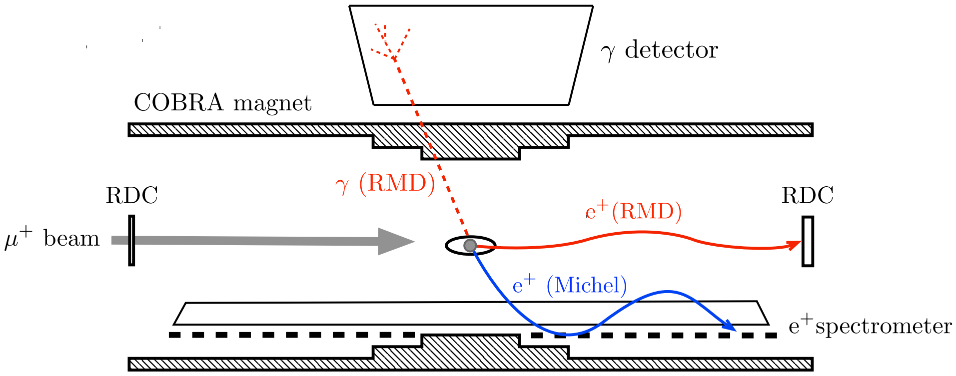

Figure 2. Schematic view of MEG II detectors.

Because a lot of positrons from Michel decays hit the RDC detector, it has to be operational in such a high hit rate environment (~ MHz). Therefore, each detector consists of a fast plastic scintillator which is finely segmented in the high rate region. Meanwhile, in order to be installed inside the superconducting solenoid, the size of the detector has to be as compact as possible (~ 20 cm). For this reason, the scintillation light is collected by using a SiPM, which is relatively small. Moreover, SiPM is insensitive to the magnetic field. Due to the high rate, random hits of positrons from Michel decays become a background for RMD detection. As shown in figure 3, these positrons are distinguishable by measuring the energy. Therefore, for further improvement of the performance, the downstream detector also has a calorimeter based on a LYSO crystal and SiPM.

The downstream detector has been already constructed and tested. The first commissioning by using the muon beam was completed. The upstream detector is still under development since it requires additional R&D concerning the operation in the muon beam. The impact on the muon beam transportation was investigated in a mockup test and simulation. The detector performance in such a high hit rate environment was evaluated.

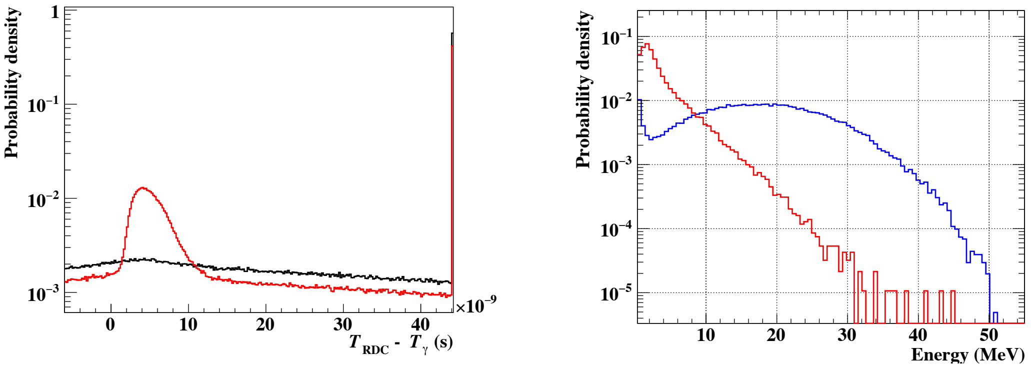

Figure 3. Left: (red) expected hit time difference between the RDC and the photon detector assuming a timing resolution of 100 ps. (black) Accidental positron from Michel decay. Right: energy deposit in the downstream detector. (red) RMD with $E_\gamma > 48$ MeV. (blue) Michel decay.

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4 Downstream detector

4.1 Detector design

The downstream detector consists of the timing counter and the calorimeter. The timing counter consists of 12 plastic scintillator bars with multiple-SIPM readout as show in figure 4. Scintillator bars have 5 mm of thickness and several different lengths (7–19 cm). There are two types of width (1, 2 cm) and the smaller width is used for central 6 scintillators in which there is a relatively high hit rate. Scintillation light is collected at two ends with two or three $3 \times 3\,\mathrm{mm}^2$ SiPMs (Hamamatsu, S13360-3050PE). They are connected in series to reduce the number of readout channels. The performance of each counter was tested by using a radiation source. A timing resolution of $\sim 90\,\mathrm{ps}$ in sigma was obtained, which is good enough for tagging RMD events.

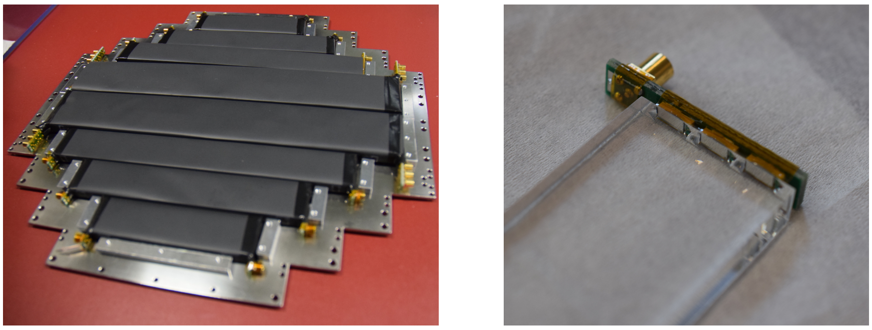

Figure 4. Left: counters wrapped with reflector and light shielding. The 6 central scintillators are wrapped together two by two. Right: plastic scintillator glued with 3 SiPMs.

Figure 5 shows the calorimeter part which is placed just behind the plastic scintillators. It consists of 76 LYSO crystals with a size of $2 \times 2 \times 2\,\mathrm{cm}^3$. Each crystal is readout with a single SiPM (Hamamatsu, S12572-025P), which is mounted on a flexible PCB. The SiPM is fixed on the backside of the crystal with a spring. The LYSO crystals are suitable for high hit rate operation due to the short decay time of 40 ns [3]. Thanks to the high light yield of the crystal, a good energy resolution was obtained at the test ($\sim 6\%$ for 1 MeV). Moreover, due to the contained radio isotope ^{176}Lu, the crystal has $\sim 2\,\mathrm{kHz}$ of intrinsic radioactivity which makes an energy peak around 600 keV. This is used for the energy scale calibration of each channel.

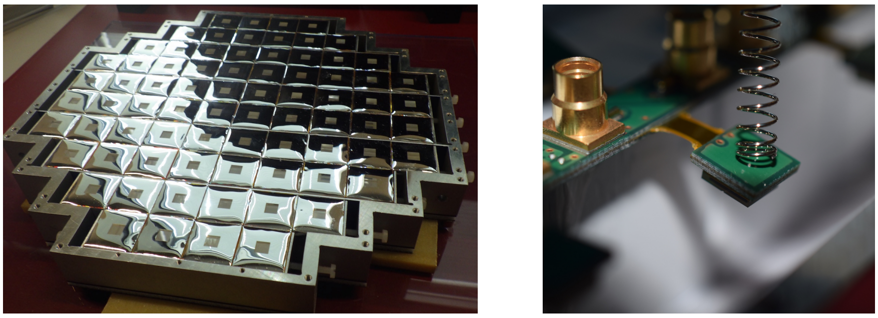

Figure 5. Left: LYSO crystals contained in a holder. Right: PCB with a spring which presses the SiPM on to the LYSO crystal. The SiPM is mounted below the PCB in the picture.

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4.2 Commissioning

The first beam test with the constructed detector was carried out in July, 2016. The capability of the background identification was demonstrated with the high intensity muon beam. As a substitution for the MEG II photon detector, 16 BGO crystals and PMTs were used. The RDC detector was inserted in the solenoid with a moving arm. The signal was transmitted through the cables to a waveform digitizer (WaveDREAM [4]), which is developed for the MEG II experiment. Before the data taking, a series of calibrations has been done. To optimize each bias voltage of SiPMs, positrons from Michel decay and intrinsic radioactivity of LYSO crystals were acquired for the timing counter and the calorimeter respectively. The absolute energy scales of BGO crystals were calibrated by using 1.8 MeV gamma-rays of ^{88}Y.

The data was acquired for a few days by triggering on a hit of any BGO crystal. In order to select only RMD candidate events, event selection was done in the following way. First, the events triggered by cosmic-rays were rejected by selecting a hit position and total energy deposit in BGO crystals. Moreover, the random hits of the positron from Michel decay were rejected by cutting events with large energy deposit in LYSO crystals. As shown in figure 6, a clear peak of RMD events was successfully observed. A more quantitative evaluation of the detector performance is currently in progress.

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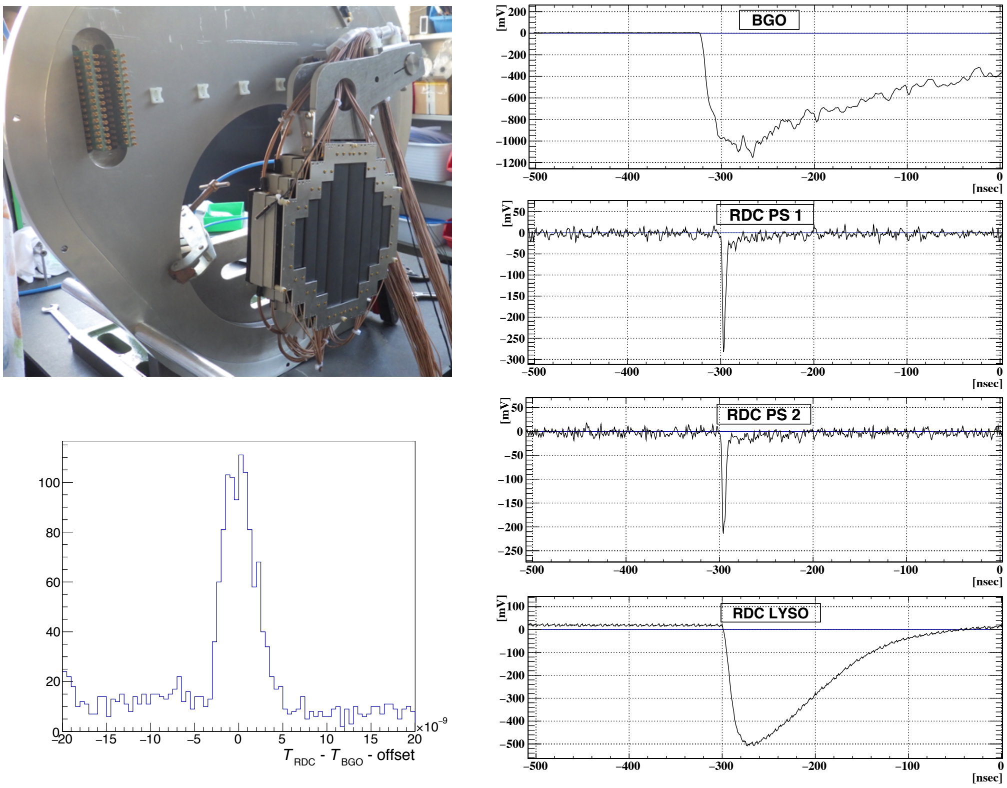

Figure 6. Top left: RDC set to the measurement position. Right: example of a RMD candidate. Waveforms of a BGO crystal, plastic scintillator (left and right side) and LYSO crystal are shown. Bottom left: hit time difference of BGO crystals and RDC after event selection.

5 Upstream detector

5.1 Detector design

As previously mentioned, the upstream detector is required to minimize the influence on the muon beam transportation. Therefore, it consists of a thin layer of scintillation fibers. About 780 square shaped fibers with a size of 250 μm are used. To reduce the number of readout channels, fibers are grouped into a few tens of bundles and each bundle end is readout with a single SiPM. The bundles are bent at right angles due to the limitation of available space around the detector (figure 7). In the previsional mechanical design, 18 bundles are used in total. A timing resolution of $\sim 500\,$ps in sigma is expected by the double sided readout.

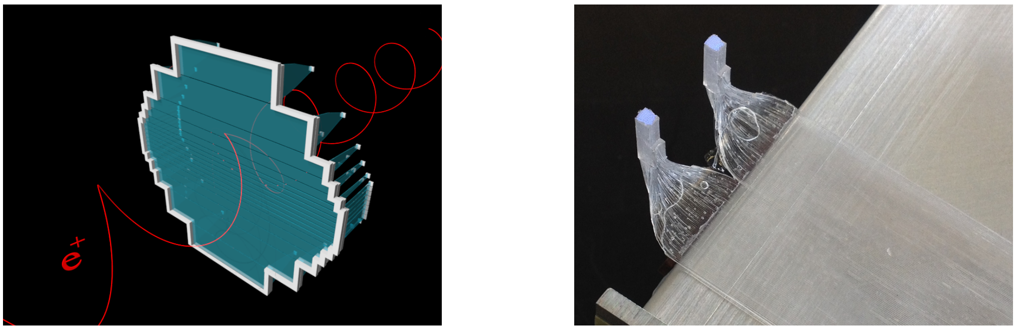

Figure 7. Left: CG image of the upstream detector. Right: bundled fibers (64 fibers × 2).

5.2 R&D

The influence on the muon beam was studied by using a mockup (230 μm thick Mylar foil), whose material thickness equals to the scintillation fiber. The beam spot size at the target position was measured with two configurations (figure 8). The beam position distribution was measured in two dimensions by moving the position of a thick depletion-layer APD. When the upstream RDC is not installed, 300 μm thick Mylar foil degrades the muon momentum. By thinning the degrader, the RDC with the same amount thickness can be installed. However, because it is not installed at the waist position, the properties of the muon beam could be affected. As a result, the beam spot area was measured to be 16% larger with the mockup. However, according to a simulation study, the bigger beam spot does not significantly affect the performance of the positron spectrometer. The efficiency loss for the signal positron is less than 1% and the momentum resolution would not be changed. Moreover, the loss of the muon stopping rate would be less than 1%.

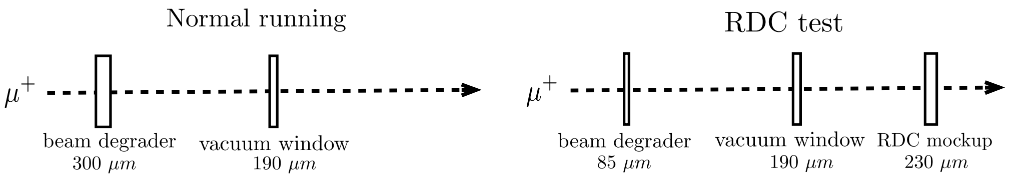

Figure 8. Schematic view of the setup.

Because of the high muon hit rate (~ 500 kHz at the central fiber), the effect of pileup muons is not negligible. In order to estimate the detector performance, the detection efficiency loss due to pileup was studied. The inefficiency due to pileup mainly depends on following two factors.

The first one is the capability to distinguish muon and positron pulses in waveform analysis. We defined the minimum time difference to distinguish the muon and positron waveform as ΔT. Since there are after-pulses of the SiPM associated with the main pulse, pileup with these after-pulses has to be also considered. We measured actual ΔT by analyzing waveform data. Each muon and positron waveform was sampled independently by using a prototype detector at the πE5 beam line in PSI. The muon and positron waveforms were mixed randomly and ΔT was determined by analyzing the mixed waveform. ΔT was estimated to be 120 ns, which is large due to the after-pulses.

The second one is the hit rate of muon and positron from RMD at each bundle, which was obtained in a simulation study. The hit rate depends on the width of the bundle of fibers and its position. In other words, the configuration of the bundle widths can be optimized by minimizing the inefficiency. The width has to be as small as possible in the high rate region, however, the total number of bundles has to be small enough.

As a result, the inefficiency due to pileup is large (~ 50%) even by using the best bundling configuration. To reduce the inefficiency, several possibilities are being considered. The first idea is to increase the total number of bundles as shown in figure 9. This might be possible by modifying the detector layout. The second idea is to make a probability density function related to the after-pulse and implement it in likelihood analysis of MEG II. In previsional estimation, we assumed that the after-pulses are always present in the timing region of 120 ns. Therefore, further reduction of the inefficiency is possible by taking into account that the after-pulses are generated only randomly after the main pulse. In order to construct a probability density function, the characteristic of the after-pulse needs to be fully understood. The third idea is to use a staggered readout as shown in figure 10. The inefficiency can be reduced by half at most by using this method. However, a high light yield at the single side is required to efficiently detect a positron signal.

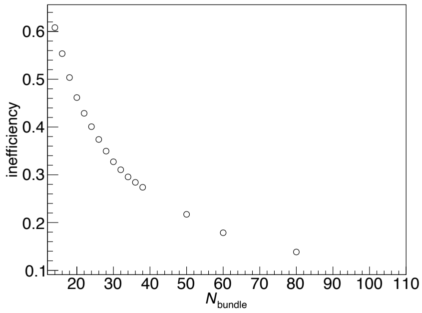

Figure 9. Total number of bundles and inefficiency with the best bundling configuration.

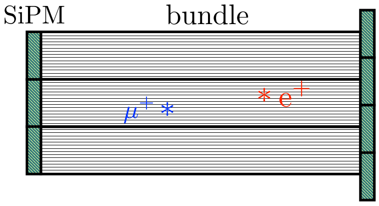

Figure 10. Schematic view of staggered readout. Pileup of muon and positron hits in the left middle SiPM is distinguishable in the other side.

Currently, performance evaluation of the upstream detector is in progress. The present results suggest that further improvement of detection efficiency is possible if we could increase the light yield of the scintillation fiber. The radiation hardness of the scintillation fiber is going to be tested at the irradiation facility in PSI.

6 Conclusion

In the MEG II experiment, the RDC will be newly installed to improve the sensitivity by 22%. Most of the background photons from RMD can be identified by detecting the low momentum positron. A compact design and good performance in a high rate environment are required for both downstream and upstream detectors of the RDC. The construction of the downstream detector has been already finished. The first commissioning was performed in the high intensity muon beam. The capability of background identification was successfully demonstrated. Currently, a series of studies for the upstream detector is in progress. We concluded that the influence on the muon beam transportation is small. On the other hand, the detection efficiency loss due to pileup muons is large ($\sim 50\%$). However, further reduction of the pileup is possible in several ways. Increasing the number of bundles or using a staggered readout are considered. Moreover, the inefficiency could be reduced in analysis by properly taking into account the characteristics of the after-pulse of the SiPM.

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