Liquid xenon calorimeter for MEG II experiment with VUV-sensitive MPPCs
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1. MEG II liquid xenon calorimeter

The MEG experiment searched for the charged lepton flavor violating decay of muon, $\mu^+ \rightarrow e^+\gamma$, with the highest sensitivity ever achieved by using the world’s most intense DC muon beam at Paul Scherrer Institut (PSI) and the innovative detectors [1]. The MEG II experiment is an upgrade of the MEG experiment [2]. The branching ratio sensitivity of MEG II is expected to reach $4 \times 10^{-14}$, which is one order of magnitude better than the sensitivity of the current MEG experiment. All detectors will be upgraded, aiming to significantly improve the resolutions to cope with twice or higher beam rate ($7 \times 10^7 \mu/s$) in the MEG II. Especially energy resolution of $\gamma$-ray detector is important as we can efficiently distinguish the signal event from the background by the $\gamma$-ray energy.

In the MEG experiment, a 900 L liquid xenon (LXe) calorimeter with 846 photomultiplier tubes (PMTs) was used to detect 52.8 MeV $\gamma$-ray coming from the signal event as LXe has several advantages such as high light yield, fast decay time, and high stopping power. This LXe detector was successfully operated in the MEG physics data taking, but its energy resolution was limited by the non-uniformity of the scintillation readout. In the MEG II experiment, 216 PMTs on the $\gamma$-ray entrance face will be replaced with 4092 Multi-Pixel Photon Counters (MPPCs, one of the SiPM families) to realize the better uniformity and granularity of the scintillation readout (Fig. 1). The layout of the PMTs on the lateral face will also be modified to reduce the energy leakage and to improve the scintillation readout uniformity. We have developed a VUV-sensitive MPPC in collaboration with Hamamatsu Photonics K.K. (summarized in Section 2). The performance of the LXe detector has been estimated by simulation and a significant improvement is expected (summarized in Section 3).

A high density and high bandwidth signal transmission system has been developed for the 4092 MPPCs (Fig. 2). The MPPCs are mounted on printed circuit boards (PCBs) which have ‘coaxial-like’ structure to reduce the noise from the outside and the crosstalk between channels. The vacuum feedthrough is also based on PCB with ‘coaxial-like’ structure and high density signal transmission has been achieved.

In addition to the new signal transmission system, the DAQ system will be renewed to cope with the increased number of channels. A new DAQ board called WaveDREAM is being developed, which integrates the functionality of the waveform digitizer, amplifier, trigger, and HV supply on a single board.

The cooling power of the refrigerator also has to be upgraded to cope with the increased external heat inflow coming from the 4000 MPPC signal cables. A more powerful GM refrigerator will be added for this purpose and its performance has already been confirmed.

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2. Development of VUV-sensitive MPPCs

There are several requirements for the MPPCs to be used in the MEG II LXe detector.

- It must be sensitive to the LXe scintillation light in vacuum ultraviolet (VUV) range ($\lambda = 175$ nm [3]).
- Its chip size must be large enough ($12 \times 12$ mm$^2$) to keep the number of readout channels manageable.
- It must be operational in LXe ($T = 165$ K).

A new type of MPPC which satisfies these requirements has been developed, in collaboration with Hamamatsu Photonics K.K. (Fig. 3) [4]. This is a discrete array of four $6 \times 6$ mm$^2$ chips. The pixel pitch of the MPPC is $50 \mu$m. A metal quench resistor is used as it has smaller temperature coefficient than polysilicon. Crosstalk and afterpulse suppression technique is implemented to improve the performance of MPPC. The sensor is covered by a VUV-transparent quartz window for protection.

High sensitivity to the VUV light is achieved by removing the protection layer of resin, optimizing the optical matching between LXe and the sensor surface, and thinning the contact layer.

The four sensor chips are connected in series in the readout PCB to avoid the large sensor capacitance due to the large sensor area, which would cause a pileup issue with a longer tail in the signal waveform. A sufficiently short timing constant ($<50$ ns) is achieved for a single photoelectron waveform with this series readout.

The performance of the VUV-MPPC in LXe has been measured, by using the setup shown in Fig. 4. Single photoelectron waveforms from a UV-LED are used for the study of the basic performance of MPPC such as gain, breakdown voltage, crosstalk probability, and afterpulse probability. A spot alpha source ($^{241}$Am) mounted on a tungsten wire is placed at the center of the setup. The scintillation light from the alpha source can be regarded as a point light source thanks to the very short range ($\sim 40$ $\mu$m) of alpha particle in LXe.

Despite the large area of MPPC, a clearly resolved single photoelectron peak can be seen, thanks to the low dark noise rate at LXe temperature. Gain is estimated to be $8 \times 10^3$ at overvoltage 7 V with series readout. Crosstalk probability is measured to be only 5% at overvoltage 3 V from the charge distribution of LED light, which was 50% without the crosstalk suppression technique.

The photon detection efficiency (PDE) for LXe scintillation light is estimated as a ratio of the detected number of photoelectrons to the arrived number of photons. The arrived number of photons is estimated from the energy of alpha source, $W$ value of LXe [5], and the solid angle from the alpha source to the sensitive area of MPPC.
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