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# The liquid xenon detector for the MEG II experiment to detect 52.8 MeV $\gamma$ with large area VUV-sensitive MPPCs

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## ABSTRACT

The MEG II experiment is searching for new physics beyond the SM (e.g. SUSY-GUT, SUSY-seesaw) through the lepton flavor violating $\mu^+ \to e^+\gamma$ decay with ten times better sensitivity than the MEG experiment. The MEG collaboration published the result of $\mathrm{B}(\mu^+ \to e^+\gamma) < 4.2 \times 10^{-13}$ at 90% C.L. in 2016, which was thirty times better result than the previous limit. As the sensitivity of the MEG experiment was already limited by the accidental background, the MEG detector had to be upgraded to reach one order of magnitude better sensitivity. The MEG experiment utilized 846 2 inch PMTs to detect scintillation light in a 900 l liquid xenon $\gamma$ calorimeter. In the MEG II experiment, 216 2 inch PMTs on the $\gamma$ incident face were replaced with 4092 MPPCs (SiPMs produced by Hamamatsu) to improve the energy and position resolutions. We started the detector commissioning with the full electronics readout channels for the first time in 2021, and soon after, we started the physics data taking. Here the LXe detector status including initial photon sensor calibration and performance will be summarized together with the expected detector performance. The PDE decrease of the SiPM observed in the high rate muon beam environment and our possible remedy will also be discussed.

## 1. Introduction

In the standard model of elementary particle physics, quark mixing is described by the CKM matrix and neutrino transition is characterized by the PMNS matrix. However, the charged lepton flavor violating (CLFV) processes have not been observed so far. The reason why only the CLFV transition is not observed up to now is yet to be understood.

In the standard model with the neutrino oscillation, the branching ratio of the $\mu \to e\gamma$ decay is heavily suppressed on the order of $10^{-54}$. However physics beyond the standard model like SUSY-GUT or SUSY-seesaw predicts rather large branching ratios on the order of $10^{-14}$. Such a branching ratio would just be accessible with the current technology suggesting there is a real chance to discover this phenomenon.

The $\mu \to e\gamma$ decay search has a long history for more than 70 years since there is no strong theoretical reason to conserve lepton flavor, and many new physics models predict large branching ratios depending on a wide parameter space. The current most stringent upper limit for $\mu \to e\gamma$ decay branching ratio is set by the MEG experiment, $4.2\times10^{-13}$ at 90% C.L.[1]

The MEG II experiment has started physics run and aims to reach a sensitivity of $6\times10^{-14}$ in three years [2]. Experiments probing other muonic CLFV decay modes are under construction and will soon be commissioned, providing a thorough and complementary investigation of the field.

The signal of the $\mu \to e\gamma$ decay is identified by a $\gamma$-positron pair in back to back geometry coinciding in time where each of the particle carries half the muon mass (52.8 MeV). There are mainly two backgrounds in our case, accidental and the radiative muon decay (RMD). The accidental background is the dominant background. It originates from a standard Michel decay positron coinciding with $\gamma$s from RMD or annihilation in flight (AIF). The accidental rate increases with the muon event rate squared and depends on detector performance. This requires a trade off between a high beam intensity to meet the statistics requirements and a low instantaneous beam intensity to suppress the

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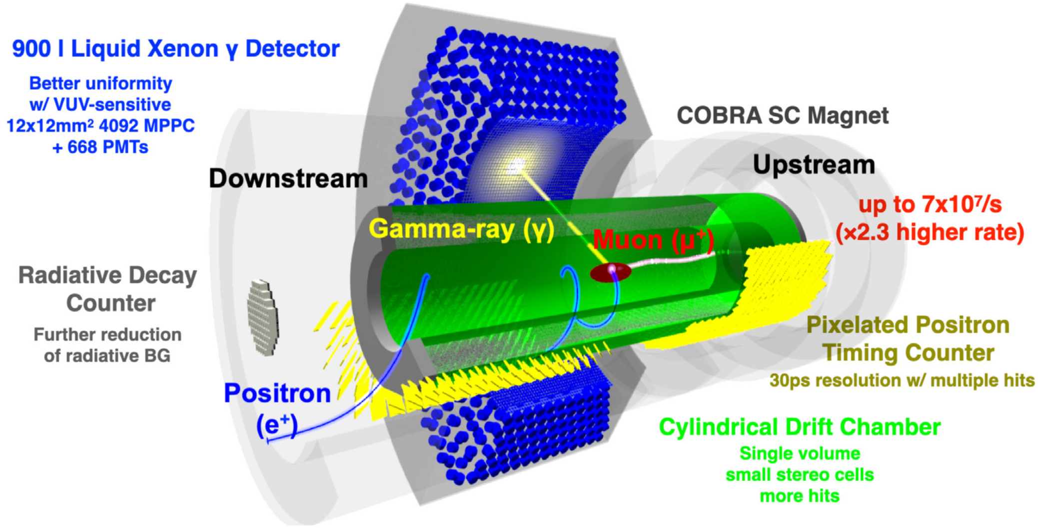

**Fig. 1.** The MEG II detector.

background. As a result, a DC muon beam is preferred and excellent detector resolutions are crucial.

The world most intense DC muon beam is available at the Paul Scherrer Institute in Switzerland. There is a 590 MeV 2.4 mA proton ring cyclotron, and the RF time structure is 50 MHz. This results in no time structure in the muon decay, and the continuous muon beam is available. The maximum intensity is above $10^8$ μ/s.

## 2. MEG II experiment and the LXe detector

Fig. 1 shows the MEG II detector. The muon beam up to $7{\times}10^7$μ/s is stopped on a target. Positrons are bent by a magnetic field which is produced by a superconducting magnet, and are tracked by the cylindrical drift chamber (CDCH). The timing is obtained by a pixelated timing counter. $\gamma$s are measured by a liquid xenon $\gamma$ detector of 900 l in which the scintillation light is detected by VUV-sensitive $12 \times 12$ mm$^2$ 4092 MPPCs and 668 PMTs.

This paper will concentrate on the MEG II liquid xenon detector. Position, timing, and energy of the signal $\gamma$s are measured by this detector. The cryostat is shaped to fit the superconducting magnets. The entrance window is very thin (0.075 $X_0$) with a honeycomb structure to allow $\gamma$s to reach the liquid xenon detector fiducial volume. The detector medium is 900 l liquid xenon which has many beneficial characteristics such as homogeneous response, high stopping power (3 g/cm$^3$), high light yield and short decay time (45 ns for $\gamma$). The scintillation light is detected by 4092 MPPCs and 668 PMTs immersed in LXe. Since the wavelength of xenon scintillation light is 175 nm and the typical liquid xenon temperature is 165 K, special photo sensors were developed in collaboration with Hamamatsu K.K. All waveforms of the sensors are recorded by waveform digitizers (WaveDAQ system developed specifically for MEG II [3]) to identify pileup events.

In 2017, the detector construction has been completed, and since then, the sensor calibration, muon beam run with reduced readout channels had been continued until 2020. The full electronics readout has finally been installed in 2021.

Fig. 2 shows the event display for the LXe detector. This is the development view, and each dot corresponds to a single photo sensor. The color represents the collected charge. The orange region shows the readout map in 2020 equipped with electronics, and all the channels are readout from 2021.

The event reconstruction and calibration will be summarized here. A five dimensional reconstruction is performed. The energy is estimated based on the sum of all photon sensors, three dimensional positions are reconstructed by the charge distribution, and the time is estimated with the average of the sensor times. There are several calibration methods, LEDs for gain estimates, $^{241}$Am $\alpha$ sources immersed in LXe for PDE and QE estimates, 17.6 MeV $\gamma$s from $^7$Li(p, $\gamma$)$^8$Be reactions, 55 and 83 MeV $\gamma$s from $\pi^- p \rightarrow \pi^0 n$ reaction. Especially the 55 and 83 MeV $\gamma$ calibration is important to know the detector performance near the signal region (52.8 MeV).

The energy resolution is estimated by these 55 MeV $\gamma$s and the background $\gamma$ events in the muon beam run. The current estimate for the resolution is about 2% based on standard deviation. The position resolution is evaluated by installing collimators in front of the LXe detector to be 2.5 mm.

The current main issue of the LXe detector during the operation is the MPPC PDE decrease in the muon beam environment. This phenomenon was observed when the LXe detector operation was started in 2017 with the muon beam, and the decrease speed was estimated that the original PDE value of 16% will go down to 2% in 100 days with the beam intensity of $7{\times}10^7$ μ/s. The cause is not fully understood yet, but surface damage by VUV-light or radiation is suspected in which the accumulated positive charge at the interface between SiO$_2$ and Si reduces the collection efficiency of the charge carriers which result in the PDE decrease. The annealing method by Joule heat which is supplied from high current directly to the MPPCs can recover the PDE which also indicates the cause might be surface damage [4]. The Joule annealing method was tried for the first time for all the MPPC channels in May 2022. The 1.7 W per MPPC was supplied by the special power supply and LED light. The power supply can provide 30 outputs at the same time, each of which is connected to 8 ch. Thus, 240 channels can be annealed in total at once. We have in total 4092 MPPCs, and 17 sets are repeated. In order to use the special power supply, we need to change the cables from our readout electronics to the power supply one by one. In total 30 h annealing plus cabling work was performed in two days per set. Thus, annealing all channels required one month to finish.

Fig. 3 shows the annealing result. The left figure shows the absolute PDE value as a function of elapsed time during annealing for one channel. As shown in Fig. 3, around 1800 min. annealing almost recovers the PDE. The right figure shows the result of the annealing for all channels. We found that the mean value of the PDE after the annealing is 0.115 which is sufficient for this year's long physics run.

## 3. Status of the MEG II experiment

Last year we have started the physics run, and the accumulated number of muons stopped on the target was $1{\times}10^{14}$. The radiative

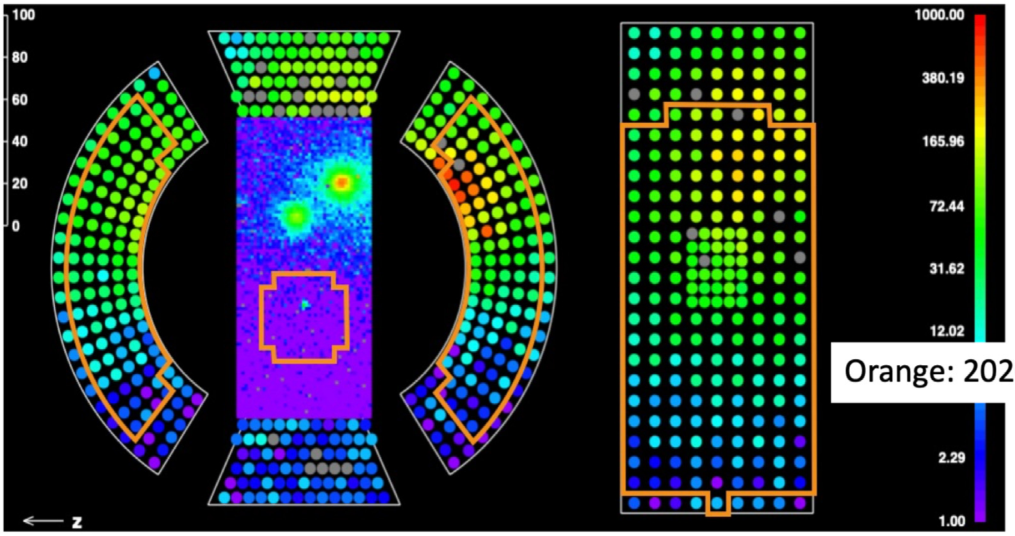

**Fig. 2.** The event display of the LXe detector.

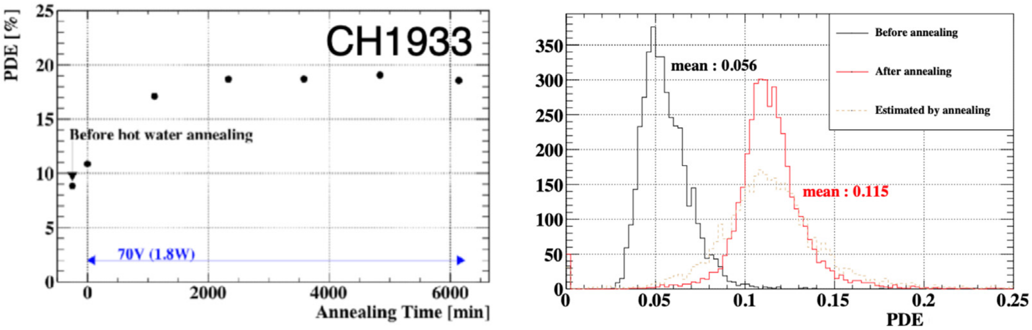

**Fig. 3.** The left figure shows an example of one channel annealing result. The horizontal axis shows the annealing time and the vertical axis shows the PDE. The right figure shows the annealing result for all the channels.

muon decay time coincidence peak is observed which confirms that the time coincidence trigger is working correctly and can provide the time resolution between $\gamma$ and positron. Currently the detector performance and the detection efficiency are carefully estimated, but the last year's data statistics were almost comparable with the MEG final result, and this year's data will reach the sensitivity beyond the MEG experiment. We will aim at $6\times10^{-14}$ in 3 years data taking.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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