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Design of a LYSO crystal calorimeter for dark photon detection in the DarkSHINE experiment

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Abstract. The DarkSHINE experiment aims to detect dark photons, a candidate for light dark matter, using a high-frequency electron beam from the Shanghai High Repetition-Rate XFEL and Extreme Light Facility. The Electromagnetic Calorimeter (ECAL) in DarkSHINE serves to precisely measure the energy of recoil electrons and bremsstrahlung photons. It is a homogeneous calorimeter composed of LYSO crystal scintillators, which was chosen for its fast decay time, high light yield, and strong radiation resistance. Through comprehensive simulations, the ECAL dimensions were optimized to 52.5×52.5×44 cm^3, balancing performance and cost. Radiation assessments revealed a maximum dose of 10^7 rad for LYSO crystals and an equivalent 1 MeV neutron fluence of 10^{13} for silicon sensors. The optimized ECAL configuration is expected to enhance sensitivity to dark photon signatures by providing precise energy measurements of recoil electrons and bremsstrahlung photons.

1 Introduction

Dark matter (DM) [1] remains one of the most compelling mysteries in cosmology and particle physics. Theoretical models suggest that DM was produced through thermal processes in the early universe, with the "freeze-out" mechanism[2] explaining its current observed density, positing a probable mass range from a few MeV to several TeV. Despite extensive searches, the specific properties and particle nature of DM remain elusive. Given that high-mass dark DM candidate particles have yet to be detected, there is growing interest in exploring the sub-GeV mass range. Accelerator-based experiments are particularly promising for the detection of light dark matter candidates, such as dark photons, a hypothetical mediator between visible and dark matter[3]. Facilities like CERN's NA64[4], LHC[5], BES-III[6], and the proposed LDMX[7] experiment aim to explore these possibilities.

The DarkSHINE experiment [9] is designed to operate within the framework of the minimal dark photon model. It is based on the Shanghai High Repetition-Rate XFEL and Extreme Light Facility (SHINE) [10]. The conceptual framework of dark photon production via dark bremsstrahlung, followed by their subsequent decay into invisible dark matter, is illustrated in Figure 1, forming the experimental foundation of DarkSHINE.

This paper delineates the design of the Electromagnetic Calorimeter (ECAL) for the DarkSHINE experiment, with a focus on the selection of materials and structural layout. The ECAL configuration has been optimized through simulation studies. Additionally, the radiation tolerance of the ECAL has been assessed, emphasizing the need for crystals and silicon sensors that can maintain high performance in high-radiation environments.

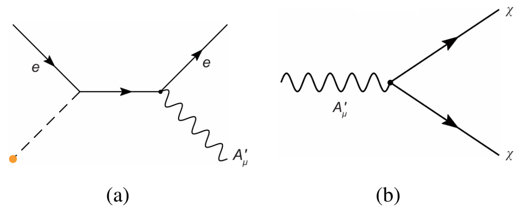

Figure 1. (a) Production of dark photons via bremsstrahlung. (b) Decay of dark photons into "invisible" modes. [8]

2 DarkSHINE experiment and ECAL design

DarkSHINE is a fixed-target experiment that focuses on the bremsstrahlung production of dark photons and measuring their invisible decay. An 8 GeV single-electron beam is planned to be utilized in the DarkSHINE experiment, with the repetition rate expected to be achieved at 10 MHz. This corresponds to 3×10^{14} electron-on-target (EOT) events during one year of the DarkSHINE experiment's commissioning.

The ECAL in DarkSHINE serves to precisely measure the energy of recoil electrons and bremsstrahlung photons. As the core detector, it is a homogeneous LYSO crystal

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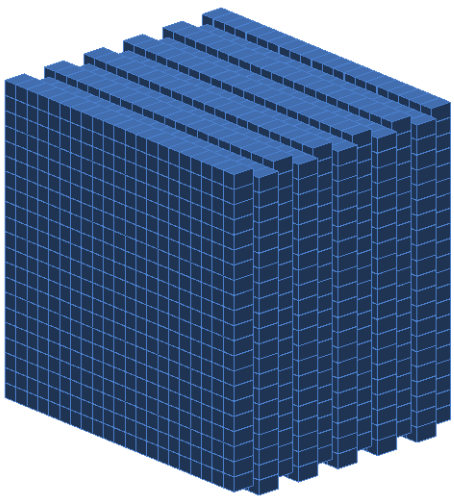


Figure 2. Structure of DarkSHINE ECAL.

calorimeter. LYSO [11] was chosen for its fast scintillation decay time (40 ns), high light yield, and excellent radiation resistance.

The ECAL, with dimensions of 52.5×52.5×44 cm^3, minimizes energy leakage into the HCAL. It comprises 21×21×11 LYSO crystals, each measuring 2.5×2.5×4 cm^3, and is read out by Silicon Photomultipliers (SiPMs). Crystals are arranged in a uniform 21×21 square pattern per layer, with successive layers offset by half the transverse crystal dimension to enhance detection efficiency and reduce gaps.

3 Simulation and optimization

3.1 Simulation

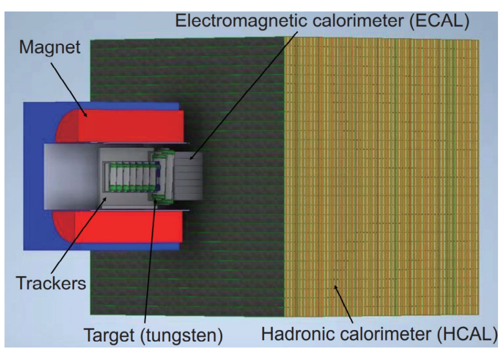
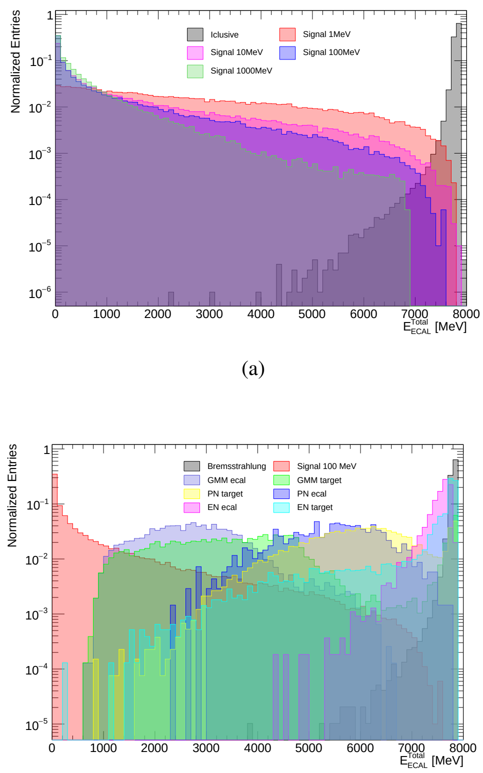


Figure 3. DarkSHINE detector system.[9]

The Monte Carlo simulation of the ECAL is performed using the DarkSHINE Software (DSS) framework based on Geant4[12]. This simulation includes the entire detector setup, alongside other components like the Tracker and HCAL. The detector configuration used in the simulation is illustrated in Figure 3. Within DSS, we can simulate inclusive events that include all background processes or individual simulations of dark photon processes and specific rare background events.

3.2 Signal and background



(a)

(b)

Figure 4. (a) Dark photon and inclusive background processes. (b) Dark photon and rare background processes.

Signal and background processes are characterized by distinct behaviors within different detectors. Typically, incident electrons are observed to pass through the target with negligible energy loss, deposit almost entire energy in the ECAL, and produce minimal signals in the HCAL.

When a dark photon is produced during the electron-on-target process, most of the incident energy transfers to it, and the recoiled electron deposits its remaining energy in the ECAL. The dark photon decays into dark matter, leaving no signal in the tracker or calorimeter, causing significant energy loss in the ECAL, typically exceeding 4 GeV (Figure 4). As the dark photon mass increases, it carries more energy from the electrons, leading to larger energy losses of the recoiled electron measured in the ECAL.

Certain background processes also contribute significantly to energy loss, such as hadron production from interactions of electrons or bremsstrahlung photons with atomic nuclei, and bremsstrahlung photon conversion into muon pairs. Such backgrounds can be effectively filtered using the tracker and HCAL. Figure 5 summarizes the main background processes in the DarkSHINE experiment and their branching ratios.

3.3 Volumn optimization

As the dark photon mass increases, it takes more energy from the incident electron, resulting in a larger recoil an-

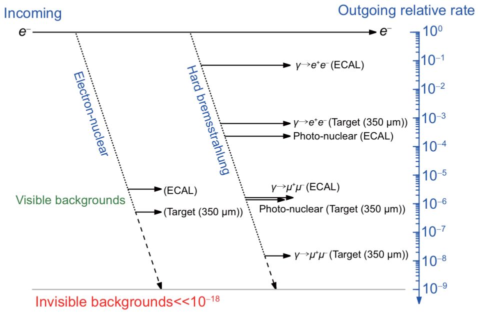


Figure 5. Major background processes and their branching ratios[9]

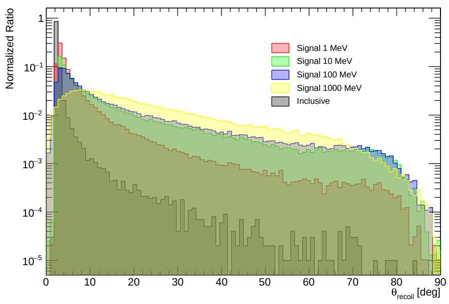


Figure 6. Recoil angle on ECAL front surface

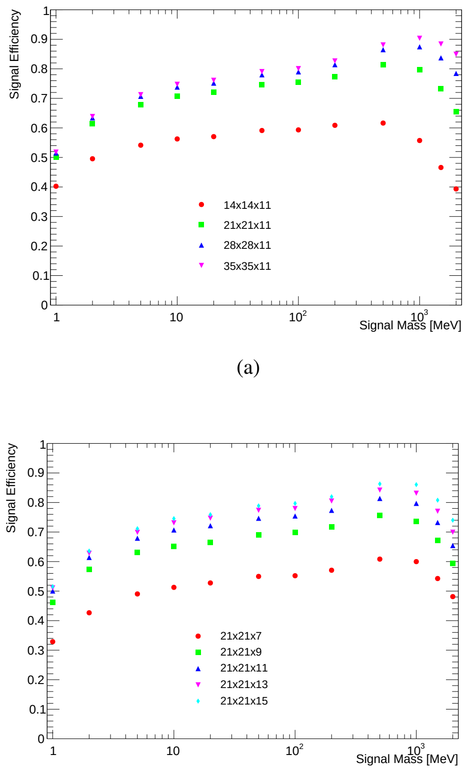
gle. Figure 6 shows the recoil angle distribution of particles hitting the ECAL's front surface for inclusive events and dark photon processes with various masses. With increasing dark photon mass, events in the peripheral region increase, leading to more dark photon events potentially missing the ECAL region. These events can be captured and vetoed by the HCAL. Increasing the ECAL volume can improve signal efficiency, but cost considerations must also be balanced.

Table 1. Signal box for calorimeters.

ECAL	HCAL
$E_{ECAL}^{total} < 2.5$GeV	$E_{HCAL}^{total} < 30$MeV, $E_{HCAL}^{MaxCell} < 0.1$MeV

A signal region for the calorimeter is defined, as shown in Table 1: the total energy in the ECAL is required to be less than 2.5 GeV, the total energy in the HCAL less than 30 MeV, and the maximum energy of a single unit in the HCAL less than 0.1 MeV. This signal region is designed to minimize background while maintaining large statistics [9]. The optimization of the ECAL is evaluated based on the number of events entering the signal region.

The individual crystal size is fixed at 2.5×2.5×4.0 cm^3, based on considerations of granularity and electronic density. The ECAL dimensions were optimized independently in transverse and longitudinal directions, keeping the other dimension constant during each optimization. Figure 7 illustrates the variation in signal efficiency with changes in these dimensions. Signal efficiency improved



(a)

(b)

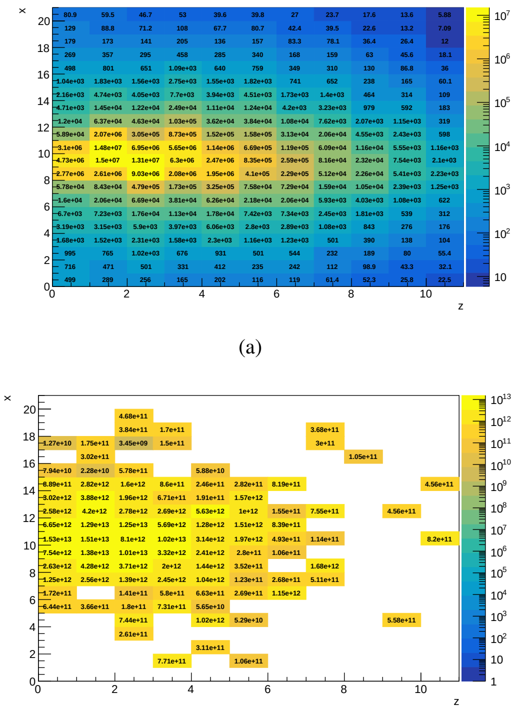
Figure 7. (a)Optimization on transverse size. (b)Optimization on longitudinal size.

with increasing ECAL volume and eventually saturated. A final configuration of 52.5×52.5×44 cm^3 was chosen to ensure high efficiency while maintaining a manageable crystal count.

4 Radiation damage

The ECAL, particularly its central region, is subjected to significant radiation doses in the high-energy, high-frequency beam environment, which could degrade its performance. To address this, radiation damage was evaluated for one year of operation at a 10 MHz repetition rate, focusing on crystal damage caused by ionizing energy loss and silicon sensor damage resulting from non-ionizing energy loss.

For ionizing energy loss, the dose absorbed by each crystal was simulated, with a maximum dose of approximately 10^7 rad (Figure 8(a)). LYSO, with its strong radiation resistance, is well-suited for this environment. For non-ionizing energy loss, the equivalent 1 MeV neutron fluence on SiPMs in the most irradiated areas reached 10^{13}, potentially increasing dark current by several orders of magnitude and rendering sensors unusable. Thus, radiation-resistant silicon sensors are essential.



(a)

(b)

Figure 8. Distribution of radiation damage in ECAL area over one year of operation (a) Radiation dose absorbed by crystals, with a maximum value of 10^7 rad. (b) Equivalent 1 MeV neutron fluence in silicon sensors, with a maximum value of 10^{13} N_{eq}.

5 Conclusions

This study presents the design and optimization of the ECAL for the DarkSHINE experiment, targeting the detection of dark photons as dark matter candidates. Constructed with LYSO crystals for their high light yield, fast decay time, and excellent radiation resistance, the ECAL was optimized to dimensions of 52.5×52.5×44 cm^3, balancing signal efficiency and cost. Radiation assessments revealed a maximum dose of 10^7 rad for LYSO crystals and an equivalent 1 MeV neutron fluence of 10^{13} for SiPMs. The optimized configuration enhances sensitivity to dark photon signatures, enabling precise energy measurements of recoil electrons and bremsstrahlung photons.

Acknowledgments

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