PROCEEDINGS OF SCIENCE

The DAMIC-M experiment: status and first results

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The DAMIC-M experiment employs thick, fully depleted silicon charge-coupled devices (CCDs) to search for sub-GeV dark matter particles. Thanks to its multiple non-destructive measurements of the pixel charge, DAMIC-M skipper CCDs achieve single-ionization charge resolution and an energy threshold in the eV-scale. We report on the progress of the experiment and first results from a prototype detector installed underground at the Laboratoire Souterrain de Modane. In particular, constraints on dark matter particles interacting with electrons are obtained in a mass range between 0.5 and 1000 MeV/c^2. We also present results of a search for diurnal modulation in the measured single-ionization charge rate which significantly improves sensitivity at the lowest masses.

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1. Introduction

The DAMIC-M (Dark Matter in CCDs at Modane) experiment searches for sub-GeV Dark Matter (DM) using skipper Charge-Coupled Devices (CCDs) under the French Alps at the Laboratoire Souterrain de Modane (LSM). DM-induced ionization events in the thick silicon bulk are detected with sub-electron resolution through non-destructive, repeated "skipper" pixel readout [1–3]. The capability of single-electron detection, combined with an extremely low dark current [4, 5], results in an energy threshold of a few eV. The completed experiment will have ≈700 g of target mass with an expected total background of a fraction of a dru [1]. With target exposures of kg-year, DAMIC-M will search for low mass WIMPs with sensitivity comparable to other experiments in construction [6], and explore with several orders of magnitude improvement DM candidates that arise in hidden-sector vector-portal DM theories [7, 8], with masses 1 eV –1 GeV.

Here we report on the status of DAMIC-M, which is scheduled to start operation in 2025, and first results on DM-e^- interactions with prototype detectors installed in the Low-Background Chamber (LBC), a set-up supporting DAMIC-M development and already operating at LSM.

2. Status of DAMIC-M

The overall DAMIC-M design is shown in Fig. 1, left. The heart of the detector is an array of fifty-two CCD modules, each with four CCDs glued on a silicon carrier wafer with patterned aluminum traces (the "pitch adapter") that carry the CCD signals (Fig. 1, right). The CCD array, protected from infrared (IR) radiation by a copper shield, is housed inside a vacuum cryostat and cooled to ≈ 130 K by a cryocooler. Electroformed (EF) copper [9–11] is employed for all components closest to the detector. Surrounding the cryostat is a 20-cm-thick lead shield for γ rays, including the inner 5 cm made from ancient Roman lead, and a 30-cm-thick high-density polyethylene neutron shield. The custom-made front-end electronics and CCD controllers are located outside the shielding. Below we highlight progress on some of the key components:

CCDs. The devices, designed by Lawrence Berkeley National Laboratory (Berkeley Lab) [12], are fabricated by Teledyne DALSA in Canada on *n*-type high-resistivity ($>10^4\,\Omega$ cm) silicon wafers. Each CCD is 9×2.25 cm^2 in size (6k×1.5k = 9 Mpixel, with pixel 15×15 μm^2) and 670 μm-thick. It features a three-phase polysilicon gate structure with a buried p-channel, where charge carriers are collected from the fully depleted silicon bulk. To reduce cosmogenic activation of tritium, the silicon exposure to cosmic rays is minimized by using a 18-ton shielded container for transport and a 5-ton shielding for storage of the wafers at Teledyne DALSA when they are not being processed. The production is well advanced (70% completed.)

CCD module array. The packaging procedures of the CCD module are finalized, with protocols that minimize surface contamination and mechanical stress in the gluing of the devices and flex cable onto the pitch adapter. Extensive mechanical, thermal and electrical tests showed that the module met all design specifications. Thermal tests of a mock-CCD array showed excellent uniformity, with a maximum temperature difference of 1.5K between modules in the array.

CCD flex cable. Flex cables wire-bonded to the CCD modules provide the required voltage biases and clocks. Given the flex proximity to the CCD (Fig. 1, left), its radiopurity is crucial to

[1] 1 dru = 1 event/kg/keV/day.

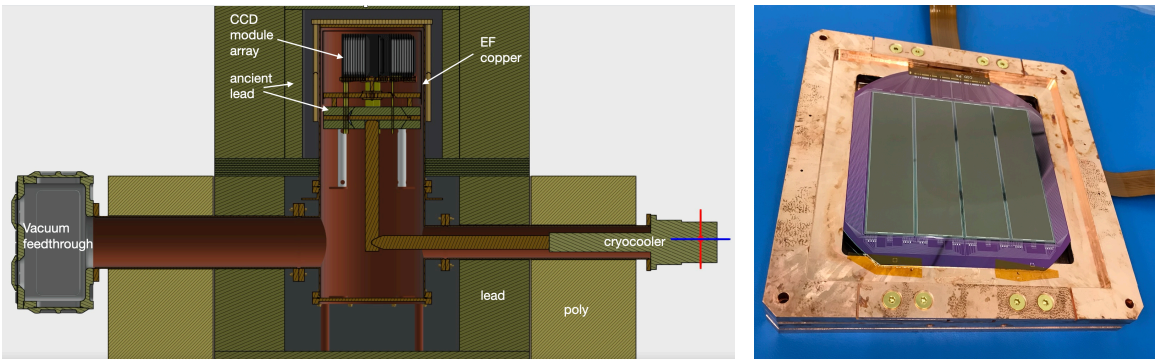

Figure 1: Left: Design of the DAMIC-M detector; some shielding components are not shown for clarity. Right: the CCD module in the copper box with lid removed prior to installation in the LBC.

meet the stringent radiogenic background specifications of DAMIC-M. A successful R&D with Pacific Northwest National Laboratory (PNNL) has resulted in flex cables with ^{238}U(^{232}Th) content $\approx$ 100(20) times lower [13] than cables previously used in DAMIC at SNOLAB, a reduction sufficient for DAMIC-M purposes. The final 1.5 m-long flex, which integrates wire-bonded bare-die JFETs and silicon resistors, has been prototyped and tested, and is ready for production.

EF copper. Thanks to the MAJORANA collaboration, we have available high-quality EF copper for all mechanical components inside the cryostat. The copper, which was grown underground, will be machined underground at Sanford Lab, and shipped to LSM in our shielded container to minimize cosmogenic activation.

3. The Low-Background Chamber and First Results

The LBC (Fig. 2, left), commissioned at the LSM in early 2022, has been essential for the progress of DAMIC-M, allowing the characterization of key DAMIC-M components in a low-background environment ($\approx$ 10 dru) and a first search for DM.

The CCDs are mounted in a high-purity, oxygen-free, high-conductivity (OFHC) copper box (Fig. 1, left.), which also acts as a IR shield. To minimize leakage current, the CCDs are operated at low temperature ($\approx$ 130 K) under vacuum (pressure $\sim 5\times10^{-6}$ mbar) inside the LBC cryostat. The CCD box is surrounded by at least 7.5 cm of very low-background lead ($\leq$ 7 mBq/kg ^{210}Pb), with the innermost 2 cm of ancient origin, to mitigate gamma radiation from components located in the cryostat. In addition, 15 cm of low-background lead (54 Bq/kg ^{210}Pb) and 20 cm of high-density polyethylene surround the cryostat to attenuate high-energy γ-rays and neutrons. All parts of the detector are appropriately cleaned to remove any surface contamination [14, 15]. Voltage biases and clocks to operate the devices are provided by a commercial CCD controller placed outside the external shielding. A Slow Control system enables the remotely controlled operation of the LBC.

A background of $\sim$10 dru was measured during the initial operation of the LBC, similar to that of DAMIC at SNOLAB [16]. This level of background matches a full simulation of the apparatus with GEANT4 [17], which includes realistic amounts of radioactive contaminants as determined by radioassay measurements and bookkeeping of cosmogenic activation time of materials.

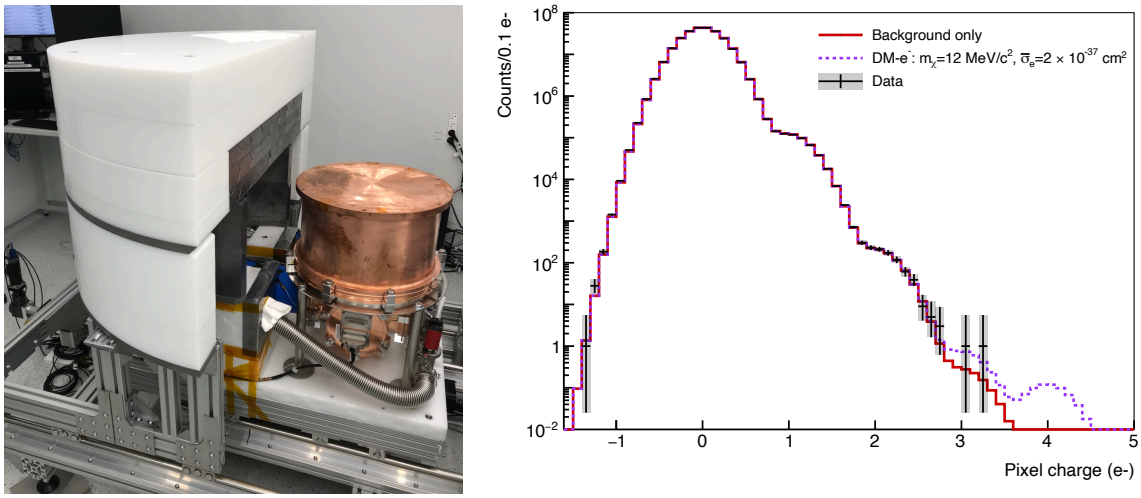

Figure 2: Left: The Low Background Chamber at the LSM, outside the movable shielding (half of it visible.) Right: Pixel charge distribution with peaks corresponding to individual charges. The red line is the fit result for the background-only hypothesis (no DM-e$^-$). The dashed violet line is the expectation for background plus a DM-e$^-$ heavy-mediator model with m_χ=12 MeV/c^2 and cross section equal to our 90% CL limit value obtained at this mass.

DAMIC-M skipper CCDs, from first prototypes to the CCD module, were characterized in the LBC. Different operating parameters (clock/bias voltage levels and clock timing widths) were evaluated to reduce clock-induced charge and optimize charge transfer. Temperature scans were performed to characterize the temperature dependence of dark current. CCDs were exposed to ionizing radiation to study its effect on dark current [18].

In 2022, we collected data in stable conditions with prototype skipper CCDs (6k×4k pixel) to perform a first search for DM-e^- interactions. In this early LBC commissioning phase, the dark current (≈20 e$^-$/mm^2/day) was several times higher than the lowest reached in CCDs [4, 5], but sufficiently low to perform a sensitive search for DM.

CCD images are first calibrated from the fitted position of the $0e^-$ and $1e^-$ peaks in the pixel charge distribution (Fig. 2, right). Then contiguous pixels with charge are joined into clusters. Those with total charge $>7e^-$ are excluded from further analysis since they are unlikely to be produced by sub-GeV DM-e^- interactions. For each cluster we also exclude several trailing pixels in the horizontal and vertical directions to account for charge transfer inefficiencies. Defects in the CCDs may release charge during the readout, appearing in the images as “hot" pixels and columns [19]. These are identified by their increased rate of pixels with $1e^-$, and rejected. Lastly, we exclude portions of the CCD with charge traps in the serial register (identified by a decreased rate of pixels with $1e^-$). After applying the selection criteria 3.68×10^8 pixels remain, corresponding to an integrated exposure of 85.23 g-days. No pixel with charge ≥ 4e$^-$ and ≤ 7e$^-$ is found, improving by one order of magnitude previous limits in silicon at these charge multiplicities [5]. We then fit the pixel charge spectrum (Fig. 2,right) as the sum of the expected DM-e^- scattering signal and the background model (Poisson dark current.) Details are in Ref. [20].

In Ref. [21] we introduce a new method to constrain DM-e^- scattering, which exploits a daily

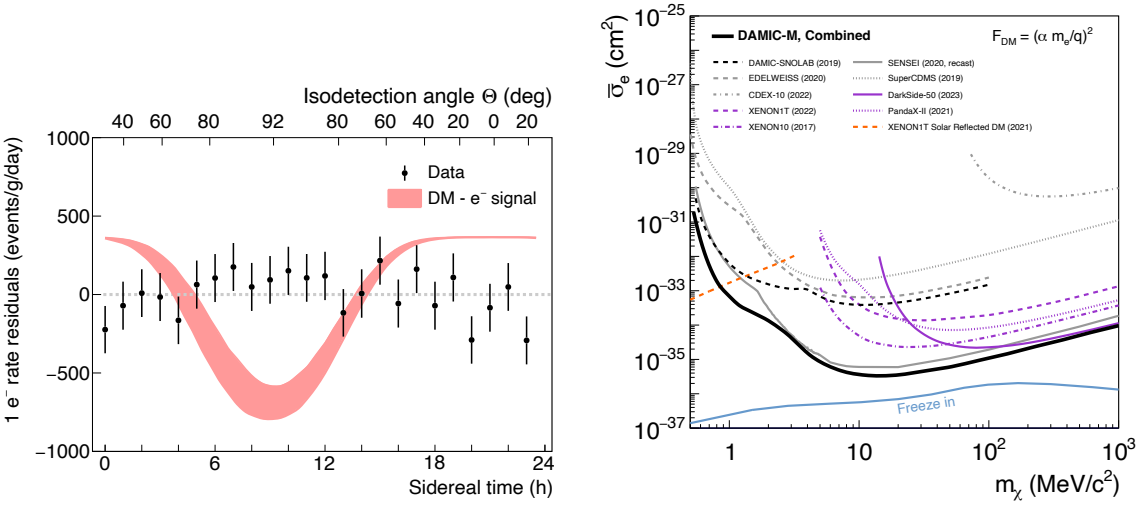

Figure 3: Left: Residual $1e^-$ rate after the subtraction of the background model, as a function of local apparent sidereal time. The light red band shows the expected daily-modulated signal for a DM particle of mass 1 MeV/c^2, $\bar{\sigma}_e = 10^{-32}$ cm^2 interacting via an ultralight dark photon mediator. Right: DAMIC-M 90% C.L. upper limits (solid thick black) on DM-e^- interactions through an ultralight mediator obtained combining results from Refs. [20, 21].

modulation of the DM signals. In fact, the velocity distribution of DM particles at the detector may be distorted by their interactions in the Earth [22–24]. Over the course of a sidereal day, the position of the detector rotates with respect to the incoming DM flux. Thus, the DM particles will travel a greater or smaller distance across the Earth at different times, leading to a daily modulation. We search for a daily modulation of the measured rate of $1e^-$ pixels (Fig. 3, left) in a portion of the data (39.97 g-days), corresponding to 63 days of uninterrupted data taking with images acquired every ≈10 min. This search is sensitive for DM masses ≤ 2.7 MeV/c^2.

In both analyses no preference is found for a DM signal at any mass and constraints are derived accordingly. The 90% C.L. exclusion limit for an ultralight mediator combining the two results is shown in Fig. 3, right. Notably, the daily modulation search improve the limits reported in Ref. [20] by up to two orders of magnitude for DM mass ≤ 2.7 MeV/c^2.

4. Outlook

The design of DAMIC-M is complete, and the detector is in its construction phase with start of operation scheduled in 2025. We will continue to operate the LBC to support the DAMIC-M program, with several upgrades and measurement campaigns foreseen. We recently replaced the OFHC copper lids of the LBC CCD box with EF copper ones (fabricated by the Canfrac Underground Laboratory facilities), which reduced the background from ∼ 10 to ∼5 dru. LBC data taking is ongoing, currently focused on background measurements (including ^{32}Si in CCDs made from the same ingot of the DAMIC-M production), and we will upgrade the set-up with the final DAMIC-M electronics in early 2024. We plan to collect few months of DM search data with optimal conditions for dark current and noise to reach 1 kg-day of exposure, which will provide a tenfold improvement over our current limits before the start of DAMIC-M installation.

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