Contribution aux exercices de prospective nationale 2020-2030

Détecteurs et instrumentation associée

TOWARD A 10-KG SKIPPER-CCD SENSOR

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1. Informations générales

Titre : TOWARD A 10-KG SKIPPER-CCD SENSOR

Acronyme : *(optionnel)*

Résumé *(max. 600 caractères espaces compris)*

Recent advances in silicon skipper-CCDs have demonstrated this technology as a powerful probe for sub-GeV dark matter. World leading results have already been produced using prototype skipper-CCD with an active mass of <0.1 gram. Pathfinder experiments using skipper-CCDs are planned for the coming years, with SENSEI-100 (~100 g) and DAMIC-M (~1 kg). The objective of this proposal is to take this sensor technology to its full potential, and enable the development of a skipper-CCD experiment with an active mass of 10 kg, and zero background events in the 2–10 electron ionization-signal region.

- ***Full cost < 10 M€***

- ***- Time scale ~ 5 years***

*Préciser le **domaine technologique** (plusieurs choix possibles)*

○ Détecteurs semi-conducteurs (Si, Ge, HgCdTe, Diamant…)

Préciser la motivation principale de recherche visée par la contribution :

○ R&D particle ID, direct search for light dark matter

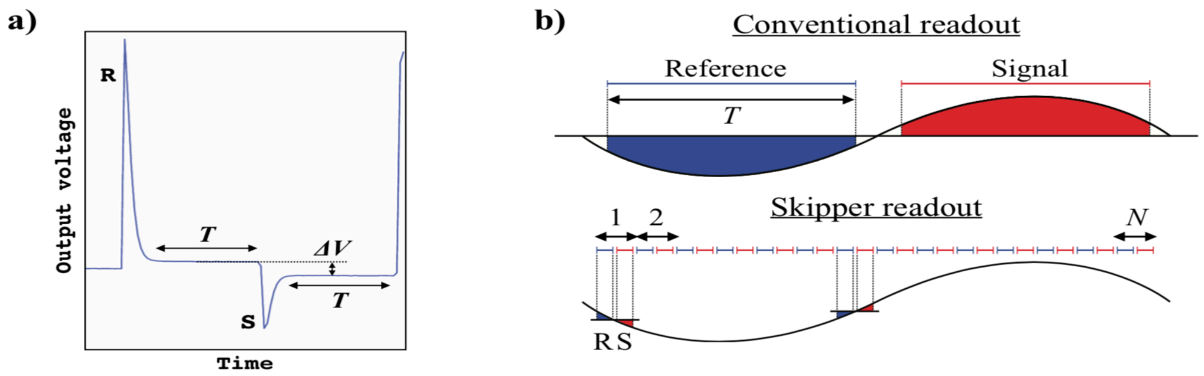

*Figure 1 : **a)** CCD output signal for one pixel illustrating a conventional Correlated Double Sampling (CDS) readout (R: reset, S: charge transfer). **b**) Skipper vs. conventional readout: during the same time of a conventional readout, the pixel charge is measured N times in skipper mode. The effect of a low-frequency noise waveform is reduced in skipper mode because the waveform changes very little during the short CDS sequence.*

2. Scientific and technical objectives

The aim of the proposed 10kg skipper-CCD detector is to acquire a 30kg-year exposure with zero background ionization events in the 2–10 e^- signal range for a highly sensitive search for dark-matter (DM) particles (see our GT06 contribution *GT06LightDMSkipper.pdf*).

Skipper-CCD technology (Fig. 1) has already demonstrated the necessary readout noise for the resolution of single charges collected per pixel, which provides the 2e- threshold. Hence, the experimental challenges that need to be overcome are in the engineering of a detector with a large number of skipper-CCD devices that satisfies the zero background requirement. The background sources for the experiment are any physical process that can generate free charge in a fully depleted silicon sensor, i.e., dark current, optical and near-infrared photons, and ionizing particles from cosmic rays and radioactive decay.

The skipper-CCD fabrication will be migrated to a new foundry process, which provides an opportunity to capitalize on existing semiconductor technology to develop devices specifically for a DM search. The baseline design for the skipper-CCDs will use the full real estate of 200-mm diameter wafers for a total of 88 Mega pixels with an area of 15x15 μm^2 per CCD. Considering a baseline wafer thickness of 1 mm, each CCD will have an active mass of 46 g. The 10 kg silicon target will consist of 218 of such large CCDs.

The detector will be optimized for fast readout to minimize the number of electrons from leakage current collected per pixel. Each CCD will feature 16 readout amplifiers for a total of 3488 channels. Assuming that single-electron resolution can be achieved with a single-pixel readout time of 4ms, the entire detector will be read out in six hours and 10^{14} pixels will be readout in a 30 kg-year exposure. The leakage current of the CCDs must be close to the theoretical expectation from bulk dark current (~10^{-7} e^-/pixel/jour) to be well below 1 pixel with 2e^- in the full exposure of the experiment.

The proposed 10 kg skipper-CCD detector is based on a mature technology. CCDs have been operated extensively for low-mass DM searches in the DAMIC experiment at SNOLAB [1,2,3]. The single-electron resolution of the skipper-CCD has already been proven [4] and recently the DAMIC-M collaboration achieved a resolution of 0.07 e^- [5] (Fig. 2). The potential of these sensors for the direct DM searches has been demonstrated by the world leading results of the SENSEI experiment [6, 7].

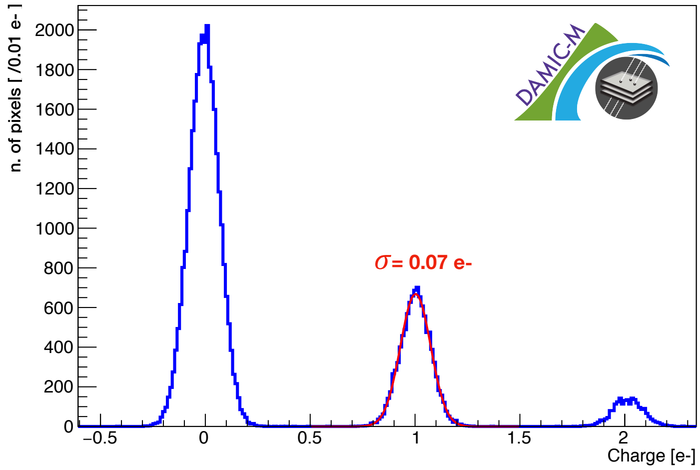

Figure 2: Pixel charge distribution. Well separated peaks corresponding to zero, one and two electron are observed, with a charge resolution of 0.07 electrons. This result was obtained with a large size, thick prototype DAMIC-M CCD with skipper readout [5].

3. Deliverables, calendar, budget

There are significant technical challenges associated with the scaling to 10 kg of active mass that will need to be addressed by a dedicated R&D program, specifically on the skipper-CCD fabrication, its electronics readout, and control of radiogenic and cosmogenic backgrounds. Major lines of work will include:

1) **Skipper-CCD fabrication.** Teledyne DALSA, the CCD foundry used so far for skipper-CCD detectors, is going to stop this production line in 2020. The fabrication of the skipper-CCDs for the 10 kg experiment will thus require implementing the relevant processes at a new foundry. This challenge also offers the opportunity to transfer the CCD fabrication into CMOS, a technology that has emerged as the industry standard for pixel photon detectors. Moving to CCD-in-CMOS has the additional advantage of fabrication on 200 mm wafers, which are 1mm thick, allowing production of more massive detectors.

2) **Skipper-CCD readout system.** The 100 gram and 1 kg scale pathfinder experiments employing skipper-CCD detectors have a limited number of readout channels, ~ 200. The 10 kg experiment will require approximately 4000 channels. The goal is to develop a low cost, scalable readout system for the 10 kg experiment.

3) **Radiogenic and Cosmogenic backgrounds.** To fully exploit the sensitivity of a 10 kg experiment and achieve background-free results, the total background must be at the level of 0.01 counts/kg/keV/day. Several R&D efforts part of the science program are planned to address this challenge.

IN2P3 has a very strong expertise regarding item 2) where both LAL and LPNHE have been involved in the ASIC design for LSST and now for DAMIC-M. The transition of the massive CCD passive array with skipper readout to CMOS technology is of great technological interest and here again the expertise of IN2P3 (for example at IPHC) would be an excellent opportunity.

This R&D project would be developed in close collaboration with the US group of SENSEI and DAMIC-M who have been recently awarded a 4M$ grant by the DOE program “Dark Matter New Initiatives” for this purpose. Contribution from IN2P3 to both the Front-End electronic design and the CMOS transfer (< 1 M€) would be an excellent opportunity to share and develop our expertise.

We estimate the duration of the R&D phase to be about 3 years, with a construction phase (driven by the CCD fabrication) of similar duration. This 10kg skipper detector would then be ready to take the lead right after the end of DAMIC-M in ~2025.

4. Impact

Development of a scientific grade pixel imager using skipper-readout on CMOS technology would provide a very high resolution (much less than 1 electron) fast read out (~kHz) sensor. This would be of interest for applications beyond pure scientific research (e.g. medical).

5. References

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[6] Orr Abramoff et al. "SENSEI: Direct-Detection Constraints on Sub-GeV Dark Matter from a Shallow Underground Run Using a Prototype Skipper CCD". In: Phys. Rev. Lett. 122 (16 Apr. 2019), p. 161801. doi: 10.1103/PhysRevLett.122.161801. url: https://link.aps.org/doi/10.1103/PhysRevLett. 122.161801.

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