Counting electrons with the Skipper-CCD

Javier Tiffenberg
Fermi National Laboratory

Aug 12, 2020
Skipper-CCD applications

Dark Matter

Neutrino Physics

Astronomy

Quantum Imaging
Goal: lower the energy threshold to look for light DM candidates

Detect DM-e interactions by measuring the ionization produced by the electron recoils. See arXiv:1509.01598

Idea: use electrons in the bulk silicon of a CCD as targets

This requires very low noise!
SENSEI: Sub-Electron-Noise SkipperCCD Experimental Instrument

SENSEI LDRD Collaboration (2015)

Develop a CCD-based detector with an energy threshold close to the silicon band gap (1.1 eV) using SkipperCCDs produced at LBL MSL

- **Fermilab**: Tiffenberg, Guardincerri, Sofo Haro
- **Stony Brook**: Rouven Essig
- **LBNL**: Steve Holland, Christopher Bebek
- **Tel Aviv University**: Tomer Volansky
- **CERN**: Tien-Tien Yu
- **Stanford University**: Jeremy Mardon

Main goals

- Build the first working detector using Skipper-CCDs.
- Validate the technology for DM and $\nu$ experiments.
- Probe DM masses at the MeV scale through electron recoil.
- Probe axion and hidden-photon DM with masses down to 1 eV.
- Single photon imaging with low dark counts.
CCD: readout

3x3 pixels CCD

Shift charge one column to the right

Shift charge in serial register one pixel down (3 times)

Serial register

Parallel register

Sens node

Amplifier

Channel stop

Capacitance of the system is set by the SN: \( C = 0.05 \mu F \).
CCD: readout

3x3 pixels CCD

Shift charge one column to the right

Shift charge in serial register one pixel down (3 times)
CCD: readout

3x3 pixels CCD

Shift charge one column to the right

Shift charge in serial register one pixel down (3 times)

The capacitance of the system is set by the SN: $C = 0.05\text{pF} \rightarrow 3\mu\text{V/e}$
CCD: readout

H  H  SW  OG 传感节点  VR

信号

基线

电压差，由于沉积的电荷
CCD: readout

signal

pedestal

voltage diff. due to deposited charge
CCD: readout

Pixel charge measurement

High frequency noise

Low frequency noise

Excellent for removing high frequency noise but sensitive to low frequencies

Voltage diff. due to deposited charge
Readout noise: empty pixels distribution, regular scientific CCD

$\sigma = 1.8 \, e$

2 $e^-$ readout noise roughly corresponds to 50 eV energy threshold
Lowering the noise: Skipper CCD

Only the readout stage is modified
Lowering the noise: Skipper CCD

- **Main difference:** the Skipper CCD allows multiple sampling of the same pixel without corrupting the charge packet.

- The final pixel value is the average of the samples:

  \[
  \text{Pixel value} = \frac{1}{N} \sum_{i}^{N} (\text{pixel sample})_i
  \]

- Idea proposed in 1990 by Janesick et al. (doi:10.1117/12.19452)
Lowering the noise: Skipper CCD

- **Main difference:** the Skipper CCD allows multiple sampling of the same pixel without corrupting the charge packet.
- The final pixel value is the average of the samples
  \[ \text{Pixel value} = \frac{1}{N} \sum_{i}^{N} (\text{pixel sample})_i \]
- Idea proposed in 1990 by Janesick et al. (doi:10.1117/12.19452)
SENSEI: First working instrument using SkipperCCD tech

Sensors

- Skipper-CCD prototype designed at LBL MSL
- 200 & 250 \(\mu\)m thick, 15 \(\mu\)m pixel size
- Two form factors 4k\(\times\)1k (0.5gr) & 1.2k\(\times\)0.7k pixels
- Parasitic run, optic coating and Si resistivity \(\sim\)10k\(\Omega\)
- 4 amplifiers per CCD, three different RO stage designs

Instrument

- System integration done at Fermilab
- Custom cold electronics
- Low Threshold Acquisition electronics: 2004.07599
- Firmware and image processing software
- Optimization of operation parameters
Image taken with SENSEI: 4000 samples per pixel (processed)
Image taken with SENSEI: 4000 samples per pixel (processed)
Image taken with SENSEI: 4000 samples per pixel (processed)
Image taken with SENSEI: 4000 samples per pixel (processed)
Charge in pixel distribution. Counting electrons: 0, 1, 2..
Charge in pixel distribution. Counting electrons: 0, 1, 2.

4000 samples

Entries 1635
$\chi^2 / \text{ndf}$ 19.6 / 25
Mean $-0.002 \pm 0.0016$
Sigma $0.06 \pm 0.001$
Counting electrons: 0, 1, 2...

Standard CCD mode: charge in each pixel is measured once

New Skipper CCD: charge in each pixel is measured multiple times

Readout-noise: 3.5 e RMS

Readout-noise: 0.06 e RMS
Noise vs. #samples - $1 / \sqrt{N}$
Counting electrons: 48, 49, 50.

4000 samples

charge [e] #entries
0 0
10 50
20 100
30 150
40 200
50 250

pix/4.17817 {(ohdu==2 && x<300 && x>35 && pix/4.17817<50 && pix<5200)}
55 Fe X-ray source

4000 samples

#entries
1200
1250
1300
1350
1400
1450
1500
1550
1600
1650
1700

charge [e]

#entries
50
100
150
200
250
300
350
400
450

pix/4.1781 + 300.2 {(ohdu==2 && x<300 && x>35 && abs(pix/4.17817-1254.7)<500.48)
55 Fe X-ray source

4000 samples

![Graph showing charge distribution with entries and charge in e units.](image)
keep counting: ..1550, 1551, 1552..
Absolute self-calibration!

The signal that corresponds to each electron peak can be counted from 0 to 2000 to produce an absolute calibration without an external reference!

We used this technique to produce the most precise measurement of the Fano factor in silicon (see: arXiv:2004.11499)
The SENSEI Collaboration

Fermilab:

Stony Brook:
- L. Chaplinsky, Dawa, R. Essig, D. Gift, S. Munagavalasa, A. Singal

Tel-Aviv:

U. Oregon:
- T.-T. Yu

Fully funded by Heising-Simons Foundation & leveraging R&D support from Fermilab
protoSENSEI: MINOS setup

- Shallow underground site reduces muon rate from cosmic rays; lead shielding reduces gamma rate from ambient radioactivity
- Cryocooler and insulating vacuum keep the CCD cold to minimize dark current
Limits on dark matter

- World best limits for light dark matter candidates
  - Left to right: $F_{DM} = (\alpha m_e/q)^2$ scattering (light mediator), absorption
SENSEI@SNOLAB

- We are building the full-scale SENSEI experiment, deep underground at SNOLAB with a low-background shield
- “Phase 1” system is operating at SNOLAB
- Vessel build and undergoing testing at Fermilab
The future of Skippers

- SENSEI@MINOS demonstrated that Skipper CCDs have the performance we need to reach theory targets
  - SENSEI@SNOLAB: 100 grams
  - DAMIC-M: 1 kg
  - Oscura: 10 kg
Neutrino physics at nuclear reactors

SMART-Skipper for faster readout

Fundamental physics of low energy interactions

Many spin-offs at Fermilab

Quantum imaging

Quantum ghost imaging

Correlated photons measured at Fermilab

Quantum cryptography

Astronomical instruments

cubeSat to look for dark matter in our galaxy
Thanks!

I'm extremely fortunate to be able to work with all the amazing people at SiDet that make all these things happen and within the wonderful SENSEI collaboration.
BACK UP SLIDES
Single electron sensitivity opens several order of magnitude in mass and cross section for small projects.

DOE report for basic research needs for Dark Matter Science.

4 amplifiers per CCD, three different RO stage designs. The design with the smallest capacitance (U1) is the one that performs better.
Readout stage design

Summing well
Output gate
Floating gate
Dump gate
Dump drain

L L U
Typical e$^-$-recoil spectrum for benchmark models

- The sensitivity is limited by the lowest charge bin.
- Background impact is reduced due to the small energy window.
- Main background for semiconductors detectors is the dark current.