SENSEI

Sho Uemura

Tel Aviv University
for the SENSEI Collaboration

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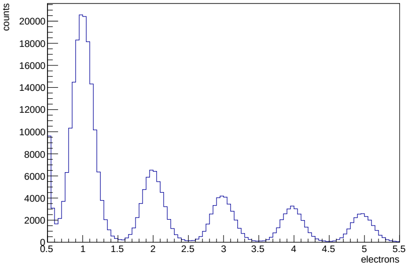
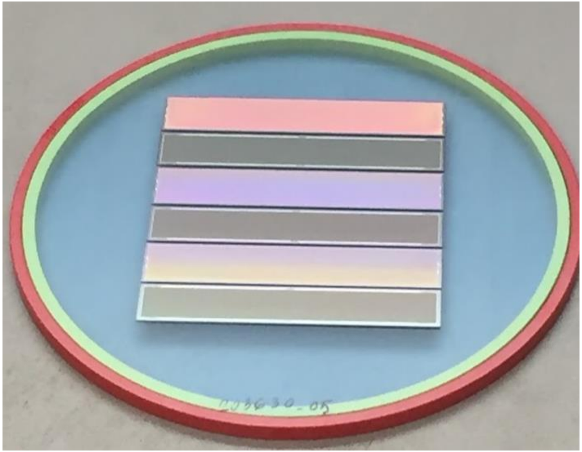
Intro to SENSEI

- Detector very similar to DAMIC (fully depleted CCD, collecting holes from e-h pairs produced by ionization), but with non-destructive “Skipper” readout
  - Sub-electron charge resolution: self-calibrating, discriminates 0, 1, 2, . . . e^-
- We are sharing our most recent published result
  - Test run: one production CCD, one month, shallow underground site with partial shield
  - arXiv:2004.11378, published in PRL
- We treat 1, 2, 3, 4 e^- events as separate channels with different cuts and analyses



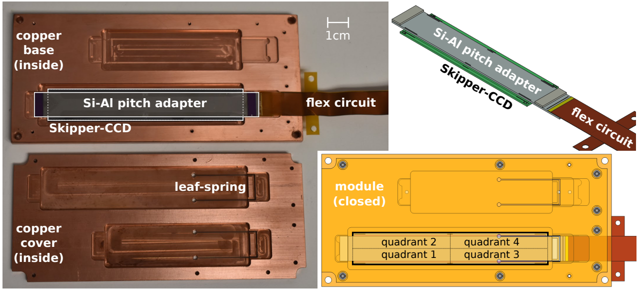
The SENSEI CCDs

- High-resistivity silicon 675 μm thick (no backside thinning), active area 1.59 $\times$ 9.42 cm^2 (1.925 grams)
- 6144 $\times$ 886 pixels (split in 4 quadrants), 15 μm pitch
- Largely identical to DAMIC
  - Same material, processing, pixel geometry
  - Different overall dimensions, readout
- Huge improvements (in dark current and amplifier luminescence) over previous SENSEI CCDs fabricated parasitically on lower-quality silicon

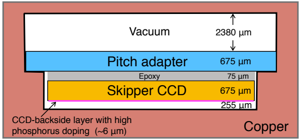


CCD package

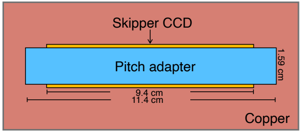
- Front side of CCD is glued (Epotek 301-2) and wirebonded to silicon pitch adapter, CCD touches nothing else
- Pitch adapter serves multiple functions:
  - Electrical interface to copper-Kapton flex cable
  - Mechanical support
  - Thermal connection to copper tray
- PA (with silicon spacers) is held in copper tray: loose fit at all points except for copper leaf spring
- PA and spacers are made from the same high-resistivity silicon as the CCDs



Side view

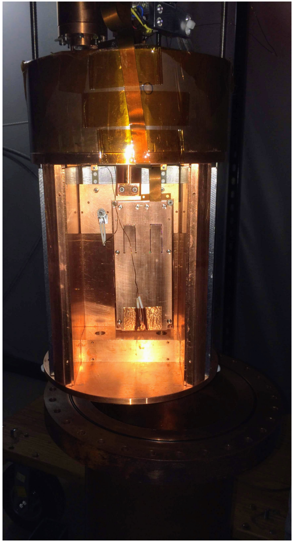


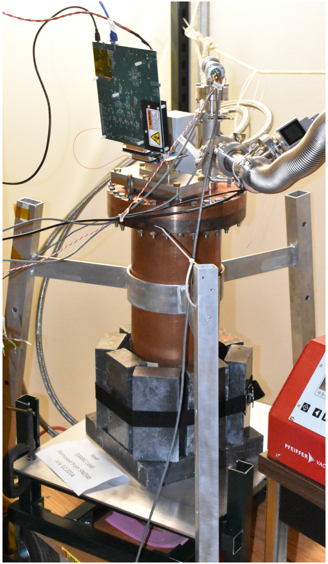
Top view



Setup in MINOS

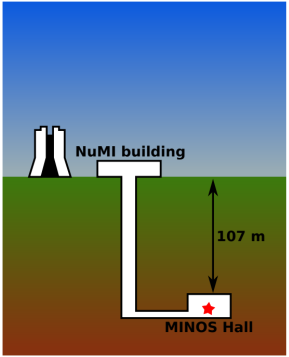
- Shielding design adapted from DAMIC: cylindrical vacuum vessel with lead "plug" above the CCD
- CCD at 135 K, biased at 70 V
- The copper tray is not light-tight and may admit blackbody photons
  - Most surfaces the tray sees are close to room T

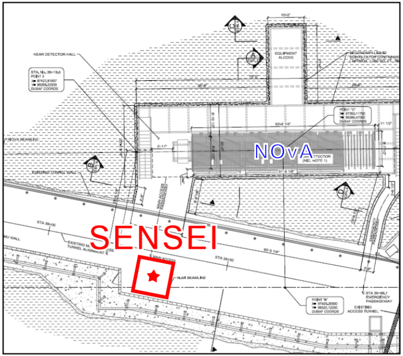


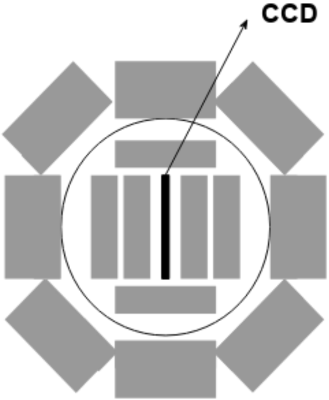


Location and shielding

- Shallow underground site (MINOS cavern at Fermilab), $\sim$ 105 m ($\sim$ 225 mwe)
- Lead shield thickness: 3 inches above, 3-4 inches to sides (but with gaps), 0 below
  - Lead is of good quality (leftover DAMIC shielding) but not ancient
  - Nothing outside the lead, very little inside (few mm of copper)

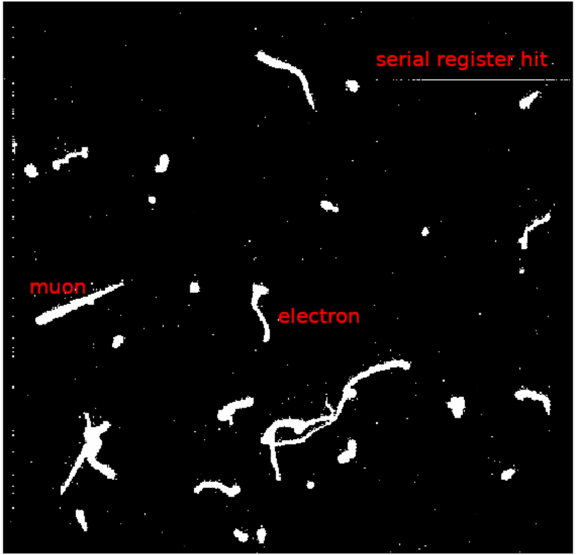






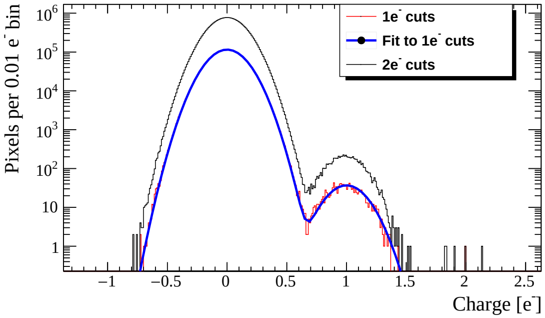
Data taking

- 22 images in the blinded dataset (Feb. 25 — Mar. 20, 2020)
  1. Erase/e-purge: manipulate bias voltages to eliminate latent image and suppress dark current
  2. 20 hours exposure
  3. 5.15 hours readout
     - ★ During readout, the image continues to accumulate hits and charge
     - ★ Skipper noise scales as $1/\sqrt{N}$: at $N = 300$ (13 ms/pixel), noise of $\sim 0.14e^{-}$
- Shown: 1/6th of one quadrant
  - Two quadrants (19.93 g-day) acceptable for 1, 2 e^{-} analyses; add part of a third (27.82 g-day) for 3, 4 e^{-}



The data

- Single-electron: background-dominated
- Multiple electrons ($2e^-$ single-pixel, $3/4e^-$ cluster): low-background
  - Coincidence of $1e^-$ processes
  - True multi-e^- processes



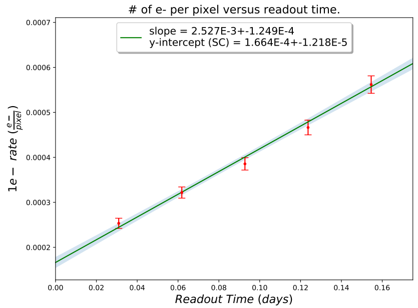
- Our measured charge spectra are continuous, but the underlying charge distribution is quantized, so our EXCESS dataset is binned by charge
  - The Gaussian widths come from readout noise, not physics
  - We count 1311.7 $1e^-$ events because we correct for $0/1e^-$ misID
- We see five $2e^-$ pixels, and no $3/4e^-$ clusters
- Geometric efficiency: some multi-e^- events will be lost when they diffuse
  - 22.8% for $2e^-$ to stay in one pixel, 76.1%, 77.8% for 3, $4e^-$ to form a contiguous cluster

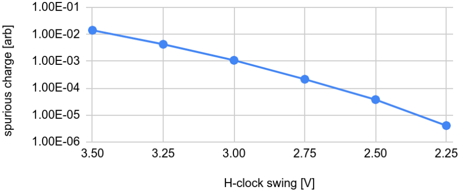
Known $1e^-$ backgrounds (paper on arXiv soon)

- Well-controlled backgrounds:
  - Bleeding (incomplete charge transfer): masked
  - CCD defects (hot pixels, bleed columns): identified and masked
  - Amplifier light: not significant
  - Intrinsic dark current (generated during exposure by thermal excitation): extrapolated, not significant at 135K
  - Spurious charge (generated during readout): measure and subtract from $1e^-$ rate
- Backgrounds that may remain:
  - Halo (excess charge near high-energy events): masked, but maybe not completely
  - Loose clusters (localized charge excesses not associated with HE events): masked for $2{+}e^-$ analyses but not $1e^-$
  - "Extrinsic dark current" (other exposure-dependent charge): shielding-dependent

Spurious charge

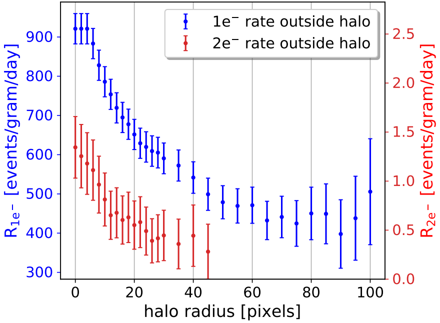
- Measurements with shorter exposures show a limiting value for the CCD charge: accounts for 649 ± 47.5 counts in the $1e^-$ data (about half of the total)
  - Since this contribution is independent of exposure time, it is not physics
  - Consistent with "spurious charge" — charge excited by voltage transitions during readout
- For the SENSEI result we subtracted the 2σ LL on 649 ± 47.5 to get 758 counts

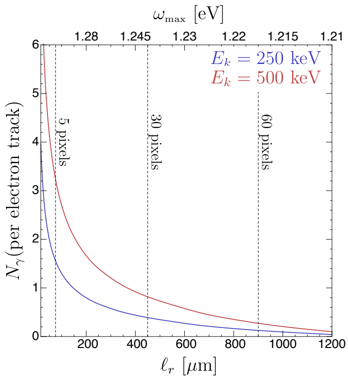




Localized charge from high-energy events

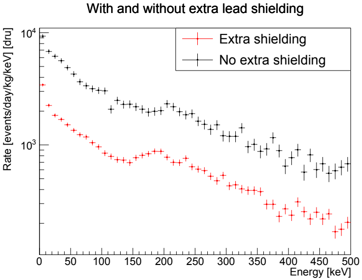
- Halo: excess of charge near high-charge pixels
  - Probably near-bandgap photons from Cherenkov radiation and electron-hole recombination (see arXiV:2011.13939)
- Loose clusters: regions with high charge density
  - May be Cherenkov photons (reflected, or generated outside of CCD)

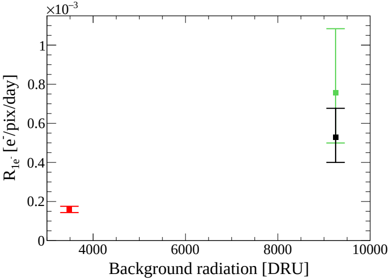


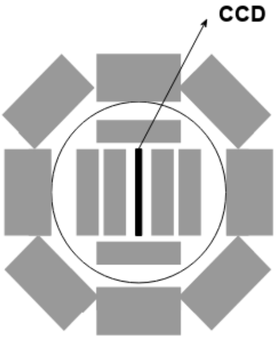


$1e^-$ rate vs. shielding

- We have data with and without the outer ring of lead bricks
- Factor of 3 reduction in the rate of high-energy tracks $\rightarrow$ similar reduction in the $1e^-$ rate
  - Radiation generates charge in halos, in loose clusters, and pseudo-uniformly
  - Again, Cherenkov+recombination produces a rate estimate consistent with what we observe

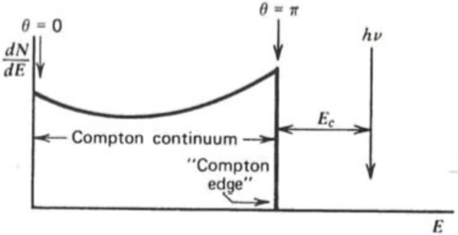


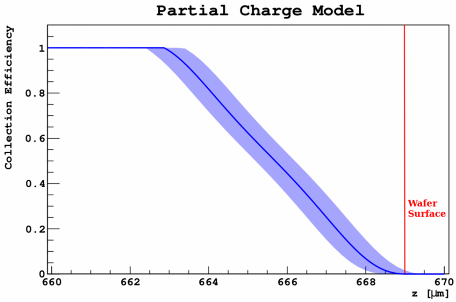




Multi-e^- backgrounds

- Low-energy tails from high-energy events (these do not contribute significantly in this dataset):
  - Compton: A gamma ray can create arbitrarily small-energy electron recoils
  - Partial charge collection: Our CCDs have a highly-doped backside layer where much of the charge is lost to recombination
- Photons over the $2e^-$ energy threshold (Cherenkov or luminescence from the epoxy?)





Counts and rates

- $1e^-$: we subtracted spurious charge, the rest is consistent with environmental effects ("extrinsic DC")
- $2e^-$: we did not subtract coincidences
- Exposure is corrected for cuts and geometric efficiency
- Energy scale: we conservatively assumed $E_e \rightarrow (1 + Floor[(E_e - 1.2\mathrm{eV})/(3.8\mathrm{eV})])e^-$
  - This is electron recoil energy

	counts	known bkgd	exposure [g-day]	rate [/g-day]
$1e^-$	1311.7	649 ± 47.5	1.38	450
$2e^-$	5	—	2.09	2.39
$3e^-$	0	—	9.03	0
$4e^-$	0	—	9.10	0

Backup: Intrinsic dark current

- Subtracting the exposure-independent charge, our 1e- rate is $1.59(16) \times 10^{-4}$ e^{-}/pixel/day
- Intrinsic dark current is the usual suspect
  - Thermal generation of electron-hole pairs, mediated by lattice defects
- However:
  - Extrapolation from higher temperatures (dashed black line) predicts $\ll 1 \times 10^{-5}$ e^{-}/pixel/day at our operating temperature of 135 K
    - ★ Suppressing surface dark current gets us from red data points to blue
- High-quality silicon has made this a subdominant background