A Cryogenic Readout IC with 100 KSPS in-Pixel ADC for Skipper CCD-in-CMOS Sensors

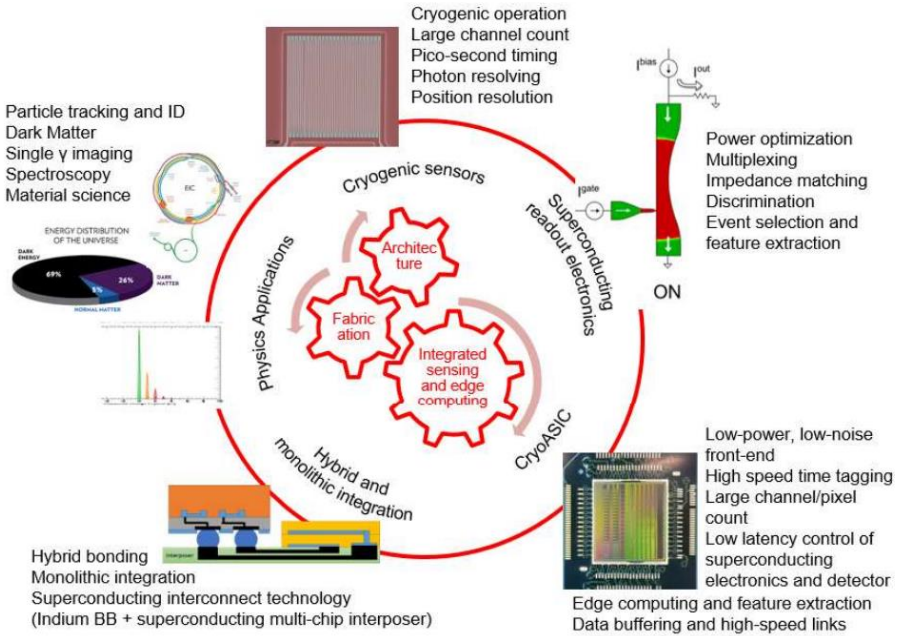
Adam Quinn

11/29/2022

CPAD 2022

Developing the Hybrid Cryogenic Detectors of the Future

- Advances in HEP, DM detection, quantum imaging demand better detectors:
  - → Extreme **spatial/temporal resolution**
  - → Extreme **environments** (cryo, rad-hard)
  - → Extremely **low noise** (< 1 e-)
- Multi-year DOE collaboration to co-design:
  - → New **sensors**
  - → New **readout electronics**
  - → New **packaging/integration**



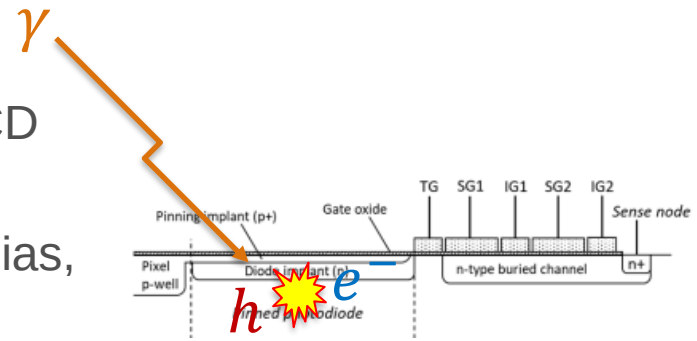
Critical technologies:

Skipper CCDs (this talk) + SNSPDs

Fermilab

Review of CCD Imaging

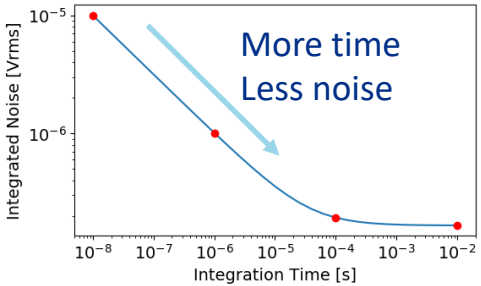
- Incident particles create e-h pairs in the CCD substrate.
- Charge carriers separate under substrate bias, and one (say e-) is captured just below the surface.

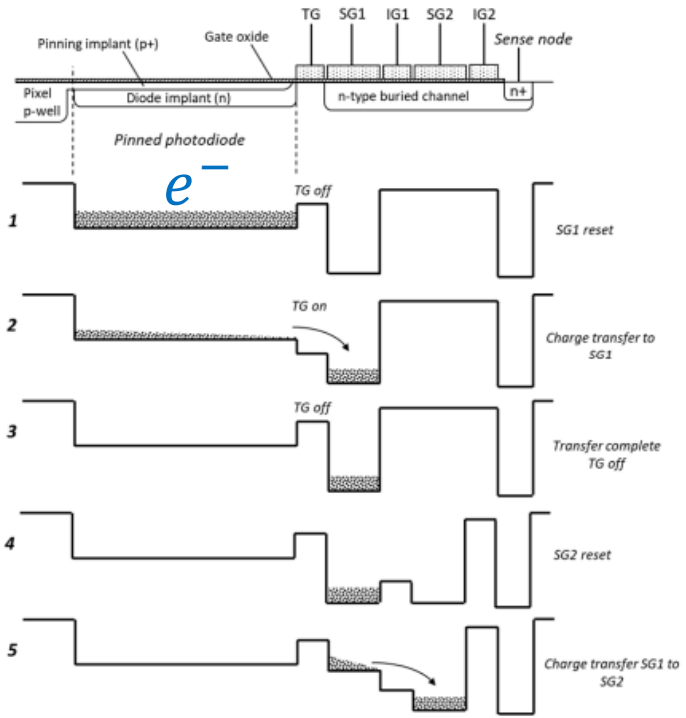


Fermilab

Review of CCD Imaging

- Incident particles create e-h pairs in the CCD substrate.
- Charge carriers separate under substrate bias, and one (say e-) is captured just below the surface.
- Charge packets create a small voltage that can be sensed by a CMOS amplifier.
- Integration of the readout reduces noise… up to a point.





Stefanov, et al. [8]

Fermilab

The Skipper-CCD Principle

- What if instead of one long sample, we took many short ones?
- Avoid shifting to 1/f-dominated region.
- Signal is correlated, noise is not; improve SNR by $\sqrt{N}$
- **Integrated noise << 1 e- is possible!**

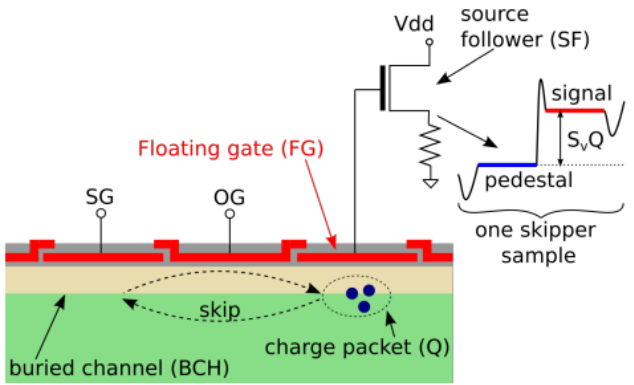
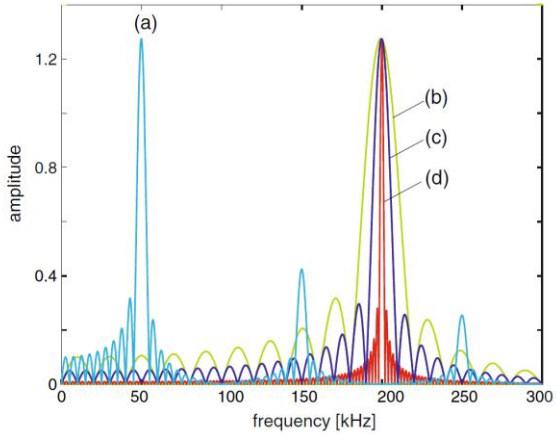
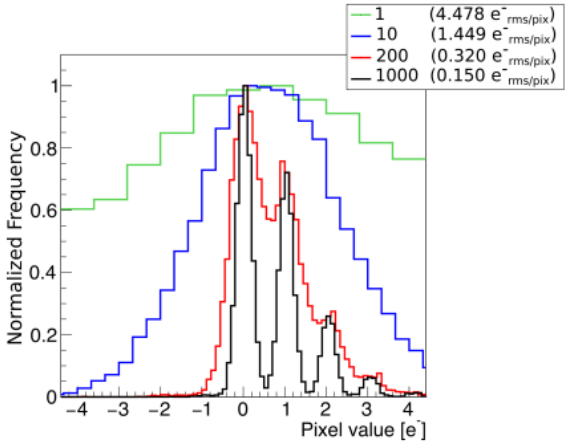


Fig. 8 Frequency response of the Skipper readout system for $T_S = 10\ \mu$s and $N = 10$ (**a**) and for $T_S = 2.5\ \mu$s and $N = 10$ (**b**), $N = 20$ (**c**) and $N = 100$ (**d**)





Images from Moroni, et al. [7]

Fermilab

Development of Hybrid Skipper-CCD-in-CMOS
and associated Fermilab talks at CPAD 2022

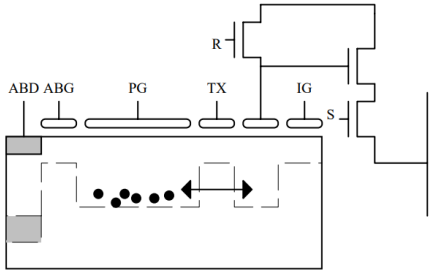
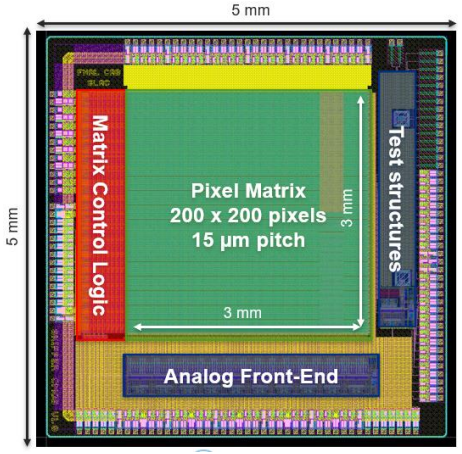
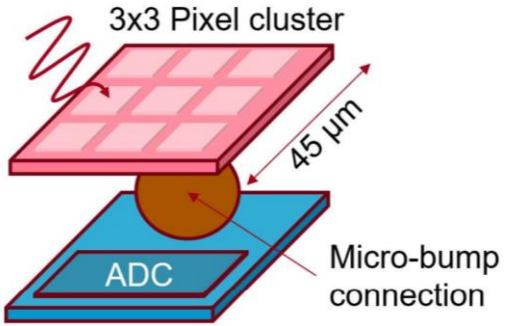


Fig. 10. JPL CMOS-compatible lateral APS.





Skipper-CCD
proposed JPL ‘93 [7]

Talk by D. Braga (9:30a Thu)

Skipper-CCD-in-CMOS
(MAPS)

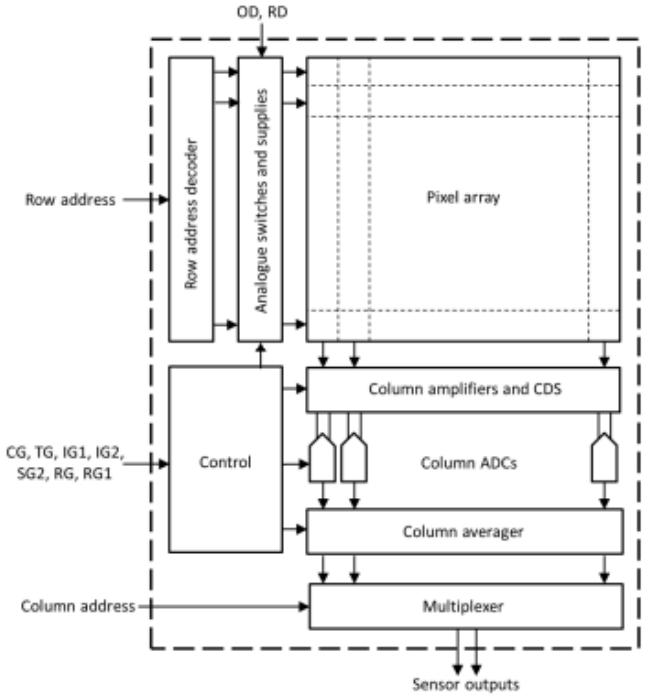
Talk by B. Parpillon (1:55p Weds)

Hybrid Readout for Skipper-CCD-in-CMOS

This Talk!

Why Hybrid Readout?

Monolithic, Column-Parallel

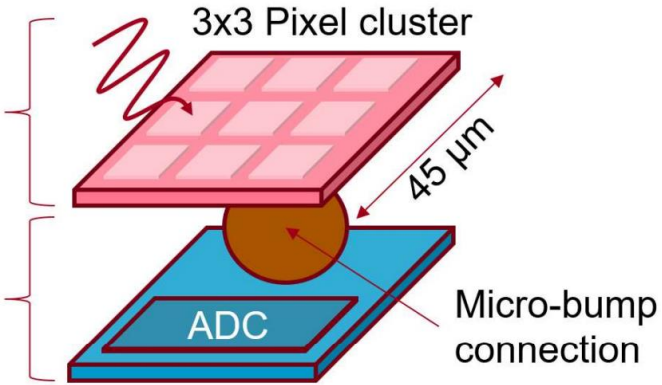


Stefanov, et al. [2]

Hybrid, Per-Pixel

Skipper ASIC:
- Pixel matrix with skipper functionality

Readout ASIC:
- ADCs
- Real-time data processing
- Fast I/Os

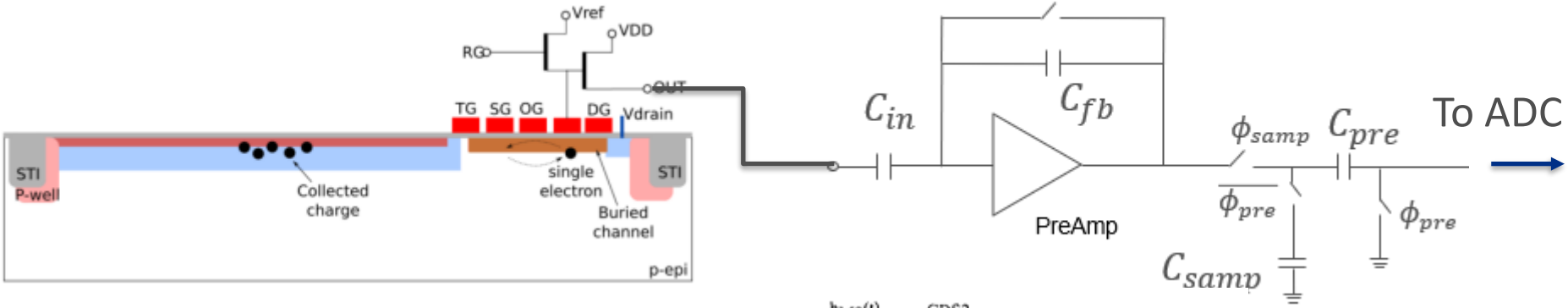


Per-Pixel readout offers $\approx O(n)$ speedup, but at a cost:

Severely constrained power and layout area for the front-end and ADC circuits.

Fermilab

How to Detect a Single Electron

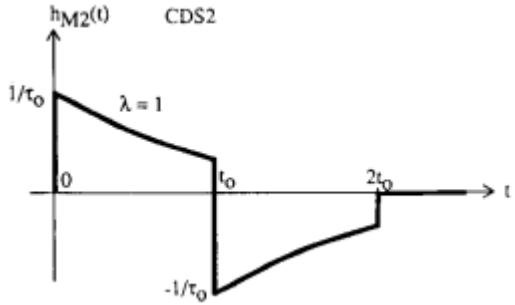


1 electron…

→ Source Follower output: 115 uV

→ Pre-Amp output: 1.15 mV

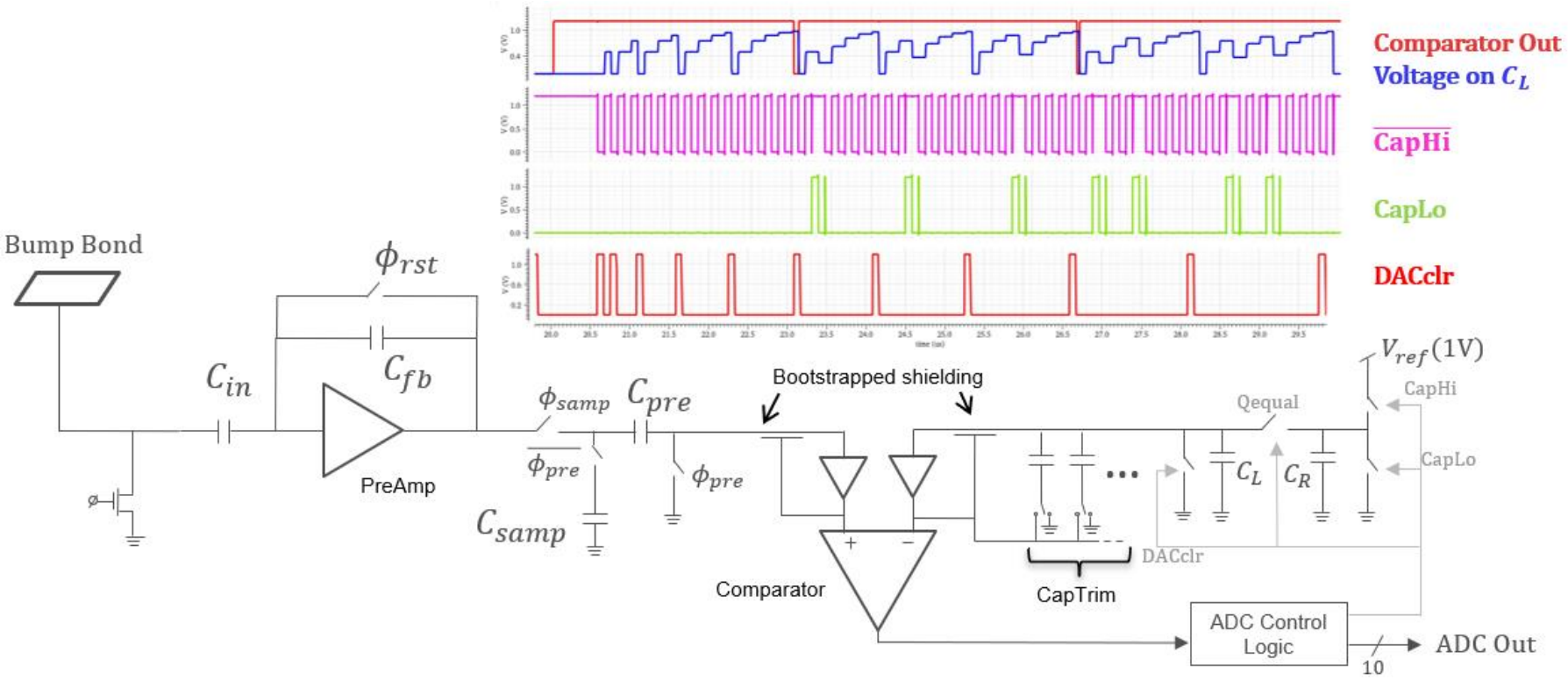
Equivalent output noise: 550 uV, or 0.48 e-



Impulse response of a CDS circuit.
H.M. Wey and W. Guggenbuhl [3]

Fermilab

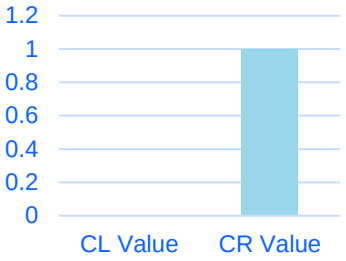
How to Detect a Single Electron (and Digitize it)



Fermilab

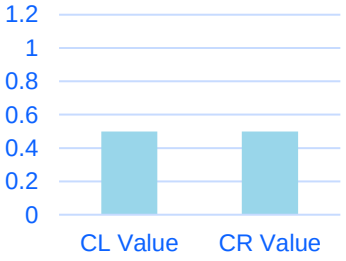
Charge Redistribution SAR ADC

1)



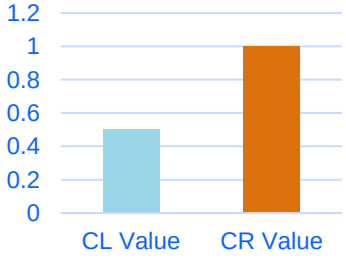
Initial state
CapHi = 1
CL = 0'b0000000000

2)



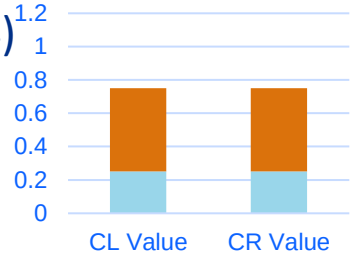
Qequal
CL = 0'b1000000000

3)



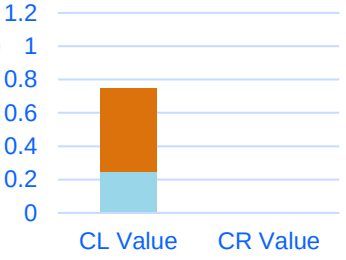
CapHi = 1
CL = 0'b1000000000

4)



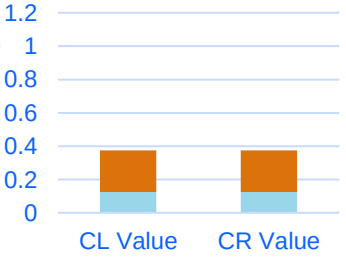
Qequal
CL = 0'b1100000000

5)



CapHi = 0
CL = 0'b1100000000

6)

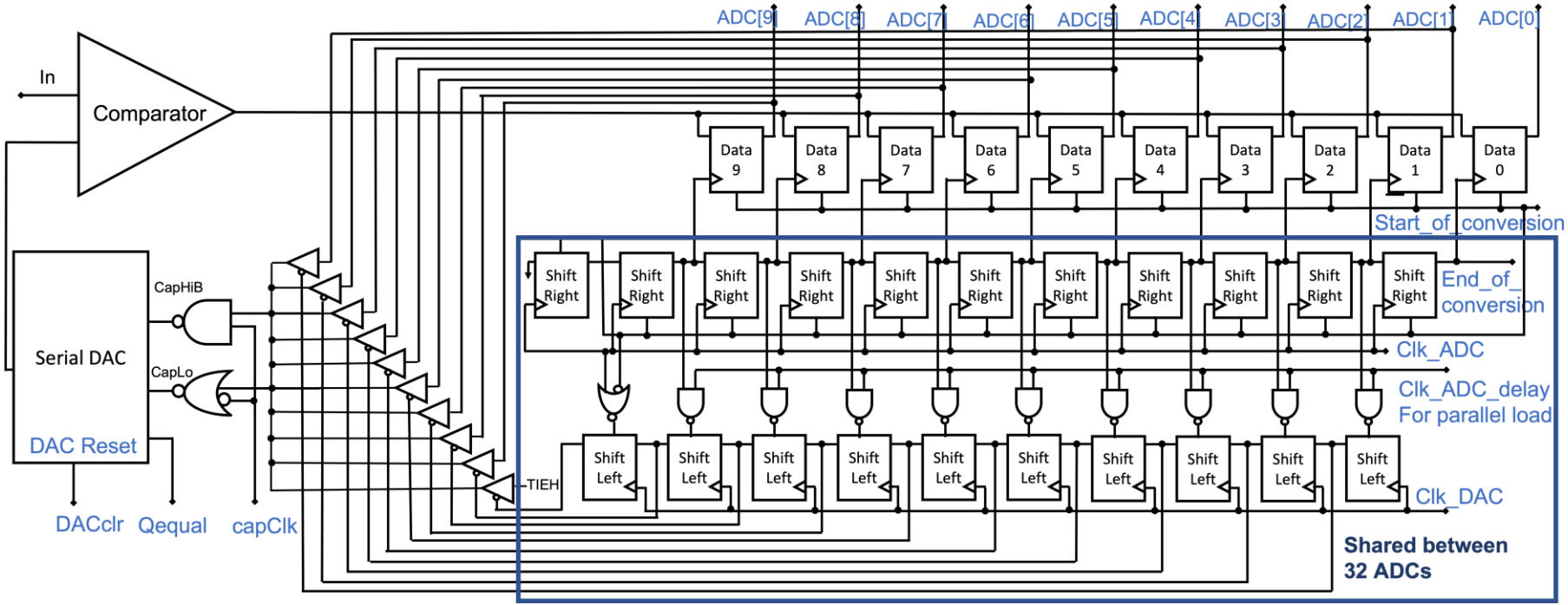


Qequal
CL = 0'b0110000000

And so on…

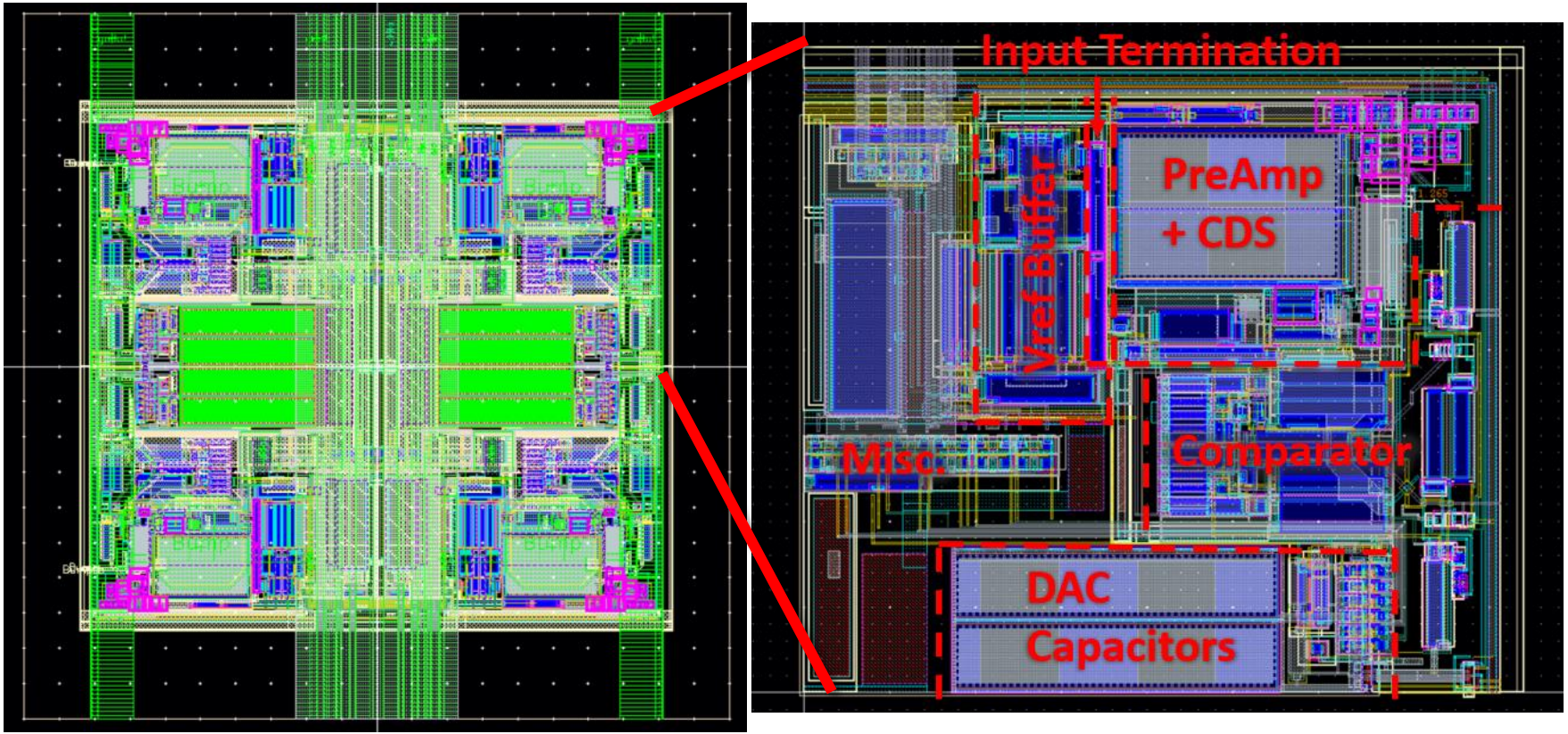
Fermilab

SAR Logic Implementation



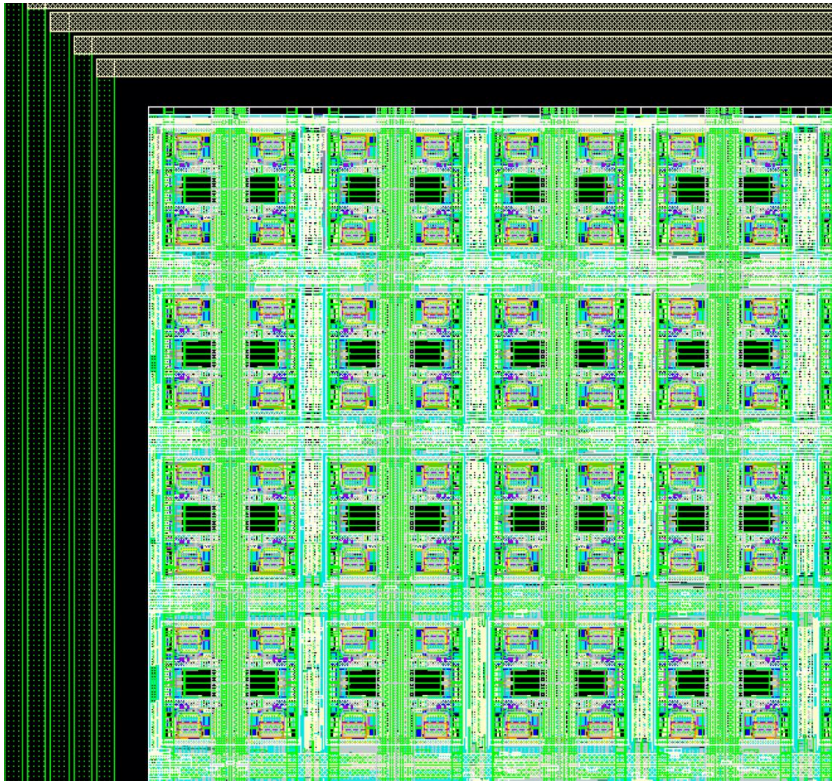
Fermilab

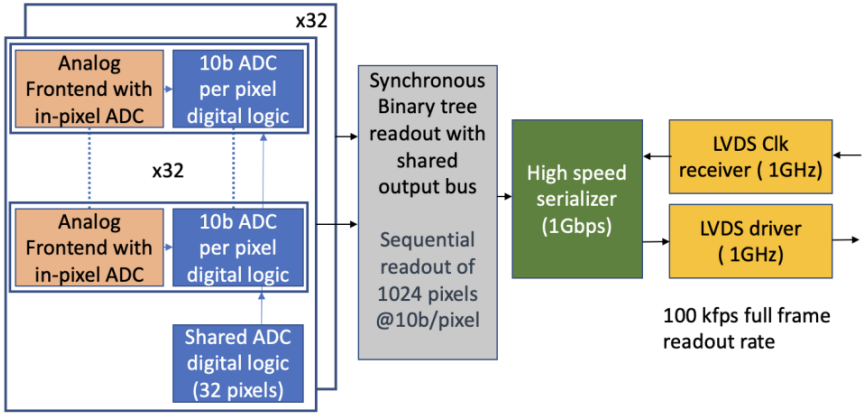
In Silicon…



Fermilab

How to Detect a Single Electron (and Read it Out)





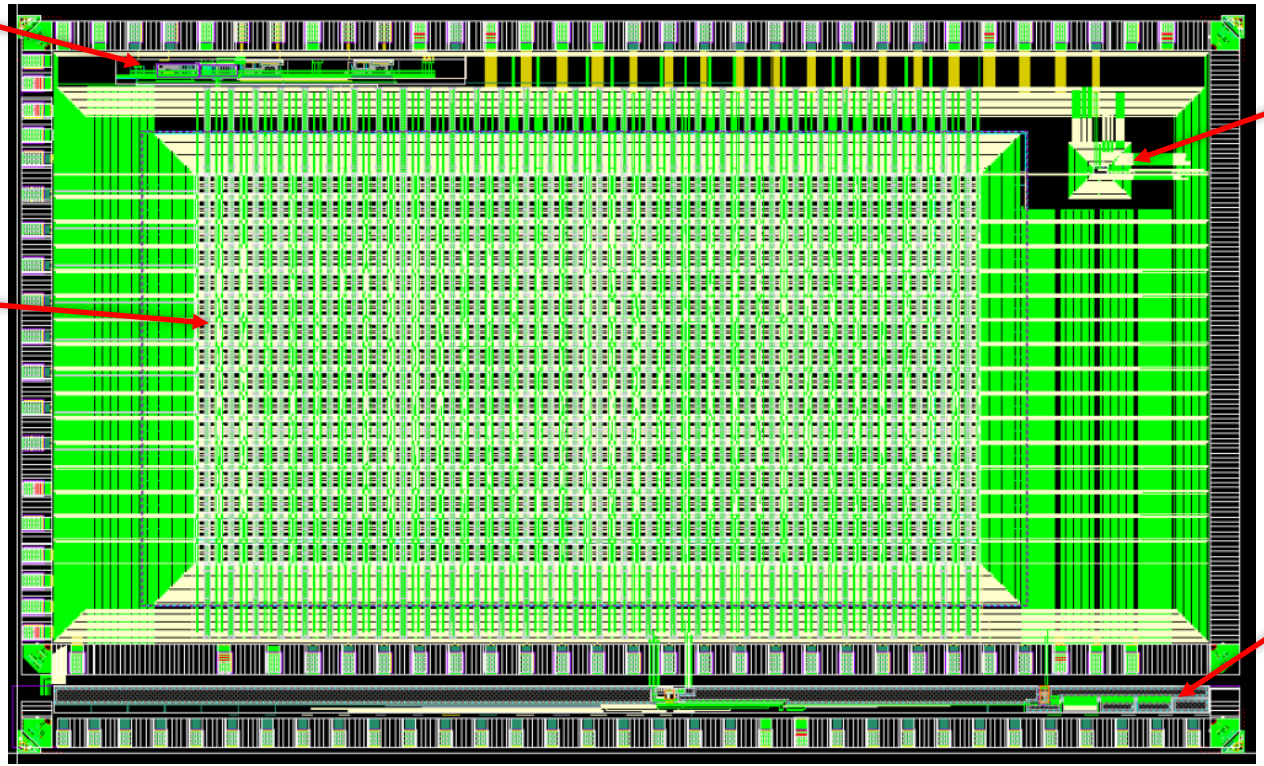
10b * 100 kHz * 1 MPix = 1 Tbps!

Data compression is important:

- Zero-suppression
- PCA
- ML-based Autoencoder

Fermilab

Test Chip 09/2022

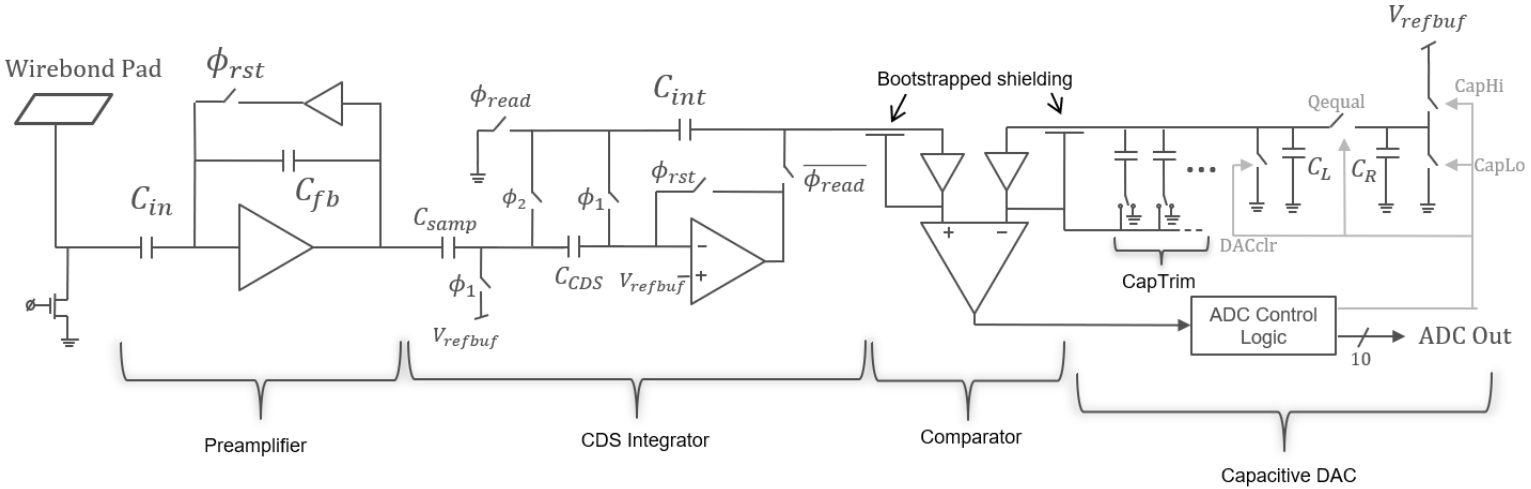


Fermilab

What's Next?

- **In-Pixel Sample Pileup**

  10x sample pileup: Noise ∝ $\sqrt{10}$ with similar (ADC-dominated) readout rate



- **SPROCKET2 Test Chip 12/2022**
- **Full-reticle tapeout in 2023**

Fermilab

Thanks to Contributors

Hybrid Cryodetector Initiative P.I.: D. Braga

Fermilab ASIC Department:

F. Fahim, S. Li, B. Parpillon, T. Zimmerman

Northwestern University:

M.B. Valentin, S. Memik

SLAC:

L. Rota, M. Sharma

References

[1] Tiffenberg J, Sofo-Haro M, Drlica-Wagner A, κ.ά. Single-Electron and Single-Photon Sensitivity with a Silicon Skipper CCD. Phys Rev Lett. 2017;119:131802. doi:10.1103/PhysRevLett.119.131802

[2] Stefanov KD, Prest MJ, Downing M, George E, Bezawada N, Holland AD. Simulations and Design of a Single-Photon CMOS Imaging Pixel Using Multiple Non-Destructive Signal Sampling. *Sensors*. 2020; 20(7):2031. https://doi.org/10.3390/s20072031

[3] H. M. Wey and W. Guggenbuhl, "An improved correlated double sampling circuit for low noise charge coupled devices," in IEEE Transactions on Circuits and Systems, vol. 37, no. 12, pp. 1559-1565, Dec. 1990, doi: 10.1109/31.101279.

[4] G. A. Carini et al., “Hybridized maps with an in-pixel a-tod conversion readout asic,” Nuclear Instruments and Methods in Physics Research, vol. 935, pp. 232–238, 2019. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0168900219304334

[5] F. Fahim et al., “A low-power, high-speed readout for pixel detectors based on an arbitration tree,” IEEE Trans. VLSI Syst., vol. 28, no. 2, pp. 576–584, 2020. [Online]. Available: https: //doi.org/10.1109/TVLSI.2019.2953871

[6] T. Zimmerman, G. Deptuch, and F. Fahim, “Compact, low power, high resolution adc per pixel for large area pixel detectors.” U.S. Patent 11,108,981, issued August 31, 2021

[7] Fossum, E.R. (1993). Active pixel sensors: are CCDs dinosaurs? *Electronic imaging.*