Front-End Computational Modeling and Design for ADAPT

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For the APT collaboration

The Advanced Particle-astrophysics Telescope (APT) [1] is a future gamma-ray/cosmic-ray mission that will combine a pair tracker and Compton telescope in a single monolithic design to include multiple layers of CsI:Na scintillators coupled with crossed planes of wavelength-shifting (WLS) fibers to localize energy deposition to ~mm accuracy, and SiPM-based edge-detectors to improve light collection and calorimetry. It will localize MeV to TeV transients such as gamma-ray bursts in real time using onboard computational hardware.

The Antarctic Demonstrator for APT (ADAPT) is a prototype high-altitude balloon mission scheduled to fly during the 2025–26 season. To estimate ADAPT's performance, we have developed a simulated model of the instrument that incorporates optical properties of its CsI:Na scintillators, measurements of WLS signal attenuation, characterizations of the SiPMs and preamplifier boards, and the effects of signal integration and event pileup.

We also update on the status of front-end data reduction. High-level synthesis (HLS) enables the logic for pedestal subtraction and signal integration across 96 ASIC channels to fit on a single Kintex-7 FPGA with sufficient throughput to handle a high sustained event rate.

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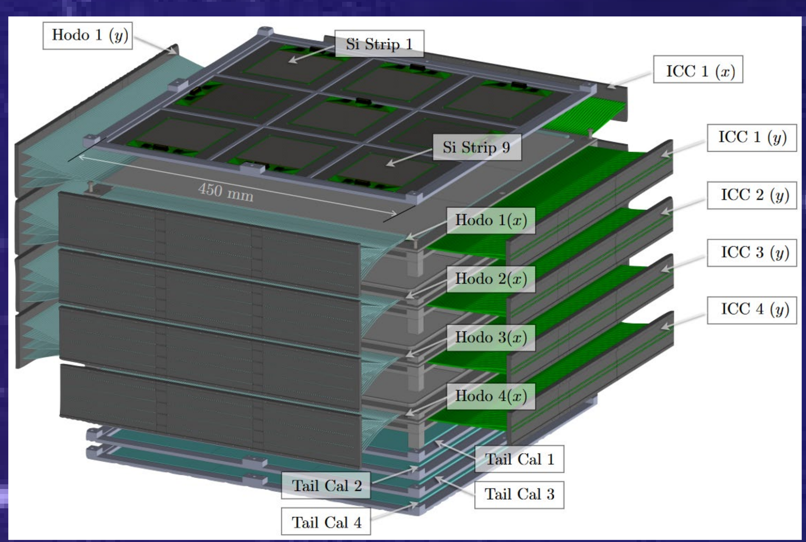
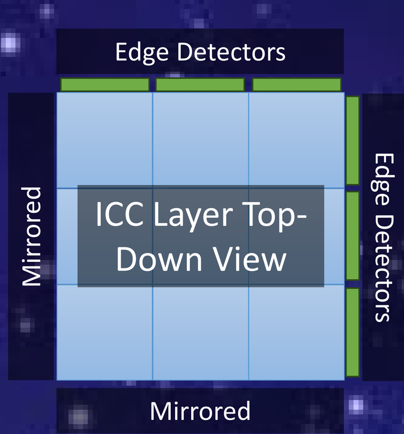
Detector Design Overview

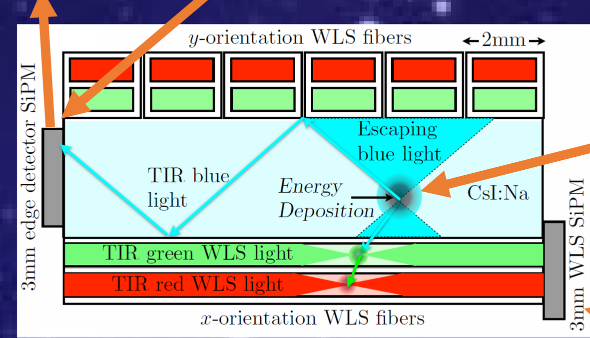
4 primary detector layers coupling an imaging CsI calorimeter (ICC) and scintillating fiber tracker hodoscope
Each ICC layer has a 3x3 arrangement of 15 cm x 15 cm x 5 mm CsI:Na scintillating crystal
Orthogonal 2mm wavelength shifting (WLS) fibers are bonded to the top and bottom of each ICC layer
SiPM-based edge detectors improve light collection and calorimetry
4 additional closely-spaced CsI:Na tail counters have edge detectors but no WLS fibers

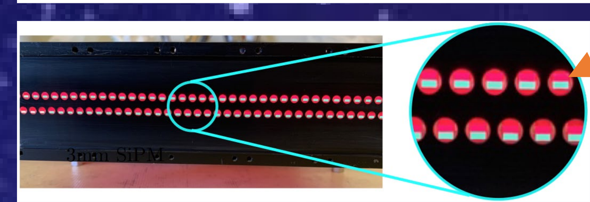


Single CsI:Na Tile Edge-On View



Edge detector comprised of 36 Hamamatsu S14160-3050HS SiPMs

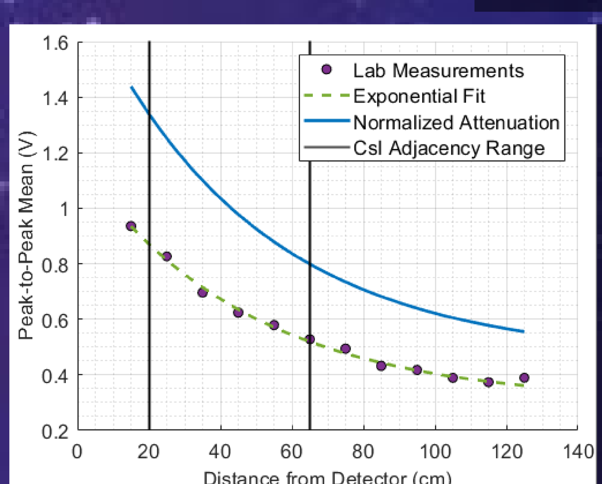




1. Gamma-ray photon Compton scatters or is photoabsorbed
2. WLS fibers each read out by Hamamatsu S14160-3050HS SiPM
3. 36 edge detector SiPMs passively combined into low- and high-gain preamplifier stages
4. 3 WLS SiPM output signals combined into single SMART [2] shaping preamplifier channel
5. 16-channel analog waveform digitizer ALPHA ASIC samples response from edge detector gain stages (1 ALPHA per layer)
6. SMART output from 225 WLS fibers sampled by 5 x 16-channel ALPHA ASICs per ICC layer-axis

WLS Fiber Characterization

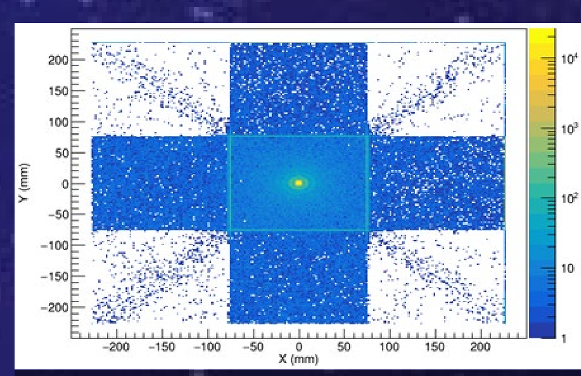
Performed lab measurements of WLS fiber attenuation and characterized SiPM PDE to model optical photon detection



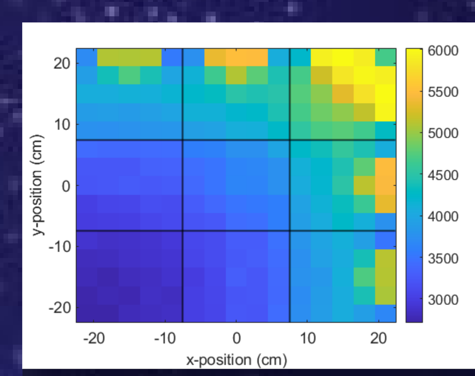
- Lab Measurements: oscilloscope voltage measurements normalized by reference measurement
- Exponential Fit: fit exponential function with y-offset
- CsI Adjacency Range: portion of fiber overlapping CsI (SiPM end 20cm from crystal)
- Original model in [3] used a constant transmission efficiency determined by lab measurements of average yield
- Normalized Attenuation: normalized to middle of CsI adjacency range
- Transmission efficiency now scaled by $0.8789e^{-0.02126d} + 0.4615$ where d is the distance in cm from the edge of tile
- Use [7] and datasheet to assign SiPM PDE of 50% for green WLS fiber light

Edge Detector Modeling

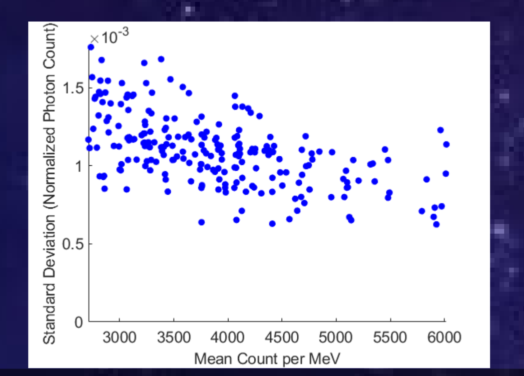
Performed optical simulations of ICC layer to model distributions of scintillated photons detected by edge SiPMs



Photon absorption positions from point-like energy deposit at center.



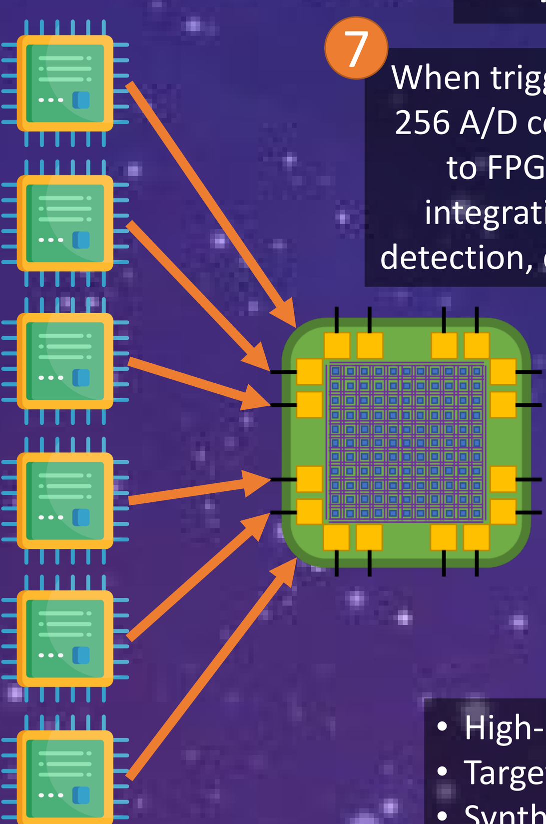
Map of positions to expected photons per MeV



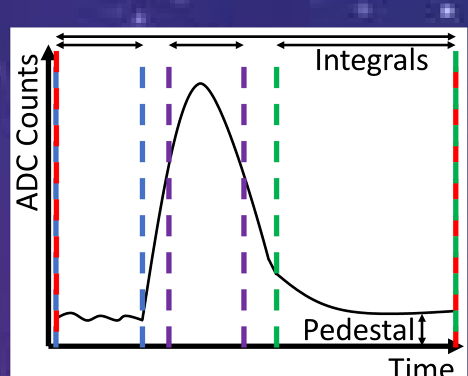
Normalized standard deviation lacks strong position dependence

- GEANT4-based simulation
- CsI:Na refractive index 1.84, yield 41,000 photons/MeV
- 1mm silicone epoxy at all tile interfaces with refractive index 1.41
- Simulated 20 energy deposits at each of 5x5 points on each tile
- Mapped absorbed photons to edge SiPM positions
- Model Gaussian distribution for captured photons
- Mean: Expected photons per MeV at closest simulated position
- Std: 0.0158 * mean per MeV, scaled by square root of energy
- Assign SiPM PDE of 45% for blue scintillation light per [7]

High-Level Synthesis of FPGA Logic



7. When triggered, 6 ALPHA ASICs read out 256 A/D converted samples per channel to FPGA for pedestal subtraction, integration, zero suppression, island detection, centroiding, and event building



8. **Pedestal Subtraction**
ADC count contribution from analog memory pedestal must be subtracted

9. **Signal Integration**
4 integrals over subsets of 256 samples (2.56 μs) to capture complete time profile of CsI scintillation

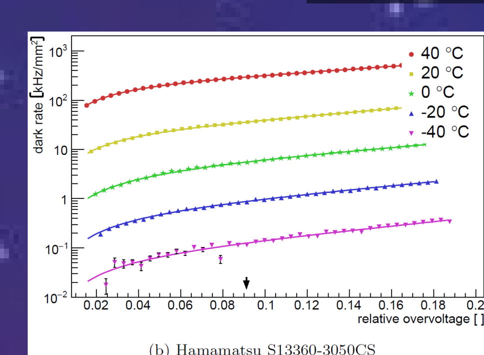
- High-level synthesis (HLS) applied to pedestal subtraction and signal integration
- Target FPGA: Xilinx Kintex 7 XC7K325T-2FFG900C
- Synthesis and emulation: Xilinx Vitis software platform
- Vectorized across 16 ASIC channels to enable SIMD processing
- Pipelined dataflow execution improves throughput
- Two implementations of signal integration:
- (1): Parallel logic block for each integral
- (2): Sequential prefix sum over samples, computing each integral by subtracting prefix sum indices corresponding to bounds

Results for parallel logic handling 6 ALPHA ASICs:

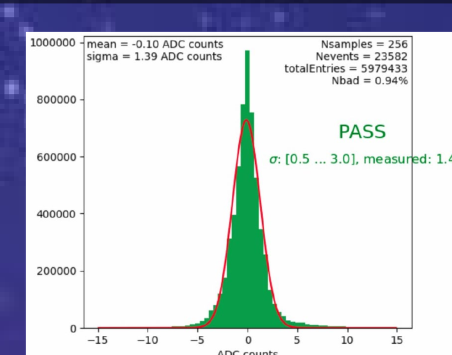
Impl.	FFs	% Util	LUTs	% Util	BRAM	% Util	II (Cycles)
(1)	30,954	7.6	71,988	35.3	450	50.6	275
(2)	27,864	6.8	60,372	29.6	540	60.7	269

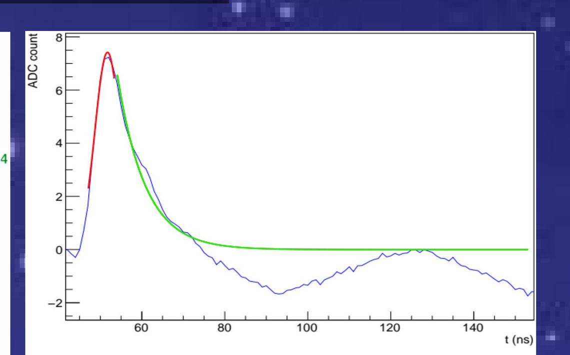
FPGA not overutilized!
(still need to synthesize zero-suppression and island detection)
Throughput supports sustained event arrivals every 3 μs

Noise Characterization



[7], Fig. 22(b)





SiPM Dark Counts
- Relative overvoltage ~5%
- Cooled to 10°C
- 70 kHz for single 3x3 mm SiPM
- 10 ns samples
- Expected counts/sample:
- 0.0021 for 3x mux WLS
- 0.1512 for 6x36 in edge detector layer

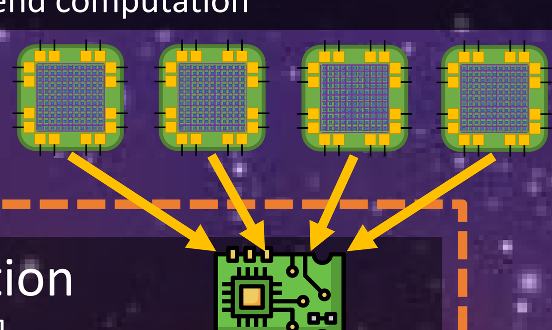
SMART Preamplifier Noise
- RMS noise per ns: $\sigma = 1.39$
- Scale by $\sqrt{3}$ for WLS
- Scale by $\sqrt{216}$ for edge detectors
- Further scale by signal integration time
- SMART single-PE impulse response modeled using 10ns Gaussian followed by 27ns exponential
- MC simulation determines mean and std for ADC count

Signal Integration
- CsI scintillation modeled as exponential distribution with mean 633 ns
- 1.5 μs integration for edge detectors
- 2.5 μs integration for WLS fibers
- Optical photon signal captured follows binomial distribution

Event Pileup
- GRB arrival times sampled from normal distribution
- Add Earth's limb particle background modeled in [6]
- Signals from multiple events may be captured in a single readout window

10. **Centroiding**
Original interaction locations and energies inferred from integrated fiber signal distributions on 1 FPGA per ICC layer

- Preliminary assessment in [4] of HLS for centroiding
- Requires 68 cycles to centroid a typical event
- Data reduced from 10ns samples to <x,y,z,E>
- Centroids sent from 4 FPGAs to CPU performing backend computation



Backend Computation

For more details, see [5]

11. **Event Reconstruction**
Centroids from each individual gamma ray are combined and used to reconstruct Compton angles

12. **GRB Localization**
Resulting annuli describing PDF of incoming source direction are intersected to infer a common source

References

[1] James Buckley. The Advanced Particle-astrophysics Telescope (APT) Project Status. In Proc. of 37th International Cosmic Ray Conference – PoS(ICRC2021), volume 395, pages 655:1–655:9, July 2021.

[2] Leonardo Di Venere. Design of the front-end electronics board based on the SMART ASIC for the Antarctic Demonstrator for the Advanced Particle-astrophysics Telescope (APT). Poster PGA0-34 (online).

[3] Wenlei Chen et al. The Advanced Particle-astrophysics Telescope: Simulation of the Instrument Performance for Gamma-Ray Detection. In Proc. of 37th International Cosmic Ray Conference – PoS(ICRC2021), volume 395, pages 590:1–590:9, July 2021.

[4] Jacob Wheelock, William Kanu, Marion Sudvarg, Zhili Xiao, Jeremy D. Buhler, Roger D. Chamberlain, and James H. Buckley. Supporting multi-messenger astrophysics with fast gamma-ray burst localization. In Proc. of IEEE/ACM HPC for Urgent Decision Making Workshop (UrgentHPC), November 2021.

[5] Ye Htet, Marion Sudvarg, et al. Prompt and Accurate GRB Source Localization Aboard the Advanced Particle Astrophysics Telescope (APT) and its Antarctic Demonstrator (ADAPT). Poster PGA1-16 (physical).

[6] Wenlei Chen. Simulation of the instrument performance of the Antarctic Demonstrator for the Advanced Particle-astrophysics Telescope in the presence of the MeV background. Poster PGA0-22 (online).

[7] A.N. Otte, D. Garcia, T. Nguyen and D. Purushotham. Characterization of three high efficiency and blue sensitive silicon photomultipliers. Nucl. Instrum. Methods Phys. Res. A 846 (2017) 106.

Mission Presentation

For more details, please see our presentation at parallel session GA10-05.
Friday, 28 July, 2023, 10:00 AM – 10:15 AM
"The Antarctic Demonstrator for the Advanced Particle-astrophysics Telescope (ADAPT)"
James H Buckley, Washington University in St. Louis

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