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A-STEP for AstroPix: Development and Test of a space-based payload using novel pixelated silicon for gamma-ray measurement

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Next-generation medium-energy gamma-ray instruments sensitive from 25 keV to 1 GeV must be able to measure and reconstruct incident photons in the photoabsorption, Compton, and pair-production regimes. Such robust functionality requires a tracker with high resolution, low noise, and low power. The monolithic CMOS active pixel silicon sensor AstroPix is a novel mission-enabling technology. AstroPix will provide the energy- and angular-resolution required of a medium-energy gamma-ray telescope while reducing noise with the dual detection-and-readout capabilities of an HVCMOS chip. Plans for A-STEP, a funded Astropix Sounding rocket Technology dEmonstration Payload, will be presented. This roughly 2U-sized payload will include three layers of AstroPix quad-chips for cosmic ray and gamma ray detection and tracking. This technology demonstration mission also strengthens the design readiness of AMEGO-X, an MIDEX-sized MeV telescope mission concept. Additional supplementary development and testing of the AstroPix project will also be considered, including A-STEP simulation efforts for environment and detector response modeling.

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1. Background

The sky is bright in medium-energy gamma rays, ranging from 10s of keV to 10s of GeV. These electromagnetic messengers could hold the key to understanding the sources of short gamma-ray bursts and play a valuable role in multimessenger astronomy, however there is no dedicated space-based mission currently that targets this MeV band. This is due in part to the difficulty of measuring MeV gamma rays - instrument-induced backgrounds swamp signals and particle track reconstruction in the Compton regime which dominates in the MeV band is more computationally complex than higher-energy gamma rays.

1.1 All-Sky Medium Energy Gamma ray Observatory eXplorer (AMEGO-X)

One mature mission concept aims to address four decades of energy to fully cover the MeV band and beyond. The All-Sky Medium Energy Gamma ray Observatory eXplorer (AMEGO-X) [3] is a medium-sized MIDEX mission concept relying on three instrument sections that work in tandem to identify and reconstruct medium-energy gamma rays from 25 keV to 1 GeV. A scintillating anti-coincidence detector acts as a veto for cosmic rays and surrounds the tracker and calorimeter instruments (Fig. 1a) on five sides. A cesium iodide calorimeter (purple in Fig. 1a) induces showering of high-energy incident photons and measures energy after the incident particle traverses through forty layers of pixelated silicon tracker (red in Fig. 1a). In order to measure incident particles in the MeV band, AMEGO-X is highly sensitive to Compton interactions of incident gamma rays within the tracker detector volume. Effective Compton reconstruction requires high energy resolution and an instrument with a low noise floor. Legacy silicon tracker technologies such as the single-sided silicon strip detectors flying on the Fermi Large Area Telescope do not meet these requirements, so AMEGO-X utilizes a silicon sensor novel for spaceflight with HVCMOS technology.

1.2 HVCMOS

For position resolution and low noise, the AMEGO-X tracker is baselined with pixelated silicon with a pixel pitch of 500×500 μm. Common in industry and other particle detection applications, the AMEGO-X tracker utilizes CMOS technology to read out every pixel without the need to bump-bond directly to every pixel. This strategy integrates signal amplification, digitization, and readout physically into the substrate of each pixel. These pixel outputs are then routed to a digital periphery on-chip which manages data readout and sensor configuration. This dual detection-and-readout capability eliminates the need for auxiliary ASIC readout electronics. In order to measure the large dynamic range of 5 - 700 keV in any pixel, an additional high voltage (HV) is applied directly to each pixel for active depletion of the 500 μm thick wafer. This HVCMOS design [5, 6] has been utilized in collider-based particle physics experiments but is novel for spaceflight.

1.3 AstroPix

The HVCMOS sensor designed uniquely for spaceflight is called AstroPix. The AstroPix development project draws heritage from a decade of development for ground-based collider physics experiments but optimizes the chip for a space environment. AstroPix must draw low power (< 1 mW/cm^2) for use in spaceflight while achieving full depletion of the 500 μm substrate in

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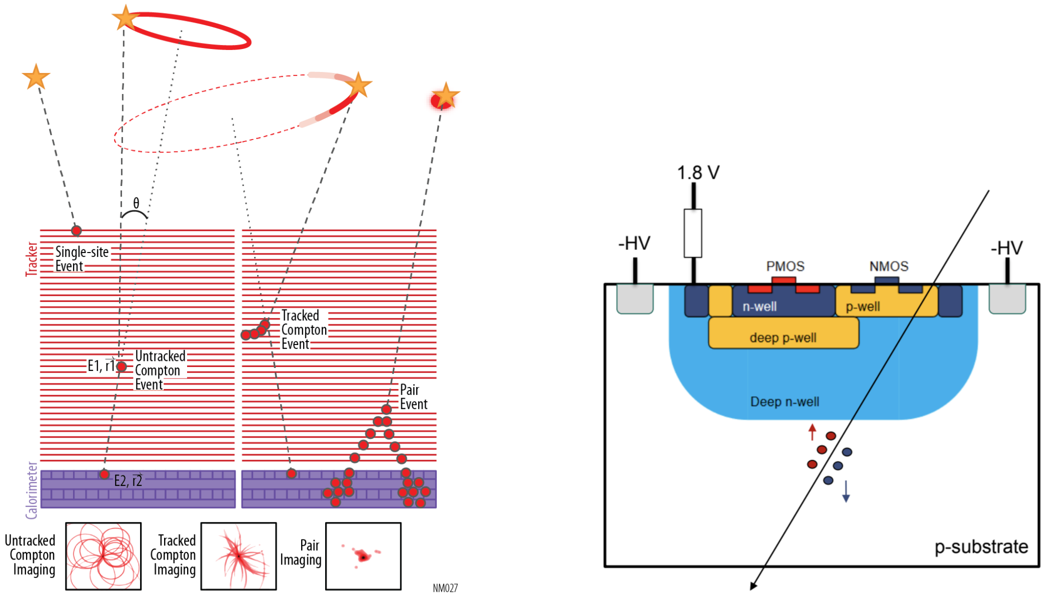

(a) AMEGO-X tracker and calorimeter systems reconstruct incident gamma rays over four decades of energy and four distinct interaction regimes.

(b) HVCMOS design allows charge collection, amplification, and digitization directly in the pixel substrate.

Figure 1: The AMEGO-X design facilitates reconstruction of four different gamma ray interaction regimes, enabled by HVCMOS technology novel for spaceflight.

relatively large 500×500 μm pixels. Individual HVCMOS circuitry in every AstroPix pixel enables measurement with a low noise floor, even when scaled to full telescope size.

AstroPix development has evolved through mindful incremental changes from a chip designed for use in the ATLAS experiment at the Large Hadron Collider. Characterization studies and performance of the first two AstroPix versions (AstroPix_v1 and AstroPix_v2) are detailed in [1], [2], [4], along with additional motivating background and design philosophy. The current chip under test is AstroPix_v3 (preliminary characterization in [7]). This evolution chronicles the growth of pixel pitch from 140×60 μm to the AstroPix design benchmark of 500×500 μm and continual decrease of analog power consumption to meet the AstroPix benchmark of <1 mW/cm^2.

AstroPix_v3 is the first AstroPix chip to be diced as a quad-chip, where four chips (Fig. 2a) are diced together off the wafer into one 4×4 cm^2 array of chips. This quad-chip will serve as the building block for larger utilizations like AMEGO-X (Fig. 2b). At the time of writing, single chips of AstroPix_v3 are being tested on benches and in radiation facilities around the world including Goddard Space Flight Center, Argonne National Laboratory, and Hiroshima University. AstroPix_v3 quad-chips are expected for bench testing by the end of 2023.

2. Astropix Sounding rocket Technology dEmonstration Payload (A-STEP)

In order to raise the Technology Readiness Level (TRL) of AstroPix for future implementation into telescopes such as AMEGO-X, the sensor and its supporting electronics must be proven in established tests involving prototypes of increasing sizes operating in space-like environments.

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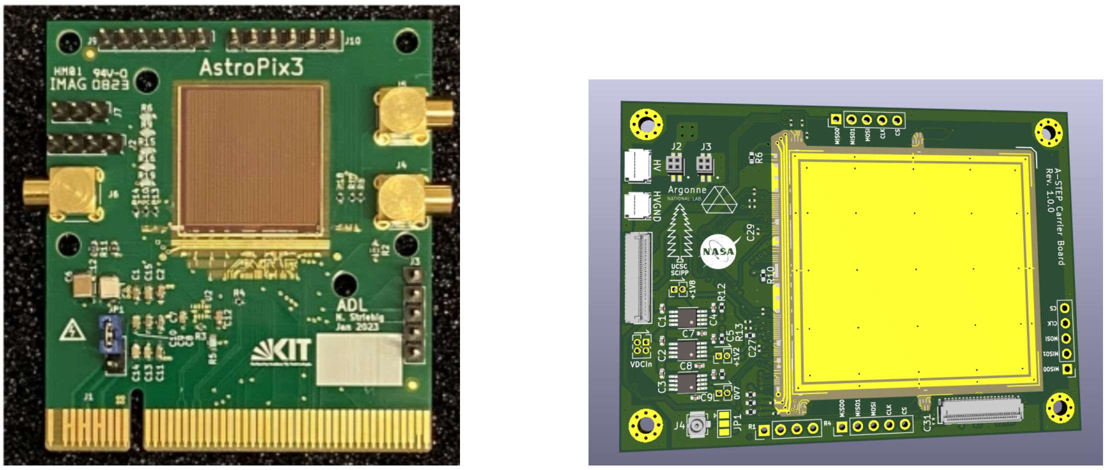

(a) One 2×2 cm^2 AstroPix_v3 chip mounted to a board for bench testing

(b) AstroPix_v3 quad-chips will be flown on custom-designed circuit boards

Figure 2: AstroPix_v3 is supported by custom-designed circuit boards for the bench testing of single chips and flight of quad-chips.

One of these tests is the Astropix Sounding rocket Technology dEmonstration Payload (A-STEP) in which a roughly 2U ($10\times10\times20$ cm^3) payload with three layers of AstroPix_v3 quad-chips will be flown on a sounding rocket. The rocket will fly on a parabolic trajectories reaching apogee exceeding 100 km during a flight of roughly 10 minutes in an environment around 20-40 C. Advantages of flying as a sounding rocket payload include the integrated support of the NASA Sounding Rocket Operations Contract and shared centralized resources from the sounding rocket itself, including a power supply, telemetry of payload data, and attitude control and data collection.

A flight opportunity with NASA Wallops Flight Facility has been identified for early 2025. A-STEP will be mounted on a 30.48 cm diameter shelf within a cylindrical volume with 12cm of vertical space. The rocket shell forming the cylinder is 0.625 cm thick aluminum and introduces passive material in front of the payload, as the instrument stack will face toward the shell. The shelf will be lined in a plastic sealant to assist in retrieval as rockets are launched over the ocean.

2.1 Mission Overview

The A-STEP mission objective is to raise the TRL of the AstroPix quad-chip for future use in AMEGO-X by operating the chip in a space-like environment. In this way, the mission is a technology demonstration. A-STEP has the goal of measuring cosmic rays during flight, as no gamma-ray events are expected during the short flight duration. These cosmic rays will appear as minimum ionizing particles (MIPs). The payload will also be used to verify models of AstroPix power consumption and the geometry of the supporting board.

Given a cosmic ray rate of 1 Hz/cm^2, A-STEP expects a data rate of 8.3 kbps and the potential reconstruction of more than 450 minimum MIP tracks through all three AstroPix layers. A separate data stream will telemeter housekeeping data during flight, including the temperature and power draw of the operating chips with a rate less than 1 kbps.

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2.2 Design Specifications

A-STEP (Fig. 3) consists of an instrument stack of three AstroPix_v3 quad-chip layers mounted on custom designed boards (Fig. 2b), an FPGA for interfacing with the instrument stack, a high voltage supply board, and a flight computer. Since the AstroPix chip handles signal digitization and readout, no front-end ASIC is needed. An additional 0.635 cm thick Aluminum housing will contain the payload, giving structural support. A window is cut in this housing to reduce passive material in front of the instrument stack. The payload is powered from a central battery supplied by the sounding rocket. One 5.3V line is required as input to A-STEP, and each board will condition this rail as needed for its own functionality.

The Diligent CMOD A7-35T FPGA development board hosts a Xilinx Artix-7 35T FPGA used for low-level clocking, commanding, and communication for the instrument stack. Clocks are used in the AstroPix chip for readout timestamping and signal definition - a time over threshold (ToT) is measured to high precision with a 200 MHz clock and correlated to incident particle energy with pre-flight calibration. The FPGA will also receive and packetize housekeeping data from the instrument stack including chip temperature and power draw, and record FPGA temperature. Control for the HV board is also managed by the FPGA board.

The HV board supplies a high voltage bias of -150V to each AstroPix chip in the instrument stack to facilitate active depletion. This board will also monitor HV power delivered to each chip and pass this information to the FPGA. The main feature of this board is the Advanced Energy 0.2US5-N-0.1 DC-DC converter which can service all three AstroPix_v3 quad chips with -150V. Each quad chip is expected to draw -40 nA with breakdown voltage of -290V. Thus A-STEP will not run at full depletion, but the provided depletion will enable the A-STEP goal of identifying MIP tracks.

A BeagleBone Black off-the-shelf single-board computer will be used as the flight computer. The computer is responsible for receiving data (from the instrument stack and housekeeping) from the FPGA and performing any further manipulation of this data before telemetry to the ground station. This manipulation may include the stripping of 'heartbeat' bytes off the data to decrease overall telemetered data rate. The computer also initializes and commands the configuration of the rest of the payload, including both the FPGA and all individual AstroPix_v3 chips in the instrument stack. This is the main interface between the payload and the sounding rocket. The flight computer delivers packetized data and housekeeping to the central sounding rocket computer which enables communication with the ground system and the live downlinking of data. This realtime data will be passed immediately to the A-STEP operations team on the ground. The payload will not accept commands during the short flight, but live monitoring of housekeeping data with a custom designed graphical user interface will occur in realtime at the ground station.

2.3 Simulation Results

A mass model developed at the University of Hiroshima simulates the geometry of the instrument stack and three AstroPix_v3 quad-chips. Preliminary studies with this mass model used the MEGALib software package to simulate the interaction of 325 MeV muons (Fig. 4). Of the nearly 136,000 simulated muons that triggered any response with the detector stack, 9.57% of events deposited a signature MIP deposition of 193 keV in all three AstroPix_v3 quad-chips. Assuming

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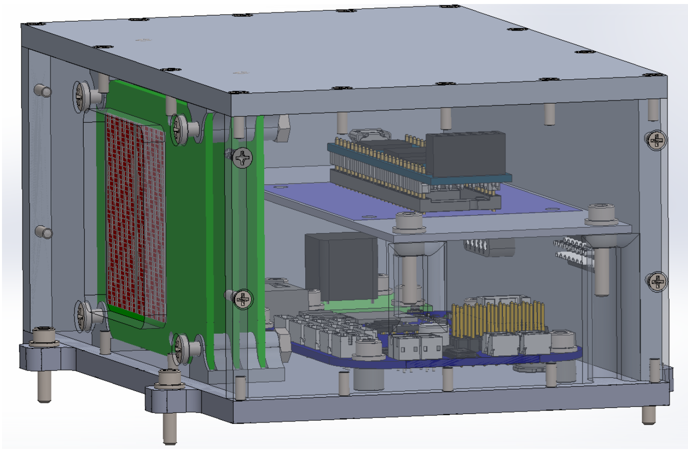

Figure 3: A-STEP consists of three AstroPix_v3 quad-chip layers (green) supported by an FGPA (top), high voltage board (bottom back), and flight computer (bottom front) occupying less than $10 \times 10 \times 20$ cm^3.

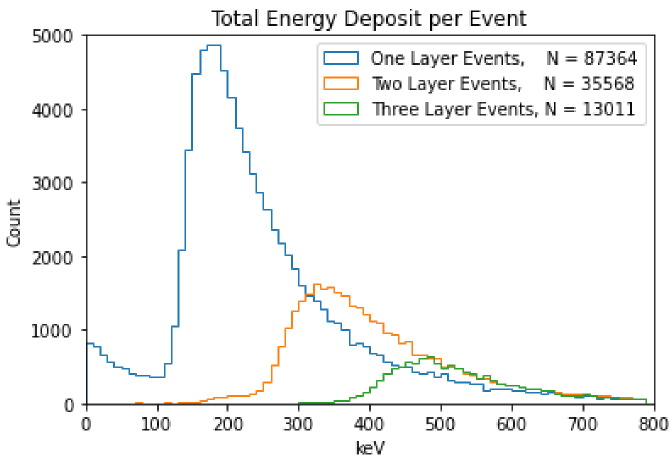

Figure 4: 9.57% of triggered MIPs are expected to leave a track through all three layers of the A-STEP instrument stack.

a 5 minute flight with a rate of 1 Hz/cm^2, 459 full tracks are expected. This “best case" value illustrates an optimistic maximum of potential MIP track data that can be collected during flight. Detector efficiency effects and rocket orientation will impact the true measurement.

3. Summary

The medium-energy gamma-ray sky is rich in information but precision instruments require advances in technology. The mission concept AMEGO-X achieves high sensitivity from 5 keV - 1 GeV with a novel pixelated silicon tracker utilizing HVCMOS technology. This sensor, AstroPix, will be tested in space on a sounding rocket with the A-STEP technology demonstration. A-STEP is in an advanced stage of design and preliminary stage of prototype testing. The payload mission is to advance the Technology Readiness Level (TRL) of AstroPix for future implementation in larger designs such as AMEGO-X, with a goal of measuring and reconstructing minimum ioninzing

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particle tracks through all three AstroPix layers of the A-STEP instrument stack. An A-STEP flight opportunity is identified in early 2025.

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