AGILE: a compact low power and low-cost instrument for characterization of solar, magnetospheric, and cosmic ray particles

A. Novikov

University of Kansas

Workshop on high energy physics and related topics at Sonora, Mexico
Aug-18 2021

AGILE Collaboration

Shri Kanekal
Ashley Greeley
Quintin Schiller

Christophe Royon
Nicola Minafra
Sasha Novikov
Florian Gautier
Tommaso Isidori
Rob Young
Gauthier Legras
William Doumerg

Outline

Objectives

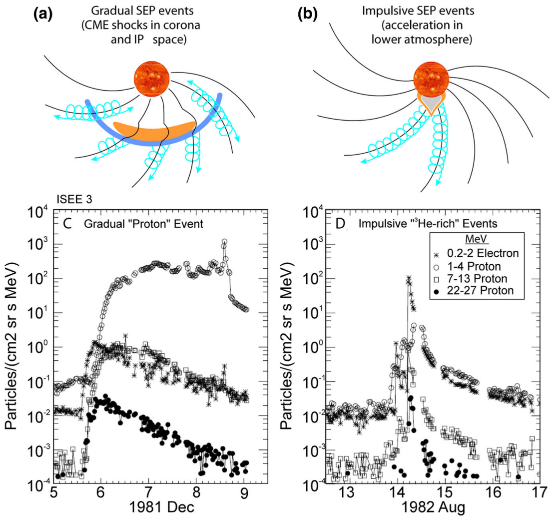
AGILE (Advanced enerGetic Ion eLectron tElescope)

- Compact low power and low-cost instrument for characterization of solar, magnetospheric, and cosmic ray particles.
- Particles of main interest:
  - **Ions (H-Fe), E=(1-100)MeV/nucl;**
  - Electrons, E=(1-10)MeV.

Main Goal

Robust real-time particle identification and energy measurement

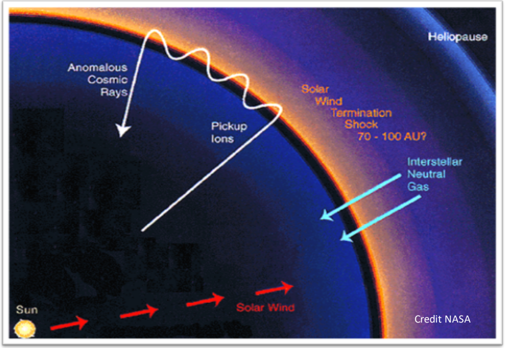
Science Motivation: Solar Energetic Particles (SEPs)



Characterization of:

- Impulsive (He-3-rich) events;
- Gradual (proton-rich) events;

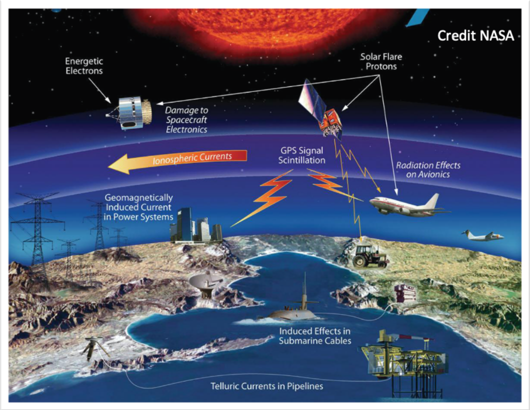
Science Motivation: Anomalous Cosmic Rays (ACRs)

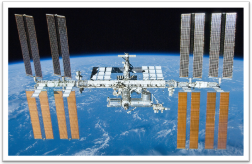


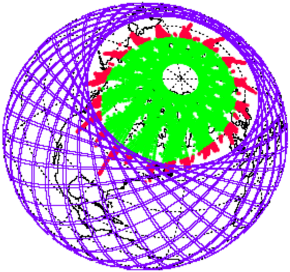
ACRs can be used for studying:

- Dynamics of energetic particles within the solar system;
- General properties of the heliosphere;
- Nature of interstellar material.

Science Motivation: Space Weather and Space Travels

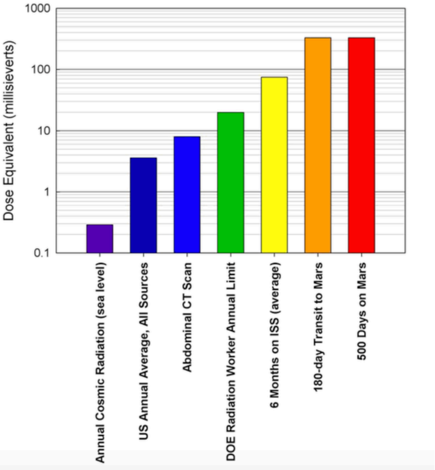


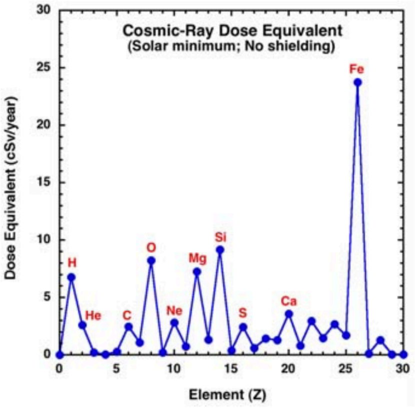




Oxygen (E>16MeV),
Oct-Nov, 1992 SEP events

Science Motivation: Space Weather and Space Travels



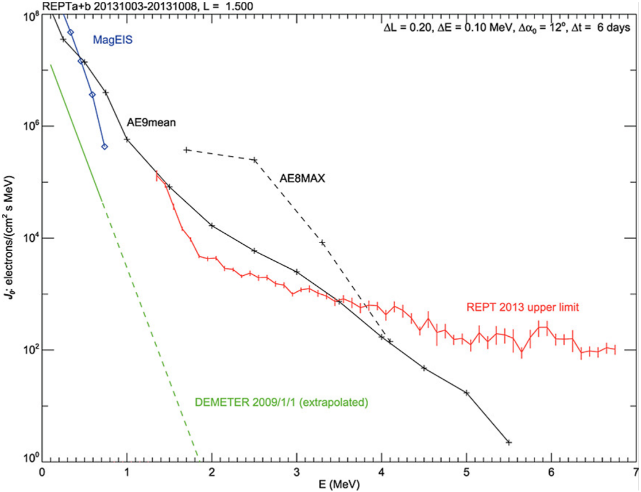


Hassler, D. M. et al, Science 343(6169), 1244797 (2014)

R.A. Mewaldt et al. 29th International Cosmic Ray Conference

Pune (2005) 00, 101-104

Science Motivation: Relativistic Electrons in the Inner Van Allen Belt



Li, X. et al, J. Geophys. Res. Space Physics, 120: 1215– 1228 (2015)

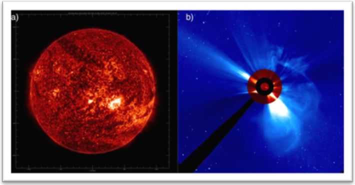
'Contaminated' by Protons

Goals

- Presence or absence;
- Dynamics (geomagnetic activity).

Science Motivation: Relativistic Electrons in the Outer Van Allen Belt

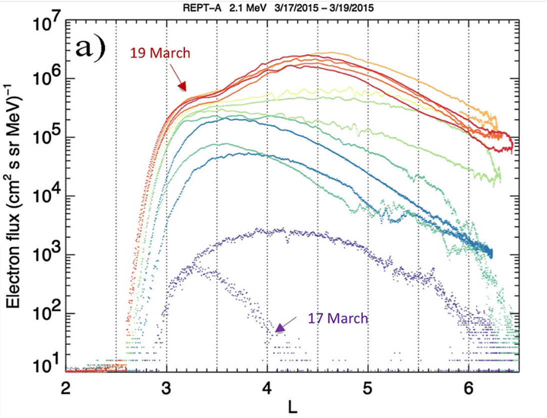
March 2015 Solar Storm



a) SDO image; b) SOHO/LASCO corona-graph

Goals

- To observe both seed and accelerated populations;
- To examine the nature of various competing acceleration, transport, loss processes.



Baker, D. N., et al. J. Geophys. Res. Space Physics, 121, 6647– 6660 (2016)

Science Motivation: Summary

Dynamics of radiation belts		Energization, transport and modulation of IP charged particles		Space weather
Relativistic electrons in the inner and outer belts	Energetic ions in the outer belt	SEP energization at IP shocks	ACR: transport and modulation	
Electrons, E=(1-10) MeV	Ions (H-Fe) E=(1-100) MeV/nucl			
High inclination LEO or Near equatorial GTO		Interplanetary Space (e.g. L1) or High inclination LEO		High inclination LEO

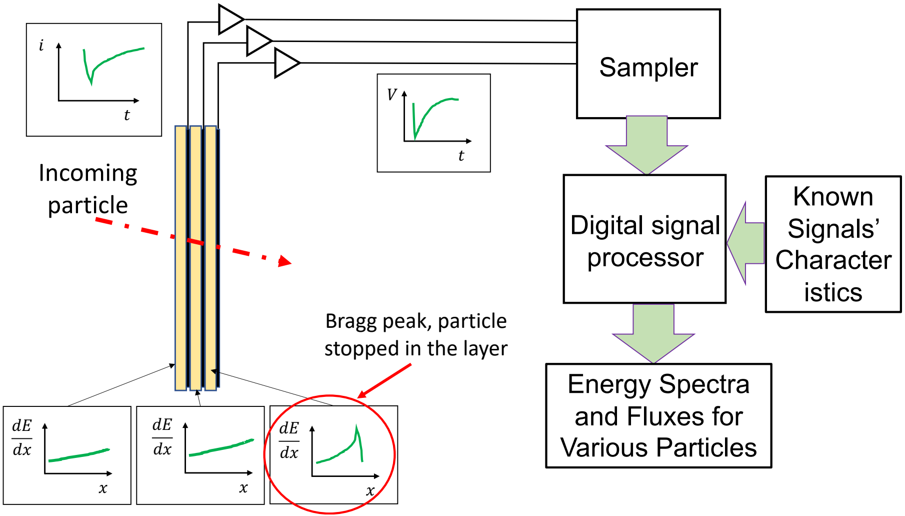
Robust **real-time particle identification and energy measurement** is very important!

Pulse Shape Discrimination (PSD)

- If a particle (ion) completely stops in detector medium (e.g. Si) its type and energy can be identified using **both time and amplitude characteristics of the produced signal**:
  - Pulse Rise Time (charge collection time) is an indicator of the depth at which the particle completely stops;
  - Amplitude is an indicator of the total energy deposited by a particle;
  - The combination of "Rise Time & Amplitude" is unique for a specific particle with specific energy;
- In contrast to "classic" $\Delta E - E$ method only one detector layer may be used;
- Fast and robust sampling is required.

AGILE will use the real-time PSD technique for the first time in space based instrumentation.

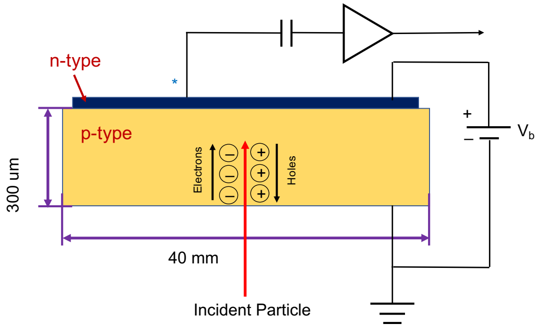
Pulse Shape Discrimination (PSD)



PSD Simulation

- "Real" hardware (commercially available Si-sensors and custom made electronics) is used:
- Statistical fluctuations, electronics' noise, sampling rate, temperature dependencies etc. are taken into account;
- Incoming particles are randomly generated:
  - Ions: H-Fe;
  - Energy: (1-100) MeV/n.

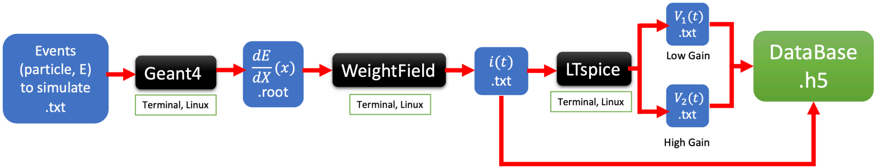
PSD Simulation: Si-Detector

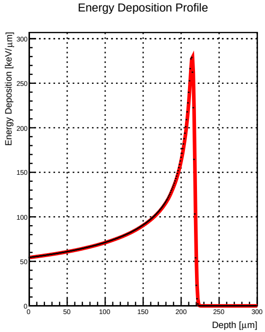


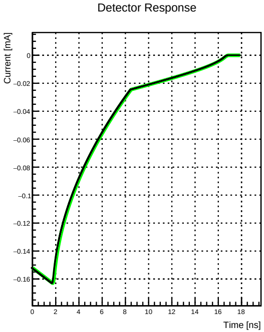
$V_{bias} = 110V; V_{depletion} = 60V$

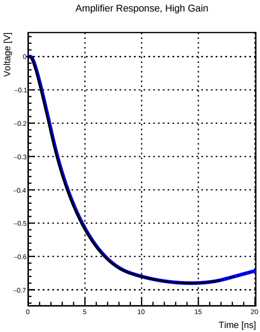
A stack of 3 300 μm Si-detectors is simulated

PSD Simulation



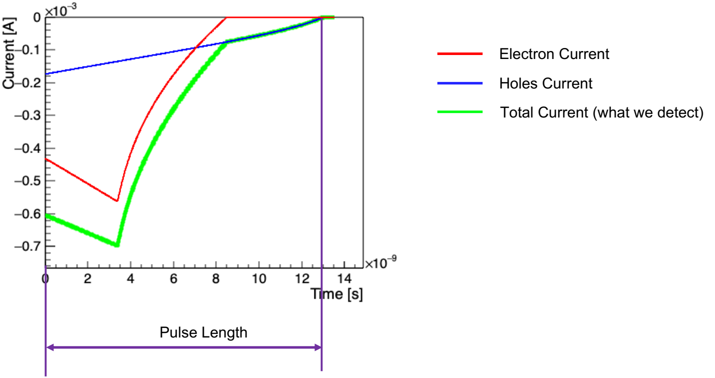






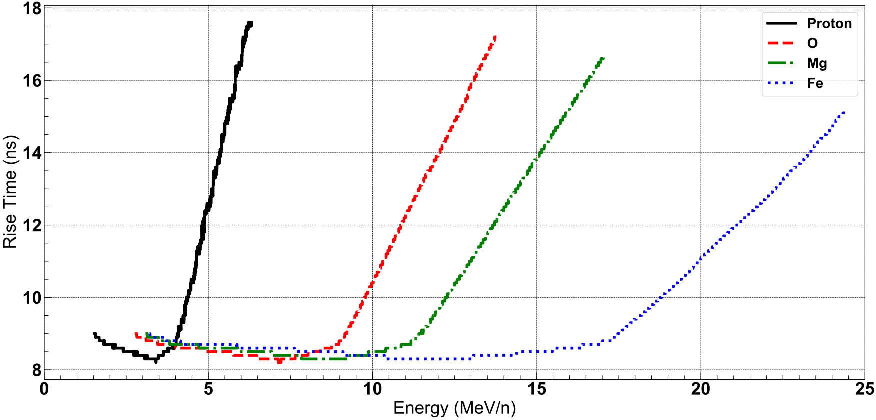
PSD Simulation: Rise Time

Pulse Rise Time ("Total Charge Collection Time" or "Pulse Length") is an indicator of the depth at which the particle stops completely



Electrons are ∼3 time faster than holes

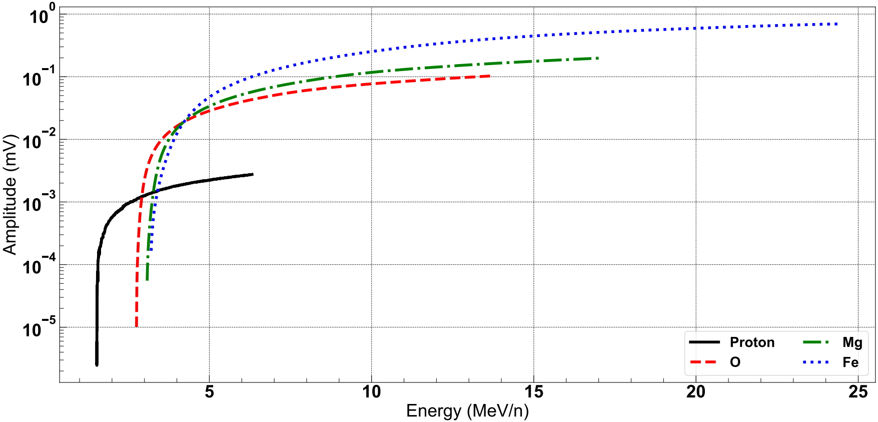
PSD Simulation: Rise Time



"Rise Time vs Energy" behaviour is different for different ions
(only particles that completely stop in the detector are shown)

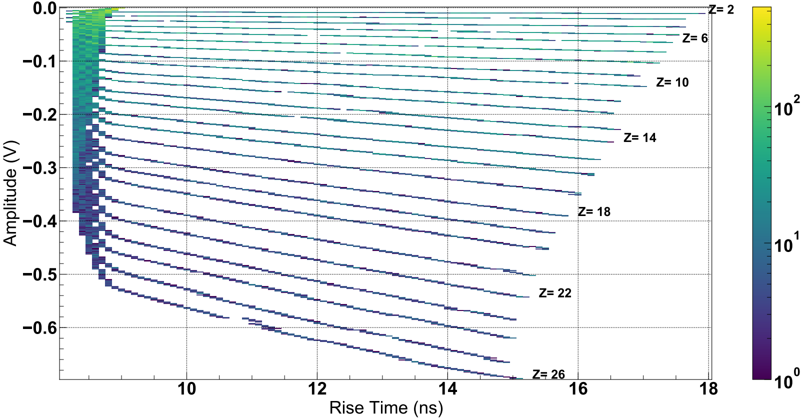
PSD Simulation: Amplitude

Signal Amplitude (or integral) is an indicator of the total energy deposited by a particle.



PSD Simulation: Amplitude vs Rise Time

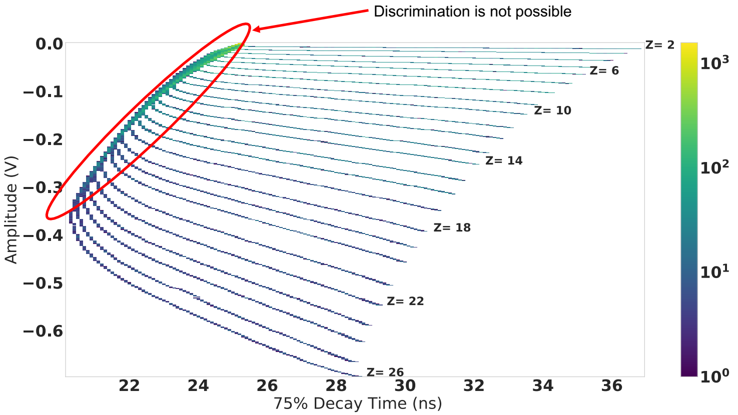
The combination of "Rise Time & Amplitude" is unique for a specific particle with specific energy



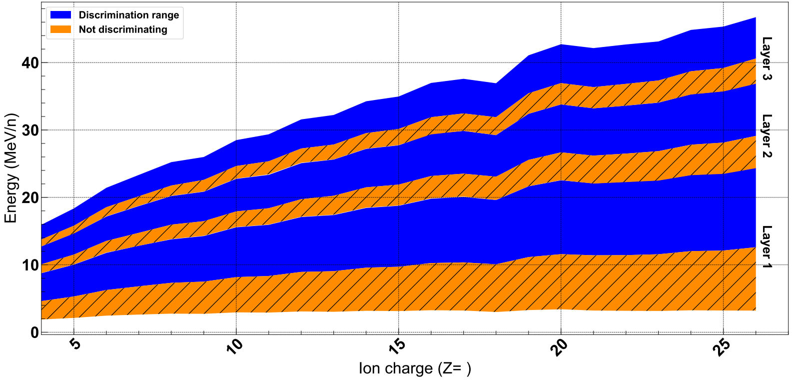
Only the particles that completely stop in the detector are shown

PSD Simulation: Amplitude vs 75% Decay time

Due to the specifics of the read-out electronics the time when the amplitude of the pulse decreases to 75% maximum value ("75% Decay time") is more effective than rise time itself.



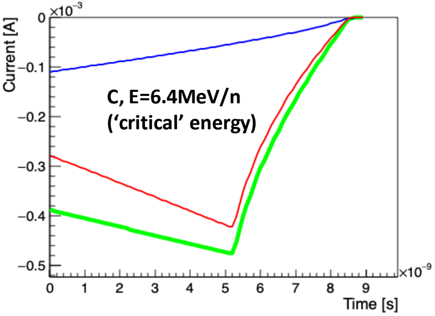
PSD Simulation: Energy Acceptance

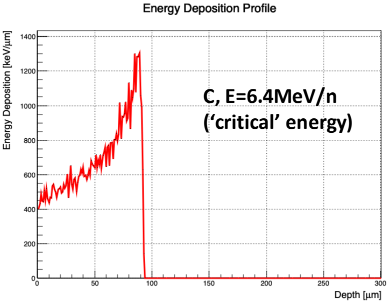


In the energy ranges where discrimination is possible its efficiency is close to 100%.

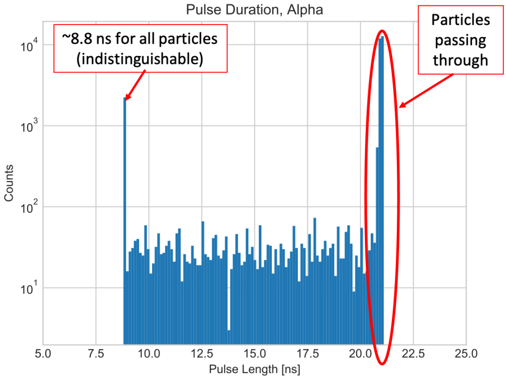
PSD Simulation: Energy Acceptance

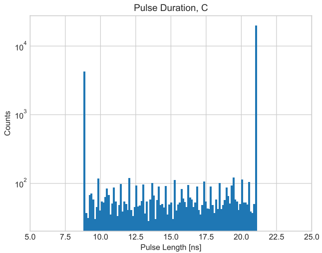
When a particle stops near a negative electrode/entrance side (low energy) the holes component of the current signal is shorter than the electrons component, thus the length of the pulses is defined only by the electron component and thus will be the same for all particles.

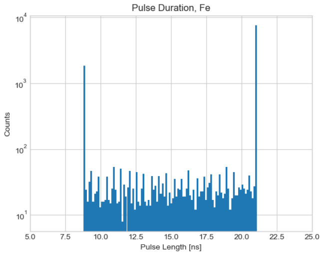




PSD Simulation: Energy Acceptance

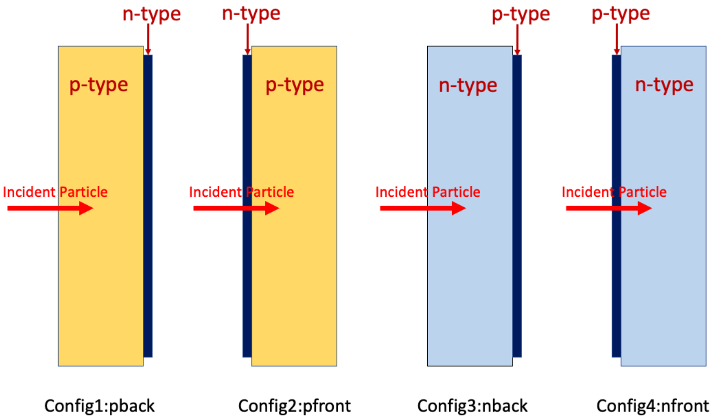






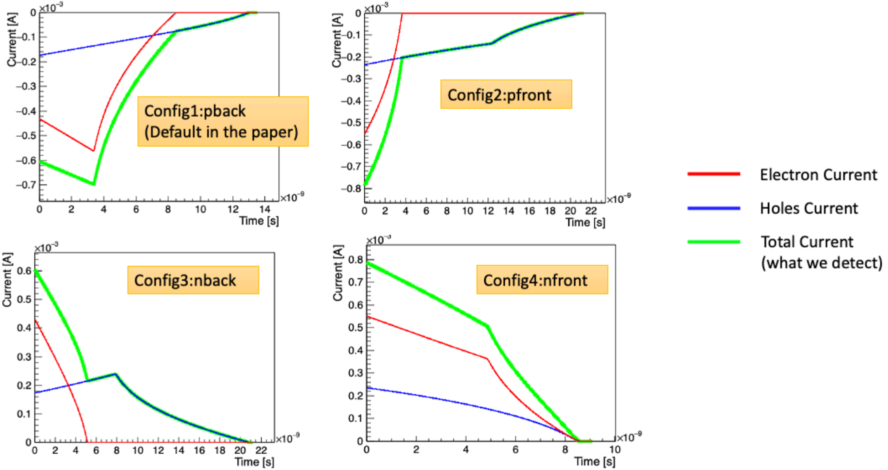
PSD Simulation: Energy Acceptance

Potential ways of improvement

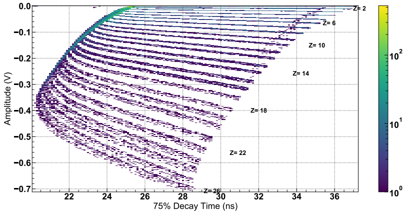


PSD Simulation: Energy Acceptance

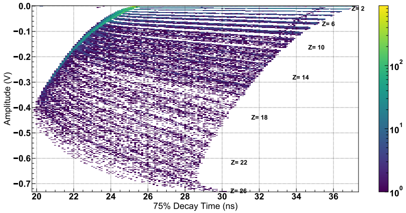
Potential ways of improvement



PSD Simulation: Incident Angle Variation



Field of view of 40°



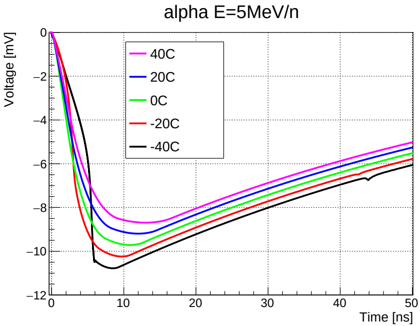
Field of view of 70°

A field of view of 40° (20° of half angle) is manageable for all ions. A wider angle makes discrimination more challenging for heavy ions.

PSD Simulation: Temperature Effects

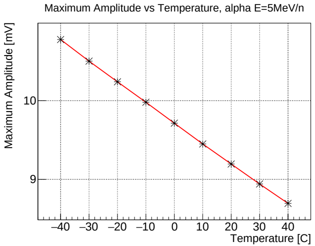
Main Factors:

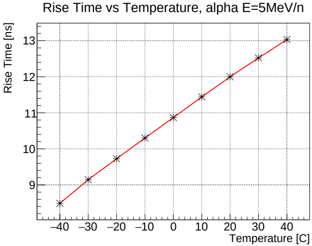
- mobility of charge carriers (electrons and holes) in the detector medium (silicon);
- energy per $e^{-}/hole$ pair in silicon;
- read-out electronics (amplifier) performance.

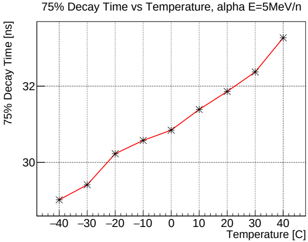


PSD Simulation: Temperature Effects

The key signal characteristics are proportional to temperature and thus can be "corrected" on-board if the ambient temperature is known.





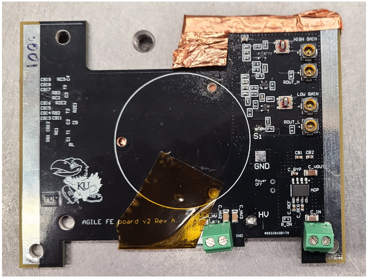


Hardware: Si-Detector & Amplifier Board

Si-Detector:

- NASA Heritage;
- MSD020 (Micron Semiconductor);
- Thickness: 300 μm;
- Diameter: 20 mm.

Amplifier Board:



- Wide range of input current (10^{-6}A to 10^{-2}A);
- Low and High Gains;
- Low noise (<1mV).

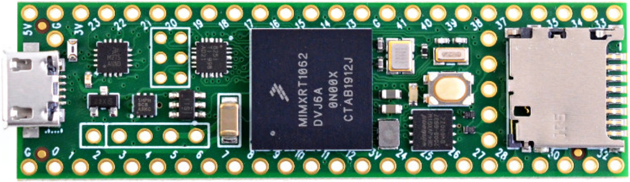
Hardware: PSEC4

Fast and robust sampling is required!
Typical pulse length ("Rise Time") is $\sim$ 10 ns.

arXiv:1309.4397

- Number of channels: 6;
- Sampling Rate: (4-15) GSa/s;
- SCA Depth: 256 samples;
- Power Consumption: < 100 mW;
- ADC DC Dynamic range: 10.5 bits;
- Bandwith: 1.5 GHz.

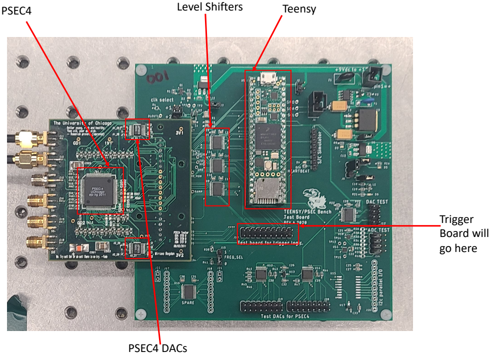
Controller: Teensy 4.1

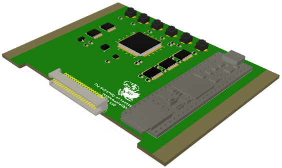


https://www.pjrc.com/store/teensy41.html

- ARM Cortex-M7 at 600 MHz;
- 1024K RAM (512K tightly coupled), 4K EEPROM (emulated);
- QSPI memory expansion, locations for 2 extra RAM or Flash chips;
- 55 digital input/output pins, 35 PWM output pins;
- 18 analog input pins;
- 8 serial, 3 SPI, 3 I2C ports;
- **Can be programmed in C**;
- **Low power (∼ 100 mA @ 5V)**

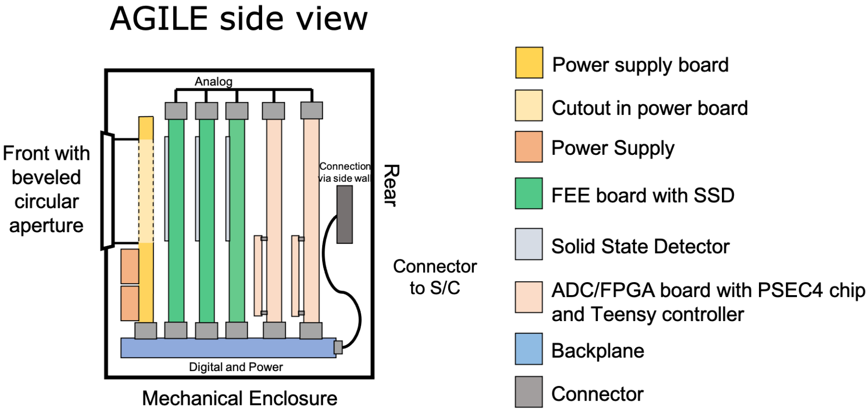
PSEC4-Teensy



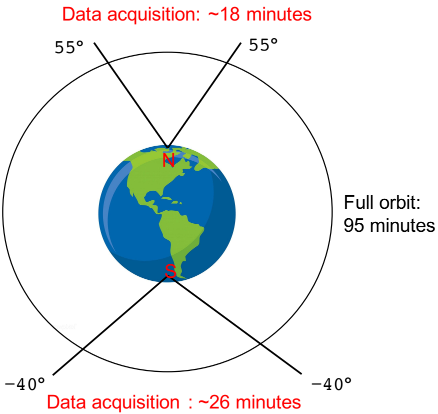


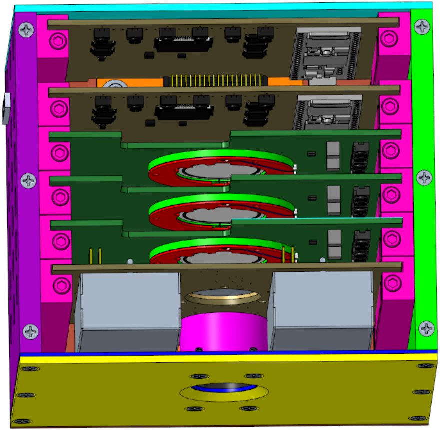
1st prototype

- Planned for launch on board a CubeSat in 2022;
- 3 layers of 300 μm Si-detectors.



1st prototype





Future Directions

- Beam Test at BNL asap;
- First prototype launch on-board CubeSat in 2022;
- More layers $\rightarrow$ wider energy range (High Energy Cosmic Rays);
- Better usage of the information from the layers a particle is passing through;
- Network of multiple AGILE instruments;

Thank you!