UFSDs with applications in cosmic ray physics and medical science

Christophe Royon
University of Kansas, Lawrence, USA
Workshop on medical and HEP, Sonora, Mexico

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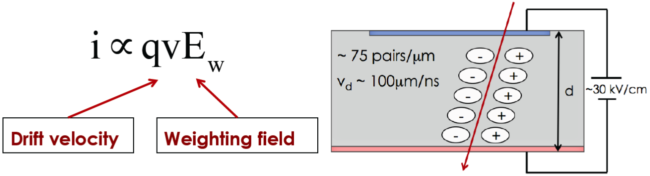
- Fast Silicon Detectors
- AGILE: Cosmic-ray applications in collaboration with NASA (arXiv:2103.00613 , NIM A, Vol. 1012 (2021) 165599)
- Medical applications (arXiv:2101.07134 , Phys. Med. 131 Biol. 66 135002)

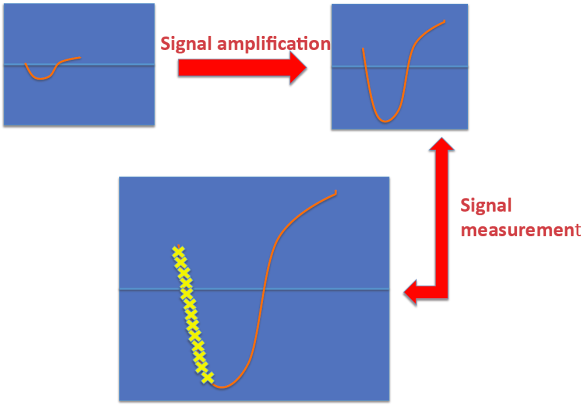
Which detectors? Silicon Low Gain Avalanche Detectors

Signal shape is determined by Ramo's Theorem:



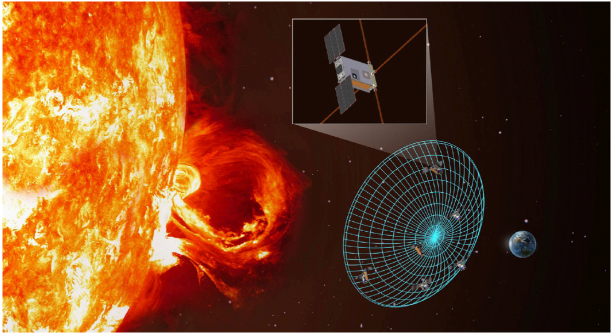
- Idea: Measuring radiation using fast silicon detectors
- Large velocity needed, which means fast detector
- Large fields and large pad to have uniform field
- Lots of charge
- We use fast silicon detectors, essential for medical and cosmic ray applications

Signal amplification and measurement



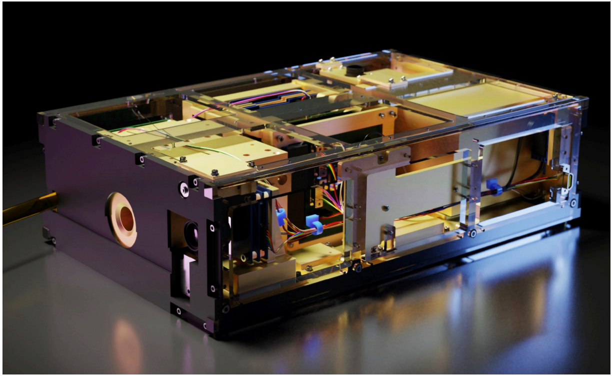
- Signal originating from a Si detector: signal duration of a few nanoseconds (fast detector)
- 1st step: Amplify the signal using an amplifier designed at KU using standard components (price: a few 10's of Euros per channel)
- 2nd step: Very fast digitization of the signal: measure many points on the fast increasing signal as an example
- Allows to measure simultanously time-of-flight, pulse amplitude and shape

Goals of AGILE (Advanced Energetic Ion Electron Telescope)



- Build a compact low power and low cost instrument for characterization of solar energetic (SEP) and anomalous cosmic ray (ACR) particles
- Focus on Ions (H-Fe), $E = (1 - 100)$ MeV/nucl, Electrons, $E = (1 - 10)$MeV, upgradable to higher energy ranges
- AGILE will perform robust real-time particle identification and energy measurement in space
- Solution: use multiple layers of fast Si detector (with or without absorbers) and analyze the amplitude and duration of the signal in the stopping layer

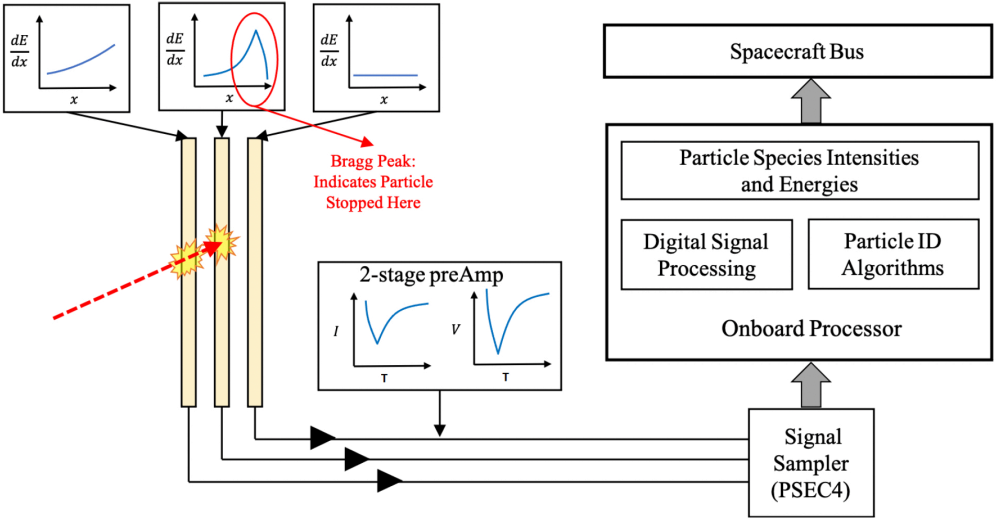
Method developed for AGILE



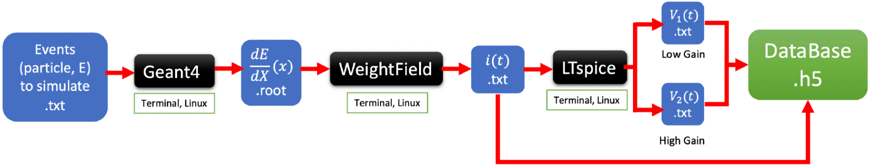
- 3 layers of fast Si detectors as a prototype

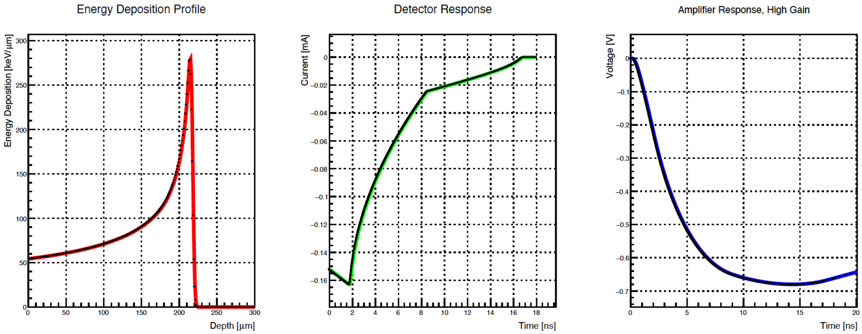
- Measurement of the signal in each layer using the fast sampling technique (1st time fast sampling will be performed in space)
- Identification of ion type (p, He, Au, Pb, etc) and measurement of their energies by measuring the amplitude and duration of signal
- Full simulation starting from the particle simulation to the interaction with the detector and the extraction of the signal
- Principle can be extended to more Si layers including absorbers to increase the energy range of measurement

AGILE schematic principle

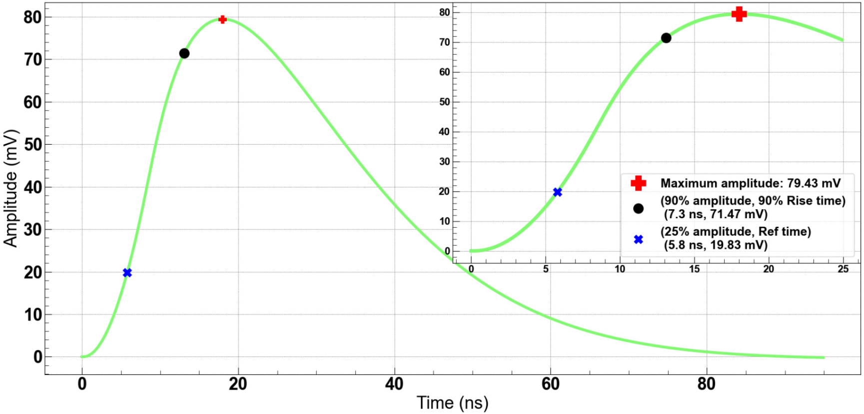


AGILE simulation



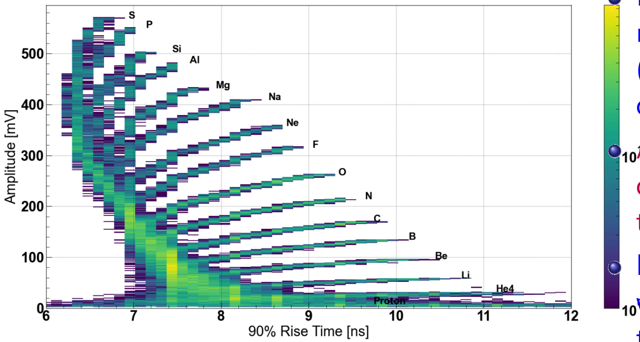


AGILE signal



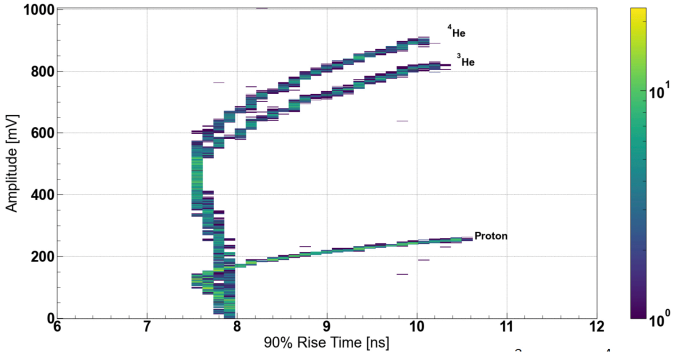
- Simulated signals of a 14 MeV/n oxygen ion that stopped in 2nd layer of AGILE
- Key characteristics: Maximum Amplitude and time to reach 90% of maximum

Particle identification with AGILE



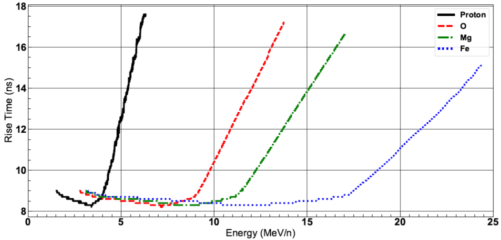
- Maximum amplitude vs time needed to reach 90% of maximum of amplitude (rise time) for p-Fe ions stopping in the detector
- Allows to obtain Particle Id since curves do not overlap for many values of rise time
- Inefficiencies for small rise time values where curves overlap (when signals are too short)

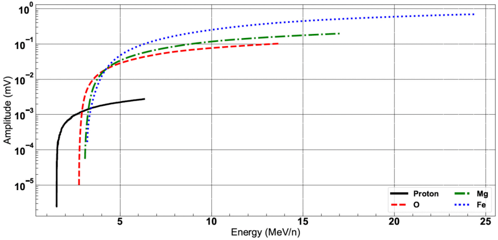
Particle identification with AGILE



- Maximum amplitude vs Rise time for Protons, ^{3}He, and ^{4}He ions
- We can distinguish ^{3}He, and ^{4}He!

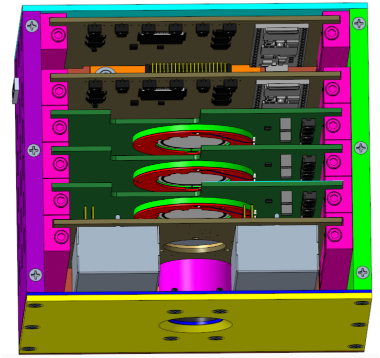
AGILE: Measuring energy of particles





- Rise time vs energy (or amplitude vs energy) allows to measure particle energy once the particle Id is known with high precision
- The energy reach depends obviously on the number of Si layers
- Launch by NASA foreseen for this year: first time we will do particle Id and energy measurement using the fast sampling technique in space!

AGILE mockup: the first prototype

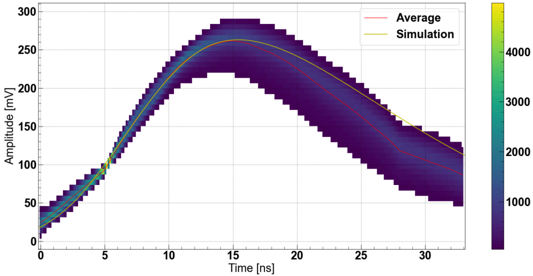


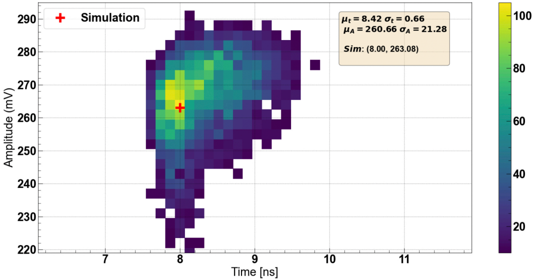
- 3 layers of 300 μm Si detectors
- Dimensioned to fit a CubeSat (10 cm$\times$10 cm)
- Flying in Fall 2024 for a 1 year mission
- Focus on ions at lower energy range (40 MeV/n)
- A further upgrade will be to add more layers (increase the energy range) and launch a network of satellites (large coverage of space)

First AGILE prototype

- AGILE prototype tested in lab at KU with a radioactive source (Americium 241)
- Beam test using different kinds of particles (p, H to Fe) at Brookhaven National lab

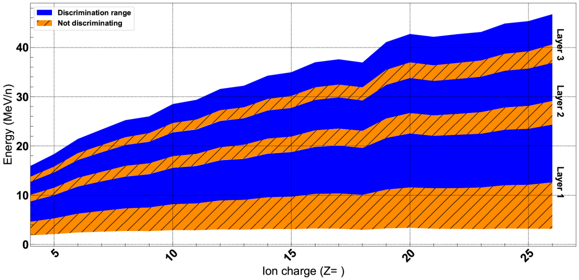
Signal from an Americium source





- Left: Amplitude vs time distribution as measured by AGILE for alpha particles (Americium 241 radioactive source) compared to simulation
- Right: Maximum Amplitude vs 90% Rise time for alpha particles measured by AGILE compared to simulated value: Good agreement
- Already good agreement between measurement and simulation
- Further tuning of simulation using beam tests at BNL

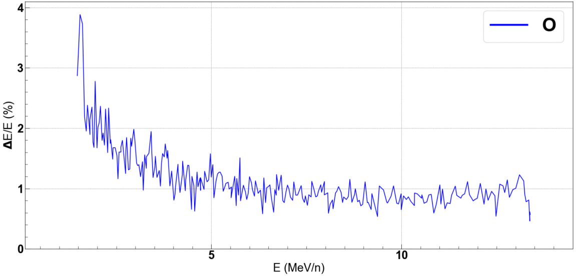
Agile performance for Particle Id and energy measurement



- Energy vs Ion Charge (Z)
- Blue regions correspond to the domains where AGILE can identify the particles and measure their energy

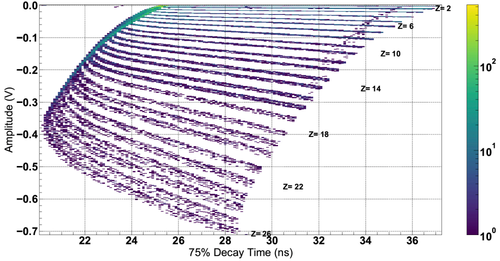
- Hatched orange regions correspond to the domain where the discrimination is not possible $\rightarrow$ inefficiency of the method (because of not enough separation in the maximum amplitude and/or rise time)
- This is fine for physics since we have very precise measurements and physics is continuous (if we want to cover these regions, we should use different widths of Si detectors)

Agile energy resolution: the example of oxygen



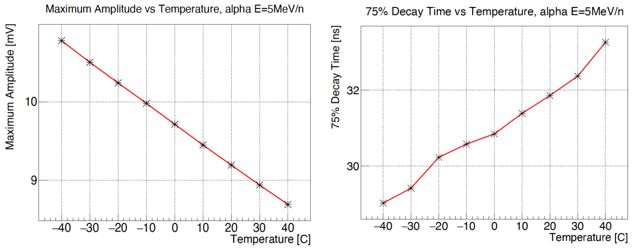
- Energy resolution due to statistical fluctuations of the energy deposition and of the number of charge carriers and electronics noise
- AGILE requirement is to achieve a precision of $\Delta E/E < 30\%$: we are well below these goals!

Angle acceptance effects



- We vary the angular acceptance of AGILE
- A field of view of 40 degrees (20 degrees of half angle) is fine for all ion determinations: wider spread of the curves max. amplitude vs rise time
- A wider angle makes discrimination more challenging

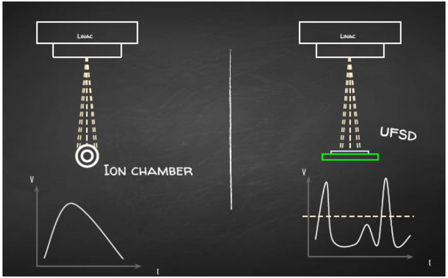
Agile temperature effects



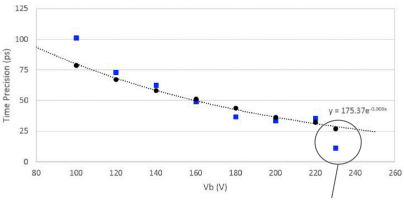
- The signal characteristics (max amplitude and rise time) depend on temperature as a linear function
- Can be easily corrected on-board since temperature will be measured with an accuracy of about 0.1 degree

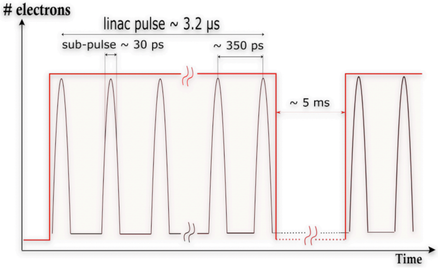
Measuring radiation in cancer treatment

- Ultra fast silicon detectors and readout system were put in an electron beam used in the past for photon therapy at St Luke Hospital, Dublin, Ireland
- Precise and instantaneous measurements of dose during cancer treatment (especially for flash proton beam treatment)
- Develop a fast and efficient detector to count the particles up to a high rate: very precise instantaneous dose measurement, no need of calibration, high granularity (mm^2)



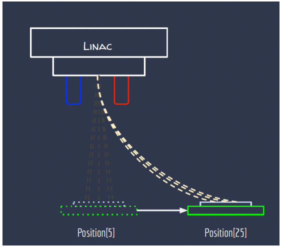
Measuring beam properties in an hospital environment

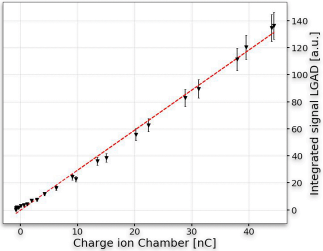




- Possible time resolution down to 10 ps (using Constant Fraction Discriminator method)
- ELEKTATM Precise Linac with pulse length about 3.2 μs long
- Each pulse sequence contains thousands of 30 ps sub-pulses separated by 350 ps (frequency of 2.858 GHz) -
- Electron beam: energy 4-18 MeV, dose rates up to 600MU/min, pulse repetition frequency of 200 Hz

Medical application: method to measure the beam properties

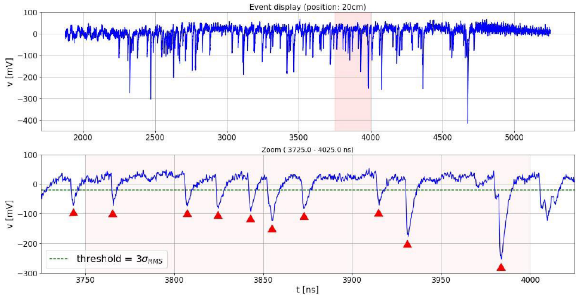


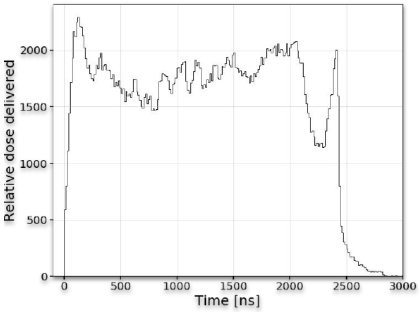


- The detector was mounted on a moving support to provide the monitoring of the beam as a function of its location
- Neodymium N40 permanent magnet 12 cm below the collimator to separate the charged and neutral particles
- The average signal in the LGAD correlates well with the ion-chamber signal!

What Si detector can do better: Single particle Id in Dublin hospital

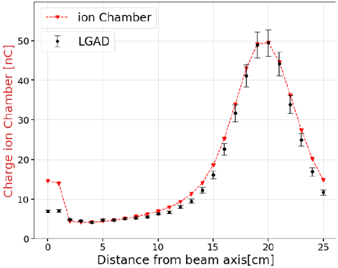
- Use UFSD and their fast signal in order to identify and measure spikes in signal due to particles passing by
- Allows measuring doses almost instantaneously

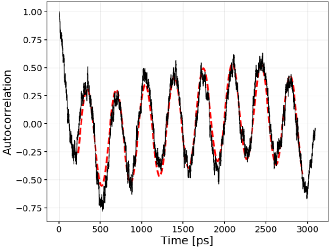




- Very precise dose measurement allowing to adapt better treatment to patients especially for flash dose treatments (brain cancer for instance)

Tests performed at St Luke hospital, University of Dublin, Ireland





- Measurement of charge deposited in Si detector compared to standard measurement using an ion chamber: good correlation
- Our detectors see in addition the beam structure (periodicity of the beam of ∼330 ps, contrary to a few seconds for the ion chamber): measure single particles from the beam
- Fundamental to measure instantaneous doses for high intensity proton therapy as example
- For more details: Arxiv 2101.07134, Phys. Med. Biol. 66 (2021) 135002

The future: use this method in flash beam therapy

- Goal 1: Design and build a fast Si dosimetry prototype
  - Develop and test a 8/16 channel readout board using the fast sampling method
  - Characterize the fast Si detectors and choose the best one for medical applications (different widths, sizes) using laser, radioactive sources
- Goal 2: Can Fast Si detector be used for dosimetry in flash beam therapy?
  - Build and test the prototype in a proton flash beam facility at the University of Kansas and count the number of electrons/protons that are produced by the accelerator
  - Measure the instantaneous dose rate dependance, linearity and dynamic range
  - Monitor a single flash pulse in order to study its structure benefitting from the good timing resolution of the Si detector
- Longer term goals: Move from a 8/16 channel readout board to a 100 or 1000 channel board that could have some commercial applications

Conclusion

- Fast timing detectors originally developed for high energy physics at KU: development of a readout electronic card using standard components for different applications
- Reconstruct full spectrum of signal coming from a fast Si detector using the fast sampling technique
- 1st application: Measure cosmic ray particles (both identify type of particles and measure their energies) in a cube sat in collaboration with NASA using the Bragg peak technique, promising results using Americium source
- 2nd application: Measure doses in flash therapy received by a patient during cancer treatment instantaneously with high accuracy by counting the number of particles
- First results in Dublin hospital show already that we see the beam structure benefitting from the fast signal properties (duration of a few ns)