AGILE Experiment

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Abstract

AGILE (Advanced enerGetic Ion eLectron tElescope) is a NASA-funded instrument currently being developed aimed to characterize solar, magnetospheric, and cosmic ray particles. The main of goal of this project is to build a compact, low-mass, low-power, and low-cost device capable of registration and discrimination of a large variety of particles (ions from H to Fe and electrons) in a wide energy range: 1-100 MeV/nucleon for ions and 1-10 MeV for electrons. In order to accomplish this, the AGILE collaboration proposed a technique (pulse shape discrimination or PSD) for the identification of particles' species and energies using very fast silicon detectors and electronics with consequent analysis of the signals in real-time. AGILE will be the first space-based instrument to use the techniques of fast on-board PSD.

1 Introduction: Science Motivation

Robust detection and identification of charged particle species and energy is a very important problem for a variety of space experiments. AGILE (Advanced enerGetic Ion eLectron tElescope) is an instrument which is being developed to register and discriminate ions (H-Fe) in the 1-100 MeV/nucleon energy range and electrons in the 1-10 MeV/nucleon range that can be used for better understanding of the charged particle energization, loss, and transport throughout the heliosphere and the radiation belts, in particular in the following studies.

1.1 Anomalous Cosmic Rays and Solar Energetic Particles

AGILE instrument is sensitive to the charged particle types and energies corresponding to the Anomalous Cosmic Rays (ACRs) and the Solar Energetic Particles (SEP), thus it should help gain better understanding of these phenomena. The origin of ACRs is the interstellar neutral gas which is ionized and then accelerated at the solar wind termination shock. There have been predictions and later evidence [1] that ACRs can penetrate the Earth's magnetosphere and get trapped in the radiation belts. Accurate measurements of the ACRs composition and fluxes in the outer belts by the AGILE instrument can results in deeper comprehension of the ACRs dynamics within the solar system, general properties of the heliosphere, and the nature of interstellar material.

With regard to SEPs, AGILE should be able to precisely measure their dynamics in particular to elucidate two types of events: impulsive (^{3}He-rich) and gradual (proton-rich). As can be seen in Fig. 1, the fluxes of various ions are different for these two types of events, and robust measurements of the particle species and energies will help to broaden the knowledge of those mechanisms on the Sun.

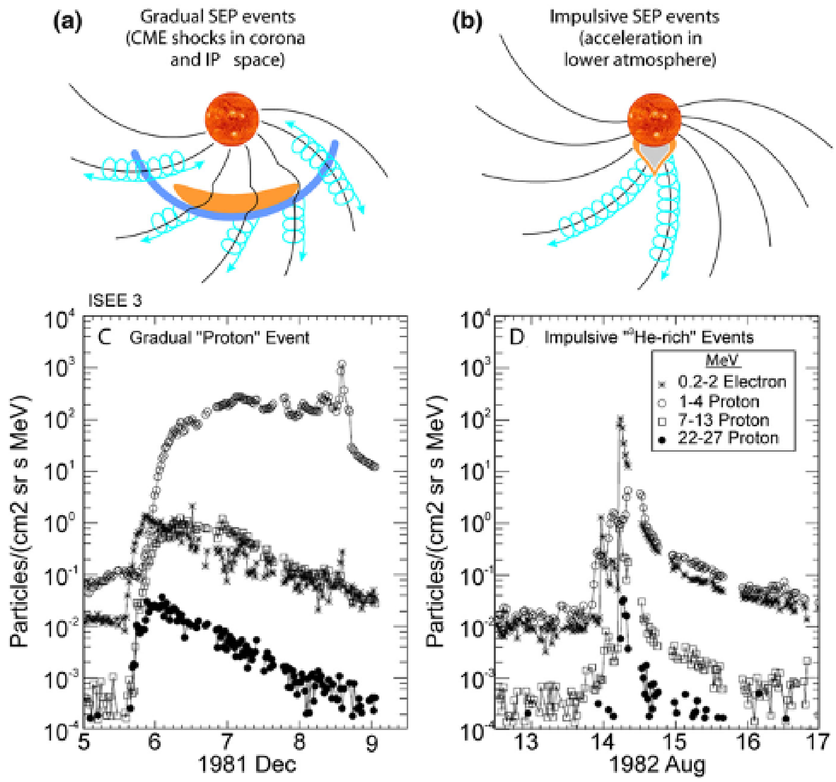

Figure 1: Gradual and impulsive SEP events, adapted from [2] and [3]. a - gradual events produced by the acceleration driven by coronal mass injection (CME) shock wave, b - impulsive events produced by a solar flare. c and d - flux profiles of different particles (protons and electrons) for the two types of SEP events discussed.

1.2 Relativistic Electrons in the Radiation Belts

The question about the presence or absence of the relativistic electrons (E >1 MeV) in the inner radiation belt still remains open since it is extremely difficult to measure these particles due to the high "contamination" of this region of space by protons [4]. Therefore using a robust technique for discrimination of particles and their energies will not only help answer this question but also will result in a deeper understanding of the electrons dynamics due to geomagnetic activity in the inner radiation belt.

Precise measurements of the relativistic electrons' energies and fluxes in the outer radiation belt will help to examine the nature of various competing acceleration, transport, and loss processes.

1.3 Space Weather and Space Travel

Another important goal of the AGILE instrument is the studies of space weather and its effects on human activities in space. For example, during geomagnetic disturbances SEP particles can reach the International Space Station orbits, which can cause significant harm to both people and on-board equipment. Since particles with different charge and mass (various ions) have different effect on both humans and hardware, e.g. the equivalent dose received by a human depends not only on the absorbed dose (energy absorbed per unit of mass), but also on the type of particle depositing this energy, it is very important to not only know the total flux of all of particles, but to differentiate it by particle types and energies. Understanding these fluxes is crucial for preparing future space travels, in particular in terms of shielding design and optimizing exposure time.

2 Instrument Description

The AGILE instrument combines the heritage of the preceeding particle telescopes, in particular MERIT (Miniaturized Electron pRoton Telescope) onboard CeREs (Compact Radiation belt Explorer) [5], and the expertise in development of the ultra fast silicon detectors and electronics for ground-based experiments [6].

The main sensitive part of the AGILE instrument is a stack of silicon (Si) detectors MSD040 [7] manufactured by Micron Semiconductor Ltd with the active area diameter of 40 mm and the thickness of 300 μm. The same detectors but with a different thickness were used in the MERIT instrument [5]. In the initial studies the number of layers is chosen to be 16. This number is sufficient to completely stop the heavy ions (e.g. Fe) with energies up to 100 MeV/nucleon and the light ones (e.g. p or α) with energies up to 30 MeV/nucleon. In order to extend the energy range for lighter ions, the number of layers can be increased and/or additional absorbing layers (e.g. Al) can be added. Some key characteristics of MSD040 detectors used in these studies are shown in Table 1: The main opera-

Active area diameter	$40mm$
Thickness	$300\mu m$
Typical Full Depletion (FD)	$< 60V$
Total Leakage Current (at FD +10V)	$< 10nA$
Capacitance (FD)	40 pF/cm^2
Resistivity	(3 – 10) $k\Omega\times cm$
Bias Voltage	$110V$

Table 1: MSD040 detectors: main characteristics

tional characteristics like thickness and bias voltage were chosen in order to get a large effective area and to cover a wide energy range while providing stable and efficient performance of the read-out electronics (both analog and digital) with regard to the detector capacitance and the signal's amplitude and length. Since the AGILE instrument covers a very wide variety of charged particles and energies, the range of signals produced by incoming particles in the Si detector is about 10^{-7} A - 10^{-2} A ($\sim$ 5 orders of magnitude) according to the simulations (see section 3). It is very challenging to use a single read-out circuit while maintaining a reasonable signal-to-noise ratio for such a wide range of input signal amplitudes; in order to address this, an amplifier with two (low and high) gains was designed, the key principles and components were adapted from the multipurpose read-out board described in work [6]. The duration of the "useful" signal in the chosen configuration is $\sim$ 20 ns.

To get the best results from the digital PSD method, the signals from the detector should be digitized with high time resolution. For this purpose a SAMPIC (SAMpler for PICosecond time pick-off) chip will be used. Originally developed for very fast timing detectors in particle physics [8] and having showed reliable performance [6], SAMPIC is a very good candidate for the AGILE signal read-out due to the following characteristics:

- The entire signal from the detector ($\sim$ 20 ns long) can be digitized and processed;
- High sampling rate: up to 15 GSa/s;
- Very high time resolution: $\sim$ 10 ps;
- Relatively low power consumption: $\sim$ 10 mW/channel;

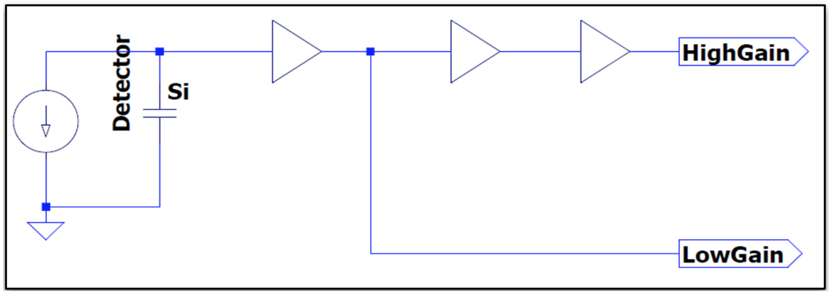

Figure 2: Two Gain Amplifier (principle schematic): the amplifier used in this work has 3 stages of amplification and two outputs. The signals with high amplitude are read-out after the first stage of amplification (low gain) and the low amplitude signals are read out at the end of the amplification circuit (high gain).

3 Pulse Shape Discrimination

The key feature of the AGILE instrument is its ability to identify charged particle species and its energy on-board a satellite (e.g. CubeSat) in real-time because the raw signals cannot be sent to the ground stations due to very limited bandwidth. In order to accomplish this, a Pulse Shape Discrimination (PSD) method [9] is proposed for implementation. The main idea of PSD is to use the fact that different particles deposit different energies along their tracks through the detector medium, leading to varying detector responses (output signals). Careful analysis of these signals and their main characteristics (both amplitude and timing) leads to a set of so-called "markers" - unique characteristics of the signals corresponding to specific particle/energy pairs. One such set of "markers" which can be used for particle species and energy discrimination is pulse rise time and pulse amplitude (proportional to the deposited energy) [10]. However to fully exploit this method, very fast detectors, front-end electronics, and read-out systems are required, which is the main reason for choosing the hardware described in section 2. It should be mentioned that AGILE will apply the on-board techniques of real-time PSD for the first time for space based instrumentation.

In order to obtain the markers mentioned above, detailed simulations of the AGILE instrument were performed. The main steps of the simulations are the following:

1. Simulation of the energy deposition profiles in every layer of the Si detector using GEANT4 toolkit;

2. Simulation of the detector response: the energy deposition profile obtained by GEANT4 is passed to Weightfield2 software [11], a simulator for silicon and diamond detectors which has been adapted for AGILE hardware and produces the current signals ($i(t)$);

3. Simulation of the amplifier output signal: the current signal is passed to the two gain amplifier model in LTspice circuit simulator [12] that produces two voltage signals (low and high gain) which then will be digitized by SAMPIC.

Fig. 3 shows an example of the simulated signals for an α-particle with the energy of 5 MeV/nucleon.

Preliminary analysis of the simulated data shows that a pair of markers which can be used to identify particle species and energy is the maximum amplitude and the rise time of the signal (similar to the approach described in [10]), for an event from 3 these values are $\sim$ 0.68V and $\sim$ 15 ns respectively. However to fully use these markers a particle should completely stop in the detector layer being considered, in this case the energy deposition has a distinct profile (Bragg-curve), causing the corresponding output pulse to have a distinct shape as well.

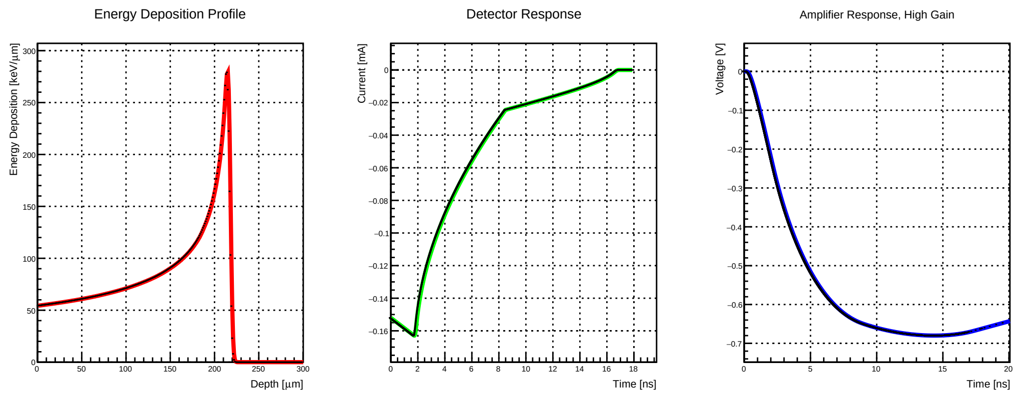

Figure 3: Output signal simulation example, from left to right: energy deposition profile simulated in GEANT4 ($\frac{dE}{dx}(x)$); detector response (current pulse ($i(t)$); amplifier (high gain) output (voltage pulse $V(t)$). The output voltage signal also has a long exponential decay part determined by RC-constant of the amplifier (not shown), which can be ignored and not digitized and stored by SAMPIC. Thus the length of the "useful" pulse is $\sim$ 20 ns.

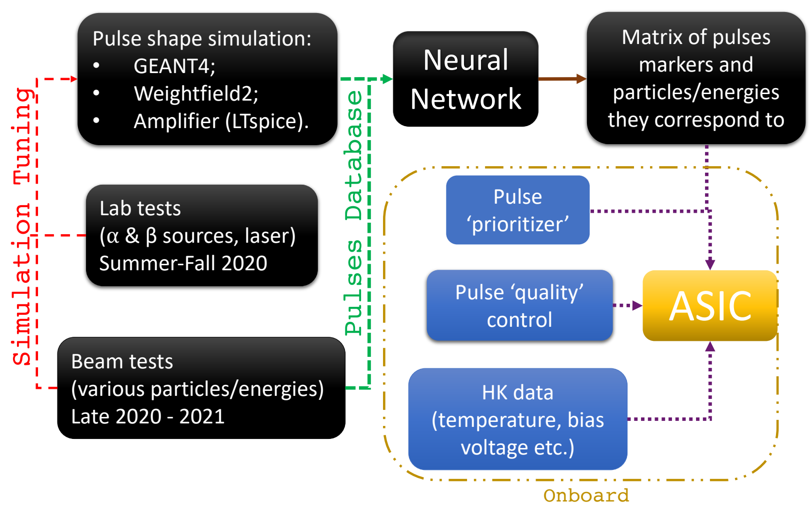

Figure 4: AGILE Pulse Shape Discrimination Method Implementation

Fig. 4 shows a simplified algorithm of PSD method implementation for the AGILE project. As mentioned above the key idea of the method is to use a set (matrix) of unique markers of the signals corresponding to specific particle species and energies. These markers are obtained via detailed simulation of the instrument response for a large variety of charged particles in a wide energy range and will be compared (tuned) with the experimental data: currently the first laboratory test are being performed, then in the late 2020 - 2021 it is planned to conduct a beam test with a variety of different ions in a wide energy range, followed by a test with an electron beam. To get better accuracy for the values of these markers, a neural network will be trained with both simulated and experimental data. In order to implement the algorithm for real-time on-board processing in a simple integrated circuit (e.g. FPGA or ASIC), the markers' matrix should be simple enough and should not use a lot of memory. Once the characteristics of a real signal (amplitude and rise time) from an incident particle are calculated they are compared with the values from the matrix, and if there is a match within a predefined confidence level the values of a particle type and energy corresponding to these markers are stored. Since the operational characteristics (e.g. ambient temperature, bias voltage etc.) of the instrument may vary during the operation time, the shape of the output signals and thus the values of the markers may change as well, however it is possible to control these characteristics (housekeeping or HK data) and adjust the markers' values accordingly. Since AGILE covers a large variety of charged particles in a wide energy range and the expected fluxes vary a lot from one particle to another (for instance the predicted probability to detect a proton is much higher than the probability to detect a heavy ion (e.g. Fe)), it is important to implement a "pulse prioritizer" which in the case of simultaneous detection of more than one particle will "sacrifice" the information about the particles with low priority and will process and store the information only about the high priority ones. The detailed simulations with their subsequent tuning should also result in a set of markers for "bad pulses" - the signals which cannot be used to identify particle type and energy with a predefined confidence level.

4 Conclusions

The AGILE instrument is currently being developed, the key goal of it is to study and differentiate a large variety of solar, magnetospheric, and cosmic ray particles in a wide energy range by means of implementing the method for on-board digital real-time pulse shape discrimination for the first time in a space-based instrument. This becomes possible due to the utilization of a very fast detection system along with very fast front-end electronics (both analog and digital). The results of the first simulations show that a charged particle type and energy can be identified using the unique characteristics ("markers") of the signals produced by this particle depositing its energy in the detector medium. Detailed analysis of the simulated data is currently in progress along with the first laboratory tests and preparations for a beam test. A similar technique can also be used to detect high energy primary cosmic rays, however in this case a larger stack of detectors and/or additional layers of high density absorbers will be needed to stop these particles.

The same ideas of using fast silicon detectors and electronics with similar pulse processing can be used for medical applications, e.g. the instantaneous dose a patient receives during radiotherapy for cancer treatment can be calculated and a beam profile can be monitored by counting every single particle passing through the detector with very high time resolution, the initial simulations and tests of such applications are currently undergoing.

Acknowledgements

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