Monte Carlo simulation of a satellite-based detector of cosmic ray ions with elemental separation from hydrogen to nickel

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Abstract. Observing cosmic rays and solar energetic particles provides important information about the solar wind and solar storms. We are working toward building a Thai detector of energetic ions from space that is inspired by the Mass Spectrometer Telescope (MAST), a satellite-based detector installed on SAMPEX of cosmic ray ions with the energy range of 0.01 to 0.5 GeV/nucleon with the objective to determine the nuclear charge and kinetic energy for nuclei with atomic number of $Z = 1$ (hydrogen) to 28 (nickel). The energy range of the detector covers the energy range of anomalous cosmic rays, Galactic cosmic rays and solar energetic particles. Therefore, observations by such a detector can provide insight into the origin and transport of these ions in cosmic rays and solar energetic particles. During solar events, measurements of the elemental composition of solar energetic particles can be compared with the composition of the solar corona. We have created a computational model of the MAST detector to simulate ion detection using the FLUKA program to measure the energy deposition of heavy ions in multiple detector components to determine their initial kinetic energy in the simulation. From the simulation results, we can identify the ions’ energies and species using established methods and calculate the geometry factor of the detector, comparing the results with previous reports.

1. Introduction

Observing cosmic rays provides important information about the solar wind and solar storms. Many instruments can be used for observing ions from cosmic rays and the solar wind. To study these particles, we are designing a satellite-based detector based on the Mass Spectrometer Telescope (MAST) which was a satellite-based detector of cosmic ray ions. MAST was installed on the Solar, Anomalous, and Magnetospherical Particle Explorer (SAMPEX), NASA’s first Small Explorer (SMEX) that was launched in July 1992 [1]. The mission ended in 2004. The MAST detector has the energy range of 10 to 500 MeV/nucleon used to determine the nuclear charge $Z$ and kinetic energy $E$ for $Z = 1$ (hydrogen) to 28 (nickel). This detector would detect solar energetic particles from the solar wind and solar storms, anomalous cosmic rays and Galactic cosmic rays that come from outside of the solar system. Anomalous cosmic ray and galactic cosmic ray ions can be distinguished by their ionic charge states. We will take advantage of this difference by using Earth’s magnetic field to distinguish their ionic charges and discriminate anomalous cosmic ray and Galactic cosmic ray ions from each other as well. We can design
a specific detector to identify ions’ energies and species using established methods to measure energy deposited in multiple detector components.

2. Methods
To detect the particles and ions in solar energetic particles and Galactic and anomalous cosmic rays, a common design was that used in the Mass Spectrometer Telescope (MAST) detector launched in 1992 (Cook et al. 1993). MAST is composed of an array of silicon solid state detectors of graduated thickness, including four position-sensitive detectors that measure the trajectories of incident nuclei [1].

2.1. MAST instrument
The MAST instrument has many layers of solid-state silicon detectors. In table 1, showing the name, types of measurement, detector type, thickness and diameter of detector in MAST instrument. As shows in table 1, each silicon detector measures energy loss $\Delta E$ of particles that penetrate the detector and trajectory of particles in layer M1 to M4. The MAST instrument measures the kinetic energy $E$ of particles that stop inside the instrument. The Bethe-Bloch formula gives an approximate energy loss $\Delta E$ and stopping power in the detector for an incident particle with atomic number $Z$ and atomic mass $A$ [2]. This shows that atomic number and atomic mass can be determined by the energy loss $\Delta E$ and kinetic energy of the particle.

From the energy deposited in each layer $\Delta E$, total kinetic energy $E$, and pathlength (which depends on the angle of the incident particle and thickness of each layer of detector) precisely measured by the detectors in MAST, we can determine the nuclear charge ($Z$) and isotope resolution by using the $\Delta E$ vs. $E$ technique [3].

2.2. The trajectory measurement
The pathlength of incident particles through the MAST detectors varies due to the angle of incidences and the thickness of each silicon detector layer. Detectors M1, M2, M3 and M4 are one-dimensional position-sensitive detectors. Each detector consists of 93-strip electrode with 0.5 mm pitch. The measurements of M1 and M3 determine the $x$-axis, while the measurements of M2 and M4 determine the $y$-axis. The results of measurements from these detectors determine the position of the energy deposited on the detector and angle of the incident particle.

**Table 1.** Design of MAST instrument.

| Detector Name | Type of Measurement | Detector Type | Thickness (mm) | Diameter (cm) |
|---------------|---------------------|---------------|----------------|---------------|
| M1            | Trajectory, $\Delta E$ | PSD SB       | 0.115          | 4.95          |
| M2            | Trajectory, $\Delta E$ | PSD SB       | 0.115          | 4.95          |
| M3            | Trajectory, $\Delta E$ | PSD SB       | 0.115          | 4.95          |
| M4            | Trajectory, $\Delta E, E'$ | PSD SB   | 0.115          | 4.95          |
| D1            | $\Delta E, E'$       | SB           | 0.175          | 4.95          |
| D2            | $\Delta E, E'$       | SB           | 0.5            | 4.95          |
| D3            | $\Delta E, E'$       | LiD          | 1.8            | 6.14          |
| D4            | $\Delta E, E'$       | LiD          | 3.1            | 6.14          |
| D5            | $\Delta E, E'$       | LiD          | 6.2            | 6.14          |
| D6            | $\Delta E, E'$       | LiD          | 9.3            | 6.14          |
| D7            | Penetration          | LiD          | 3.1            | 6.14          |

PSD: Position Sensitive Detector, SB: Surface Barrier, LiD: Lithium Drifted
Figure 1. MAST detector model constructed in this work, plotted using the program FLUKA FLAIR.

3. Results
From the Monte Carlo simulation in FLUKA program version 2011.2c.6, we simulated the beams of ions shot into the detector modeled after the MAST instrument [4]. The detector model that use in this simulation as we see in figure 1, is modeled after MAST in 1992, showing each layer of solid-state detectors in this instrument. The results can be used to determine atomic number and atomic mass by $\Delta E$ vs. $E$ technique, and determine the angle and position. The results from the simulation can be used to calculate the angle, mass, and position resolution and the energy range of the detector.

Figure 2. The range of nuclear charge and energy per nucleon of each particle which the detector is capable of measuring and resolving the nuclear charge. The curved lines show the boundaries between energies of particles that stop in each detector.
The results from simulation show the kinetic energies of ions with certain nuclear number that penetrate the detectors and stop inside of the instrument. From these results we see the roughly energy range of each ion with different nuclear number as in figure 2 that shows the roughly boundaries of kinetic energy of ion per nuclear charge of each nuclei that detectors in instrument. From figure 2, we can roughly estimate energy range of each ion in each detector.

Figure 3. Showing the position resolution: Histogram of error in the position calculated from detector signals in the simulation compared with the actual position in the simulation. And the angular resolution: Histogram of error in the angular calculated from detector signals in the simulation compared with the actual position in the simulation respectively.

In figure 3, shows the position and angular resolution respectively, calculated from results of the Monte Carlo simulation. The results from calculation give a position resolution less than 0.021 cm. The angle resolution is less than 0.021.

Figure 4. Energy loss $\Delta E$ (MeV) in detector D1 vs. total kinetic energy $E$ (MeV) of incident particle. There are separate tracks for incident particles of atomic number $Z = 1$ to 28.

Energy measurements of detectors in the instrument, which are needed to determine identifications of particle, help approximating the energy in each detector as energy loss and estimate the kinetic energy [5]. Then we can take the energy loss in detectors to determine nuclear number according to $\Delta E$ vs. $E$.
technique. This technique shows nuclear charge and incident kinetic energy of heavy particle to affect energy loss in each detector layer.

The graph in figure 4 shows the energy loss $\Delta E$ in detector D1 in MAST instrument vs. the kinetic energy of the incident particle. As Bethe-Bloch formula shows, $\Delta E$ in detector’s material depends on the atomic number and atomic mass of the particle. From $\Delta E$ vs. $E$ technique, we can separate the lines in the graph that represent particles with different atomic numbers for varying kinetic energy. From this technique, we can see the particle with unique nuclear number separation from each other. The separation shows nuclear charge of the particles that penetrating and stop inside the instrument to have significantly effect to the energy loss in each detector in the instrument and its incident kinetic energy of particle. From these results, we can distinguish nuclear charge and even atomic number of particle from this technique.

![Figure 5.](image)

**Figure 5.** The graph show geometry factor of heavy particle vs. kinetic energy per nucleon of $^3\text{He}$, $^4\text{He}$, $^{12}\text{C}$, $^{14}\text{N}$, $^{16}\text{O}$, $^{28}\text{Si}$, $^{56}\text{Fe}$ and $^{58}\text{Ni}$ respectively.

The geometry factors shown in figure 5 are of $^3\text{He}$, $^4\text{He}$, $^{12}\text{C}$, $^{14}\text{N}$, $^{16}\text{O}$, $^{28}\text{Si}$, $^{56}\text{Fe}$ and $^{58}\text{Ni}$ as a function of the kinetic energy of particles (GeV/nucleon) stopping in the instrument based on the results from Monte Carlo simulation. The geometry factor is for the nuclei which stop in the instrument’s volume. Position-sensitive detectors in the instrument capable of determining the position and angle of the incident particle help to determine the isotope of the particle. Lighter nuclei have a smaller geometry factor. The results from simulation indicate that the detector is more sensitive to heavier nuclei. We see in figure 5 that nuclei heavier than oxygen ($^{16}\text{O}$) have a wider energy range in the figure 2 and larger geometry factor.
4. Conclusions
The results from simulation show a position resolution less than 0.02 cm and angular resolution less than 0.021. The results from calculation show the capability of elemental analysis of nuclei with \(Z = 1\) to 28 by using the \(\Delta E\) vs. \(E\) technique to determine the atomic number. The simulation shows the instrument’s capability to measure the kinetic energy of each incident particle. The geometry factor from simulation indicates that the instrument of MAST is more sensitive to heavier nuclei and heavier nuclei have a wider energy range. The results from calculations and simulation indicate that the instrument is suitable for elemental analysis and even more suitable to detect and analyze the heavier nuclei than lighter nuclei (having atomic number less than \(^{16}\)O).

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