

The medium-energy electron detector on board CSES-02

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Key Points:

- The medium-energy electron detector (MEED) on board China's second Seismo-Electromagnetic Satellite (CSES-02) offers the first detection of medium- and high-energy electron spectra in multiple directions in a 500 km sun-synchronous orbit.
- Among the indicators in the detection payloads, one includes nine directions of a low-energy segment, and the other includes three directions of a high-energy segment, all of which have been verified through ground calibration tests.
- The detection data on the energy spectrum, direction, and pitch angle distribution of medium- and high-energy electrons obtained from *in situ* measurements will play an important role in exploring new methods for short-term prediction and early warning of large earthquakes.

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Abstract: The medium-energy electron detector on board China's second earthquake-monitoring satellite can measure the energy, flux, and direction of medium- and high-energy electrons within the satellite's orbit. These data may provide the technical means for exploring new technologies and methods for earthquake monitoring and prediction. This work presents a description of the scientific objectives, key technical specifications, payload design, and results of ground calibration and verification for the payload.

Keywords: China's second Seismo-Electromagnetic Satellite (CSES-02); medium-energy electron detector; energy spectrum; particle direction; pitch angle distribution; earthquake monitoring

Plain Language Summary

On June 14, 2025 (Beijing time), China's second Seismo-Electromagnetic Satellite (CSES-02) was successfully launched from the Jiuquan Satellite Launch Center in China. The medium-energy electron detector (MEED), which is one of nine scientific payloads on board, could detect the energy and flux of medium-energy electrons (with an energy range of 25–400 keV) in nine directions as well as high-energy electrons (with an energy range of 0.4–3.2 MeV) in three directions and was first in orbit. Combined with observation data from other payloads, acquisition of the energy spectrum, direction, and pitch angle distribution information by the MEED will play an important role in earthquake monitoring and short-term forecasting.

1. Introduction

As the first operational satellite under the Medium- and Long-term Development Plan for China's Civil Space Infrastructure, the China Seismo-Electromagnetic Satellite (CSES; Shen XH et al., 2018) is designed with a lifespan of 6 years. China's second Seismo-

Electromagnetic Satellite (CSES-02) carries a total of nine scientific payloads, including an electric field detector (Diego et al., 2025) jointly developed by China and Italy, a high-energy particle detector (Savino, 2024) developed by Italy, and several payloads developed by China, such as the medium-energy electron detector (MEED), Langmuir probe, plasma analyzer, and ionospheric photometer. These payloads are tasked with conducting quasi-real-time monitoring of global parameters related to the electromagnetic field, electromagnetic waves, ionosphere, and neutral atmosphere (Shen XH et al., 2013). They will also capture electromagnetic anomalies and atmospheric phenomena, such as thunderstorms and lightning, triggered by geological and human activities. This capability will significantly enhance early detection, risk assessment, and monitoring and warning capabilities for major natural disasters, such as earthquakes, tsunamis, volcanic activities, and thunderstorms. Additionally, the satellite will provide data support for industries such as emergency management, resource mapping, and communication and navigation (Shen XH et al., 2020; Zeren ZM et al., 2025).

The MEED on board CSES-02 is a critical instrument for detecting electron radiation characteristics in near-Earth space. It can perform *in situ* measurements of the energy spectrum, direction, and pitch angle distribution of both medium- and high-energy

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electrons, as well as their temporal evolution and other key parameters. The on-orbit detection data obtained can effectively complement the in-orbit observations of other payloads and data from ground-based networks, providing valuable data support for exploring new methods of short-term and imminent earthquake prediction and early warning. Figure 1 shows a physical image of the MEED.

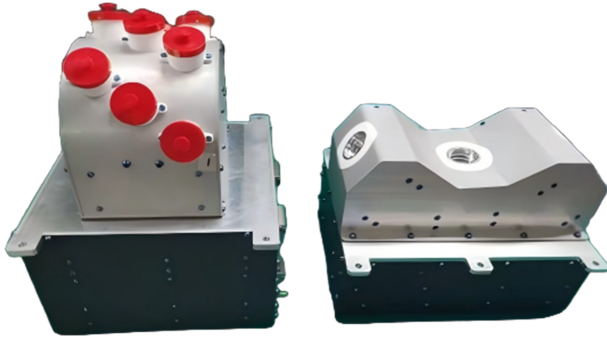


Figure 1. Photograph of the MEED on CSES-02.

2. Scientific Objectives

The CSES-02 satellite represents a major scientific and technological initiative by China. Its mission objective is to collect global data on space electric fields, magnetic fields, and particle radiation and to establish a technical platform for monitoring key physical parameters, such as the space electromagnetic field, electromagnetic waves, ionospheric plasma, and high-energy particle precipitation. This platform is expected to provide critical technical support for the development and exploration of new technologies and methods for earthquake monitoring and prediction.

During the earthquake preparation phase, electromagnetic radiation is generated and propagates into the atmosphere. Although part of this radiation travels along the waveguide between the Earth's surface and the ionosphere, another portion penetrates the ionosphere and magnetosphere, propagating along the Earth's magnetic field lines (Akhoondzadeh, 2024; Quattrocioni et al., 2024).

Electromagnetic radiation generated during the earthquake preparation phase can propagate along the Earth's magnetic field lines and enter the inner radiation belt. This radiation resonates with the trapped particles in the radiation belt, altering their pitch angle and inducing particle precipitation. This phenomenon leads to a sharp increase in the number of particles detected by the satellite, commonly referred to as particle bursts (PBs; Palma et al., 2021; Wang L et al., 2025). Because of the drift of charged particles along magnetic shells, the satellite can observe these sudden increases in particle counts across a broad longitudinal range.

In addition, low-frequency electromagnetic radiation can resonate with high-energy particles oscillating at their bounce frequency within the radiation belt, further enhancing the effect. These PBs can propagate around the Earth along the magnetic field lines. As a result, ionospheric or particle disturbances may occur not only near the earthquake epicenter but also in the magnetic conjugate region of the epicenter along the magnetic field lines (Giannattasio

et al., 2022; Martucci et al., 2023).

The abnormal high-energy particles observed prior to large earthquakes may be associated with the precipitation of radiation belt particles triggered by electromagnetic radiation (Yan R et al., 2024). This radiation is thought to be generated during the earthquake preparation process and propagate into the magnetosphere and ionosphere. Such phenomena may indicate large-scale electromagnetic field disturbances and reflect complex coupling interactions among the lithosphere, atmosphere, ionosphere, and magnetosphere.

Prior to seismic activity, strong disturbances in high-energy charged particles within the radiation belt are commonly observed. Research data from both domestic and international studies have shown that large-scale bursts of high-energy charged particles are closely associated with seismic events. These PBs are considered one of the potential precursors to earthquakes. Therefore, the detection of high-energy charged particles can provide valuable reference data to support more accurate earthquake prediction. This detection method has already been widely adopted in some international satellite missions (Friis-Christensen et al., 2006; Parrot et al., 2006).

Wave-particle interactions in the magnetosphere are the key factors causing dynamic processes such as particle acceleration and loss. Interactions between various wave types and radiation belt particles can lead to particle precipitation and pitch angle scattering. The electromagnetic waves generated by seismic activity are also capable of inducing such interactions, thereby contributing to the observed variations in radiation belt particle behavior.

Because of their extremely small mass, electrons in space are highly sensitive to electromagnetic field variations, especially medium-energy electrons with energies above several tens of kiloelectron volts. Under the influence of electromagnetic waves, these electrons can undergo significant changes in both their energy spectra and pitch angles (Benck et al., 2008).

In summary, the MEED performs *in situ* measurements of key characteristics of medium- and high-energy electrons in the orbit of CSES-02, including energy spectra, directional distribution, and pitch angle distribution, to study their temporal and spatial evolution. In addition, it effectively enables interaction with data from other onboard payloads and ground-based observation networks. This interaction supports the exploration of new methods for short-term and imminent earthquake prediction and early warning.

3. Main Technical Specifications

The CSES-02 satellite operates in a sun-synchronous orbit at an altitude of 500 km and an inclination of 98°. During its on-orbit operation, the satellite is exposed to three primary sources of high-energy particle radiation: trapped particles in the Earth's radiation belts, galactic cosmic rays, and high-energy particles generated by solar activities (Bühler et al., 1996).

Galactic cosmic rays are high-energy charged particles that enter the solar system from all directions in the galaxy. In free space

beyond the Earth's magnetosphere, these particles are generally considered isotropic. Galactic cosmic rays consist of particles with extremely high energy and very low flux. They are primarily composed of electrons and heavy ions with high atomic numbers. Their typical energy range exceeds the gigaelectron volt level, and their flux is approximately 4 particles/(cm²·s) (Simpson, 1983). The energy spectrum and flux of galactic cosmic rays are governed by long-term variations within the solar system and interplanetary space. However, they are not related to natural phenomena such as earthquakes.

Solar high-energy particle events are bursts of high-energy charged particles emitted by the sun during solar flares and coronal mass ejections (Waterfall et al., 2023). The primary components of solar high-energy particles are protons, electrons, and alpha particles (3%–15%), along with a small fraction of heavy nuclei. These events occur sporadically and lack regular periodicity. Their occurrence is solely driven by solar activity and is unrelated to terrestrial activities or natural phenomena, such as earthquakes.

The Earth's radiation belts consist of high-energy particles that are stably trapped by the Earth's magnetic field (Van Allen, 1959). These particles are primarily high-energy protons, electrons, and a small number of heavy ions. Because the earthquake electromagnetic monitoring satellite operates within the Earth's radiation belts, particle detection mainly occurs in the South Atlantic Anomaly (SAA) region, where radiation belt particles are more prominent. Particles in the radiation belts exhibit three characteristic motions constrained by the Earth's magnetic field: gyration, bounce, and drift (Jiao WX et al., 1999). Their flux demonstrates strong directionality and varies regularly with the pitch angle. The relationship between the flux distribution and pitch angle of particles is closely related to various space physical processes and terrestrial activities. Therefore, the effects of earthquakes can manifest as detectable changes in the number of particles within the Earth's radiation belts.

In the Earth's radiation belts, protons and electrons account for more than 90% of the total particle population. In addition, because electrons have a much lower mass than protons, their flux distribution varies more significantly with the pitch angle, making electrons more sensitive to pitch angle variations induced by earthquakes. Consequently, international earthquake-related studies primarily focus on electrons as the key particle for analysis (Hu JL et al., 2025).

Geomagnetic waves generated by earthquakes can influence the pitch angle distribution of charged particles in the Earth's radiation belts. Therefore, the distribution and variation characteristics of radiation belt particles are critical observation targets for the particle detection payload on board the earthquake-monitoring satellite.

Figure 2 illustrates the spatial distribution of 200–300 keV high-energy electrons at an orbital altitude of 500 km, as simulated by the AE-8 MAX model. The results demonstrate that these electrons are predominantly concentrated within the SAA region, whereas additional high-flux bands are clearly observed across the northern and southern polar auroral zones, forming distinct high-latitude enhancements alongside the SAA core.

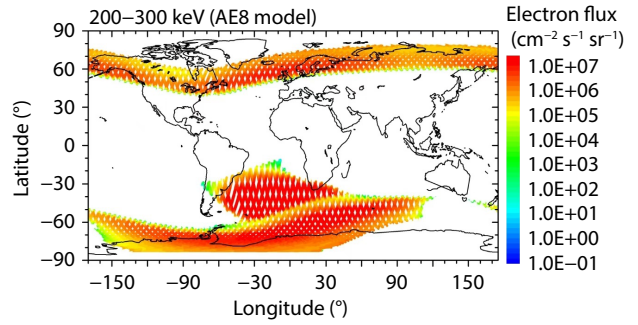


Figure 2. Distribution of high-energy electrons in the radiation belt at an orbital altitude of 500 km.

During earthquakes, the low-frequency waves generated by seismic activity propagate into space, causing variations in the pitch angle of radiation belt particles. These variations lead to changes in the directional flux of particles. It is important to note that the seismic geomagnetic waves primarily alter the existing directional distribution of radiation belt particles rather than generating new high-energy particles. Therefore, the original energy spectrum of radiation belt particles remains a key observation target for the high-energy particle detector on board the earthquake-monitoring satellite.

As shown in Figure 3, high-energy electrons in the radiation belt span an energy range from 100 keV to several megaelectron volts, with electron counts above 4 MeV being negligible.

During earthquakes, electromagnetic radiation induces changes in the pitch angle of radiation belt particles, which can trigger particle precipitation. Therefore, PBs are closely related to pitch angle variations. The pitch angle is defined as the angle between the direction of particle motion and the magnetic field line, ranging from 0 and 180°. In the low-orbit space environment, the pitch angle distribution of particles is distinctly anisotropic, with a peak

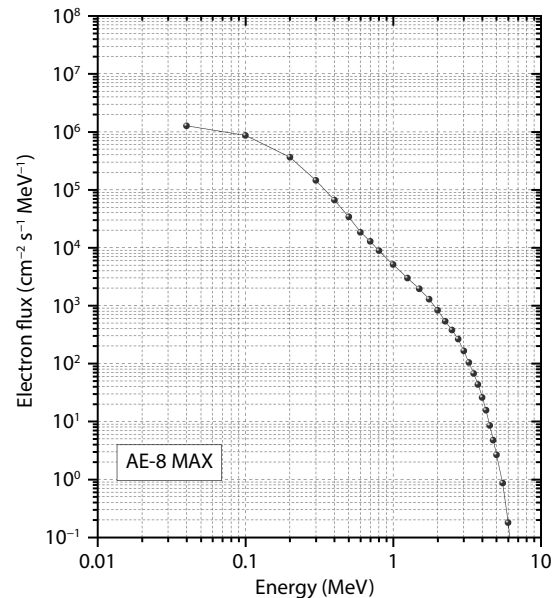


Figure 3. Integral energy spectrum of high-energy electrons in the radiation belt.

around 90° and gradually diminishing intensity toward 0° and 180°.

In summary, the MEED on board CSES-02 performs *in situ* monitoring of key parameters, such as the energy spectrum and directional distribution of medium- and high-energy electrons along the satellite's orbit. The main technical specifications of the MEED are listed in Table 1.

The pitch angle mentioned above can be calculated by using either the theoretical geomagnetic field vector in the Geographic Coordinate System (GEO) Coordinate system provided by the International Geomagnetic Reference Field (IGRF) model, or the measured magnetic field vector in the satellite body coordinate system obtained by the onboard magnetometer.

4. Payload Design

4.1 Detection Method

The semiconductor telescope measurement method is based on the principle of measuring high-energy particles through their energy loss and penetration characteristics (Wimmer-Schweingruber et al., 2020; Yang Z et al., 2022). To minimize the energy loss of medium-energy electrons in the entrance window, the payload's entrance window is made extremely thin or sometimes eliminated entirely. The sensor system utilizes two or more semiconductor detectors, combined with electronic circuits for measurement. The fundamental principle behind this method relies on the difference in the penetration ranges between protons and electrons. By applying appropriate discrimination thresholds and coincidence–anticoincidence circuits, the system can measure and identify particle types. The division of energy channels is achieved through discrimination thresholds, whereas the identification between protons and electrons is realized through coincidence and anticoincidence circuits. Specifically, protons have a shorter range and greater energy loss per unit distance, whereas electrons exhibit a longer range and lower energy loss per unit distance. Therefore, by analyzing which detectors are triggered and the corresponding discrimination thresholds, the system can measure the energy of the incident particle and identify its type. In the specific design, to ensure the purity of electronic measurement, it is necessary to consider the physical design of the actual probe to provide an effective logical working mode so as to effectively eliminate proton or other particle interference (Shen GH et al., 2023).

This detection method has been widely applied in typical medium-

energy electron detection payloads such as the FY-3 (FengYun-3) satellites and MEPED (medium-energy proton and electron detector) on board the POES (Polar Operational Environmental Satellites; Selesnick et al., 2020; Ye YG et al., 2023), which will not be further elaborated here.

The MEED on board CSES-02 covers an energy range of 25 keV–3.2 MeV. By considering the measurement principle, measurement direction, and practical engineering constraints, the hardware consists of two detection heads connected by a signal transmission cable. The detection components of the MEED include the low-energy segment (MEED-L) and the high-energy segment (MEED-H), with the transmission cable facilitating communication and signal transfer between them.

The MEED-L measures low-energy electrons in the range of 25–400 keV and includes nine low-energy electron probes, along with a dedicated electronics unit. In addition, the MEED-L receives signals transmitted from the MEED-H, which are uniformly processed and packaged by the electronics unit of the MEED-L before communication to the satellite.

The MEED-H measures high-energy electrons in the range of 0.2–3.2 MeV and consists of three high-energy electron probes connected with a preamplifier circuit and a digital acquisition circuit. Because of the extremely weak signal generated by particle deposition in semiconductor sensors, the signals generated by the MEED-H probes need to undergo specialized noise reduction processing before being transmitted to the MEED-L. This processing includes the use of low-noise preamplifiers, shielding structures, and grounding measures. At the same time, the signals will also pass through circuits such as main amplification and peak holding. Therefore, when transmitting the signal from these probes to the MEED-L, only shielded cables can be used, and no other special processing is required. To ensure the measurement field of view (FOV) of the probes, both the MEED-H and MEED-L are installed on the –Z surface outside the satellite cabin, with the normal of the FOV center facing the sun, thus ensuring that there is no obstruction within the FOV of each probe.

4.2 Detection Technology

4.2.1 Design of the MEED-L

The MEED-L comprises two main components: the directional detection system and the electronic system. The directional detection system consists of nine identical subprobes designed to measure the electron energy spectrum. Each subprobe consists

Table 1. Main technical specifications of the MEED.

Item	Technical specifications ^a
Energy range	~25 keV–400 keV for MEED-L; ~200 keV–3.2 MeV for MEED-H
Energy resolution	10% (@200 keV)
Angular resolution	Nine detection directions within 161°, with 25° in each direction for MEED-L; Three detection directions within 160°, with 60° in each direction for MEED-H
Flux measurement error	10% (Ground calibration)

^aMEED-L, low-energy segment of the MEED; MEED-H, high-energy segment of the MEED.

primarily of a collimation system, a light-blocking layer, a semiconductor detector system, and supporting electronic circuits. A sketch of a 3D model of the MEED-H is shown in Figure 4.

The collimation structure is installed outside the electron detector to restrict the instrument's detection FOV (Zhang SY et al., 2014). Additionally, the collimator provides shielding that helps reduce interference from obliquely incident particles, such as high-energy protons and electrons. By considering the collimator-defined FOV, the physical dimensions of the instrument, and the shielding conditions, the final geometric factor of the instrument can be determined through Monte Carlo simulations (Douglass and Bezak, 2012; Khoo et al., 2022). This geometric factor serves as the basis for subsequent data processing (Hou DH et al., 2020).

The semiconductor detector system is the core of the entire instrument's measurement capability. It utilizes two stacked silicon semiconductor detectors in a telescope configuration to measure the energy spectrum of medium-energy electrons. By analyzing the signal amplitude from each detector and applying an optimized logical working mode, the system accurately determines the spatial energy spectrum of electrons (Ye ZH, 1986; Jiao WX, 2002). A key challenge in this process is selecting the optimal logical working mode to obtain precise energy spectra while minimizing cross-channel particle interference.

The electronic system collects signals from the detectors, performs logical operations as defined in the physical design of the instrument, sorts and counts electron energy spectra, and finally packages the data for communication with the satellite. The internal structure of the MEED-L probe is shown in Figure 5.

The collimator system serves two functions: (i) to define an appropriate

detection FOV, thereby determining the geometric factor of the probe (Zhang SY et al., 2014), and (ii) to provide shielding that reduces interference from particles incident obliquely from the sides onto the sensor. The collimation system primarily includes the external structure of the probe and the internal antiscattering components.

The external structure includes a semicircular outer supporting and shielding framework, along with nine subprobes. The overall external housing is cylindrical and divided into three columns. The semicircular outer layer is also designed to facilitate secure installation of the subprobes. To further minimize the interference of particles incident obliquely from the side on the measurement results, a 3-mm-thick composite shielding material is applied on the outer surface of the probe.

The nine probes of the MEED-L are distributed along a semicircular arc segment and can be divided into three groups, each containing three probes. Each probe ensures a measurement FOV with a cone angle of 25° through structural design, and all nine probes can cover a measurement sector of 161° in space.

To mitigate the inference caused by elastic scattering of electrons within the detector materials, an antiscattering device is incorporated inside the high-energy electron probes. Notably, electron scattering inside materials is relatively severe, especially for medium-energy electrons in the range of tens to hundreds of kilo-electron volts. Therefore, to reduce electron scattering within the collimator, a serrated structure is designed inside it. This structure increases the number of scattering events for electrons entering outside the FOV, causing them to be absorbed by the serrated surfaces, thereby reducing the interference caused by scattered electrons.

The probe's light-blocking layer serves two primary purposes. First, it shields the detector from interference caused by sunlight. When sunlight strikes the silicon detector directly, it generates a large number of spurious counts, which disrupt the normal detector operation. Second, the light-blocking layer shields the detector from proton interference, preventing protons from entering the silicon detector system.

The light-blocking layer consists of a $3\text{-}\mu\text{m}$ -thick Mylar film, whose two surfaces are coated with 150 nm aluminum to enhance reflectivity. A $3\text{ }\mu\text{m}$ Mylar light-blocking layer can effectively block protons below 400 eV and electrons below 10 keV. Because the measurement threshold of the instrument begins at 25 keV, the energy loss of a 25 keV electron passing through the $3\text{ }\mu\text{m}$ Mylar layer is approximately 5 keV, leaving a residual energy of 20 keV, which falls within the measurable range of the electronics. The energy loss of 25 keV electrons in a $3\text{ }\mu\text{m}$ Mylar film is shown in Figure 6. The straight line corresponding to the 25 keV energy point in the figure illustrates that the energy is completely deposited in the $3\text{-}\mu\text{m}$ -thick Mylar layer, that is, all the energy is lost, with only a very small portion remaining.

The function of the semiconductor sensor is to detect charged particles entering the probe. Considering factors such as the linear response range, energy resolution, and spatial adaptability, ion-implanted silicon semiconductor sensors currently offer the best

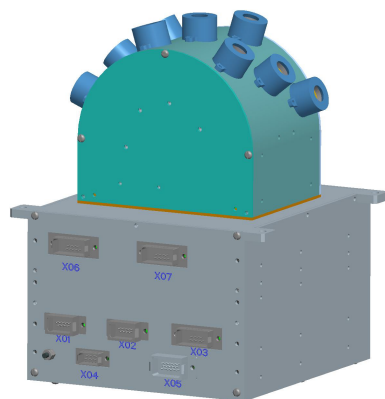


Figure 4. Sketch of a 3D model of the MEED-L.

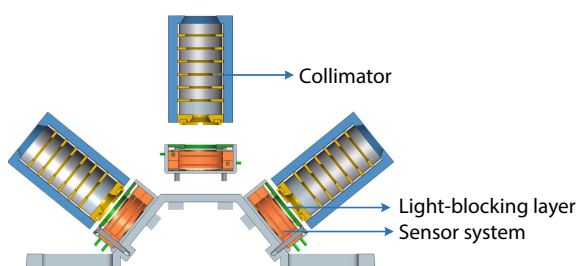


Figure 5. Internal structure of the MEED-L probe.

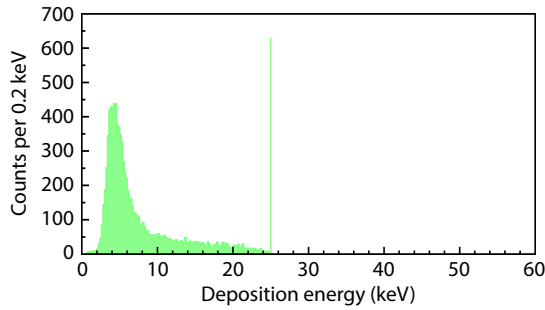


Figure 6. Energy loss of 25 keV electrons in a 3 μm Mylar film.

overall performance.

The sensor system uses two ion-implanted silicon semiconductor sensors (D1 and D2). These sensors measure the energy loss of energetic particles as they pass through, converting that energy into electrical signals for further processing by the instrument's electronic circuits. By analyzing the signal amplitude and applying appropriate logical operation modes, the system can determine the particle energy spectrum and flux. Ion-implanted semiconductor sensors provide excellent energy resolution and are currently the mainstream choice for this type of measurement.

To accurately measure low-energy electrons, it is essential to capture the total incident energy. Therefore, all the electrons within the target energy range must be completely stopped within the silicon detector. Figure 7 shows the extrapolated penetration range of electrons in the silicon detector. For example, 400 keV electrons have an extrapolated range of approximately 475 μm . Therefore, the silicon detectors are designed with a thickness of 500 μm to ensure full energy absorption.

Both sensors D1 and D2 have a thickness of 0.5 mm. To minimize unnecessary energy loss in the dead layer of the sensors, custom ultra-thin dead-layer silicon detectors are used. These customized silicon detectors have an active area of 8×8 mm, a dead-layer thickness below 150 nm, and extremely low noise characteristics. Their junction capacitance is less than 30 pF, and the dark current is below 10 nA. This low noise significantly improves the signal-to-noise ratio of the instrument.

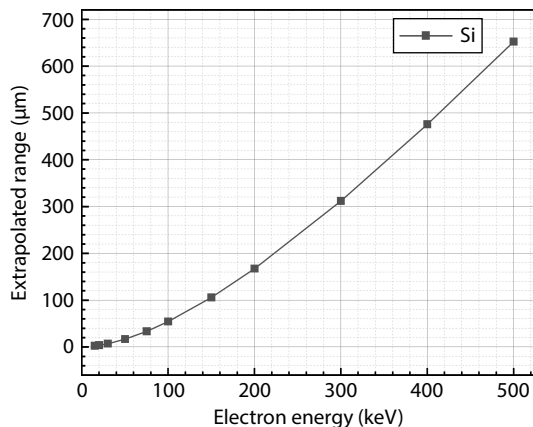


Figure 7. Extrapolated range of electrons in silicon. Si = silicon detector.

Each subprobe contains two silicon detectors. These detectors first perform anticoincidence discrimination. Specifically, if detector D2 generates an anticoincidence signal, it indicates that the incident particle is within the target measurement range. In this case, the signal from detector D1 is subjected to pulse amplitude discrimination to divide it into the corresponding energy channels. If detector D2 does not produce an anticoincidence signal, it indicates that the particle is a high-energy particle beyond the measurement range and is therefore discarded.

4.2.2 Design of the MEED-H

Similar to the MEED-L, the MEED-H adopts the classical multilayer silicon stacked semiconductor telescope measurement method. The system mainly consists of a collimation system, a semiconductor detector system, and an electronic processing system. A sketch of a 3D model of the MEED-H is shown in Figure 8.

The three subprobes of the MEED-H are distributed along a measurement band, with each probe having a viewing angle of 60° , collectively covering 180° in projection on the measurement plane. Together, the three probes form an omnidirectional measurement coverage of 160° on the projection plane.

To minimize the elastic scattering effect of electrons within the materials, an antiscattering device is added inside the MEED-H, with the aim of preventing measurement interference caused by electron scattering. The internal structure of the MEED-H probe is shown in Figure 9.

The light-blocking layer of the MEED-H is made of a 15- μm -thick aluminum film (Figure 10). This layer effectively blocks protons

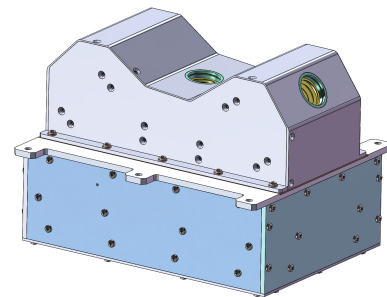


Figure 8. Sketch of a 3D model of the MEED-H.

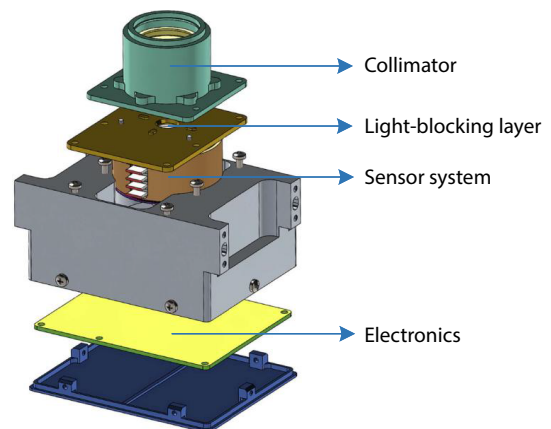


Figure 9. Internal structure of the MEED-H probe.

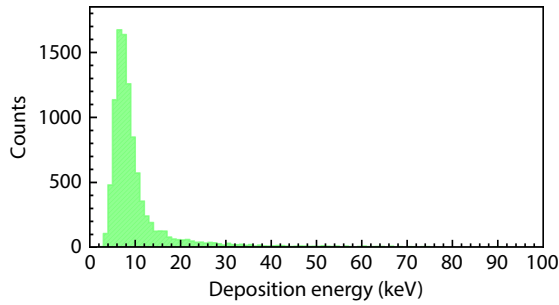


Figure 10. Energy loss of 200 keV electrons in a 15 μm Al film.

below 1 MeV and electrons below 30 keV. The measurement range of the instrument begins at 200 keV. For 200 keV electrons, the energy loss within the light-blocking layer is approximately 20 keV, leaving a residual energy of 180 keV for detection.

The sensor system uses six ion-implanted silicon semiconductor sensors (D1–D6). Sensor D1 has a thickness of 300 μm and a smaller sensitive area of $\Phi 12$ mm. Sensors D2–D6 have a thickness of 1 mm and a sensitive area of $\Phi 20$ mm.

In total, six sensors are used in the detector, which are grouped into three signal channels for data processing: the first sensor (D1) forms an independent signal channel (A1), the second and third sensors (D2 and D3) are combined into one channel (A2), and the remaining three sensors (D4, D5, and D6) are combined into one channel (A3). The energy channel division and logical operation mode of MEED-H are shown in Table 2. In addition, the MEED-H stores and transmits the signal amplitude data of each detected particle, enabling a more detailed analysis on the ground.

4.3 Electronics Design

The electronics design of the MEED consists of independent front-end sensor readout electronic systems located inside both the MEED-H and MEED-L, and a common digital processing system housed in the MEED-L. Among them, the MEED-H features three identical probe structures, each connected to the MEED-L electronics unit via internal cables within the same payload. The signals from these three probes are uniformly processed by the

electronics unit. Likewise, the nine probes of MEED-L, which share identical designs, are integrated with the electronics unit in a combined configuration.

For both the high-energy and low-energy sections, each probe's readout electronic circuit primarily includes a charge-sensitive preamplifier circuit that receives output pulse signals from the sensors, followed by a filtering and shaping circuit, a main amplifier, and a follower circuit. The shared circuitry within the MEED-L electronics unit mainly handles peak-hold signal acquisition, scientific data processing, engineering parameter acquisition, and scientific data packaging and buffering. Ultimately, it transmits the data packets to the satellite platform through the bus interface.

5. Ground Calibration Results

After the prototype development of the MEED was completed, ground calibration tests were conducted to validate and accurately determine its actual detection performance across various technical parameters. These calibration indicators included energy resolution, linearity, accuracy of energy channel division, flux measurement accuracy, and angular calibration. The detailed principles, methods, and procedures for these calibrations are available in other related references and are not discussed here (Hou DH et al., 2023; Wang LP et al., 2024).

Because of the differences in the energy range specifications of the instrument, different calibration methods were used. For medium- and high-energy electrons within an energy range of 25 keV to 1.5 MeV, the electron accelerator facility at the National Space Science Center, Chinese Academy of Sciences, was primarily used. For electrons with energies between 1.5 and 3.2 MeV, because no suitable electron accelerator in China is currently capable of calibrating space-borne payloads above 1.5 MeV, an equivalent signal source and conventional linear extrapolation method were used (Hou DH et al., 2023).

The electron accelerator device at the Space Science Center can generate electrons with energies from 10 keV to 1.5 MeV, with an adjustable beam flux ranging from 10^3 to 10^9 $\text{cm}^{-2}\cdot\text{s}^{-1}$. It is the

Table 2. Energy channel division and logical operation mode of MEED-H.

Energy channel	Energy range (MeV)	Logical operation mode
E1	0.2–0.3	$A1_{0.20} \cdot \overline{A1}_{0.30} \cdot \overline{A2}_{0.25} \cdot \overline{A3}_{0.2}$
E2	0.3–0.4	$A1_{0.30} \cdot \overline{A1}_{0.40} \cdot \overline{A2}_{0.25} \cdot \overline{A3}_{0.2}$
E3	0.4–0.5	$\overline{A1}_{0.60} \cdot A2_{0.25} \cdot \overline{A2}_{0.38} \cdot \overline{A3}_{0.2}$
E4	0.5–0.6	$\overline{A1}_{0.60} \cdot A2_{0.38} \cdot \overline{A2}_{0.50} \cdot \overline{A3}_{0.2}$
E5	0.6–0.8	$\overline{A1}_{0.80} \cdot A2_{0.50} \cdot \overline{A2}_{0.70} \cdot \overline{A3}_{0.2}$
E6	0.8–1.0	$\overline{A1}_{1.0} \cdot A2_{0.70} \cdot \overline{A2}_{0.90} \cdot \overline{A3}_{0.2}$
E7	1.0–1.5	$\overline{A1}_{1.2} \cdot A2_{0.1} \cdot (A2 + A3)_{0.93} \cdot \overline{(A2 + A3)}_{1.43}$
E8	1.5–2.0	$\overline{A1}_{1.2} \cdot A2_{0.1} \cdot (A2 + A3)_{1.43} \cdot \overline{(A2 + A3)}_{1.94}$
E9	2.0–3.0	$\overline{A1}_{1.2} \cdot A2_{0.1} \cdot (A2 + A3)_{1.94} \cdot \overline{(A2 + A3)}_{3.00}$

only comprehensive facility in China capable of simulating the space electron radiation environment, making it ideal for testing and calibrating medium- and high-energy electron detection instruments.

Through ground-based accelerator calibration experiments, combined with the analysis and processing of simulation data for the MEED on CSES-02, indicators such as energy resolution, actual energy channel boundaries, and the others mentioned above were thoroughly verified. Table 3 summarizes the instrument's performance indicators and their conformity with design requirements.

Next we briefly introduce the angular resolution calibration test of the instrument. Using the signals generated by accelerator-produced particles, we rotated the instrument within its detection FOV. The starting angle was defined as the angle at which the detector first registered a response, and the ending angle was the point at which the detector response disappeared. The angular range between these start and end points was taken as the effective FOV angle of the instrument.

During the experiment, 250 keV electrons generated by the accelerator were incident onto the detector. The angular measurement results for the MEED-L are shown in Figure 11.

As the electron beam slowly scanned across the probe, the test results showed that the response decreased as the incident direction deviated from the probe's normal axis and reached its maximum when the beam was perpendicular to the probe surface. The rotation test results indicated that the FOV angles for the nine directions met the design specification of 25°. Furthermore, electrons of the same energy exhibited identical response efficiencies across the different probes. Table 4 summarizes the consistency among directions during rotation.

According to the rotation results, the nine MEED-L probes each had a FOV angle of 25°, meeting the design specifications. The maximum deviation in response consistency among all directions did not exceed 5.70%, and the angular deviation was within 3.5%.

Similarly, angular calibration for MEED-H was performed using 250 keV incident electrons, and the measurement results are presented in Figure 12. The angular rotation tests confirmed that the FOV angles of the three MEED-H directions met the design specification of 60°. Table 5 summarizes the consistency and angular deviations among three directions during rotation.

6. Summary

As a key instrument for measuring electron radiation in near-Earth

Table 3. Ground calibration results of the MEED.

Item	Expected results	Achieved results
Energy range	~25 keV–400 keV	Direction 1: 24.82 keV–49.08 keV–85.59 keV–142.1 keV–253.7 keV–402.5 keV Direction 2: 24.52 keV–49.98 keV–85.35 keV–142.5 keV–251.0 keV–405.2 keV Direction 3: 24.31 keV–49.68 keV–85.35 keV–142.1 keV–252.4 keV–407.8 keV Direction 4: 24.62 keV–50.28 keV–85.55 keV–141.1 keV–249.2 keV–405.4 keV Direction 5: 24.72 keV–49.08 keV–85.22 keV–142.1 keV–252.4 keV–406.2 keV Direction 6: 24.92 keV–49.68 keV–85.38 keV–142.1 keV–249.6 keV–398.5 keV Direction 7: 24.52 keV–50.28 keV–85.65 keV–142.5 keV–255.8 keV–406.6 keV Direction 8: 24.60 keV–50.28 keV–85.45 keV–143.1 keV–249.0 keV–404.7 keV Direction 9: 24.72 keV–49.38 keV–85.22 keV–142.1 keV–250.1 keV–405.2 keV
	~200 keV–3.2 MeV	Direction 1: 198.4 keV–298.4 keV–401.7 keV–603.4 keV–800.3 keV–1005.0 keV–1301.0 keV–2000.7 keV–3203.1 keV Direction 2: 199.4 keV–302.5 keV–394.1 keV–601.5 keV–803.0 keV–998.3 keV–1301.0 keV–1995.9 keV–3203.2 keV Direction 3: 198.4 keV–302.8 keV–409.0 keV–598.6 keV–803.6 keV–997.3 keV–1303.0 keV–2002.5 keV–3203.2 keV
Energy resolution	10% (@200 keV) for MEED-L	Direction 1: 8.47% @200 keV Direction 2: 8.56% @200 keV Direction 3: 8.92% @200 keV Direction 4: 9.23% @200 keV Direction 5: 9.20% @200 keV Direction 6: 9.17% @200 keV Direction 7: 9.92% @200 keV Direction 8: 9.90% @200 keV Direction 9: 9.48% @200 keV
	10% (@200 keV) for MEED-H	Direction 1: 9.87% @200 keV Direction 2: 9.16% @200 keV Direction 3: 9.39% @200 keV
Angular resolution	Nine detection directions within 161°, with 25° in each direction for MEED-L	Each is better than 3.5%
	Three detection directions within 160°, with 60° in each direction for MEED-H	Each is better than 1.67%
Flux measurement error	10% (ground calibration)	MEED-L: 5.39% MEED-H: 4.53%

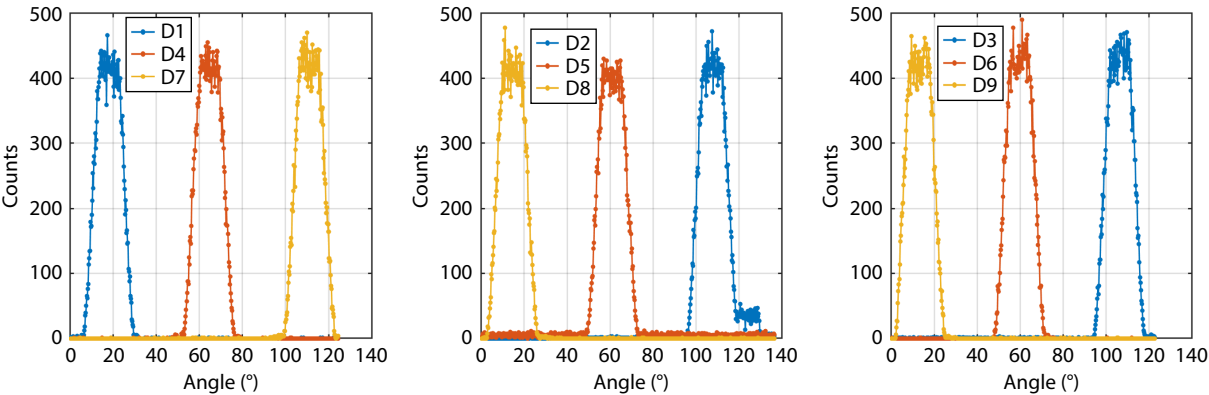


Figure 11. Response of the MEED-L in each direction during angular rotation.

Table 4. Consistency among different directions during rotation.

Deviation	Direction								
	1	2	3	4	5	6	7	8	9
Consistency deviation (%)	3.07	0.00	3.29	0.22	5.70	2.41	1.32	0.66	1.32
Angular deviation (%)	3.00	0.56	2.44	1.36	1.68	0.92	1.08	2.30	3.50

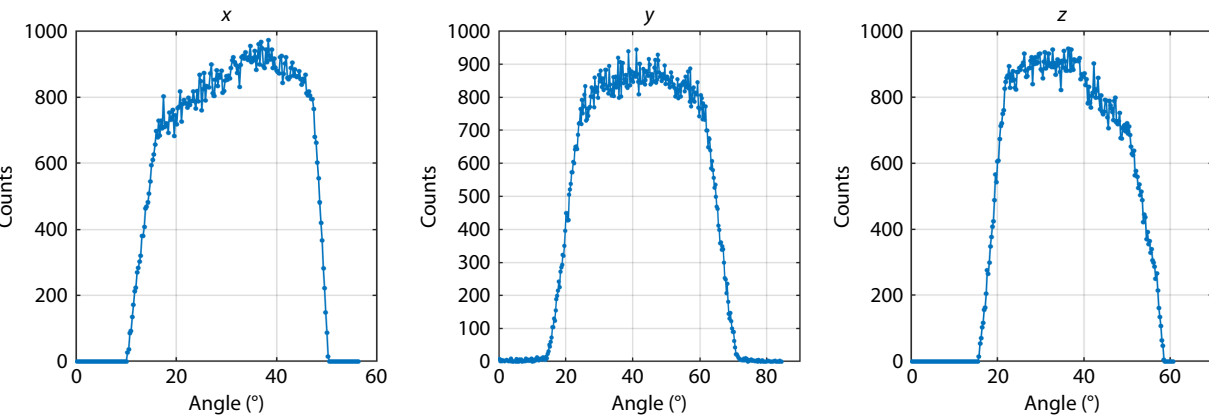


Figure 12. Response during angular rotation for different MEED-H directions.

Table 5. Consistency of each MEED-H direction during angular rotation.

Deviation	Direction		
	x	y	z
Consistency deviation (%)	0.81	1.20	0.39
Angular deviation (%)	1.67	0.01	1.17

space on board CSES-02, the MEED has successfully passed a comprehensive series of ground performance tests during the development phase, with all technical indicators meeting or exceeding the mission requirements. Following the satellite’s launch and deployment into orbit, preliminary detection data were acquired, including the energy spectrum, direction, and pitch angle distribution of medium- and high-energy electrons along the satellite’s orbit. Currently, in-depth data analysis, processing, and on-orbit testing are being conducted. In the future, the MEED will continue to collaborate with other onboard payloads and ground-based observation networks. Therefore, it is

expected to play a vital role in the exploration of new approaches for short-term and imminent earthquake prediction and early warning.

Conflict of Interest

The authors declare no conflicts of interest related to this study.

Data Availability Statement

No data were used or created for this research.

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