Accelerator Simulation Test Technology for Space Single Event Effects and Applications Postprint

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Abstract

The space environment contains abundant high-energy particles. When individual high-energy particles traverse spacecraft shielding and bombard electronic devices, they induce single-event effects such as logic state upsets and functional anomalies, thereby affecting the reliable operation and mission success of spacecraft. Ground-based accelerator irradiation testing to simulate space single-event effects is a critical means for evaluating the risk of single-event errors in electronic devices for space applications; only devices whose single-event effect resistance metrics meet aerospace application requirements can be used in spacecraft. The primary space radiation particles encountered by spacecraft are heavy ions and protons, which also induce the most significant single-event effects. Conducting ground simulation tests for single-event effects in aerospace devices mainly relies on heavy ion accelerators and proton accelerators. To meet single-event testing requirements, it is necessary to develop technologies such as large-area beam expansion and uniformization, high-precision rapid beam diagnostics, and efficient test terminals for high-volume testing missions. This paper focuses on introducing the heavy ion single-event effect simulation testing technology, proton single-event effect simulation testing technology, and heavy ion microbeam technology for identifying radiation-sensitive regions in devices at the China Institute of Atomic Energy, as well as the applications of these technologies in risk assessment of single-event effects in aerospace devices.

Full Text

Preamble

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Abstract

The space environment contains numerous high-energy particles. When a single high-energy particle passes through a spacecraft's shell and bombards electronic devices, it triggers single event effects such as logic state upsets and functional anomalies, thereby affecting the reliable operation of spacecraft and mission success. Ground-based accelerator irradiation tests that simulate space single event effects are crucial means for evaluating the risk of single event errors in electronic devices for space applications. Only devices whose single event effect resistance indicators meet aerospace application requirements can be used in spacecraft. The primary space radiation particles encountered by spacecraft are heavy ions and protons, which also induce the most significant single event effects. Ground simulation tests for single event effects in aerospace devices mainly rely on heavy ion accelerators and proton accelerators. To meet the requirements of single event effect testing, it is necessary to develop technologies such as large-area beam expansion and homogenization, high-precision beam rapid diagnosis, and efficient test terminals that can handle large-volume testing tasks. This paper focuses on introducing the accelerator-based heavy ion single event effect simulation test technology, proton single event effect simulation test technology, and heavy ion microbeam technology for identifying radiation-sensitive regions in devices at the China Institute of Atomic Energy, as well as the application of these technologies in risk assessment of single event effects in aerospace devices.

Keywords: Space radiation, Single event effects, Simulation test
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Accelerator Simulation Test Technology and its Application for Single Event Effect Evaluation in Space

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Abstract: [Background] The space environment contains numerous high-energy particles, and a single high-energy particle passing through a spacecraft shell bombards the electronic devices within, triggering single-particle effects such as device logic state upset and function failures, which, in turn, affect spacecraft operation reliability and mission accomplishment. [Purpose] Notably, ground accelerator irradiation tests provide an important and effective means for simulating space single event effects and for predicting the risks of single event effect rates for electronic devices in space applications. Generally, electronic devices can be used in spacecraft only if their resistance radiation indicators meet astronautical application requirements. [Methods] Spacecraft are typically exposed to space radiation particles, primarily heavy ions and protons; therefore, single event effect simulation testing for electronic devices relies predominantly on heavy ion and proton accelerators. To address the requirements of single event effect testing, technologies such as large-area beam expansion and homogenization, high-precision beam current diagnosis, and efficient test terminals have been developed to fulfill the requirements of various test tasks. [Results] Particular focus is placed on the CIAE's (China Institute of Atomic Energy) heavy ion single event and proton single event effect simulation test techniques and the heavy ion microbeam technique for radiation sensitive area identification for electronic devices. Subsequently, the aforementioned techniques are applied to a single event effect risk evaluation for astronautical electronic devices. [Conclusions] In the future, the demand for radiation-resistant devices is expected to continue to increase in the aerospace, nuclear industry, and other radiation application fields. It is, therefore, necessary to further exploit the irradiation potential of existing domestic single event effect simulation equipment and establish new accelerator platforms with improved capacity for single event effect simulation testing.

Key words: Space radiation, Single event effects, Simulation test

Introduction

Interactions between high-energy particles in the space environment and electronic devices can lead to device parameter degradation, performance decline, and even functional failure. This phenomenon is known as space radiation effects, which mainly include single event effects (SEE), total ionizing dose (TID) effects, and displacement damage (DD) effects. Space radiation particles have high energies but low flux densities, making the impact of single event effects triggered by individual high-energy particles particularly prominent. According to statistics, 45% of in-orbit failures in electronic systems are caused by radiation effects, with single event effects accounting for approximately 86% of these cases[1]. In the 1990s, China also observed functional failures in multiple satellites due to device single event effects. For example, in 1990, China's first and second Fengyun satellites experienced attitude control loss due to single event effects in onboard computers after 39 and 159 days in orbit, respectively. In 1992, before the launch of the Dongfanghong-3 satellite, the Fifth Academy of Aerospace (China Aerospace Science and Technology Corporation) collaborated with the China Institute of Atomic Energy to conduct China's first accelerator irradiation test for single event effects using the Beijing HI-13 tandem accelerator, evaluating the single event effect sensitivity of key devices. Since then, ground-based accelerator simulation research on space single event effects in China has officially commenced and entered a period of rapid development.

The space radiation environment is complex, making it difficult for ground-based accelerators to directly simulate the real space radiation environment. The energy range of space radiation particles can cover from eV to TeV with a continuous energy distribution and diverse directions of motion[2]. In contrast, particles produced by ground accelerators typically have energy ranges from MeV to GeV[3], and higher energies lead to higher construction costs and poorer cost-effectiveness for single event effect irradiation tests. Furthermore, ground accelerators cannot simultaneously generate and irradiate particle beams with multiple species, wide energy ranges, and multiple incident directions. Currently, both domestically and internationally, irradiation tests mainly use accelerators to produce single-species, single-energy particles to simulate radiation effects in devices rather than directly simulating the space radiation environment. Additionally, spacecraft have long operational periods in orbit, making it impractical for ground-based accelerator simulation tests to achieve continuous particle irradiation throughout the entire mission lifetime. The common approach is to employ accelerated testing, using high-flux particle beams from accelerators to irradiate for tens of minutes to several hours, simulating the low-flux particle irradiation that spacecraft experience over years to decades in orbit. Therefore, ground-based accelerator irradiation tests for simulating space single event effects primarily adopt a combined approach of effect simulation and accelerated testing to conduct device irradiation experiments, obtain single event effect cross-sections, and provide data support for error rate prediction and targeted hardening of devices in space applications.

Single event effects occur during spacecraft operation in orbit, but the majority of research and testing work is conducted on the ground. To determine whether electronic devices can be used in spacecraft, ground simulation tests must be performed using appropriate accelerator beams. For heavy ion single event effects, it is necessary to measure the relationship curve between the device's single event effect cross-section and the heavy ion linear energy transfer (LET) value (typically requiring 5 test points)[4]. Similarly, for proton single event effects, the relationship curve between the device's single event effect cross-section and proton energy must be measured. Based on these measurements, combined with the heavy ion and proton radiation environments of the spacecraft's operational orbit, the error rate of single event effects for the device can be predicted. Only devices whose single event effect resistance performance indicators meet mission requirements can be used in spacecraft. Furthermore, irradiation tests using accelerator beams can reproduce in-orbit failures, identify radiation damage weak links and critical devices, and validate the effectiveness of hardening measures implemented in devices, thereby guiding targeted single event effect hardening and improving radiation resistance performance. Space radiation particles are primarily protons and heavy ions; therefore, simulation tests for single event effects in aerospace devices mainly rely on heavy ion accelerators and proton accelerators. This paper focuses on introducing the accelerator-based heavy ion single event effect simulation test technology, proton single event effect simulation test technology, and heavy ion microbeam technology for identifying radiation-sensitive regions in devices at the China Institute of Atomic Energy, as well as the application of these technologies in risk assessment of single event effects in aerospace devices.

Heavy Ion Single Event Effect Simulation Test Technology

The accelerators currently used in China for aerospace device single event effect simulation test research mainly include the Beijing HI-13 tandem accelerator at the China Institute of Atomic Energy and the Heavy Ion Research Facility in Lanzhou (HIRFL) at the Institute of Modern Physics, Chinese Academy of Sciences. These two accelerators have undertaken the majority of single event effect test evaluation tasks for aerospace devices in China.

The Beijing HI-13 tandem accelerator offers the advantage of conveniently and quickly changing particle LET values, facilitating the measurement of the relationship curve between device single event effect cross-section and particle LET values. However, its disadvantages include relatively low energy and short range, requiring tests to be conducted in vacuum environments and necessitating pre-processing of test samples such as decapping and thinning. The HIRFL accelerator features high particle energy and long range, simple sample pre-processing, and allows tests to be performed in atmospheric environments. However, changing particle LET values is complex and requires days or even weeks, making it primarily suitable for verification testing of single event effect LET thresholds at high LET values.

The Beijing HI-13 tandem accelerator was constructed in 1987, delivering DC beams primarily for fundamental nuclear physics research. In 2009, to address the specific requirements of single event effect testing, a new beamline was split from the R20 pipeline in the second experimental hall of the HI-13 tandem accelerator using a deflection magnet, establishing a dedicated irradiation facility for heavy ion single event effects, as shown in Figure 1 [Figure 1: see original paper]. The particle beam generated by the accelerator is directed to the R20 branch beamline, passing through a Y-direction steering magnet, a set of doublet quadrupole magnets, X and Y direction slit devices, X and Y direction triangular-wave two-dimensional asynchronous scanning magnets, and a collimator before irradiating the device sample. Additionally, the beamline is equipped with fluorescent screens for beam diagnostics and beam monitoring detectors. Device samples are mounted on a sample holder in a vacuum target chamber, which can accommodate three standard irradiation boards of 25 cm $\times$ 25 cm.

Figure 1. Specialized irradiation equipment for heavy ion single event effects based on the Beijing HI-13 tandem accelerator

Single event effect simulation tests require particle beams that can cover device samples with uniformity better than 90% and penetration depth greater than 30 m in silicon[5]. To meet the need for large-area uniform particle beams in single event irradiation tests, a triangular-wave two-dimensional asynchronous magnetic scanning technology based on different frequencies and identical amplitudes is employed to obtain heavy ion beams with beam spot area of 50 mm × 50 mm at the sample irradiation plane, beam distribution uniformity better than 90%, and fluence rate continuously adjustable from 10^2 to 10^6 ions $\cdot$ cm^{-2} $\cdot$ s^{-1}[6]. To address the insufficient ion energy of high LET value beams from the tandem accelerator, which fails to meet the requirement of range greater than 30 m in evaluation tests, a high-charge-state heavy ion beam tuning technology was developed. Under fixed terminal voltage conditions of the tandem accelerator, double stripping and ion selection techniques are employed to achieve generation of high-charge-state ions. Through electric and magnetic field simulation and terminal voltage stabilization technology, ions in quasi-equilibrium charge states with identical magnetic rigidity but different energies (charge states with high stripping probability and strong beam current) are used as pilot beams to establish the beam path, enabling transmission and control of high-charge-state ions with stripping probabilities two to three orders of magnitude lower than conventional beams, effectively increasing beam energy and range. Currently, the heavy ion single event effect dedicated irradiation facility at the Beijing HI-13 tandem accelerator covers particle beam LET values ranging from 0.4 to 65.6 MeV $\cdot$ cm^2 $\cdot$ mg^{-1}, with Si range greater than 30 m, as shown in Table 1 .

Table 1. Typical beam parameters for single event effect experiments using the Beijing HI-13 tandem accelerator

Based on the HI-13 tandem accelerator for single event effect testing, numerous evaluation and qualification tests have been conducted on the radiation resistance performance of aerospace devices, covering most types of aerospace electronic devices in China. This work has supported the development of domestically produced radiation-hardened devices and ensured high reliability in space applications such as the BeiDou navigation system, manned spaceflight, and space stations.

Proton Single Event Effect Simulation Test Technology

Improvements in spacecraft performance depend on the use of high-performance advanced devices. The widespread adoption of ultra-deep submicron and nanometer devices has greatly enhanced satellite capabilities. However, the reduction in device feature sizes decreases critical charge, increasing device sensitivity to single event effects. Compared to the past, proton-induced single event effects have become significantly more prominent and represent one of the primary factors affecting satellite operational reliability. Unlike heavy ion-induced single event effects, proton-induced single event effects involve not only direct ionization contributions but also contributions from secondary particles produced through nuclear reactions. The latter is triggered by ionization from secondary charged particles generated through nuclear reactions between protons and device materials, with cross-sections dependent on incident proton energy and device materials, typically four to five orders of magnitude smaller than heavy ion single event effect cross-sections[7]. However, in the space radiation environment, particularly in medium and low Earth orbits, the flux of high-energy protons is substantial, and the resulting single event effects are far greater than those produced by heavy ions under the same conditions, becoming one of the main threats to reliable satellite operation.

Research on proton single event effect testing in China started relatively late, with a long-term lack of proton sources above 30 MeV. In recent years, China has gradually constructed several proton accelerators with energies above 30 MeV, primarily including the 100 MeV proton cyclotron at the China Institute of Atomic Energy, the 200 MeV proton cyclotron at the Northwest Institute of Nuclear Technology, and the 300 MeV proton cyclotron at Harbin Institute of Technology.

The 100 MeV Proton Cyclotron at China Institute of Atomic Energy (CYCIAE-100), independently developed by the China Institute of Atomic Energy, is China's first medium-energy proton accelerator. CYCIAE-100 successfully produced its first beam in July 2014 and entered the trial operation phase in June 2016, with the first experiments conducted being proton single event effect simulation tests for devices. The proton single event effect simulation test facility established based on the 100 MeV proton cyclotron is shown in Figure 2 [Figure 2: see original paper]. The proton beam is extracted from the main accelerator body, passes through a deflection magnet into the proton irradiation beamline, then through a Y-direction steering magnet, a set of doublet quadrupole magnets, a double scattering target, a degrader, and a collimator before irradiating the device sample. Additionally, the beamline is equipped with fluorescent screens for beam diagnostics and beam monitoring detectors. Device samples are mounted on a sample holder that can accommodate three standard irradiation boards of 25 cm × 25 cm, with irradiation tests conducted in atmospheric environments.

The CYCIAE-100 has a beam current range of 10 nA to 200 A and a frequency of 50 MHz, with beam intensity three to seven orders of magnitude higher than required for single event effect testing[8]. By installing a beam sieve at the particle injector, beam defocusing magnets and beam-limiting slits in the bunker area, the proton beam intensity is significantly reduced within the bunker region. Simultaneously, a double scattering target is employed to expand and homogenize the proton beam. Additionally, to obtain the relationship curve between single event effect cross-section and proton energy, a binary degrader system was designed to enable rapid switching of different proton energies[9]. This achieves proton beams with energy range quasi-continuously adjustable from 30 to 100 MeV, fluence range from 10^2 to 10^{11} $p \cdot cm^{-2}$, and beam distribution uniformity better than 90% within a 100 mm × 100 mm area[8,10]. Based on the CYCIAE-100 proton single event effect simulation test facility, a series of evaluation and qualification tests for radiation resistance performance of aerospace devices have been completed, including Static Random-Access Memory (SRAM), Field Programmable Gate Array (FPGA), and others[11-12], supporting the establishment of test methods and industry standards for proton single event effect testing in China.

Figure 2. Proton single event effect simulation experiment equipment based on a 100 MeV proton cyclotron

Heavy Ion Microbeam Technology

The development of radiation-hardened aerospace devices typically follows an iterative process of 'design-manufacture-test-redesign,' which is extremely costly. The key to improving device radiation resistance, shortening the cycle time, and reducing design and development costs lies in early identification and localization of single event sensitive weak links during the development process, clarifying the physical mechanisms of the effects, and thereby enabling targeted hardening. Heavy ion microbeams can identify effect-sensitive regions and the mechanisms of charge generation, amplification, and collection, providing quantitative relationships between these and device cell layout, dimensions, materials, and process parameters. This makes heavy ion microbeam technology a powerful tool for radiation-hardened device design and effect mechanism research.

The heavy ion microbeam facilities currently used in China for identifying single event effect sensitive regions in devices mainly include the pinhole-type microbeam facility based on the Beijing HI-13 tandem accelerator at the China Institute of Atomic Energy and the focusing-type microbeam facility based on HIRFL at the Institute of Modern Physics, Chinese Academy of Sciences. The former requires fabrication of high-precision pinholes with dimensions of 1-3 m; the latter has comparable beam spot size but presents greater difficulty in beam tuning.

The heavy ion microbeam irradiation facility based on the Beijing HI-13 tandem accelerator is shown in Figure 3 [Figure 3: see original paper]. After entering the vacuum target chamber, the beam passes through a pre-collimator and a micron-sized pinhole to become a micron-sized beam spot. During irradiation, a microchannel plate detector is used to monitor particle fluence by detecting secondary electrons produced when particles pass through a carbon foil. Before sample irradiation, the sample region to be irradiated and the pinhole are positioned using a microscope. The sample and pinhole then remain stationary, the microscope is moved away from the beam path, and irradiation begins. Different regions of the sample are irradiated by moving the precision translation stage on which the sample is mounted[13].

Simultaneously, a single event upset imaging technique has been established. During heavy ion microbeam point-by-point scanning of devices, an effect detection system automatically monitors and stores information such as device upset addresses, bit numbers, irradiation coordinates, and fluence at each point, displaying the upset region in real-time as a two-dimensional map. By correlating upset information with positional information, inversion analysis of effect data is achieved, enabling a localization accuracy of 0.5 m, as shown in Figure 4 [Figure 4: see original paper].

The microbeam direction remains constant while the mobile platform moves the sample in small steps. When entering the first sensitive region, the measured effect count begins to increase. When the entire sensitive region is within the microbeam spot, the effect count enters a plateau. As the platform continues to move, when the second sensitive region also enters the microbeam spot, the effect count increases again. By statistically analyzing the relationship between effect counts and beam spot position, and analyzing the relationship between sensitive region shape and effect counts, radiation-sensitive regions can be identified, forming a device radiation-sensitive region effect distribution map.

Based on the HI-13 tandem accelerator heavy ion microbeam facility, a series of heavy ion microbeam test studies have been conducted, primarily including SRAM, inverter chains, and others[14], providing data support for targeted hardening of radiation-hardened devices and research on radiation effect mechanisms.

Figure 3. Heavy ion microbeam equipment based on the Beijing HI-13 tandem accelerator

Figure 4. Inversion method for locating radiation sensitive areas in electronic devices during a microbeam irradiation test

To improve the localization accuracy of device radiation-sensitive regions, even though the beam spot is micron-sized, sub-micron localization accuracy can be achieved through smaller step (0.1 m and below) movement scanning. In the future, as device feature sizes continue to decrease, nanobeam technology will need to be developed to achieve nanometer-scale localization and identification of device radiation-sensitive regions.

Conclusion

Space radiation effects affect the reliability of electronic devices used in spacecraft. Ground-based accelerator simulation of space single event effects is the primary approach both domestically and internationally for evaluating and qualifying device resistance to single event effects. Space radiation particles are mainly protons and heavy ions, and large-scale nuclear facilities such as heavy ion accelerators and proton accelerators are primarily relied upon for conducting aerospace device single event effect simulation tests. Currently, research on heavy ion single event effect mechanisms and applications in China mainly relies on the HI-13 tandem accelerator at the China Institute of Atomic Energy and the heavy ion cyclotron accelerator at the Institute of Modern Physics, Chinese Academy of Sciences. Research on proton single event effect mechanisms and applications mainly relies on the 100 MeV proton cyclotron at the

China Institute of Atomic Energy. Additionally, the 200 MeV proton cyclotron at the Northwest Institute of Nuclear Technology and the 300 MeV proton cyclotron at Harbin Institute of Technology have also entered trial operation phases. Heavy ion microbeam technology is valuable for localizing and identifying device radiation-sensitive regions. Limited by beam spot size, device sensitive region localization accuracy can only reach the sub-micron level. In the future, the demand for radiation-hardened devices and technologies in fields such as aerospace and the nuclear industry will continue to increase. It is necessary to further exploit the application potential of existing domestic single event effect simulation test facilities while also planning new, more capable scientific research platforms for single event effect testing.

Author Contribution Statement

CHEN Qiming was responsible for test organization, and drafting and revision of the manuscript; GUO Gang was responsible for overall facility planning and construction and project funding support; SUI Li was responsible for research program guidance; LIU Jiancheng was responsible for heavy ion facility commissioning; ZHANG Yanwen was responsible for proton facility commissioning; ZHANG Fuqiang was responsible for uncertainty analysis of beam measurement data; YIN Qian was responsible for proton facility beam diagnostics; HAN Jinhua was responsible for proton beam expansion; ZHANG Zheng was responsible for microbeam facility commissioning; SUN Haohan was responsible for microbeam localization inversion.

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Note: Figure translations are in progress. See original paper for figures.