Multi-Anode Photomultiplier Tube reliability analysis and radiation hardness assurance for the JEM-EUSO Space mission

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Abstract: Reliability assessment is concerned with the analysis of devices and systems whose individual components are prone to fail. This analysis documents the process and results of reliability determination of the JEM-EUSO PhotoMultiplier Tube (PMT) component under the Total Ionizing Dose (TIDs). In terms of TIDs, the PMTs that may fail due to this type of radiation is of the order of 246 PMT from a total amount of 4932 PMT, which cover the focal surface of the telescope. This means a reliability of around 95%. However, the calculations show that the reliability of the “failing components”, the remaining 5% of the PMTs, is around 80% in five years of operation of the JEM-EUSO Space Mission. Therefore, it can be concluded that around 99% of the PMT’s in terms of TIDs will complete their operation without failure, ensuring the success of the mission as far as radiation TIDs is concerned.

Keywords: JEM-EUSO, PMT’s, Reliability, Radiation.

1 Introduction

JEM-EUSO [1] is a large imaging telescope designed to study the Ultra-High Energy Cosmic Rays (UHECR) at energies above 10^{20} eV. Looking downward the Earth from the International Space Station (ISS) it will detect such particles observing the UV light generated by Extensive Air Showers (EAS) the UHECRs develop in the atmosphere. The scientific objectives of the mission include charged particle astronomy and astrophysics, with the aim at extending the measurement of the energy spectra of the cosmic radiation beyond the Greisen-Zatsepin-Kuzmin (GZK) effect [2], together with the detection of Extremely High Energy Gamma Rays (EHIGR) and of Extremely High Energy Neutrinos (EHEN).

JEM-EUSO is being designed to operate for 5 years on board the ISS orbiting in a Low Elevation Orbit (LEO) around the Earth at altitude of about 400 km. As for any mission to be operated in space, JEM-EUSO must comply to specific requirements, i.e. high radiation doses, unaccessibility and remote controlled operation. That is why the reliability analysis and radiation hardness assurance is extremely important in order to determine the tolerance and redundancy requirements within the system as previous studies [3][4] show in case of FPGA which also applies to PMTs.

The design and the construction of the JEM-EUSO telescope is a real technical challenge, as it involves the use of new technologies from the laboratories of both industrial and research in areas as diverse as large optical and accurate Fresnel lenses, a technique of photo detection highly sensitive with very accurate resolution, and very innovative analog and digital electronics as well.

2 Objectives

The main aim of this work is to determine the radiation hardness assurance to evaluate its present and potential reliability of the JEM-EUSO Photomultiplier Tube (PMTs) implemented on the focal surface of the Space telescope, in order to ascertain the viability for this mission, since the PMT is a critical part of the instrumentation.

3 Analysis

PMTs have been used in the past from UV to near-IR photon detection. When used in combination with scintillation or Cherenkov materials, they can also detect more energetic ionising radiations. PMTs consist of a vacuum tube containing a cathode with a high photoelectric yield, and a series of dynodes with high secondary electron yield, each dynode biased to a steadily increasing potential before the anode is reached. The potential gradient ensures amplification with the multiplication of the number of electrons so that a single particle can release typically 10^6 electrons which can be detected electronically [5][6].

Background events can be induced in a PMT by one or more of the following mechanisms:

- Direct ionisation of the cathode or dynode by a particle producing secondary electrons.
- Fluorescence, or more generally scintillation, in any optical components of the PMT (or instrument which are in-line-of-sight of the photocathode) induced as a result of ionisation by an incident particle.
- Cherenkov radiation induced in any optical components of the PMT (or instrument) from particles above the Cherenkov threshold for the material.
Previous space missions like HIPPARCOS measured background effects on PMTs due to Cherenkov and fluorescence processes from radiation-belt electrons, magnetospheric electron events and solar proton events [7, 6].

4 Radiation Hardness Assurance

The Radiation Hardness assurance of PMT’s for their qualification requires meeting stringent radiation tolerance levels. The majority of radiation hardness assurance have so far focused on laboratory test, therefore, as a first step towards understanding the long-term reliability of PMT’s in hostile radiation environments, it is required to perform an analytical and theoretical, probabilistic estimation which predicts the reliability of the PMT’s in space environments and radiation conditions for JEM-EUSO. Its focal surface is a spherical curved surface, of area 4.5 m\(^2\) and it is covered with about 5,000 Multi-Anode PhotoMultiplier Tubes (MAPMT) Hamamatsu R11265-03-M64 MOD: MAPMT. The focal surface detector consists of Photo-Detector Modules (PDMs), each of which consists of 9 Elementary Cells (ECs). The EC implements 4 units of MAPMTs. Therefore, about 1,233 ECs or about 137 PDMs are arranged on the whole focal surface with 384,000 pixels [8].

4.1 Total Ionizing Dose Radiation Hardness Assurance Model

TID is defined as the amount of energy deposited by ionisation or excitation in a material per unit mass of material. Since the dose is dependent on the target material, the dose is expressed in rad(Si). The components most sensitive to TID are active electronic devices such as transistors and integrated circuits (ICs). Their sensitivity thresholds typically range from 1 krad(Si) to 1 Mrad(Si) depending on the technologies used. Total Ionising dose (TID) degradation in microelectronics results from the build up of charge in insulating layers, and has a cumulative effect on electronics, resulting in a gradual loss of performance and eventual failure [5].

Provided that the particle intensity and spectrum does not change significantly travelling through the material, TID can be determined from the charged particle fluence at the surface of the material, and the electronic stopping power of the particle based on the approximate formula:

\[
D = \frac{1}{\rho} \int_{E_1}^{E_2} \psi(E) \frac{dE}{dx}(E) dE
\]  

where \(\rho\) is the mass density of the material, \(\psi(E)\) is the differential energy spectrum defined between \(E_1\) and \(E_2\), and \(dE/dx\) is the stopping power in units of energy loss per unit particle pathlength.

The TID for the JEM-EUSO Mission was calculated using the SPENVIS computer software [9] as well as the orbital parameters of the international space station (Table 1). Appropriate parameter values for JEM-EUSO were collected and then used as input for SPENVIS. The basic parameters for the mission were the type of trajectory path, Mission Duration, Start data and mission Space Segments. According to the results shown by SPENVIS, and taking a 3 mm shielding for JEM-EUSO, the dose rate will be mostly due to trapped protons, and bremsstrahlung (Fig. 1) for a total dose estimate of 10 krad (Fig. 2), which leads to conclude that the type of radiation and shielding is the appropriate.

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<th>Table 1: the international Space station in orbit (ISS)</th>
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![Fig. 1: SPENVIS PMT total mission dose](9)](9)

![Fig. 2: Dose as a function of shielding](9)](9)

The reliability of a PMT under TID may be evaluated, according to [11], taking into account that the probability...
of failure is equal to the probability that its TID exceeds its hardness. Then, when a component with a radiation hardness $H$, received a TID $x_D$, the reliability $R(t)$ of the component may be calculated by the joint distribution function:

$$R(t) = \int_0^\infty \int_0^x f(x_D, x_H, t) dx_H dx_D$$  \hspace{1cm} \text{(2)}$$

where $f(x_D, x_H)$ is the joint distribution function, $x_D$ is the TID received by PMT in one year; $x_H = \frac{x_D}{t}$, is the ratio between the TID received and the radiation hardness of the PMT; and, $t$ is the exposure time to the radiation in years.

LEO refers to orbits in the 100-1,000 km altitude range, which includes Earth-Observing Satellites (EOS). A special case is the Space Station (ISS) at $\sim 400$ km. The environment in LEO is fairly benign, with a typical dose rate of $x_D = 0.1$ krad/year.

For a mission with a typical duration of 3-5 years, the total dose is $< 0.5$ krad [12]. Hence, taking into account a radiation hardness for JEM-EUSO of $H = 10$ krad [8], the PMT time-dependent reliability is as follows:

$$R(t) = e^{-x_H} \int_0^\infty e^{-x_D} dx_D dx_H = e^{-x_H}$$

\hspace{1cm} \text{with} \hspace{1cm} x_H = \frac{x_D}{t} \hspace{1cm} \text{(3)}$$

An approach to comprise the reliability estimation due to TIDs is analyzing its behavior over time. In any case, considering JEM-EUSO time mission is 5 years and according to equation [3] the PMTs reliability is around 95% in case of one PMT. This behaviour is shown in Figure 3.

If we assume higher (TIDs) radiation levels, obviously, the reliability of the PMTs will have a considerable decrease. Taking a look at Figure 4 assuming that the radiation be now $H = 20$ krad total dose, the reliability range would roughly fall between a maximum of 80% and a minimum of 70%.

The estimation obtained by applying the total ionizing dose radiation hardness assurance model provides the reliability for a single PMT. Hence, to determine the reliability of all PMTs that will be used in the JEM-EUSO telescope focal surface, it is necessary to apply the Poisson distribution. This is shown in Figure 5. In this case, for a total amount of 4932 PMTs, 246 are expected to fail with a probability of 2.5% of getting that specific number of failure. It does suggest that the PMT designed for JEM-EUSO is robust and highly reliable against the influence of TIDs.

As a final step in determining the reliability of the JEM-EUSO PMTs under TIDs influence, it is necessary to know the reliability of the components that are expected to fail. Following the Poisson cumulative distribution, this analysis has been carried out and the result is shown in Figure 7. This plot can be considered as a further confirmation that JEM-EUSO PMTs meet specific requirements for Space environment. It also shows that concerning the 246 PMTs that are "expected" to fail, their reliability is around 80%.
Fig. 6: 3D view of reliability vs time due to TIDs according to the Total Ionizing Dose Radiation hardness assurance model

Fig. 7: Accepted number of failures of PMTs under the influence of TIDs

5 Conclusions

The reliability of a PMT to be operated for space applications is closely related to the exposure it may have against Total Ionizing Dose. A method to calculate the reliability and radiation hardness assurance of PMTs under the effects of TIDs has been presented. This technique introduced a model which estimates the effects of the accumulation of TIDs in the PMTs during the time in which it is operating in Space.

In terms of Total Ionizing Dose (TIDs), the number of PMTs that may fail due to this type of radiation is of the order of 246. However, the calculations show that the reliability of these components that could fail is around 80% in five years of operation. Therefore, it is reasonable to conclude that around 99% of the PMT’s in terms of radiation TIDs will complete their operation without interruption, ensuring the success of the mission as far as regards radiation TIDs.

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