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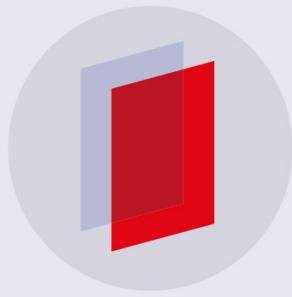
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LIDAL (Light Ion Detector for ALTEA): a compact Time-Of-Flight detector for radiation risk assessment in space

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Abstract. Manned space missions towards Moon and Mars planned in the next decades require a reliable radiation risk assessment considering the long time exposure of astronauts (up to years) to different radiation fields. The radiation environment inside a human space habitat, generated by the interaction of the Galactic Cosmic Rays and occasionally of Solar Particle Events with the spacecraft hull, is peculiar due to its composition (ions from Hydrogen to Iron, knock out neutrons) and the large kinetic energy range of the particles. For this reason the risk assessment approach used for astronauts in space is quite different from the one used on Earth. In this approach the risk for astronauts is evaluated calculating factors which score the risk in function of physical characteristics of the single particle, like the *quality factor Q* (related to the radiation ionizing power) or the squared ratio between the charge (Z) and velocity (β) of the particle (Z^2/β^2).

LIDAL-ALTEA (Light Ion Detector for ALTEA - Anomalous Long Term Effects on Astronauts) is an experimental apparatus which will allow to evaluate for the first time in the field the Z^2/β^2 risk factor of the single detected particle on-board the International Space Station.

The LIDAL system is a Time-Of-Flight detector designed to work paired to three Silicon Detector Units of the ALTEA, which will measure the deposited energy of the passing particle. The velocity of the particle (β), calculated from the Time-Of-Flight measurement performed by LIDAL, allows to evaluate the particle electric charge once related to the deposited energy measured by ALTEA. A first LIDAL prototype has been developed by the University of Rome "Tor Vergata" and tested at TIFPA (Trento Insistute for Fundamental Physics Applications) proton beam line, in order to evaluate the timing performances of the detector. Results are briefly presented and the current status of the apparatus production is discussed in view of the launch scheduled for 2019.

1. Introduction

Next manned missions in space towards Moon and Mars require reliable radiation risk assessment for astronauts, considering their long time exposure (years) to radiation fields that occasionally can be quite high. For this reason a detailed characterization of the radiation spectra inside human space habitats is needed. LIDAL-ALTEA (Light Ion Detector for ALTEA - Anomalous Long Term Effects on Astronauts) is a compact apparatus currently developed to fly on-board the International Space Station (ISS) to characterize the radiation environment inside the human space habitat. In high latitude tracts of the ISS orbit, the radiation field inside ISS modules mimics the expected one in spacecrafts during deep space missions [1]. For this reason its detailed characterization might be crucial to plan manned missions far from Earth. LIDAL is a Time-Of-Flight (TOF) detector designed to work paired to three ALTEA Silicon Detector Units (SDUs), which measure the particle deposited energy in silicon. TOF measurement performed by LIDAL, used to evaluate the speed of the particle (β), allows to evaluate also its charge Z once related to the particle deposited energy measured by ALTEA (see Fig. 1). These quantities can be used to calculate the factor Z^2/β^2, which scores the exposure risk for astronauts [2].

Performances of the technological solutions chosen to reach the designed time resolution (less than 120 ps of σ), such as fast plastic scintillators, PMTs (Photo Multiplier Tubes), fast discriminator chip and High performance TDC (Time to Digital Converter) chip (HpTDC), have been verified by developing a first LIDAL prototype. The prototype has been tested at proton beam line at TIFPA (Trento Insistute for Fundamental Physics Applications) in Trento. The results, briefly presented in this work, allowed to design the final version of the detector. The Engineering Model of the apparatus will be ready by the end of October 2018, while the Flight Model is manifested to be sent on-board the ISS in spring 2019. Next sub-sections introduce the risk assessment in space and explain how the LIDAL-ALTEA apparatus fulfills technical requirements needed to have data for a reliable risk assessment for radiation exposure in space.

1.1. Radiation field in human space habitats

During manned missions in space the astronauts are exposed to the *so-called* primary radiation fields which surround the spacecraft and to the secondary radiation fields, generated by the interaction of the primaries with the spacecraft hull. The main components of the primary radiation fields are the Galactic Cosmic Rays (GCRs) and the Solar Particle Events (SPEs). GCRs consist of ions, from Hydrogen to Iron, with kinetic energies that peak around 2 GeV/A, where A is the mass number. This radiation field is isotropic and is always present in each point of the Galaxy, but, concerning the manned missions in Low Earth Orbit (like ISS), its dynamics depends upon the spacecraft position along its orbit. Particles from SPE (Solar Particle Events) are mostly protons emitted by flares or CME (Coronal Mass Ejections) of the Sun: therefore they can hit the spacecraft sporadically, depending also upon the position of the spacecraft.

The secondary radiation fields, generated by the interaction of primary particles with the spacecraft hull, consist in knock-out neutrons and ions generated by the nuclear fragmentation process. This component, summed up to the primary component, interacts with tissues and organs of astronauts.

1.2. Risk Assessment on Earth and in space: a different approach

The risk assessment for radiation exposure is based, both on Earth and in space, on two kinds of quantities: the physical quantities and the radio-protectional ones. Physical quantities are measured using a particle detector: the absorbed dose D is one of the most important ones and gives the infinitesimal deposited energy released in the infinitesimal volume of mass. The radio-protectional quantities are evaluated starting from the physical ones: the most important are the *Equivalent Dose H_t*, related to the *deterministic effects* and the *Effective Dose E*, related to *stochastic effects*. Deterministic effects appear after exposure to high doses: they

are characterized by the existence of dose threshold above which, certainly, an effect on human tissue/organ is manifested. Stochastic effects can manifest after long exposure to quite low doses: there is no dose threshold and the linear correlation between the dose and the severity of effect is generally assumed but not demonstrated. The Equivalent (H_t) and Effective (E) doses are evaluated according to the equations:

$$H_t = \sum_r w_r D_{r,t}$$

$$E = \sum_t w_t H_t = \sum_{r,t} w_t w_r D_{r,t}$$

$$(1)$$

where $D_{r,t}$ is the absorbed dose by a tissue t delivered by a radiation r, w_r and w_t are risk factors whose meaning is explained below. The factor w_r weighs the risk associated to a certain type of radiation in function of its ionization power. According to the International Commission on Radiological Protection (ICRP) prescriptions [3], w_r for a nuclear fragment is 20 times the w_r for a photon, due to the higher ionization power of the ion. The factor w_t weighs the tissue or organ radio-sensibility: tissues/organs with higher cell reproduction rate are more radio-sensible than those with lower cell reproduction rate [4].

For high doses (deterministic effects) the risk is evaluated using data from Hiroshima/Nagasaky nuclear bomb explosions, criticality accidents in nuclear plants and cell cultures exposed to high doses for example at accelerators. Results coming from the latter approach are also extrapolated to lower doses to evaluate the risks for stochastic effects, studied also with the epidemiological approach (statistical). Risk assessment for astronauts and evaluation of radio-protectional quantities in space, such as the equivalent dose, require a quite different approach because of the fundamental differences between the two radiation environments

. To evaluate the equivalent dose in space, a blind use of w_r tabulated by ICRP for exposure to the cosmic ions spectrum ($w_r = 20$ for every ion), cannot allow to differentiate the contribution of different ions interacting with the tissues or organs. For this reason in space the equivalent dose is calculated by replacing the factor w_r in eq.1 with the quality factor Q (defined according to ICRP [3]) which weighs the dangerousness of a particle in function of its Relative Biological Effectiveness (RBE) [3] and its Linear Energy Transfer (LET).

Nowadays it is known that also the equivalent dose is not the best radio-protectional quantity to use for risk assessment in space: the concept of equivalent dose itself is based on homogeneous irradiation of the tissue or organ. The exposure to cosmic ions field of tissue/organs is generally not homogeneous and the related risk is a function of the track position with respect to the cell. For these reasons other factors which can weigh accordingly the risk are currently under investigation. According to Ref. [2] a suitable factor related to the risk is the ratio Z^2/β^2 of the Bethe-Bloch equation. This ratio is proportional to the ionizing power of the particle: higher ionization powers mean more kinetic energy transferred by the particle to the tissue, where it can damage cells and DNA. The functional behaviour of the ratio can be explained by the following considerations. At a first glance the interaction between an ion and the atomic electrons in the tissue hit by the particle occurs through the ionic electric field, which grows with the particle charge Z. At the same time an ion with lower velocity will stand more time in proximity of the atoms, ionizing them more effectively and transferring to them more energy with respect to a fast traveling ion. For these reasons a heavier ion with lower kinetic energy can deliver to the tissues higher doses with respect those delivered by a light fast traveling ion.

LIDAL-ALTEA apparatus is designed to measure the physical quantities to calculate this ratio for the first time in space particle by particle. TOF measurements performed by LIDAL allow to measure the β factor, while the ion charge Z is evaluated through PID (Particle Identification as shown in Fig.1), where the ion discrimination is performed by applying Bethe-Bloch equation.
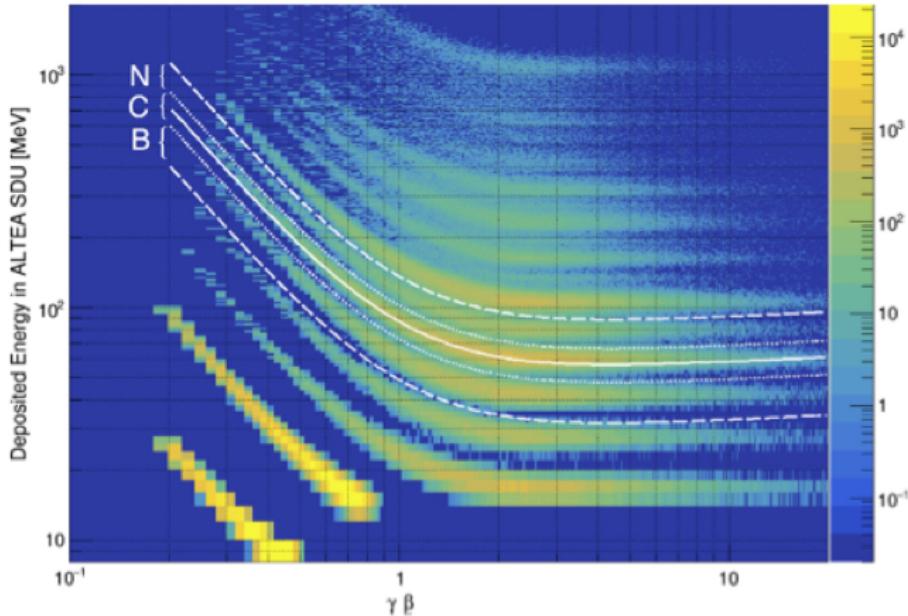
Figure 1. Expected spectrum acquired by LIDAL-ALTEA in 20 days of data taking. The white lines are the values of the Bethe Bloch equation for Boron, Carbon and Nitrogen ions. On Z axis (right) are shown the counts.

2. LIDAL detector and the prototype tests

In order to fulfill time resolution requirements for LIDAL apparatus (below 120 ps of σ, according to the simulations shown in Fig.1), state-of-the-art technological solutions suitable for space application have been chosen. Very fast plastic Scintillators (EJ-230 [5]) with 500 ps of rise time have been coupled, using PMMA light guides, to Hamamamatsu R988OU-110 PMTs (570 ps of rise time [6]). The output signal is processed by a NINO chip, a fast pre-amp and discriminator developed by CERN [7], and sent to a HpTDC chip used in High resolution mode (time resolution/channel 25 ps) [8]. A first prototype has been developed at "Tor Vergata" University and tested at TIFPA proton beam line to evaluate the timing performances of the detectors. The prototype uses two fast scintillators (dimensions $90 \times 25 \times 8$ mm) coupled, through two PMMA light guides placed at both ends of scintillator bar, to two PMTs. The distance between the scintillators can be set at 60 and 65 cm. More details about prototype apparatus and measurements results can be found in Ref.[9]. After equalization of the delay signal lines among the PMTs, several runs at different energies have been taken in the auto-trigger condition (AND condition between the two scintillators[1]). Two examples of TOF distributions are shown in Fig. 2 For protons in energy range between 70 and 230 MeV available at TIFPA beam line, time resolutions between 70 and 80 ps (σ) have been measured. The light collected at PMTs resulted to be plenty, giving PMT output signals larger than 2V in slightly undersupplied power conditions (about 900 V). This evidence led to a reduction of dimensions of final plastic scintillators to $80 \times 20 \times 4$ mm, a solution which can boost also the time performances in terms of signal timing development [9].

[1] No external trigger was applied in order to have conditions similar to the real ones in space.
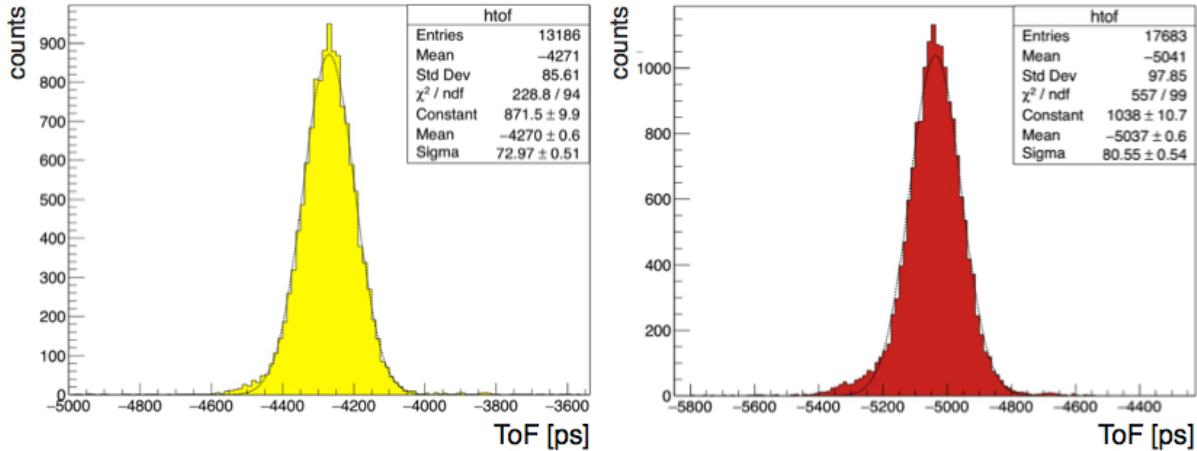
Figure 2. Left: TOF distribution for 159 MeV proton measured with a baseline of 65 cm. Time resolution (σ) is 73 ps. Right: TOF distribution for 159 MeV proton measured with a baseline of 60 cm. Time resolution (σ) is 81 ps. More details on the measurements can be found in Ref.[9].

3. Future perspective and conclusions

The LIDAL-ALTEA apparatus is manifested to be sent on-board the International Space Station in 2019. The results obtained during the measurements campaign at TIFPA proton beam line have been used to finalize the design of the detector. In particular the design of the electronic boards has been successfully completed and their production process started. The 32 scintillators units needed to realize the Engineering and the Flight Model of the apparatus are being realized at the University of "Tor Vergata". Each unit consists of a plastic scintillator coupled to two PMTs through two light guides. The optical contact between the scintillator and the light guides and between the light guides and PMTs is realized through optical cement EJ-500 [10]. Preliminary studies on tensile strength have been carried out on scintillators glued with light guides giving a breaking point higher than 7 MPa. The gluing procedure is done using specifically designed tools which allow to fulfill the required mechanical tolerance of 100 μm. Temperature and humidity are continuously checked using environment sensors. The PMTs are characterized before the gluing procedure by coupling them with scintillators realized for the first prototype and by exposing them to a Sr-90 source. After the gluing procedure the final scintillator unit is tested using the same radioactive source and the two responses are compared.

The LIDAL-ALTEA engineering model is scheduled to be ready in October 2018. Two beam tests are scheduled to characterize and calibrate the detector. The first will be held at TIFPA proton beam line in December and the second will be held at GSI (Helmholtzzentrum fur Schwerionenforschung GmbH) in February 2019, to calibrate the Flight Model apparatus with different species of ions.

References

[1] Narici L *et al.* 2017 *Scientific Reports* **7**, 1644.
[2] Cucinotta F 2013 *NASA TP* 217375 118121.
[3] *ICRP Publication* 92 2003 **4**.
[4] *ICRP Publication* 103 2007 **2-4**.
[5] *Fast timing EJ-228, EJ-230* available at: http://www.eljentechnology.com/products/plastic-scintillators/ej-228-ej-230. (Accessed July 2018).
[6] *Hamamatsu R9880U PMT series* available at: http://www.hamamatsu.com/resources/pdf/etd/R9880U_TPMH1321E.pdf (Accessed July 2018).

[7]   Aghinolfi F *et al.* 2004 *IEEE Trans. Nucl. Sci.* **51** 1974-1978.

[8]   Christiansen J 2004 *"HpTDC High Performance Time to Digital Converter Version 2.2"* available at
      https://cds.cern.ch/record/1067476/files/cer-002723234.pdf (accessed September 2018.

[9]   Rizzo A *et al.* 2018 *Nuclear Inst. and Methods in Physics Research A* **898** 98104.

[10] *EJ-500 optical cement datasheet* available at : https://eljentechnology.com/images/products/data_sheets/$EJ-500.pdf$ (Accessed July 2018).