Hardware and software methods for radiation resistance rising of the critical infrastructures

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Abstract: Recently, it has become evident that continuous operation of critical infrastructures in space has turned into a matter of utmost priority for communications, command and control, reconnaissance and surveillance, global positioning and geodesy, navigation and timing. Space operations are also increasingly integrated into civilian activities such as Earth observation, weather prediction, assessing the impact of human activity on global climate, research and exploration. Spacecraft hardware depend on electronic components that must perform reliably over missions measured in years and decades. Space radiation is a primary source of degradation, as it poses reliability issues that can finally result in potential in the operation of these electronic components. Although simulation and modelling is valuable to understand the radiation risk for microelectronics, there is no substitute for testing. Although the effort of testing may be difficult and expensive, it is small compared to the cost of a radiation-induced failed mission, which can go up to hundreds of millions of euros. We report some methods to ensure Rad-Hard by Design, Rad-Hard by Process and Rad-Hard by Software, as well as associated testing methods by using laser-plasma accelerated particles. Thus, the PW laser facilities in Magurele at INFLPR (CETAL) and ELI-NP have the potential to become relevant for space applications, and to make a significant contribution for enhancing the reliability of critical infrastructures submitted to radiations from space, or in case of nuclear accidents like those in Chernobyl and Fukushima.

Keywords: digital social order, cybercrime, cybersecurity

INTRODUCTION

The interest for radiation-hardening applications is continuously rising, fueled by the vital importance of high-reliability, radiation-hardened and radiation-tolerant components, for both aerospace and defence applications [1]. Space radiation is an important source of problems, which poses reliability issues that might result in potential failure for electronic components and systems, producing spacecraft and instrument degradation, electric charging of the spacecraft or noise generated by particles that hit the detectors area, etc.

Space radiation consists primarily of ionizing radiation which exists in the form of high-energy, charged particles. There are three naturally occurring sources of space radiation: trapped radiation, galactic cosmic radiation (GCR), and solar particle events (SPE).

1. Cosmic rays come from all directions and

consist of approximately 85% protons, 14% alpha particles, and 1% heavy ions, together with x-ray and gamma-ray radiation. Most effects are caused by particles with energies between 0.1 and 20 GeV. The atmosphere filters most of these, so they are primarily a concern for spacecraft and high-altitude aircraft.

2. Solar particle events (SPEs) come from the direction of the sun and consist of a large flux of high-energy (several GeV) protons and heavy ions, accompanied by X-ray radiation. A solar explosion is illustrated in Figure 1.

3. The Van Allen radiation belts contain electrons (up to about 10 MeV) and protons (up to 400 MeV) trapped in the geomagnetic field. The particle flux in the regions farther from the Earth can vary severely depending on space weather and the magnetosphere. Due to their position, the van Allen belts represent a major threat for satellites.

Typical sources of exposure of electronics to ionizing radiation are the Van Allen radiation belts, nuclear reactors in power plants for sensors and control circuits, particle accelerators for control electronics particularly particle detector devices, residual radiation from isotopes in chip packaging materials, cosmic radiation for spacecraft and high-altitude aircraft, and nuclear blasts for potentially all military and civilian electronics.

Secondary particles might result from the interaction of other kinds of radiation with structures around the electronic devices. Nuclear reactors produce gamma radiation and neutron radiation which can affect sensor and control circuits in nuclear power plants. Particle accelerators produce high energy protons and electrons, while the secondary particles generated by them inflict significant radiation damage on sensitive control and particle detector components, of the order of magnitude of 10 MRad[Si]/year for systems such as the Large Hadron Collider (LHC). Nuclear explosions produce a short and extremely intense surge spanning a wide spectrum of electromagnetic radiation, electromagnetic pulses (EMP), neutron radiation, and a flux of both primary and secondary charged particles. In case of nuclear war they pose a potential concern for all civilian and military electronics. Chip packaging materials were an insidious source of radiation that was found to be causing soft errors in new
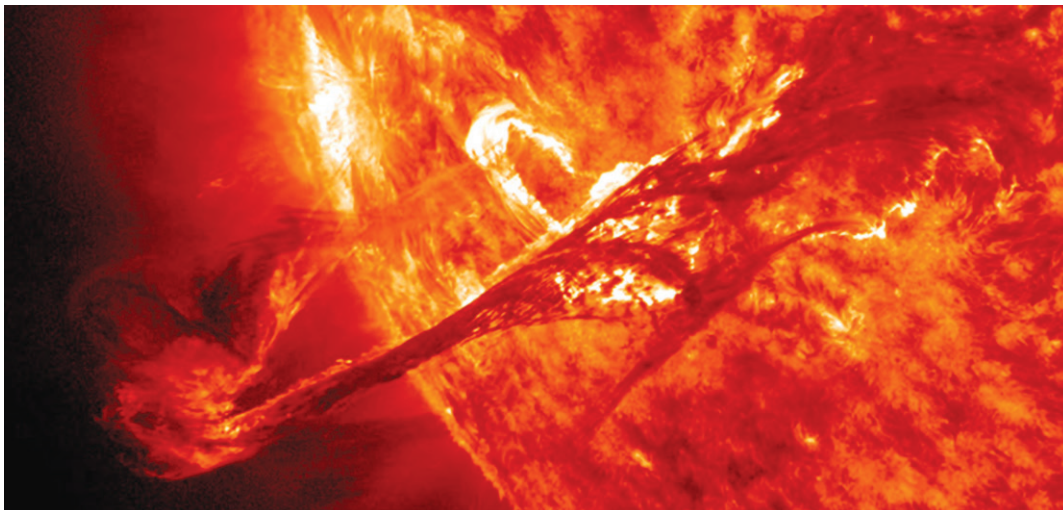

Figure 1: *A gorgeous filament eruption as seen by NASA's Solar Dynamics Observatory. This coronal mass ejection (CME) is a significant release of plasma and accompanying magnetic field from the solar corona, an aura of plasma that surrounds the Sun. Coronal mass ejections, can disrupt radio transmissions and cause damage to satellites and electrical transmission line facilities. Energetic protons released by a CME can cause an increase in the number of free electrons in the ionosphere with the enhancing radio wave absorption. (Image Credit NASA)*

DRAM chips in the 1970s. Traces of radioactive elements in the packaging of the chips were producing alpha particles that occasionally discharged some of the capacitors used to store the DRAM data bits. These effects have been reduced today by using purer packaging materials and employing error-correcting codes to detect and often correct DRAM errors.

SPEs generally involve low-energy particles, following solar activity (Figure 1), that can be blocked using shielding. They can be sudden and intense, however, creating a real danger both for biological material and opto-electronic components and systems (Figure 2). The basic approach when investigating space radiation effects is to replicate the space environment to the largest extent possible. Unfortunately, the complex mechanisms that are typical for space radiation and the large number of parameters involved render such an attempt a very difficult task, which is raising very demanding challenges.

The biological effects of radiation exposure vary and are not entirely understood, as well as the damage effects, either reversible or not, inflicted upon electronic components. A better characterization of the underlying mechanisms requires a good characterization of the deep space environment and use of shielding that can protect against all possible forms of radiation exposure. The most distinct feature of space radiation, particularly trapped radiation, is the exponential energy spectra of particles.

The biological and instrumental (hardware) degradation that can result from the disturbance caused by high energy particle radiation, requires detailed investigations of the energetic particle radiation incident on the space ship, and detailed knowledge about how the radiation varies in time. The risks associated with radiation exposure cannot be measured directly. Therefore, measurements of Total Ionizing Dose (TID) and estimations of displacement damage (DD) and Single Event Effects (SEE) must be performed. One of the biggest challenges of Solar system exploration is the variety of extreme environments that orbiters, landers and probes must encounter and survive. The severe radiation environment in the cosmic space, particularly in the radiation belts of the planets (Figure 3), is a major challenge for satellite equipment, and Radiation Hardness

Figure 2: *The energetic particles within a sun coronal mass ejection can penetrate the walls of spacecraft and pose a radiation risk to astronauts and the technology they depend on. They can interfere with satellites, disrupting radio communication, GPS, earth surveillance systems, etc. (Photo credit NASA)*
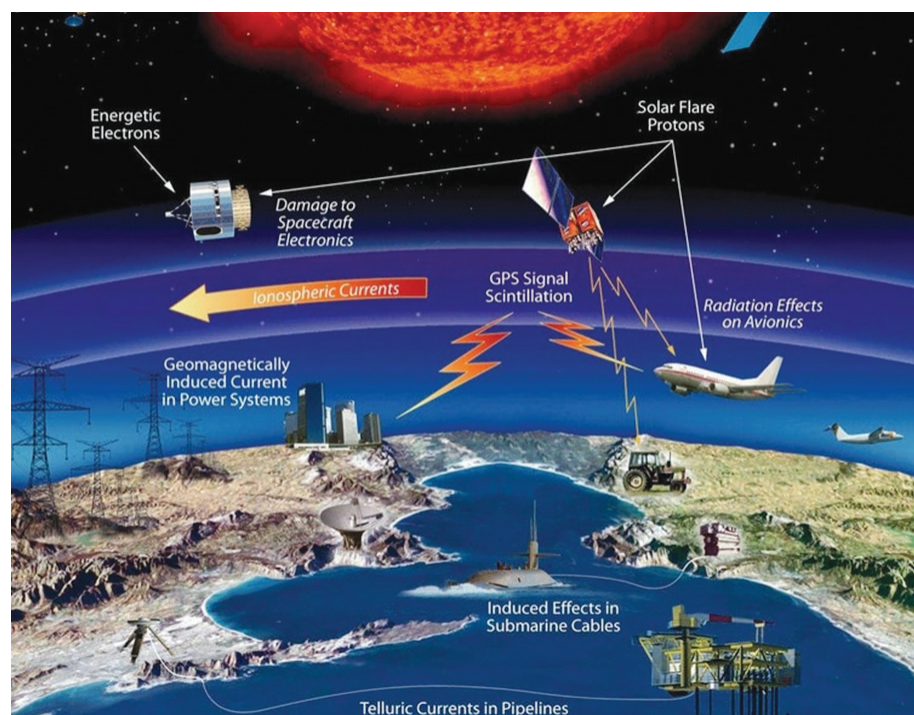
Assurance (RHA) is accordingly important for mission hardware. Spacecraft missions require evaluating potential radiation damages, then implementing appropriate design to prevent these damages, as well as radiation hardness testing of critical components.

Radiation effects that induce catastrophic effects for instrument and spacecraft design can be classified into three categories, with respect to the cause of degradation:

• Total Ionizing Dose level (TID)

• Total Non-Ionizing Dose level (TNID) or Non-Ionizing Energy Loss (NIEL)

• Single Event Effect (SEE)

Degradation from TNID or displacement damage is cumulative, long-term non-ionizing damage induced by protons, electrons, and neutrons. These particles produce defects mainly in optoelectronic components such as APS, CCDs, and opto-couplers.

Displacement damage also affects the performance of linear bipolar devices but to a lesser extent. SEEs result from ionization by a single particle as it passes through a sensitive junction of an electronic device. Environmental sources considered for single event effects (SEE) include galactic cosmic rays, alpha particles, protons, and neutrons. The effects to be considered include single-event upset (SEU), single-event latchup (SEL), single-event burnout (SEB), single-event gate rupture (SEGR), and single-event transients (SET).

Devices that depend on bulk physics for operational characteristics, such as solar cells, particle detectors, and photonic/electro-optic components, show displacement damage sensitivity. Radiation particles such as neutrons, protons, and electrons scatter off lattice ions, which can result into local damage of the material structure. The band gap structure might change, which has a direct outcome on the fundamental semiconductor properties that will degrade.

For example, the output power delivered by a spacecraft solar array degrades during the mission life of a spacecraft because of displacement damage. Another example of displacement damage is an increase in the recombination centres in a particle detector, ultimately leading to increased noise and consequent decreased energy resolution. Displacement damage also is important for photonic and electro-optical integrated circuits such as charge-coupled devices (CCDs) and opto-isolators. The amount of displacement damage is dependent on the incident particle type, incident particle energy, and target material. Displacement damage is similar to TID in that the effect is cumulative [2].

The basic approach when studying space radiation is to reproduce the space environment to the largest extent possible. Unfortunately, the complex mechanisms that are typical for space radiation and the large number of parameters involved render such attempt a very difficult task, which raises highly demanding challenges. Hence, various parameter regimes and several type of radiation sources are required in order to reproduce space radiation. Space radiation is known not to be monoenergetic, as it spans a broad energy band. The problem associated to classical radiation sources lies in the fact that they can only deliver monoenergetic particles. This explains the quest for much more adequate, broadband radiation sources and new methods to accelerate charged particles (electrons, protons, ions), suited for space radiation studies.

Although simulation and modelling are valuable tools to characterize the radiation risk for electronic and optical components, there is no substitute for testing, and an increased use of commercial-off-the-shelf parts in spacecraft and other critical infrastructures may actually increase requirements for testing, as opposed to simulation and modelling.

The testing procedure raises issues related to the proton, electron and gamma radiation spectra, which should supply information about the radiation levels to which satellites are exposed (such as the Van Allen radiation

belts). In 2010 a German group has suggested the use of very high power lasers, because laser accelerated particles exhibit a spectrum that is well suited to perform such tests [3]. Moreover, extra advantages occur related to the scale of the experiment volume and simultaneous exposure to different types of radiation [4].

Figure 3: A cutaway model of the radiation belts with the 2 Van Allen Probes satellites flying through them. The Van Allen radiation belt represents an area of energetic charged particles surrounding the Earth, most of which them originating from the solar wind, that are captured and retained by the planet magnetic field. (Image Credit: NASA)
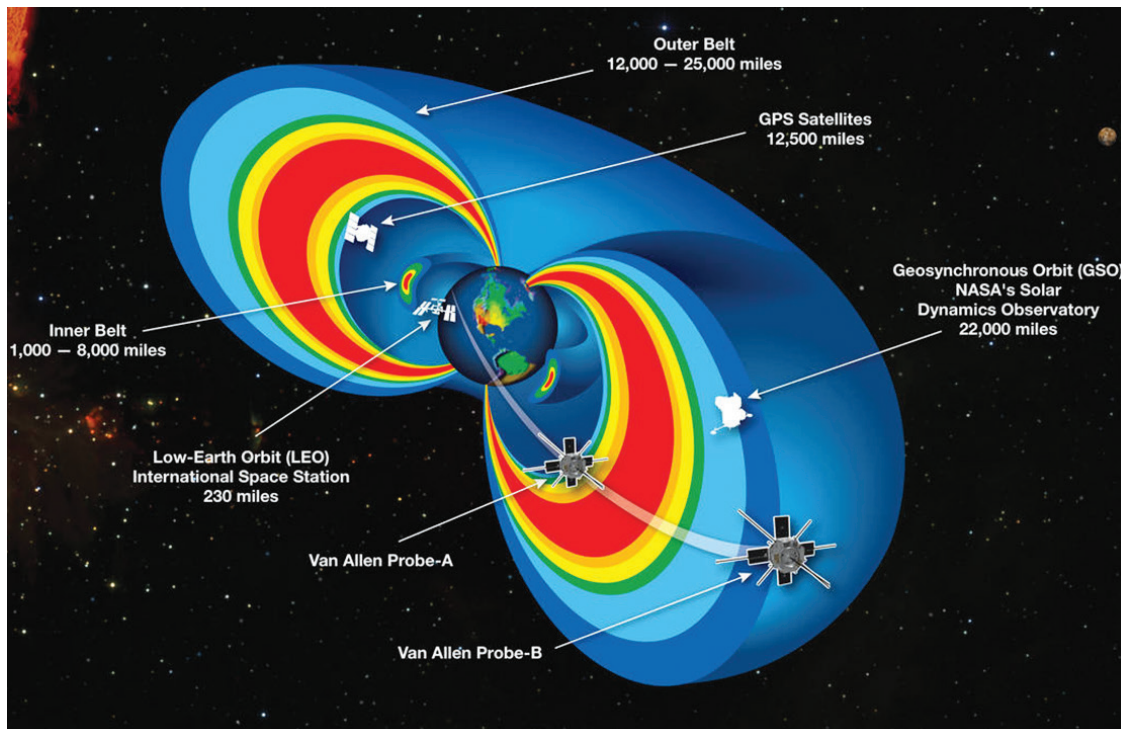
A difference with respect to the cosmic radiation is the pulsed mode of the laser-plasma acceleration of particles, but that could be an advantage which enables one to also study nonlinear and collective phenomena [4, 5]. Preliminary tests and results obtained by using laser-plasma accelerators indicate that such an approach might represent an optimum solution when it comes to reproducing space radiation and assess its damaging effects on spacecraft and satellite instrumentation [1, 3].

The Laser-Plasma Acceleration of Particles for Radiation Hardness Testing (LEOPARD) project, implemented in INFLPR, has addressed radiation hardness testing for both hardware components and software. Hardware testing is related to the behaviour of components and systems subject to intense radiation fluxes, and implies fundamental research in interaction of radiation with matter, in plasma physics or nuclear physics, as well as applied research - for example to optimize and calibrate the particle fluxes on a target. Software testing on the other hand refers to the programs that control the hardware at various levels, whose built-in redundancy can compensate for hardware faults.

Under these circumstances, the LEOPARD project has focused on exploiting the existing infrastructures and the available expertise in INFLPR, UPB and CITST. In Romania, the advantage of using the ELI-NP infrastructure (www.eli-np.ro) that comprises very high power laser systems (~ 10 PW) will consist in a sensibly larger list of facilities, while it could also be upgraded (extended) to perform tests on more complex systems such as "Radiation Hardening" by Systems and Software for example.

A first step would imply using the CETAL facility (a 30 J PW class laser, that delivers 30 fs pulses at 0.1 Hz, provided by Thales-Optronique) available at the National Institute for Laser, Plasma and Radiation Physics (INFLPR), that would account for a range of laser powers up to 1 PW. It is worth mentioning that it is possible to perform experiments at lower powers, around 300 TW, and higher repetition rates. Thus, efficient radiation hardening tests and experiments can be performed using state of the art techniques and hardware, in complete synergy with the skilled human resource involved in the CETAL and ELI-NP projects.

In terms of laser parameters required, one of the main objectives lies in getting an optimized laser spot on a solid target, for a laser intensity higher than 1019 W/cm2.

When calculating radiation doses, an important parameter that has to be known is the beam intensity and the energetic distribution of the laser accelerated particles, a mandatory condition to ascertain the absorbed dose (exposure). Passive dosimetry involves the use of a specific material to record the radiation dose, followed by reading and assessment of the detector response. The method is not adequate for measuring instantaneous dose rates, but it is highly successful and it represents a good choice for measuring the integrated radiation dose, as is the case for radiation hardening applications.

Passive dosimetry methods can be classified as: (1) thermoluminiscent (TL) dosimetry - based on a class of solid materials that are able to store the energy they are exposed to, and release it upon heating as photons; (2) optically stimulated luminescence (OSL) dosimetry - it uses solid materials that emit light when stimulated by certain ranges of photon energies, at far better quality with respect to TL dosimeters; (3) film dosimetry, based on radiochromic materials which change colour when exposed to radiation. As coloration is proportional to the incident radiation dose, radiochromic films (RCFs) enable direct radiation dose estimation; (4) Solid State

Nuclear Track dosimetry (PADC CR39). After exposure the detector is etched with a suitable solution, which reveals the damaged zones or tracks of particles. The number of tracks and their geometry represents a measure of the particle characteristics.

The experimental set-up used in these experiments [6] is presented in Figure 4. It consists of two systems: the first system is used to precisely align (toggle) the target in the laser focus, while the second system is employed to optically characterize the laser spot profile. The optical analysis system is placed in front of the target holder system.
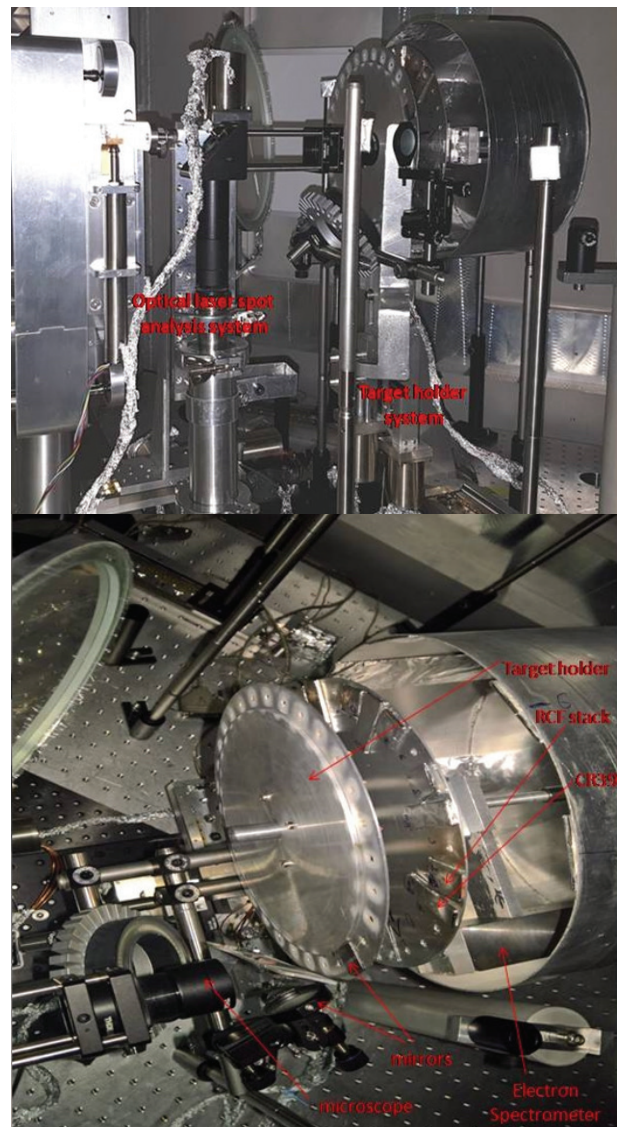

Figure 4: Experimental set up: a) general view; b) detailed target holder system.

The target holder system is made of two metallic plates, as shown in Figure 4. The first plate holds the targets, and the second plate holds the passive detectors (within 3 cm distance with respect to the targets). Both plates are rotated simultaneously by an electronically driven mechanical stage. Behind the second plate lies a magnetic spectrometer (within 4cm distance from the second metallic plate) used to detect the accelerated electrons, generated as an outcome of the interaction between the high power laser and the solid target (see Figure 1b). A cylinder rotates around the magnetic spectrometer, whose inner surface holds the radiation detectors (radiochromic films - RCFs). The incidence angle of the laser beam on target is 45o.

The optical analysis system located in front of the target consists of an optical microscope coupled with an optical camera. The system allows direct observation of the laser beam on target. Thus, the influence of the target surface morphology on the laser spot profile can be analyzed and optimized before each single laser pulse-solid target interaction.

A 100 μm thick mylar foil was placed between the parabolic mirror and the target system, positioned so as to eliminate reflexions that might occur on optical surfaces (see the left side of Figure 5b). Even if the foil was never punctured, it was replaced after each set of experiments, in order to avoid cumulative damage on the foil. The foil serves to protect the parabolic mirror against eventual debris originating from the target.

The experimental method used to fully reconstruct the laser-accelerated proton beam parameters is the radiochromic film imaging spectroscopy (RIS), which offers advantages such as a high spatial resolution and a high degree of spatial uniformity (better than 95%). The RIS method allows characterization of proton beams concerning real and virtual source size, envelope and (micro)divergence, normalized transverse emittance, phase space and proton spectrum. Calibrated GafChromic RCF type films can be used, arranged in a stack configuration, as spatial and energy resolved film detectors. High energy protons penetrate through the first films, loose kinetic energy then scatter, and finish by getting fully stopped as they reach films that are located deeper in the stack. Thus, each film layer can be associated to a certain proton energy. The measured total deposited energy in a specific RCF is the convolution of the spectrum with the response function of the RCF. To obtain the particle number spectrum, a deconvolution operation must be performed. The energy resolved proton distribution obtained from the film stack completes the beam reconstruction. We consider RCF type films with an aim to achieve 2D and 3D high-resolution dosimetry. In our project, the experimental results will be checked against numerical simulations (mainly performed with GEANT4 and SRIM). FLUKA might also be used, as the CETAL team develops competences in this direction. Geant4 is a toolkit for simulating the passage of particles through matter. It describes (1) tracking of particles through a geometry composed of different materials, (2) their interactions with the electrons and nuclei encountered, and (3) the creation of other particles as an outcome of these interactions.

Radiological use of laser-plasma accelerated electrons implies a well-defined dosimetric characterization. Apart from retrospective precise dose determination and dose homogeneity control by means of Faraday cup and GafChromic films, Monte Carlo simulations performed with the code GEANT4 could allow "a priori" characterization of dosimetric properties of relativistic electron beams produced in laser-plasma acceleration. The GEANT4 library can be used to retrieve the dose delivered to biological samples, as it has been recently extended with processes that account for the modelling of early biological damage induced by ionising radiation at the DNA scale.

RCF can provide an accurate two-dimensional map of the absorbed dose, with sub-mm spatial

resolution possibly even down to the order of tens of μm, depending on the type used. The radiochromic medium, in appropriate quantities and forms, can be used for a wide range of doses from 10^{-3} Gy up to 10^4 Gy, and this makes it attractive to many practical areas of radiation dosimetry. A state of the art RCF film scanner (Epson) can be used to read the GafChromic films.

The Secondary Standard Dosimetry System type UNIDOS with proper ionisation chamber can be used to perform absolute dosimetry and calibrate all relative dosimetry detectors (GafChromic films, OSL detectors, solid state nuclear track detectors etc.). This dosimetry system provides traceability to the PTB primary standard. All calibrations are performed respecting reference conditions of radiation beam characteristics.

Different software methodologies have been studied [7, 8] for decision-making that render computing systems resilient to operational errors which appear during their operation in high radiation fluxes of accelerated particles. Subsequently, a physical platform was designed, the CUBERTS platform, for which we developed a simulator of the proposed architecture and function. The CUBERT distributed software system allows participation of a large number of potentially faulty components in a network that can itself be faulty in certain areas. As faults are inevitable in the outer space environment, the system uses redundancy and replication to achieve fault tolerance. The basic concept is to efficiently replicate computing operations, as well as data finite processing and storage resources. The purpose of the simulator is to facilitate the development of software applications running in parallel on each of the platform nodes (e.g. 32, 64, etc. number of nodes) providing a simple way to detect errors and test / evaluate different algorithms dedicated to platform runtime.

Each node runs an independent instance of a software application. In addition, the software application manages a list of all application modules and continuously checks if a new message is sent from one of the neighbouring nodes. When a message is sent, all nodes are notified of about this event that they must instantly process. In addition, each node is notified at constant time intervals to update its internal status. The purpose of such an update event is to allow the modules to initiate and perform different types of actions at different moments of times.

The platform executes sequentially all the instructions that are performed across all nodes, while the simulator is able to mimic the delay that occurs when the nodes communicate. The simulator is also able to simulate the hostile environment in which the CUBERT platform should operate. This is achieved by randomly removing computational nodes that are subsequently reactivated with the entire memory erased.

The status of the platform can be visualized using a dedicated graphical interface. The interface also accepts commands that can be sent to the simulator in order to modify various parameters of a simulation run. For example, one can modify the computation node removal rate to test how a particular algorithm behaves in a more hostile environment. Various error messages that occur during simulation are also displayed by the graphical interface. The software application has been developed with the purpose to support a large number of application modules.

Another important aspect, concerning the laser-plasma particle acceleration is related to the electromagnetic pulse (EMP) generated as an outcome of the interaction between the laser pulse and different types of targets [9]. Such an aspect represents an issue of large interest for the PW class lasers, due to the possibility of EMP propagation along the beam line system used to carry the laser pulse. In order to guard against exceeding the radiation threshold that would result in mirror and diffraction grating

damage, the laser pulse is expanded up to diameters of tens of cm, which implies inner diameters for the Al transport line of the same order of magnitude. These beam lines behave as a cylindrical waveguide, thus enabling propagation of EMP with frequencies higher than hundreds of MHz. Recent experiments performed at the Lawrence Livermore Natl Lab-LLNL (USA) and CEA (France) were focused at determining the characteristic frequencies for these EMPs, as they depend on the target holder geometry, on the coupling mode with the ground electric potential, as well as on the geometry of the interaction chamber which acts like a resonant cavity. Electric field intensities up to values of 500 KV/m have been measured, for frequencies higher than 1 – 2 GHz (up to tens of GHz). These EMPs are practically one order of magnitude larger than those generated at the Earth surface by high altitude nuclear blasts. The solutions to mitigate the damaging effect inflicted by these pulses upon control and measurement instrumentation depend on the particular configuration of every PW class infrastructure, while they represent a niche of high interest for most of the laboratories involved. According to estimations made for the ELI-NP infrastructure, EMPs reaching 50 MV/m could result during operation [10]. We have developed techniques to simulate and measure such pulses, in an attempt to identify and implement the most adequate solutions using shielding and absorber materials, adapted to every experimental configuration. The techniques we have developed are the object of two patent applications [11, 12].

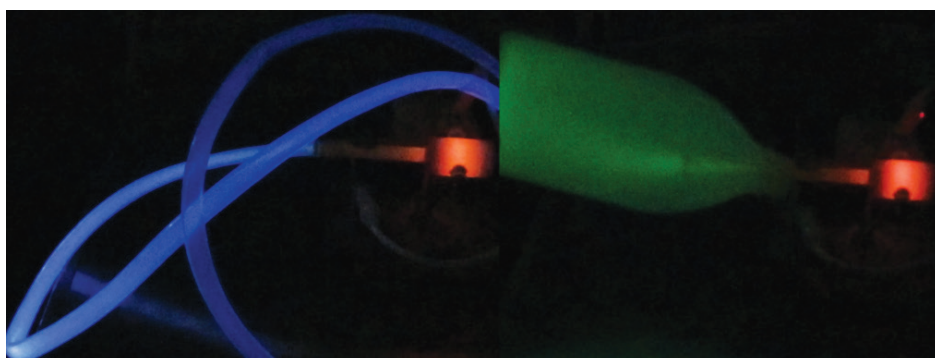*Figure 5: Aurora Borealis from the International Space Station. (Image Credit: ESA/NASA)*

Figure 6: Lights as in Aurora Borealis, in our laboratory (US7229589 B2-2007-06-12, RO132404 A2-2018-02-28).

The use of high voltage pulse generators is based on a high repetition rate of fast transient filamentary discharges in nitrogen flux [13]. These fast discharges, with time durations in the ns range, induce not only HV transients but might also generate run away electrons at atmospheric pressure, whose energy is able to dissociate nitrogen molecules. Thus, induced plasma-chemical reactions at Standard Atmospheric Temperature and Pressure conditions present similarities with the ones induced by energetic particles (Aurora Borealis), as they generate an almost identical fluorescence spectrum (Figure 5 and Figure 6). Particularly, line-shape of the peak at 557.7 nm indicates that the emission is from the $O(^1S)N_2$ excimer, similar with aurora green line [15].

The plasma-chemical reactions, that take place in the upper atmosphere, are responsible for OH radical creation, an efficient natural chemical and biological cleaning process for the atmosphere [14]. Thus, among other applications of such atomic nitrogen generator was a new method of fast decontamination [13] of medical instrumentation, and for rapid intervention after an accident or terrorist attack that would lead to biological contamination [16]. This technique could also be extended for aerospace applications, in particular to avoid biological contamination or microorganism proliferation.

DISCUSSIONS AND CONCLUSIONS

The Laser-Plasma Acceleration of Particles for Radiation Hardness Testing (LEOPARD) project, implemented in INFLPR, has addressed radiation hardness testing for both hardware components and software. Hardware testing is related to the behaviour of components and systems subject to intense radiation fluxes, and implies fundamental research in interaction of radiation with matter, in plasma physics or nuclear physics, as well as applied research - for example to optimize and calibrate the particle fluxes on a target.

Software testing on the other hand refers to the programs that control the hardware at various levels, whose built-in redundancy can compensate for hardware faults. Under these circumstances, the LEOPARD project has focused on exploiting the existing infrastructures and the available expertise in INFLPR, UPB and CITST, focusing on developing new competencies based on national and international collaborations, and the involvement of leading young scientists, with the aim of developing systems and procedures for testing components and complex equipment intended for space applications.

The main purpose of the LEOPARD project was to determine the effect of an external flux of laser-plasma accelerated particles, that can be accompanied by electromagnetic pulses, X or gamma radiations at different energies and intensities, upon both the operating characteristics and parameters, as well as upon the program controlling the operation of the tested components and equipment.

Based on such tests, the project has provided relevant information for the design and fabrication of electrical, electronic, optical, and mechanical components/equipments on-board satellites, spacecraft or airplanes flying at very high altitudes.

Thus, the high-power laser equipment in Magurele has the potential to become relevant for space applications [17] and to make a significant contribution for enhancing the reliability of critical infrastructures as the LEOPARD project goes further by means of an ESA contract [6].

ACKNOWLEDGEMENTS

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