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FAST NEUTRON IRRADIATION FACILITIES FOR ELECTRONICS AND MATERIALS

NEW OPPORTUNITIES AT SPALLATION SOURCES IN EUROPE

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Neutrons are the neutral particle probe of choice for the investigation of materials at the atomic scale. The delicate, precise and highly penetrating nature of low-energy (thermal) neutron beams make them ideal to study non-destructively the structure and dynamics of matter with atomic resolution. However the interaction of high-energy (fast) neutrons with materials can have disruptive effects on the functioning of electronic devices and on the mechanical integrity of materials. Fast neutrons are found naturally in the atmosphere, in space environments, or produced in reactors- and accelerator-based neutron sources. New opportunities to investigate the effects of high-energy neutrons for the screening of microchips and structural materials are operational or under development at the ISIS pulsed neutron and muon source (UK) and the European Spallation Source ESS (SE). The Italian contribution to these efforts, set within the CNR programmes on neutron sciences, has its most recent display on the ChipIR beam line at ISIS and the neutron Irradiation Module at the ESS. These will represent unique venues to carry out accelerated tests of electronic chips in the fast-neutron atmospheric environment and to obtain information on the behavior of next-generation metallic alloys under high fluxes of neutrons up to GeV energies.

1 Introduction

A sudden blast of votes on an electronic voting machine, an unexpected dive on a transoceanic flight, beams of stainless steel becoming brittle and decreasing their density. This is what can happen when high-energy neutrons interact with electronic chips or with atoms in the lattice of solid materials.

Interaction of neutrons with atomic nuclei is intimately connected to the fact that, unlike the interaction of charged particles such as protons or ions with nuclei, neutrons do not have to overcome the Coulomb repulsion to penetrate into the nucleus, and have therefore a high penetration into materials. When high-energy neutrons collide with an electronic

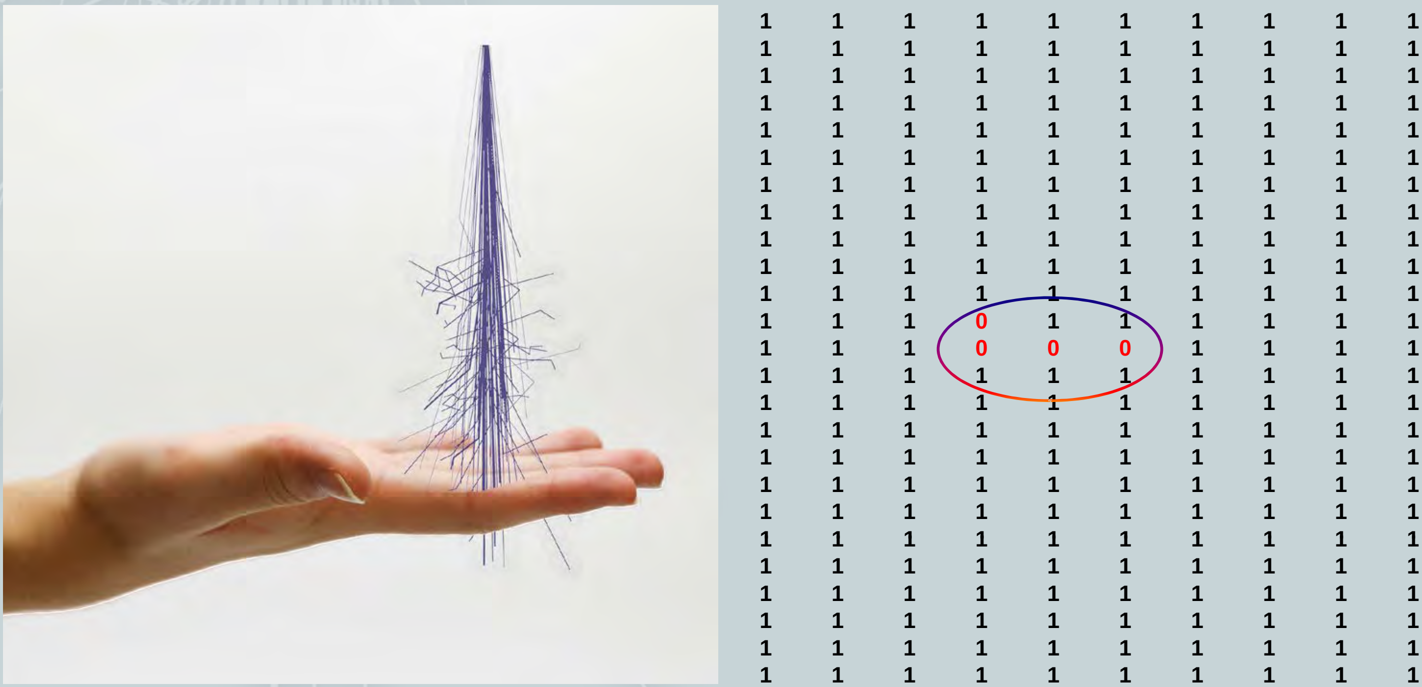


Fig. 1 The flux of high-energy neutrons on the surface of the Earth can induce errors in electronic devices. Left: in some locations about three neutrons per second may hit a surface as large as an open hand. Right: an experiment carried out in 1979 demonstrated that a single-radioactive-atom decay can change up to four memory cells in a computer memory: the readout of a portion of a 64 kb DRAM showed that cells changed their content from a one to a zero by bringing a dilute alpha-emitting source close to the device [1].

device, or with a metal, they interact directly with the nuclei, producing charged secondary particles, such as protons or alpha particles, that can in turn interact with the electrons in the material, giving rise to ionisation. Elastic collisions can knock out atoms from their equilibrium position, while inelastic collisions may transmute the atoms, creating radioisotopes.

The resulting damage due to neutron radiation can be permanent, such as the damage due to the displacement of atoms from their equilibrium positions (displacement damage), or transient, such as that associated to the ionization, induced by a single neutron interaction, which may deposit bursts of free electron-hole pairs and produce a current spike that, in an electronic device may alter the data, leading to an error.

The latter phenomenon is well known in aerospace, and became an established field of research and development in the late 1970s with the work of J.F. Ziegler, who suggested that cosmic rays were a substantial contributor to electronic reliability [1].

High-energy particles are naturally present in the Earth's atmosphere, in avionic, and space environments. Among these, neutrons are generated as a secondary component from the interaction of primary cosmic ray particles with the molecules composing the atmosphere, aircraft and spacecraft components, or the surface of planets [2]. For example, on the Earth's surface, and depending on altitude and latitude, the atmospheric neutron flux can reach values of the order of 10^{-1} n cm^{-2} s^{-1} (see fig. 1) [2].

A famous case of suspected "cosmic-rays influence" on political elections was reported in 2003 in Belgium [3], where 4096 (2^{12}) votes were unexpectedly added to an electronic voting machine. Investigations indicated that the most probable origin of this malfunctioning was a "soft error", that is, a nondestructive functional error induced by energetic ion strikes, induced by the impact of cosmic-ray particles with the voting systems' electronics. An even more critical failure related to cosmic-ray–induced electronics malfunctioning, happened on October 7th 2008 during the cruise of the QANTAS flight from Singapore to Perth, when the aircraft's flight control computers commanded the aircraft to pitch down. The aircraft suddenly pitched nose down for a few seconds; the resulting forces were sufficient for almost all the unrestrained occupants to be thrown to the aircraft's ceiling, causing more than 120 injured, which were fortunately recovered after an emergency landing. In 2011, the Australian Transport Safety Bureau released a report on the investigation of the accident, concluding that a potential triggering event was a "single-event effect (SEE) resulting from a high-energy atmospheric particle striking one of the integrated circuits within the CPU module" [4].

In general, a small fraction of the energy lost by a fast neutron passing through a medium is imparted to create atomic displacements. However in high-flux neutron radiation environments, such as fission and fusion reactors or modern accelerator-driven spallation neutron sources, this form of damage has a strong impact on the reliability and operation of a plant or a neutron research facility [5].

As early as 1942, in Fermi's reports on the operation of the uranium-graphite reactor, E.P. Wigner pointed out that the intense fluxes of high-energy neutrons created in the fission events would cause the displacement of carbon atoms from their equilibrium positions in the graphite lattice [6]. For every fission reaction, neutrons with MeV energies would transfer part of their energy into the graphite lattice destruction, and it was anticipated that the forthcoming challenges in the prediction of the behavior of reactor components exposed to prolonged irradiation would hardly be solved. The swelling and distortion of graphite under the bombardment of fast neutrons from nuclear fission was called the "Wigner disease", and led to intense activity on solid-state physics and materials research [7]. The quantification of this type of damage is the *displacement per atom*, dpa, a parameter expressing the average number of atomic displacements induced by fast-neutron irradiation; the latter is often accompanied by the ratio of the amount of helium produced per *displaced atom*, the so called He/dpa ratio, expressing the effect of neutron-induced reactions where alpha particle are created and generate helium atoms, which aggregate in bubbles, embrittling the materials [5].

The advent of spallation neutron sources, with neutron energy spectra extending up to 3 GeV, and intense fluxes of fast neutrons, has opened up new opportunities to fulfil the needs of knowledge of testing electronic devices and structural spallation materials under fast-neutron irradiation.

The Italian involvement in the design, construction, and exploitation of neutron irradiation stations at spallation neutron sources is supported by the neutron science program at Consiglio Nazionale delle Ricerche (CNR), within the framework of the agreements with the Science and Technology Facilities Council (STFC) collaboration in scientific research at the spallation neutron source ISIS (UK) and within the agreement with the European Spallation Source (ESS) ERIC (SE).

2 Man-made environments for accelerated neutron testing of electronic chips: the ChipIR beam line at ISIS

Following pioneering experimental work in 2007 [8], a new facility, named ChipIR was designed to look at how silicon microchips respond to cosmic neutron radiation.
The latter was realized within a British-Italian collaboration under the international CNR-STFC agreements 2008-2014 and 2014-2020. ChipIR is located at the ISIS pulsed neutron and muon source at the Rutherford Appleton Laboratory, UK, and incorporates many features to help users of the facility perform test measurements accurately and efficiently. One-hour exposure in the beam is equivalent to hundreds to thousands of years in the real environment! ChipIR is able to deliver an atmospheric spectrum of neutrons up to an energy of 800 MeV, with a variable collimated beam and large area beam. Flux levels with small beams for components reach values of the order of 10^7 n cm^{-2} s^{-1}, and large systems have more modest fluxes. Up to 1×1 m^2 systems can be irradiated. By achieving its performance goals, ChipIR is poised to become the premier neutron SEE test facility in the world, with about 3000 annual operating hours [9]. Among the most recent measurements carried out during the user programme, safety critical computing systems [10], as well as Commercial Off The Shelf (COTS) components [11] were tested by Italian teams, in collaboration with the ChipIR scientists. As an example, the measurements on commercial components show how the response of systems based on CCD and SRAM for stratospheric balloon experiments respond to the impact of neutrons with energies up to hundreds of MeV. The fast-neutron effects on the CCD are reported schematically in fig. 2 [11].

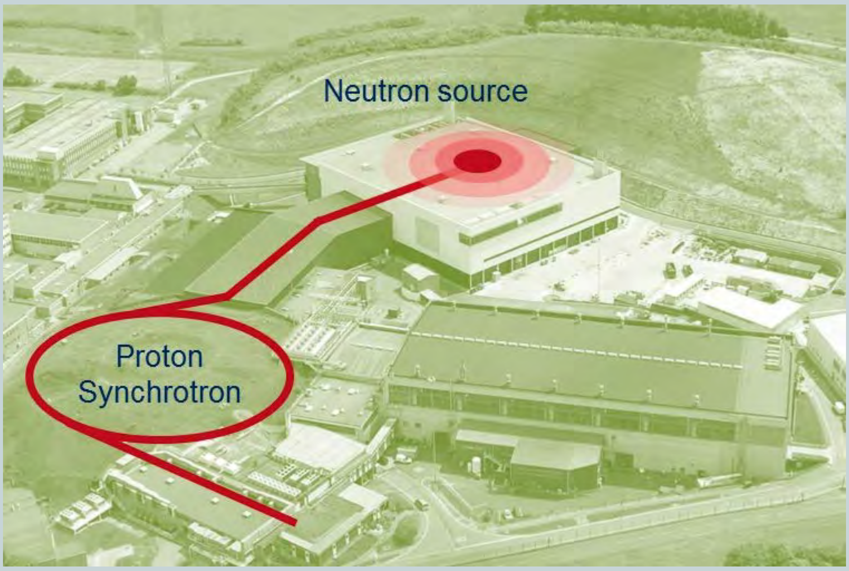
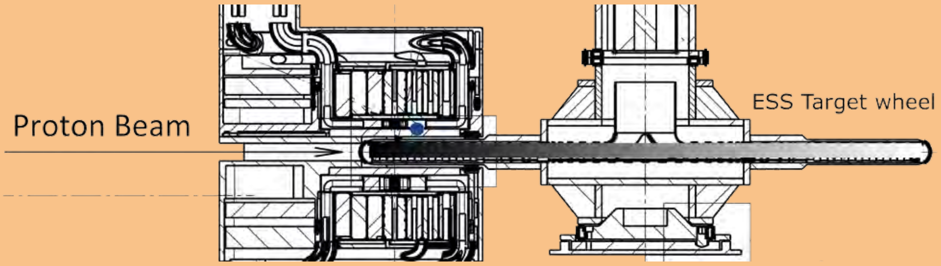


Fig. 2 Top: Schematics of the neutron production layout at ISIS. Bottom: Rendering of the charge generation clusters induced by the impact of the ChipIR neutron beam on a CCD for irradiation exposures of approximately 33 ms. The CCD was exposed at 90 degrees with respect to the CCD plane, therefore neutrons arrive sideways. Multiple (long) tracks clusters are due to fast-energy neutrons. Single (dot-like) track clusters are due to low-energy neutrons [11].

3 Healing from Wigner's disease

Knowledge of structural materials' response to the displacement damage induced by neutrons of energies up to 2 GeV will help the development and research on sustainable materials for current and next-generation accelerator-based sources. Within the framework of the CNR In-Kind contributions to the ESS construction phase, a dedicated effort is devoted to design and build instrumentation for advancing the knowledge of displacement damage at unprecedented extremes of energies and intensity (2 GeV proton energy, 5 MW power delivered to the target). The neutron Irradiation Module at the European Spallation Source will make use of the high-intensity fast-neutron spectrum to study the behaviour of the materials used in the facility, and will be used to support ESS own program of target station R&D. By studying how these materials are affected by radiation, estimates of the material degradation in radiated components will allow to optimise of the design and lifetime of regularly replaced target components. Samples to be irradiated shall be located as close as possible to the target material, in a position offering both a representative radiation spectrum and an acceptable disturbance of moderators' performance. The module will be located in the ESS water moderator and will be passively cooled by the moderator's water flow. The enclosure, consisting of a cylinder-shaped vessel of less than 15 cm length, and 1.7 cm diameter, will contain 192 miniature samples composed of relevant structural materials such as special stainless steels, high performance aluminium alloys, titanium-vanadium alloys and low-activation stainless steel for extreme neutron radiation



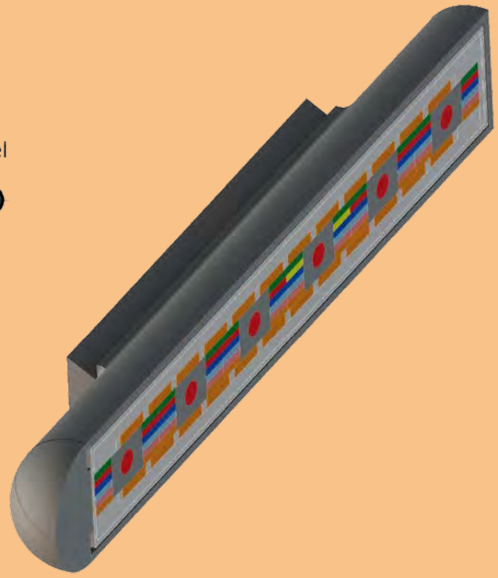


Fig. 3 Left: Schematics of the positioning of the irradiation module in the ESS target and moderator assembly. The blue point marks the position of the module within the water moderator. Right: Cross cut of the module showing the vessel and the enclosure with the 192 miniature samples to be irradiated by the ESS fast-neutron flux.

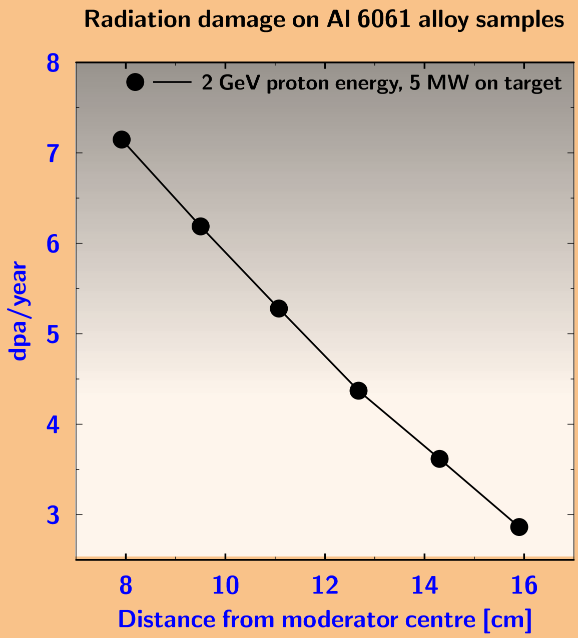


Fig. 4 Left: Map of displacement damage across the samples for tensile tests in the module. Right: Displacement damage per year of the aluminium alloy samples for tensile tests as a function of the distance from the moderator centre, for proton energy of 2 GeV, 5 MW of power on the target, and 5400 hours of operation per year.

environment. The radiation effects on the mechanical, thermal, electrical, microstructural properties will be carried out by comparing examinations on irradiated and non-irradiated samples. The layout of the module within the ESS tungsten wheel, target and moderator assembly is shown in fig. 3.

The module will be installed in the moderator within 2017 and is expected to receive its first neutrons before 2020. The performance of the module has been calculated using state-of-the-art Monte Carlo techniques and will allow to obtain a radiation damage in the range of 7 dpa/year and a gas production of approximately 15 He/dpa.

The calculated map of displacement damage across the samples for tensile tests in the module, and the displacement damage of the aluminium alloy samples as a function of the distance from the moderator centre are reported in fig. 4 [12].

4 Outlook

The forthcoming years will fulfill the promise to significantly advance the knowledge of the response of materials and electronics to fast-neutron radiation environments. As ChipIR enters in its full user programme, it is expected that users from the electronics, aerospace, electronics safety, from space to ground, and beyond, will gather enough information to help screening the next generation of microchips from neutron-induced malfunctioning. On a longer time scale, the examination of irradiated samples at ESS will provide unique knowledge to help developing the next-generation structural materials for extreme radiation environments. We expect that much of what will be found most interesting in these investigations will be unexpected.

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