Annex –'Daughter' Projects

Project **HARDEST- HANE HARDENING FOR SATELLITE SYSTEMS**

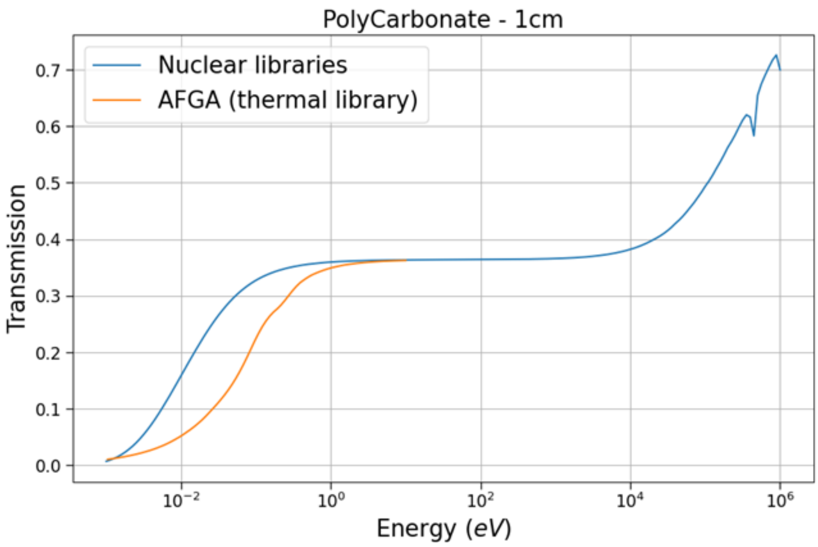
Proponents ISIS@MACH ITALIA jointly with Thales Alenia Space Italia (TASI) (TA for target-specific Case Study 3)

Abstract
Over the last years, major countries and alliances have started preparing for the defence of space. One of the most significant threats arises from nuclear detonation of nuclear bombs at high altitude (HANE). Among other factors, the war in Ukraine and the continued nuclear testing conducted by North Korea in the last years have made the risk of nuclear threat ever more concrete. The protection of military satellite systems (both on board and on the ground) becomes a necessity and a technological challenge of our days. The experiments conducted by the USA and the Soviet Union in the 1960s have demonstrated an important vulnerability of satellite systems not protected from this type of threat, and next-generation devices are required to satisfy the requirement of protection against such threats.
The aim of the HARDEST project is to define the requirements for protection of electronic devices used in space applications against HANE threats, studying and developing parametric models of physical phenomena and software tools predicting the effects of a high-altitude nuclear detonation. The results will support future activities in the design and validation of hardening and mitigation solutions to be adopted in this field.

Technical description
A main objective of the project is to identify novel composite materials to minimize the effects of a HANE threat on a satellite or electronic device. For such purpose, sample materials will be irradiated at research infrastructures exposing them to several sources of radiation, including electrons, gamma rays and neutrons. The models used will be tested with simulations and experiments and will allow to define a baseline for future tests. Therefore, we will first carry out a phase of testing materials already available and used in satellite missions and, subsequently, we will evaluate innovative materials that will allow to have a significant increase in terms of optimization of cost and weight compared to the materials currently used for shielding.

In particular, the IM@IT unit of the University of Roma Tor Vergata has a consolidated know-how in the modelling of attenuation and transport of neutron radiation in complex neutron and gamma radiation fields. Recent results include the measurements of the attenuation factor, over up-to seven decades of the incident neutron energy, of several complex shielding materials, such as baritic cement. The group has also developed a method for the modelling of the total neutron scattering cross section of polymer materials as a function of the molecular composition and chemical-physical characteristics (Average Functional Group Approximation-AFGA). The AFGA method, which was recentrly included into the GEANT4 Monte Carlo transport code, will be used for the prediction of the shielding properties of the materials to be designed and developed within HARDEST.

A use of this approach, exemplified in the following figure, allows to quantify the effect of the properties of the polymer properties of the material of interest with an accuracy superior to that achievable with the simulation code due to the use of the nuclear standard library, and finally to evaluate the effects of prompt and delayed neutrons after detonation. In the energetic regions of slowing down of neutrons, the nuclear standard libraries overestimate the transmission of radiation, and consequently the thickness and mass of the material used for shielding or encapsulation.



Neutron transmission, as a function of the incident energy of the particle, through a shielding layer of polycarbonate, as estimated using AFGA and compared to the nuclear libraries available at present.

The inclusion of these effects has a practical impact on the evaluation of the thickness of homogeneous materials and composites used for nuclear hardening, including the time of neutron activation induced by the slowing of neutrons for the initial radiation effects and the residue after detonation.

Within the HARDEST project, the materials tested and the survey objects will include systems such as, for example, polyethylene (possibly borate), as the outer layer, to attenuate beta radiation (minimizing the bremsstrahlung component) and moderate neutrons; one intermediate layer of plastic coated with tungsten (up to 8 g/ml and 90% tungsten content) or similar material as further screening for beta and gamma radiation; An inner layer of mu-metal (iron-based) or similar material, which can be used as a shield for EM fields at high frequency (15-250 MHz) or as a shield for X rays from a second generation layer shielding the previous ones.

The materials to be studied will be obtained commercially or synthesized (e.g., with 3D printing) in such a way as to optimize the dimensions and weight of the screen. At a parity of shielding capacity, materials will be selected that allow minimizing the effects of neutronic activation, which could cause malfunctions of the electrical device even in the phase after the electromagnetic pulse. Once the optimal material is defined through Monte Carlo simulations of the transport of radiation in the material, the material will be irradiated to the research infrastructure, through a mode of access with confidential management of experimental data, with a source of electrons, gamma rays, and neutrons.

Project <u>**HiCHIP:**</u> **Radiation hardness tests of hard Si/SiC/GaAs/GaN based chips and chip components of pacing-based devices for biomedical applications.**

Proponents: ISIS@MACH ITALIA jointly with Thales Alenia Space Italia (TASI) (TA for target-specific Case Study 3)

Problem addressed

Who?	ISIS@MACH ITALIA
What?	Radiation hardness and characterisation of hard Si/SiC/GaAs/GaN based chips and chip components of pacing-based devices for biomedical applications. The proponents agreed on the involvement of TASI (and of the other companies mentioned) to use the devices and related hardware & software specifications necessary to prepare the devices for the experimental tests. Access to the testing infrastructures will be guaranteed by the IM@IT within the framework of the agreement with the UK testing facility.
When?	2023 - 2025
Where?	National IM@IT Units
Why?	To enhance chips' design tools, device reliability, susceptibility of SRAM bit cells designed to be immune to Single Event Upsets.

Abstract
The primary goal of the proposed study is to conduct accelerated neutron tests of the single-event-effect (SEE) occurrence in both modern hard Si/SiC/GaAs/GaN based chips devices and in chip components of pacing-based devices for biomedical applications – e.g. pacemakers and implantable cardioverter defibrillators (ICD)- to evaluate their robustness for deployment in ground level, avionic applications and micro-and nano satellites. The *pacing* systems market demands chips with high device reliability and longevity to avoid the patient discomfort and risk associated with device replacement or malfunction.
Additionally the materials composing the soft and hard devices will be characterised at ISIS (2D and 3D) by thermal neutron to measure the residual stress and defects at the interface of the chips. Materials-to-circuits characterisation will be performed using the instrument suite of IM@IT, each of which is individually optimised for the study of different types of matter.
This project will allow to acquire a deeper understanding of neutrons impact on the electronics behaviour in hard based devices as well as the first understanding of electronics behaviour in modern hard Si/SiC/GaAs/GaN based chips and chips in pacing devices for biomedical applications. This will make possible to characterize and deliver to chip manufactures the probability of occurrence of functional damages of neutron Single Event Effects (Soft Error) in the control electronics of the devices, in order they can create more reliable and radiation-resistant chips.

Work packages (WP)
WP 1 – Fast Neutrons radiation Hardening Tests of hard and soft [ISIS (Chipir and Nile beamlines)]. Objective of this WP is to provide both Trans-National and Virtual access to IM@IT and ISIS within the project which can offer instrumentation, tools, and know-how in the framework of radiation hardness tests using fast neutrons.
WP 2 –Thermal Neutrons semiconductor materials analysis (2D and 3D) using ENGIN-X, IMAT, VESUVIO neutron beamlines. Objective of this WP is to provide both Trans-National

and Virtual access to IM@IT and ISIS, which can offer instrumentation, tools, and know-how in the framework of semiconductor materials analysis using thermal neutrons.
WP 3 – Materials-to-circuits characterisation using the instrument suite of IM@IT [X-diffraction, reflectometry, SANS, USANS, Microscopy, SEM-EDS] and ISIS [prompt gamma activation analysis (PGAA), Objective of this WP is to provide both Trans-National and Virtual access to IM@IT and ISIS which can offer instrumentation, tools, and know-how in the framework of characterizations of semiconductor materials, especially at the atomic and nanometric scales.
WP 4 – Industrial Engagement and creation of a national business case for radiation hardness, by using consolidated methodologies and resources at major European infrastructures such as ESS, ILL and ESRF.

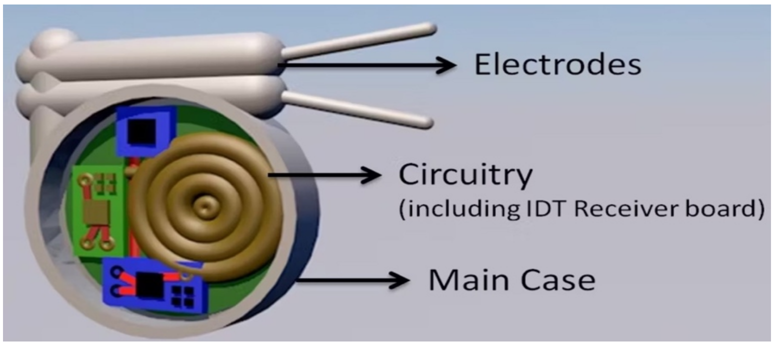
Deliverables (D)
D1 (month 14): Report on the experimental procedure of irradiation tests ISIS, data analysis and results on the fast neutron radiation hardening tests on hard Si/SiC/GaAs/GaN.
D2 (month 16) Report on the experimental procedure of irradiation tests ISIS, data analysis and results on the impact of neutron on the reliability of the chip of the pacing devices.
D3 (month 20) Report on the results of the 2D and 3D analysis at the atomic level of semiconductor materials, materials-to-circuits, of residual stress, and of defects at the interface of the hard devices with thermal neutrons.
D4 (month 24) Report on the results of Materials-to-circuits characterisation with thermal neutrons and optical characterizations at the atomic level of the pacemaker.

Aim of the research
Neutrons produced by cosmic ray interacting with atmospheric constituents, and with avionic and space components are present from ground level to aerospace and space altitudes. Therefore, electronic devices on aircrafts in atmosphere and in heavily shielded spacecrafts (*e.g.* the international space station) are subject to functional damages of neutron Single Event Effects.

Experimental Plan
We plan to conduct Accelerated Irradiation Neutron (AIN) tests of the single-event-effect (SEE) occurrence in modern Si/Sic/GaAs/GaN based devices and, for the first time, of the chip component of *pacing* systems (Pacemakers or defibrillator medical devices).

- **AIN tests of Si/Sic/GaAs/GaN**
  Wide-Bandgap materials such as silicon carbide (Sic) and gallium nitride (Gan) have gained popularity in recent years. These are mature technology and has become a viable alternative to silicon-based power devices and GaAs in high-efficiency and high-power density applications. The Si/Sic/GaAs/GaN based devices operating in various environments will be tested to measure their susceptibility to neutrons. We will also examine various error mitigation techniques as well as the susceptibility of SRAM bit cells designed to be immune to Single Event Upsets.
  Si/SiC/GaAs/GaN based devices available. The devices will be provided by Thales Alenia Space Italia (TASI) and ST Microelectronics or by other national manufacturers we are currently in contact with.
- **AIN tests of pacing systems – Pacemaker device**
  For the first time a chip component of a pacemaker will be irradiated under neutron beams to test the possible presence of SEE. We plan to record two distinct signals: a) the 'ouput-signal' registered by the pacemaker programmer once the devise is located at a terrestrial

environment; b) the ‘ouput-signal’ registered by the pacemaker programmer under irradiation tests at the Chipir or NILE.
Pacemaker Device available. The device will be provided by MEDICO srl Italia or by other national manufacturers we are currently in contact with. The manufacturers that currently produce pacemakers for the world market are Abbot, Biotronik, Boston Scientific, MEDICO, Medtronic and Microport. Each of these companies have adopted over time different strategies to increase the security and longevity of their devices, both as regards the type of materials used for batteries (for example Li/MnO2) or the type of algorithms for managing pacemaker functions. This has led in recent years to almost double the life of the devices and to significantly reduce the size, circumstance which makes these medical devices increasingly subject to functional damages of neutron Single Event Effects (Figure 1).



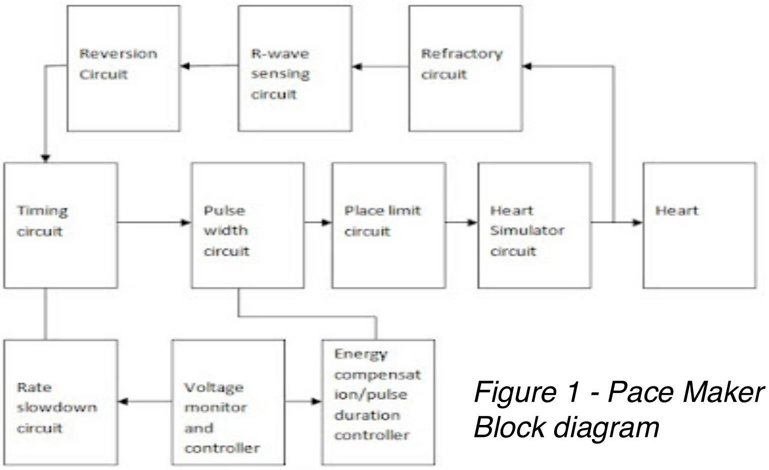


Figure 1 - Pace Maker Block diagram

Methodology

- **AlN of Si/SiC/GaAs/GaN and pacing systems**

The irradiation tests of hard and soft based devices will be carried out at the Chipir and/or NILE neutron beamlines operating at ISIS pulsed neutron and muon source a world-leading centre for research located at the STFC Rutherford Appleton Laboratory in Oxfordshire, England. ChipIr (for Chip Irradiation) is the unique beamline dedicated to the irradiation of microelectronics and is specifically tailored to the study of Single-Event Effects (SEEs). Neutrons are naturally present in the earth’s atmosphere, at sea level and even more abundant at aircrafts altitudes, in avionics and heavily shielded spacecrafts. They are generated by spallation reactions which occur when energetic protons (> 100 MeV) interact with atomic nuclei. This process takes place in the upper atmosphere, from the interaction of primary cosmic rays, but also in a spallation source like ISIS, where protons are accelerated up to 700 or 800 MeV and are collided against a tungsten target to produce neutrons. For this reason, a spallation source can be used to reproduce an atmospheric-like spectrum, with the resulting spectrum extending up to the energy of the accelerator. In the case of ChipIr, the design of the instrument is optimized to mimic the

terrestrial and atmospheric neutron spectrum, with a flux many orders of magnitude higher than the natural one to enable accelerated testing of electronic devices. Neutrons themselves do not deposit charge in the device, rather they transfer their energy via inelastic and elastic reactions with the substrate (silicon), and hence they produce secondary ions which deposit charge in the device' sensitive volume according to their respective LET. A scheme of the ChipIr Facility at ISIS is presented in Figure 2.
The hard and soft based devices will be placed in front of the neutron source. A green cross mark constructed of two laser pointing beams will be used for indicating the centre of the neutron beam to assist the positioning of the devices correctly in front of the beam. Due to the very long range of neutrons, there will be no need to decapsulate the devices under test. The experiment will be controlled from the screened room using a laptop computer. The boards need to be supplied with the appropriate voltages through the patch panels which connect the screened room and the irradiation room. The irradiations will be performed while a cadmium foil placed in front of the neutron beam, to reduce the number of thermal neutrons. A circular drum and a set of jaws, that can move independently, can define a beam from cm dimension (pencil) up to 0.4 m aperture (flood). The beam in the experiment can be collimated down to 70x70 mm. to avoid any influence on other electronic components. The measured flux of neutrons above 10 MeV is approximately 1.4×10^{10} n/cm^2. The source is considered as a point like source at 13.9 meters from sample position and the flux decreases with $1/r^2$.

- **Characterizations of hard and soft devices**
  The hard devices will be 2D and 3D characterised to measure the residual stress and defects at the interface of the chips:
  - using a suite of thermal neutron beamlines at ISIS Facilities*, i.e.* ENGIN-X, IMAT, VESUVIO, and the suite of equipment at the Medium Range Facilities
    The pacemaker device will be 2D and 3D characterised:
  - using a suite di optical and microscopes instrumentation at the Medium Range Facilities

Research Task.
Accelerated irradiation fast neutron tests will be performed at ISIS facility.
Characterization thermal neutron tests on chips will be performed at ISIS and IM@IT Facilities

Description:

a) IM@IT – ISIS Facility – TASI (or other providers) teams will carry out the identification of biomedical devices and components to be tested and provide the **AIN tests and Characterizations of all devices** plans during months 1-6 of the project at ISIS Facility;

b) IM@IT - TASI (or other providers) teams will carry out the experimental proposals preparation at IM@IT during months 7-10 of the project; c) IM@IT - ISIS Facility - TASI (or other providers) teams will carry out the neutron irradiation tests at ISIS (UK) during months 12-17 of the project; IM@IT - TASI (or other providers) teams will carry out data analysis and deliver final reports during months 18-24 of the project.

Military/Dual Valence
"Radiation hardness assurance" is increasingly needed in industry and in those small and medium-sized enterprises active in the aerospace and nuclear research sectors, with an increasing number of devices exposed to radiation of greater intensity and for longer time periods, and the consequent need for an appropriate assessment of the radiation resistance of the systems used. Results of this project will help to protect safety critical systems and national infrastructure against the effects of severe neutron space weather.

The tests and analysis methods (SEE and study of residual stress at the interface) proposed in this project will yield information that can mitigate risk by means appropriate for the military mission and the radiation threat. This may include cataloguing ways to minimize the rate or occurrence, minimize the effect, recover normal operations, or bound the probability of occurrence.
Radiation test and analysis approaches must control and minimize the predominant sources of uncertainty associated with each radiation threat.
A changing paradigm can be achieved by gaining a greater understanding of how the devices are affected by SEE for specific parts of the architecture and how it is possible to mitigate these as part of the design; for example, the determination of the minimum charge to upset an electronic component, makes it possible to redesign the component to limit charge build below the upset threshold.
This approach can foster finding the characteristics dominating error rates and developing mitigation as integral part of the design. This contrasts with a retrospective hardening approach which largely relies on general redundancy, performance reduction or expensive (and slow) hardening. Such an achievement would allow to revert the scenario for smarter routes towards SEE mitigation in complex devices, and at the same time provide essential knowledge for the development of European based technologies for components with increased reliability.

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Project **EU-SEE Forum for intercultural exchange on Sustainable MAnagement of Cultural Heritage - SMACH Forum.** Central Europe Initiative Know-how Exchange Programme - CEI- KEP CALL

Proponents: ISIS@MACH ITALIA in partnership with City of Venice, Ss. Cyril and Methodius University, University of Belgrade, Sarajevo School of Science and Technology, University of Montenegro (TA for target-specific Case Study 2).

Problem addressed.

Who?	ISIS@MACH ITALIA
What?	promoting know-how exchange between the SEE Region on sustainable cultural heritage management in relation to climate change and other sustainability challenges
When?	2024 - 2026
Where?	National IM@IT Units
Why?	To contribute to support intercultural cooperation, sustainability of local cultural heritage and communities, and enhancement of climate resilience

Abstract

SMACH Forum will promote mutual exchange of systematic, interdisciplinary good practices along with research on cultural policies, heritage management and heritage science expertise among the different SEE heritage institutions, and also with the different existing European platforms such as E-RIHS, Joint Programming Initiative (JPI) and Cultural Heritage Research in Europe (ARCHE). It will eventually establish and launch an EU-SEE forum on sustainable cultural heritage management, shared heritage science research and policy, bringing together EU and SEE researchers, policy-makers and international platforms.

Work packages (WP)

WP 1 – Mapping of critical research, good practices and policy initiatives of sustainable cultural heritage management in Europe and SEE Region. The activity will be carried out through desk research, survey and interviews with key stakeholders at different levels. The results will be gathered in a report that will provide the state of the art on current existing research, initiatives, policies as well as of relevant management bodies in the Region. This report will be conceived as the second step of the SMACH report on the needs in the Region.

WP 2 – Developing a sustainable cultural heritage strategy tailored for SEE Region. This activity will be based on the organization of an International Colloquium on sustainable management of cultural heritage at one of the provider partner's facilities. The colloquium will aim at presenting and discussing the results of the mapping with key stakeholders from national and international authorities, including representatives of other SEE and EU organizations, international platforms such as JPI, ARCHE, E-RIHS, ECCO, ICCROM, and the project partners. etc. to develop a joint statement for feasible cost-effective sustainable cultural heritage management in the Region.

WP 3 – Know-how exchange program to foster awareness, **build capacities on sustainable cultural heritage management, and promote intercultural exchange among research and policy between EU and SEE Region**. This activity will include the organization of 1 national event at each of the beneficiary partners/target countries (around

12 participants each) to present the outputs of activities 1 and 2 to local key stakeholders; a series of online training session, also concerning the access to ISIS@MACH ITALIA, for all of the participants to the local events and beyond to favour the interregional networking, involving also the work with UNESCO Chair holders in the Region, giving special attention also to science diplomacy.

WP 4 – Establishment and Launch of the EU-SEE Forum on sustainable Cultural Heritage Management. It will be based on the organization of 1 top level meeting for policy makers at one of the provider partner's facilities, to establish a Forum bringing together EU and SEE researchers; 1 final workshop as dissemination event of the results of the project and promotion of the Forum, to be organised possibly in the Region, in collaboration with the Italian Embassies and/or within or back to back to existing events, e.g. the Conference of Ministers of Culture.

Deliverables (D)

D1 (month 8): 1 report mapping current research, initiatives, stakeholders, policy and decision-making bodies in the field of sustainable management of cultural heritage in the Region;

D2 (month 12): 1 shared strategy for future collaboration on sustainable cultural management, research and policy-making within the Region, with the EU and EU international platforms.

D3 (month 18): 1 joint statement for feasible cost-effective sustainable cultural heritage management tailored on the SEE Region.

D4 (month 16): know-how exchange program involving over 40 stakeholders and researchers from the Region, to support sustainable cultural heritage management, whether locally or globally.

D5 (month 18): a EU-SEE Forum bringing together researchers, policy-makers and EU platforms to promote intercultural exchange and collaboration on cultural heritage management in the Region.

Aim of the research

SMACH Forum aims at promoting know-how exchange between the SEE Region on sustainable cultural heritage management in relation to climate change and other sustainability challenges.

Experimental Plan

We plan to train the participants in the know-how exchange program to the use of the ISIS@MACH ITALIA tools to the Sustainable MAnagement of Cultural Heritage.

Project: **CHARMANT - Extreme space weather and its impact on the aging human body, biological systems, and terrestrial electronic systems**

Proponents: ISIS@MACH ITALIA (TA for target-specific Case Study 3)

Abstract
Study of the extreme space weather and its impact on the human aging, biological systems, and development of a new class of neutron detectors to measure neutron flux (and doses) in terrestrial, atmospheric and space environments.

Research Activity (2024-2025)
The project will investigate the effects of natural ionizing radiation on the aging of the human body and their changes depending on the type and the intensity of environmental neutron radiation. On the Earth's surface, for example, the dose induced by neutron radiation, both primary and secondary, can change depending on the latitude and altitude, as well as on the characteristics of the immediate vicinity (rivers, lakes, snow, mountains) and becomes increasingly important at transatlantic flight altitude, in low Earth orbit (LEO), and in space. The physical aging of the human body and other biological systems depends on the type and intensity of environmental neutron radiation. The combination of a better understanding of both the cause (through monitoring of terrestrial-atmospheric-space neutron radiation) and the effect (through characterization and irradiation tests with analytical facilities) of extreme space weather conditions on the aging of the human body, biological systems, and terrestrial electronic systems will enable our society to be more resilient to the potential large-scale disruption of such space weather events. While it is certain that such extreme space weather events will occur, it is uncertain is when and how large the extreme weather event will be. A new Neutron Prototype Compact Monitor (nPCM) is being designed to monitor neutron doses in terrestrial, atmospheric, and space environments. Such nPCM is beyond the state of the art of existing standards, equipped with standardized and compact IGY and NM64 detectors, much easier to transport, more efficient, and with extended spectroscopic capabilities.

Mid- and long-term technical and scientific objectives.
To create and operate one latest generation nPMC monitor is the key to study the nature and type of those extreme space weather events that have resulted and will continue to result in a strong increase in the flux of fast neutrons both on the ground and at atmospheric level and in aerospace. The neutron monitor at the MRF2 by IM@IT will be the first of the latest generation in Italy. The Italian nPMC monitor will operate to record neutrons at terrestrial level (intensity, frequency and energy spectrum of events called GLE - Ground Level Enhancement Events). The latter are a particular subset of solar particle events in which particles coming from the Sun have sufficient energy to generate effects that are measurable on the Earth's surface.
To perform characterization tests on above materials and devices - e.g. Lab-On-Chip, Organ-On-Chip, mock-up of human body, biomedical devices implanted in humans (e.g., artificial heart and pacemaker, defibrillators), Si/GaAs/GaN based devices etc. - will be carried out using the MRF1 suite and MRF2 of IM@IT and the beam lines of ISIS Facility for irradiation (also accelerated) such as ChiPIR, ENGIN-X, IMAT e Nile.
Based on accelerated tests, the simultaneous measurement of neutron flux and aging effects on human body/biological system mock-up will allow adapting these results to the final application, i.e. estimating the aging effects caused by neutrons at different altitudes and latitudes, and in space.

ISIS@MACH ITALIA

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