Application of the FAIR Facility to Space Radiation Research

Final Report – Executive Summary

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Executive Summary

The radiation environment in space has severely adverse effects on humans, electronics and materials. The most challenging part of the environment for our understanding of the effects are the highly charged highly energetic (HZE) particles. This study looks at the possibilities FAIR offers for space radiation research. There are two main parts: first the open issues and needed research in space radiation involving heavy ions of high energy and second the requirements a facility for this research should meet checked against the possibilities at FAIR.

Open issues and needed research

The possible space radiation research is structured into the following topics:

- Radiobiological effects on human beings
- Electronic components
- Shielding materials
- Calibration of instruments
- Materials

Radiobiological effects on human beings

Human space exploration requires a quantitative understanding of the dangers man faces in space. This includes the effects of the radiation received by the astronauts. Most of the uncertainty on space radiation risk is associated to the poor knowledge of the biological effects of galactic cosmic rays (GCR) and ions from solar particle events.

FAIR will be the main European ground-based facility for experimental research in space radiation risk assessment and development of countermeasures. FAIR will impose on the experience of the IBER project ,which has been running at GSI from 2008 to 2012 with funding from ESA and National Space Agencies supporting specific experiments from different European countries (Germany, France, Belgium, and Italy). IBER produced excellent results and was essential

for building a European scientific community in space radiation radiobiology research.

IBER supported applications covering all topics in space radiation research. With the progress of knowledge in the past few years, it is likely that the FAIR project will be more focused, especially on the following topics.

- With the increased knowledge on the risk for interplanetary missions, it is now clear that countermeasures are needed for a safe exploration program. Studies on drugs, and dietary supplements are highly desirable for reducing the risk in long-term manned space missions due to radiation exposure.

- Most of our knowledge on radiation effects is derived from acute exposures. Extrapolation to low dose-rate, such as the one experienced in space, is affected by large uncertainties. Chronic exposures at accelerators are prohibitive for the large amount of beamtime needed, but smart solutions for testing the differences between acute and chronic exposures should be pursued at FAIR.

- Most of the ground-based radiation research studies in the past years concentrated on carcinogenesis, but they also clarified that late degenerative tissue effects, particularly for the CNS and cardiovascular system, may have a large impact on radiation risk estimates in space. Whilst no evidence of a low-dose threshold for carcinogenesis was found, the dose-response curve for noncancer late effects does not seem to be linear, and research in this field is highly needed.

The SIS18 accelerator can produce heavy ion beams up to 1 GeV/n, and can therefore be used for many of these studies. Cave A and Cave M are essential tools for radiobiology studies, and these experimental rooms should remain in the future facility. SIS100, however, will allow experiments at higher energies (around 10 GeV/n), a region which gives an important contribution to the effective dose in space. Very few studies so far have measured radiobiology of charged particles at energies >1 GeV/n

Electronic Components

Open issues concerning electronics involving relativistic heavy ions are twofold. First, there are possible effects that are different for ions of higher energy than for lower energy (e.g. SEEs due to nuclear reactions). The quantitative impact of these effects remains still unclear, although models exist that should be verified with high energy ions. Then there are new technologies that simply cannot be tested with low energy ions due to the limited range of the ions, since currently, for reasons of cost and ease of use, low energy facilities are systematically used as part of the space radiation hardness assurance process

Regarding energy effects, there has so far only been one campaign to compare the effects of heavy ions of several MeV/n to 1 GeV/n. The device, the ESA SEU monitor, was of older design but very thoroughly characterized at different accelerator facilities. There were some unexpected results that could not be completely answered with simulations of the device. Based on this, a preliminary research program for energy effects on modern Si-based microelectronics should include:

- An extension of the measurements of the SEU monitor up to 10 GeV/n. Although the SEU monitor is of older design, its character as a reference device, that was tested at nearly all relevant accelerators for radiation effects in Europe and that was intensively simulated, makes it a must for any research on energy effects.

- A repetition of the program of the SEU monitor with devices with higher SEU thresholds (hardened) as well as SEL measurements. SEL is an effect with an intrinsic high threshold (the SEU monitor is SEL free). The devices should contain at least tungsten, possibly other new materials recently used in novel IC designs. A first step would be comparisons of 10 – 30 MeV/n ions e.g. at RADEF and KVI with 100 – 1000 MeV/n ions at SIS-18 in cave A/M. These tests could later be extended to energies up to 10 GeV/n at SIS-100 in the BIOMAT cave. This program should help to answer the very relevant question of the magnitude of the energy effects under realistic GCR conditions and whether it will be necessary to use very high energy heavy ions for qualification in the future.

Other materials are also already used in other areas than digital microelectronics. Wide band gap materials such as SiC and GaN are increasingly used in power and high-frequency devices. These materials have a wider band gap and higher density than Si-based devices. It is therefore important to investigate the possible influences of the ion energy on the track structure in these devices.

A contribution of nuclear reactions to effects in devices can also originate from the packaging. Since the sudden occurrence of unexpected destructive events is a major hardness assurance concern, the influence of the micro environment created by the interaction of the packaging and high energy ions should be further investigated.

Other than the effect of the energy regarding interactions of the ions provided by FAIR, the very high penetration depth of these ions has experimental advantages that could be exploited in the following studies:

- There is a strong interest for using state of the art microprocessors or even system on a chip (SoC) devices in space. These devices have high requirements on cooling. Without a heat spreader made out of copper of several hundreds of µm thickness, the device will be damaged during operation because of excessive heat. Thus tests at all at low energy accelerators are not feasable. A series of interesting COTS devices could be qualified for application in a space environment. The SIS-18 energies will probably suffice for these tests.

- An alternative for qualification tests would be to use high energy protons (which might be easier and cheaper to come by) and model the heavy ion response. This would need a series of tests of state of the art devices with high energy protons and heavy ions to verify a possible model. These tests could be combined with the previous study by extending to proton tests.

- The current trend in the evolution of Si-based microelectronic integrated circuits is to create 3-dimensional structures. There are already commercial available 3D NAND-Flash devices with several tens of active layers stacked on top of each other. These structures cannot be tested with low energy ions, due to the large depths of the sensitive volumes alone. For radiation tests ion beams are needed that provide constant LET over the whole stack (64 layers as of summer 2016, steady growing). Because of their commercial availability, 3D NAND-Flash devices could serve as representative components to develop general Radiation Hardness Assurance methods for 3D technologies including new failure mechanisms.

- It might be commercially more interesting to test whole boards or systems, than to qualify every part separately. Because of the high penetration depth of the beams it would be feasible to make a campaign, where a large number of devices are tested simultaneously by stacking several boards in a row. A first study would be a proof of concept of how many devices could be tested in one campaign.

- Extending the previous point, whole systems or even small satellites could be tested at FAIR with the 10 GeV/n beam to e.g. investigate the effectiveness of mitigation techniques on system level.

Shielding Materials

To mitigate the effects of ionizing radiation, spacecraft can use shielding. Shielding transport calculations can use deterministic codes, such as the HZETRN used by NASA, or Monte Carlo codes such as GEANT4, used by ESA, PHITS and FLUKA. Transport codes heavily rely on measured nuclear cross-sections. Even cross-sections for protons, which have been studied extensively, both experimentally and theoretically, show disagreements by a factor of 2 between the values calculated from models and measurements. To reduce the uncertainties in any radiation transport code being used for such calculations, precise measurements of interaction cross-sections are required in order to benchmark the codes.

An extensive database of current measured cross-sections has been recently compiled by NASA, and this work is very useful to highlight the missing values. The authors stress that "the energy range of greatest interest for GCR studies is approximately 100 MeV/n to 10 GeV/n." This is exactly the energy range that is covered by FAIR. The report clearly identifies the missing data and gives recommendations on the order of importance the missing data should be compiled.

For composite materials, new shields based on nanomaterials, proprietary screens with undisclosed exact composition, complex in situ planetary resources, and so forth, code predictions have high uncertainties or may be completely lacking. Accelerator-based measurements are in those cases an essential tool to characterize the shield.

Calibration of instruments

Particle physics experiments in space have a major advantage because they can be operated in nearly background-free environment to study the composition and energy of galactic cosmic rays. However, these experiments must be calibrated on earth with similar ions detected or encountered during the mission.

Materials

The space environment is very hostile to many spacecraft materials and components due to the combined action of radiation, extreme temperature, and vacuum conditions, as well as impacting hypervelocity micro-particles. All of these influences can be tested at FAIR. A research program should also establish whether the relatively low GCR fluxes in space are able produce noticeable damage effects in relevant material. Possible cosmic ray triggering of electrostatic discharges from satellite surfaces that have become electrostatically charged by the plasma environment, could also be investigated.

Requirements to a research facility and the possibilities at FAIR

The community requirements on the beam characteristics show the largest possible span each of particle energies and fluxes. As FAIR is optimized by design to achieve beams of high energy and high intensity, the upper limits of the requirements are met excellently. Achieving low energies (e.g. < 0.1 GeV/n) or fluxes (some 10 $cm^{-2}s^{-1}$) with FAIR is deemed challenging but not impossible. Lower intensities will still be available at the existing SiS18 facilities, but there energies above 1 GeV/n are not accessible.

Requirements on the experimental infrastructure at the BIOMAT beamline of the APPA cave, like alignment systems, moveable tables etc. as well as the on-site dosimetry are met generally very well. Some specialized setups like e.g. a vacuum chamber were not planned for standard instrumentation but could be installed for the few experiments that require these.

The requirements for additional infrastructure outside of the irradiation area are met very well, with e.g. cell laboratories with biosafety level BSL 1 and electronic workshops available outside the radiation controlled area.

The definition of administrative regulations is ongoing and cannot be clarified at this point. Most of the requirements are however explicitly or implicitly linked to the mode of operation of the facility. As FAIR is driven by a scientific program dedicated to scientific excellence, all beam time requests have to pass a scientific council. This procedure is usual for research institutions of this scale. We assume that for community members from industry or applied sciences another procedure should be conducted. It will at least introduce significant lead time from the initial proposal to the approval and scheduling of beam time and introduces a major risk for projects as proposals might not get approval.

Altogether there is a very good match between the requirements of the community and the technical and infrastructural scope planned at the FAIR facility.

As the requirements and scheme of appliance is however not known yet and as the scientific council may be open to workable solutions, no final conclusion can be made here.