Topical: Proton-beam Facilities for Biological, Materials, and Technology Research

Submitted by

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1. Proton Radiation Impacts on Space Exploration

Protons dominate the particle radiation environment in interplanetary space, being the most abundant particles in both Solar and Galactic Cosmic Ray (GCR) radiation. The GCR proton spectrum has a broad peak from 200 to 500 MeV [Changran, et al. 2015], while Solar Proton Event (SPE) emissions have a spectrum that drops off more sharply above about 100-200 MeV [Xapsos, et al. 2000]. Humans, plants, materials, coatings, assemblies, instruments, and electronics are all susceptible to this radiation making research into the impact of proton radiation critical for enabling long-term exploration of space and allowing humanity to become a multi-planet species [National Academies, 2021].

Materials are also profoundly affected by space radiation. From mechanical to thermal to optical to electrical properties, particle radiation modifies exposed surfaces to penetration depths of centimeters depending on the material and the particle energy. Complex interactions may occur in woven or multi-layer layups and coatings, and chemical reactions can be driven by radiolysis including volatile evolution that may produce spacecraft contamination. While space exposure experiments in low-Earth orbit [e.g., the MISSE experiments, deGroh, et al. 2008] can be used to characterize some of these effects, the particle energy spectrum near Earth is not the same as in deep space or in Jupiter orbit, or even in the vicinity of the Moon, and it cannot be controlled during the experiment (only monitored). Furthermore, it is quite expensive to take even small amounts of material to space for such experiments. Numerical simulation of radiation penetration and damage is growing increasingly sophisticated, however detailed estimation of the resulting effects on mechanical or electrical properties remains difficult to obtain, especially for complex assemblies, material layups, or geometries.

Mechanical assemblies, electronics, cables, optics, detectors, and instruments that operate in space also need to be tested to ensure that performance and durability requirements are met. While this is routinely done to ensure such equipment survives the mechanical and thermal conditions of the launch and space environment, radiation requirements are typically only established for some materials and certain electronic parts such as ASICS or CPUs [National Academies, 2018]. Particularly when designing smaller payloads which cannot accommodate extensive shielding mass, being able to affordably demonstrate radiation tolerance for instruments and sub-assemblies could enable more efficient and capable payloads. As noted by the National Academies [2018], an increasingly tolerant risk posture and changing mix of satellite operators will make the demand for proton testing facilities increase.

A priority for space travel will be the development of crop plants that thrive in the space radiation environment. There is a growing literature on the effects of ionizing radiation on plant growth and reproduction (e.g., Mousseau and Møller, 2020; Boratyński et al 2016, Gudkov et al., 2019), and most studies report negative effects of even moderate doses of gamma radiation, especially for reproduction (e.g., Møller and Mousseau 2015, 2017; Møller et al 2016). Studies of the effects of heavy ions have been exclusively conducted using acute high dose rates with no opportunity to assess growth and development (e.g., at the NSRL). None of these studies have been performed using anything approaching a realistic approximation of the chronic low dose rate environment found in space. In addition, given the apparent lack of evolutionary adaptation, even in environments around Chernobyl where sufficient time has passed to assess such responses, a more intensive approach to breeding and selecting resistant genotypes will be needed if we are to meet our goals of developing space crops. Alternatively, genetic engineering or editing techniques could be used to enhance use high fidelity DNA repair mechanisms, suppress ROS species, and increase antioxidant production to protect from IR damage (Ludovici et al., 2020; Li et al., 2019; Furukawa et al., 2010).

A dedicated proton irradiation facility would enable screening of plant genetic variability for radiation tolerance and the establishment of selection experiments where crosses, or genetically engineered plants can be tested for novel responses. In addition, this beam line would permit rapid screening of thousands of plants from radioactive areas for tolerance. For example, there are many species of plants growing in Chernobyl and atomic bomb test sites that could harbor genetic variation for radiation tolerance, but it is currently impossible to screen the plants for anything other than gamma radiation resistance. This could identify genetic variants or molecular pathways associated with resistance that could be incorporated into space crops once they are understood.

The availability of a large-scale facility to permit such screening and artificial selection is thus essential for the success of future long-term space flights. The addition of biological and materials science testing to the base of microelectronics testing will stress the market

2. Present State of NASA Access to Proton Beam Facilities

In 2016, NASA, DOE, and the Air Force commissioned the National Academies to study testing locations in the US for “radiation-hardened electronics for spacecraft” [National Academies, 2018]. That study complemented ongoing work at NASA to maintain a current inventory of facilities for such testing.

> The [NASEM Report] committee has found that the radiation-testing infrastructure system is fragile; it is already experiencing long wait times and rising testing prices, and it could easily suffer major strains if even a single major facility closes down suddenly. The possibility of a sudden closure was realized in 2014 when the Indiana University Cyclotron Facility (IUCF) ceased operations (due to declining revenues from its primary business of treating cancer patients). [from, National Academies, 2018]

There are currently heavy ion test capabilities available at the NASA Space Radiation Laboratory at Brookhaven National Lab, the Lawrence Berkeley National Lab, the National Superconducting Cyclotron Lab/Facility for Rare Isotope Beams, and several universities. However, high energy protons (approximately 200 MeV) are the predominant radiation risk to spacecraft positioned hundreds of kilometers to approximately 6000 kilometers in altitude, which is comparable to the proton energy levels used by proton cancer treatments.

Proton cancer treatment centers are used by NASA and others for space radiation hardness testing of electronics and the hourly cost for access to these centers is a fraction of that at the heavy ion accelerator facilities. The number of proton cancer treatment centers is increasing: there are currently almost 40 such centers operating or planned in the US [proton-therapy.org/map], which is up from the four that existed a decade ago. However, the newer facilities generally have fewer beamlines due to cost, size, or regulatory considerations. For example, the MedStar Georgetown University Hospital opened in 2018 with a single beamline [Berkowitz, 2018]. A beamline reserved for NASA research, which could be developed at larger facilities such as Hampton University and the University of Pennsylvania, would allow for the installation of specialized equipment (e.g., vacuum, extreme temperatures, vibration, etc.) and long-term testing.

3. Leveraging Medical Proton Facilities

SPEs represent a significant hazard to spacecraft electronics as well as a health issue for potential manned interplanetary missions. For this reason, it is desirable to have the capacity to simulate the proton spectrum of such an event in test facilities. For this purpose, different proton therapy centers have developed the necessary technology to precisely recreate solar flare spectrum reported from events such as those of September 29th, 1989 [Xapsos, et al., 2000]. An example of this technology is a rotating energy shifter that simulates the proton energy spectrum of a solar flare by the team at MGH [Cascio and Sarkar, 2008]. This shifter consisted of a rotating modulating wheel with different thicknesses that would produce a beam with a very similar spectral energy as SPEs. This setup had the disadvantage of being restricted to the spectral conditions resulting from the design of the modulator. Also, the sample had to be placed close to the modulating wheel and the dose was uniform over only a 4cm diameter field.

Current proton technology is based on the use of actively scanned proton beams to precisely deliver protons to any point in space within fields of 30x40 cm2 at isocenter. The advantage of using such hardware-free delivery method over the passive method described above is that the beam can be tailored to the desired spectral properties to be simulated. The disadvantage is that any beam scanning delivery has an intrinsic time structure defined by the time the scanning process takes to reach a point of interest in space, which could potentially affect the dose rates during the experiment. Luckily, the dose rate of SPEs is low enough for this time structure not to be an issue, making this method the most versatile and easy to implement in modern proton centers with testing capabilities. This method has been successfully used at the University of Pennsylvania [Lin, et al. 2014], and allowed to irradiate large animals in very similar SPE spectral conditions with very uniform fields.

To our knowledge, no other testing facility is able to precisely replicate SPE spectral conditions. These facilities are able to deliver a desired number of protons to a given sample, but those proton beams do not necessarily have the same energy spectrum as actual SPEs. As radiation effectiveness is (inversely) correlated with proton energy, the correct designing of the spectral properties of the proton beam is essential to generate valuable data for the space exploration community.

Current research trends in medical applications of proton beams include development of FLASH proton therapy and proton arc therapy. The beam time demand for such development is increasing at a fast rate, and the experimental beam lines, such as that at the University of Pennsylvania, are being adapted for these types of deliveries, which creates a conflict with the use of these beams for other purposes.

4. A Purpose-Built Laboratory Facility

While there are several suitable proton facilities available for NASA research, it is clear from the previous discussion that a proton radiotherapy facility with the capacity to build an experimental line that is able to adapt to current research interests in the field, but also to other research interests in fields not directly related to clinical applications of proton beams, would represent an excellent opportunity to streamline experiments that produce critical data for space exploration. A dedicated facility would not have to work around patient requirements or operations, reducing operational complexity and costs to NASA. Specialized environmental chambers would offer a range of conditions under which electronics, materials, plants, or animals could be tested. Cubesat form factors up to 12U could be accommodated, allowing entire systems to demonstrate functionality under a range of dosage regimes.

5. An Opportunity for Partnership with an HBCU

The Hampton University Proton Therapy Institute has the irradiation resources necessary to meet the conditions specified above, including a beamline and room set aside for research work. This facility could be developed with the intention to fulfill the needs of the entire NASA research community. No other large proton therapy center offers the capability to generate an experimental beam tailored to such a large range of experimental specifications or the usability of a dedicated laboratory space separate from patient activities. Additionally, this is the only such facility operated by a Historically Black College or University, providing NASA a unique opportunity to develop a major facility at an HBCU. The research and training opportunities afforded by such a facility would aid in diversifying NASA’s workforce and the nation’s STEM workforce, generally.

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