GCR Simulator Development Status at the NASA Space Radiation Laboratory

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Solar Energetic Particles, Solar Modulation and Space Radiation:
New Opportunities in the AMS-02 ERA
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Outline

• Brief overview

• Reference field specification
  - External (free space) vs. internal (shielded tissue) environments

• General beam selection strategy

• Discussion and summary

Note: Most of the content described in this presentation can be found in:


Full reference list and citations for models used can also be found in the document (not included here)
Overview

• Long term exposure to GCR presents a serious health risk to astronauts
  - Large uncertainties connected to the biological response
  - Main goal of the NASA/HRP radiobiology experimental research program is to mitigate the risk through uncertainty reduction and countermeasure development

• Radiobiology experiments are performed to reduce uncertainties and understand basic mechanisms for carcinogenesis, CNS and cardiovascular effects
  - Most experiments have been performed with individual ion species and/or energies
  - Approach is guided in part by desire to understand basic mechanisms
  - Heavily influenced by facility constraints and cost

• GCR environment is a broad spectrum of particles and energies
  - Difficult to provide in a laboratory

• NSRL has matured to a point where simulating a “broad” spectrum of particles and energies in a single experiment is feasible from a facility and cost perspective
  - Still can’t simulate full GCR spectrum in one experiment but can do better than a single particle and energy (e.g. $^{56}$Fe at 1 GeV/n)
Overview

• The “GCR simulator” is not intended to take the place of single beam studies
  - Single beam studies are needed to examine and improve understanding of basic mechanisms
  - Also needed to test, develop, and validate theoretical and computational models
  - Developing use-cases for GCR simulator through ongoing community discussions

• The GCR simulator should be viewed as a new and enabling technology that enhances current capabilities
  - Provides opportunity to test models derived from single beam studies in more realistic scenario
  - Improves operational efficiency of NSRL, which in turn, improves efficiency for single beam studies

• The notion of a GCR simulator is not new
  - It has been discussed for decades, and was always a goal of the space radiobiology program
  - The accelerator facility has now matured to a point where implementation is realistic
Overview

- The GCR simulator is intended to deliver deep space, shielded tissue environment to biological targets in a laboratory setting
  - Used to study a range of space radiobiology questions
  - Provides a more realistic scenario for countermeasure development and testing

- Many of the details associated with GCR simulator design will depend on biological question and endpoints being studied

- Some aspects may be “standardized” across experiments
  - Saves time and cost
  - Enables subsequent cross comparisons and validation
  - “Standard” conditions do not have to be universally applied if investigators have a good scientific rationale for deviation

- Two aspects allow for some standardization
  - Reference field specification: which environment are we simulating?
  - General beam selection strategy: how can we pick beams to do the simulation?
External and Internal Fields

• The external field is modified as it passes through shielding and tissue
  - Slowing down due to atomic processes
  - Attenuation and breakup of heavy ions due to nuclear collisions
  - Secondary particle production

Selected particle spectra in free space (left pane) and behind 5 g/cm² of aluminum and 30 g/cm² of water (right pane) during solar minimum
An important question is whether to design the simulator using the free space, external field or local tissue field.
External and Internal Fields

- **External field approach**

  Beams selected to represent external, free space field before shielding.

- **Local tissue field approach**

  Beams selected to directly represent shielded tissue field.
External and Internal Fields

- Facility constraints have a significant impact on simulator design
  - Current NSRL limits: protons (2.5 GeV) and heavier ions (1.0 GeV/n)
  - Upgrade: protons (4.0 GeV) and heavier ions (1.5 GeV/n)

| Fraction of effective dose delivered by energies within NSRL energy constraints |
|-------------------------------------------------|----------------|----------------|
| Energy cutoff description                       | Free space approach | Local field approach |
| Current NSRL energy constraints                  | 47%              | 88%             |
| Upgrade NSRL energy constraints                  | 63%              | 91%             |

- Results for female phantom behind 20 g/cm² of aluminum shielding during solar minimum
- Other scenarios and exposure quantities lead to qualitatively similar results
External and Internal Fields

- Results indicate that energy constraints at NSRL limit the feasibility of simulating the external, free space GCR field
  - Missing ~half of the exposure

- Preliminary GCR simulator design will focus on reproducing the shielded tissue field

Local tissue field approach

Beams selected to directly represent shielded tissue field

Beam

Biological target
Reference Field Specification

- Shielded tissue field in space depends on many factors
  - Tissue location within body
  - Shielding material, thickness, and geometry
  - Solar activity

- Looked at variation associated with each of these factors
  - A single reference field for deep space can be defined

- Observed variation is likely within
  - GCR environmental model uncertainty (at least 20%)
  - Combined physics and transport modelling uncertainty
  - Experimental design uncertainty: representing broad GCR spectrum with relatively few mono-energetic beams
Reference Field Specification

• Variation in local tissue field was examined as a function of
  - Tissue location, shielding configuration, shielding material, solar activity

• Realistic vehicle shielding and simplified spherical shielding was considered
  - Habitat demonstration unit (HDU) adapted for 1-year free space mission
  - Cislunar vehicle concept
  - ISS location in US Lab near overhead racks
  - STS location in mid-deck (often referred to as DLOC 2)
Reference Field Specification

• Tissue exposure values vary by less than 20% behind a range of shielding configurations
  - Variation is within even the GCR environmental model uncertainty (~±20%)
  - Increased variation in dose equivalent associated with HZE breakup
  - Blood forming organ (BFO), bladder, and breast appear as representative tissues
  - 20 g/cm² aluminum appears as representative shielding
Reference Field Specification

- LET spectra show little variation across tissue locations and shielding configurations
  - Spectra appear as qualitatively similar
  - Variation below 200 keV/µm is likely within experimental design uncertainty
  - Variation above 200 keV/µm makes negligible contributions to exposure
Reference Field Specification

• Main difference in LET spectra between solar extremes is overall magnitude
  - Multiplied solar maximum results by 1.85
  - Constant factor nearly corrects discrepancies across the entire LET domain
  - Solar activity does not qualitatively change the shape of the LET spectrum
Reference Field Specification

- Reference field specification for GCR simulator
  - Female BFO behind 20 g/cm² spherical aluminum shielding during solar minimum conditions

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<Q> is notation for average quality factor

*Figure 1: Kinetic energy vs. flux for neutrons, hydrogen, and helium. Full reference field is shown in comparison to reference field without hydrogen and helium contributions.*
General Beam Selection Strategy

- General beam selection strategy is tied to reference field fluence
  - Hydrogen and helium represented in energy domain
  - Heavy ions represented in LET domain
  - Beam intensities computed by integrating reference field fluence over bin limits
  - Heavy ion beams chosen from lookup tables to match LET values
General Beam Selection Strategy

- Hydrogen and helium components explicitly represented in energy domain
  - Greater emphasis given to hydrogen and helium because they account for 81% of dose and 67% of dose equivalent
  - Combination of degrader system and energy switching implemented
General Beam Selection Strategy

- Heavy ion \((Z > 2)\) contributions represented in the LET domain
  - Do not want rapid variation (Bragg peaks) occurring within animals
  - Require heavy ions to be energetic enough to pass through animal model
  - Use LET look-up tables to select ions for each bin
General Beam Selection Strategy

- Lower energy portion of hydrogen and helium spectra is being represented by using polyethylene degrader system
  - Similar procedure as previously implemented for SPE simulator
  - Need to determine number of low energy bins required to achieve reasonably smooth internal exposure profiles

Ellipsoidal tissue phantom to represent mouse

Dimensions: 7 cm (major axis), 3 cm (minor axis)
Mass: 33 grams

Reference field hydrogen and helium energy spectra
General Beam Selection Strategy

Dose profiles within phantom exposed to <150 MeV protons

- Internal variation appears to be controlled with as few as 10 energy bins for low energy portion of hydrogen spectrum
  - Bragg peaks obvious if 3 or 5 bins are used
  - Similar results found for alpha beams used to represent helium component
  - Using more than 25 bins starts to reach fidelity of degrader system at NSRL
Example Beam Selection

- Remaining analyses will consider the following case
  - 10 low energy bins for protons and alphas
  - 5 high energy bins for protons and alphas
  - 15 LET bins for HZE component
Beam induced spectral quantities are in good qualitative agreement with reference field
- Reasonable agreement across full range of LET values
- \((Z'/\beta)^2\) spectrum provides a somewhat independent check since beam selection was not guided by this quantity
Example Beam Selection

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- Cell nucleus hits computed by assuming cross sectional area of 100 µm²
- Hits/cell results consistent with previous calculations by Curtis et al.
Summary

- Facility constraints limit the ability to simulate the external, free space field directly
  - Proposed simulator design instead focuses on reproducing the local tissue field

- Variation in the induced tissue field was examined
  - A single reference environment for deep space is reasonable at this time

- An approach for beam selection in the simulator was presented
  - The approach is tied directly to the reference environment flux
  - Allows systematic improvements to be made
  - Spectral quantities and integrated quantities are reasonably well represented
  - Optimization procedures could be developed to improve overall agreement

- Drawbacks of the proposed strategy include
  - Neutron and π/EM components
  - Lower energy constraints for HZE particles associated with animal models
  - These drawbacks could be addressed by augmenting the existing design if necessary
Backup: Example Beam Info

- Proton beam information for example study

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Backup: Example Beam Info

- Alpha beam information for example study

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Backup: Example Beam Info

- HZE beam information for example study

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