Validation of NASA Space Radiation Analysis Tools with ISS Radiation Environment Monitor (REM) Data

Martha S. Clowdsley¹, Steven A. Walker², Xu Xiaojing³, H. Lee Abston¹, Nicholas A. Vitullo⁴, Tony C. Slaba¹, Steve R. Blattnig¹, Dustin R. Whitlow⁴, Charles J. Wittkopp¹, Frank L. Boyer¹, Francis F. Badavi², Christopher J. Mertens¹, John W. Norbury¹

¹NASA Langley Research Center, Hampton, VA
²Old Dominion University, Norfolk, VA
³Science Systems and Applications, Inc., Hampton, VA
⁴Analytical Mechanics Associates, Inc., Hampton, VA

SEP, Solar Modulation and Space Radiation: New Opportunities in the AMS-02 ERA
October 18-23, 2015
Honolulu, Hawaii
Radiation Exposure Analysis Process

- Shielding models
- Environment models
- Physics models

Radiation transport models

Dosimetric and/or Biological response
Cross Sections $\sigma_i$, $\sigma_{ij}$  PHYSICS  (NUCFRG, QMSFRG)

Boltzmann TRANSPORT Eqn $\Rightarrow$ FLUENCE $\phi_i$ $[\text{#/cm}^2/\text{MeV}]$ (HZETRN)

$$
\left[ \frac{\partial}{\partial x} - \frac{\partial}{\partial E} S_i(E) + \sigma_i(E) \right] \phi_i(x, E) = \sum_j \int_{E}^{\infty} dE' \sigma_{ij}(E, E') \phi_j(x, E')
$$

Dose $D(x) = \sum_i \int_0^\infty dE S_i(E) \phi_i(x, E)$ [Gy = J/kg]

Dose Equivalent $H(x) = \sum_i \int_0^\infty dE Q(L_i(E)) L_i(E) \phi_i(x, E)$ [Sv]

Effective Dose $E = \sum_T w_T H_T$ [Sv] $\Rightarrow$ Risk

BIOLOGY $Q(L_i), w_T$

$L_i \equiv \frac{dE}{dx} \approx S_i(E)$
Overview

• Measurements made with the Radiation Environment Monitor (REM) units currently onboard the International Space Station (ISS) provide an opportunity to perform end-to-end validation of radiation analysis tools used by NASA to predict astronaut exposure.

• This validation effort is being performed under the NASA Advanced Exploration Systems (AES) RadWorks project.

• This work is on-going. The current status is reported in this presentation.

1NASA JSC Imagery Online website
Detector Locations Used for Validation

- Dose in silicon and dose equivalent in tissue have been calculated for 3 ISS REM locations: US Lab, Node 1, and Cupola
- As an additional check, dose in tissue and dose equivalent in tissue have been calculated for the Tissue Equivalent Proportional Counter (TEPC) location in the Service Module (SM)
Updates to ISS CAD models

ISS CAD models were updated to accurately reflect the shielding mass surrounding the detectors:

- Overlapping parts and holes in the models fixed
- Volumetric models created for parts represented only as surfaces
- Internal rack placement updated to match current configuration
- Part masses updated to agree with best available information at the rack and large component level

<table>
<thead>
<tr>
<th>Module</th>
<th>Final CAD Model Mass (lbm)</th>
<th>In Space Module Mass (lbm)</th>
<th>Source on In Space Mass</th>
</tr>
</thead>
<tbody>
<tr>
<td>Airlock</td>
<td>22,604.37</td>
<td>22,594.00</td>
<td>B. Baker</td>
</tr>
<tr>
<td>Columbus</td>
<td>36,158.75</td>
<td>38,138.36</td>
<td>ISS Mass Properties Spreadsheet</td>
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<tr>
<td>JEM</td>
<td>88,128.28</td>
<td>87,610.94</td>
<td>ISS Mass Properties Spreadsheet</td>
</tr>
<tr>
<td>Node 1</td>
<td>22,986.37</td>
<td>22,986.38</td>
<td>ISS Mass Properties Spreadsheet</td>
</tr>
<tr>
<td>Node 2</td>
<td>30,646.38</td>
<td>35,933.72</td>
<td>ISS Mass Properties Spreadsheet</td>
</tr>
<tr>
<td>Node 3</td>
<td>49,170.18</td>
<td>46,238.64</td>
<td>SPIDER database/ISS Mass Properties Spreadsheet</td>
</tr>
<tr>
<td>PMA 1</td>
<td>2,494.82</td>
<td>2,494.59</td>
<td>B. Baker/ISS Mass Properties Group</td>
</tr>
<tr>
<td>PMA 2</td>
<td>2,494.47</td>
<td>2,494.59</td>
<td>B. Baker/ISS Mass Properties Group</td>
</tr>
<tr>
<td>PMA 3</td>
<td>2,492.76</td>
<td>2,494.59</td>
<td>B. Baker/ISS Mass Properties Group</td>
</tr>
<tr>
<td>SM</td>
<td>53,264.57</td>
<td>54,260.64</td>
<td>SPIDER database/ISS Mass Properties Spreadsheet</td>
</tr>
<tr>
<td>US Lab</td>
<td>55,676.12</td>
<td>55,676.00</td>
<td>B. Baker/ISS Mass Properties Group</td>
</tr>
</tbody>
</table>

*This effort is ongoing – Updated modules shown*
Once the CAD models were updated and the detector locations were identified within the CAD models, the entire ISS model was ray-traced at each location, providing a distribution of the shielding materials surrounding each of the detectors.
Computational Procedure

• Environment boundary conditions computed for points at 2 minute intervals along the ISS trajectory
  – GCR modulated by the Earth’s magnetic field
  – trapped protons
  – albedo neutrons
• Flux spectra versus shield thickness databases computed using HZETRN
• Flux databases converted into dose in silicon, dose in tissue, and dose equivalent in tissue versus thickness databases for each trajectory point
• Dose and dose equivalent computed for each trajectory point
  – First, interpolated over the dose versus thickness database for each ray
  – then integrating over all the rays in the ray-trace
Baseline Analysis Assumptions

• External radiation environments are modelled as isotropic, except where the Earth’s shadow blocks the GCR environment
• All trapped protons energetic enough to penetrate the ISS pressure vessel occur within the South Atlantic Anomaly (SAA)
  ➢ Removal of trajectory points between 2.5 and 47.5 degrees South and 12.5 – 77.5 degrees West will result in the removal of all penetrating trapped protons
• GCR environment model: Badhwar-O’Neill 2013
• Vertical cutoff rigidity model: Stormer’s model
• Trapped proton environment model: AP8 (Badavi time dependence and normalization)
• Rays in the ray-trace: 9002
• ICRP 60 quality factor used to calculate dose equivalent
Calculation Results – Dose Rate

Dose Rate in Silicon, Nov. 16, 2013

- Calculated results appear to accurately model the time dependence of the varying dose rate within ISS
- Similar trends for all 4 detectors
Calculation Results – US Lab Dose Rate

Dose Rate in Silicon, Nov. 16, 2013

- SAA Passes
- Closer to the Poles
- Near the Equator
Average Dose Rate (2 minute bins)

- Calculated results appear to under-predict measurements.
- The under-prediction appears to be larger near the equator, where the magnetic field rigidity is largest.
Dose rate plotted against the rigidity of the Earth’s magnetic field.

Under-prediction of mean for US Lab detector:
- ~18% at low rigidity (most like free space)
- ~60% at high rigidity

Results were similar for the other detector locations.
Dose equivalent was calculated, because it is more directly related to human risk than dose.

Better agreement between calculated and measured results than for dose.

Under-prediction of mean for the US Lab detector:
- ~6% at low rigidity
- ~49% at high rigidity

Results were similar for the other detector locations.

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US Lab Dose Eq. Rate in Silicon, Nov. 16-25, 2013

- Dose equivalent was calculated, because it is more directly related to human risk than dose.
- Better agreement between calculated and measured results than for dose.
- Under-prediction of mean for the US Lab detector:
  - ~6% at low rigidity
  - ~49% at high rigidity
- Results were similar for the other detector locations.
Investigation of Calculation Under-Prediction

The sensitivity of calculated results to various model assumptions has been examined:

• Geometry/Shielding
  - Pressure Shell Areal Density – minimal impact on calculated dose
  - Materials Definition in CAD Models – underestimation of the quantities of heavy metals in the ISS could result in a small underestimation of dose rate
  - Number of Rays in Ray-Trace – 1002 rays shown to be adequate

• Environment Modeling
  - GCR Model – Dose rates using Badhwar-O’Neill 2010, Badhwar-O’Neill 2013, and Matthia 2013 are all similar
  - Magnetic Field Models – Tsyganenko model compared to simpler IGRF model, IGRF model adequate for ISS orbit during quiet time
  - Use of Isotropic GCR Environment - adequate for calculating dose inside ISS
  - Assumption that Energetic Trapped Protons only occur in the SAA – may not be correct, see next page

• Transport Calculation
  - Interpolation over pre-calculated Dose vs. Shield Thickness databases – only small impact on calculated dose rates
  - Use of HZETRN Transport Algorithms – Recently completed multi-code transport benchmarks for aluminum targets indicate that HZETRN may under-predict dose and dose equivalent for thick shields
    - Slaba to present result at February NASA HRP workshop
PAMELA Measurements

- Recent PAMELA (Payload for Antimatter Exploration and Light-nuclei Astrophysics) measurements include a high energy proton component not represented in current trapped proton models
- Preliminary analysis shows that inclusion of these protons might correct part of the systematic under-estimate at high cutoff rigidities
- However, PAMELA is a directional measurement looking directly away from Earth
- More information about the angular distribution and time dependence of these protons is needed
- AMS-02 measurements may help
Summary

• An effort to validate radiation analysis tools with ISS REM measurements is underway.
• Dose and dose equivalent rates have been calculated and compared to ISS REM and TEPC measurements.
• Calculated results accurately model the time dependence, but under-predict the total dose and dose equivalent rates.
• This under-prediction varies from less than 20% for dose equivalent at high latitudes to more that 60% for dose near the equator.
• A number of model assumptions related to geometry, environments, and transport calculation have been investigated to better understand their impact on the calculation under-prediction.
  – Most of the model assumptions examined had minimal affect on results.
  – However, the possible under-prediction of the HZETRN transport code for thick shields and high energy protons not represented in current trapped proton environment models are deemed worthy of future study.
Acknowledgements

• This work is funded under the NASA AES RadWorks project.
• Thanks to the RadWorks leadership team, Bobbie Gail Swan, David Moore, Edward Semones, and Catherine Mcleod, for their enthusiastic support.
• Thanks to Amir Bahadori, Nicholas Stoffle, Ryan Rios, Martin Kroupa, and Andrew Welton, past and present members of the NASA JSC Space Radiation Analysis Group, for their help obtaining ISS CAD models and REM detector data, and for their willingness to answer questions about both topics.
• Thanks to Bruce Baker of the ISS Mass Properties Group for his help gathering mass information for the various ISS modules.
Impact of AMS-02 Measurements on Reducing GCR Model Uncertainties

T.C. Slaba\textsuperscript{1}, P.M. O’Neill\textsuperscript{2}, S. Golge\textsuperscript{3}, J.W. Norbury\textsuperscript{1}

\textsuperscript{1}NASA Langley Research Center, Hampton, VA
\textsuperscript{2}NASA Johnson Space Center, Houston, TX
\textsuperscript{3}University of Houston, Houston, TX

Solar Energetic Particles, Solar Modulation and Space Radiation: New Opportunities in the AMS-02 ERA
October 18-23, 2015
Honolulu, Hawaii, USA
Outline

• Radiation exposure analysis overview
• Initial sensitivity and uncertainty quantification results
• Galactic cosmic ray (GCR) models
• Impact of AMS-02 measurements on reducing uncertainties
Impact of GCR Model Uncertainty

- GCR protons account for >50% of the total exposure behind shielding\(^1\)
- GCR alphas are the next largest contributor
- Ions with \(Z > 2\) and energy below 500 MeV/n (ACE) account for less than 5% of the exposure

Relative contribution (%) of each boundary ion/energy group to effective dose behind 20 g/cm\(^2\) aluminum during solar minimum\(^1\).

<table>
<thead>
<tr>
<th>Boundary energy interval (GeV/n)</th>
<th>&lt; 0.25</th>
<th>[0.25, 0.5]</th>
<th>[0.5, 1.5]</th>
<th>[1.5, 4]</th>
<th>&gt; 4</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>(Z = 1)</td>
<td>1.2</td>
<td>5.4</td>
<td>18.2</td>
<td>18.4</td>
<td>14.8</td>
<td>58.1</td>
</tr>
<tr>
<td>(Z = 2)</td>
<td>1.2</td>
<td>2.2</td>
<td>4.1</td>
<td>2.9</td>
<td>1.7</td>
<td>12.2</td>
</tr>
<tr>
<td>(Z = 3-10)</td>
<td>&lt; 0.1</td>
<td>3.3</td>
<td>3.8</td>
<td>1.3</td>
<td>0.8</td>
<td>9.1</td>
</tr>
<tr>
<td>(Z = 11-20)</td>
<td>&lt; 0.1</td>
<td>0.2</td>
<td>6.6</td>
<td>2.0</td>
<td>1.1</td>
<td>10.0</td>
</tr>
<tr>
<td>(Z = 21-28)</td>
<td>&lt; 0.1</td>
<td>&lt; 0.1</td>
<td>4.7</td>
<td>3.8</td>
<td>2.1</td>
<td>10.6</td>
</tr>
<tr>
<td>Totals</td>
<td>2.5</td>
<td>11.1</td>
<td>37.4</td>
<td>28.4</td>
<td>20.5</td>
<td>100.0</td>
</tr>
</tbody>
</table>

Impact of GCR Model Uncertainty

• GCR model uncertainty induces roughly ±20% error on effective dose\(^{(2)}\)
  – Results below for Badhwar-O’Neill (BON) 2014 GCR model\(^{(3)}\)

![Effective dose versus shield thickness during solar minimum](image)

• Error bars represent uncertainty associated with GCR model only

• For nominal vehicle shielding (>10 g/cm\(^2\)), relative errors are roughly ±20%

The Badhwar O'Neill (BON) galactic cosmic ray model is used at NASA as input into radiation transport codes for
- vehicle design, mission analysis, astronaut risk analysis
- other models used as well (discussed in later slides)

BON model revisions are based on the same fundamental framework
- Model equations are solved to describe particle transport through solar system
- Solar activity is described by a single parameter related to observed sunspot numbers
International Models and Comparisons

- GCR models tend to agree reasonably well at highest energies\(^{(2)}\)
  - Effects of solar modulation are less pronounced
  - Significant contributor to exposure behind shielding

- Matthia et al. (DLR) recently developed a simplified form of Nymmik’s model\(^{(6)}\)
  - Shown to be reasonably accurate\(^{(2,6)}\)

- Nymmik (MSU) has developed a semi-empirical model\(^{(4,5)}\) (not shown)
  - Used by Russian Space Agency & others (DLR, ESA)
  - Official update has not been provided recently

\[\text{GCR proton & alpha flux compared to measurements}\]

\[\text{Protons:} \quad \text{Matthia} \quad \text{BON2014} \quad \text{PAMELA meas.}\]

\[\text{Alphas:} \quad \text{Matthia} \quad \text{BON2014} \quad \text{PAMELA meas.}\]

International Models and Comparisons

- Exposures behind shielding are in good agreement if updated GCR models are used
  - BON2014 and Matthia are within 10% of each other, on average, over past 40 years
GCR Model Development

- GCR models are developed and validated using available measurements
  - Short duration, high energy, balloon and satellite measurements
  - Low energy, continuous measurements from ACE/CRIS (most of the available measurements)
  - Current gap in measurement database for continuous, high energy measurements

<table>
<thead>
<tr>
<th>Name</th>
<th>Flight</th>
<th>Time</th>
<th>Ions (Z)</th>
<th>Energy (GeV/n)</th>
<th>Data pts.</th>
</tr>
</thead>
<tbody>
<tr>
<td>ACE/CRIS</td>
<td>Satellite</td>
<td>1998-present</td>
<td>5-28</td>
<td>0.05 – 0.5</td>
<td>8288</td>
</tr>
<tr>
<td>AMS</td>
<td>STS-91</td>
<td>1998</td>
<td>1, 2</td>
<td>0.1 – 200</td>
<td>58</td>
</tr>
<tr>
<td>ATIC-2</td>
<td>Balloon</td>
<td>2002</td>
<td>1, 2, 6, 8, 10,...,14, 26</td>
<td>4.6 – 10³</td>
<td>55</td>
</tr>
<tr>
<td>BESS</td>
<td>Balloon</td>
<td>1997-2000, 2002</td>
<td>1, 2</td>
<td>0.2 – 22</td>
<td>300</td>
</tr>
<tr>
<td>CAPRICE</td>
<td>Balloon</td>
<td>1994, 1998</td>
<td>1, 2</td>
<td>0.15 – 350</td>
<td>93</td>
</tr>
<tr>
<td>CREAM-II</td>
<td>Balloon</td>
<td>2005</td>
<td>6-8, 10, 12, 14, 26</td>
<td>18 – 10³</td>
<td>42</td>
</tr>
<tr>
<td>HEAO-3</td>
<td>Satellite</td>
<td>1979</td>
<td>4-28</td>
<td>0.62 – 35</td>
<td>331</td>
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<td>IMAX</td>
<td>Balloon</td>
<td>1992</td>
<td>1, 2</td>
<td>0.18 – 208</td>
<td>56</td>
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<td>IMP-8</td>
<td>Satellite</td>
<td>1974</td>
<td>6, 8, 10, 12, 14</td>
<td>0.05 – 1</td>
<td>53</td>
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<tr>
<td>LEAP</td>
<td>Balloon</td>
<td>1987</td>
<td>1, 2</td>
<td>0.18 – 80</td>
<td>41</td>
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<td>1, 2</td>
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<td>PAMELA</td>
<td>Satellite</td>
<td>2006-2009</td>
<td>1, 2</td>
<td>0.08 – 10³</td>
<td>472</td>
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<td>TRACER</td>
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<td>2003</td>
<td>8, 10, 12,...,20, 26</td>
<td>0.8 – 10³</td>
<td>55</td>
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<td>1974</td>
<td>4-14, 16, 20, 26</td>
<td>0.35 – 52</td>
<td>131</td>
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<td>Minagawa</td>
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<td>1975</td>
<td>26, 28</td>
<td>1.3 – 10</td>
<td>16</td>
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<td>Muller</td>
<td>STS-51</td>
<td>1985</td>
<td>6, 8, 10, 12, 14</td>
<td>50 – 10³</td>
<td>16</td>
</tr>
<tr>
<td>Simon</td>
<td>Balloon</td>
<td>1976</td>
<td>5-8</td>
<td>2.5 – 10³</td>
<td>46</td>
</tr>
</tbody>
</table>
**Galactic Cosmic Ray Model Development**

- Recent work has significantly reduced model uncertainties\(^{(3)}\)
  - More rigorous approach to model calibration and validation – resulted in BON2014
  - Determined measurements (energies) most important for exposure quantities behind shielding
  - Model parameters calibrated using optimization methods with an emphasis on higher energies
  - Comprehensive validation metrics applied to quantify model uncertainty
  - Process can include new measurements and is repeatable

Widely used GCR models are mainly semi-empirical.
- Data are needed to refine free parameters in models.

AMS-02 data will serve two important functions:
- Provide substantial data for independent validation (i.e. data not used to tune model)
- Fill important data gaps to enable improved parameter calibration

Current schedule for using AMS-02 for GCR measurements is mainly driven by impact on exposure:
- Monthly GCR proton measurements for energies greater than 500 MeV
- Next step is to analyze GCR alphas
- Specific heavy ions will be emphasized later
Impact of AMS-02 Data

- If GCR proton and alpha uncertainty is cut in half
  - Uncertainty estimate drops from roughly \( \pm 20\% \) to \( \pm 15\% \)

**Effective dose versus shield thickness during solar minimum**

- Error bars represent uncertainty associated with GCR model only
- Blue error bars represent current model uncertainties
- Red error bars represent assumed modified uncertainties with AMS-02 measurements
Impact of AMS-02 Data

- If GCR proton and alpha uncertainty is entirely removed
  - Uncertainty estimate drops from roughly $\pm 20\%$ to $\pm 5\%$

**Effective dose versus shield thickness during solar minimum**

- Error bars represent uncertainty associated with GCR model only
- Blue error bars represent current model uncertainties
- Red error bars represent assumed modified uncertainties with AMS-02 measurements
Summary

• Widely used GCR models rely on available measurements
  – Measurements used directly for development and validation
  – Updated models are in reasonable agreement
  – GCR models induce roughly +20% uncertainty on effective dose behind shielding

• AMS-02 will fill an important gap in the measurement database
  – Significant need for high energy, time-resolved proton and alpha measurements
  – Current measurement database is dominated by ACE/CRIS
  – ACE/CRIS measurement domain induces less than 5% of exposure behind shielding

• Proton and alpha measurements from AMS-02 will reduce model uncertainties
  – Possibility exists to have a significant impact on reducing overall exposure uncertainties
GCR Simulator Development Status at the NASA Space Radiation Laboratory

T.C. Slaba, J.W. Norbury, S.R. Blattnig

NASA Langley Research Center, Hampton, VA

Solar Energetic Particles, Solar Modulation and Space Radiation: New Opportunities in the AMS-02 ERA
October 18-23, 2015
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Note: Most of the content described in this presentation can be found in:

Slaba, T., Blattnig, S., Norbury, J., Rusek, A., La Tessa, C., Walker, S.,
GCR Simulator Reference Field and a Spectral Approach for Laboratory Simulation.
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 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
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
External and Internal Fields

• 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

<table>
<thead>
<tr>
<th>Energy cutoff description</th>
<th>Free space approach</th>
<th>Local field approach</th>
</tr>
</thead>
<tbody>
<tr>
<td>Current NSRL energy constraints</td>
<td>47%</td>
<td>88%</td>
</tr>
<tr>
<td>Upgrade NSRL energy constraints</td>
<td>63%</td>
<td>91%</td>
</tr>
</tbody>
</table>

- 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 modeling uncertainty
  - Experimental design uncertainty: representing broad GCR spectrum with relatively few mono-energetic beams

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

- Reference field specification for GCR simulator
  - Female BFO behind 20 g/cm² spherical aluminum shielding during solar minimum conditions
• 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
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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Beam induced spectral quantities are in good qualitative agreement with reference field
- Reasonable agreement across full range of LET values
- \((Z'/?)^2\) spectrum provides a somewhat independent check since beam selection was not guided by this quantity
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