GCR Simulator Development Status at the NASA Space Radiation Laboratory

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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:

Slaba, T.C., Blattnig, S.R., Norbury, J.W., Rusek, A., La Tessa, C., Walker, S.A., GCR Simulator Reference Field and a Spectral Approach for Laboratory Simulation. **NASA Technical Paper 2015-218698** (2015).

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

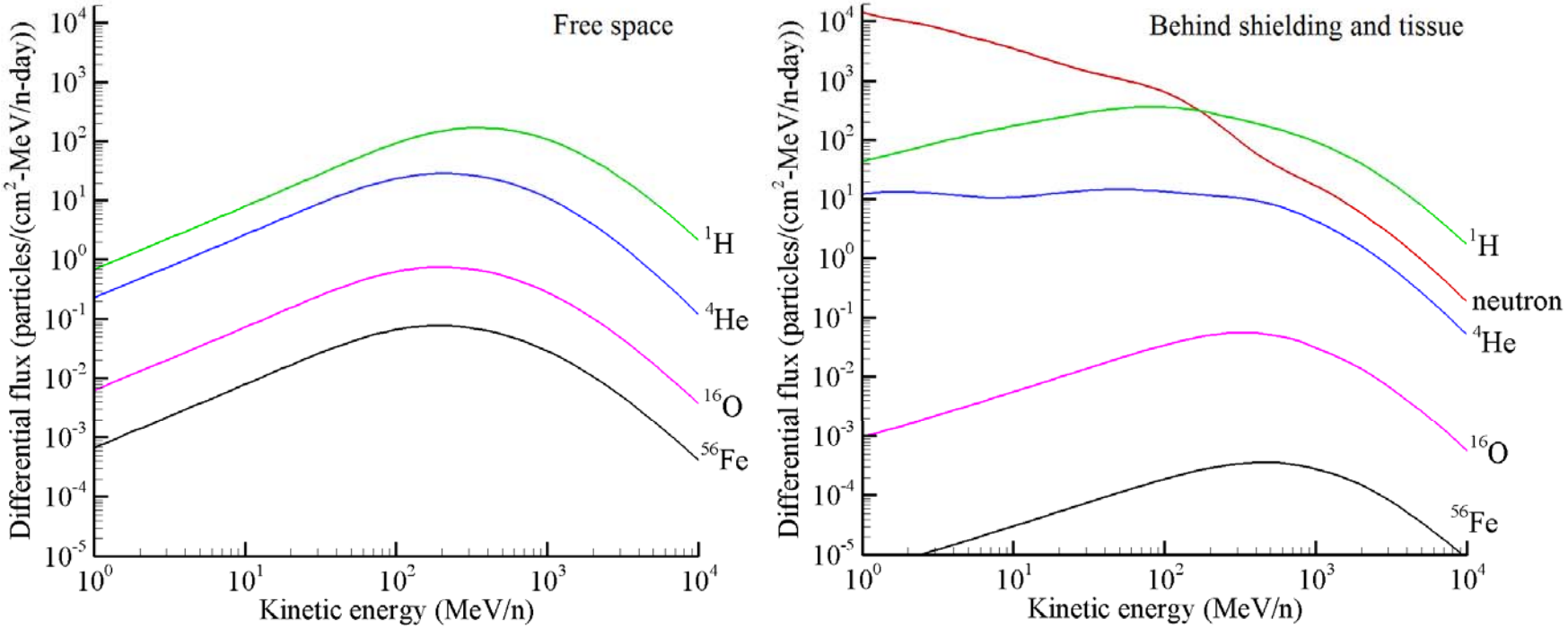
- Many of the details associated with GCR simulator design will depend on biological question and endpoints being studied

- 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

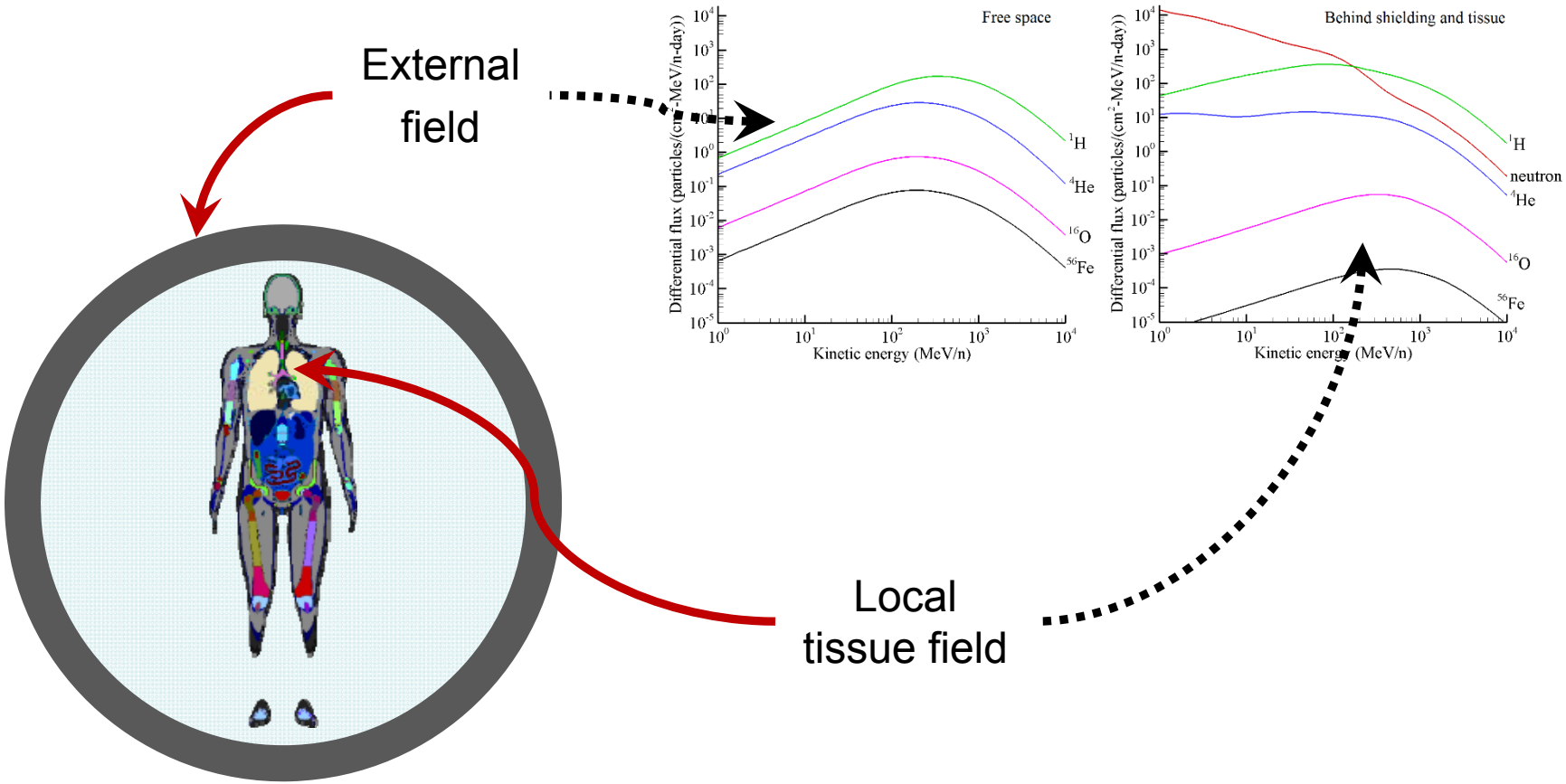
- The external field is modified as it passes through shielding and tissue
  - Slowing down due to atomic processes
  - Attenuation and breakup of heavy ions due to nuclear collisions
  - Secondary particle production



Selected particle spectra in free space (left pane) and behind 5 g/cm^2 of aluminum and 30 g/cm^2 of water (right pane) during solar minimum

External and Internal Fields

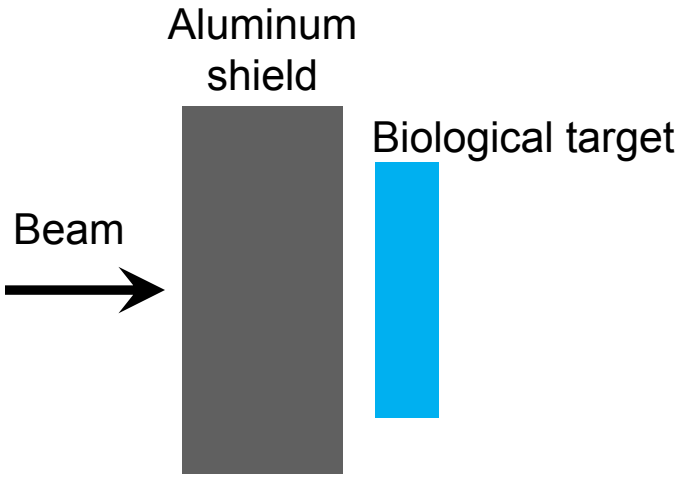
- An important question is whether to design the simulator using the free space, external field or local tissue field

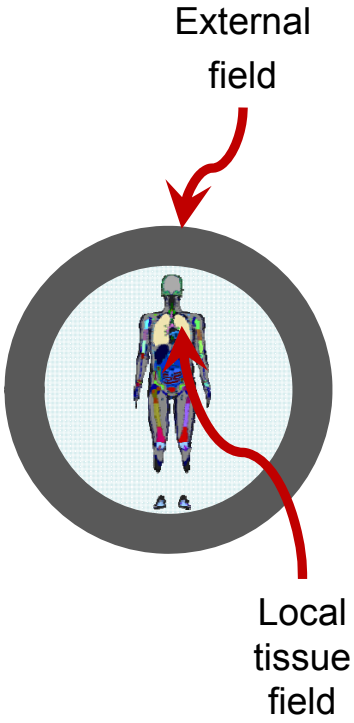


External and Internal Fields

- External field approach

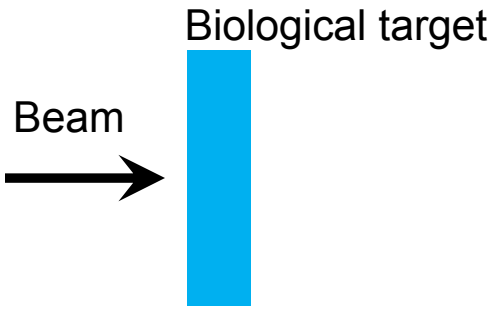
Beams selected to represent external, free space field before shielding





- 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

Energy cutoff description	Free space approach	Local field approach
Current NSRL energy constraints	47%	88%
Upgrade NSRL energy constraints	63%	91%

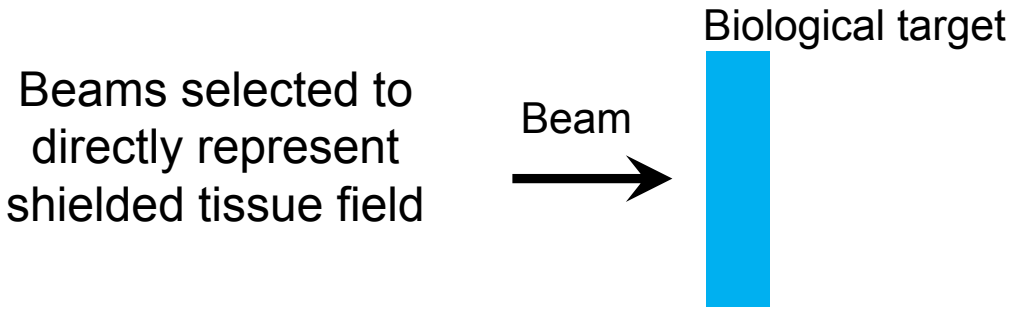
- Results for female phantom behind 20 g/cm^2 of aluminum shielding during solar minimum
- Other scenarios and exposure quantities lead to qualitatively similar results

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

<u>Local tissue field approach</u>



Reference Field Specification

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

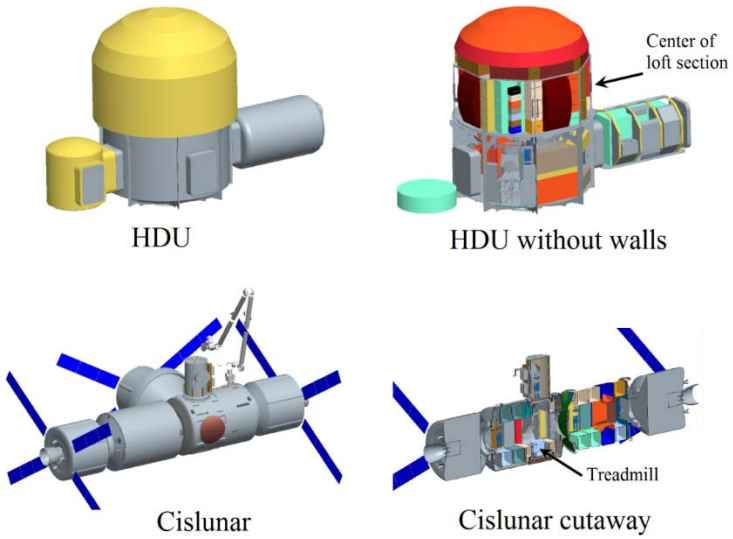
- Looked at variation associated with each of these factors
  - A single reference field for deep space can be defined

- 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

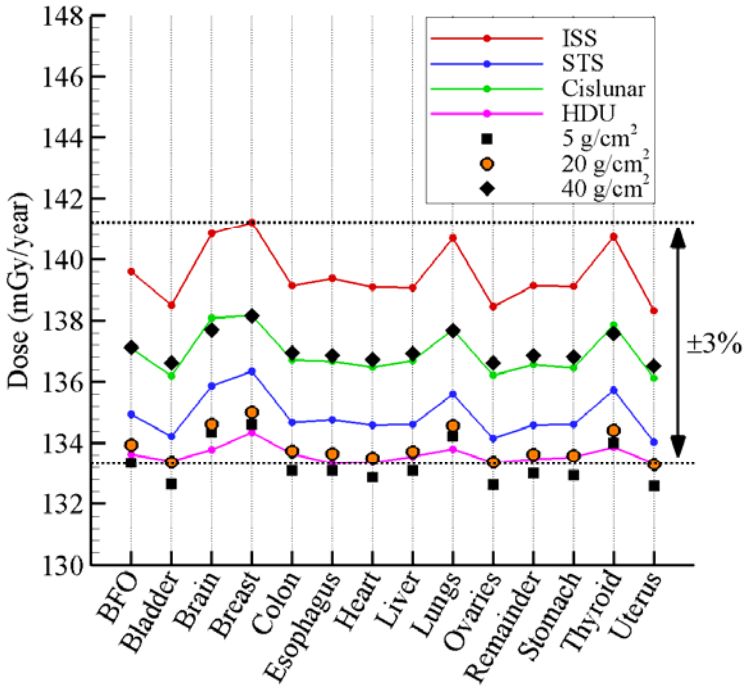
- Variation in local tissue field was examined as a function of
  - Tissue location, shielding configuration, shielding material, solar activity

- 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)

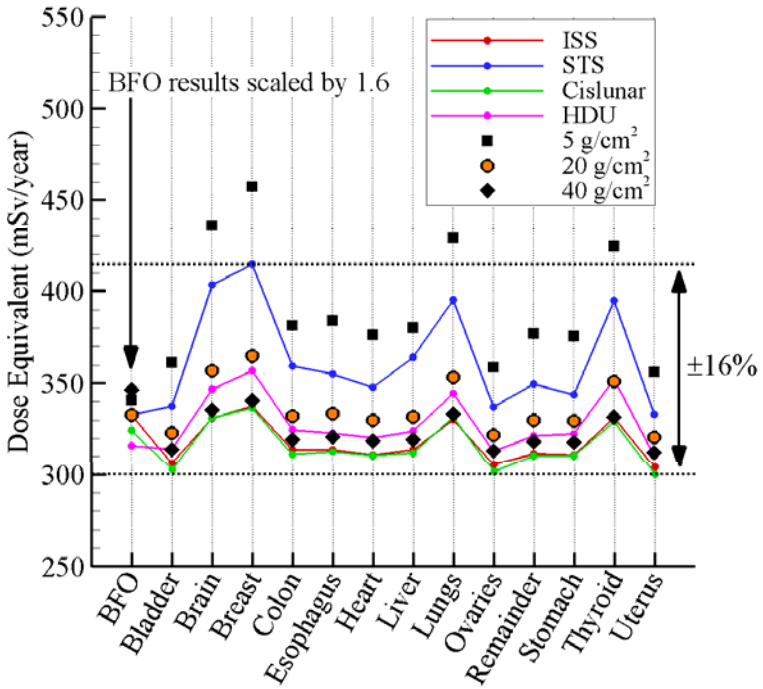


Reference Field Specification

Tissue dose variation behind shielding



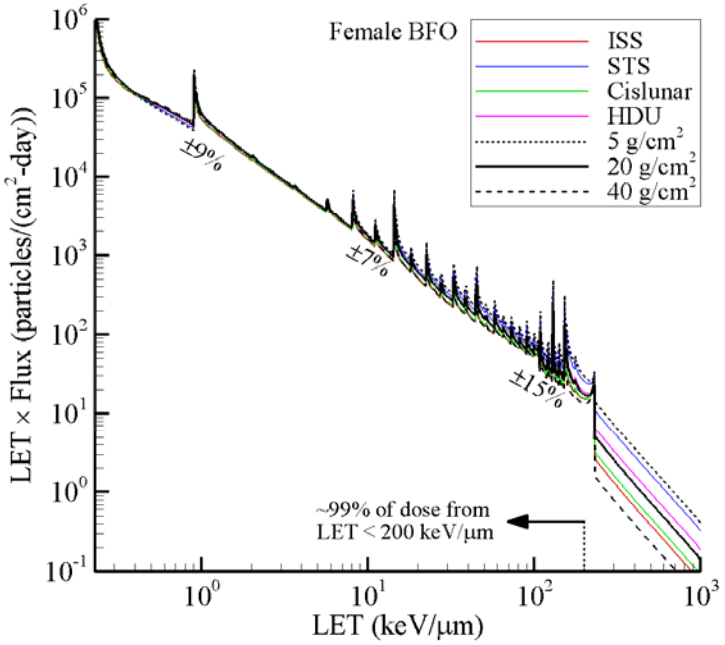
Tissue dose equivalent variation behind shielding



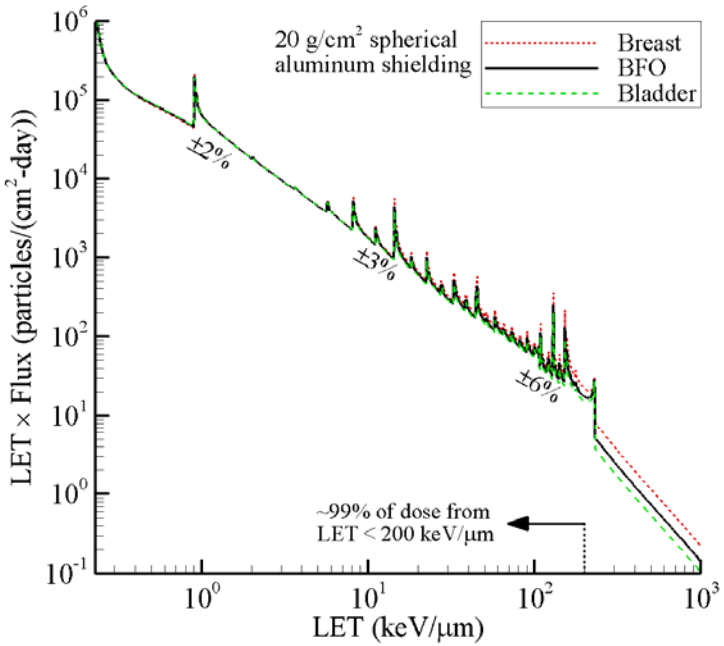
- Tissue exposure values vary by less than 20% behind a range of shielding configurations
  - Variation is within even the GCR environmental model uncertainty (~±20%)
  - Increased variation in dose equivalent associated with HZE breakup
  - Blood forming organ (BFO), bladder, and breast appear as representative tissues
  - 20 g/cm^2 aluminum appears as representative shielding

Reference Field Specification

Female BFO LET spectra behind shielding



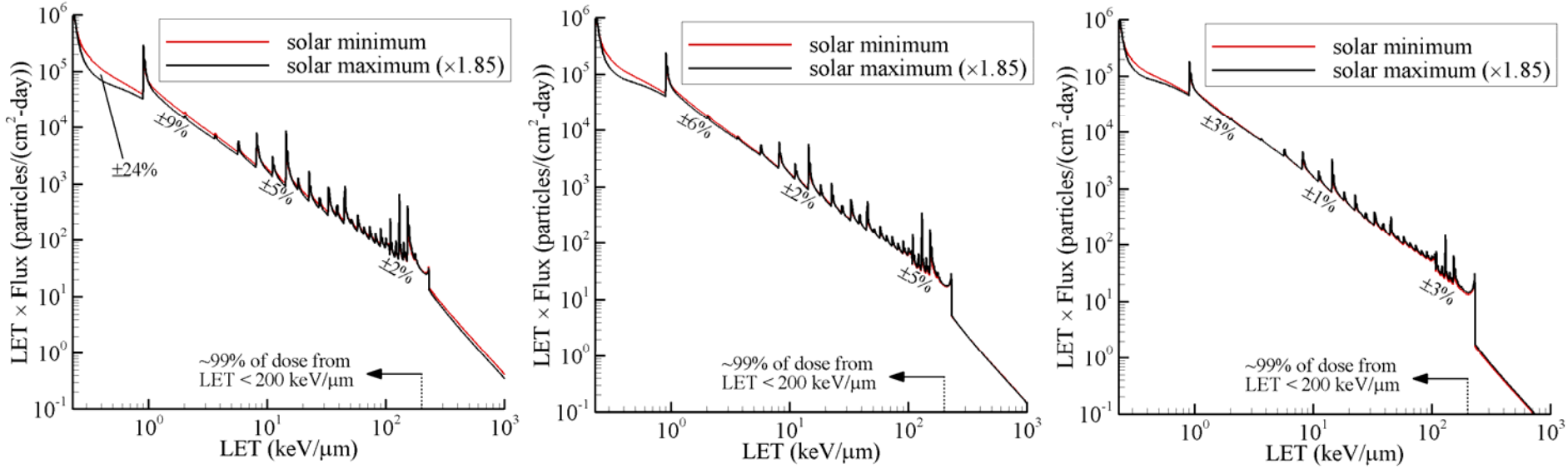
Tissue LET spectra behind shielding



- 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

LET spectra in female BFO behind 5 g/cm^2 (left), 20 g/cm^2 (middle), and 40 g/cm^2 (right) aluminum shielding



- 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

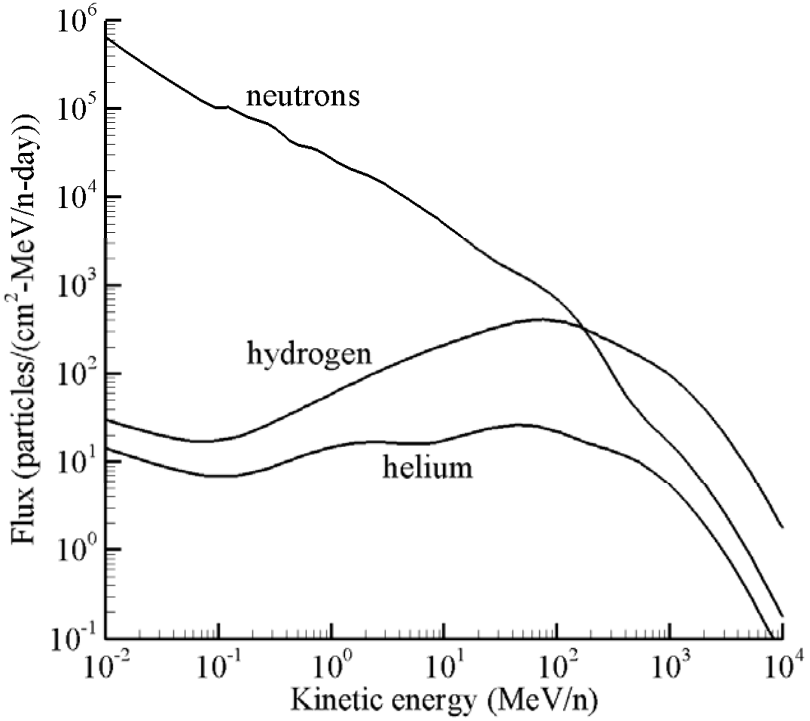
Reference Field Specification

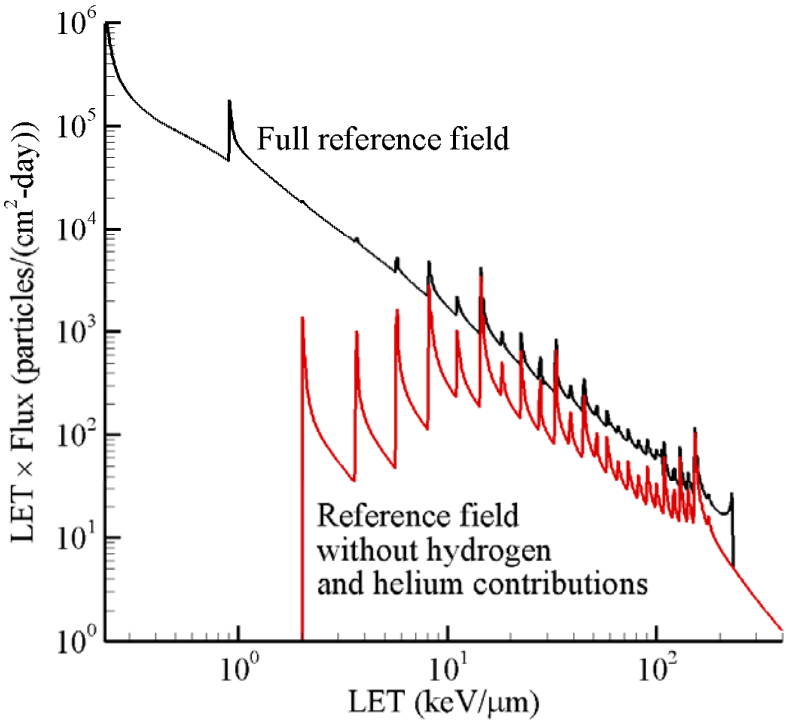
- Reference field specification for GCR simulator
  - Female BFO behind 20 g/cm^2 spherical aluminum shielding during solar minimum conditions

Annual reference field quantities

	Avg. hits per cell nucleus	Dose (mGy)	Dose Eq. (mSv)	<Q>
hydrogen	126	86.0	131.1	1.5
helium	7	22.5	93.8	4.2
HZE	0.5	8.9	73.3	8.2

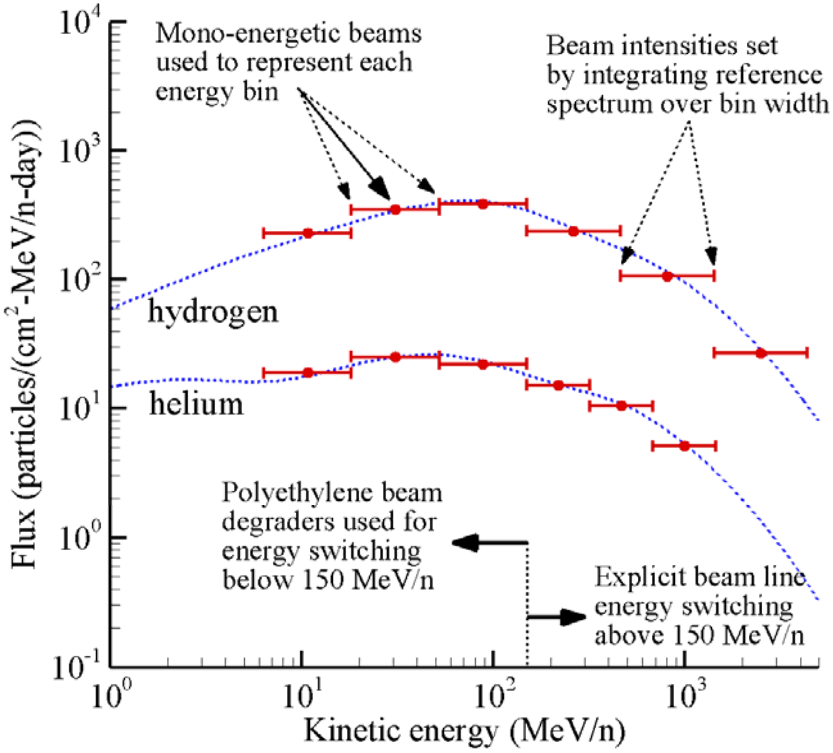
<Q> is notation for average quality factor

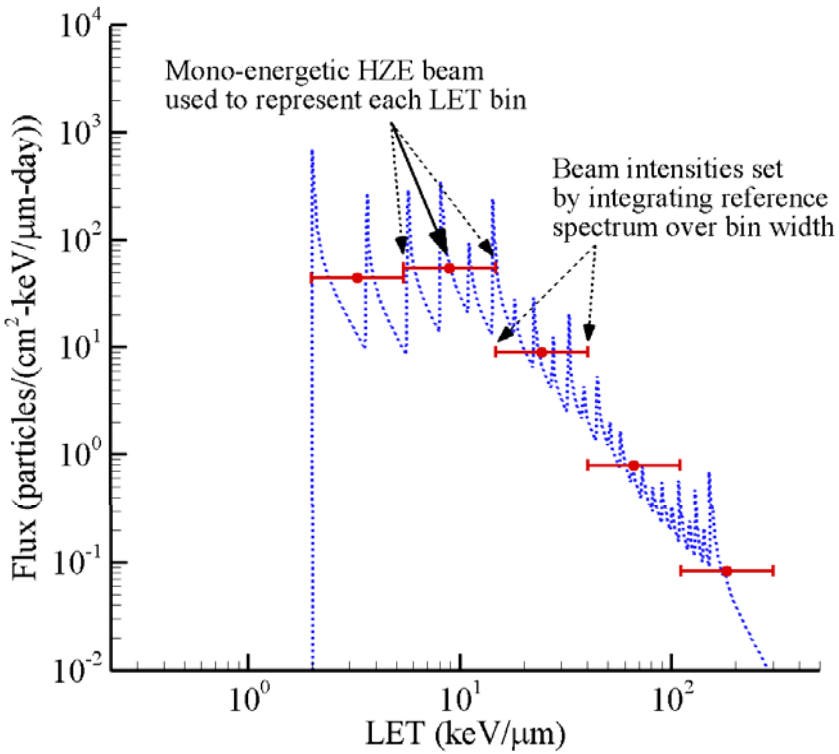




General Beam Selection Strategy

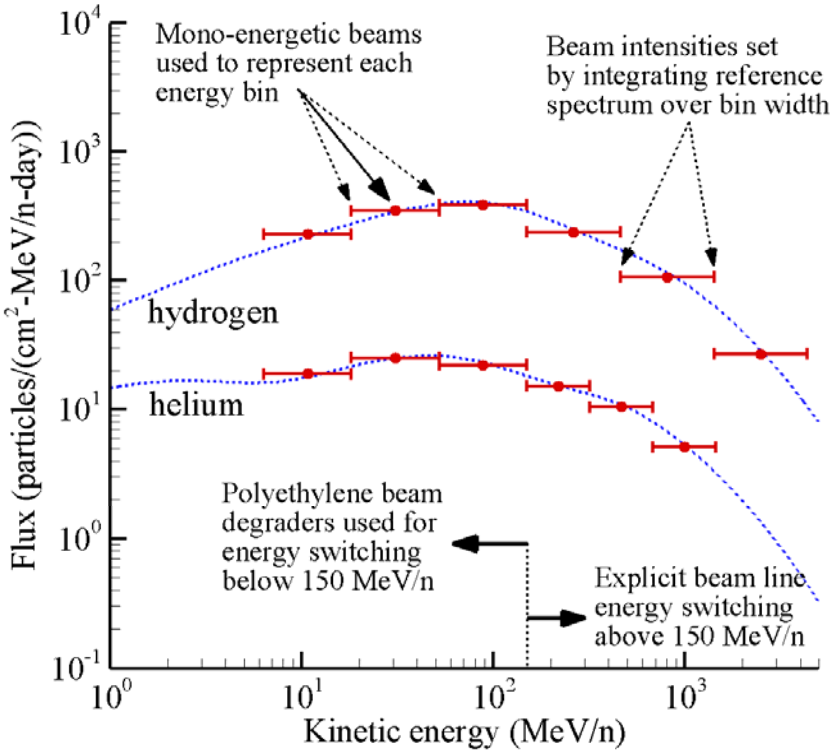
- General beam selection strategy is tied to reference field fluence
  - Hydrogen and helium represented in energy domain
  - Heavy ions represented in LET domain
  - Beam intensities computed by integrating reference field fluence over bin limits
  - Heavy ion beams chosen from lookup tables to match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

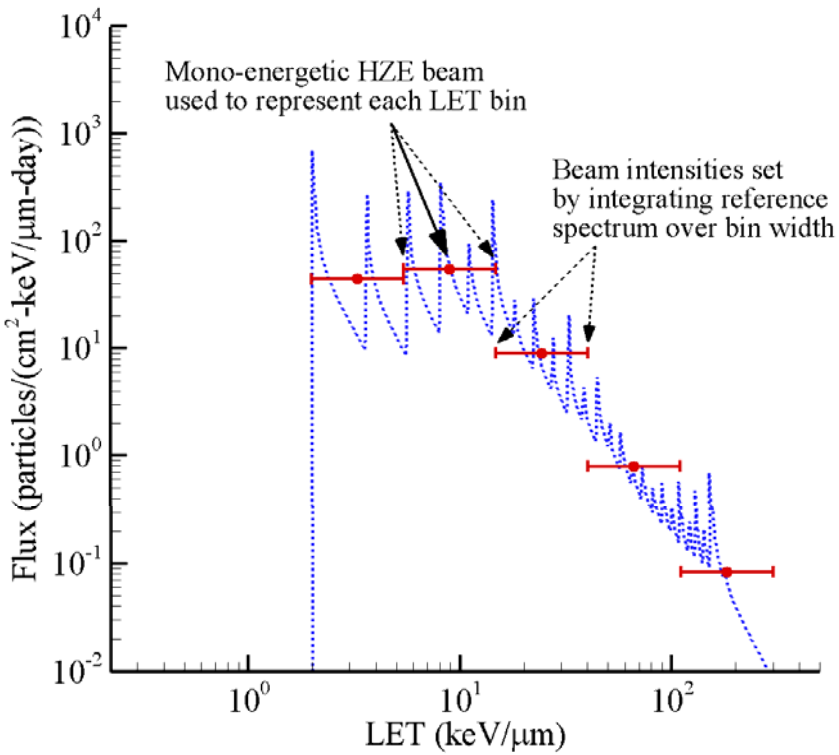




General Beam Selection Strategy

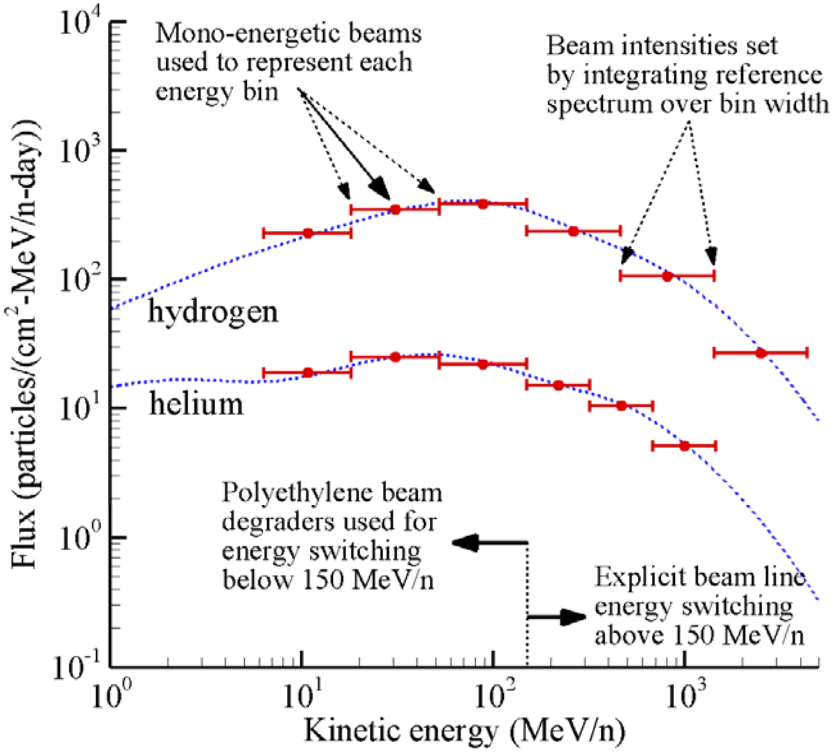
- Hydrogen and helium components explicitly represented in energy domain
  - Greater emphasis given to hydrogen and helium because they account for 81% of dose and 67% of dose equivalent
  - Combination of degrader system and energy switching implemented

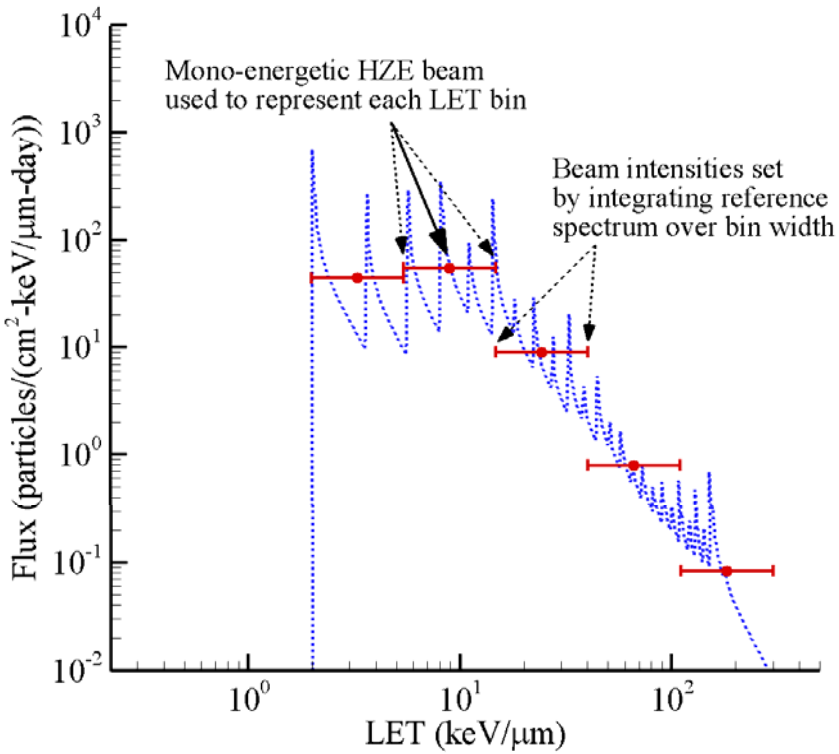




General Beam Selection Strategy

- 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

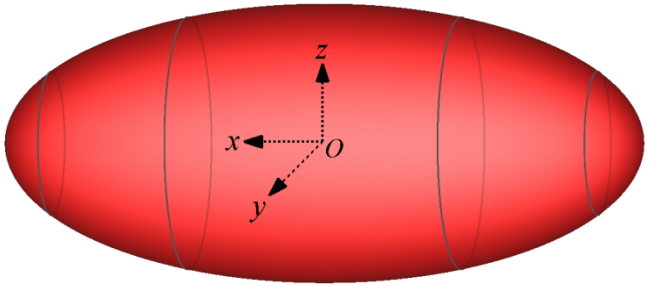




General Beam Selection Strategy

- 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

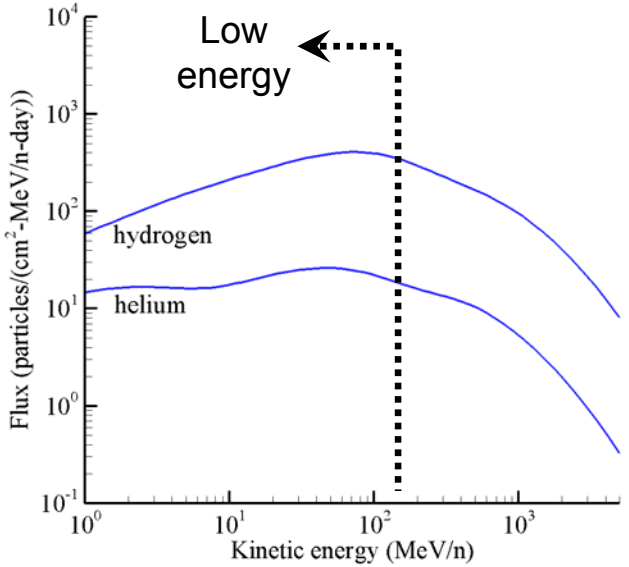
Ellipsoidal tissue phantom to represent mouse



Dimensions: 7 cm (major axis), 3 cm (minor axis)

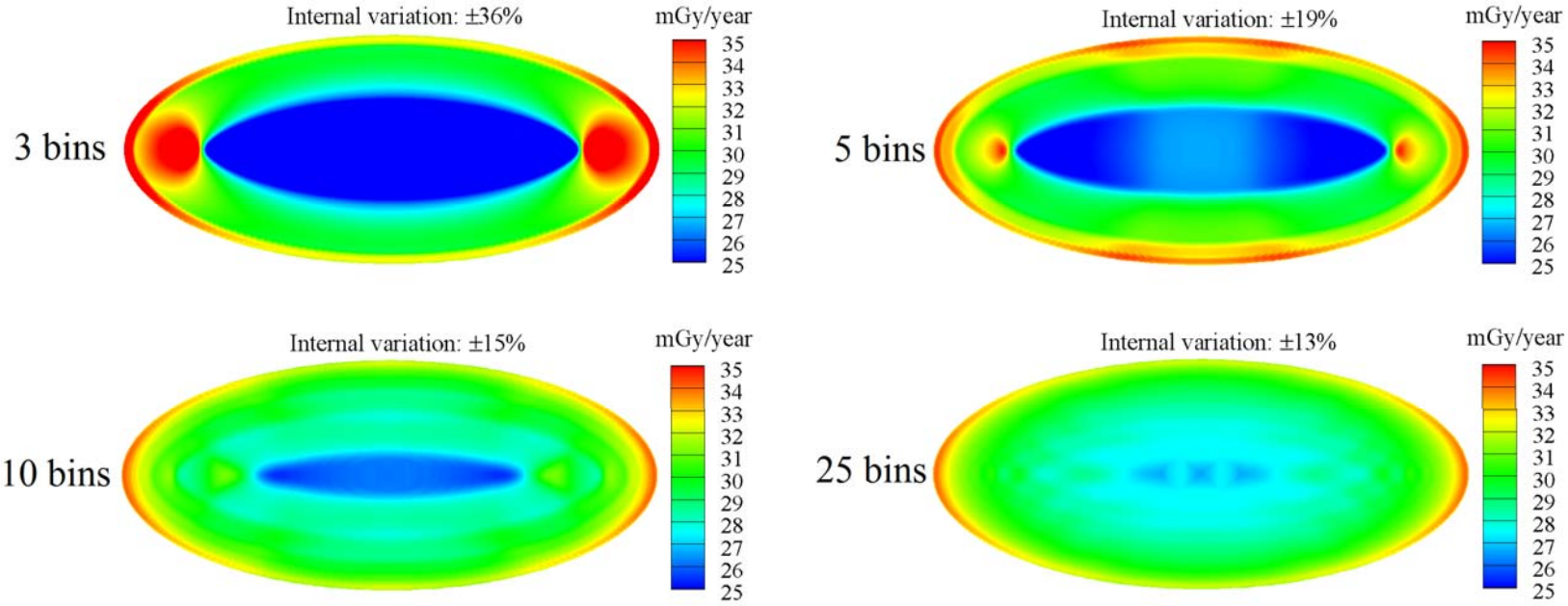
Mass: 33 grams

Reference field hydrogen and helium energy spectra



General Beam Selection Strategy

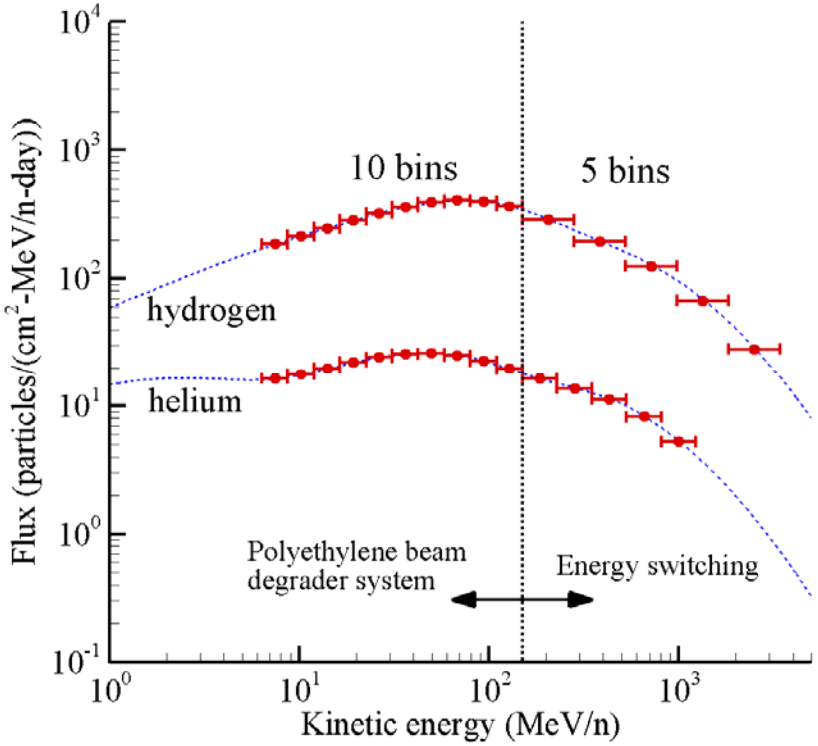
Dose profiles within phantom exposed to <150 MeV protons

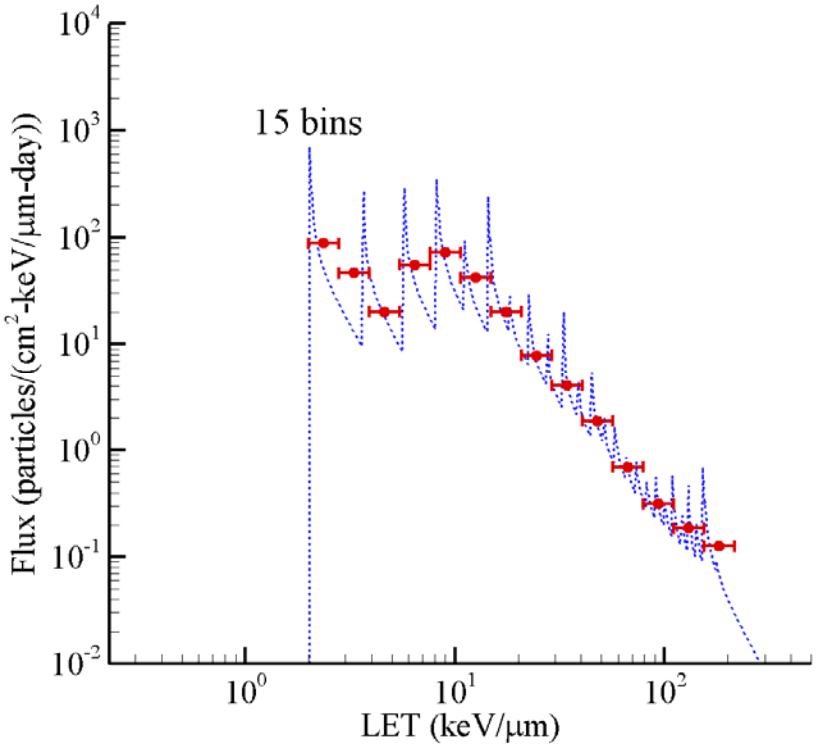


- Internal variation appears to be controlled with as few as 10 energy bins for low energy portion of hydrogen spectrum
  - Bragg peaks obvious if 3 or 5 bins are used
  - Similar results found for alpha beams used to represent helium component
  - Using more than 25 bins starts to reach fidelity of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

Example Beam Selection

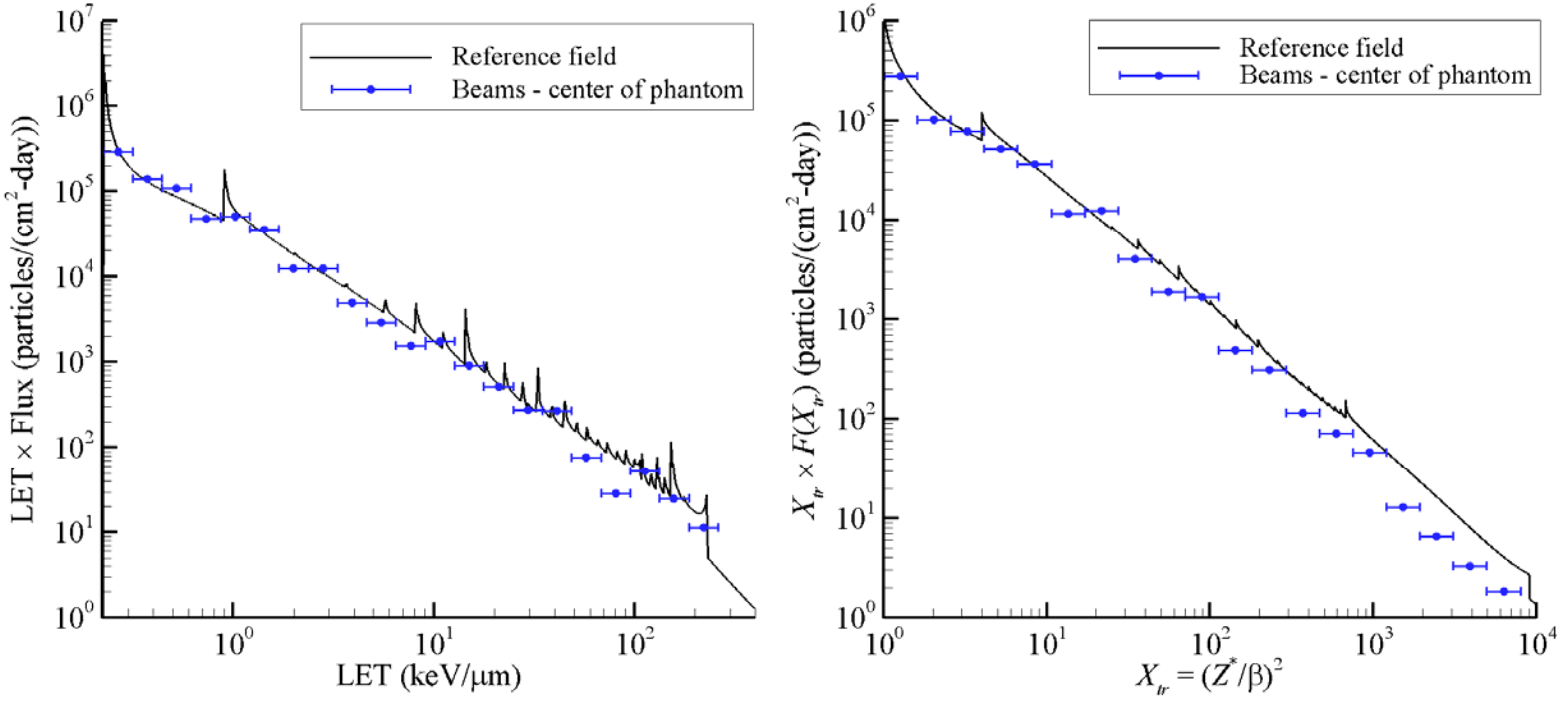
- Remaining analyses will consider the following case
  - 10 low energy bins for protons and alphas
  - 5 high energy bins for protons and alphas
  - 15 LET bins for HZE component





Example Beam Selection

Comparison of reference field spectra to beam induced quantities at center of phantom (isotropic irradiation)



- 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

Reference field integrated quantities

	Avg. hits per cell nucleus	Dose (mGy)	Dose Eq. (mSv)	<Q>
hydrogen	126.0	86.0	131.1	1.5
helium	7.0	22.5	93.8	4.2
HZE	0.5	8.9	73.3	8.2

Beam induced integrated quantities at center of phantom

	Avg. hits per cell nucleus	Dose (mGy)	Dose Eq. (mSv)	<Q>
hydrogen	105.0	71.2	95.5	1.3
helium	4.5	16.3	49.7	3.0
HZE	0.3	8.3	67.0	8.1

- Cell nucleus hits computed by assuming cross sectional area of 100 μm^2
- 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

A	Z	Energy (MeV/n)	LET (kev/μm)	$(Z^*/\beta)^2$	Intensity (#/cm^2-year)	Dose (mGy/year)
1	1	7.4	6.4	63.8	1.6×10^5	1.48
1	1	10.2	5.0	46.7	2.5×10^5	1.83
1	1	14.0	3.8	34.3	4.0×10^5	2.25
1	1	19.2	3.0	25.2	6.3×10^5	2.73
1	1	26.4	2.3	18.6	9.8×10^5	3.30
1	1	36.2	1.8	13.7	1.5×10^6	3.91
1	1	49.6	1.4	10.2	2.2×10^6	4.52
1	1	68.0	1.1	7.7	3.2×10^6	5.02
1	1	93.3	0.8	5.8	4.3×10^6	5.30
1	1	128.1	0.7	4.4	5.4×10^6	5.31
1	1	205.0	0.5	3.1	1.4×10^7	9.62
1	1	383.2	0.3	2.0	1.7×10^7	8.53
1	1	716.0	0.26	1.5	2.1×10^7	7.99
1	1	1337.9	0.23	1.2	2.1×10^7	6.04
1	1	2500.0	0.22	1.1	1.6×10^7	5.35

Backup: Example Beam Info

- Alpha beam information for example study

A	Z	Energy (MeV/n)	LET (kev/μm)	$(Z^*/\beta)^2$	Intensity (#/cm^2-year)	Dose (mGy/year)
4	2	7.4	25.6	255.3	1.4×10^4	0.53
4	2	10.2	19.8	186.9	2.1×10^4	0.61
4	2	14.0	15.4	137.0	3.2×10^4	0.72
4	2	19.2	11.9	100.7	4.9×10^4	0.86
4	2	26.4	9.2	74.2	7.4×10^4	0.99
4	2	36.2	7.1	54.9	1.1×10^5	1.12
4	2	49.6	5.5	40.9	1.5×10^5	1.20
4	2	68.0	4.3	30.6	2.0×10^5	1.23
4	2	93.3	3.4	23.2	2.5×10^5	1.21
4	2	128.1	2.7	17.7	2.9×10^5	1.14
4	2	185.2	2.1	13.2	4.7×10^5	1.43
4	2	282.3	1.6	9.8	6.0×10^5	1.41
4	2	430.3	1.3	7.5	7.5×10^5	1.41
4	2	656.0	1.1	6.1	8.4×10^5	1.33
4	2	1000.0	1.0	5.2	8.2×10^5	1.16

Backup: Example Beam Info

- HZE beam information for example study

A	Z	Energy (MeV/n)	LET (kev/μm)	$(Z^*/\beta)^2$	Intensity (#/cm^2-year)	Dose (mGy/year)
7	3	736	2.4	13.1	2.5×10^4	0.09
7	3	331	3.3	19.8	1.9×10^4	0.09
7	3	189	4.6	29.3	1.1×10^4	0.08
11	5	788	6.4	35.5	4.4×10^4	0.41
12	6	887	9.0	48.9	7.9×10^4	1.03
12	6	365	12.6	74.7	6.4×10^4	1.18
16	8	644	17.5	98.7	4.3×10^4	1.11
16	8	306	24.5	148.3	2.3×10^4	0.84
23	11	590	34.2	194.2	1.7×10^4	0.85
28	14	988	47.8	256.9	1.1×10^4	0.76
32	16	755	66.7	369.4	5.7×10^3	0.55
39	19	781	93.2	514.0	3.6×10^3	0.48
47	22	682	130.2	728.1	3.0×10^3	0.56
56	26	682	181.8	1016.8	2.8×10^3	0.74