Galactic Cosmic Ray Simulator Design at NSRL

Tony C. Slaba
NASA Langley Research Center

NASA Space Radiation Summer School
Brookhaven National Laboratory
June 19, 2015

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)

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).

Overview

- Long term exposure to GCR presents a serious health risk to astronauts with large uncertainties connected to the biological response
  - Main focus of radiobiology experimental research program is to reduce these uncertainties

- In order to reduce these uncertainties, radiobiology experiments are performed to 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 but also heavily influenced by facility constraints and cost

- Complicating feature of the GCR problem is that broad range of energies and particles found in space are 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

- Important to understand that development of a “GCR simulator” does not mean single beam studies are not useful or needed
  - Single beam studies are needed to examine and improve understanding of basic mechanisms where limited knowledge currently exists
  - Also needed to test, develop, and validate theoretical and computational models

- Instead, the simulator design should be viewed as the development of a new technology that provides new capabilities
  - Provides opportunity to test models derived from single beam studies in more realistic exposure 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 development goal of the space radiobiology program
  - What is new is that the accelerator facility has matured to a point where preliminary implementation is now realistic

Overview

- The GCR simulator at NSRL 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

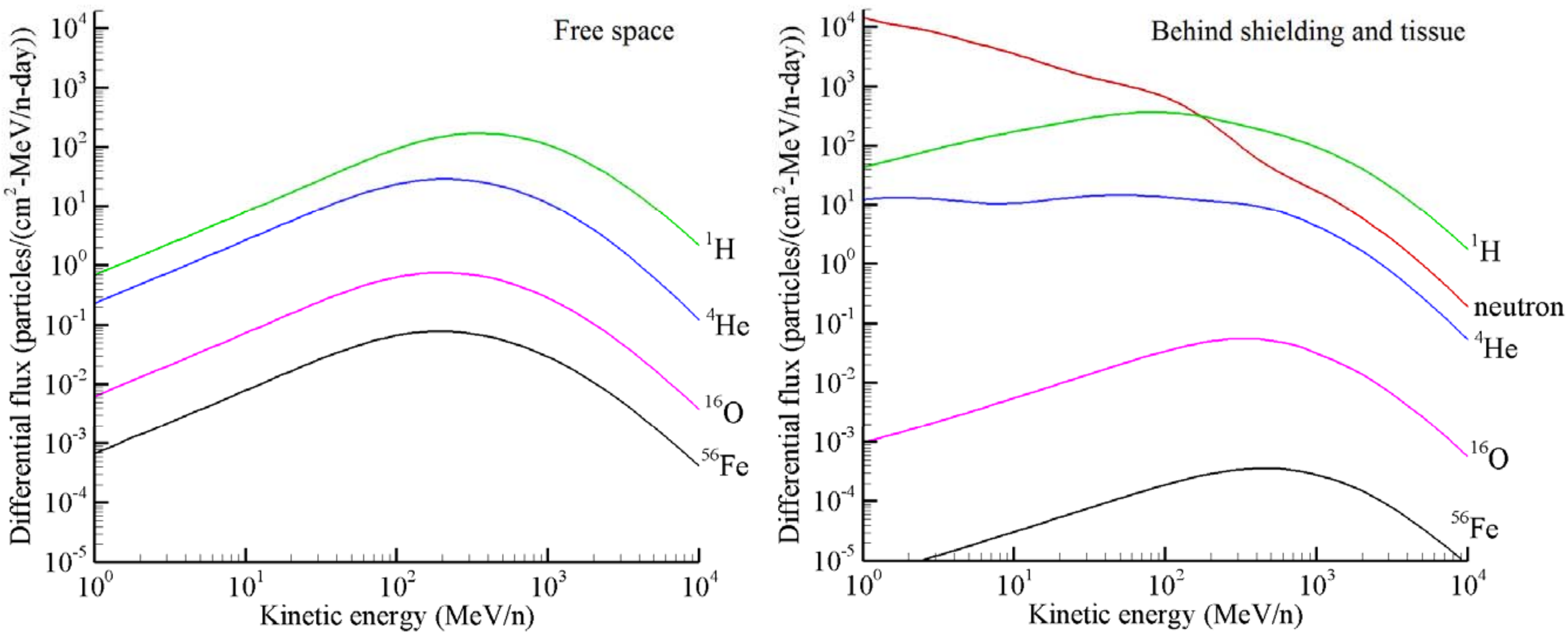
- Many of the details associated with GCR simulator design will depend on biological question and endpoints being studied

- Some aspects may be "standardized" across experiments
  - Enables subsequent cross comparisons and validation
  - Saves time and cost

- Two aspects allow for some standardization
  - Reference field specification: which environment are we simulating with beams
  - General beam selection strategy: how can we pick beams to simulate the environment

External and Internal Fields

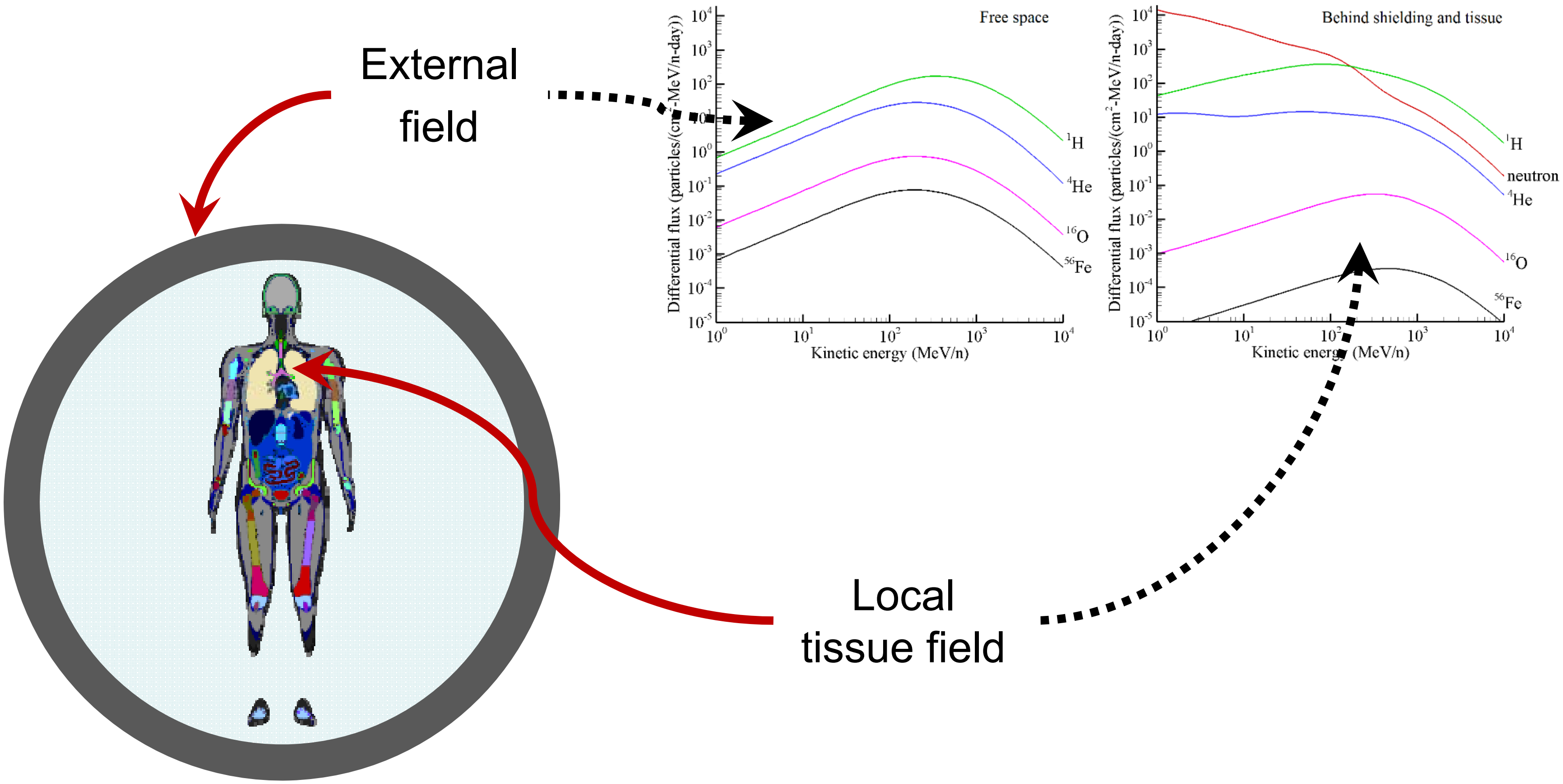
- The external GCR field is modified as it passes through shielding and tissue
  - Slowing down due to atomic processes
  - Attenuation and breakup of heavy ions due to nuclear collisions
  - Secondary particle production
  - Plot below (right) for minimal shielding (5 g/cm^2) and average tissue (30 g/cm^2)



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

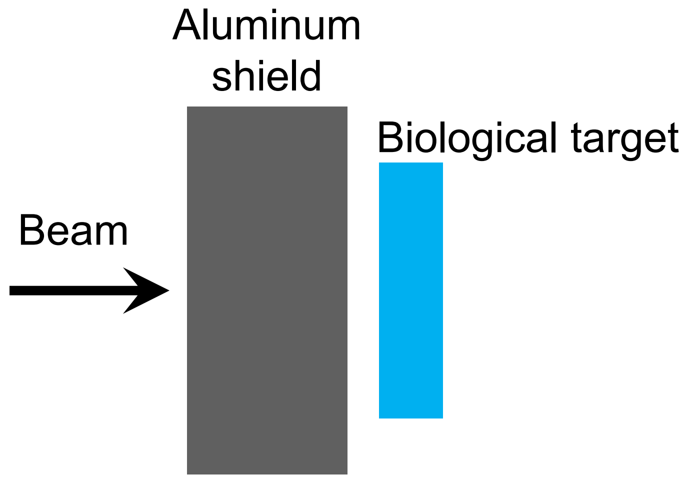
- An important question is whether to design the simulator using the free space, external field or local tissue field

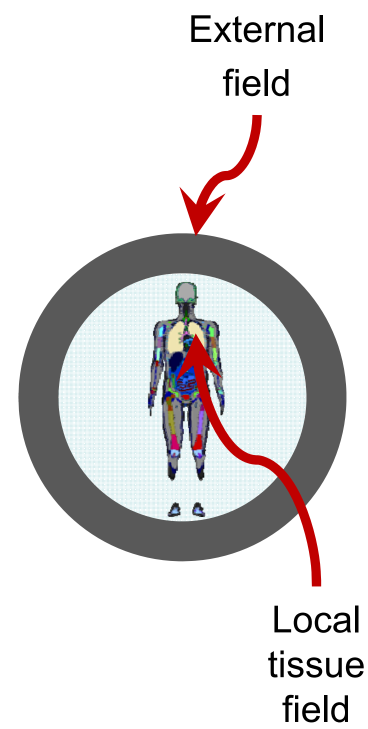


External and Internal Fields

- <u>External field approach</u>

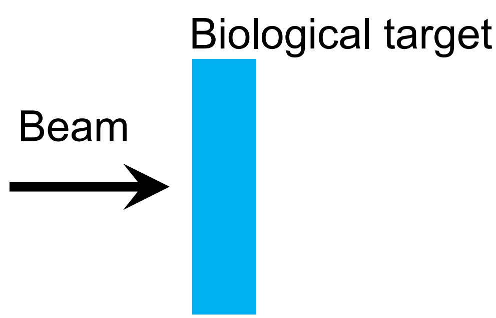
Beams selected to represent external, free space field before shielding





- <u>Local tissue field approach</u>

Beams selected to directly represent shielded tissue field



External and Internal Fields

- Facility constraints have a significant impact on choosing the approach

- NSRL Energy constraints
  - Current: protons (2.5 GeV) and heavier ions (1.0 GeV/n)
  - Upgrade: protons (4.0 GeV) and heavier ions (1.5 GeV/n)

- Table below gives fraction of effective dose delivered by energies within NSRL energy constraints
  - Female phantom behind 20 g/cm^2 of aluminum shielding during solar minimum
  - Other scenarios and exposure quantities lead to qualitatively similar results

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

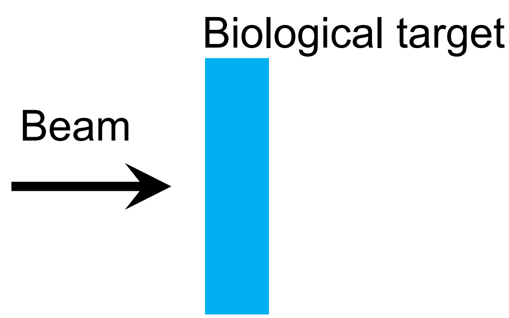
External and Internal Fields

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

- GCR simulator will focus on directly reproducing the shielded tissue field

<u>Local tissue field approach</u>

Beams selected to directly represent shielded tissue field



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 and concluded that a single reference field for deep space can be identified

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

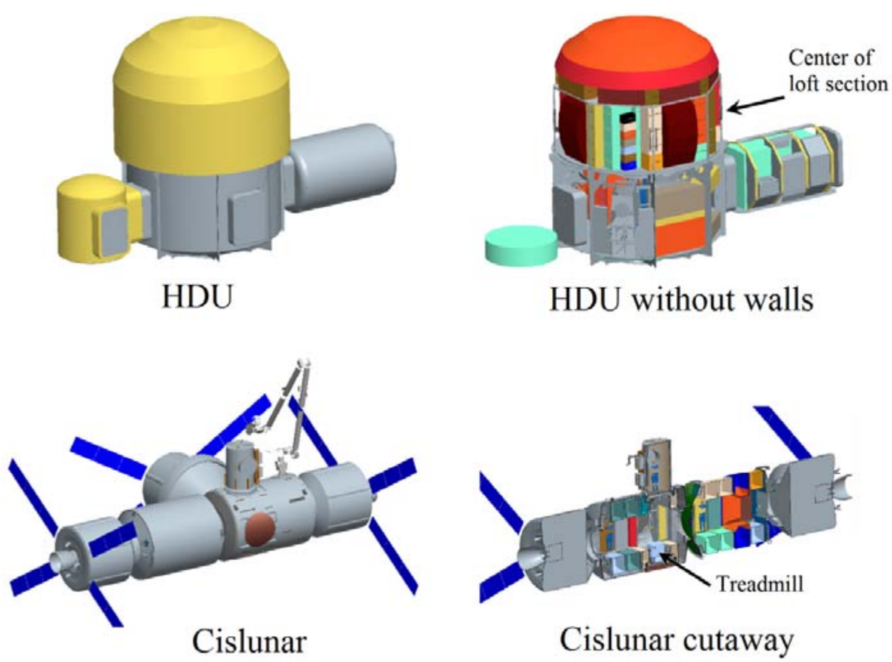
Variation in Local Field

- Variation in local tissue field will be examined as a function of
  - Tissue location
  - Shielding configuration
  - Shielding material
  - Solar activity

- Models
  - GCR environment computed with the 2010 Badhwar-O'Neill GCR model
    - Solar minimum: June 1976
    - Solar maximum: June 2001
    - All results shown for solar minimum except for comparisons focused on solar activity
  - HZETRN transport code with π/EM and bi-directional neutron transport (ray-by-ray)
  - Female phantom (FAX)
  - NASA-Q and effective dose tissue weights implemented where applicable
  - Q-factor uncertainties from NSCR2012 implemented where applicable

Variation in Local Field

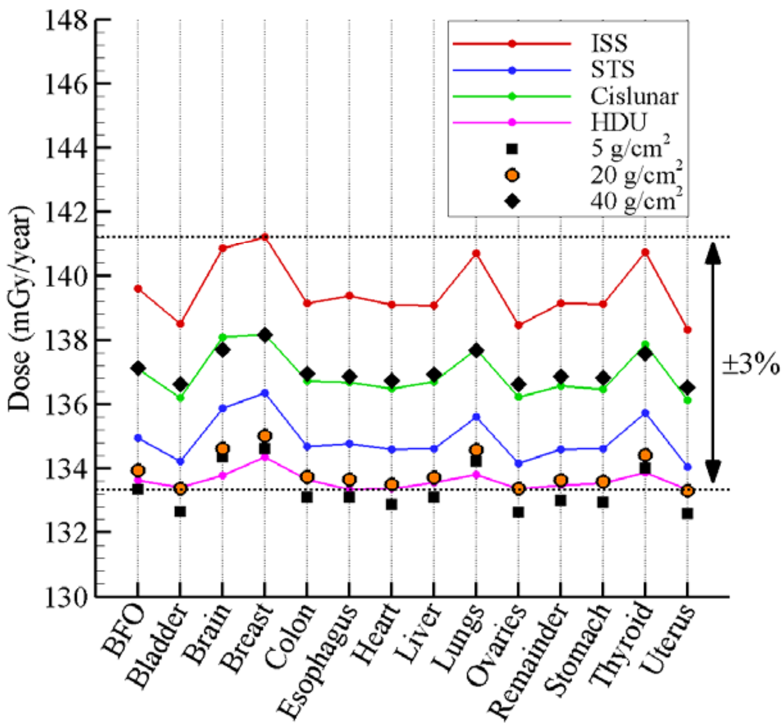
- Will consider spherical aluminum shielding (5 g/cm^2, 20 g/cm^2, 40 g/cm^2) along with four realistic shielding geometries
  - Habitat demonstration unit (HDU) adapted for 1-year free space mission
  - Cislunar vehicle concept
  - ISS location in US Lab near overhead racks
  - STS location in mid-deck (often referred to as DLOC 2)

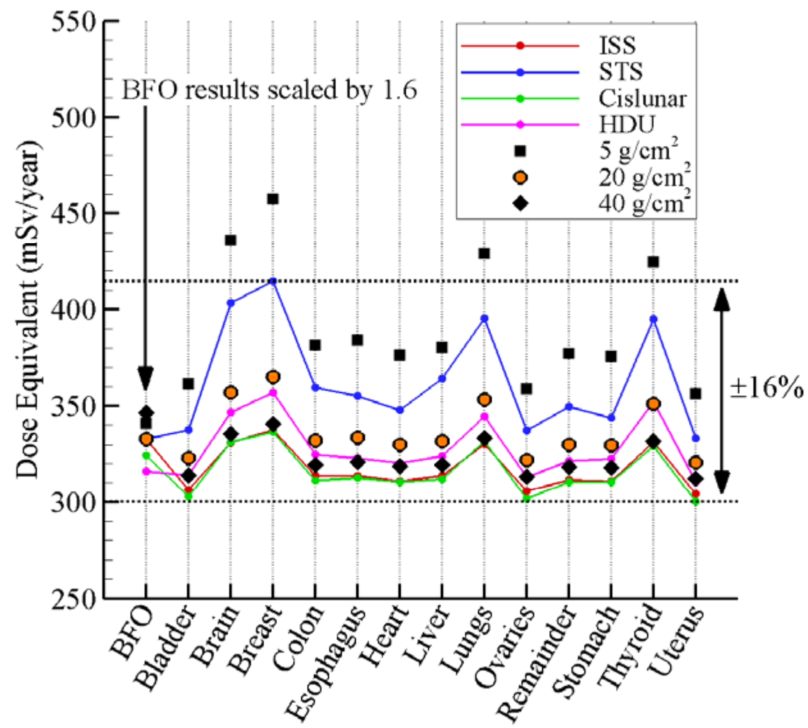


HDU
HDU without walls
Cislunar
Cislunar cutaway

Variation in Local Field – Shielding

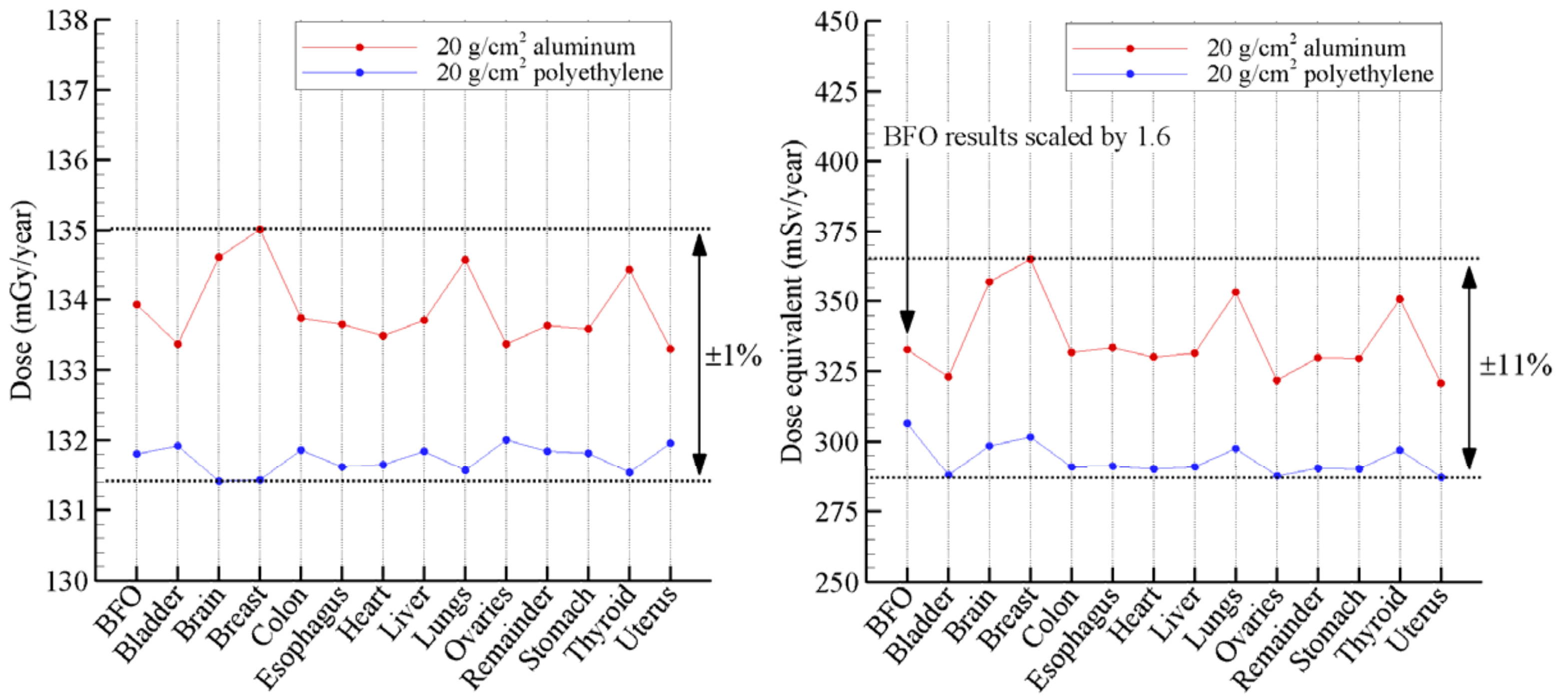
- Plots below show tissue doses and dose equivalents behind shielding
  - Variation is within even the GCR environmental model uncertainty (~±20%)
  - Increased variation in dose equivalent associated with HZE breakup
  - Bladder, BFO and breast appear as representative tissues
  - 20 g/cm² aluminum appears as representative shielding





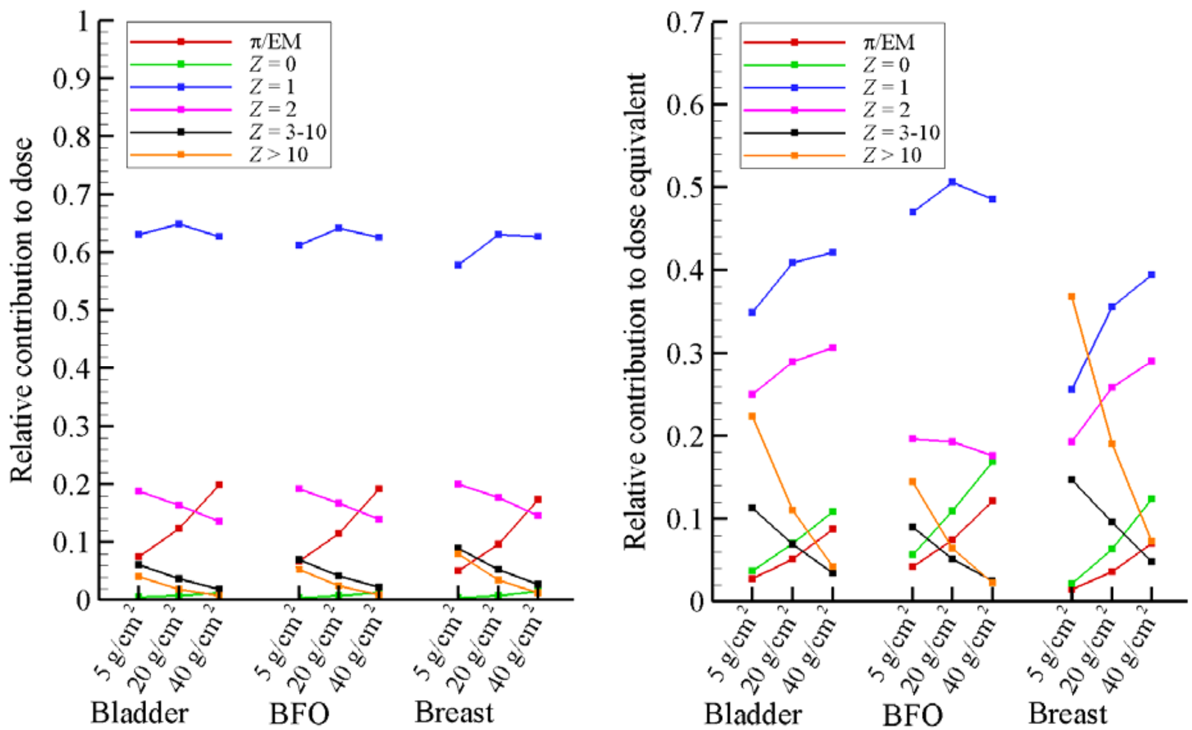
Variation in Local Field – Shielding

- Shielding material also contributes to variation in exposure quantities
  - Current technology suggests deep space vehicle will be comprised of mainly aluminum with some parasitic shielding mass (polyethylene)
  - Plot below shows tissue exposure values behind 20 g/cm^2 of aluminum or polyethylene
  - Variation is within experimental design uncertainty



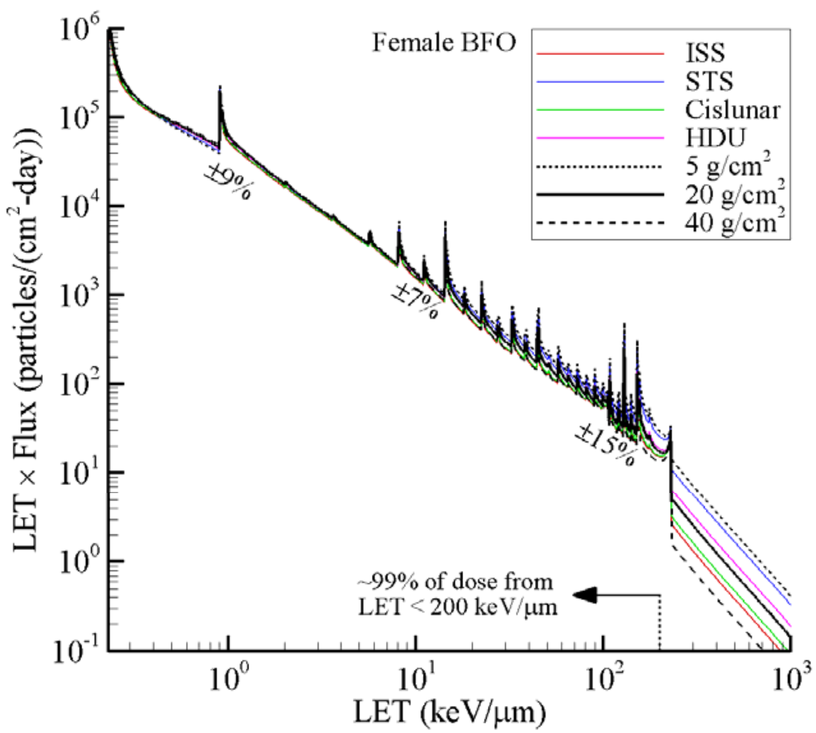
Variation in Local Field – Shielding

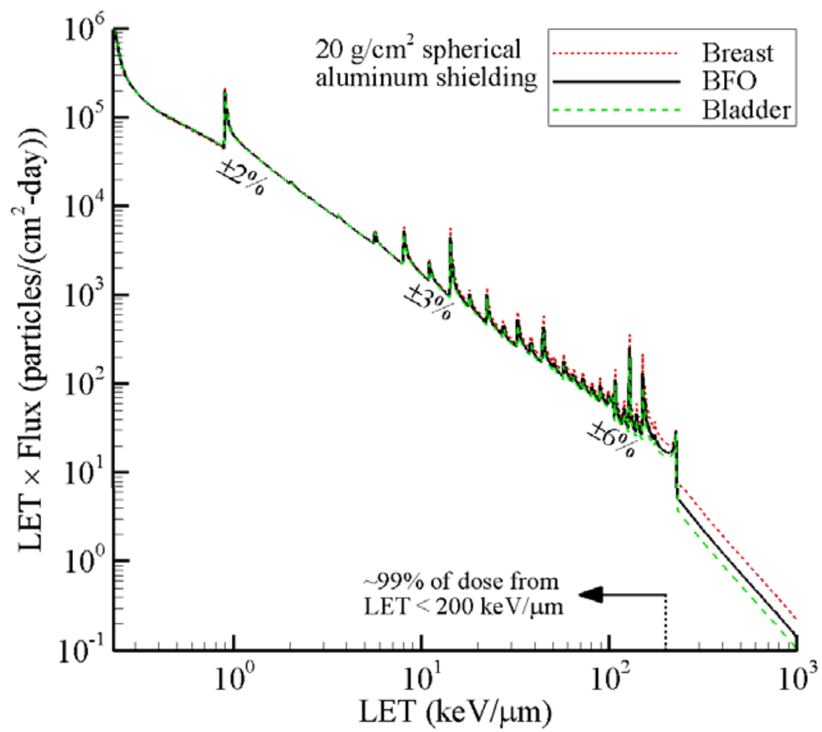
- Plots below show relative contribution to dose and dose equivalent for various charge groups
  - Protons and alphas account for more than half of the exposure
  - Breakup of HZE component can be clearly seen in breast dose equivalent
  - Relative contributions of particles types show some variation, but likely within experimental design uncertainty



Variation in Local Field – Shielding

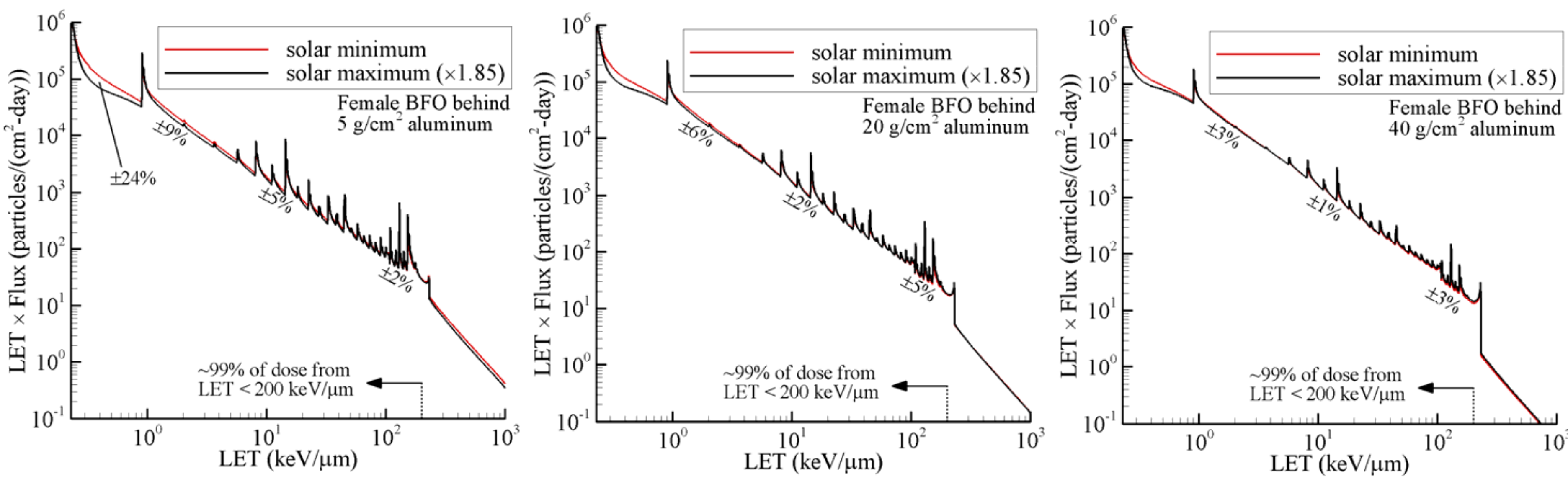
- LET spectral comparisons in different shielding configurations and tissues
  - Variation associated with shielding appears small below 200 keV/μm
  - Variation is likely within experimental design uncertainty
  - Spectra appear as qualitatively similar





Variation in Local Field – Solar Activity

- During solar max, the GCR spectrum is attenuated below several GeV/n
  - Plots below compare solar minimum and solar maximum results
  - Solar maximum results have been scaled by 1.85
  - Constant factor of 1.85 nearly corrects discrepancies associated with solar activity across the entire LET domain
  - Suggests main difference between solar extremes is magnitude of exposure, not the shape of the LET spectrum

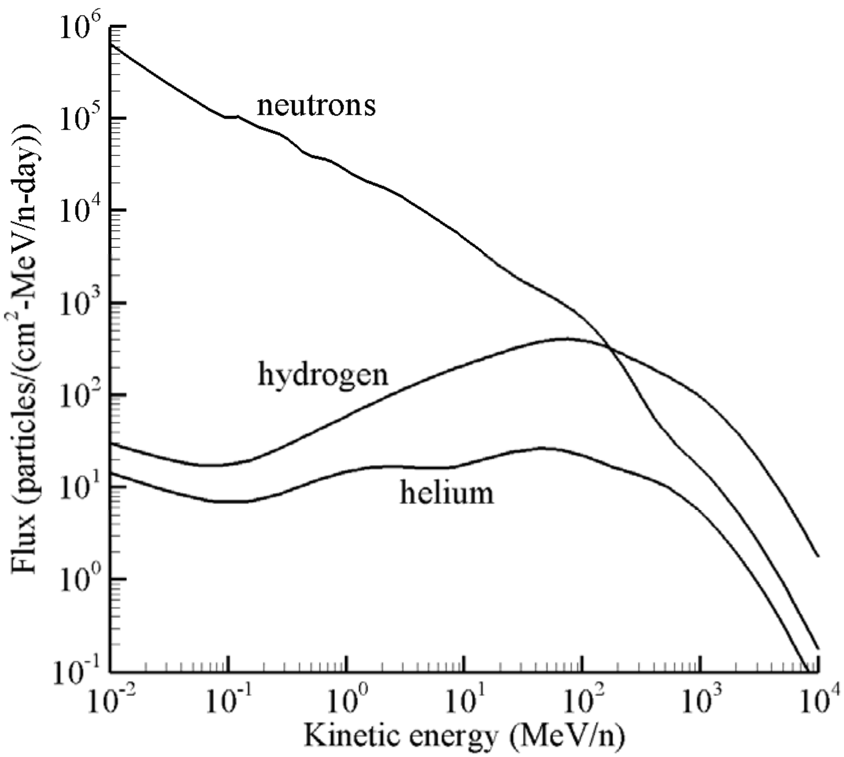


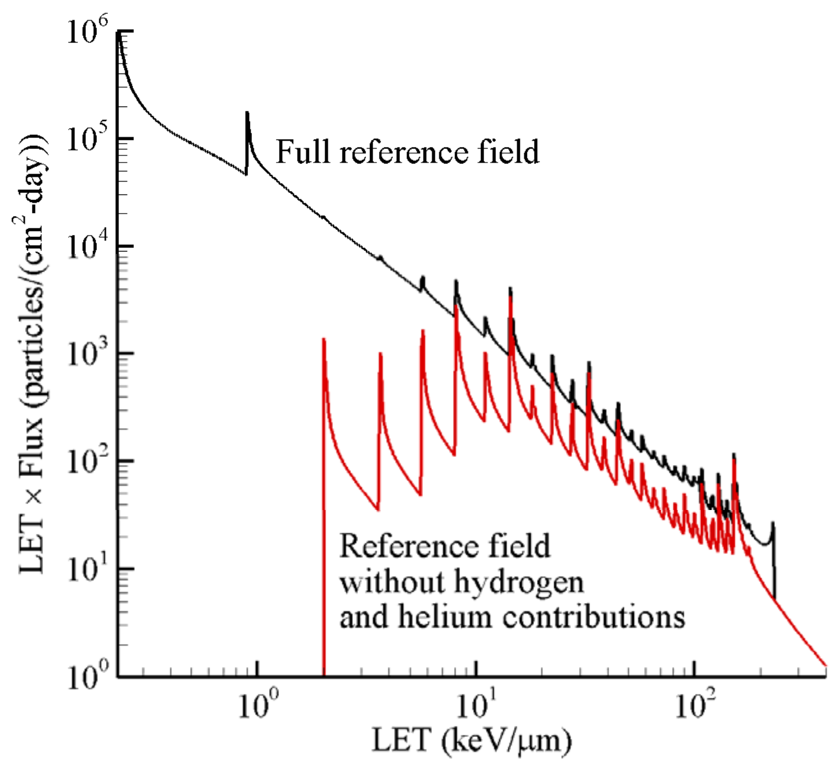
Reference Field Specification

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

Annual reference field quantities

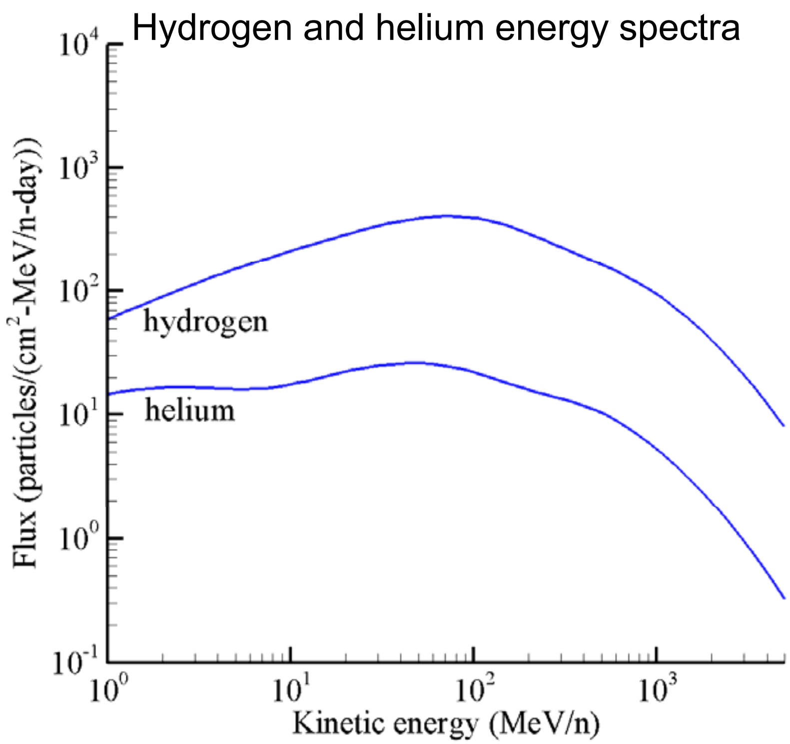
	Avg. hits per cell nucleus	Dose (mGy)	Dose Eq. (mSv)	<Q>
hydrogen	126	86.0	131.1	1.5
helium	7	22.5	93.8	4.2
HZE	0.5	8.9	73.3	8.2

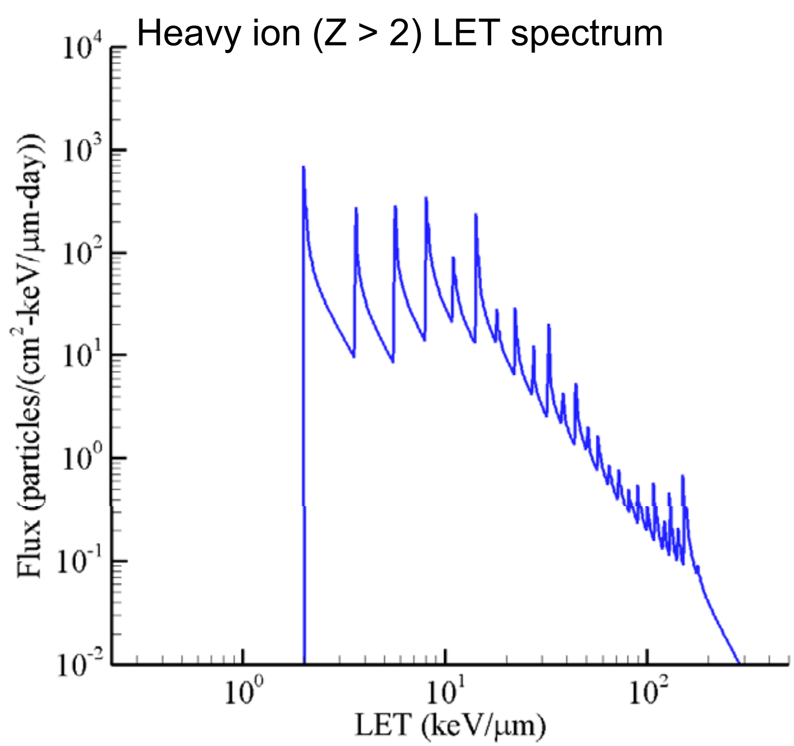




General Beam Selection Strategy

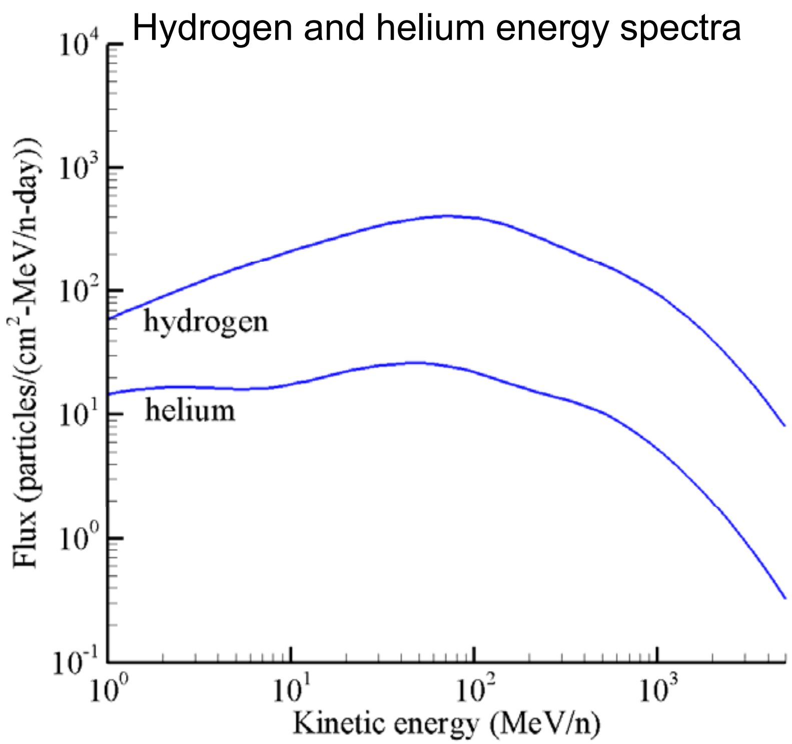
- Plots below show physical quantities that describe the charged particle components of the reference field
  - neutrons and π/EM component not included

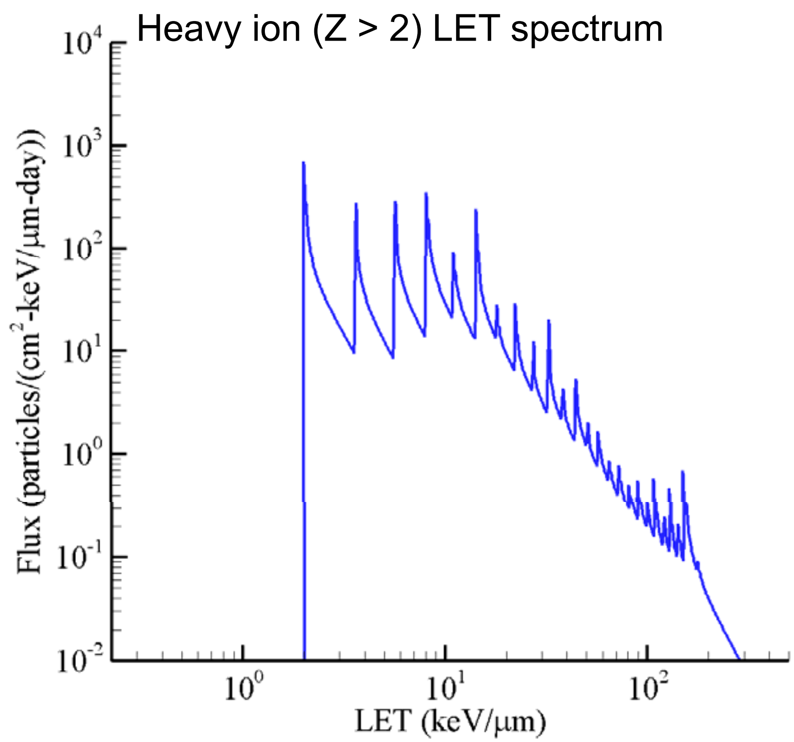




General Beam Selection Strategy

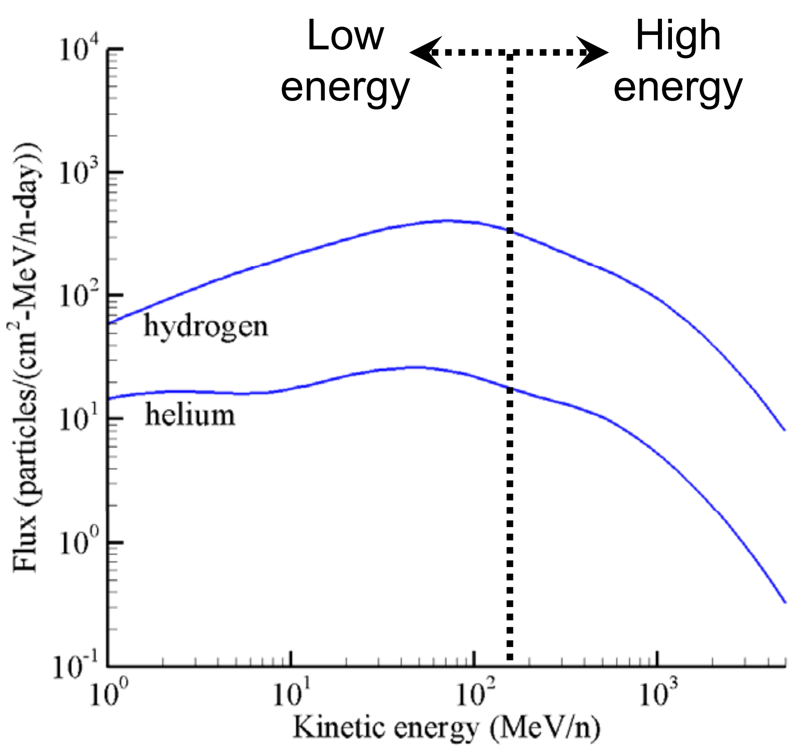
- Hydrogen and helium are explicitly represented in energy domain and HZE ions are collectively represented within the LET spectrum
  - Greater emphasis/fidelity in simulator design for hydrogen and helium
  - Account for 81% of dose and 67% of dose equivalent
  - Other ions could be explicitly represented as well (trade against time/cost)

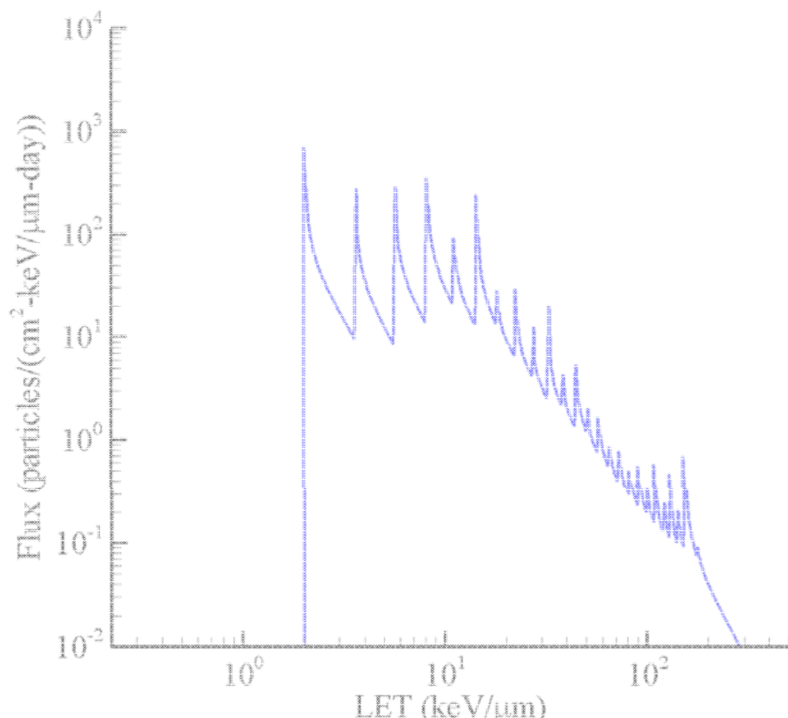




General Beam Selection Strategy

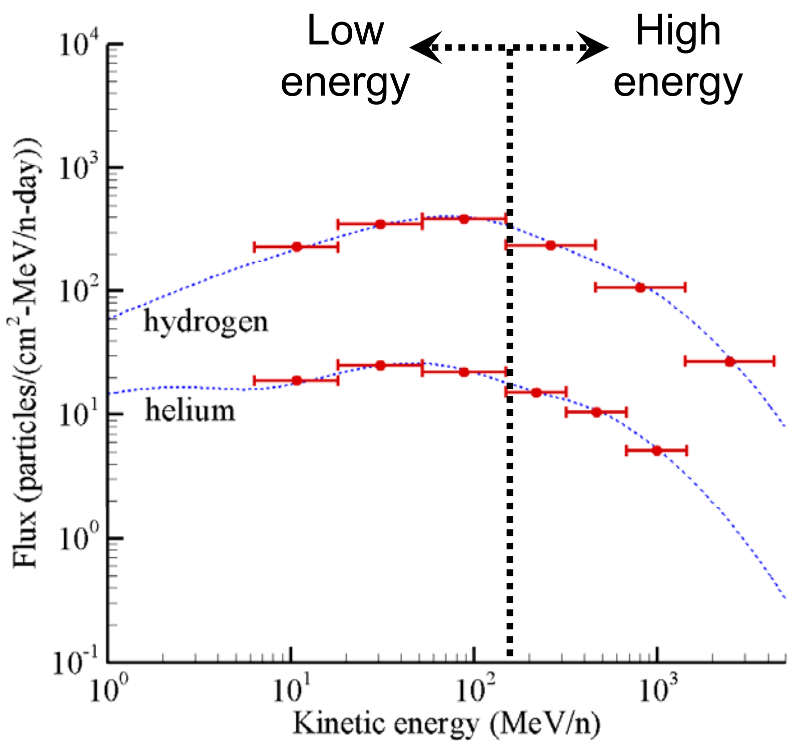
- For hydrogen and helium
  - Break energy domain into two pieces
  - Low energy particles that might stop in mouse (<150 MeV/n)
  - Higher energy particles that will pass through mouse (>150 MeV/n)

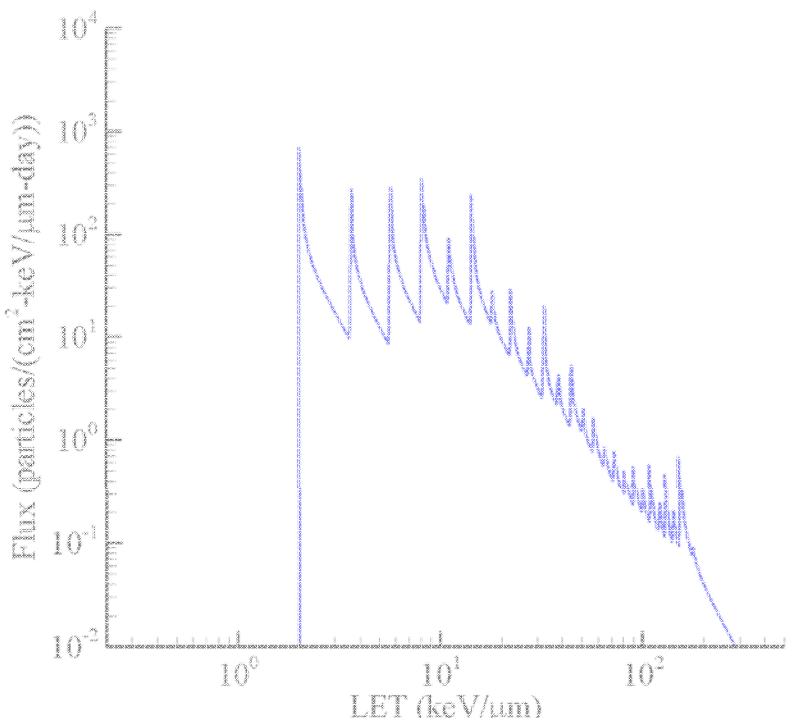




General Beam Selection Strategy

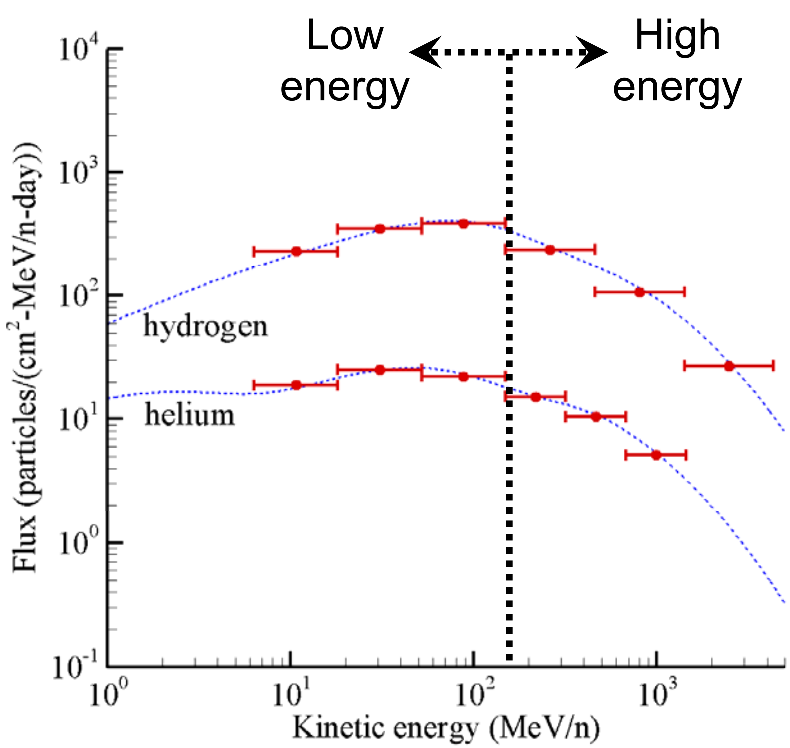
- For hydrogen and helium
  - Bin the low and high energy domains separately
  - Each bin represented by a mono-energetic ion beam
  - Protons and alphas used to represent hydrogen and helium, respectively

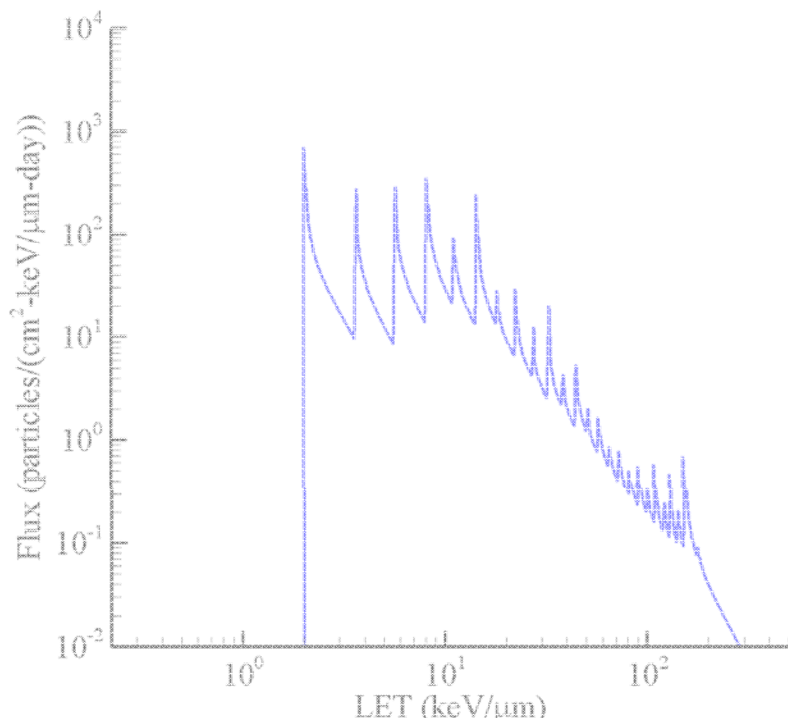




General Beam Selection Strategy

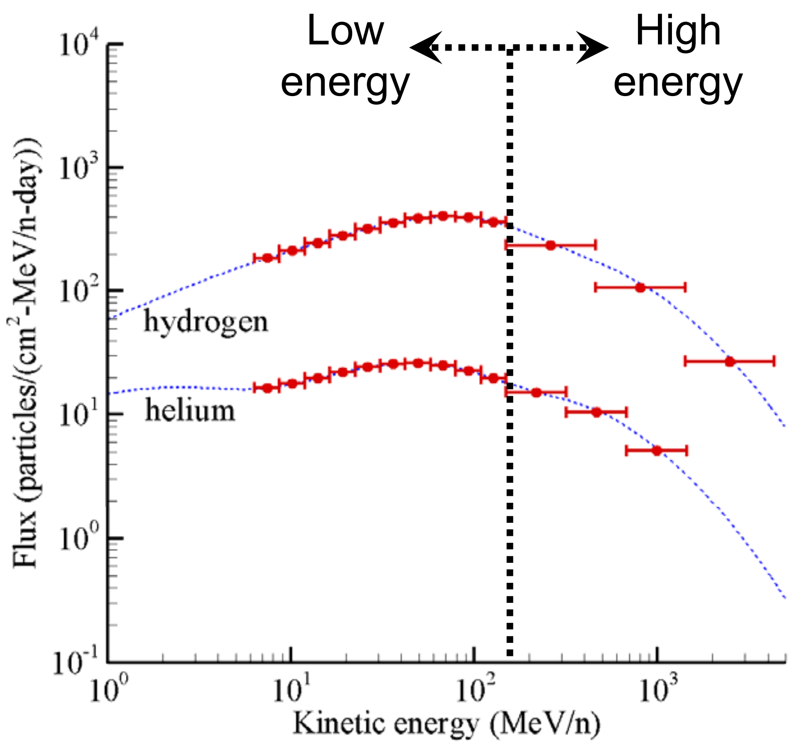
- High energy beams provided directly from accelerator (i.e. energy switching)
- Low energy beams achieved by using polyethylene degraders
  - Similar procedure as previously implemented for SPE simulator
  - Allows finer resolution for stopping particles thereby reducing exposure gradients within animals

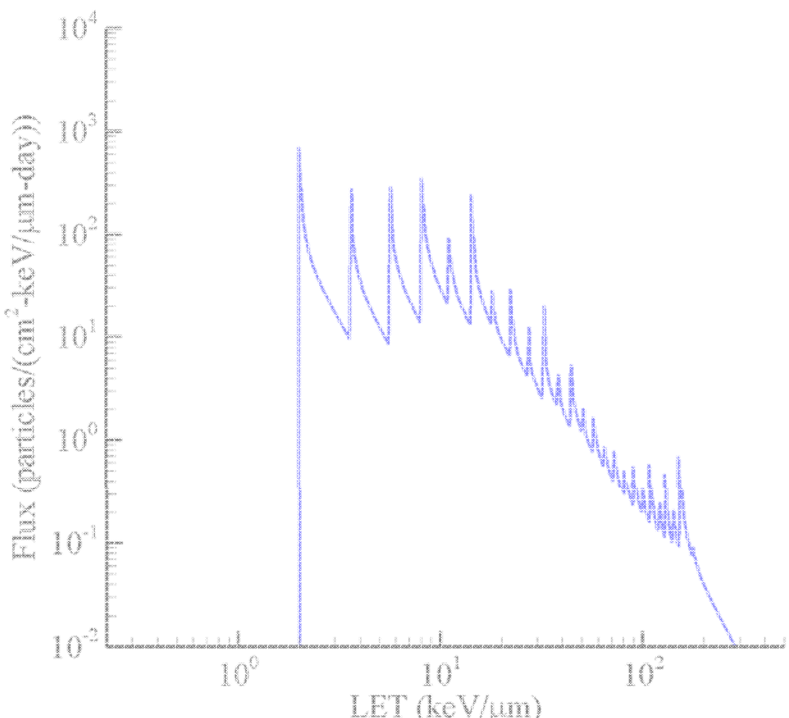




General Beam Selection Strategy

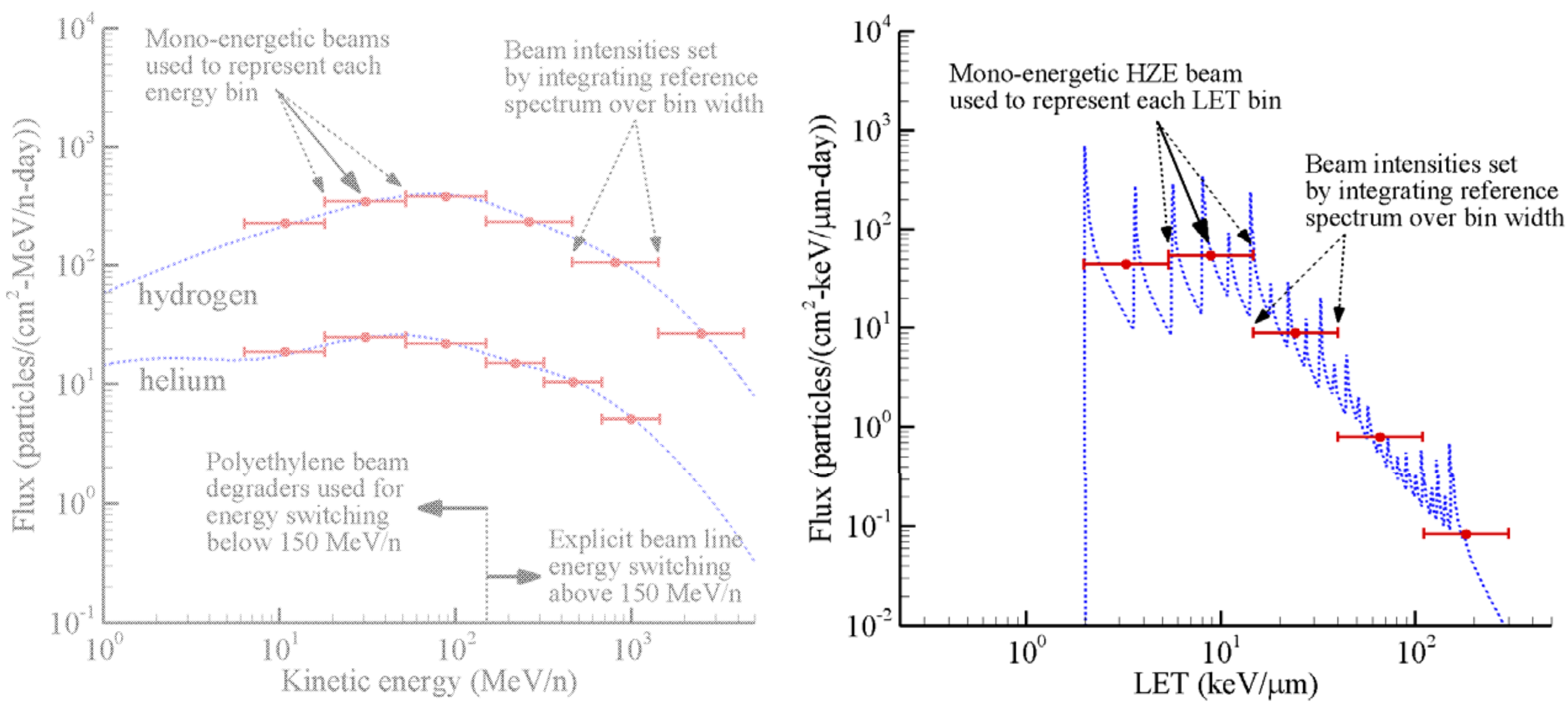
- High energy beams provided directly from accelerator (i.e. energy switching)
- Low energy beams achieved by using polyethylene degraders
  - Similar procedure as previously implemented for SPE simulator
  - Allows finer resolution for stopping particles thereby reducing exposure gradients within animals





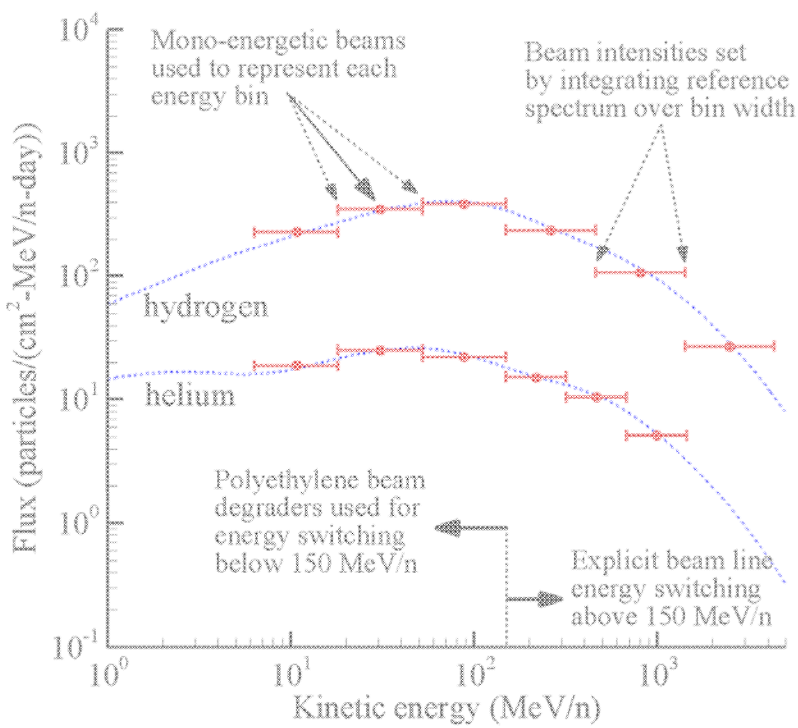
General Beam Selection Strategy

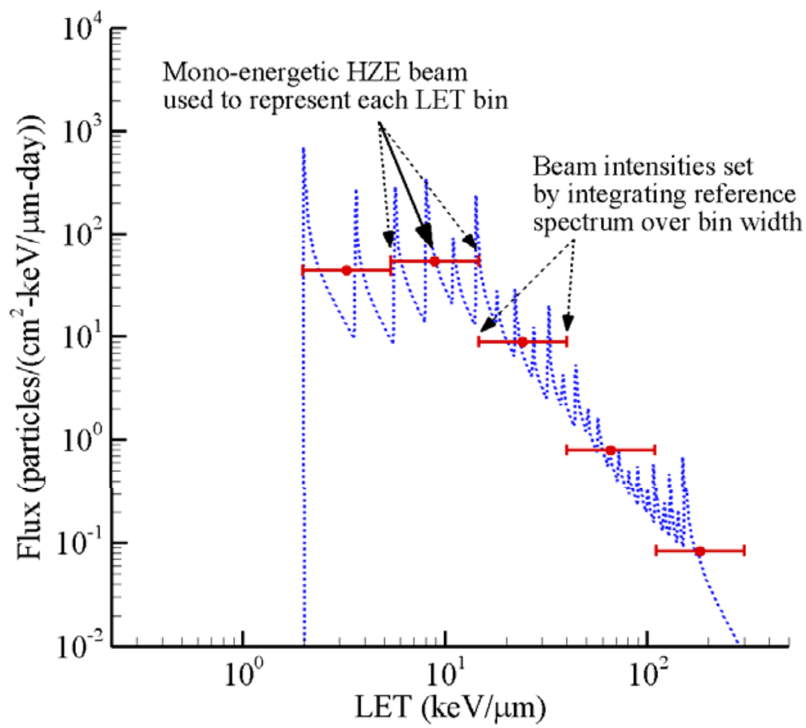
- A similar binning procedure is used to represent HZE component
  - Bin the LET domain for HZE particles
  - Each bin represented by mono-energetic HZE beam
  - Can use look-up tables and energy constraints to determine which ion/energy to use for each bin



General Beam Selection Strategy

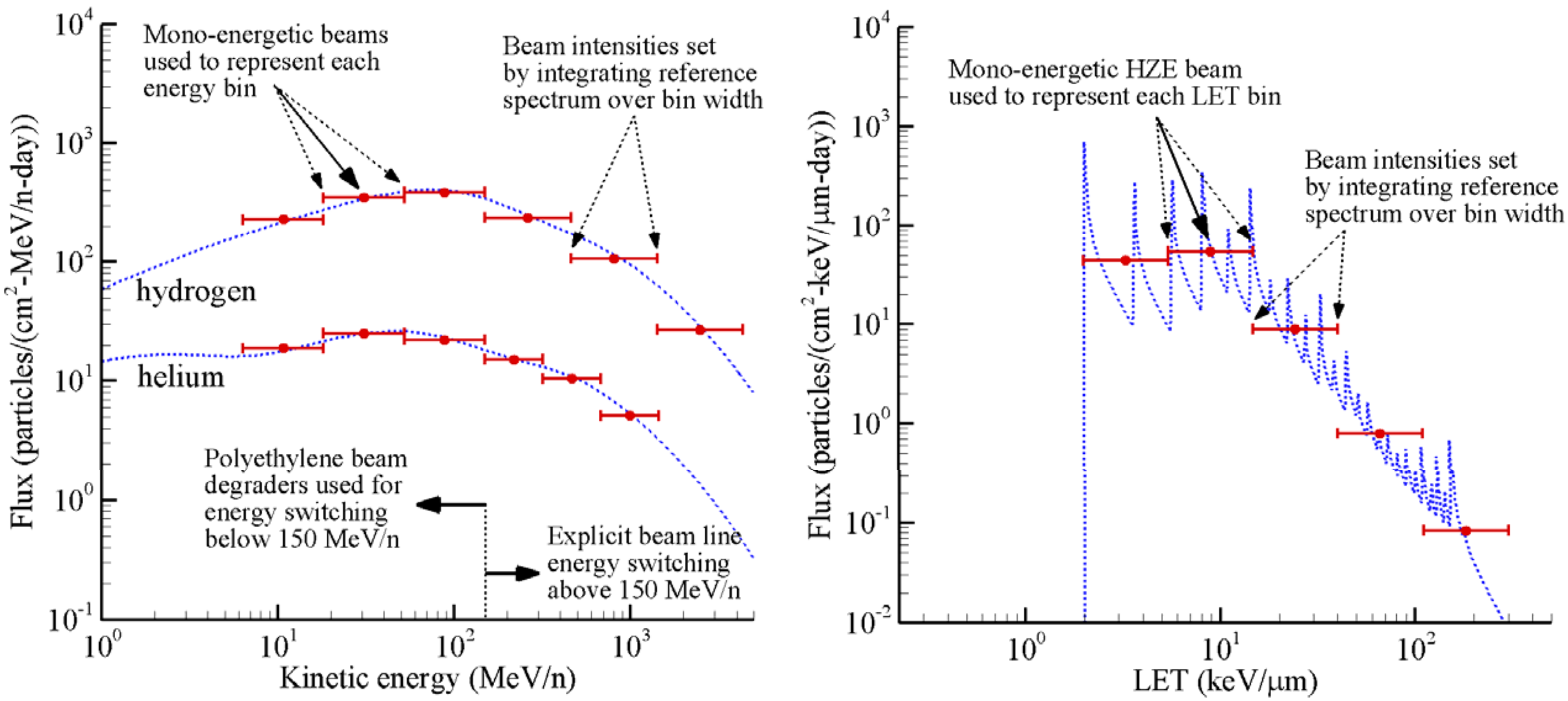
- Energies are now constrained below
  - Do not want rapid variation (Bragg peaks) occurring within animals
  - Not implementing degrader approach for each heavy ion (time/cost constraints)
  - Ions need to be energetic enough to reach at least ~9 cm





General Beam Selection Strategy

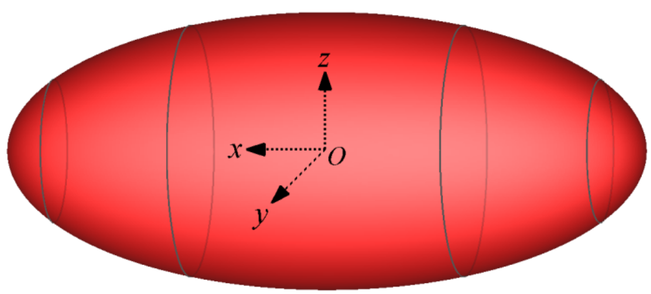
- General beam selection strategy is now set
  - Allows for precise beam specification (ion, energy, intensity) tied directly to physical spectrum of reference field
  - Convergence testing performed to see how many bins are needed
  - Convergence testing also provides cost-benefit information of using more beams

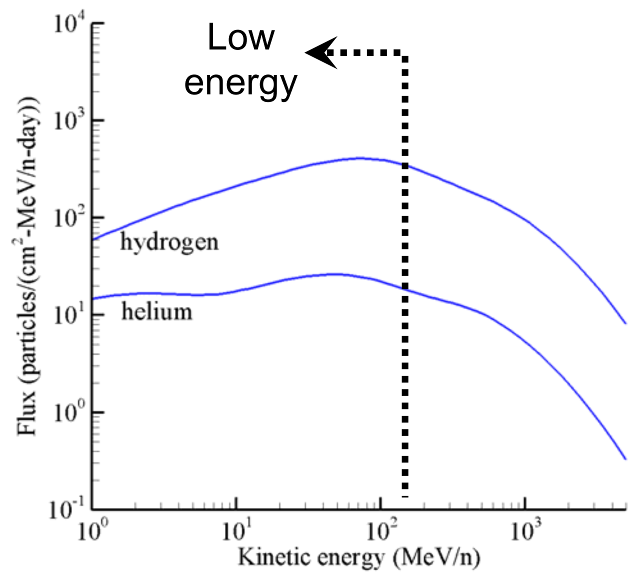


General Beam Selection Strategy

- 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

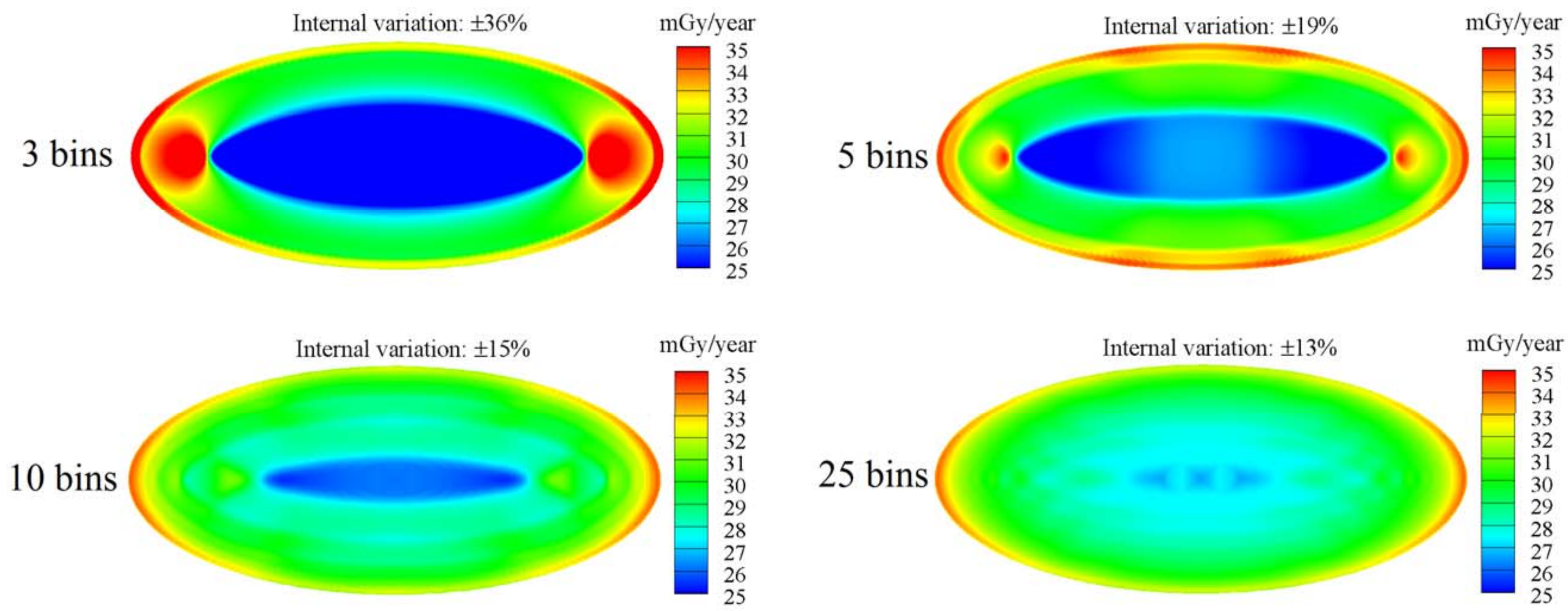
- Considered an ellipsoidal tissue phantom to represent mouse
  - Mass: 33 grams, major axis length: 7 cm, minor axis length: 3 cm
  - Exposed phantom to isotropic irradiation of low energy proton beams (<150 MeV/n)
  - Systematically increased number of bins used to represent low energy spectrum





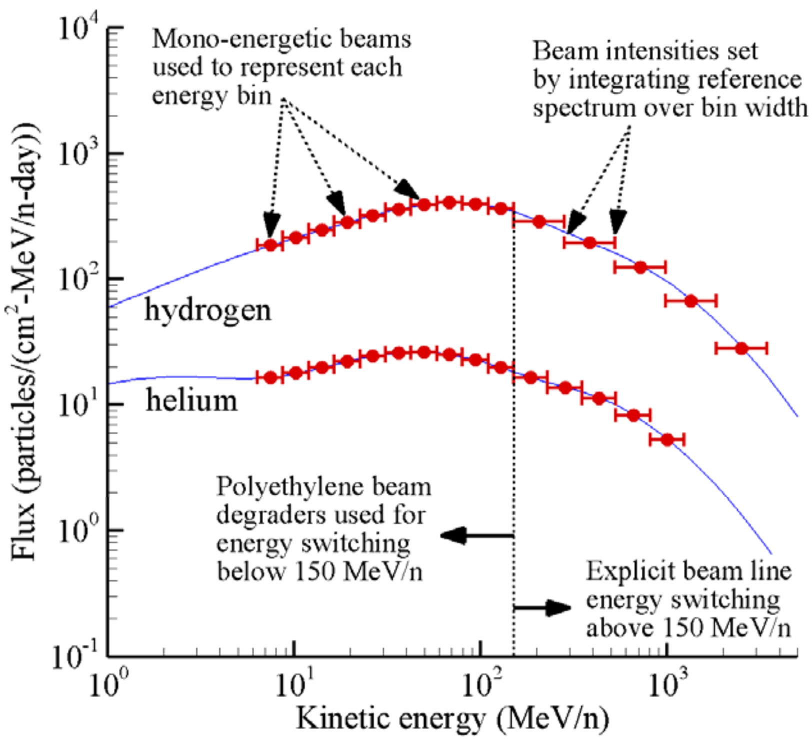
General Beam Selection Strategy

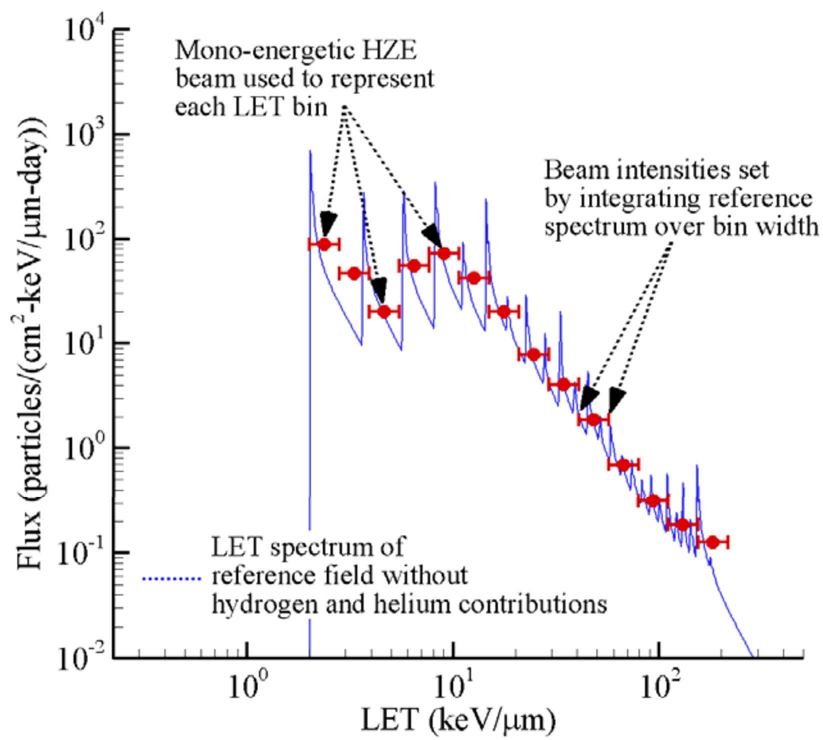
- Plots below show dose profiles within phantom
  - Internal variation measured as relative difference between min/max values
  - Local variation appears to be controlled with as few as 10 bins
  - Using more than 25 bins starts to reach limits of polyethylene degrader fidelity (0.025 cm)



Example Beam Selection

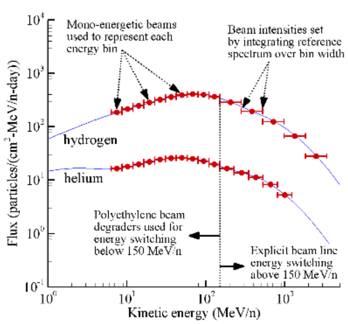
- Remaining analyses will consider the following case
  - 10 low energy bins for protons and alphas
  - 5 high energy bins for protons and alphas
  - 14 LET bins for HZE component

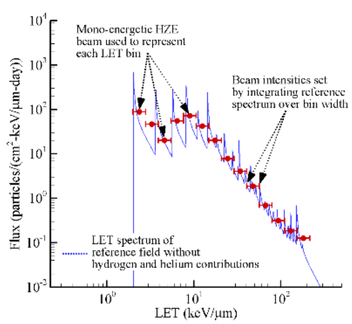


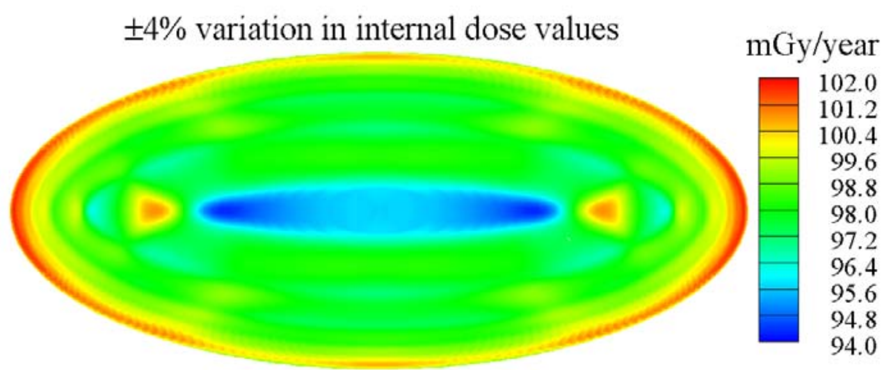


Example Beam Selection

- Internal exposure variation in ellipsoidal phantom under isotropic irradiation is shown below
  - Relatively smooth internal dose profile
  - Previously established that 10 low energy bins for hydrogen and helium are sufficient
  - Higher energy hydrogen and helium beams will not range out in phantom
  - HZE beams explicitly chosen to reach at least 9 cm

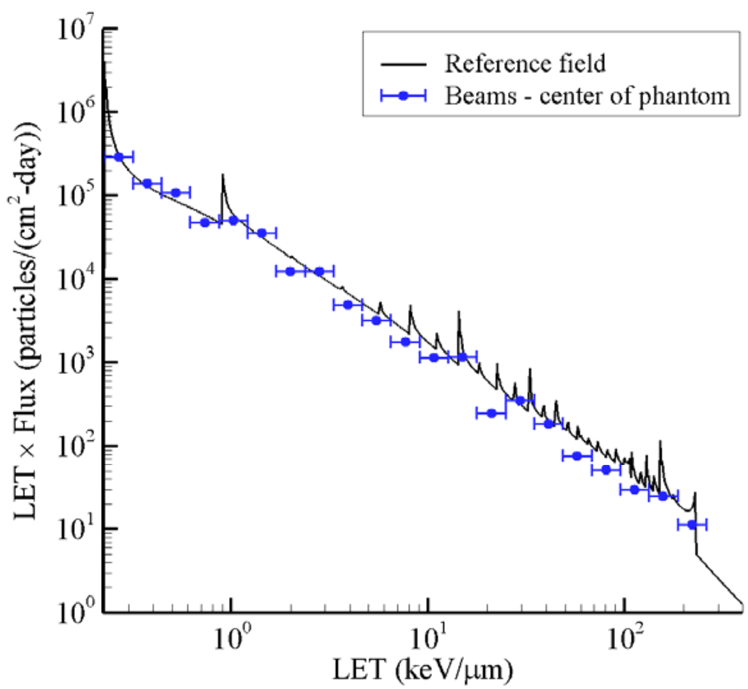


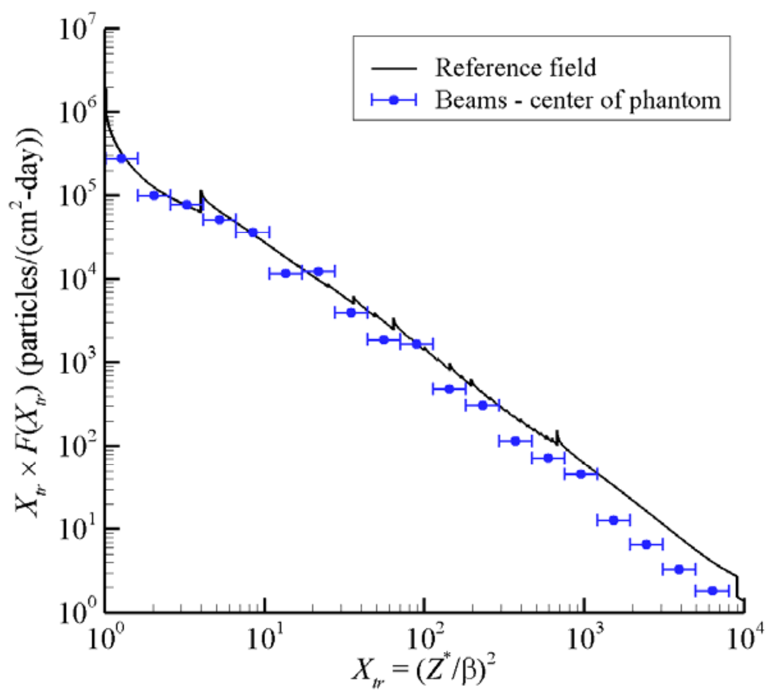




Example Beam Selection

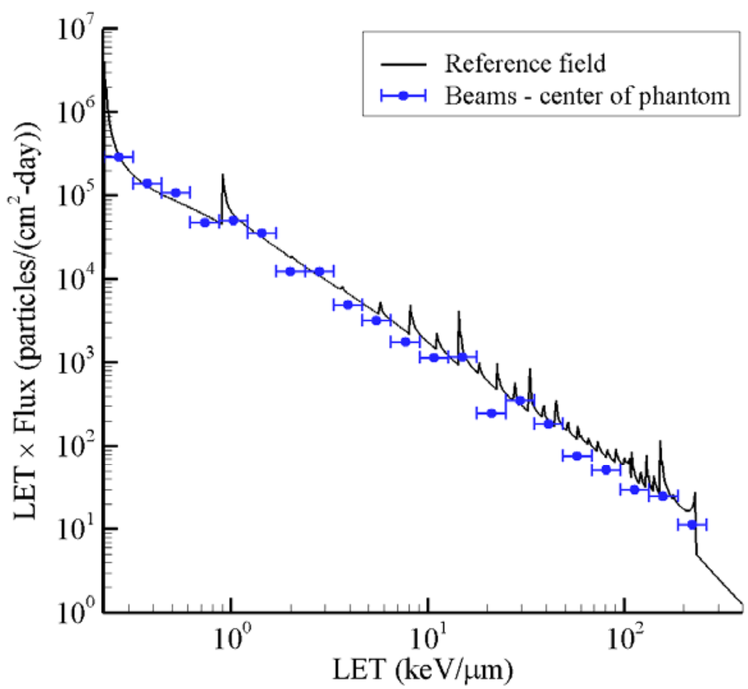
- Left pane shows the differential LET spectrum of reference field compared to spectrum induced by beams at center of phantom (isotropic irradiation)
  - Qualitatively good agreement across the LET spectrum

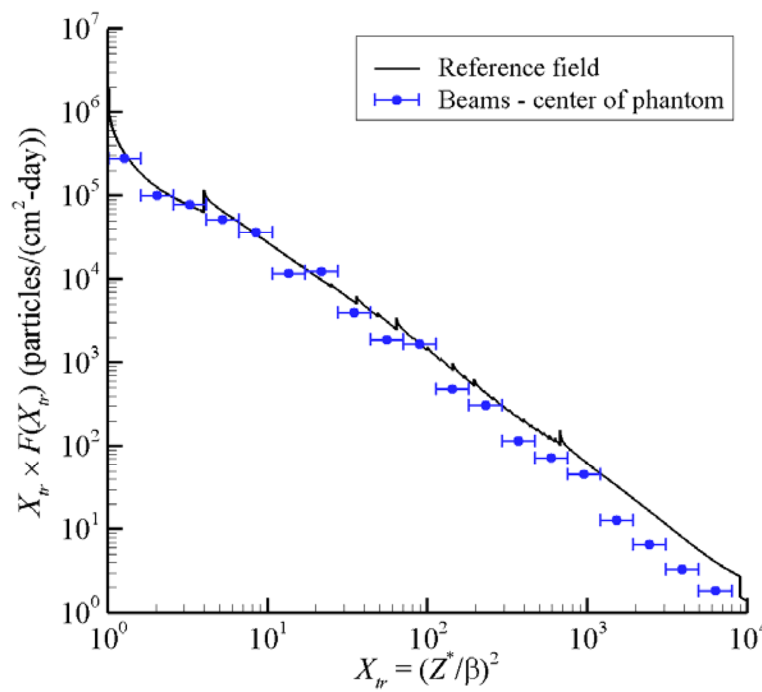




Example Beam Selection

- Right pane shows the differential $X_{tr} = (Z^*/\beta)^2$ spectrum of reference field compared to spectrum induced by beams at center of phantom (isotropic irradiation)
  - $(Z^*/\beta)^2$ spectrum provides somewhat of an independent check since beam selection was not guided by this quantity
  - Qualitatively good agreement across the $(Z^*/\beta)^2$ spectrum





Example Beam Selection

- Tables below show integrated quantities from reference field and beams
  - Cell nucleus hits computed by assuming cross sectional area of $100\ \mu m^2$
  - Hits/cell results consistent with previous calculations by Curtis et al.

Annual reference field 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 quantities at center of phantom

	Avg. hits per cell nucleus	Dose (mGy)	Dose Eq. (mSv)	<Q>
hydrogen	105.0	71.2	96.2	1.3
helium	4.5	16.3	50.0	3.0
HZE	0.3	8.3	65.5	7.9

Summary

- Current (and upgraded) 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, and it was determined that 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 and allows systematic improvements to be made
  - Spectral quantities and integrated quantities are reasonably well represented
  - Optimization procedures could be developed to improve overall agreement across all quantities

- Drawbacks of the proposed strategy include
  - Possible lower energy constraints for HZE particles associated with animal models
  - Neutron and π/EM components
  - 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

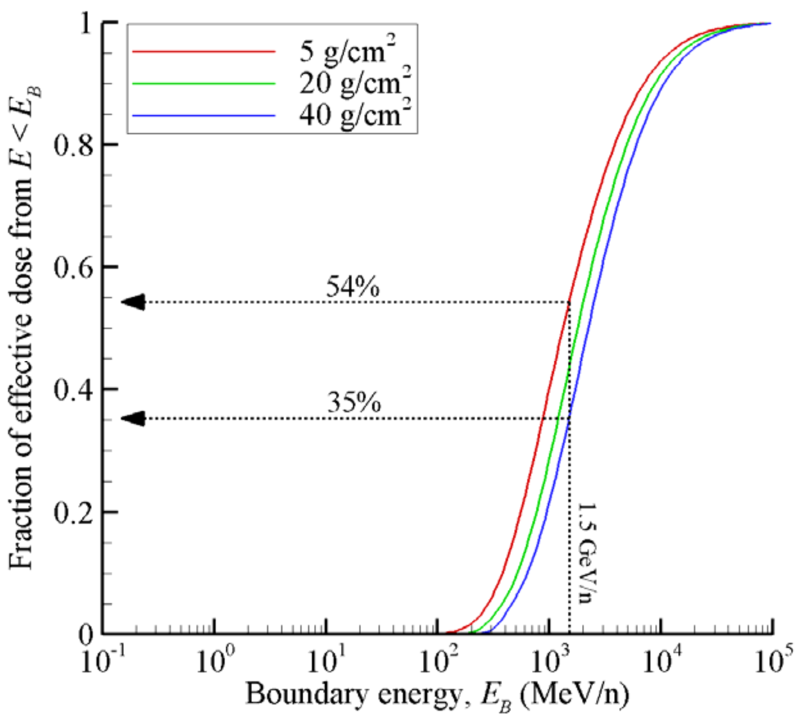
- HZE beam information for example study

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

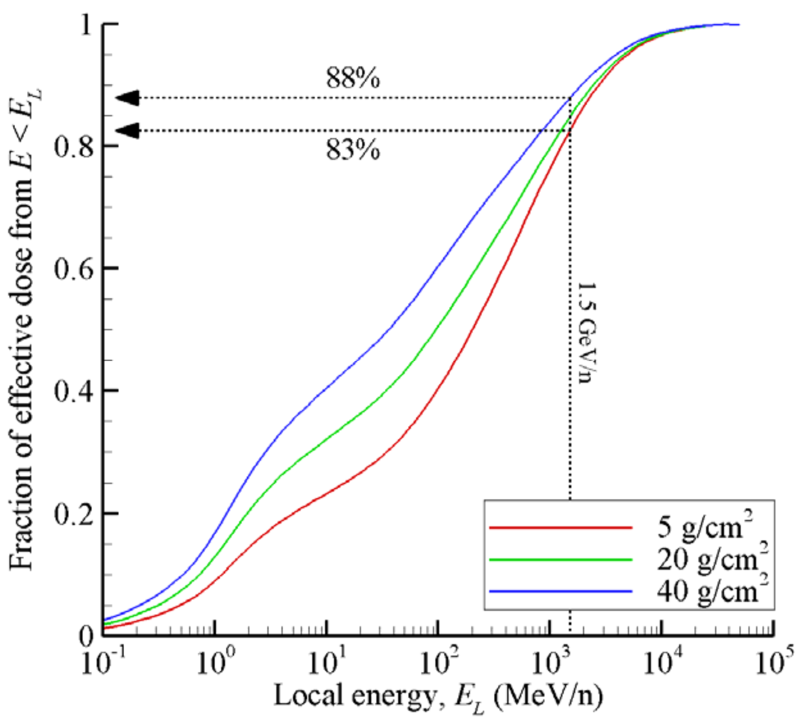
Backup: External and Internal Fields

- Plots below show fraction of effective dose as a function of boundary and local energies for thicknesses of aluminum shielding
  - Current NSRL constraints appear to be restrictive if external, free space field is simulated
  - Appears energy domain of local tissue field can be well represented

<u>Simulator design related to external field</u>

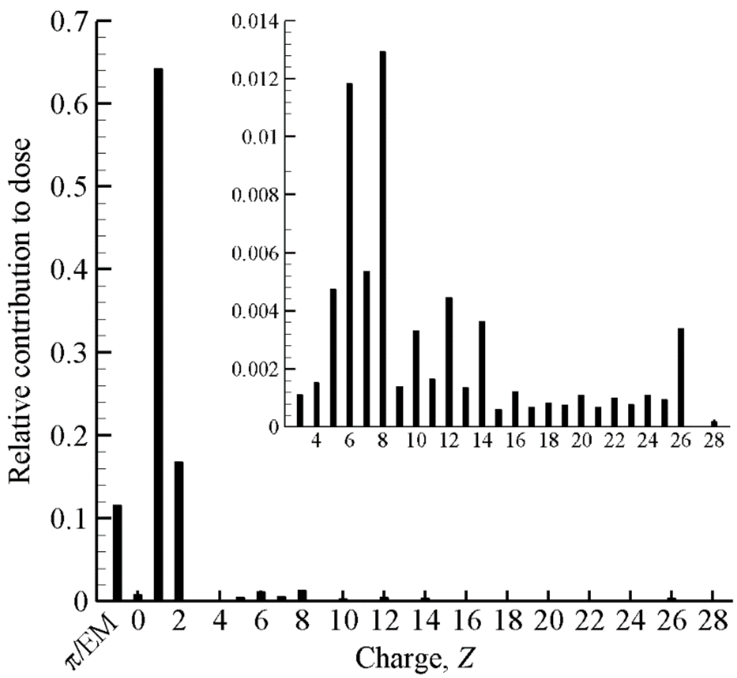


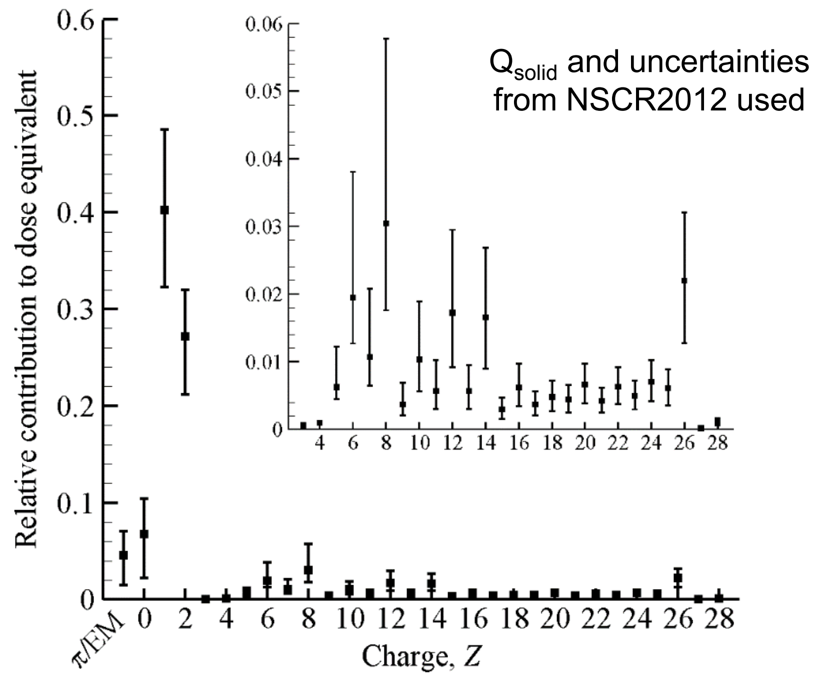
<u>Simulator design related to local tissue field</u>



Backup: Sensitivity Analysis

- Plots below show relative contribution to dose and dose equivalent from various particles in the reference field
- Z = 1 and Z = 2 contributions dominate
  - 81% of dose and 67% of dose equivalent
- Z > 2 contributes 7% to dose and 21% to dose equivalent
  - Z = 6,7,8,10,12,14,20,26 appear amplified compared to other heavy ions





Backup: Sensitivity Analysis

- Another point to consider is the self-shielding provided by an animal model
  - May want to avoid Bragg peaks or rapid exposure gradients within mice
  - Localized tissue exposures may be difficult to reproduce in subsequent studies
  - Table below gives energies needed to reach 9 cm

Z	E to reach 9 cm (MeV/n)	E to reach 80 cm (MeV/n)
1	109	393
2	109	393
6	204	806
7	224	898
8	242	987
10	277	1166
12	308	1336
14	339	1499
26	475	2334

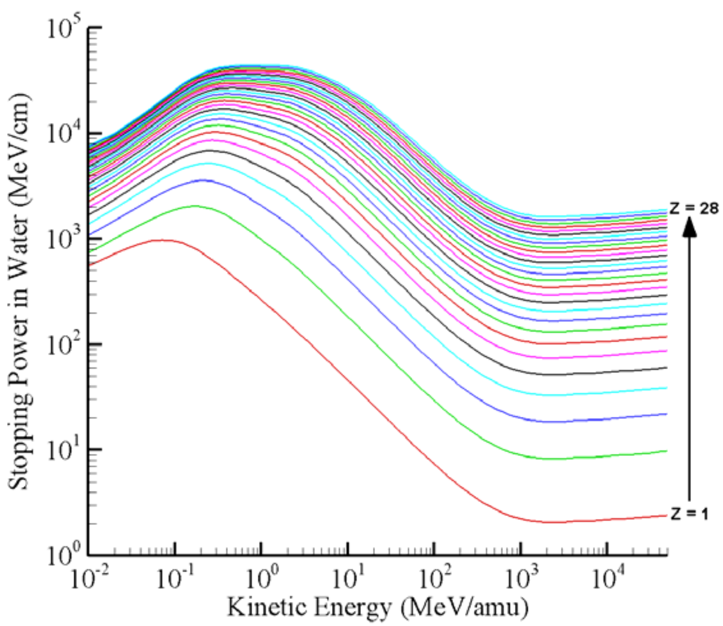
BACKUP: LET and X_{tr} spectra

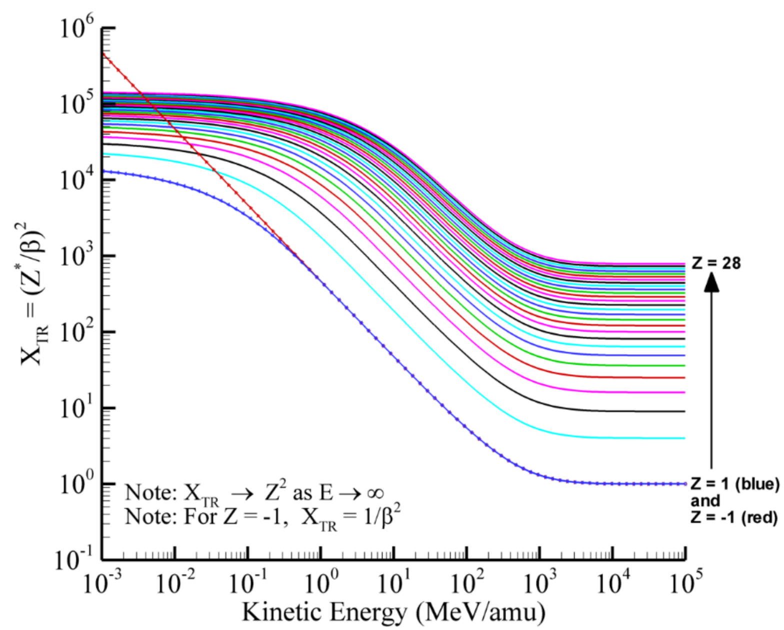
- LET spectrum is computed from flux

$$\frac{d\phi(L)}{dL} = \sum_Z \frac{d\phi(Z,E)}{dE}\left|\frac{dE}{dL}\right| = \sum_Z \frac{d\phi(Z,E)}{dE}\left|\frac{dL}{dE}\right|^{-1}$$

- X_{tr} spectrum is computed from flux

$$\frac{d\phi(X_{tr})}{dX_{tr}} = \sum_Z \frac{d\phi(Z,E)}{dE}\left|\frac{dE}{dX_{tr}}\right| = \sum_Z \frac{d\phi(Z,E)}{dE}\left|\frac{dX_{tr}}{dE}\right|^{-1}$$





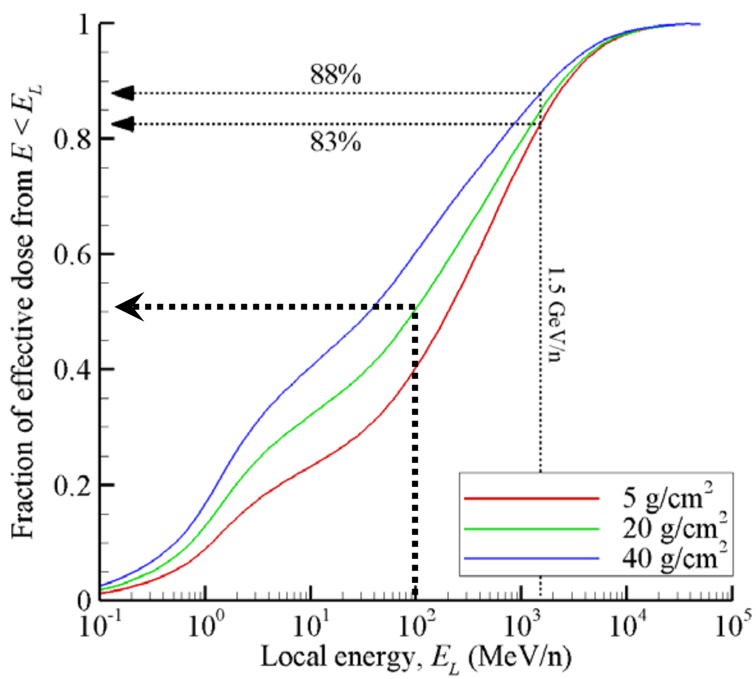
Backup: Discussion

- Proposed strategy for beam selection provides a systematic approach for reproducing the reference field LET spectrum and related quantities
  - Sensitivity analyses and energy constraints provide supplementary information
  - Integrated quantities such as a dose, dose eq., and <Q> well represented
  - Track structure spectrum reasonably well represented even though it wasn't targeted
  - Optimization strategies could be pursued to improve overall agreement across all quantities considered

- Proposed strategy does have some drawbacks
  - Track structure characteristics
  - Lower energy constraint associated with ion stoppage in animal model
  - Neutron and π/EM components

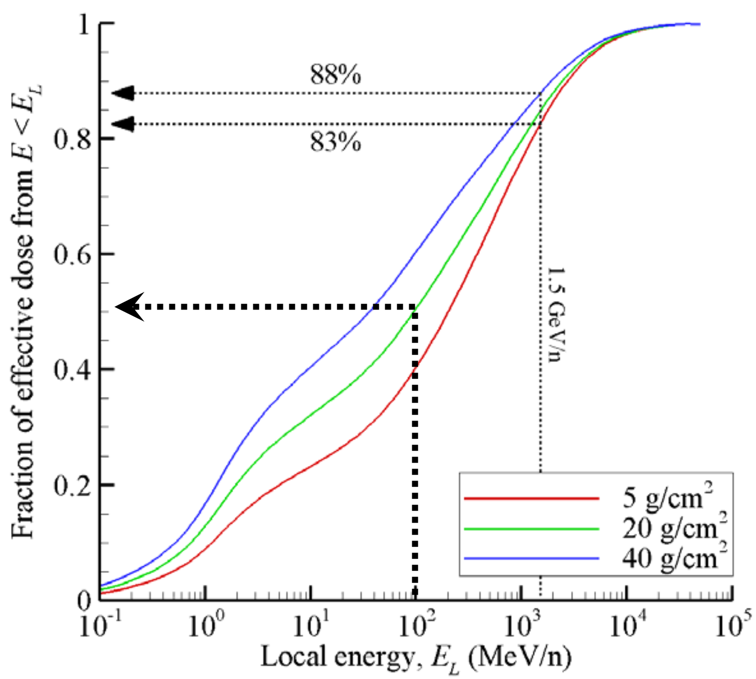
Backup: Discussion

- Track structure
  - Proposed strategy represents $F(X_{tr})$ spectrum reasonably well
  - Due to energy constraints, most beam energies were focused in the 200 MeV/n – 600 MeV/n range
  - Unclear if track structure characteristics of simulator will closely represent what might be expected in space
  - Especially important given ~half of the exposure is delivered by energies below 100 MeV/n



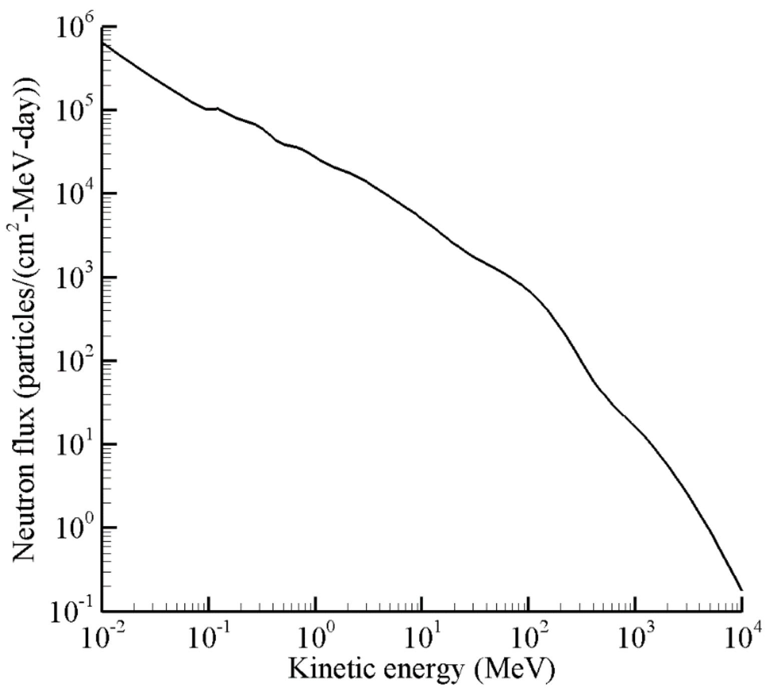
Backup: Discussion

- Lower energy constraint
  - Lower energy ions contribute significantly to exposure but are not explicitly included in simulator design
  - For cell cultures, the lower energy constraint could be relaxed
  - Proposed strategy could be modified to include a spectrum of low energy ions (degraders) but would require further analysis to integrate into the simulator design
  - Could leave design as-is and augment with increased complexity at a later date



Backup: Discussion

- Neutrons
  - Neutron spectrum of reference field shown below
  - Neutron dose is defined here as energy deposited by heavy target fragments (Z > 2) produced in nuclear collisions (elastic recoil and inelastic products)
  - Most of the exposure comes from neutrons between 1 MeV and 1 GeV



Backup: Discussion

- Neutron beam not currently available at NSRL
  - Even if it were, a pure neutron spectrum would induce a different exposure than what is defined presently
- Could represent heavy target fragment spectrum in some way, but might be difficult
  - Could use models to predict heavy target fragment spectrum (<10 MeV ions) and implement degraders to provide continuous spectrum
  - Could replace low energy target fragments with high energy ions with much higher Z value (i.e. same LET)
- Could also just ignore neutron component for now (and π/EM cascade)
  - Neutrons contribute small amount to dose and 7% to dose equivalent for reference environment
  - Likely this much error in any simulator design
  - Could again view the neutron and π/EM components as augmentations to the existing design to be added at a later date