CRaTER Measurements of Tissue-Equivalent Shielding in the GCR

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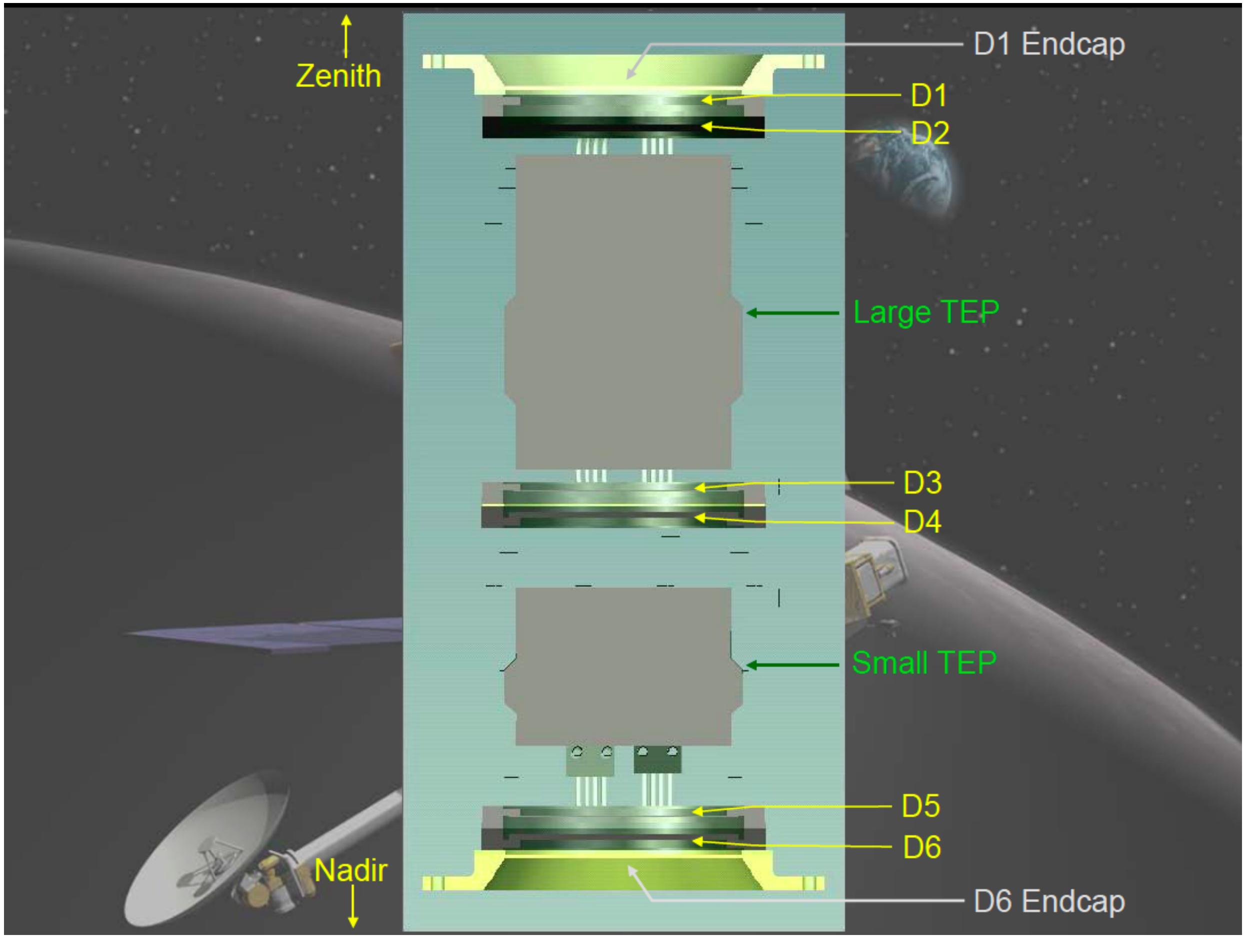
Outline

- CRaTER Overview
- Calibration and some general consideration for silicon detectors
- Matching low-LET and high-LET spectra
- Shielding analysis
- “Out of cone” study
- Conclusions

CRaTER – Overview

- Aboard Lunar Reconnaissance Orbiter.
- Launched July 2009.
- Orbit circularized at 50 km altitude, September 2009.
- CRaTER has been operating successfully for almost 3 years.
- Basic idea: measure LET from GCR's and SEP's at different depths of tissue.

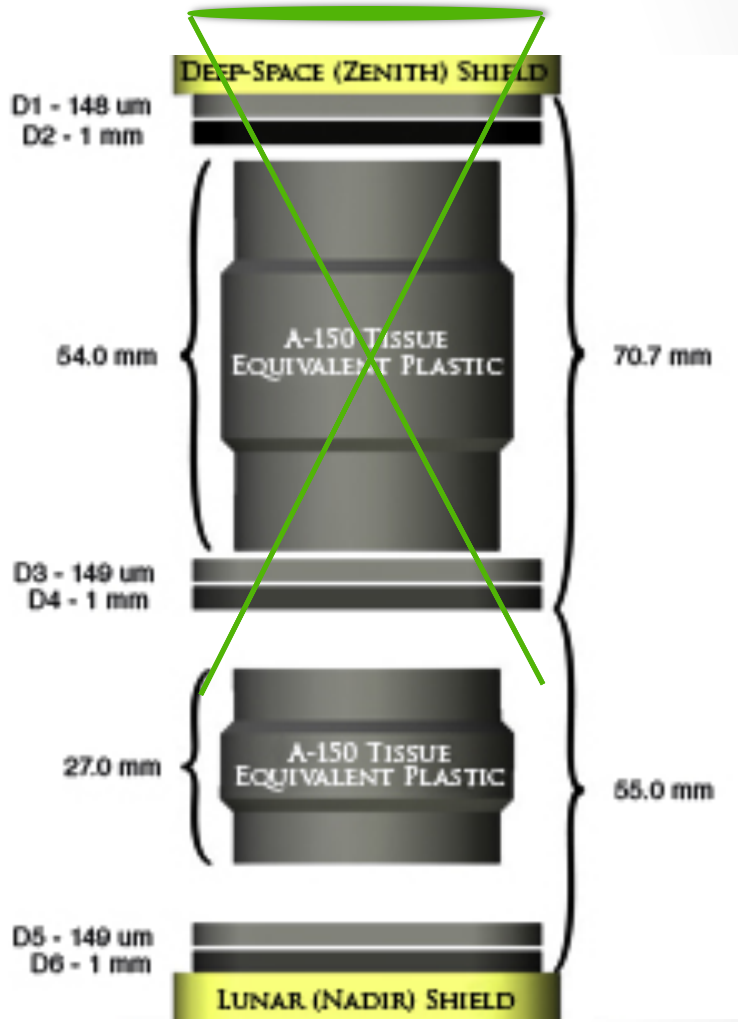


Thick detectors (1 mm deep) record ΔE in silicon from about 100 keV (protons) to ~ 88 MeV (relativistic Si) with saturation at higher ΔE.

Thin detectors (148 μm deep) have low gain in electronics, they do not record Z=1 or relativistic helium, but Fe is on scale.

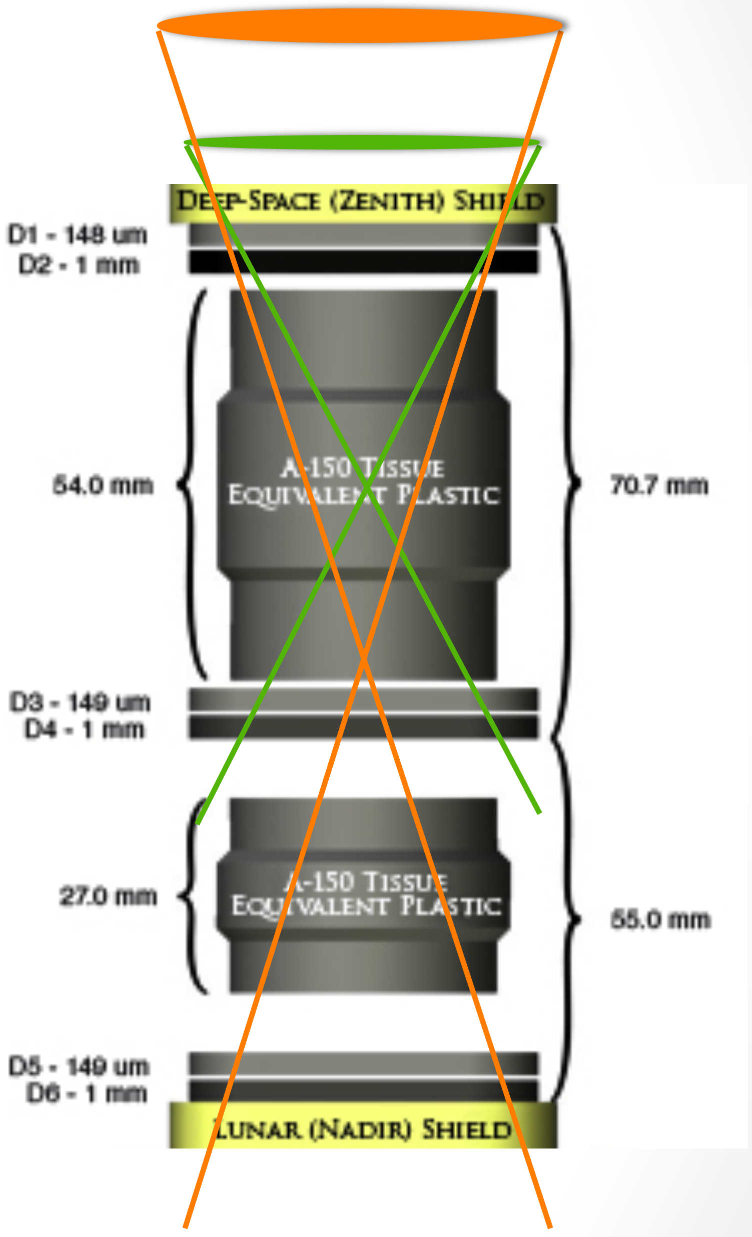
Fields of View

- Geometry factors:
  - D2-D4: 1.91 cm^2 sr, half-angle θ = 15°.



Fields of View

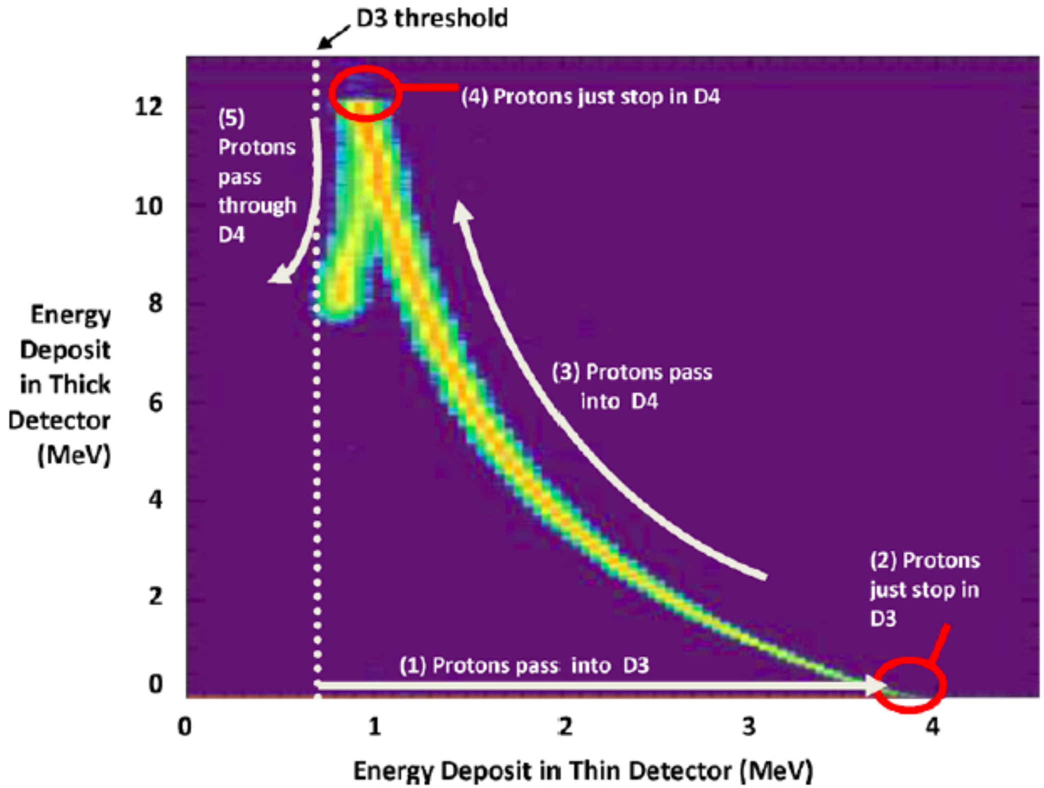
- Geometry factors:
  - D2-D4: 1.91 cm^2 sr, half-angle θ = 15°.
  - D2-D6: 0.62 cm^2 sr, half-angle θ = 8.4°.
- Expect ~ 3x as many D2-D4 coincidences as D2-D6.



CRaTER Operation

- CRaTER records all triggered events.
- Full event records sent down.
- Trigger = hit above threshold in any detector, i.e., no coincidence requirement.
  - Thresholds set to be just above noise.
- Large data files – in ASCII format, ~ 1 GB/day.
  - A lot of filtering needed (and a lot of disk space).

Calibration

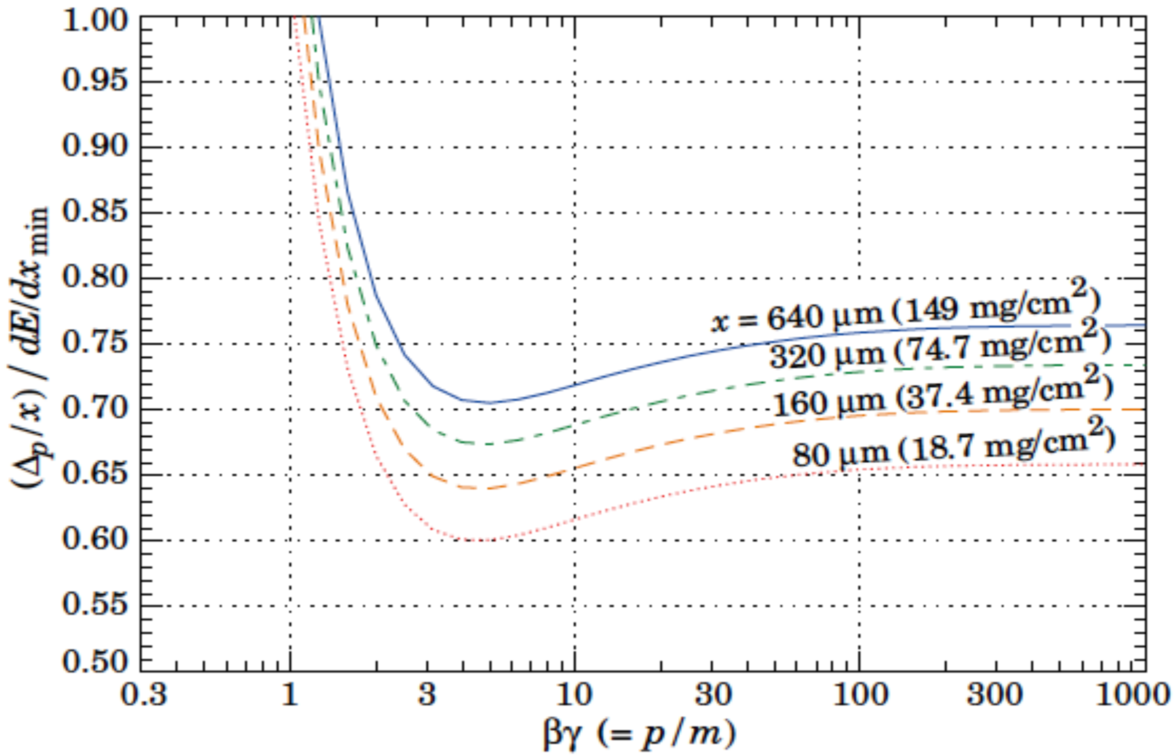


- Major goal: obtain LET spectra vs. depth from GCR.
- Measure dE/dx in silicon, but want to know LET in water.
- Stopping protons were used to get PH → ΔE factors.

Calibration

- Bichsel: "It is known that for low-energy particles *W* does depend on particle type and speed… caution is necessary with the energy calibration of silicon detectors."
  - Calibration with low-energy protons may also be off, if the W at low energy ≠ W at higher energies.
- Implication: Use high-energy data for calibration, not low energy.
  - That means we have to understand effects of straggling = individual large energy transfers.

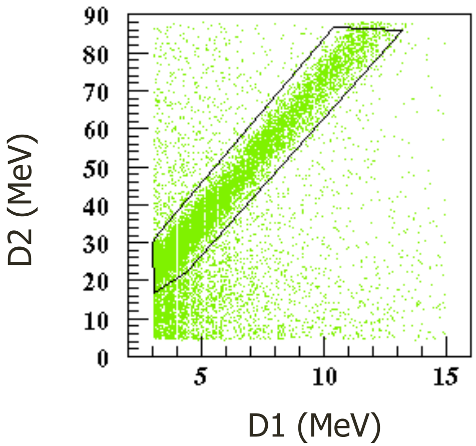
Straggling in Thin Si Detectors

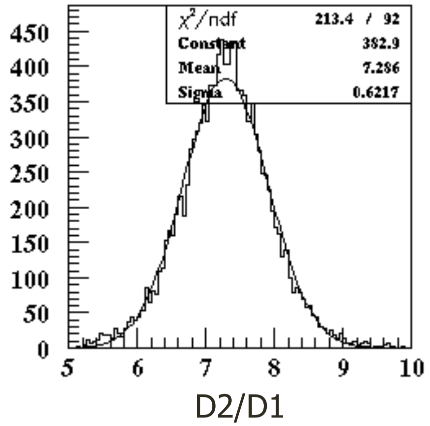


- Often-overlooked point: ***most probable energy deposit per unit length is a function of detector depth***.
- At high energy, Δ_p / x = a + b ln(x).
- Most probable energy deposit always < average dE/dx.

Straggling in CRaTER Data

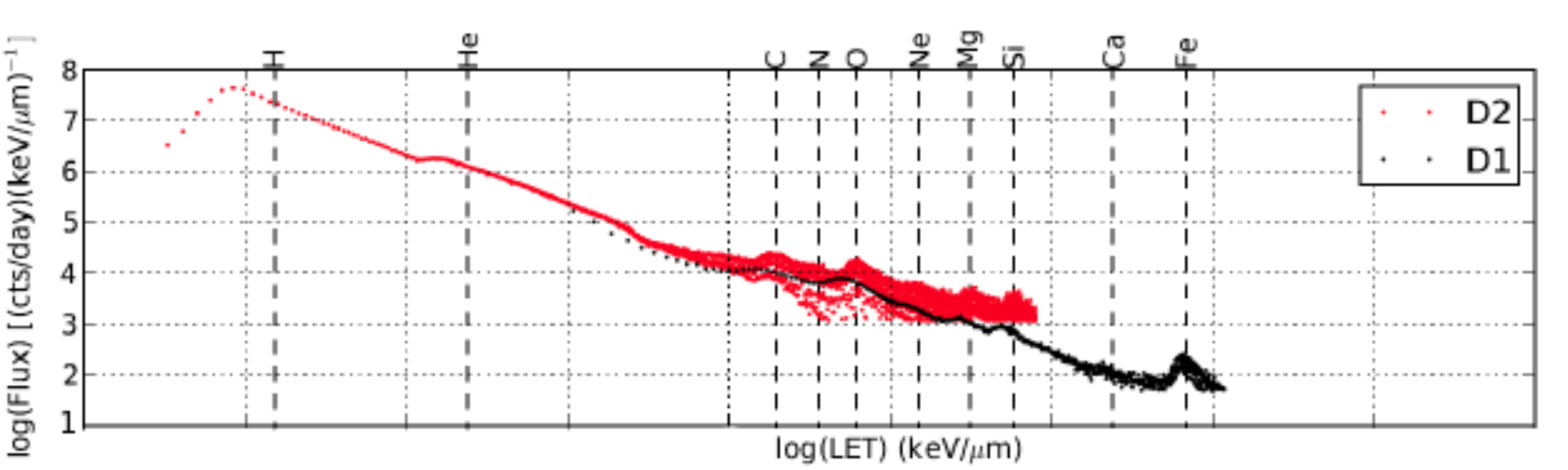
- Consider, e.g., D2 vs. D1 scatter plot.
- Select region where particles are well-measured by both.
- If dE/dx was independent of depth, ratio of ΔE's would = ratio of depths, 1000/148 = 6.76. But find ratio of 7.22 with nominal calibration.





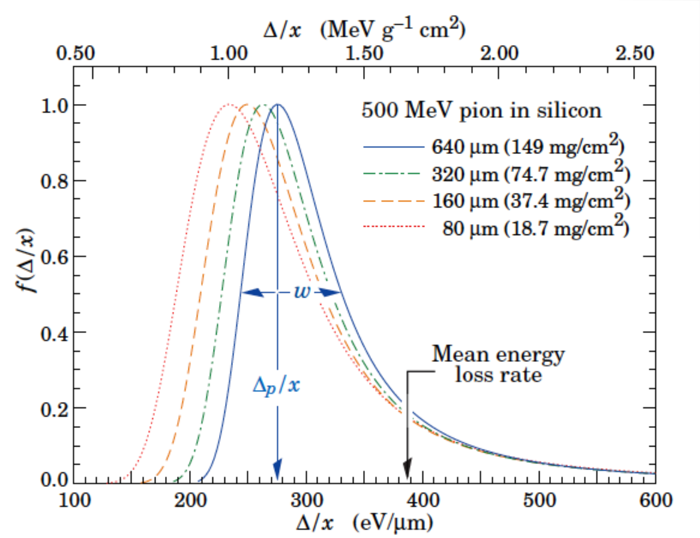
Matching up Spectra

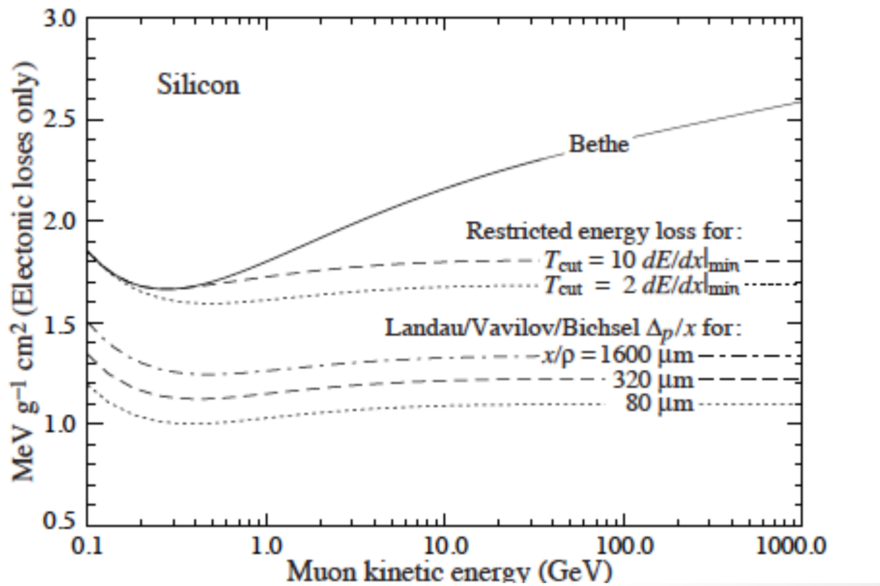
- Consider dE/dx spectrum using D1/D2 pair with nominal calibration.
- Recall D2 saturates around 88 keV/μm, while D1 has a full range dE/dx of ~ 2000 keV/μm.
  - D1 takes over at high dE/dx – but how to transition?
- dE/dx distributions don't match up.
- Predictable from Δ_p considerations –element peaks are shifted to the left in the thin detector (D1).
  - Initially thought to be a calibration error, but it's not.



Recipe for Calibration

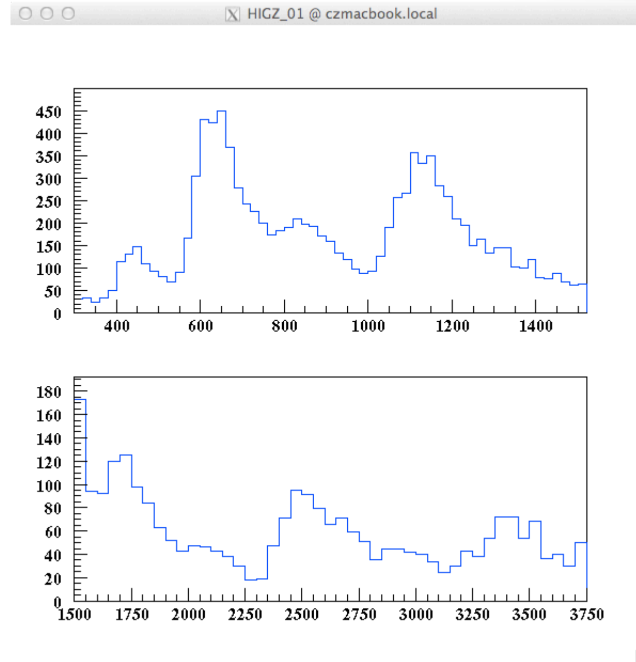
- *PDG: "The mean of the energy loss given by the Bethe equation…is ill-defined experimentally and is not useful for describing energy loss by single particles."*
- We should use the most probable energy loss = peak value in a high-energy beam (or GCR), and account for straggling when we convert to LET in water.
  - Also needs to be included when we match up spectra from thin and thick detectors.

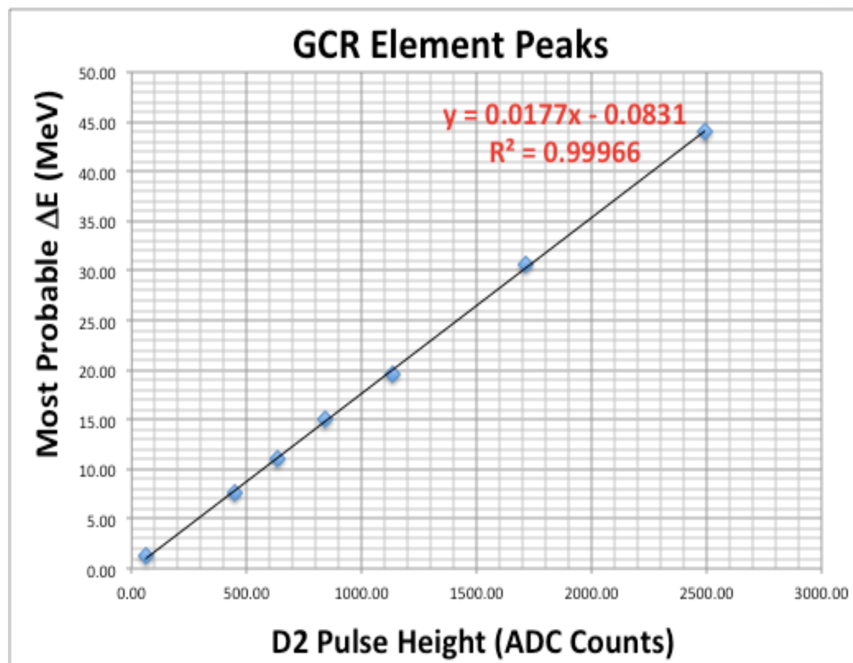




D2 Calibration

- Select heavy ions that penetrate entire stack, with energy deposits in D2-D4-D6 all consistent within +- 10%.
- Identify He, B, C, N, O, Ne, and Mg peaks.
- Fit slope differs by ~20% from nominal.

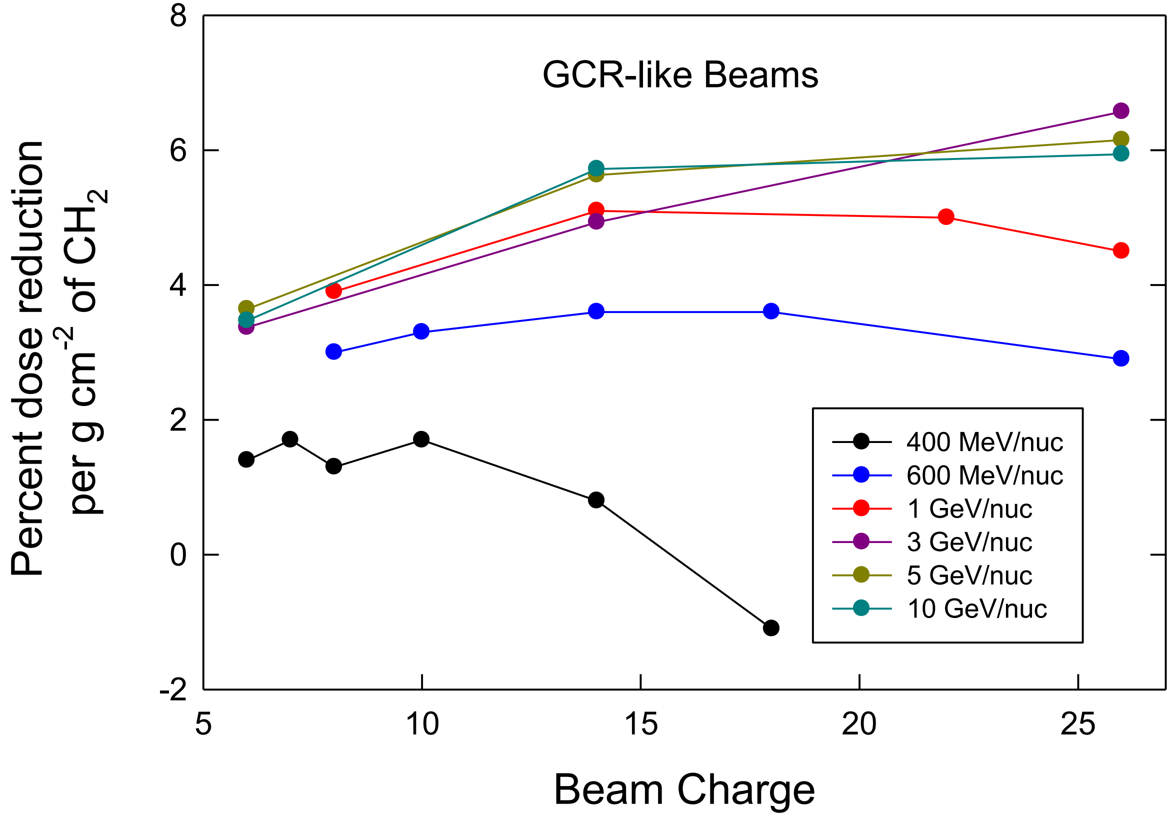




Shielding Analysis – Basic Idea

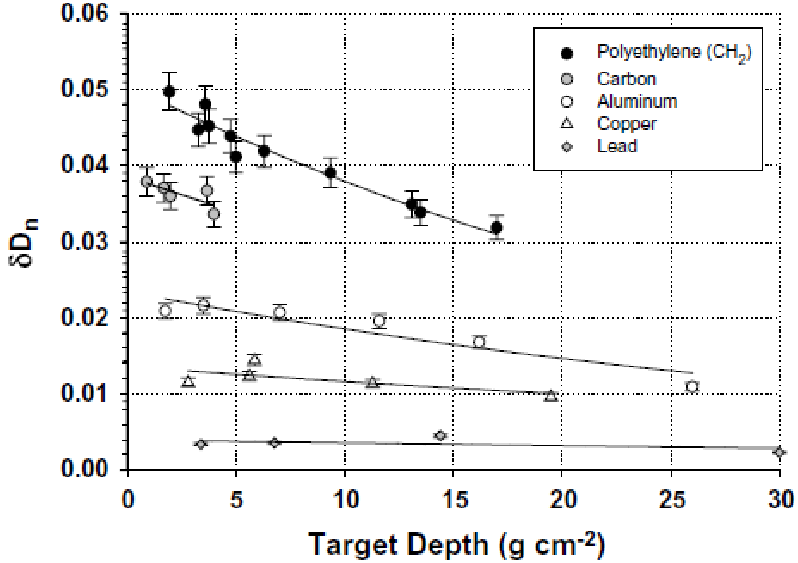
- Define δD_n = normalized dose reduction (per g cm^{-2}) = $(1 - \langle LET \rangle_{after} / \langle LET \rangle_{before})/\rho x$ where before and after refer to a target of areal density ρx.
- LBL group did a lot of analysis of CH_2 shielding (similar to TEP) with GCR-like beams.

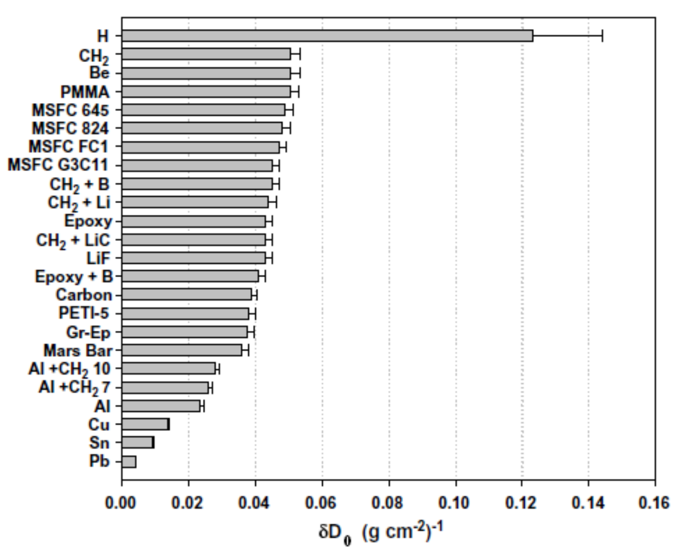
Accelerator Data



- Above 1 GeV/nuc, modest energy dependence.
- For a given energy, little dependence on species, for 600 MeV/nuc and up.

Multiple Depths of a Material

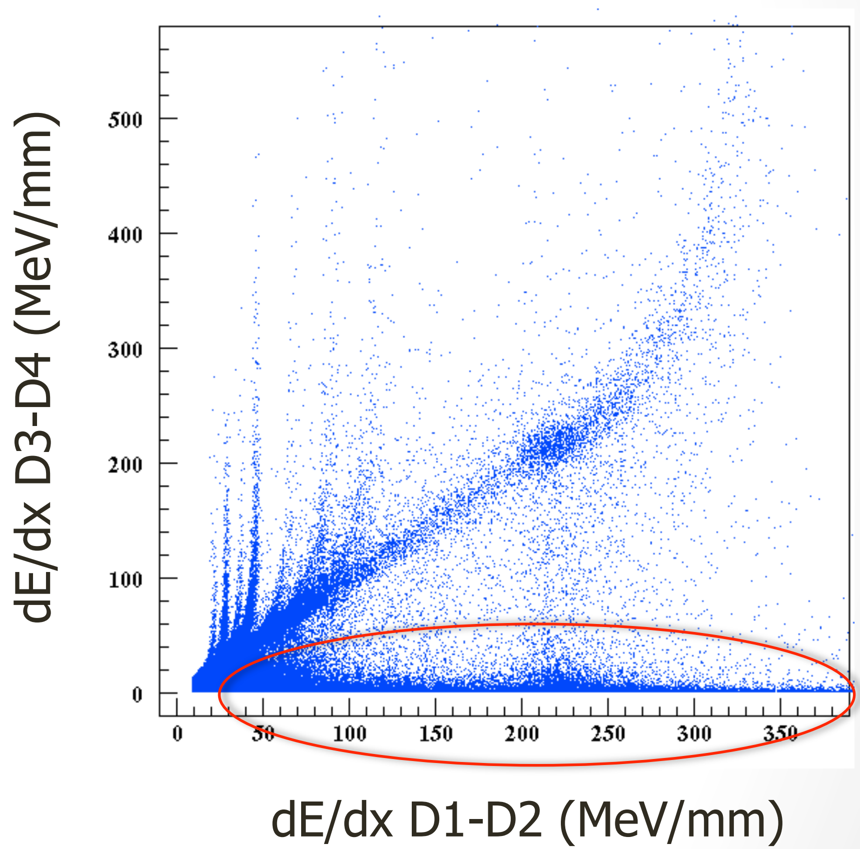




- Accelerator data for δD_n vs. shield depth show ~ exponential behavior.
- Fit to get "δD_0" i.e. the shielding effectiveness at zero depth.
- Note, CH_2 has $\delta D_0 = 0.051$.
- Lower Z → larger δD_0.
- Can do similar analysis of CRaTER data:
  - Compare D1/D2 and D3/D4, get 2 points, fit exponential with no free parameters.
  - Include D5/D6 in the analysis to get a free parameter and meaningful goodness of fit.

Shielding of GCR by TEP

- Select Z > 5 in D1-D2.
- GCRs penetrate TEP, things happen:
  - Some ions fragment.
  - Some ions slow down.
  - Some ions stop.
- Region near 0 in D3-D4 is very heavily populated – need to make a cut, but where?



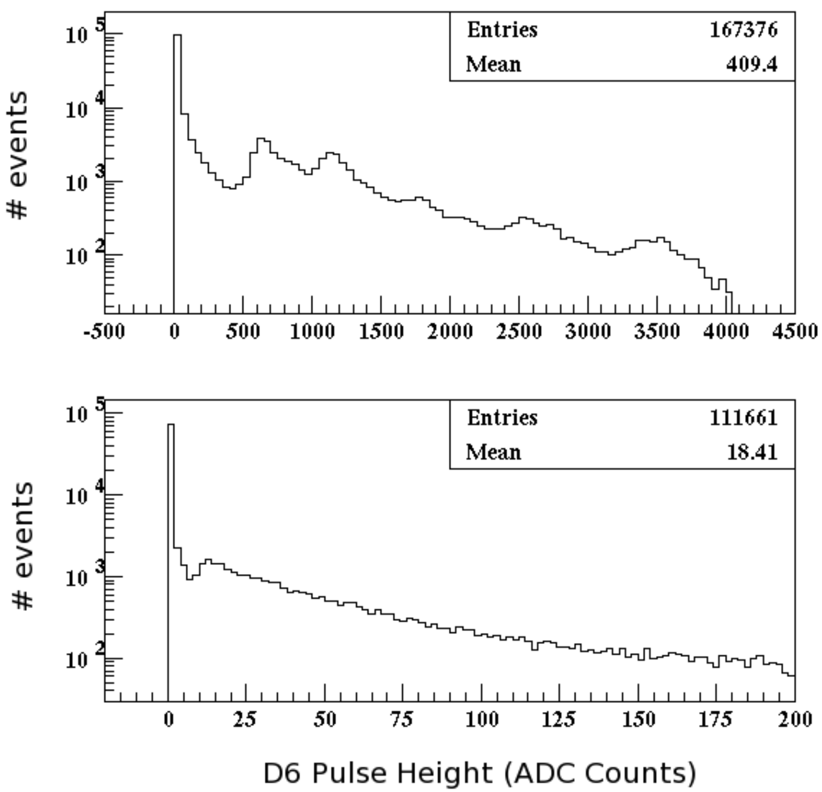
Coincidence Requirements

- We know we have to define an event sample with coincidences, otherwise we are dominated by side-penetrating events.
- So, what is a valid coincidence event?
  - With 6 detectors in 3 pairs, we have many possible definitions, and all of them contain implicit selection cuts.

Coincidences and Consequences

- Requiring thin detectors in the coincidence leaves out Z=1 and Z=2 events. E.g., a heavy ion fragments in TEP1 and D5 only sees a proton – do we really want to throw that out?
  - Maybe we have to, as we will see.
- If we require D5 and/or D6 we are imposing a species-dependent energy cut, because ions – or the fragments they produce – must have enough range to get through TEP2.

“Scruff”



- As an exercise, select events with well-correlated energy deposits in D2 & D4 (C, N, O up to Si), then look at D6.
  - 167k events selected.
- Based on geometry, expect 68% outside D2-D6 cone, should have 0 energy in D6 – but actual number near 0 is ~ 45%.
  - Any stopping ions would increase the expected fraction of 0’s to > 68%.

Impact of Scruff on Shielding Analysis

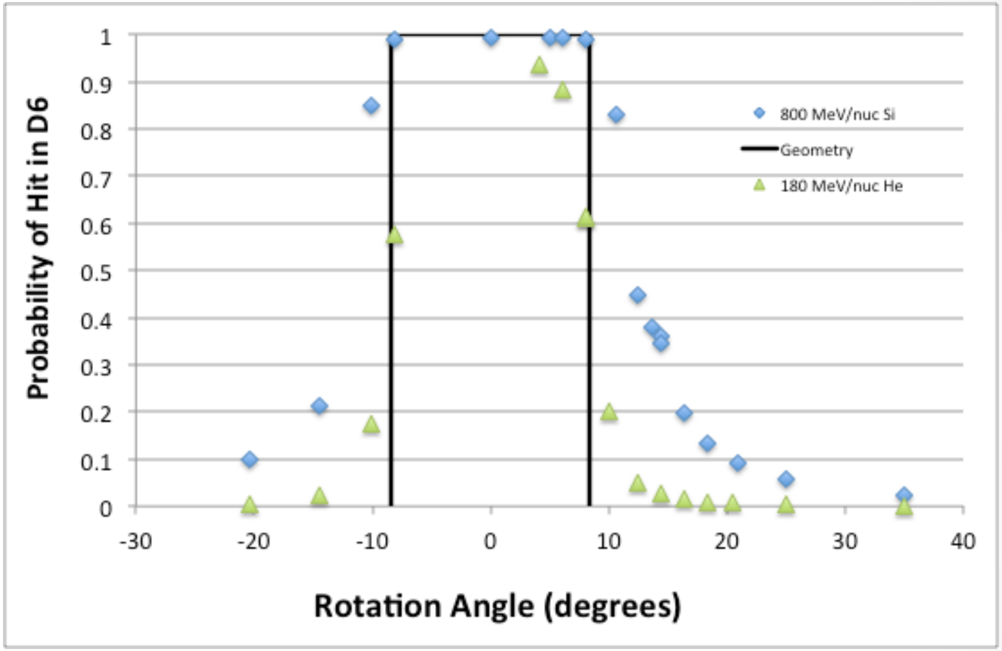
- There are fewer 0's in D6 than naively expected because of secondary production, i.e., scruff.
  - We think most of it is δ-rays.
  - Took CRaTER Engineering Model to HIMAC to test this hypothesis, more on that in a second…
- Similarly, events in D2 but outside D2-D4 cone will produce scruff in D4.
- We cannot distinguish a δ electron caused by an out-of-cone ion from a low-LET projectile fragment.
- This makes trouble for the shielding analysis and for any sensible measurements of LET spectra at depth.

Impact of Scruff on Shielding Analysis, continued

- The scruff causes us to let in out-of-cone events with low (but non-zero) LET in the downstream detectors.
  - If these events had 0 energy downstream we'd just exclude them as being out of cone.
  - These events increase apparent shielding. Revisiting the definition…
- $\delta D_n = (1 - \langle LET \rangle_{after} / \langle LET \rangle_{before})/\rho x$
- We have a good measurement of $\langle LET \rangle_{before}$ but $\langle LET \rangle_{after}$ is strongly influenced by scruff.

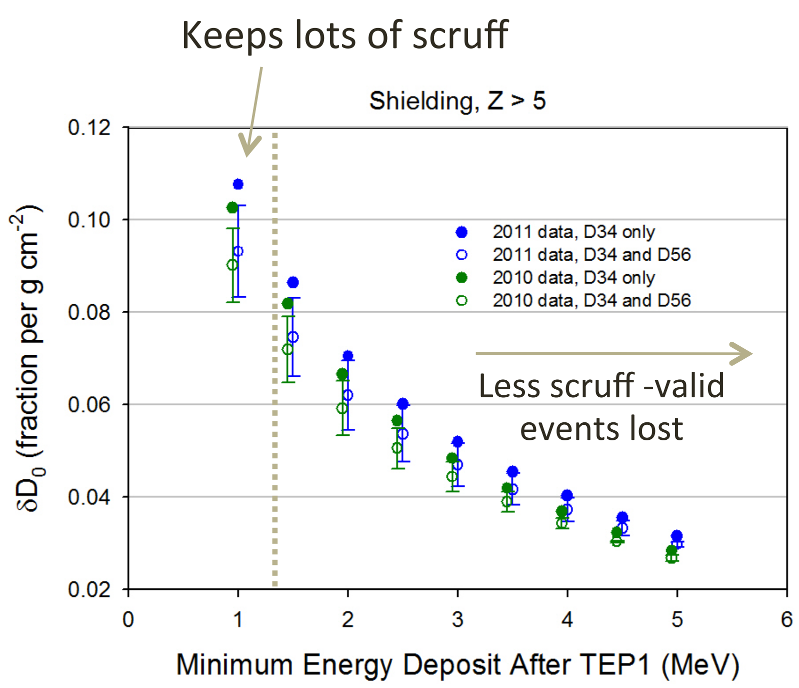
CRaTER @ HIMAC

- Ran 4 beams to study systematics
  - H at 160 MeV.
  - He at 180 MeV/nuc.
  - **Si at 800 MeV/nuc ---->**
  - Fe at 500 MeV/nuc.
- δ-ray production is energy-dependent so we used the highest energy beam available.
- CRaTER was mounted on a rotating stage, data taken at many angles.



Clearly see effects of δ-ray production and/or fragmentation in high-energy Si beam data, much smaller effect with lower-energy He beam.

Shielding or Scruff?



- Very high values of δD_0 when cut value is low – this includes many out-of-cone particles that produce scruff.
  - Recall polyethylene gave $\delta D_0 \sim 0.05\ (g\ cm^{-2})^{-1}$.
  - TEP should be less effective than CH_2.
- Modeling needed – as cut value increases, all or nearly all scruff is removed, but also valid fragmentation events.

Conclusions

- Set out to use flight data to validate shielding predictions that came from accelerator data.
  - Ended up needing accelerator data!
- Main analysis problem is scruff that cannot be easily eliminated.
- Can models (GEANT4, PHITS) accurately simulate the scruff?
- Accelerator data should provide good test.
- This is just one of several analyses that can be done with the CRaTER data – others are easier.
  - Data published on dose rates, albedo protons from the lunar surface.
  - Others remain to be published including SEP fluxes, LET distributions, shielding analysis, & study of elemental fluxes.
- The CRaTER data set is available via the NASA Planetary Data System (PDS), or talk to me.