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Linear Accelerator Electron Testing of Composite Materials for Space Applications

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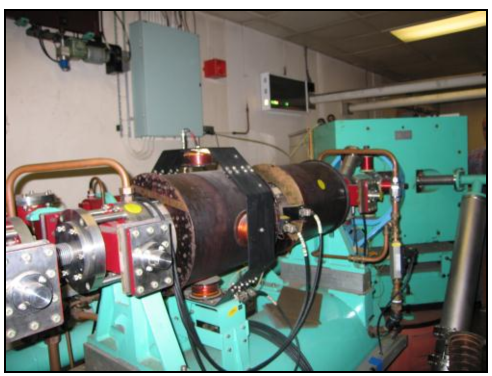

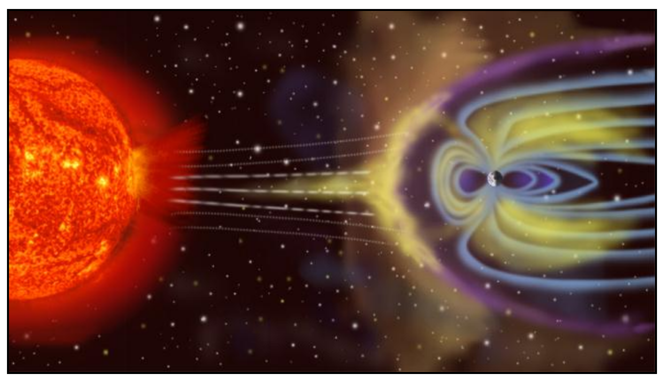

HEART 2008

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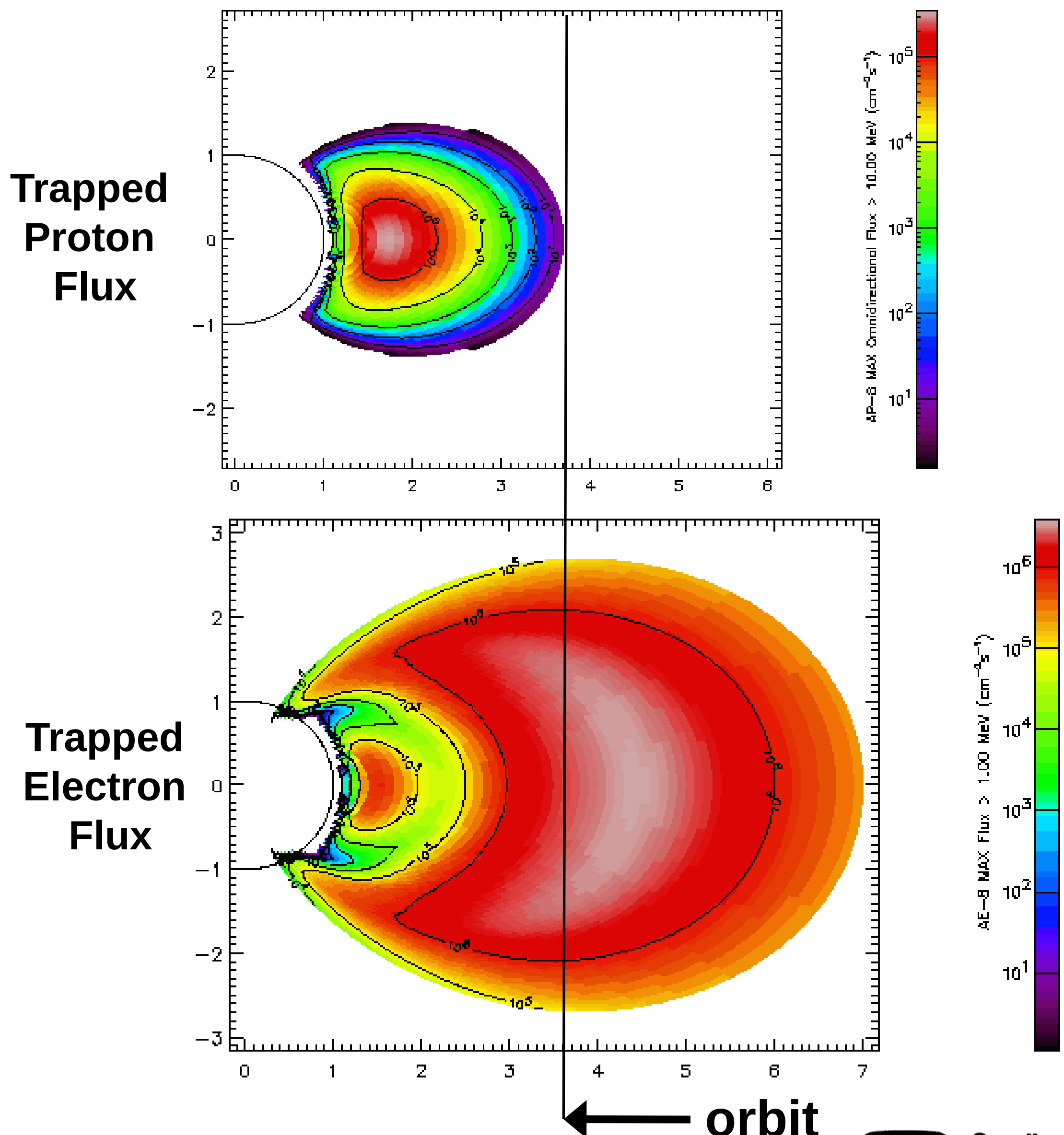
Earth's Trapped Radiation Environment

- TID in Earth orbits dominated by trapped protons and electrons.
- LEO orbits dominated by protons.
- Higher orbits, like GPS or GEO dominated by electrons.
- For electronics, dose depth curves will be quite different.
- For shielding, the best type and combination of materials will also be different.
- Our work focused on electron-dominated orbits, GPS: 20,200 km altitude, specifically.



Altitude in Earth radii (6400 km)

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Physics of Shielding

- Protons will be continuously slowed down by scattering from atomic electrons – higher Z has greater stopping power.
- Collisions with nuclei will become important for thick shielding – lower Z will be more effective in reducing proton energy.
- Electrons are also continuously slowed down by scattering from atomic electrons – again, higher Z has greater stopping power.
- However, slowing electrons create Bremmstrahlung X-rays which can be hard to stop – higher Z creates more X-rays, but stops them more effectively.
- Best shielding depends on particle type, energy, and thickness needed.

Z = # of protons in nuclei = atomic number

H: Z=1
C: Z=6
O: Z=8
Al: Z=13
Ta: Z=73
W: Z=74

hydrogen 1 H 1.0079																		helium 2 He 4.0026
lithium 3 Li 6.941	beryllium 4 Be 9.0122												boron 5 B 10.811	carbon 6 C 12.011	nitrogen 7 N 14.007	oxygen 8 O 15.999	fluorine 9 F 18.998	neon 10 Ne 20.180
sodium 11 Na 22.990	magnesium 12 Mg 24.305												aluminium 13 Al 26.982	silicon 14 Si 28.086	phosphorus 15 P 30.974	sulfur 16 S 32.065	chlorine 17 Cl 35.453	argon 18 Ar 39.948
potassium 19 K 39.098	calcium 20 Ca 40.078		scandium 21 Sc 44.956	titanium 22 Ti 47.867	vanadium 23 V 50.942	chromium 24 Cr 51.996	manganese 25 Mn 54.938	iron 26 Fe 55.845	cobalt 27 Co 58.933	nickel 28 Ni 58.693	copper 29 Cu 63.546	zinc 30 Zn 65.39	gallium 31 Ga 69.723	germanium 32 Ge 72.61	arsenic 33 As 74.922	selenium 34 Se 78.96	bromine 35 Br 79.904	krypton 36 Kr 83.80
rubidium 37 Rb 85.468	strontium 38 Sr 87.62		yttrium 39 Y 88.906	zirconium 40 Zr 91.224	niobium 41 Nb 92.906	molybdenum 42 Mo 95.94	technetium 43 Tc [98]	ruthenium 44 Ru 101.07	rhodium 45 Rh 102.91	palladium 46 Pd 106.42	silver 47 Ag 107.87	cadmium 48 Cd 112.41	indium 49 In 114.82	tin 50 Sn 118.71	antimony 51 Sb 121.76	tellurium 52 Te 127.60	iodine 53 I 126.90	xenon 54 Xe 131.29
caesium 55 Cs 132.91	barium 56 Ba 137.33	57-70 *	lutetium 71 Lu 174.97	hafnium 72 Hf 178.49	tantalum 73 Ta 180.95	tungsten 74 W 183.84	rhenium 75 Re 186.21	osmium 76 Os 190.23	iridium 77 Ir 192.22	platinum 78 Pt 195.08	gold 79 Au 196.97	mercury 80 Hg 200.59	thallium 81 Tl 204.38	lead 82 Pb 207.2	bismuth 83 Bi 208.98	polonium 84 Po [209]	astatine 85 At [210]	radon 86 Rn [222]
francium 87 Fr [223]	radium 88 Ra [226]	89-102 * *	lawrencium 103 Lr [262]	rutherfordium 104 Rf [261]	dubnium 105 Db [262]	seaborgium 106 Sg [266]	bohrium 107 Bh [264]	hassium 108 Hs [269]	meitnerium 109 Mt [268]	ununnilium 110 Uun [271]	unununium 111 Uuu [272]	ununbium 112 Uub [277]		ununquadium 114 Uuq [289]				

*Lanthanide series	lanthanum 57 La 138.91	cerium 58 Ce 140.12	praseodymium 59 Pr 140.91	neodymium 60 Nd 144.24	promethium 61 Pm [145]	samarium 62 Sm 150.36	europium 63 Eu 151.96	gadolinium 64 Gd 157.25	terbium 65 Tb 158.93	dysprosium 66 Dy 162.50	holmium 67 Ho 164.93	erbium 68 Er 167.26	thulium 69 Tm 168.93	ytterbium 70 Yb 173.04
* *Actinide series	actinium 89 Ac [227]	thorium 90 Th 232.04	protactinium 91 Pa 231.04	uranium 92 U 238.03	neptunium 93 Np [237]	plutonium 94 Pu [244]	americium 95 Am [243]	curium 96 Cm [247]	berkelium 97 Bk [247]	californium 98 Cf [251]	einsteinium 99 Es [252]	fermium 100 Fm [257]	mendelevium 101 Md [258]	nobelium 102 No [259]

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Composite Materials

• Composite materials are attractive due to their high structural strength and relatively low weight.

• Restrictions on size and weight of a payload (dictated by launch vehicle) make composite materials desirable for electronics enclosures.

• Unfortunately, reduced weight likely means reduced radiation shielding.

• Plan A: Design payload for minimum weight, and use radiation-hardened electronics or spot shielding to compensate for reduced box shielding.

• Plan B: Find a combination of composite and high-Z material that will reduce weight and not increase the dose inside the box.

• We chose Plan B – replace 100 mil Al with a composite/high-Z material.
-- for our ongoing program, this allows easy insertion without redoing analysis or adding spot shielding.

How can we 'qualify' the composite materials as rad shields?

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Qualifying Composite Materials

• Qualification is often done through analysis, test, or both.

• Analysis requires detailed understanding of composition – not always available due to manufacturing process.

• Testing must be done carefully – shielding properties depends on particle type and energy, not total dose.

• There is no source, except for space itself, that gives the trapped electron spectrum.

• We propose a combination of test and analysis:

1) Test with electrons in the 1-5 MeV energy range.

2) Compare test results with transport simulation.

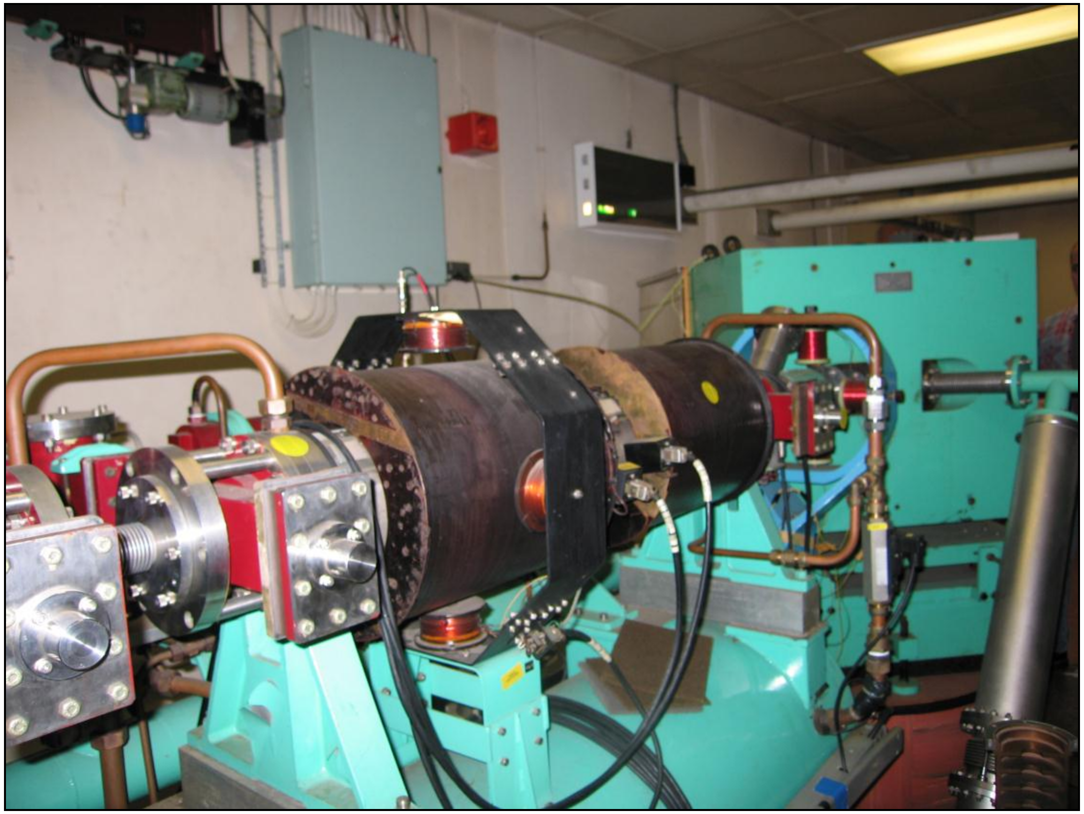
-- good agreement implies good understanding of composition.

3) Run transport simulation using space spectrum.

• Simple alternative – with scannable monoenergetic source, show that composite material works as well, or better, than Al at all relevant energies.

NPL Linear Accelerator Test

- Tests performed at the National Physical Laboratory in the UK.
  - 270 degree magnet provides fairly monoenergetic source
  - short pulses allows for p-i-n diode dosimetry – real time, large pulse number statistics, high precision comparison between samples.



Composite Structures

Solid Sheets

100 mils Al sheet

80 mils C fiber Composite +
5 mils Ta sheet

BACK

FRONT

Spray

250 mils GMB Composite +
Ta spray (5, 10, and 15 mils)

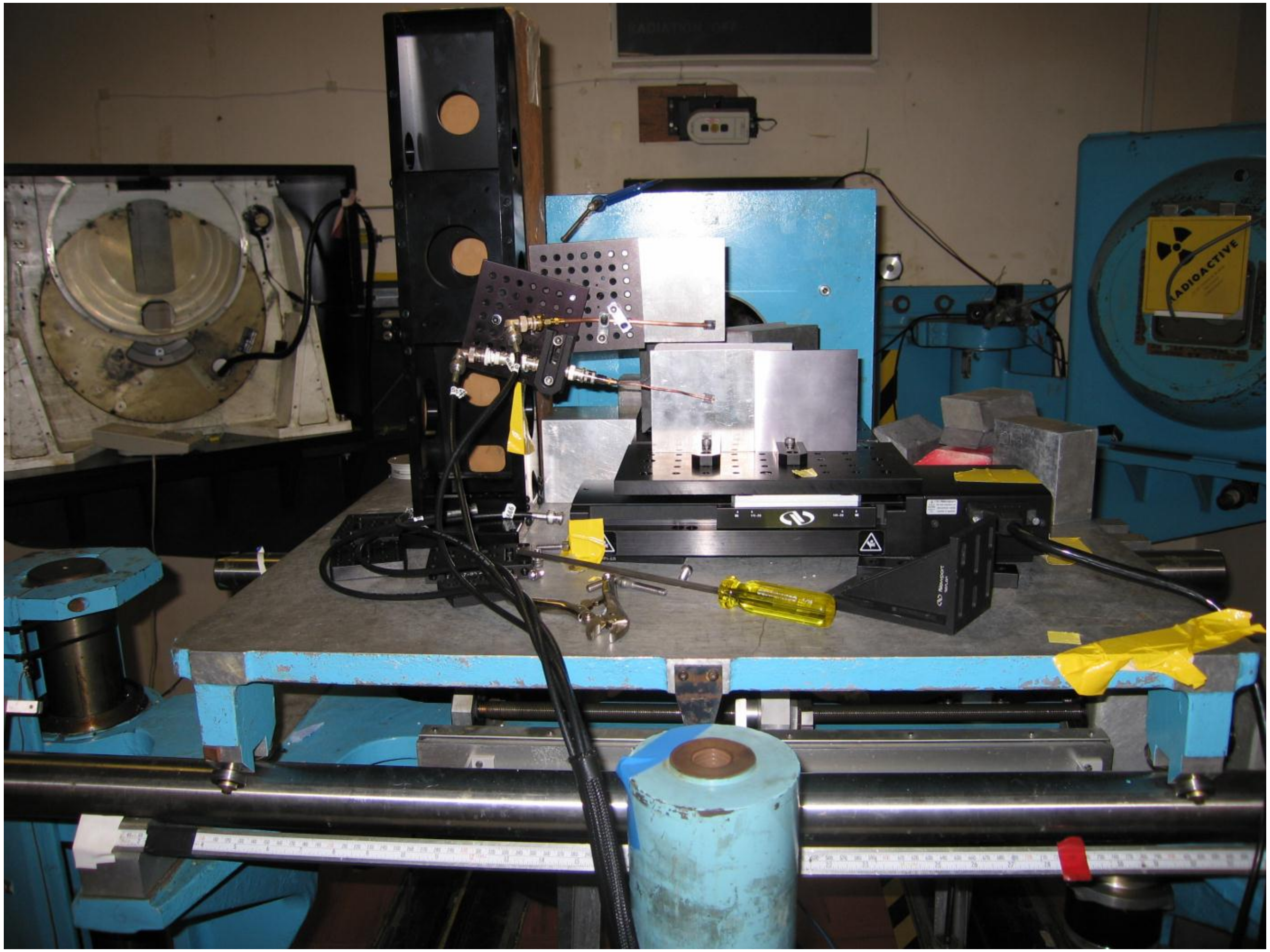
~~**Meshes**~~

Powders

100 mils Composite +
Dense layer of W powder + epoxy

58, 116, and 250 mils Silicone +
W particles (0%, 2%, 4%,
6%, 8%, and 10%)

Test Setup



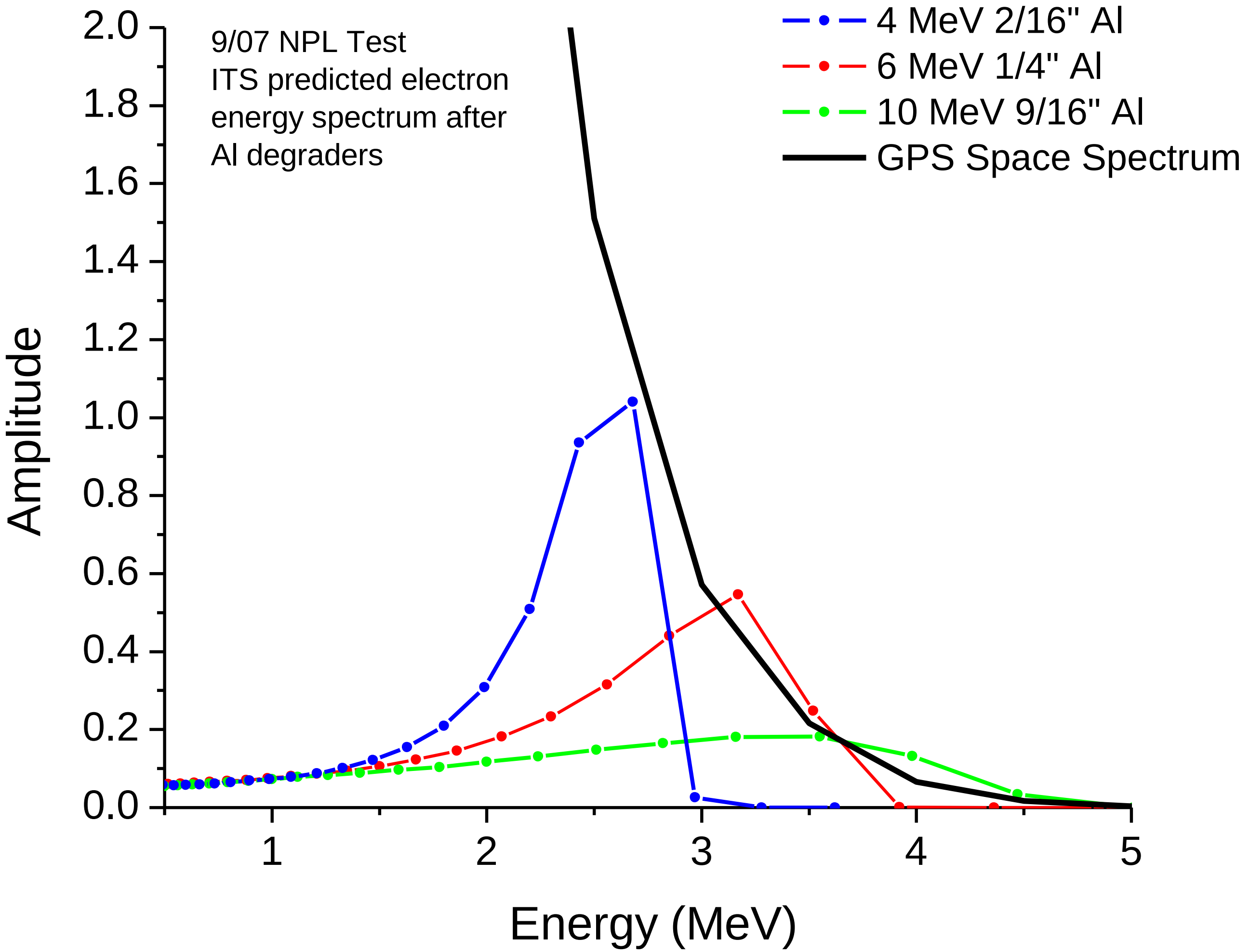
Reduce Scatter

Data Acquisition

- Used biased p-i-n silicon photodiodes (wrapped).
- LeCroy LC334A 500 Mhz single-shot oscilloscope.
- Averaged signal pulse area over 100 pulses (Sequence Mode).
- Normalized reference 100 mil Al sample to main reference p-i-n.
- Moved stage to get normalized signal behind composite sample.
- Method allowed comparison of shielding performance to within 1-2 %.

NPL vs. Space Spectrum

Dial in specific energies (4MeV, 6MeV, 10Mev) and use degraders at the NPL. Want samples to shield all three exptl spectra.



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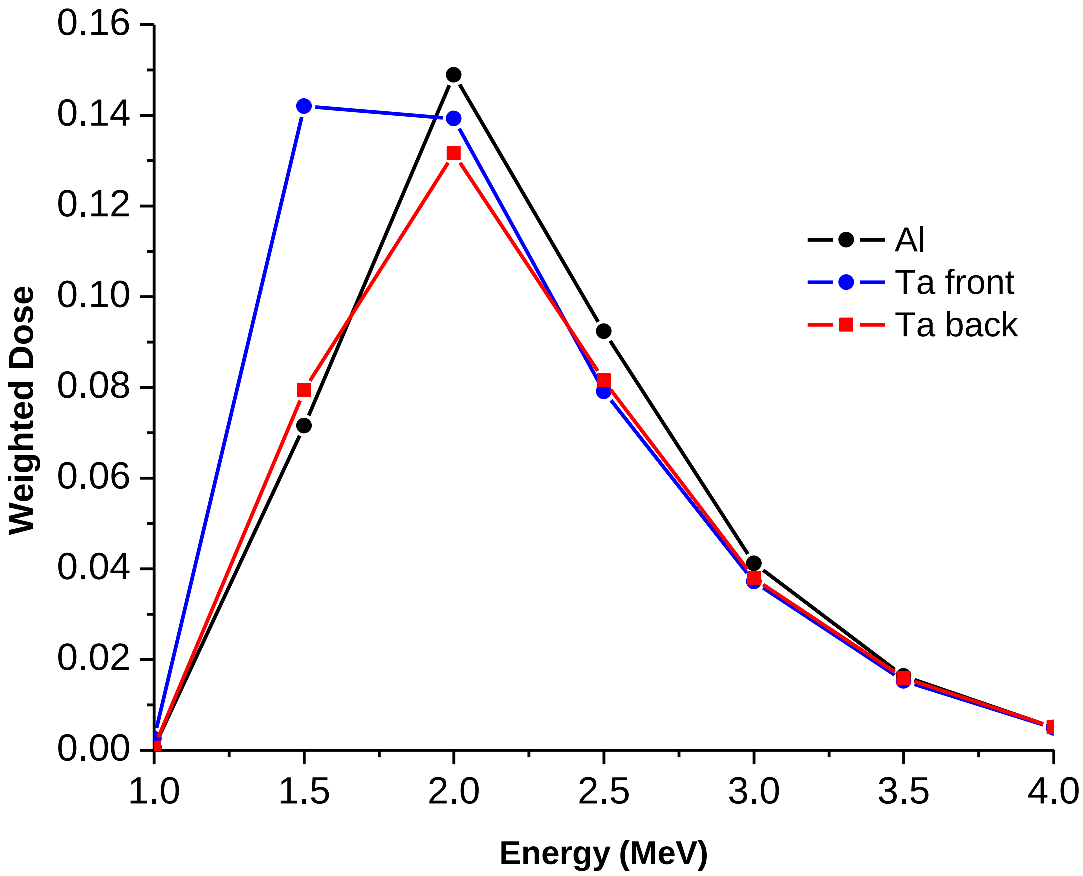
Which Energies Contribute Most?



- Obtained by multiplying calculated dose at each energy by GPS spectral weighting factor.
- Illustrates how much the dose at each energy contributes to overall dose in space.
- Ideally, ground tests should cover the 1 to 4 MeV range.

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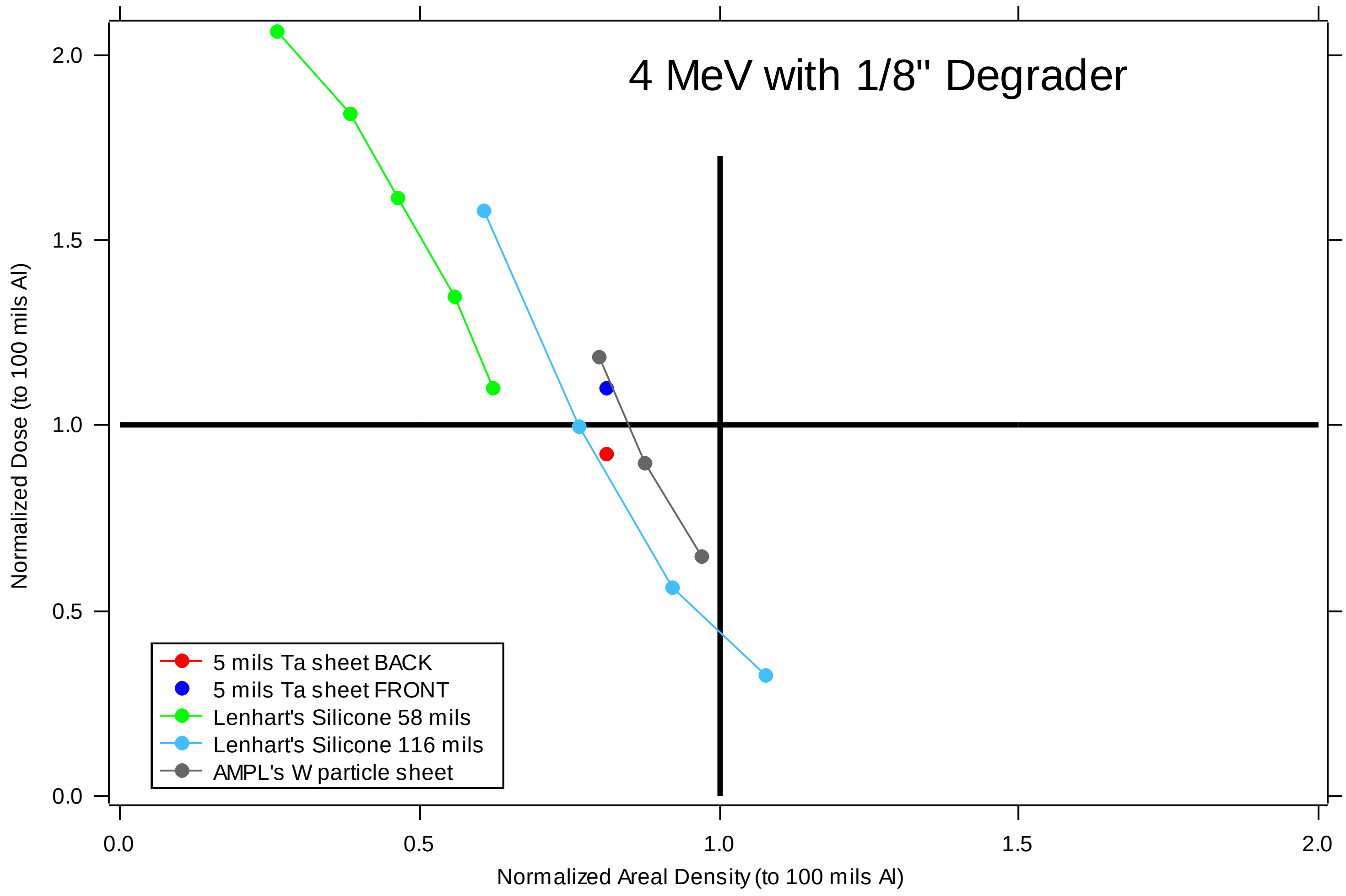
Linac Tuned to 4 MeV



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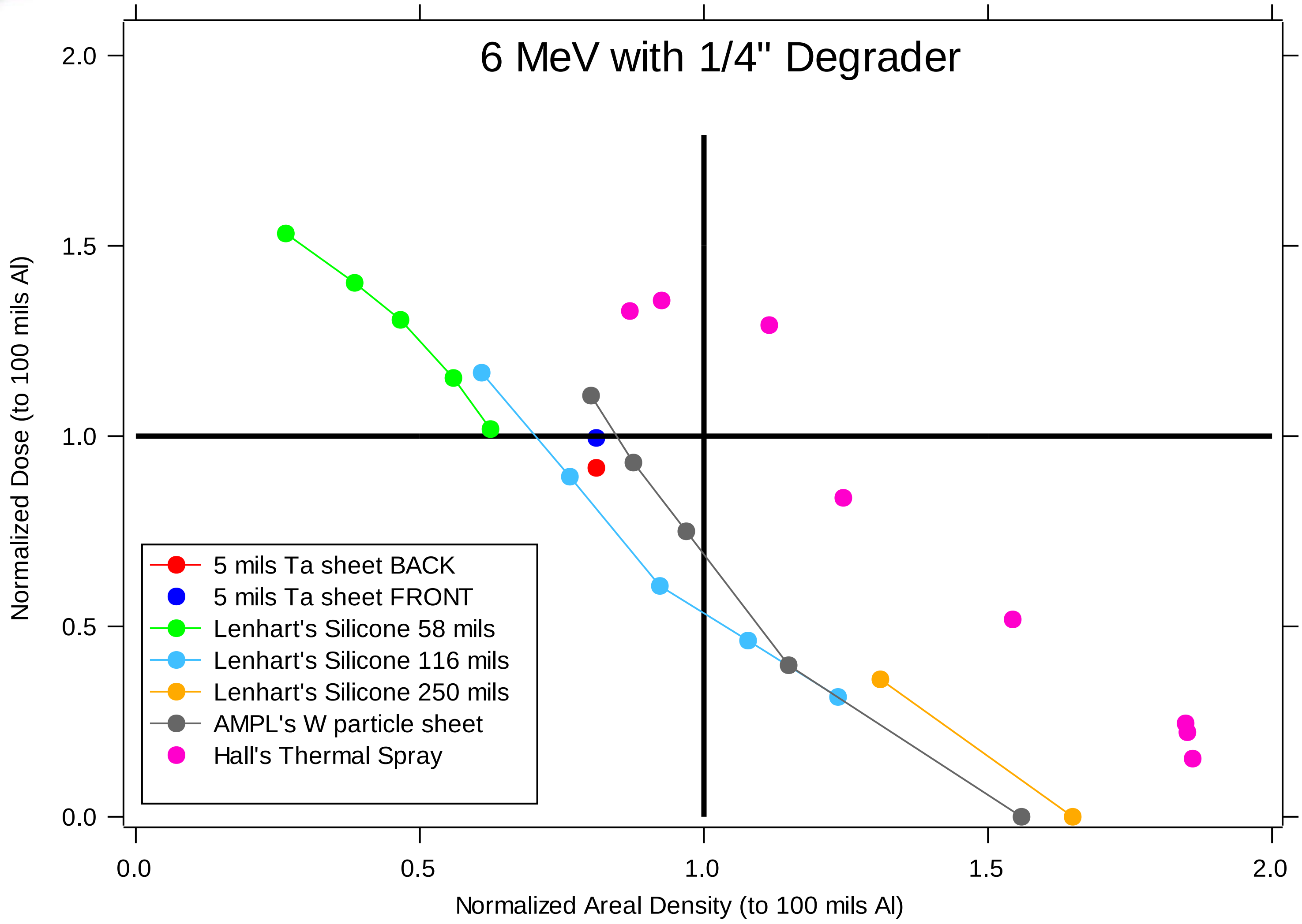
Linac Tuned to 6 MeV



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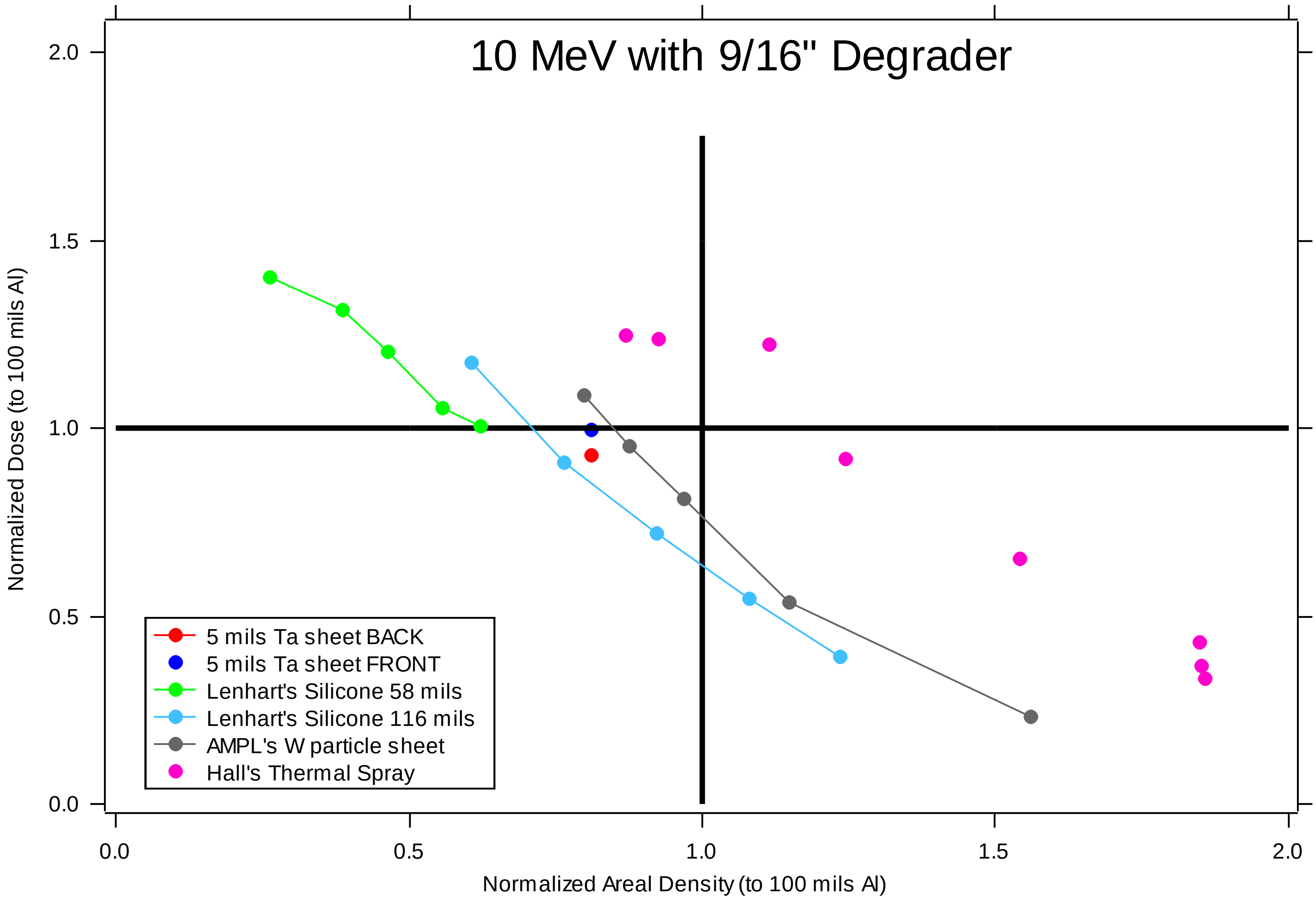
Linac Tuned to 10 MeV



Conclusions

• Particle type and energy are important for testing shielding properties.

• For shielding electrons in space, using composite with Ta works well.

• Use as much high-Z material as possible, and put towards the inside.

• NPL linear accelerator allows precise comparisons of shielding property relative to a reference sample.

Further Considerations

• Facilities like Kent State's NEO beam facility allow for simpler (less precise) qualification – used for our flight box lid.

• None of these results can be generalized to LEO orbits.

• Manufacturing/structural and EMI concerns will likely prove to be more difficult to deal with than the radiation issues – all solvable.