Proton Testing: Opportunities, Pitfalls and Puzzles

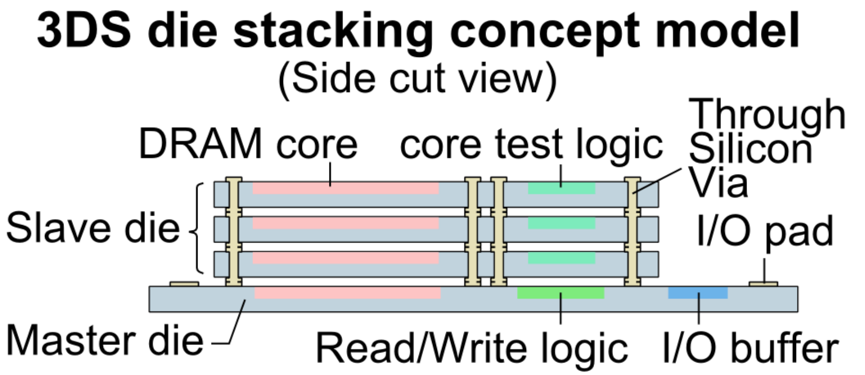
Ray Ladbury, NASA Goddard Space Flight Center

To be presented by Raymond L. Ladbury at the Single Event Effects (SEE) Symposium - Military and Aerospace Programmable Logic Devices (MAPLD) Workshop, La Jolla, CA, May 22-25, 2017.

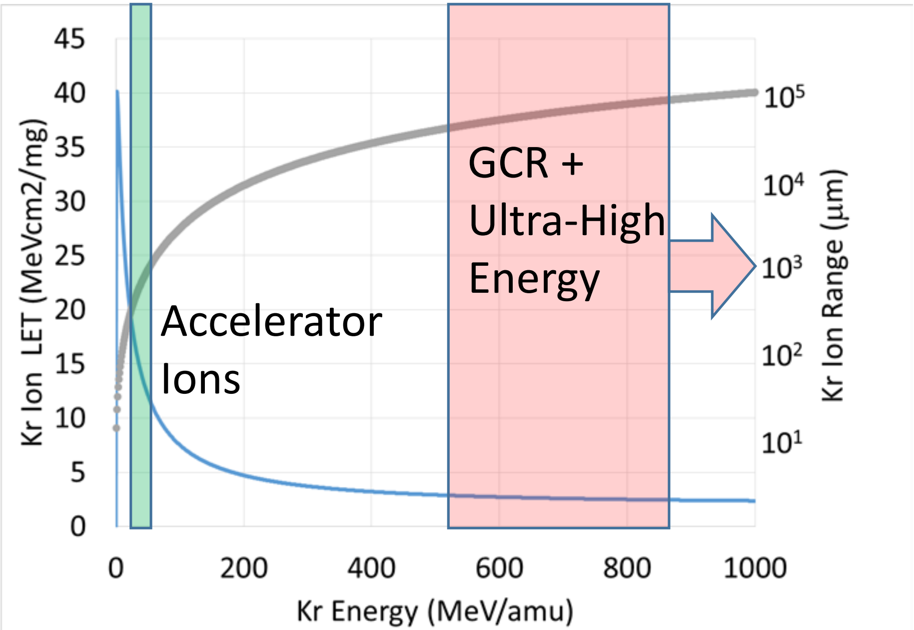
Key to Abbreviations and Symbols

$\forall$	Logical symbol meaning "For all"	LET	Linear energy transfer
δ	Delta	p	Proton
ρ	Density	Q	Charge
σ	Cross section	SDRAM	Synchronous DRAM
3DS	Three-dimensional stacked	SEB	Single-event burnout
C	Capacitance	SEE	Single-event effect
DRAM	Dynamic random-access memory	SEGR	Single-event gate rupture
DSEE	Destructive single-event effect	SEL	Single-event latchup
E	Energy	SV	Sensitive volume
GCR	Galactic cosmic ray	VDS	Drain-source voltage
GPU	Graphics processing unit	WC	Worst case
IC	Integrated circuit	xstr	Transistor
I/O	Input/output	Z	Ion atomic number

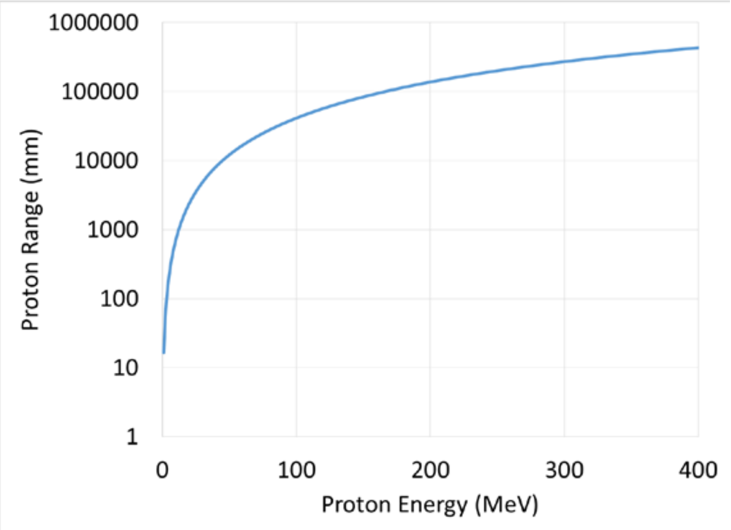
Can Protons Bound Heavy-Ion SEE Risk and Why Would We Want Them To?



- State-of-the-art ICs and packages often highly integrated
- Significant overburden blocks ions from device SV
- Extensive and risky modification often needed to ensure charge generated in SV



- Accelerator ion ranges 10s-100s of µm of Al
- GCR ions penetrate 10s of cm Al
- High-energy protons attractive
  - Penetrate >10 cm of overburden
  - Generate light ions in SV
  - Fluxes persist over most of proton range-so box-level testing feasible

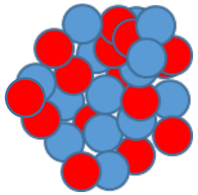


To be presented by Raymond L. Ladbury at the Single Event Effects (SEE) Symposium - Military and Aerospace Programmable Logic Devices (MAPLD) Workshop, La Jolla, CA, May 22-25, 2017.

Outline

- Generation of Recoil and Cascade Ions by Protons
- Recoil, Accelerator and GCR Heavy-Ion Environments
  - Ion Energies and Destructive SEE
  - Test Coverage
  - When are These Differences Important?
- Timely Issues
  - What About Proton-Induced Fission
  - Does Scaling Help or Hurt?
- Conclusions: Challenges, Caveats and Recommendations

Recoil Ion Characteristics for 200-MeV Protons



Ion Species

- <<1% have Z < 6
- <18% have 5 < Z < 10
- ~78% have 10 ≤ Z ≤13
  - ~63% Na, Mg and Al
- 4.5% Si, <0.05% P
- Most common ion is Mg (~30%)
- Only one proton out of 289100 produces a recoil ion
- Evaporation
  - Including He ~doubles total ion count (LET up to 1.5 MeVcm^2/mg and range~10 μm)

Energies and Ranges

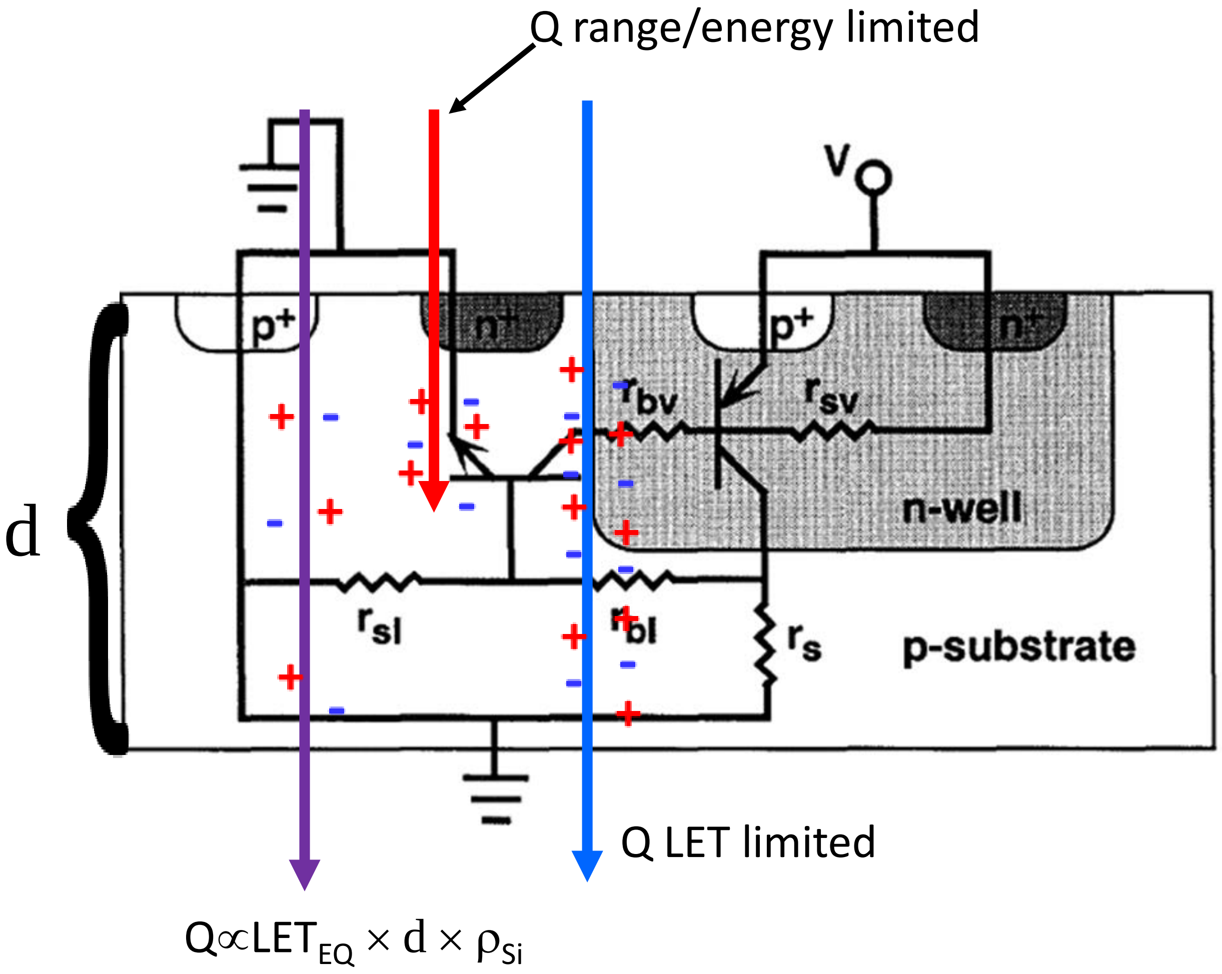
- Z<6—energies largely above Bragg Peak, but fluxes negligible
- 5 < Z < 10—>80% have energy >Bragg Peak
  - Flux down 10x for E>11 MeV
- 10 ≤ Z ≤13—<1% have energy >Bragg Peak
  - Flux down >10x for E > 6 MeV
  - Ranges < 4 μm for >90% in this range
- Si and P fluxes negligible for practical purposes

Other Characteristics

- Angular distribution fairly flat out to 90° to incoming proton
- Standard wisdom: p generate LETs up to ~15 MeVcm^2/mg in Si, but
  - Almost no P ions generated
  - For Si, max LET is 14.5 MeVcm^2/mg, but <5% of recoil ions are Si, and they are all below Bragg Peak
  - For Ne-Al, energy below Bragg Peak
  - For hardness assurance purposes, risky to assume LET>10-12 MeVcm^2/mg even for shallow SV
- For ion that causes SEE, Z, energy, angle are all unknown

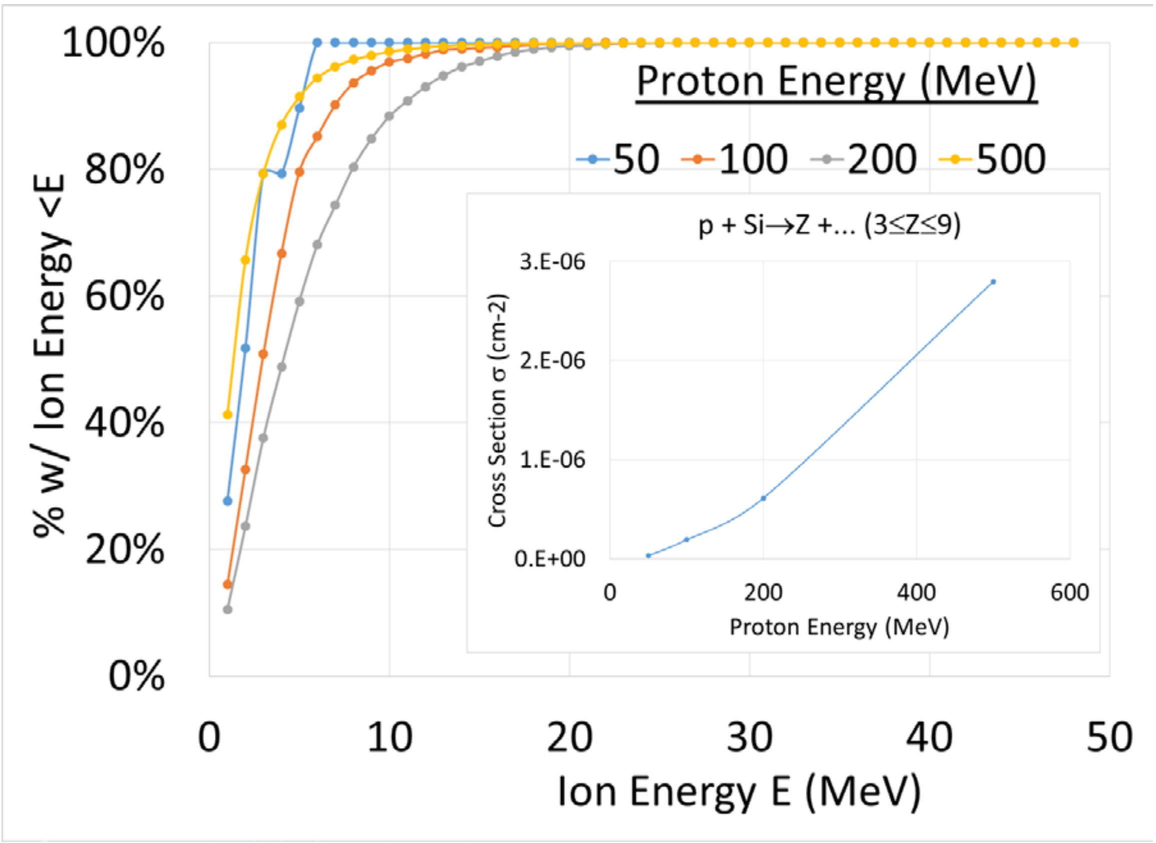
Proton Challenge I: Recoil Ranges and DSEE

- SEE susceptibility increases not with LET, but with charge, $\mathbf{Q = C \times \rho \times \int_0^{\ell} LET(x)dx}$
  - Q generated by proton recoil ions may be limited by their energy/range rather than LET, especially for SEE with deep SV
- For DSEE, SV depths often >> range of recoil ions
  - For SEL, charge collected well into substrate, ~10s of μm
  - For SEB, cross section diminished if ion range <~30 μm
  - For SEGR, charge collected down to bottom of epi layer, 10-100 μm depending on rated VDS
- Define $\mathrm{LET_{EQ}}$ in terms of energy deposited in SV $\mathrm{E_{Dep}}$, SV depth d and Si density ρ_{Si}.
  - $\mathbf{LET_{EQ} = E_{Dep} / (\rho_{Si} \times d)}$
  - $\mathrm{LET_{EQ}}$ facilitates translating proton results to mission performance
  - If SV depth unknown, assume representative WC for the SEE mode of interest



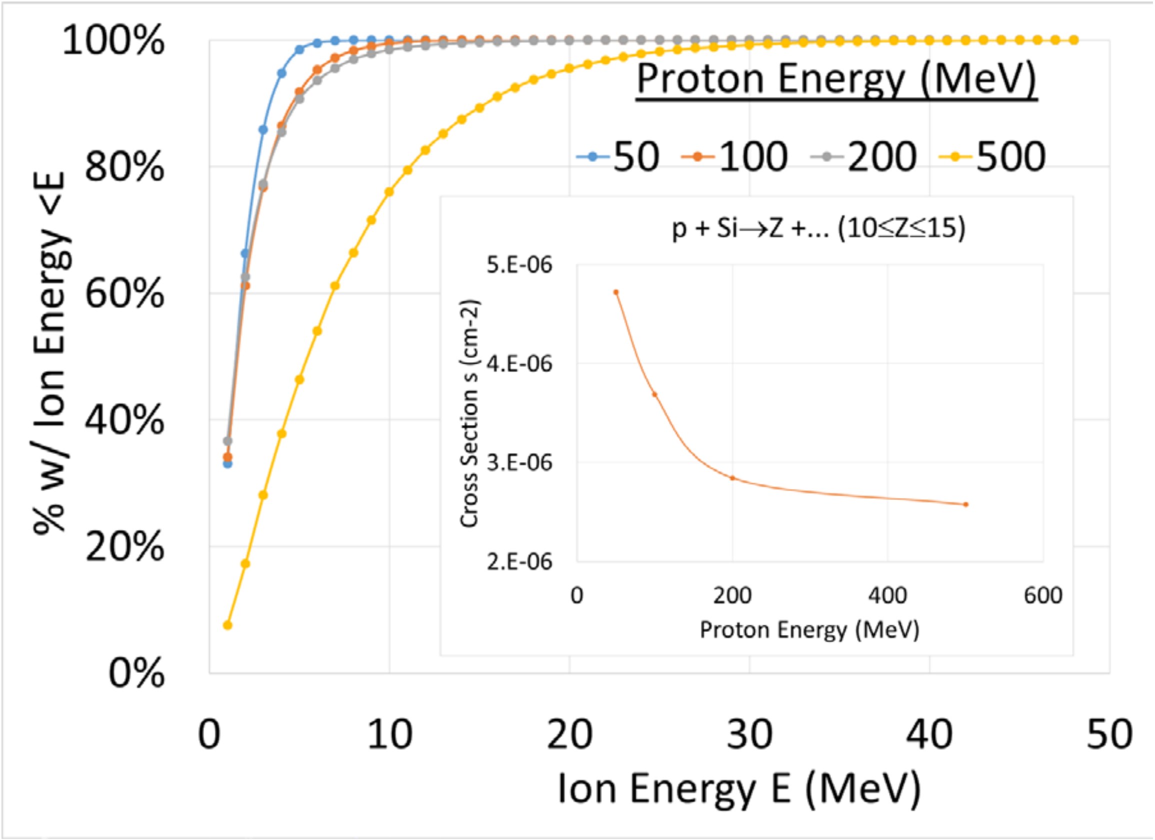
Role of Proton Energy

For Recoil Ions w/ $3 \leq Z \leq 9$



- For high proton energies (>200 MeV), increase in inelastic σ results in large increase in ions w/ Z<10, but with lower average energy

For Recoil Ions w/ $10 \leq Z \leq 15$



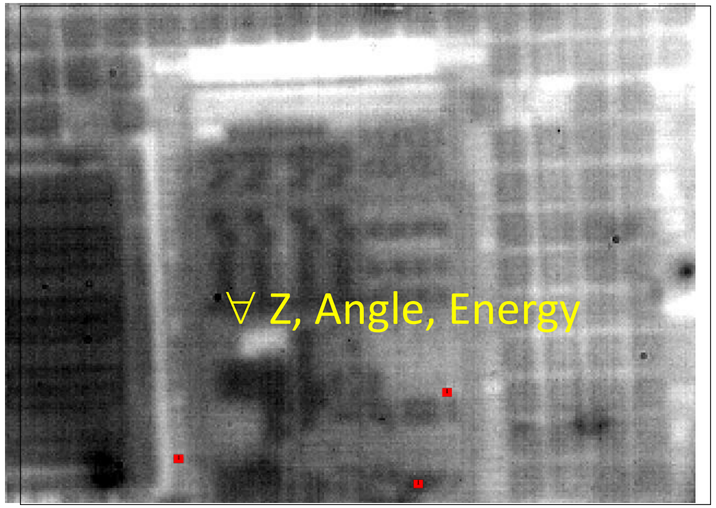
- For high proton energies (>200 MeV), σ for $Z \geq 10$ drops slightly but ion energy increases; however, detection probability improved only if SV depth <~10 μm.

Relative Coverage of Proton and Heavy-Ion SEE Tests

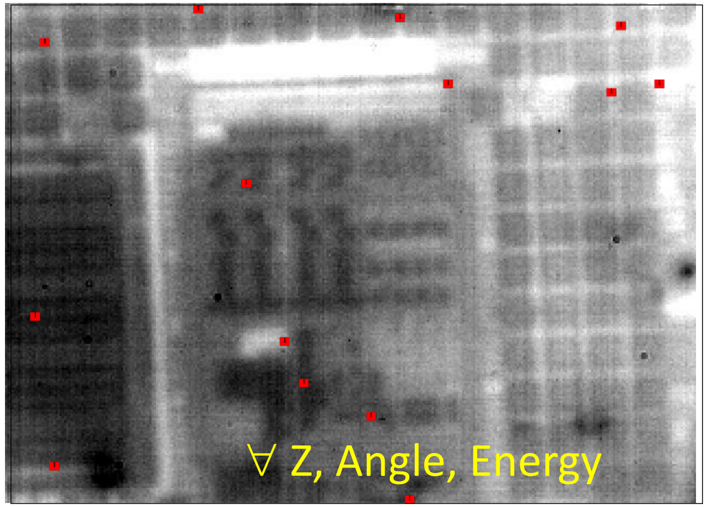
Infrared micrograph of a portion of a 512 Mb SDRAM ~60×70 μm^2

- Shows both memory cells and control logic (~2005); Red spots simulated random recoil ion hits w/ 1μm^2 area

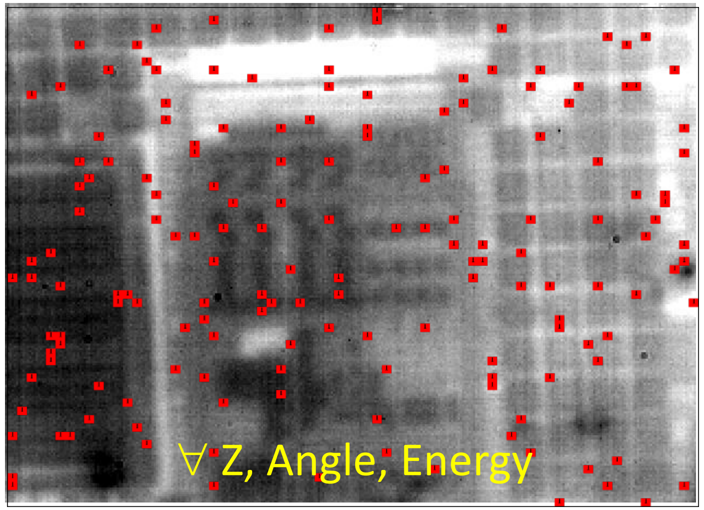
1E10 200 MeV protons/cm^2



1E11 200 MeV protons/cm^2

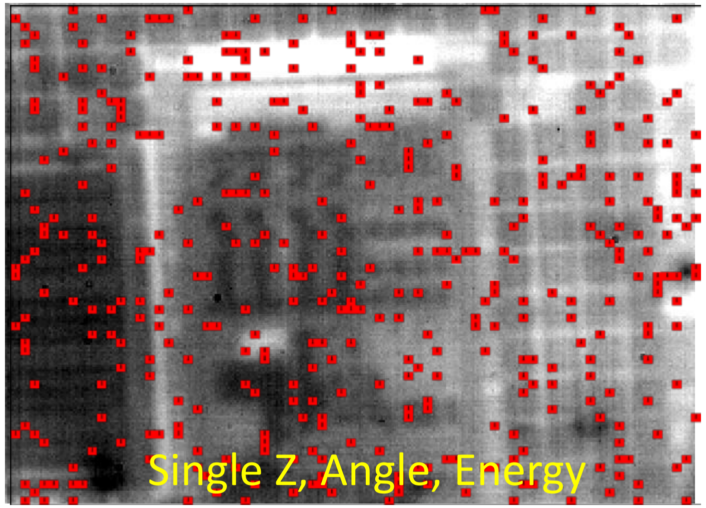


1E12 200 MeV protons/cm^2



20% of areas this size get 0 hits for 10^{10} cm^{-2}

- Coverage: You can't discover an SEE mode unless you hit the feature responsible for it
- Simplest measures: ions/cm2; transistors/ion…
- 200-MeV protons, ~1/289100 protons generates recoil ion, but every one adds to dose
  - 10^{12} protons/cm^2: 3.46E6 recoil ions/cm^2, 58.6 krad(Si)
  - 10^7 15 MeV/u Ar ions: 1.2 krad(Si)

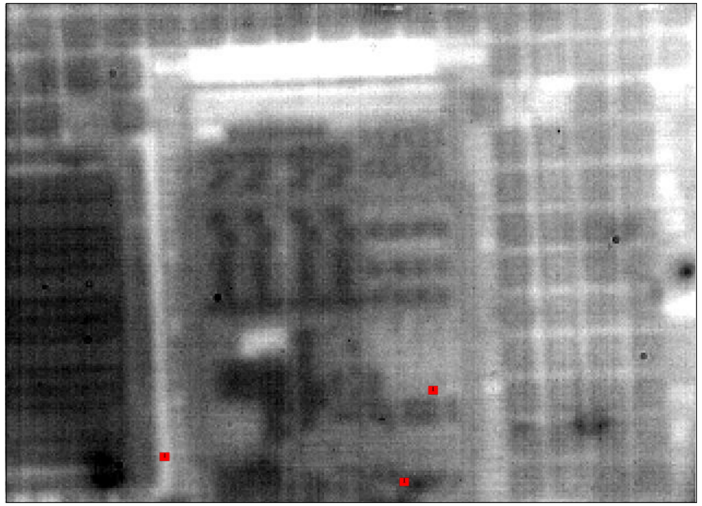


Coverage from 1E7 ions/cm^2

Coverage II: Scaling Increases the Stakes

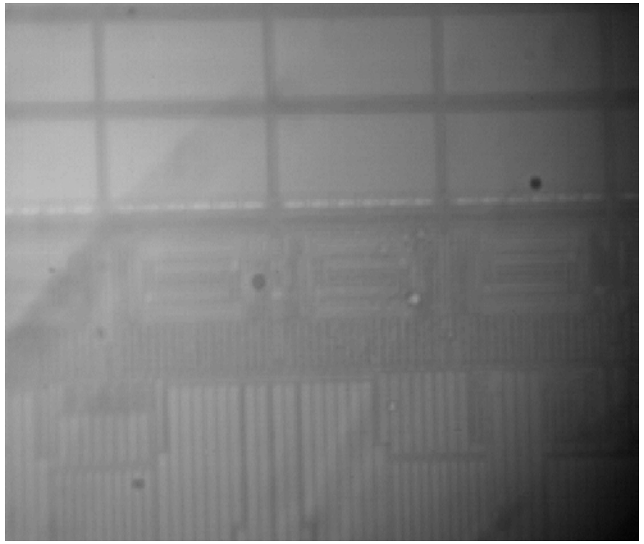
Does this fairly represent proton-recoil coverage?

Elpida 512 Mbit SDRAM (EDS5108) w/ 130 nm CMOS has ~0.31 xstr per μm^2 (2005)



- What about repeated similar structures?
  - They help, but you'd need >289 repetitions to come close to heavy-ion coverage
- Are the red squares fair ion track representations?
  - Ion track size difficult to define, but probably <<1 μm^2
  - But transistor size~3.2 μm^2, so probably OK for this case

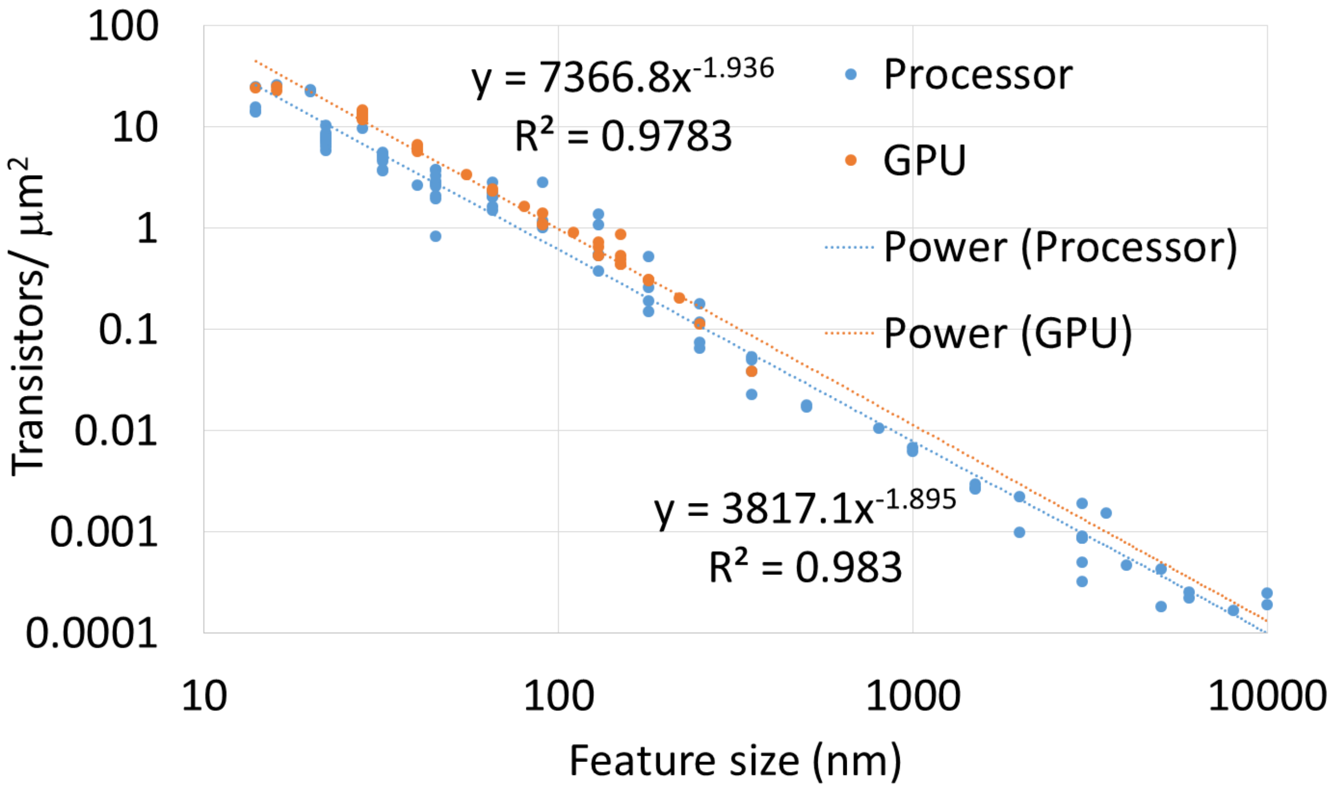
Does CMOS scaling affect this conclusion?



Samsung K4B2G0846 DDR3 SDRAM w/ 35 nm CMOS has ~4.6 xstr per μm^2 (2012). Only gross feature sizes visible @~1 μm resolution

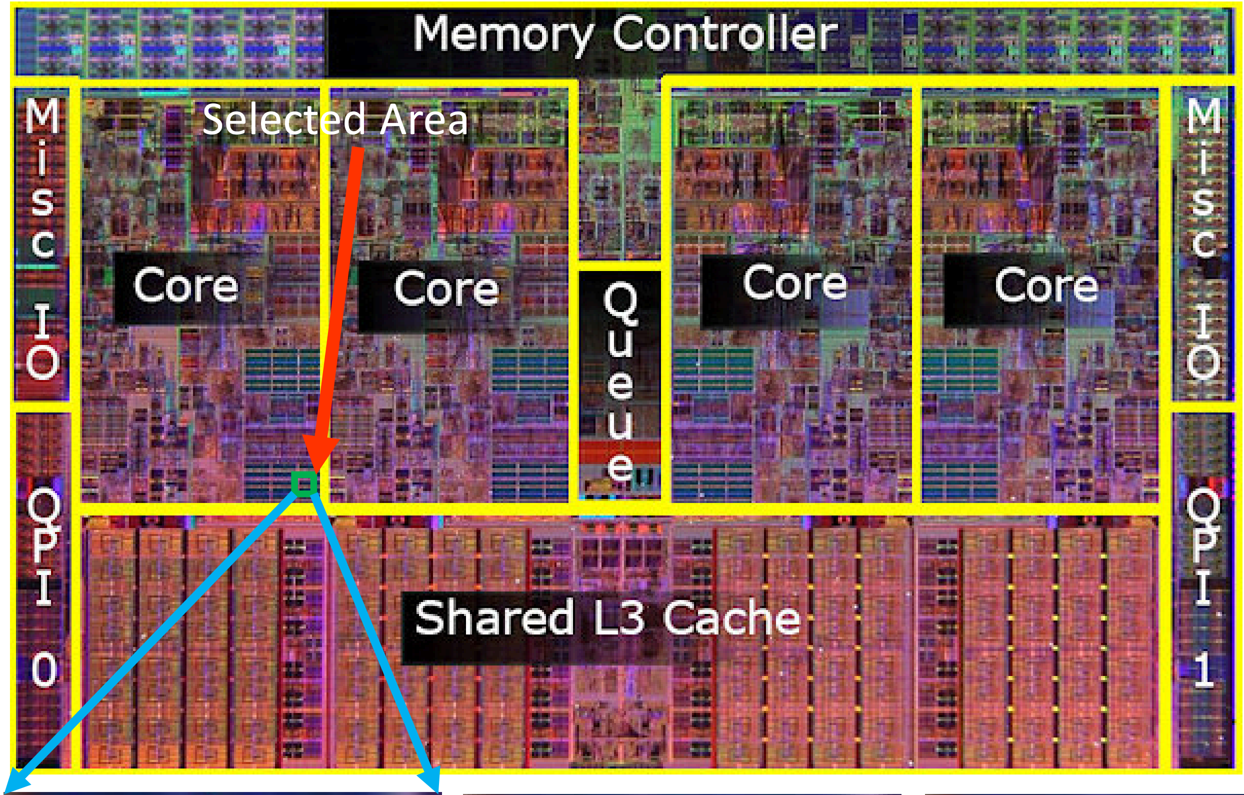
- Below ~65 nm feature size, >1 transistor per μm^2
- Track structure important, but what defines a track?
- Depends on radial charge distribution (depends on Z, E)
- Also depends on device sensitivity—how much charge needed to cause SEE.

Feature Size and Complexity: Just Geometry?

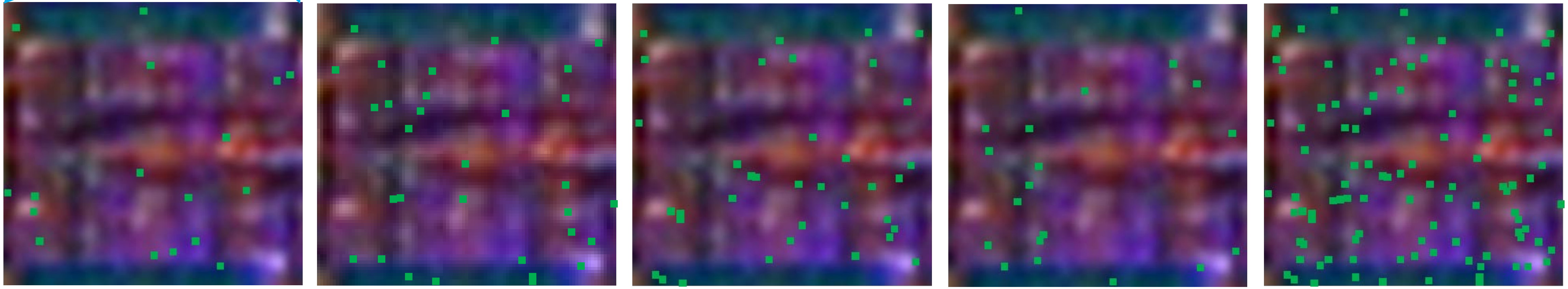


- Naïve expectation gives transistor density increasing ~(Feature Size)$^{-2}$.
  - Roughly true for microprocessors and GPU since 1971 (10 μm feature size)
  - Similar trends hold for DRAMs and Flash
- Area on chip equates to xstr count
  - 2891 μm^2 per ion corresponds to
  - 130 nm: ~900 transistors
  - 65 nm: 3300 xstr— ~Intel 8008
  - 45 nm: 7800 xstr-- ~1.2× Intel 8085
  - 22 nm: 23000 xstr— ~0.8 Intel 8088
- Imagine testing any of these w/ single ion
  - Average value—37% of such areas get no ion hits at all
- Complexities of areas left untested scale inversely w/ proton/ion flux

Combining Data for Similar Features: Intel I7 Quad Core (45 nm-2008)

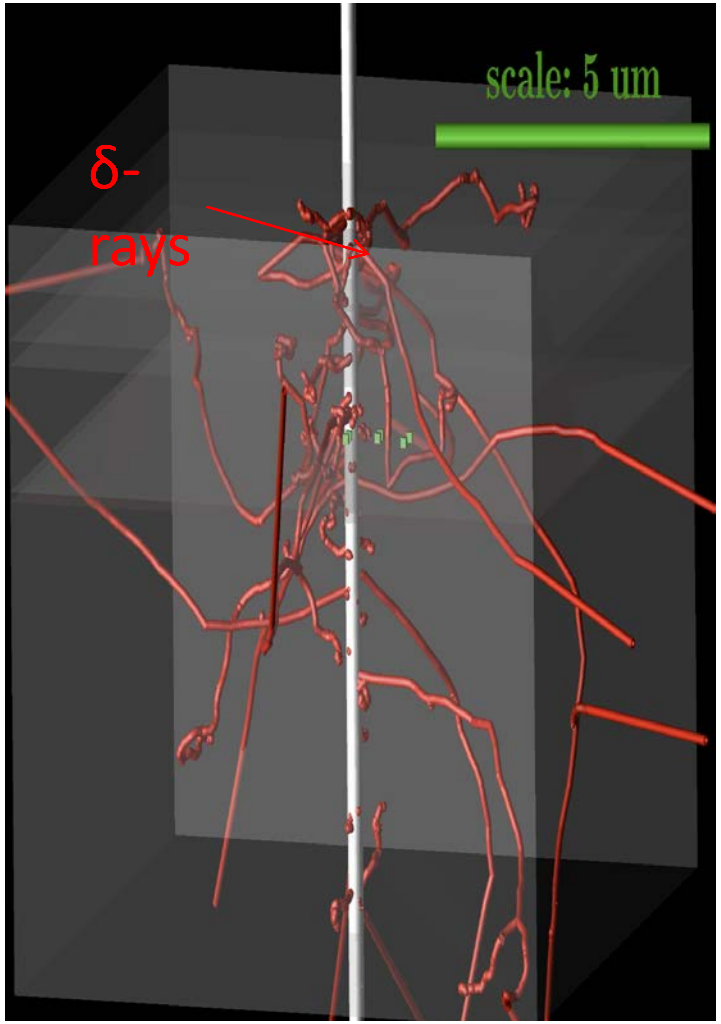


- Green square in left-most core represents 315 µm square (~275000 transistors) or one Intel 80386
- Expand region ~23x to show individual ion hits (green dots) from 10^{10} 200-MeV protons/cm^2
- Each green dot ~6 µm on a side—and ion hit is somewhere in there.
- Left 4 squares on bottom could be repeated trials or same area in 4 different quads
- Right-most square combines hits for all 4 quads

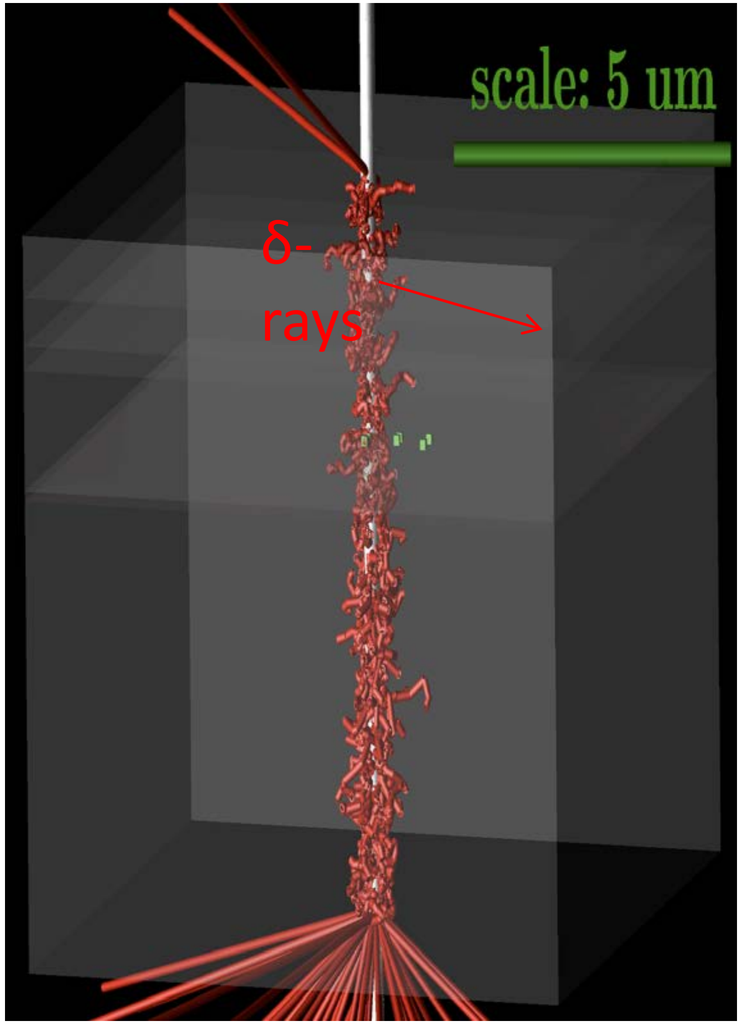


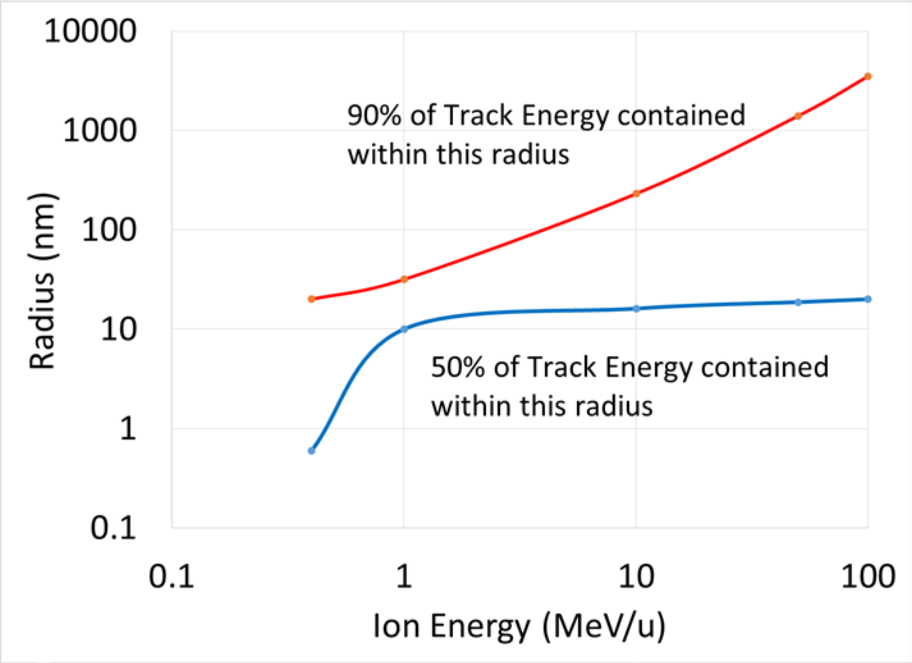
Ion Track Structure: It's All About The Deltas

28 GeV Fe ion (500 MeV/u)



280 MeV Fe ion (5 MeV/u)





Track radius depends on how much we care if some energy escapes. High-energy ions generate energetic, long-range δ electrons. See Murat et al., TNS 2008, p. 3046.

Used by permission from Robert Reed

Does Scaling Help or Hurt Efforts to Constrain Heavy-Ion SEE w/ Protons?

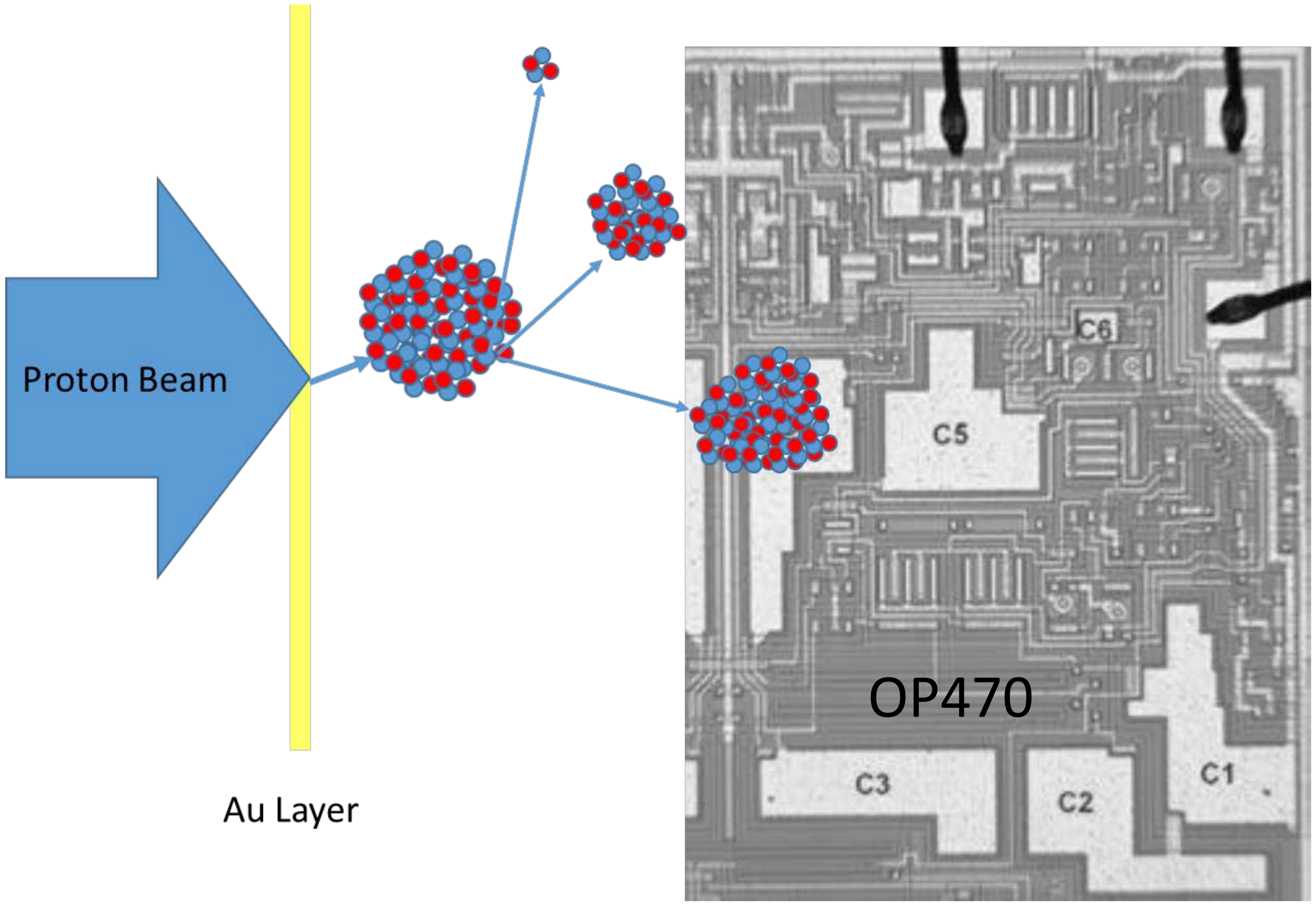
Well, it could help…

- Onset LET decreases w/ feature size
  - More ions to detect susceptibility
- σ vs. LET rises rapidly w/ increasing LET
  - Higher σ facilitates detection if present
- Supply voltages are decreasing, so maybe SEL susceptibility will decrease as well…?
  - Conflicting evidence—seems to be true for SDRAMs, but processors, FPGAs, SRAMs still prone to SEL
- TID tolerance of deep submicron CMOS increasing
  - May allow testing to higher proton fluence without risk of device failure or alteration of SEE performance via TID/SEE synergistic effects

On the Other Hand…

- Proportion of protons generating recoil ions constant—still 1 per 289100 200-MeV protons
  - Device complexity (# transistors/μm^2) continues to increase
  - State space continues to get more complex as devices add functionality.
- Lower critical charge coupled with multiple transistors per μm^2 means track structure effects more important
  - GCR, SPE and accelerator ion tracks 50-1000x broader than proton recoil tracks
  - Hardening of commercial chips against neutrons (e.g. using DICE Latch) may not work in space
    - Proton testing might not reveal this.

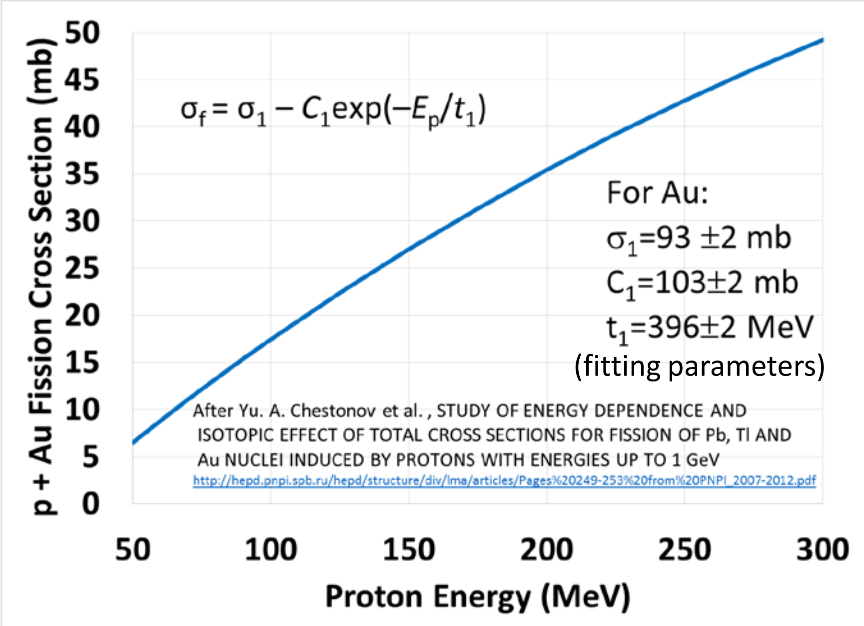
Proton-Induced Fission: Can We Use Its Powers For Good?

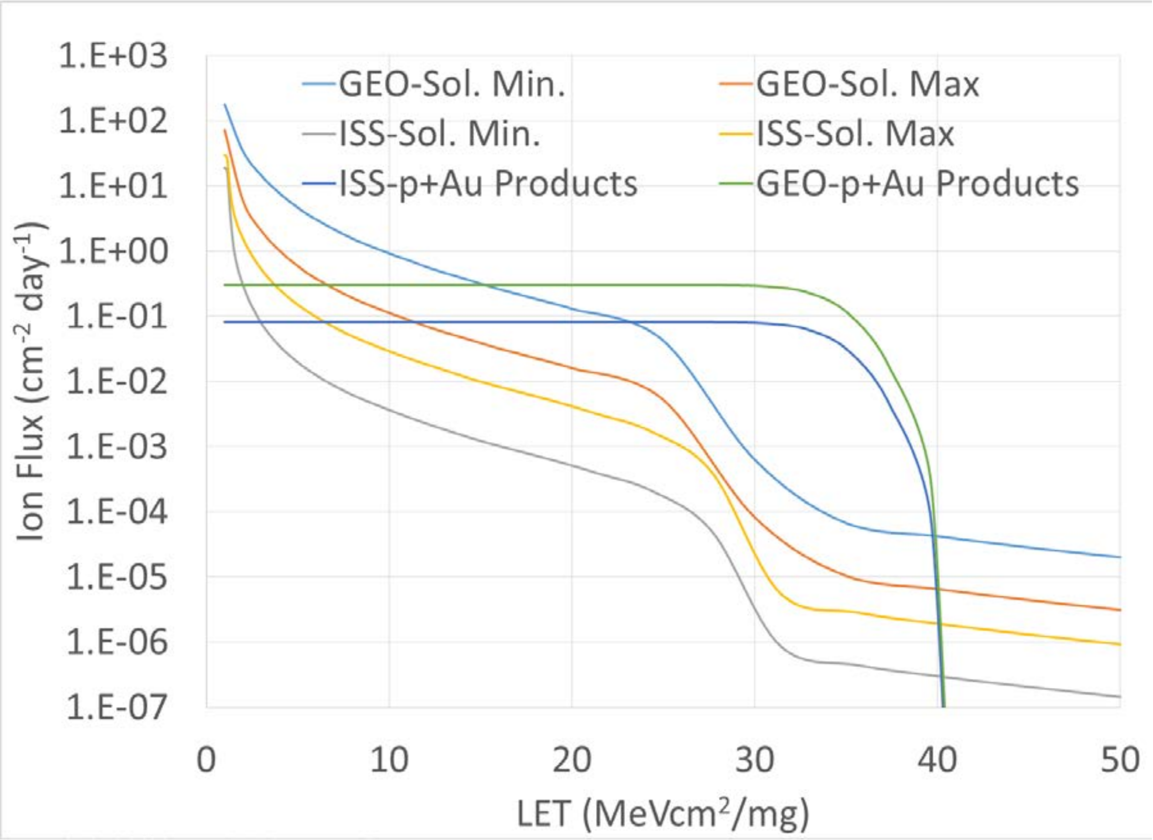


- Mechanism: Proton beam knocks Au nucleus out of Au layer
- Excited Au nucleus oscillates then fissions into two nuclei (30<Z<50)
- Fission fragment strikes capacitor, depositing enough charge to rupture capacitor oxide (<100 nm)
- Failure more likely if ion incident normally to device surface
- Almost all energy of fission ions comes from fission rather than from incident proton
- Ions have short range.

Well, There's Good News and Bad News

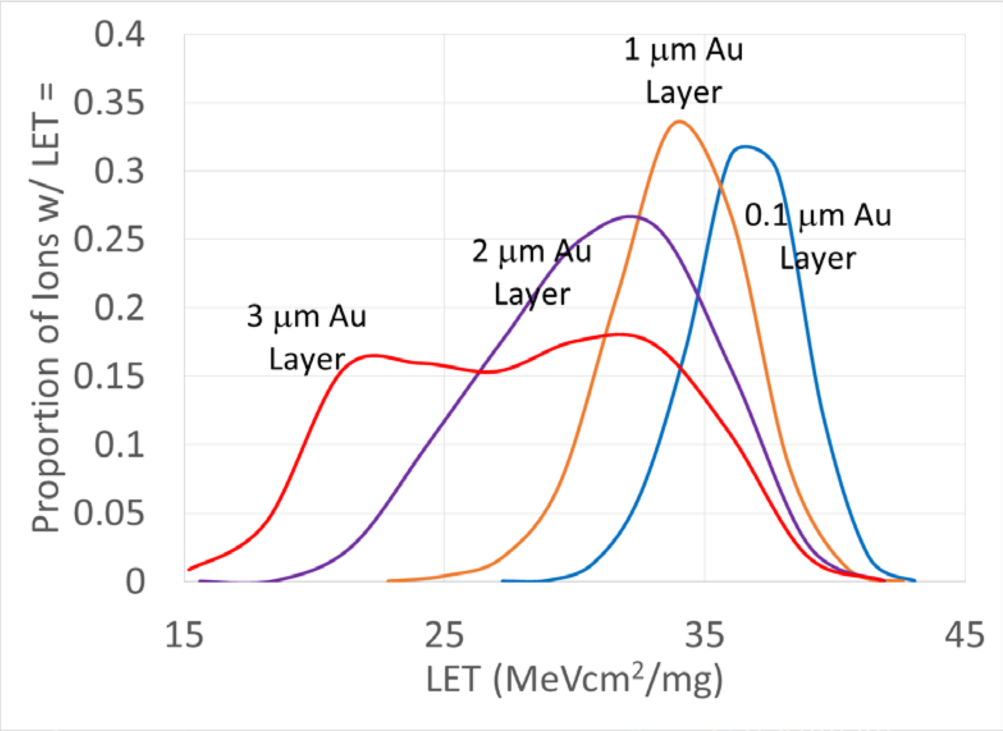
- Cross section per Au nucleon~35 mbarn, or 3.5E-26 cm^2 @ 200 MeV
- 1 cm^2 of 1-μm thick Au foil has ~5.9E18 Au nuclei
- Daughter products have 30<LET<40 $MeVcm^2/mg$
- 10^{10} 200-MeV $p/cm^2 \rightarrow$ 2100 Au fissions per μm Au
  - Even 3 μm Au$\rightarrow$6300 fissions. Even if >1 ion per fission, coverage likely >3x worse than for p + Si recoil ions

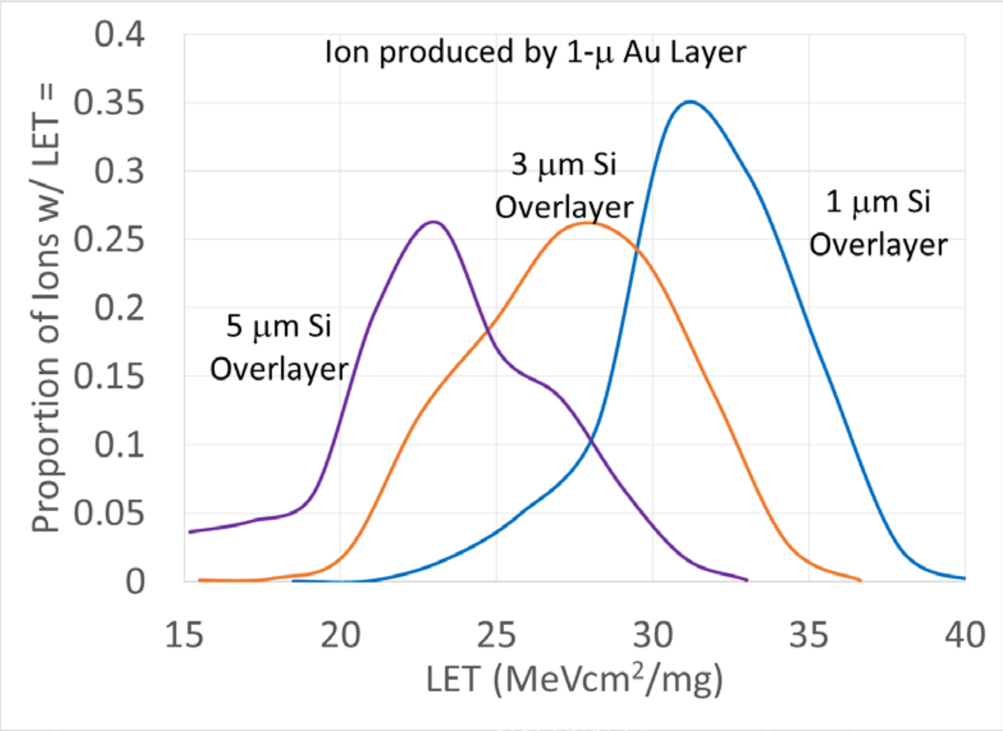




Although high LET, daughter products are short range (<17 μm), well below Bragg Peak, and produced outside of die.

Nuclei Must Traverse Overlayers to Reach SV





- Each additional μm of Au produces more ions but also degrades ions already produced.
- WC fission product range in Au is ~6.5 μm

- Overburden on top of SV degrades LET spectrum
- May include passivation, oxides, metal, etc.
- Range in Si <17 μm

The same factors that keep this threat from killing us on orbit limit its usefulness for SEE testing w/ Protons

Could p on Au Fission Testing Work? If so, how?

Challenges and Limitations

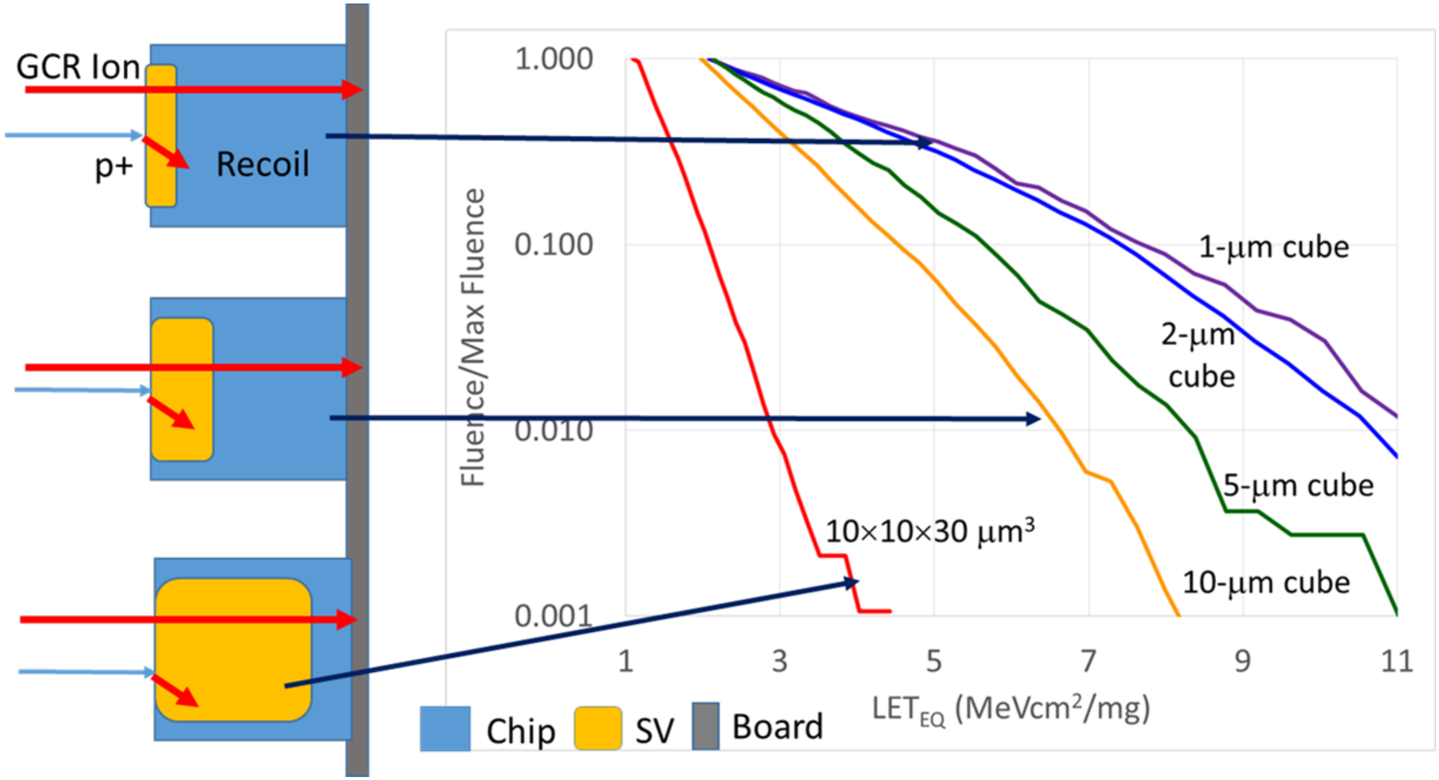
- Fission fragment flux limited
  - Even with 3 μm Au and 10^{12} 200-MeV p/cm^2, get <10^5 ions/cm^2, ~1 ion/1000 μm^2
  - Ions produced in 3 μm Au have ~flat distribution from 20-35 MeVcm^2/mg
- Fission products originate outside of Si
  - Must traverse Au layer and overlayer above SV
  - Degrades LET spectrum and may reduce flux if >~10 μm Si equivalent overburden
- Cannot know which ion causes a given SEE
  - Z, Energy, angle all uncertain
  - Yields limited understanding of SEE mechanisms
  - Estimating bounding rate very difficult

Making It Work…Sort Of

1. Measure thickness of overburden (passivation, metallization, etc.)
2. Perform Test in Vacuum if possible and/or place foil on top of die
3. Obtain Au or Pb foils 2-3 μm thick
4. Perform TID testing in advance to determine limiting proton fluence
   a) Higher-energy proton beam lowers dose/fission
5. Perform test to high fluence w/o foil, then with
6. If SEE mode seen with, but not without foil:
   a) 10 MeVcm^2/mg<LET_0<20-35 MeVcm^2/mg -or-
   b) You got lucky in the run with the foil
7. At least, you now know about the new SEE mode
8. Multiple runs increase confidence in results

Board-Level Testing Just Makes Things More Complicated

- Ability to test at board level one of the biggest draws for protons
- Board-level testing means giving up even more information
  - Test detects far fewer SEE modes
    - Some not detected due to accelerated nature of test
    - Some masked temporally or logically –may be different during different operation stages
- Part-to-part variability difficult to evaluate w/o testing many boards
  - Don't even think about differences in synergistic interactions
- It's not just protons—board-level testing w/ heavy ions poses similar issues (e.g. overburden affects ion LET)



- LET_{EQ} means same proton fluence will mean different things for different SEE modes—even in same device
- Proton test cannot be optimized to detect each SEE mode
  - Test is the same whether for SET or SEGR

Relative Advantages of Heavy-Ion and Proton Testing

Heavy-Ion Testing	
Advantages	**Limitations**
More likely to reveal Destructive SEE (DSEE) modes	Limited ion range may preclude testing some parts/require others be repackaged/modified
Lower TID per ion allows higher fluence/better coverage for test	Testing at board level difficult; at box level, impossible
Known ion Z, energy, LET and angle better elucidate SEE mode mechanism/physics of failure	Heavy-ion testing costly; high-energy facilities even more so
Greater fidelity to Space Ion Environment	Heavy-ion facilities overbooked, difficult to schedule beam time
Can select ion characteristics to tailor test to physics of failure of SEE mode of interest	

Proton Testing	
Advantages	**Limitations**
Long proton range ensures ions reach depth of SEE sensitive volume	Likely to underestimate DSEE risk if it reveals susceptibility at all.
Can test highly integrated, complex parts/boards/systems without modification	High TID* limits recoil ion fluence. At board/system level, weakest part limits test fluence
Can save money if testing done at system level	Test result interpretation can be complicated, especially for system-level tests
	Inability to control characteristics of recoil ions means less understanding of SEE mechanisms
	Cannot tailor test to specific SEE modes of concern

Important Advantage

Important Limitation

*TID=Total Ionizing Dose—cumulative energy lost by all ionizing particles that goes into generating charge in material

Conclusions

- Testing with proton recoils means giving up information
  - Inability to control recoil ion Z, E, angle limits understanding of SEE mechanisms and dependencies
  - Limited reliability for revealing destructive SEE modes and other modes with deep SV
  - Coverage limited by TID susceptibility of part(s). Adequate coverage depends on:
    - Density and complexity of parts and degree of repetition in circuitry within part (e.g. multiple cores, lots of memory, etc.)
    - Whether variability of SEE response across the part is of interest
    - Onset LET for SEE and rapidity with which σ vs. LET rises (affects # of particles that can cause an effect)
- May be useful to look at complexity of device as # transistors/ion or rough equivalent IC

Proton Fluence (200 MeV)	Ion Fluence	Ion Density (μm^2/ion)	90 nm CMOS (xstr per ion)	45 nm CMOS (xstr per ion)	22 nm CMOS (xstr per ion)
10^{10} cm^{-2}	34590 cm^{-2}	2891	2009 (~Intel 4004)	8035 (>Intel 8086)	32142 (>Intel 8088)
10^{11} cm^{-2}	345900 cm^{-2}	289.1	201	804	8035
10^{12} cm^{-2}	345900 cm^{-2}	28.91	29	80	320
2.89×10^{12} cm^{-2}	1×10^{7} cm^{-2}	10	7	28	112

Conclusions II

- Effect of scaling is complicated, with conflicting trends
  - Positive: Scaling *generally* improves TID hardness, allowing testing to higher fluence
  - Positive: Lower voltages suggest lower SEL susceptibility, lowering importance of ion range
  - Positive: Generally lower onset LET and more rapid rise of σ vs. LET$\rightarrow$more fluence to detect SEE modes
  - Negative: Concept of LET breaks down; energy deposition for <45 nm qualitatively different between high-energy and low-energy ions
    - Protons may not detect susceptibilities to MBU and DSEE, underestimate susceptibility of hardened technology
  - Negative: Increased density means coverage worsens ~inverse square of feature size
- Same factors limiting proton-induced fission impact on orbit limits its hardness assurance impact
  - Fission products short range (<17 μm in Si, <6.5 μm in Au) and on low-energy side of Bragg Peak
  - Fission occurs outside of die, necessitating transport across Au layer and device overburden
  - Coverage for fission products even poorer than for recoil ions
  - **BUT**, may reveal some susceptibilities missed by conventional proton testing
- Board-level testing
- Protons not a panacea for hard/expensive-to-test parts. Sometimes, it's the best last resort we have