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Development of a Proton Only Board-Level Testing Guideline

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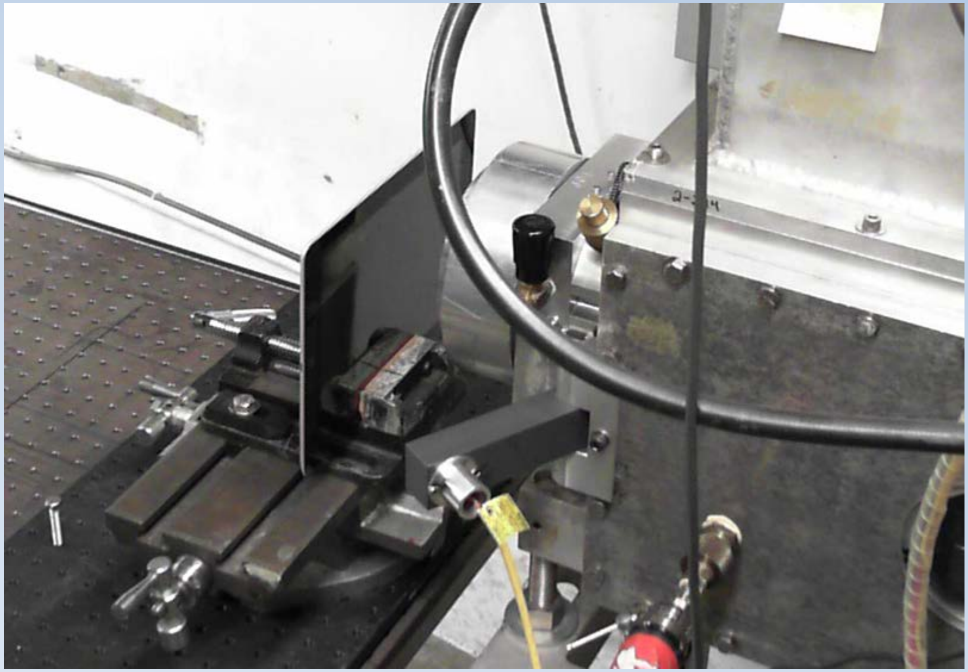
Outline

- Background and Motivation
- The Good, the Bad, and the Ugly
- Testing – Guideline Info
- Analysis & Theory
- Future & Recommendations
- Conclusions

What Guideline?

- People are testing boards, boxes, and other assemblies with only protons
- This is of … limited value
- And there are significant ways that tests can be of even less value
- NEPP is developing a proton board-level testing guideline to explore this problem



iPad irradiation at UC Davis

- See also the NEPP low-energy proton test guideline: http://radhome.gsfc.nasa.gov/radhome/papers/MRQW2012_Pellish.pdf

Motivation: Why?

- Single Event Effects are expensive to test
  - Should test with heavy ions
  - Devices must be exposed

- Proton-only testing is being used by…
  - Higher risk NASA missions
  - Aggressive commercial

CubeSats deployed from ISS

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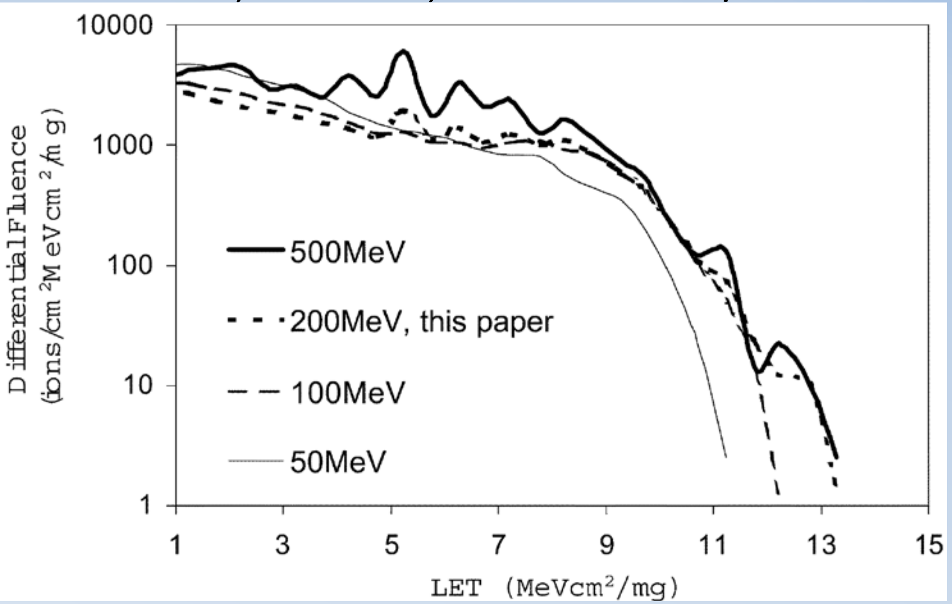
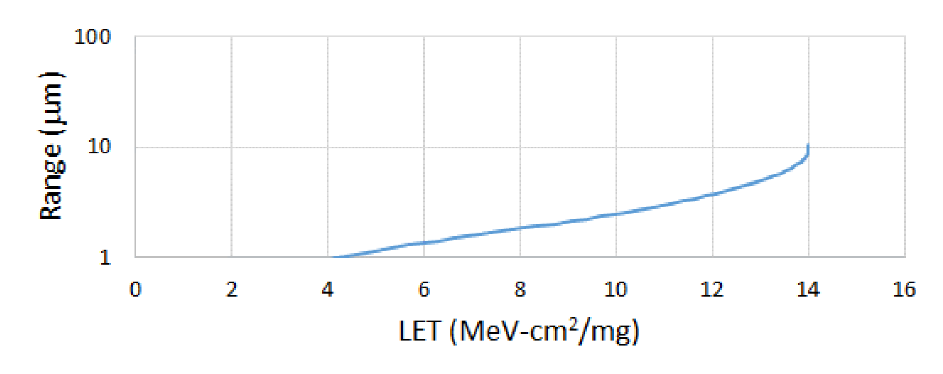
Can Protons Work?

- Protons do (sort-of) simulate the environment
  - Nuclear reactions
  - ISS environment simulated up to a rough cutoff
  - Results can be applied to other environments
    - Understand sensitive volumes (SVs)
    - Environment heavy ions
- But reaction particles are inherently short-ranged

Heimstra, IEEE TNS, 2003 – $1\times10^{10}/cm^2$



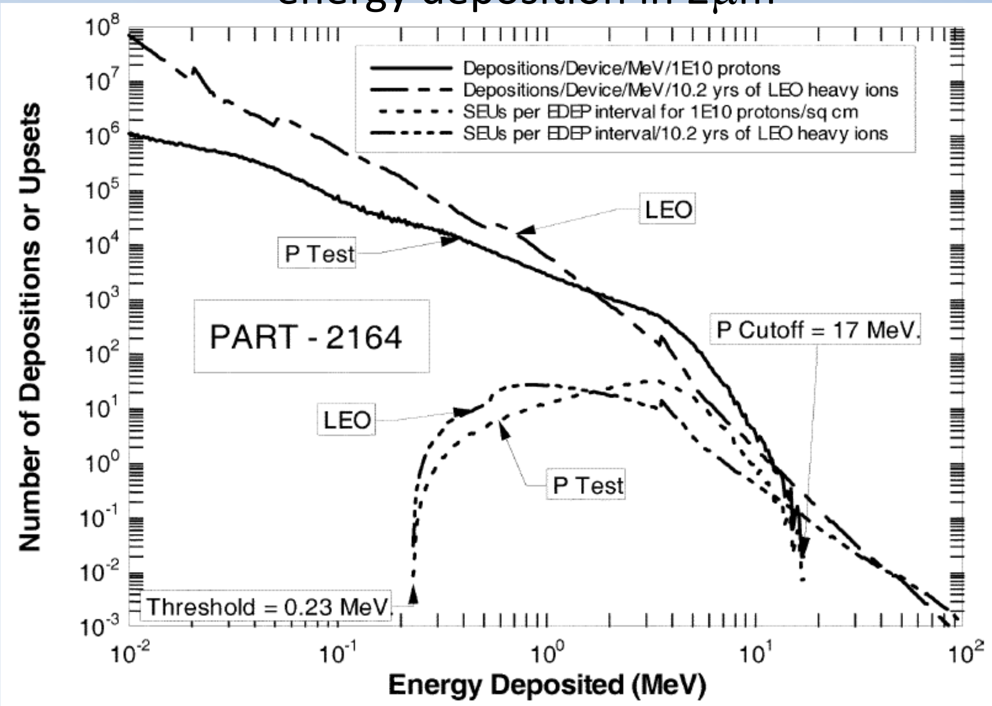
200 MeV p+ Silicon Recoils in Silicon



Protons Have Limitations

- In a 2μm sensitive depth…
  - $1\times10^{10}/cm^2$ 200 MeV Protons
  - More protons can be used
- Proton recoils give energy depositions similar to heavy ions
  - But leave high LET gap
  - More protons weakly affect the gap region
- But not all SEE modes are this shallow
  - More later

Foster, IEEE TNS, 2008 –
energy deposition in 2μm



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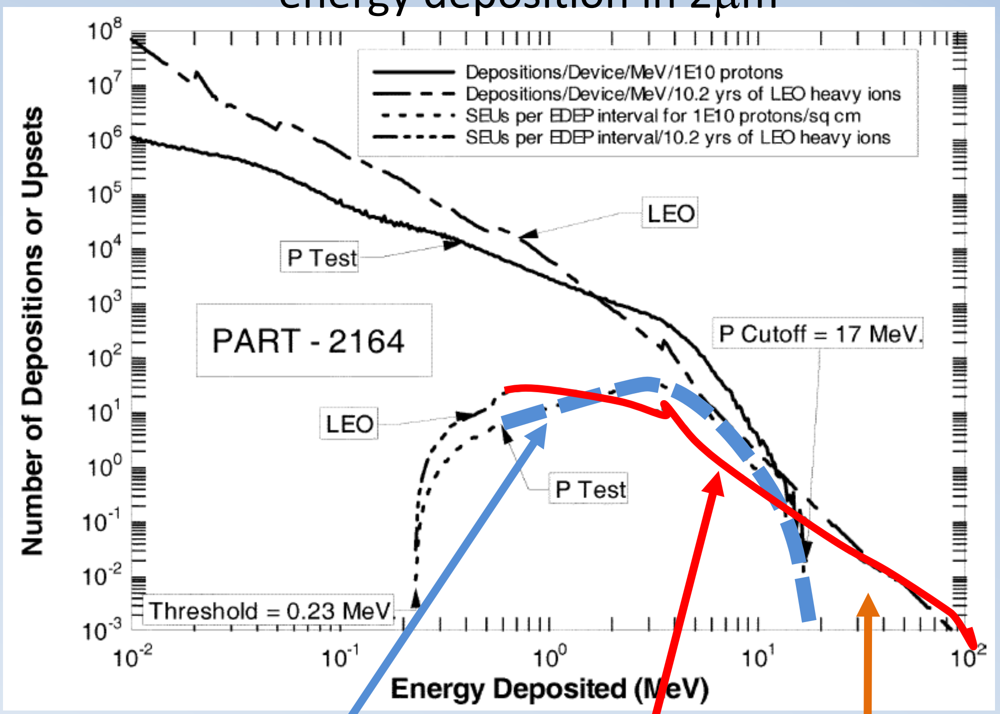


Events during proton testing

Events during 10 year ISS mission

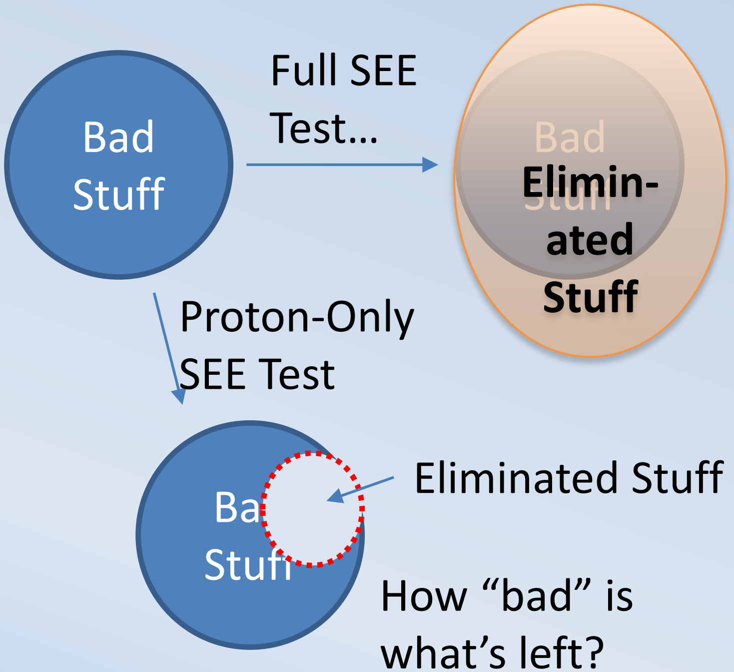
Gap

Similar to LET 14

Motivation: Problems

- The space environment is not just protons
- Heavy ions have much higher LETs than proton recoils… and higher deposited energy in sensitive volumes (SVs)
- Heavy ion tests allow exploration of angular sensitivity

- The bottom line is that you're going to miss a bunch of stuff…
- But you are establishing some increased robustness – it just might not be enough



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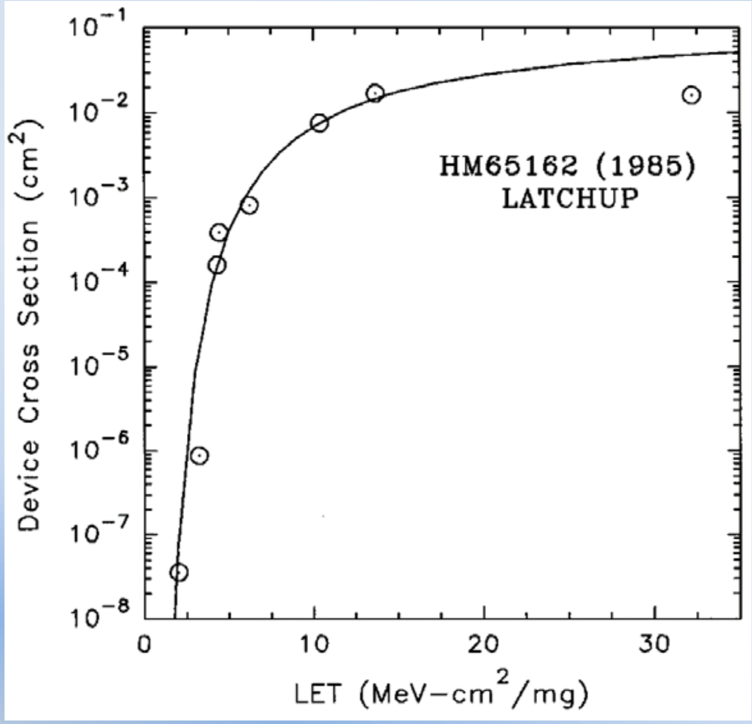
Motivation: Example

- How bad can the “gap” be – what’s missed by a $1\times10^{10}/cm^2$ proton test
- One example bad part is the HM65162 (1985) SRAM



- Has SEL at very low LET
  - Energy cutoff discussed above suggests SEL should be seen
  - Actually has ~40% of no SEL in $1x10^{10}/cm^2$ protons
- ISS SEL rate is about 0.01/device-day
- Similar observation - NEC4464

Motivation: Future

- Not likely to go away:
  - Package on Package
  - Limited beam penetration on 3D Circuits
  - Heat sinks and thermal management
- Mission design
  - If limitations are understood, design could benefit
- We should establish best practices in the use of proton board-level testing.

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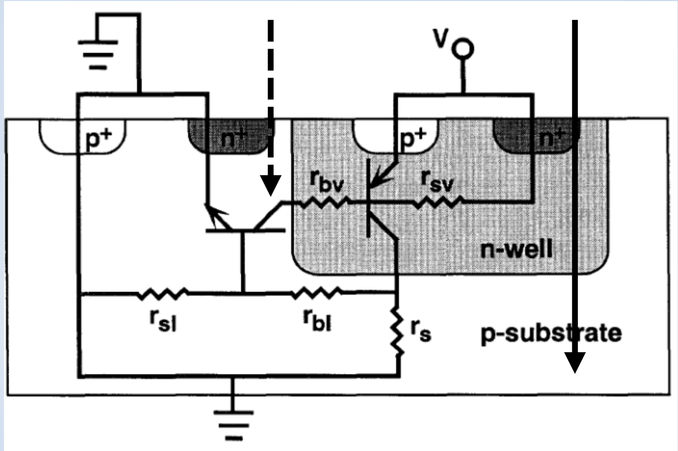
The Good, the Bad, …

- Good
  - Low cost
  - Can test in flight-like situation
  - No testing is really bad, some parts have DSEE @ .1/day
  - It has been used, to some success on ISS missions
  - Bit upsets, SEUs, and SETs are easily caused by proton events, though only a limited subset of them may be observed.
- Bad
  - The SEEs proton testing is worst for, are the worst things:
    - SEL
    - SEB
    - SEGR
  - Ions generated are low(er) Z
  - Ion range limited to ~10μm
  - May be difficult to observe and isolate rare events from test artifacts



Ladbury, 2015 – SEL requires deep charge collection

and the Ugly

- But it does work – a little
  - What you’re getting is so minimal that a bad test or **misinterpretation could be worse than no test**
- The results are not great
  - At 1e10 fluence, resulting DSEE rate is only constrained to 0.01/day (worst case, due to bad actors) – For ISS orbit
  - 1e11 does much better, but value not quantified yet
- And some theory is frustrating
  - Proton recoils have flat angular distribution
  - If something does happen, you know little about angle

- Most frustrating: It is probably, on-average, much better than the worst-case established…
  - How likely are worst-case devices?

Scaling & Technology

- Scaling impact is complicated and could make things better or worse for all SEE types
- Scaling doesn't really affect the event types with the biggest problems – SEL, SEGR, and SEB
  - These transistors (i.e. power) don't really get scaled
  - Scaling by itself makes SEL worse, but decreasing voltage improves SEL – it could get better or worse…
- For other SEE types, the reduction in SV size is improving the effectiveness of proton testing
  - Small SVs, low threshold charge
- Several working on this issue – see NSREC

Testing: Summary

- The guideline is about testing – here’s an overview:
  - Planning, exposure level, test device
  - Facilities
  - Preparation
  - Test operation

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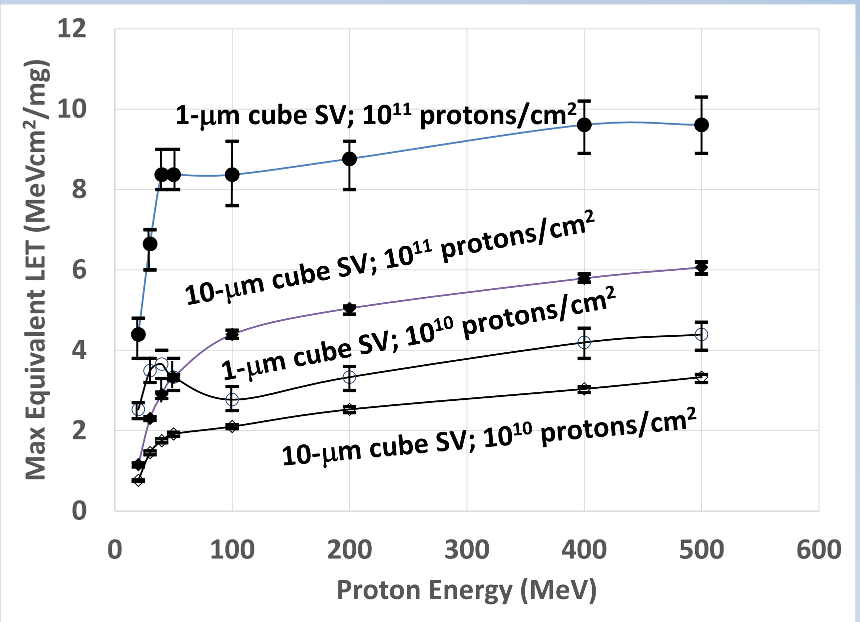
Planning

- There are some parts with failure rates around 0.1/device-day in ISS orbit. You're here without test data.
- Test boards must use the same devices as flight units
- With proton testing, 1e10/cm^2 results in DSEE rates around 0.01/device-day
  - 1e11/cm2 improves this, but hard numbers are limited
- Must consider exposure level and SEE types
- If possible plan to use two energies to enable use of Bendel 2-parameter



Ladbury, IEEE TNS, 2015

Equivalent LET = Energy / (ρ*d_{SV})
Max Equivalent LET requires 2.3 recoils

Facilities

- For proton-only testing, 200 MeV is heavily desired. (Required to meet claims given in guideline.)

Facility	Location	Type	Energy, MeV	Availability
Tri-University Meson Facility	Vancouver, CAN	Cyclotron	480	Ok, but 4x/year
Slater Proton Treatment and Research Center at Loma Linda University Medical Center (LLUMC)	Loma Linda, CA	Synchrotron	250	4-8 weeks?
Mass General Francis H. Burr Proton Therapy (MGH)	Boston, MA	Cyclotron	235	Booking 8 months out
NASA Space Radiation Lab (NSRL)	Brookhaven, NY	Synchrotron	2500	Ok, but $$

- Ideally, synchrotrons would be avoided due to beam structure impact on testing
- Other proton facilities are available, but require direct communication/discussion for each user

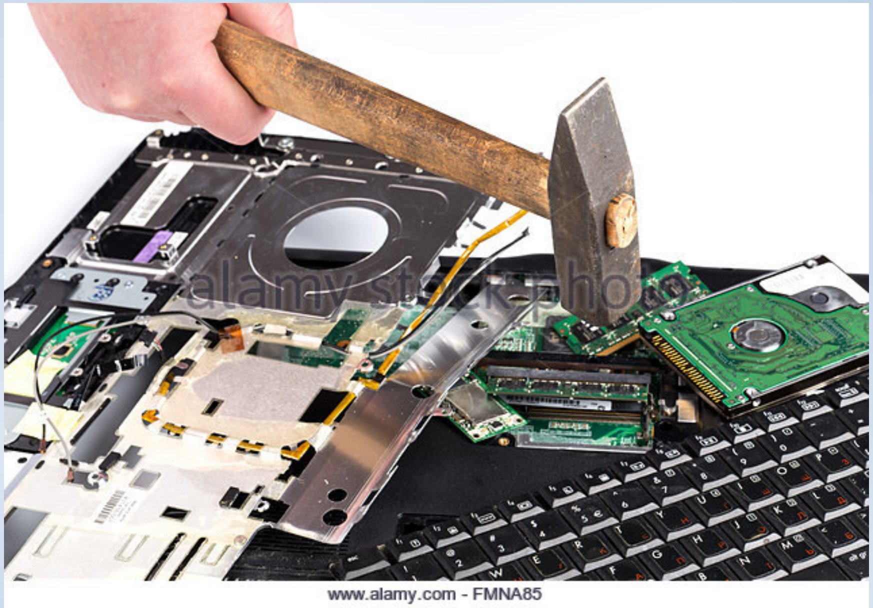
Preparation

- Test boards/equipment
  - Remove bulky heatsinks
  - Remove/don't install shielding (we're not testing the shielding predictions)
  - Limit beam exposure of any non-test equipment
- Work with facility regarding shipping – especially to Canada
- During exposure, all items in the beam will be exposed to TID
  - Generally, TID levels over 3 krad(Si) are likely to cause problems with boards (but it could happen lower) – **Be careful of unit TID limits!**
  - $1\times10^{12}/cm^2$ would be best for a proton test, but $1\times10^{11}/cm^2$ might be a reasonable compromise.
    - $1\times10^{12}/cm^2$ provides close to $1\times10^{7}/cm^2$ recoils – similar to heavy ion coverage

Proton Energy	Dose for $1\times10^{10}/cm^2$	Dose for $1\times10^{11}/cm^2$	Dose for $1\times10^{12}/cm^2$
50 MeV	1.6 krad(Si)	16 krad(Si)	160 krad(Si)
100	0.94	9.4	94
200	0.58	5.8	58
500	0.36	3.6	36

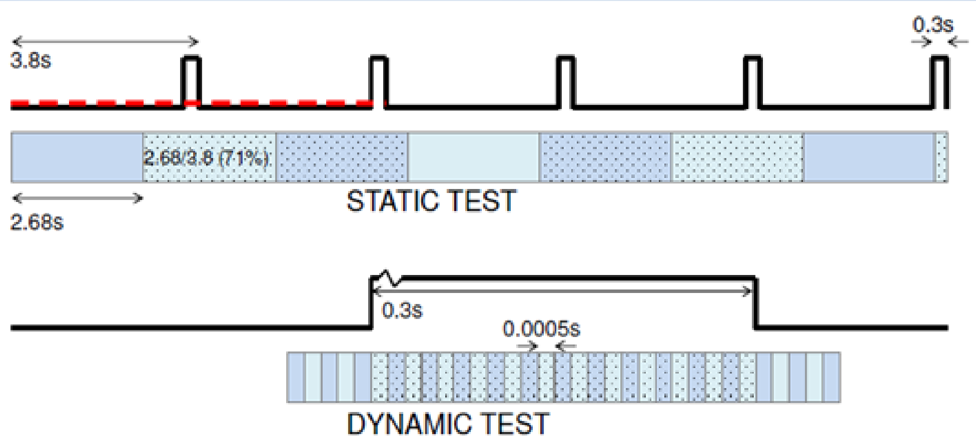
Test Methods - I

- Verify the beam details by requesting beam diagnostic information from the operator
  - Radiochromic film, scan information, or other
- Ensure the test board(s) are positioned far enough away to expose all electronics.
- If multiple boards are used, may want to put Radiochromic film between each unit
  - But it measures dose, not particle fluence…



Test Methods - II

- Operational test modes should be considered carefully
  - Test for normal system response (flight-like application) and recovery (if possible stop the beam during recovery)
    - Typically doesn't have good prognostics or diagnostics
  - Designs specifically for an accelerated test (design for test)
    - Identify errors and increase coverage – but requires careful development
- Try to observe as many error modes as possible
  - Strange, rare event types my be dangerous
    - If there is something rare that may cause a big operational problem, it is more important to study than 100s of events that are easily handled
  - But they may be test artifacts



Guertin, RADECS Workshop, 2012

- Test operations should keep in mind the beam structure – i.e. synchrotron vs. cyclotron
  - For static tests, beam structure only really causes problems with figuring out live time.
  - But for dynamic tests, it is important that the test does not alias with the beam delivery…

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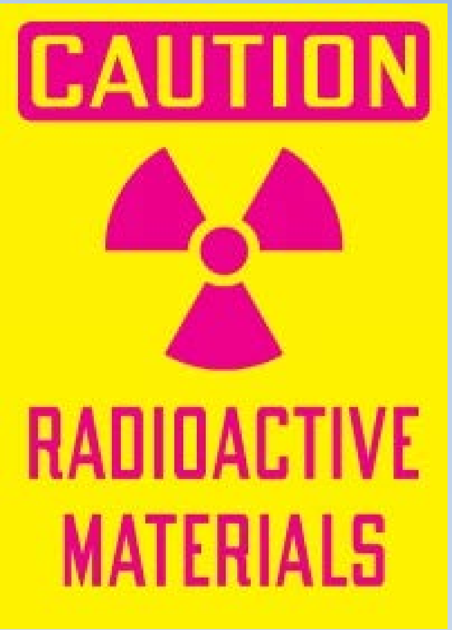
Finish Up



- Be prepared to not have your equipment for a couple weeks due to activation (months with 1×10^{12})
  - Will be worse with higher energies and higher exposures
  - Shipping regulations vary, discuss with the test facility
- Ideally, a post-irradiation burn-in may help identify latent damage
- All observed error types should be documented before leaving the facility
- Obtain test logs, exposure information, and ensure any shipping or facility exit requirements are handled.

Analysis & Theory

- For SEEs with less than 1-2μm SV depth
  - The relation between the number of events in a $1\times10^{10}/cm^2$ test, and the predicted rate for ISS, is estimated by the PROTEST code
  - Most bit upsets and SEFIs have this depth, but fluence dictates coverage of observed modes.
- For DSEE – SEL, SEB, and SEGR, the resulting rate is based on worst-case devices from sampling
  - If this was handled as a regular engineering problem, the hard limits could easily result in worse predictions than no testing (the secondary ions are weak and the device geometry is unknown).
  - But the likelihood of worst-case devices actually being in your design is hard to gauge.
- Specific rates based on fluence, number of observed events, and event type, are TBD (except for $1\times10^{10}/cm^2$ test for ISS)

Future/Recommendations

- Alternate environments need improved study of cutoff LET and residual risk
  - Other LEO, GEO, and maybe surface of Mars?
  - Each SEE category would have different claims to be established

- It’s all about statistics…
  - Recommendations about how to build with multiple architectures to avoid systematic problems?
- For real mission assurance improvement, technology information can augment testing

Conclusion

- Proton-only testing to "improve" assurance of systems has, and will be used – but it is potentially very limited in value.
  - Effective LET cutoff is low for damaging SEE
  - Ideally would test with at least $1\times10^{12}/cm^2$

- We need to make sure test methods are good to ensure the (limited) value of this type of testing is not compromised
  - Guideline in development
  - Configuration of test, collection of data, selection of fluence/etc.

- The theoretical limitations of this approach are significant, but the practical experience of test groups indicate that it can result in 10-100x improvement over predictions with no testing – for ISS orbit.