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Lessons and Recommendations for Board-Level Testing with Protons

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ABSTRACT

Protons with sufficiently high energy, provided in a broad field covering on the order of $0.1m^2$ can be used to perform board-level testing for single event effects (SEE). NASA has used this approach for board-level testing over the last 20 years. Although many difficulties inherent in SEE testing are simplified when using a board-level test, including reduced cost, the method is inherently risky because of the limited value of the collected data and the potential to make critical mistakes when performing SEE testing this way, leading to data of less value. Historically, NASA's approach to proton board-level testing has been limited to lower criticality applications. However, with users both inside and outside NASA using this method for higher levels of mission assurance, we have put together a set of lessons and recommendations to improve the value of data collected using this method. Focus areas covered include test preparation, test execution, and interpretation of results.

OVERVIEW

Proton testing of flight-like boards using beams in excess of 200 MeV, with fluences of $1\times10^{10}/cm^2$ to $1\times10^{11}/cm^2$, is a way to achieve a limited amount of assurance at significantly reduced cost compared to a traditional parts program approach. This paper reviews this assurance method, with a focus on recommendations for effective implementation, some of which are motivated by lessons learned from the implementation of this approach. The approach of using protons as the only test for a flight board was largely documented and developed by O'Niell of the NASA Johnson Space Center.[1,2] The reason for using the method was to provide a limited amount of radiation data on systems that were to be used on the International Space Station [ISS] and that would not be part of any critical system for the primary mission or astronaut safety. Partially because of the effective success, the method picked up support as a potential way to qualify systems. It is important to note that the method leaves a fairly high upper bound for the possible system-level failure rate in the event that a test article passes, at approximately one permanent damage event in 100 days for modern components in the ISS orbit. And it is important to note that the ISS orbit environment, is one of the most benign space radiation environments. Because of the focus of the method on the ISS orbit, this paper assumes ISS orbit for all stated rates, and compares all other discussed environments to the ISS orbit, unless otherwise noted.

Why Board-Level Proton Testing is Liked

The primary reasons people like proton board-level testing are the benefit in cost and schedule for a program, and the ease in performing the testing. Secondarily, by using the approach people can provide some level of assurance on a pre-built assembly which a program has no ability to have manufactured explicitly for them. For example, a commercial off the shelf (COTS) computer system can simply be purchased and put in front of the beam with needing to design or build the board from scratch or needing to request that the manufacturer build the board with qualified parts.

A subsystem or flight board contains on the order of seventy distinct active electronic components. Under a traditional parts approach, some of those components might be radiation-hardened for thousands of dollars per component, while others will be evaluated for performance in the system, including radiation testing on the order of $10,000 or more per component. This makes the traditional approach for a flight board cost on the order of $0.5-$1 million for a single board. By contrast, an existing COTS board can cost as little as a few $100, has a very short lead time, and can be tested using a proton-only evaluation method for as little as a few $1000. This tremendous savings is very attractive to flight programs. However, this approach leaves a significant amount of risk which will be addressed in the next subsection.

Focusing on the potential benefits, however, we will here discuss what the method can do well. Proton testing at the board level specifically targets single event effects (SEE) where a charged particle causes an ionization trail in a component, leading to misbehavior of an electronic circuit. In space, the particles that can cause SEE are essentially limited to protons and heavy ions (anything with Z > 1). The ionization comes from the linear energy transfer (LET) which is a measure of the energy deposited via ionization into the circuit. The LET follows from the Bethe formula for energy loss, which is proportional to Z^2. Because of this, it is obvious that protons are terrible stand-ins for heavy ions. Instead, protons can approximate some of the heavy ion spectra through nuclear reactions where atoms in the tested electronics are ejected. Heimstra has developed the set of LET plots for common nuclear products in component interactions with protons at 500 MeV.[3] At lower energy (such as the standard 200 MeV used in board level testing), the secondary particle peak LET shown in Figure 1 is usually achieved, but the range is limited to around 10 μm. Another way to discuss the produced particle spectrum is to look at the energy deposition in a sensitive volume (SV) of a given size, which was shown to vary from around 14 to 17 MeV for parts with SVs smaller than 2 μm correlating to LETs of around 17 MeV-cm^2/mg.[4] The key, however, is that this is the maximum energy deposition that can be achieved from a proton secondary, which presents a hazard discussed in the next subsection.

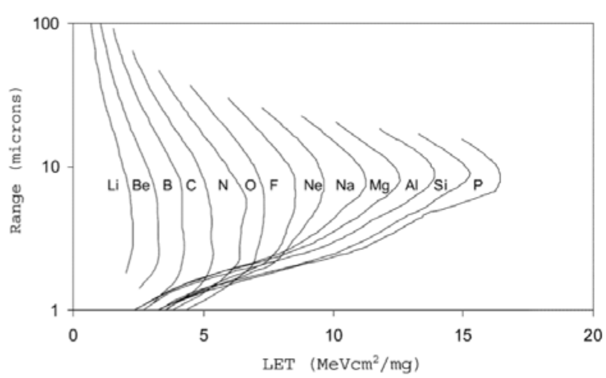

Figure 1: Range versus LET for ions generated in 500 MeV proton interactions in Si devices (Heimstra 2003).[3] © 2003 IEEE

The most obvious use of the test method is that if a board fails in a proton test, it will clearly have problems on orbit. Thus, this test method is useful for screening out problematic equipment.

If a failure is observed but is considered to be tolerable, proton-only board-level testing can provide useful on-orbit rates. We will discuss this in the section on interpretation of results. It turns out that if a lot of events occur in proton testing, then proton testing can give a very good estimate for the rate of those events happening in space. This follows from the analysis of the overlap of energy depositions in space compared to energy depositions in proton tests, which is shown in Figure 2.[4]

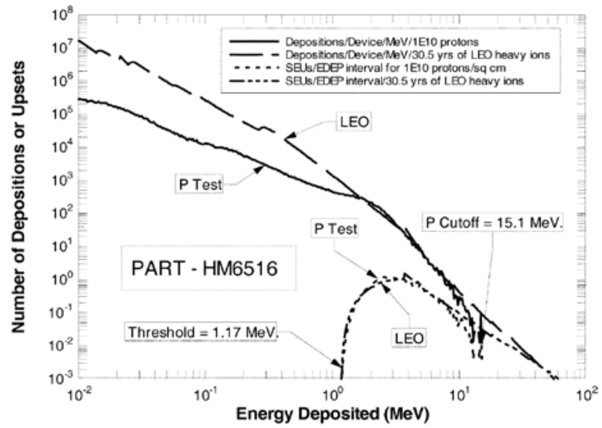

Figure 2: Energy deposition and LEO (ISS) vs. proton test (P Test) rates for the HM6516.[4] Note that for energy depositions between 1 and 10 MeV, the proton test produces nearly the same event ratios as the ISS environment. The portion above the cutoff of 15.1 MeV only contributes a small fraction to the space rate, making the test results good for estimating the space rate. © 2008 IEEE

Where the Hazards Are

Although initially put forward by O'Niell, the larger radiation effects community has explored the method, usually focusing on limitations. Some examples can be found in the literature.[5,3,6] Unfortunately, proton only radiation testing has several sources of hazards in its application, even from the appropriateness and test planning angle.

Proton-only testing is intrinsically not very good for heavy ions. Exposures of 1×10^{11}/cm^2 only result in a grand total of about 1×10^5/cm^2 of heavy ions traveling through the active portions of an integrated circuit. This covers all of ions that can be found in proton secondaries. Typically, a heavy ion test will consist of single-LET beams taken to 1×10^7cm^2, with typically two to three beams used in the LET range of proton secondaries. Thus, the test method is at least 100x weaker than normal heavy ion tests, and lacks fidelity to determine the shape of the cross section curve in the critical "knee region" where the cross section is rapidly increasing through the lower LETs.

Proton-only testing is intrinsically not very good for most orbits, primarily as a corollary to not being good for heavy ions. Using protons as the only test particles is fairly decent in the ISS orbit because the environment is affected by the lower portions of the trapped proton belts and the South Atlantic Anomaly (SAA), which are sources of proton events. In the ISS orbit, the typical Galactic Cosmic Ray (GCR) spectrum is reduced by about a factor of four by the Earth's geomagnetic shielding, significantly reducing the heavy ions that could strike a spacecraft. And the Earth's geomagnetic shielding greatly reduces the number of heavy ions from solar flares. In mid-Earth orbit (MEO), which is dominated by trapped particles, proton-only testing may be viable, but the total ionizing does (TID) in MEO is likely to rule out the use of COTS assemblies. Every other environment has significantly more heavy ions, so that proton-only testing leaves significant failure risks untested. Essentially relegating system reliability below 0.1 catastrophic failures/system-day. Real systems may do better than this, because the best we can do is provide an upper limit. But occasionally (perhaps only one mission in 100), 10-day mission mean time to failure (MTTF) in a harsher heavy ion environment will occur.

Unfortunately, the use of protons to test for SEE performs the poorest for the most problematic SEEs – SEB, SEGR, and SEL.[7] These SEE types have deep charge collection, or large SVs, so the range of the proton secondaries is critical. As shown in Figure 2, there is essentially a cutoff above which proton secondaries cannot produce energy deposition events with more than around 15 MeV. If the SV collects charge along 10 µm, then the energy per unit length, or the LET, goes down. The cutoff LETs are shown for 1- and 10-µm sensitive volumes for $1\times10^{10}/cm^2$ and $1\times10^{11}/cm^2$ proton test runs. Note that the effective high LET achieved by using a 200 MeV proton beam on a 10 µm-cube SV is about 5 MeV-cm^2/mg. Unfortuantely, in ISS orbit, there are about 100 particles per year with LETs above this number. SEB, SEGR, and SEL all have SVs with sizes similar to, or larger than, the 10 µm-cube.

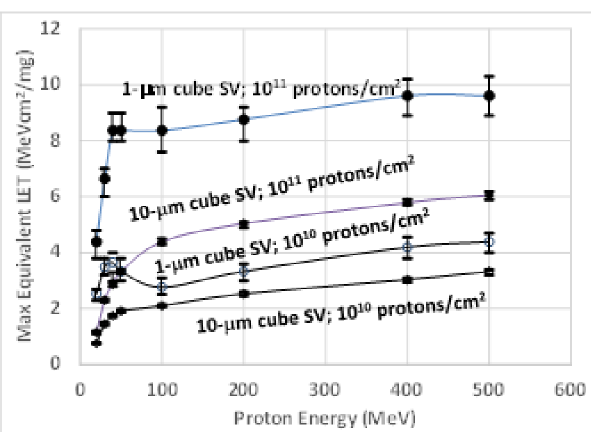

Figure 3: Maximum LETEQ produced by the given proton fluence in the given SV versus proton energy.[7] © 2015 IEEE

If we based the foundations for the use of the proton-only test method to the hard theory discussed above, the method would be useless because the potential worst case situation would be that a board passes the test with no failures, but has a space rate for catastrophic (damaging) events of about 0.3/system-day. In reality, we think the most useful thing to do is base recommendations on worst-case actors. An extensive write up on this subject is available in the NASA Electronic Parts and Packaging Program (NEPP) book of knowledge on this subject.[8] In that document it is pointed out that the worst devices known to have a relatively high probability of passing a $1\times10^{10}/cm^2$ proton test have a space rate for SEL of about 0.01/device-day. Because of the problem with the inability to create energy deposition events in excess of around 17 MeV, increasing the fluence only marginally benefits this, and we suggest using 0.003/device-day if a device passes a $1\times10^{11}/cm^2$ proton test with no damaging events.

Review and Recommendation Areas

In order to keep ideas organized, we focus on individual portions of the test methodology. The methodology is broken down as follows. Planning for the use of board-level proton testing is the first thing the potential user should consider. After this, preparation for testing is necessary, covering preparation of equipment, design of experiments, and everything related to how to run the equipment and collect data. The next area for consideration is actual execution of the test. And finally is the interpretation of the results.

Organization of the Paper

This paper is primarily arranged around the review and recommendation areas just discussed. Where appropriate we include some specific situations that have been observed in board-level proton tests, and explore some suggestions for ways to make the method more useful. At the end of each review section we provide a set of recommendations to avoid potential problems and ensure a more reliable dataset. After reviewing each area, we conclude the paper.

TEST PLANNING

Test planning in critical for the use of this method because the choice to even use board-level proton testing must be driven by the assurance requirements of a mission, tied to the mission environment.

The Best Result Is Only Marginally Good

The HM6516 discussed above is a single example of a part that would result in a space rate of 0.01/device-day for SEL [recall that by default all rates discussed are for ISS orbit unless otherwise noted]. But this part is old and its problems likely are related to its construction. However, the problems with the number of particles of a given LET and the resulting energy depositions indicated in the paper by Ladbury and exploring the energy deposition suggested by Foster, as discussed above, lead to the conclusion that newer devices may actually be worse, and that SEB and SEGR may be just as problematic as SEL.[4] In the absence of worst-case actors to push the worst-case rate down, we stick with the 0.01/device-day for damaging SEE, and indicate it is an engineering guidance rather than a hard rule. If $1\times10^{11}/cm^2$ is used, this can be pushed down to 0.003/device-day. Exploring how to perform a test up to $1\times10^{12}/cm^2$ resulted in unrealistic expectations and test efforts (requiring 30 test articles and days of beam time), and is not recommended.

Test What You Fly

The old adage "test like you fly" is meant to reflect using hardware the same way during test as will be used in flight. Here we are saying you must make sure that you have the same components, the same board design, and you are using everything the same way as in flight. Unfortunately, it is unlikely you will be able to do this. Because of this, it is recommended to match everything as well as possible. In fact, if the equipment does not match sufficiently, the test data will be essentially useless. Extreme care should be taken to ensure that any differences are unlikely to result in significantly flawed test results.

Recommendations – Test Planning

1. Test as early in the cycle as possible, otherwise it will be impossible to respond to failures.
2. To the extent possible, ensure you plan to irradiate the same board (same components, board revision, etc.) as the flight board. This includes attempting to verify that all markings on all devices match.
3. Any situation where components on the test article differ from the flight units should be carefully reviewed to ensure that the difference is in components will not invalidate the results. This is best accomplished by showing that the flight and test components are unlikely to be the leading cause for SEEs on either unit.
4. Allow at least eight months for securing beam time. This can be booked ahead but released between one and two weeks before the actual test date. So it is good to book time ahead if you suspect you need it.
5. Test at a facility with at least 190 MeV protons. This is necessary to keep TID on $1\times10^{10}/cm^2$ below 1 krad(Si) and to provide higher energy recoil particles. See Heimstra for information on energy impact on secondary particle spectra.[3]
6. Determine if your environment has significantly more GCR than ISS orbit.
7. You will only achieve 0.01/system-day failure rate for a $1\times10^{10}/cm^2$ test. This only decreases to 0.003/system-day for a $1\times10^{11}/cm^2$ test (which requires at least three test units in order to avoid failures in sensitive devices such as analog or power components that can fail below 5 krad[Si]).
8. Do not plan to test to $1\times10^{12}/cm^2$ because of the risk of TID failures contaminating the data and the very long test time due to swapping out thirty test units.

TEST PREPARATION

Test preparation involved the period leading up to the actual test. The goals of test preparation are focused around arriving at the test facility able to completely perform the required tests and obtain the desired data. Below is a list of recommendations for test preparation.

Test Units

Note that the method discussed here involves irradiation of entire boxes of electronics for flight. 200 MeV protons can easily penetrate through inches of aluminum, circuit boards, heat sinks, and components. Even though the range is long, the data collected is of higher quality if the beam goes through limited amounts of heterogenous material. This partially follows because the more material the beam goes through, the more degraded and scattered it is. However, 200 MeV protons can be used to penetrate at least six circuit boards and a limited amount of aluminum (less than an inch) without significantly compromising the test beam.

Recommendations – Test Preparation

1. Contact the facility to obtain the details and recommendations specific to the facility. This includes things like cable lengths, access to internet connections, shipping and receiving, and training requirements. This may include contacting multiple facilities and creating a superset of experiment requirements.
2. If possible, perform a walkthrough of the facility a few weeks before the test.
3. Discuss parameters with the beam facility: beam size, time and space structure of the beam, flux, flux range, positioning equipment, and any other critical parameters for your test.
4. Determine if the facility can accommodate the full size of your test hardware.

5. Other facility contact information – start and stop time, days where you can access the test setup, where/how to handle shipping & receiving, and how the facility handles storage of activated hardware.
6. Note that most test boards will have to stay at the facility a from a few days for low exposure, possibly up to a couple months. It is the discretion of the facility to determine whether hardware is safe for transit after exposure. You can avoid this delay by working the radiation safety officer in your own organization. Typically, even groups with good radiation shipping capability allow activated equipment to remain at the test facility until safe for transit.
7. Develop a full set of test hardware, including wiring, to simulate running at the facility. This is non-trivial because voltage drops can exceed 20% and communications can fail with very long cable runs necessary at proton facilities.
8. Write up a detailed tests plan including: set of devices or units under test (DUTs/UUTs); full exposure requirements (individual exposures planned per run tend to be impossible to plan beforehand); operational configuration or configurations (be careful about TID).
9. When designing the behavior of the test equipment, use an accelerated operation (i.e. do not use software from a "cruise" stage where the system is essentially dormant; use fully-functional software).
10. Ensure that the time structure of the beam does not cause aliasing with the test behavior, such as accidentally lining up a low-utilization operation during the window when the beam is running.
11. Ensure test plan does not include more than 2 krad(Si) delivered to any one UUT. (We recommend if failures occur near the TID limit that a contingency plan of achieving the overall fluence level without exposing a single UUT to more than ~600 rad(Si) be considered, and consider discarding the failed UUT as a potential TID failure.)
12. Establish shipping plan, including support electronics.

TEST EXECUTION

Test execution involves the on-site performance of SEE testing. Recommendations for this activity are presented after a couple specific topics are covered.

What is a Test Run

SEE testing is primarily broken into "runs" which are originally intended to approximate one solid beam exposure with setup before and data collection after the beam exposure. In reality, the whole period of a run is time that can be used to make observations. Because of the ad-hoc nature of a run, any significant deviation from the definition given here should be noted in the test log and test report.

Recommendations – Test Execution

1. Keep a test log including: run number; DUT/UUT identification; time; fluence; flux; target position; article position; stimulus definition (e.g. what software is running, what is the hardware configuration?).
2. Follow a well-controlled test procedure.
3. Track the total exposure on each test unit.
4. Do not waste time tracking down the cause of unique events whose signature only occurs once or twice.
5. If an unexpected event keeps happening (i.e. it is not unique), try to figure out what it is.
6. If an unexpected hard failure happens and can be isolated, consider exploring the cause as it might be possible to isolate and remove a poorly performing device.
7. Avoid stacks of more than six boards.
8. Avoid blasting through heat sink material.
9. Consider using cooling fans instead of heatsinks if heat is an issue.
10. Do not allow unnecessary material, especially metal, in front of the beam. This minimizes how much equipment will have to remain at the facility due to activation.
11. If a board is mounted at 90° to the main set of boards in a unit, either test two units, with one at 0° and the other at 90°, or rotate all test articles so that all boards are around 45° to the beam. If something other than 0° and 90° is used, the fluence should be multiplied by the cosine of the angle.
12. Use runs of length > 60 s if possible, with at least 10 seconds between events.
13. If the parameters of #11 are not achievable, consider lowering the flux.
14. If the test system has some inherent resiliency to SEE (for example, it is fault tolerant), be careful to use low enough flux (taking into account the

time structure) to reduce the likelihood of failures during fault recovery.

INTERPRETATION OF RESULTS

Because some events will have high numbers, while others (hopefully) are not observed at all, interpretation of results can be a difficult problem. Although the industry standard is to provide a test report for any SEE testing performed, the type of testing we are discussing here is precisely the type of testing for which the totality of reporting may be a set of rates for various SEE types in the target environment.

A Pragmatic Approach to No Events

For general SEE, if no events are seen, then one can use an upper bound estimate of 3.7 for a 95% confidence interval on the population's actual sensitivity.

For damaging SEE, if events are seen it is strongly recommended that the event be analyzed for impact, and if possible, the failing component be replaced with something with better SEE performance. There is a gray area between zero and twenty events where the actual event rate should be taken as 0.01/system-day in ISS orbit for $1\times10^{10}/cm^2$ exposure, and 0.003/system-day for $1\times10^{11}/cm^2$ exposure.

Recommendations – Interpretation of Results

1. If time and budget permit, write a test report.
2. For damaging SEE, use the numbers indicated above, or scale for number of events above twenty. I.e. assign for 0.01/system-day catastrophic failure rate for $1\times10^{10}/cm^2$ exposure, and 0.003/system-day catastrophic failure rate for $1\times10^{11}/cm^2$ exposure.
3. For other event types, you can use 0.0005 (1/2000) / system-day scaled to the number of events observed. If desired, a confidence interval can be added can be approximated by using Poisson confidence intervals on the number of observed events.
4. Do not combine test results from different test configurations unless the specific result is independent of the test configuration.

CONCLUSION

Proton-only board level testing can be a helpful way of providing a limited amount of assurance to a flight article for a small amount of money.

Besides just planning for the logistical details of performing a proton test, this test approach has other difficulties that create the possibility for misinterpreting the results.

We have provided recommendations, covering all aspects of testing. These recommendations begin with how to determine if this type of test can benefit you, all the way to the proper interpretation of the number of failures. We have also quickly explored the issues related to ensuring that your results will actually apply to your flight article.

Because this method is heavily grounded in observations, it is important that key examples that counter the recommendations be brought up in the larger community. Specifically, although we have provided event rates based on worst case actors, we may not have fully identified the worst case actors and any additional worst case actors should be known to the community, especially if they are worse than the numbers.

Acknowledgement

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