# Lessons and Recommendations for Board Level Testing with Protons

**Steven M. Guertin**

**steven.m.guertin@jpl.nasa.gov**

**818-321-5337**

**Jet Propulsion Laboratory / California Institute of Technology**

**Acknowledgment:**

This work was sponsored by:

The NASA Electronic Parts and Packaging Program (NEPP)

# Acronyms

| | |
|---|---|
| DUT | Device Under Test |
| ISS | International Space Station |
| JPL | Jet Propulsion Laboratory |
| LEO | Low Earth Orbit |
| LET | Linear Energy Transfer |
| MeV | million electron-Volts |
| MOSFET | Metal Oxide Semiconductor Field Effect Transistor |
| NASA | National Aeronautics and Space Administration |
| NEPP | NASA Electronic Parts and Packaging Program |
| SEE | Single-Event Effects |
| SEL | Single-Event Latchup |
| TID | Total Ionizing Dose |
| TRIUMF | Tri-University Meson Facility |
| UUT | Unit Under Test |
| Vgs | gate-to-source Voltage |

# Outline

- What is board-level testing with protons?
- What are the potential problems?
- It has be useful… why?
- Test planning
- Test preparation
- Test execution
- Test interpretation
- Lessons Learned (note, not in paper)
- Summary

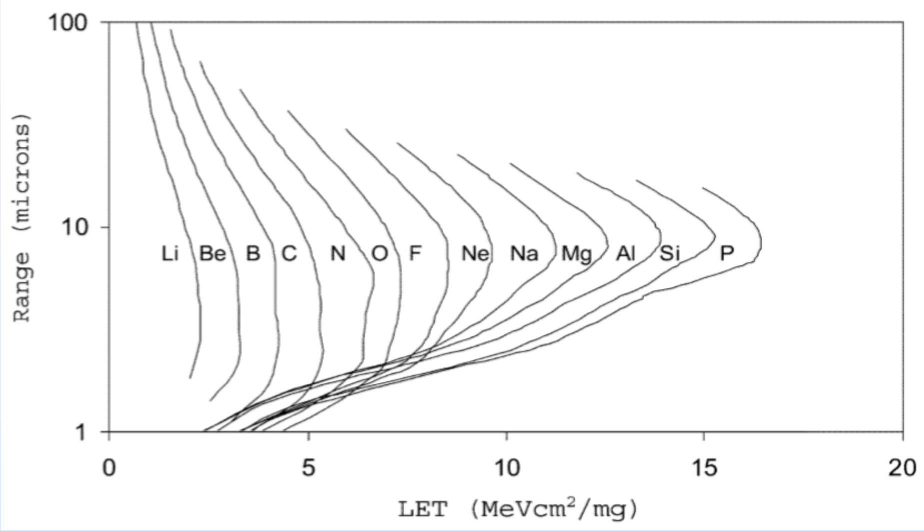
# Board Level Testing Done Right

- For radiation hardness assurance, is there a simple and cheap way to:
  - Do single-event effects testing of a board, all at once?
  - And simulate much of the space environment at once?
  - Sort of, but you may miss a lot…
- If you have the right combination of
  - Mild environment
  - Short duration
  - Willingness to accept risk
- What do you do?
  - Test with high (~200 MeV) protons. (Next slide…)
- How good is it?
  - Questionable – worse if done wrong. (Rest of the talk.)
  - But it does give good fault injection, similar to using neutrons to inject errors at the board level.

# Why 200 MeV?

- Protons are a proxy for heavy ions because their secondaries give LETs in excess 14 MeV-cm²/mg.
- The higher the energy of the beam, the higher the energy (not LET) of the secondaries.
  - Total deposited energy is higher, so they are more space-like.
- Higher energy is better.
  - Increased range improves damaging SEE effectiveness
  - Higher LETs in space are mostly Fe – missing in proton secondaries…

Heimstra, 2003 – for 500 MeV protons




- But higher energy is not readily available, and doesn't really improve things much.
  - Max LET is still only around 14 MeV-cm²/mg
  - Overall range is better
  - Options like Los Alamos (800 MeV) and TRIUMF (500 MeV) exist.

# 200 MeV Is a Sweet-Spot, but…

- **It is good for proton secondaries.**
- **Higher proton energy also reduces dose.**
- **It puts SEE test facilities in-line with medical facilities.**

California Protons
CANCER THERAPY CENTER

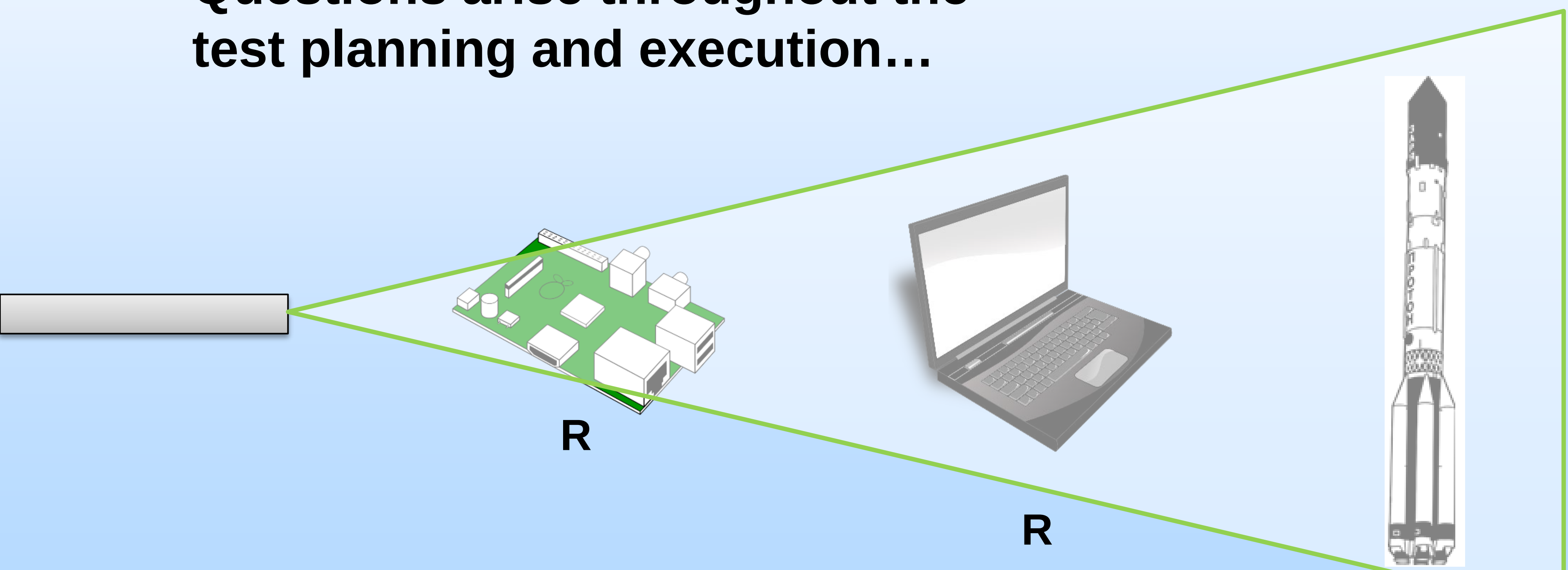
MAYO CLINIC



- **Dozens of facilities…**

# There Are Many Potential Issues

- **Test results are not well-defined, because system size can be arbitrary**
  - **Assume the test results in a system rate of R…**
- **Questions arise throughout the test planning and execution…**




**Or…**$R\sqrt{N}$**? With N something like the number of circuits**

# Scorecard

- The proton board-level testing method has a history of success
- But it is not supported by solid engineering or physics

- Have previous practitioners have been conservative in using the approach?
  - Maybe
- Have we been lucky that systems worked well?
  - Probably. Might even be “accidentally” mitigating damage
  - NASA has only used this in non-critical systems
- Have some failures not been reported?
  - Difficult to say on the NASA side – probably logged, but not necessarily brought to attention of radiation people
  - Suspect situation is worse in most other organizations

# Moving Forward

- **Approach is driven by data on worst parts – is there really enough data yet?  Most likely no.**
  - **Why would anyone take proton data on a part that is observed to have SEL with an LET of less than 10?**
  - **Why take heavy ion data in a part that has SEL with protons?**
- **Given the inherent limitations of the method, how can we achieve the best results?**
- **We will explore some specific situations and a couple lessons learned.**

# Test Planning

- **You can only reliably achieve 0.01-0.003 damaging events per system day in LEO – if this is not good enough, heavy ions are required. (NEPP Board Proton Testing Book of Knowledge)**
  - **Higher assurance claims are not grounded in physics or engineering, but may "seem" to work.**
- **Test early in the cycle, so the results can be used. Don't just hope the results will be ok.**
  - **Normal RHA flow, but often missed for this approach.**
- **Test the same board as the flight board – same parts – manufacturer and part number should match.**
  - **"good engineering" says they really need to be the same, but people are often trying to justify "similar devices"**
- **Reserve beam time 8 months ahead of time. Proton beam time is difficult to schedule.**
- **Use beam energy of at least 190 MeV in order to keep TID on articles below 1 krad(Si) when irradiating to $1 \times 10^{10}/cm^2$.**

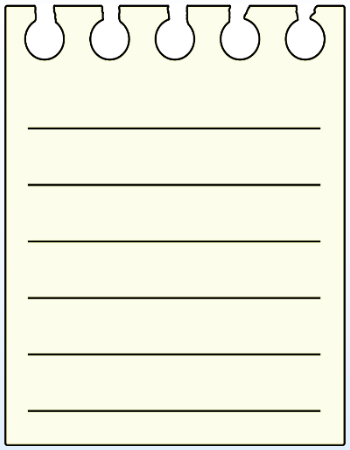
# Test Preparation

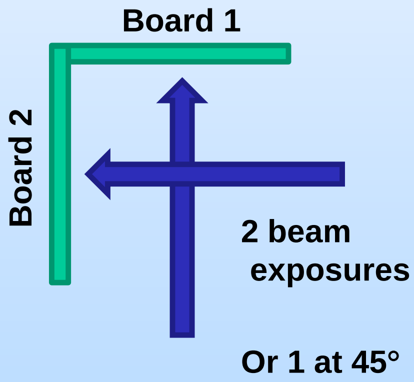
- Contact facility to get details and recommendations for use of the facility.
- If possible, perform a walkthrough of the facility a few weeks before the actual test.
- Discuss beam parameters with the facility: time and space structure, flux & flux range, etc.
- Determine if the facility can accommodate the full size of your hardware.
- Hardware usually cannot ship for at least a few days after the test.
- Test the full setup (including full cable length) before arriving at the facility.
- More info in the paper.

Photo: Irradiation of iPad at UC Davis – due to spot size, multiple irradiation sites were necessary.

# Test Execution

- **Keep a test log including:**
  - **run number**
  - **DUT/UUT identification**
  - **time, fluence, flux**
  - **etc…**
- **Use cooling fans instead of heatsinks (keep fans out of beam) – if possible**
- **Avoid stacks of 6 or more boards**
- **Test with proton beam normal to the test boards**
  - **If boards are mounted 90 degrees to each other, test multiple units with beam normal to the board surfaces**
  - **If angles are used, multiply the fluence delivered by the cosine of the angle of incidence.**
- **Use beam exposures with duration > 60 s, with at least 10 s between events, or consider slowing down the beam.**





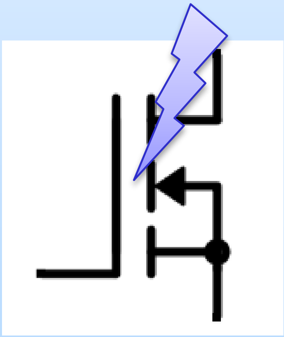

**More in the paper**

# Test Interpretation/Reporting

- **It would be great to have a detailed test report, but a simple summary of the test and observations should be a minimum**
- **If damaging events are NOT SEEN, use the following estimations:**
  - **0.01 events/system-day for $1\times10^{10}/cm^2$ or**
  - **0.003 events/system-day for $1\times10^{11}/cm^2$**
- **For non-damaging events (transients, bit upsets, etc.)**
  - **N * 0.0005 events/system-day for $1\times10^{10}/cm^2$ where N is the number of observed events.**
  - **This scales for higher test fluences.**
- **If damaging events are seen, use the larger of estimates above.**

# Lesson: Be Ready to Use Test Results

- **During one board level test, a permanent failure was observed.**
- **Because the schematics were available, and a radiation expert (familiar with parts list reviews) was on hand…**
  - **A list of at-risk parts was identified**
  - **List was narrowed down by circuit implementation**
  - **Further narrowed down by failure (no power delivered)**
- **Identified a MOSFET operating at >80% of rated Vgs in the design**
  - **Recommendation is < 50%**
  - **Circuit testing showed the MOSFET had failed**



- **Were able to swap in alternate (with higher Vgs) that enabled system to work and not fail in radiation.**

# Lesson Learned: Flight-Like Operation

- Test approach was to have all board operations cycled through during exposure
  - Complex applications made to target all board operations – multiple applications
- The board was dependent on a commercial PowerPC processor running Linux, with the operations in a test program.
- Actual observations were primarily kernel panics due to unhandled exceptions.
  - No value was obtained from different software applications
- None of the special test applications showed SEEs because operating system was primary weak point.
- Lesson: Don't develop a lot of extra test operations outside of flight use

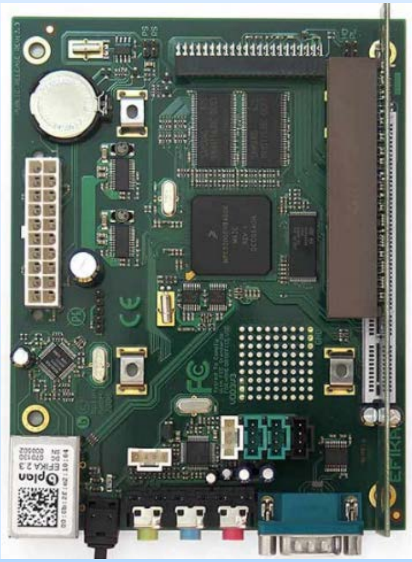


Photo: Efika 400MHz PowerPC SBC

# Summary

- **Proton testing can be used in lieu of normal assurance (including heavy ions) if**
  - **Environment is weak (i.e. LEO, ISS, Mars Surface)**
  - **Mission is short or can handle high risk**
  - **You are OK with only having a data point on performance and not really achieving hardness assurance.**
- **Physics and engineering both suggest fairly high rates for possible damaging SEE**
  - **0.01 to 0.003/system-day for ISS orbit when testing with $1\times10^{10}$-$1\times10^{11}$/cm$^{2}$.**
- **To ensure the test method provides results that can be trusted to these levels, we provide recommendations.**
  - **Test Planning**
  - **Test Preparation**
  - **Test Execution**
  - **Text Interpretation/Analysis**