

Title | *High Reliability Electronics for LIGO*
 Author | *R. Abbott, Caltech*
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1. Overview

Advanced LIGO will see an increase in the use of electronic subassemblies within the vacuum system envelope. The inaccessibility of in-vacuum electronics, coupled with the high cost of repair, necessitates the use of more stringent electronics design practices.

This note is intended to be a living document evolving as we become aware of additional areas that compromise reliability in electronics, or become aware of better countermeasures.

2. Failure Modes

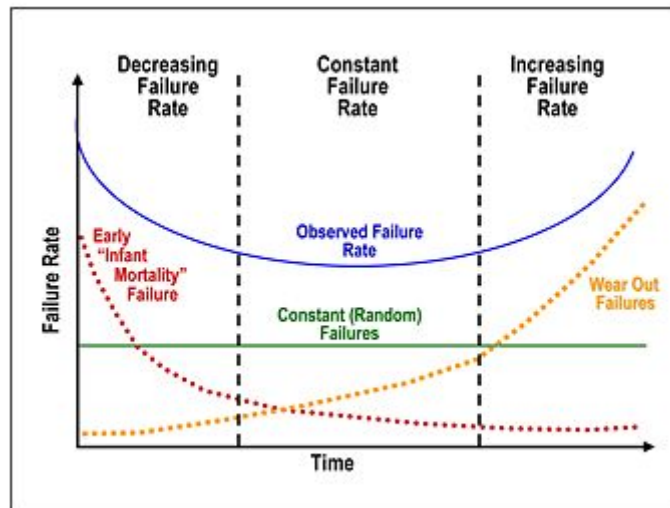
Summary of failure modes

- Infant Mortality
- Application of Reversed Polarity DC Power
- High Inrush Currents upon Application of DC Power
- Unbalanced DC Power Supplies
- Over Voltage Transients and noise on Input and Output Wires
- Component De-rating
- Miscellaneous Topics

3. Infant Mortality

The well-known “bathtub curve” describes the observed failure rate of components vs. time. As the name implies, it looks like a bathtub.

Figure 1 Bathtub Curve



Mitigation - Careful selection of quality components coupled with sensible usage will obviously lower the observed failure rate for a given scenario. Beyond this, it may be useful to institute a burn-in period for critical electronics so that the susceptibility to early infant mortality failure can be managed.

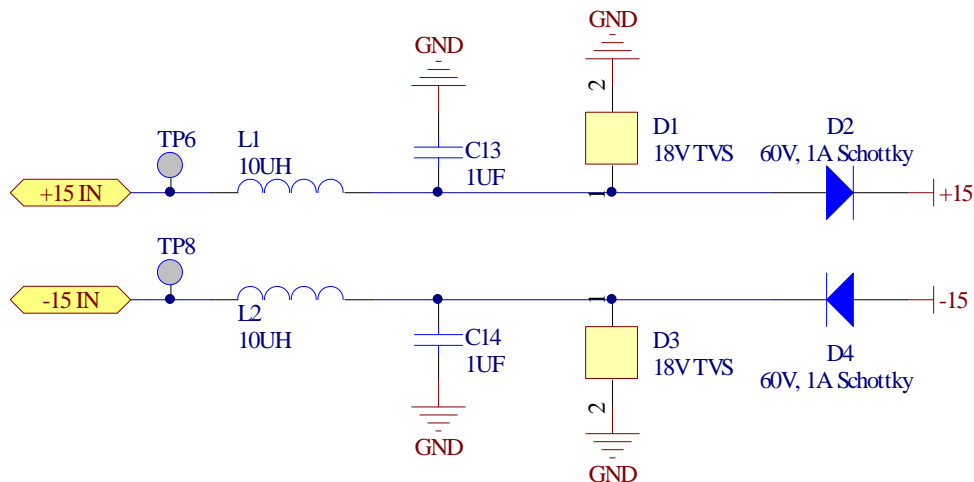
4. Inadvertent Application of Reversed Polarity DC Power

Certainly, anyone who has been with LIGO for any appreciable amount of time has seen his or her fair share of this sin. Even momentary application of reverse voltages to a circuit can cause permanent damage to active and passive components resulting in shortened lifespan or immediate failure.

Mitigation – Several design methods have been successfully employed to avoid reverse polarizing electronics:

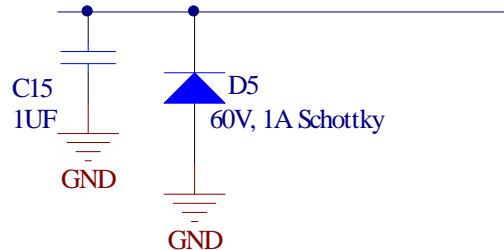
- Adherence to “Standard LIGO Electrical Interfaces”, T060123. This document establishes standards for connections between electronics used at LIGO, and addresses the more common scenarios encountered in the electrical connections between systems. I recommend this as the first line of defense.
- Diodes in series with the power feeds have been successfully used. The relatively large voltage drop across the diode renders this technique more useful in low power applications. Diodes D2 and D4 in figure 2 illustrate this technique. Schottky diodes are preferable due to the low voltage drop during forward biased operation. Worthy of note is the interaction between the inductors, L1 and L2 with the capacitors, C13 and C14. This type of situation can create resonances that are not helpful. De-Q the inductors as needed to avoid ringing.

Figure 2



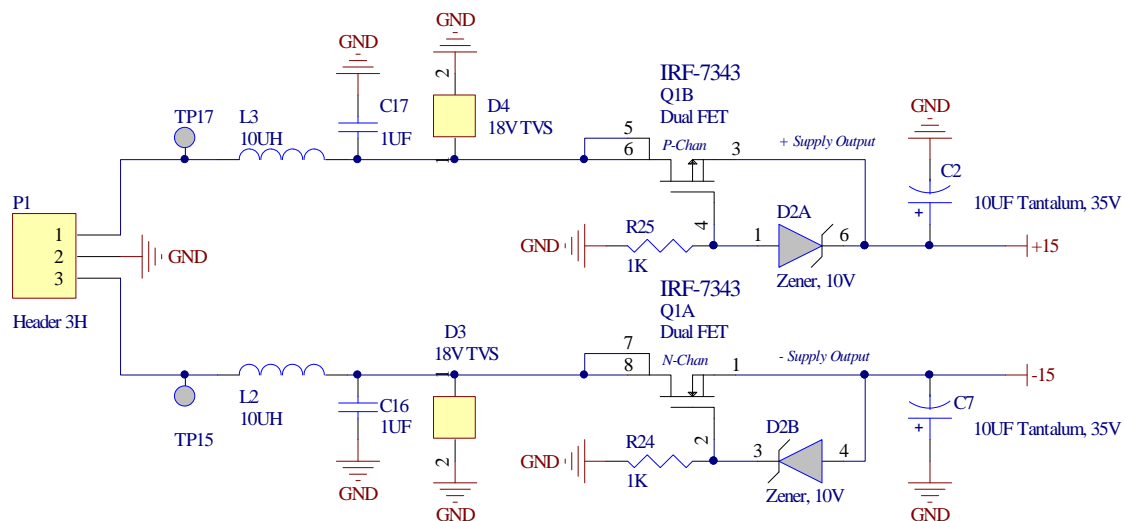
- The parallel configuration, as shown in figure 3 should be avoided. Although the parallel configuration provides a clear indication that the DC power is connected backwards, it could result in failure of the relatively fine gauge wire used in the in-vacuum wiring harnesses. In a situation where the in-vacuum wiring is threatened by high current, fuses or other positive means must be used to protect the in-vacuum wiring.

Figure 3, don't do this on power feeds



- MOSFET Reversed Polarity Protection – For applications where the voltage drop across a Schottky diode is a problem, a complimentary pair of MOSFET transistors has been used. This circuit has less power dissipation, which can be useful for higher power in-vacuum electronics. Figure 4 shows a schematic using the commonly available IRF-7343 Dual MOSFET.

Figure 4, reverse polarity protection



During operation, the MOSFET on-resistance is typically less than 0.1 ohms. L2 and L3 must be “lossy” ferrite based inductors with impedances of ~1 kohm or more at 100 MHz to avoid ringing.

5. Hi In-rush Current upon Application of DC Power

This category focuses on the damage to capacitors used to filter DC power supplies. It is standard in industry to quote the use of a series current limiting resistor in series with a high quality, low equivalent series resistance (ESR) capacitor. The value of the resistor depends on the in-circuit voltage of the capacitor. For example, a capacitor with a dielectric rating of 35 volts and an ESR of 0.05 milli-ohms is used to filter a 10-volt power line. At the instant the 10 volt supply is connected, the theoretical peak current is $10/0.05$ amps, or 200 amps. In reality, nature is probably a bit more kind and things conspire to reduce that number, but the point is still clear. The high peak current can cause failure of the capacitor. Tantalum capacitors have a nice capacity to self-heal in some circumstances, but there are certainly

thresholds that will result in an immediate and catastrophic failure. Unfortunately, tantalum capacitors almost never fail as an open circuit, but prefer the more spectacular short circuit scenario.

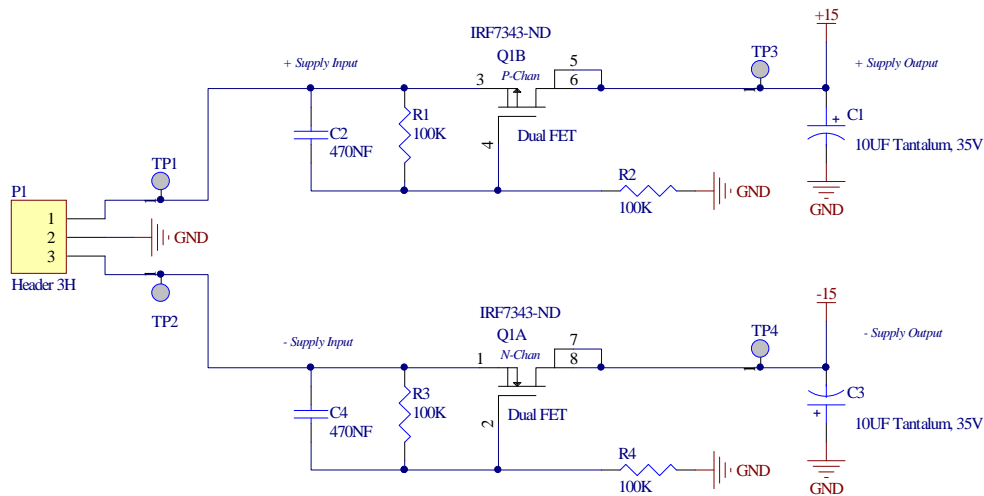
Hot swapping is the act of connecting an electronic device to an energized power supply. This practice is common at LIGO. I have personally measured the rise-time on a 10uF tantalum capacitor directly connected to a 15-volt supply, and the whole thing is over in less than 10usec. This raises the issue of how switches are used to energize circuitry.

It is conceivable that a designer could have a local power switch, which upon the instant of contact closure, could apply a rapid voltage step to a circuit. This, in turn provides the means to force excessive current through capacitors. Therefore, it is would be best to locate the switch upstream of a local power regulator board, and let the regulator take the hit, rather than jamming a pulse of destructive current into a sensitive circuit. The stability of some commercial voltage regulators depends on a low equivalent series resistance (ESR) tantalum capacitor to be included on the input side of the regulator. When an upstream switch closes, this capacitor is subjected to a high inrush of current.

Mitigation – In March 2019, a decision was made to insert a 1 to 1.5-ohm, 1-watt resistor in series with all tantalum filter capacitors exposed to direct feed from external DC power sources. The decision to include this series resistor is based on a NASA study by Alexander Teverovsky, “Derating of Surge Current for Tantalum Capacitors”. In most LIGO applications where a tantalum capacitor is exposed to high inrush current, the device’s steady-state operating current is only a few hundred milliamperes, so the voltage drop is not of major consequence, however this should be evaluated to ensure sufficient voltage overhead for regulation in a given design.

In an alternate approach, when power is applied to the circuit shown in figure 5, the MOSFETs turn on slowly, thus limiting the current into the tantalum capacitors. For +/- 15-volt applications, the turn on transient takes about 1msec.

Figure 5, Soft-start circuit.



6. Unbalanced DC Power Supplies

Some op-amps draw excessive current through parasitic internal diodes when only one of the two power rails is present (“rail” in this context, refers to one polarity or the other, of a bipolar power supply. Examples might be; +/-12 volts DC, +/-15 volts DC etc.). This leads to excessive heating and possible failure of the IC. Unfortunately, attempts to find amplifiers without this tendency have not been very successful. It is still common to find some applications that can only be properly served by these ill-tempered devices.

Scenarios leading to unbalanced DC power supplies include failure or deliberate removal of one power rail, blown fuses, wiring errors, board level component failure etc.

Mitigation – We have yet to utilize a board level solution suitable for inclusion into in-vacuum modules. Whenever possible, we use ganged switches and circuit breakers that simultaneously remove or apply both power rails. Figure 6 shows a commercial thermal circuit breaker that acts as an on/off switch as well as providing over-current protection. These devices are commonly used at the chassis level at LIGO.

Figure 6, Dual Circuit Breaker/ On-Off Switch



7. Over-voltage on Input and Output Lines

Sources of over-voltage include: Overshoot from under-damped power supplies and power distribution components, inadvertent application of higher than intended voltage, lightning or other sources of environmental transients, electrostatic discharge etc. These voltages are transmitted by the wiring serving a remotely located piece of equipment. Unfortunately, given the high current nature of typical power supplies at LIGO, there are not any viable solutions to the simple application of the wrong voltage. For example, if a 15-volt supply were connected to a 5-volt load, a typical 18-volt LIGO power supply would likely destroy any zener based protection scheme quite rapidly.

Mitigation – Several means have been used to limit over-voltage transients

- Procedural – Before applying power to a device, have in mind the anticipated current and voltage you expect to see. Carefully watch the power supply meters to verify the predicted response. Following this process will raise the probability that any zener protection device will survive the abuse.
- Resistive Isolation – Whenever permissible by design, a series resistor is a cheap and predictable isolation between distribution wiring and a sensitive design.
- Transient Voltage Suppressors – Figure 7 shows a surface mount transient voltage suppressor. These tiny devices are available in a wide variety of breakdown voltages, and can be of a unipolar or bipolar voltage breakdown nature. They are extremely fast (1psec) and are appropriate for use at their rated voltage. These devices have been successfully used in the ELIGO OMC.

Figure 7 Littelfuse® SMAJ Series, 400W Transient Voltage Suppressor



Inductive Isolation and RFI Filters – The use of a series inductor at the board level of an in-vacuum assembly must be approached with some care. A typical high quality RF inductor on a power feed will resonate with the de-coupling capacitors commonly found on a circuit board. The voltage-ringing transient associated with this resonance can easily double the applied voltage in the presence of a sharp rise-time voltage step, not to mention causing a peak in the response of the filter. Care must be taken to use “lossy” ferrites or resistive damping to control the ringing, and each design should be bench tested with this in mind.

8. Component De-rating

Operating electronic components well below their maximum ratings can have a significant impact on reliability. See the graphs in figures 8 and 9 to see how de-rating can affect the failure rate of tantalum capacitors.

Figure 8 Correction to failure probability vs. temperature

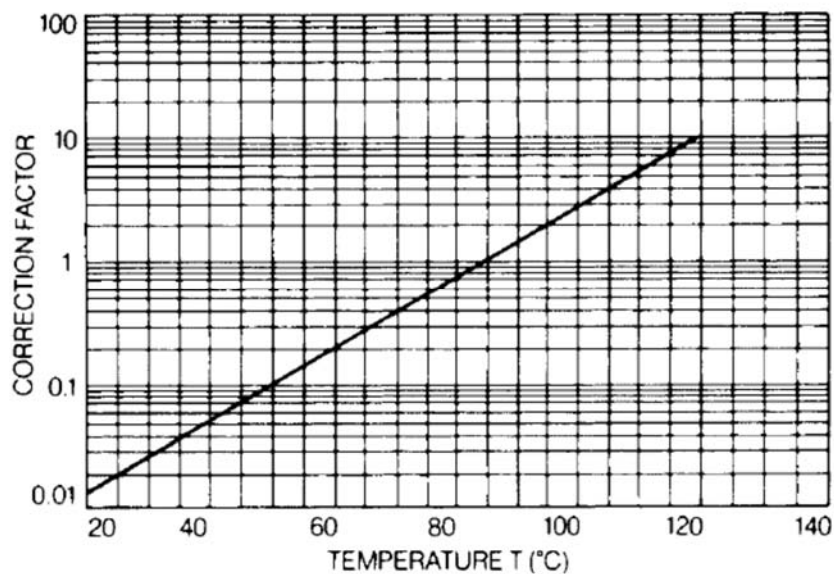
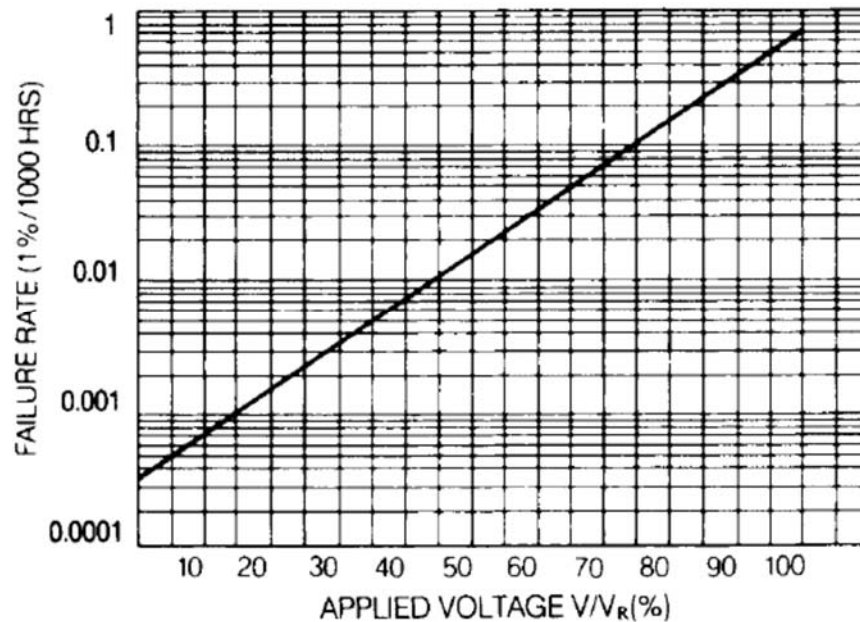


Figure 9 Correction to failure probability vs. voltage de-rating



It is easy to see how a relatively small change to a bill of materials can have a profound effect on reliability.

9. Miscellaneous Topics

As a collection point for random topics, the next section will likely expand over time

Connectors – Cable connectors used within a sealed electronics pod should be minimized by design and eliminated wherever possible. Preference should be given to directly soldered wires. Mating contact surfaces should be gold plated.

Relays – When relays are required in a high reliability design, it is sometimes possible to put contacts in parallel to create a type of built-in spare thus reducing the failure probability. The Omron G6H series of surface mount relays has been used with good results, and has a contact rating of 2 million cycles.

Cable Crosstalk – It is important to evaluate the coupling of wires within bundles to preclude the possibility of design failure. This type of design flaw can result in the same amount of misery as an actual component failure. As the wire-to-wire coupling increases, systems with gain first exhibit noise amplification, but then can actually form a local oscillation with neighboring systems.

Unfortunately, these types of problems are not always visible during bench testing, so the systems must be evaluated in situ

10. Case Study

In January of 2013, circuits associated with the Radio Frequency Photo Detectors (RFPDs) had been designed and built for use in the aLIGO interferometers. These circuits had a susceptibility that would result in failure if the either polarity of the DC power were lost. An event at the rack level caused the +18VDC power to be absent while the -18VDC power was still applied. The net result was the immediate destruction of three complex and expensive RFPDs. Even if the positive supply were to be restored, the RFPDs would still be latched up and drawing 15 to 20 times the nominal current.

An analysis of the problem found that certain factors existed that contributed to the susceptibility of this design to failure. A summary of key factors includes:

- The use of integrated circuit operational amplifiers that require special attention to power supply sequencing. These chips (AD85xx and AD86xx) offer excellent performance, but many will self-destruct upon loss of one polarity of DC power supply voltage. The RFPDs were re-designed to avoid these chips where necessary to ensure no remaining sensitivity to losing a single DC power form.
- It was found during testing that the loss of one polarity of DC voltage causes a back feeding effect resulting in the positive 15VDC regulator being driven negative, or the negative 15VDC regulator being driven positive. This sets the stage for an enhanced level of susceptibility to catastrophic latch-up. The mitigation was to put reverse biased clamping diodes across the positive and negative regulated power rails. A silicon 1N4001 diode proved quite effective.
- The RFPDs are powered from a dedicated power conditioning chassis. This chassis provides soft start on power up, reverse polarity protection, and missing supply protection. However, this is not much use if the RFPD head is powered and unpowered by unplugging the cable from the head. The proper method for powering and un-powering an RFPD would be to use the on/off switch on the back of the RFPD power-supply chassis. Failure to do this will circumvent the soft start circuit and result in large inrush currents into the tantalum capacitors used to filter the power supplies in each RFPD. Eventually, the large surge current can result in failure of the capacitor. Unfortunately - as previously mentioned - these capacitors fail as a short circuit.