National Aeronautics and Space Administration

Single-Event Transients Evaluation of Emerging Point-of-Load Converters using the New JPL Pico-Second Pulsed Laser System

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NASA Electronic Parts and Packaging (NEPP) Program
Office of Safety and Mission Assurance

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1.0 INTRODUCTION

As demand for high-speed, on-board, digital-processing integrated circuits (ICs) on spacecraft increases (FPGAs and DSPs in particular), the need for the next generation of point-of-load (POL) regulators becomes a prominent design issue. Shrinking process nodes have resulted in core rails dropping to values close to 1.0 V, drastically reducing margin and increasing the impact of single-event transients (SETs) to POL regulators that power digital ICs.

The goal of this task is to perform SET characterization of several emerging commercial POL converters and to provide a discussion of the impact of these results on state-of-the-art digital processing ICs through laser and heavy ion testing. This work is funded through the NASA Electronic Parts and Packaging Program (NEPP) and is performed in conjunction with NASA Goddard Space Flight Center's (GSFC) radiation effects and analysis group.

This year, the NEPP POL radiation task was assigned to study the impact of load conditions and input voltage on the SET response of emerging POL regulators. Pulsed laser techniques have shown some promising results in recent years and are becoming a standard when it comes to screening devices before heavy ion characterization or identifying sensitive circuits not discernable with broad-beam testing. It is now admitted that, with good calibration, laser pulses can simulate heavy ion effects in analog circuits. As a result, the primary focus of the task was to take advantage of the temporal and spatial charge injection capabilities of the pulsed laser system to further investigate manufacturer broad-beam testing.

Leveraging Rosa Leon's (JPL) and Jack Shue's (GSFC) test capabilities for POL characterization (i.e., DC-parametric, transient response and frequency response) and Dakai Chen's (GSFC) heavy ion test results made this work a truly collaborative effort. A secondary effort was to identify radiation issues or additional space requirements that might not be addressed for commercial applications of POL converters.

2.0 DEVICE OVERVIEW

Based on several discussions and previous broad-beam testing performed both by manufacturers and GSFC's radiation group, several commercially available POL regulators were selected to investigate SETs observed with the JPL pulsed laser system. The targeted test devices were all buck (step-down converters) for which the targeted application is a two-stage power architecture that requires a typical intermediate voltage of about 5 V dc. International Rectifier's SBB503R3S, Intersil ISL70001SRH, MS Kennedy 5920, and Crane MS0507 were subjected to laser screening. Due to the variety of components used to design these DC/DC switching power converters (devices designed in CMOS and BiCMOS technologies, power devices, etc.), several single-event effects are probable to occur (SEL, SEU, SEB, and SEGR). With respect to SEE laser testing for this type of design, SEB and SEGR are very unlikely to occur during testing. SEL is susceptible to occur in BiCMOS design blocks and SEU when logic is used in PWM circuits. That being said, the focus of this testing was to evaluate the devices' sensitivity to the single-event transient phenomena and provide complementary information such as the identification of sensitive circuits and transient magnitude with different conditions (i.e., bias and load). It should be noted that single photon laser testing has two main limitations: 1) the laser pulse cannot go through metal, which means it is probable that some transients observed with heavy ion might not be observed with laser; and 2) the correlation between heavy ion linear energy transfer and laser pulse energy is difficult, which indicates that only worst-case estimates can be provided from a laser test.

2.1 International Rectifier SBB503R3S

The IR SBB503R3S is a hybrid, "radiation-hardened," non-isolated POL capable of converting a 4.5V to 5.5V input voltage to standard voltage outputs, including 1.0V to 3.3V. This POL is capable of a high efficiency (~ up to 89%) and an output power up to 30 W. The nominal switching frequency is 400 kHz [1]. A block diagram of the device is shown in Figure 1. The regulation technique in this design uses a combination of voltage and current mode control. The PWM and High-Side Gate driver are the areas susceptible to create transients.

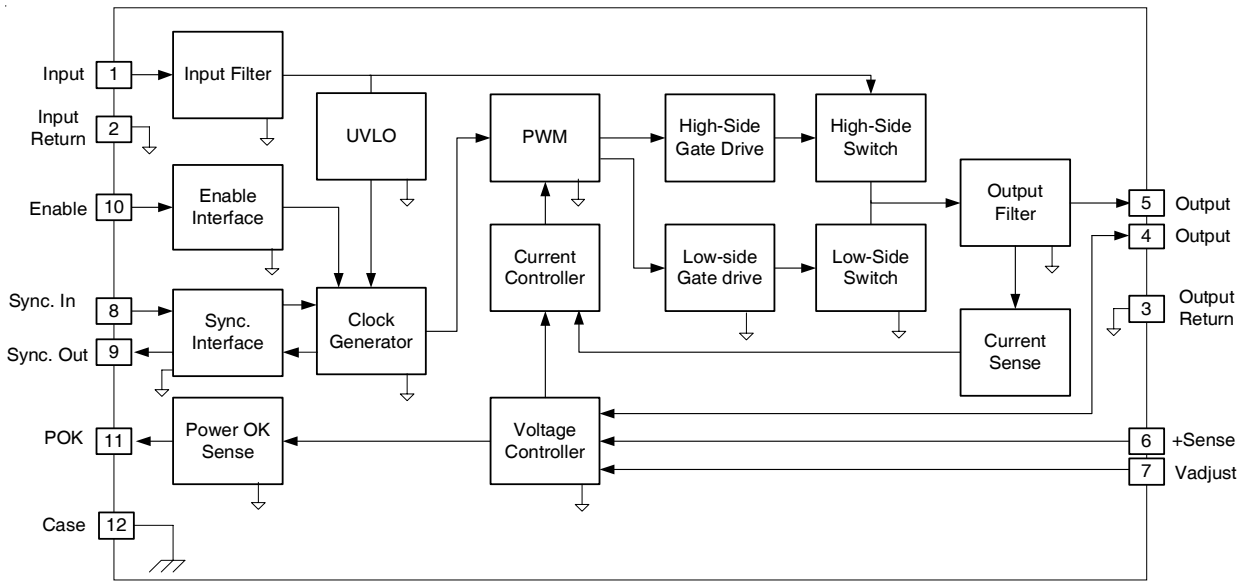


Figure 1. Block Diagram of the IR SBB503R3S

2.2 Intersil ISL70001SRH

The Intersil ISL70001SRH is a radiation-hardened monolithic synchronous buck regulator capable of converting an input voltage of 3V to 5.5V to an output that is adjustable from 0.8V to 85% of the input voltage with a high efficiency (~ up to 89%). The output load-current capacity is 6 A at a junction temperature up to +125°C. The nominal switching frequency is 1 MHz. A block diagram of the device is shown in Figure 2. To harden the design, Intersil used a triple modular PWM block [2].

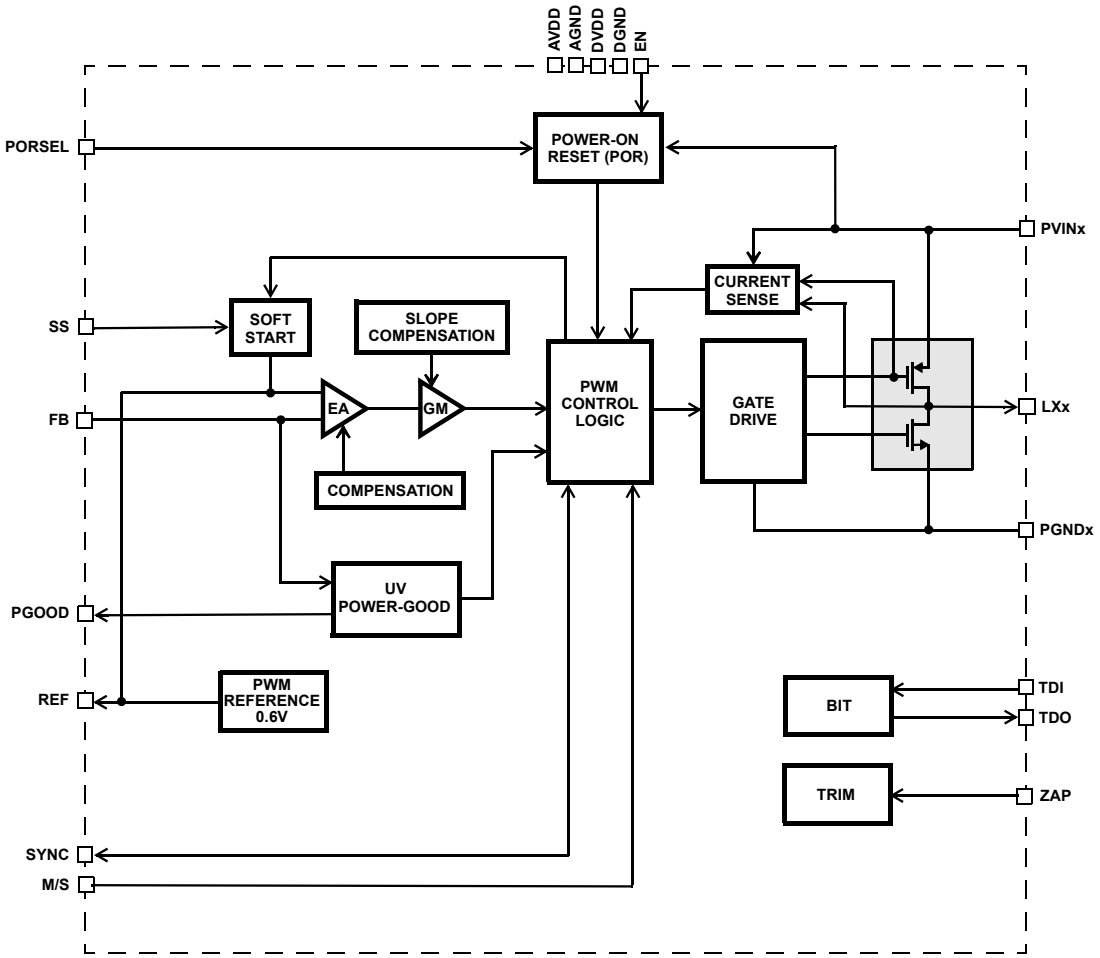


Figure 2. Block Diagram of the Intersil ISL70001SRH

2.3 MS Kennedy 5920RH

The MS Kennedy 5920RH is a radiation-hardened linear regulator with an input voltage range of 2.9V to 6.5V. The 1.5V and 2.5V fixed output devices were tested for this work. The devices are capable of delivering 5A of output current, with a typical dropout of 0.3V with a 3A load. The device has an external shutdown function as well as internal latching overload protection [3].

2.4 Crane MFP0507S

The Crane Interpoint MFP0507S is a single-output, non-isolated POL regulator that can supply any voltages between 0.8V DC and 3.3 V DC. The rated output current is 7 A at 0.8 V and 5 A at 3.3V. The input voltage range is from 3.3 V to 6 V; however, the selected output voltage should not exceed 80% of the input voltage. Its maximum output power of 16.5 W is with output set for 3.3V and 5A. Maximum output power with the output voltage set for 0.8 V and 7 A is 5.6 W [4].

3.0 FACILITIES, EXPERIMENTAL SETUP, AND DEVICE PREPARATION

3.1 Facilities

To simulate the effect of heavy ions, we used the JPL pulsed laser system. The laser system is a mode-locked Ti:sapphire cavity pumped by a 5 W diode-pumped solid-state laser at 532 nm. A laser beam with a 2 ps pulse width was tightly focused through a microscope objective onto the device under test (DUT). During the test, the Ti:sapphire's output beam had a wavelength range of 800 nm, with typical power between 400 and 600 mW, making it possible to simulate heavy ion effects with relative high linear-energy-transfer (LET) values. The system also incorporates a motorized three-axis stage to move the DUT and scan the area with resolution better than 100 nm. Figure 3 describes the system.

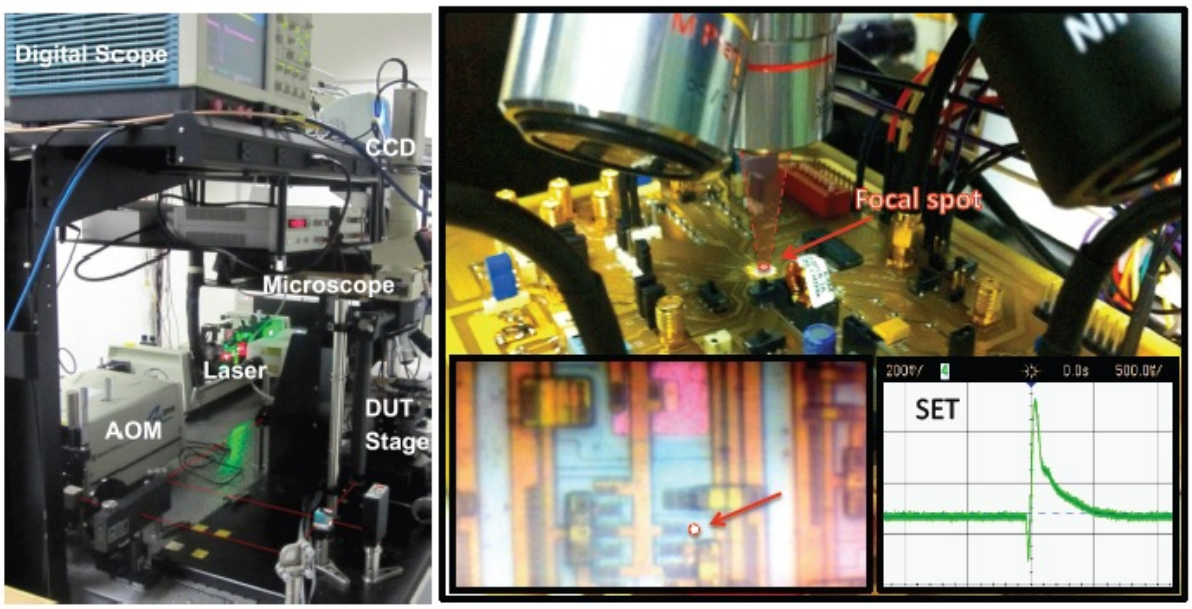


Figure 3. The laser system (left) delivers light to the DUT stage. The objective lens of the microscope focuses the pulsed laser light onto the DUT (right) while a CCD camera images the circuit (lower left inset). A digital scope records the voltage transients (lower right inset) while the device position is precisely moved by a computer-controlled, 2-axis translation stage.

3.2 Equipment/Test Setup

The general test setup for both the pre-irradiation measurements and the irradiation measurements is shown in Figure 4. Table 1 describes the equipment specifics. An Agilent 3 channel power supply provided the DUT's input voltage supply. Power was controlled and monitored via custom Visual Basic software. High impedance (10 MΩ) voltage probes were used to monitor the DUT's output. The function generator was used to switch resistive loads on and off via a MOSFET for step-load change measurements (used for pre-irradiation measurements only).

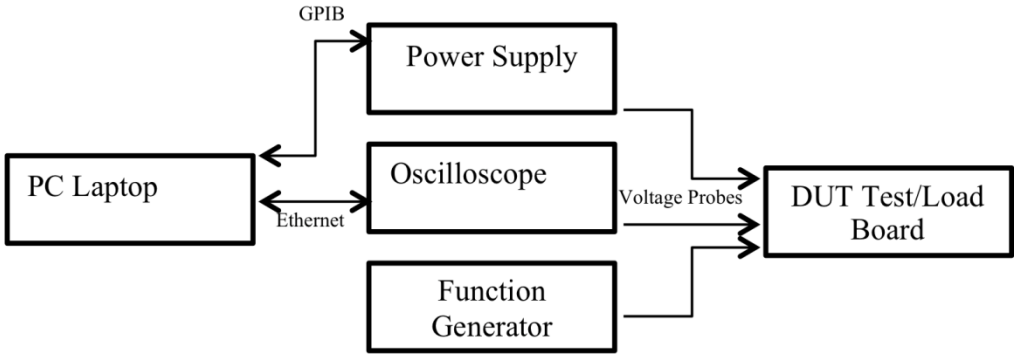


Figure 4. Test Setup Block Diagram

Table 1. Equipment List

Equipment	Kind	Cal Date	Tag
Agilent 6623A	Power Supply	9/13/11	1713945
Agilent MSO6034A	Oscilloscope	6/21/11	2208632
Agilent 33220A	Function Generator	-	2534121
AM 503B	Current Probe	4/21/11	-
Agilent 4294A	Impedance Analyzer	9/21/11	2219954

3.3 Test Samples

Only a limited number of devices were provided for this evaluation. All devices tested were provided at no-cost by the manufacturers, and only one POL was a fully integrated design. Test samples are identified in Table 2. Figures5-8 show die structures of each POL.

Table 2. Test Samples

Part Number	Quantity	Type	Package type	Manufacturer
ISL70001SRH	1	Bi-CMOS	Hermetic	Intersil
SBB503R3S	1	Bi-CMOS	Hermetic	IRF
MSK5920-1.5 MSK5920-2.5	1 ea.	Bi-CMOS	Hermetic 5 pin metal FP	MSK
MFP0507S	2	Bi-CMOS	Hermetic	Interpoint

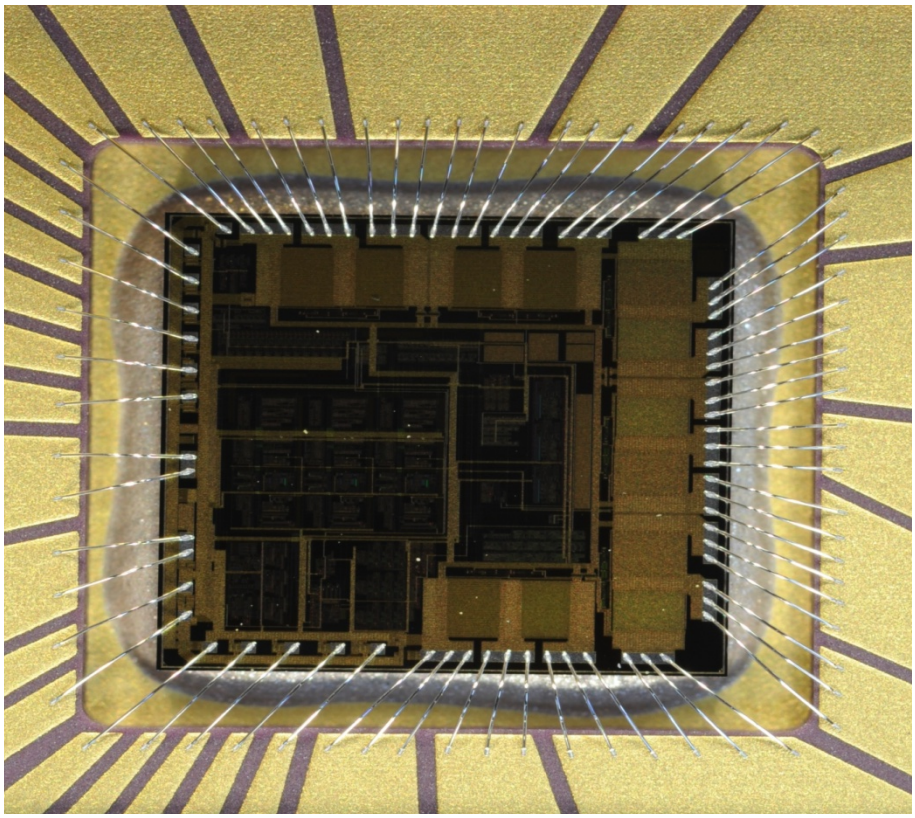


Figure 5. Die image of the Intersil ISL70001SRH.

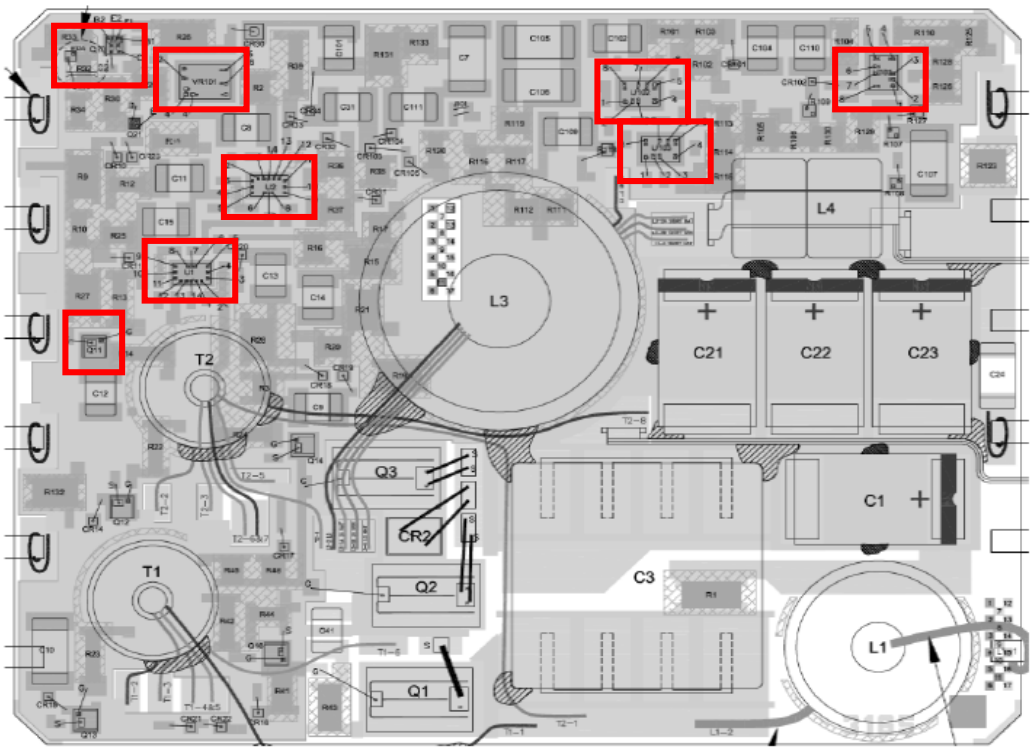


Figure 6. Layout of the International Rectifier SBB503R3S. The potentially sensitive ICs are indicated by red outlines.

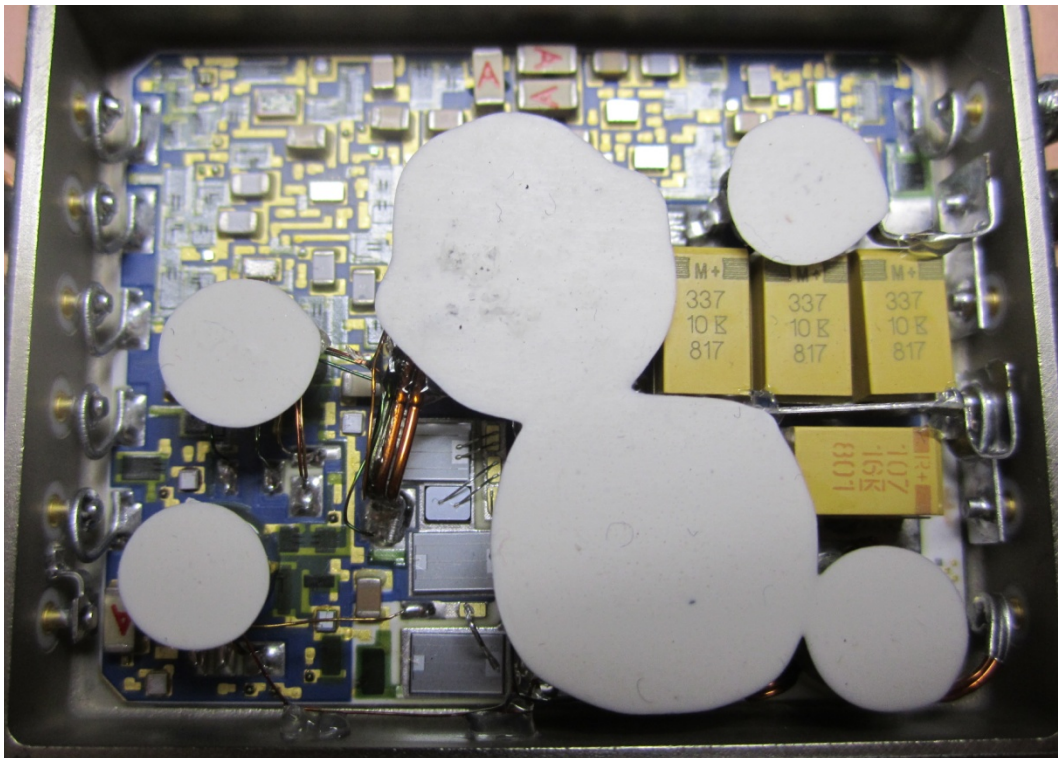


Figure 7. Image of the International Rectifier SBB503R3S hybrid.

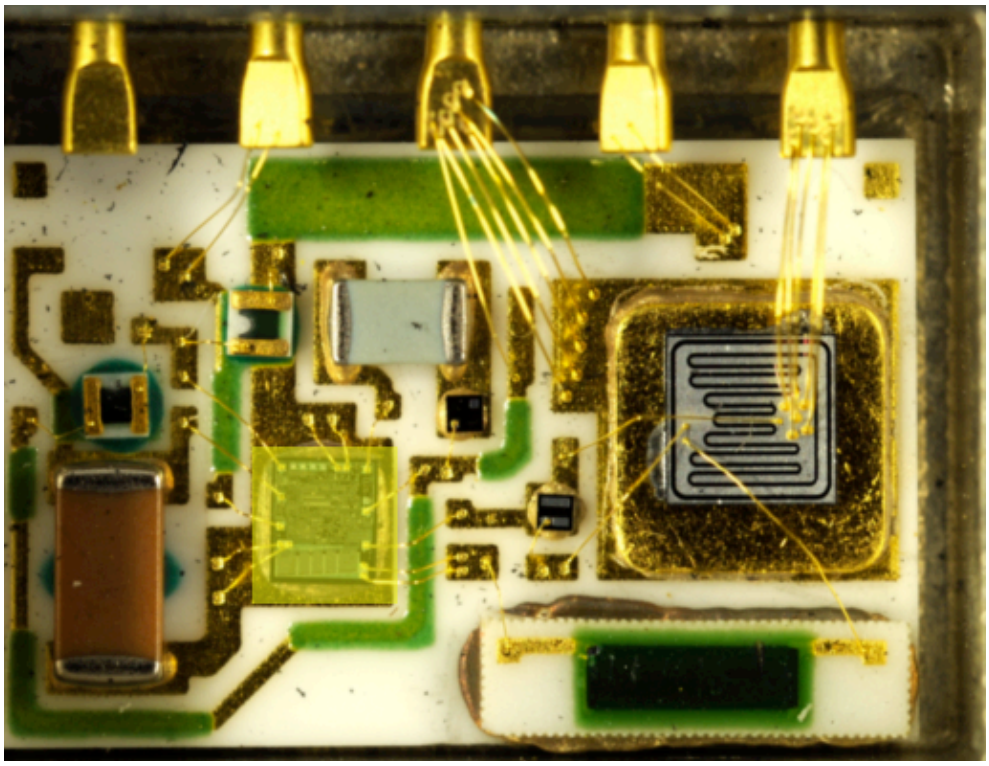


Figure 8. Die image of the 2.5V MSK5920. The yellow highlighted region is the region of interest where the laser scanning took place. The die in question is an RH1573 die.

3.4 Device Preparation and Test Boards

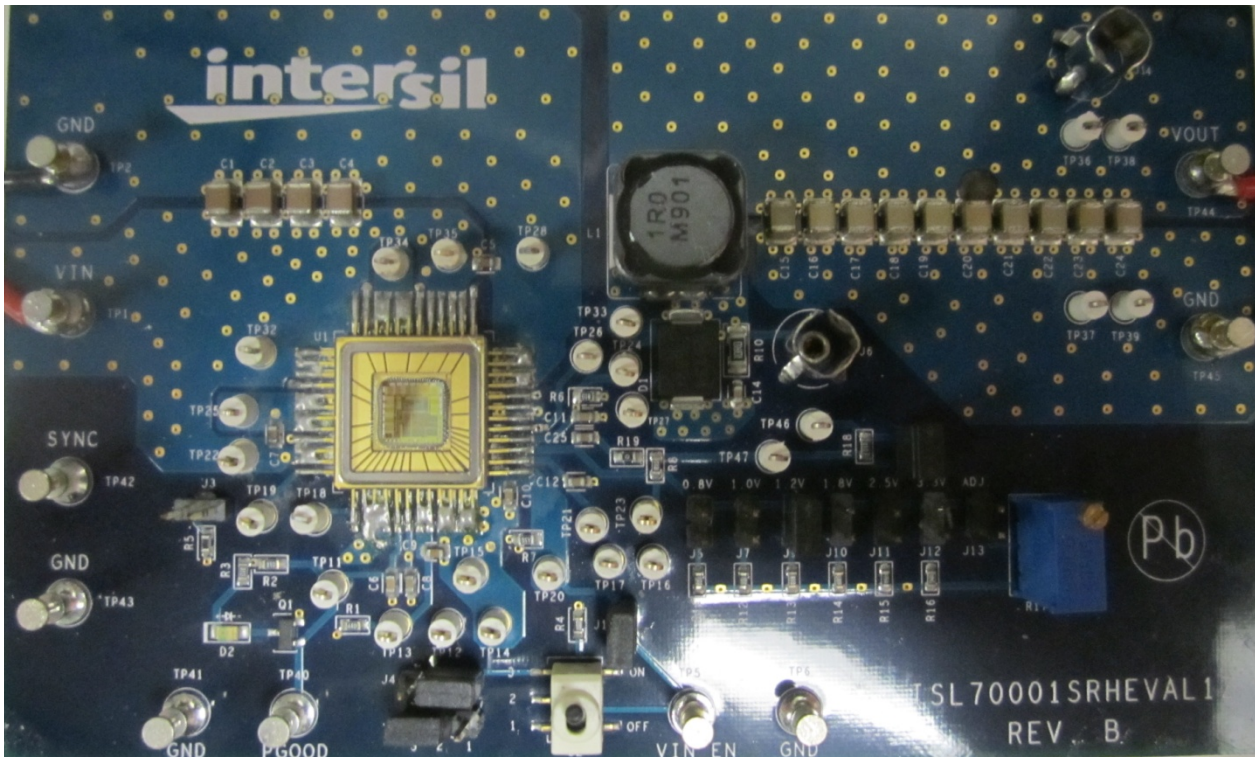


Figure 9. Photo of the Intersil ISL70001SRHEVAL1 evaluation board.

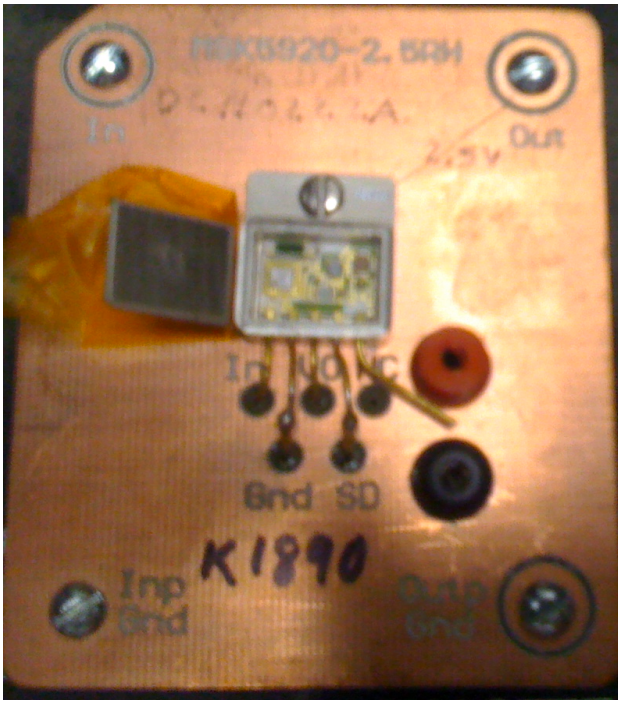


Figure 10. The 2.5V MSK5920 daughter card.

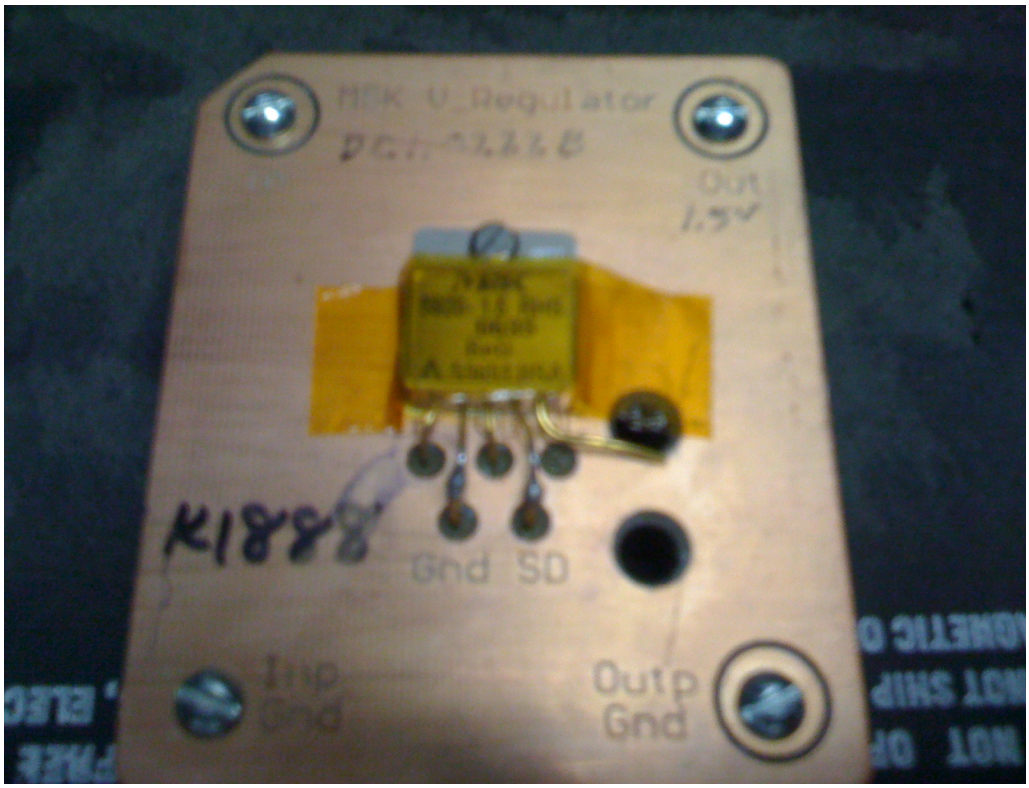


Figure 11. The 1.5V MSK5920 daughter card.

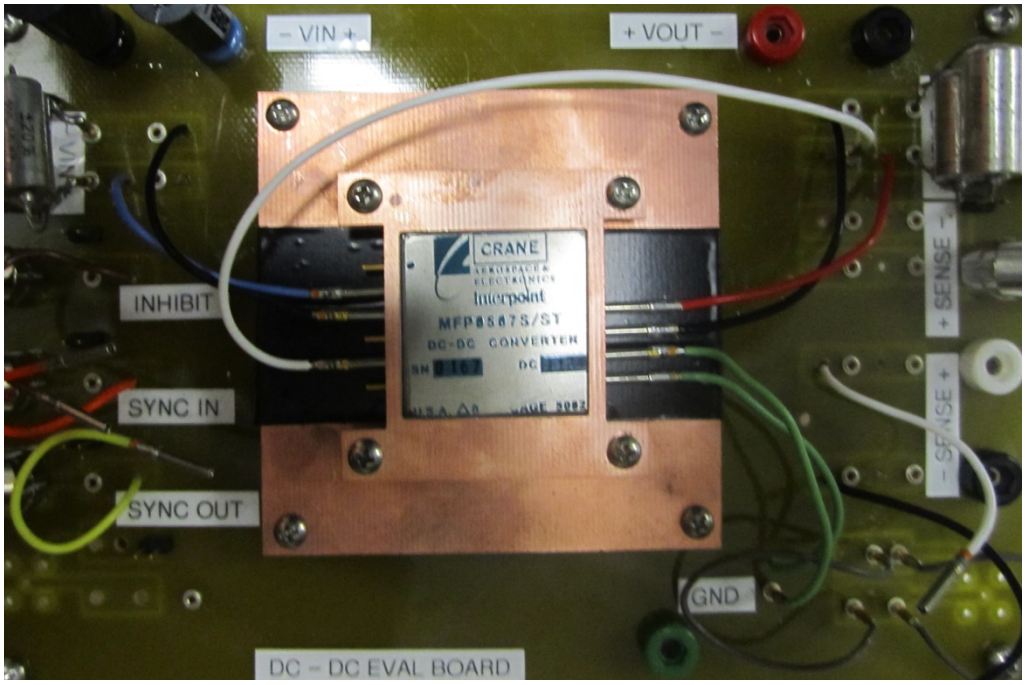


Figure 12. The Interpoint Crane MFP0507S test board.

4.0 TEST PROCEDURE

This section outlines the general test procedure that was followed for the testing of all of the aforementioned devices.

4.1 Pre-Irradiation Measurements

Check board and device functionality.

a) Measure the converter efficiency as a function of input voltage and compare with datasheet specification
b) Measure transient voltage overshoot with load step changes (full to half load) and compare with datasheet specification
c) Check the converter regulation through the entire range of input voltage and load conditions

4.2 Irradiation Conditions

To simulate heavy ion effects, we used the JPL pulsed laser system with different energy.

a) Perform a laser energy calibration by using existing heavy ion data on a known candidate device (i.e., LM124 from NSC)
b) Measure the output voltage and detect any transient pulses for the worst-case bias conditions
c) Scan and irradiate every IC of the hybrid converter shown in Figure 6 and record any existing transients

4.3 Failure Criteria

The failure criteria were defined as (1) failure if transients measured exceed the transient voltage overshoot with load-step changes (full to half load) datasheet specification, (2) interruption of the device functionality induced by charge collection in a sensitive area of the converter, and (3) the regulator goes unstable for a specific bias/load condition.

5.0 TEST RESULTS

5.1 Pre-Irradiation Measurements

Figures 13 and 14 illustrate the turn-on, turn-off, and step-load measurements. Those measurements are typically a good indicator of the loop stability of both linear and switching DC-DC converters. In the case of a linear regulator, it is shown that the ESR of the output capacitor has a significant impact on the loop stability (see section 5.4.). As a result, when possible, ESR was intentionally introduced to the output of the regulator.

5.1.1 ISL70001SRH

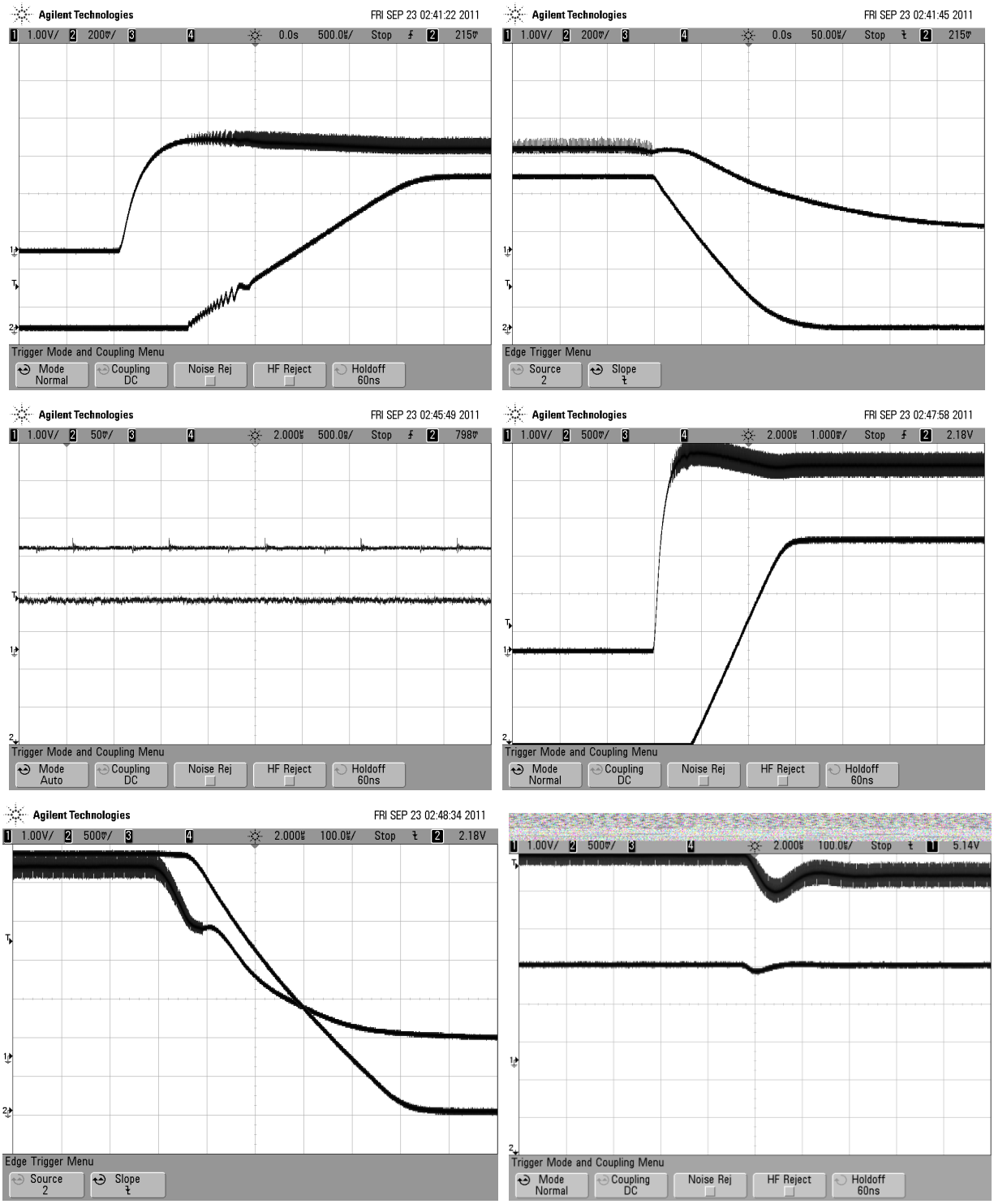


Figure 13. Turn-on, turn-off, and step-load measurements for the Intersil ISL70001SRH. The top left is the 0.8V turn-on, top right is 0.8V turn-off, middle left 0.8V switching load. The middle right, bottom left, and bottom right are the 3.3V turn-on, turn-off, and switching load measurements, respectively.

5.1.2 SBB503R3S

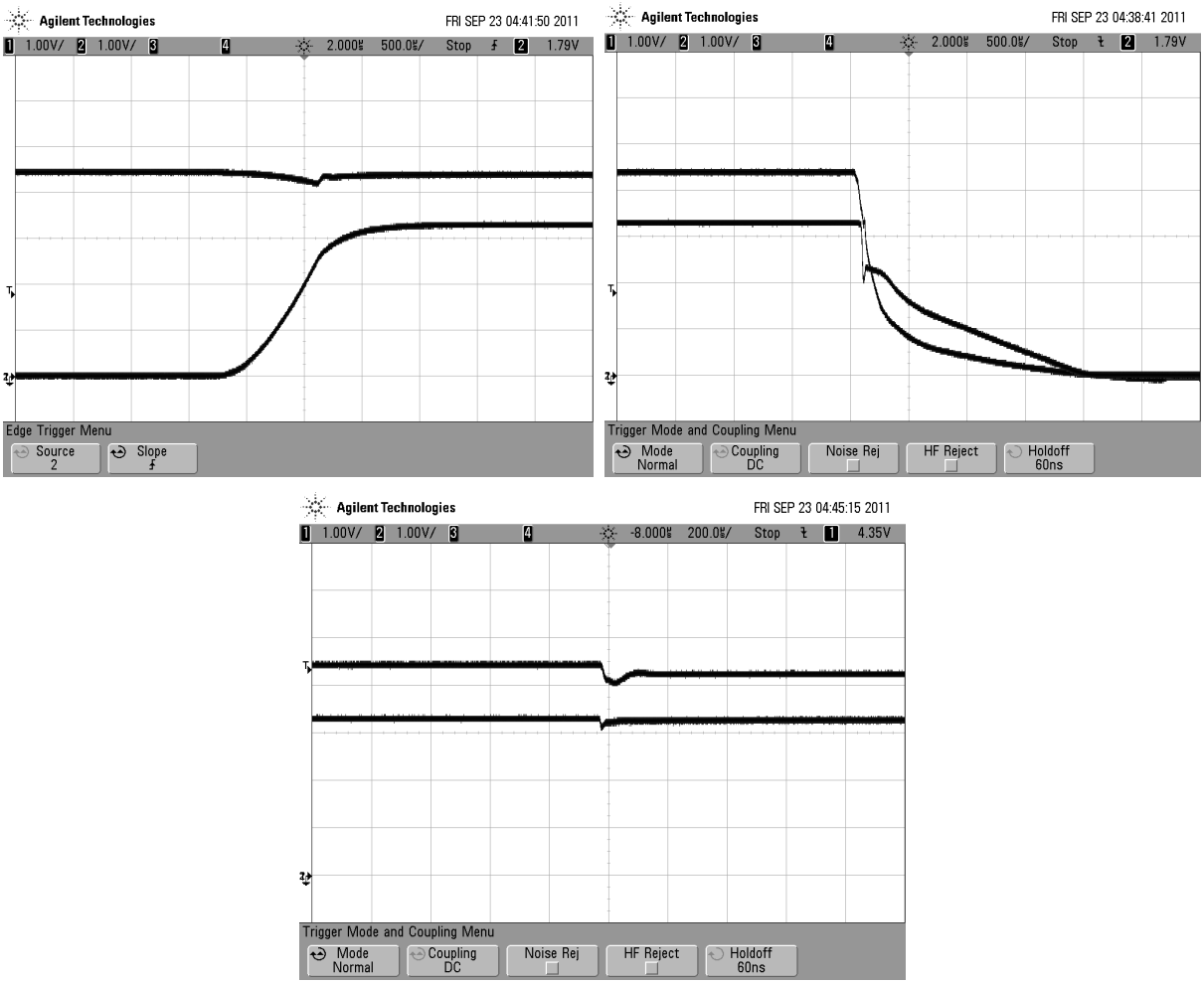


Figure 14. Turn-on, turn-off, and step-load measurements for the International Rectifier SBB503RS3. The top left is the 3.3V turn-on, top right is 3.3V turn-off, middle left is the 3.3V switching load.

5.1.3 MSK5920

It is well known that the output capacitor of a linear regulator can make it oscillate if the capacitor is not correctly selected. Indeed, every real capacitor contains unwanted parasitic elements that degrade its electrical performance. The most important elements are the Equivalent Series Resistance (ESR) and the Effective Series Inductance (ESI). While the ESI tends to limit the capacitor effectiveness at high frequencies, the ESR is the primary cause of regulator loop instabilities. In addition, with respect to radiation, the dependence of the SET shape is also likely to be affected by ESR, and it is often the case that we find discrepancies in the SET data of a same device tested by different agencies. It is also possible that SET can introduce some unexpected instability for configurations that appear to be stable electrically.

The loop response of a typical regulator is shown below in Figure 15. The most important point is that for a stable loop, the gain must cross below 0 dB before the phase angle reaches 180°. A phase angle of 180° means that the signal being fed back around the loop is actually positive feedback and will cause oscillations to occur. In a linear regulator, the output capacitor is required to force the gain to roll off fast enough to meet the stability requirements. If the ESR value is not adequately selected, the “zero frequency” can get low enough to cause the instability. Typically manufacturers provide a range of values to ensure stabilities of their devices.

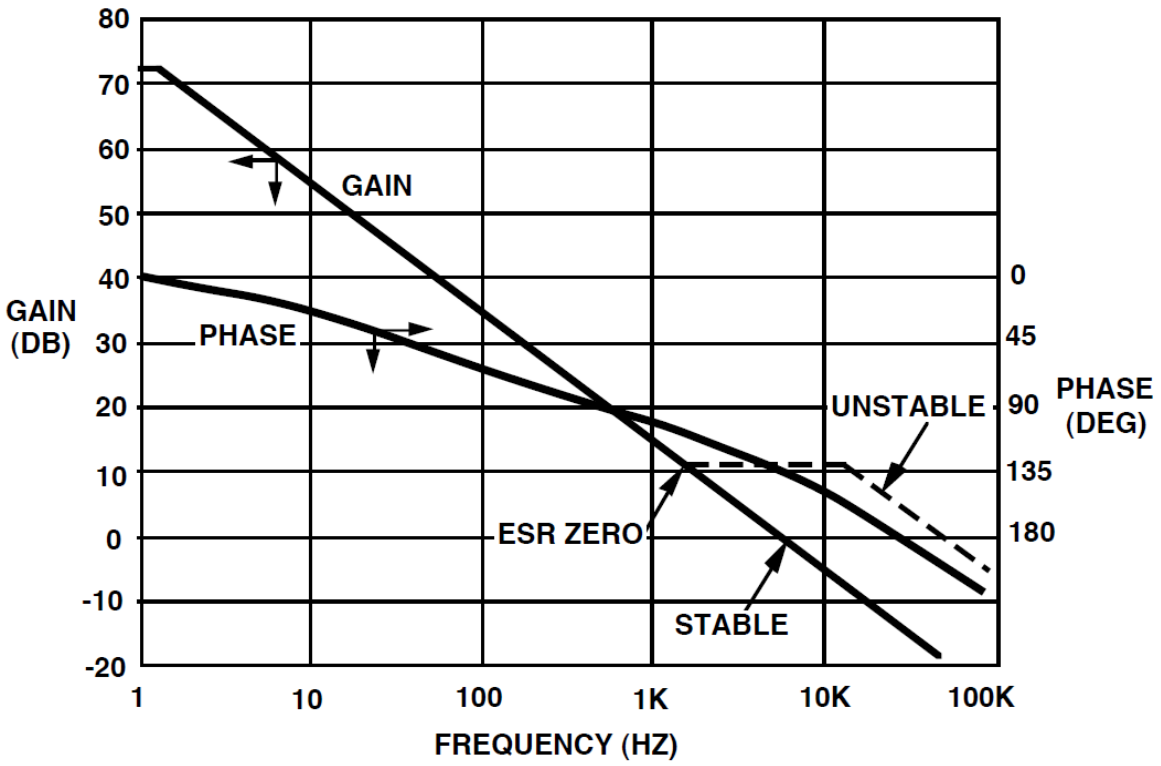
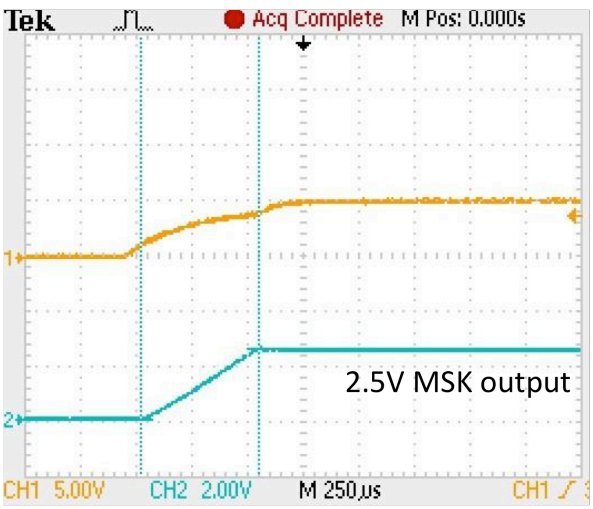


Figure 15. Example of loop gain plot for a regulator.

The MSK5920RH part is considered in this study. It is an ultra-Low Dropout (LDO) positive linear regulator that is commonly used in flight project. As explained above, LDO regulators (also called single PNP regulator) rely on the ESR of the output filter capacitor to ensure stability. The LDO regulator output has high output impedance that results in the RC load behaving as a dominant pole to the frequency loop. To obtain stable operation, it is essential to obtain an output capacitor with the ESR value within the determined range provided by the manufacturer and to pay close attention to the layout to minimize unwanted parasitic elements. A common practice to evaluate the stability of a converter is to perform a turn-on test. This is particularly true when standard loop gain and phase measurements are not accessible within the devices. Figure 16 illustrates two extreme cases: one when the regulator is stable after a turn-on test and one that is unstable, meaning that the LDO output exhibits some unacceptable oscillation (400 mV Pk-Pk) due to the wrong ESR capacitor value being used.

For the MSK5920, M.S. Kennedy made recommendations for output capacitor with selected ESR. Values are summarized in Table 3. In this table, MSK revised their recommendations for output capacitor selection. Rev. O recommended using a 220 uF tantalum output capacitor, while in rev. P this recommendation was changed to four low ESR 220 uF capacitors specifically of the type CWR29FB227 from AVX, screened to an ESR of 57 mOhm maximum. The change in recommendation was initiated based on stability analysis performed by one of their customers. (Note that while the analysis was performed for the MSK5820, this device can be considered identical in electrical performance to the MSK5920, the only difference being in the passivation of the internal IC.) This change has been a concern for most NASA programs because these modifications could lead to instabilities in their design.

Stable Turn-On Characteristics
MSK5920



Unstable Turn-On Characteristics
MSK5920

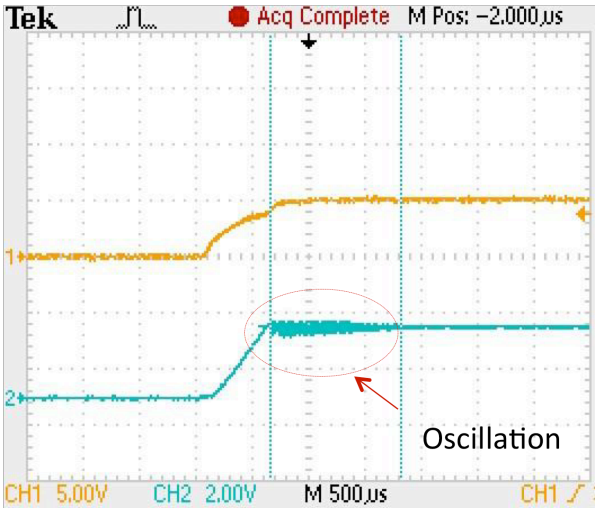


Figure 16. Illustration of a stable and unstable turn-on test for the MSK5920. For this particular case, a value 220 uF capacitor with an ESR > 100 mohm was used. The peak-to-peak amplitude of the oscillation was over 200 mV.

Table 3. MSK output capacitor/ESR recommendations for stabilities

Rev	Capacitor Recommendation	ESR Recommendation	Comments
H	One 220 uF surface mount tantalum	0.1 to 1.0 Ohm	CWR19, 10V, meets this recommendation
O	One 220 uF surface mount tantalum	None	
P	Four 220 uF surface mount tantalum CWR29FB227 (AVX p/n TAZH227K010L)	< 57 mOhm	CWR29 must be screened to meet lower ESR

A few examples of both stable and unstable measurements are shown below. The remainder of the configurations is exemplified in Appendix A. Figures 17–23 and Figures A1–A13 in Appendix A show the power-on and step-load change measurements; results are outlined in Table 4. Four cases were considered:

- Damped indicates a damped oscillation was observed.
- Driven indicates the observed oscillation was sustained.
- Pass indicates no recordable oscillations were observed.
- Fail indicates the regulator failed to regulate.

Table 4. Summary of findings about stability studies with turn-on and step-load test.

Generic Number	Vin	Input Capacitor	ESR (mOhm)	Output Capacitor	ESR (mOhm)	Series Res (Ohm)	Turn On (min Load)	Load Switching (min to max)
MSK5920-1.5	5V	47uF CWR29	125	220uV 10V CWR19	338	0	Damped	Driven
MSK5920-1.5	5V	47uF CWR29	125	220uV 10V CWR29	40	0	Pass	Pass
MSK5920-1.5	5V	47uF CWR29	125	220uV 10V CWR29	40	0.1	Damped	Pass
MSK5920-1.5	5V	47uF CWR29	125	220uV 10V CWR29	40	0.5	Pass	Fail
MSK5920-2.5	5V	47uF CWR29	112	220uV 10V CWR29	413	0	Damped	Driven
MSK5920-2.5	5V	47uF CWR29	112	220uV 10V CWR19	51	0	Pass	Pass
MSK5920-2.5	5V	47uF CWR29	112	220uV 10V CWR19	51	0.1	Pass	Pass
MSK5920-2.5	5V	47uF CWR29	112	220uV 10V CWR19	51	0.5	Pass	Fail

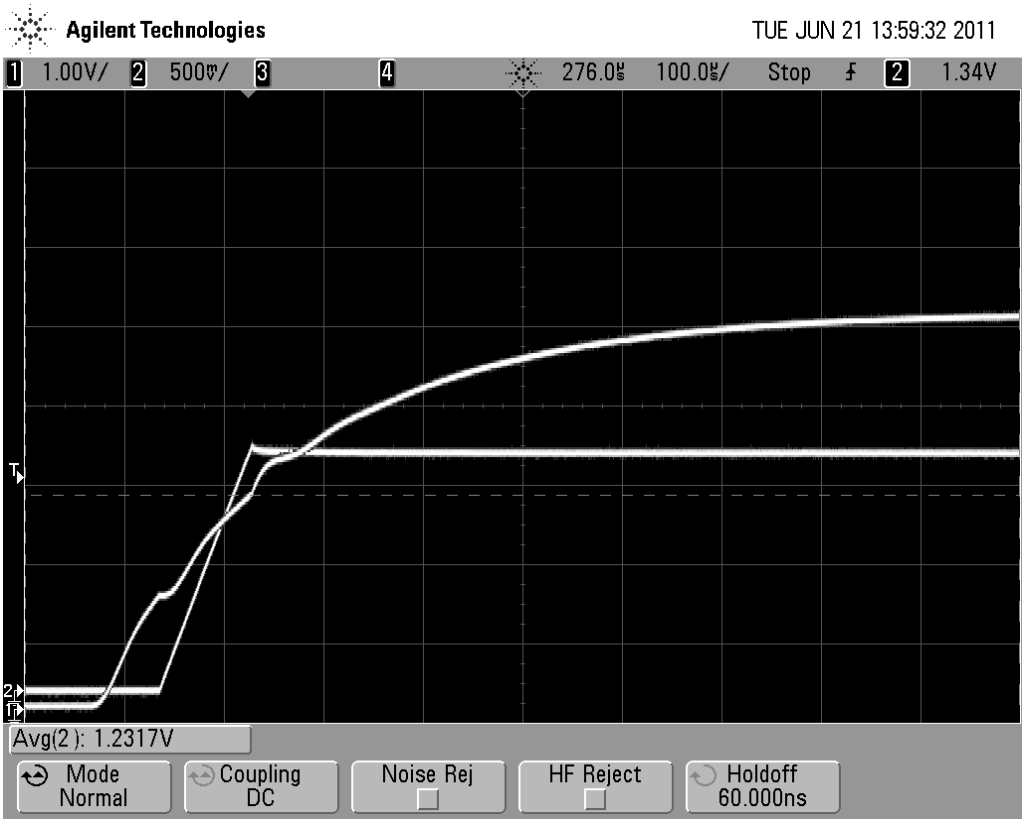


Figure 17. The 1.5 V MSK5920 turn-on curve with minimum load. Channel 1 is the input power supply and channel 2 is the regulator's output. The output capacitor was a CWR29 220uF 10V device (SN R0244) with a measured ESR of 40 mOhm.

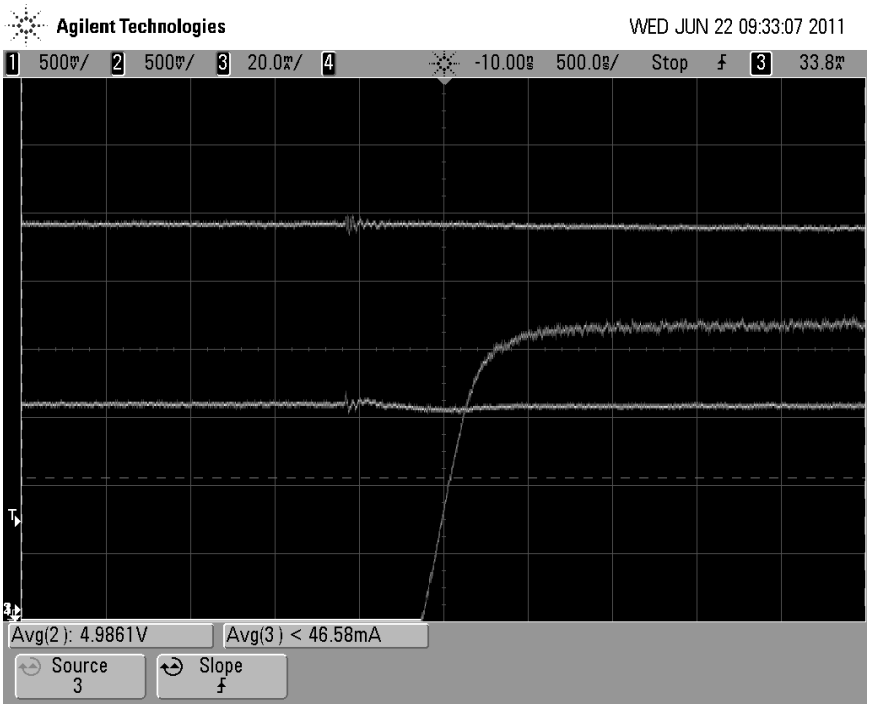


Figure 18. The 1.5 V MSK5920 low to high switching load characterization is shown here. The top trace is the input power supply and the middle trace is the regulator's output. The capture was triggered on the rising edge of the output supply current. The output capacitor was a CWR29 220uF 10V device (SN R0244) with a measured ESR of 40 mOhm.

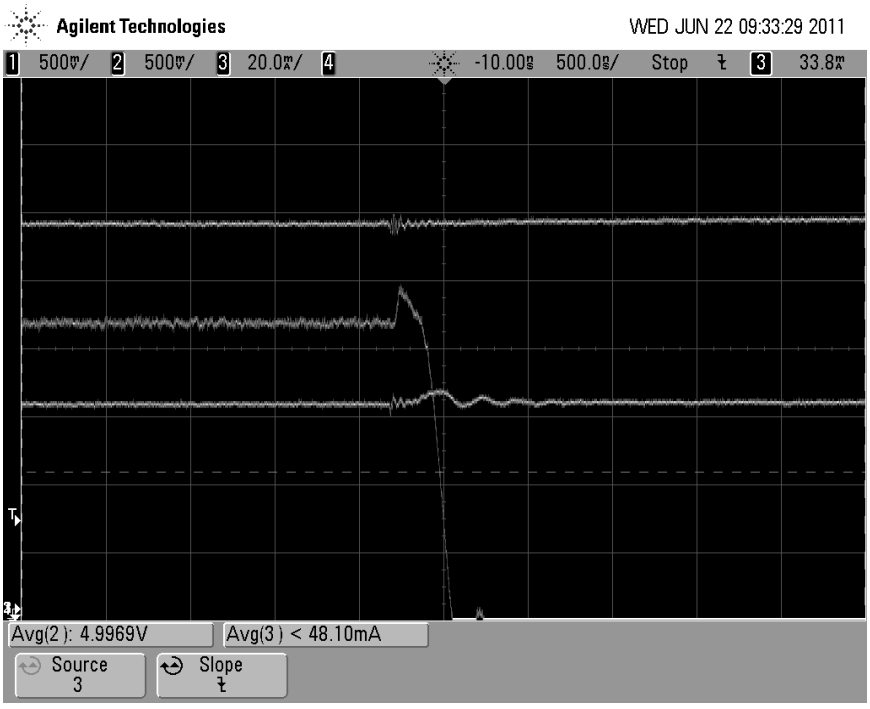


Figure 19. The 1.5 V MSK5920 high to low switching load characterization is shown here. The top trace is the input power supply and the middle trace is the regulator's output. The capture was triggered on the falling edge of the output supply current. The output capacitor was a CWR29 220uF 10V device (SN R0244) with a measured ESR of 40 mOhm.

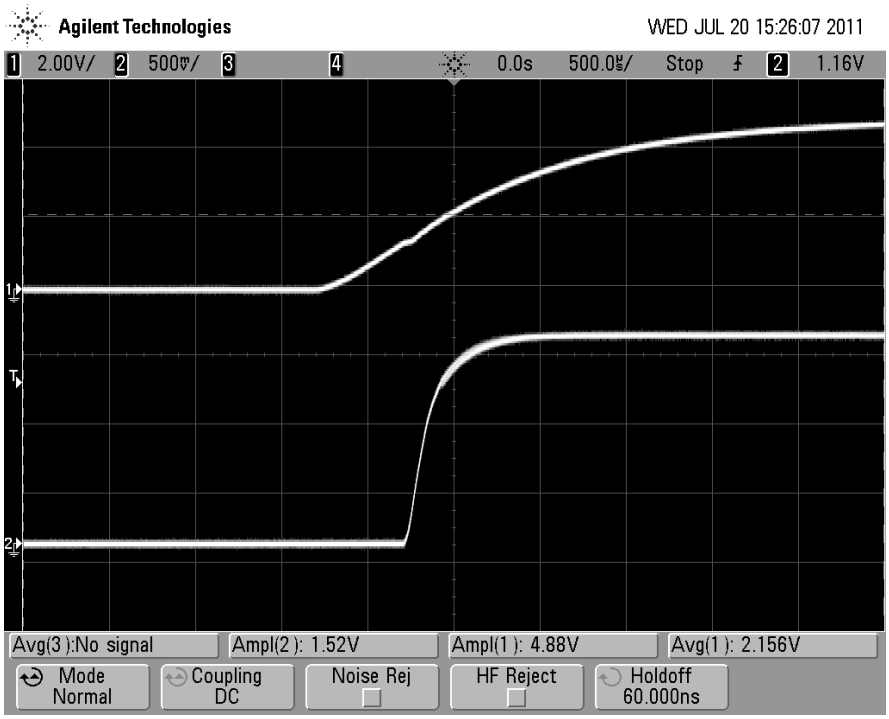


Figure 20. The 1.5 V MSK5920 turn-on curve with minimum load. Channel 1 is the input power supply and channel 2 is the regulator's output. The output capacitor was a CWR29 220uF 10V device (SN R0244) with a measured ESR of 40 mohm. A 0.5 ohm series resister was inserted in line with the regulator's output and the tantalum output capacitor.

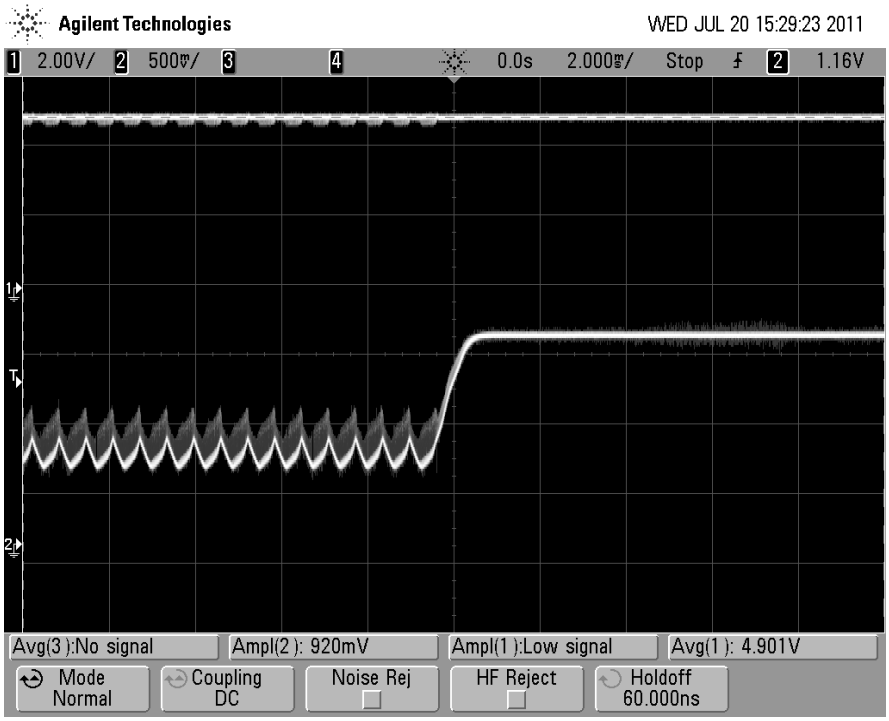


Figure 21. The 1.5 V MSK5920 high to low switching load characterization is shown here. The top trace is the input power supply and the bottom trace is the regulator's output. The output capacitor was a CWR29 220uF 10V device (SN R0244) with a measured ESR of 40 mOhm. A 0.5 ohm series resister was inserted in line with the regulator's output and the tantalum output capacitor. Note that the device is not regulating when at full load.

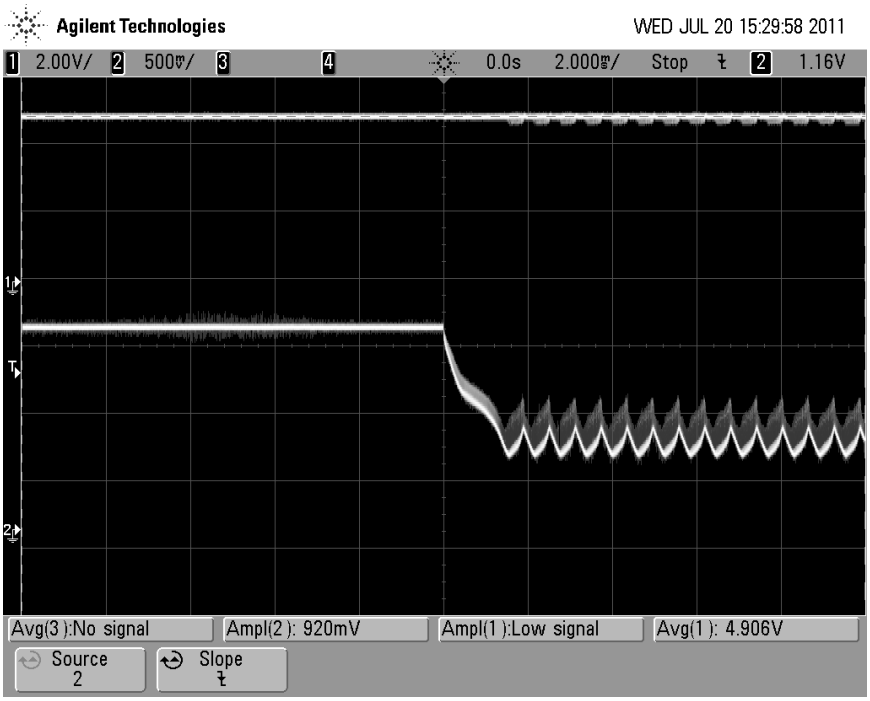


Figure 22. The 1.5 V MSK5920 low to high switching load characterization is shown here. The top trace is the input power supply and the bottom trace is the regulator's output. The output capacitor was a CWR29 220uF 10V device (SN R0244) with a measured ESR of 40 mOhm. A 0.5 ohm series resister was inserted in line with the regulator's output and the tantalum output capacitor. Note that the device is not regulating when at full load.

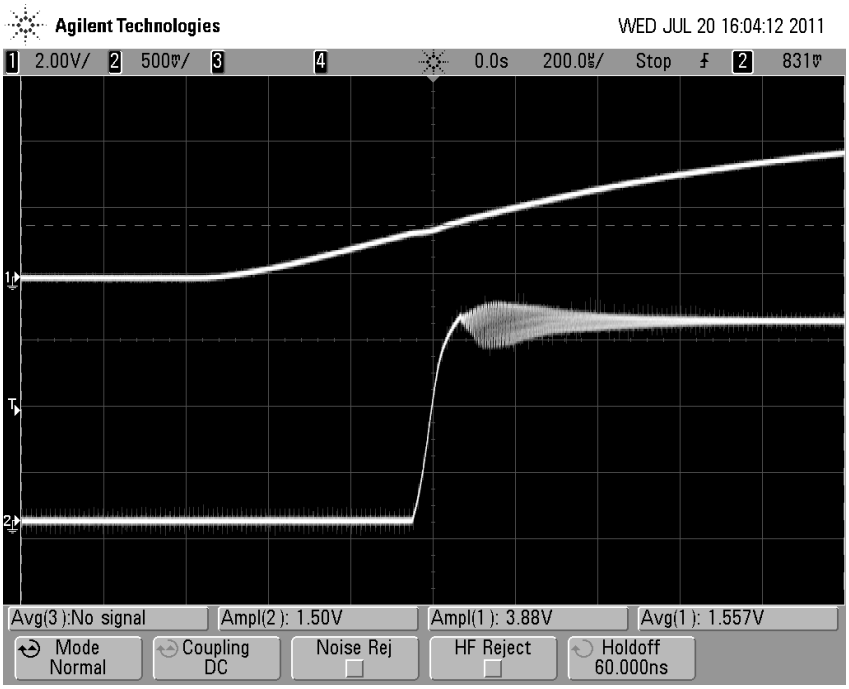


Figure 23. The 1.5 V MSK5920 turn-on curve with minimum load. Channel 1 is the input power supply and channel 2 is the regulator's output. The output capacitor was a CWR29 220uF 10V device (SN R0244) with a measured ESR of 40 mohm. A 0.1 ohm series resister was inserted in line with the regulator's output and the tantalum output capacitor. Note the damped ringing on the output.

For this pre-irradiation evaluation done on the MSK5920 devices, the following recommendations and observations could be concluded, with respect to the rev. H/O and rev. P recommendations:

- Both configurations appeared to be stable.
- Oscillations in the four-220uF configuration were observed but were attributed to the added inductance of the stacked capacitor configuration used; later tests confirmed that, with proper layout, no oscillation is observed.
- A single capacitor with ESR < 0.1 Ohm exhibited oscillations.

Note that while these tests roughly validate the rev. K and rev. P recommendations, stability of low dropout regulators is dependent on many factors specific to a circuit, e.g., layout, actual dynamic load, and stray inductance/capacitance/impedance. Optimally, for any given circuit application, a good design practice would include determination/validation of adequate phase and gain margin. However, with this particular device, it is not possible to do this by direct test due to a feedback loop internal to the device. Further, this cannot be obtained by simulation without a detailed model of the internal LT1573 controller.

In the following sections, it should be noted that the MSK5920 has only been evaluated for single-event transients in a stable configuration based on MSK recommendations. In FY12, we will focus on identifying whether, for some specific conditions (bias and load) or specific ESR values, SETs can induce instabilities. This testing will include evaluations under dynamic loading.

5.1.4 MFP0507S

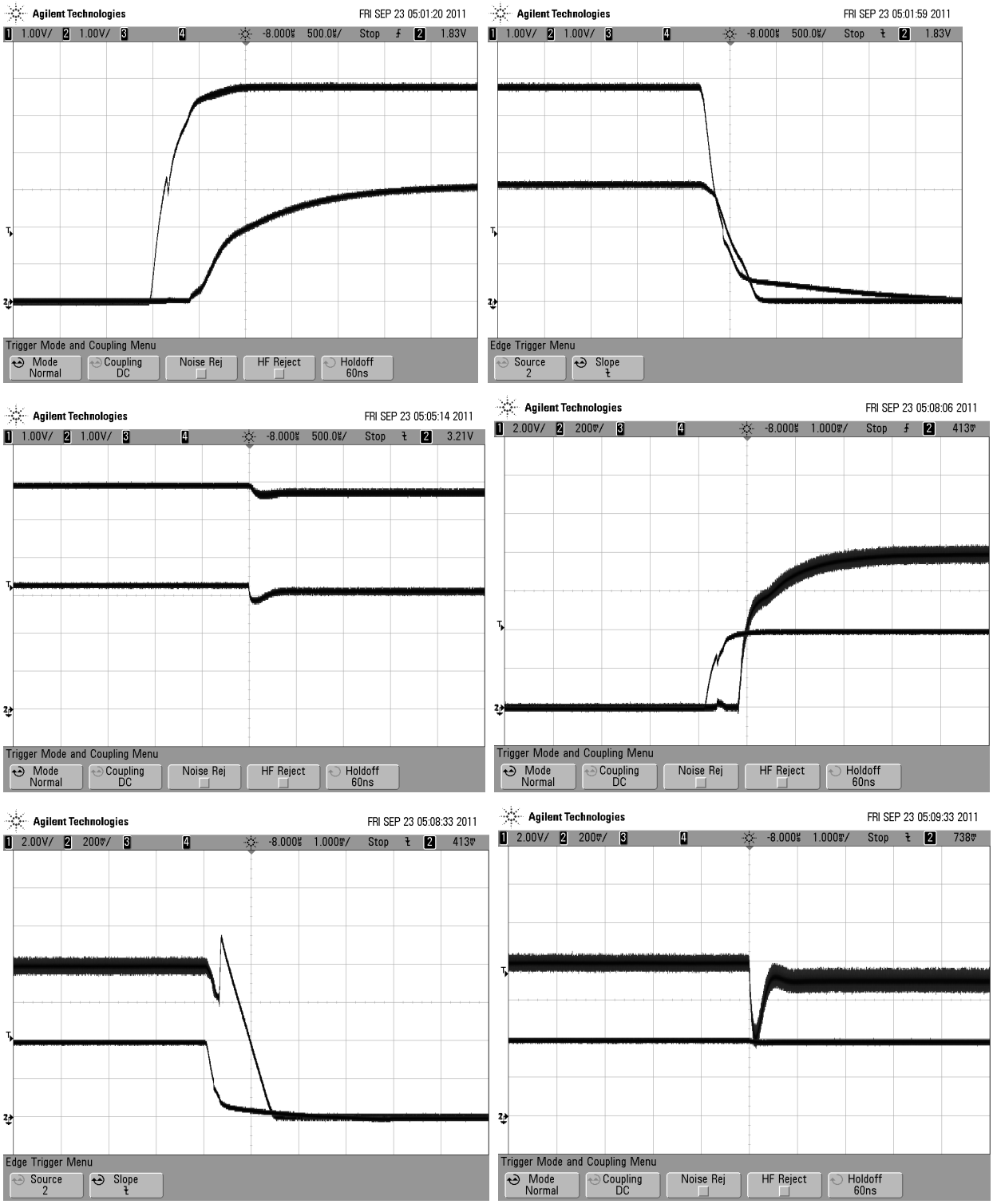


Figure 24. Turn-on, turn-off, and step-load measurements for the Crane MFP0507S. The top left is the 3V turn-on, top right is 3V turn-off, middle left 3V switching load. The middle right, bottom left, and bottom right are the 0.8V turn-on, turn-off, and switching-load measurements, respectively.

5.2 Irradiation Results

In the previous section, we evaluated all the selected DC-DC converters for regulation, stability, and efficiency with different input voltages and load conditions (i.e., min–max input voltage, min–max output voltage and high, mid and low loads). All devices appeared to be stable and show characteristics close to the datasheet specification. The following section present results about the SET laser characterization.

5.2.1 ISL70001SRH

The manufacturer published an IEEE data workshop paper in 2010. In this work, a complete SEE evaluation was performed on the ISL70001SRH POL for various input voltages and load conditions. The objective was to demonstrate the validity of their hardening approach that consisted of using some redundancy schemes in the pulse width modulation (PWM) portion of the circuit. Results in Figures 25 and 26 show that possible transients were eliminated (within ~1% of the regulation window). These results were validated with an LET up to 86.4 MeV.cm^2/mg and for a wide variety of parts.

However, the manufacturer noticed during the SEE test some SETs and SEFI-type events (i.e., causing a restart of the converter) and attributed those events to multiple ion hits due to high flux beam testing. Figure 27 illustrates this type of event. Consequently, they needed a laser evaluation to confirm their result.

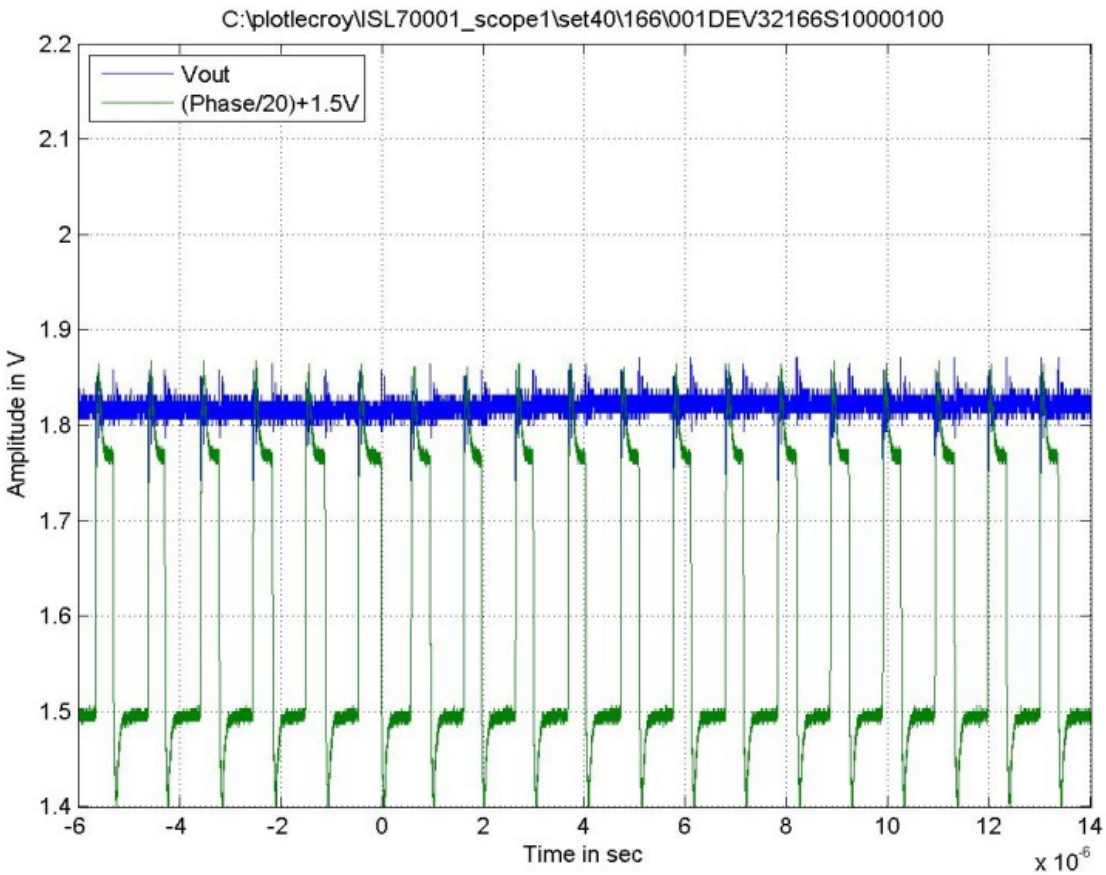


Figure 25. Typical benign pulse width modulator SET event for an LET of 43 MeV-cm^2/mg (heavy ions) for the unhardened ISL70001SRH device. The lower trace shows the LX pulses as the regulator switches the input power on and off; this pulse train will be reconstructed into DC by the output LC low pass function. The upper trace represents the DC output voltage of the converter. The SET is seen in the slight widening of the LX pulse just before the t=0 mark. The effect of the SET event on the DC output voltage is less than 1%.

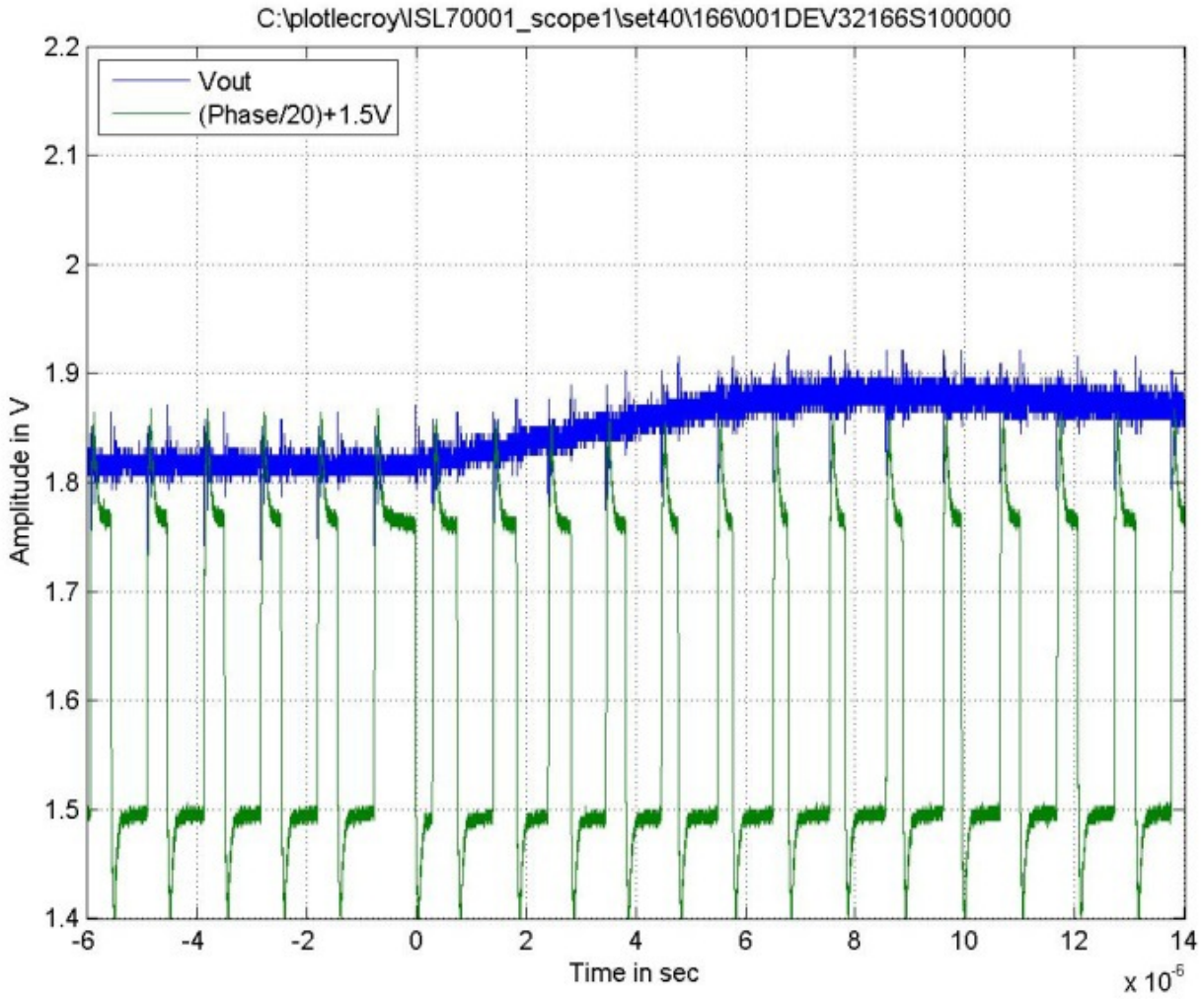


Figure 26. Disruptive pulse width SET event, also at LET of 43 MeV-cm^2/mg. The lower trace shows six wide pulses followed by recovery (off-screen) of the DC-DC converter. The upper trace represents the DC output voltage; the effect of the SET event on the DC output voltage is about 90mV. This SET signature showed strong flux dependence, suggesting double ion events in the PWM control loop.

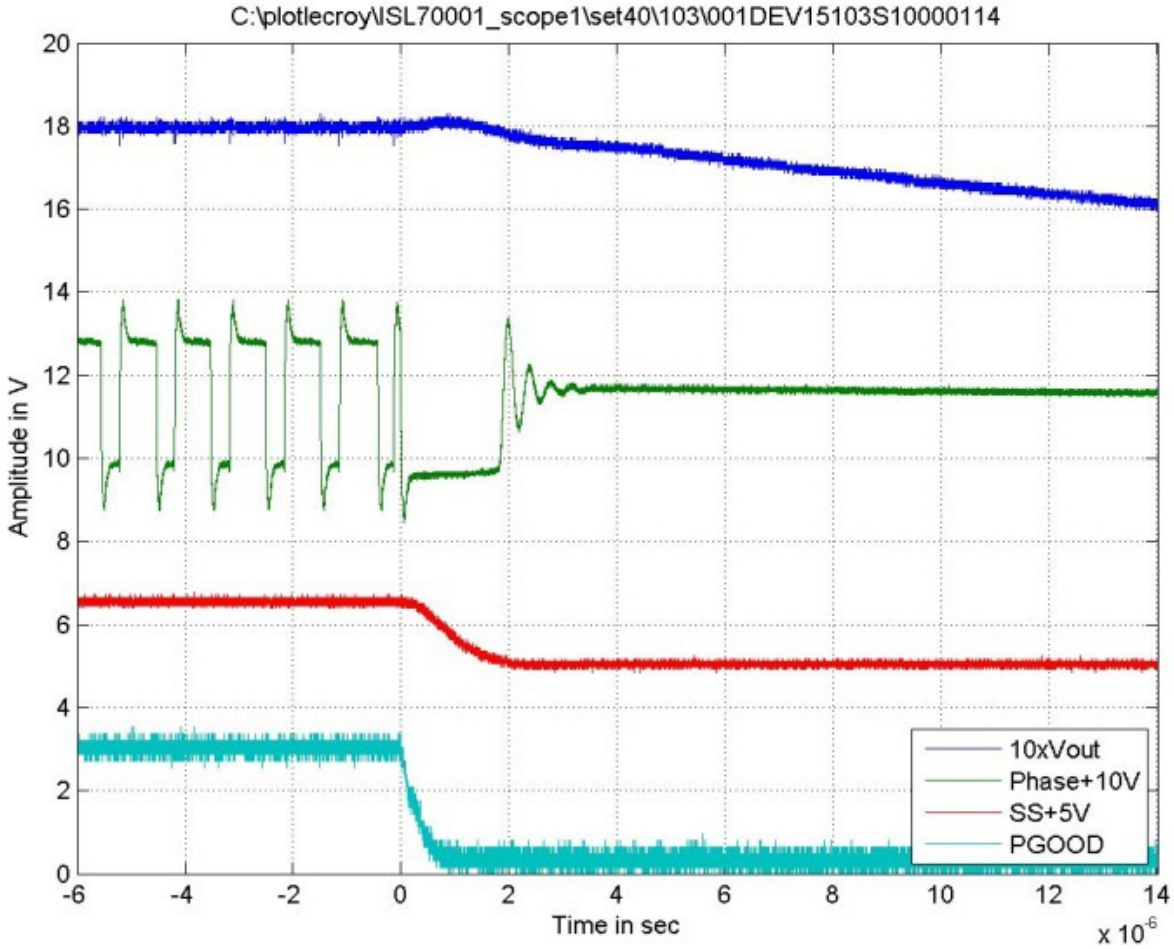


Figure 27. SEFI signature at 3 V supply. The functional interrupt results in a controlled shutdown of the converter with no preceding transients. Switching terminates (both power FETs are OFF), both PGOOD and SS reset, and the part proceeds through a normal soft start sequence (which is well beyond the time scale of this plot) without external intervention.

The entire die in Figure 5 was scanned with the laser over varying bias conditions. The laser energy selected was 350uW. We predict, for this technology, this energy is representative of LETs well above the LETs from heavy ions used to test this device. While we did observe some photocurrent effects, we did not observe any true SET or shutdown modes. Our results confirm the assumption proposed by Intersil.

5.2.2 SBB503R3S

This device has been evaluated by International Rectifier, and their evaluation guarantees SEL/SEGB/SEGR immunity up to an LET of 87 MeV.cm^2/mg. However, IR reports some single-event transient sensitivity (see Figure 28). This test was performed for only one bias condition. More investigations with varying bias and load conditions were needed.

A summary of IR heavy ion evaluation at Texas A&M is as follows:

The 10058SC series hybrid passed all of the SEE tests. Both SN 0743009 and SN 0743010 were exposed to LET levels of 37, 60 and 87 MeV-cm2 / mg. At 37 MeV-cm^2/mg (Krypton ions) exposures, SN 0743009 and SN 0743010 passed the SEE test successfully without any anomaly. At 60 MeV-cm^2/mg (Xenon ions) exposures, SN 0743009 and SN 0743010 passed the SEE test successfully without any

anomaly. However, the hybrids did experience output voltage fluctuations as high as ~60mV or 1.8%., SN 0743009 and SN 0743010 passed the SEE test successfully without any anomaly. However, the hybrids did experience output voltage fluctuations as high as ~100mV or 3.0%. Waveforms of these output voltage fluctuations can be found in Figure 28.

All sensitive ICs outlined in Figure 6 were scanned with the laser over various energies and with varying bias conditions. The laser energies selected were 253uW and 450uW. We predict, for this technology, these energies are representative of LETs well above the LETs from heavy ions used to test this device. While we did observe a few locations that induced a sagging voltage on the order of 10mV (due to photocurrents), we did not observe any true SETs. While a small SET was observed during the heavy ion testing by IR, we may not have been able to access this sensitive region with the laser due to metallization on the IC.

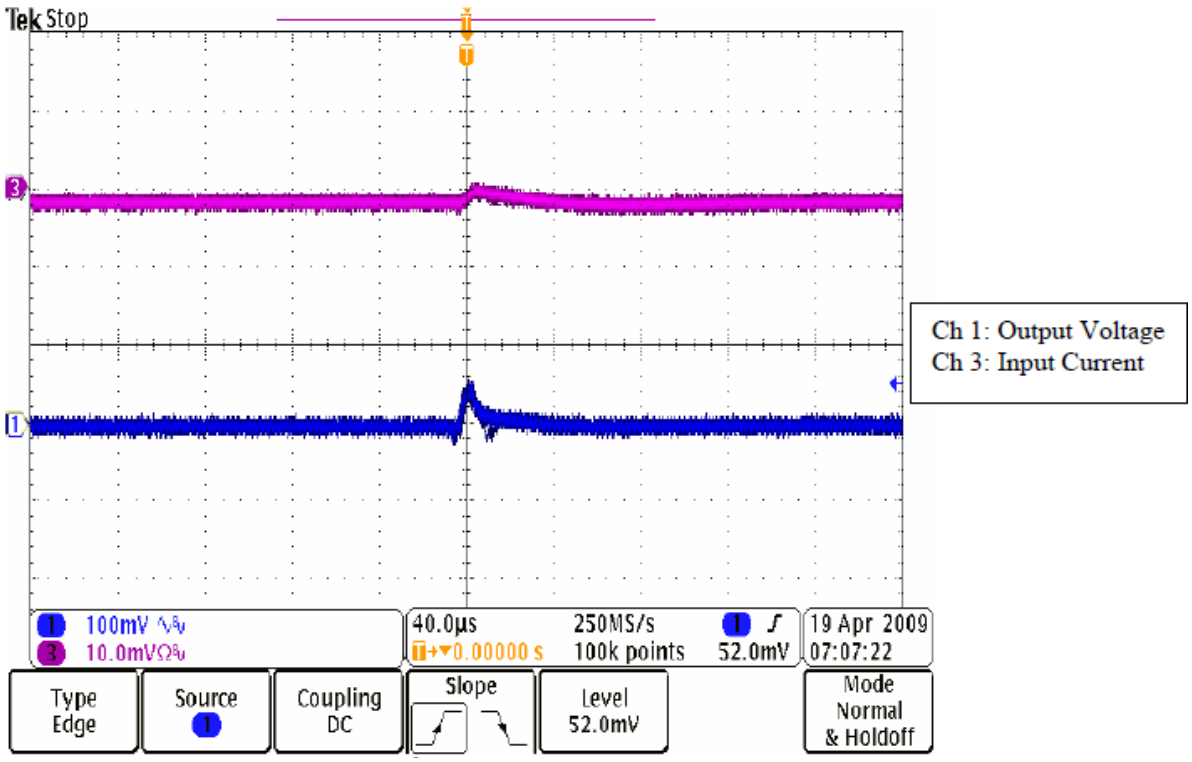


Figure 28. Run #59 at 87.3 MeV-cm2/mg (5.5V In)

5.2.3 MSK5920

We used the JPL laser system to study the SET response of the MSK5920 LDO. Measurements were only taken on configurations that showed stable (non-oscillatory) outputs. Table 5 summarizes the results of the testing.

Table 5. Irradiation Measurement Results

Generic Number	Vin	Output Capacitor	ESR (mOhm)	Series Res (Ohm)	Laser Energy (pJ)	SET Results
MSK5920-1.5	5V	220uV 10V CWR29	40	0	13	A small cross-section of small SET (see Figure 29 for the worst case observed) was recorded. The maximum recorded amplitude was 160mV and less than 1μs in duration. Only one oscillatory state was recorded; see Figure 30. Furthermore, a shutdown mode was observed, whereby the device output went to 0V and required an input voltage power cycle to regain regulation. 13pJ is the approximate laser energy threshold for this event. This event was not observed in the laser testing performed on the MSK5820 in [3]. It was later discovered this event was due to an exuberant amount external light (from the light used to view the die). When this was reduced, the shutdown mode was no longer observed.
MSK5920-2.5	5V	220uV 10V CWR19	51	0	14	No SETs were recorded.

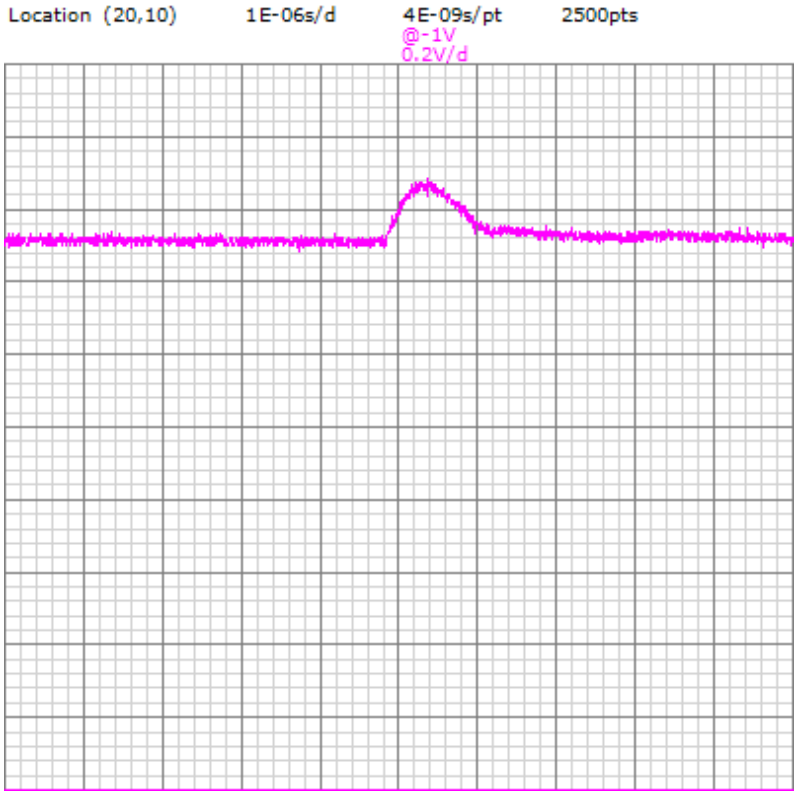


Figure 29. Worst-case SET recorded for the 1.5V MSK5920. The SET was 1 μs in duration and 160mV in amplitude.

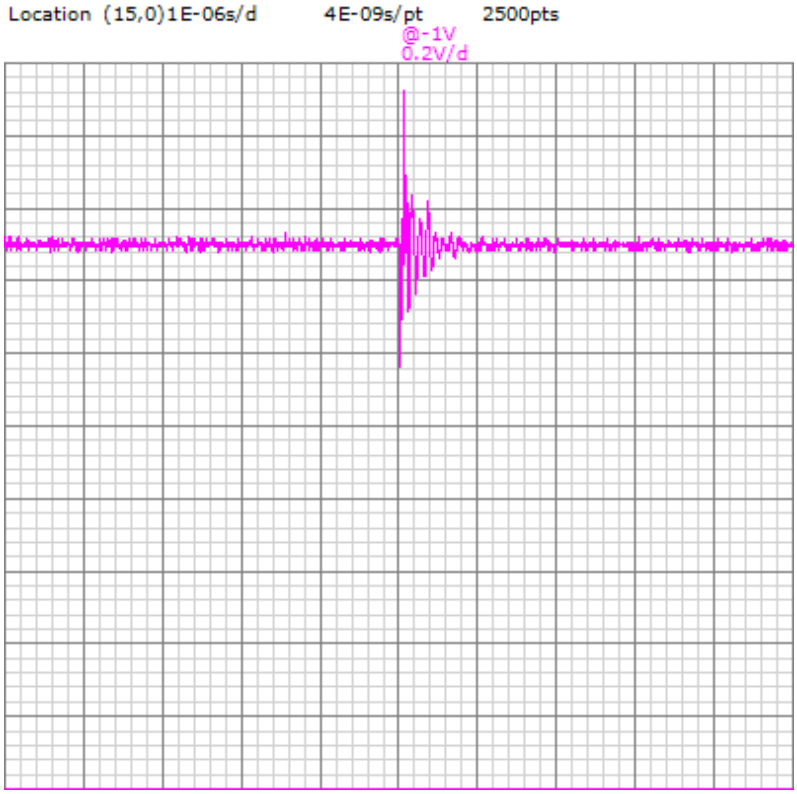


Figure 30. Oscillatory mode recorded for the 1.5V MSK5920. This was a singular occurrence; no other oscillations were observed. The oscillation duration was under 1 μs.

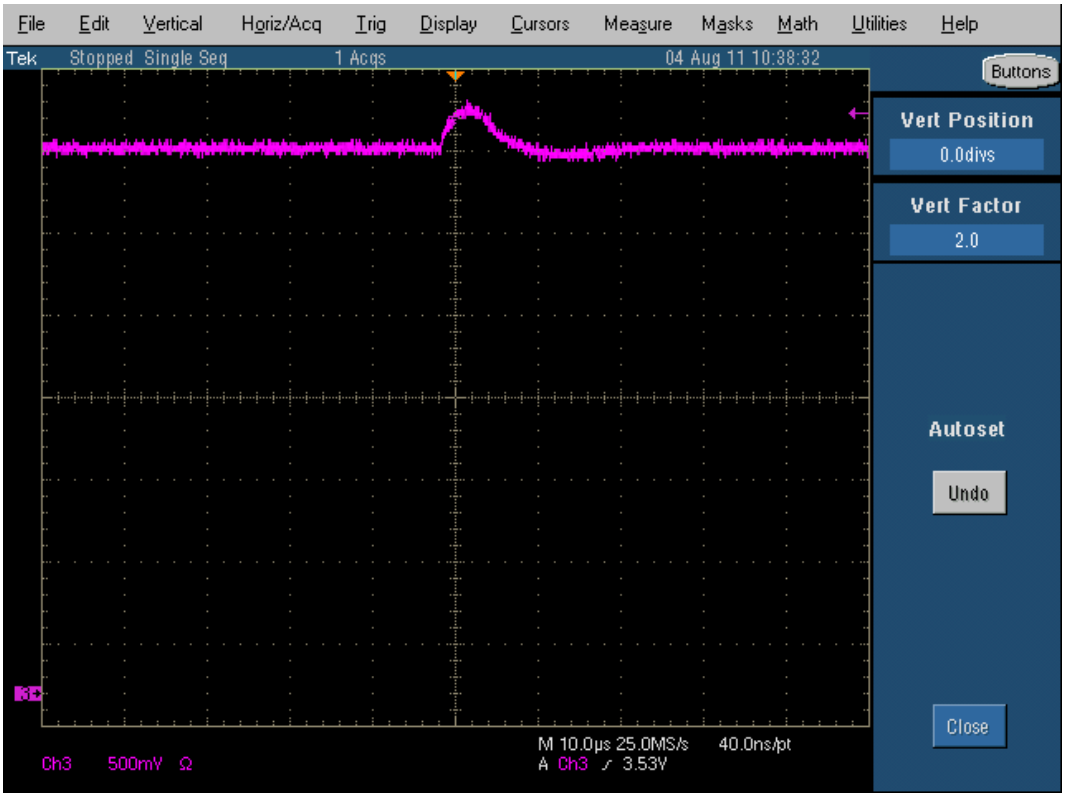


Figure 31. Worst-case SET recorded for the RH1086. The laser energy was set to 14pJ. The SET is approximately 300 mV in amplitude and 10 µs in duration with the 20uF output capacitor configuration. No SET were observed with the 47uF output capacitor

5.2.4 MFP0507S

A heavy ion test campaign was performed by GSFC radiation group, and some transients were recorded during the evaluation, as shown in Figure 32. Several test conditions were considered for this assessment: an input nominal voltage of 6V with and without loading and also with loading conditions of 30, 50, 70, and 100% with both .8V & 3.3V outputs. The goal of the laser evaluation is to identify the sensitive region of the POL and to extend the evaluation to other conditions such as input voltages.

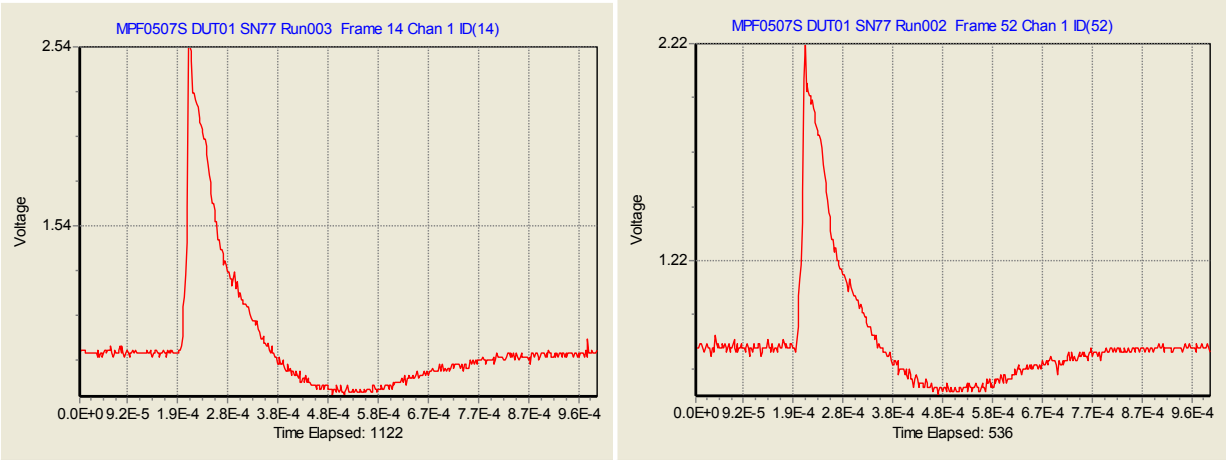


Figure 32. Charts 1&2: worse-case transients of approx 1.74V and 200 µs with 0.8V output.

SET Characterization

This hybrid converter has several integrated circuits. Among them, an LM136 voltage reference, a LM158 operational amplifier (used as the compensator circuit), and TC44xx drivers that are used prior to the power FETs train. Several bipolar transistors and diodes are used as well. During the laser test, we evaluated each of the ICs for different load conditions and input voltage (min and max).

The circuit during the test used a 220 uF input tantalum capacitor and a 330 uF output capacitor as recommended by the manufacturer datasheet. The additional capacitor at the converter output helped minimizing ripple noise and provided a clean output as shown in Figure 33. The ripple is minimal and has a value of about 24 mV peak to peak, which is well within the regulation window. Figure 34 shows a photo of the test setup with the DUT operating and ready to be irradiated.

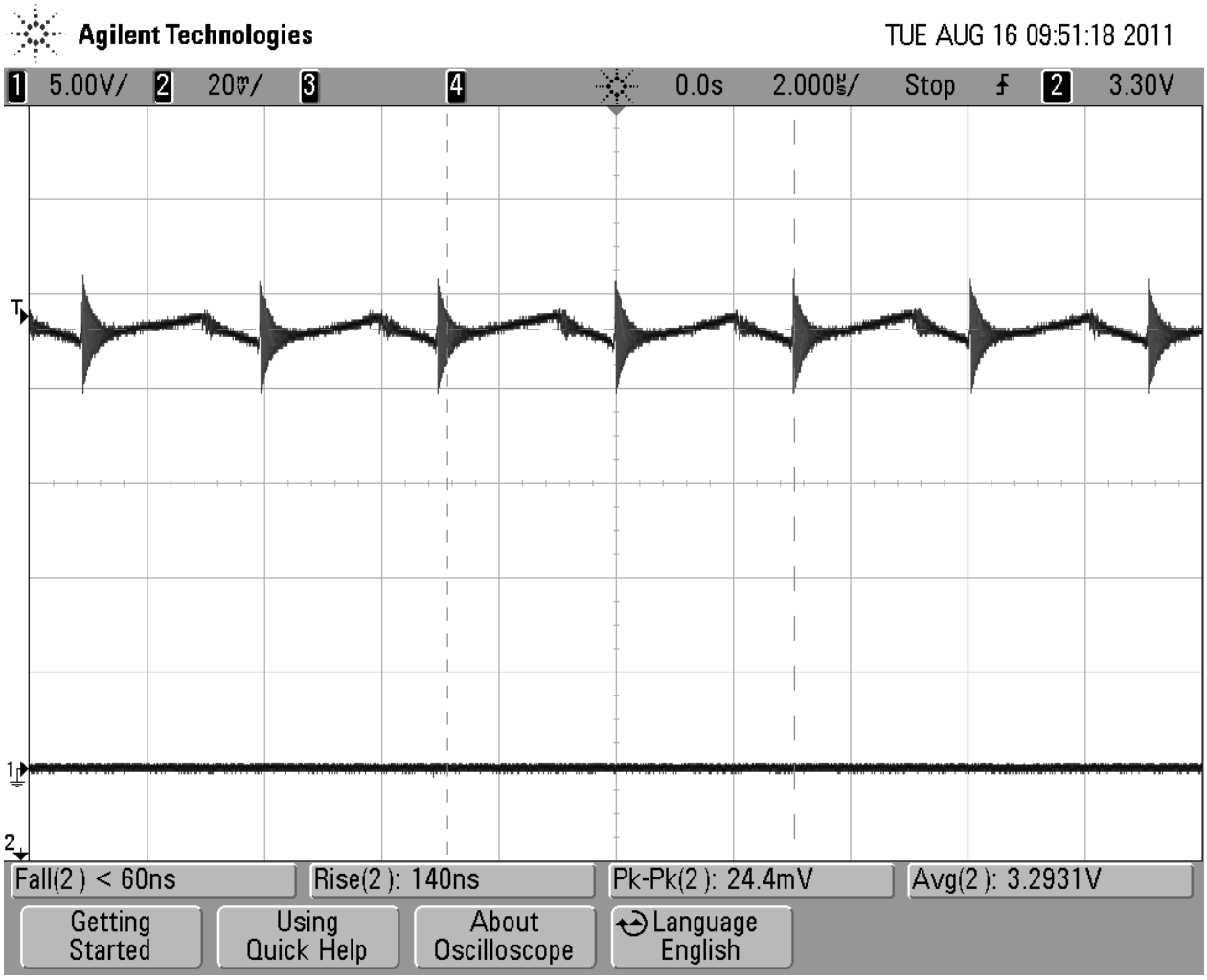


Figure 33. Normal operation of the converter during operation. 24 mV peak-to-peak ripple was measured using input and output capacitor recommended by the manufacturer.

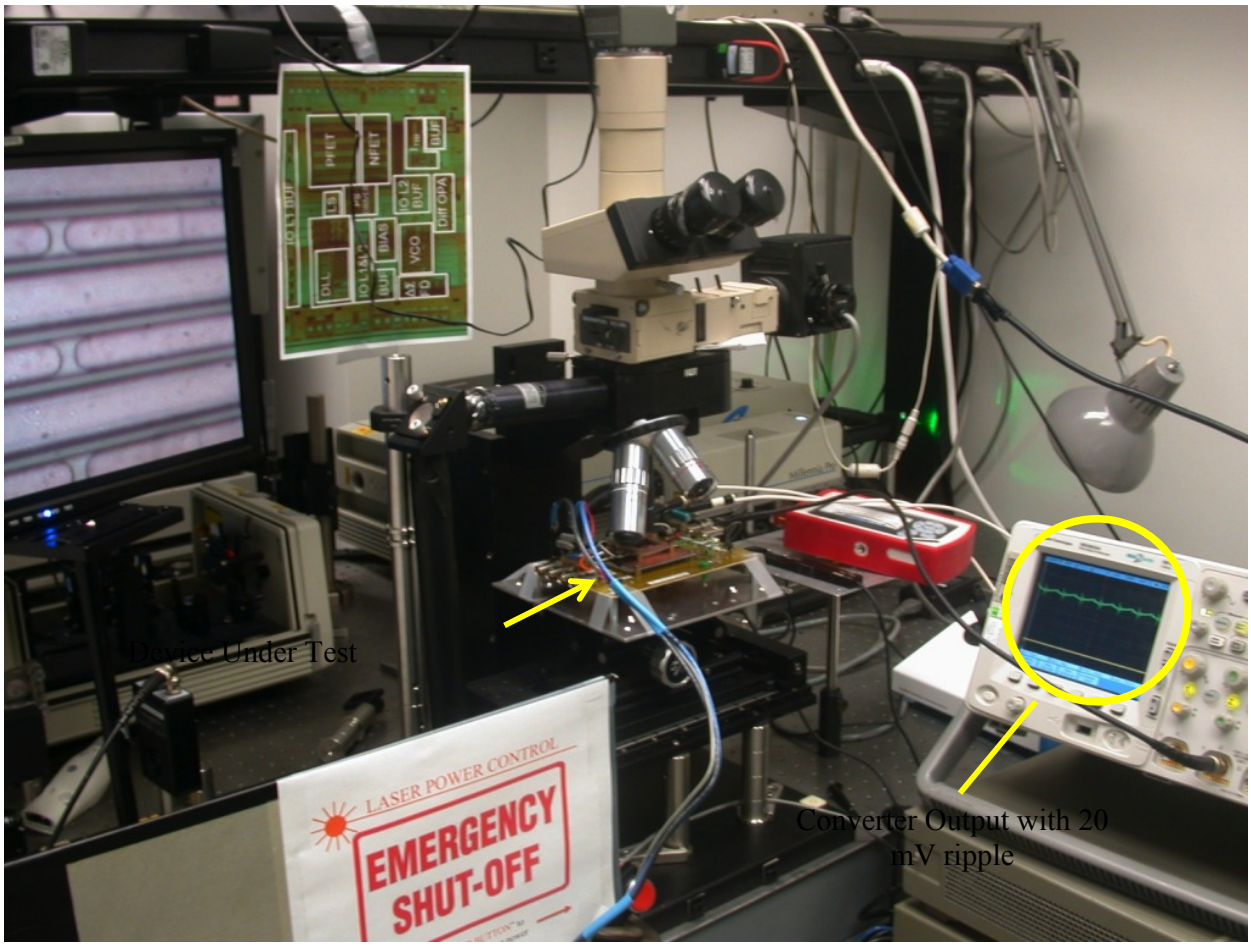


Figure 34. Photograph of the test setup. The converter output was monitored using an Agilent 6000 oscilloscope. In the photograph, a clean 20 mV ripple is represented. The DUT was irradiated while operating for different input voltage and load conditions.

During the first set of laser irradiation, some unexpected observations were made. Those first results indicated that the converter operation was strangely affected by the combination of laser pulse and microscope light in some sensitive portion of the TC44xx and LM158 operational amplifier. Indeed, we noticed that the power supply current limiting features would force the device to go off state in some cases. If this feature was not used, then we noticed some SEE-induced effects that are not really transients but more like the output voltage going unstable.

For instance, when testing at the 5 V, 2A, 3.3 V output condition, a laser energy of 8 pJ appeared to be the energy threshold. While scanning the LM158, large-signal oscillation and low-frequency oscillation were observed. This was triggered in the LM158 operational amplifier. It was later found that the external light caused this (the light used to illuminate the die through the microscope). Once the light was reduced in the system, the error mode was no longer observed. These types of event were also occurring when irradiating the sensitive region of the TC44xx circuit. The next section shows the transient measured for different laser energy and conditions of operation. The transistors shown in Figure 35 were the sensitive transistors.

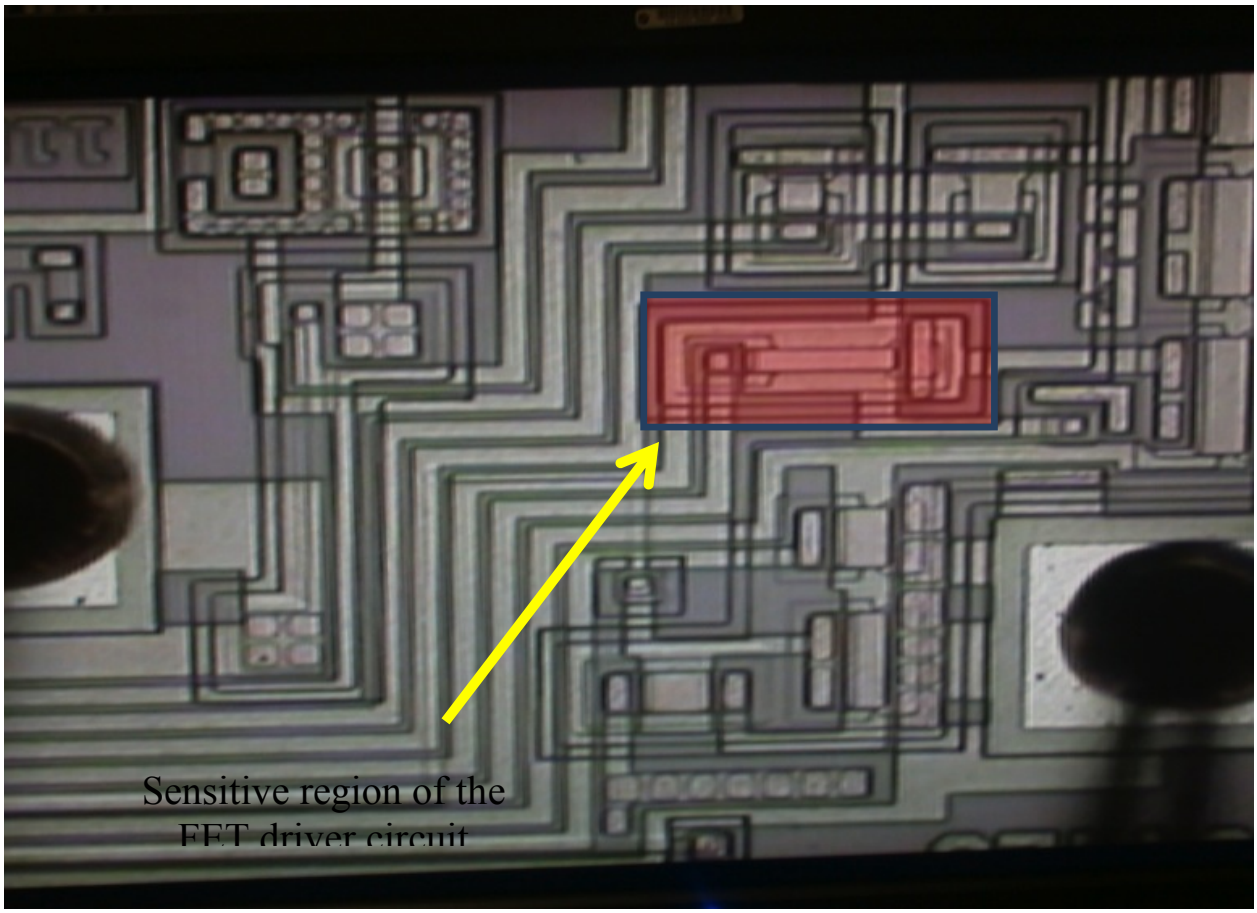


Figure 35. The sensitive region in the design has been in the pre-driver circuit. Two chips are used to drive the FET, and both show some sensitivity at equal location. The area is highlighted in red.

5.2.4.1 MFP0507S—Observed Single-Event Transients

Figures 36–39 show the most typical transients observed during the laser testing for different conditions of operation and laser pulse energy. The TC44xx driver was found to be the most sensitive IC.

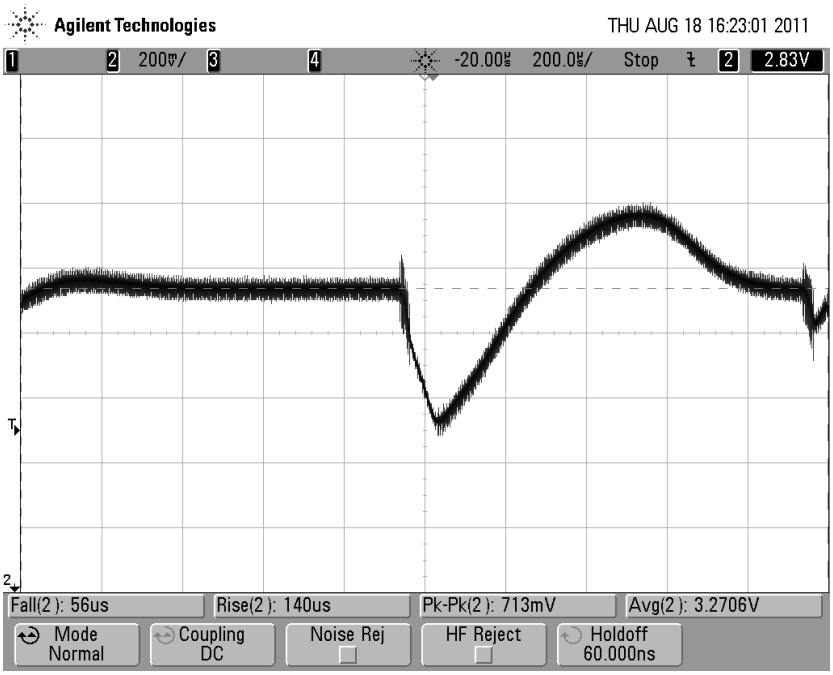


Figure 36. Typical worst-case transient recorded at the converter output by hitting the sensitive region of the driver circuit (TC44xx). The laser pulse energy was 35 pJ (corresponding to an LET > 100 MeV-cm^2/mg). The transient amplitude was about 700 mV and several hundred μs in duration. Bias conditions were 4.5 V input, 3.3 V output, and 5 amps.

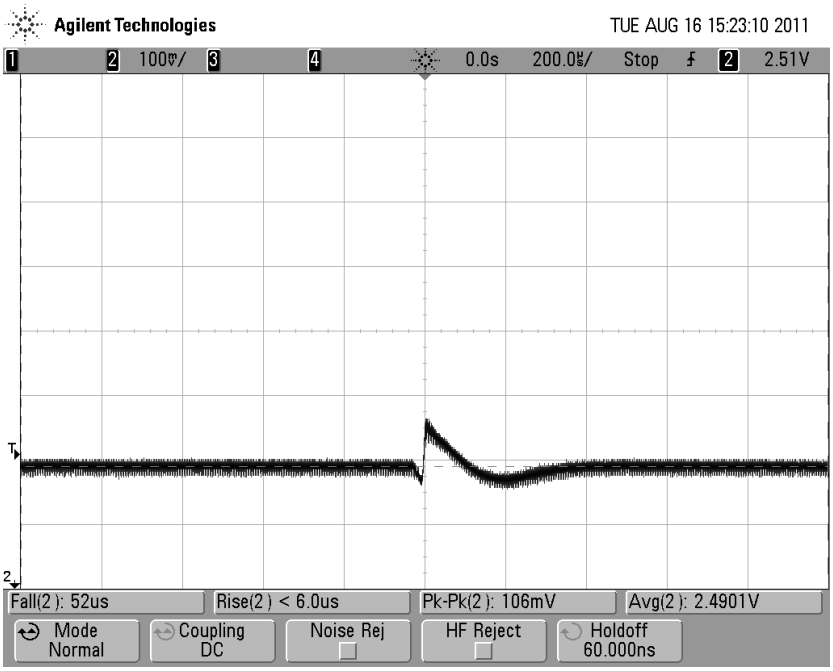


Figure 37. Typical worst-case transient recorded at the converter output by hitting the sensitive region of the driver circuit (TC44xx). The laser pulse energy was 25 pJ (corresponding to an LET ~ 80 MeV-cm^2/mg). The transient amplitude was about 700 mV and several hundred μs in duration. Bias conditions were 4.5 V input, 2.5 V output, and 0.5 amps.

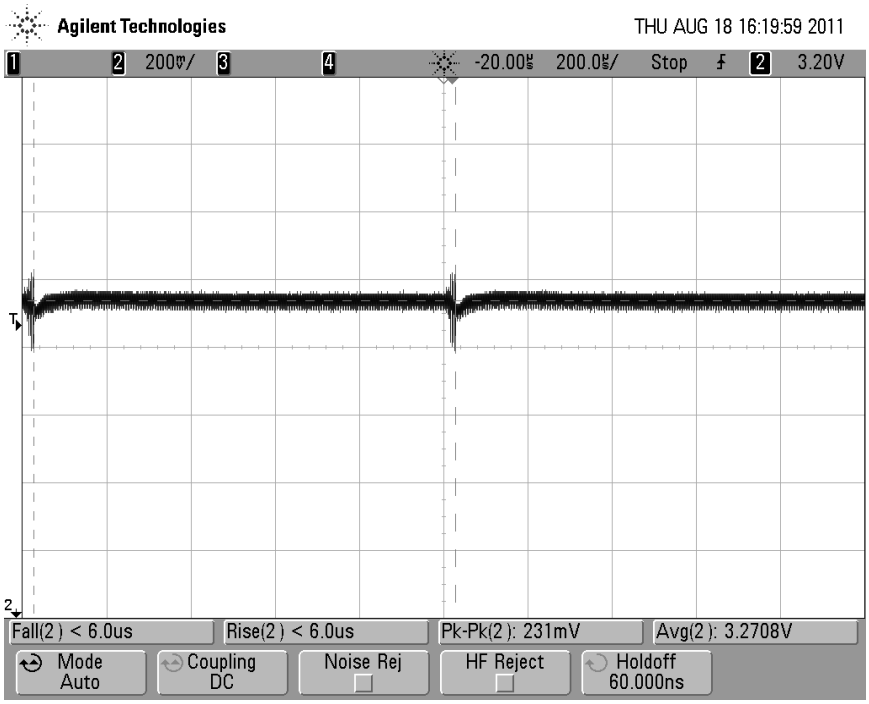


Figure 38. Typical worst-case transient recorded at the converter output by hitting the sensitive region of the other driver circuit (TC44xx). The laser pulse energy was 35 pJ (corresponding to an LET > 100 MeV-cm^2/mg). The transient amplitude was about 200 mV and 50 μs in duration. Bias conditions were 4.5 V input, 3.3 V output, and 3 amps.

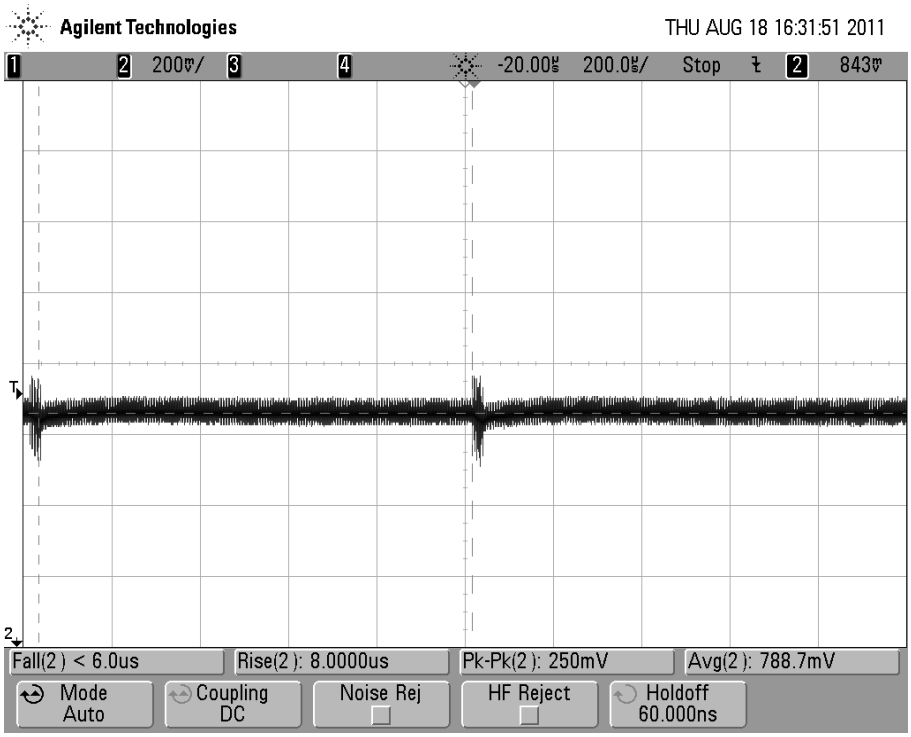


Figure 39. Typical worst-case transient recorded at the converter output by hitting the sensitive region of the other driver circuit (TC44xx). The laser pulse energy was 35 pJ (corresponding to an LET > 100 MeV-cm^2/mg). The transient amplitude was about 200 mV and 50 μs in duration. Bias conditions were 5.8 V input, 0.8 V output, and 0.5 amps.

Hits on Other Blocks

The voltage reference LM136 was irradiated for worst-case bias conditions, and no transients were recorded at the output. It is likely that Interpoint uses a low-pass filter at the voltage reference output to filter any possible transient perturbations and affect the closed-loop operation.

The LM158 operational amplifier was irradiated for worst-case bias conditions, and no transients were recorded at the output. It is likely that transients at the LM158 output are not long enough to affect to PWM output signal of more than one cycle. In this case the converter output is not affected because of the LC filter following the power train.

5.2.4.2 MFP0507S—General Observations

Several transients were recorded during the laser irradiation that are similar to the one observed experimentally described in the GSGC report. They were observed for all conditions of operation and for specific loads. However, it was found that the combination of laser pulse and microscope light was causing the triggering of those events, resulting in a non-real effect. We believe that the heavy ion data should be looked at because we are not sure if those transients are real.

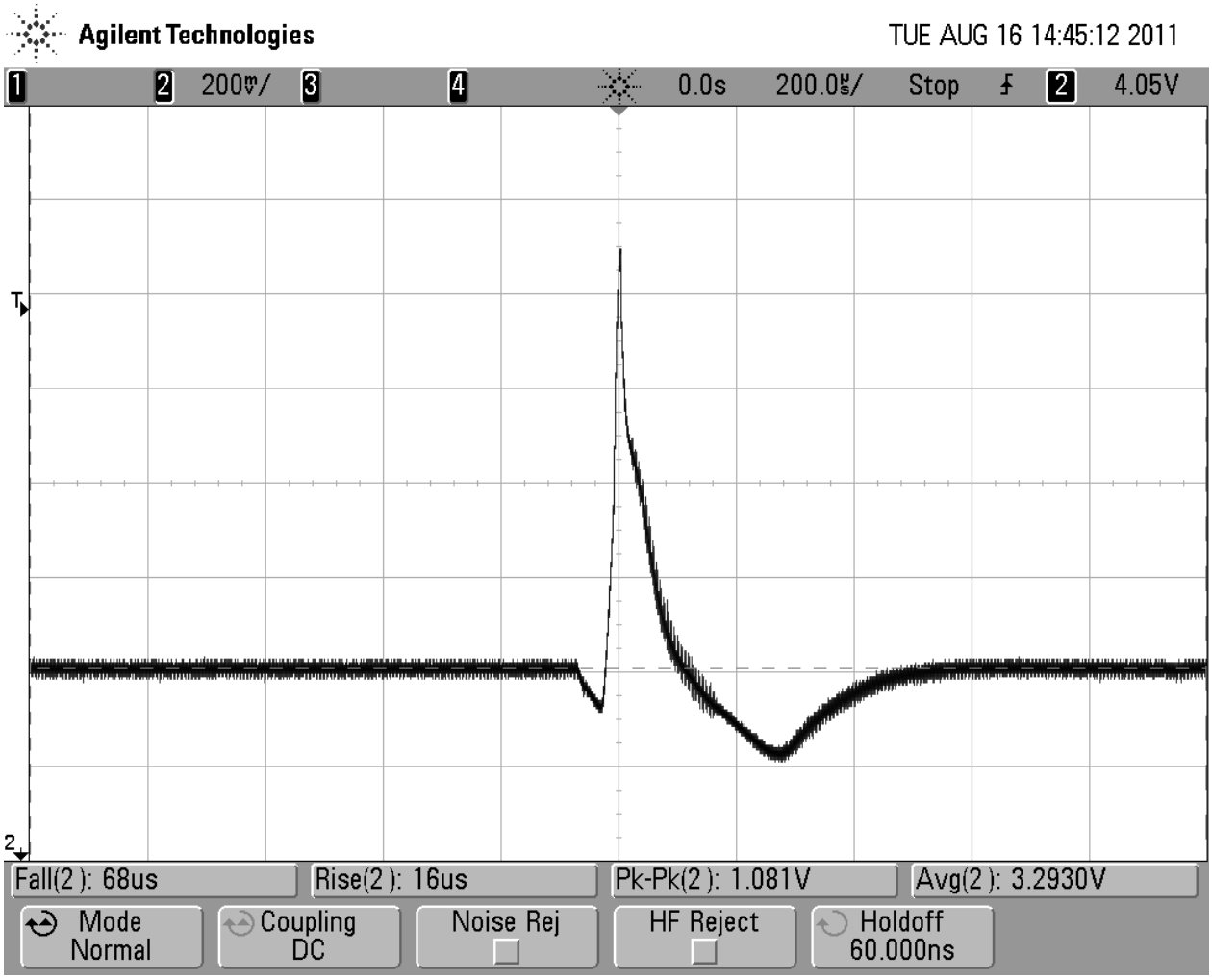


Figure 40. Typical transient induced by laser pulse and light at the sensitive region of the driver circuit. Shapes are very similar to the ones observed experimentally during heavy ion test.

5.2.4.3 MFP0507S—Conclusions

Some transients were observed when hitting a sensitive portion of the power train FET drivers circuit. The sensitive area has been identified. The device tends to show a worse transient response at high input voltage, high load and high output current. A transient similar to the one observed during SEE testing was attributed to the combination of laser strikes and microscope light.

As recommended by the manufacturer, we use a 220µF capacitor at the input and a 330µF at the output. As shown in Figure 33, the device behaved very nicely and showed a ripple of only 20 mV at 3.3 V output, (< 1% regulation).

6.0 CONCLUSIONS AND FUTURE WORK

Based on several discussions and previous broad-beam testing performed both by manufacturers and GSFC radiation group, several commercially available POL regulators were selected for further evaluations using the new JPL pulsed laser systems. The tested devices were all buck (step-down converters) and were the following: the SBB503R3S from International rectifier, the ISL70001SRH from Intersil, the MSK5920 LDOs from MS Kennedy, and the MFP0507 from Crane Interpoint. The focus of this testing was to evaluate the devices' sensitivity to the single-event transient phenomena and provide complementary information such as the identification of sensitive circuits and transient magnitude with different conditions, i.e., bias and load. It should be noted that single photon laser testing has two main limitations: 1) the laser pulse cannot go through metal, which means that it is probable that some transients observed with heavy ion might not be observed with laser; and 2) the correlation between heavy ion linear energy transfer and laser pulse energy is difficult, which indicates that only worst-case estimates can be provided from a laser test.

The following observations were made:

SBB503R3S

The various ICs of this hybrid converter were scanned with the laser with various energies for different conditions. We observed a few locations for which the laser induced some sagging voltage on the order of 10 mV (due to photocurrents); however, no true SETs were observed. While a small SET was observed during the heavy ion testing by IR, it is possible that we were not able to access the sensitive region with the laser due to metallization on the IC.

ISL7001SRH

The full IC was scanned with the laser over varying bias and load conditions. While we did observe some photocurrent effects, we did not observe any true SETs or shutdown modes like the ones observed during the heavy ion test. Our results confirm the assumption proposed by Intersil and validate their SET hardening approach.

MSK5920

Devices were only evaluated under stable conditions per the manufacturer recommendations. The maximum recorded amplitude was 160mV and less than 1μs in duration. A shutdown mode was observed, whereby the device output went to 0V and required an input voltage power cycle to regain regulation. However, it was later discovered that the shutdown mode was due to the combination of laser pulse and an exuberant amount of external light (from the light used to view the die). In FY12, we will focus on identifying whether, for some specific conditions (bias and load) or specific ESR values, SETs can induce instabilities. This testing will include evaluations under dynamic loading as suggested by Jack Schue (GSFC).

MFP0507

Some transients were observed when hitting a sensitive portion of the power train FET drivers circuit. The sensitive area has been identified. The device tends to show a worse transient response at high input voltage, high load and high output current. A transient similar to the one observed during SEE testing was attributed to the combination of laser strikes and microscope light. Discussion with GSFC is ongoing to find out if this worst-case transient type is real.

7.0 REFERENCES

[1] *SBB503R3S Datasheet;* International Rectifier: El Segundo, CA, October 1, 2010. http://www.irf.com/product-info/datasheets/hirel/sbb501s.pdf (accessed September 13, 2011).

[2] Radiation Hardened and SEE Hardened 6A Synchronous Buck Regulator with Integrated MOSFETs. International Recitifier: Milpitas, CA, May 23, 2011. http://www.intersil.com/data/fn/fn6947.pdf (accessed September 13, 2011).

[3] *MSK Rad Hard Ultra Low Dropout Positive Linear Regulator Datasheet.* M.S. Kennedy Corp: Liverpool, NY, January 2011. http://www.mskennedy.com/documents/5920RHrp.pdf (accessed September 13, 2011).

[4] Maximum Flexible Power (MFP) Single Output Point of Load Datasheet: Crane Aerospace & Electronics, Redmond, WA, September 13, 2011. http://www.interpoint.com/product_documents/mfp_dc_dc_converters.pdf (accessed September 13, 2011).

APPENDIX A- IMPACT OF ESR ON LDO STABILITIES

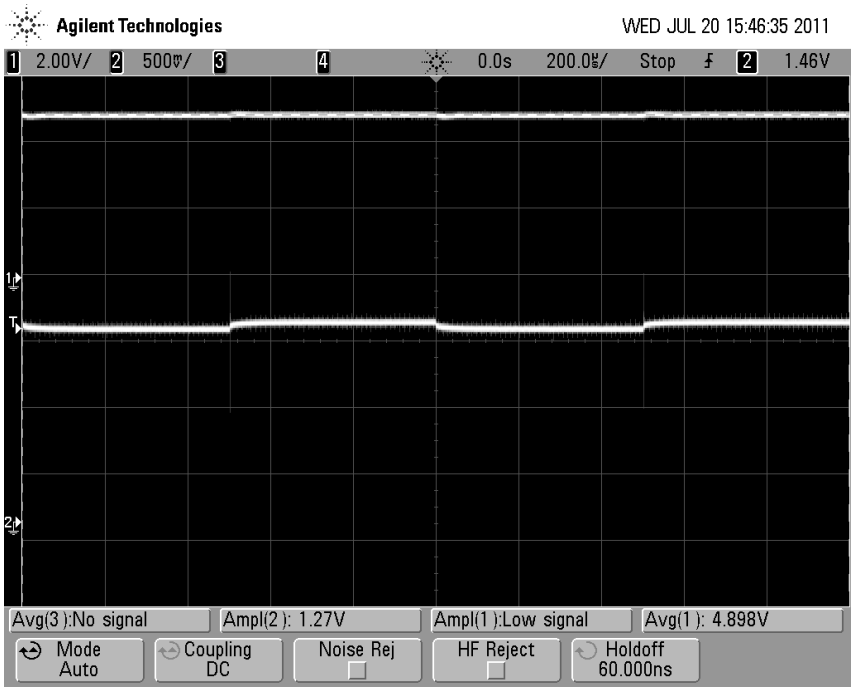


Figure A1. The 1.5 V MSK5920 low to high, high to low switching load characterization is shown here. The top trace is the input power supply and the bottom trace is the regulator's output. The output capacitor was a CWR29 220uF 10V device (SN R0244) with a measured ESR of 40 mOhm. A 0.1 ohm series resister was inserted in line with the regulator's output and the tantalum output capacitor. Note the short output spike at each load change.

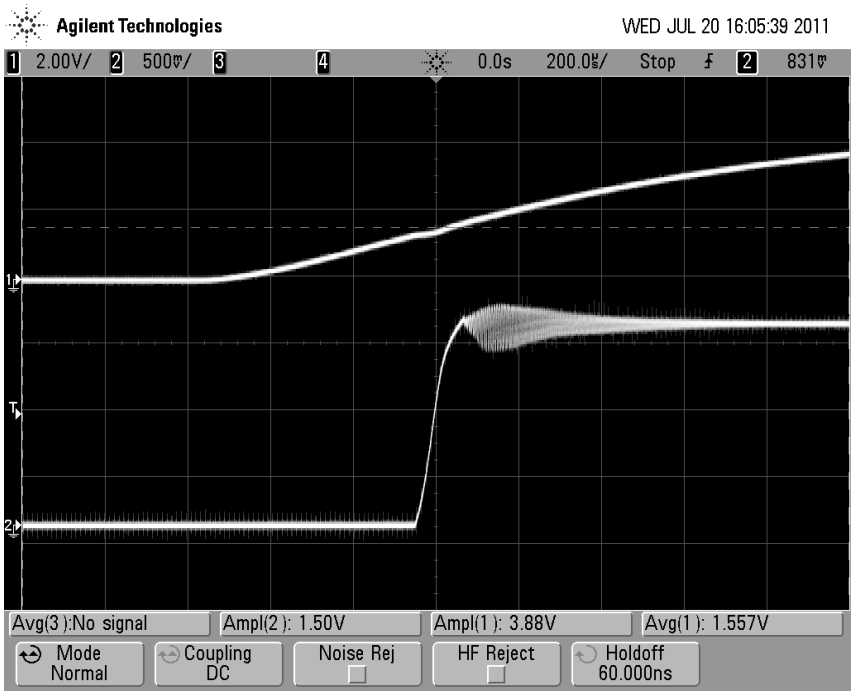


Figure A2. The 1.5 V MSK5920 turn-on curve with minimum load. Channel 1 is the input power supply, and channel 2 is the regulator's output. The output capacitor was a CWR19 220uF 10V device (SN R0240) with a measured ESR of 338 mohm. Note the damped ringing on the output.

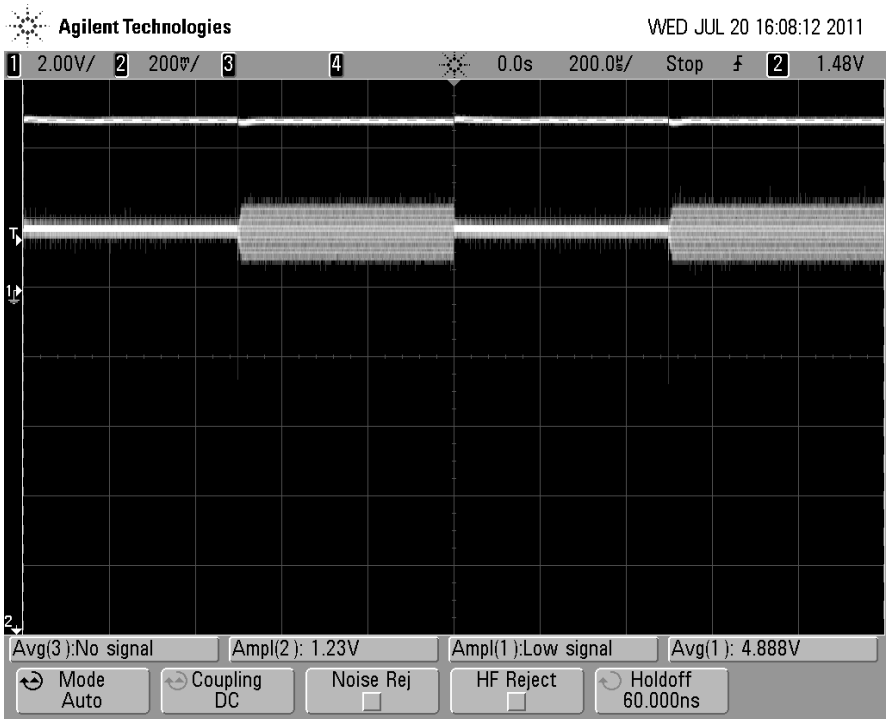


Figure A3. The 1.5 V MSK5920 low to high, high to low switching load characterization is shown here. The top trace is the input power supply, and the bottom trace is the regulator's output. The output capacitor was a CWR19 220uF 10V device (SN R0240) with a measured ESR of 338 mOhm. While the output still regulates at high load, there is observable sustained ringing.

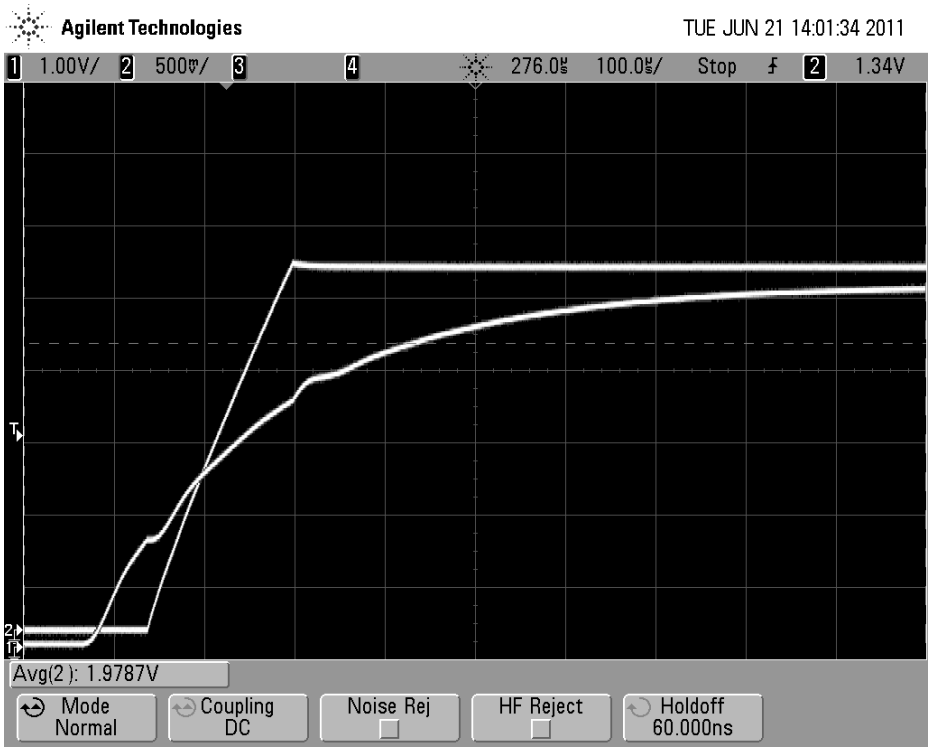


Figure A4. The 2.5 V MSK5920 turn-on curve with minimum load. Channel 1 is the input power supply, and channel 2 is the regulator's output. The output capacitor was a CWR29 220uF 10V device (SN R0231) with a measured ESR of 51 mOhm.

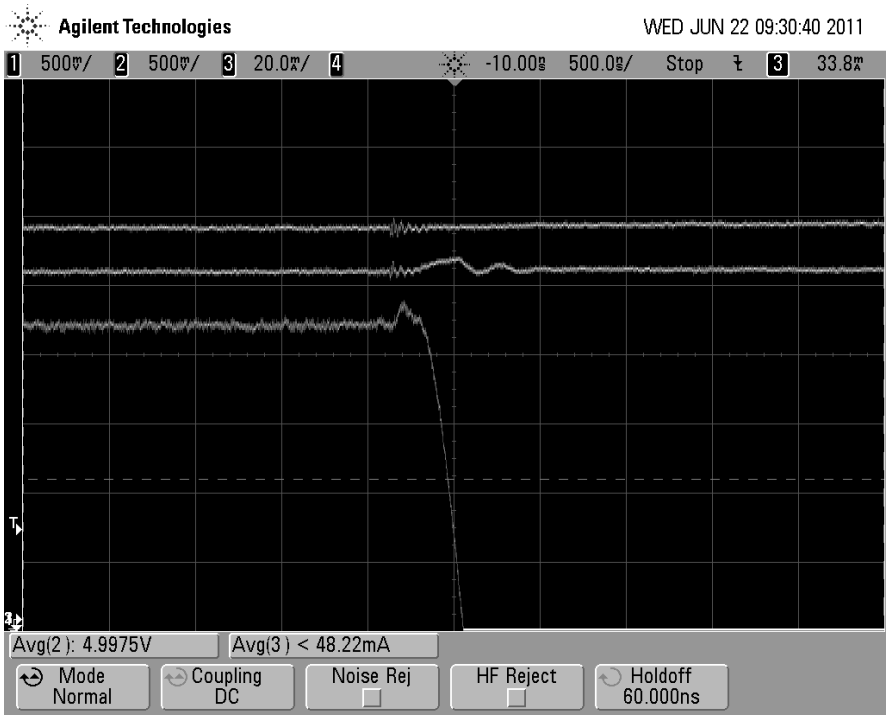


Figure A5. The 2.5 V MSK5920 high to low switching load characterization is shown here. The top trace is the input power supply, and the middle trace is the regulator's output. The capture was triggered on the falling edge of the output supply current. The output capacitor was a CWR29 220uF 10V device (SN R0231) with a measured ESR of 51 mOhm.

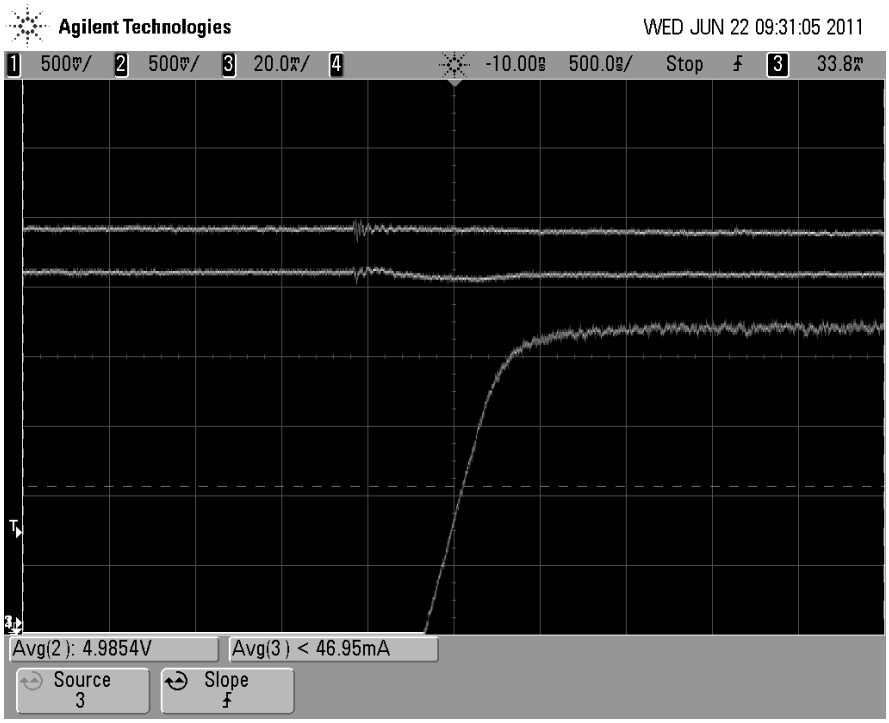


Figure A6. The 2.5 V MSK5920 low to high switching load characterization is shown here. The top trace is the input power supply, and the middle trace is the regulator's output. The capture was triggered on the rising edge of the output supply current. The output capacitor was a CWR29 220uF 10V device (SN R0231) with a measured ESR of 51 mOhm.

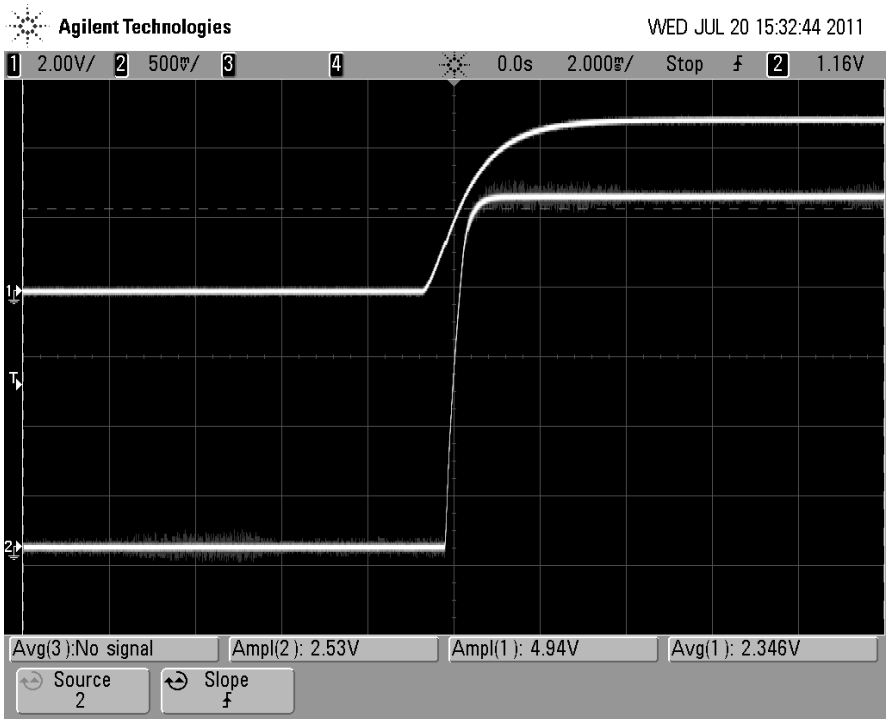


Figure A7. The 2.5 V MSK5920 turn-on curve with minimum load. Channel 1 is the input power supply, and channel 2 is the regulator's output. The output capacitor was a CWR29 220uF 10V device (SN R0231) with a measured ESR of 51 mohm. A 0.5 ohm series resister was inserted in line with the regulator's output and the tantalum output capacitor.

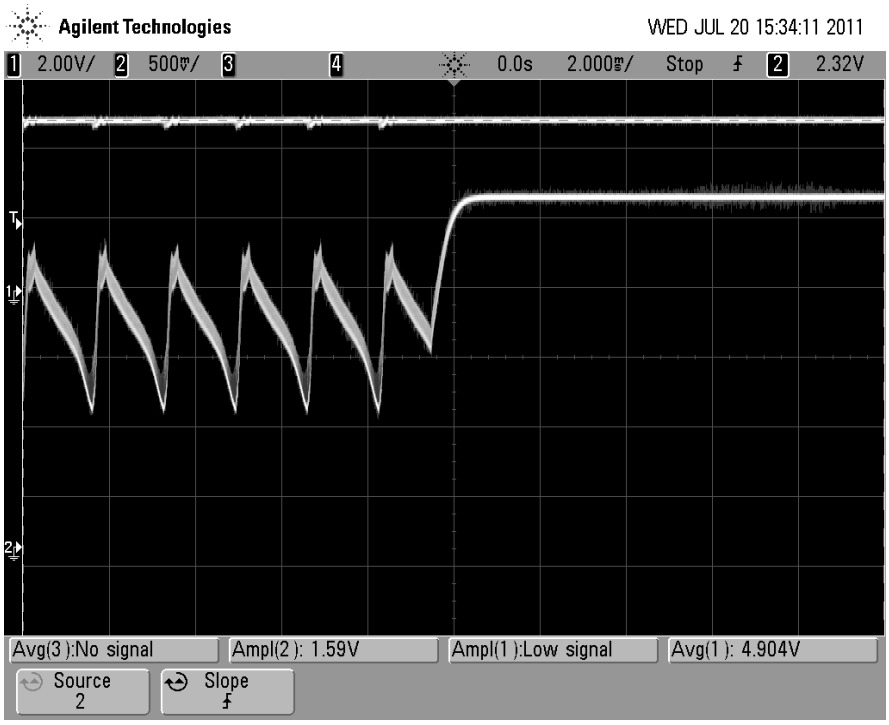


Figure A8. The 2.5 V MSK5920 high to low switching load characterization is shown here. The top trace is the input power supply, and the bottom trace is the regulator's output. The output capacitor was a CWR29 220uF 10V device (SN R0231) with a measured ESR of 51 mOhm. A 0.5 ohm series resister was inserted in line with the regulator's output and the tantalum output capacitor. Note that the device is not regulating when at full load.

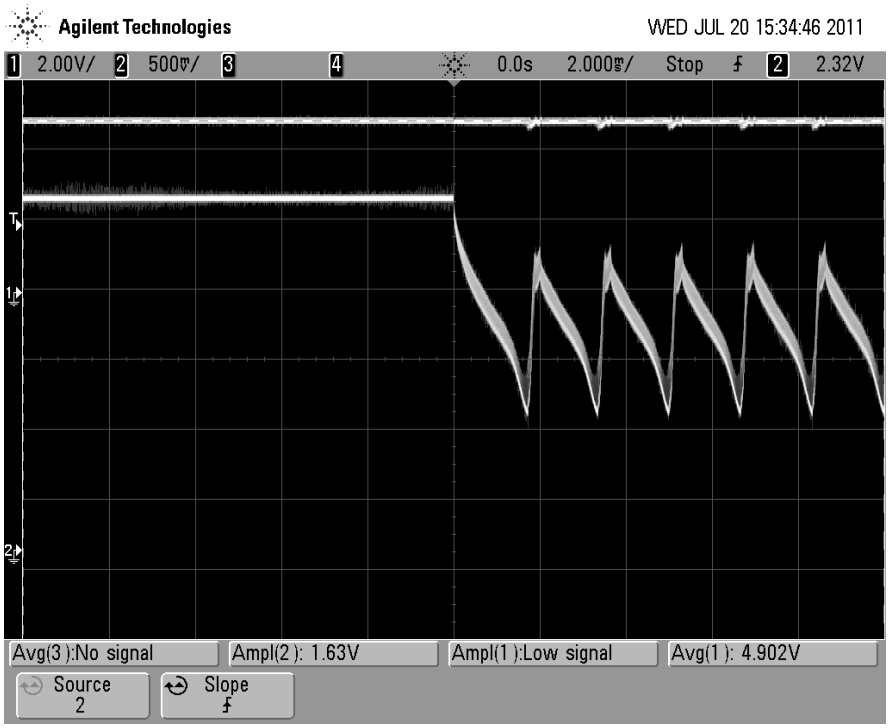


Figure A9. The 2.5 V MSK5920 high to low switching load characterization is shown here. The top trace is the input power supply, and the bottom trace is the regulator's output. The output capacitor was a CWR29 220uF 10V device (SN R0231) with a measured ESR of 51 mOhm. A 0.5 ohm series resister was inserted in line with the regulator's output and the tantalum output capacitor. Note that the device is not regulating when at full load.

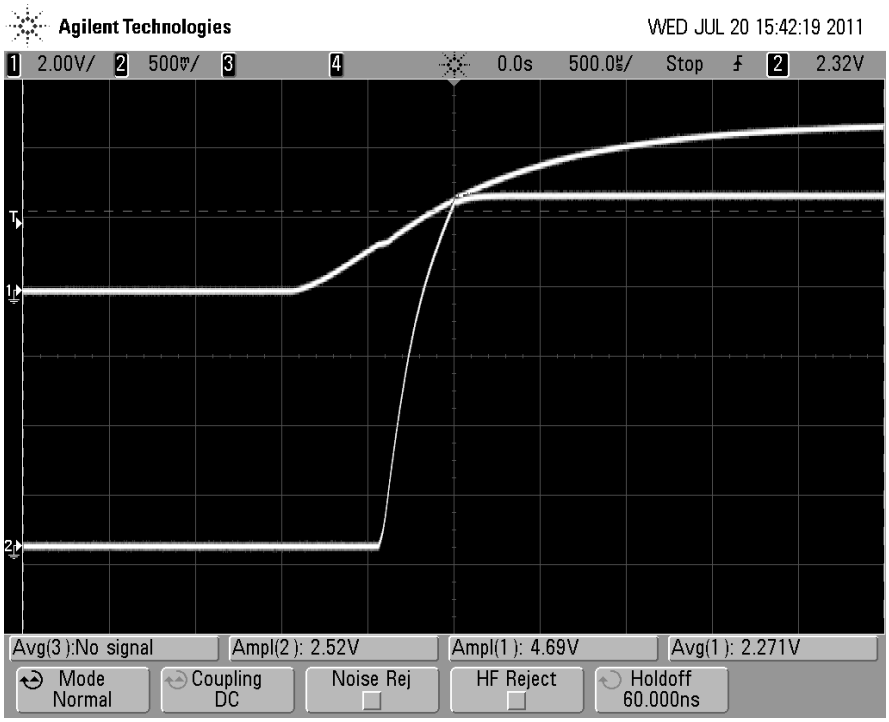


Figure A10. The 2.5 V MSK5920 turn-on curve with minimum load. Channel 1 is the input power supply, and channel 2 is the regulator's output. The output capacitor was a CWR29 220uF 10V device (SN R0231) with a measured ESR of 51 mohm. A 0.1 ohm series resister was inserted in line with the regulator's output and the tantalum output capacitor.

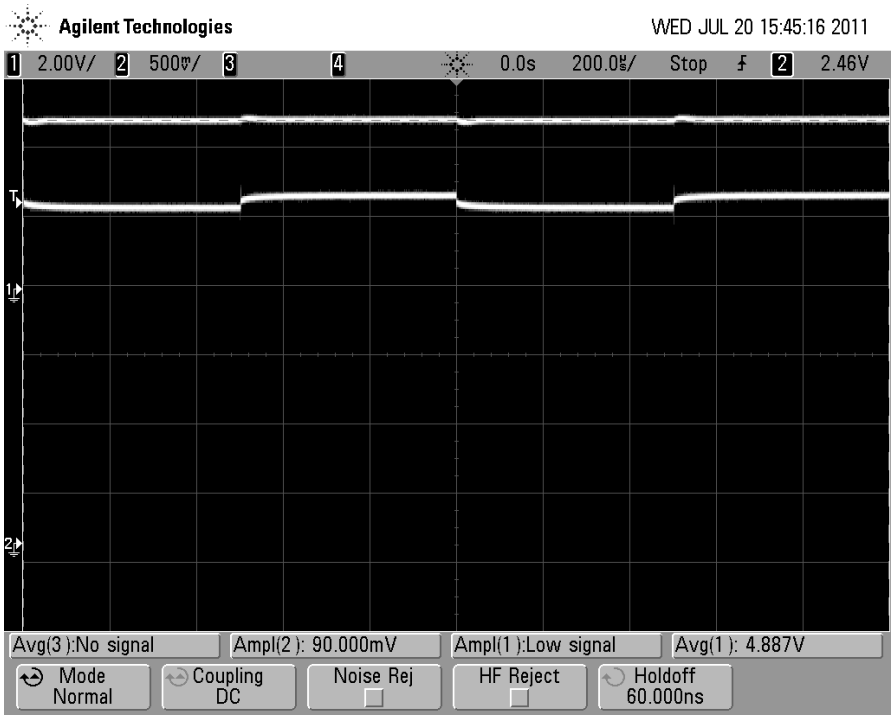


Figure A11. The 2.5 V MSK5920 low to high, high to low switching load characterization is shown here. The top trace is the input power supply, and the bottom trace is the regulator's output. The output capacitor was a CWR29 220uF 10V device (SN R0231) with a measured ESR of 40 mOhm. A 0.1 ohm series resister was inserted in line with the regulator's output and the tantalum output capacitor. Note the short, small output spike at each load change.

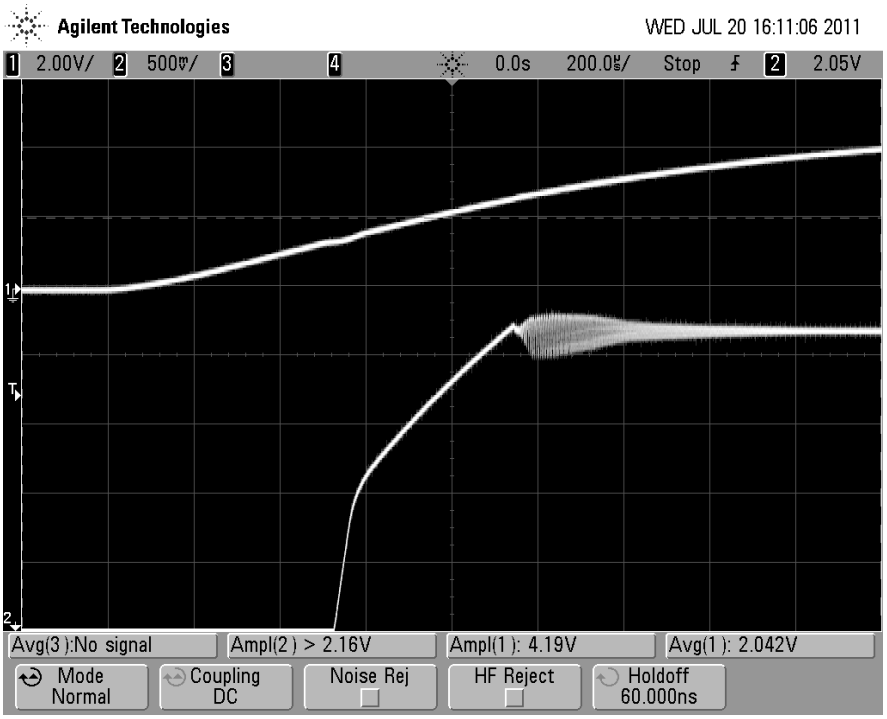


Figure A12. The 2.5 V MSK5920 turn-on curve with minimum load. Channel 1 is the input power supply, and channel 2 is the regulator's output. The output capacitor was a CWR19 220uF 10V device (SN R0235) with a measured ESR of 413 mohm. Note the damped ringing on the output.

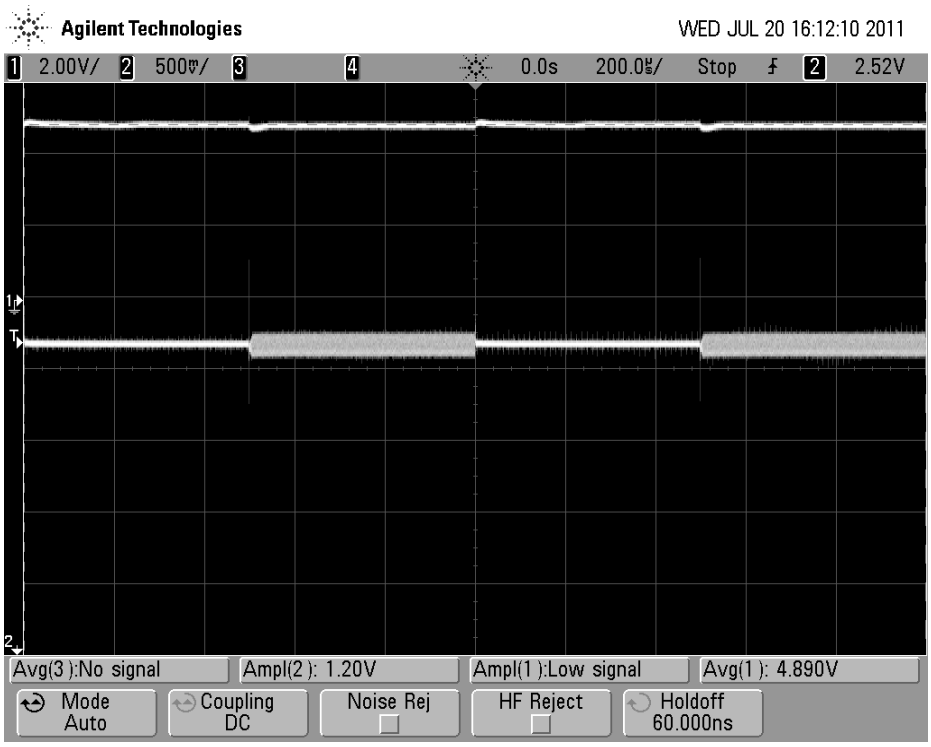


Figure A13. The 2.5 V MSK5920 low to high, high to low switching load characterization is shown here. The top trace is the input power supply, and the bottom trace is the regulator's output. The output capacitor was a CWR19 220uF 10V device (SN R0235) with a measured ESR of 413 mOhm. Note the ringing while at the maximum test load.