Defense Threat Reduction Agency

National Aeronautics
and Space Administration

Point-of-Load Devices for Space

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Objectives

- Evaluate the suitability of point-of-load regulators and DC/DC converters for current and future NASA missions
  - Leverage the specifications of currently available radiation hardened and commercial-off-the-shelf devices against NASA application requirements
  - Evaluate susceptibility to the radiation environment and electrical reliability
- Develop test guideline for the space radiation community
  - SEE test board design considerations
  - Impact of circuit configurations on SETs

Working Group Description

- **Team**
  - JPL: Philippe Adell and Greg Allen,
  - GSFC: Dakai Chen and Jack Shue (expert consultant)
  - Other contributors: Dennis Nguyen, Tien Nguyen, and Christopher Stell from JPL, A. Phan, T. Wilcox, and A. Topper from GSFC
- **Collaborate with vendors for Radiation Hardened (Radhard) and commercial-off-the-shelf (COTS) devices:**
  - M.S. Kennedy, Linear Technology, Texas Instruments, Peregrine, International Rectifier, Interpoint/Crane, Aeroflex, Intersil, S.T. Microelectronics, 3-D Plus and Microsemi
- **Reliability**
  - Evaluate electrical performance over extreme operation range including temperature
  - Develop multi-stage power distribution architecture with currently available POL devices
  - Perform stress test to validate POL performance over a long period of time
- **Radiation**
  - Perform radiation testing: heavy-ion, pulsed-laser, protons, and/or Co-60
  - Identify failure/degradation modes
  - Determine radiation testing challenges and develop proper test techniques
  - Develop test guideline

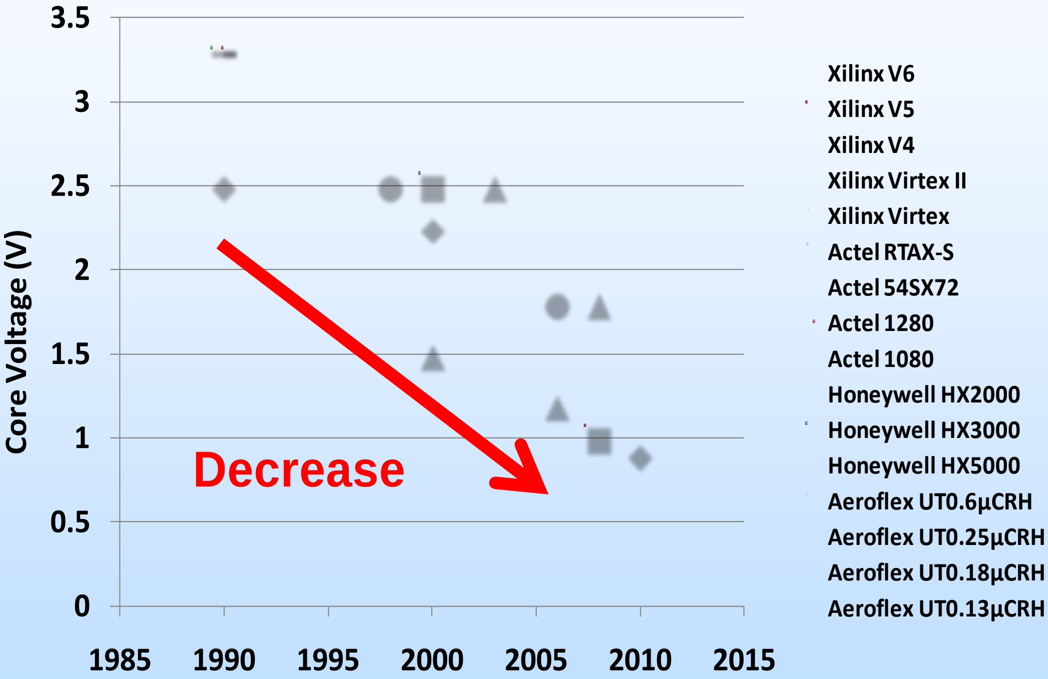
Devices Under Study

Part Number	Manufacturer	Assurance level	Device type	Input Voltage	Output Voltage	Output Current
MSK5820-2.5RH	MS Kennedy	Radhard	Low -voltage-drop-out (LVDO)	2.9 to 6.5 V	2.5 V	3 A
MSK5900RH	MS Kennedy	Radhard	LVDO	2.9 to 7.5 V	Vdo = 0.3 V	4 A
MSK5810RH	MS Kennedy	Radhard	LVDO	2 - 7.5 V	Adjustable down to 1.5V	5 A
IRUH330	International Rectifier	Rad hard	LVDO	5 V	Adj down to 0.7 V	3 A
TPS7A4901	Texas Instruments	COTS	LVDO	3 to 36 V	1.2 V	0.15 A
TPS79133	Texas Instruments	COTS	LVDO	-3 to 6 V	3.3 V	0.1 A
ISL70001SRH	Intersil	Radhard	Buck regulator	3V to 5.5V	Adjustable down to 0.8 V	6 A
MSK5059RH	MS Kennedy	Radhard	Buck regulator	16 V	Adjustable down to 1.8 V	4.5 A
PE9915X	Peregrine	Radhard	Buck regulator	5 V	3.3 V and 1.8 V	10 A (3.3 V)
MFP0507S	Interpoint	Radhard	DC/DC converter	6 V	3.3 V and 0.8 V	7 A (3.3 V) 5 A (0.8 V)
SBB503R3S	International Rectifier	Radhard	DC/DC converter	4.5 to 5.5 V	3.3 V	9.1 A
SA50-28	Microsemi	Rad hard	DC/DC converter	28 V	5 V	10 A

- **Devices evaluated since 2011 for reliability and radiation performance**
- **Planning radiation testing and reliability studies for newly released and in-development devices from TI, Aeroflex and 3D-plus**

Motivation

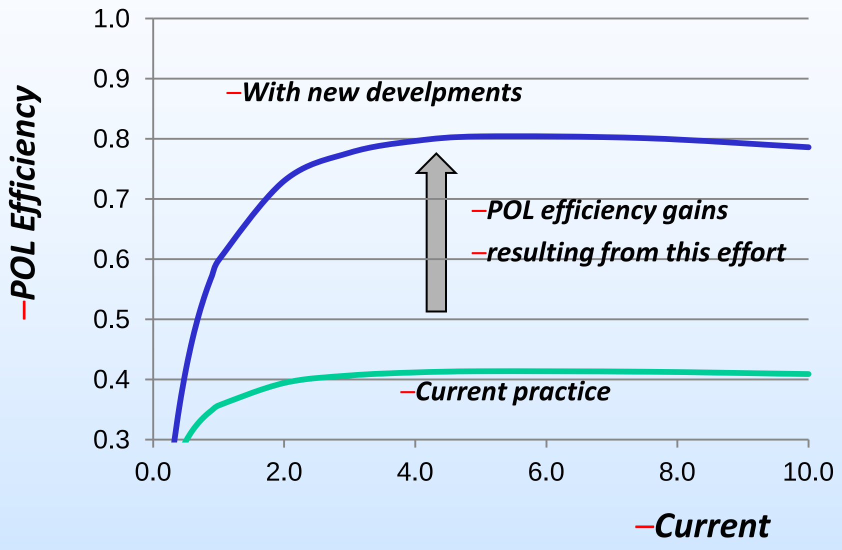
- As demand for high-speed, on-board digital processing ICs spacecraft increases, point-of-load (POL) regulator becomes a prominent design issue for power systems
- Shrinking process nodes have resulted in core rails dropping to values close to 1.0 V and with relatively high output current
- This drastically reduces design margins to standard switching converters or regulators that power digital ICs



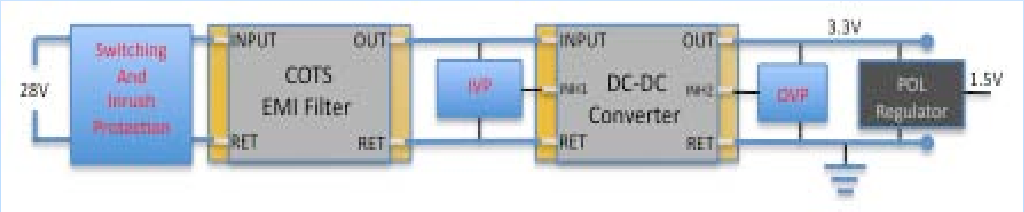
Power System Architecture

- Current practices use large COTS hybrid power conversion modules and custom circuitry to meet minimum design principles and requirements for spacecraft applications.

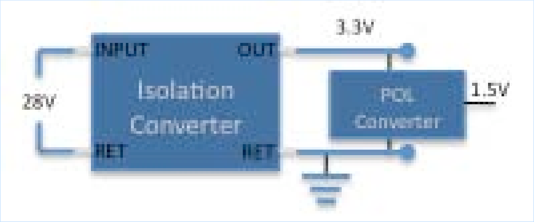
- Architecture with POL converters use two stages system distribution scheme incorporating the necessary features for FP, FT, OVP, UVL, sequencing and improves efficiency from η < 50% to η > 80%.



–CURRENT PRACTICE



–NEW DEVELOPMENT



–*Typically POL development focuses: 1) FP, FT OVP and Sequencing;*

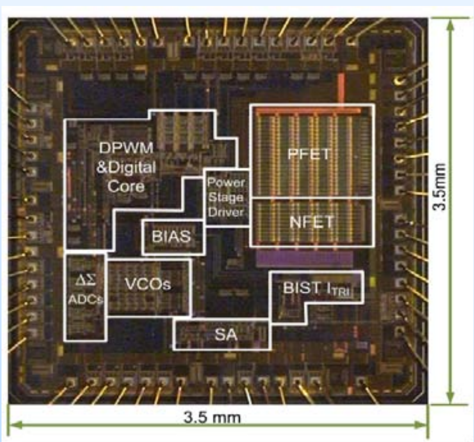
– *2) Efficient POL conversion and 3) Immunity to Single event transient*

POL Types

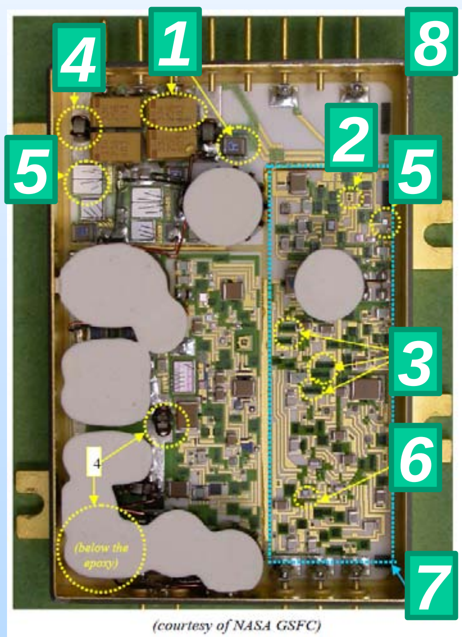
– *Integrated devices*
  - *Linear regulator*
  - *Non-isolated DC-DC*

– *Hybrid switching converters*
  - *Isolated (magnetic) or non-isolated*
  - *High efficiency*
  - *Can step-up (boost), step-down (buck)*

– *Hybrid Linear regulators*
  - *Low efficiency*
  - *Can only step down*
  - *Fast transient response*

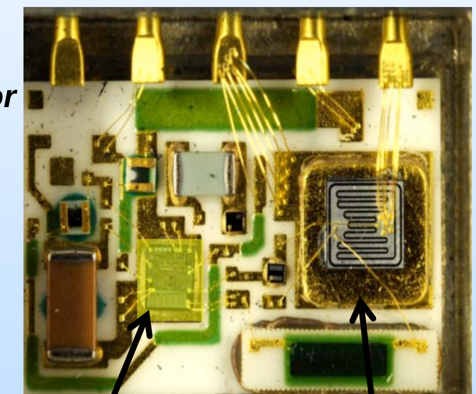


Switch + Control



(courtesy of NASA GSFC)

1. capacitor
2. chip resistor
3. thick film resistor
4. magnetic device
5. discrete
6. ICs in die form
7. ceramic substrate
8. package



IC control

Power Bipolar

Packaging and layout is a critical component of POL designs for reliability

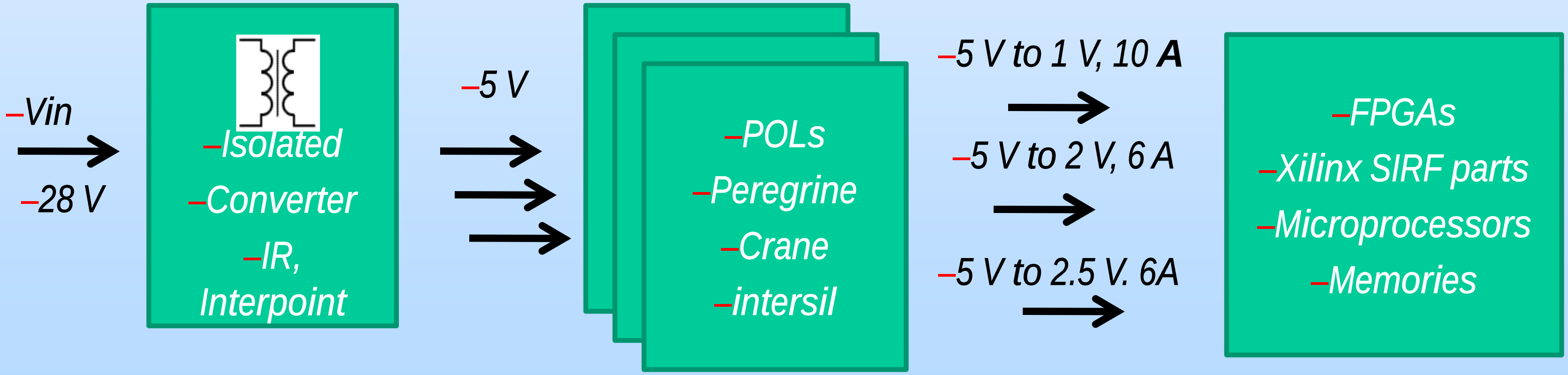
Reliability

- In FY2011, assessment of available POL regulators was carried out to determine use conditions that had acceptable performance.
  - Among the tests performed were efficiency, turn-on, load transient response, synch., at different temperatures.
  - Several potential problem areas were identified, mainly at low temperature.
  - In addition, two stages system implementation preliminary assessment was conducted for performance comparison between manufacturers

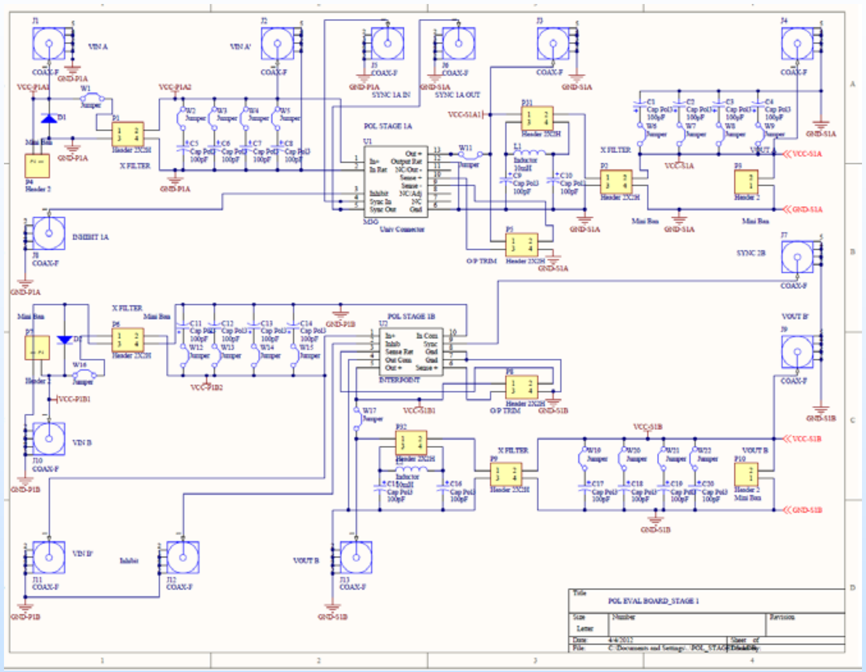
- In FY2012, the objective is to develop a matrix of performance by implementing a power distribution architecture by using available POLs in combination with the most common isolated converters used in NASA programs.

Objectives

- **Perform standard measurements on state of the art commercial POL regulators as they become available**
- **Continue investigating the limits of operation for the different POLs at low and high temperature**
- **Perform a matrix of performance comparison when POLs operating in two stages system architecture**

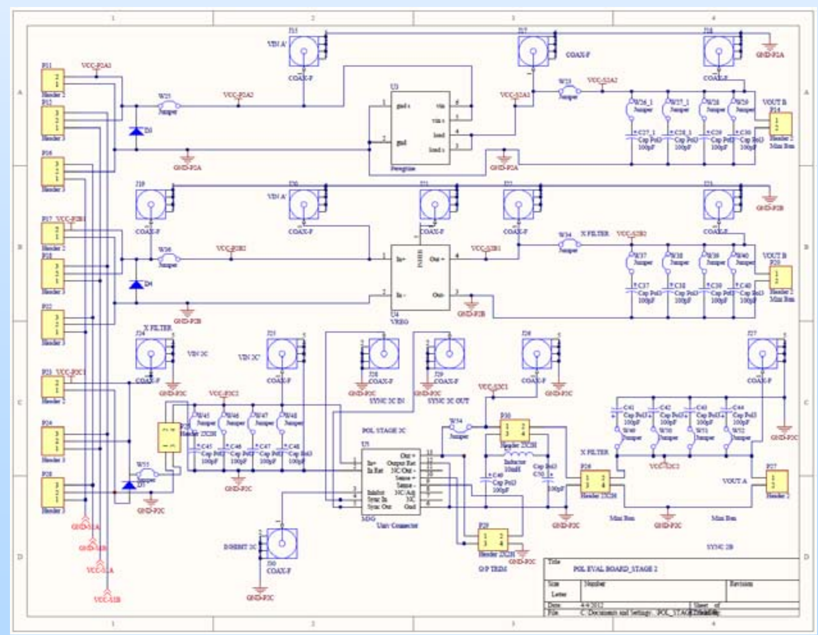


Two stages modular board Implementation



– *First stage*

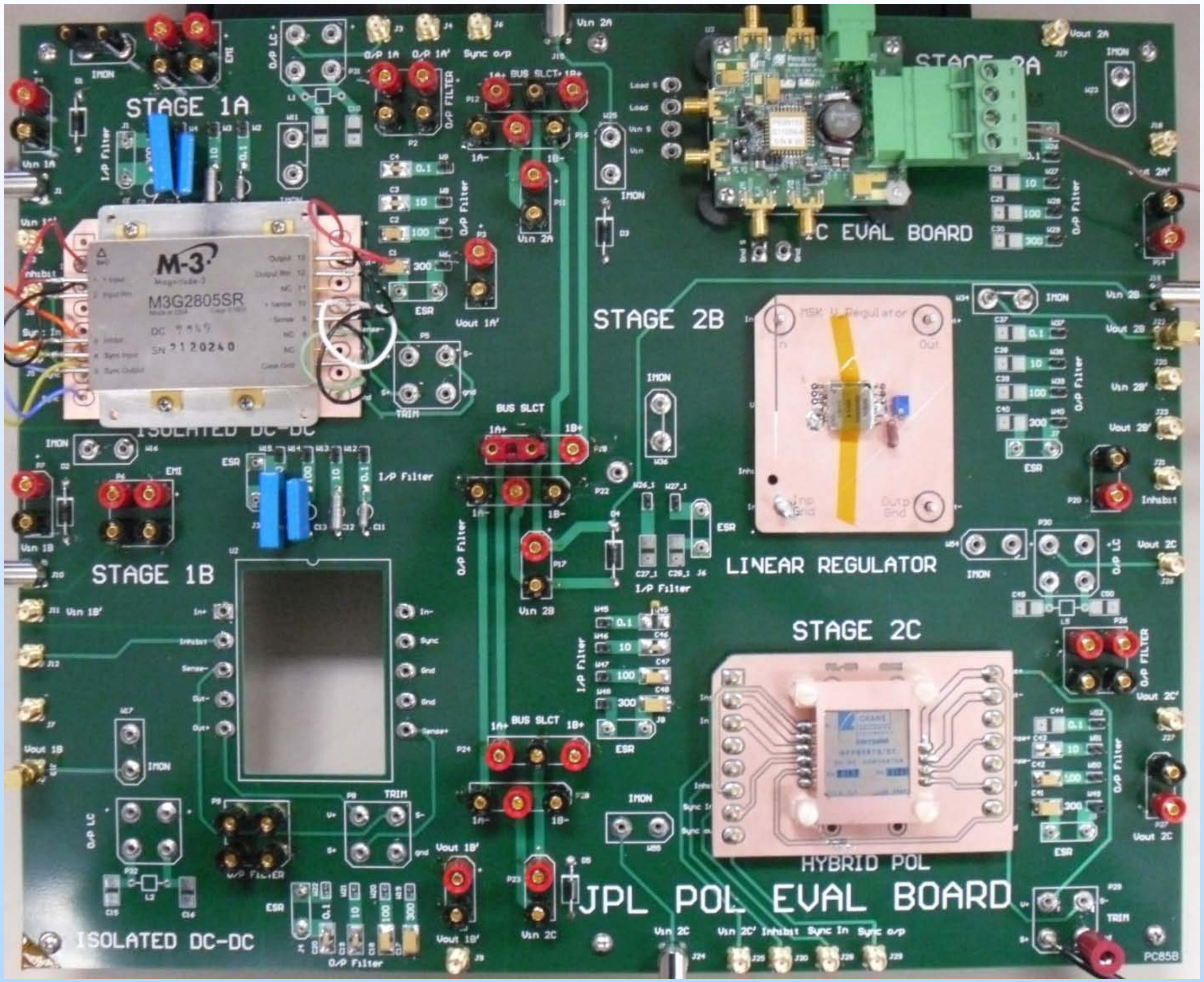
- – *Two flights isolated DC-DC converters 28 V to 5 V*
- – *M3G2805RS from International Rectifier*
- – *SMTR285R5S from Interpoint*
- – *Adaptable to other isolated converters*



– *Second stage*

- –*Various POL listed in Table I*
- – *Eval boards*
- – *Linear regulators*
- – *Hybrid POL*

Board Description

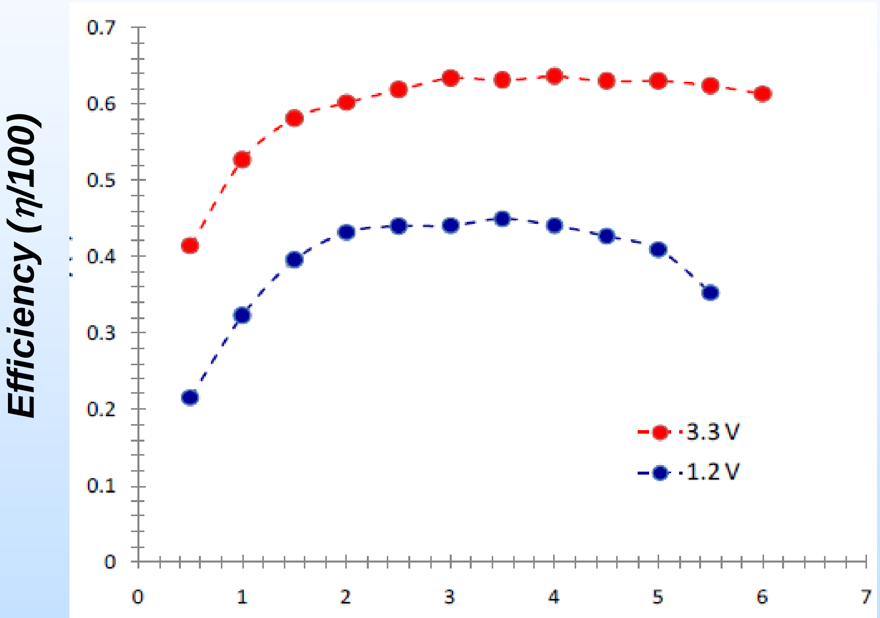


Characteristics

- *Input Voltages/Currents*
- *Output Voltages/Currents*
- *Efficiency Measurements*
- *Dynamic load measurements*
- *FFT measurements*
- *Line regulation*
- *Load regulation*
- *EMI filter option*
- *various filtering LC, RL*
- *Exercise systems with R, L, C*
- *Adaptable for SET testings*
- *Close to real applications*

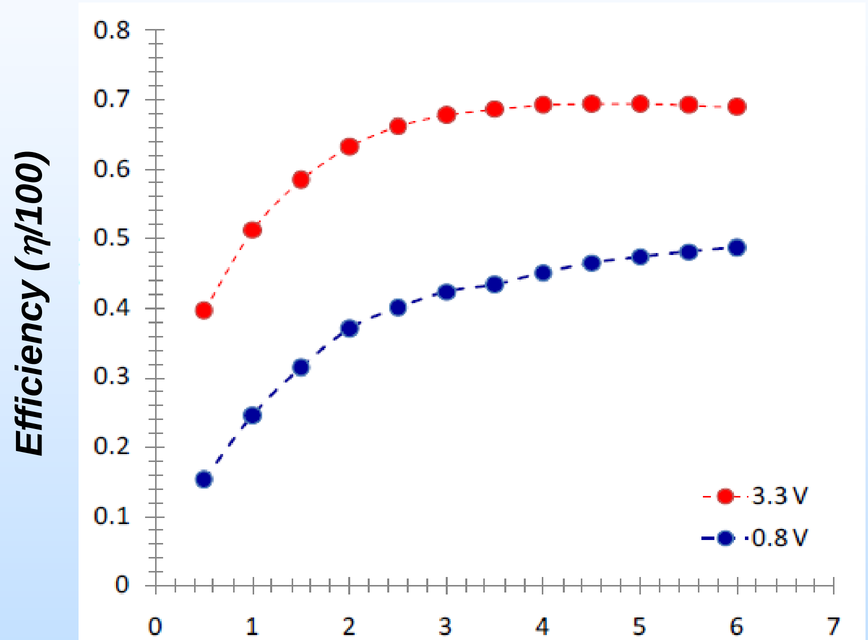
Parameter “h”

Intersil ISL7001



Load current (A)

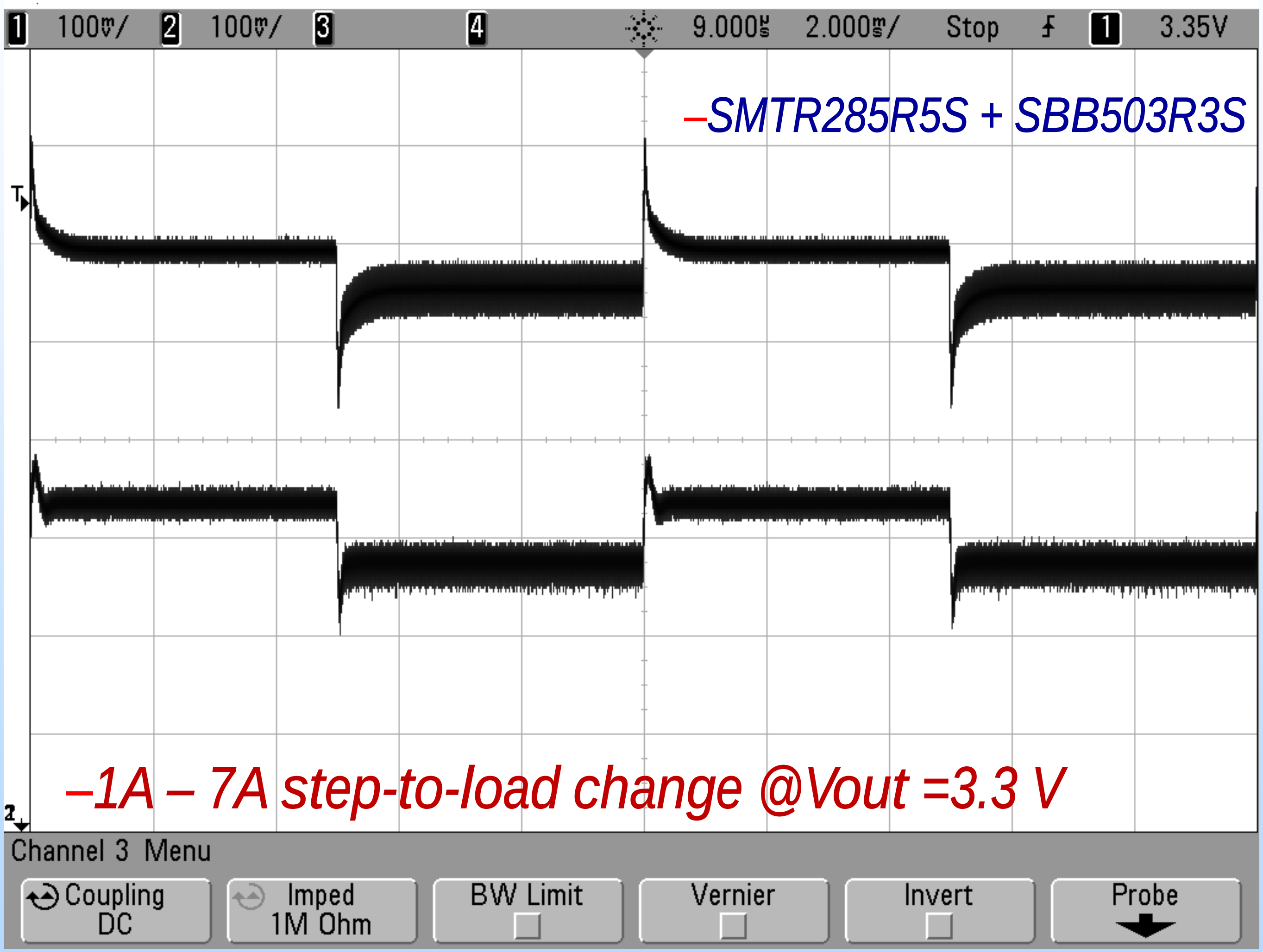
Crane MFP0507



Load current (A)

- **End-to-end efficiency plot with the combination of IR MG32805SR + ISL7001 or MFP0507S Conditions: 28 V input, 5 V intermediate voltage, and 0.8, 1.2 or 3.3 V output vs load (0-6 A)**

Step Load Change



Plans

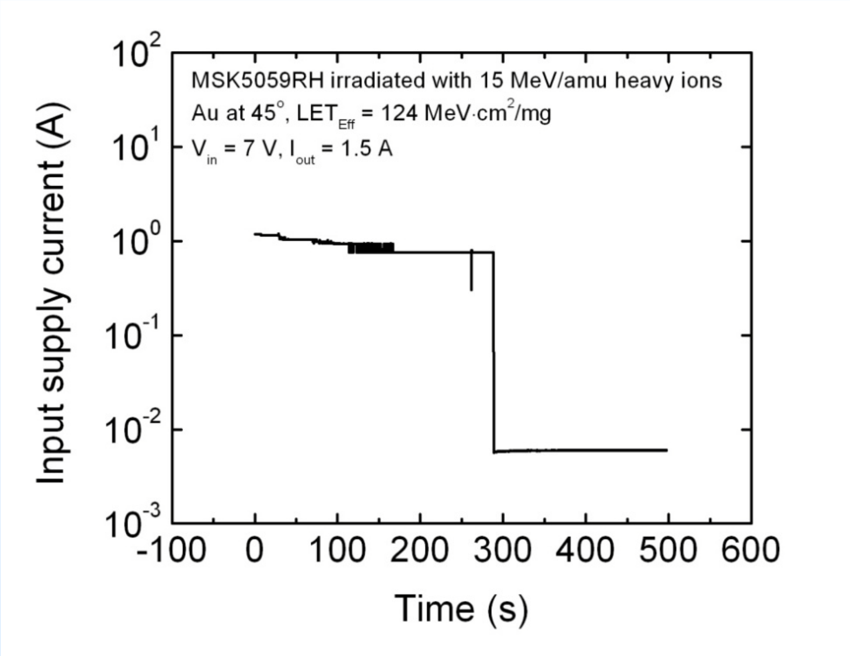
- Matrix of performance for POLs operating in two stage architecture with isolated converters used in NASA programs
  - Use a variety of common 28 V isolated converters
    - Interpoint (in-house), International rectifier (in-house) and VPT
  - Develop a modular characterization board to test and compare POL performances in a power distribution architecture
    - Impact of ESR
    - Input capacitance
    - Load regulation
    - Line regulation
    - Exercise system with various variable
    - Adaptable to SET characterization
  - Report of issues of stability and limits of performance
- Continue evaluate emerging POL design
  - Likely will be Texas Instrument, Aeroflex and 3Dplus
- Stress test for to evaluate performance for flight-like application

Radiation Susceptibility

- **Radiation can cause various degradation and failure modes in POL devices which may impact system level performance**
  - **Total Ionizing Dose and Displacement Damage**
  - **Single Event Transient (SET)**
    - **Localized ion strike on a sensitive node resulting in voltage/current spikes**
    - **SETs can propagate through multiple stages of the power architecture and cause catastrophic failure to a Microprocessor/FPGA**
  - **Functional Interrupt (i.e. output dropout)**
    - **Self-recoverable or requiring power cycle**
  - **Destructive Event**
    - **Single Event Latchup, Single Event Burnout, and Single Event Gate Rupture**

Radiation-induced Output Dropout

MSK5059RH Radhard buck regulator from MSK



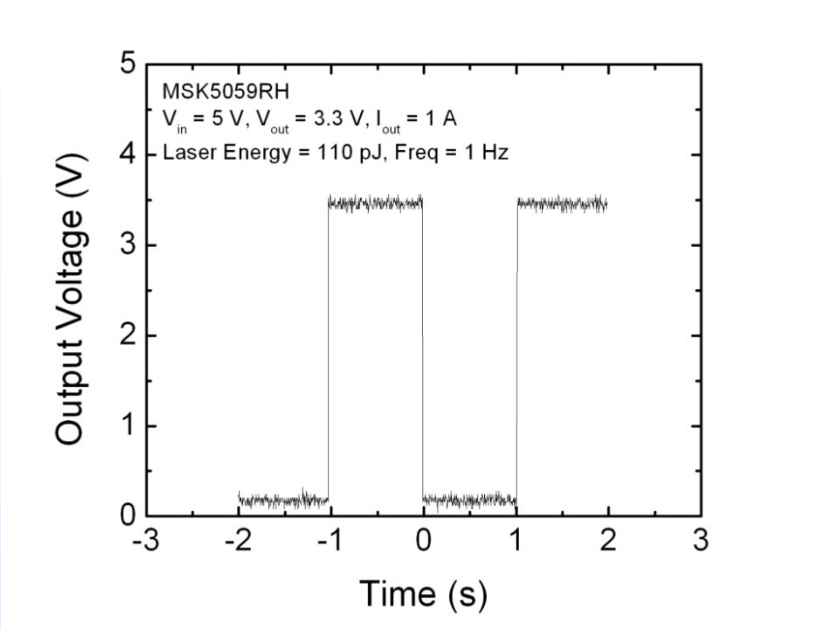
- **Tested at TAMU cyclotron facility with 15 MeV/amu cocktail heavy-ions**
- **Testing challenges:**
  - **Design/fabricate SET test board to suppress output ripple oscillation and provide proper heat dissipation**
- **Output dropped at LET_{eff} = 124 MeV·cm^2/mg**
  - **Thermal shutdown?**
  - **Single event latchup?**

- **400 nm high speed bipolar process, hybrid design**
- **Tested with V_{in} = 7 V, V_{out} = 3.3 V, I_{out} = up to 1.5 A**

Investigate what caused the output dropout

Dropout from PN Junction Capacitor

MSK5059RH Radhard buck regulator from MSK

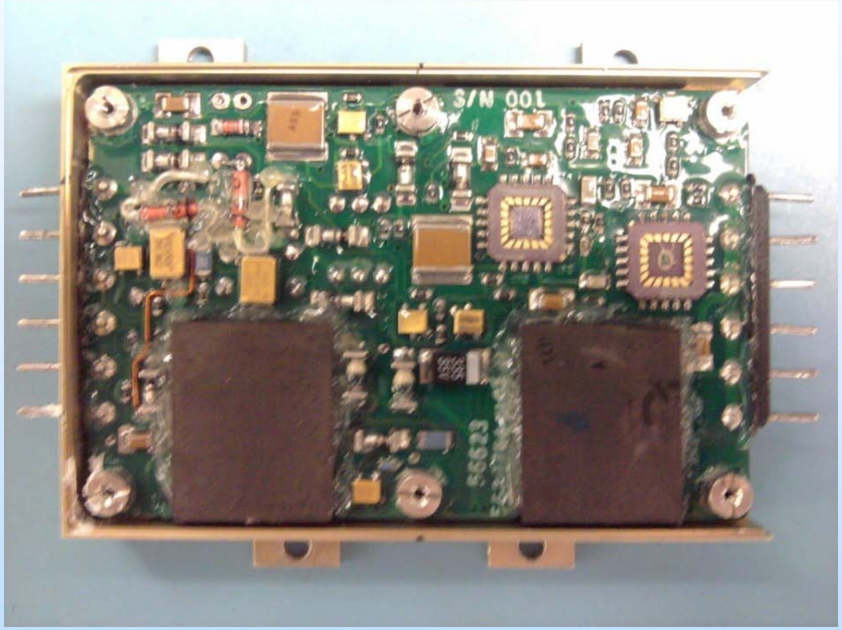


- **Tested with pulsed-laser at the Naval Research Laboratory (NRL)**
- **Observed dropout for strikes on the junction capacitor overlaying the C-B of NPN that controls the reference voltage**
  - **Dependent on laser pulse frequency**
- **Laser energy threshold 55 to 110 pJ, correspond to ~ 165 to 330 MeV·cm^2/mg**
  - **Similar LET_{th} as events from heavy-ion test**
- **Not a concern for most missions due to the high energy threshold**

Laser testing identified sensitive component causing dropout

Dropout from Soft-Start Upset

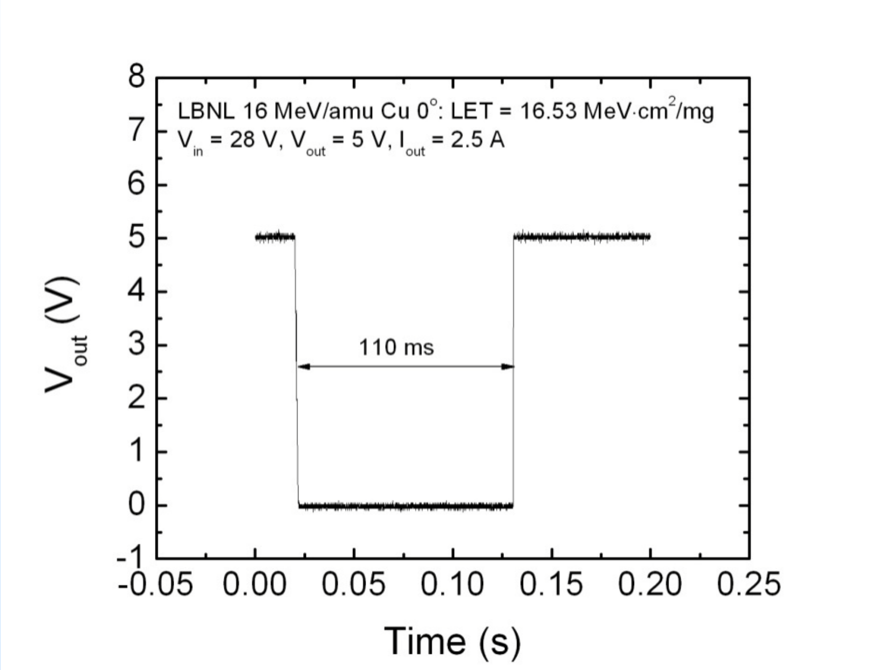
Radhard DC/DC Converter from XX



- V_{in} = 28V, V_{out} = 5 V, I_{out} = 10 A continuous
- Tested at Lawrence Berkeley National Laboratory with 16 MeV/amu cocktail heavy-ions in vacuum
- Testing challenges:
  - Vacuum chamber introduced noise
  - Surface mount technology with ICs on front and backside of PCB

Dropout from Soft-Start Upset

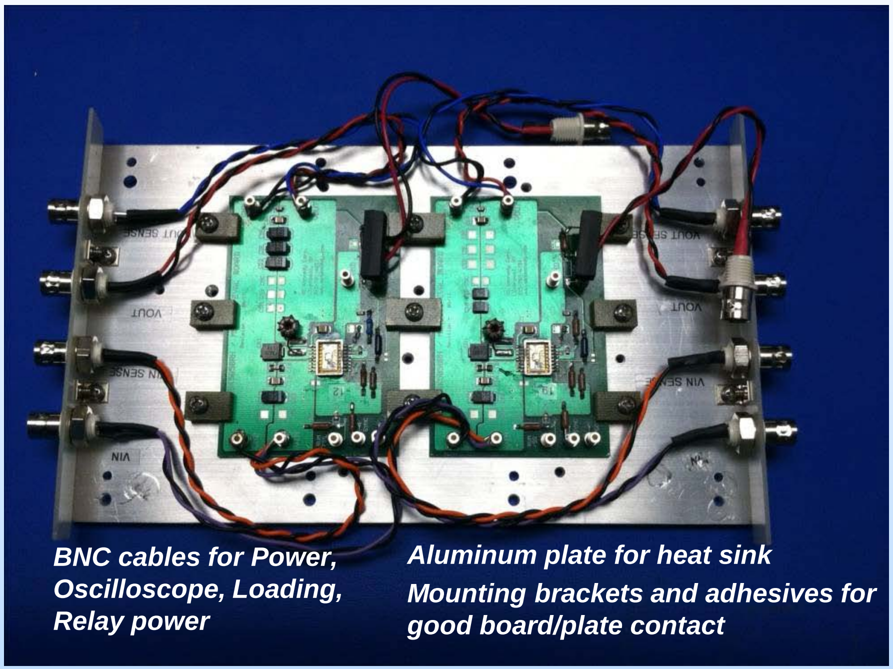
Radhard DC/DC Converter from XX



- **Observed output dropouts lasting 110 ms**
- **Single Event Upsets in the PWM initiated soft-start**
  - **Supervisory circuitry shuts off device for 100 ms when output drops below 4 V**
- **Features designed for device reliability can drastically influence the SEE response**
- **Test findings prompted redesign**

SET Characterization

MSK5058RH Buck Regulator from M.S. Kennedy

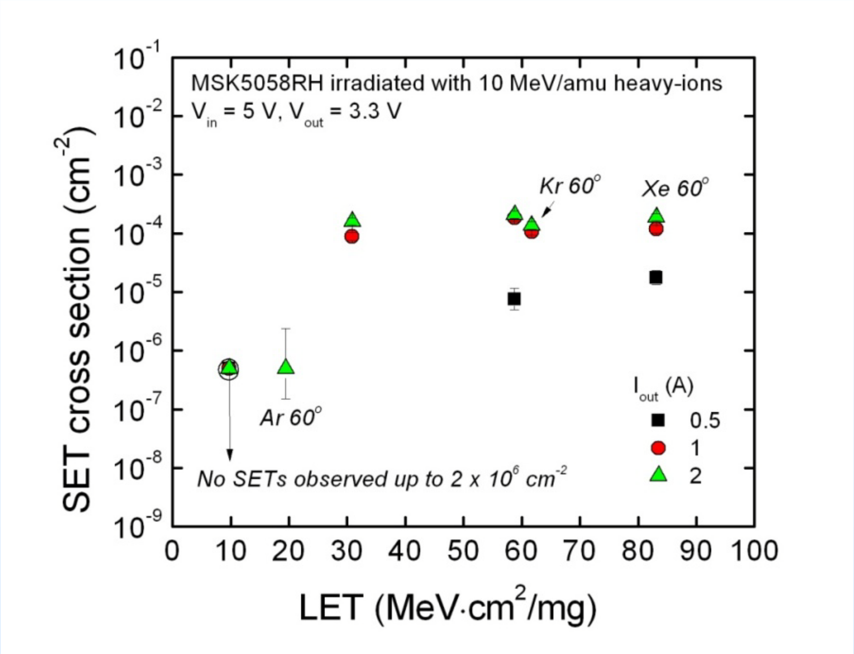


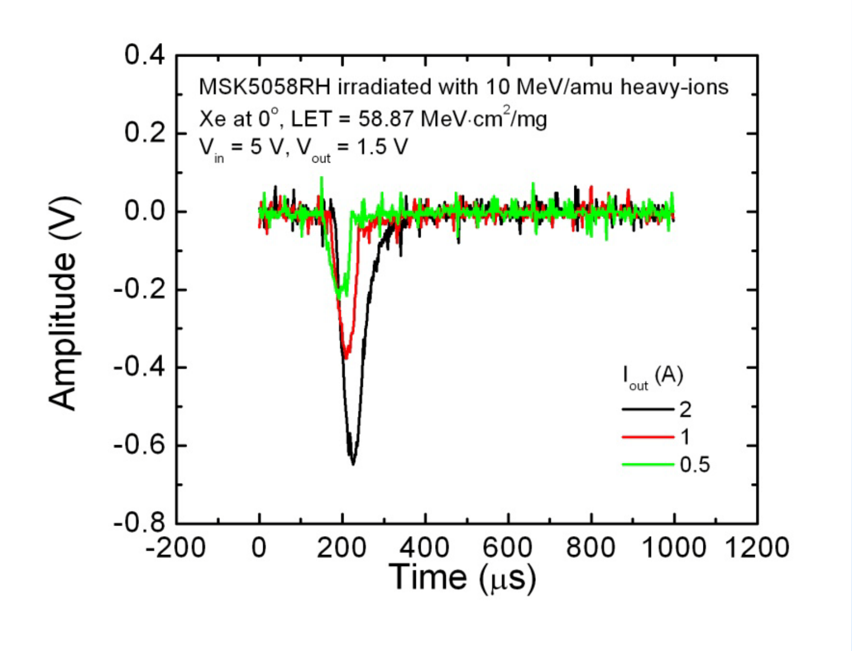
- **Hybrid design, RH3480 die from Linear Technology, BIPC150 1.5 µm bipolar process**
- **V_{in} = 3.6 to 36 V, V_{out} = 0.79 to 20 V, Maximum 2A continuous output load**

- **Heavy-ion irradiation at LBNL with 10 MeV/amu heavy-ions in vacuum**
- **Pulsed-laser testing performed at NRL and JPL**
- **Testing challenges**
  - **Vacuum environment**
  - **Heat dissipation: needed to shut off device following high current modes (case temperature < 55°C)**
  - **Long cables introduce high resistive drops for high output loads**
  - **Facility (vacuum chamber) introduced noise ~ 600 mV_{pp}**

SET Characterization

MSK5058RH Buck Regulator from M.S. Kennedy

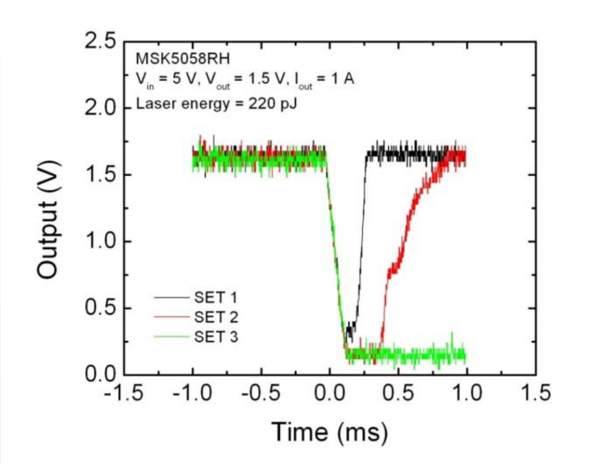




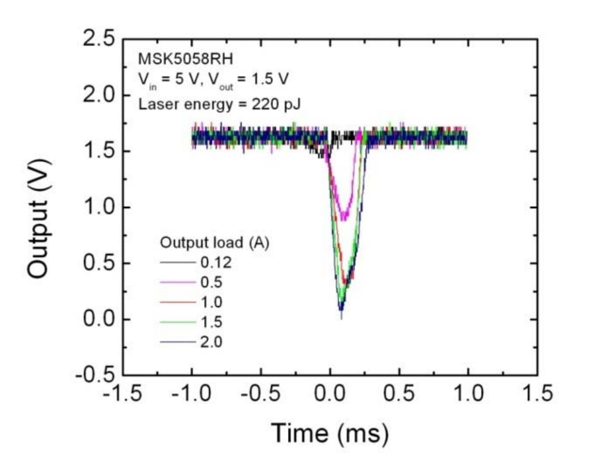
- **No destructive event or functional interrupt (dropout) up to LET = 83 MeV·cm²/mg**
- **Mission error rate can be calculated from cross section**
- **Determine the significance of SET (amplitude and duration)**
- **SET magnitude and cross section dependent on output current load**

SET Characterization

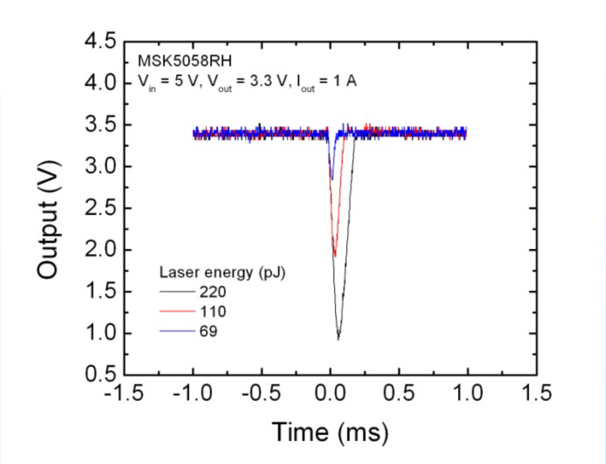
MSK5058RH Buck Regulator from M.S. Kennedy



PNP transistor in the voltage reference loop



PNP transistor for setting the Power Good threshold



PN junction capacitor for voltage reference compensation

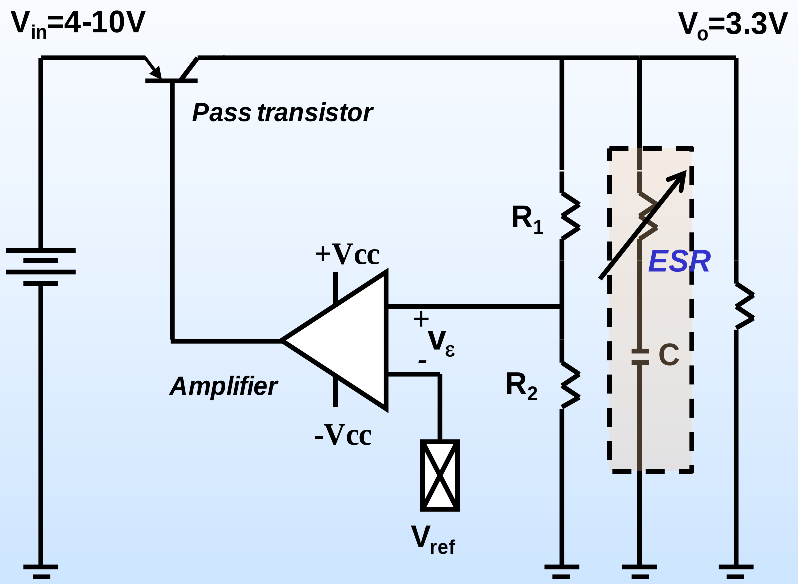
- **Pulsed-laser testing identified sensitive locations**
- **SETs most significant from the voltage reference PNP**
  - **Dropouts occur for very high energies (220 pJ): not a realistic concern for space**

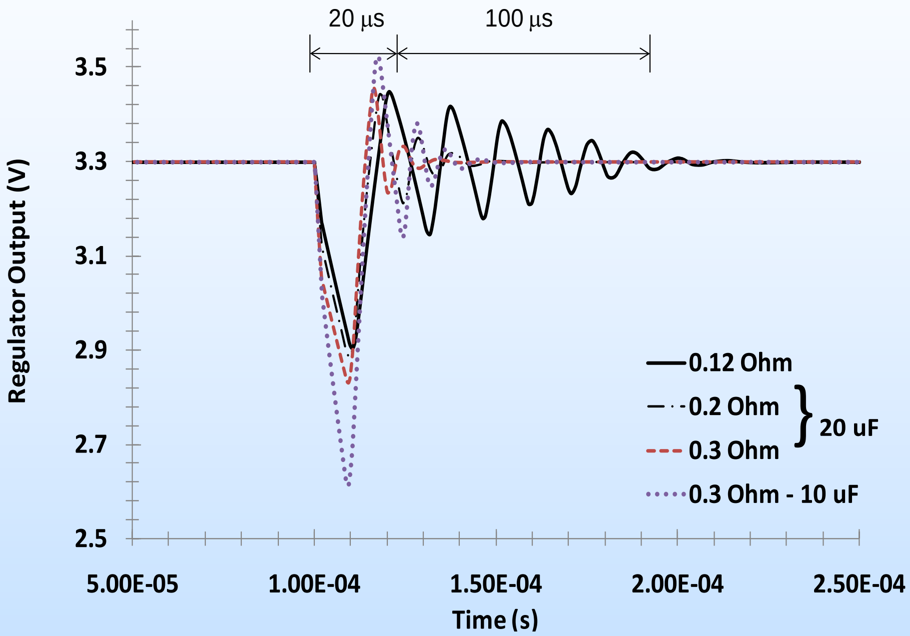
Investigation of Circuit Configurations

- **JPL lead effort to investigate the effects of circuit configurations and device operating conditions on SET characteristics**
  - **Output capacitor selection (ESR values)**
  - **Output loading type (resistive vs. electronic load)**
  - **Device operating conditions (Input voltage and output load)**

- **Provide test recommendations and insights to the space radiation community**
  - **G. Allen, P. Adell, D. Chen, and P. Musil, "Single Event Transients Testing of Linear Regulators,"** ***to be presented at the 2012 NSREC***

Spice Modeling

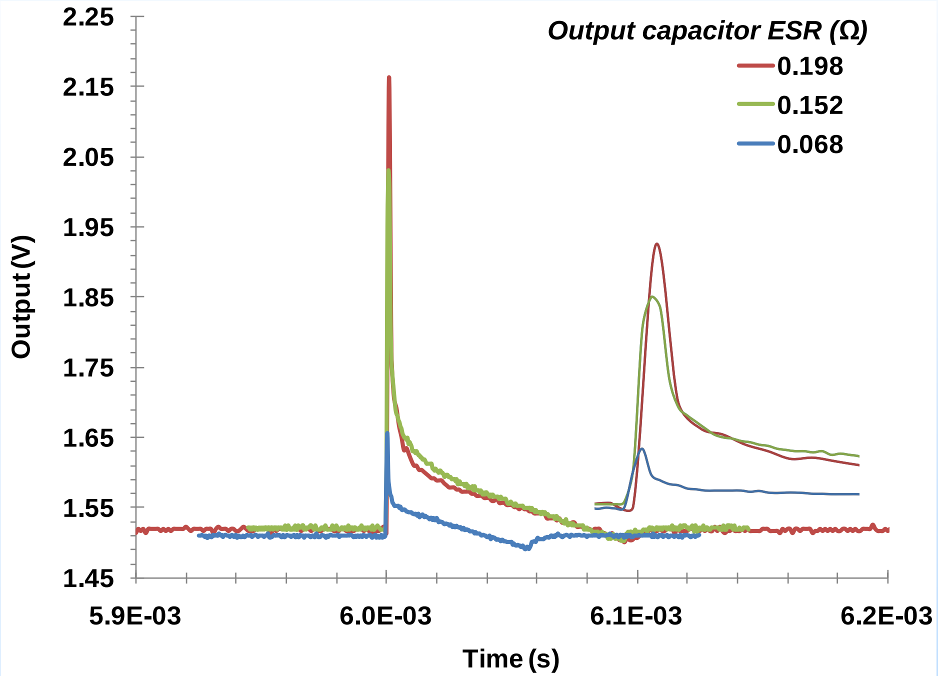




- Simulated ion strike on a sensitive transistor in the amplifier
- ESR value of the output capacitor influences the SET peak amplitude and settling time
- Improper capacitor selection can cause significant oscillation and induce prolong instability (100 µs)

Laser-induced SETs – ESR Impact

MSK5920RH Radhard Low Voltage Dropout Regulator (LVDO) from MSK

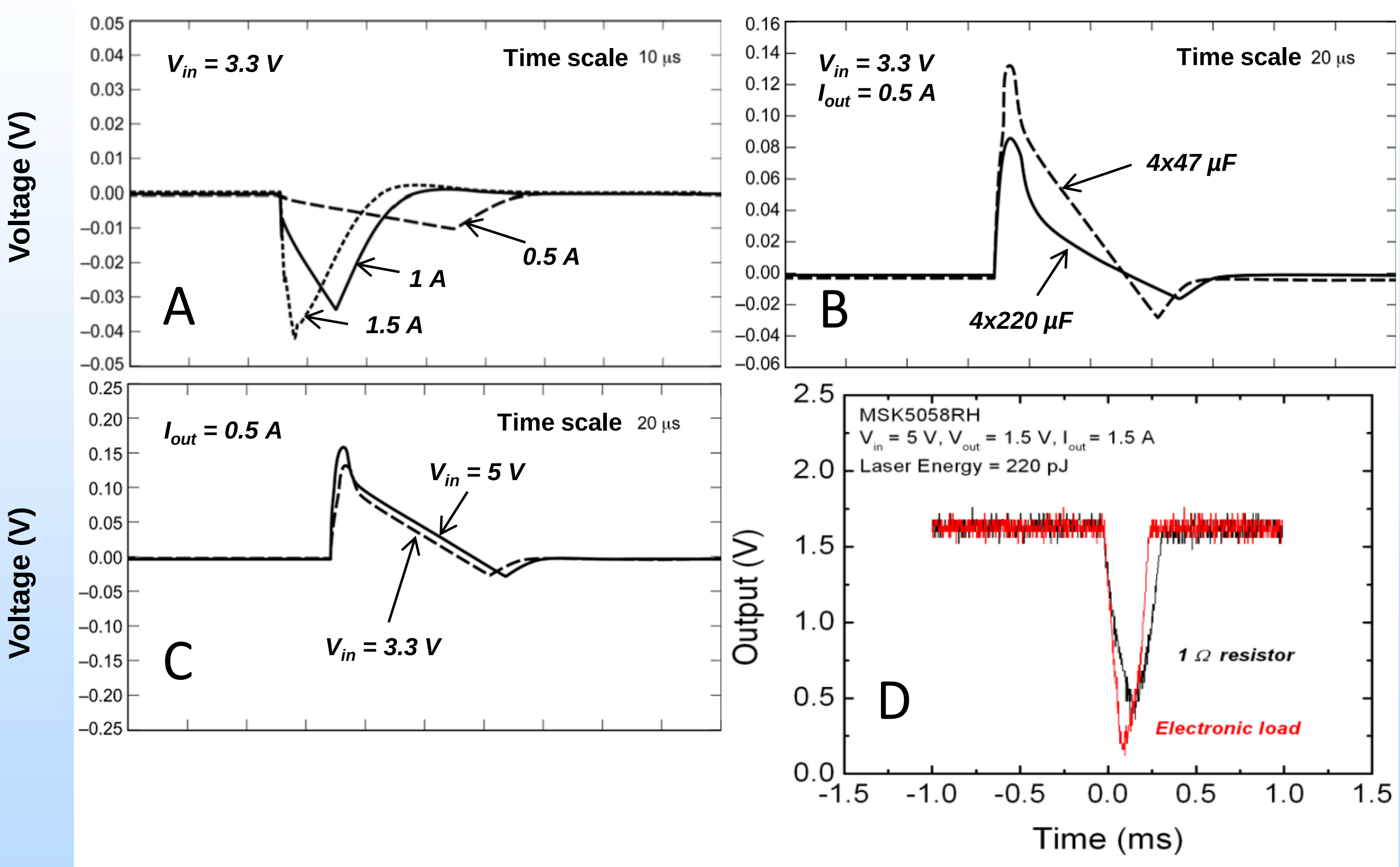


Laser energy 55 pJ, output 1.5 V, Vin 5 V, 50 mA

- V_{in} = 2.9 to 6.5 V, V_{out} = 1.5 V, I_{out} = 5 A
- Tested with pulsed-Laser at JPL
- Evaluated different output capacitors with various ESR values
- Manufacturer recommended ESR values:
  - Less than 180 mΩ for many applications
  - Less than 57 mΩ for most stringent applications
- SET magnitude increases with increasing capacitor ESR
  - Similar response has been observed for MSK5900
  - Effect worse at low load current

Impact of Device Test Conditions

MSK5058RH Buck Regulator from M.S. Kennedy



SET response varies with input voltage, load conditions and load types

Conclusion

- The various process technologies and distinct design architectures of modern POL devices lead to a variety of distinct radiation responses
  - Different mechanisms can trigger functional interrupts (output dropouts)
  - SET characteristics depend on device operating conditions and circuit configurations
    - Pulsed-laser a good tool for SET evaluation
- Identified SEE testing challenges and determined solutions which will aid in developing test guideline for space radiation community