Design of a New Switching Power Supply for the ATLAS TileCal Front-End Electronics

TWEPP 2012

Gary Drake

Senior Engineer

Argonne National Laboratory, USA

On Behalf of the ATLAS Tile Calorimeter System

Oxford, England

Sept. 20, 2012

TileCal in the ATLAS Detector

⇒ **There are 256 modules in the detector, ~10,000 readout channels**

Switching Power Supply for ATLAS TileCal – G. Drake – TWEPP – Oxford, England – Sept. 20, 2012

Block Diagram of the TileCal Power Dist. System

- Block Diagram of the TileCAL Power Distribution System:

The ATLAS TileCal Low Voltage Power Supply (LVPS)

Block Diagram of the LVPS Box:

Stage 2

Picture by Ivan Hruska

Range of Voltages: 5:1
Range of Currents: 62:1

⇒ One Basic Brick Design
Different Component Values

⇒ Note: No Redundancy...

The ATLAS TileCal LVPS (Cont.)

- Full Custom Design
 - Novel switching DC-DC power supply; 300 KHz
 - Original design by Ivan Hruska
- Features:
 - Custom, compact, high-efficiency, 250 Watt
 - 8 different voltages → Customized bricks
 - Water cooled; System interface & monitoring
 - Environment: Magnetic field; Radiation tolerant
- 256 boxes on detector, 2048 bricks, + spares
- **Reliability is Important → Infrequent Access**

Brick Type	Nominal Voltage	Nominal Current
-5MB	-5.3	5.6 / 4.2
+5MB	+5.4	11.1 / 8.3
+15MB	+14.5	0.45 / 0.34
+3DIG	+3.45	4.74 / 3.56
+5DIG	+5.30	5.6 / 4.2
-15HV	-14.5	1.55 / 1.16
+5HV	+5.0	0.18 / 0.14
+15HV	+14.5	0.29 / 0.22

View of Box, Cover Removed

4 Bricks above Cold Plate
4 Bricks Below Cold Plate

Side View of Box, Cover Removed

Water Connectors
Cold Plate (In Middle)
Flat Cable to ELMB (On Bottom)

Individual Brick (Not to Scale)

Pictures by B. Palan

Switching Power Supply for ATLAS TileCal – G. Drake – TWEPP – Oxford, England – Sept. 20, 2012

TileCal LVPS Redesign Project

■ Original production

- Produced in 2005
- Installed on detector in 2006-2007
- Performance & reliability concerns developed:
 - Board fabrication problems
 - Assembly & soldering problems
 - Substantial rework
 - Stability problems
 - Spontaneous tripping on detector → Noise
 - Hard failures on detector - ~6-10 per year
 - Later – tripping correlated with beam →

■ Redesign project

- Community was concerned about long-term reliability
- Review recommendation in 2009: Consider new design
- ANL Elec. Eng. Group collaborating since 2006, took on redesign project
 - ⇒ **Thorough evaluation of problems & testing**
 - ⇒ **Conclusion: Redesign best way to address issues**
 - ⇒ **Goals:**
 - ⇒ **Address issues**
 - ⇒ **Minimize system perturbation**
 - ⇒ **Design “drop-in” replacement**

Post-assembly modifications

Burned capacitors

Original Bricks: Spontaneous Tripping, Non-Destructive

Original Brick

ANL “Blue Brick”

Brick Issues & Improvements

Improved Reliability

Critical Issues

- Reduce Noise
- Opto-Isolator latch-up
- Thermal Management
- Better ESD protection of ICs

Medium-Impact Issues

- Improve stability
- Improve trip circuitry
- Power sequencing
- Fabrication and soldering quality
- Capacitor Voltage Ratings

Non-Critical But Highly Desirable

- Start-up pulse current
- Eliminate pre-loads
- Improve monitoring circuitry
- IPC specs for assembly
- Reduce/improve tuning

Improved Performance

Output Noise

Thermal Image

Tripping on Noise

⇒ **Improved noise performance will reduce tripping**

⇒ **Other improvements in reliability as well**

The ATLAS TileCal LVPS (Cont.)

■ Block Diagram of New Brick

■ Function of the Controller Chip

- Modulate the pulse width of the clock driving the switching, based on feedback

- When the output voltage is too high, reduce the pulse width
- When the output voltage is too low, increase the pulse width

Discussion of Improvements to Design

■ Critical Issue: Reduce Noise

⇒ *What we did:*

- Add/improve ground planes
- Add/improve filtering
- Careful attention to return currents

V7.3.0 – Internal Layers
(Colors = Cu)

Output Noise

- +5MB @ 13A
- 2.05V p-p
- 154 mV RMS

Output Noise

- +5MB @ 13A
- 99 mV p-p
- 6.4 mV RMS

Output Noise

- +5MB @ 13A

— Old Version

— New Version

Improvements to Design (Cont.)

■ Critical Issue: Opto-Isolator Latch-up

⇒ *The symptoms:*

- Bricks would latch up spontaneously
- Can persist for a long time...

⇒ *The cause:*

- Undocumented requirement for extra bypass capacitors

⇒ *What we did:*

- Add bypass capacitors to inputs
- Add bypass capacitors to power pins

Brick Block Diagram

Opto-Isolator Circuit Schematic

Improvements to Design (Cont.)

■ Critical Issue: Thermal Management

⇒ *The symptoms:*

- U1 (controller chip) & U2 (FET driver) had high failure rates

⇒ *A possible cause:*

- Insufficient thermal coupling to cold plate

⇒ *What we did:*

- New layout to get chips over cold plate
- Add thermal foam (Gap Pad) to couple chips to cold plate

Brick Block Diagram

Implementation

Bergquist Gap Pad 1500S30

Original Version

- +5MB @ 13A

New Version

- +5MB @ 13A

© 2013 Pearson Education, Inc. or its affiliate(s). All rights reserved. No part of this publication may be reproduced, stored in a retrieval system, or transmitted, in any form or by any means, electronic, mechanical, photocopying, recording, or by any information storage or retrieval system, without prior written permission from Pearson Education, Inc. or its affiliate(s).

- ⇒ **A possible cause:**
 - *Overload on input pins (→ Noise?)*
- ⇒ **What we did:**
 - *Add diode protection to input pins*

Summary of Design Changes

Improved
Reliability

■ Critical Issues

- Reduce Noise.....
- Opto-Isolators.....
- Thermal Management.....
- Better input protection of U2.....

■ What we have done:

- ⇒ More ground planes; improved filtering
- ⇒ Filter supply & input pins
- ⇒ U1 & U2 over cold plate; Use Gap Pad
- ⇒ Add diode protection of inputs

■ Medium-Impact Issues

- Address stability.....
- Improve trip circuitry.....
- Power sequencing.....
- No kludges
- Fabrication and soldering quality
- Tantalum capacitors.....

- ⇒ Feedback completely redesigned
- ⇒ Simplify secondary; OVP & OCP Logical OR
- ⇒ New regulator with programmable delay
- ⇒ No kludges in production
- ⇒ Will use approved vendors
- ⇒ Use 25V caps on 15V sec. out., not 16V

■ Non-Critical But Highly Desirable

- Start-up Pulse current.....
- Eliminate pre-loads.....
- Improve monitoring circuitry.....
- IPC specs for assembly.....
- Reduce/improve tuning...

- ⇒ New regulator with programmable delay
- ⇒ No preloads → New feedback design
- ⇒ Differential techniques
- ⇒ Design adheres to IPC specs
- ⇒ Tuning of OVP now 1 step process

Improved
Performance

Radiation Tests of Bricks

- Needed to redo radiation tolerance studies
 - ⇒ *We used ~same parts, but was something missed?*
 - ⇒ *Requested by Atlas review committee...*

- Requirements:

<u>Photons (TID)</u>	<u>Neutrons (NIEL)</u>	<u>Protons (SEU)</u>
37 KRad	6E12 n/cm2-sec	1.7E12 p/cm2-sec
Safety Factor: 70	Safety Factor: 20	Safety Factor: 20

- We performed 8 Sessions – Dec. 2010 – Apr. 2012
 - Photons (TID) @ BNL, 1.2 MeV from Co-60
 - Neutrons (NIEL) @ UMass-Lowell, U-235 reactor
 - Protons (SEE) @ Mass Gen, 200 MeV radiation treatment

- Results:

- Photons: Slow degradation; No failures
- Neutrons: Slow degradation, No failures
- *Protons: Found Single Event Upset with controller chip*

- Further study of SEU

- Energy scan found dependence on energy
(SEUs not seen before in tests at 60 MeV)

- ⇒ *We found a fix to the SEU problem - Confirmed*
- ⇒ *SEU energy dependence not part of specs!!!*
- ⇒ *Have now developed tools & techniques to make these measurements in the future*

@BNL

@Lowell

@MGH

The SEU Problem

- What is happening:

Soft-start capacitor
External component
Value controls startup delay

© 2013 Pearson Education, Inc. or its affiliate(s). All rights reserved. Pearson Education, Inc., publishing as Pearson Benjamin Cummings, 101 Philip Drive, Assinippi Park, New York, NY 10984-2135

- **Solution to the SEU Problem**

- ⇒ **Tested in Building 175 on all bricks**
 - ⇒ **No overshoot on cold start**
 - ⇒ **No trips from SEU**
 - ⇒ **No damage to electronics**
 - ⇒ **No abnormal behavior in DAQ**
 - ⇒ **All other faults work normally**

- **An elegant solution to a nasty problem, requiring only 2 additional parts**
 - Diode is forward biased during cold start → Normal startup
 - Diode is reverse biased for an SEU → Fast recovery since $C_{ap} \sim 0$

⇒ ***Has been incorporated into final design, V7.5.0***

Final SEU Testing at MGH

- Session: April 1, 2012
 - Energy scan: 60 MeV, 80 MeV, 100.5 MeV, 140 MeV, and 216 MeV
 - Used (4) V7.5.0 bricks without SEU fix
- Preliminary Results:

- ⇒ *Can clearly see an energy threshold...*
- ⇒ *Analysis continuing... → Collaboration with UW-Madison*
- ⇒ *Will publish an Atlas Note shortly*

Final Photon Testing at BNL

■ Session: April 3, 2012

- The test was run over a period of 13 hours
- Accumulated a total dose of ~37 krad
- The output voltages and currents were monitored continuously through this period
- Modest changes to some of the monitored values were observed
- The inflection point in the plots seen at about 37 krad corresponds to the time the source was closed
- There were no hard failures during the test

⇒ Retest to look for opto-isolator failure at high dose

⇒ Found none → OK

⇒ Atlas Note forthcoming

Switching Power Supply for ATLAS TileCal – G. Drake – TWEPP – Oxford, England – Sept. 20, 2012

Further Studies

SEU Energy Dependence

- Theory: Bendel Parameters
 - ⇒ *Well known in space instrumentation*
 - ⇒ *Not well known in HEP instrumentation*
- Formed research project: ANL & UM-Madison + students
 - ANL: J. Proudfoot, G. Drake, R. Stanek
 - UW: Bruce Mellado, Abhirami Senthilkumaran, Anusha Gopalakrishnan
- Study & characterization of SEU effect in semiconductors underway
 - Function of feature size of devices
- Expect that this will influence future radiation tolerance specs
 - ⇒ *Paper coming at 2012 IEEE NSS*

Reliability

- The power supplies have had a history of reliability problems
 - Single point failures, no redundancy
 - No analytical study done on reliability of circuitry
 - ⇒ *Typically not done in HEP instrumentation either*
- New bricks expected to be better but no analysis done
- Formed research project: ANL & UM-Madison + students
 - ANL: J. Proudfoot, G. Drake, R. Stanek
 - UW: Bruce Mellado, Abhirami Senthilkumaran, Anusha Gopalakrishnan
- Study & characterization of failure rates, MTBF
- Expect that this will influence future design methodology
 - ⇒ *Paper coming at 2012 IEEE NSS*

Device Cross-section (σ)

Proton beams:

$$\sigma = \frac{N_{\text{events}}}{\Phi} \quad (\text{cm}^2)$$

Heavy ion beams:

$$\sigma = \frac{N_{\text{events}}}{\Phi \cos \theta} \quad (\text{cm}^2)$$

Stapor et al., IEEE-TNS, Vol 37-6, 1990

Our result: Probability of Failure-free operation:

R(t = 2 years)	R(t = 5 years)	R(t = 10 years)	R(t = 20 years)
0.993	0.982	0.965	0.932

⇒ *Expect ~2 failures per year*

Project Summary to Date

■ Project Time Line

- Prototype design cycle begun ~June, 2009
- V7.1.0 – December, 2009, Quantity 10 bricks
 - Tested at CERN in Box 066
 - ⇒ *Ran in long-term test since Mar. 2010 → ~1.5 yrs*
 - ⇒ *No significant problems, Now stopped* **Box 0_p***
- V7.3.1 – November, 2010, Quantity 64 (→ 80) bricks
 - Delivered 5 boxes to CERN (+ 1 from Oct. = 5 boxes total)
 - Tested at CERN, “medium-term” test, ~1-2 months
 - **Boxes 1-5 installed on detector during Dec. 2010 shutdown**
 - ⇒ *Ran in long-term test Nov.-Dec., 2010 → ~30-45 days*
 - ⇒ *4 trips on detector to date → ~600 days* **Boxes 1_p-5_p***
 - ⇒ *(Real SEU?...)*
- Production Readiness Review – Aug. 17, 2011
- V7.5.0 – December, 2011, Quantity 320 bricks
 - Delivered 40 boxes to CERN **Boxes 6-45**
 - Installed on detector
 - → Total of 45 boxes on detector
 - ⇒ *1 trip on detector to date → ~240 days*
- V7.5.1 – January, 2012-present, Quantity 2080 bricks
 - We are in production now, nearly complete
 - ⇒ *Will install remaining supplies during 2013 shutdown*

Performance on Detector

Trips in detector by module

⇒ **Current Numbers (as of Sept. 1, 2012):**

⇒ 8404 trips of old bricks

⇒ 4 trips of pre-production boxes (5 on detector)

⇒ 1 trip of production boxes (40 on detector)

Noise Comparison – RMS/ σ

Noise Comparison – Correlated Noise

EBC39 high gain correlation 2010-12-01

EBC39 high gain correlation 2011-03-05

Production Testing of Prototypes at Argonne

■ Test List:

- Frequency response & stability
- Voltage range (@ minimal load)
- Voltage range (@ nominal load)
- Stable operating range vs. voltage
- Stable operating range vs. current
- Output voltage vs. output current
- Voltage trip level vs. load
- Current trip level vs. load
- Output noise vs. output voltage
- Output noise vs. output current
- Output noise frequency spectrum
- Clock duty factor vs. output voltage
- Clock jitter vs. output voltage
- Clock duty factor vs. output current
- Clock jitter vs. output current
- Voltage monitor output vs. output voltage
- Current monitor output vs. output current
- Input voltage monitor read-back
- Input current monitor read-back
- Temperature monitor read-back
- Burn-in @ ~nominal load
- Check for abnormal tripping

⇒ ***Multiply by X8...***

Tests needed for each brick type

⇒ ***Goal for production: ~0.5 hrs./brick
(Not all tests, not as extensive...)***

⇒ ***Box assembly & QA additional time***

Brick Checkout

- Block Diagram of New Test Stand

© 2013 Pearson Education, Inc. or its affiliate(s). All rights reserved. Pearson Education, Inc., publishing as Pearson Benjamin Cummings, 101 University Avenue, New York, NY 10017-2423.

Summary

- Redesign project of ATLAS TileCal front-end power supplies is nearing completion
 - Begun in 2009
 - Steady progression of prototype development, pre-production, and production
 - Will have full replacement complete in 2013 shutdown
 - New design addresses several performance issues
 - Noise
 - Latch-up of opto-isolators
 - Thermal management
 - SEUs in controller chip
 - Tripping as a function of luminosity
 - + others...
 - Current status of 45 boxes on detector
 - Only 4 trips of pre-production boxes in ~600 days
 - ⇒ **Probably real SEUs...**
 - Only 1 trip of production boxes in 240 days
 - Radiation Tolerance Measurements & Analysis
 - Tolerance to photons & neutrons OK
 - Discovered SEU problem with controller chip
 - SEU probability has energy dependence, ~80 MeV threshold
 - ⇒ **Not specified in radiation tolerance specs...**
 - Problem has been addressed with circuit modification
 - Study under way to incorporate theoretical Bendt Curves
 - Reliability analysis
 - Have developed reliability models for the new power supply
 - Expect ~2 failures per year
 - Next Gen: Redundancy
 - Production checkout is nearing completion at Argonne
 - 2400 bricks total, 300 boxes
 - 45 boxes installed on detector to date; Performance looks very good
 - On track to complete on time & on budget
- ⇒ **LVPS Replacement should significantly improve the performance of the TileCAL Detector**

Switching Power Supply for ATLAS TileCal – G. Drake – TWEPP – Oxford, England – Sept. 20, 2012