Available online at www.sciencedirect.com

SciVerse ScienceDirect

Physics Procedia 37 (2012) 181 – 189

Physics Procedia

Elsevier Editorial System(tm) for Physics Procedia
Manuscript Draft

Manuscript Number: TIPP11-D-12-00002

Title: Detector Powering in the 21st Century Why stay stuck with the Good old 20th Century methods?

Article Type: Full Length Article

Section/Category: Experimental Detector Syst.

Corresponding Author: Dr Satish Dhawan,

Corresponding Author's Institution: yale

First Author: Satish Dhawan

Order of Authors: Satish Dhawan; richard sumner, phd

Abstract: Future Collider Physics Detectors are envisioned with large granularity but we have a power delivery problem unless we fill a large fraction of the detector volume with copper conductors. LHC detector electronics is powered by transporting direct current over distances of 30 to 150 meters. This is how Thomas Alva Edison powered his light bulb. For example, CMS ECAL uses 50 kiloamps at 2.5 volts, supplied over a cable set with a transmission efficiency of only 30%. The transmission loss becomes waste heat in the detector that has to be removed. We have been exploring methods to transmit the DC power at higher voltage (low current), reducing to the final low voltage (high current) using DC-DC converters. These converters must operate in high magnetic fields and high radiation levels. This requires rad hard components and non-magnetic (air core) inductors.

doi:10.1016/j.phpro.2012.02.353

***Publishing Agreement Form**

Click here to download Publishing Agreement Form: TIPP2011_publishingAgreement.doc

Detector Powering in the 21st Century

Why stay stuck with the Good old 20th Century methods?

Satish Dhawan[a], Richard Sumner[b] a*

[a]*Yale University, New Haven CT*
[b]*CMCAMAC, Pomona, N.Y.*

Abstract

Future Collider Physics Detectors are envisioned with large granularity but we have a power delivery problem unless we fill a large fraction of the detector volume with copper conductors. LHC detector electronics is powered by transporting direct current over distances of 30 to 150 meters. This is how Thomas Alva Edison powered his light bulb. For example, CMS ECAL uses 50 kiloamps at 2.5 volts, supplied over a cable set with a transmission efficiency of only 30%. The transmission loss becomes waste heat in the detector that has to be removed. We have been exploring methods to transmit the DC power at higher voltage (low current), reducing to the final low voltage (high current) using DC-DC converters. These converters must operate in high magnetic fields and high radiation levels. This requires rad hard components and non-magnetic (air core) inductors.

keywords: detector power; dc-dc converter; rad hard; air core inductors;

1. Introduction

The Yale group was a late joiner in the CMS collaboration in 2001. Latecomers are typically assigned sub systems that are considered trivial but for which no solution is at hand. Yale's urgent job was to implement a system to power the ECAL detector (ECAL required 40% of the total power consumption of

* Corresponding author. Tel.: 203 432 3377; *E-mail*: Satish.Dhawan@Yale.edu

the CMS experiment). We designed a system using radiation hard low drop out linear regulators (LHC4913 from ST Microelectronics). The system supplies 50,000 amps to the front end trigger tower electronics of the CMS ECAL [1]. The 115mm by 94 mm Low Voltage Regulator cards (LVR) were designed at Yale and assembled by a local company. These cards were given a 48 hour burn in at full power and tested. A total of 35,000 regulators were used.

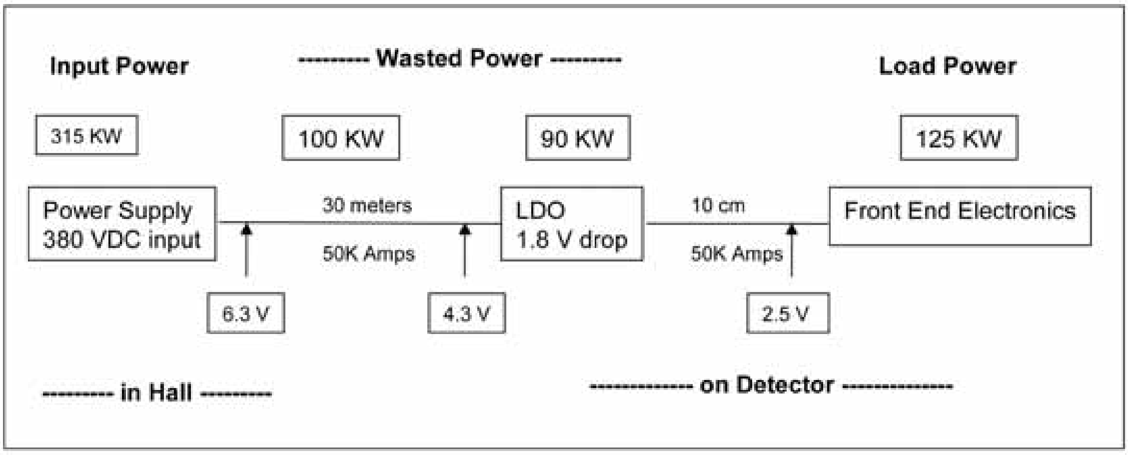

Figure 1 CMS-ECAL power delivery system

To deliver 125 KW to the front end electronics, 90 KW is dissipated in the voltage regulators and another 100 KW is lost in the transmission lines from the power supply. This is an extra 190 KW of heat to be removed from the detector. The large copper power cables and the infrastructure needed to remove the extra heat represent a substantial amount of dead (inactive) material in the detector.

Towards the end of this project, we started to ask the question “Is there a better way”. Since all the HEP collider experiments are in a magnetic field of at least 1 Tesla, there should not be any magnetic material used in the system. Further the radiation hardness requirements of the components used depends upon the location of the sub-detector with respect to the collision point. After finishing this project for CMS, DoE decided that Yale University should switch from CMS to ATLAS and we decided to look at the powering of the ATLAS tracker for the high luminosity super LHC upgrade.

2. Power Conversion

In the electrical power utility distribution grid the AC power is transmitted at high voltage (low current) and transformed to lower voltage (high current) by magnetic (iron) transformers. For Collider detectors, DC-DC conversion is a realistic option for improving power delivery efficiency. A buck converter [2] is a circuit topology that can transform DC power using only one inductor. The energy is pumped into the magnetic field at the higher voltage and withdrawn at the lower voltage. If the buck converter operates at a high frequency, the required inductance can be quite small, and an air core inductor can be used in high magnetic fields.

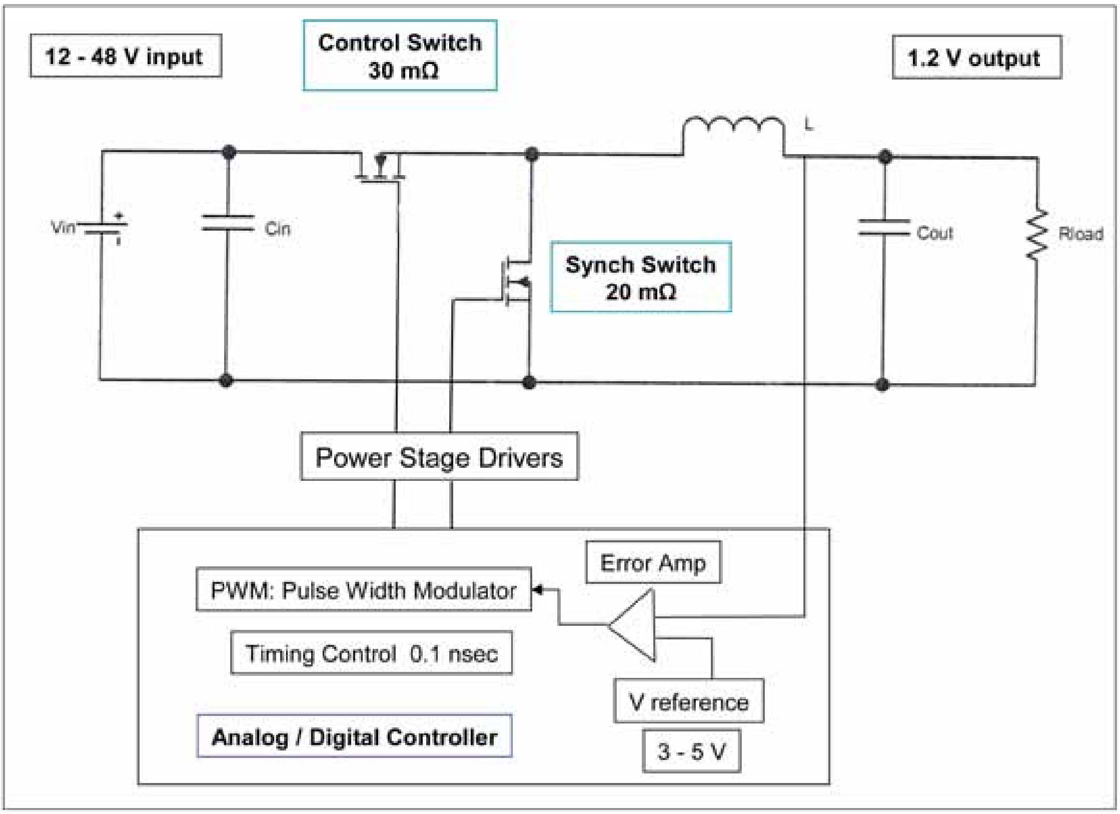

Figure 2 Buck Controller showing Power stage, Inductor, Power Stage Drivers and PWM

Shown in figure 2 is a typical synchronous buck converter design. The simplest basic design contains five main components. These are the capacitors (Cin & Cout), the inductor (L), the high-side switch (control switch), the low-side switch (synch switch) and the Pulse Width Modulator (PWM). Each of these components has special requirements and different vulnerabilities to the environment.

In considering the input and output capacitors, (Cin & Cout), there are many commercial ceramic chip capacitors that meet the temperature and radiation requirements of the environment and so this component will not be discussed further.

Commercial designs use inductors with magnetic (iron, ferrite, etc.) cores to increase the inductance per unit volume and reduce the overall size. However, magnetic core inductors can be saturated by an external magnetic field. A 2 Tesla static magnetic field will saturate any magnetic core inductor. This mandates the use of an air core inductor. In physical size an air core inductor is much larger than a magnetic core component with the same inductance. Notice that the minimum inductance value in a buck converter design is inversely proportional to the switching frequency. Thus by increasing the switching frequency the inductor value (and physical size) is reduced.

The high-side and low-side switches are very similar in function. Both devices profit from fast switching speed (low switching losses) and low channel resistance. However for an input to output voltage ratio of 10 the high-side switch will be on 10% of the time and the low-side switch 90% of the time. It becomes relatively more important to optimize the high side switch for switching losses and the low side switch for channel conduction (Ohmic) loss. At a 1 MHz switching frequency the high-side switch is on for 100 nsec. For efficiency and control the rise and fall times should be < 10% of this or about 10 nsec. This in turn puts more stringent requirements on the PWM.

The Pulse Width Modulator integrated circuit provides control and voltage regulation. The requirement for the PWM is to provide sufficient current drive with fast rise and fall times to quickly change the state of the upper and lower switches. This obviously becomes more difficult as the frequency increases.

3. Radiation Resistance of Components

The semiconductor components in figure 2 must be radiation hard for the most demanding applications, such as for the inner detectors. As R&D for the present LHC has demonstrated, sub-micron CMOS processes have the capability to be radiation hard. Additionally, there is a large amount of industrial development of buck regulators due to the need for point-of-load power delivery with high efficiency. These two facts led members of this collaboration to research and test commercial buck regulators for radiation hardness. We hoped to leverage the large industrial R&D investment with the expectation that either a complete commercial solution might emerge, or that industrial developments would point the way to a semi-custom solution.

We have had little previous experience with testing semiconductor devices in a radiation environment. In discussion with many experts involved in IC design and radiation testing, we learned from Mark Raymond of Imperial College that custom integrated circuits designed in a 0.25 μm CMOS process tend to be radiation hard [3,4]. We have found that in CMOS circuits, a thin gate oxide is a necessary condition for radiation hardness. The breakdown voltage of a 5 nm oxide barrier is less than 6 V, but it can be extended by drain extension techniques such as LDMOS (Laterally diffused MOS) structures. Using ion implants and field shaping the voltage gradient under the gate is reduced and can allow up to 15 V on the drain. IHP Microelectronics [5,6] has developed this fabrication process and thus a rad hard x10 buck converter can be developed to convert 12 V to 1.2 V. LDMOS transistors are used for RF power amplifiers for cellular base stations where they operate at 48 V. Unfortunately these use thicker oxide layers and are not radiation tolerant.

We have tested a commercial DC-DC converter in 0.25 μm CMOS (Enpiron EN5360) operating at 5 MHz. We irradiated this device to 100 Mega-Rads of Gamma radiation while under load at BNL in 2007 [2,7]. There was no noticeable change in the conversion efficiency or the output voltage. This is what is called beginners luck! If this device had failed, it would have been the end of this effort. Then the first question that arose was "How is the 5 MHz operating frequency of this DC-DC converter going to affect the very sensitive custom designed amplifiers of the ATLAS Silicon tracker". In 2007, we went to Rutherford Appleton Laboratory in UK with an air core solenoid inductor on a Linear Technology DC-DC converter evaluation board to test noise injection into the ATLAS silicon tracker electronics To our pleasant surprise the noise was small and manageable. Later this board was inserted into the 7T field of a Yale chemistry NMR magnet with no effect on the output voltage [8].

The requirements of the high radiation tolerance and high operating voltage of the power switch in the Buck converter can be met in principle by using a wide band gap material like Gallium Nitride (GaN).For the past few years, we have been evaluating GaN devices and these are very radiation hard. Converters in this technology are also capable of higher conversion efficiency due to the lower on resistance and no reverse recovery losses. The lack of reverse recovery losses is more important as frequency is increased. There is work going on to produce higher speed drivers for the GaN power stage. An efficiency of higher than 90% is achievable for 48 v to 1 v converters and has been measured by our group. We have tested buck converters with air core inductors to 7T fields in the Yale Chemistry NMR laboratory.

Many noise tests of converters with silicon detectors were done at Yale and BNL. The latest tests were done in September of 2009 at Liverpool with the ATLAS upgrade silicon tracker. This work was reported at the 2009 TWEPP conference in Paris [8,9].

4. Air Core Inductors

For operation in very high magnetic fields, an air core inductor is essential. Using a ferrite core inductor and adding magnetic shields both increases the dead material in the detector and, in the case of a silicon tracker, will distort the local magnetic field. The magnetic material movement during ramping may produce mechanical stress on wiring connections. We have designed an air core inductor that is embedded in a standard 4 layer PCB [6]. It has 4 identical spirals, one on each layer. The two inner spirals are connected in series and are the inductor. The outer two are connected to ground and act as a shield. Tests with silicon strip detectors have shown them to be a very effective at reducing radiated switching noise. A test PCB with this inductor and commercial buck converter ICs was designed. It delivers 6 amps at 1.2 – 3.3 V output with 15 V input.

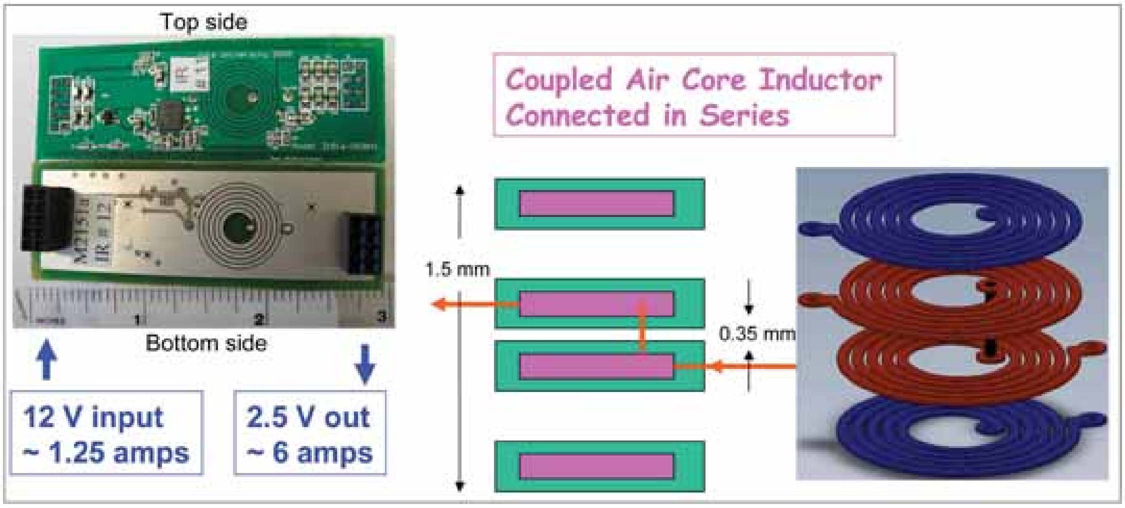

Figure 3. Test card with shielded spiral inductor in the printed circuit board.

5. Industry trends

Power supplies using switching power converters are smaller, lighter and less expensive than linear supplies that use 60 Hz AC transformers and rectifiers. They can incorporate power factor correction circuits (required in many countries) and be more efficient (energy Star requirements). As a result switching power supplies are widely used in industry and almost universally used in consumer electronics. The “wall wart” that recharges your portable electronics (cell phones, iPads, etc.) and is used for almost all low-power electronic devices, the “power brick” that powers your laptop, and the power supply in your desktop PC all use switching power supplies and DC to DC converters. Industrial motor drives, hybrid automobiles and renewable energy sources (solar panels and windfarms) all use DC to DC converters. Computer data centers distribute 385 V DC (generated with power factor correction) to racks of servers where DC to DC converters generate the low voltages required by the computer chips.

This very large market is a result of large R&D investments by the semiconductor industry over the last 50 years. The industry continually strives to produce more efficient and higher frequency power semiconductor devices. For example in 2004 Intel Corporation came out with a standard for DrMOS devices which incorporate the driver circuits into the same package as the power FET device. This was widely adopted and lowered the cost of the computer power supply while improving its efficiency.

Digital control of power converters is being used to improve the efficiency at light load and at high frequency (by adjusting the drive signal timing).

Portable devices such as smart phones must produce several different voltages from it's 3 Volt battery. This requires very small, light weight DC to DC converters. Co-packaging is being used to integrate all parts (Capacitors, switches, inductor and PWM) of the converter into one very small, low mass molded package. This reduces the size and weight of these portable devices. Two examples of commercially available co-packaged DC to DC converters are shown in figure 4. These require no external components.

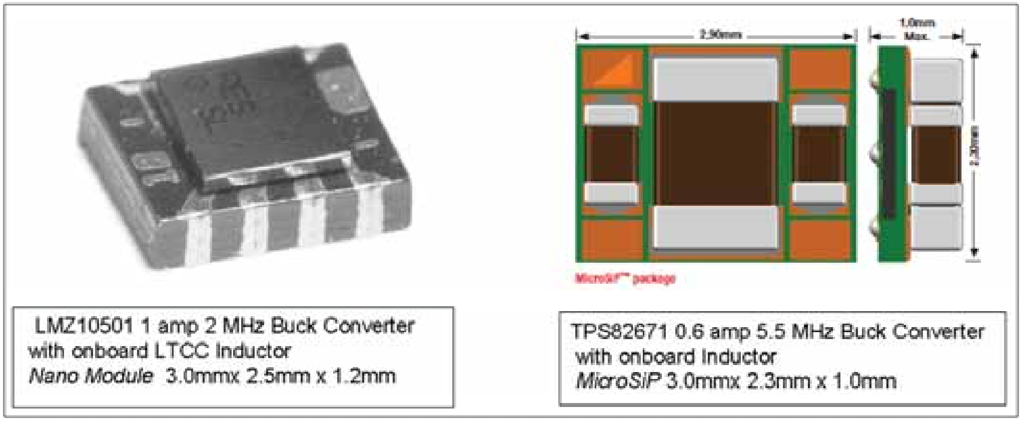

Figure 4. Two examples of commercial DC-DC converters in very small packages.

Currently several companies are developing Gallium Nitride on Silicon. This can produce GaN integrated circuits such as high-speed amplifiers and GaN power devices with the drivers included. They will enable DC to DC converters operating at higher frequencies than Silicon devices. GaN devices are expected to be rad hard and will doubtlessly be used in space and satellite hardware and in military electronics. This low cost rad hard property may also result in a new generation of low cost satellites.

6. Conclusions

There is great excitement in the semiconductor industry in providing compact and efficient power conversion solutions for portable consumer devices and for the large data centers that provide content for the internet. There are several startup companies working on more efficient devices using Silicon and wide bandgap semiconductor materials such as GaN. EPC [10] is the first company to make GaN on silicon power devices commercially available. Over the next year or two we expect to see parts that include an analog/digital PWM controller with drivers and GaN power switches all co-packaged in a micro smd form. We also expect to see GaN technology power switches with integrated drivers. This will be radiation hard and suitable for HEP. High speed and rad hard power devices will be readily available and inexpensive. This will allow a new generation of efficient power distribution systems for collider detectors. For more detailed information about the topics presented, including previous papers and seminars, please visit the Yale web site for power electronics, *shaktipower.sites.yale.edu* .

Acknowledgements

We have had many very useful discussions with people in the Power Electronics Industry and would like to thank the following people for exceptional interaction. Arnold N. Alderman of Anagenesis Inc; Alex Lidow, Bhasy Nair & Johan Strydom of Efficient Power Conversion Corp; John Roberts of GaN Systems Inc, Jeff Nilles of National Semiconductor, Richard Nowakowski of Texas Instruments, and members of U.S.PSMA (Power Sources Manufacturers Association).

References

[1] S. Dhawan, D. Lynn, H. Neal, R. Sumner, M. Weber and R. Weber “Ideas on DC-DC Converters for Delivery of Low Voltage and High Currents for the SLHC/ ILC Detector Electronics in Magnetic field and Radiation environments. 12th LECC 2006 (Workshop on Electronics for LHC and Future Experiments), Valencia, Spain 25-29 September 2006. Conference Proceedings
[2] S. Dhawan, O. Baker, H. Chen, R. Khanna, J. Kierstead, F. Lanni, D. Lynn, C. Musso, S. Rescia, H. Smith, P. Tipton, and M. Weber “Development for the Atlas Inner Detector Upgrade” Trans. Nucl. Sci., vol. 57, NO. 2, APRIL 2010
[3] . S. Saks, M. G. Ancona, and J. A. Modolo, “Radiation effects inMOS capacitors with very thin oxides at 80 K,” IEEE Trans. Nucl. Sci., vol. NS-31, no. 6, pp. 1249–1255, Dec. 1984.
[4] . R. Oldham (editor), “Ionizing Radiation Effects in MOS Oxides”, World Scientific Publishing Company (June 2000) ISBN 981-02-3326
[5] K. E. Ehwald, Ed. et al., “High performance RF LDMOS transistors with 5 nm gate oxide in a 0.25 □ m SiGe:C BiCMOS technology,” in Proc. Int. Electron Devices Meeting,Washington, DC, Feb. 2–5, 2001, pp. 40.4.1–40.4.4, IEDM Tech. Dig. 2001.
[6] F.Faccio, CERN/PH/ESE, Jan. 2009, private communication on radiation testing of SGB25VD.
[7] S. Dhawan, O. Baker, P. Tipton, J. Kierstead, D. Lynn, S. Rescia, M. Weber, ”High Radiation Resistant DC-DC Converter Regulators for use in Magnetic fields for LHC High Luminosity Silicon Trackers” TWEPP 2007 (Topical Workshop on Electronics for Particle Physics” Prague, Czech Republic. 3 -7 September, 2007
[8] S. Dhawan, O. Baker, H. Chen, R. Khanna, J. Kierstead, F. Lanni, D. Lynn, C. Musso, S. Rescia, H. Smith “Progress on DC-DC Converters for Si Tracker for the sLHC Upgrade”. Proceedings of TWEPP 2009 (Topical Workshop on Electronics for Particle Physics” Paris, France. 21-25 September, 2009.
[9] S. Dhawan, O. Baker, H. Chen, R. Khanna, J. Kierstead, F. Lanni, D. Lynn, C. Musso, S. Rescia, H. Smith. “Buck Converter Development for the Inner Detector Environment of the sLHC Upgrade” In preparation. To be submitted to Trans. Nucl. Sci., vol.
[10] EPC (Efficient Power Conversion Corp) 909 N. Sepulveda Blvd, STE 230, El Segundo, CA 90245