Radiation Resistant DC- DC Power Conversion with Voltage Ratios > 10 Capable of Operating in High Magnetic Field for LHC Upgrade Detectors

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Abstract

Commercial power converters that have voltage ratios greater than ten and are capable of running near the LHC collision region would increase the efficiency of the power distribution system of the ATLAS Silicon Tracker high luminosity upgrade. The devices must operate in a high magnetic field (2 T) and be radiation hard to ~50-100 Mrad and ~10^{15} N_{eq}/cm^2. These converters are to be mounted on the same multi-chip modules as the ASIC readout chips or in close vicinity without introducing any additional readout noise due to the high switching frequencies. Such devices will permit higher voltage power delivery to the tracker and thus increase overall power efficiency by limiting the ohmic losses in the stretch of cable (about 100 meters) between the tracker and the power sources.

I. Introduction

There is a clear need for a new system of power delivery for the upgraded Atlas Silicon Tracker for the SLHC. With the planned changes the existing powering scheme will have an estimated efficiency of about 10% if the existing cables are reused. Due to space and mass constraints these cables would be difficult to change or made larger. A system featuring DC-DC converters with a voltage ratio of ten would result in an estimated efficiency on the order of 70-80% using the existing cables.

One approach to DC-DC conversion utilizes the buck regulator architecture. DC-DC buck converters with our electrical requirements are commonly used in the commercial market. We have been surveying and testing currently available devices to understand the present state of the art.

The challenging environment and the limited volume impose formidable technical requirements. Foremost in unique requirements is operation in a high magnetic field. This necessitates the use of an air core inductor, requiring high switching frequencies that lie in the bandwidth of the readout ASIC. Because of this, switching noise introduced by the converter into the data is a serious concern. In addition, the radiation hardness of the devices, and the relatively high voltage ratios needed are also of primary concern.

In 2007, we had tested a number of devices that, although lacking the high voltage ratios required, enabled us to learn a number of lessons. For example, one device that we irradiated with gammas up to 100 Mrad showed no change in performance. This proved that at least one commercial device was inherently radiation hard. Also, we conducted noise tests with our own custom module utilizing current Atlas ABCD Asics connected to a large silicon strip detector and mounted with a daughter buck regulator board. There was no noise increase due to switching noise on the power and ground. However, magnetic/electrical pickup on the 8 cm silicon strips from the air-core inductor required shielding to reduce the noise to a satisfactory level.

Commercial requirements are now driving the development of a new generation of converters with voltage ratios greater than 10. Following are the results of the irradiation of some of these new converters. Additionally, we have fabricated and tested several small µH inductors with the results reported below.

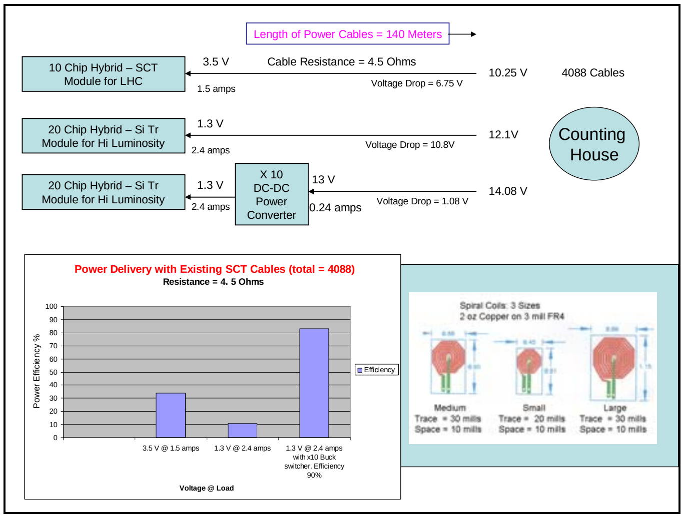

Figure 1: Power Distribution Schemes, Efficiencies and Air Coils.

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II. Need for New Methods of Power Distribution

The LHC inner detector electronics currently use low voltage DC power supplies located a long distance away (30 m for CMS and 140 m for ATLAS detector). Here we examine a power supply solution for the upgraded silicon tracker which would use 10 times more detecting elements for a future SLHC that would be designed to deliver 10 times higher luminosity

The Power Delivery plot in Figure 1 illustrates the problem. At present 10.25 V power is delivered by 4088 power cables each with a resistance of 4.5 Ω. The 10 chip ASIC readout it supplies needs 1.5 amps @ 3.5 Volts. This results in a power delivery efficiency of ~33% as shown in the bar graph. In an upgraded ASIC design with finer lithography and x2 more chips, the voltage required is estimated to drop to 1.3 V. Using the same power delivery scheme and the same cables would decrease the power delivery efficiency to 10%. By placing a DC-DC converter with a voltage ratio, $V_{in}/V_{out} = 10$ on the 20 chip hybrid Kapton PCB would provide an efficiency of 70 - 80%. However, unlike the existing scheme, this places the converter down in the harsh environment of the silicon tracker.

Some of the requirements for a buck converter used in the upgraded Silicon Tracker would be:

- High radiation tolerance ~ 100 Mrad, 10^{15} n_{eq}/cm^2
- Magnetic field immunity to 2 Tesla or higher.
- Construction from nonmagnetic materials
- High efficiency
- Air core Inductors – Solenoid, Toroid, Spirals etched on Kapton

As stated in the introduction this study began in 2007 with some of the newer COTS (Commercial off the Shelf) commercially available power converters to determine whether any were inherently radiation hard. The very first selected chip (EN5360) survived 100 Mrad of ^{60}Co exposure without any noticeable damage. This was followed by studying noise issues since these chips switch in the low MHz range. These results were reported at the TWEPP 2007 in Prague [1].

III. Selected Commercial Devices and Performance

The focus for the past year has been to evaluate additional commercial converters that may provide higher input to output voltage ratios and to test a few devices with ^{60}Co radiation. Table 1 lists a few commercial devices selected on the basis of the following criteria:

1. New products/designs.
2. Finer lithography, preferably 0.25 µm CMOS.
3. Higher input/output voltage ratio.
4. Single die fabrication (exception, the Maxim device that has 3 chips including 2 external FET Switches.
5. Additional products from Enpirion. The EN5360 had previously survived 100 Mrad of ^{60}Co. EN5382 is a similar chip made by the same company.
6. Availability of PC Evaluation Boards to speed up the evaluation process and allow standardized testing.

Semiconductor companies are working on Buck converters designed to meet the needs of the embedded industrial and blade computing applications, where 12 Volts is distributed to local PC boards with multiple buck converters to generate multiple voltages for microprocessors, IO, FPGAs etc. For these applications, vendors are working to achieve higher values of V_{in}/V_{out} by using higher frequencies to decrease the size of inductors and capacitors.

Table 1: Selected Commercial Devices.

Manufacturer	Evaluation Board @ Yale	Device	Type	Vin	Iout	Technology	Frequency MHz
ST	Yes	ST1S10	Monolithic	18	3	BCD	0.9
TI	Yes	TPS62110	Monolithic	17	1.5	BCD 0.25 um	1
IR	Yes	IRDC 3822	MCC 3 Chips	21	4		0.6
Maxim	Yes	MAX 8654	Monolithic	12	8		1.2
Intersil	Yes	ISL8502	Monolithic	14	2.5	CMOS 0.6 um	1.2
Analog Devices	Yes	ADP21xx	Monolithic	5.5	2+2 amps	CMOS 0.35 um	1.2
Enpirion	Yes	EN 5360 Internal Inductor	Monolithic	5.5	6	CMOS 0.25 um	5
Enpirion	Yes	EQ 5382D	Monolithic	5.5	0.8	CMOS 0.25 um	4

Most of the selected devices can run at higher voltage ratios. However, this is at a cost of lower efficiencies due to high rms current losses. This is shown in Figure 2 for ST1S10

Generally, the chips are designed for lower switching losses in the top MOSFET [1] while the bottom MOSFET is designed for lower ohmic resistance. This is because the top MOSFET is on for a much smaller period of time then the bottom MOSFET with the switching losses being a much larger fraction of the total power in the top device. As an example, for a 10:1 voltage ratio the top MOSFET switch is on for 10% of the time while the bottom MOSFET is on 90% of the time.

In addition, these converters specify minimum turn on times of about 100 ns. This then limits the maximum operating frequency to about 1 MHz for a 10:1 V_{in}/V_{out}. The chip itself may be able to operate at a much higher frequencies.

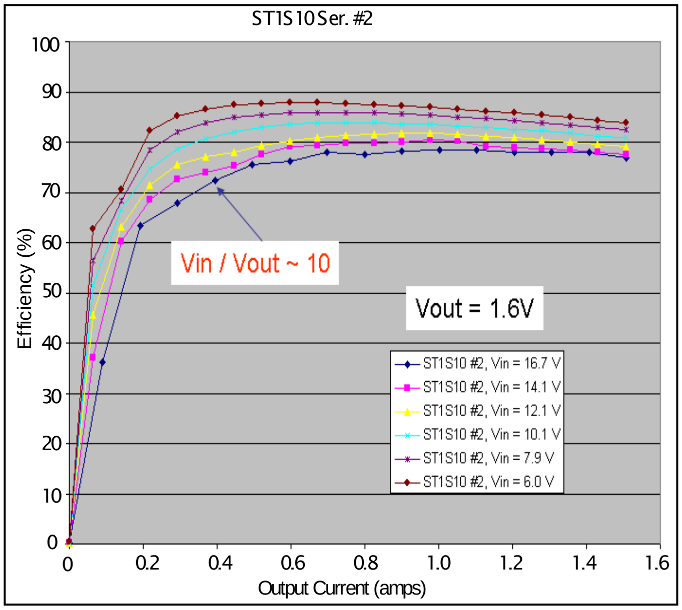


Figure 2:.Measured Curves on ST1S10 Illustrating That the Efficiency is Lower for Higher Voltage Ratios.

IV. Air Core Coils and AC Resistance Effects

This year we have explored coil designs and commercial converter chips. The solenoids and toroids tested last year were thicker components and were difficult to flatten. It may be possible to wind a toroid with specially shaped and laser cut copper foil [2].

Figure 3 shows the power conversion efficiency versus output current and compares the factory mounted ferrite inductor provided on the evaluation PCB and an air core solenoid of lower inductance. The efficiency gap between the two inductors is greatest at lower currents.

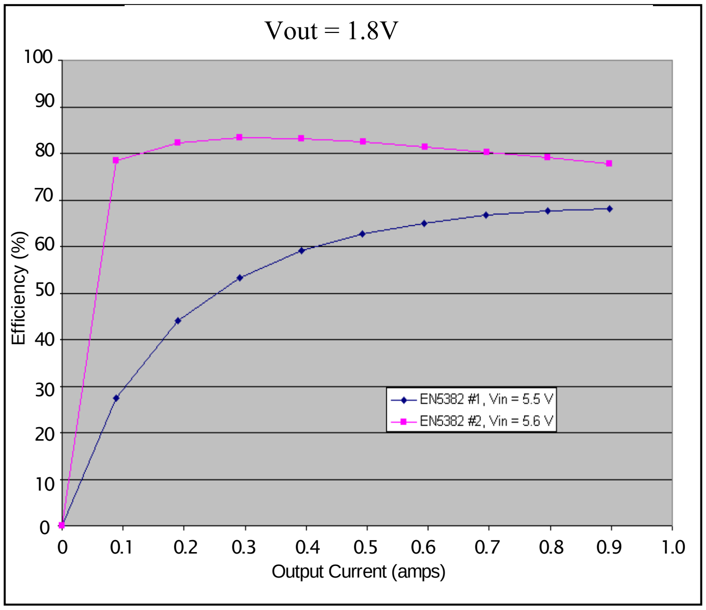


Figure 3: Efficiency versus Output Current. #2 has Ferrite Inductor. #1 has lower inductance Air Coil.

In this effort we have limited the study to flat coils (Figure.1) that can be buried in PC boards to minimize RF leakage. In the use of these flat inductors there are some resistance effects beyond the normal DC resistance which affect the design. There is an increase in the AC resistance that in general is caused by 2 independent effects, the skin effect and the proximity effect.

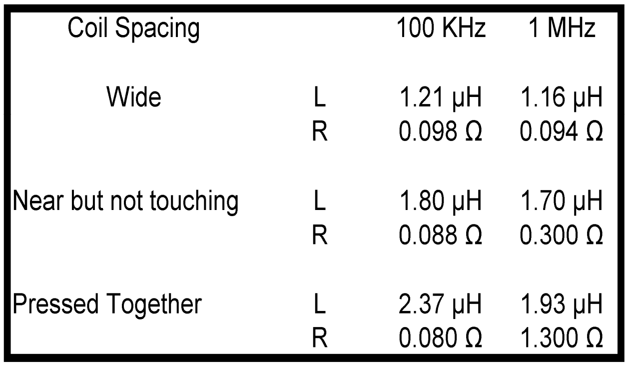
The skin effect forces the current to be carried near the surface of the conductor. To analyze this note that the coil designs in Figure 1 use two ounces of Copper/ft^2 for the coil traces. At a switching frequency of 1 MHz, the skin depth in copper is 66 µm while the thickness of the 2 oz copper trace on the PCB is 70 µm. Hence, at 1 MHz, there is no appreciable change in the AC resistance with respect to the DC case caused by the skin effect.

The proximity effect [3-5] significantly increases the AC resistance of an adjacent conductor. A changing magnetic field will influence the distribution of an electric current flowing within an adjacent conductor due to induced eddy currents thus reducing the cross section for the current flow.

The additional resistance increases electrical losses which, in turn, reduce efficiency and complicate the cooling of the coils. We investigated connecting multiple spiral coils in series and close proximity to increase inductance as this may be necessary to achieve the inductance necessary for a high V_{in}/V_{out} ratio.

Measurements were made with two of the large coils of Figure 1 connected in series. The increase in inductance and resistance was measured versus coil spacing at frequencies of 100 kHz and 1 MHz. The resistance increase is x16 when the coils are pressed together and a factor of 3 to 4 when close but still separated. See table 2.

Table 2: Proximity Effects of L and R vs. Spacing.



Coil Spacing		100 KHz	1 MHz
Wide	L	1.21 µH	1.16 µH
	R	0.098 Ω	0.094 Ω
Near but not touching	L	1.80 µH	1.70 µH
	R	0.088 Ω	0.300 Ω
Pressed Together	L	2.37 µH	1.93 µH
	R	0.080 Ω	1.300 Ω

To further illustrate this effect, 3 medium coils from Figure 1 were connected in series and placed parallel to each other with spacers in between them. Figure 4 shows the results of the efficiency change with different Mylar spacers and copper clad boards on the outside.

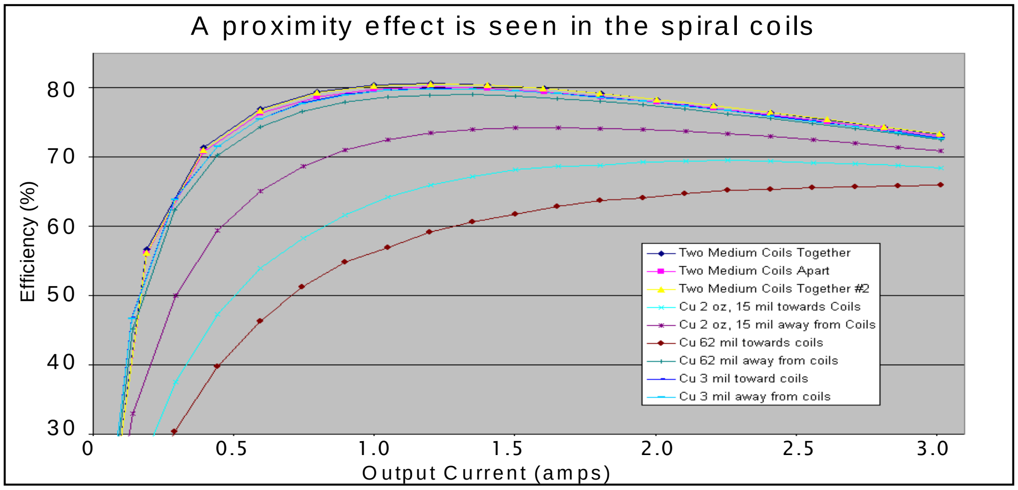


Figure 4: Proximity Effect Results for Selected Configurations.

V. Radiation Testing

Manufacturer designed evaluation boards (Figure. 5) were used for all converter device testing. The same connector is used on each board for interchangeability.

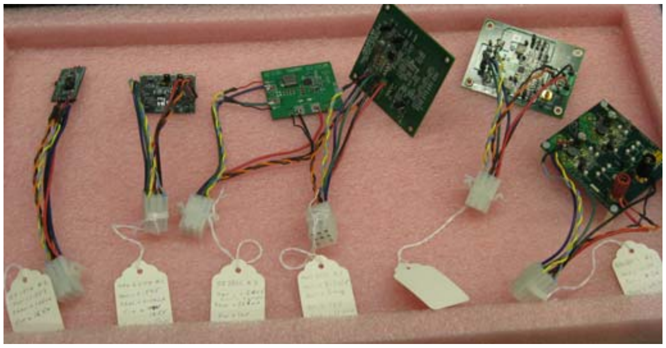


Figure 5: Evaluation Boards.

The boards were irradiated at the BNL Gamma Irradiation Facility which contains a 2500 Curie ^{60}Co source. Generally a converter was biased at the maximum input operating voltage and an output load of about 1 amp. The dose rate for all converters was 200 krads/hour. The input and output currents and voltages were monitored and periodically recorded by a scanning DVM before, during and after irradiation. During irradiation most of the devices developed problems and the exposure was stopped. Only the EN5360 continued to function properly as noted in Table 3.

Table 3 also includes the observed damage modes for the devices tested.

VI. Enpirion Devices

In radiation testing in 2007 the Enpirion device EN5360 exhibited little radiation damage while in 2008 all tested irradiated devices from all manufacturers showed significant damage at doses less than 200 krad including another Enpirion chip EN5382 This motivated us to retest the EN5360 chip in 2008 to confirm the 2007 results.

Table 3: Irradiation Results

Device	Time in Seconds	Dose before Damage Seen (krads)	Observations Damage Mode
TPS 62110	720	40	Increasing input current
ISL 8502	730	40.6	Increasing input current
MAX 8654	850	47.2	Loss of output voltage regulation
ADP 21xx	1000	55.6	Loss of output voltage regulation
ST1510	2250	125	Loss of output voltage regulation
IR3822	2500	139	Increasing input current
EN5382	2000	111	Loss of output voltage regulation
EN5360 #3	864000 Tested in 2008	48000	MINIMAL DAMAGE
EN5360 #2	Tested in 2007	100000	MINIMAL DAMAGE

To do this a second EN5360 was irradiated up to a total dose of about 48 Mrads. The exposure was not continuous and was interrupted at several points. During irradiation input and output voltages and currents were measured and recorded. The input voltage and the resistive output load were fixed throughout the entire irradiation.

During irradiation the input current initially increased until a dose of about 1.5 Mrad was reached; then it monotonically decreased until the irradiation was stopped. The other parameters used to determine efficiency, namely input voltage, output voltage and output current remained constant. The efficiency then changes inversely to the input current and is shown in Figure 6 for the first 18 Mrad of dose. The increase in efficiency shown is opposite to what would normally be expected. Typically, efficiency would remain constant or decrease with radiation dose.

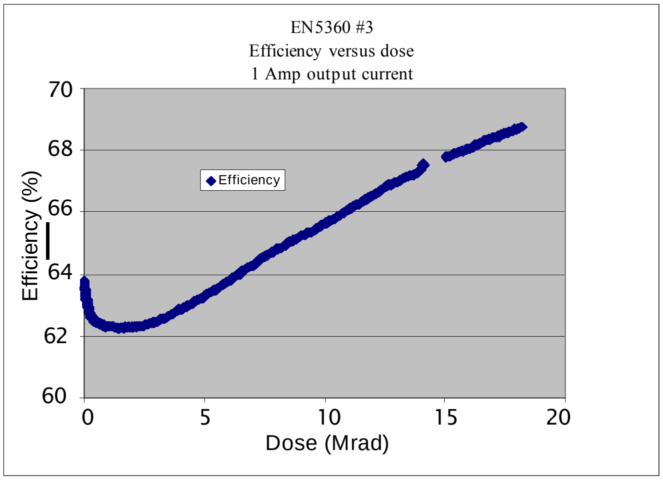


Figure 6 Efficiency change during irradiation at a constant output current of 1 Amp for an EN5360 DC-DC Converter

This behavior continued during the remainder of the irradiation with some recovery occurring during periods when the irradiation was halted. By the time 48 Mrad was reached the efficiency was about 76%. Shown in Figure 7 below are the before and after irradiation efficiency measurements made at Yale on the same device which confirm the observations during irradiation.

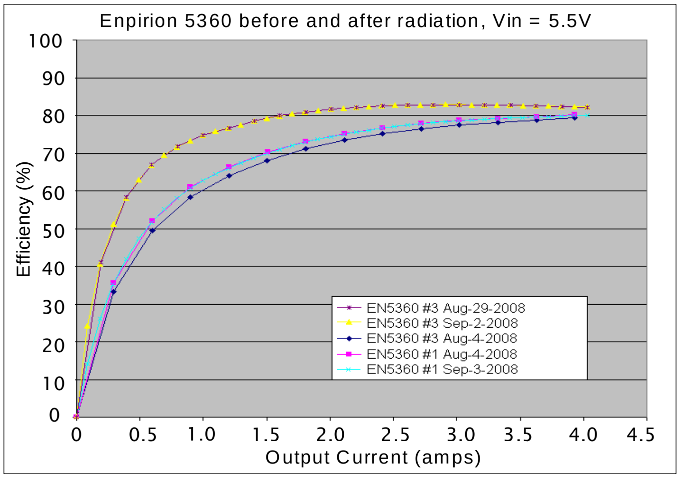


Figure 7: Efficiency Enhancement caused by Gamma Radiation: Verifying the unradiated eval board behaved the same in the testing setup reaffirmed that the changed bias current caused the efficiency to shift. Comparing data and calculating values showed this to be true

The EN5360 was produced by IHP Microelectronics foundry in Germany while successor devices which show radiation damage at much lower doses are fabricated by Dongbu HiTek semiconductor in South Korea. Both use a 0.25 µm CMOS process, but some differences in the foundry processes and/or in the device circuit design make the EN5360 radiation hard.

Recently Los Alamos National Laboratory irradiated an EN5360 and its successor EN5365 with heavy ions and protons for space satellite qualification [6]. They concluded that while both are suitable for their purposes, the EN5360 showed no effect well beyond their proton dosage limit while EN5365 exceeded their proton dosage limits. Hence for the lower orbit space applications both of these devices are suitable.

VII. Conclusion / Future Work

Enpirion EN5360 demonstrates that a commercial COTS device can be radiation hard. While we have reason to expect some next generation high voltage ratio 0.25 µm devices might similarly prove rad-hard, all of the devices we tested showed radiation damage at doses less than 200 krad. We are attempting to understand differences in the IHP fabrication process that lead to a successful device. Additionally, as next generation devices come on the market we will use the infrastructure we developed to quickly evaluate these devices.

VIII. References

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