Commercial-Off-the-Shelf DC-DC Converters for High Energy Physics Detectors for the sLHC Upgrade

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***Abstract*— A new generation of Commercial-Off-the-Shelf (COTS) buck-type converters built using advanced short channel "high voltage" CMOS processes have the potential to operate near the interaction region of the proposed Super Large Hadron Collider (sLHC) upgraded accelerator. The benefit would be a simpler DC power distribution system and an increase of the overall power efficiency by allowing higher voltage power delivery to the front-end electronics, thus limiting the ohmic losses. The devices must operate in a high magnetic field and be able to withstand both high doses of ionizing radiation and large neutron fluence. These converters are to be mounted on the same readout boards as the sensitive front-end electronics or in close proximity without introducing any additional noise due to the high switching frequencies. Radiation hardness and noise test results will be reported.**

***Index Terms*—DC-DC Power Conversion, MOSFETs, Noise, Radiation Effects**

I. Introduction

THE upgrade for the ATLAS Silicon Tracker for the sLHC is clearly going to need a new approach for the power supply system. The existing power supply system provides power to the electronics of the Silicon Tracker from supplies that are located outside the detector volume via cables. Due to the increased power requirements of the sLHC, if this present cabling/topology is re-used for the upgraded Silicon Tracker, ohmic losses would cause the overall efficiency to be about only 10%. Also due to space and mass constraints it is also impractical to increase the cable sizes or even to change the cables. One way to meet the increased power requirements using the existing cabling is to use DC-DC buck converters with an input/output voltage ratio higher then ten. This approach has the potential of providing an estimated efficiency of about 70-80% as shown in Fig. 1. Several different manufacturers produce buck converters which meet the Silicon Tracker electrical and cabling requirements.

Manuscript received June 15, 2009. This work was supported in part by the U.S. Department of Energy.

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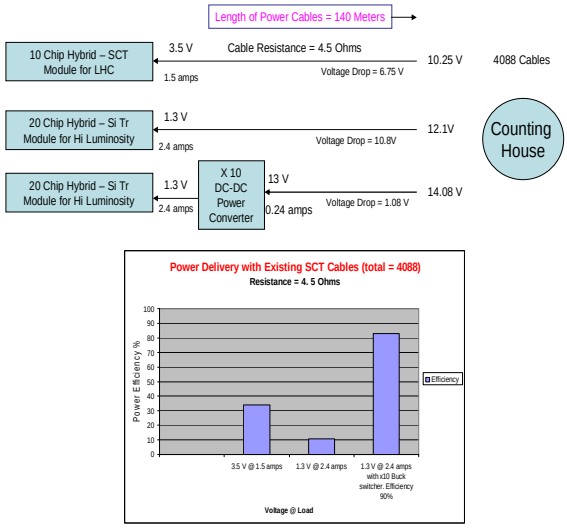


Fig. 1. Efficiency using existing cabling

However, it is not the electrical requirements alone which are an issue. The most challenging aspect of the design is the extreme environment. Shown below are some of the test and design requirements needed.

- Magnetic field immunity to 2 T or higher.
- High radiation tolerance ~ 100 Mrad, 10^{15} n/cm^2 (1 MeV equivalent)
- Construction from nonmagnetic materials
- High efficiency
- Air core Inductors – Solenoid, Toroid, Spirals etched on Kapton

Foremost in unique environmental requirements is operation in a 2 T magnetic field. This necessitates the use of an air core inductor or air core transformer. The limited space available makes the use of a buck converter more practical than the use of a standard switching topology using a transformer (e.g. Half Bridge). In addition there is no isolation needed between the input and output voltages. To limit the value of the inductance required by the buck converter (limiting the physical size of the inductor) requires high switching frequencies (> 1 MHz) 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.

The radiation environment is also very challenging. It requires that the buck converter be produced in a potential radiation tolerant technology like a 0.25 µm or smaller size MOS technology [1]. The use of a technology with this feature size generally limits the overall voltage rating of the devices to 3.5 volts with typical 5 nm gate oxide thickness. The voltage ratio that is required for this application is about 10 with an input voltage of 15 volts and an output voltage of 1.5 volts. The input voltage of 15 V affects the drains of the MOSFETs and not the controller circuitry. The voltage rating of the drain can be extended to higher voltages using an extended drain approach or an LDMOS (laterally diffused MOS) structure. To the best of our knowledge no MOSFETs with voltage ratings of 15 V or greater have been qualified to ionizing radiation doses approaching 50 Mrad to 100 Mrad.

II. SELECTED COMMERCIAL BUCK CONVERTERS

Testing was first initiated in 2007 on Commercial off the Shelf (COTS) buck converters. This was done in order to establish whether commercially available parts would meet the radiation hardness requirements and noise characteristics needed in the application. Although sometimes lacking the high voltage ratios required, the testing enabled us to learn a number of essential points allowing for further development.

TABLE I: SELECTED COMMERCIAL DEVICES

Manufacturer/ Device	Type	V_{in}	I_{out}	Technology	Frequency (MHz)
ST/ ST1S10	Monolithic	18	3	BCD	0.9
TI/ TPS63110	Monolithic	17	1.5	BCD 0.25 µm	1
IR/ IRDC 3822	MCC 3 Chips	21	4		0.6
Maxim/ MAX 8654	Monolithic	12	8		1.2
Intersil/ ISL8502	Monolithic	14	2.5	CMOS 0.60 µm	1.2
Analog Devices/ APDP21xx	Monolithic	5.5	2+2 Amp	CMOS 0.35 µm	1.2
Enpirion/ EN 5360 Internal Inductor	Monolithic	5.5	6	CMOS 0.25 µm	5
Enpirion/ EQ 5382D	Monolithic	5.5	0.8	CMOS 0.25 µm	4

A. CHARACTERIZATION

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

At the present time semiconductor companies are working on buck converters designed to meet the needs of the embedded industrial and blade computing applications, where 12 V 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 voltage ratio V_{in}/V_{out}, and smaller size by using higher switching frequencies to decrease the size of inductors and capacitors required. Manufacturer designed evaluation boards (Fig. 2) were used for all converter device

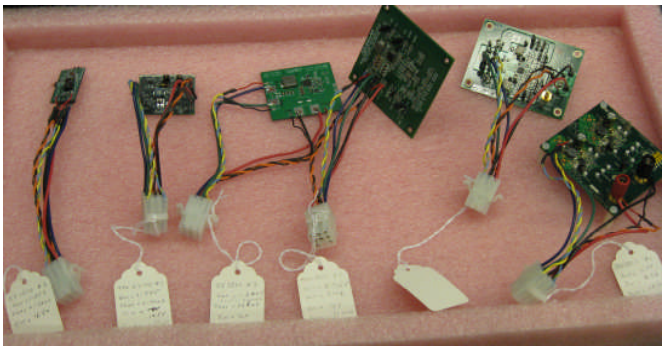


Fig. 2. Selected buck converters used for qualification and radiation testing

testing. The same connector is used on each board for interchangeability.

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 Fig. 3 for the buck converter ST1S10.

Generally, the chips are designed for lower switching losses in the top MOSFET 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.

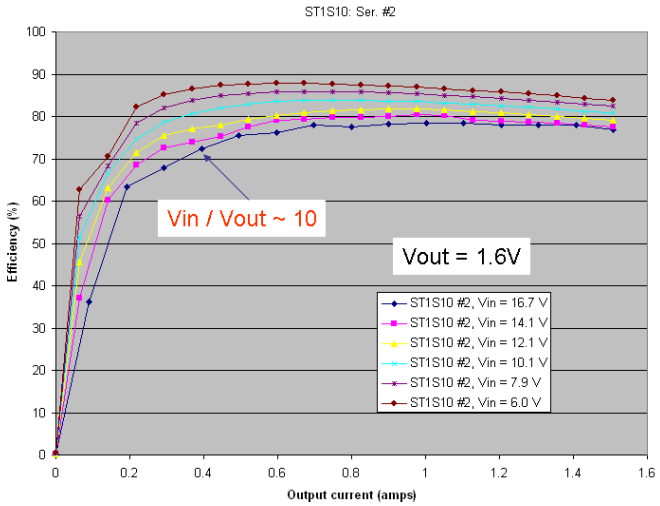


Fig. 3. Measured Curves on ST1S10 Illustrating That the Efficiency is Lower for Higher Voltage Ratios

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.

B. RADIATION TESTING OF BUCK CONVERTERS

The boards were irradiated at the BNL Solid State Gamma-ray Irradiation Facility which houses a 2000 Curie ^{60}Co source. Typically, during irradiation a converter was biased at the maximum input operating voltage and an output load of about 1 A.

Table II: COTS Buck Converter 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 #2	Tested (2007)	100000	MINIMAL DAMAGE
EN5360 #3	Tested (2008)	48000	MINIMAL DAMAGE

The dose rate used for all buck converter irradiations was 2 x 10^5 rad/hr. 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 ended. Contained in Table II are the results of ionizing radiation testing on selected commercial buck converters.

The 2007 radiation response of the EN5360 (to 100 Mrad) was much superior to any other tested buck converter. The result was so divergent from other buck converters, including another converter from Enpirion (EN5382), that the measurement was repeated in 2008.

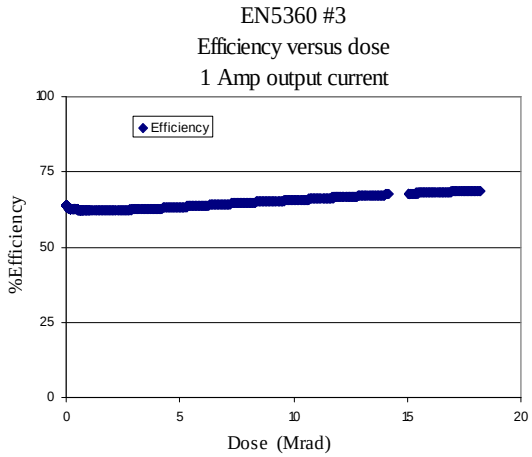


Fig. 4. Efficiency change during irradiation at a constant output current of 1 Amp for an EN5360 DC-DC Converter

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

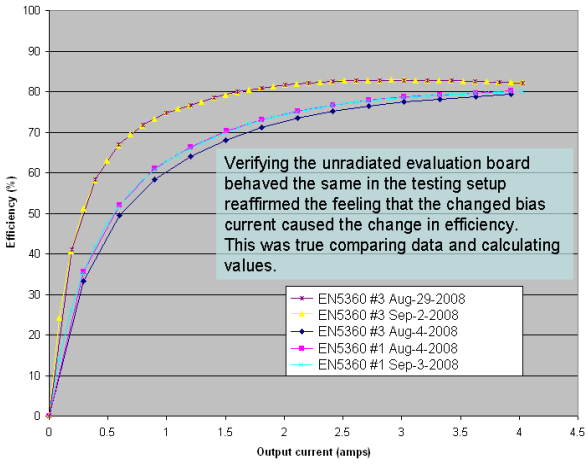


Fig. 5. Efficiency enhancement caused by gamma radiation

Initially, the input current 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 (input voltage, output voltage and output current) remained constant. The efficiency then changed inversely to the input current and is shown in Fig. 4 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.

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 Fig. 5 are the before and after irradiation efficiency measurements made on the same device which confirm the observations during irradiation.

C. Noise Measurements of DC-DC Converters

We tested a few DC-DC converters to evaluate their noise performance and effects in different ATLAS sub-detector readout electronics systems

The DC-DC converter Enpirion EQ5382D was tested with a silicon strip detector in November 2007. The test setup is shown in Fig. 6. 512 silicon strip sensors can be read out by four ATLAS ABCD chips. We had one ABCD chip wire bonded to sensors and 128 channels were read out. An Enpirion EQ5382D was running at 5 MHz with an external air core inductor, and supplied 3.3V analog power to all four ABCD chip. As a reference, we repeated the noise measurement with a 3.3V laboratory power supply.

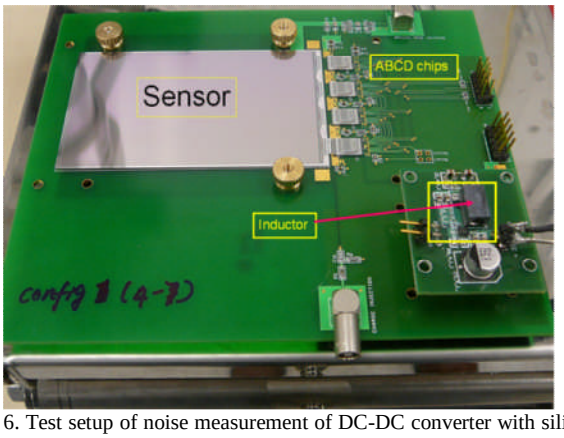


Fig. 6. Test setup of noise measurement of DC-DC converter with silicon strip detector

The results of the noise measurement are shown in Fig. 7. The equivalent noise charge (ENI) was greater than ~3750 electrons (30 mV rms) with the DC-DC converter. In comparison, the noise was only ~1625 electrons (~13 mV rms) using commercial bench top power supply. After additional capacitor was added at the output terminal of the DC-DC converter, and additional shielding was provided with copper tape, the noise performance improved to ~2000 electrons (~16 mV rms).

This test demonstrated that a reasonably good noise performance with proper filtering and shielding could be achieved in the silicon strip detector powered by the commercial DC-DC converter with an air core inductor.

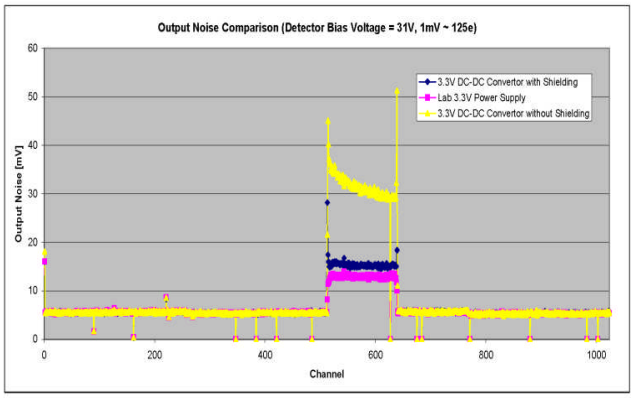


Fig. 7. Noise measurement of silicon strip detector with DC-DC converter and lab power supply.

III. AIR CORE COIL DEVELOPMENT

DC-DC buck converters need an inductor, usually a toroid with a ferrite core. The requirement for operation in a magnetic field for sLHC experiment (up to 2 T for the inner tracker, and ~0.05 mT for powering LAr readout electronics) led to the development of a non-ferromagnetic spiral inductor which can be embedded in the PC board. Fig. 8 shows some of the designs developed and tested. It may be possible to wind a toroid with specially shaped and laser cut copper foil [2].

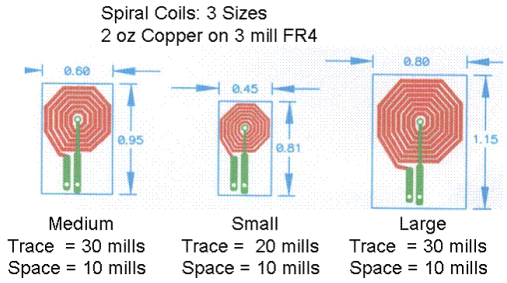


Fig. 8. Spiral inductors built as copper conductors embedded in the DC-DC converter PCB.

Fig. 9 shows the power conversion efficiency versus output current and compares the factory mounted ferrite inductor provided on the evaluation PCB with an air core solenoid of lower inductance. As seen, the efficiency gap between the two inductors is greatest at lower currents.

Spiral flat inductors exhibit some resistance effects beyond the normal DC resistance which affects the performance and therefore the design. There is an increase in the AC resistance that in general is caused by two 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 Fig. 8 use 71 µm copper thickness (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; hence, at 1 MHz,

the skin effect causes no appreciable change in the AC resistance when compared to the DC case.

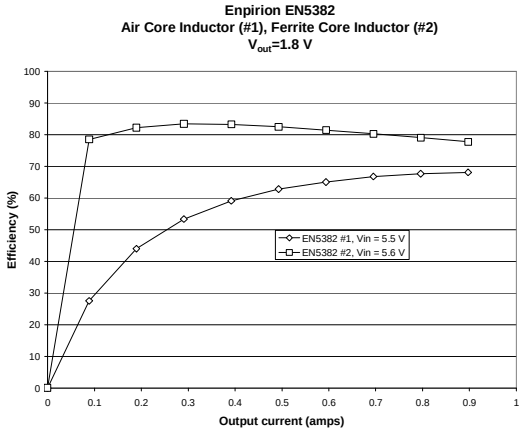


Fig. 9. Efficiency versus Output Current for #1 Ferrite Inductor and #2 Lower Value Inductance Air Core Inductor.

The proximity effect [3]-[5] significantly increases the AC resistance of an adjacent conductor. A changing magnetic field will influence the distribution of the 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, reduces efficiency and complicates the cooling of the coils. We investigated connecting multiple spiral coils in series and close proximity to increase the inductance. This may be necessary to achieve the inductance necessary for a high V_{in}/V_{out} ratio at the available switching frequencies.

Table III: 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

Measurements were made with two of the large coils of Fig. 8 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 a factor of 16 when the coils are pressed together and a factor of 3 to 4 when close but still separated (see Table III). To further illustrate this effect, 3 medium coils from Fig. 8 were connected in series and placed parallel to each other with spacers in between them. Fig. 10 shows the efficiency change with different Mylar spacers and copper clad boards on the outside.

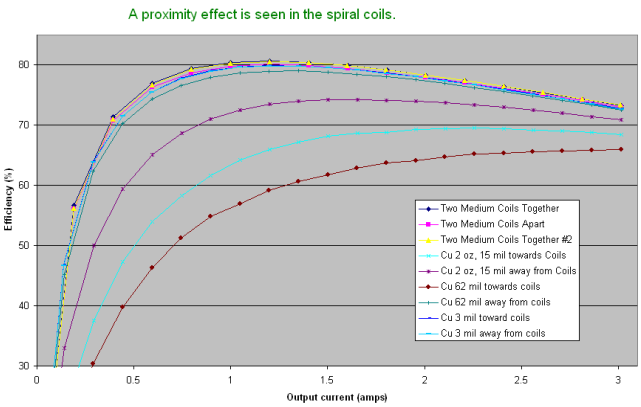


Fig 10. Change in efficiency caused by resistance change due to proximity effect for different coil size and varying coil separations

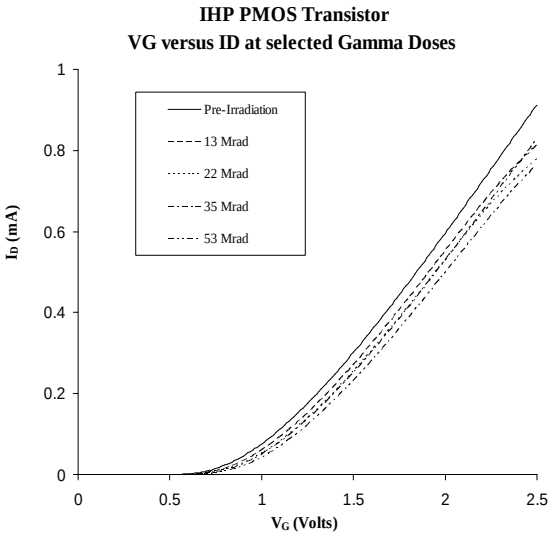
IV. LDMOS TRANSISTOR DEVELOPMENT

Upon investigation it was determined that the Enpirion EN5360 DC-DC converter that was found to be radiation tolerant to at least 100 Mrad was fabricated by the IHP Microelectronics Foundry in Germany. Other devices made by Enpirion which show radiation damage at much lower doses were fabricated by Dongbu HiTek semiconductor in South Korea. Both foundries use a 0.25 µm process.

It has been observed [6]-[7] that the 0.25 µm technology and smaller feature sizes can have a great resistance to ionizing radiation effects. A primary ionizing radiation effect is hole trapping in the gate oxide which causes a negative bias change in gate threshold voltage. In thinner oxides (< 7 or 8 nm) the trapped positive charge may tunnel out of the oxide making the threshold voltage shifts much smaller in size.

The drawback to using the smaller feature technology is that their voltage rating is less than what is necessary for the MOSFET switch of the buck converter which need 15 V or greater. The EN5360 converter has a maximum input voltage of V_D = 5.5 V which is much less than the required input voltage. IHP 0.25 µm technology also has an LDMOS process which allowed for the fabrication of transistors with voltage ratings > 12 V by abating the voltage in the drift region of the device [8]. The belief then is that this structure would be radiation tolerant *AND* have the higher voltage rating needed for the buck converter.

For testing of the LDMOS process the IHP foundry had produced a structure with both PMOS and NMOS devices which could typically be biased with 12-14 V. However, the test die were produced without any of the normal protections incorporated in commercial devices. Because of this many of the devices were damaged during either the bonding process or during the handling later during irradiation and measurement. However enough devices survived to test the general radiation tolerance of the devices.



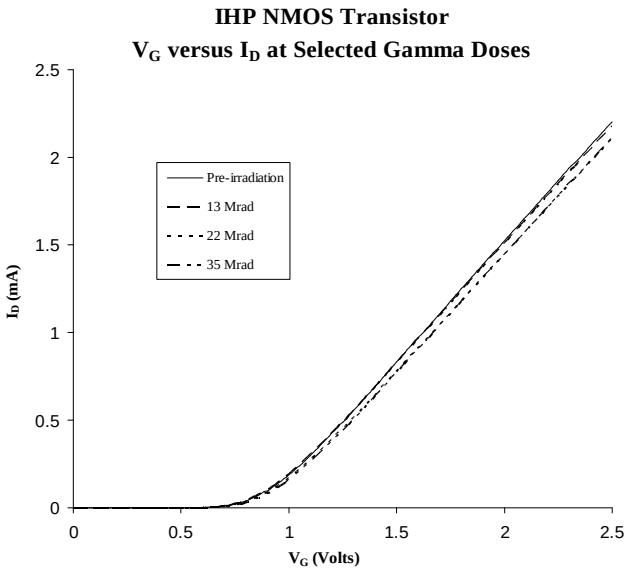
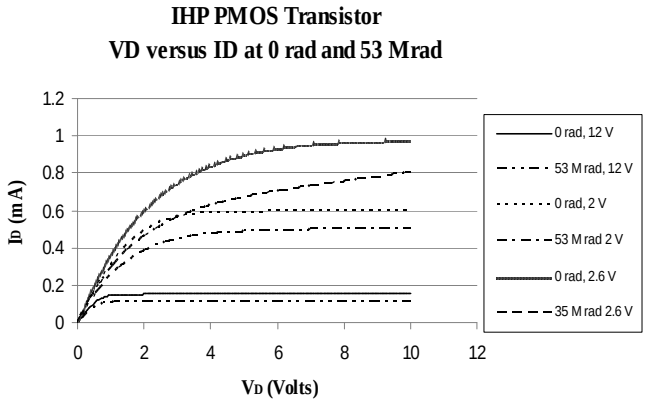


Fig. 11. a and b I_D versus V_G at selected ionizing radiation doses for an IHP PMOS and NMOS transistor. For the PMOS transistor V_G and I_D (normally negative) are displayed as absolute values

The test die were irradiated with ^{60}Co gamma rays to determine what changes if any were induced by the irradiation. During the irradiation both transistors were biased in a nonconductive state. The NMOS transistor was biased with $V_D = V_S = 0$ V and $V_G = +2.5$ V. The PMOS transistor was biased with $V_S = V_G = 0$ F, $V_D = -10$ V. These bias states have the effect of inducing an electric field in the gate oxide which is generally accepted as making the radiation effects more severe. The results obtained during the irradiation were quite encouraging and typical results for the NMOS and PMOS transistors are shown in Fig. 11 and 12.



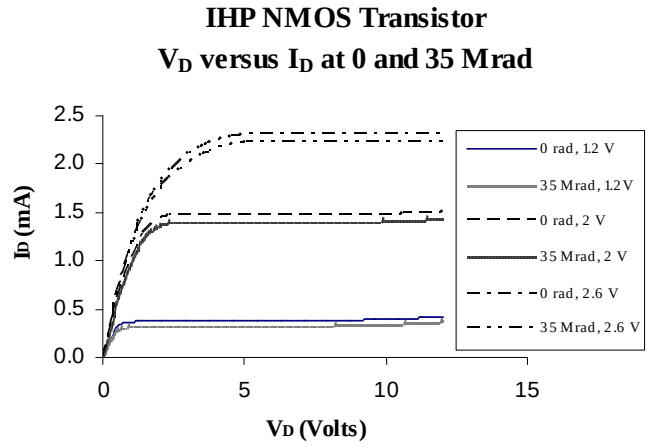


Fig. 12. a and b Shown are selected measurements of I_D versus V_D at selected values of V_G before and after irradiation. In the PMOS plot V_G, V_D and I_D (normally negative are displayed as absolute values. The NMOS device shows a slight increase in what can be interpreted as channel resistance. However, the transconductance appears to be little affected. In the PMOS device the change is more severe showing both increases in channel resistance and significant effects on the transconductance of the device.

Fig. 11a indicates that the gate threshold voltage of the PMOS device is slightly affected up to the maximum exposure doses of 53 Mrad; Fig. 11b shows that the gate threshold voltage of NMOS transistors is little affected if it is affected at all up to the ionizing dose of 35 Mrad. After reaching 35 Mrad all of the NMOS transistors were damaged by an improper bias and so the irradiation on the NMOS was not continued.

Fig. 12b of the NMOS device shows a slight increase in what can be interpreted as channel resistance with little change in transconductance comparing the unirradiated state with the change after 35 Mrad. Fig. 12a shows that in PMOS devices the change is more severe. Both channel resistance and transconductance show more significant changes compared to the NMOS. However, both the NMOS and the PMOS devices demonstrate significant resistance to changes induced by ionizing radiation. These devices were also measure by [9] with both x-rays for ionizing dose and protons for displacement damage effects with similar results.

Note that the current of the test devices is measured in mA when the requirement needs about 500 mA. However, it is anticipated that the devices could be paralleled make them capable to sustain the necessary current levels.

V SUMMARY AND FUTURE WORK

In this paper a strategy has been discussed on how to meet the requirements for a power supply system for the Silicon Tracker upgrade. There are a number of very stringent environmental and performance requirements that require an innovative approach and solution.

The magnetic field requirement of operating in a 2 T field can be met by using a DC-DC buck converter with an air core inductor which uses no magnetic sensitive materials. The inductor can be spirally wound and embedded in a pc board. The size, inductance and noise requirements can be met by operating at high switching frequencies with some nominal shielding for the noise.

The requirements for high radiation immunity can be met by at least one commercial technology (IHP Microelectronics) which could be used to produce a radiation tolerant buck converter controller and MOSFET switch could be integrated into one IC using a 0.25 μm technology and LDMOS process. Alternatively, the controller and switches could be produced as discrete devices if a higher voltage alternative is found for the buck converter switch.

The next steps would be to continue to investigate commercial products and investigate other possibilities for the buck converter switch.

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