Buck Converter Development for the Inner Detector Environment of the SLHC Upgrade

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***Abstract*— Future upgrades to the detector subsystems such as calorimeters and inner trackers at the Super-LHC (SLHC) will require more efficient power delivery systems. The combined factors of a harsher environment, limited volume, and increased current make this a challenging task. This paper is a continuation of work that was started in 2007 on the potential use of commercial buck converters at SLHC for efficient power delivery. No commercial buck converters tested have met all electrical and environmental requirements. It has become necessary to consider a custom buck converter design and to qualify and test single components that could be incorporated into an overall design. The approach described here will consider the requirements of the Atlas Silicon Tracker Upgrade as a case study. Promising radiation test data on potential switches is presented as well as an air core inductor design.**

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

I. INTRODUCTION

The upgrade of the Large Hadron Collider (known as the Super Large Hadron Collider or SLHC) will require corresponding upgrades to the SLHC experiments' subsystem detectors. For the inner tracking regions, the higher instantaneous luminosity will require higher density detector segmentation and a corresponding increase in readout electronics density. This increased electronics density will require a similar increase in power consumption. As mass and space constraints do not permit a similar increase in power cable cross section, a new and more efficient method of power delivery is necessary.

For the case of the Atlas Inner Silicon Tracker upgrade, it has been estimated [1] that the efficiency of power delivery to the upgraded tracker would be less than 10%, with 90% of the loss occurring in the long (~ 100 m) power cables if the current topology is retained. In order to limit such ohmic losses in the cables, a high voltage, low current power delivery approach is required. One such topology features the use of DC-DC converters located near the detector front-end ASICS that step down the cable high voltage to the lower voltages (≤ 1.5 V) required by modern deep submicron ASICs. With an input to output voltage ratio of 10 or better, an overall power delivery efficiency of 80% or greater may be expected [1].

Two main classes of DC-DC converters are capacitive converters (e.g. charge pumps) and inductive converters. For the higher ratios of DC-DC conversion required for power delivery efficiency, inductive converters typically are more efficient. For that reason our research has focused on inductive converters, and in particular the simplest of such converters, the buck regulator (illustrated in Fig 1).

Industry, driven by the need for more efficient consumer products, has developed a large array of small sized and high current buck regulators. For inner tracker applications there are additional severe environmental requirements that make the development of an adequate buck regulator challenging. First, the large magnetic fields (~2 T at ATLAS) prevent the use of magnetic inductor cores that would saturate in such a field. Thus air-core inductors that require higher frequency operation are necessary. Second, higher proton luminosities result in the inner detector electronics being subjected to much greater integrated ionizing radiation and neutron equivalent exposures than at the current LHC. This precludes the use of many commercial technologies. The important environmental conditions are listed in Table I.

TABLE I
Environmental Factors for Power System in Silicon Tracker

Condition	Details
Static Magnetic Field	> 2 Tesla
Total Ionizing Dose (TID)	100 Mrad
NIEL (1 MeV neutron equivalent)	1 x 10^{15} n/cm^2
Temperature	243 K

In 2007 we decided to test a number of commercial buck regulators with ionizing radiation to see if the industrial trend toward deep submicron processes would produce a radiation hard commercial buck regulator. We understood that we would need to make such a regulator work with an air core replacement of its ferrite inductor. The first regulator we tested, the EN5360 from Enpirion, survived what we consider the most challenging requirement, irradiation to a 100 Mrad ionizing dose [1]. This particular converter had a conversion ratio of 4, below our requirement of ~10 or greater. However we were encouraged by this result and proceeded to test the array of devices listed in Table II. No other converter survived

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such doses, though we note National’s LM2864 survived to 3 Mrad, sufficient for many applications outside of the inner tracking region. To verify that our initial irradiation of the EN5360 was not flawed, we irradiated a second EN5360 to a dose of 48 Mrads and observed no significant changes.

TABLE II
TID Test Results of Selected DC-DC converters

Company	**Device**	**Oxide Thickness (nm)**	**Dose before Damage**	**Observation Damage Mode**
IHP	ASIC	5	53 Mrad	slight damage
XYSemi	MOS FET	7	52 Mrad	Minimal damage
XYSemi	XP5062	12.3	44 krad	Loss of output voltage regulation
TI	TPS54620	20	23 krad	abrupt failure
Intersil	ISL 8502	unknown	40.6 krad	Increasing input current
IR	IR3822	unknown	139 krads	Increasing input current
IR	IR3841	9 & 25	13 krads	Loss of output voltage regulation
ST	ST1510	unknown	125 krad	Loss of output voltage regulation
Epirion	EN5365	5	85 krad	Increasing input current,
Epirion	EN5382	5	111 krads	Loss of output voltage regulation
Epirion	EN5360 #2	5	100 Mrads	No significant Changes
Epirion	EN5360 #3	5	48 Mrads	No significant changes
National Semi.	LM2864	11.8	3 Mrads	Short after power recycle

As the EN5360 was uniquely radiation hard, we investigated its technology and found it was produced using a 0.25 μm CMOS technology which included a LDMOS (Lateral Diffused Metal Oxide Semiconductor) process from IHP Microelectronics. All Enpirion products that failed the ionizing radiation test were made using a process from a different manufacturer. We reported in [1] our investigation into MOSFETs made from the IHP process. In this work we report on the radiation hardness of MOSFETs produced from another manufacturer’s LDMOS process. We further report on promising irradiation studies of Gallium Nitride (GaN) transistors from several manufacturers. In addition to the transistor switches, we discuss the radiation hardness of the each element needed for a complete buck regulator design, with emphasis on recent work into air core inductor design.

Following is a short discussion on buck converter topology and components. Also covered are updated details on a coreless inductor design that can be used with a buck converter. Finally there are radiation-testing results on potential switches for this topology.

II. BUCK CONVERTER TOPOLOGY

Shown in Figure 1 is a synchronous buck converter design. A simple basic design contains 5 main components. These are the output capacitor (C_{out}), the inductor (L_{Buck}), the high-side switch (in series with the input voltage V_{in}), the low-side switch and the Pulse Width Modulator (PWM). Each of these components can have special electrical requirements and different vulnerabilities to the environment. Depending on the design parameters additional components such as a MOSFET driver to change switching state rapidly and/or a level shifter to drive the high side switch are required. In selecting the output capacitor, C_{out}, many commercial ceramic chip capacitors are available that meet the temperature and radiation requirements of the inner detector and so this component will not be discussed further.

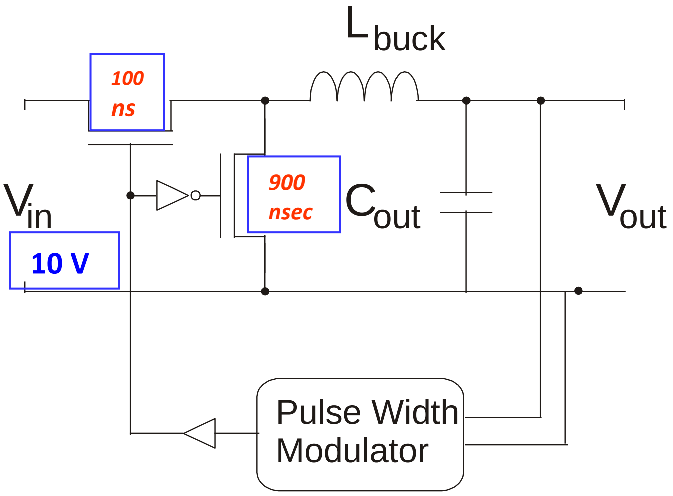

Fig. 1. A synchronous Buck Converter illustrating the components. In this example the switching frequency is 1 MHz and the input/output voltage ratio (V_{in}/V_{out}) is 10.

As stated earlier, in the environment of the Silicon Tracker the 2 Tesla magnetic field would saturate a typical commercial inductor with a magnetic core. This mandates the use of a nonmagnetic “air core” inductor for L_{Buck}. However, in physical size an air core inductor is much larger than an equivalent magnetic core component per unit inductance. To compensate for this, note that the minimum inductance value required in a buck converter design is inversely proportional to the switching frequency [3]. Thus by increasing the switching frequency the inductor value (and physical size) may be reduced. This is discussed further in section III.

The high-side and low-side switches are very similar in function. Both devices profit from a fast switching speed (low switching losses) and a low channel resistance. However, for an input to output voltage ratio of 10, the high-side and low side switches will be on 10% and 90% of the time respectively. Because of this it is more important to optimize the high side switch for switching speed and the low side switch for channel resistance. At a 1 MHz switching frequency the high-side switch is on for only 100 ns (We use 1 MHz as a baseline as this is on the order of the highest frequencies presently employed by commercial buck regulators). For efficiency and control the rise and fall times should be < 10% of this or about 10 ns. This places stringent requirements on the switch drivers.

The PWM provides control and regulation in the buck converter. Additionally it must provide sufficient current with fast rise/fall times to quickly change the state of the upper and lower switches. This becomes more difficult as the frequency increases. In principle the control and regulation functions of the PWM should be implementable in a standard radiation tolerant deep submicron CMOS process (≤ 0.25 µm). However the switch drive functions, in particular for the high side switch, are a challenge that we have yet to address. This remains a topic for future R&D.

III. NONMAGNETIC CORE INDUCTOR DEVELOPMENT

As noted above a DC-DC buck converter operating in the Silicon Tracker environment needs a nonmagnetic core inductor to operate in the high static magnetic field (up to 2 Tesla). This led to our development of a non-magnetic coreless spiral inductor embedded in a PC board. Fig. 2 shows one of the designs developed and tested. Other designs were developed and reported on previously [1].

To estimate the approximate size of the inductance needed for the converter, the minimum inductance (L_{min})can be expressed as a function of the input voltage, V_{in}, the output voltage V_{out}, the peak inductor current (I_{pk}) and the time the high-side switch is on (t_{on}) as expressed in equation 1. [3]

$$L_{min} = (V_{in} - V_{out})\, t_{on} / I_{pk} \qquad (1)$$

For the upgraded Silicon Tracker the estimated output voltage and current are V_{out} = 1.5 V at I_{out} = 2A. If we design for a V_{in}/V_{out} = 10 and a switching frequency of 1 MHz then V_{in} = 15 volts, and t_{on} = 100 ns. I_{pk} can be estimated as I_{pk} = 1.5 x I_{out} = 3A. Using these values L_{min} = 0.45µH. The inductor shown in Fig. 2 achieves an inductance of 0.6 µH with a diameter of about 1.5 cm. While this is still somewhat large (though perhaps sufficient) for the inner tracker, we hope to achieve an increase in the regulator frequency to 3-5 MHz that will permit a corresponding decrease in L_{min} and the inductor's physical size.

The nonmagnetic core inductor shown in Fig. 2 is constructed in a 4 layer PCB. The inner 2 layers consist of 5-turn spirals connected in series to form a 0.6 µH inductor. The outer two layers are added to shield the surrounding circuitry from switching noise broadcast by the inductor. When used for shielding, the outer spirals are normally connected to ground at one end. However, it was observed that effective shielding is provided even if the outer spirals are left floating. The optimal distance between the inner spirals that maximized the inductance while minimizing proximity effect losses was empirically determined. The distance between the inner and outer layer coils was determined by the PCB manufacturing process but was found to provide sufficient shielding in tests with ATLAS silicon modules.

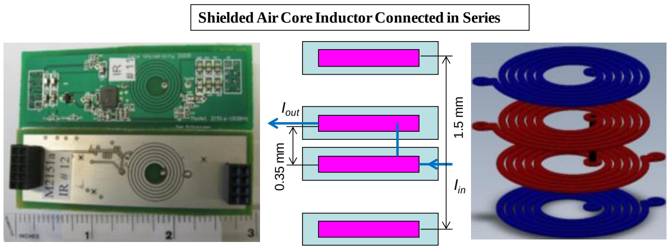

Fig. 2. Coreless 0.6 µH multilayer inductor developed for a buck converter which would operate in a magnetic field. The shielding spirals are separated by a larger distance from the inductor spirals so as not to affect the inductance flux paths.

IV. UPPER AND LOWER SWITCH DEVELOPMENT

A. LDMOS SWITCHES

CMOS technologies with a 0.25 µm or smaller feature size are good candidates for producing a radiation hard switch. These technologies have often been shown to be very resistant to damage from ionizing radiation that afflicts CMOS technologies with larger feature sizes and thicker gate or field oxides [4,12]. It has also been observed that CMOS technologies in general are not greatly affected by displacement damage effects caused by high energy neutrons or protons. It is also noted that destructive single event effects are absent or rare in devices operated with V_{DS} ratings of ≤ 100 volts.

The typical radiation damage in MOS technologies is trapped positive charge in the gate oxide and field oxide layers. Ionizing radiation generates ionization pairs (holes and electrons) with many of the holes and electrons recombining. However¸ a fraction of the electrons, being more mobile than holes, migrate out of the oxide, leaving uncompensated holes behind. These positive charges may be immobilized in a trap within the oxide or migrate to a boundary where they either recombine with an electron or become trapped. This creates a positive charge imbalance which increases with increasing ionizing dose and in the gate oxide is exhibited as a negative shift in the gate threshold voltage of the device. The direction of the voltage shift is the same for both p and n channel devices. In principle with sufficient exposure the threshold shift will cause an n-channel enhancement mode device to become a depletion mode device that will always be conducting when $V_{GS} \geq 0$ V; in principle a p-channel enhancement mode device would require an ever larger negative gate voltages to turn on but would remain controllable.

Ionizing radiation induced threshold shifts are generally not observed or observed to a much lesser degree in 0.25 µm and smaller CMOS technologies. An accepted explanation for this radiation hardness [4] is that near the oxide-polysilicon and oxide-channel boundaries of the gate, electrons tunnel and recombine with the trapped positive oxide charge (see Fig. 3). In principle, if the oxide thickness is less than some critical value, all of the trapped holes in the oxide will be within electron tunneling range and will recombine (with electrons) resulting in no shift in gate voltage [4]. A sufficiently thin gate oxide is not the only feature of the CMOS technology which is needed for radiation hardness but is likely necessary [5, 6].

Our previous work reported that a radiation hard DC-DC converter produced by Enpirion was fabricated in a 0.25 µm CMOS technology by IHP Microelectronics in Germany [1]. Within this technology is a transistor process, Lateral Diffused Metal Oxide Semiconductor (LDMOS) that permits higher drain-source voltages (>12 volt) than is typical for most 0.25 µm CMOS technologies. LDMOS transistors fabricated in this technology were irradiated with ^{60}Co gammas with good results [1]. Subsequently another manufacturer, XYSemi, was determined to have a similar LDMOS process produced in a 0.25 µm CMOS technology from a different foundry. MOSFET devices produced from this source are tested for radiation hardness and reported here.

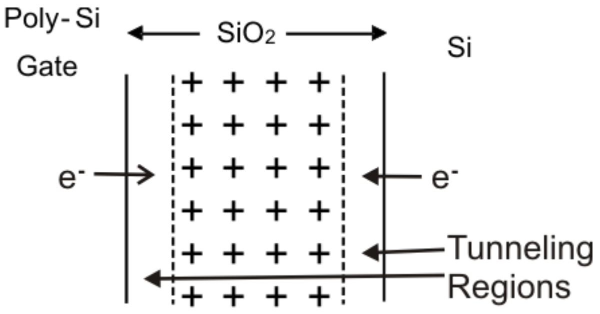

Fig. 3. Section through the gate oxide of a MOS device showing the regions of charge trapping and tunneling/recombination.

Shown in Fig. 4 is the effect of gamma and neutron radiation on gate voltage (V_{GS}) versus drain current (I_{DS}) for a XYSemi MOSFET. All the measurements were made with an Agilent B1500A Semiconductor Parameter Analyzer. Although the MOSFET is designed to carry 2 Amperes of current, for thermal reasons the overall testing was limited to 100 mA.

Data is shown for the device before and after irradiation to 53 Mrad with ^{60}Co gammas (irradiations performed at Gamma Facility at Brookhaven National Laboratory). During gamma irradiation the device's gate was biased (V_{GS} = 1.5 V) and the drain and source tied to ground (V_{DS} = 0 V). The device was measured immediately after irradiation.

The same device that was irradiated with gammas was subsequently irradiated with a neutron (1 MeV equivalent) fluence of 5 x 10^{14}/cm^2. This was done at the High Flux Neutron Facility at the University of Massachusetts at Lowell. The exposure was done without any bias but with the drain and source tied together. This exposure made the device radioactive causing a 1 month delay before the device could be shipped back for measurement.

Note that there is little change in the response of the device to either gamma or neutron radiation. This makes this device and technology a potential candidate for the upper and lower switches in a buck converter. The overall voltage rating (V_{DS} = 16 V) makes this device suitable for use in a buck converter for the Silicon Tracker but may be too low for some applications.

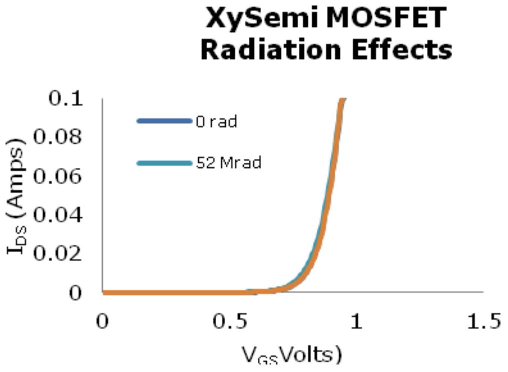

Fig. 4. XYSemi LDMOS Device: Effect of ^{60}Co Gamma radiation followed by neutron radiation on the V_{GS} versus I_{DS} curve on the same device.

Another test on the XYSemi MOSFET was done with 800 MeV protons at the LANSCE Facility at Los Alamos National Laboratory. A comparison of the I_{DS} versus V_{GS} curve before and after the proton irradiation is shown in Fig. 5. The device was irradiated with a fluence of 10^{15} protons/cm^2. During the exposure the device's gate was biased (V_{GS} = 2.5 volts) and drain and source were tied to ground (V_{DS} = 0 volts) similar to what was done in the gamma radiation test. For thermal reasons the current was limited to 100 mA.

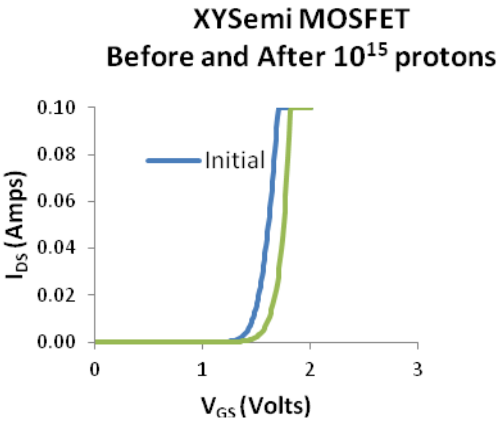

Fig. 5. XYSemi LDMOS Device: Effect of 10^{15}/ cm^2 of 800 MeV protons on the V_{GS} versus I_{DS} curve. Note that shift is in opposite polarity from the expected shift normal to ionizing radiation effects.

As in the neutron exposure this device became activated during the exposure causing a delay of 2 months between the times that the device was irradiated and when it could be measured. Note that in contrast to the previous test with the ionizing radiation followed by neutron irradiation, we now obtain a threshold shift. However, the shift is in the opposite direction from what is typically observed in irradiated devices. As discussed earlier the shifts caused by ionizing radiation are caused by trapped positive charge in the gate oxide causing the gate threshold voltage to shift in the negative direction. The mechanism for the positive direction threshold shift observed here is not understood, but we note that the magnitude is small.

B. GaN SWITCHES

Another candidate for a buck converter switch is a High Electron Mobility Transistor (HEMT) manufactured in Gallium Nitride (GaN) technology. HEMTs are very high frequency devices with operating frequencies that can be greater than 100 GHz [7, 8]. GaN devices are also reported as being very radiation resistant with few effects seen in devices up to 500 Mrad [9,10] Both depletion mode and enhancement mode devices are possible in this technology. A depletion mode device is more difficult to use because a negative voltage on the gate is required to turn it off. This requires an additional voltage and additional components to use in a buck converter topology. However, depletion mode devices were the only commercially available GaN devices until very recently [11]. An enhancement mode GaN HEMT was introduced in 2010.

Radiation damage in GaN HEMTs, if any, is not well understood at this time. However, the devices can be tested with radiation and characterized. Depletion mode devices from Nitronex, Cree and Eudyna were tested with ^{60}Co gammas, protons and neutrons as show in Table III. Also included is an enhancement mode device from Efficient Power Conversion (EPC) which was tested with gammas and protons. All radiation exposures were made at the same facilities used for the MOSFETs.

TABLE III Radiation Testing Matrix for GaN Devices

Company	Device	60Co	Neutron Fluence (cm^{-2})	Proton Fluence (cm^{-2})
Nitronex	25015	17.4Mrad	5×10^{14}	1×10^{15}
Cree	40010		5×10^{14}	1×10^{15}
Eudyna	EGNB010	43 Mrad	5×10^{14}	1×10^{15}
EPC	EPC1015	64 Mrad		1×10^{15}

Shown in Fig. 6 is V_{GS} versus I_{DS} for a Nitronex 25015 HEMT for a 5×10^{14} neutron exposure. During the neutron exposure all the devices were unbiased. Very little change in behavior was observed for Nitronex, Cree and Eudyna devices due to the neutron exposure.

Shown in Fig. 7 is V_{GS} versus I_{DS} for a Eudyna EGNB010 HEMT exposed to 43 Mrad of ^{60}Co gamma radiation. During ^{60}Co gamma irradiation the devices were clocked (switched on and off) at a frequency of 1 kHz and current limited to a value of I_{DS} = 65 mA. Again like the neutron exposures, very little change in behavior was observed for all depletion mode devices due to gamma radiation.

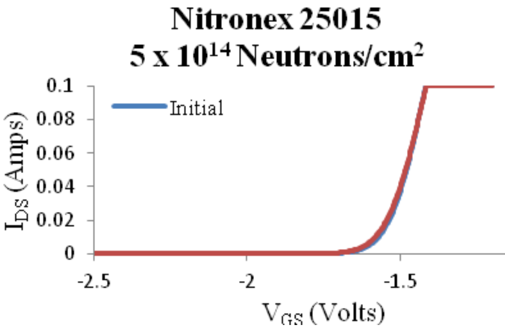

Fig. 6. Nitronex 25015 HEMT irradiate with 5×10^{14} neutrons (1 MeV equivalent). Little change is observed in the response.

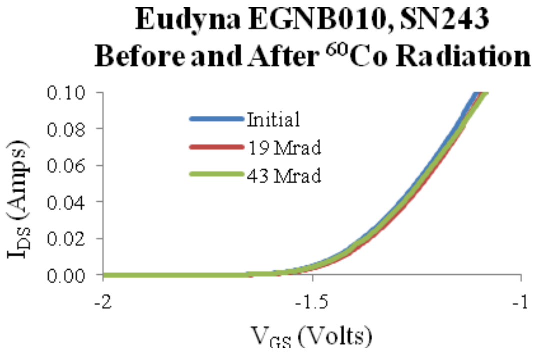

Fig. 7. Eudyna EGNB010 GaN HEMT, V_{GS} versus I_{DS} at V_{DS} = 10 volts and selected doses of ^{60}Co gamma radiation. Little change is apparent even after 43 Mrad of ionizing radiation.

Radiation measurements were also made on enhancement mode HEMTs manufactured by EPC. Gamma irradiation exposures were made on two EPC 1015 devices biased in different fashions. One device was "clocked" at a frequency of 1 kHz with V_{GS} switching between 0 and 4 V, V_{DS} = 24 V DC and I_{DS} limited to 24 mA. The 2nd device was biased at V_{GS} = 4 V and V_{DS} = ground. V_{GS} versus I_{DS} measurements were made at selected doses.

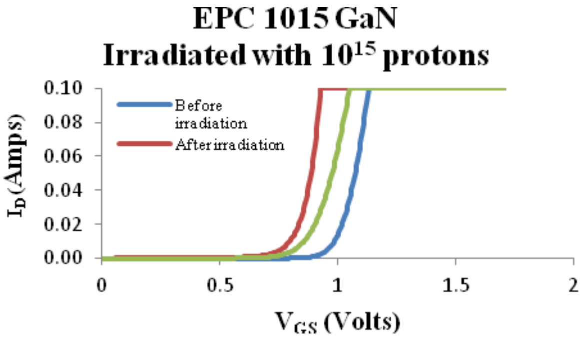

Fig. 8. EPC 1015 HEMT before and after 10^{15} protons/cm^2. During exposure V_{DS} = 24V with a 1 kOhm resistor current limiting the channel to 24 mA. The device was "clocked" with a V_{GS} = 4 V at a 1 kHz frequency.

As a function of dose these measurements were difficult to interpret as the V_{GS} versus I_{DS} behavior of the device changed in a non-systematic fashion. Qualitatively, both devices reacted in a similar way to the radiation. An important observation is that the devices survived an exposure of 64.3 Mrad with no severe effects.

Two devices were similarly biased and exposed to 800 MeV protons at the LANSCE Facility. Shown in Fig. 8 is V_{GS} versus I_{DS} for an enhancement mode GaN HEMT from EPC before and after irradiation with 10^{15} protons/cm^2. Irradiation time was approximately 1 day.

During irradiation the “clocked” device was monitored to verify performance. No changes were observed. After irradiation the devices were placed in cold storage. Again as in previous proton exposures the devices were activated and were retained at LANSCE until they had decayed enough for shipping. The devices were shipped from Los Alamos to Brookhaven in dry ice and measured within 24 hours of arrival. After annealing at room temperature for 1 week the devices were measured again. The DC biased device had qualitatively similar threshold behavior to the clocked device that is shown in Fig. 8.

V. CONCLUSIONS AND FUTURE WORK

A buck converter is a possible candidate for a future power supply in upgrades of calorimeter and tracker systems in the SLHC. Past testing of commercial converters has not found any that meet the requirements of most detectors [1]. This leads to the testing of individual components which could be integrated into a custom buck converter design. For the purposes of illustration, the requirements of the Silicon Tracker in the Inner Detector of ATLAS were used as a case study.

In the Silicon Tracker the requirements for the capacitor can be met using existing commercial components. Because of the magnetic field the inductor will have to be in a custom design utilizing a nonmagnetic core. One possible solution is demonstrated here. One unaddressed challenge is the PWM and in particular its FET drivers. This remains a challenge for future R&D. We have demonstrated the radiation hardness of two promising technologies for the high and low side switches that have sufficient V_{DS} ratings.

LDMOS devices are qualified in most respects for use in SLHC applications with voltage rating requirements of ≤ 16 V and could be used in the Silicon Tracker. GaN FETs (specifically e-GaN) are likely candidates for all SLHC applications with input voltages of ≤ 100 volts. In general the GaN devices have superior characteristics to the LDMOS devices in having higher voltage ratings (up to 200 volts) and being able to operate at much higher switching frequencies. Both GaN and LDMOS devices tested here have survived the radiation environment.

In future effort the general behavior of the high-side and low-side switches and inductor of a converter can be initially tested without incorporating the regulation and control functions of a PWM. This can be done by providing an external clock driver to the switches in place of the PWM driver. Effectively this would be a voltage divider which would convert V_{in} to V_{out} in a fixed ratio. There would be no sense or feedback circuitry for voltage regulation. This allows the characterization of the switches and inductor as a function of switching frequency and magnetic field. In particular the frequency behavior of the inductance and the resistance of coreless inductor designs need to be understood as well as the issues involved in driving LDMOS or GaN switches at high frequencies.

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