Powering Future Particle Physics Detectors

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Justification:

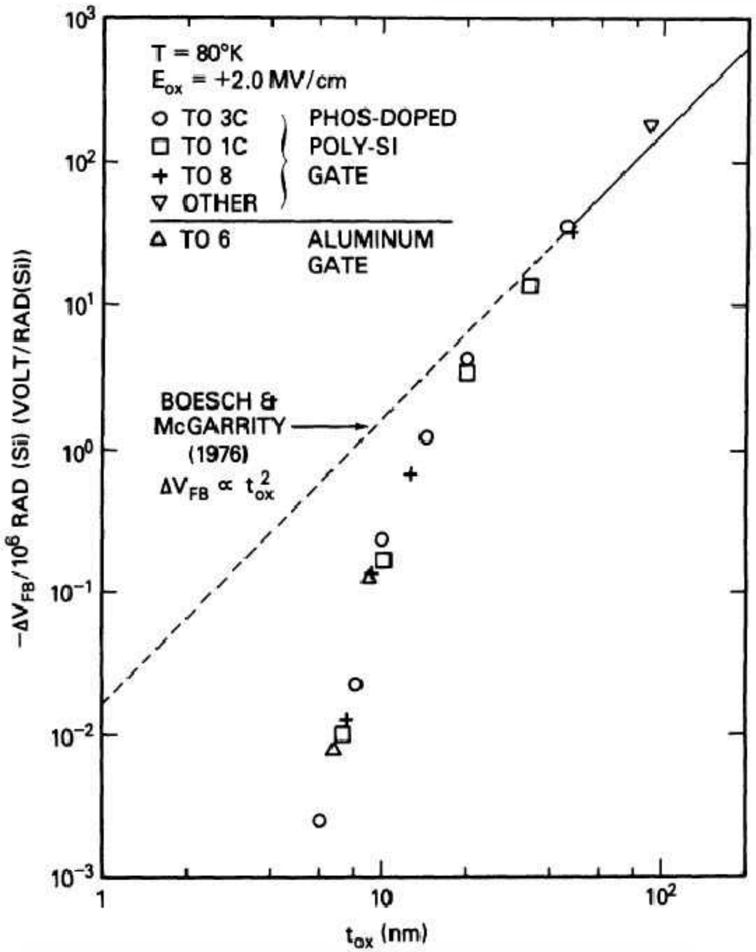
The front-end electronics in large particle physics detectors is located on, or very close to the detectors themselves and must operate in high radiation environments and high magnetic fields. The thousands of readout chips require tens of thousands of amperes at low voltage. Delivering this power deep inside the detector efficiently and without compromising the physics capabilities of the detector is a challenging engineering problem. The use of DC- DC converters at the point of load allows the required power to be delivered at higher voltage and lower currents and thereby reduce the cabling required.

DC-DC converters are ubiquitous in consumer and industrial electronics and there is substantial industrial R&D to make very efficient converters. Portable consumer electronics require very small converters. This need drives the industrial development toward higher frequency converters which require smaller inductors. Higher frequency and lower inductance allows the design of DC-DC converters with air core inductors, which can operate in a high magnetic field. Converters using an inductor consisting of traces on a PC board can be quite small (a few square cm) and very low mass while still providing 5 A of output current at low voltage.

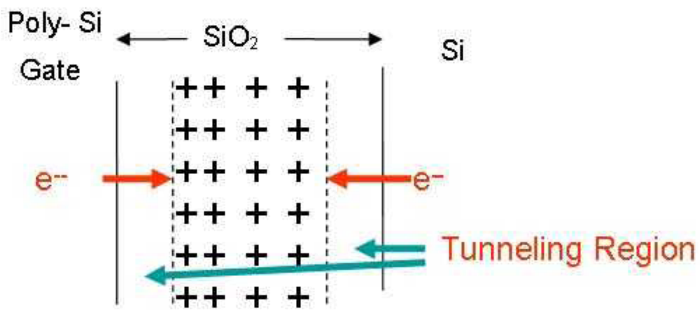
http://shaktipower.sites.yale.edu/

Threshold shift in MOS transistors with Radiation vs Oxide Thickness

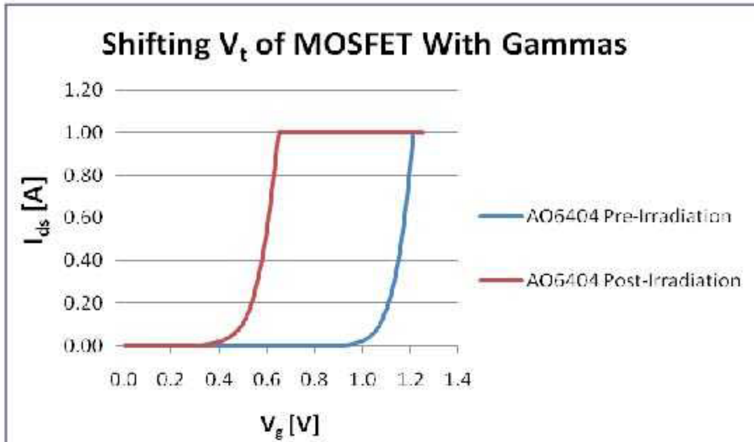
Threshold Shift vs Gate Oxide Thickness



Sachs et. al. IEEE Trans. Nuclear Science NS-31, 1249 (1984)



Hole removal process by tunneling in thin-oxide MOS Structures



Book. Timothy R Oldham "Ionizing Radiation Effects in MOS Oxides" 1999 World Scientific

12-Apr-13
Satish Dhawan
Yale University

Some Radiation Tests Results - Thin Gate Oxide

Company	Device	Oxide Thickness (nm)	Dose before Damage	Observation Damage Mode	Foundry / Process
IHP Microelectronics	Process Test FET	5	53 Mrad	Minimal damage	SG25V GOD
XYSemi	2 amp MOS FET	7	52 Mrad	Minimal damage	HVMOS20080720
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	
Enpirion	EN5365	5	85 krad	Increasing input current,	0.25 µm CMOS Dongbu Hi-Tek
Enpirion	EN5382	5	111 krads	Loss of output voltage regulation	0.25 µm CMOS Dongbu Hi-Tek
Enpirion	EN5360 #2	5	100 Mrads	No significant Changes	IHP Microelectronics 0.25 µm CMOS
Enpirion	EN5360 #3	5	48 Mrads	No significant changes	IHP Microelectronics 0.25 µm CMOS
National Semi.	LM2864	11.8	3 Mrads	Short after power recycle	Maine PVIP25

Radiation Tolerance of CMOS Devices

Company	Device	Process	Foundry	Oxide	Dose before	Observation
		Name/ Number	Name	nm	Damage seen	Damage Mode
IHP	ASIC custom	SG25V GOD 12 V	IHP, Germany	5	53 MRads	Minimal Damage
XySemi	FET 2 A	HVMOS20080720 12 V	China	7	52 Mrads	Minimal Damage
XySemi	XP5062	HVMOS20080720	China	12	44 Krads	Loss of output regulation
Enpirion	EN5365	CMOS 0.25 µm	Dongbu HiTek, Korea	5	64 Krads	Increasing input current
Enpirion	EN5382	CMOS 0.25 µm	Dongbu HiTek, Korea	5	111 Krads	Loss of output regulation
Enpirion	EN5360	SG25V (IHP)	IHP, Germany	5	100 Mrads	Minimal Damage
National	LM2864	PVIP25	In House	11.8	3 Mrads	Loss of output. Short after power off/on

Table I. Radiation Tolerance of Devices with thin oxide

LDMOS Structure
Laterally Diffused
Drain Extension

High Voltage / high Frequency
Main market. Cellular base stations

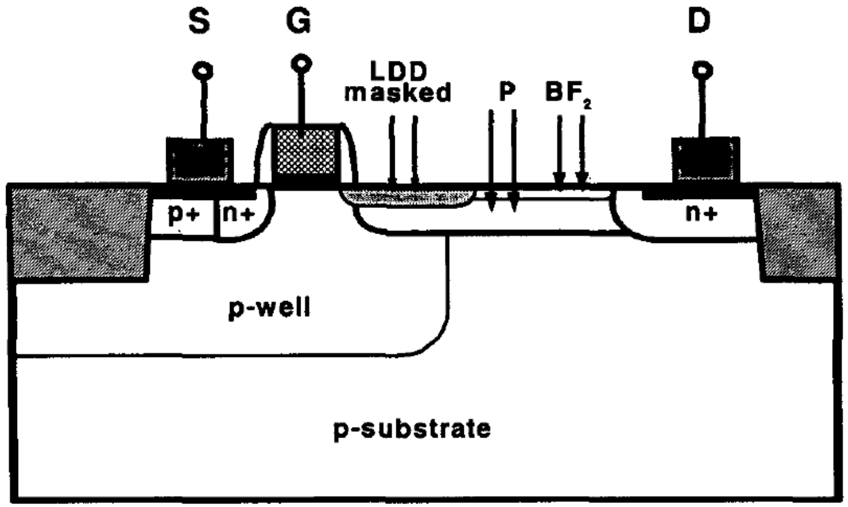


Fig.1: Schematic cross-section of the RF-LDMOS transistor.

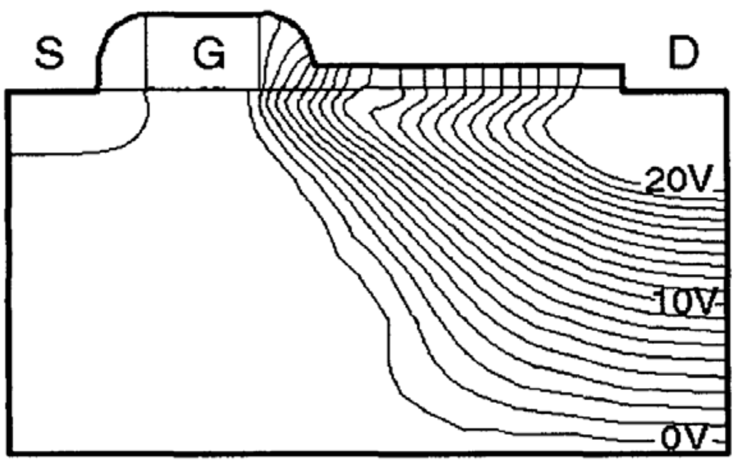


Fig.3a: Potential distribution at the highest operating voltage (20V) with $V_G = 0V$ (LDMOS 3 from Table 1).

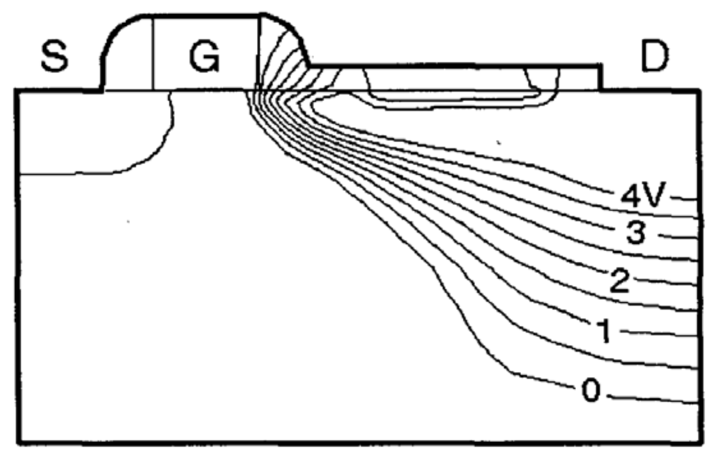
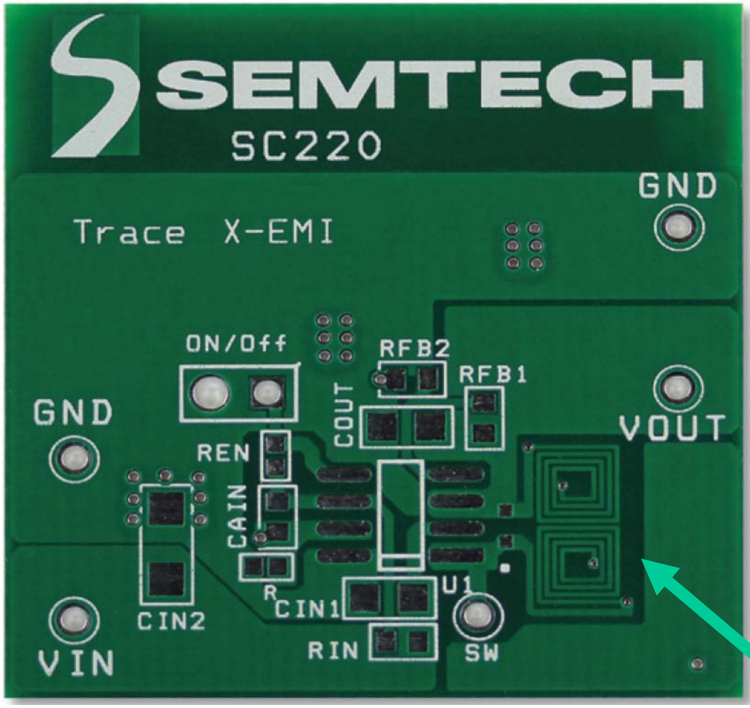
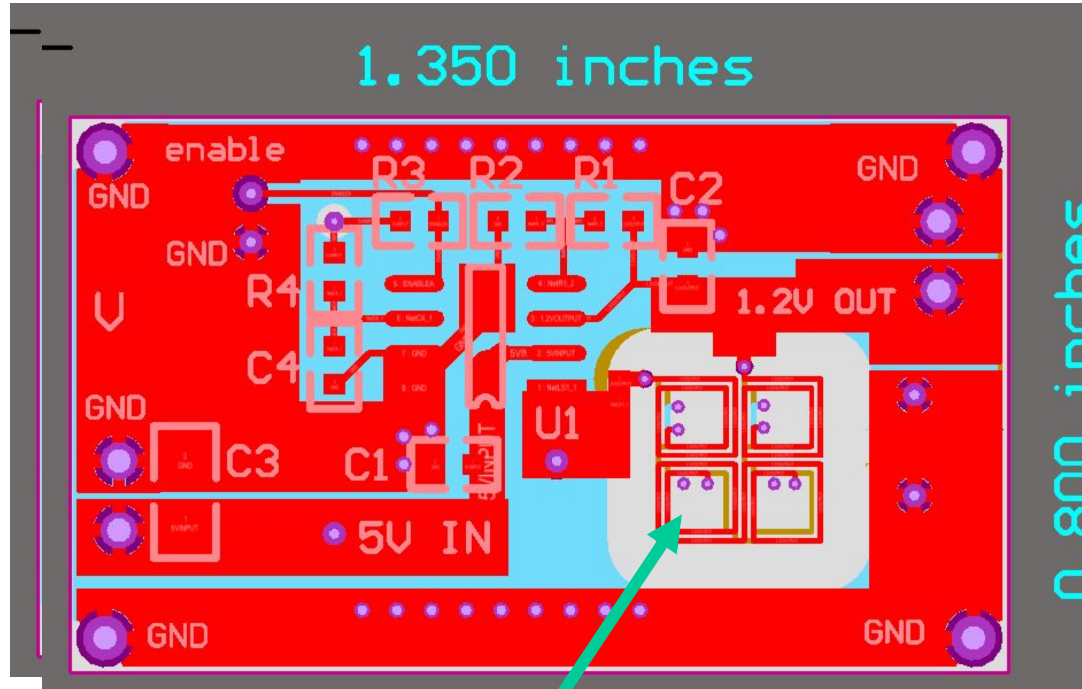


Fig.3b: Potential distribution at the lowest operating voltage (4V) with $V_G = 0V$ (LDMOS 3 from Table 1).

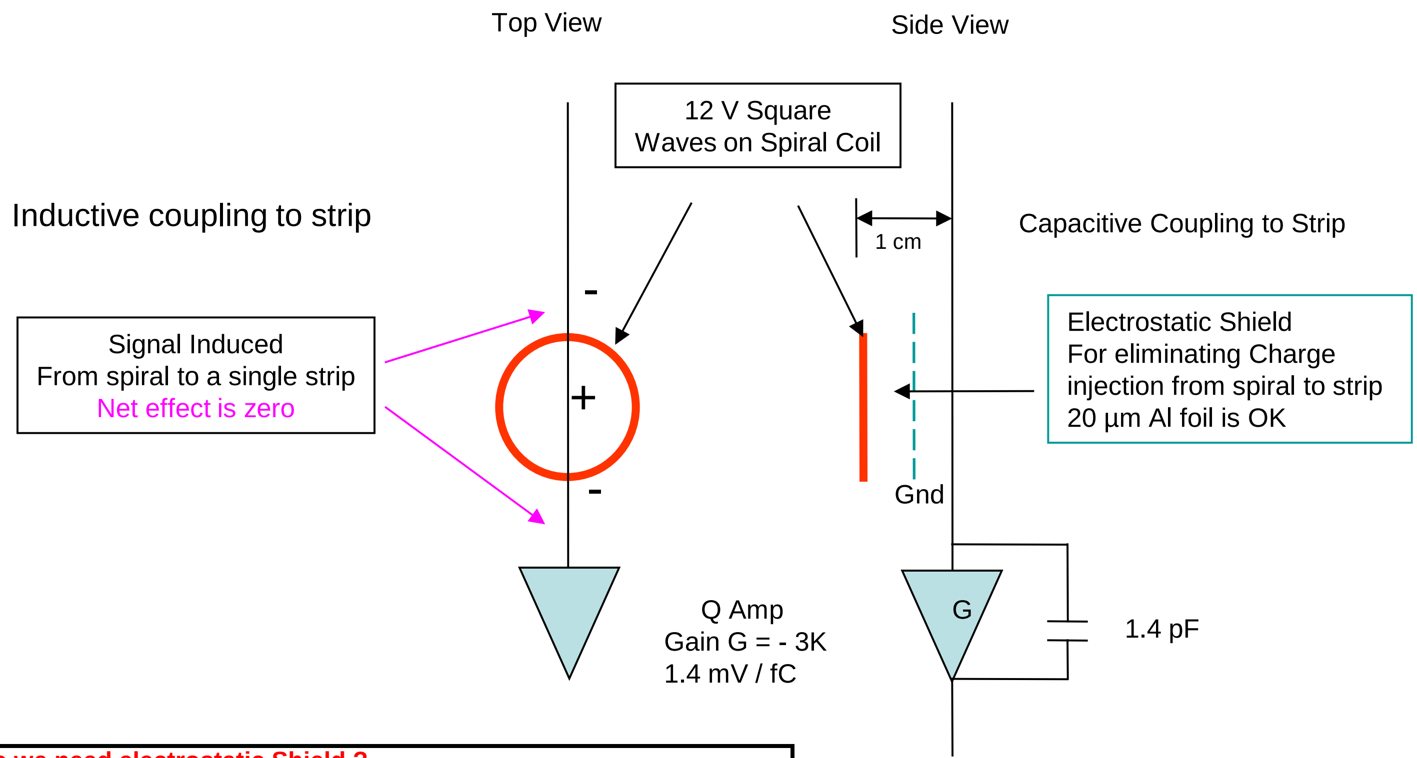
High performance RF LDMOS transistors with 5 nm gate oxide in a 0.25 µm SiGe:C BiCMOS technology: IHP Microelectronics
Electron Devices Meeting, 2001. IEDM Technical Digest. International
2-5 Dec. 2001 Page(s):40.4.1 - 40.4.4



Top view of an evaluation board with X-EMI inductor



The external field from a flat spiral coil can be substantially reduced by combining coils with the field alternating in opposite directions. The figure shows 4 small square coils in series. The total coil is less than 6 mm square. Aa single spiral with the same inductance is also about 6 mm diameter. The field of the square coils extends less than half the distance from the plane of the pcb as the single spiral, and falls off much faster with distance due to cancellation of the fields from the coils with the other polarity.



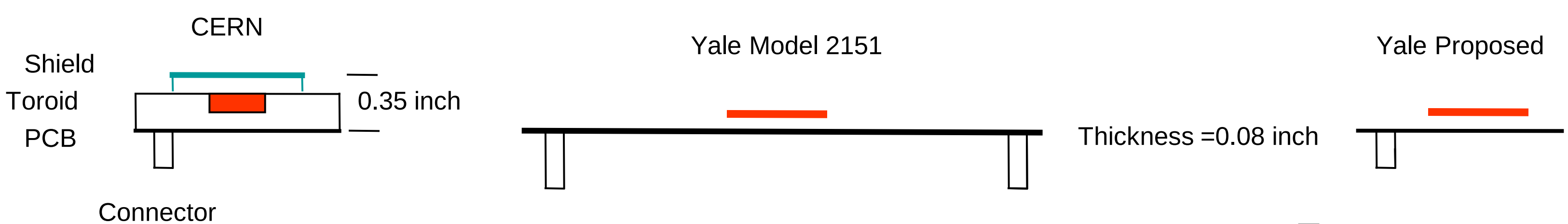
Why do we need electrostatic Shield ?

Parallel Plate Capacitance in pF = 0.225 x A x K / Distance

	Inches	C in femto farads
Area =	1	
Distance =	0.4	500
GLAST = .5 x 1.3	0.6	
per strip= 0.6 /48	0.0125	6.25

1 volt swing on spiral coil will inject Q= 6 femto Coulombs

Charge from one minimum ionizing particle (1 mip) = 7 femto Coulombs

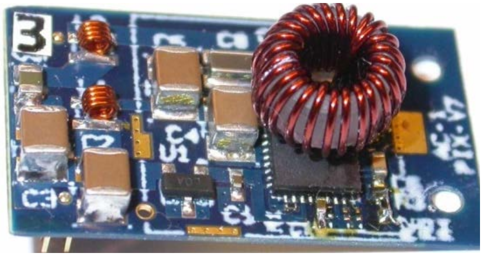


Grid = 0.1”

July 31, 2012

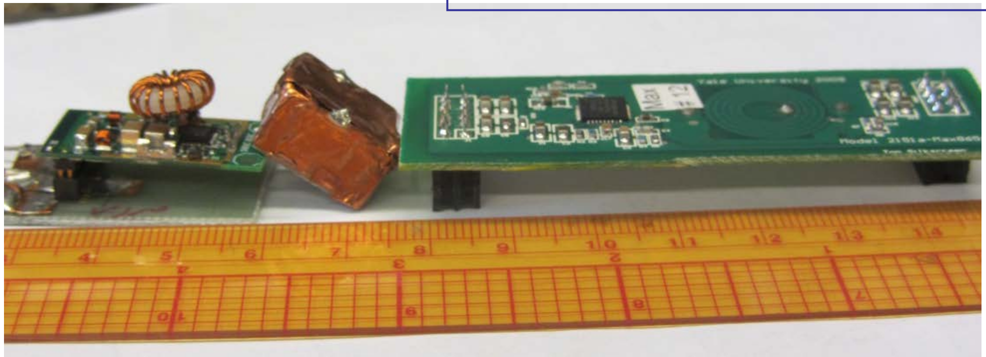
August 4, 2012

Another air core Toroid solution



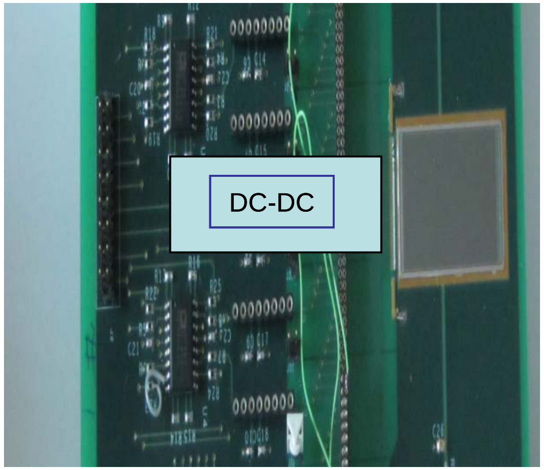
An air core Toroid solution with shield

2009 Yale Solution with Embedded air core Spiral inductors in a 4 layer Standard PCB. Not shown an electrostatic 10 µm Al foil Shield

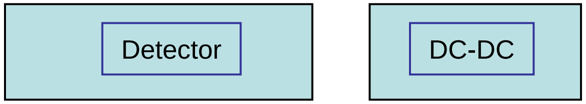


Yale version can be made same size as the Toroid solution by changing power connectors

Location of DC-DC converter 1 cms above Detector

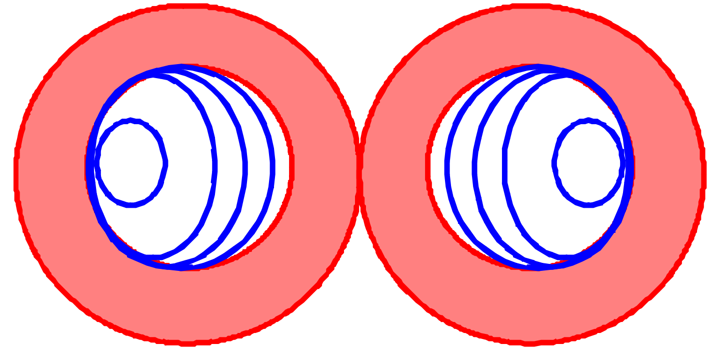


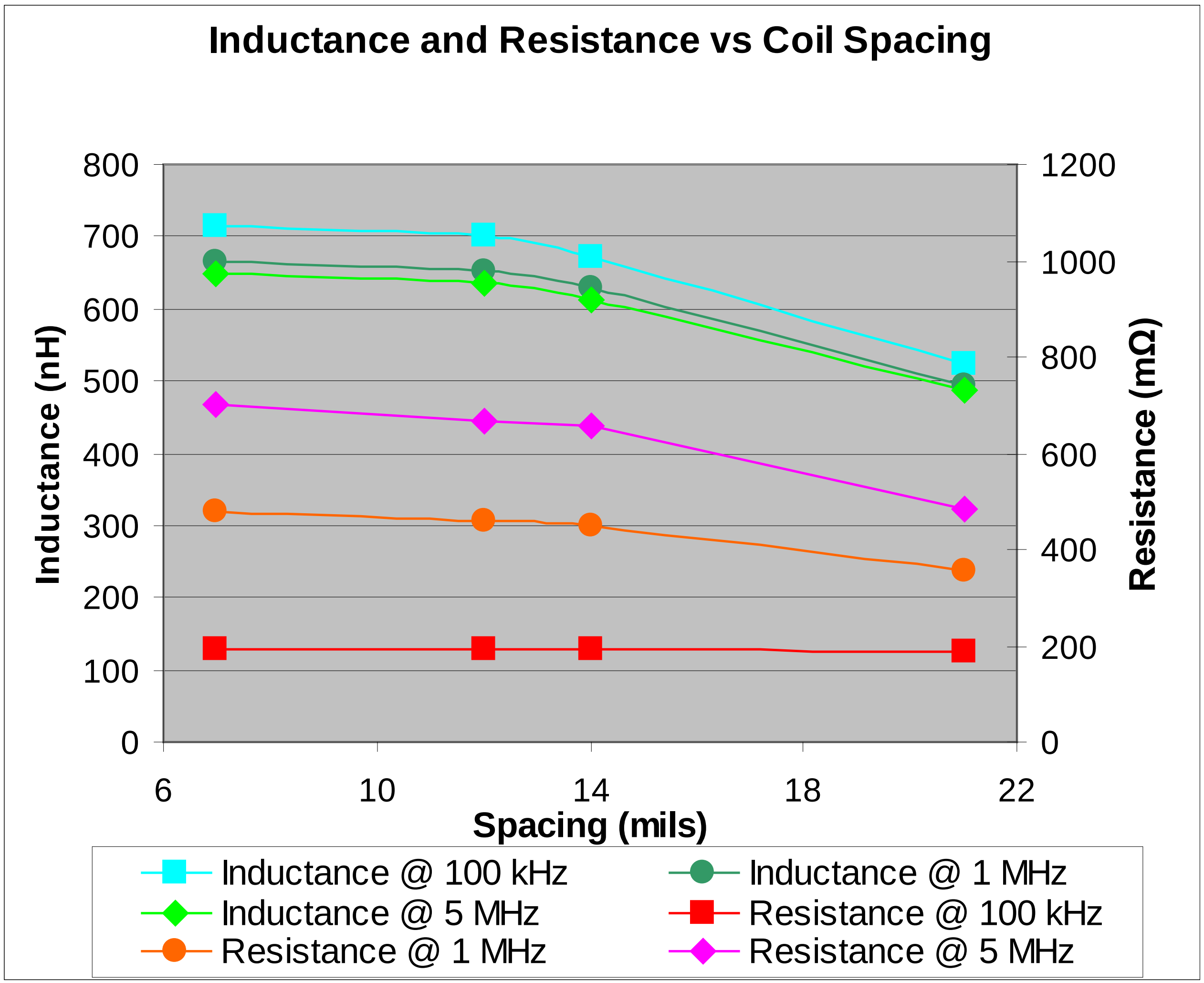
Detector from previous slide

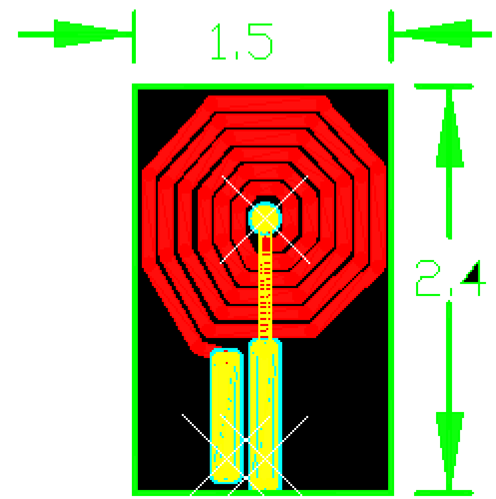


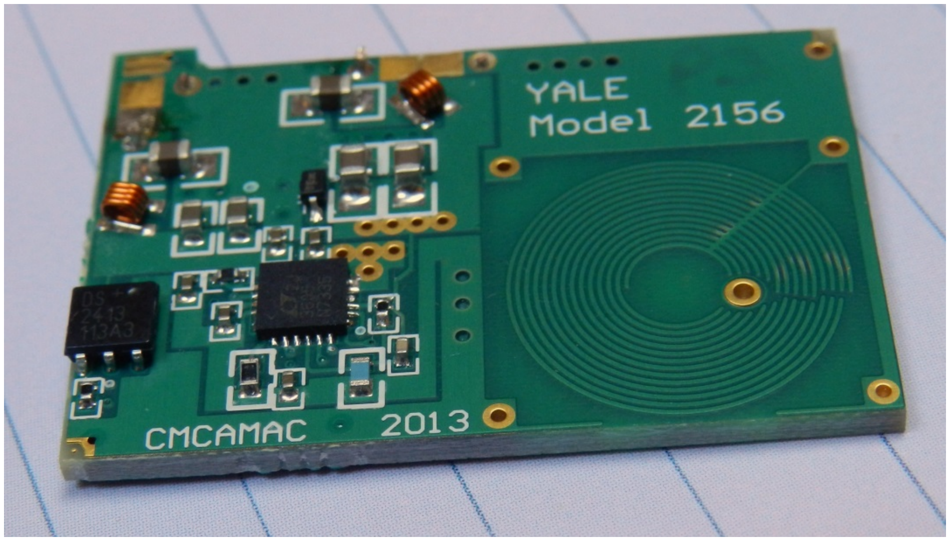
Location of DC-DC converter in same plane as detector

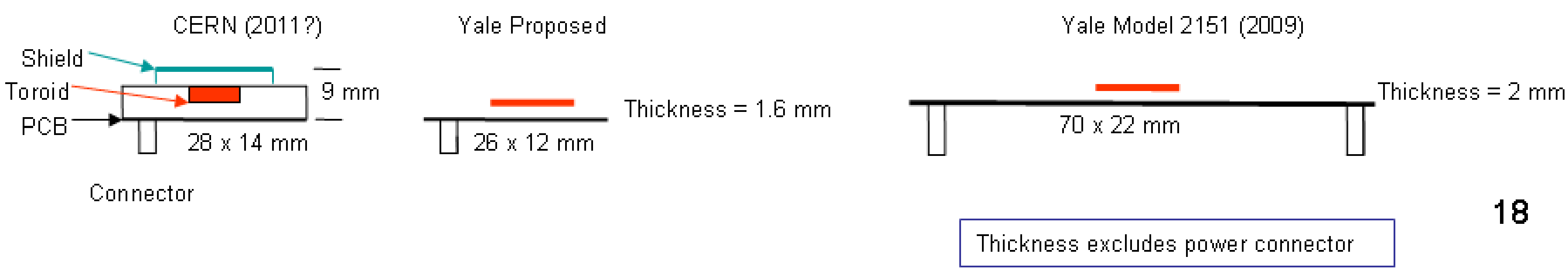
Proximity Effect








YALE
Model 2156
CMCAMAC 2013


CERN (2011?)
Shield
Toroid
PCB
9 mm
28 x 14 mm
Connector
Yale Proposed
Thickness = 1.6 mm
26 x 12 mm
Yale Model 2151 (2009)
Thickness = 2 mm
70 x 22 mm
Thickness excludes power connector
18

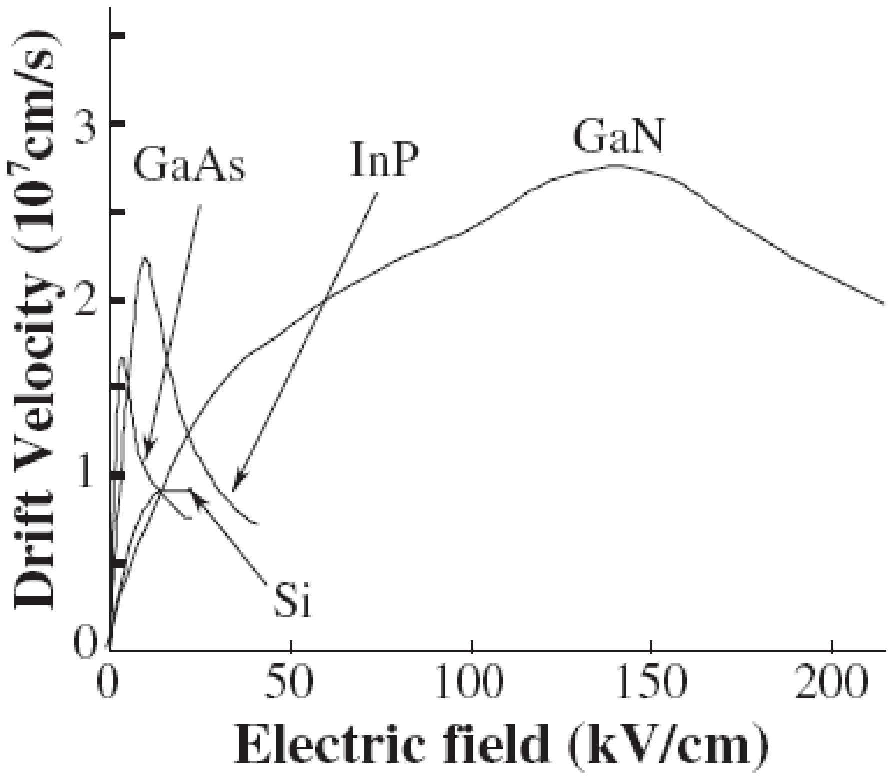


Fig. 8. Dependence of drift velocity of semiconductors on electric field. GaAs and InP have high mobilities (slope of drift velocity–electric field relation in the low-electric-field region); however, their drift velocities decrease in the high-electric-field region. On the other hand, GaN shows high drift velocity in the high-electric-field region.

H. Okumura. Present Status and Future of Widegap Semiconductor High-Power Devices, Jpn. J. Appl. Vol. 45. No. 10A (2006)

High Voltage Multiplexing for Silicon Detector Systems. **David Lynn (BNL)**

Traditionally in silicon detector systems each sensor receives it own high voltage (HV) bias over a dedicated pair of wires from its own HV power supply. This permits a failed sensor to be disabled without affecting the operation of other sensors. It also permits the simple monitoring of sensor currents at the power supply source.

Future large scale silicon detector systems at hadron colliders require high voltage bias to be delivered to a large number of sensors numbering in the tens of thousands. To provide each sensor its own bias with the traditional approach would require a large number of cables that will result in high mass and difficulty in routing. The large number of HV supply modules will result in a high cost.

One alternative is to power a group of modules with a single HV supply. The primary drawback of this approach is that a failed sensor causes the loss of all other sensors on its HV supply bus. Additionally only the summed current of a group of sensors is monitored.

An alternative approach is to bias a group of sensors on a single bus, but to have remote controlled switches that can disable a malfunctioning sensor. The requirements on the switch are severe in that it typically must be extremely radiation hard, operate in a magnetic field, and operate at voltages > 500 V. The magnetic field requirement limits the choice to semiconductor switches. The high radiation requirement eliminates power MOSFETs, and the radiation requirements in conjunction with high voltage makes the use of bipolar switches difficult or impossible.

Two relatively new technologies being developed for commercial high voltage switching applications are Gallium Nitride (GaN) and Silicon Carbide (SiC). GaN devices are expected to operate at 600 V and SiC devices at 1200 V or 1700 V. Literature searches as well as preliminary irradiations (for GaN) indicate that transistors made in these technologies have the potential to be extremely radiation hard. A large number of companies are pursuing these technologies, although to date only a few provide commercially available products. Other companies require non-disclosure agreements to access their devices.

A program of investigating these technologies is underway for LHC applications. Initially it involves working with companies to obtain samples of their prototype devices and arranging a program of irradiations at various facilities in Europe and the US. Systems architecture design and prototyping with groups of silicon sensors are in progress. Designs for slow-controlled monitoring of individual detector currents are being developed. It is expected that such R&D will find application to other detector systems as well as for radiation-hard DC-DC power delivery.

The Power Distribution Challenge **Steen Hansen** Fermilab

The present scheme used at the LHC of large conductors conveying very high currents with the use of linear regulators is at the limit of feasibility. As currents go up losses go up, heat from these losses must be removed from the detector which in turn incurs an additional power penalty. For the detector upgrades this issue needs to be addressed. One avenue of inquiry is switch mode power supplies capable of operating in the high radiation and high magnetic fields present within the LHC detectors. On a more modest scale the tracker and calorimeter for the Mu2e experiment at Fermilab will also operate in a radiation and magnetic field environment. Power supply design should be an integral part of the detector system design. Leaving this critical aspect out of the preliminary design phase has up to now been an all too common occurrence.

An attractive model for power distribution is that used by telecommunications infrastructure. The distribution occurs in three stages. Line voltage is first converted to 300V DC with a power factor correction stage. This voltage is then converted to 48V using DC-DC converters. The conversion of line voltage to 48V is typically done in one unit. Efficiencies approaching 90% for line to 48V conversion is routine. Forty-eight volts is then distributed to multiple locations. At each location 48V is converted to a crudely regulated intermediate voltage – typically seven to 12 Volts. Finally, DC-DC converters placed adjacent to the chips they power supply voltages in the range 0.9V to 3.3V.

Given the distribution model one can imagine that the conversion to 48V takes place outside the detector volume, while it would be highly desirable to distribute 48V within the detector. The motivation for higher voltages is the reduction of losses in conductors of a given area which goes as the square of the current. How can a system with telecomm architecture be built given the constraint of ambient magnetic fields and high radiation? One could argue that going from two to three volt supply to six volt supply would be sufficient to bring conduction losses down to workable levels. Nevertheless if a workable 48V converter could be demonstrated, it would give significant advantages to any system design.

Design Issues

The presence of the ambient magnetic field precludes the use of ferrite cores for the inductors and transformers used by switch mode converters. Practical air core magnetics have much lower inductance values than their ferromagnetic counterparts, forcing converters to operate at much higher frequencies. However, the operating frequencies of commercially available switchmode controllers has been steadily increasing with a corresponding reduction in the size of the inductor. At switching frequencies greater than 10MHz, air core inductors are in fact preferred. Those devices which operate at the highest frequencies are typically fabricated in a small feature size CMOS process which is intrinsically radiation hard. As to power devices, gallium nitride transistors appear to have great promise. They exhibit performance superior to their silicon counterparts and are also intrinsically radiation hard.

R&D Program

The distribution scheme naturally suggests two lines of inquiry: the 48V converter and the point of load converters. The availability of a 48V converter would significantly reduce the constraints imposed on the design of the point of load converters. Work needs to be done on design of the air core magnetics, the design of the control and driver circuits for various converter topologies and comprehensive radiation testing of candidate designs. An effort of this scale, though modest in comparison that devoted to detector development, requires the collaboration of multiple institutions, each with a particular area of interest and expertise.