Power Distribution in a CMS Tracker for the SLHC

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Abstract

An upgraded tracker for CMS will need a new architecture for powering to keep the power dissipated in the power cables to acceptable levels. Inductor topologies to reduce the stray magnetic field are discussed together with measurements of the magnetic field produced by prototype inductors. A transformer based DC-DC converter has the potential to produce a high step-down ratio whilst producing a low stray field and retaining high efficiency. The relative merits of buck configuration and transformer based DC-DC converters are discussed.

I. INTRODUCTION

A tracker for use in CMS with an upgraded LHC (SLHC) will need finer granularity whilst having the same, or less, dead-material[1]. This will imply either the same or less power consumption. This can be achieved by using readout chips with a smaller feature size: the current rises with the increased number of channels but the power consumption stays the same due to the reduced supply voltage. In the current tracker the power dissipated in the low voltage supply cables in comparable with the power dissipated by the active electronics. If the same architecture is retained for an upgraded tracker the dead material will rise significantly, either in terms of thicker cabling or cooling pipes to remove the increased power dissipated in the cabling. A new system architecture is required. The two currently proposed involved the use of serial powering and/or DC-DC converters[2]. Aspects of DC-DC converters using magnetic fields as an energy storage/transfer mechanism are discussed here.

The baseline configuration for a DC-DC converter based scheme is the buck converter. Energy is repeatedly drawn from the input supply stored in the magnetic field generated by an inductor and then liberated to the output. A description of the buck converter and a discussion of the challenges involved in its use in the high radiation, high magnetic field environment of a CMS or Atlas tracker are described elsewhere[3]. Buck converters have the advantage of simplicity and compactness. To be competitive in terms of system efficiency with serial powering approach a DC-DC converter based scheme needs to achieve a step-down ratio between the input and output voltages in the region of ten. To achieve this ratio whilst retaining a high conversion efficiency is challenging in a buck converter where a high step-down ratio implies a high mark-space ratio for the switches. An additional challenge for a DC-DC converter based on magnetic components is electro-magnetic interference (EMI) with the readout chips caused by the time-varying magnetic field generated by the converter.

The EMI produced by a DC-DC converter can be reduced by using an inductor which produces smaller stray field, using a configuration - such as a transformer based design - that produces less stray field, or shielding the magnetic field. The use of a toroidal inductor, a planar transformer and shielding are discussed.

II. TOROIDAL INDUCTOR FABRICATED IN PCB

A toroidal inductor has lower external field than a solenoid of equivalent inductance. It is possible to fabricate a rectangular section toroid in a printed circuit board, following the example of fabricating a toroid in CMOS technology[4]. The inductance of a rectangular toroid of N turns with inner and outer diameters d_i , d_o and height h is approximately $L \approx (N^2 h\mu_0/2\pi)\log(d_o/d_i)$. An inductor with inner and outer radius of $12mm$ and $28mm$ respectively was constructed in a standard PCB process of 1.6mm height. Figure 1 shows a photograph of the test inductor. The 30 turn inductor is predicted to have an inductance of $244nH$. The measured impedance, at 100kHz was $240 \pm 20nH$. The DC resistance was measured as $205 \pm 20m\Omega$. From this it can be seen that constructing an inductor suitable for use in a 1-Amp DC-DC buck converter would be challenging. For such a device an inductance in the region of $500nH$ with a DC resistance of much less than $100m\Omega$ is needed[5]. By using multiple layers and filled vias an inductor with suitable characteristics could probably be fabricated, but the extra cost and complexity would negate the benefit of the increased integration allowed by building magnetic components into the PCB of the DC-DC converter. However, it would be possible to construct an inductor of lower inductance suitable for use as part of an output filter for a transformer-based design.

Even an ideal toroid produces some external magnetic field. If the the current input and output in the same position it can been seen that in addition to the many turns around the core of the toroid the current undergoes a single turn around the axis perpendicular to the plane of the core. This field can be reduced by either fabricating two toroids on top of each other connected in series to as to cancel the external field or by using a conductive shield. Since the inductor will be fabricated in a board with power and ground planes the latter solution will be implemented in any case.

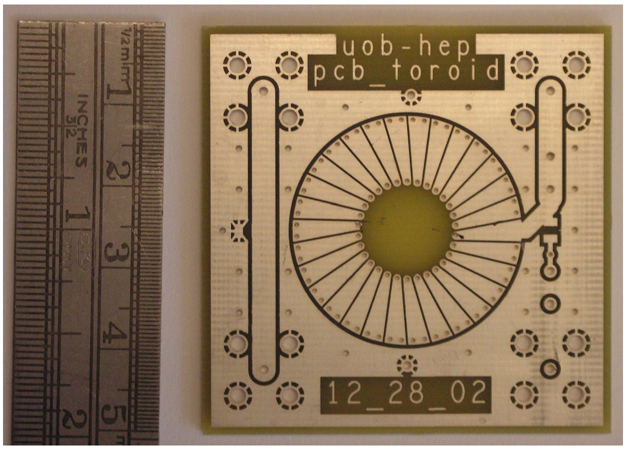

Figure 1: Photograph of 244nH test inductor

III. MEASUREMENT OF MAGNETIC FIELD

A variety of inductors were connected to the tracking generator output of a Hewlett Packard HP8560A spectrum analyser and the magnetic field measured using a Hameg HZ530 "near field probe". The inductor and the field probe were held in a non-conducting support separated by $100 \pm 5mm$ aligned along the axial direction to within 5^o. Figure 2 shows the arrangement (but not the supports). The field probe has no absolute calibration, but its response is linear and enables comparative measurements to be made.

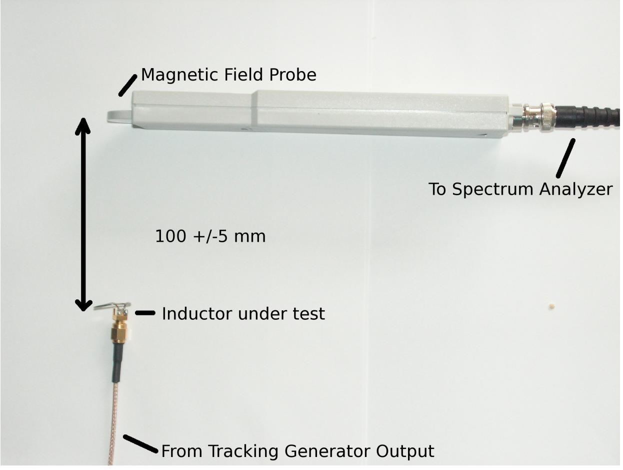

Figure 2: Arrangement of inductor and field probe for magnetic field measurement

Figure 3 shows the relative magnetic field as a function of frequency with a variety of inductors. The inductors are driven with a fixed voltage and the sensitivity of the field probe varies strongly with frequency, hence it is not straightforwards to calculate the magnetic field as a function of drive current and frequency. However, some conclusions can be drawn. Table 1 gives the measured field strength for three different arrangements of air-core inductor together with the inductance measured by using an inductance bridge. The inductors are Coilcraft 132-19 solenoidal inductors, with nominal inductance $470nH$. The magnetic field for a single inductor and two inductors mounted side by side with the magnetic field in their core oriented in the same direction are almost the same. This is because the magnetic field per unit current is approximately twice as large as for one coil, but the inductance approximately doubles so the current drops by a factor of two. For two inductors mounted so the the magnetic field from each coil are in opposite direction the magnetic field is a factor of $20dB$ lower, whilst the inductances for the two arrangements are within measurement errors. This indicates that the electromagnetic interference from radiated magnetic fields in a DC-DC converter can be greatly reduced by careful choice of inductor geometry.

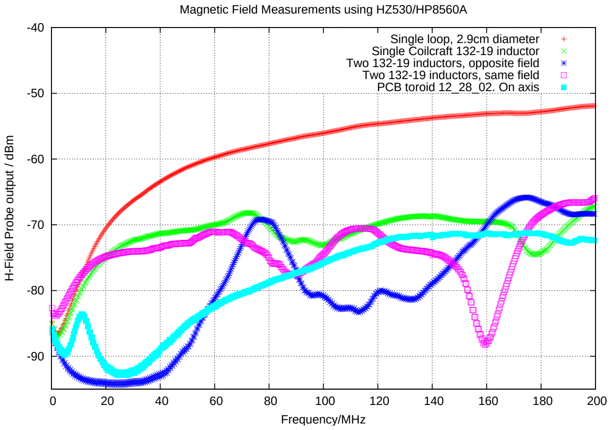

Figure 3: Relative magnetic field at 10cm produced by a variety of inductors

Configuration	Inductance/nH ±10%	Magnetic Field at 20MHz (arb. units)
Single Coilcraft 132-19	477	-75dB
Two 132-19, parallel field	940	-75dB
Two 132-19, anti-parallel field	915	-94dB

Table 1: Inductance and relative magnetic field of of air-core solenoids

IV. TRANSFORMER BASED DC-DC CONVERTER

At high step-down ratios a transformer based DC-DC converter is preferable to a buck configuration. The step down ratio is largely determined by the ratio of the number of turns between the primary and secondary windings. Regulation of the output voltage can be achieved by altering the mark-to-space ratio of the switches driving the primary winding. For resonant converter voltage regulation can be achieved by changing the drive frequency. To increase the degree of integration the transformer can be constructed inside the printed circuit board. It has been pointed out[6] that an advantage of a transformer based converter is that almost all the magnetic field generated by the primary winding is cancelled out by the secondary. The low external field also implies that the transformer can be screened without significantly affecting its operation. A schematic showing a transformer based DC-DC converter is shown in 4. In practice the rectifying diodes would be replaced by a synchronous rectifier. The schematic is taken from the data sheet of a commercial component[7] intended to enable the construction of low-noise DC-DC converters. A differential output noise of less than $10\mu V$ RMS is claimed for the example circuit.

The characteristics of a planar transformer were simulated and a prototype constructed. With the Figure 5 shows the prototype transformer constructed. The transformer has a 4:1 windings ratio and is constructed as an eight layer printed circuit board with $30\mu m$ copper foil separated by $50\mu m$ dielectric. The outer diameter is $28mm$. The magnetic field produced was simulated under a variety of different conditions. Figure 6 shows the field lines when the primary coil was energized with 0.25A and the secondary coil left open. Figure 7 shows the field lines with the primary energized with 0.25A and the secondary with 1A. It can be seen that the external field is greatly reduced.Figure 8 shows the field density for a transformer with the primary and secondary energized and shielded with $35\mu m$ of copper foil at a distance of $200\mu m$ from the outer windings. The field is reduced still further. Table 2 lists the magnetic field predicted at $10cm$ in an axial direction from the centre of the transformer. Even with copper shielding foils only $200um$ from the outer layers of the transformer the power dissipated in the shield is predicted to be only 2.8mW with 250mA/1A in the primary/secondary windings.

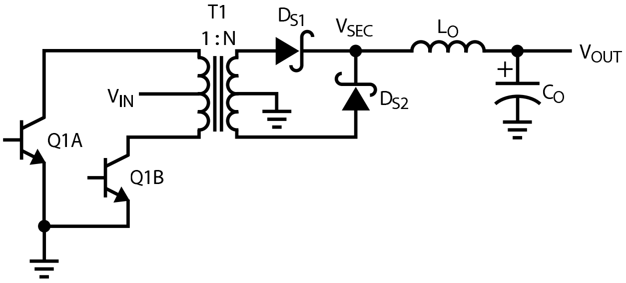

Figure 4: Sketch of transformer based DC-DC converter

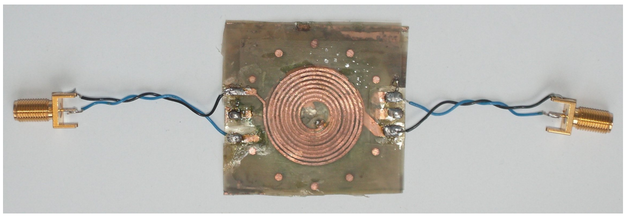

Figure 5: Photograph of prototype planar transformer

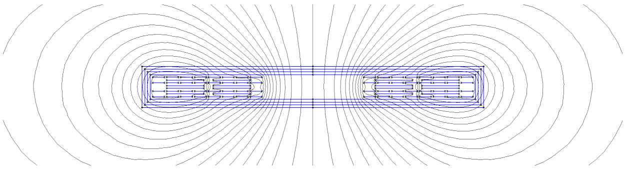

Figure 6: Magnetic field lines from a planar transformer with only primary energized

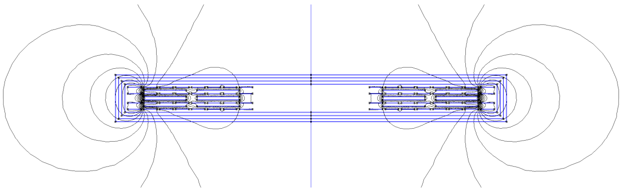

Figure 7: Magnetic field lines from planar transformer with both primary and secondary energized

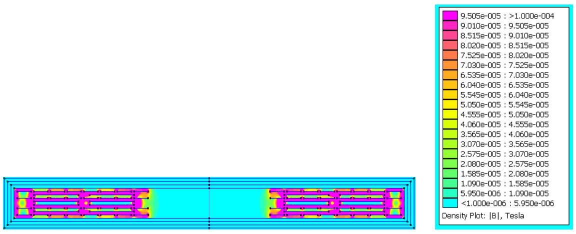

Figure 8: Magnetic field density from planar transformer with primary and secondary energized with 0.25A, 1A. Shielded at a distance of $200\mu m$.

Configuration	Magnetic Field at 10cm
Primary energized with 250mA	287nT
Primary/secondary energized with 250mA/ -1A	12nT
Primary/secondary energized with 250mA/-1A. Screened at $200\mu m$	60pT

Table 2: Magnetic field produced by planar transformer

V. MODULE TEST STAND

A test-stand based in the ARC test-system[8] for tracker modules is being constructed in order to test experimentally noise pick-up in a tracker module. In addition a system for measuring the common and differential mode conducted electrical noise, similar to those set up in CERN and Aachen[9] is being set up. This will allow the noise produced by a prototype DC-DC converter to be measured and also its effect on a CMS tracker module. The physical arrangement of the module test-stand is shown in figure 9

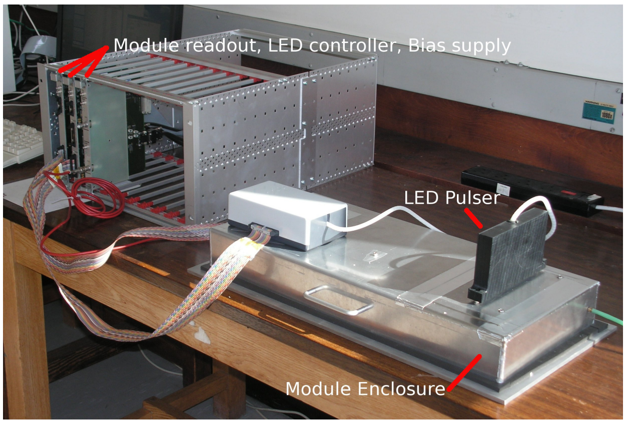

Figure 9: Physical arrangement of ARC test-stand for single CMS tracker module

VI. DISCUSSION

Powering a CMS tracker at the SLHC will require a powering scheme that can supply electrical power at a higher voltage and hence lower current than the supply for the front-end electrical circuitry. The relative merits of a system based on serial powering or DC-DC converters are discussed elsewhere[2] Within the family of DC-DC converters based on magnetic fields for energy transfer transformer-based converters have the possibility for a higher step-down ratio and lower EMI than a buck configuration. However, system issues such as simplicity and compactness may override these factors.

VII. ACKNOWLEDGEMENTS

The authors would like to thank Brian Hawes for providing us with planar transformer prototypes and simulations. We are also grateful to the University of California Santa Barbara for providing us with the components needed to construct a module test-stand.

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