Powering of Detector Systems

Satish Dhawan, Yale University
Richard Sumner, CMCAMAC LLC
Agenda
Prior / Current Status
   LDO Powering Efficiency
   Buck Converter
   Frequency limited by FeCo
   Commercial Devices limited by 200 KHz – 4 MHz - Core losses

Higher Frequency > smaller components

Wireless Charging, Intel 4th Generation Core
Air Core Toroid vs Planar (spirals). PC Traces @ > 100 MHz
Shielding Electrostatic & RF

ATLAS Tracker

Future
Power Efficiency _ Inefficiency _ Wasted Power

Power delivery Efficiency = 30 %
with Power for Heat Removal = 20 %
Fig SR

Synchronous Rectification

V Input

Pulse Width Modulation Controller Chip

Feed Back

Crucial element - Inductor
Low DCR for output current
Shielding to sensor
Cooling

Q1
Q2
L
I Out

R1
R2
C out
GND

V Output

V OUTPUT
**Plug In Card with Shielded Buck Inductor**

**Coupled Air Core Inductor Connected in Series**

- Top: 3 Oz PCB 57
- Bottom: 0.25 mm Cu 19.4

**Different Versions**

- **Converter Chips**
  - Max8654 monolithic
  - IR8341 3 die MCM

- **Coils**
  - Embedded 3oz cu
  - Solenoid 15 mΩ
  - Spiral Etched 0.25mm

**Spiral Coils Resistance in mΩ**

<table>
<thead>
<tr>
<th></th>
<th>Top</th>
<th>Bottom</th>
</tr>
</thead>
<tbody>
<tr>
<td>3 Oz PCB</td>
<td>57</td>
<td>46</td>
</tr>
<tr>
<td>0.25 mm Cu Foil</td>
<td>19.4</td>
<td>17</td>
</tr>
</tbody>
</table>

**Noise Tests Done:** sLHC SiT prototype, 20 µm AL Shield
MAX8654 with embedded coils (#12), external coils (#17) or Renco Solenoid (#2)

Vout=2.5 V

From Fermilab Talk 041310
Test Silicon Strip Detector

64 strips- 228 µm pitch
Size 15mm x 35mm
Substrate Thickness = 410µm

Output Op amp
Charge Sensitive Pre-amp
Cremat CR-110
Switch Matrix
Select 8 strips of 64
For analog output

64 Parallel Al Strips
Length = 35 mm
Width = 56µm
Pitch = 228 µm

August 4, 2012
**Why do we need electrostatic Shield ?**

Parallel Plate Capacitance in pF = $0.225 \times A \times K / \text{Distance}$

<table>
<thead>
<tr>
<th>Area</th>
<th>1</th>
<th>Distance</th>
<th>0.4</th>
<th>GLAST = $0.5 \times 1.3$</th>
<th>0.6</th>
<th>per strip = $0.6 / 48$</th>
<th>0.0125</th>
<th>C in femto farads</th>
<th>6.25</th>
</tr>
</thead>
</table>

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

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

Measurement of RF field (by eddy current loss) vs distance

34 mil thick 4 layer PCB

36 mm

15 mm

Spacers 2, 8 & 32 mil thick

4 mil Copper Tape

4 mil thick Mylar

25 cms x 25 cms

Spiral Inductor

Measure IC current vs distance between spiral & copper tape
Put finger pressure between copper tape and PCB

Yale University
January 2, 2014
No Lines 9 turns
Spiral 7 turns
Lines 9 turns
No Spiral 7 turns
Eddy Current Loss vs Distance between Spiral to Copper Tape

normalized for Panel 11

Current in mA  Distance in mils
Diagram 1: Eddy Current Field Depth of Penetration & Density

Skin effect arises when the Eddy Currents flowing in the test object at any depth produce magnetic fields which oppose the primary field, thus reducing the net magnetic flux and causing a decrease in current flow as the depth increases.

Alternatively, Eddy Currents near the surface can be viewed as shielding the coil’s magnetic field, thereby weakening the magnetic field at greater depths and reducing induced currents.

Eddy Current is used in the inspection of ferromagnetic and non-ferromagnetic materials. The principle of Eddy Current based inspection is explained below.
Seminar 9: Wireless charging of EV  
Chris Mi . U of Michigan

Al Plate 600 mm x 800mm 1 mm thick for mechanical strength

Frequency = 85 KHz  
Power transmitted = 10KW  
Inefficiency without Al shield = 20 %  
Inefficiency with Al shield = 1 %  
Power loss in Car metal without Al shield = 2 KW  > 15C rise in temperature  
Power loss in Al shield = 0.1 KW

Yale University  
March 21, 2014
Wireless Power Groups

- Automobile Charging
- Cell phone Mats - 3 Groups. Each has > 50 companies involved
- Wireless Kitchen - ISM Band 6.78 MHz & multiples. GaN
Intel 4th Generation Core Processor: June 2013

- Input = 1.8V
- Maximum Current = 700 Amps
- Output ~ 1 V Multiple Domains – up to 16 Phases
- Turn output On when needed
- Inductors on Die / on Package
- Efficiency = 90%

**TABLE I. COMPARISON OF FIVR TO PREVIOUSLY REPORTED INTEGRATED VOLTAGE REGULATORS**

<table>
<thead>
<tr>
<th></th>
<th></th>
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<th></th>
<th></th>
</tr>
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<tbody>
<tr>
<td>Process node</td>
<td>130 nm</td>
<td>90 nm</td>
<td>45 nm</td>
<td>22 nm</td>
</tr>
<tr>
<td>Switching Frequency</td>
<td>60 MHz</td>
<td>100 MHz</td>
<td>80 MHz</td>
<td>140 MHz</td>
</tr>
<tr>
<td>Unity Gain Freq</td>
<td>5 MHz</td>
<td>Not Published</td>
<td>Not Published</td>
<td>80MHz</td>
</tr>
<tr>
<td>Efficiency</td>
<td>85-88%, 3.3V:1.0V</td>
<td>76%</td>
<td>83%, 1.5V:1.0V</td>
<td>90%, 1.7V:1.05V</td>
</tr>
<tr>
<td>Total Output Imax capability</td>
<td>50 A</td>
<td>Limited by first stage and</td>
<td></td>
<td>Limited by first stage and thermals (Up to 700 A)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>thermals (Up to 400 A)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Imax/VR die area</td>
<td>1.3 A/mm²</td>
<td>8 A/mm²</td>
<td>1.7 A/mm²</td>
<td>31 A/mm²</td>
</tr>
<tr>
<td>Voltage rail count</td>
<td>4</td>
<td>20</td>
<td>1</td>
<td>8 to 31</td>
</tr>
<tr>
<td>Phase count</td>
<td>16</td>
<td>320</td>
<td>4</td>
<td>49 to 360</td>
</tr>
<tr>
<td>Integration level</td>
<td>MCM³</td>
<td>MCM³</td>
<td>Integrated into network die</td>
<td>Integrated into CPU die</td>
</tr>
<tr>
<td>Inductor technology</td>
<td>Package trace, &amp; magnetic discrete</td>
<td>Magnetic thin-film on VR die</td>
<td>Discrete wire-wound air core</td>
<td>2D array of package trace</td>
</tr>
<tr>
<td>Capacitor type</td>
<td>Ceramic package caps</td>
<td>Ceramic package caps</td>
<td>Die Cap</td>
<td>Die Cap - MIM</td>
</tr>
<tr>
<td>Cout per Max Amp</td>
<td>2000 nF/A</td>
<td>not published</td>
<td>15 nF/A</td>
<td>7 nF/A</td>
</tr>
</tbody>
</table>

* MCM – Multi Chip Module – the active circuitry is on a separate die assembled on the same package

Mac Pro Air !!!
ATLAS DC-DC Powered Stave

STV10 DC-DC Convertor From CERN group
Based on commercial LT chip
10V in, 2.6V out, up to 5A

Peter W Phillips
STFC RAL
14/11/11
Last Proposal to DoE to develop Inductors

- 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

Generic / Project funding???
Planar Coil – “Up Close and Personal”

Double Trigger Noise (DTN)

**With Toroid Converter**
Reference measurement (CERN STV10 converter) @ 0.5fC

- CERN converter registers zero occupancy until 0.5fC, then registers 528/244 hits

**With Planar Converter**
Approx <3mm from wire bonds with improved reference @ 0.5fC

- For conducted noise configuration, Planar coil registers zero occupancy (even at 0.5fC)
- Only when close to asics are hits registered, 3/2 counts at 0.5fC, see above

**Comments inserted by Yale University**

**Noise in Electrons Measured @ Liverpool**
cern stv10 noise  589, 604 average = 601
yale planar noise  587, 589 average = 588
noise with dc supplies (no dcdc) = 580
assuming the noise adds in quadrature, extract noise due to dcdc converter:
cern stv10 Additional noise = 157
yale planar Additional noise = 96
Planar Converter uses the same components except Inductor coil

- Thickness of stv = 8 mm vs 3mm for Planar
- Shield to Silicon strips are Electrostatics & Eddy current
- Bottom side shield 2 mm from Planar coil traces
- Can be mounted on the sensor with 50 μm Kapton
- Cooling via sensor
<table>
<thead>
<tr>
<th>Date</th>
<th>Time</th>
<th>Location</th>
<th>Description</th>
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</thead>
<tbody>
<tr>
<td>3-Feb-14</td>
<td>3:30 PM</td>
<td>Yale University</td>
<td>Comparison of Coils for DC-DC Converters</td>
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<table>
<thead>
<tr>
<th>Model</th>
<th>CERN AMIS5MP Data Sheet</th>
<th>Yale 9 mm ID proto coil</th>
<th>Yale 9 mm ID proto coil</th>
<th>Yale 9 mm ID estimated</th>
<th>Yale 6 mm ID Model 2156</th>
<th>Yale 6 mm ID Model 2156a</th>
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<tbody>
<tr>
<td>coil shape</td>
<td>oval toroid</td>
<td>2 layer spiral</td>
<td>2 layer spiral</td>
<td>2 layer spiral</td>
<td>2 layer spiral</td>
<td>2 layer spiral</td>
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<tr>
<td>Total number of turns</td>
<td>29</td>
<td>8</td>
<td>6</td>
<td>6</td>
<td>7</td>
<td>9</td>
</tr>
<tr>
<td>conductor</td>
<td>Cu wire</td>
<td>Cu wire</td>
<td>Cu wire</td>
<td>Cu wire</td>
<td>pcb trace</td>
<td>pcb trace</td>
</tr>
<tr>
<td>equivalent wire gauge</td>
<td>25</td>
<td>22</td>
<td>22</td>
<td>25</td>
<td>28</td>
<td>29</td>
</tr>
<tr>
<td>Coil dimensions</td>
<td>mm 10 x 15</td>
<td>mm 14.5 OD</td>
<td>mm 13 OD</td>
<td>mm 12 OD</td>
<td>mm 14.5 OD</td>
<td>mm 15.5 OD</td>
</tr>
<tr>
<td>thickness</td>
<td>mm 4.00</td>
<td>mm 1.80</td>
<td>mm 1.80</td>
<td>mm 1.20</td>
<td>mm 0.50</td>
<td>mm 0.50</td>
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<tr>
<td>Inductance</td>
<td>nH 430</td>
<td>nH 836</td>
<td>nH 469</td>
<td>nH 469</td>
<td>nH 487</td>
<td>nH 811</td>
</tr>
<tr>
<td>DC Resistance</td>
<td>mOhms 39</td>
<td>mOhms 18</td>
<td>mOhms 13</td>
<td>mOhms 26</td>
<td>mOhms 47</td>
<td>mOhms 83</td>
</tr>
<tr>
<td>Weight grams</td>
<td>Grams 0.537</td>
<td>Grams 0.978</td>
<td>Grams 0.702</td>
<td>Grams 0.360</td>
<td>Grams 0.203</td>
<td>Grams 0.220</td>
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<tr>
<td>Length of Wire</td>
<td>mm 370</td>
<td>mm 336</td>
<td>mm 240</td>
<td>mm 240</td>
<td>mm 221.000</td>
<td>mm 307.000</td>
</tr>
<tr>
<td>Power Loss in Coil @ 4 Amps</td>
<td>Watts 0.608</td>
<td>Watts 0.288</td>
<td>Watts 0.208</td>
<td>Watts 0.416</td>
<td>Watts 0.752</td>
<td>Watts 1.328</td>
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<tr>
<td>normalized weight</td>
<td>1.00</td>
<td>1.82</td>
<td>1.31</td>
<td>0.67</td>
<td>0.38</td>
<td>0.41</td>
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<tr>
<td>normalized power loss</td>
<td>1.00</td>
<td>0.47</td>
<td>0.34</td>
<td>0.68</td>
<td>1.24</td>
<td>2.18</td>
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<tr>
<td>DC DC ripple current in inductor</td>
<td>RMS Amps 0.657</td>
<td>0.340</td>
<td>0.602</td>
<td>0.602</td>
<td>0.580</td>
<td>0.348</td>
</tr>
</tbody>
</table>

Note: the Inductor ripple current produces the AC magnetic field, which must be shielded from the sensors.
PCB size = 8 mm x 26 mm

Proposed Thinner Converter: Coil

Yale Model 2156a
PCB size = 24 mm x 36 mm
Coil size = 16 mm dia. Embedded in 4 layer PCB. Inner 2 layer spirals are in series is the inductor.
2 versions: Total 6 or 9 turns
Hand wound coil (Short solenoid) is 24 AWG. Lower DCR for same inductance

No magnetic materials

Question on Air Core Coil (change to oval shape as width is limited)
Take this coil and squeeze/stretch it to 8 mm x 26 mm.
wire size 24 - 28 AWG  Frequency 2 MHz; Later 10 MHz
L = 800 nH
Losses are limited by DCR and not ACR.
# of turns = ?
ACR & DCR with wire Gauge

Embedded Spirals
Disabled for the hand wound coil
Height = 2 mm plus shield

Toroid Inductor with Shield on toroid
height = 8 mm

Yale University
April 07, 2014
Coil to fit in 8 mm x 22mm
Embed in PCB?
AWG 24

5 turns. Inductance = 715 nH
DCR = <100 mΩ

Lower Inductance

- 2 turns vs 5 turns
- Higher Ripple current
- Shield distance is higher
- More lost power in shield
We want to understand the efficiency costs of the external shield for the planar coils.

For a given planar coil we would like a plot of the energy loss in the shields as a function of distance from the coil. There should be a shield on each side of the coil placed symmetrically. The inductance of the coil changes as the distance to the shields changes. Since the ripple current is inversely proportional to the inductance this must be included in the calculation.

I expect that the energy loss in the shield will be linearly proportional to the ripple current but we should check this by simulating two different ripple currents for the same configuration.

For each coil configuration we would like to plots, inductance and energy loss over a range of shield distances from 0.5 mm to 10 mm with appropriate step sizes. The energy loss plot should be for 1 amp at the 10 mm spacing, with the current increasing as the inductance decreases. The frequency should be 2 MHz. Use five mill thick copper for the shields.

Start with the standard nine turn two layer coil and see how it goes. After that we will want to try other coil configurations and possibly other shield thickness and material.
Two Stage DC-DC Power Conversion & Distribution

DC Input

48 V

Control Inputs

48 V in, 5 V out
DC-DC
PWM Controller
Odyssey Chip 5 mm Sq
~ 5 MHz Operation
Air Core Inductor

GaN Switches for Higher Efficiency

Output Bus
5 V @ 10 A

Low mass Flex cables

40 DC-DC
Converters
Yale Model 2153

130 nm front end chips

40 FE Chips

FE Chips

FE Chips

DC-DC

48V in – 5V @ 10 A out

Fewer of these modules further from the detector/sensors

Status

Model 2153: Prototype for coil configurations under Test
Model 2153: Odyssey Chip Eval Board under NDA

5V in – 1.2V @1 A out

Many of these modules close to the detector/sensors
Low mass chip scale package small Air Core Inductor.
Test 6, 9 and 20 MHz Converters

Yale University

Model 2153 & 2154

May 2012
Semtech SC220: 20 MHz 0.6 Amps:
North / South Coils for far Field cancellation
DCR becomes a problem

Enpirion EL711: 18 MHz 0.6 Amps
GaN Update

- 600 Volt is the holy grail
- EPC is the only one delivering Devices thru distribution
- LM5113: driver for eGaN
- 1Q2015: Half bridge. (2LM5113 + FETS) in 6mm x 5mm x 1.5mm. 5-10 MHz External PWM
- GaN driver on FET Die Several companies. Panasonic Roadmap 2016
Why Yale design needs GaN

- No magnetic materials – All instruments in 4 Tesla magnetic field
- Design Goal = Size of converter 8 mm x 26 mm x 4 mm thickness including eddy current shield
- Vin = 12 V; Vout = 2.5 V / 1.5 V; I_out = 3 Amps  Frequency = 2 MHz
- Toroid leak H fields: Spiral /Planar 2 layer 9 turn > Inductance = 800 nH
- Need Low DCR & Lower mass to reduce noise created by protons passing thru inactive material
- Lower ripple current limits H field range > thinner package
- Why GaN? High frequency > smaller inductor & passives. Smaller footprint

Current Design / Status

CERN design size is ok but thickness = 9 mm

Yale design thickness is ok. Footprint ok for circuit only but no room for inductor

Size of PCB = 23 mm x 35 mm x 1.5 mm plus shield

Spiral inductor embedded in 4 layer PCB. Spirals are 15 mm dia.

New Design

Fold Coil > Squeeze 2 layer spiral to oval shape

Oval Aircore Toroid

Short Solenoid > Low DCR

What GaN Buys us

Higher operating frequency
> smaller air core inductor & lower DCR
Higher efficiency > Lower heat loss
Smaller package PowerSoC technology
Closing Remarks

- 48 V into Detector: 2 Stages
- IC 2 step: 12 V > 1.2V High efficiency
- GaN: Driver on Die may be Rad Tolerant
- Need lower power loss in detector