Powering of Future Detector Electronics - commercial solutions?

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Yale University

SiD Workshop at Argonne National Laboratory
June 3-5, 2010
Agenda

- Power efficiency issues / problems CMS-ECAL Example
- What can we do?
- A commercial Rad Hard Converter - EN5360 can still buy it
- Buck Converter
- Plug in cards with Air Coil
- Noise Test with Detectors
- Magnetic Field 7 T – no effect
- Why need Thin Oxide
- LDMOS: Radiation Test Results
- GaN Wide band Gap materials
- Converters 36V – 1.2V & 48V -1.8
- Industry Developments & Market Trends
- Power Pulsing for SiD
- Power Supply Current Reduction
- Remarks / Milestones
CMS ECAL: Electromagnetic Calorimeter
80 Amps Power supply for 4 LVR Boards
Power Supply @6.3V 30 meters away
3K Boards x 16 amps = 48 Kamps
Magnetic Field 4T in CMS
Power Delivery Efficiency < 40%

CMS ECAL: Electromagnetic Calorimeter
11 Regulators each with Output Current maximum = 2.5 amps
Operating Current ~ 16 amps
Power Input 4.3 Volt Analog 4.3 Volt Digital
Motherboard for VFE Cards
FE card
Thermisters (Total = 3)

LVR: Low Voltage Regulator
CMS ECAL: 5 Oodles (50 Kamps).

- Power Supply output = 315 KW
- Power loss in Leads to SM = 100 KW
- Power loss in Regulator Card = 90 KW
- Power Delivered @ 2.5 V = 125 KW

1 Oodle = 10,000 amps

# of Power Supplies ~ 700
# of ST LDO Chips = 35 K
LHC Radiation Hard made by ST Microelectronics
# of LVR Cards = 3.1 K.

Yale: Designed, built, burn-in and Tested.

- SM: Super Module
- Junction Box
- SM: Super Module
- Junction Box

2x16 mm² (AWG 6)
Vdrop = 2V
Pd = 128 W

1 to 3 m

50 mm² (AWG 00)

Power Delivery Efficiency = 40%
NOT INCLUDED
1. Power Supply efficiency
2. Water cooling
3. Removal of Waste heat
4. Air Conditioning
Power Chain Efficiency for CMS ECAL

Represents the efficiency of power delivery to a physics detector, e.g. ECAL

From Experts Efficiency %

Guess work Efficiency %

Power delivery Efficiency = 30 %

with Power for Heat Removal = 20 %
What can we do?

• Is there a better way to distribute power for physics detectors?
  – Learn from Semiconductor Industry
  – Use Commercial Technologies – *No Custom ASIC Chips*

• How do we handle these unique environments
  – High Radiation
  – Magnetic Field > 2 T
  – Load ~1 V & Oodles (=10 Kamps) of current

• Feed High Voltage and Convert - *like AC power transmission*
Found out at Power Technology conference 0.25 µm Lithography

- Irradiated Stopped on St. Valentines Day 2007
- We reported @ TWEPP 2008 - IHP was foundry for EN5360
Synchronous Buck Converter

Controller
Low Voltage

Power Stage - High Volts

PWM: Pulse Width Modulator

V reference

Buck Safety

Control Switch
30 mΩ

Synch Switch
20 mΩ

Minimum Switch ON Time
Limits Max Frequency
10 nsec @ 10 MHz

Lower Voltage Ratio
>>> Higher Frequency
& Smaller Coil

Control Switch: Switching Loss > I^2
Synch Switch: Rds Loss Significant

Vout = 11%

Vout = 50%

100 ns

900 ns
Plug In Card with Shielded Buck Inductor

Coupled Air Core Inductor Connected in Series

Spiral Coils Resistance in mΩ

Different Versions

- Converter Chips
  - Max8654 monolithic
  - IR8341 3 die MCM

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

<table>
<thead>
<tr>
<th></th>
<th>Top</th>
<th>Bottom</th>
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</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>

12 V

2.5 V @ 6 amps
Noise Tests with Silicon Sensors

**Plug in Card**
1 cm from Coil facing Sensor
20 µm Al foil shielding

**Test @ BNL**
512 Strips – 100 µm Pitch
51 mm x 84 mm
Only One Chip Bonded

**Test @ Liverpool**

**Radiated Noise**
No Conducted Noise

<table>
<thead>
<tr>
<th>Coil Type</th>
<th>Power</th>
<th>Input Noise electrons rms</th>
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<tbody>
<tr>
<td>Solenoid</td>
<td>DC - DC</td>
<td>881</td>
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<tr>
<td>Solenoid</td>
<td>Linear</td>
<td>885</td>
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<tr>
<td>Spiral Coil</td>
<td>DC - DC</td>
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</tr>
<tr>
<td>Spiral Coil</td>
<td>Linear</td>
<td>664</td>
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</table>
Threshold Shift vs Gate Oxide Thickness

\[ \Delta V_{FB} = \alpha t_{ox}^2 \]

- \( T = 80^\circ K \)
- \( E_{ox} = +2.0 \text{ MV/cm} \)

\[ \Delta V_{FB} = 10^{10} \text{ V/RAD} / \text{Si} \]

\( t_{ox} \) (nm)


Hole removal process by tunneling in thin-oxide MOS Structures

Tunneling Region

\( \text{Si} \)

\( \text{SiO}_2 \)

\( \text{Poly-Si} \)

\( \text{Gate} \)

Dosage = 150 Krads
**CERN ASICs**

**Mantra: Deep sub micron is more rad hard Why?**

<table>
<thead>
<tr>
<th>Lithography</th>
<th>Process</th>
<th>Operating Voltage</th>
<th>Operating Thickness</th>
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<tbody>
<tr>
<td>0.25 µm</td>
<td>6SF</td>
<td>2.5</td>
<td>5</td>
</tr>
<tr>
<td>0.13 µm</td>
<td>8RF</td>
<td>1.2 &amp; 1.5</td>
<td>2.2</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2.2 &amp; 3.3</td>
<td>5.2</td>
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</tbody>
</table>
Can We Have
High Radiation Tolerance & Higher Voltage Together ???

Higher radiation tolerance needs thin oxide
while higher voltage needs thicker oxide – Contradiction ?

Controller : Low Voltage

High Voltage: Switches – some candidates HV & Thin oxide

LDMOS, Drain Extension, Deep Diffusion etc

>> 20 Volts HEMT GaN on Silicon, Silicon Carbide, Sapphire
High performance RF LDMOS transistors with 5 nm gate oxide in a 0.25 μm SiGe:C BiCMOS technology: IHP Microelectronics

2-5 Dec. 2001 Page(s):40.4.1 - 40.4.4
IHP NMOS Transistor
$V_G$ versus $I_D$ at Selected Gamma Doses

IHP PMOS Transistor
$V_G$ versus $I_D$ at selected Gamma Doses

XY Semi ($VD = 12V$)
2 Amp FET- HVMOS20080720 Process

VI Curves after Gamma irradiations
### Thin Oxide Devices (non IBM)

<table>
<thead>
<tr>
<th>Company</th>
<th>Device</th>
<th>Process</th>
<th>Foundry</th>
<th>Oxide</th>
<th>Dose before</th>
<th>Observation</th>
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<tbody>
<tr>
<td>IHP</td>
<td>ASIC custom</td>
<td>SG25V GOD 12 V</td>
<td>IHP, Germany</td>
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<td></td>
<td>Minimal Damage</td>
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<tr>
<td>XySemi</td>
<td>FET 2 amps</td>
<td>HVMOS20080720 12 V</td>
<td>China</td>
<td>7</td>
<td></td>
<td>Minimal Damage</td>
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<tr>
<td>XySemi</td>
<td>XP2201</td>
<td>HVMOS20080720 15 V</td>
<td>China</td>
<td>12 / 7</td>
<td>1Q2010</td>
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<tr>
<td>Enpirion</td>
<td>EN5365</td>
<td>CMOS 0.25 µm</td>
<td>Dongbu HiTek, Korea</td>
<td>5</td>
<td>64 Krads</td>
<td></td>
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<tr>
<td>Enpirion</td>
<td>EN5382</td>
<td>CMOS 0.25 µm</td>
<td>Dongbu HiTek, Korea</td>
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<td>111 Krads</td>
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<tr>
<td>Enpirion</td>
<td>EN5360 #2</td>
<td>SG25V (IHP)</td>
<td>IHP, Germany</td>
<td>5</td>
<td>100 Mrads</td>
<td>Minimal Damage</td>
</tr>
<tr>
<td>Enpirion</td>
<td>EN5360 #3</td>
<td>SG25V (IHP)</td>
<td>IHP, Germany</td>
<td>5</td>
<td>48 Mrads</td>
<td>Minimal Damage</td>
</tr>
</tbody>
</table>

**Necessary condition for Radiation Hardness - Thin Gate Oxide**

*But not sufficient*

- **IHP:** Epi free, High resistivity substrate, Higher voltage, lower noise devices
- **Dongbu:** Epi process on substrate, lower voltage due to hot carriers in gate oxide
Gallium Nitride Devices Tested in 2009

**RF GaN**  20 Volts & 0.1 amp
- 8 pieces: Nitronex  NPT 25015: GaN on Silicon
- ✓ Done Gamma, Proton & Neutrons
- ✓ 65 volts  Oct 2009

- 2 pieces: CREE CGH40010F: GaN on SiC
- 6 pieces: Eudyna EGNB010MK: GaN on SiC
- ✓ Done Neutrons

**Switch GaN**
- International Rectifier GaN on Silicon
  Under NDA

Gamma:  @ BNL  
Protons:  @ Lansce  
Neutrons:  @ U of Mass Lowell
FET Setup for Proton Radiation Exposure

Source

Gate

Drain

FET

100

30 m

330 2 Watts

Power Supply

V out = 20 Volts

DMM DC mV

1 Ω

~ 0.070 Amps

Pomona Box

Reading = ~ 0.035 Amps @ 50% Duty Cycle

30 m

Max operating V & I Limit Power by duty cycle

Pulse Generator

0.1 – 2 MHz

50 % Duty Cycle

0 to - 5 V

GND

50 Ω Terminator

2 Shorted FETs

Rad vs wo Bias
200 Mrads of Protons had no effect – switching 20 V 0.1 Amp Parts still activated after 7 months
New GaN Devices for Power Switching

Converter Efficiency Inputs = 12, 24 & 36 volts
output ~ 1.2 v

EPC9001 #2 Efficiency vs Output Current
Constant Frequency = 566 KHz: Pulse width = 124 - 240 ns:
Vout = 0.95 - 1.34V: L = 3.9 µH, 4.8 mΩ

EPC9001 #2 Efficiency vs Output Current
Constant twd = 240 ns: Frequency = 164 - 568 kHz
Vout ~ 1.2V: L = 3.9 µH, 4.8 mΩ
Converter Efficiency Inputs = 24 & 36 volts output ~ 1.8 v

Longer On Time improves efficiency (Lower Frequency)
Set up with Resistor Load (Alternate is Active Load)
Server Power System Distribution from IBM

1. AC Distribution - 208/230/115V
   - Servers, Blade Servers, Workstations
2. 12V DC Distribution
   - Blade Server Chassis, Low end and Midrange Servers, Workstations
3. 48V Distribution in a Rack
   - High End Server Applications
4. 350V DC Distribution in a Server Rack or a Rectifier Cabinet
   - Main Frame Servers

International Workshop on Power Supply On Chip
Sept 22nd - 24, 2008
Cork, Ireland

What is happening outside HEP?
AC - DC Power Efficiency Challenge by IBM September 2007

Front End Supply (FES) - 240 Vac to 400 Vdc
Intermediate Bus Supply (IBS) - dc-dc, 12 Vdc
Point of Load (POL) Supply - dc-dc, 1.2 Vdc

<table>
<thead>
<tr>
<th></th>
<th>FES</th>
<th>IBS</th>
<th>POL</th>
<th>Plug-to-Processor</th>
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<tbody>
<tr>
<td>Recent</td>
<td>93%</td>
<td>95%</td>
<td>88%</td>
<td>78%</td>
</tr>
<tr>
<td>Best Immediate</td>
<td>95%</td>
<td>98%</td>
<td>90%</td>
<td>84%</td>
</tr>
<tr>
<td>IBM Challenge</td>
<td></td>
<td></td>
<td>90%</td>
<td></td>
</tr>
<tr>
<td>Needed</td>
<td>98%</td>
<td>98%</td>
<td>94%</td>
<td>90%</td>
</tr>
</tbody>
</table>
Remote Sense for SiD with wires & Impedance Measurement

1. Measure Vout
2. Reduce current by 10%
3. Measure new Vout after settling time

Note: do this quickly, so voltage at remote load does not change (large C at load to ensure this)

4. Calculate resistance of wires (effectively)
5. Set new Vout so load voltage is OK
6. Repeat

LT4180 Virtual Sense Controller

Pulsed Power Schemes
- Make impedance measurement before beam Bunches
- Copper wires temperature effect with pulsed power ??

Impedance measurement is used for Li batteries remaining charge for Netbooks, hand held gadgets etc.

1 volt wiring drop 50 mV in Vout
**LHC CONVERTERS VS RADIATION [2010]**

- Rad Tolerant Design *or* standard Design with low Rad sensitivity *(safe components)*
- Standard Design *and* Rad sensitivity unknown *(too many components, sub-assemblies...)*

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<table>
<thead>
<tr>
<th>Converter</th>
<th>Units</th>
<th>Description</th>
</tr>
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<tbody>
<tr>
<td>LHC120A-10V</td>
<td>191</td>
<td>60 A @ 8 V 752 units</td>
</tr>
<tr>
<td>LHC600A-10V</td>
<td>272</td>
<td></td>
</tr>
<tr>
<td>LHC13kA-18V</td>
<td>16</td>
<td></td>
</tr>
<tr>
<td>LHC13kA-180V</td>
<td>8</td>
<td></td>
</tr>
<tr>
<td>LHC600A-40V</td>
<td>25</td>
<td></td>
</tr>
<tr>
<td>LHC4..8kA-08V</td>
<td>168</td>
<td></td>
</tr>
</tbody>
</table>

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Is it possible to do this Power Train in GaN? Investigate ???
Air Coil DC-DC Converter

Vin 12 V

Plug in card
Maxim / IR

3 meters Twisted pair AWG 24

Turn off Spike with
1 amp load = 27 V
FWHM = 80 nS

Load = 3 amps (Electronic):

Enable Gate

Vout = 2.5 V

Charging Cout

KPiX
ASIC Chip

Vin

Vin P

Power Switch

Gate

Power Switch

Digital

SiD Powering Pulsing

Yale University May 30, 2010
Power Delivery to HEP Detectors

- Need Increase in Power Delivery Efficiency for environment & budget
- Energy and Power are high priorities of current (and future) administration
- Power will be critical for next generation of HEP experiments: power bill and physics reach
- Radiation Hardness: Silicon LDMOS 15 V few amps
- Gallium Nitride could be a game changer: 100 Volts, tens of amps. Opportunity for Beam line power supplies

- Increase emphasis on Power Electronics in US is needed. In Asia it is a Glamorous field. Best and the brightest going into this. Tremendous Economic opportunity

- In US no support for this type of R&D.
  In general, limited support for generic detector R&D.

- This R&D is needed for a viable US HEP program.
What can be achieved by DC-DC Developments?

- Current Reduction from Power Supply by DC-DC near Load Losses > Current² x Resistance
  - with Silicon: a Current Reduction of 10 achievable
  - with GaN: a Current Reduction 50 possible

- Increase Power Delivery Efficiency by > x2 CMS example

- Remote Sense for SiD
- Lower Voltage ratio > > Higher Frequency Air Coil
Top of the World is Cool but lonely!
Let us keep it cool with highly efficient PS
Swimming is Great at the North Pole

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