R&D for SLHC at 1. Phys. Institut B, RWTH Aachen University – Novel Powering Schemes for the Strip Tracker

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• The problem of tracker powering
• Proposed solutions
• DC-DC conversion
• Plans of our group
• Measurements & studies:
  – System test
  – EMC measurements
  – Simulation of material
• Summary
• Outlook
The Problem of Strip Tracker Powering

- Silicon strip trackers are power-hungry
  - *Current CMS strip tracker needs 33kW*

- Power supplies are located outside of detector area
  ⇒ Power is brought in via 50-100m long copper cables

- Operating voltage is low (1-2V) ⇒ currents must be high
  ⇒ Large voltage drop on cables: $V_{\text{drop}} = R \cdot I$
  ⇒ Efficiency loss: $P_{\text{cables}} = R \cdot I^2$
  - *Current strip tracker: $P_{\text{cables}} = 34kW$ ( = 50% of total power!)*

- Space for power cables is tight
The Problem of Strip Tracker Powering

- Power cables contribute significantly to material budget
- Power needs cooling, which contributes again to material budget
Electronics will move to smaller feature size (0.25μm → 0.13μm?)
⇒ Readout chip supply voltage will decrease (1.2V for 0.13μm)
⇒ Power consumption per channel will decrease
  (study by M. Raymond: 2.7mW/strip → 0.5mW/strip)

Higher track density needs increased granularity ⇒ more power needed

Track trigger seems to be crucial to maintain trigger rate
⇒ more complex front-end electronics will need additional power

Space for cables will remain the same, and access is hardly possible
⇒ power cables must probably even be re-used

Material budget should decrease rather than increase!

Numbers depend on design (# of layers etc.), but there is consensus that powering the tracker is one of the biggest challenges at SLHC!
• Classical approaches:
  – Independent powering (Atlas strip tracker)
  – Parallel powering (CMS strip tracker)

• New approaches:
  – Serial powering
  – Parallel powering with DC-DC converters
Serial Powering vs. DC-DC Conversion

Serial powering:

\[ V_{\text{drop}} = R \cdot I_0 \]
\[ P_{\text{drop}} = R \cdot I_0^2 \]

Parallel powering with DC-DC conversion:

\[ g = \frac{V_{\text{in}}}{V_{\text{out}}} \gg 1 \]
\[ P_{\text{drop}} = R \cdot I_0^2 \cdot \frac{n^2}{g^2} \]

- R&D in Atlas well advanced, but not yet started in CMS
- Many implications:
  - Modules are on different ground potential
  - Read-out must be AC coupled
  - How to avoid loss of chain
  - Difficult to deliver different voltages …

- Being studied within Atlas & CMS trackers
- Appealing solution, since more „standard“
- Many technologies and designs exist (e.g. inductor or capacitor-based)
- Switching might cause noise
- Efficient, rad.-hard, low-noise and magnetic field tolerant converter does not yet exist
The Buck Converter

„Buck converter“ is simplest inductor-based step-down converter:

Conversion ratio $g > 1$:
$$ g = \frac{V_{\text{in}}}{V_{\text{out}}} $$

Switching frequency $f_s$:
$$ f_s = \frac{1}{T_s} $$

Duty cycle $D = g$:
$$ D = \frac{T_1}{T_s} $$

- Technology must work in 4T magnetic field
  → ferrites saturate; air-core inductors must be used
- Air-core inductors tend to radiate noise
- Suitable air-core coils are typically large and rather massive
• **Lutz Feld**: team leader

• **Waclaw Karpinski**: electronics engineer
  + support from electronics workshop

• **Katja Klein**: HGF Fellow (4 years)

• Three diploma students:
  – **Jan Sammet**: *System test measurements with DC-DC converters*
  – **Rüdiger Jussen**: *Development and test of radiation hard magnetic field tolerant DC-DC buck converter* (in collaboration with CERN PH-ESE group)
  – **Jennifer Merz**: *Simulation of material budget of various powering schemes*
• Contribute to the development & characterization of magnetic field tolerant and radiation hard DC-DC buck converters, in coll. with CERN PH-ESE group

• Investigation of system aspects of novel powering schemes
  – DC-DC conversion
  – Serial powering? (low acceptance within tracker upgrade group)

• Noise susceptibility measurements
  – Noise injection into silicon strip modules
  – Noise injection into DC-DC converters

• Simulation of material budget of different powering schemes

• R&D proposal submitted and approved (December 2007)

• Funding via BMBF and special seed fund of RWTH Aachen university
• Collaboration with CERN PH-ESE group (Federico Faccio et al.)

• CERN group developed transistor technology and converter chip, we developed and produced the PCB (Waclaw Karpinski)

• Prototypes are delivered and testing has started

• We contribute to the characterization
  – Test of magnetic field tolerance
    - Up to 1.2T in Aachen
    - 4.0T and 7.0T at FZ Jülich
  – Irradiation tests
  – EMC tests
  – Efficiency measurements
• Preparation of system test set-up with current strip tracker substructures (petals)
  – Set-up with 4 modules sufficient for many measurements
  – Upgrade to full petal set-up planned

• Operation of current (and future) strip tracker substructures with custom rad-hard & magnetic field tolerant DC-DC converters

• Operation of current strip tracker substructures with of-the-shelf DC-DC converters to understand system issues (Jan Sammet, KK)
• Market survey (W. Karpinski) with main criteria:
  – high switching frequency → small size of passive components
  – high conversion factor
  – sufficient current (~1A) and suitable output voltages (1.25V and 2.5V)

• Enpirion EN5312QI:
  – Small footprint: 5mm x 4mm x 1.1mm
  – $f_s \approx 4$ MHz
  – $V_{in} = 2.4V – 5.5V$ (rec.) / $7.0V$ (max.)
  – $I_{out} = 1A$
  – Integrated planar inductor

Internal inductor in MEMS technology

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• 4-layer adapter PCB (Waclaw Karpinski) (see back-up slides for schematics)
• Plugged between Tracker End Cap (TEC) motherboard and FE-hybrid
• 2 converters provide 1.25V and 2.5V for FE-hybrid
• Input and output filter capacitors on-board
• Input power provided externally or via TEC motherboard
• Various designs (L, S, ...)

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System Test Setup

• TEC petal with InterConnect Board
• Four ring-6 modules powered & read out
• Petal housed in grounded metall box
• Optical readout
• Optical control communication
• Thermally stabilized at +15°C
• Final components (spares)
• Official DAQ software

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System Test Analysis

- Pedestal = mean signal of a strip without particles
- Noise = fluctuation around pedestal value
- Common mode (CM) = common fluctuation of subset of strips from pedestal value; calculated per APV
- Raw (or total) noise includes CM contribution
- 1 Module has 512 strips, 1 APV-chip has 128 strips
- For experts: all distributions are in peak mode (deconvolution mode similar, though)
- 250V bias voltage
- Input voltage for converter: $V_{in} = 5.5V$
Effect of Converter

Effect of DC-DC converters - peak mode

- No converter
- L type
- S type

Powered via ICB

⇒ Raw noise increases by 5-10%
⇒ Design of PCB has significant impact
⇒ Further optimization seems possible
Effect of Converter

- Broader common mode distribution
- Huge increase of noise at module edges, APV edges and "bad" strips
- Interpretation tricky due to on-chip CM subtraction, but indications that size of edge strip noise is measure for real CM and cannot be ignored

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Effect of Low DropOut Regulator

- **Low DropOut Regulator (LDO):** linear voltage regulator with small voltage drop ("drop out")
- Linear technology VLDO regulator LTC3026 connected to output of EN5312QI DC-DC converter
- LDO reduces voltage ripple and thus noise significantly
- Noise is mainly conductive and differential mode

**Effect of LDO with internal inductor**

- No converter (30426)
- L3 without LDO (30405)
- L3 with LDO (30589)

**Effect of LDO with internal inductor**

- No converter
- L type without LDO
- L type with LDO, dropout = 50mV

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Effect of External Air-Core Inductor

Enpirion **EN5382D** (similar to EN5312QI) operated with external inductor:

- Air-core inductor Coilcraft 132-20SMJLB; L = 538nH
- Ferrite-core inductor Murata LQH32CN1R0M23; L = 1μH

From data sheet

![Circuit Diagram](image)

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Effect of External Air-Core Inductor

- No converter
- Internal inductor
- External ferrite inductor
- External air-core inductor

\[\text{Pos. 6.4}\]

- Huge noise induced by air-core inductor
- With air-core coil cross talk between modules is observed
- Noise is mainly radiated (back-up slides)

\[\text{Pos. 6.3}\]

(Converter is on 6.4)
Enpirion with different Air-Core Inductors

- Different self-made coils tested
- Improvement with toroid not as drastic as naively hoped for
- Coil design being studied by Bristol group

“Wire toroid”

“Strip toroid”

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Shielding the Converter

- Enpirion with air-core solenoid wrapped in copper or aluminium foil
  - Shielding helps
  - Aluminium shields as good as copper
  - No improvement for thickness > 30 μm
- Shielding increases the material budget

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Distance to FE-Hybrid

- PCB “S’“ and cable used to vary distance between converter and FE-hybrid
- Dramatic improvements can be reached
- Effect is combination of distance and additional filtering (hard to disentangle)
- Space constraints on future tracker structures?

“Solenoid S’“

“S’ put 4cm away“

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Standardized EMC set-up (Rüdiger Jussen), similar to set-up at CERN (G. Blanchot)

- Power Supply
- LISN
- DUT
- Load

- Converter
- Current probe (calibrated coil)
- Line impedance stabilization network (isolates DUT from PS)
- Copper ground plane
- Spectrum analyzer
- Load

Power supply
Common Mode & Differential Mode

Common Mode (CM)

Common Mode extraction: $I_{CM}$

Differential Mode (DM)

Differential Mode extraction: $2I_{DM}$

Details in back-up slides
Enpirion with Internal Coil

- $V_{in} = 5.5V$
- Load only at 2.5V
- Switching frequency plus higher harmonics visible
- CM typically dominates

- $V_{in} = 5.5V$
- Load only at 2.5V
- Switching frequency plus higher harmonics visible
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CERN Converter

- $V_{in} = 5.5V$
- $f_s = 1MHz$
- Load only at 2.5V
- PCB with ferrit core coil (to avoid additional effects from radiated noise)
- More and higher peaks than Enpirion
- Systematic measurements have just started

![Graphs showing frequency response of CERN Converter](image)

355. SWREG2 11, 1.0MHz 5.5Vin, 495lin, 2.50V@Load, magn core, Output CM

4. SWREG2 11, 1.0MHz 5.5Vin, 495lin, 2.50V@Load, magn core, Output DM
CERN Converter

All plots:
Output CM
$V_{in} = 5.5V$
Load at 2.5V

319. SWREG2-11, 0.5MHz, 5.5Vin, 508In, 2.50V@Load, mag-core, Output CM

$f_s = 0.5MHz$

343. SWREG2-11, 0.83MHz, 5.5Vin, 466In, 2.50V@Load, mag-core, Output CM

$f_s = 0.83MHz$

335. SWREG2-11, 1.0MHz, 5.5Vin, 495In, 2.50V@Load, mag-core, Output CM

$f_s = 1.0MHz$

335. SWREG2-11, 1.5MHz, 5.5Vin, 542In, 2.50V@Load, mag-core, Output CM

$f_s = 1.5MHz$
Material Budget of Current Strip Tracker

Material Budget Strip

- Support
- Sensitive
- Cables
- Cooling
- Electronics
- Other
- Air

Electronics
Cables
MB Electronics & Cables of Current TEC

Patch panel: cables on bulkhead

Petals: motherboards, modules

Power cables

Optical ribbons

Motherboards
Analog Opto-Hybrids
Kapton circuits
FE-hybrids

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Simulation of a DC-DC Converter

- DC-DC converter simulated in CMSSW (Jennifer Merz)
- Current PCBs used as baseline
- Aim: understand order-of-magnitude of contribution to material budget

Simulated components:
- PCB substrate (FR4)
- Copper traces (4 layers)
- Resistors and capacitors
- 1 air-core toroid coil
- Connector
- 1 chip

- Individual components have been smeared and distributed to the volume available close to the FE-hybrid
- Mass $m = 6.2\text{g}$ (real: $m \approx 7\text{g}$)
Simulation of a DC-DC Converter

Preliminary

\[ \frac{x}{X_0} \]

\( \Rightarrow \) Contribution is significant (but probably a bit overestimated)

\( \Rightarrow \) Needs to be refined & combined with improvements in motherboards and cables
• We have performed system test measurements based on commercial buck converters
• Measures to control conductive and radiative noise have been studied: passive filtering, LDO, shielding, coil design, distance of converter
• The first custom prototype converter has been delivered, characterization has started
• Might want to explore alternative technologies, e.g. inductor-less
  – Charge pump devices have been received from Berkeley group
• A Tracker Upgrade Power WG has been created (contact: KK)
  – WG meetings every two months
  – https://twiki.cern.ch/twiki/bin/view/CMS/SLHCTrackerPower
Outlook towards Next Funding Period

Work on a system concept including

- **Support**
  - explore new materials, e.g. carbon foam

- **Cooling**
  - study CO$_2$ evaporative cooling
  - small test system has been designed, looking for a company

- **Power distribution**
  - based on DC-DC converters or
  - Serial Powering

- **Electronics system integration**
Back-up Slides
Comparison of Schemes

- Consider detector system with n modules: $P_{\text{det}} = n \cdot I_0 \cdot V_0$
- Voltage drop on cables and power loss $P_{\text{cable}}$ calculated within each scheme
- Efficiency $= \frac{P_{\text{det}}}{P_{\text{total}}} = \frac{P_{\text{det}}}{(P_{\text{det}} + P_{\text{cable}})}$

### Efficiency vs. number of modules, for $R = 2 \Omega$, $I = 0.5 \text{ A}$, $U = 1.2 \text{ V}$

- Independent powering
- Parallel powering
- Serial powering
- DC-DC conversion, gain = 5
- DC-DC conversion, gain = 10
Integration into CMS End Cap System

- 4-layer adapter PCB (W. Karpinski)
- Plugged between Tracker End Cap (TEC) motherboard and FE-hybrid
- 2 converters provide 1.25V and 2.5V for FE-hybrid
- Input and output filter capacitors on-board
- Input power external or via TEC motherboard
Integration into CMS End Cap System

L-type:
Larger flat PCB, 1 piece

S-type:
Smaller inclined PCB, 2 pieces

TEC motherboard
(InterConnect Board, ICB)

Front-end hybrid

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High efficiency is one of the challenges for the design of a DC-DC converter
Efficiency decreases with load and conversion ratio
Efficiency loss must be taken into account in any scheme with DC-DC converters
Radiative Noise from Air-Core Coils

- Sinus signal from frequency generator used to power solenoid coil (here $f = 11$ MHz)
- Increase of module noise even if coil is not connected to module $\rightarrow$ noise is radiated
- Different coils tested, no clear winner

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Common Mode & Differential Mode

**Common Mode extraction:**

\[ I_{DM} + \frac{1}{2} I_{CM} - ( - I_{DM} + \frac{1}{2} I_{CM} ) = I_{CM} \]

**Differential Mode extraction:**

\[ I_{DM} + \frac{1}{2} I_{CM} - ( - I_{DM} + \frac{1}{2} I_{CM} ) = 2I_{DM} \]