R&D on Novel Powering Schemes
at RWTH Aachen University

FSP-CMS Meeting
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• The problem of tracker powering
• Proposed solutions
• DC-DC conversion
• Plans of our group
• First measurements
• 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

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**Material Budget Strip**

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**Material Budget Pixel**
• Electronics will move to **smaller feature size** (0.25\(\mu\)m → 0.13\(\mu\)m?)
  ⇒ Readout chip supply voltage will decrease (1.2V for 0.13\(\mu\)m)
  ⇒ 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:

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

- Much experience in Atlas tracker, but none in CMS tracker
- Many implications:
  - Modules are on different grounds
  - How to avoid loss of chain
  - Clean power up scenario
  - 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
Comparison of Schemes

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

![Efficiency vs. number of modules, for $R = 2 \ \Omega$, $I = 0.5 \ \text{A}$, $U = 1.2 \ \text{V}$](image)

- Independent powering
- Parallel powering
- Serial powering
- DC-DC conversion, gain = 5
- DC-DC conversion, gain = 10
The Buck Converter

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

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

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 - currently under discussion within CMS tracker

• 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)

• Funding via BMBF and special seed fund of RWTH Aachen university
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Development & Test of Buck Converter

- Collaboration with CERN PH-ESE group (Federico Faccio et al.)
- CERN group develops transistor technology and converter chip
- We develop and produce a PCB for the converter
- We will contribute to the characterization of this converter
  - Test of magnetic field tolerance
    - Up to 1.2T in Aachen
    - 4.0T and 7.0T at Forschungszentrum Jülich
  - Irradiation tests
  - EMC tests
  - Efficiency measurements

Chip and PCB are currently in production; characterization measurements can hopefully start in July.
• 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
  – Custom converters from CERN PH-ESE not available for system test before August

• Operation of current strip tracker substructures with of-the-shelf DC-DC converters to understand system issues
Commercial Buck Converter EN5312QI

• 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
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

TEC motherboard
(InterConnect Board, ICB)

Front-end hybrid

S-type:
Smaller inclined PCB, 2 pieces

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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
• 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
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

Effect of DC-DC converters - peak mode

- No converter
- L type
- S type

Powered via ICB

⇒ 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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=> Performance with converter does not depend on # of modules operated with converter
=> A converter on position 6.4 does not spoil the performance of modules without converter (e.g. 6.3)
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

![Ripple Rejection Graph](image)

**Ripple Rejection**

- **V_{BST}** = 5V
- **V_{IN}** = 1.5V
- **V_{OUT}** = 1.2V
- **I_{OUT}** = 800mA
- **C_{OUT}** = 10μF

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Effect of Low DropOut Regulator

LDO reduces voltage ripple and thus noise significantly

Indicates that noise is mainly conductive and differential mode
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

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Effect of External Air-Core Inductor

Effect of different inductors on position 6.4

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

Pos. 6.4

$\Rightarrow$ Huge noise induced by air-core inductor

$\Rightarrow$ With air-core coil cross talk between modules is observed
Radiative Noise from Solenoid Coil

- Sinus signal from frequency generator used to power solenoid coil
- Increase of module noise even if coil is not connected to module → noise is radiated
- Noise emitted (and absorbed) over wide frequency range
- Different coil geometries under investigation

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Shielding the Inductor

⇒ Coil wrapped in copper foil (70µm thick)
⇒ Shielding helps!
⇒ Shielding increases the material budget
⇒ Further studies (thickness, material) will be done
• We have performed system test measurements based on commercial buck converters
• Conductive noise might be controllable (e.g. with LDO regulator)
• Control of radiated noise from air-core coil appears to be more difficult
• We will perform similar tests with custom converters soon

• Might need to explore alternative technologies, e.g. inductor-less
• CMS tracker management is currently defining the SLHC plans
  – There is preference for DC-DC conversion wrt serial powering
• A Tracker Upgrade Power WG has been created (contact: KK)
  – WG meetings every two months
  – https://twiki.cern.ch/twiki/bin/view/CMS/SLHCTrackerPower