Power Provision for the Tracker Upgrade - Power WG Activities & R&D at Aachen

Katja Klein
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CEC Meeting, April 21st, 2009
• Introduction

• Activities within the Tracker Upgrade Power Working Group
  ▪ Overview
  ▪ R&D at RWTH Aachen
    – System test with CMS tracker modules
    – Converter noise spectra
    – Detector susceptibility
    – Material budget analysis
    – Summary & outlook

• Conclusions
Why is a new powering scheme needed?

**SLHC**: increase of peak luminosity from $10^{34}\text{cm}^{-2}\text{s}^{-1}$ to $10^{35}\text{cm}^{-2}\text{s}^{-1}$ until ~ 2019

**Consequences for CMS silicon tracker power provision:**

- Number of charged particles in tracker increases by a factor of ~20
  ⇒ sensitive element size must decrease (occupancy) ⇒ **more readout channels**
- Tracker information to be incorporated into level-1 trigger to keep current trigger rate
  ⇒ track trigger layers with **more complex readout electronics** needed
- Front-end electronics deploys smaller feature size CMOS process (250nm → 130nm ...)
  ⇒ Savings in power/channel, but ...
  ⇒ ...**lower operating voltage** ⇒ higher currents ⇒ larger power losses ~ $I^2$
- Decrease of **material inside the tracker** is a main objective
- **No space** for additional power cables and **no access** to current services

⇒ **A new powering scheme seems inevitable for the strip tracker.**
Parallel powering with DC-DC conversion

Conversion ratio \( r = \frac{V_o}{V_{in}} < 1 \)

\( \Rightarrow \) Lower input currents and power losses:

\[ I_{in} = I_0 \cdot r \quad \& \quad P_{drop} = R_{cable} \cdot I_0^2 \cdot r^2 \]

Power Task Force recommendation (Jan. 09):

“The ‘Task Force’ recommends that the **baseline powering system** for an upgraded CMS Tracking system **should be based on DC-DC conversion**, with **Serial Powering maintained as a back-up solution**. [...] It is important that design decisions taken during this process do not preclude reverting to the back-up solution at a later date.”

(P. Sharp (chair), F. Arteche, G. Dirkes, F. Faccio, L. Feld, F. Hartmann, R. Horisberger, M. Johnson, K. K., M. Mannelli, A. Marchioro, B. Meier, M. Raymond)
DC-DC Converters

- Many technologies (inductor-based, capacitor-based...) and types exist
- Inductor-based converters provide large currents and are very efficient
  - the **buck converter** is often studied as the simplest inductor-based variant

\[ V_{\text{in}} \approx 12V \Rightarrow \text{HV-tolerant semi-conductor technology needed} \rightarrow \text{radiation-hardness} \]

\( V_{\text{in}} \approx 12V \Rightarrow \text{HV-tolerant semi-conductor technology needed} \rightarrow \text{radiation-hardness} \)

Ferrites saturate for \( B > \sim 2T \)
\[ \Rightarrow \text{air-core inductor needed} \]

Switching noise

- bulky
- radiates noise

Efficiency

Material budget

Space constraints

Schematic scheme of a buck converter (feedback control loop not shown)
The Tracker Upgrade Power WG

Working group has been established in April 2008

- Convenor: K. K.
- Meets roughly every two months
  - Five meetings so far
- [https://twiki.cern.ch/twiki/bin/view/CMS/SLHCTrackerPower](https://twiki.cern.ch/twiki/bin/view/CMS/SLHCTrackerPower)
- HyperNews forum “SLHC Tracker Power“ (hn-cms-slhc-tracker-power@cern.ch)
  Please subscribe for meeting announcements!

Tasks of the WG:

Identify and investigate novel powering schemes;
identify and develop a solution (solutions) for the tracker subsystems;
develop a working system including all relevant components.

Relevant R&D Proposals:

- RWTH Aachen; UK (Bristol); CEC (Karlsruhe); Fermilab/Iowa/Mississippi
• Phase-1 pixel upgrade: 4 barrel layers and 3 end cap disks
  – BPIX: 1612W → 2598W; cannot be supplied by current power supplies

• **The question is: how to power this BPIX detector?** (FPIX has no problem)
  1. Modify & use existing CAEN power supplies (A4603); still under study
  2. Use switched-capacitor DC-DC converters ("charge pump") (lower mass!)
     a. With ratio 1:2 for analog and digital power (not standard CMOS)
        ($V_{ana} = 1.7V, V_{dig} = 2.5V$)
     b. With ratio 2:3 for analog power only, in combination with modified PS
     c. ...

\[
\begin{align*}
\text{Phase A} \\
&\begin{array}{c}
+ \quad + \quad + \quad + \quad + \\
&\begin{array}{c}
1 \quad 2 \quad 3 \quad 4 \\
&\begin{array}{c}
\text{Load} \\
V_d \\
\end{array}
\end{array}
\end{array}
\end{align*}
\]

\[
\begin{align*}
\text{Phase B} \\
&\begin{array}{c}
+ \quad + \quad + \quad + \quad + \\
&\begin{array}{c}
5 \quad 6 \quad 7 \\
8 \quad 9 \quad 10 \\
&\begin{array}{c}
\text{Load} \\
V_d \\
\end{array}
\end{array}
\end{array}
\end{align*}
\]

\[n = \text{number of parallel capacitors}\]
\[I_{out} = n \cdot I_{in}\]
\[r = 1 / n\]

Small currents, but low mass
PSI: On-Chip Charge Pump

- 1:2 prototype
- $I_{out} = 24\,mA$ (1 ROC)
- 0.25 $\mu$m IBM CMOS
- External capacitors
- To be done: measurement of noise behaviour with ROC

Beat Meier, 7.10.2008

<table>
<thead>
<tr>
<th>$f$ [MHz]</th>
<th>$P_{SC}$</th>
<th>$P_{Ri}$</th>
<th>$P_{out}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>2 %</td>
<td>14 %</td>
<td>84 %</td>
</tr>
<tr>
<td>20</td>
<td>4 %</td>
<td>15 %</td>
<td>81 %</td>
</tr>
<tr>
<td>40</td>
<td>8 %</td>
<td>18 %</td>
<td>74 %</td>
</tr>
</tbody>
</table>

Output Voltage: low ripple

5 mV/div
US: Power Distribution Studies

- Use **CAPTAN DAQ system for power distribution studies with pixel ROC**
- Dedicated plug-in boards for DC-DC or Serial Powering developed
- Tests planned with off-the-shelf converters, inductors & switched cap. regulators, and with **Serial Powering Interface Chip** (SPI)
- First noise measurements without & with converters ~ few weeks
- Reliability study and failure mode analysis, **system modelling**

http://indico.cern.ch/getFile.py/access?contribId=1&resId=0&materialId=slides&conflId=52199

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CERN: Custom Buck Converter ASIC

• F. Faccio, St. Michelis et al. (CERN electronics group): very active group!
  
• Buck controller ASIC in HV compatible AMIS I3T80 technology (0.35μm CMOS)
  - First prototype “AMIS1“ (summer 2008): large switching losses
  - Second improved prototype “AMIS2“ submitted, expected back in May 09

• IHP (Frankfurt/Oder) SiGe BiCMOS technology (SGB25VD)
  - Irradiation tests (X-rays up to 350Mrad TID, p) of LDMOS transistors: ok for r > 20cm
  - Submission of buck ASIC planned for May 09

\[
\begin{align*}
V_{in} &= 3.3 \text{ – } 12V \\
V_{out} &= 1.2, 1.8, 2.5, 3, 5V \\
I_{in} &< 4A \\
f_{s} &= 400kHz \text{ – } 3MHz
\end{align*}
\]

Efficiency [%] vs. \( f_s \) [MHz]
\( V_{in} = 10V, V_{out} = 2.5V \)

http://indico.cern.ch/getFile.py/access?contribId=3&resId=2&materialId=slides&confId=52199
**CERN: Other Activities**

- **Topology** optimization (currently tailored for Atlas)
  Custom DC-DC converters for distributing power in SLHC trackers, St. Michelis, TWEPP-08

- **Noise measurements**, e.g. with TOTEM modules
  Noise Susceptibility Measurements of Front-End Electronics Systems, G. Blanchot, TWEPP-08

- Converter, PCB and air-core inductor **simulation** & optimization

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**Conversion stage 1 (ratio 4-5.5)**
- $V_{in}=10V \Rightarrow$ high-V technology
- Same ASIC development for analog and digital, only feedback resistive bridge is different

**Conversion stage 2 (ratio 2)**
- Embedded in controller or readout ASIC
- Closely same converter for analog and digital (different current, hence different size of switching transistors); macros (IP blocks) in same technology
• Toroidal air-core inductor manufactured into PCB
  – 35μm copper layers, 30 turns
  – L = (240 ± 20) μH (100kHz), \( R_{DC} = (205 \pm 20) \) mΩ → too high
  – Form-factor for Aachen PCB with CERN ASIC, to be tested

• Finite Element Modelling of planar air-core transformer
• Designing a transformer-based converter with air-core planar transformer
  – magnetic energy is transferred, not stored → low noise emission
• Single module ARC test-stand and EMI noise test-stand operational

\[ I_p = 0.25A \quad I_s = 0A \]

\[ I_p = 0.25A \quad I_s = 1A \]

\[ r = \frac{n_3}{n_1} \cdot D \]

Power Distribution in a CMS Tracker for the SLHC, D. Cussans et al., TWEPP-08

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Power provision for the tracker upgrade
## Power WG Activities

<table>
<thead>
<tr>
<th>Topic / Scheme</th>
<th>Electronics development</th>
<th>System tests</th>
<th>Material budget</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>DC-DC conversion</strong></td>
<td><strong>Non-isolated inductor-based:</strong> CERN (technology, chip</td>
<td></td>
<td>Aachen</td>
</tr>
<tr>
<td>(baseline solution)</td>
<td>development, simulation); Aachen (PCB); Bristol (air-core</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>coil)</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Transformer-based:</strong></td>
<td>Bristol</td>
<td>Fermilab, Iowa, Mississippi (pixels)</td>
<td></td>
</tr>
<tr>
<td></td>
<td><strong>Charge pump:</strong> PSI (pixels); CERN (strips)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Piezo-electric transformer: -</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Serial powering</strong></td>
<td>(Fermilab)</td>
<td>Fermilab, Iowa, Mississippi (pixels);</td>
<td>Aachen</td>
</tr>
<tr>
<td>(back-up solution)</td>
<td></td>
<td>Rochester? (strips)</td>
<td></td>
</tr>
<tr>
<td><strong>Implementation</strong></td>
<td>Karlsruhe (Powering via cooling pipes)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Power supplies, cables: not covered</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
• **Lutz Feld**: team leader

• **Waclaw Karpinski**: electronics engineer
  – plus electronics workshop team

• **Katja Klein**: Helmholtz Alliance fellow (4-years from April 08)

• **Jan Sammet**: PhD student

• Two diploma students:
  – **Rüdiger Jussen**
  – **Jennifer Merz**
• **Investigation of system aspects of DC-DC conversion schemes**
  – With current tracker structures & commercial and custom DC-DC converter chips
    (Documented in Jan Sammets Diploma thesis CMS TS-2009/003)

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

• **Contribute to the development & characterization of magnetic field tolerant & rad-hard buck converters, in coll. with CERN PH-ESE group**
  – Duplicate CERN EMI test-stand for converter noise characterization
  – PCB development
  – Magnetic field test

• **Simulation of material budget of different powering schemes**

→ **Integration of DC-DC converters into upgrade strip tracker structures**
  – Concept
  – PCB development / integration
  – System tests with new chips / modules / substructures
• Commercial buck converters used to systematically investigate effects on CMS FE-electronics (custom converters still in early prototyping phase)

• Enpirion EN5312QI & EN5382D: \( f_s = 4\text{MHz}, \ V_{\text{in}} < 7\text{V}, \ I_{\text{out}} = 1\text{A} \)

• Each silicon module is powered by 2 buck converters (1.25V, 2.50V)

• Many PCB variants: ferrite/air-core inductor, solenoid/toroid, Low DropOut reg., ...
System-Test Set-Up

- A lot can be learned from current CMS tracker hardware
- Move to SLHC readout chips and module prototypes asap - not before 2010

CMS Silicon Strip Petal

Ring 6 modules

Motherboard

FE-hybrid with 4 APV25 chips:
- 128 x pre-amplifier, CR-RC shaper, pipeline
- analogue readout
- 50ns shaping time

Raw noise of module 6.4 with “conventional“ powering via PS.
Results from System-Test

--- No converter
--- Toroid converter
--- Toroid converter + 30μm shield
--- Toroid converter + LDO
--- T. converter + LDO + 30μm shield

\[ \Rightarrow \text{Current FE-electronics is sensitive to conductive and radiated converter noise} \]
\[ \Rightarrow \text{With a combination of filtering and shielding noise increase is negligible} \]
\[ \Rightarrow \text{Improve PCB layout, develop efficient filtering and low mass shielding (ongoing)} \]
\[ \Rightarrow \text{Learn about converter noise and coupling mechanisms} \]

Note: edge strips noisier than others \( \rightarrow \) on-chip Common Mode subtraction fails \( \rightarrow \) see “real“ CM
Electromagnetic Compatibility Test Set-Up

- Standardized test set-up for cond. Common & Differential Mode (CM/DM) noise
- Quick characterization & comparison of converters, indep. from detector system
- Enables comparisons betw. different institutes

\[ I_{DM} - \frac{1}{2} I_{CM} \rightarrow \text{LISN} \rightarrow \frac{1}{2} I_{CM} + I_{DM} \rightarrow \text{DUT} \]

- Power Supply
- Load
- LISN: Line impedance stabilization network; isolates DUT from PS
- Spectrum Analyzer
- Converter
- Load
- Signal source
- Noise source
- Copper ground
- Current probe

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Low DropOut (LDO) Regulator

- Linear voltage reg. with small voltage drop
- Linear technology VLDO regulator LTC3026
- LDO reduces voltage ripple = DM noise
- Module noise significantly reduced
  $\rightarrow$ high sensitivity to DM mode noise

**Effect of LDO with internal inductor**

- **No converter**
- **No LDO**
- **With LDO, dropout = 50mV**

**DM without LDO**

<table>
<thead>
<tr>
<th>Peak</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>29.09dB μA</td>
</tr>
<tr>
<td>2</td>
<td>17.87dB μA</td>
</tr>
<tr>
<td>3</td>
<td>12.21dB μA</td>
</tr>
</tbody>
</table>

**DM with LDO**

<table>
<thead>
<tr>
<th>Peak</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2.80dB μA</td>
</tr>
<tr>
<td>2</td>
<td>0.00dB μA</td>
</tr>
<tr>
<td>3</td>
<td>0.00dB μA</td>
</tr>
</tbody>
</table>

Katja Klein (RWTH Aachen)
• Study detector susceptibility vs. frequency to identify critical frequency bands
• Inductive injection of DM & CM sinus currents into cables (**bulk current injection**)

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**Noise Susceptibility vs. Frequency**

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• Higher susceptibility to injection into 1.25V line (pre-amplifier reference voltage)
• Higher susceptibility to Differential Mode noise
• Expect peak at $1/(2\pi \cdot 50\text{ns}) = 3.2\text{MHz}$ from shaper
• **Broad peak at $\sim 6-8\text{MHz}$** ⇒ “system response“ measured rather than APV response
Coupling to Bias Ring

- Edge strips are noisier due to cap. coupling to bias ring
- Bias ring connected to 1.25V instead of ground
  ⇒ susceptibility decreases drastically
- Results specific to current module design, but set-up will be very useful once SLHC modules exist

![Graph showing raw noise counts vs frequency]

APV25 pre-amplifier

- V125
- V250
- VSS=GND

Edge strips are noisier due to cap. coupling to bias ring

Bias ring connected to 1.25V instead of ground

⇒ susceptibility decreases drastically

Results specific to current module design, but set-up will be very useful once SLHC modules exist
Powering scheme changes MB of
- Electronics (+ converter, - PCBs)
- Cables (inside the tracker)
- Cooling (local efficiency)

Estimate MB for powering schemes
- within the official software (CMSSW)
- for current tracker geometry
- focus on Tracker End Caps (TEC)

Caveat: results can only be indicative!
Assumptions:
- \( r = 1/8 \)
- 1 converter per module, on FE-hybrid

Simulated components:
- Kapton substrate (30mm x 33mm, 200\(\mu\)m)
- 4 copper layers (20\(\mu\)m each, 2x100\%, 2x50\%)
- Toroid (42 copper windings, plastic core)
- Resistors & capacitors
- Chip (Si, 3mm x 2mm x 1mm)
• Voltage drop $dU$ between power supply and detector fixed to current maximal value
• Cable cross-section $A$ for a given current $I$: $A = \rho \cdot L \cdot I / dU$

• Lower currents in ICBs if converter near module
• New ICBs “designed“
• Power loss required to be $< 10\%$
### MB for the TEC

<table>
<thead>
<tr>
<th>Component</th>
<th>Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>TEC motherboards</td>
<td>-52.9%</td>
</tr>
<tr>
<td>TEC power cables</td>
<td>-65.7%</td>
</tr>
<tr>
<td>TEC electronics &amp; cables</td>
<td>-27.3%</td>
</tr>
<tr>
<td><strong>Total TEC MB</strong></td>
<td><strong>-7.5%</strong></td>
</tr>
</tbody>
</table>

**Original TEC MB**

**TEC with DC-DC conversion**

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Power provision for the tracker upgrade
Serial Powering vs. DC-DC Conversion

Implementation of SP (inspired by Atlas talks):

• All modules of a petal powered in series
• Additional components per module: chip, Kapton, bypass transistor, 6 capacitors and 3 resistors/chip for AC-coupling
• Power loss in motherboards !< 10%
• Cable cross-sections calculated as before

<table>
<thead>
<tr>
<th>Savings [%]</th>
<th>SP</th>
<th>DC-DC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power cables</td>
<td>72.4</td>
<td>65.7</td>
</tr>
<tr>
<td>Motherboards</td>
<td>51.6</td>
<td>52.9</td>
</tr>
<tr>
<td>Electronics &amp; cables</td>
<td>34.3</td>
<td>27.3</td>
</tr>
<tr>
<td>Total TEC</td>
<td>9.4</td>
<td>7.5</td>
</tr>
</tbody>
</table>

⇒ Serial Powering performs slightly better than DC-DC conversion
Summary & Outlook

• **System-tests** with current tracker structures give valuable insight
• Bottom line: **with LDO, shielding and toroid coils noise increase is negligible**
• Need to move to SLHC prototypes asap – new readout chip expected for 2010

• Measurements of converter noise spectra with **EMC set-up** very useful
• Susceptibility set-up with **BCI** ready; automation needed for deeper understanding
• Scanning table to study inductive coupling in preparation

• **Material budget** analysis indicates possible improvement of the order of 7% for DC-DC conversion and 9% for Serial Powering

• Improvement of **PCBs**, shielding and coil design is ongoing
• Start to think about converter **integration**
Conclusions

• A lot of detailed useful work is ongoing, but ...

• ... many questions still (and soon) to be answered.

For phase-2:

  – What conversion ratio do we really need/want?
  – Do we really need/want a charge pump in addition to a buck-like converter?
  – Where and how do we integrate the converter(s)?
    On the FE-hybrid? On the motherboards?
  – Specifications: output current, switching frequency, conversion ratio, noise etc.

• Still many different layout proposals and module designs on the market
  → develop concrete implementations that are consistent with all proposals...
Back-up Slides
07.01: R&D on Novel Powering Schemes for the SLHC CMS Tracker;
by RWTH Aachen (contact person: Lutz Feld), submitted in October 2007;
status: approved

07.08: R&D in preparation for an upgrade of CMS for the Super-LHC by UK groups;
by University of Bristol, Brunel University, Imperial College London, Rutherford
Appleton Laboratory (contact person: Geoff Hall), submitted in October 2007;
status: approved

08.02: An R&D project to develop materials, technologies and simulations for silicon
sensor modules at intermediate to large radii of a new CMS tracker for SLHC;
by University of Hamburg, Karlsruhe University, Louvain, HEPHY Vienna, Vilnius
University (contact person: Doris Eckstein), submitted in March 2008;
status: approved

08.04: Power Distribution System Studies for the CMS Tracker;
by Fermilab, University of Iowa, University of Mississippi (contact person: Simon
Kwan), submitted in June 2008;
status: approved
Open and Edge Channels

- 128 APV inverter stages powered via common resistor ⇒ on-chip common mode subtraction
- Common mode in noise distributions coupled in after inverter (via 2.5V)
- “Real“ CM appears on open channels that do not see the mean CM
- Edge channels are special: coupled to bias ring which is AC referenced to ground ⇒ strong noise if pre-amp reference (1.25V) fluctuates wrt ground ⇒ this is not subtracted

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Power provision for the tracker upgrade
PCB Development

- Aim for compactness and low mass
- Study possibilities for efficient low mass shielding (e.g. Parylene-coating)
- Study and improve noise filtering
- First prototype being characterized; very promising
- New PCBs based on EN EQ5382D in May

Enpirion EQ5382D
Converter Noise

**Internal ferrite inductor**

- 6mV<sub>pp</sub> 4 MHz ripple
- 9mV<sub>pp</sub> high f ringing from switching edges

• Noise can be measured with active differential probe and oscilloscope ⇒ painful
• Spectrum analyzer needed to quickly measure complete noise spectrum
Common Mode & Differential Mode

Common Mode (CM)
- Signal source
- Noise source
- Stray capacitance
- Reference ground surface

Common Mode extraction: $I_{CM}$

Differential Mode (DM)
- Signal source
- Noise source
- Load

Differential Mode extraction: $2I_{DM}$

Current Probe → Spectrum analyzer
Air-Core Inductors

- Two noise structures specific for air-core coils:
  - “Wings”: decrease with shielding ⇒ radiation
  - “Combs”: decrease with LDO ⇒ conductive
- Increase of cond. noise confirmed by EMC set-up

![Graphs showing noise comparison](image)

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Power provision for the tracker upgrade
Module Noise vs. Converter Noise

- Correlation between module & converter noise clearly seen (but not 1)
- Both EMC test-stand and system test give valuable information
On-chip CM subtraction is hiding real system response ⇒ concentrate on edge strips

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• Cable reflections can occur if cable length \( L = n \cdot \frac{\lambda}{4} \)
e.g. \( f = 90\text{MHz} \Rightarrow \lambda = \frac{c}{f} = 2.2\text{m} = 2L \)
• Peaks must move down if cable length is increased \( \checkmark \)
⇒ Useful frequency range is below \(~30\text{MHz}\)
APV Readout modes:

- **Peak**: 1 sample is used, $\tau = 50\text{nsec}$
- **Deconvolution**: weighted sum of 3 consecutive samples, $\tau = 25\text{nsec}$
Is it better to place the converters further outside?

⇒ Lower contribution from converter itself, but higher currents in motherboards

- Savings in electronics & cables: **21.6%** (cf. **27.3%**)
- Total TEC savings: **6.0%** (cf. **7.5%**)

⇒ Slight advantage for position near module
1-Step vs. 2-Step Conversion Scheme

Buck converter plus switched-capacitor converter ("charge pump")

Pro: 2-step scheme provides more flexibility and avoids high conversion ratio
Con: Efficiencies multiply and system is more complex

Implementation as before, but:
- \( r = \frac{1}{4} \cdot \frac{1}{2} \)
- charge pump: chip, PCB, 3 copper layers, 2 x 1\( \mu \)F caps

\[ \Rightarrow \text{Total TEC savings if both steps on hybrid: 7.0\% (cf. 1-step: 7.5\%)} \]
\[ \Rightarrow \text{Total TEC savings for buck on petal rim: 7.0\% (cf. 1-step: 6.0\%)} \]
• Tests performed with **7T NMR-magnet** at Forschungszentrum Jülich, close to Aachen

• Enpirion converter, CERN SWREG2, LBNL charge pump tested
  – both versions with air-core and ferrite coils

• **Result:** converters with air-core inductors and charge pump worked fine; converters with ferrite inductors stopped working or lost their efficiency

\[ U_{\text{out}} = 2.5\text{V} \]