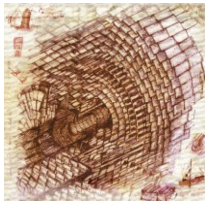

System Tests with DC-DC Converters for the CMS Silicon Strip Tracker at S-LHC

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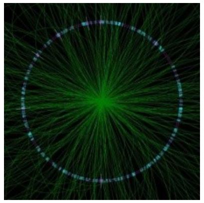
1. Physikalisches Institut B

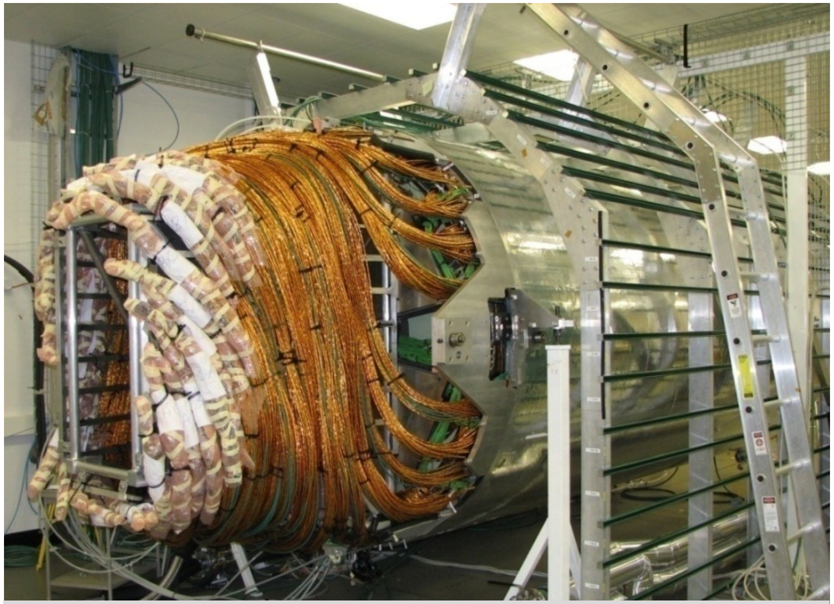
RWTH Aachen University

Topical Workshop on Electronics for Particle Physics
Naxos, Greece
September 17th, 2008



Outline

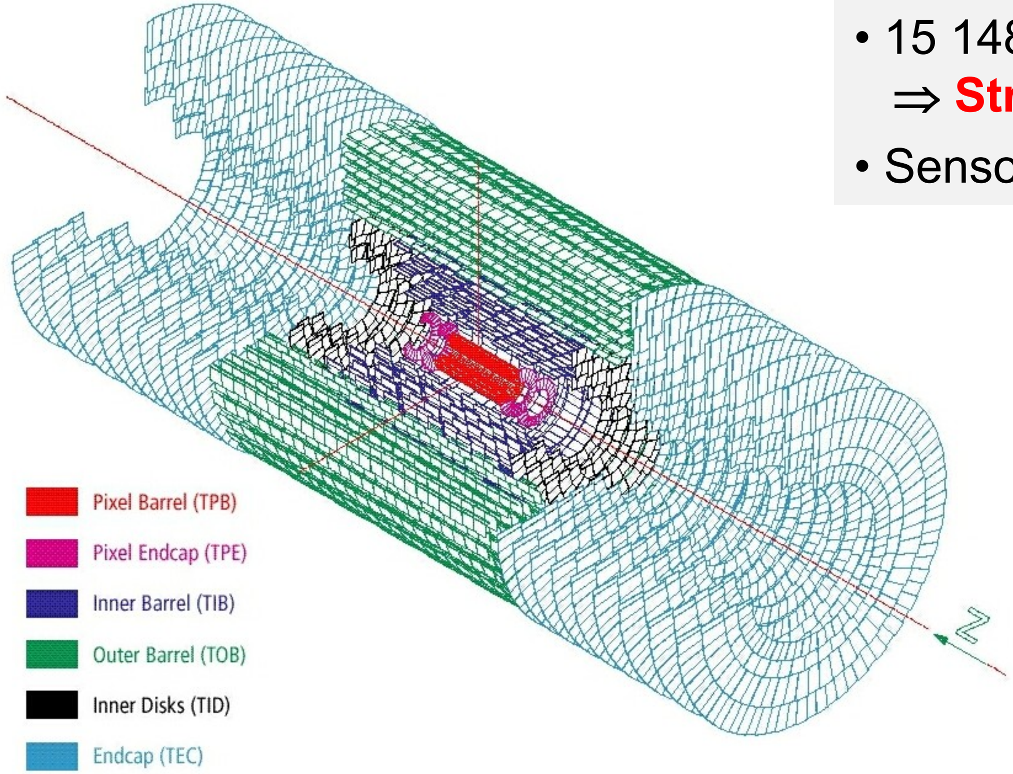
- Powering the CMS Silicon Strip Tracker
- DC-DC Conversion
- System Test Measurements
  - Commercial converters
    - with internal ferrite inductors
    - with external air-core inductors
  - Custom converters
    - CERN SWREG2 buck converter
    - LBNL charge pump
- Summary & Outlook

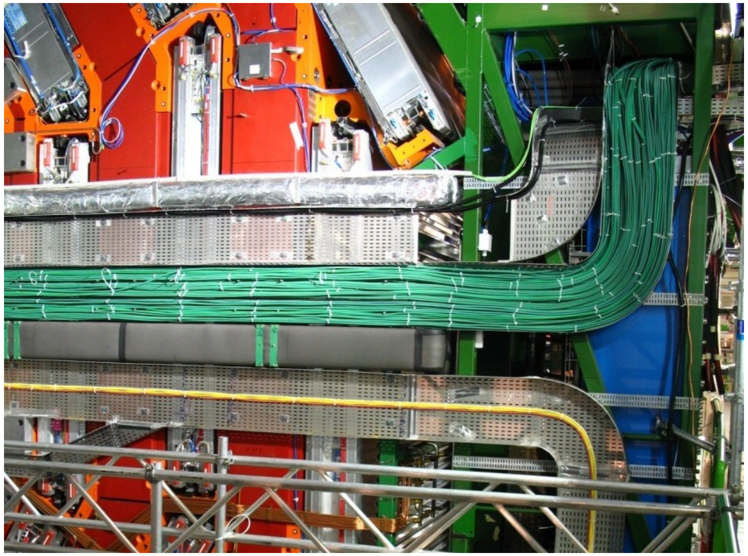


Strip tracker with cables, waiting for installation

Current Strip Tracker Power Consumption

- 15 148 silicon strip modules a 2-3W
  ⇒ **Strip tracker needs 33kW of power**
- Sensor operating temperature below -10°C

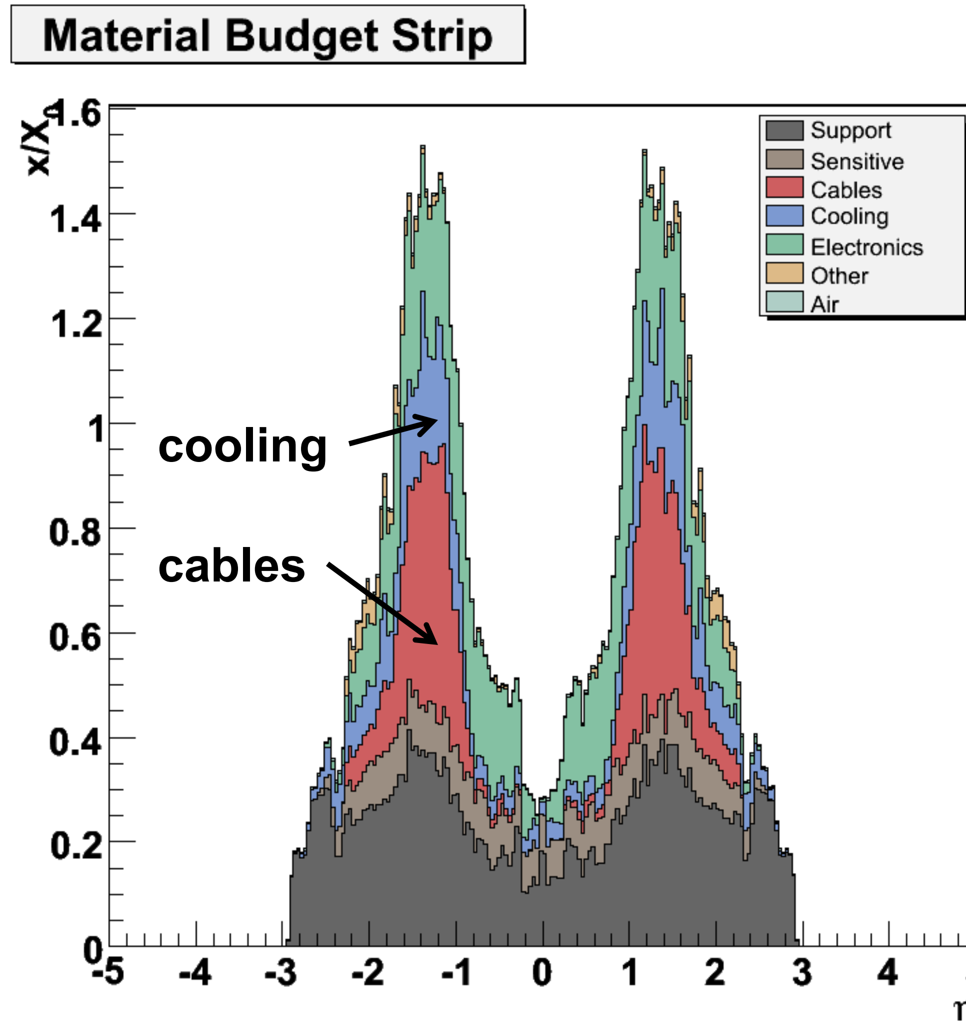




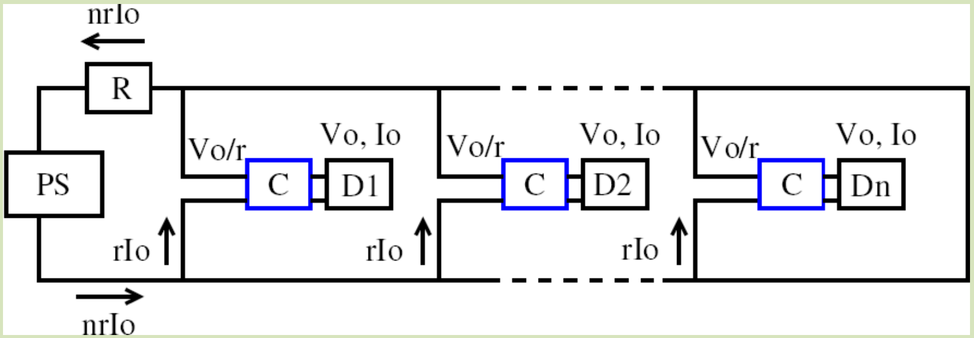
- Groups of 2-12 modules are powered in parallel
- Powered via ≈ 50m long cables from power supplies (PS) on balconies
  ⇒ **Power loss in cables amounts to 34kW = 50% of total power**
- Complex routing of services; exchange for SLHC not considered an option

Strip Tracker Upgrade

- Design of CMS tracker upgrade still under discussion
- Smaller feature size (probably 0.13μm) saves power per channel
- Increase of granularity and complexity costs power
- Material budget must not increase and services shall be recycled
  ⇒ **new powering schemes need to be exploited**
- R&D on powering is ramping up, a CMS Working Group exists since April 2008 (contact: KK)

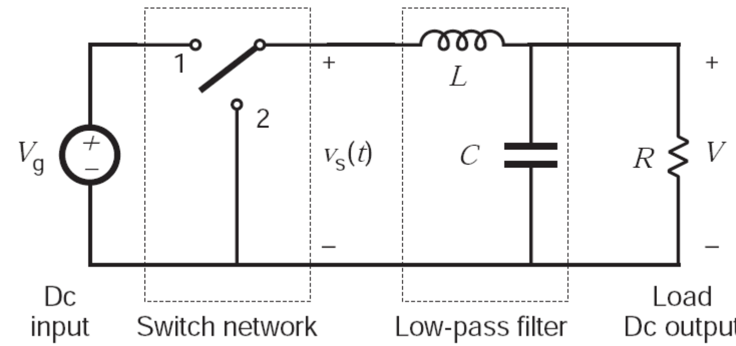


DC-DC Conversion Basics



Conversion ratio r = $V_{out} / V_{in} << 1$

$P_{drop} = R \cdot I_0^2 \cdot n^2 \cdot r^2$



Buck converter: simplest ind.-based step-down converter

- **Many technologies and designs (inductor-based, capacitor-based, piezo...)**

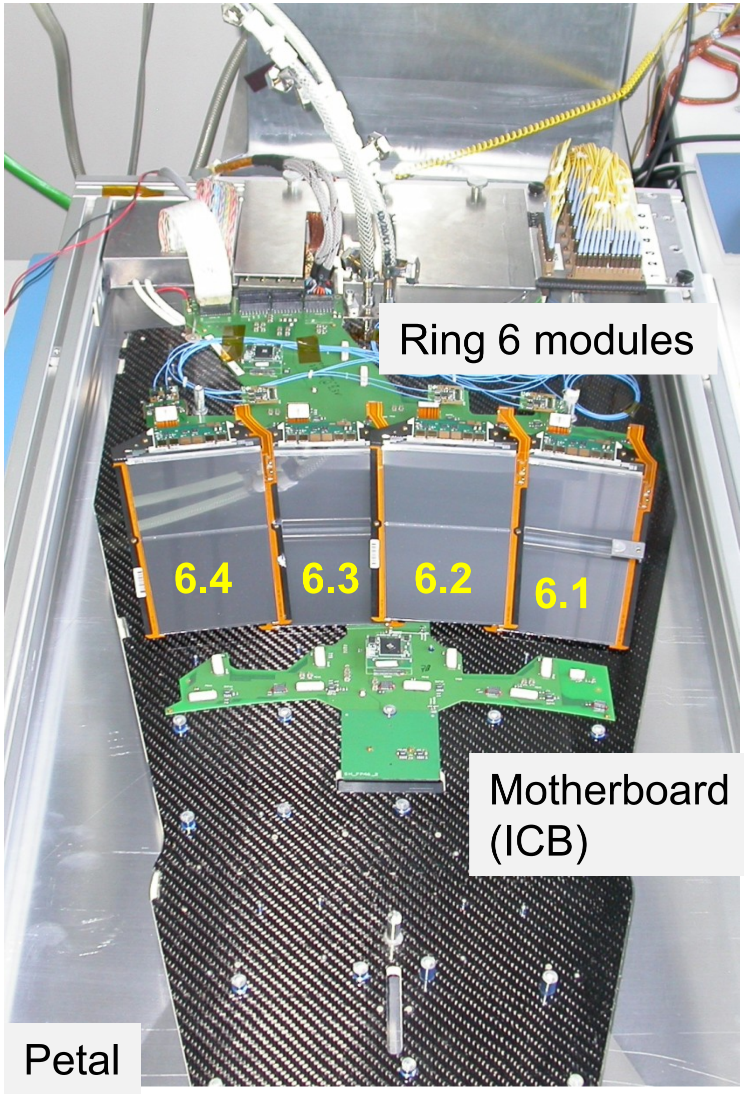
+ Classical way of module operation, powering “factorizes“ from system & module design
+ Different voltages can be provided by the same circuit
+ Flexible: several conversion steps (i.e. on substructure and on module) can be combined
- High frequency switching present in all designs → switching noise to be expected
- Efficiency typically 70-90%
- Transistors must stand high V_{in} → non-standard chip technology to be used
- Ferrites saturate in magnetic field → inductors must have air-cores → radiation of noise

The System Test

Goal:
Understand if and how DC-DC conversion could be used to power the upgrade strip tracker; identify potential show-stoppers

- Prototypes of tracker upgrade readout chips, modules or substructures do not yet exist
  $\Rightarrow$ current tracker hardware must be used!
- Avoid to “tune“ R&D to current system
- Still a lot can be learned with current system

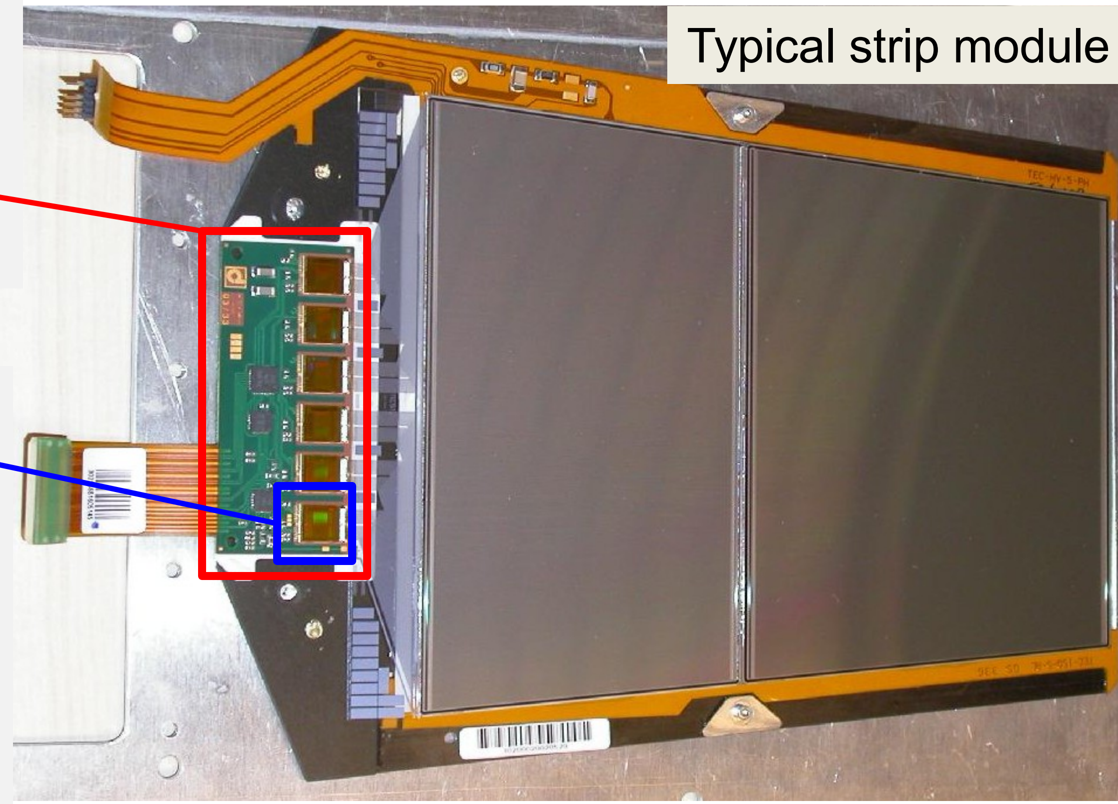
- Tracker end-cap (TEC) “petal“ with four modules powered & read out
- Optical readout & control communication
- Thermally stabilized at +15°C



A Current CMS Strip Tracker Module

Frontend-Hybrid with
- **4 or 6 APV25 readout chips**
- PLL chip for timing
- Multiplexer chip
- DCU chip for control

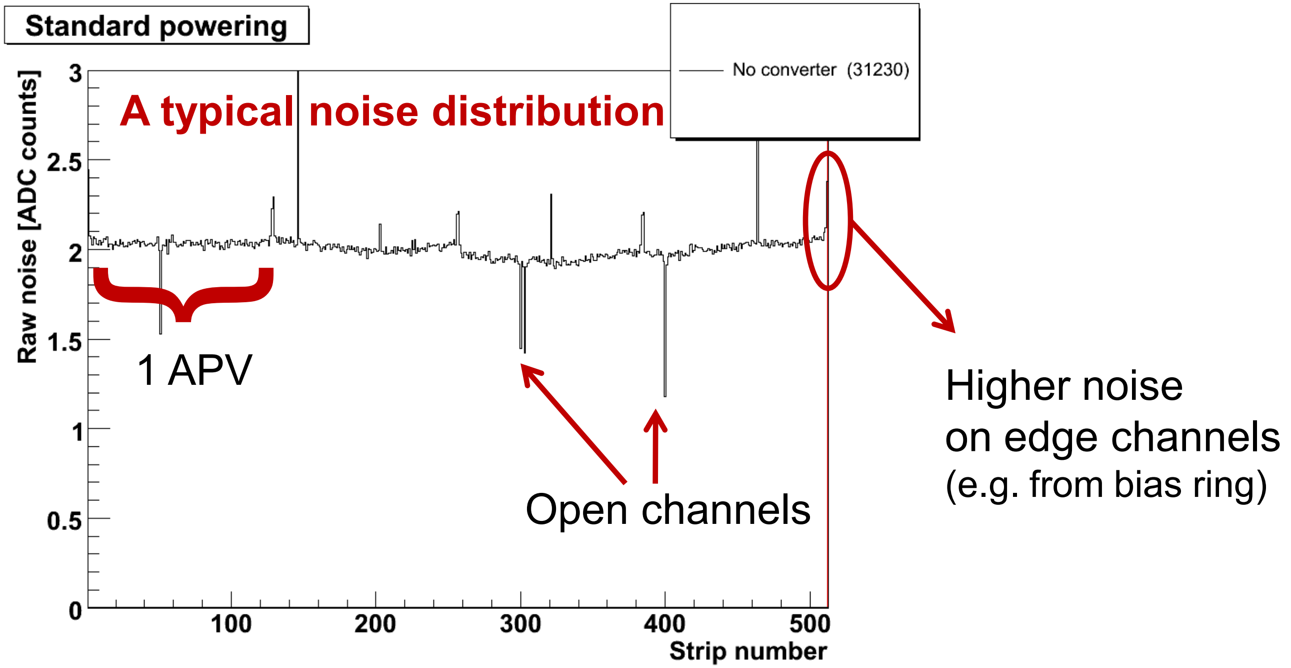
APV25 readout chip:
- 0.25 μm CMOS
- 128 strips per APV
- **analogue readout**
- per channel: pre-amplifier, CR-RC shaper, 4 μs pipeline
- τ = 50ns



- **Supply voltages**: **1.25V & 2.5V** for analogue readout and 2.5V for digital control ring
- **Currents per APV**: 0.12A at 2.5V and 0.06A at 1.25V
- **Power consumption** of 4 (6) APV module including optical conversion: **1.8W (2.7W)**

Definitions and Analysis

- **Pedestal** = mean signal of a strip without a particle traversing the sensor
- **Raw (or total) noise** = RMS of fluctuation around pedestal value
- **Common mode** (CM) = common fluctuation of subset of strips, calculated per APV
- The raw noise includes the common mode contribution
- One module has four APVs a 128 strips = 512 strips
- Most tests performed in “peak mode“ = 1 sample read out per event



Measurements with commercial buck converters with internal ferrite-core inductor

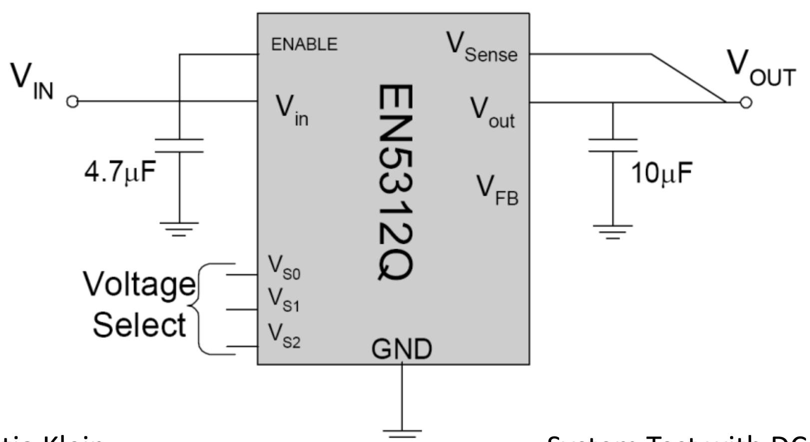
Commercial Buck Converter EN5312QI

Criteria for market survey:

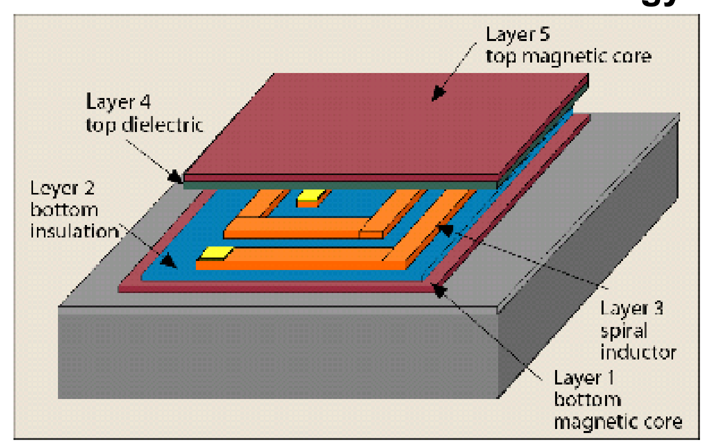
- High switching frequency → small size of passive components
- High conversion factor
- Sufficient current (~1A) and suitable output voltages (1.25V and 2.5V)

⇒ Enpirion EN5312QI:

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

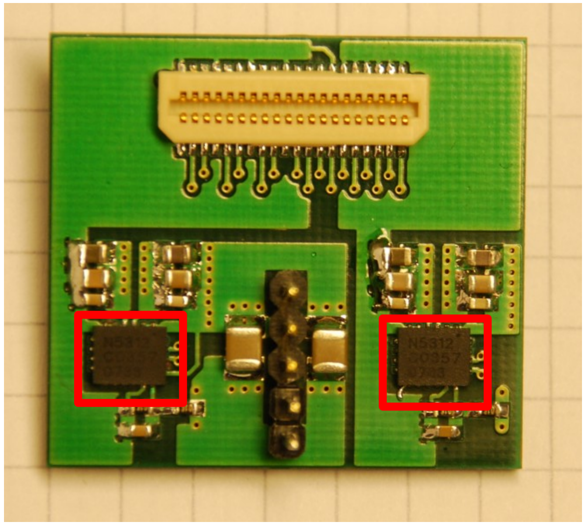


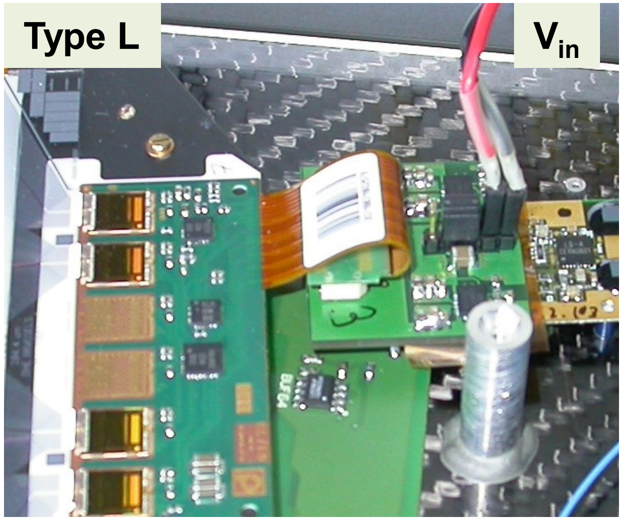
Internal inductor in MEMS technology

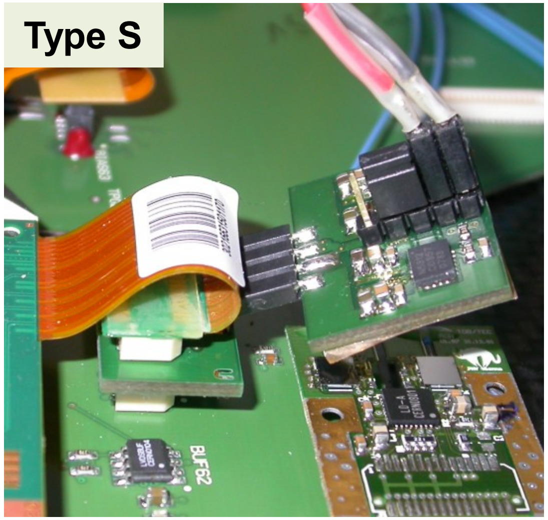


Integration onto TEC Petal

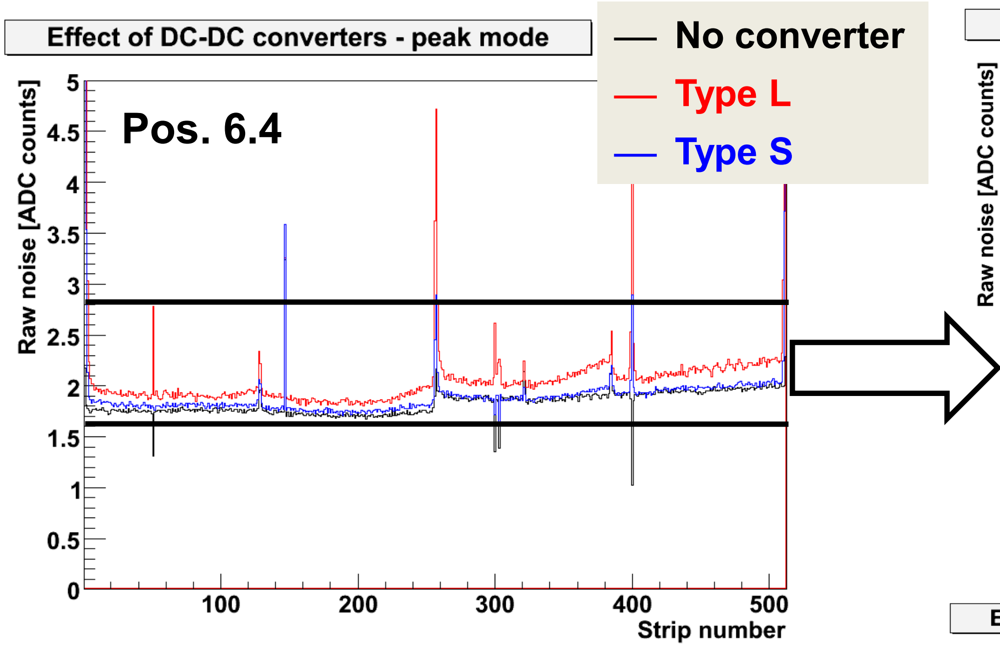
- 4-layer PCB with **2 converters** provides 1.25V and 2.5V for front-end (FE) hybrid
- One PCB per module, plugged between motherboard and FE-hybrid
- Input and output filter capacitors on-board
- Input power (V_{in} = 5.5V) provided externally or via TEC motherboard
- Various designs
  (type L: larger board with integrated connector, type S: smaller board with separate connector)

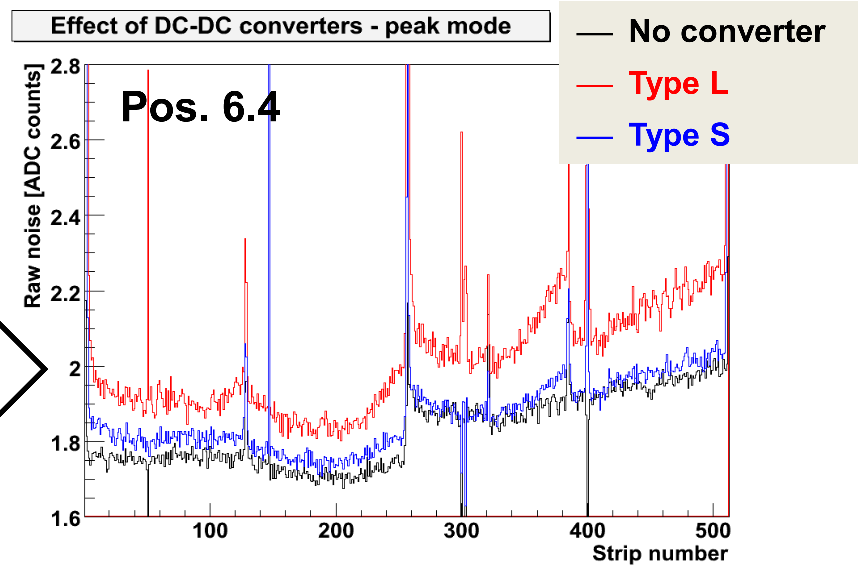


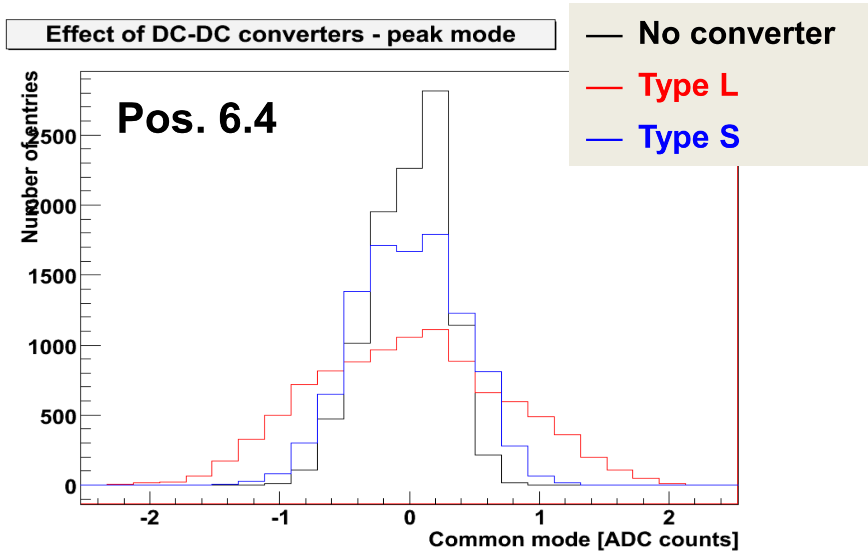




Raw Noise with DC-DC Converter



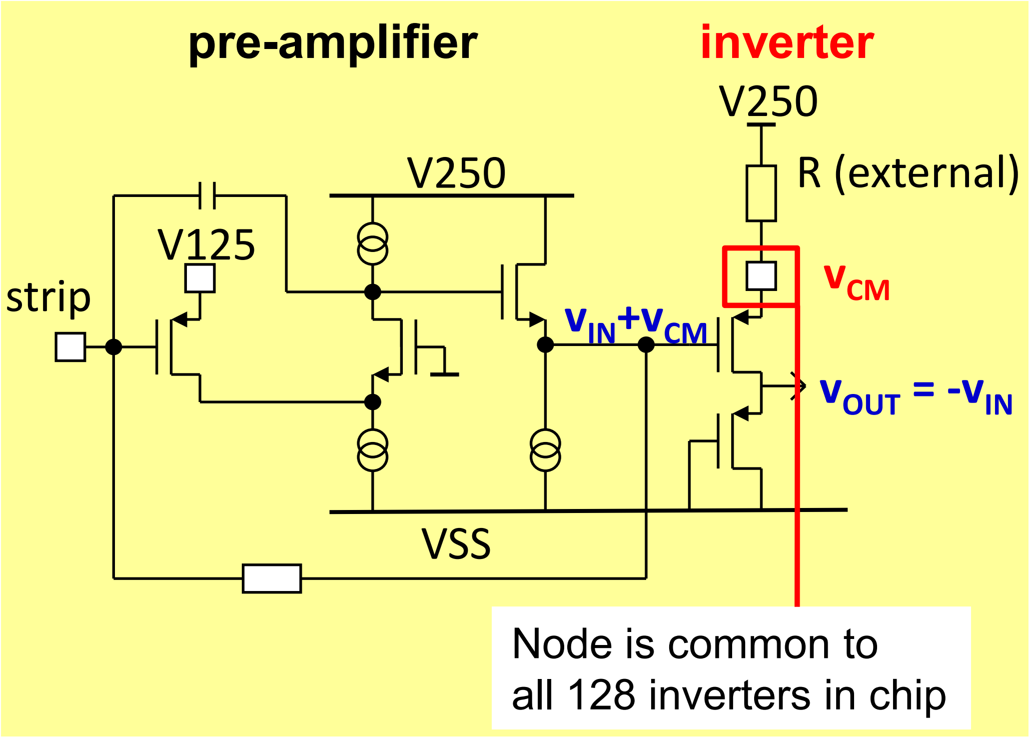


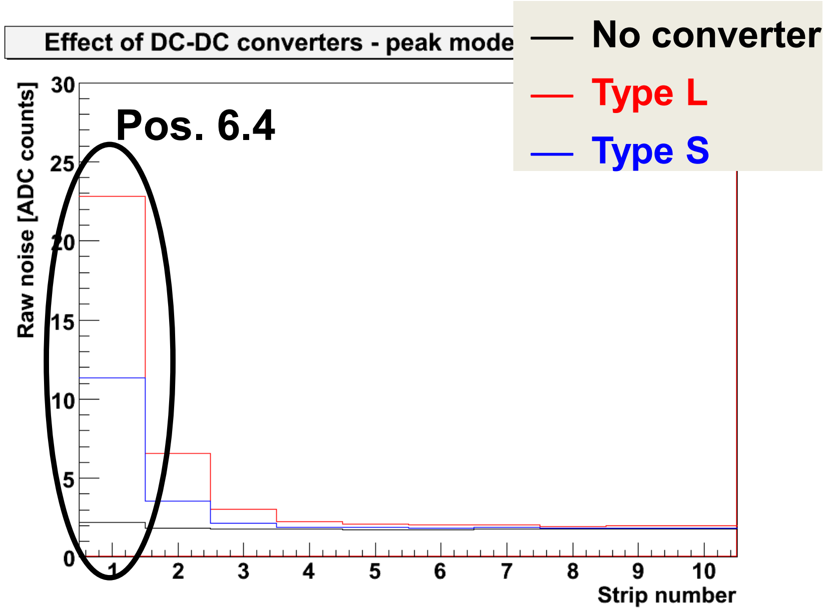


- Raw noise increases by up to 10%
- Large impact of PCB design and connectorization
- Broader common mode distribution
- Most optimization studies performed with L

Edge Channels with DC-DC Converter

- 128 APV inverter stages powered via common resistor ⇒ **on-chip common mode subtraction**
- CM appears on strips that see different CM than regular channels (open & edge channels)
- Huge increase of noise at module edges and open strips with DC-DC converter
- Indicates that large fraction of CM (both via 1.25V & 2.5V) is already subtracted on-chip
- Visible common mode in noise distributions probably coupled in after inverter (via 2.5V line)



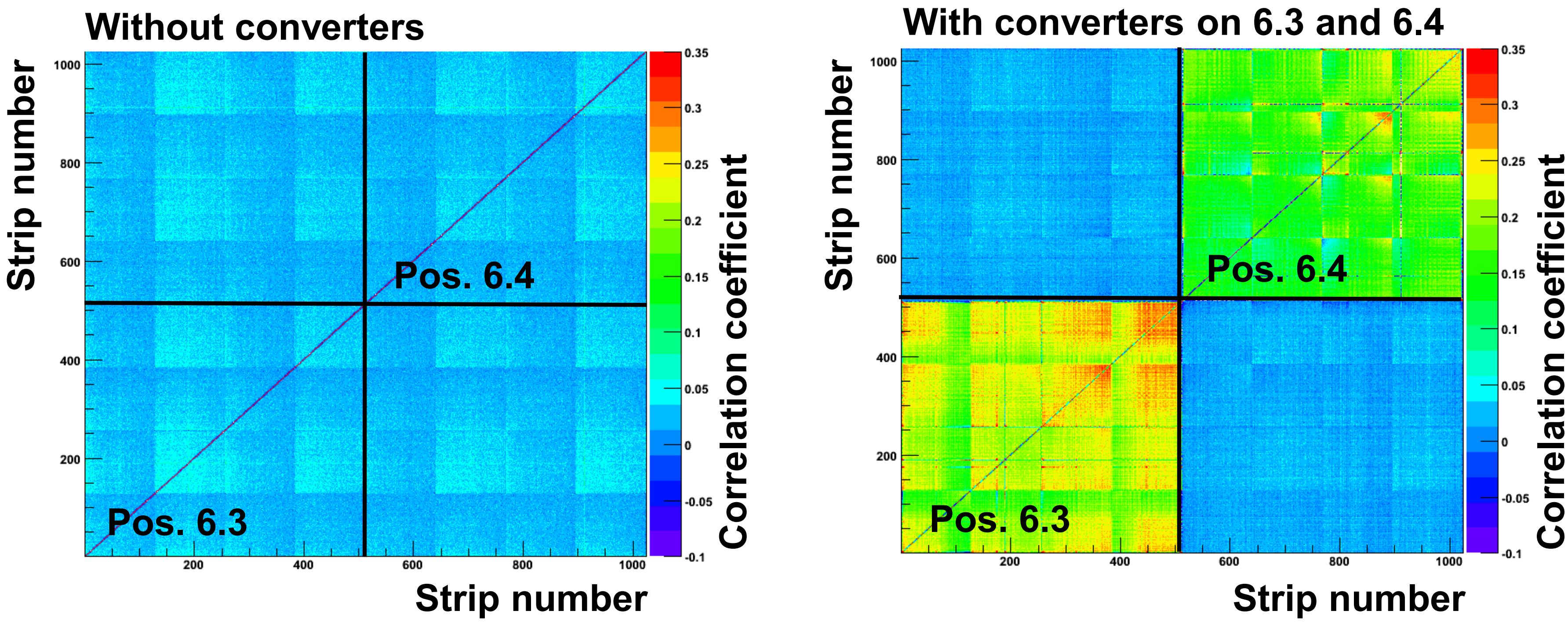


Cross-Talk

Two adjacent modules (6.3, 6.4) powered with EN5312QI converters

⇒ study **correlations between pairs of strips** i, j (r = raw data):

$$corr_{ij} = (\langle r_i r_j \rangle - \langle r_i \rangle \langle r_j \rangle) / (\sigma_i \sigma_j)$$

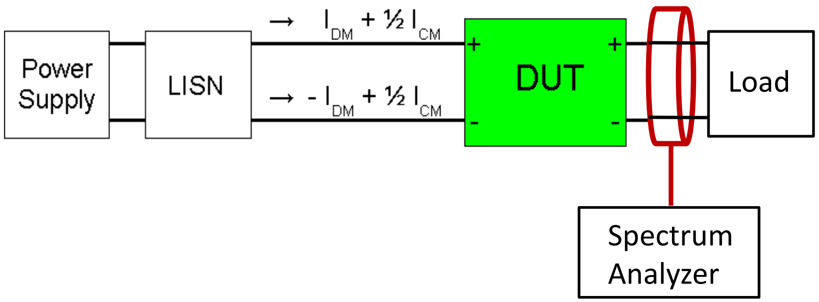


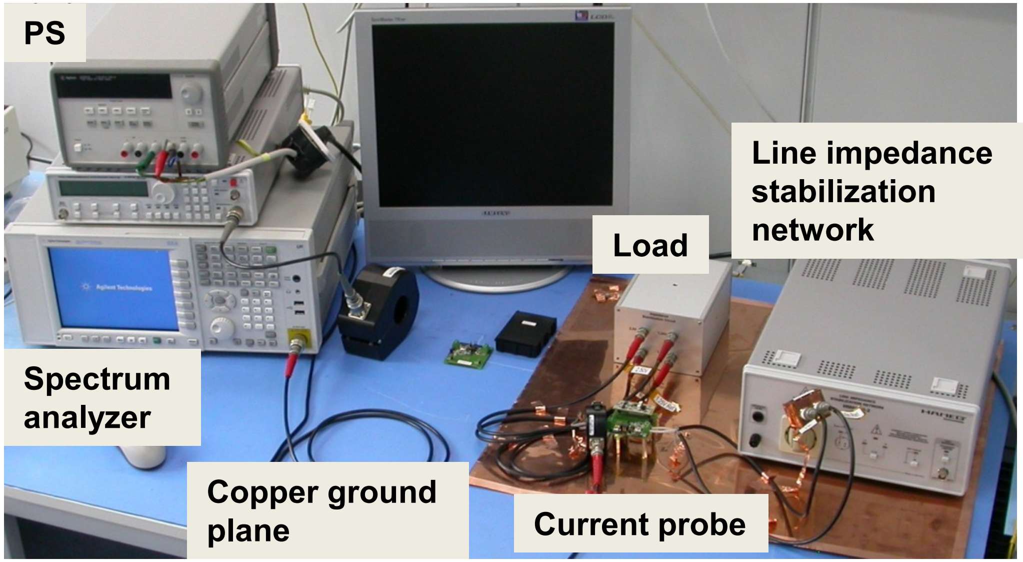
⇒ High correlations only within single modules (= common mode)

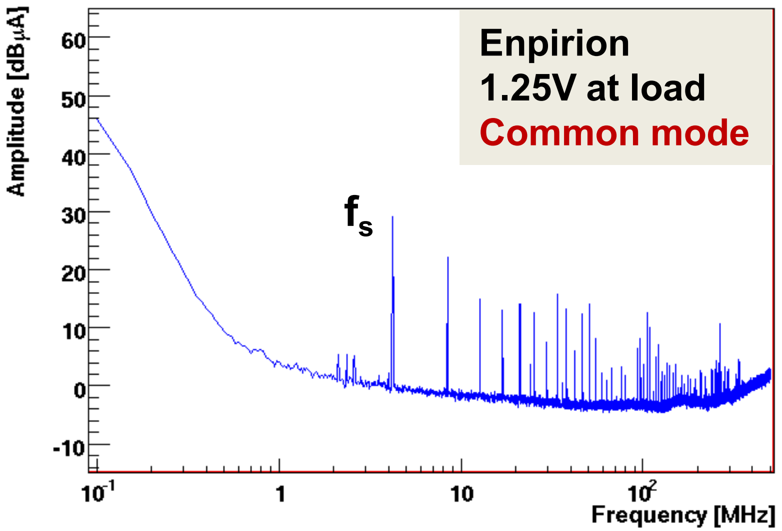
⇒ No cross-talk between neighbouring modules

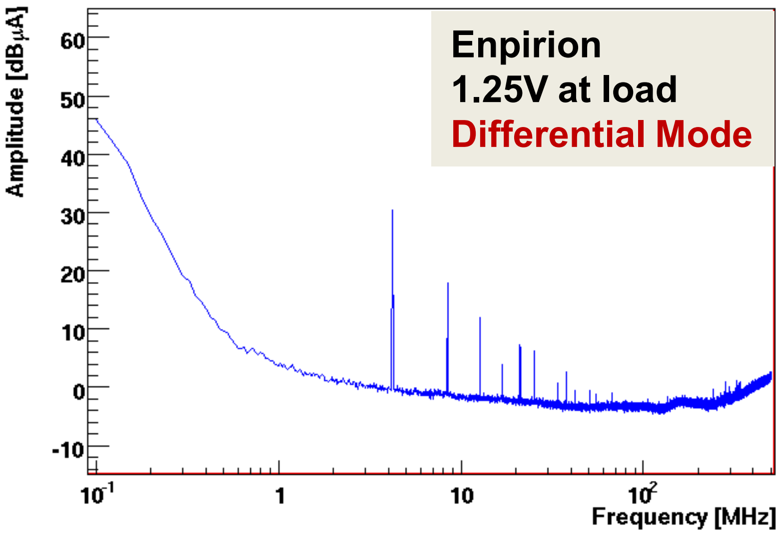
Converter Noise Spectra

Standardized EMC set-up to measure **Differential & Common Mode** noise spectra (similar to set-up at CERN)



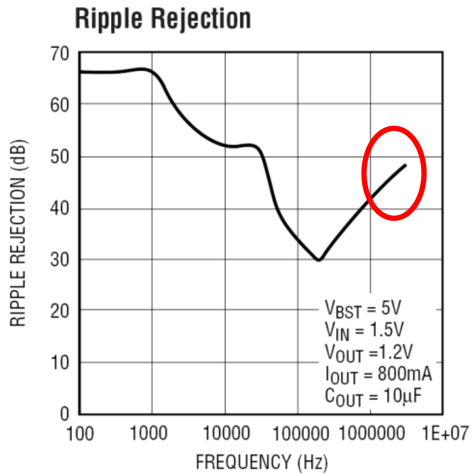


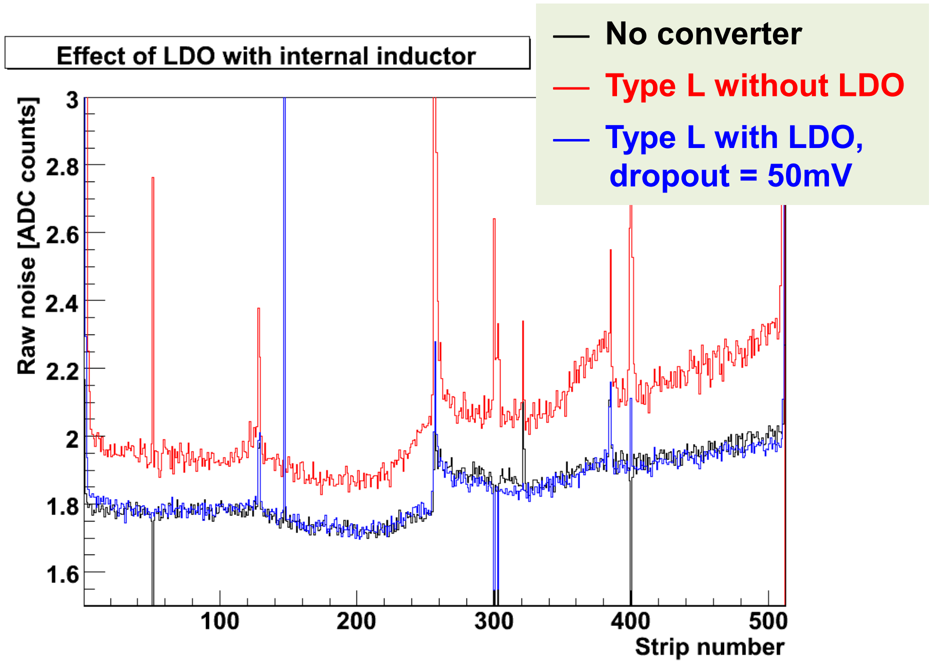


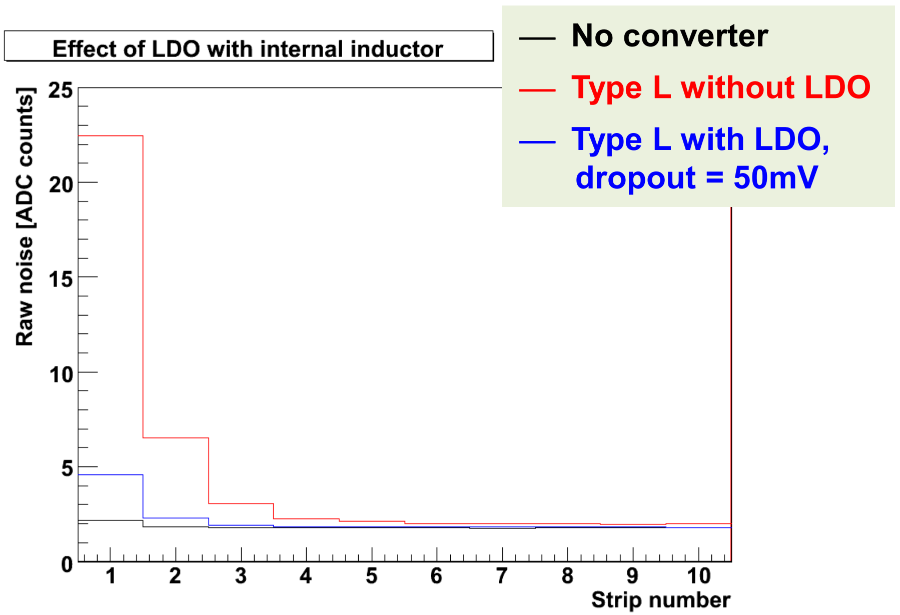


Combination with Low DropOut Regulator

- **Low DropOut Regulator (LDO)** connected to output of EN5312QI DC-DC converter
- Linear technology VLDO regulator LTC3026
- LDO reduces voltage ripple and thus noise significantly
  ⇒ **Noise is mainly conductive and differential mode**
- Would require a rad.-hard LDO with very low dropout







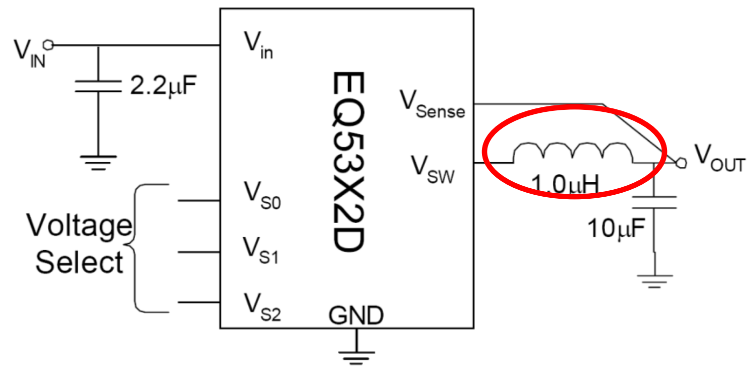
Measurements with commercial buck converters with external air-core inductor

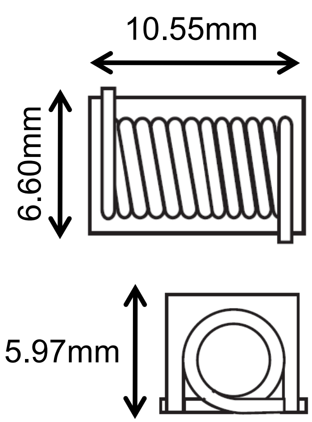
External Air-Core Inductor

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

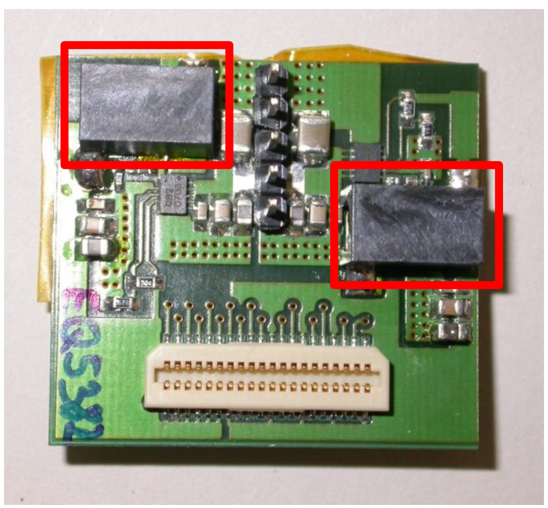
- Air-core inductor Coilcraft 132-20SMJLB; L = 538nH
- Ferrite-core inductor Murata LQH32CN1R0M23; L = 1μH

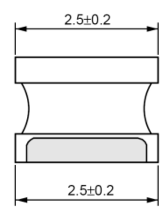
From data sheet



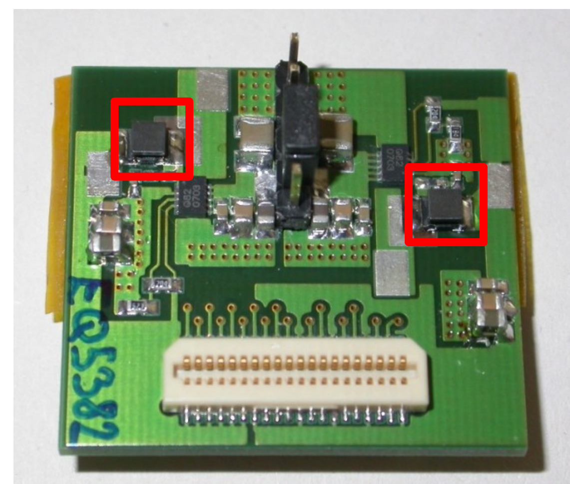


Air-core inductor

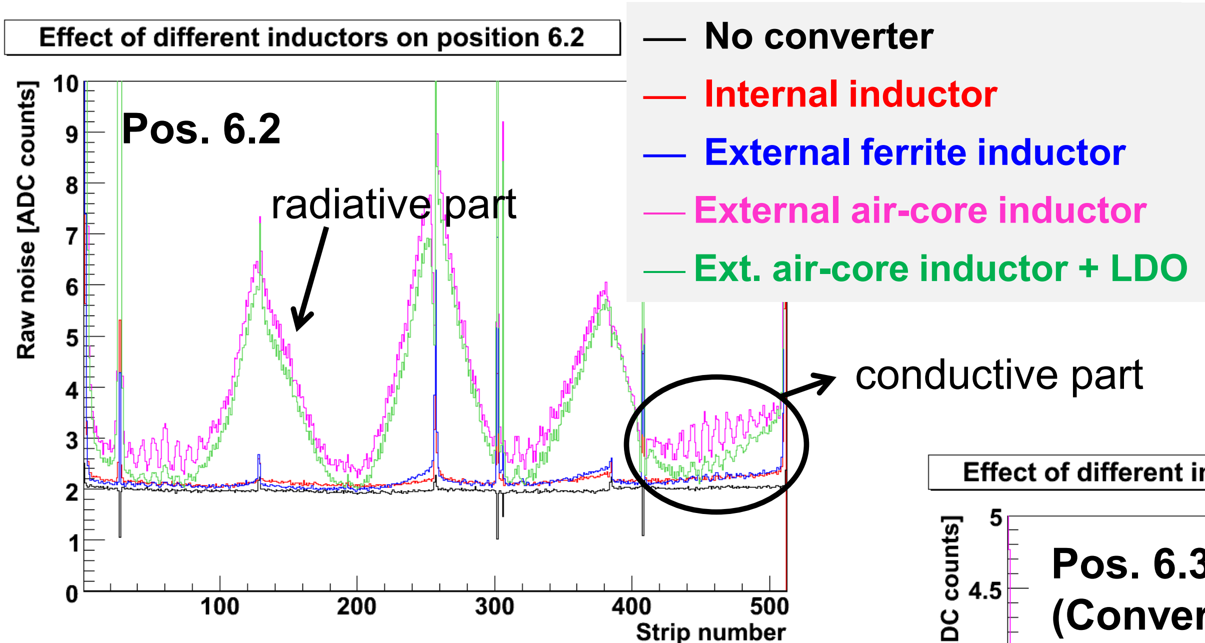


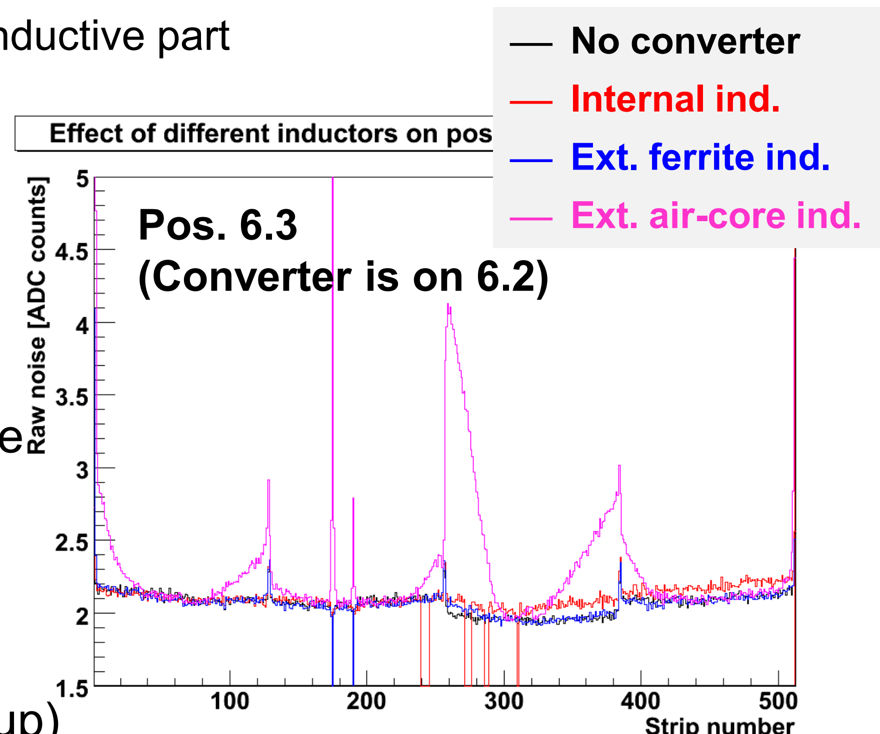


Ferrite-core inductor



External Air-Core Inductor

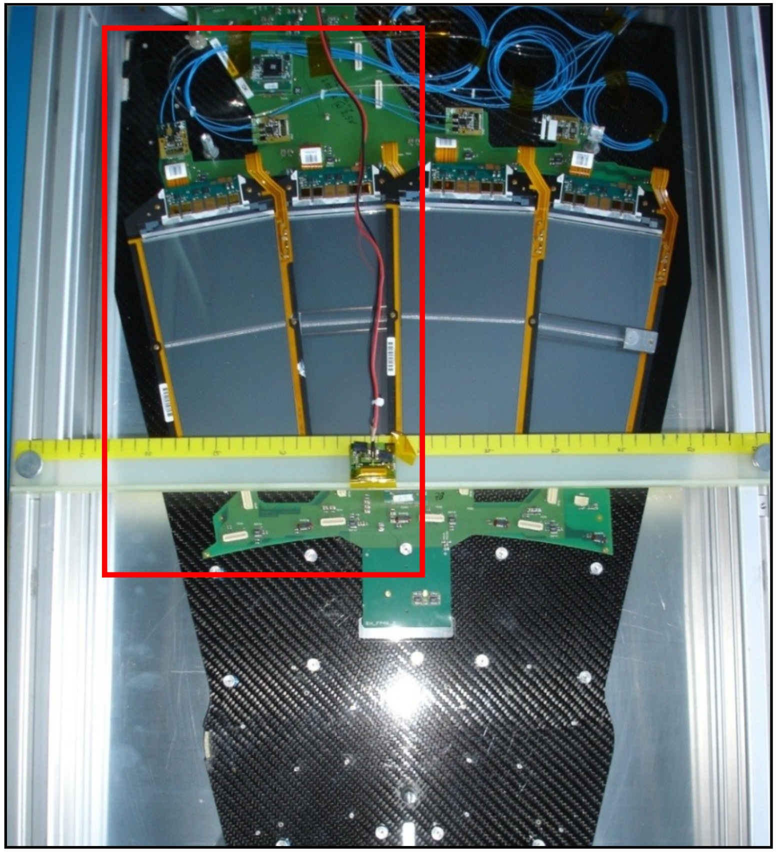


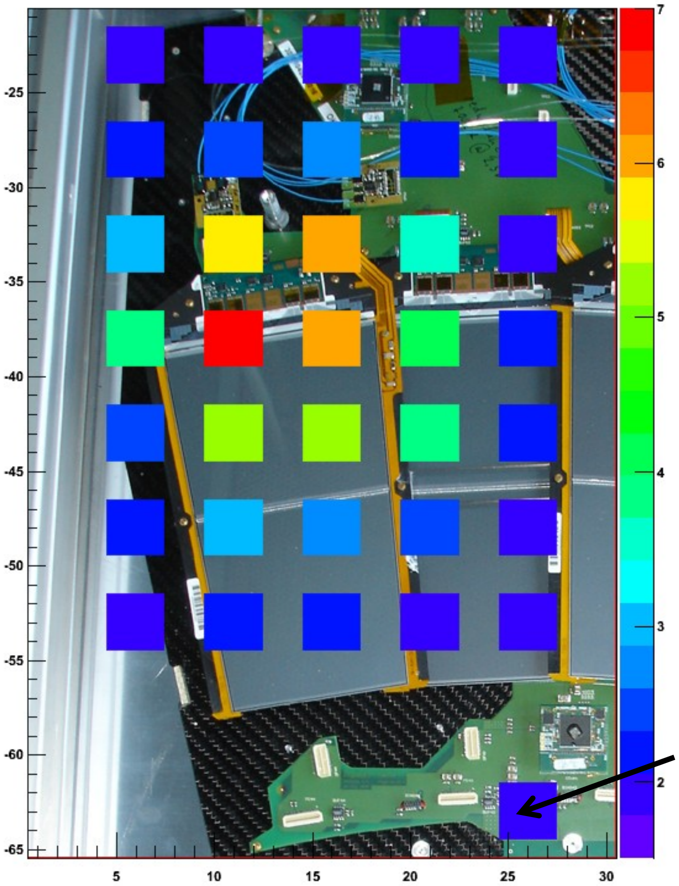


- Huge wing-shaped noise induced by air-core inductor, even on neighbour-module
- Conductive part increases as well
- Both shapes not yet fully understood
- LDO leads only to marginal improvement
- Slight improvement with toroids (see back-up)

Radiative Noise from Air-Core Coil

- Module “irradiated“ with detached converter board

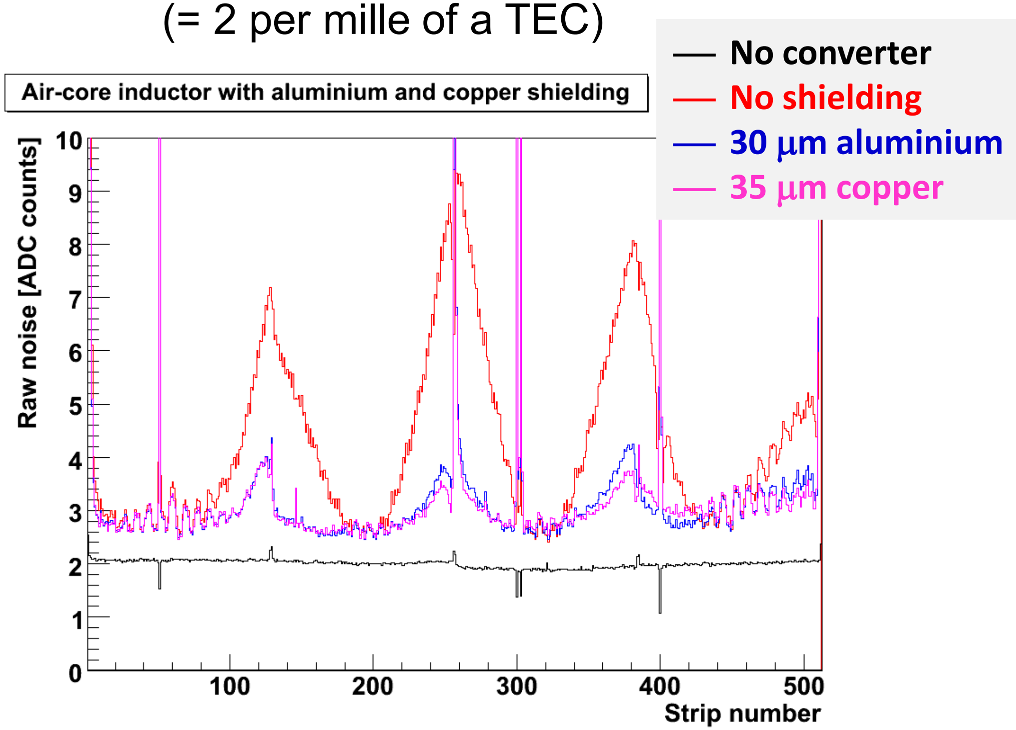


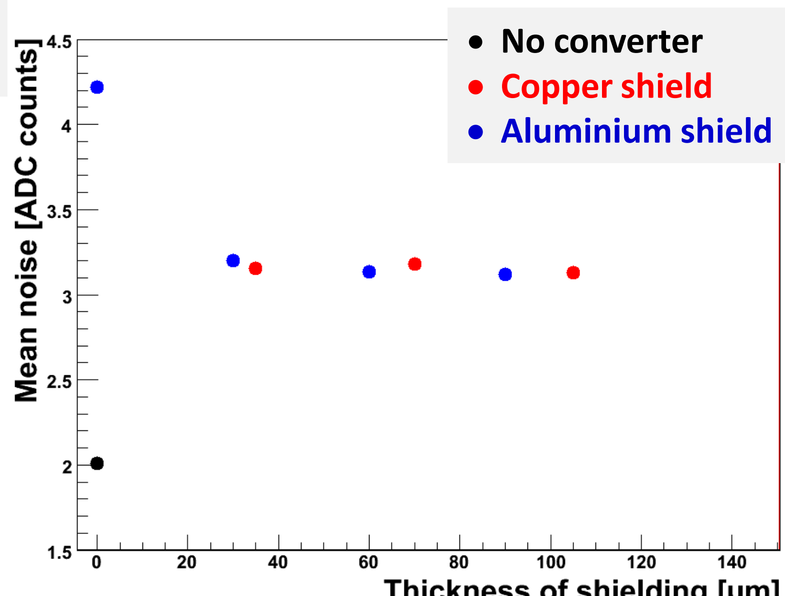


- Increase of mean noise even if converter is not plugged → noise is radiated
- Noise pick-up not in sensor but close to APVs

Shielding the DC-DC Converter

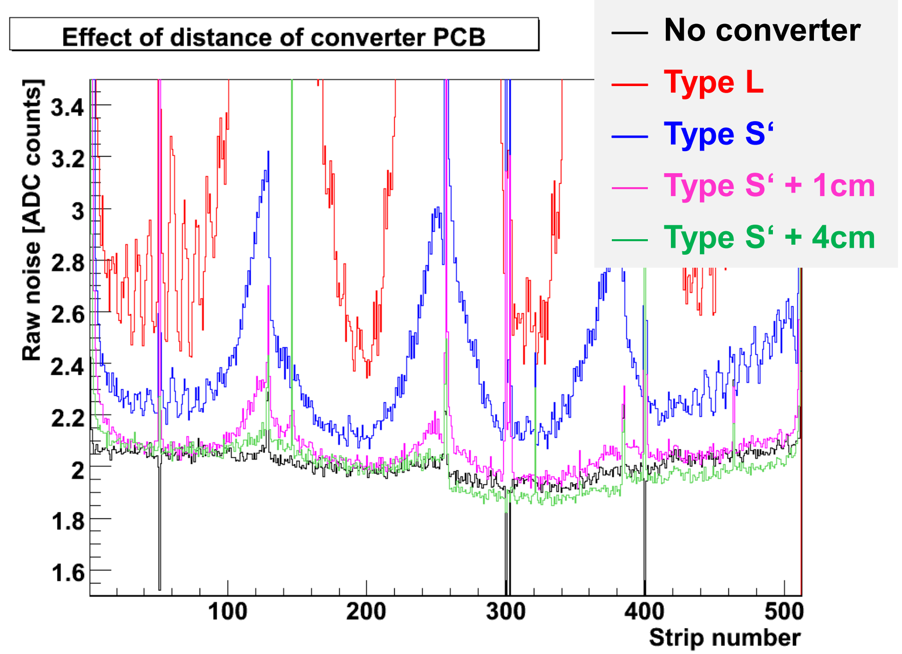
- Enpirion with air-core solenoid **wrapped in copper or aluminium foil**
  - ✓ Floating shield helps ⇒ **magnetic coupling**
  - ✓ Aluminium shields as good as copper
  - ✓ No further improvement for thickness > 30μm
- Shielding increases the material budget
  - – Contribution of $3x3x3cm^3$ box of 30μm alum. for one TEC: 1.5kg (= 2 per mille of a TEC)



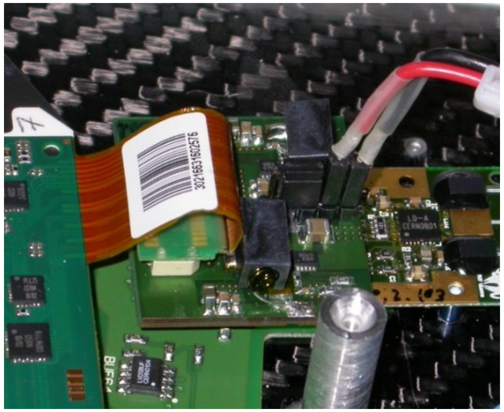


Distance betw. Converter and FE-Hybrid

- The distance between converter and FE-hybrid has been varied using a cable between board and connector
- Sensitivity to distance is very high!
- Effect is a combination of distance and additional filtering
- Placing the buck converter at edge of substructure is an option

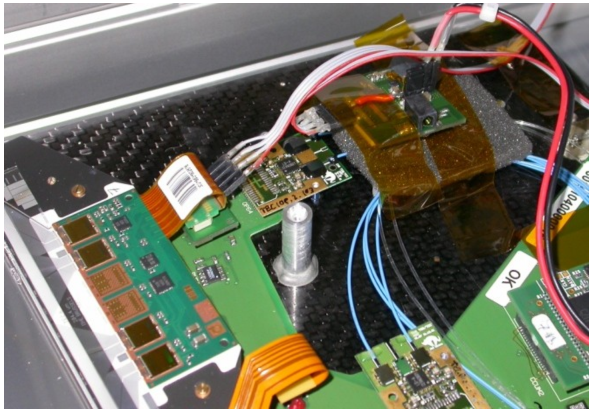


Type L with Solenoid



Type S‘ with Solenoid

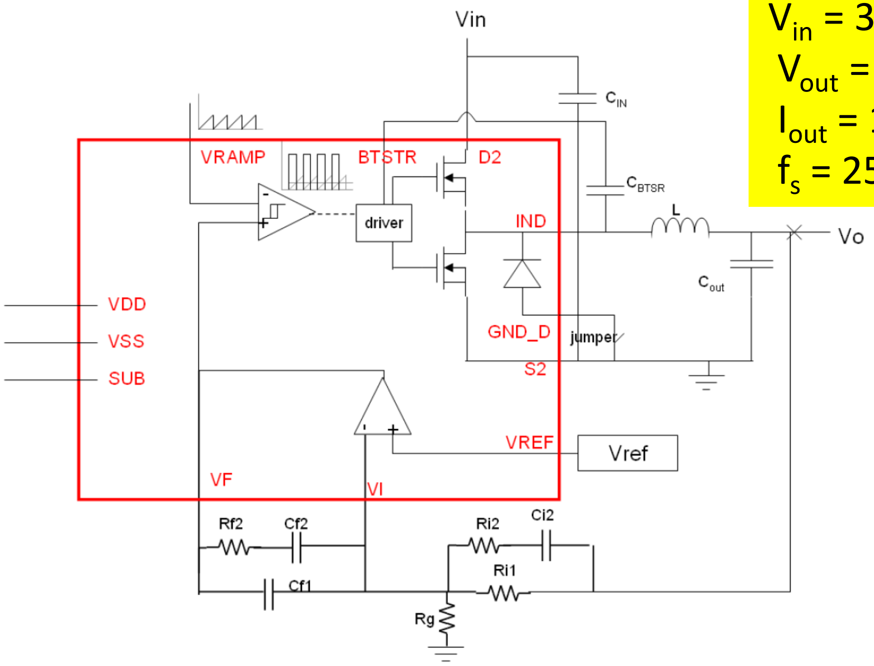
Type S‘ 4cm further away



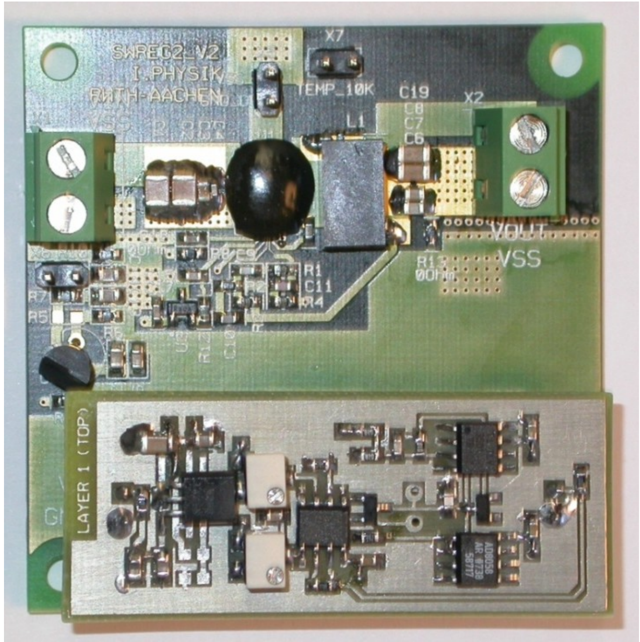
Measurements with custom DC-DC converters

The CERN SWREG2 Buck Converter

- *Single-phase buck PWM Controller with Int. MOSFET* dev. by **CERN** (F. Faccio et al.)
- HV compatible AMI Semiconductor I3T80 technology based on 0.35 μm CMOS
- Many external components for flexibility
- PCB designed by RWTH Aachen University



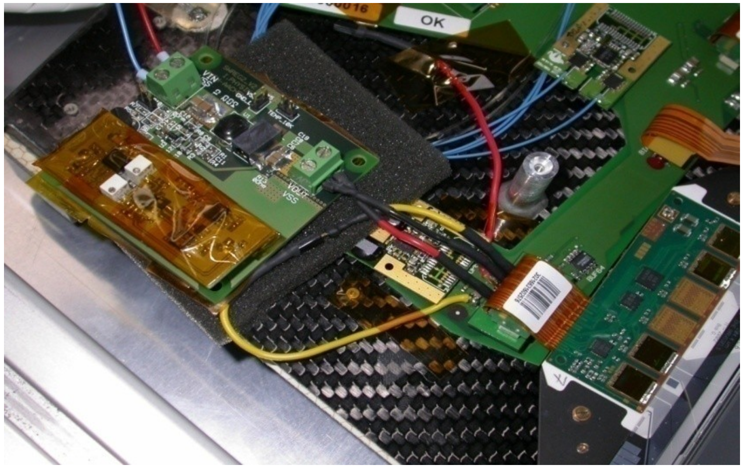
V_{in} = 3.3 – 20V
V_{out} = 1.5 – 3.0V
I_{out} = 1 – 2A
f_s = 250kHz – 3MHz

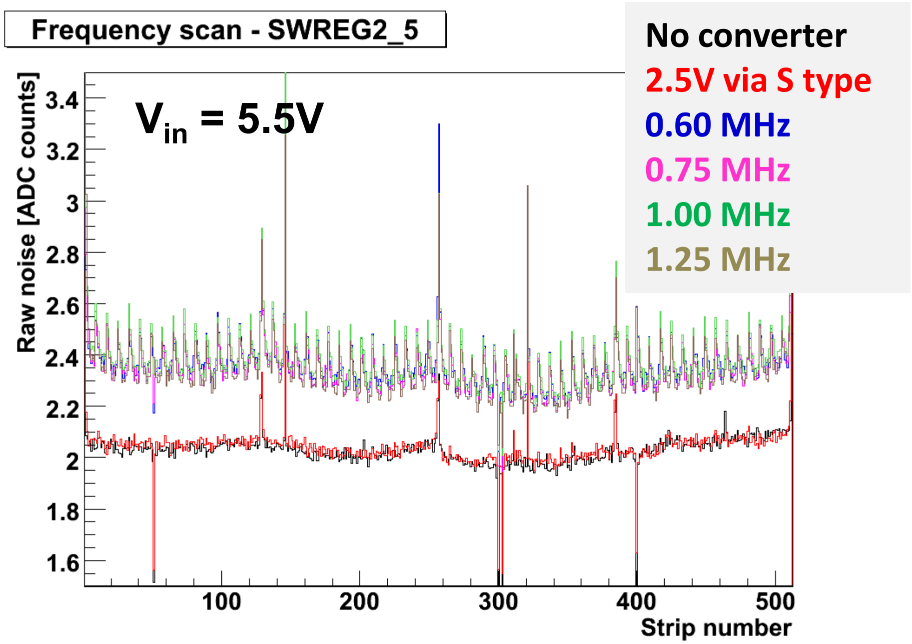


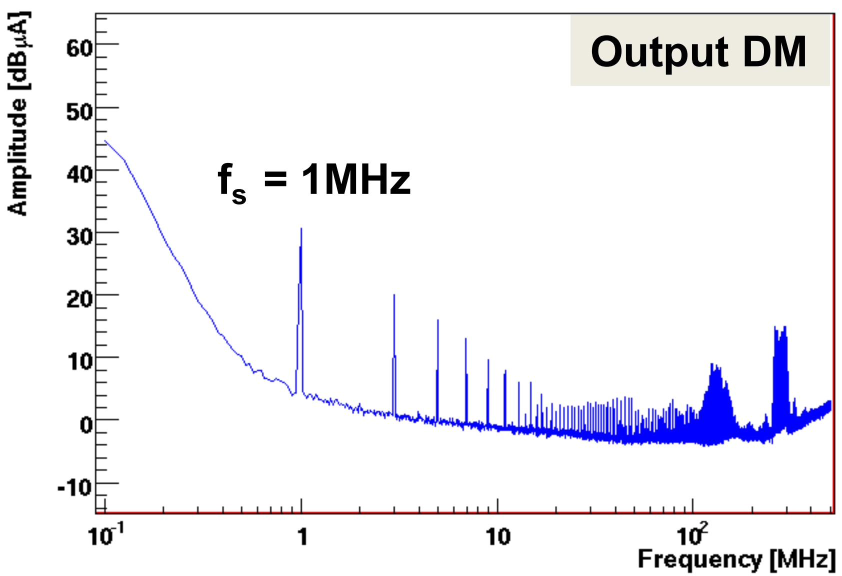
S. Michelis (CERN) et al., *Inductor based switching DC-DC converter for low voltage power distribution in SLHC*, TWEPP 2007; and poster 24 at TWEPP 08.

The CERN SWREG2 Buck Converter

- PCB located far away from module
  ⇒ conductive noise measured
- SWREG2 provides only 2.5V to FE-hybrid
- Noise increases by about 20%
- 8-strip ripple structure understood to be artefact of strip order during multiplexing; converters affects readout stages of APV

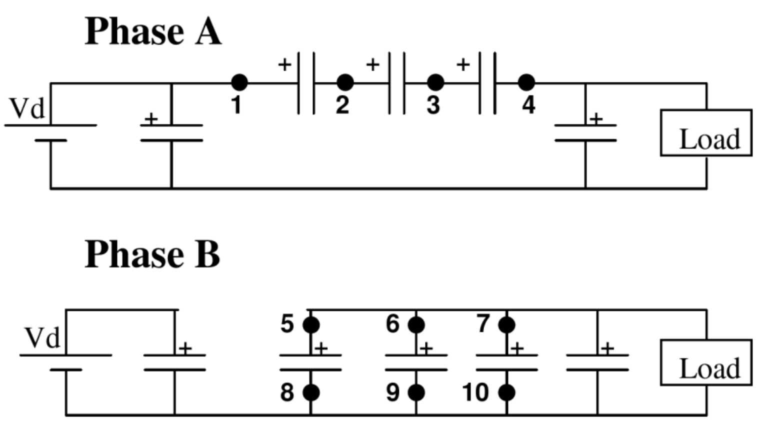






The LBNL Charge Pump

- Simple **capacitor-based** step-down converter: capacitors charged in series and discharged in parallel $\rightarrow I_{out} = n \cdot I_{in}$, with n = number of parallel capacitors
- At **LBNL** (M. Garcia-Sciveres et al.) a n = 4 prototype IC in 0.35 μm CMOS process (H35) with external 1μF flying capacitors has been developed (0.5A, 0.5MHz)



Pros:

– No air-core coil → less noise, less material

Cons:

– Switches must be rad.-hard and HV safe

– Many switches → mat. budget, switching losses

– Switching noise

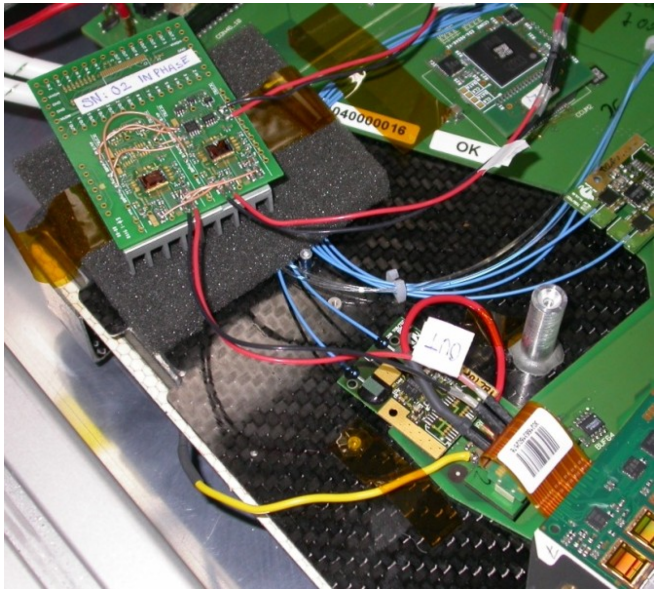
– Restricted to low power applications

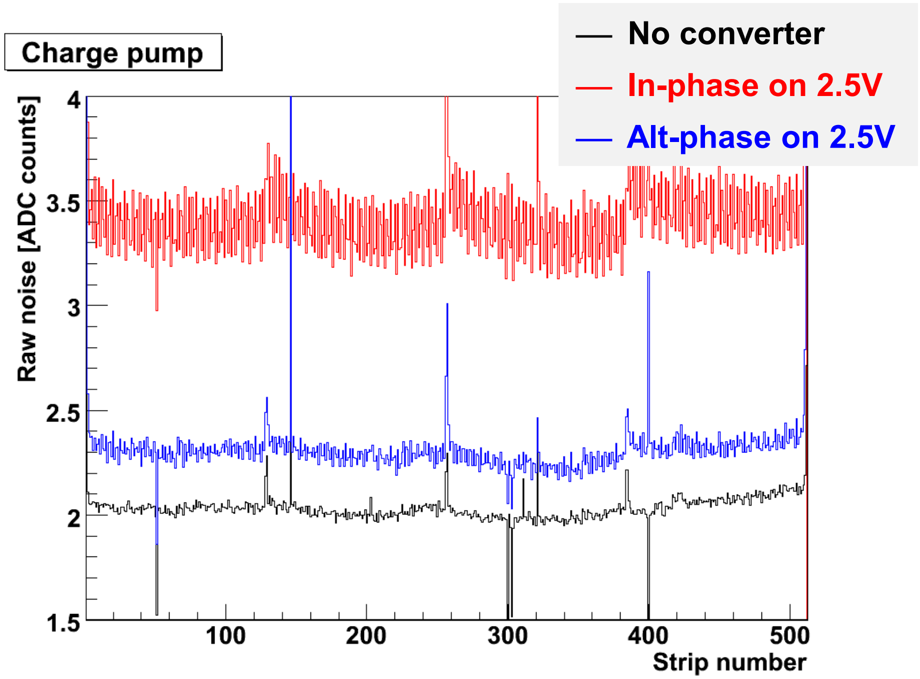
– No feedback control

P. Denes, R. Ely and M. Garcia-Sciveres (LBNL), *A Capacitor Charge Pump DC-DC Converter for Physics Instrumentation,* submitted to IEEE Transactions on Nuclear Science, 2008.

The LBNL Charge Pump

- Two converters connected in parallel: tandem-converter
  - f_s = 0.5MHz (per converter)
  - In-phase and alternating-phase versions
- Tandem-converter connected either to 2.5V or 1.25V
- Noise increases by about 20% for alternating phase
- Next step: combination with LDO





Summary & Outlook

- Using commercial buck converters, we have gained first experience with DC-DC conversion and the associated problems
- Measures to minimize conductive and radiative noise have been studied
- Radiated noise appears to be biggest draw-back of ind.-based topologies; but operation at the edge of the substructure seems feasible
- Tests of first prototypes of custom converters has started & will continue
  - Buck converter from CERN, charge pump from LBNL group
- A radiation-hard LDO would be beneficial

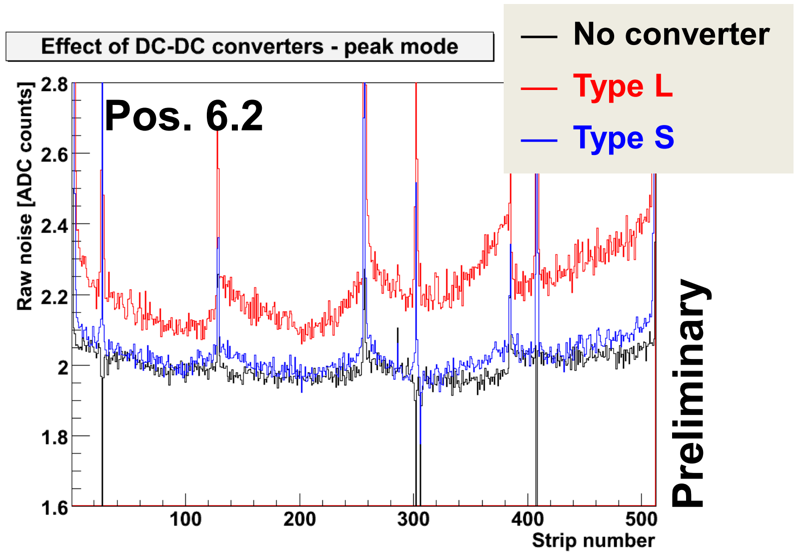
- Noise susceptibility studies are planned to understand better the effects
- A realistic powering scheme, including also power for optical components, bias voltage and controls, has to be worked out

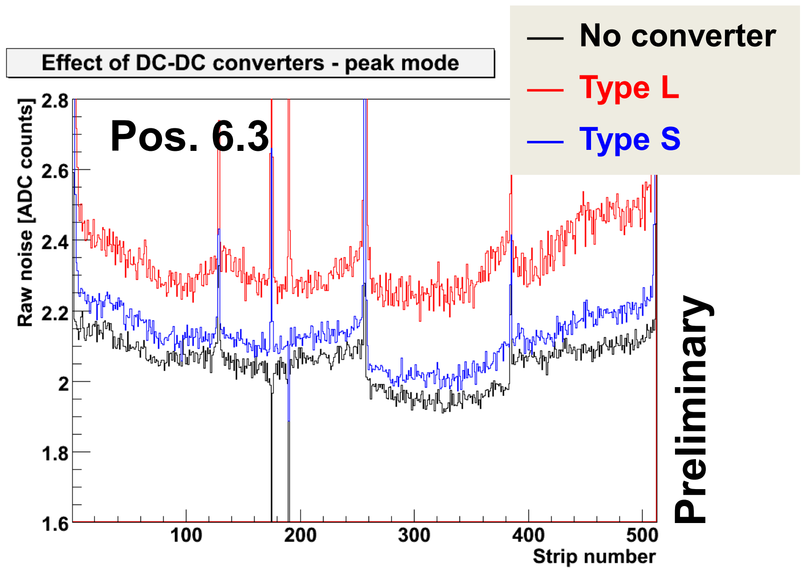
Thanks to F. Faccio et al. (CERN) and M. Garcia-Sciveres et al. (LBNL) for providing the converter protoypes!

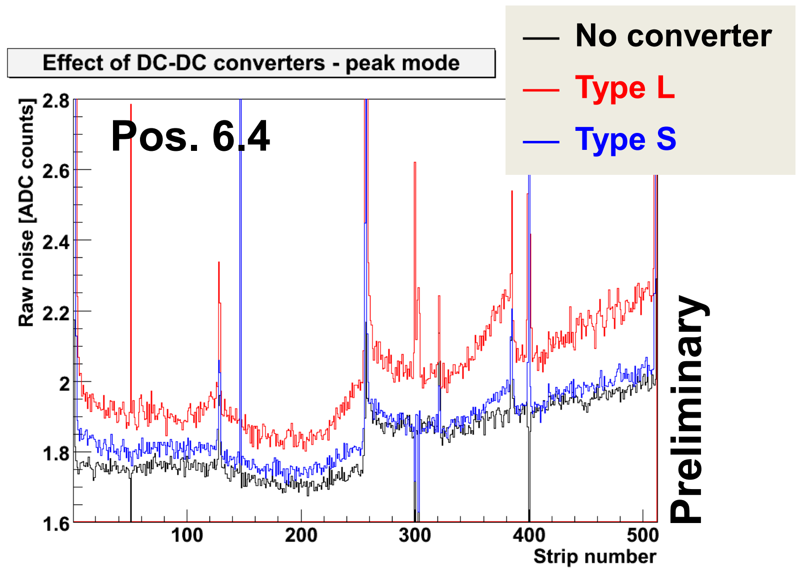
Back-up Slides

Raw Noise on Different Positions

On position 6.1 type L does not fit



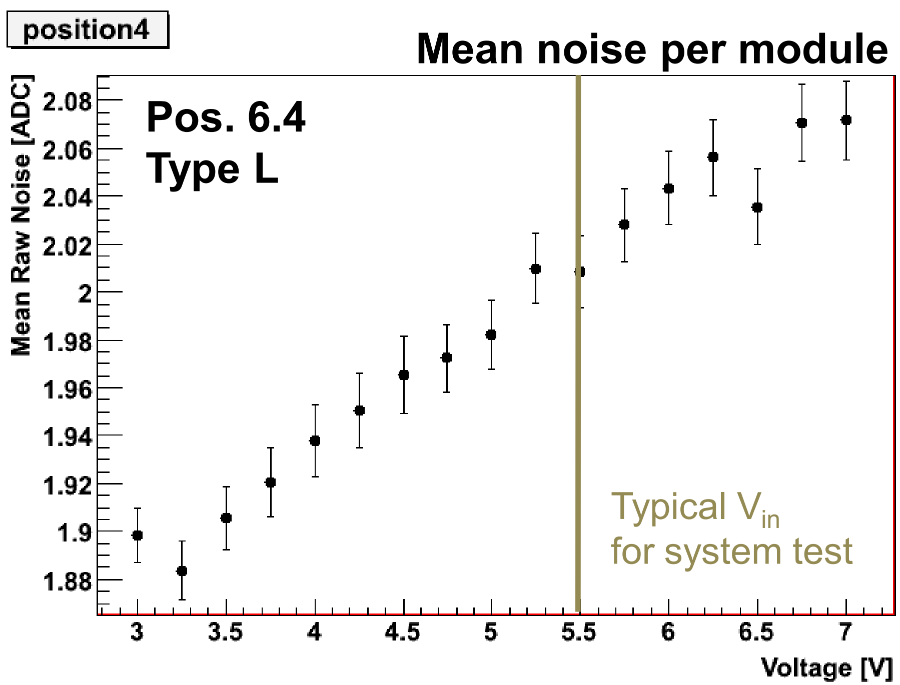




Noise versus Conversion Ratio (V_{out}/V_{in})

- V_{out} fixed to 1.25V & 2.5V ⇒ change of V_{in} leads to change of conv. ratio $r = V_{out} / V_{in}$
- Output ripple δV_{out} depends on duty cycle D (D = r for buck converter):

$$\delta V_{out} \sim \frac{1}{LC_{out}} \frac{1}{f_s^2} \frac{V_{out}}{V_{in}} (V_{in} - V_{out}) \Rightarrow \frac{\delta V_{out}}{V_{out}} \sim (1-D) \frac{1}{LC_{out}} \frac{1}{f_s^2}$$

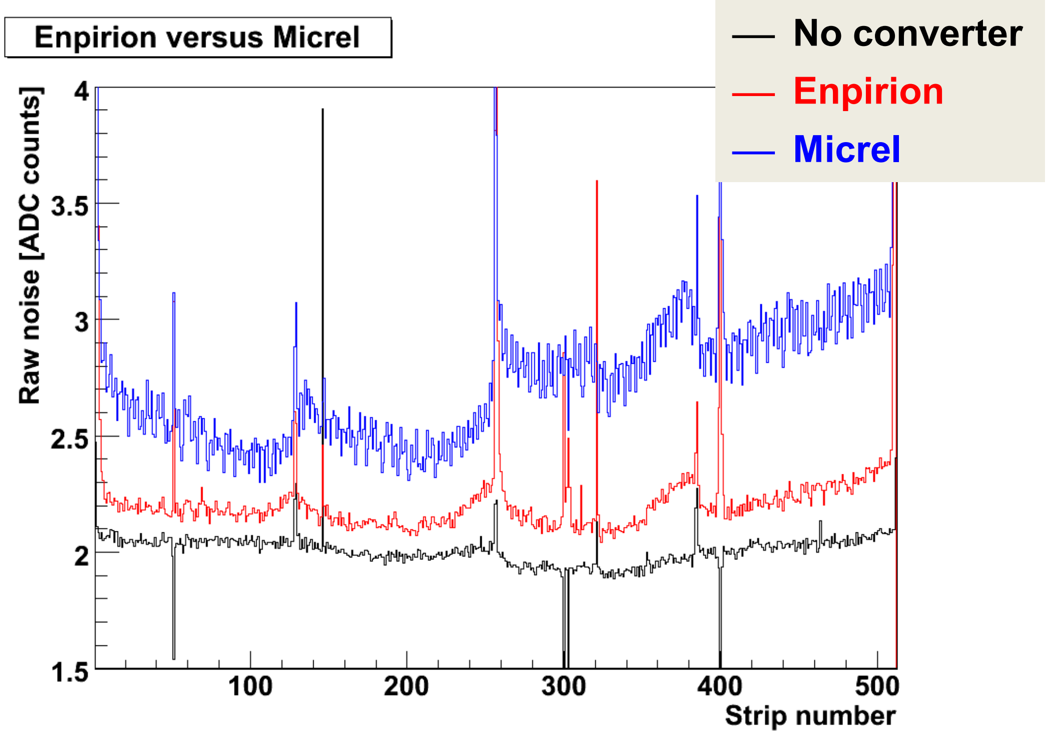


⇒ Mean noise increases for lower conversion ratio

Other Commercial Converters: MIC3385

Are we looking at a particularly noisy commercial device? ⇒ **Micrel MIC3385**

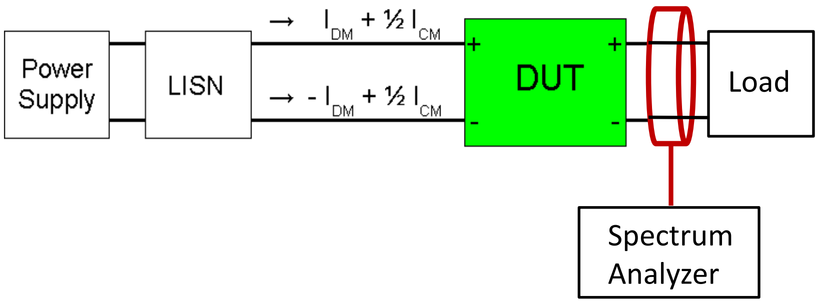
- f_s = 8 MHz
- V_{in} = 2.7–5.5 V
- footprint 3 x 3.5 mm^2

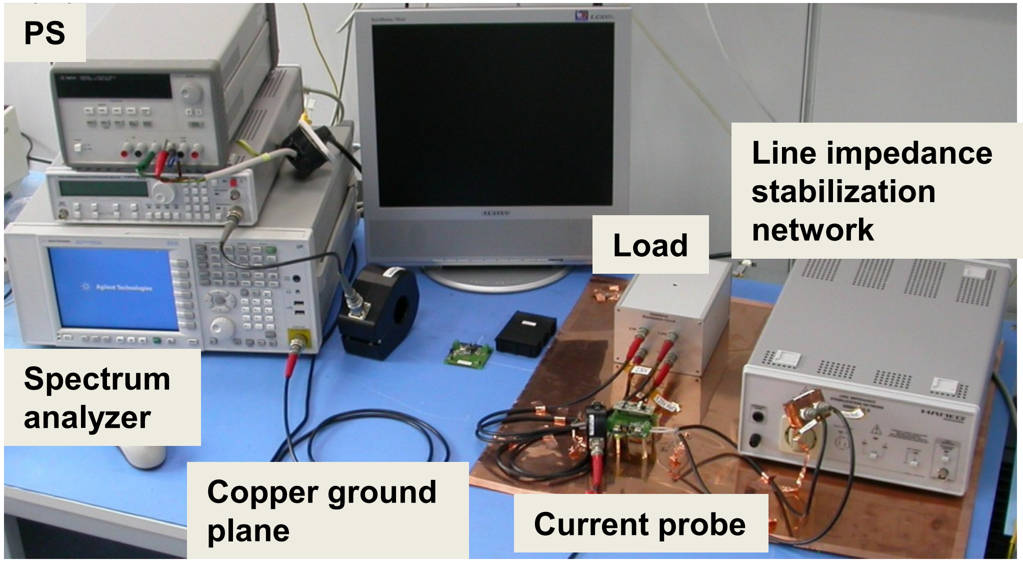


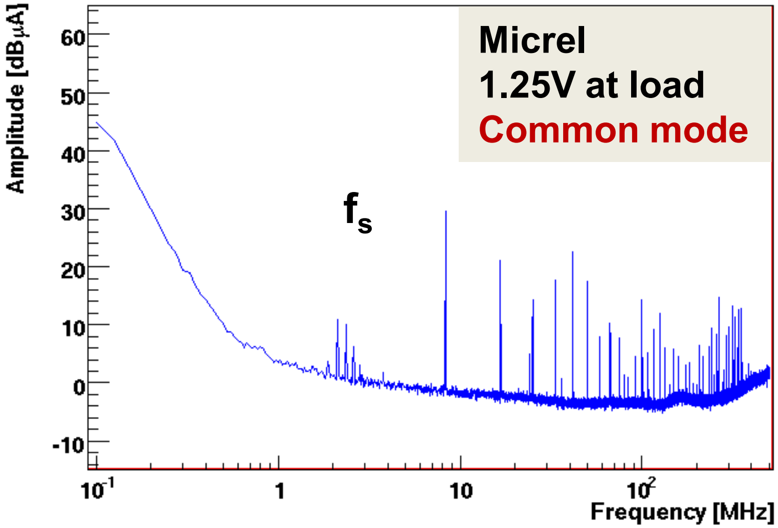
⇒ No evidence that EN5312QI is exceptionally noisy

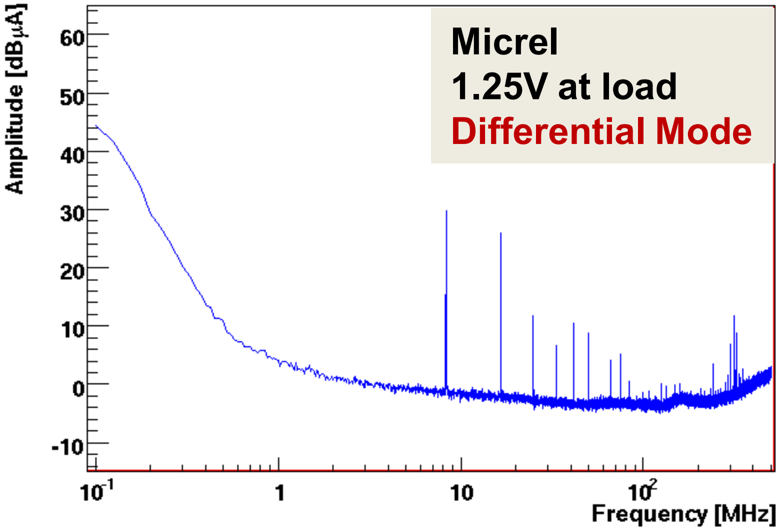
Converter Noise Spectra

Standardized EMC set-up to measure **Differential & Common Mode** noise spectra (similar to set-up at CERN)



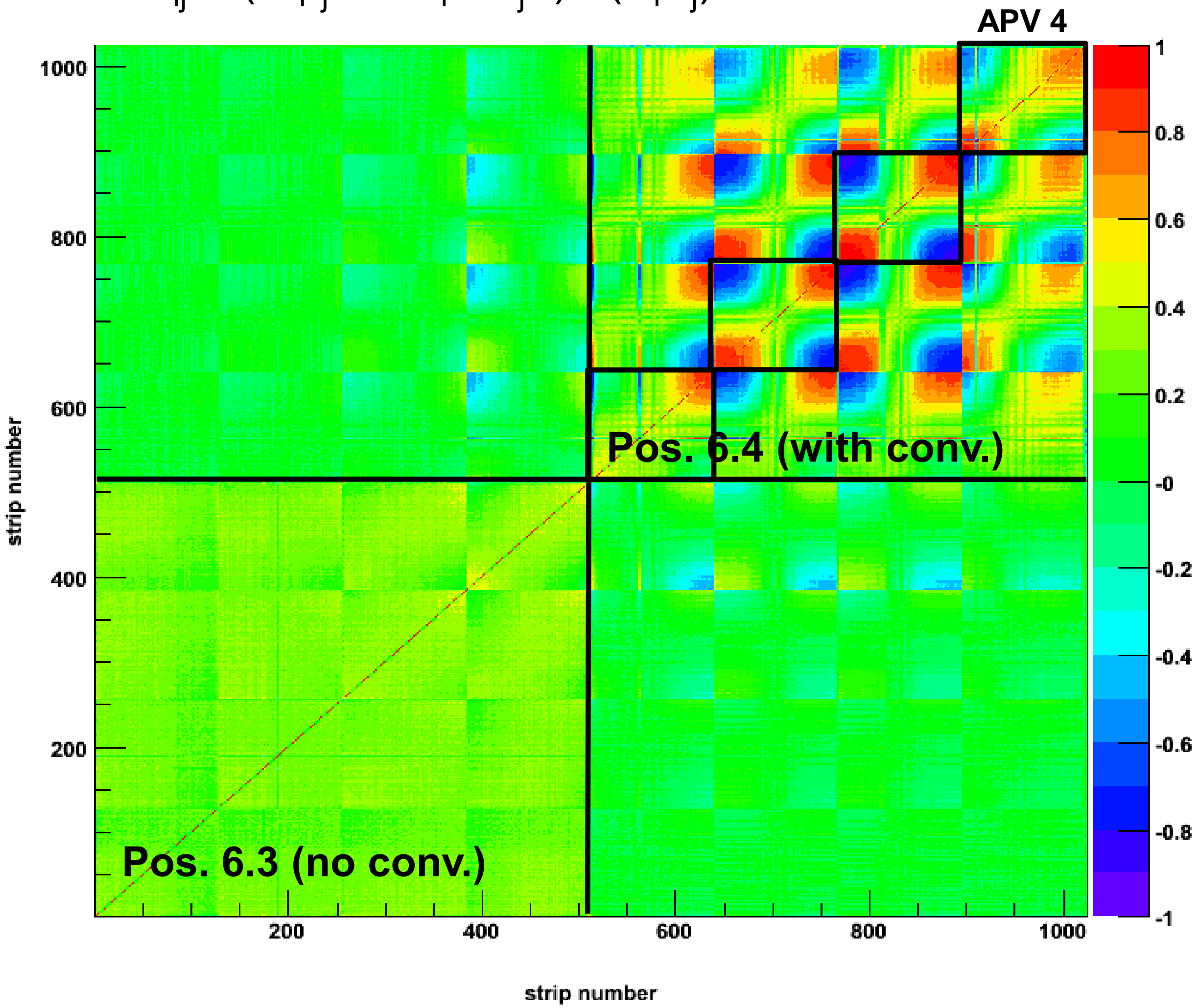






Correlations with External Air-Core Inductor

$corr_{ij} = (\langle r_i r_j \rangle - \langle r_i \rangle \langle r_j \rangle) / (\sigma_i \sigma_j)$



Per APV:

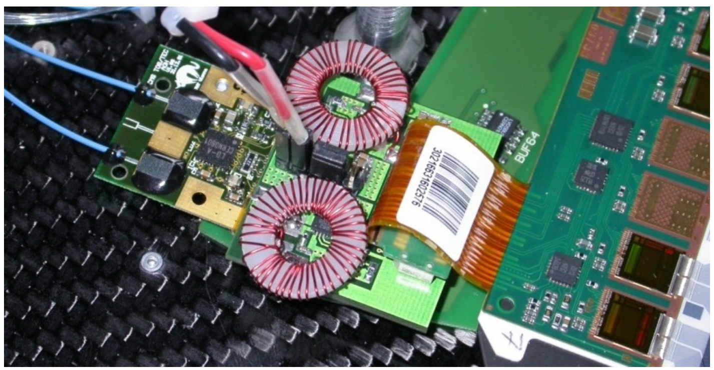
- two halfs of 64 strips
- strips within each half are highly correlated (90%),
- but two halfs are strongly anti-correlated (-80%)

- 50% correlations also on module 6.3 (no converter)

External Air-Core Toroids

- As expected, toroid coils radiate less than solenoids
- Significant improvement already observed with simple self-made toroid coil
- Coil design being systematically studied by D. Cussans et al. (Bristol) (*Poster 107*)

Toroid wiggled from copper wire



Toroid wiggled from copper strip