Powering R&D
at Aachen IB

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Katja Klein, Jennifer Merz, Jan Sammet

CMS Tracker Upgrade Power WG
CERN, 7. 10. 2008

Outline

- Introduction
- Commercial Buck Converters
- APV25 Features
- CERN Buck Converter
- BNL Charge Pump
- Summary and Outlook

Introduction

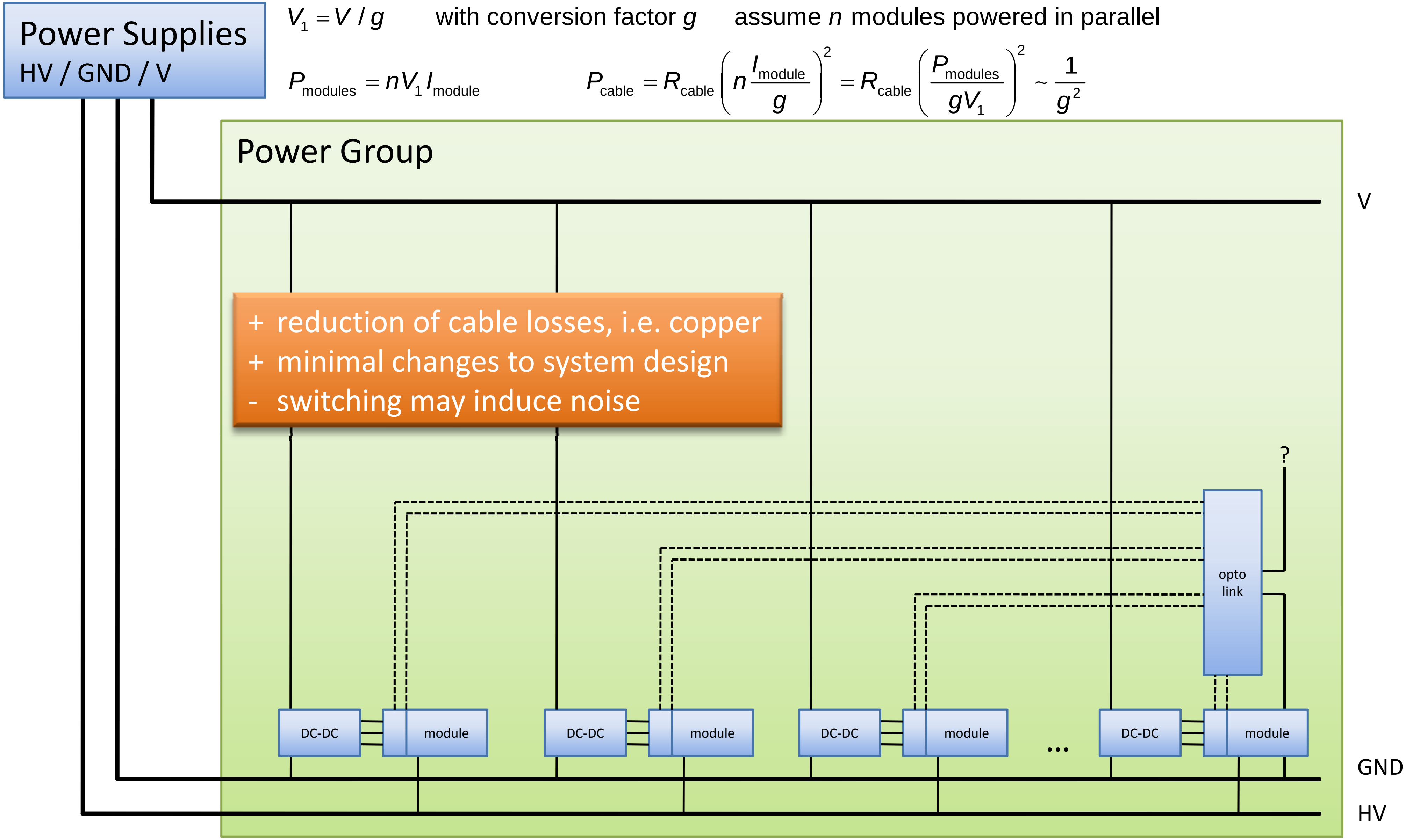
- CMS-R&D Proposal 07.01 „**R&D on Novel Powering Schemes for the SLHC CMS Tracker**” approved in October 2007
- **workplan**:
  - establish test bed for novel powering schemes: one petal (prototype, currently 4 modules) + read-out system — DONE
  - set up Electromagnetic Interference test stand to measure conductive (calibrated pick-up coils) and radiated (near field probes) noise — DONE
  - assemble and test DC-DC converters from commercial components — ~DONE
  - develop and test radiation hard DC-DC converters — ONGOING
  - investigate alternative schemes (serial powering) — NOT STARTED
  - simulate implications for material budget — ONGOING
  - "…development of a detector sub-system which is supplied at a voltage much higher than the actual ASIC supply voltage and therefore much reduced current"
- **people**: Feld, Jussen, Karpinski, Klein, Merz, Sammet

DC-DC Power Conversion

$V_1 = V / g$ with conversion factor g assume n modules powered in parallel

$P_{\text{modules}} = n V_1 I_{\text{module}}$

$$P_{\text{cable}} = R_{\text{cable}} \left(n \frac{I_{\text{module}}}{g} \right)^2 = R_{\text{cable}} \left(\frac{P_{\text{modules}}}{g V_1} \right)^2 \sim \frac{1}{g^2}$$

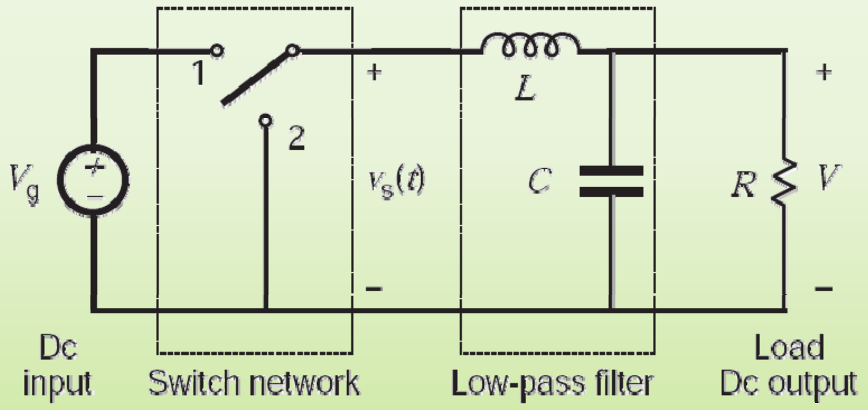


- \+ reduction of cable losses, i.e. copper
- \+ minimal changes to system design
- \- switching may induce noise

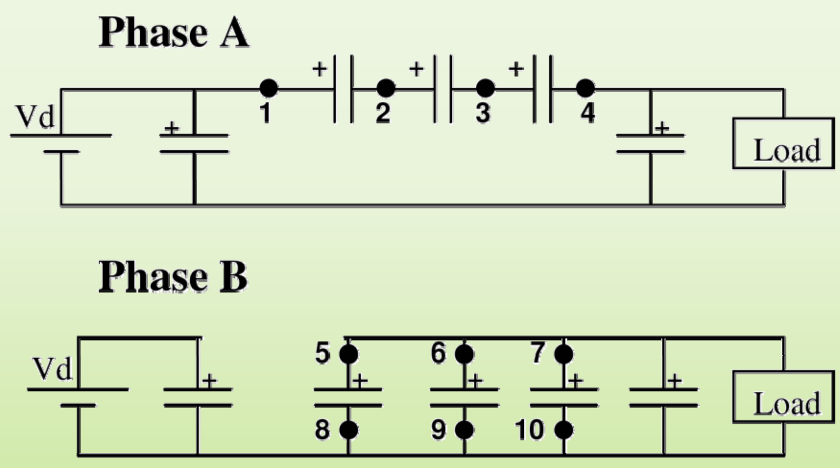
DC-DC Converters

- many different designs
- inductor based converters
  - current capacity up to several amps
  - ferrite cores saturate in 4 Tesla field

    → need to use air core coils
- capacitor based converters
  - are limited in current to few 100 mA at most
  - no inductors needed, can be very compact and may be even included in FE ASIC
- all need rad-hard "high voltage" transistors as switches
- efficiency typically 70 – 90 %
- switching noise is a concern

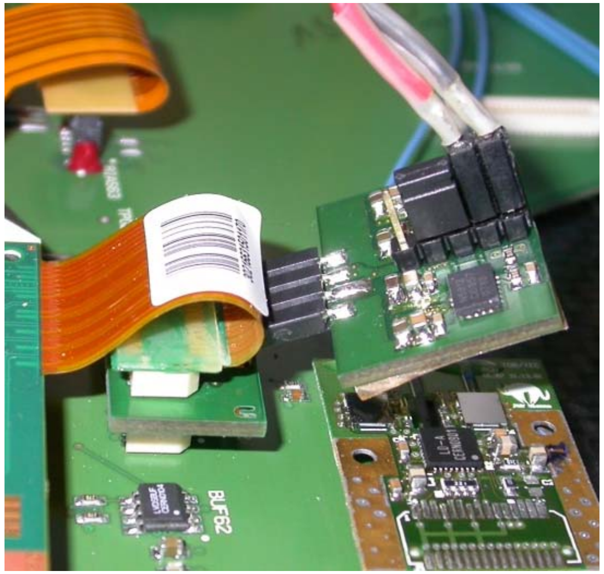


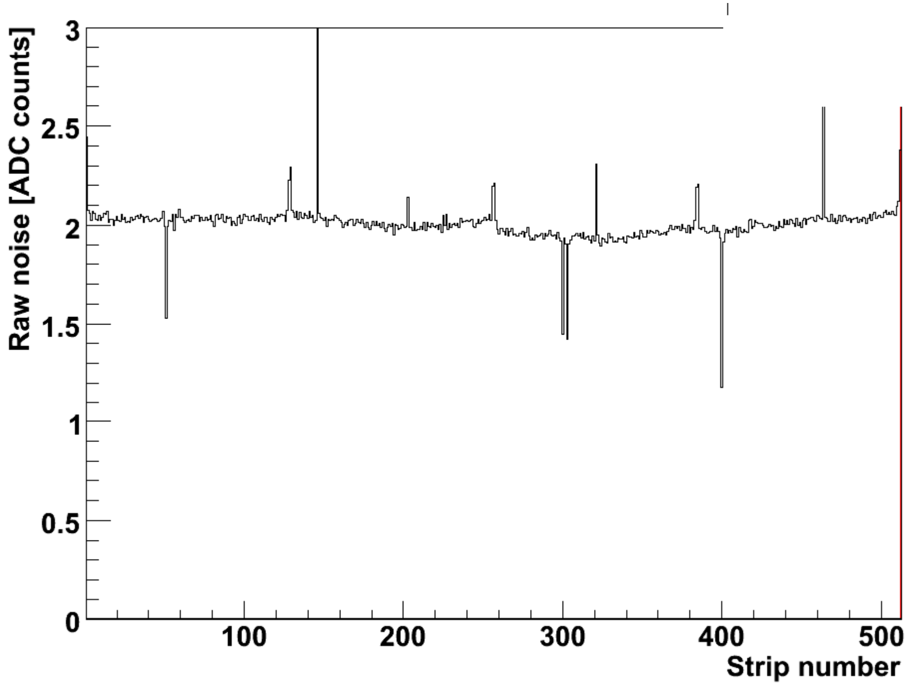
Inductor Based "Buck Converter"



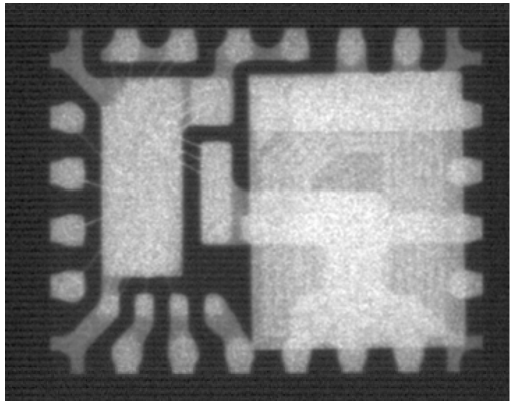
Capacitor Based "Charge Pump"

System Test with a TEC Petal

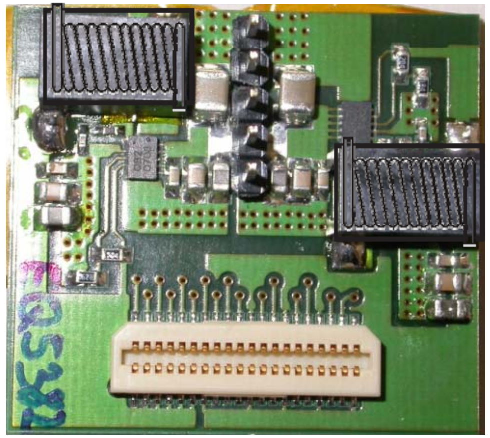




Commercial Inductor Based DC-DC Converters



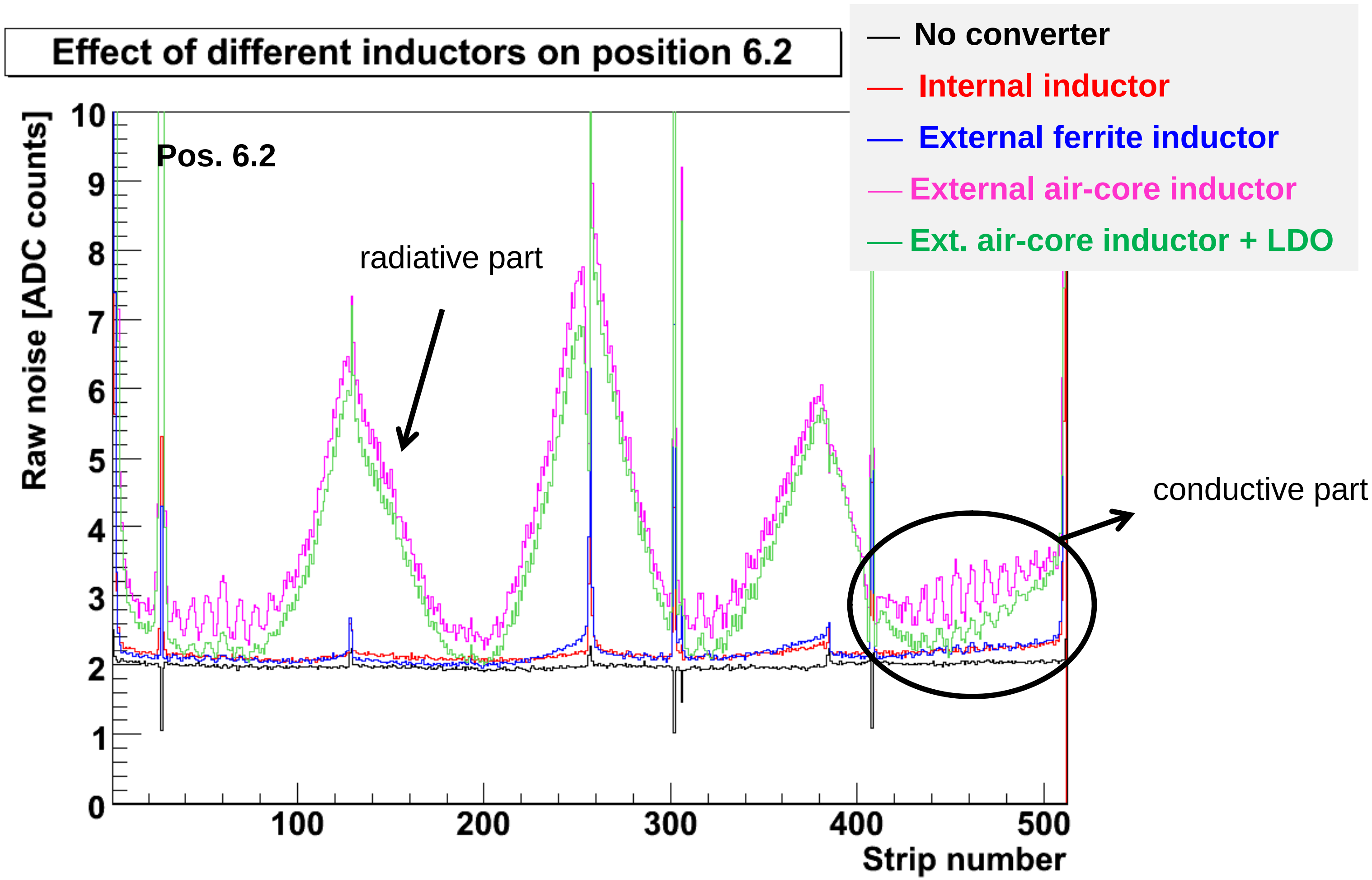
- Enpirion EN5312QI
  - switching frequency fs ≈ 4 MHz
  - Vin = 2.4V – 5.5V (rec.) / 7.0V (max.)
  - Iout = 1A
  - integrated planar inductor



- Enpirion EN5382D (similar to EN5312QI) operated with external inductor
  - air-core inductor Coilcraft 132-20SMJLB (538nH)
  - ferrite-core inductor Murata LQH32CN1R0M23 (1μH)

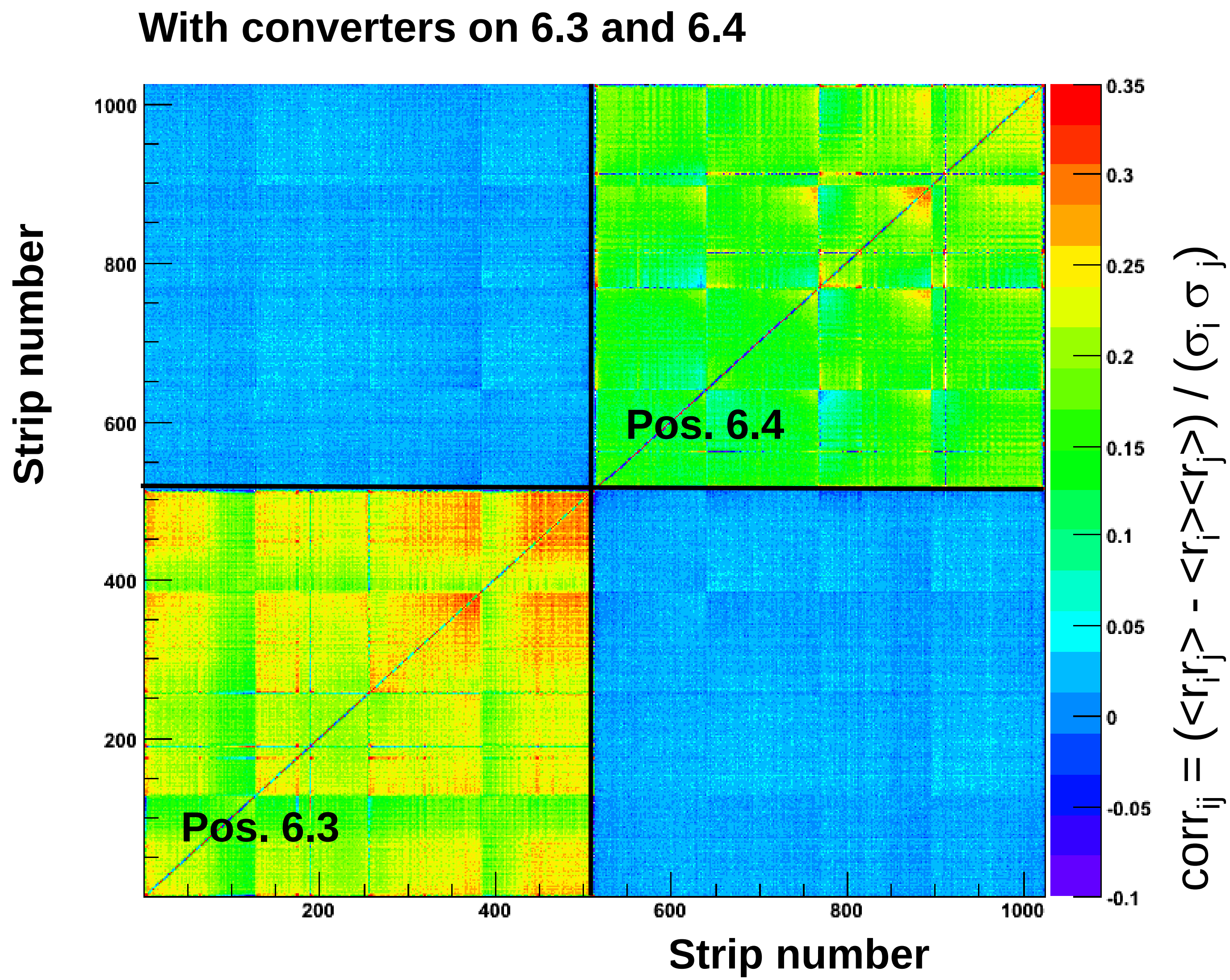
- 4-layer PCB with 2 converters provides 1.25V and 2.5V
  - Input power (Vin = 5.5V) provided externally or via TEC motherboard
  - Various designs: type L: larger board with integrated connector, type S: smaller board with separate connector

System Test with Commercial DC-DC Converters



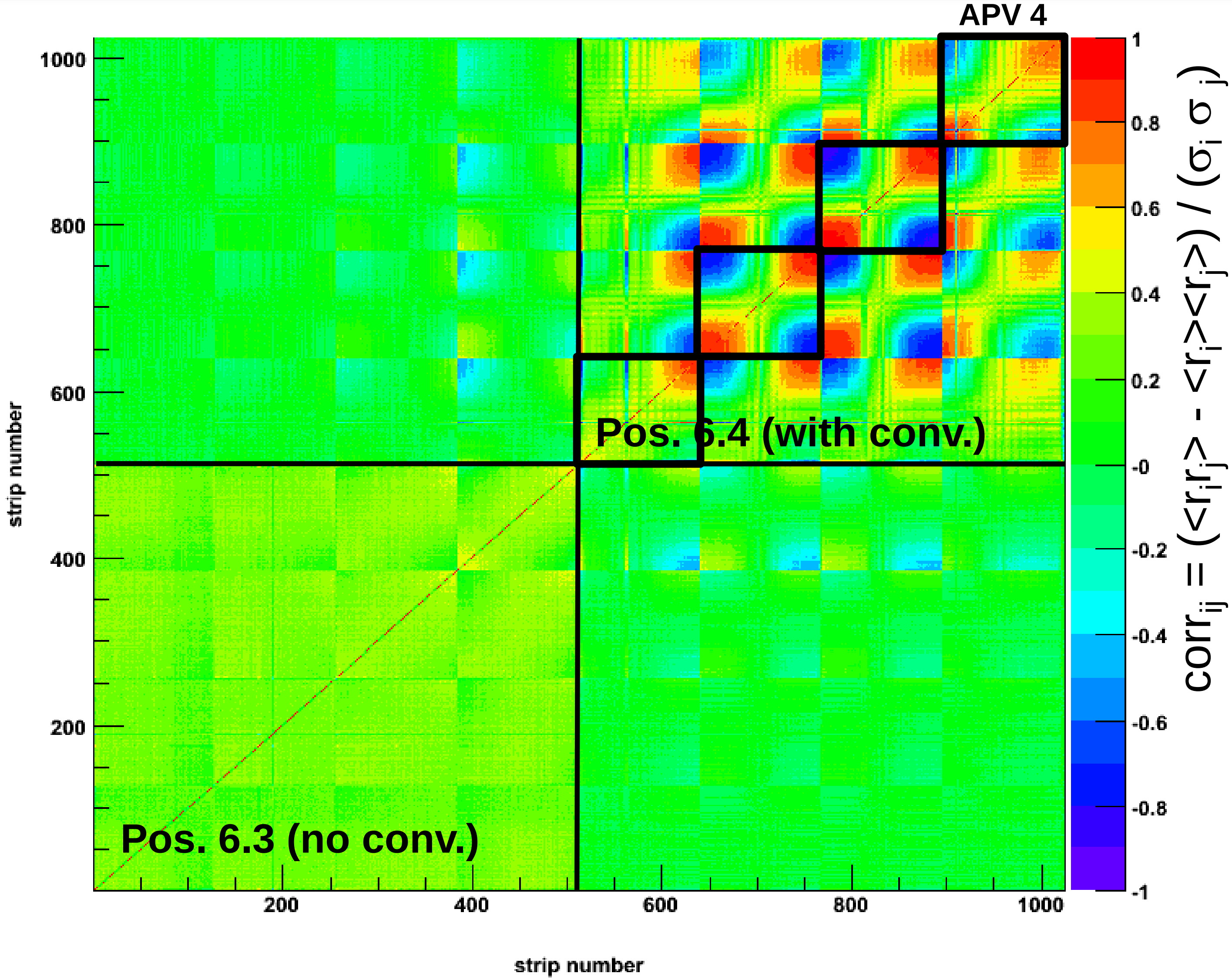
- internal or external ferrite core inductor: 10% noise increase
- air-core inductor: huge noise increase, interference with module both radiative and conductive
- “radiative part” can be reproduced by an air core coil converter (not connected to a module) above hybrid
- “conductive part” can be reproduced by noise injection into the cables (see later)

Channel-to-channel Correlation with internal Ferrite-core Coils



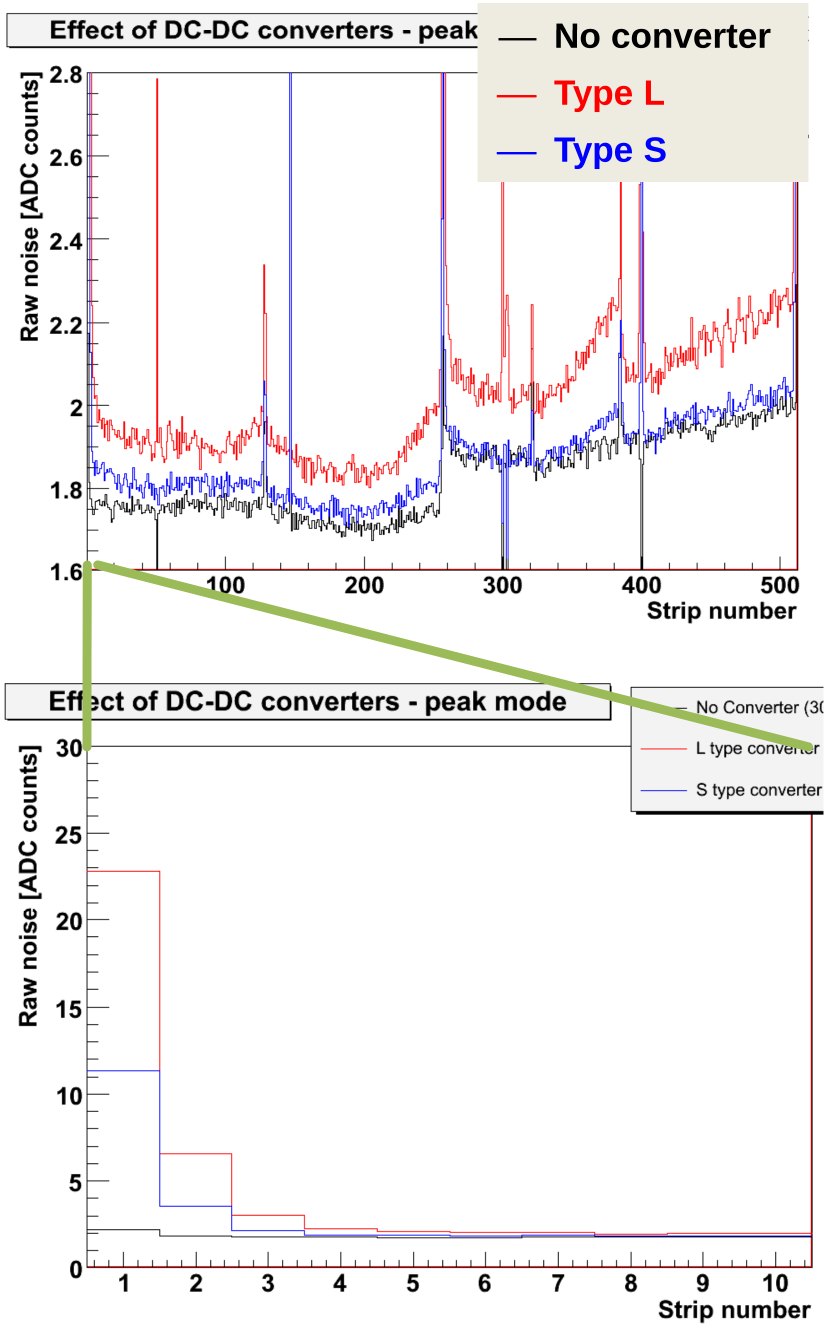
- correlated noise within each module
- no correlation between modules

Channel-to-channel Correlation with Air-core Coils

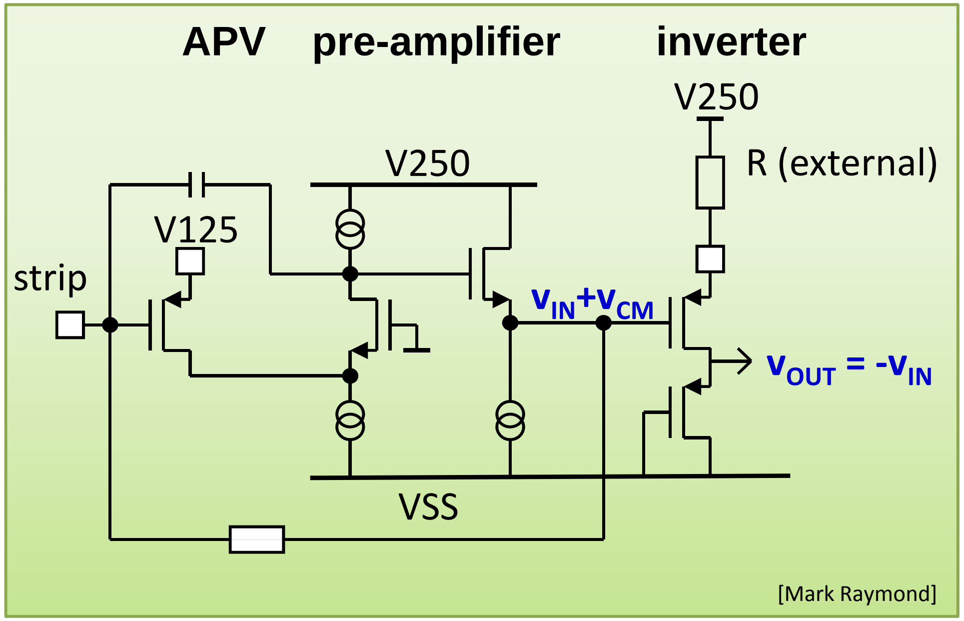


- left and right side of each APV are strongly anti-correlated
  → linear common mode with slope changing event-by-event
- correlated noise also on neighboring module

APV Lesson 1: on chip common mode subtraction

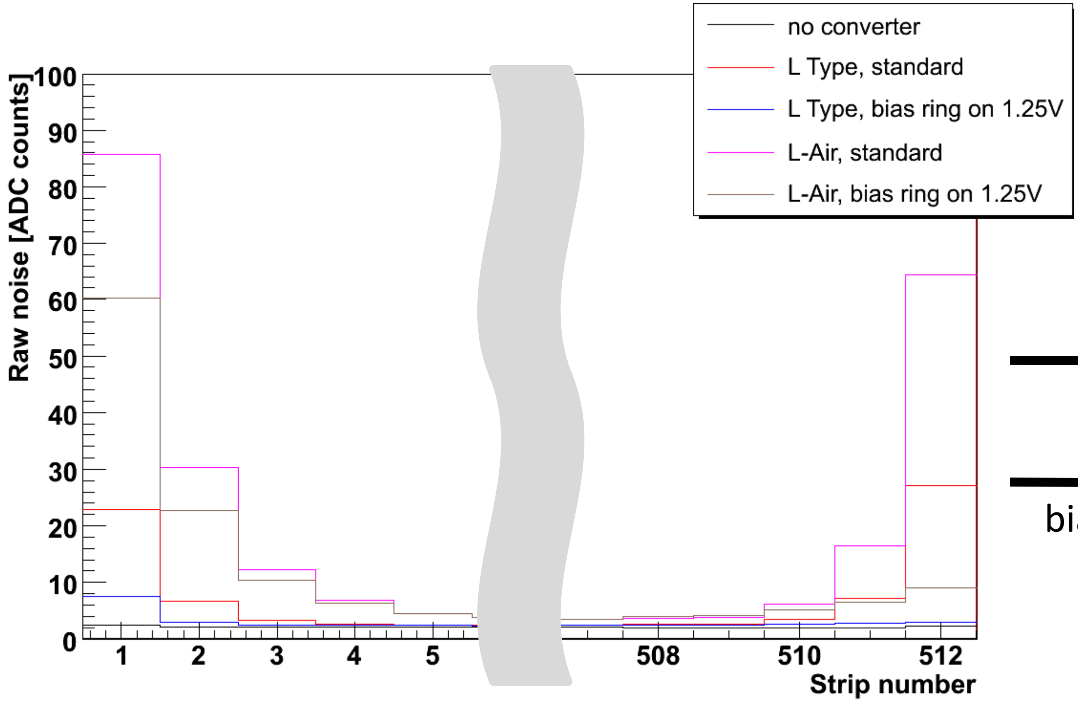


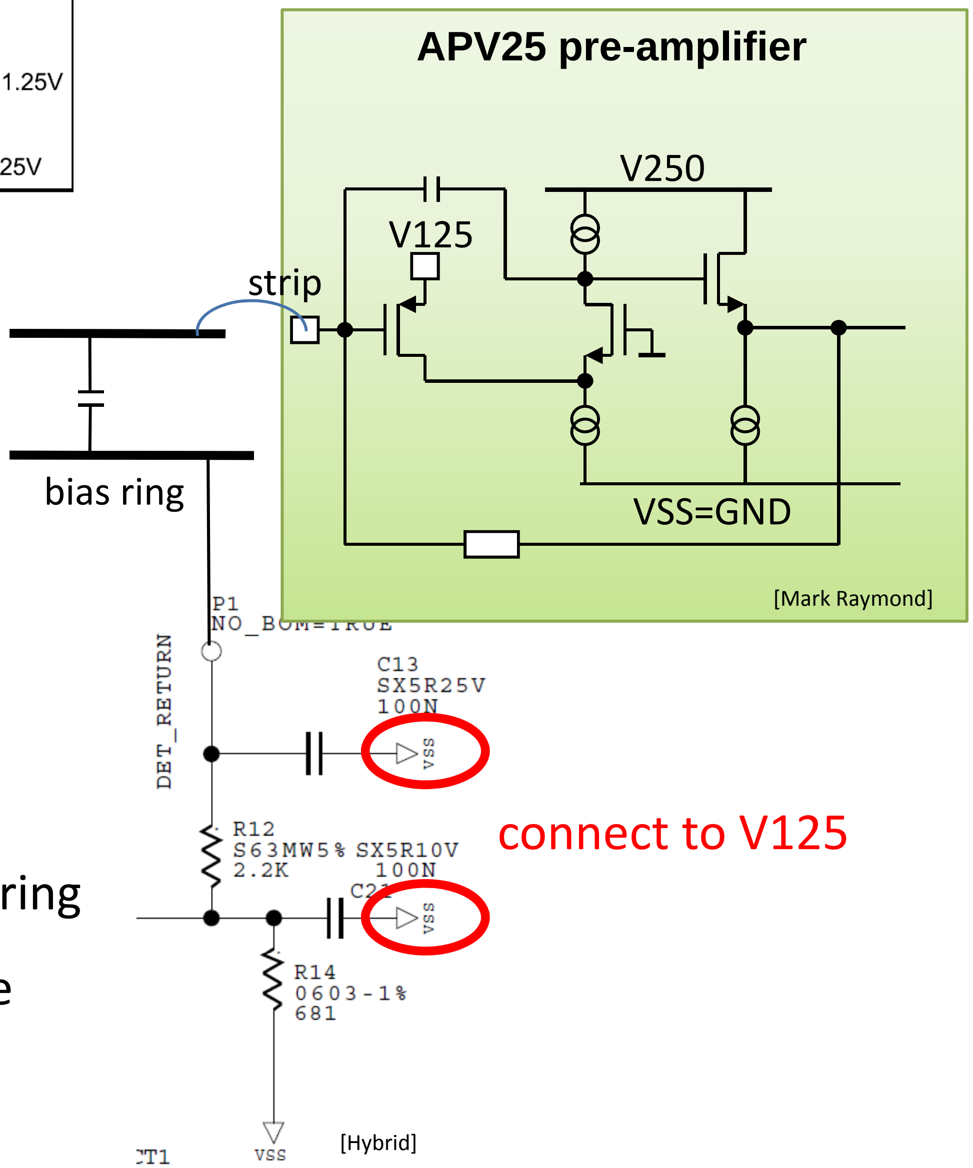
- APV contains on-chip common mode noise subtraction
- there can be more common mode noise than the output data show
- output for irregular channels is affected by this common mode subtraction:
  - un-bonded (low noise) channels become noisy
  - higher common mode on edge channels is not fully subtracted
- un-bonded channels indicate true common mode noise



APV Lesson 2: module edge strip noise

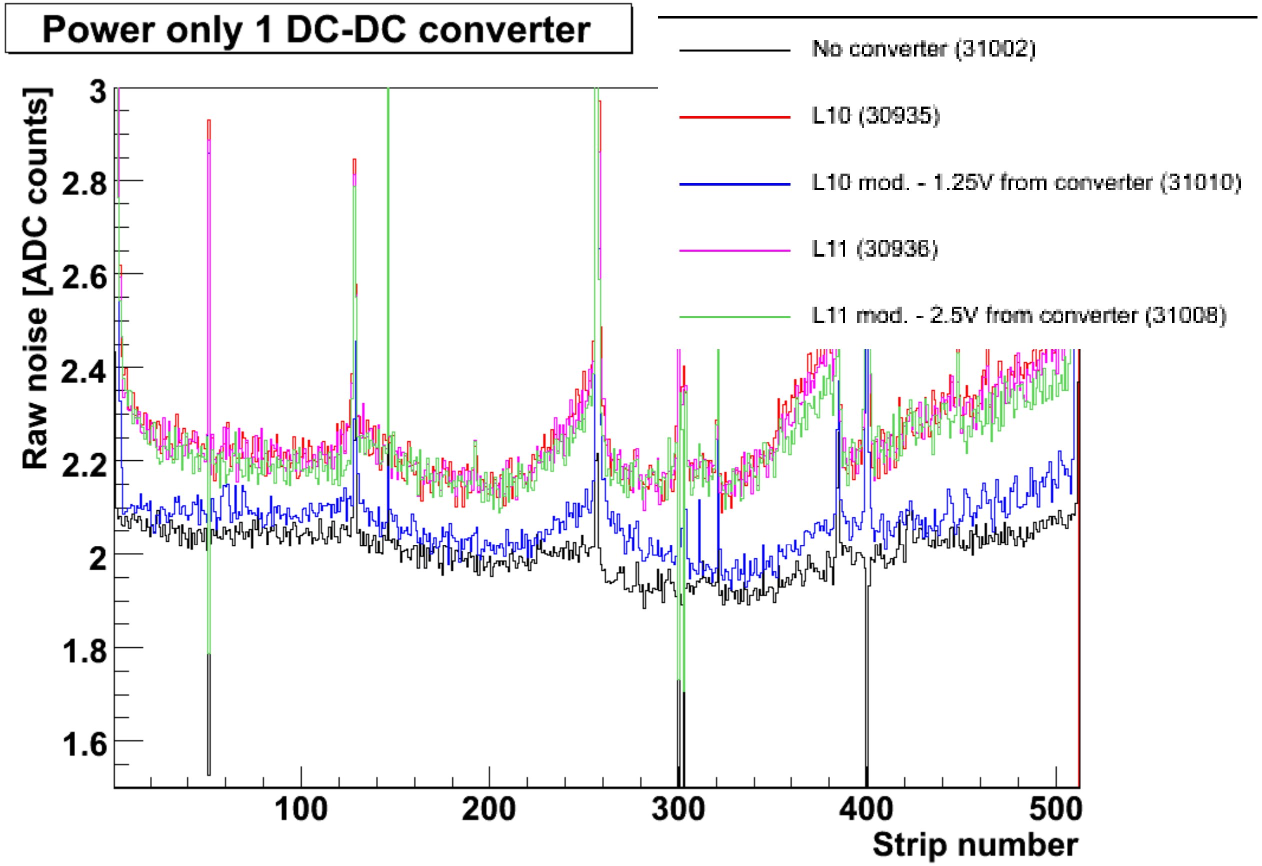
- compare AC referencing of sensor bias ring to either GND or V125 on the hybrid

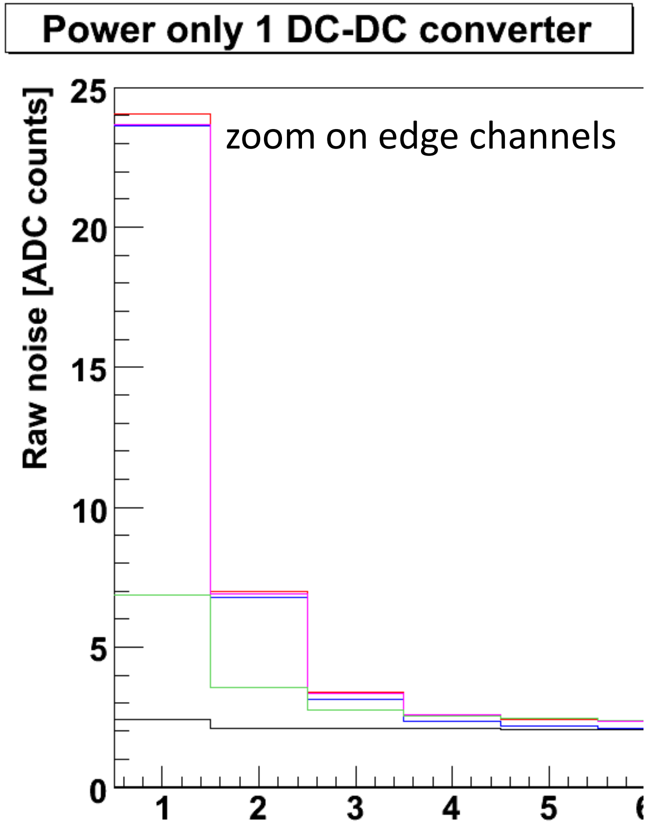




- module edge strips are noisier because of their capacitive coupling to the sensor bias ring which is AC referenced to hybrid GND in the current CMS tracker

APV Lesson 3: compare noise on 2.5 V and 1.25V line



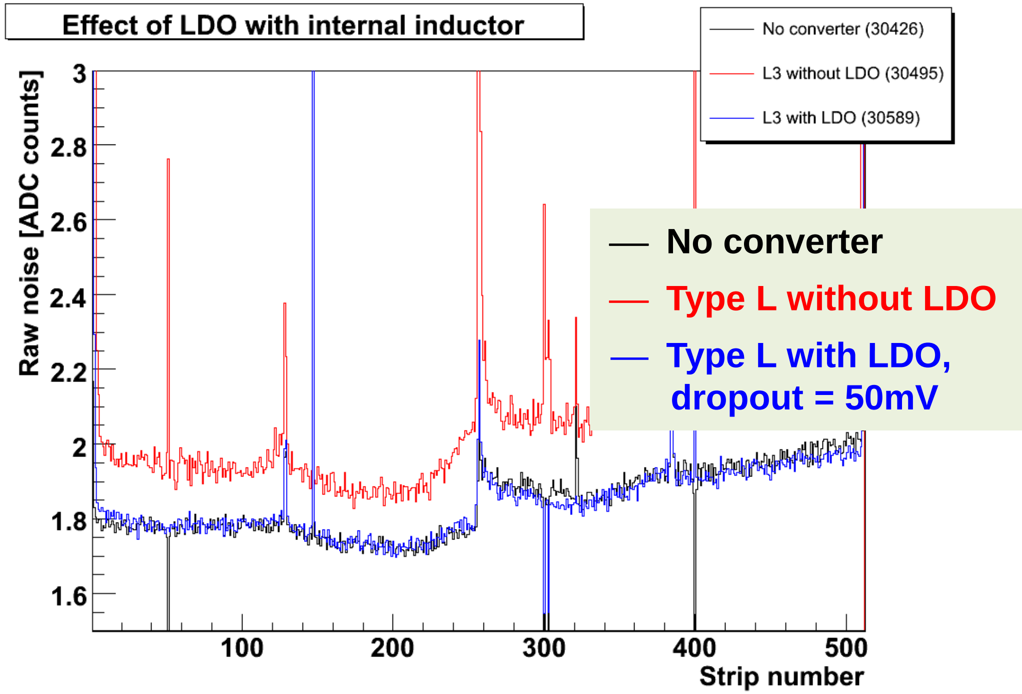


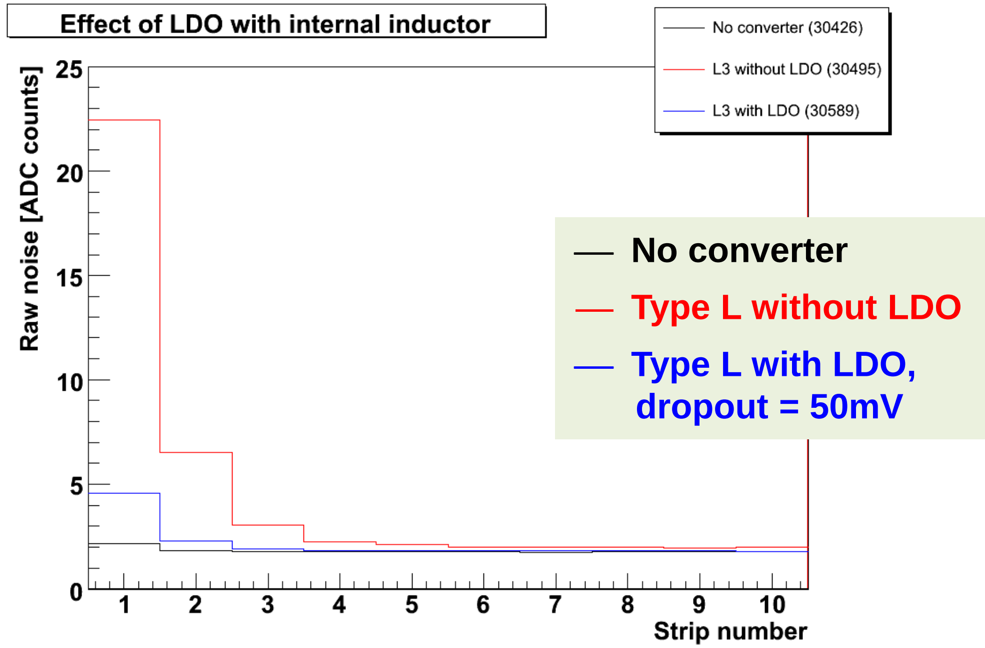
- power via converter either on 1.25 V or 2.5 V line (other line powered normally)
- overall noise increase is caused by noise on 2.5 V line

  explanation: noise on 1.25 V line affects mostly the input stage and will be strongly reduced by on chip common mode subtraction
- module edge strip noise most sensitive to 1.25 V line

  explanation: APV lesson 2

Low Drop-Out Regulator

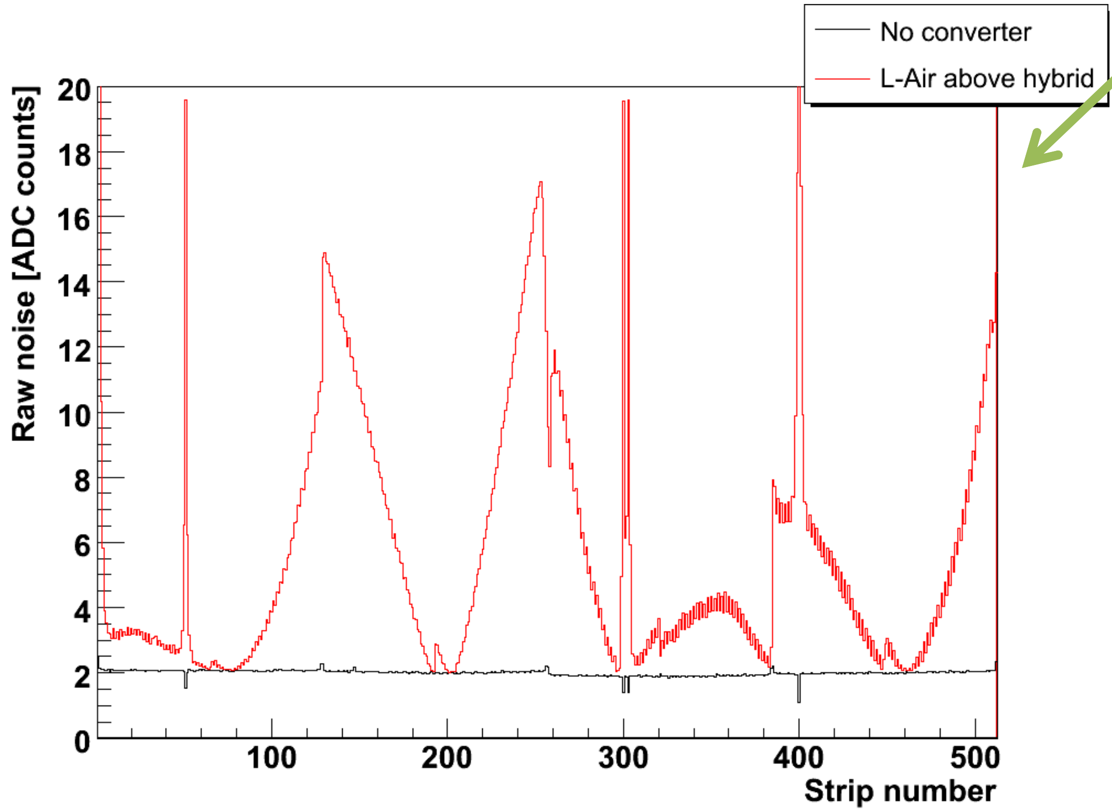


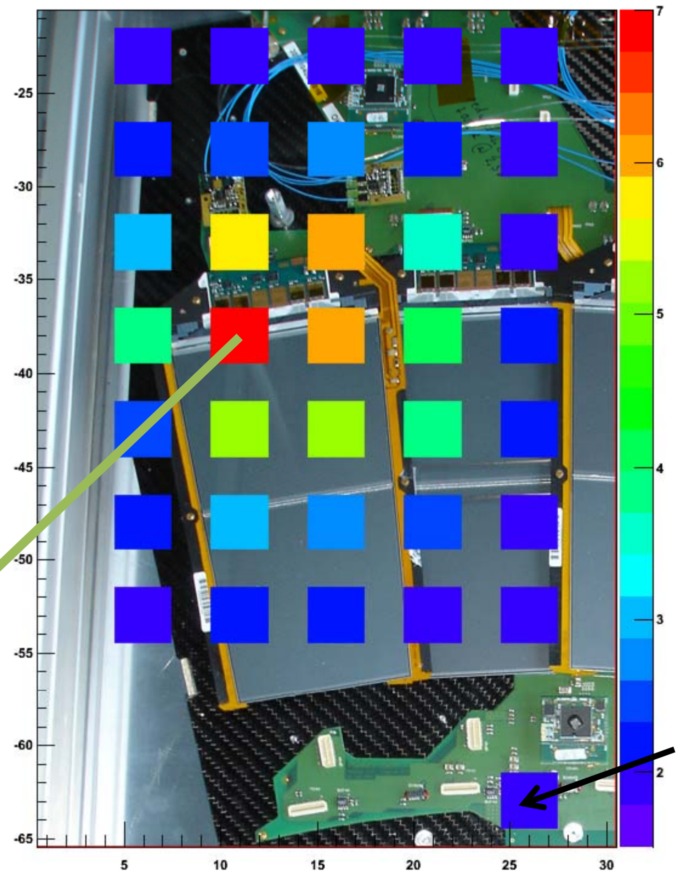


- measurements with ferrite core coils
- connect LDO regulator LTC3026 to output of EN5312QI DC-DC converter
- observation: with ferrite core inductors noise is mainly conductive and differential mode
- radiation hard LDO required

Radiative Interference

- scan across petal with an air-core inductor converter (modules powered w/o converter)
- noise increase due to radiated EM fields, strongest interference close to hybrid

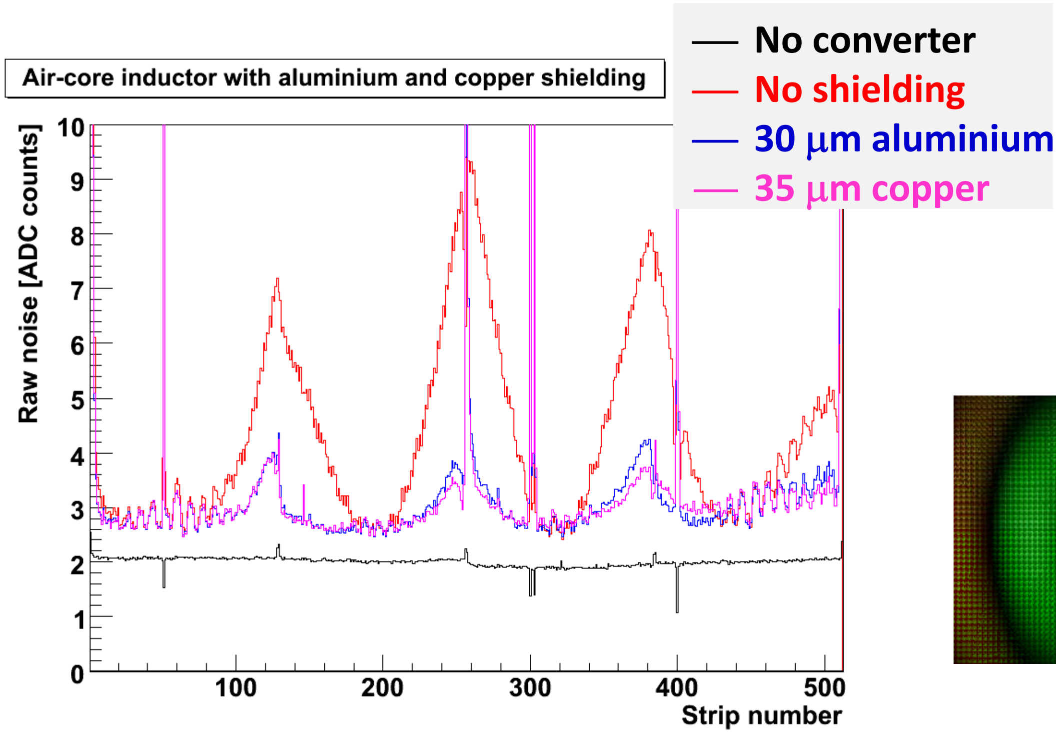


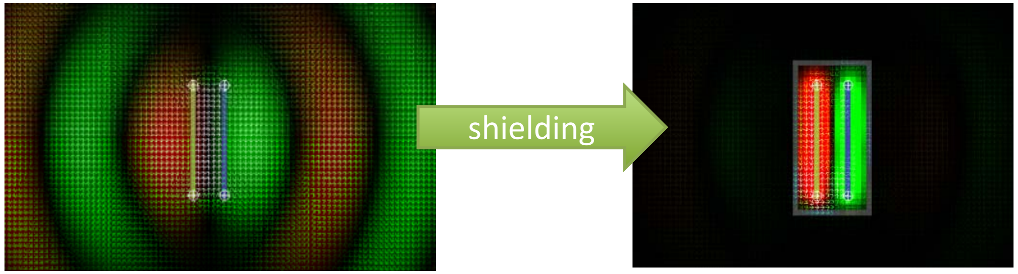


Mean noise of 6.4 [ADC counts]

Reference without converter

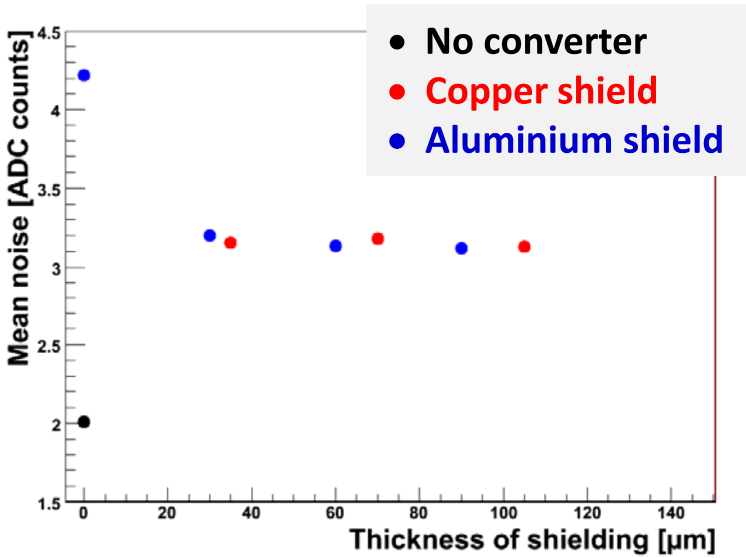
Shielding





[http://www.falstad.com/emwave2/]

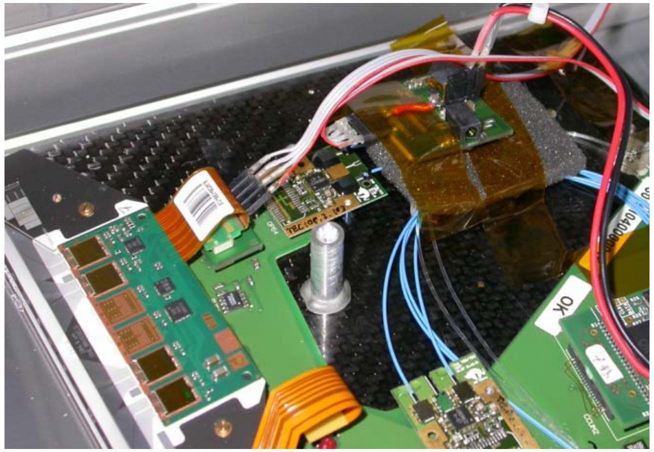
- radiative interference can be eliminated to a large extend by shielding the converter with 30 µm aluminum (no further improvement for thicker shield)
- contribution of 3x3x3cm3 box of 30µm alum. for one TEC: 1.5kg (= 2 per mille of a TEC)

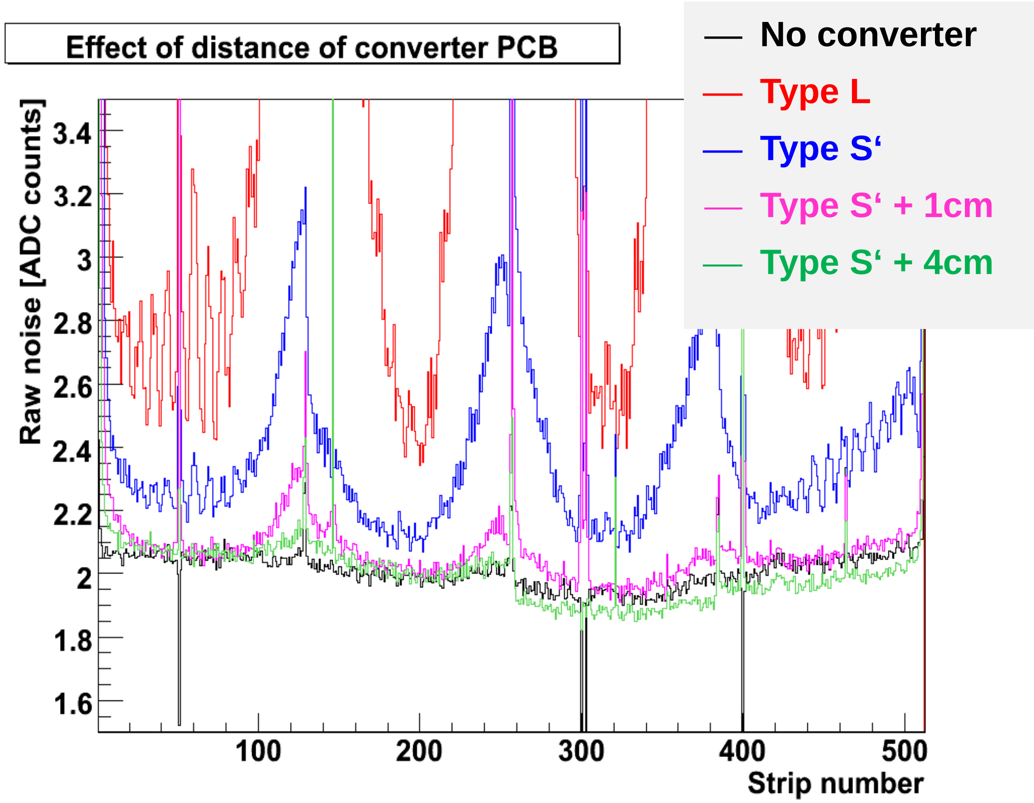


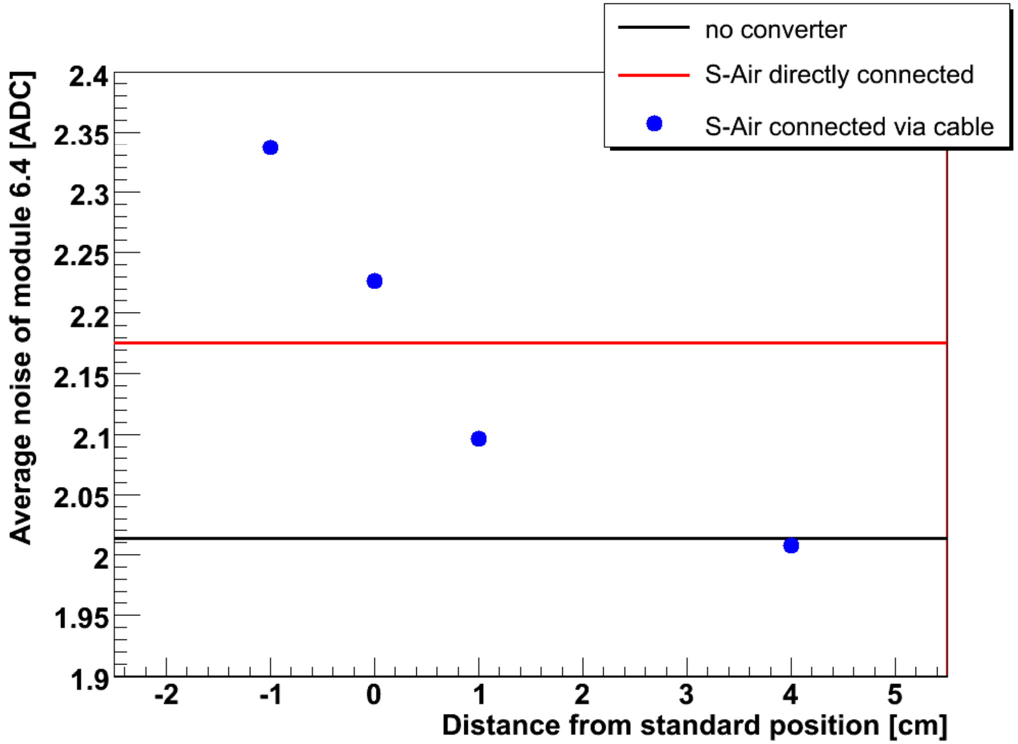
Converter Placement

- measurements with air core solenoids
- noise level depends strongly on distance between converter and hybrid

Type S‘ 4cm further away

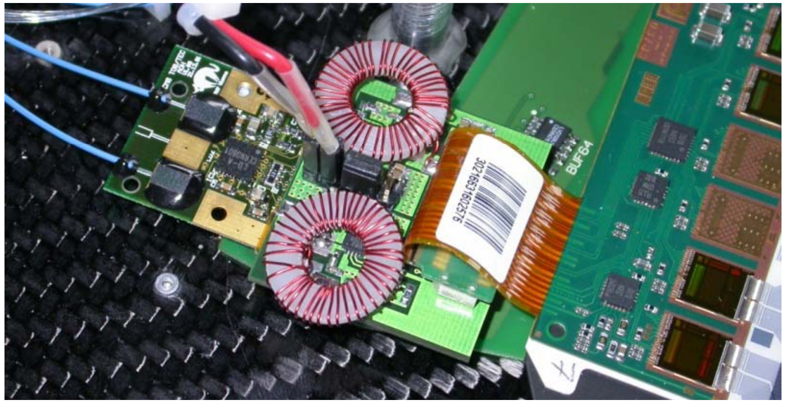




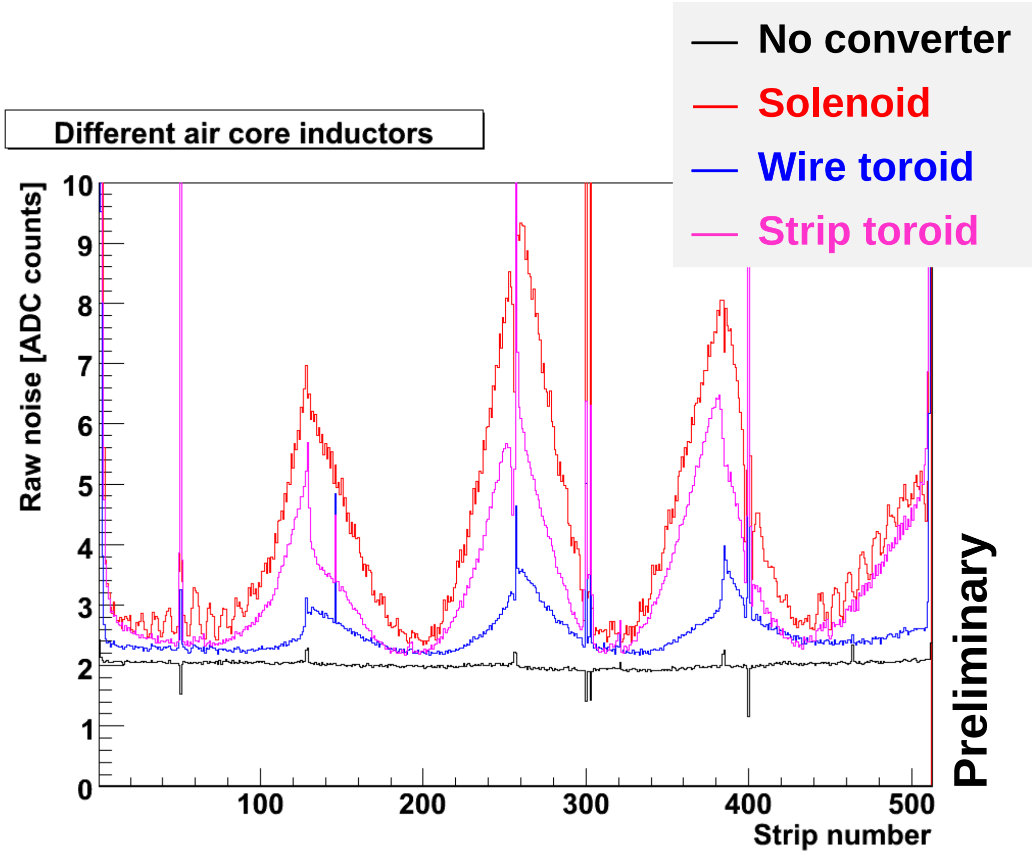


Toroid Inductors

Toroid wound from copper wire

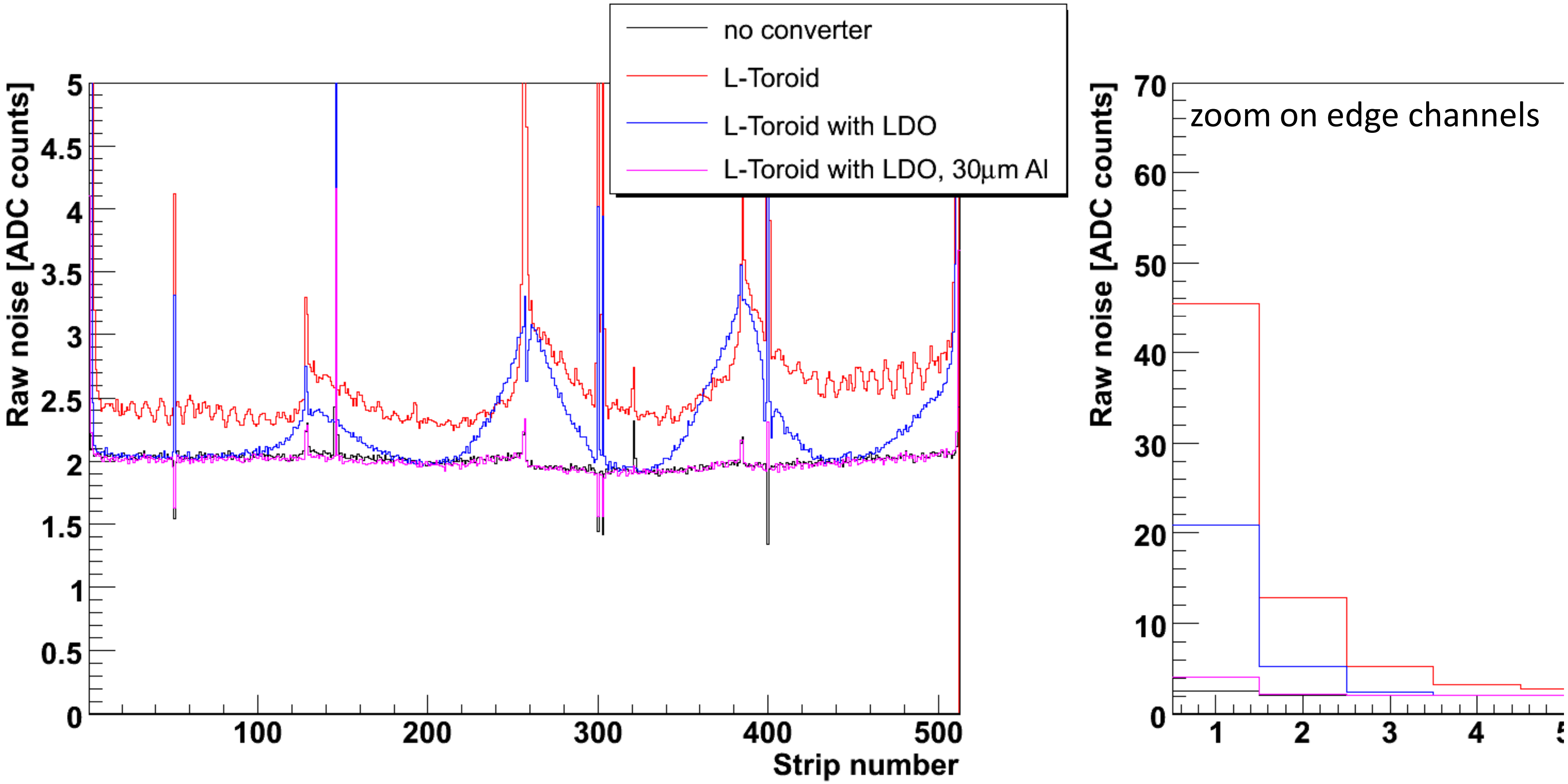


Toroid wound from copper strip



- toroid inductors may radiate less power
- nota bene: interference also depends on location of inductor
- Bristol group working on PCB based toroids

Optmizing the Converter



- Toroid: radiative and conductive noise
- Toroid with LDO: radiative noise
- Toroid with LDO and 30µm aluminum shield: hardly any noise increase (!)
- need to test solenoid with LDO and shielding

CERN Buck Converter

- collaboration with CERN PH-ESE group (F. Faccio et al.)
- CERN: ASIC development

  RWTH: converter PCB, system tests
- first prototype "SWREG2"

  (AMIS I3T80 0.35µm CMOS) received in August

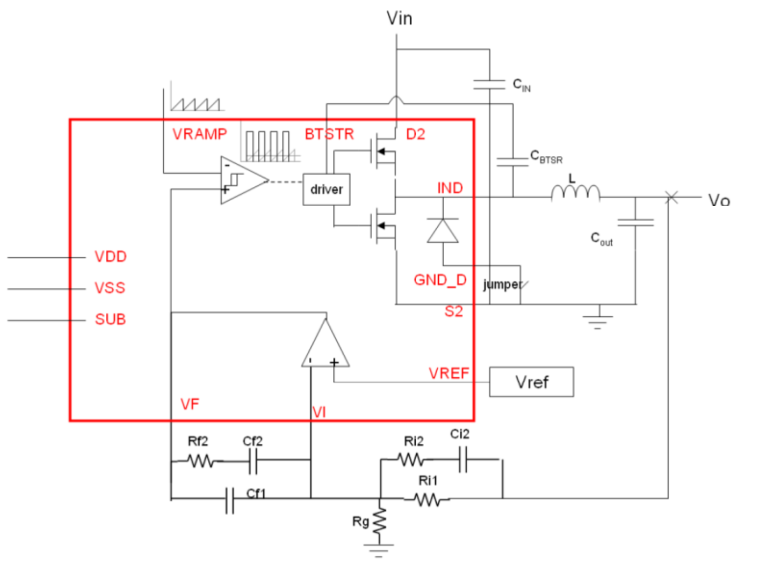
  [**S. Michelis (CERN) et al., *Inductor based switching DC-DC converter for low voltage power distribution in SLHC*, TWEPP 2007.**]

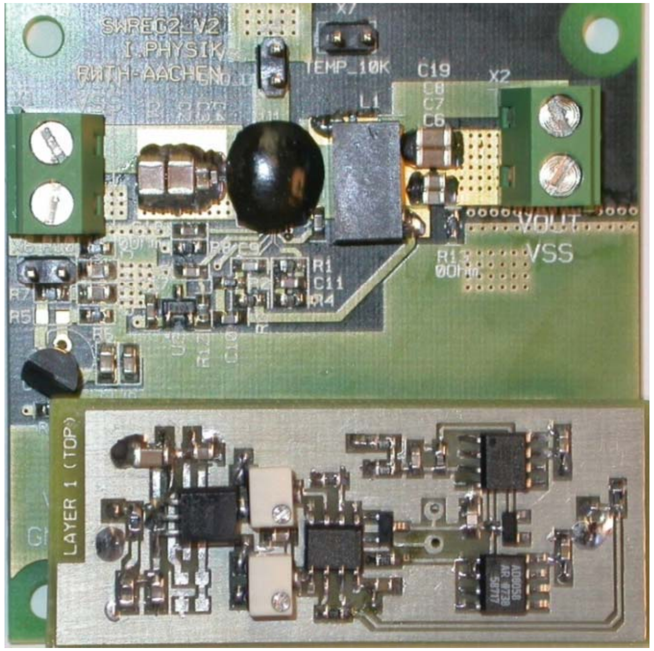
  V_{in} = 3.3 – 20V

  V_{out} = 1.5 – 3.0V

  I_{out} = 1 – 2A

  f_s = 250kHz – 3MHz



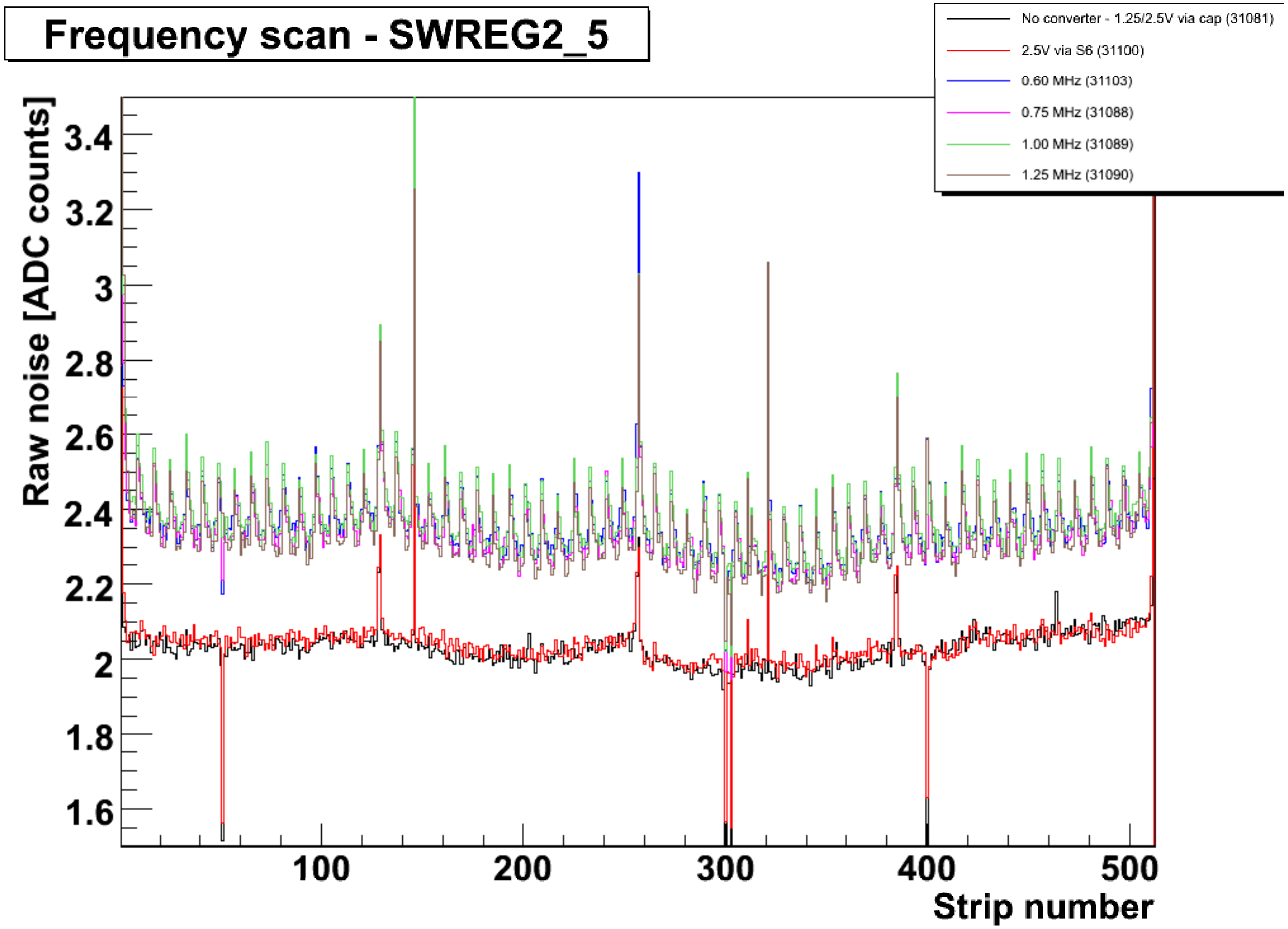


- rad-hard to X-rays, but not to charged particles

  → CERN looking into more rad-hard designs/processes
- first system test results

System Tests with SWREG2

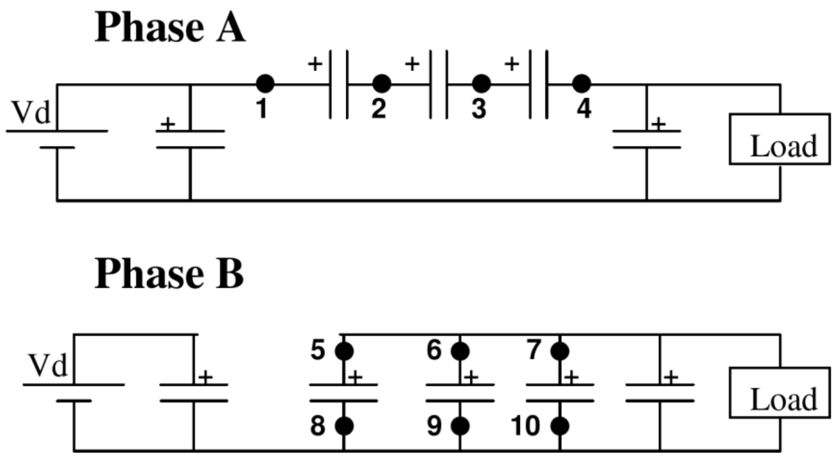
- PCB with air-core coil, but located far away from module ⇒ noise is conductive
- SWREG2 provides 2.5V to chips, 1.25V taken from ICB motherboard
- V_{in} = 5.5V

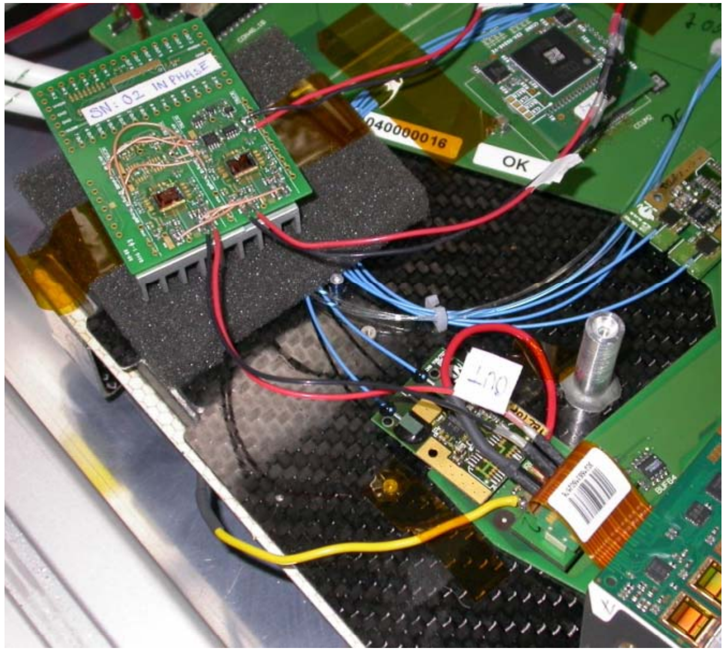


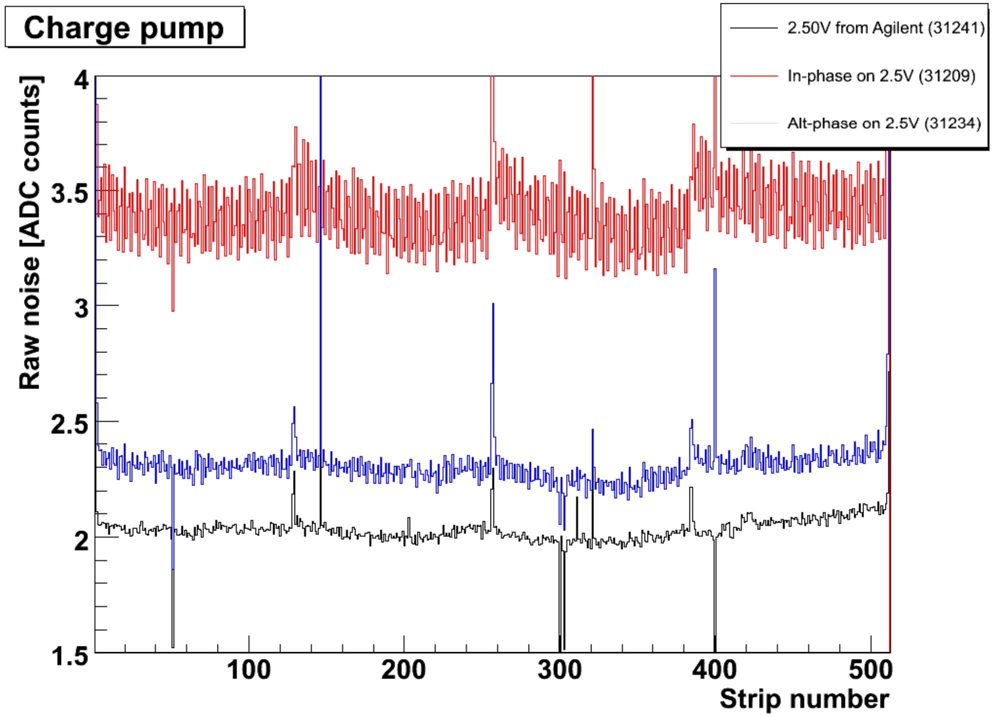
- 15% noise increase
- sawtooth structure introduced by APV multiplexing (APV Lesson 4)
- noise performance not satisfactory

Capacitor Based DC-DC Converter

- **LBNL** Charge Pump: n = 4 prototype IC in 0.35 μm CMOS process (H35) with external 1μF flying capacitors (0.5A, 0.5MHz)
  [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.]
- noise performance not satisfactory

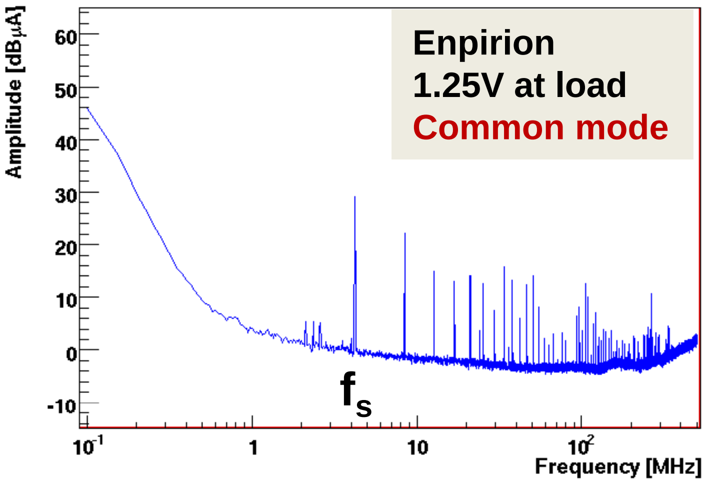


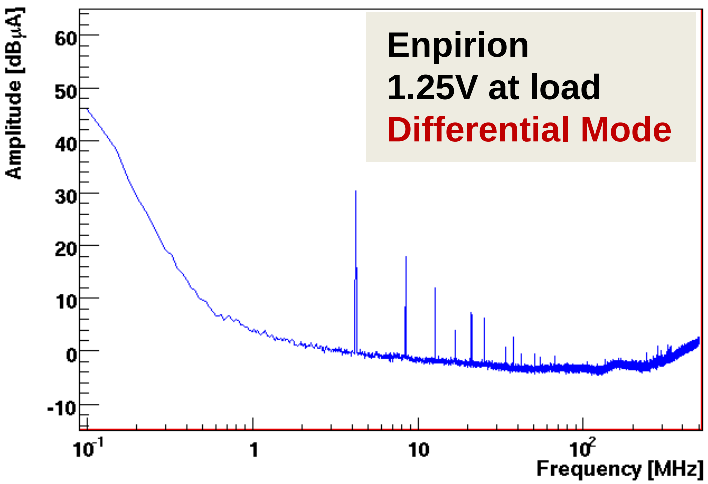


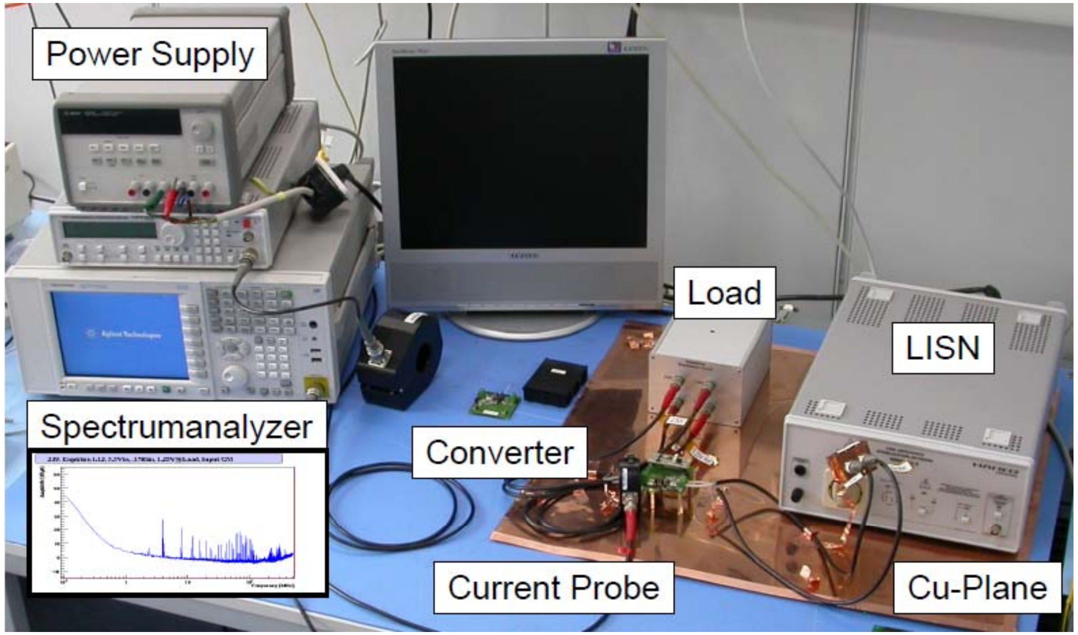


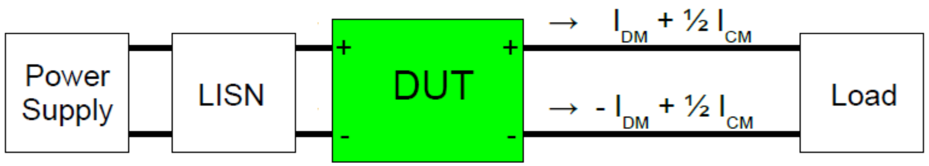
EMI Test Stand

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

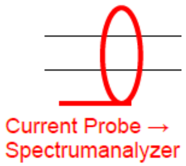






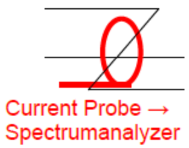


CM-Setup:



$I_{DM} + ½ I_{CM} - I_{DM} + ½ I_{CM} = \mathbf{I_{CM}}$

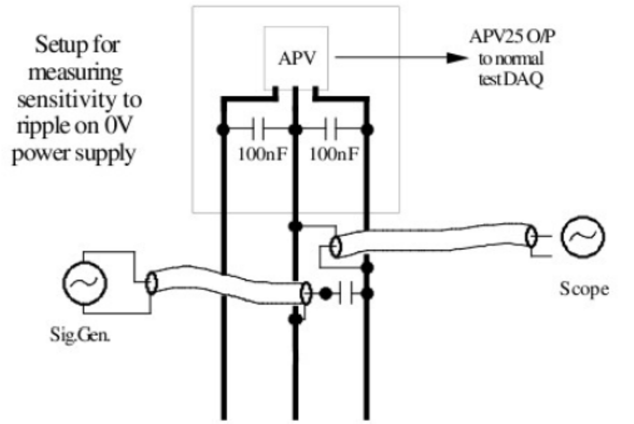
DM-Setup:



$I_{DM} + ½ I_{CM} - (- I_{DM} + ½ I_{CM}) = \mathbf{2 \cdot I_{DM}}$

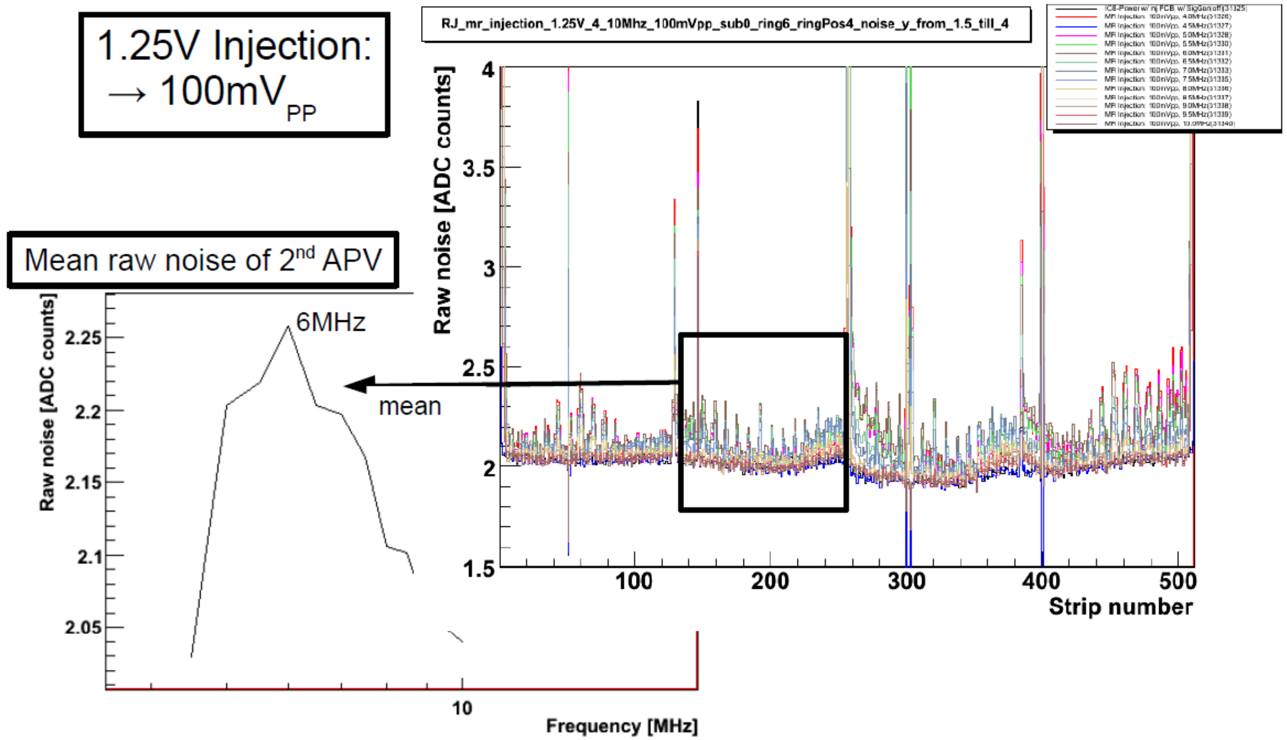
Differential Noise Injection into Power Lines

Example configuration for 1.25V ripple injection



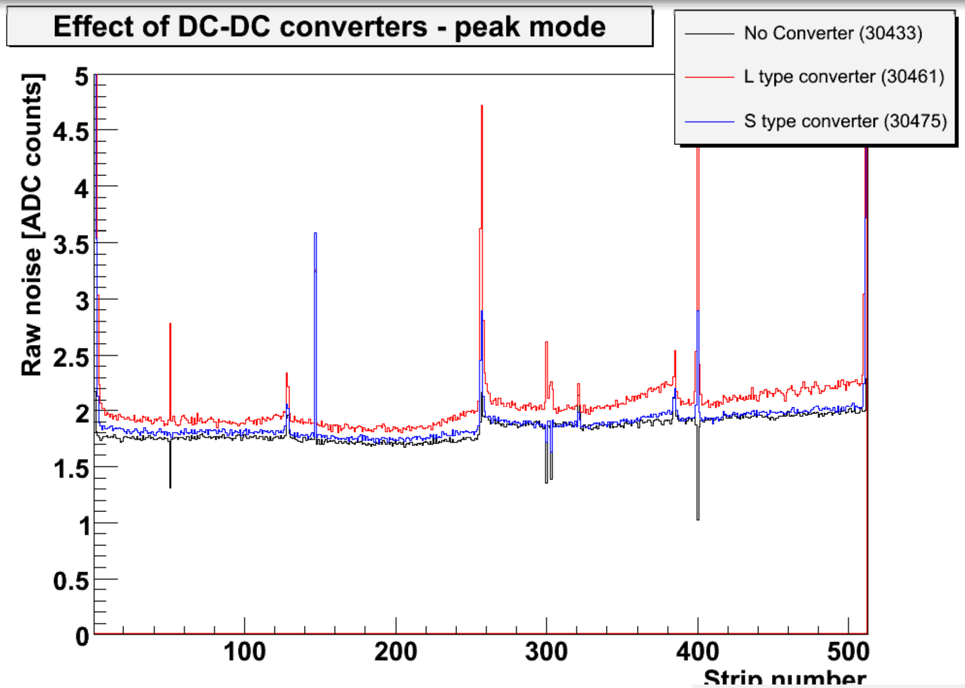
[Mark Raymond]

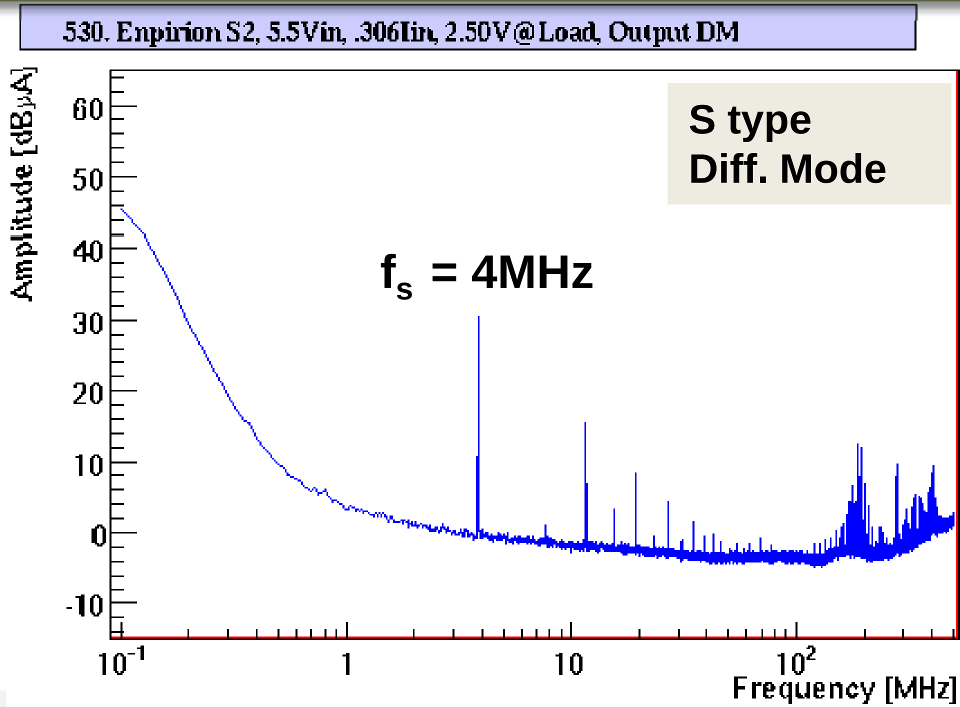
1.25V Injection:
→ $100mV_{PP}$

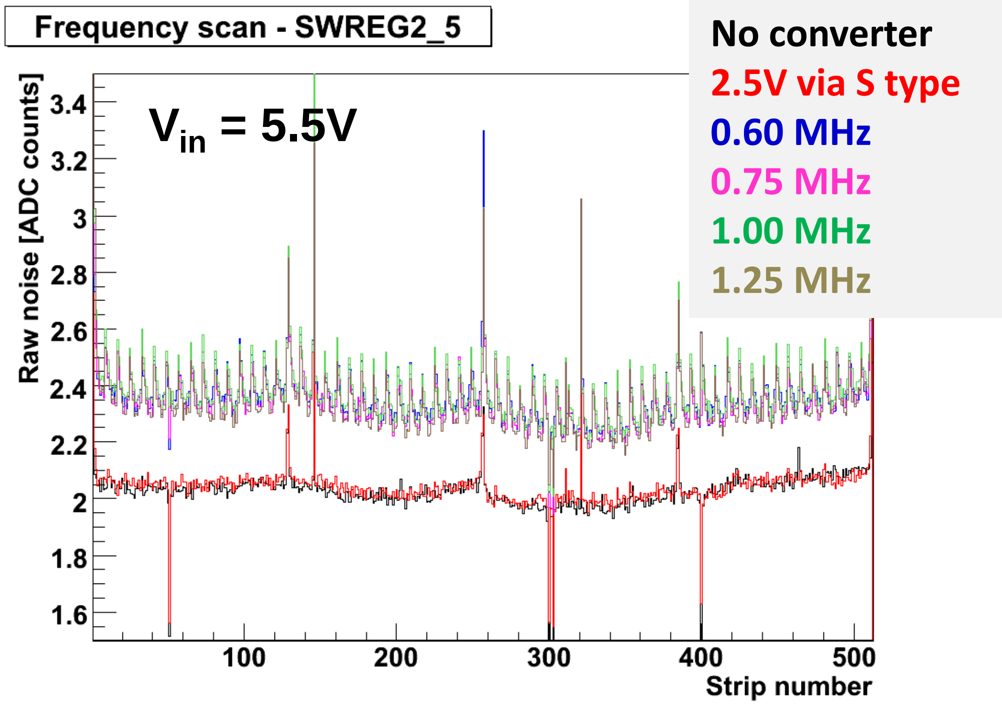


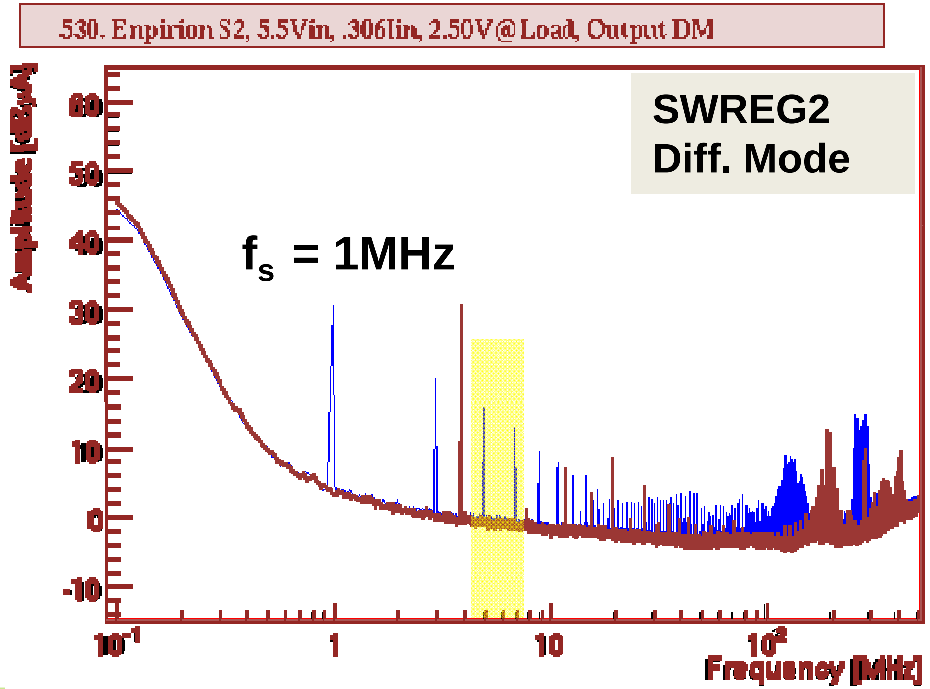
- inject differential noise into 1.25 V line via capacitor
- modules on a petals appear to be most sensitive to noise around 6 MHz
- similar result for injection into 2.5 V line

Frequency Spectrum vs. Noise



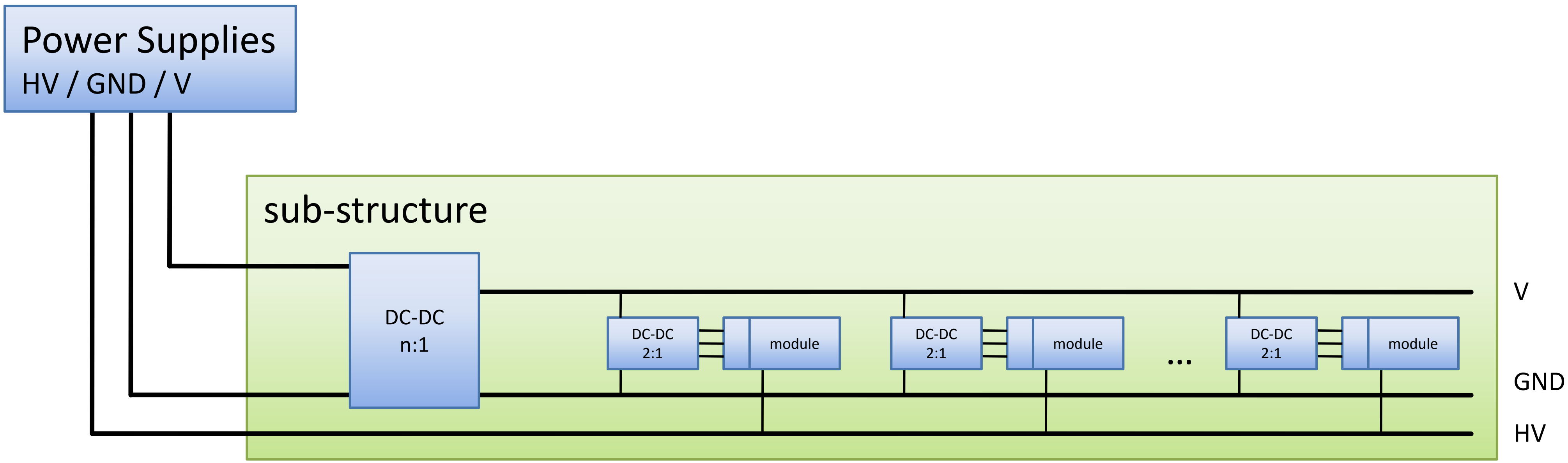






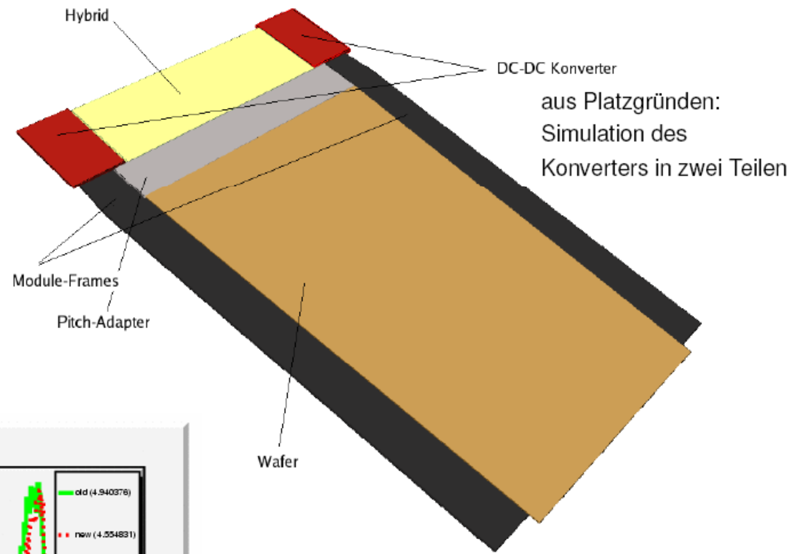
Possible Power Distribution of a SLHC Tracker Sub-Structure

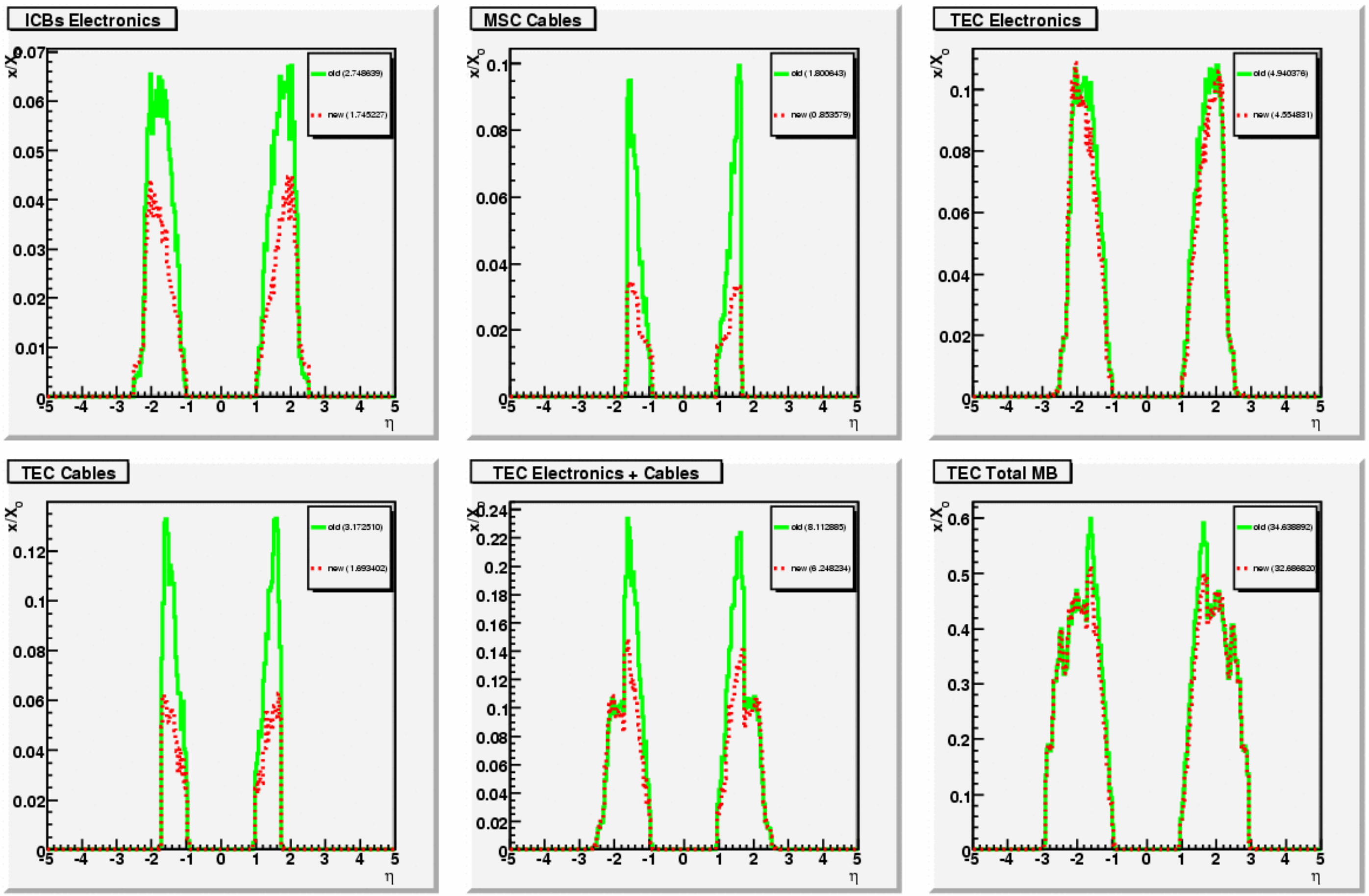
- n:1 conversion at edge of sub-structure using buck converter
  - seems feasible from EMI point of view
  - power loss in supply cables decreased by factor n^2 * (conversion efficiency)^2
- additional 2:1 conversion at each module/FE-ASIC would further decrease cable losses and allow for reduction of copper on sub-structure ICB
  - for buck converter EMI might be tolerable with shielding and LDO
  - charge pump ?



Material Budget

- implement changes to material budget into Geant4 model of current tracker (so far only TEC considered)
- in this example one 10:1 converter per module: total TEC material budget reduced by 5.6%





Summary

- novel powering schemes are mandatory for SLHC tracker
- DC-DC conversion offers required supply currents while keeping system layout simple
- system test measurements with DC-DC converters have been performed
- many symptoms in current test system are due to actual APV25 (and hybrid) layout
  - might be different for the SLHC FE ASIC
  - some understanding achieved
- switching noise of buck converters can be controlled even with air core inductors when converter is not too close to FE hybrid and/or shielded
- radiation hard switch still to be developed

Outlook

- gain better understanding of correspondence between converter noise spectra and noise induced into the modules
- optimize buck converter by improved inductor and shielding design
- evaluate “interleaved buck converter”
- develop radiation hard converter ASIC (CERN)
- further tests of charge pumps
- follow closely the developments on serial powering