CMS Upgrade Workshop – Fermilab, 30th of October, 2009

DC-DC Converter Development at RWTH Aachen University

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Federal Ministry of Education and Research

SLHC-PP 2008 • 2011 PREPARATORY PHASE LARGE HADRON COLLIDER UPGRADE

RWTH AACHEN UNIVERSITY

Outline

→ This talk only coveres the R&D with commercial converter ASICs

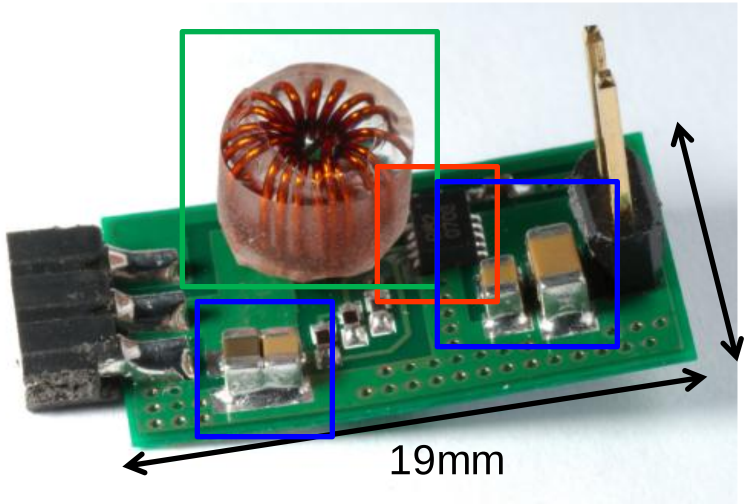
- Aachen Buck Converters with commercial ASICs

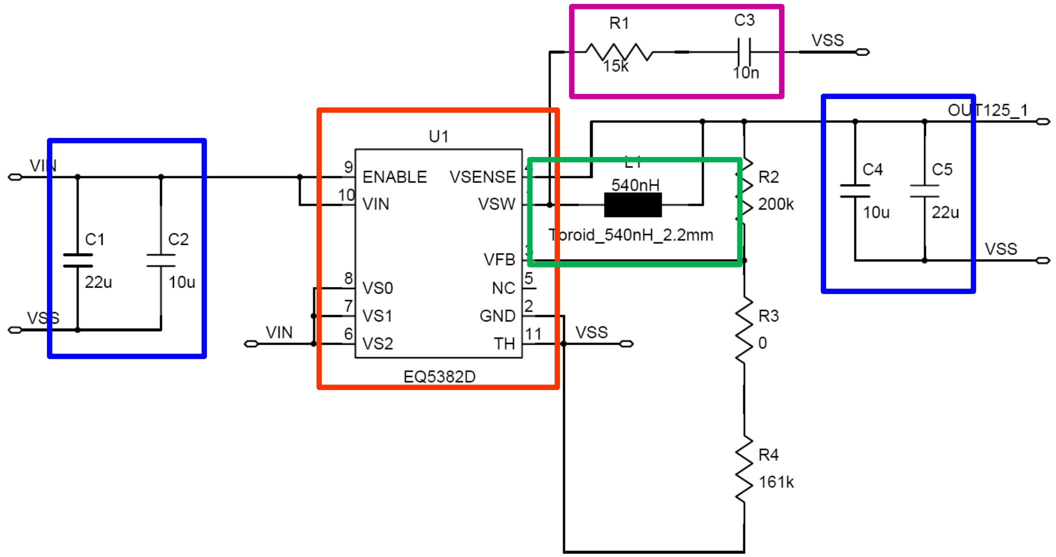
- Efficiency Measurements
- System Test Measurements with Strip Tracker Modules
- Converter Noise Measurements (EMC)

- Summary

Aachen DC-DC Converter PCBs

Idea of Aachen R&D: develop Converters based on **commercial non-radiation-hard** buck converter ASICs; optimize for low mass, low space, low noise; and study in system test





PCB:
2 copper layers a 35µm
FR4 200µm
V = 12x19mm² x 10mm
m = 1.0g

Chip: Enpirion **EQ5382D**
V_{IN} = 2.4-5.5V(rec.) / 7.0V(max.)
$I_{OUT} \leq$ 0.8A
V_{OUT} = 1.30V / 2.55V
$f_S \approx$ 4MHz

External air-core inductor:
Custom-made toroid, ∅ ≈ 6mm
L = 600nH (200nH)
R = 80mΩ (40mΩ)

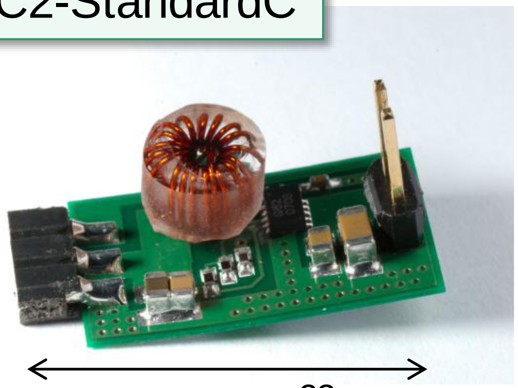
Input / output filter capacitors

Snubber to reduce ringing

New Buck Converter PCBs

Three different converter PCBs → different geometry and filter-capacitor assembly:

AC2-StandardC

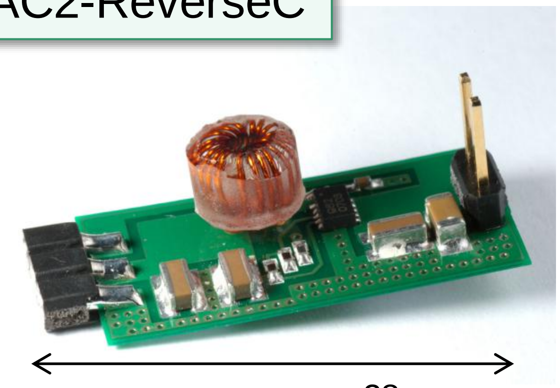


23mm

AC2-StandardC

- Standard capacitors

AC2-ReverseC

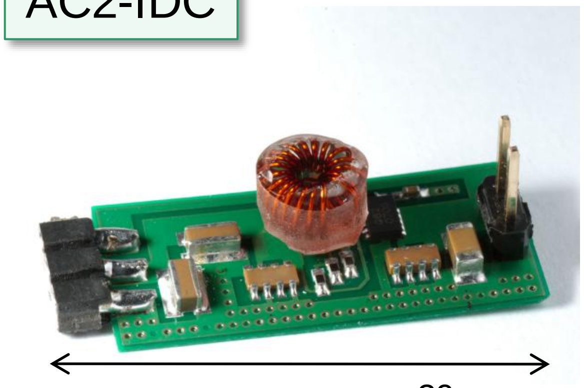


28mm

AC2-ReverseC

- Reverse geometry caps

AC2-IDC

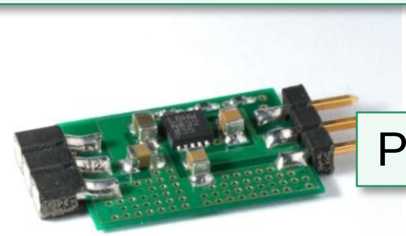


30mm

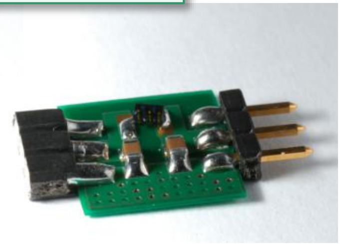
AC2-IDC

- 2 Inter-Digitated Capacitors (IDC) with eight terminals

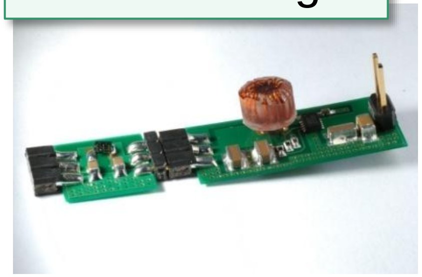
Low Drop-Out (LDO)

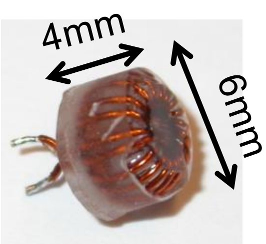


Pi-Filter

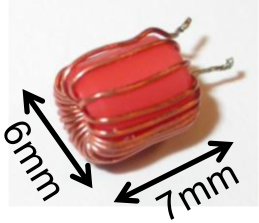


Modular design:





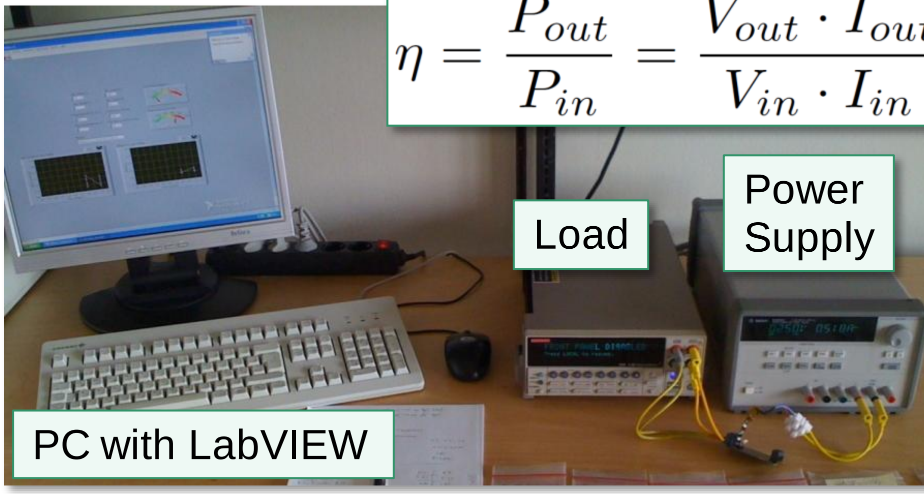
"Tiny Toroid"
L = 200nH
R_{DC} = 40-50mΩ
m = 0.2g



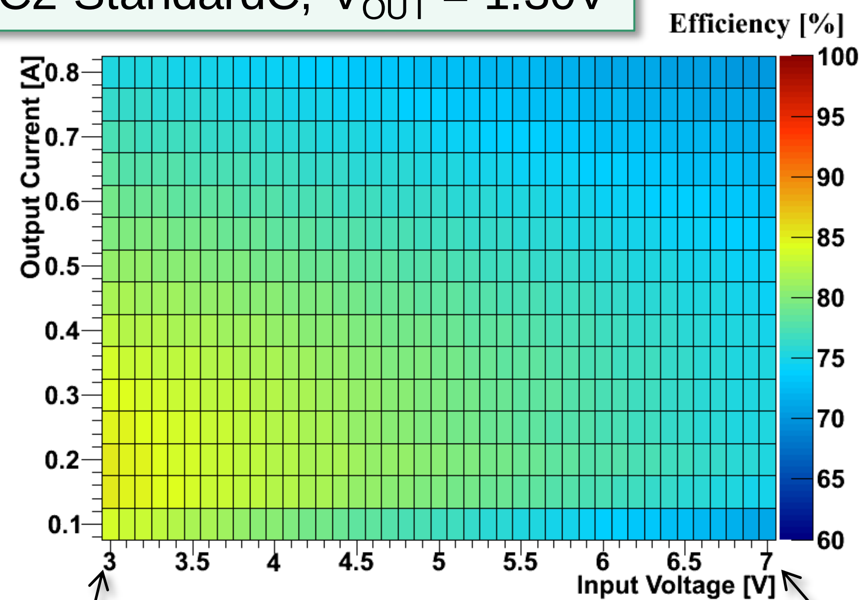
"Mini Toroid"
L = 600nH
R_{DC} = 80-100mΩ
m = 0.3g

Efficiency Measurements

$$\eta = \frac{P_{out}}{P_{in}} = \frac{V_{out} \cdot I_{out}}{V_{in} \cdot I_{in}}$$



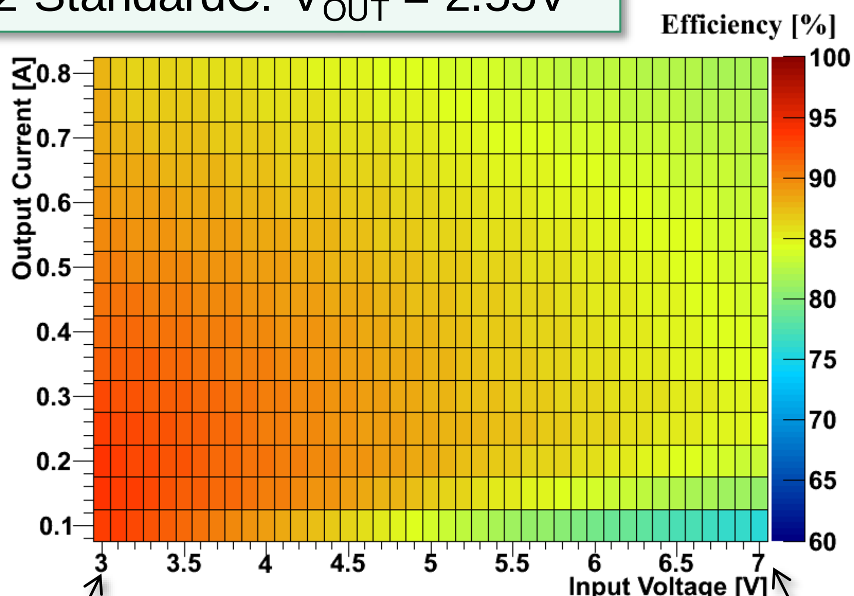
AC2-StandardC, V_{OUT} = 1.30V



r = 2.3

r = 5.4

AC2-StandardC: V_{OUT} = 2.55V



r = 1.2

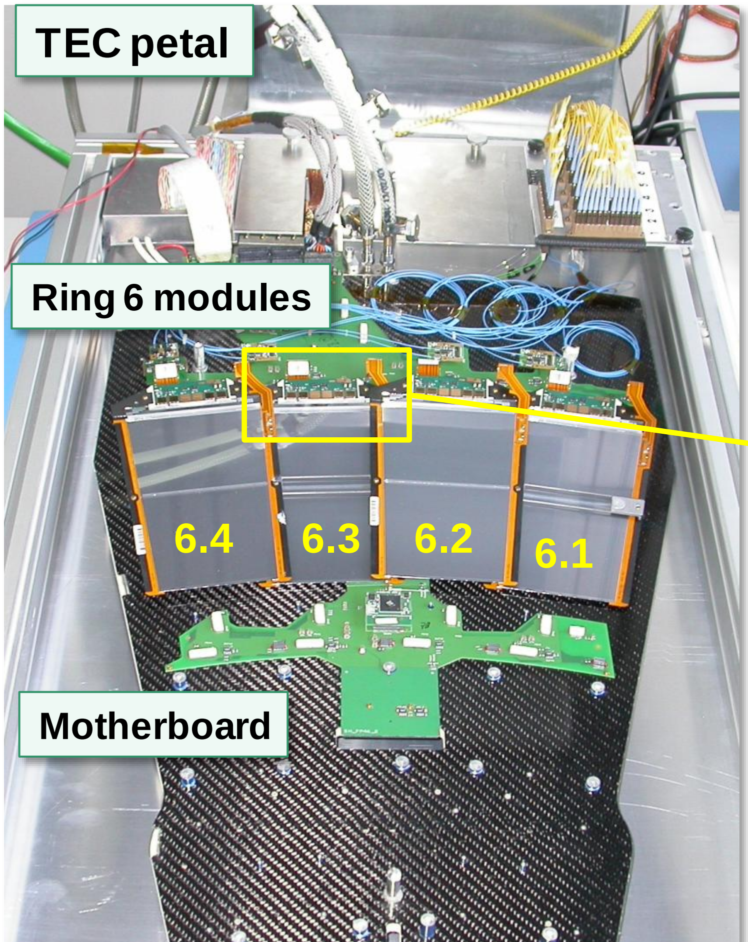
r = 2.7

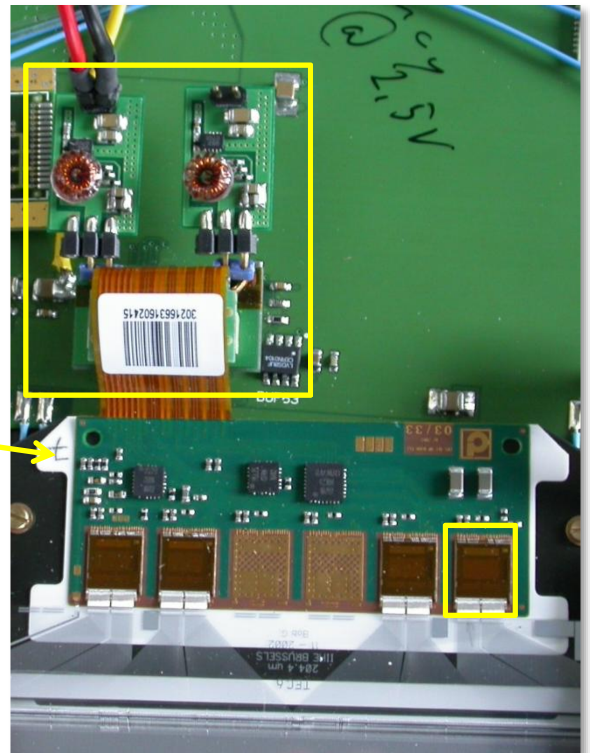
- Inductor: Mini Toroid (L = 600nH)
- Efficiency is 75-85% for V_{OUT} = 1.30V
- For smaller conversion ratio, η is up to 10% higher (V_{OUT} = 2.55V; η = 85-95%)

System Test Set-Up of current Strip Tracker

SLHC readout chips and module prototypes not available before 2010/11

→ We believe a lot can be learned from current CMS strip tracker hardware

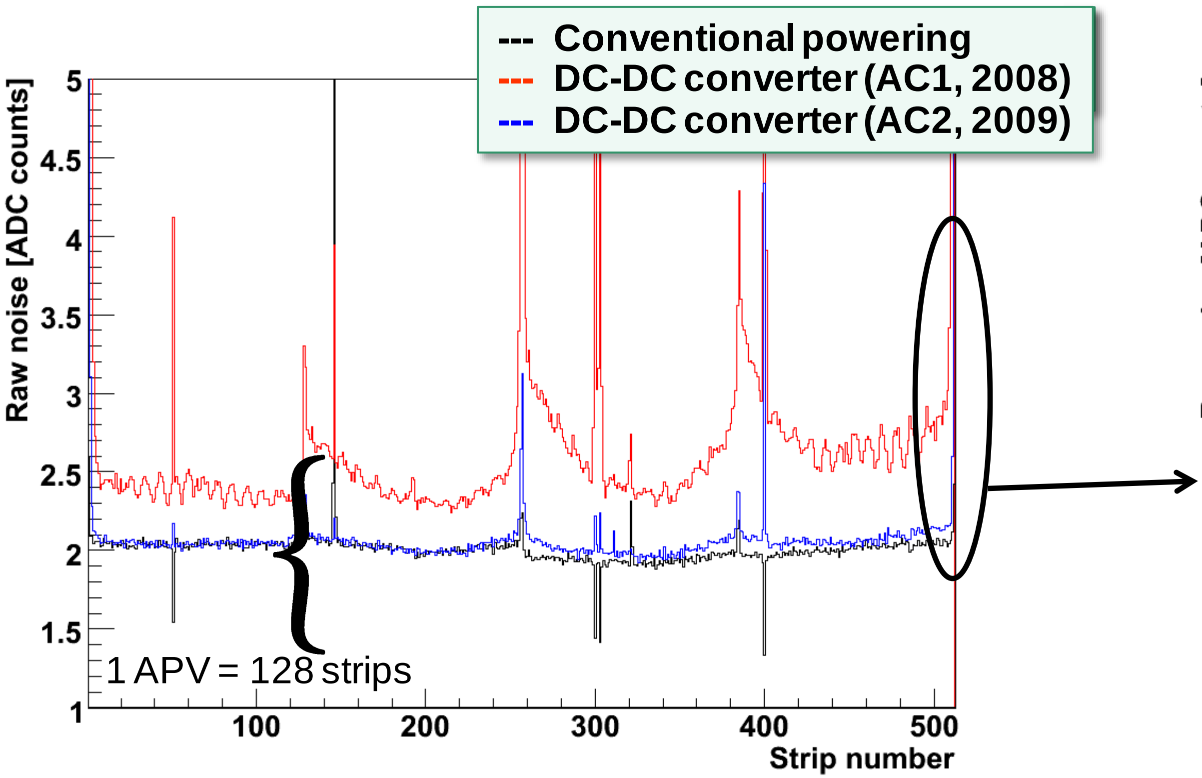


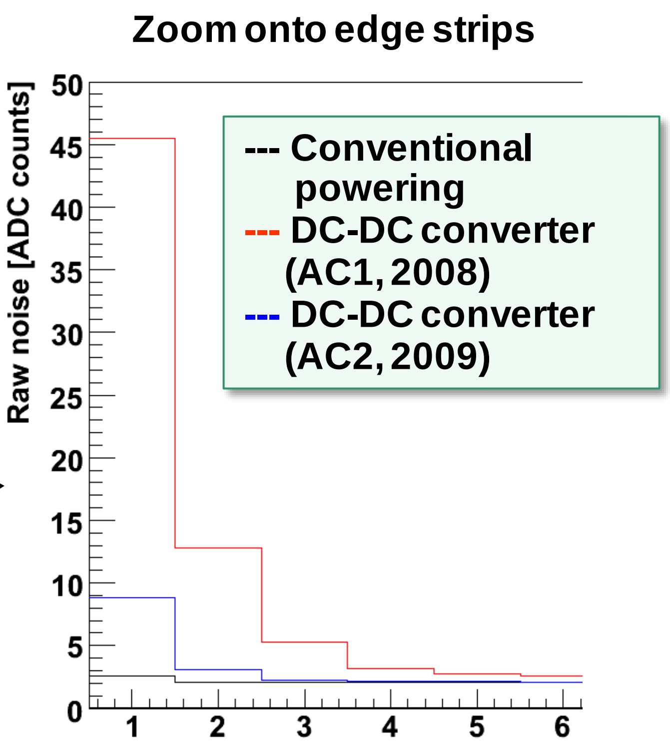


APV25 readout chip:
- 0.25µm CMOS
- 128 channels
- **analogue readout**
- per channel: pre-amp., CR-RC shaper, pipeline
- τ = 50ns
- 1.25V & 2.50V supply
- $I_{2.50V}$ = 120mA
- $I_{1.25V}$ = 60mA

- Two DC-DC converters per module
- Integrated via additional adapter
- V_{IN} from external power supply

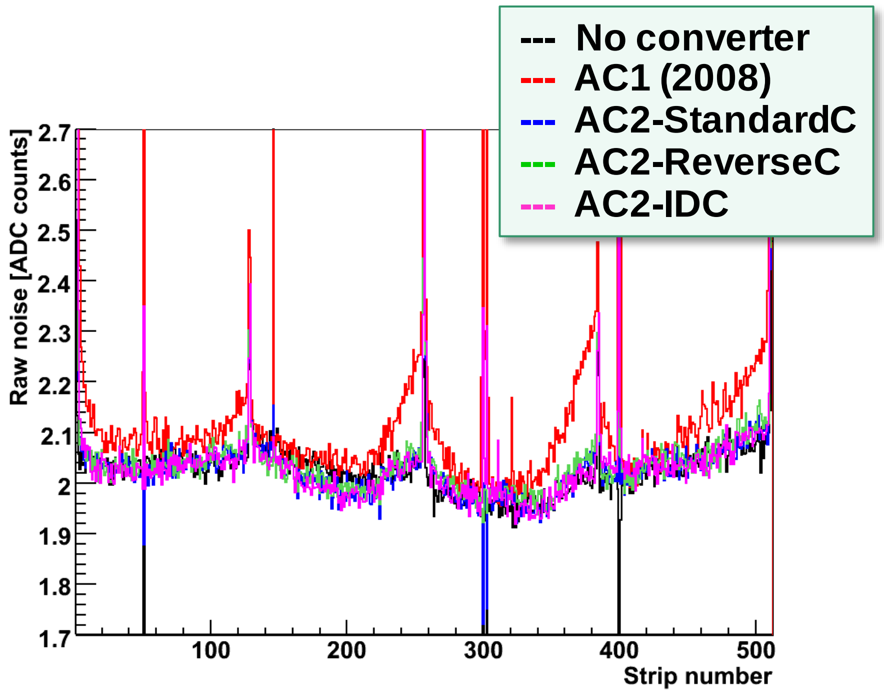
Module Noise





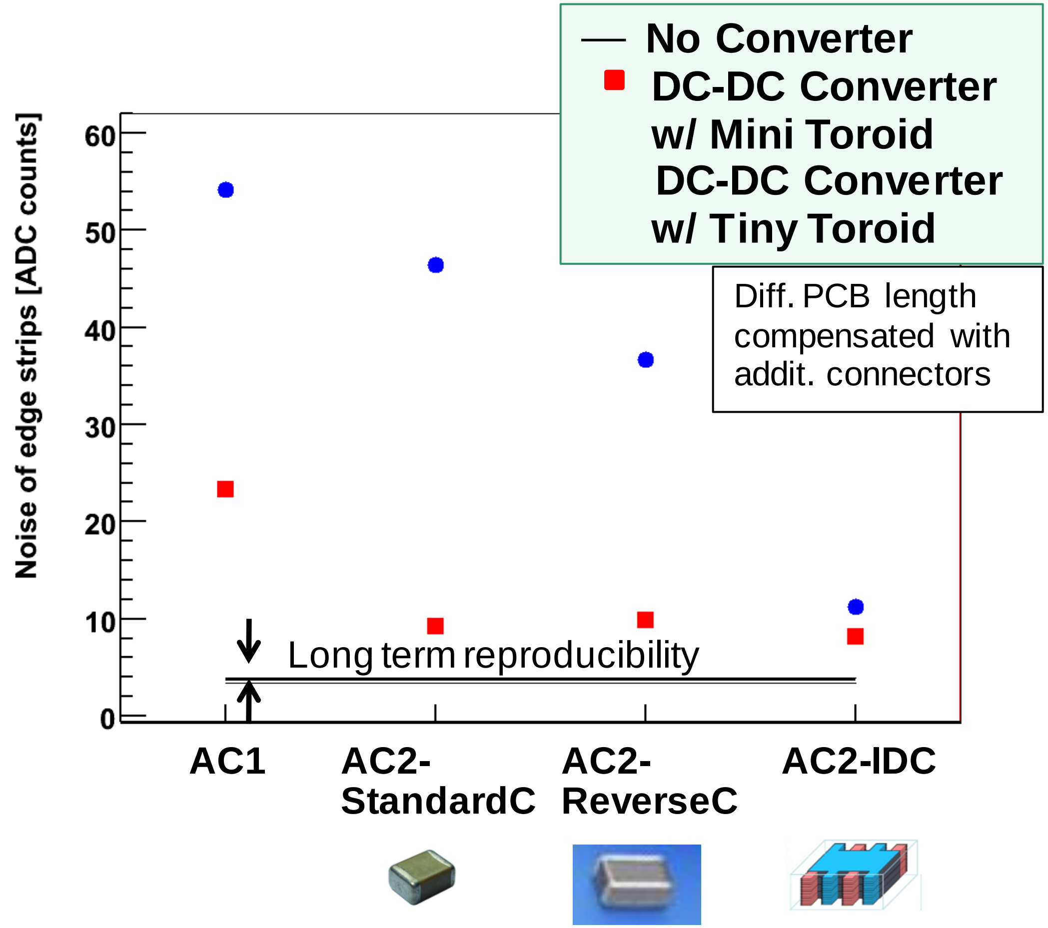
- Raw noise: RMS of fluctuation around pedestal value
- Edge channels are particularly sensitive (explanation in back-up slides)
- Large increase with previous generation of boards (**AC1, 2008**), in particular on edge strips; both conductive (ripple) and radiative (inductor) contributions

Noise of the Aachen Converters



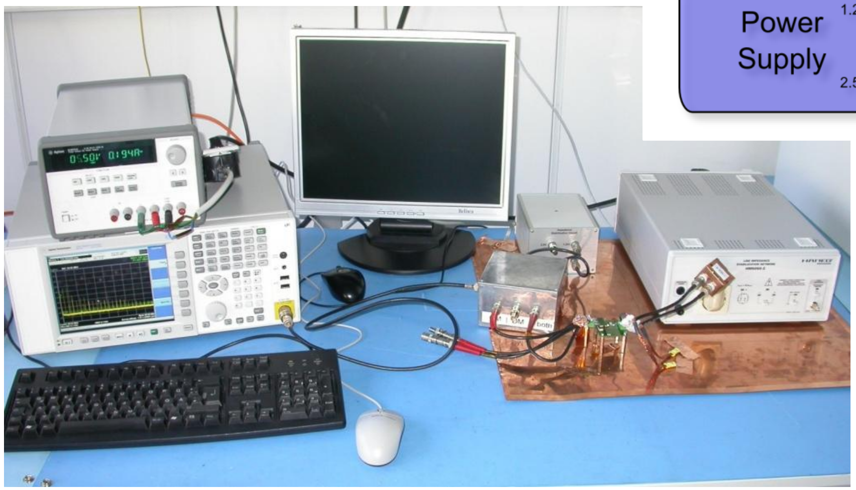
Sensitive variable chosen for all following comparisons:

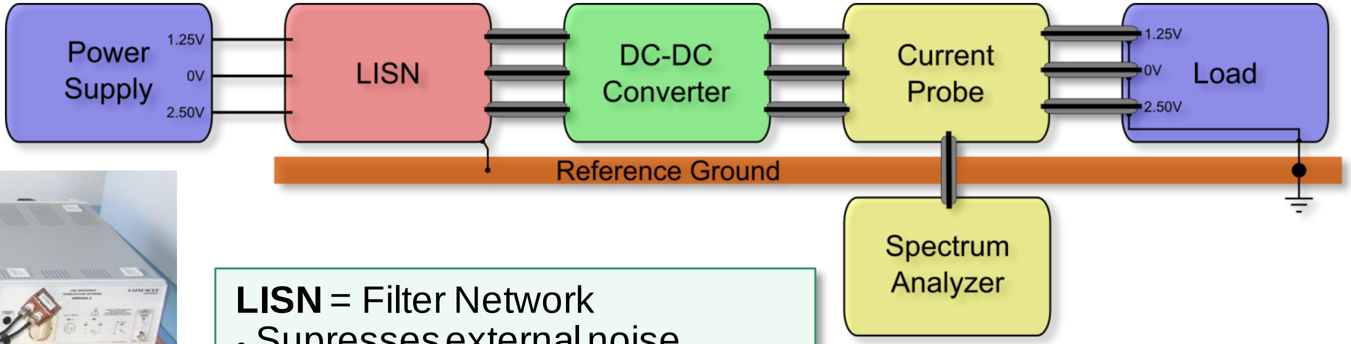
$$N = \sqrt{N_1^2 + N_{512}^2}$$



- Lower noise than with 2008 boards
- Mini Toroid shows lower noise and 5-30% higher efficiency ($\Delta I_L = V_L \cdot t_{ON} / L$)
- Boards with IDCs perform best

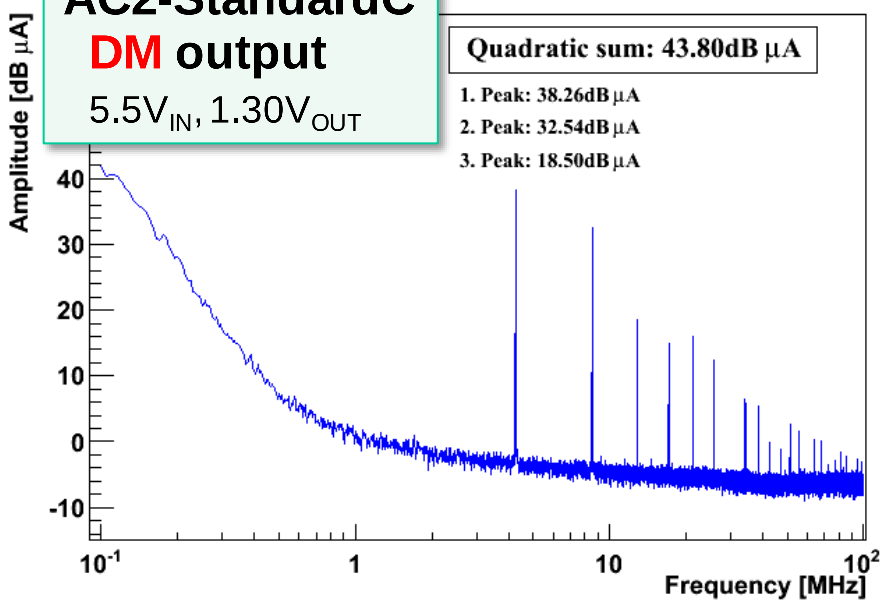
Converter Noise Spectra (EMC Studies)



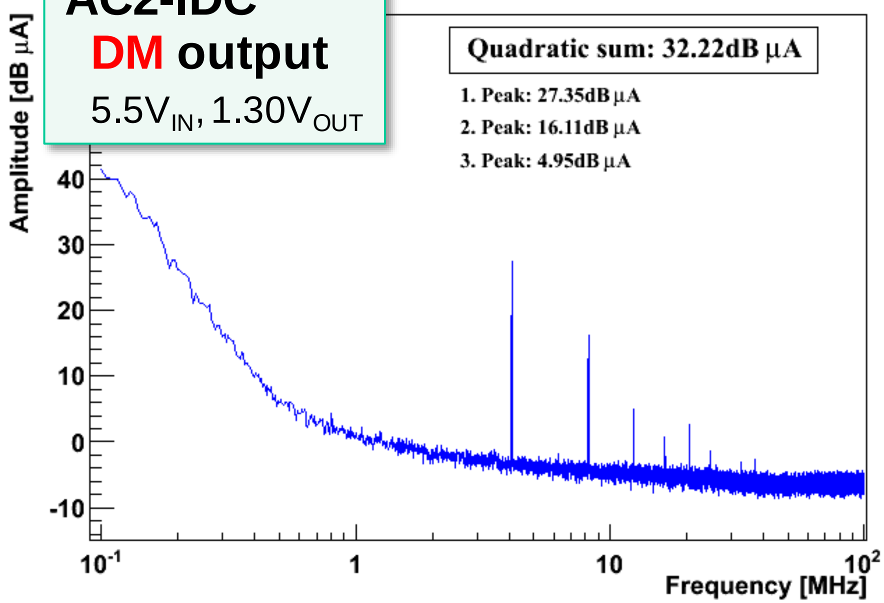


LISN = Filter Network
- Supresses external noise
- Avoids reflection of the noise currents inside the test system

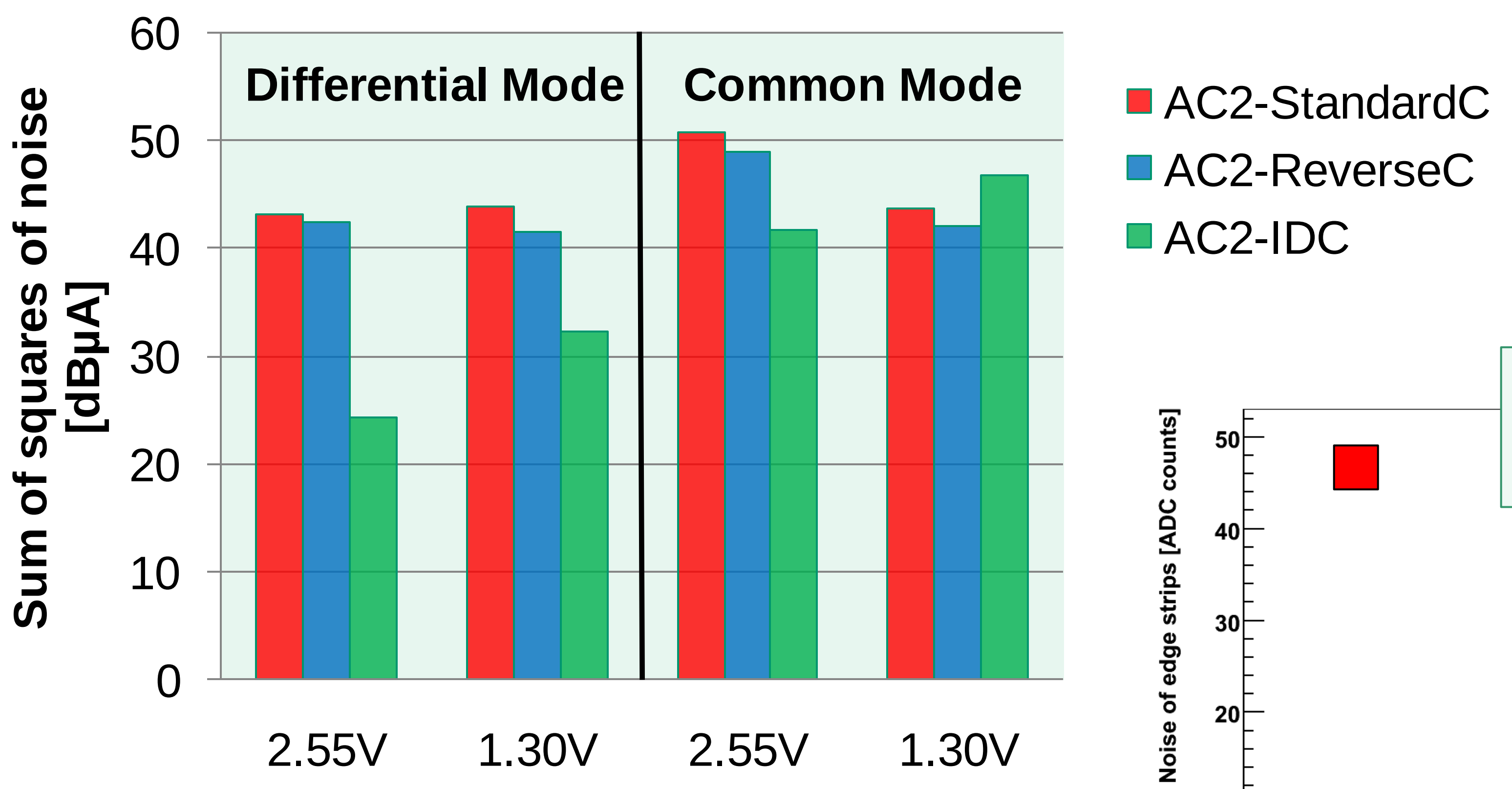
AC2-StandardC
DM output
5.5V_{IN}, 1.30V_{OUT}

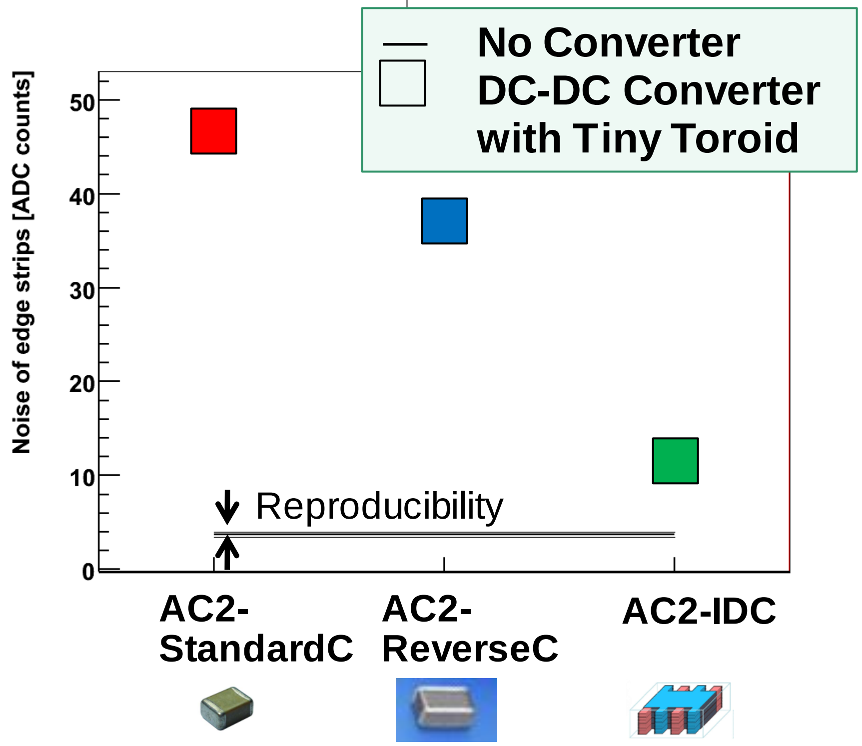


AC2-IDC
DM output
5.5V_{IN}, 1.30V_{OUT}



Converter Noise Spectra (EMC Studies)

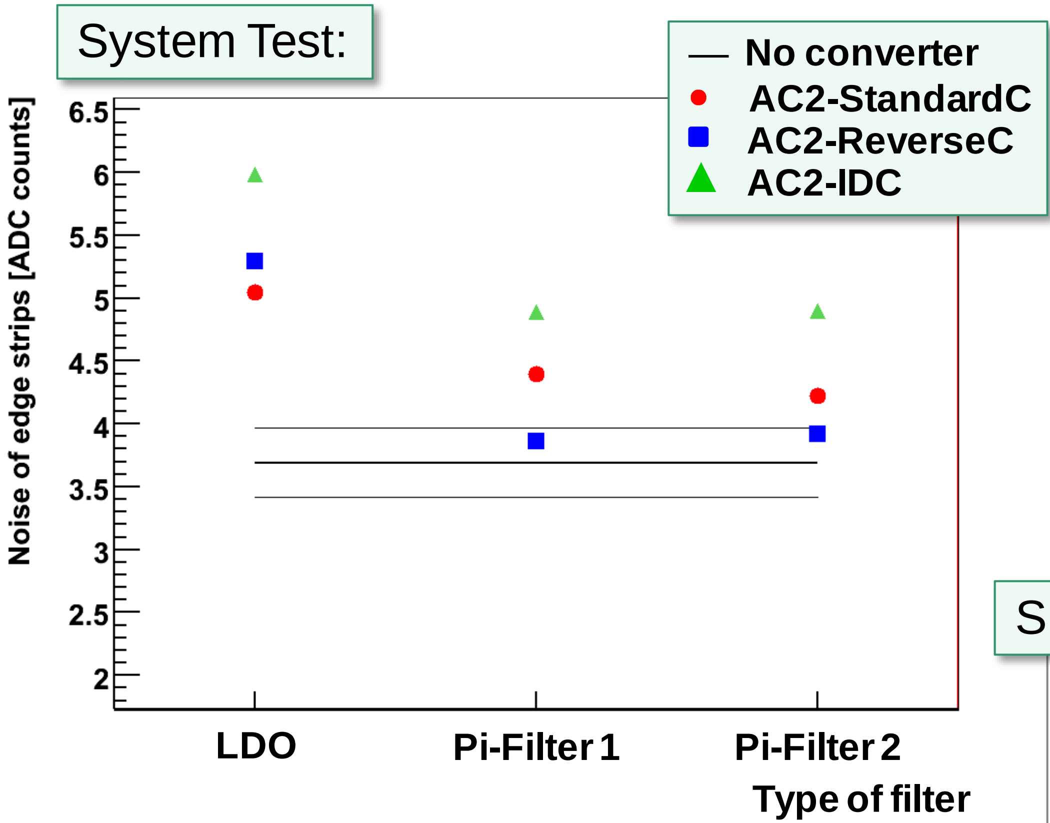


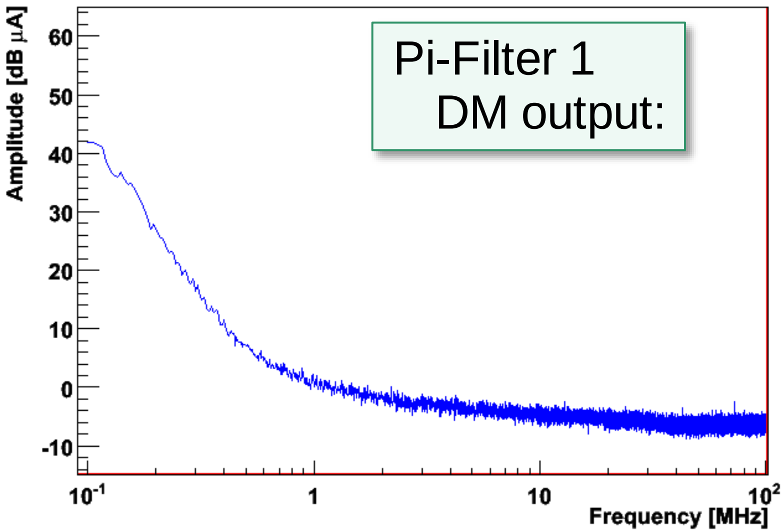


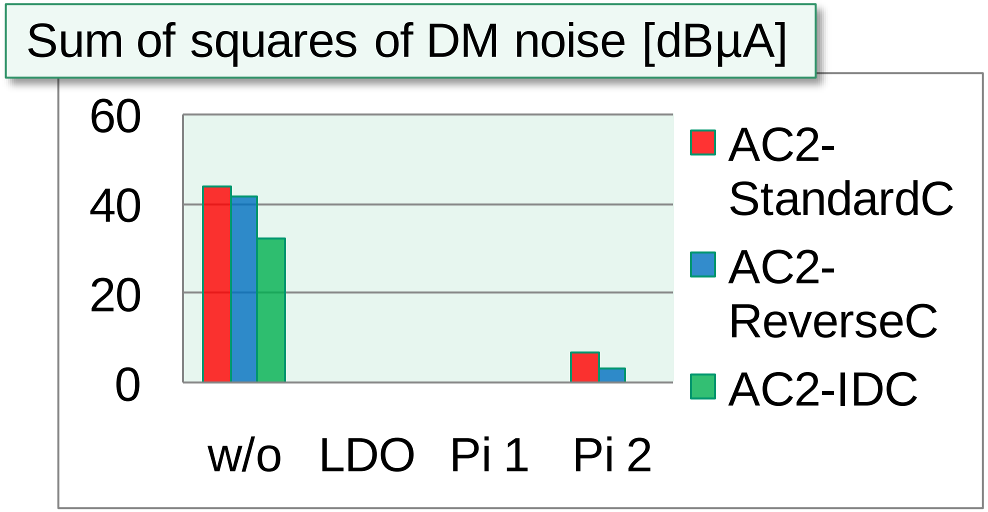
→ Lowest Differential Mode noise from AC2-IDC board

→ But higher Common Mode noise with AC2-IDC for 1.30V?

Noise Filters: π-Filters vs. LDO





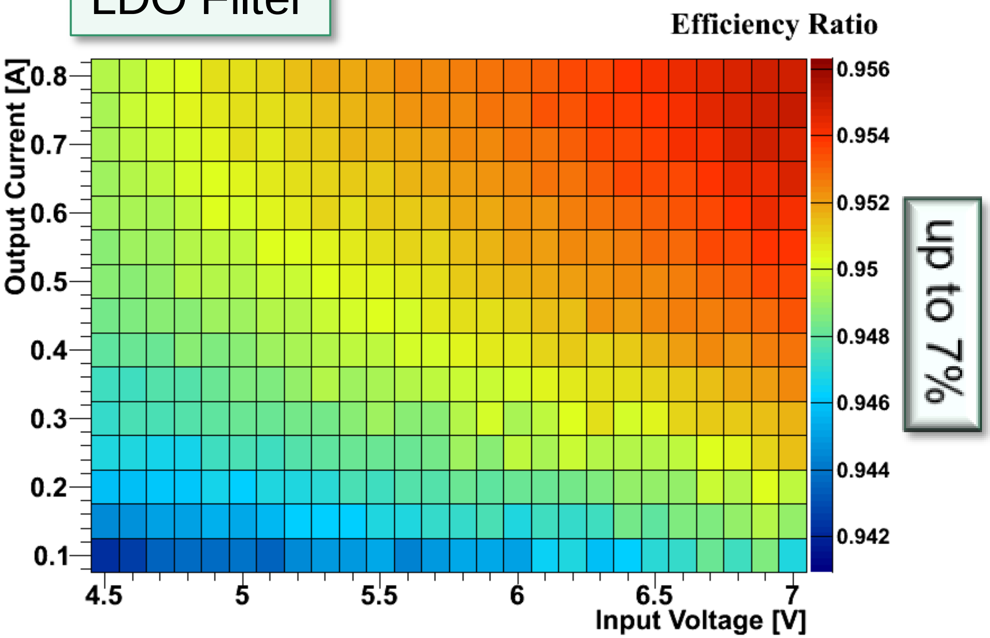


- π -filters are as effective as LDO regulator!
- AC2-IDC performs “worst“ with filters/LDO; likely reason: higher CM

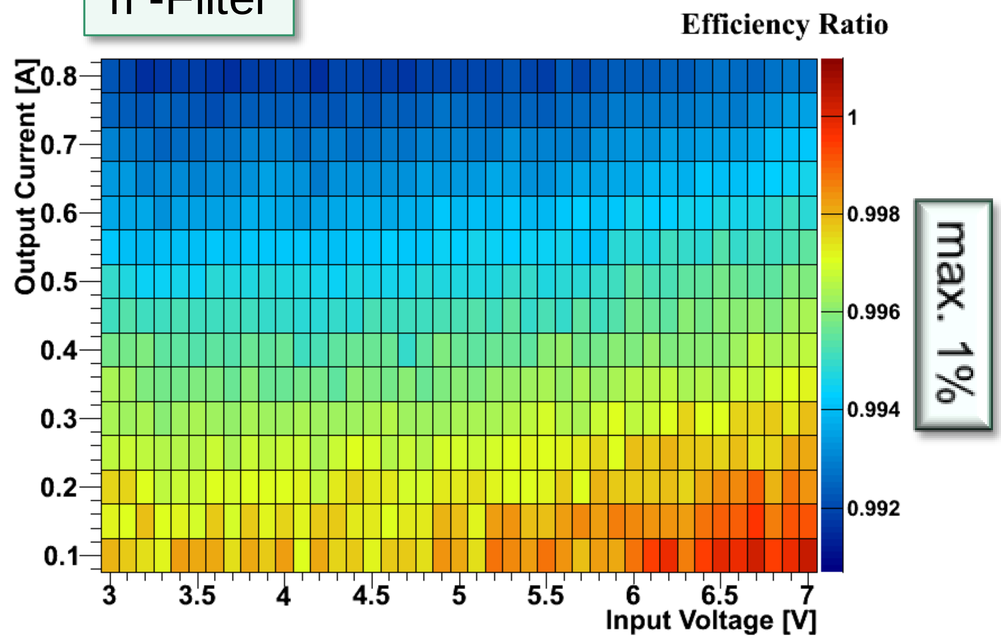
Efficiency with LDO (π-Filter) / efficiency without LDO (π-Filter)

was measured for all board types, filters and V_{OUT} = 1.25V and 2.50V;
e.g. standard capacitors, 1.25V:

LDO Filter



π -Filter



- Losses of up to 7% observed with LDO regulator (50mV drop out voltage)
- Losses with our π-Filters stay below 1%
- π -filter clearly preferred

Summary

- Buck Converters with commercial non-radiation-hard chips have been developed that add very little noise into the current tracker system

- Small, low-mass 600nH air-core toroids with low R_L have been fabricated

- π-Filters reduce the noise to the level of conventional powering with < 1% efficiency loss, and are preferred over LDOs

- We are now studiing the integration of custom rad-hard converters developed by the CERN PH-ESE Group (F. Faccio, S. Michelis, ...)

- Measurements of the Converters with the ASICs from CERN are ongoing, results will be presented in the next Power WG Meeting at CERN in November

BACKUP – SLIDES

DC-DC Powering Scheme for CMS at SLHC

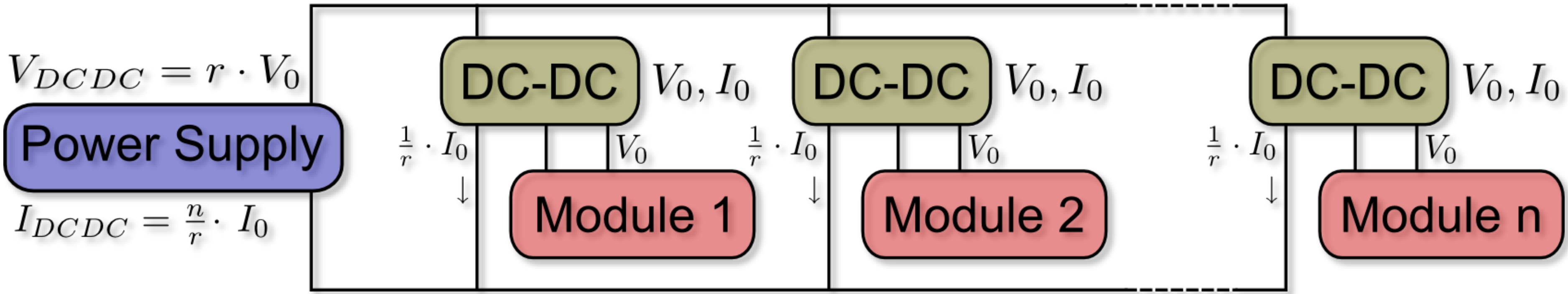
The total power consumption of the new CMS Tacker will increase:

- Power cables to the tracker have to be reused, no space for add. ones
- Lower voltage (ASIC technology)

  → Current in the cables to the Tracker will increase, even if the power consumption would stay the same

  → A new powering scheme is mandatory: **DC-DC conversion:**

Convertion ratio:
r = V_{IN} / V_{OUT} (r>1)



- n modules are powered in parallel
- DC-DC Buck Converters:

Cable losses: (r = 4, Efficiency η = 80%)
→ without converter: P_{Cable} = 30.0 kW
→ with converter: P_{Cable} = 2.3 kW

  - Convert higher input voltage to a lower output voltage
    "Step-down Converter" $U_{in} > U_{out} \rightarrow I_{in} < I_{out}$
  - Losses without DC-DC: $\mathbf{P_{cab} = R \cdot I^2}$
  - Losses with DC-DC Conversion: $\mathbf{P_{cab,DCDC} = R \cdot (n \cdot I_0)^2 \cdot (1/r)^2 = R \cdot I^2 \cdot (1/r)^2}$

Challenges

DC-DC Converters: **Buck Converters**

- **High-voltage tolerant (up to 12V) and radiation-hard ASICs needed:**
  - Up to ~10^{15} n/cm^2 (1MeV neutron equivalent) and ~100Mrd (TID)
    → **CERN** AMIS2: **Prototype** for radiation hard Converter [F. Faccio et al.]

- **Efficiency:**
  - $$\eta = \frac{P_{out}}{P_{in}} = \frac{V_{out} \cdot I_{out}}{V_{in} \cdot I_{in}}$$

  → **Efficiency Measurements**

- **Inductors:**
  - CMS Tracker: B=3.8T
    → Converters have to be magnetic field resistant
  - Ferrite material saturates in a strong magnetic field
    → Use of air-core coils inevitable
  - Air-core coils are bulky and radiate noise

  → **Magnetic Field Tests**

- **Converter switching noise:**
  - Switching device (f_{SWITCH} ~ MHz)
  - Additional source of noise in the system

  → **Spectrum Analysis (Converter Noise)**
  → **System Test Measurements (With current CMS Tracker Hardware)**
  → **Susceptibility Measurements**

- **Material budget:**
  - Material budget of the new CMS Tracker should decrease, even with converters

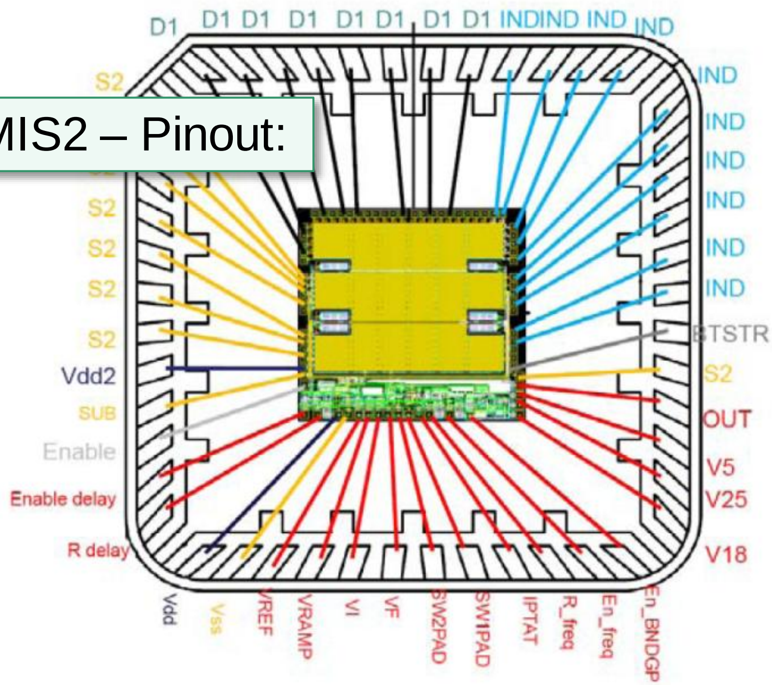
  → **Simulation of the MB**
  → **R&D: CO_2-Cooling Test System**

- **Space constraints:**
  - Where can the Converters be placed? Maximum dimensions?

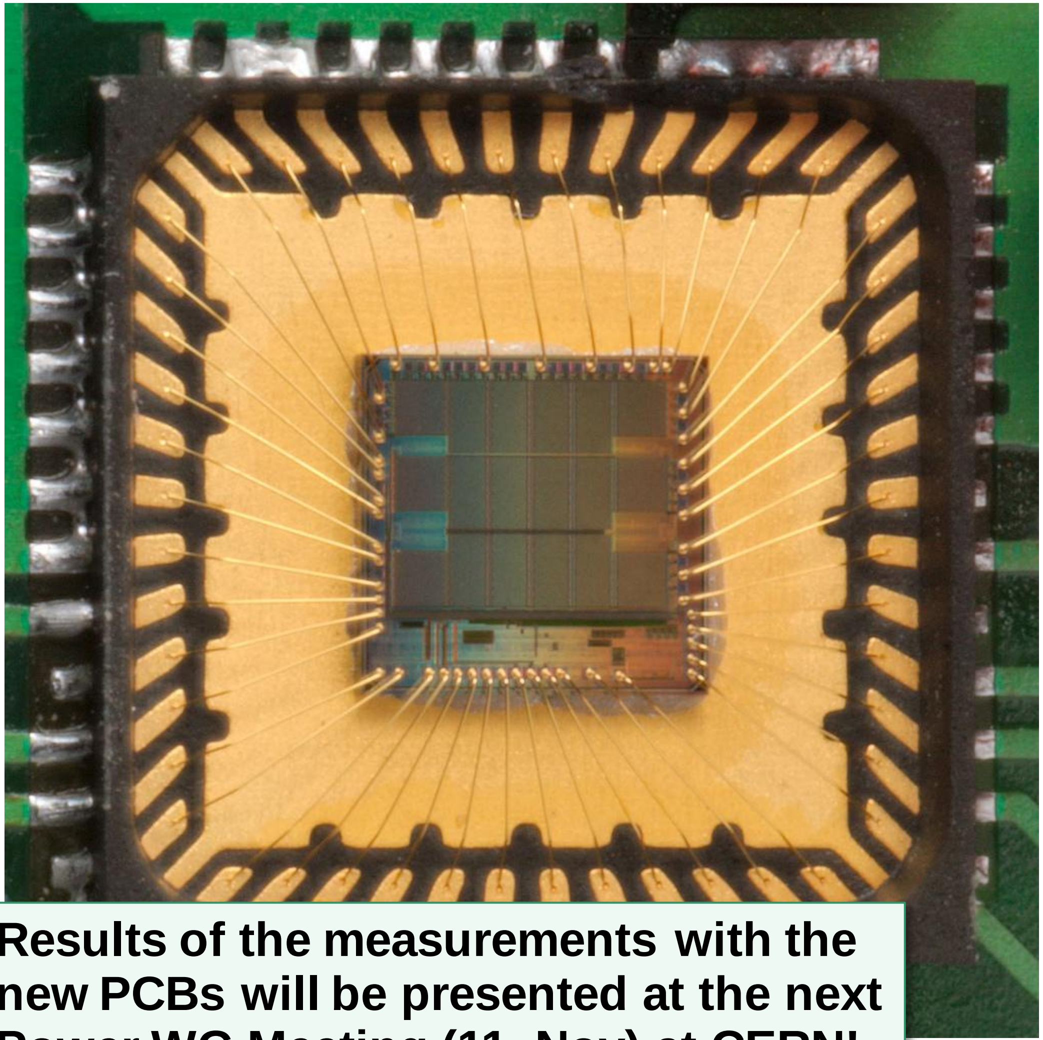
AMIS2 – Chip & Technology

- Package: QFN32
- V_{OUT} = 1.2..5V; I_{OUT}<2.8A; f_{SW}=0.6..3MHz
- Tested up to 300 Mrad = 3000 kGy with only 2% efficiency loss (after annealing)
- Integrated feedback loop with bandwidth of 20KHz
- Internal voltage reference
- Lateral HV transistors are used as power switches
- Noise and efficiency on upcoming slides

AMIS2 – Pinout:



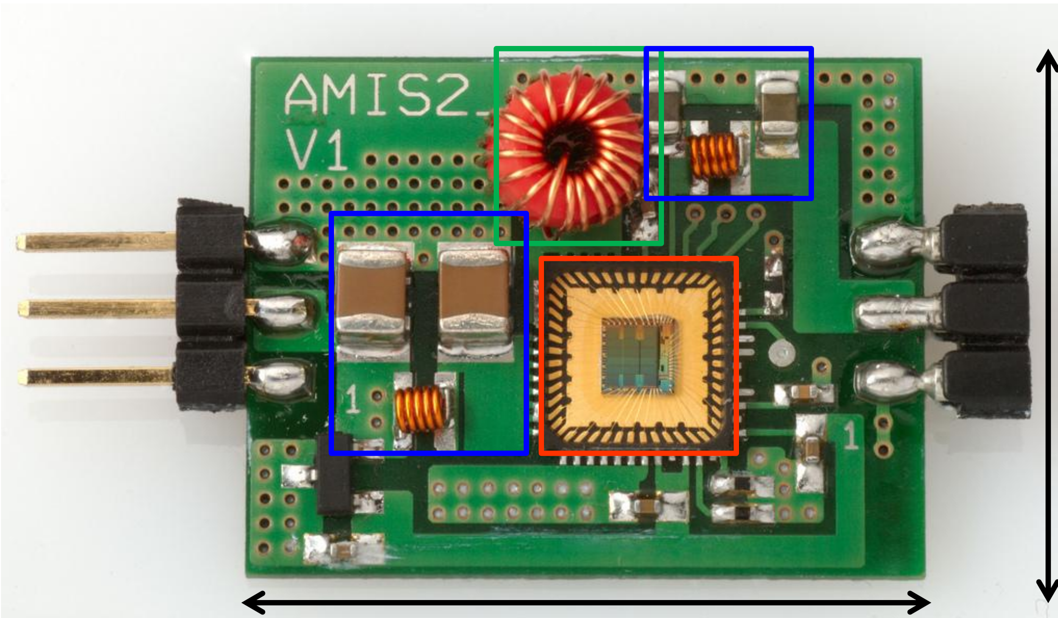
AMIS2 – Picture:



Results of the measurements with the new PCBs will be presented at the next Power WG Meeting (11. Nov) at CERN!

AMIS2 – Converter PCBs

Aachen R&D: develop Converters based on (**not yet) radiation-hard** buck converter ASICs; optimize for low mass, low space, low noise; and study in system test



19mm

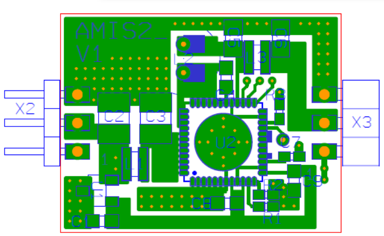
25mm

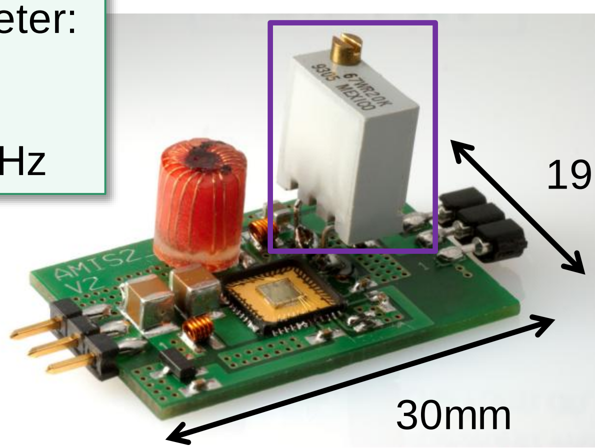
PCB:
2 copper layers a 35µm
FR4 1mm
V = $19 \times 25 mm^2 \times 10mm$
m = 2.5g

Chip: AMIS2 by CERN
V_{IN} = 6-11V(rec.) / 12V(max.)
$I_{OUT} < 3A$
V_{OUT} = 1.2V and 2.50V
$f_S \approx 1MHz$

External air-core inductor:
Custom-made toroid, ∅ ≈ 6mm,
height = 7mm, L = 600nH, R = 80mΩ

20kΩ Potentiometer:
m = 3,7g
A = $19 \times 30 mm^2$
f_S = 600kHz..3MHz





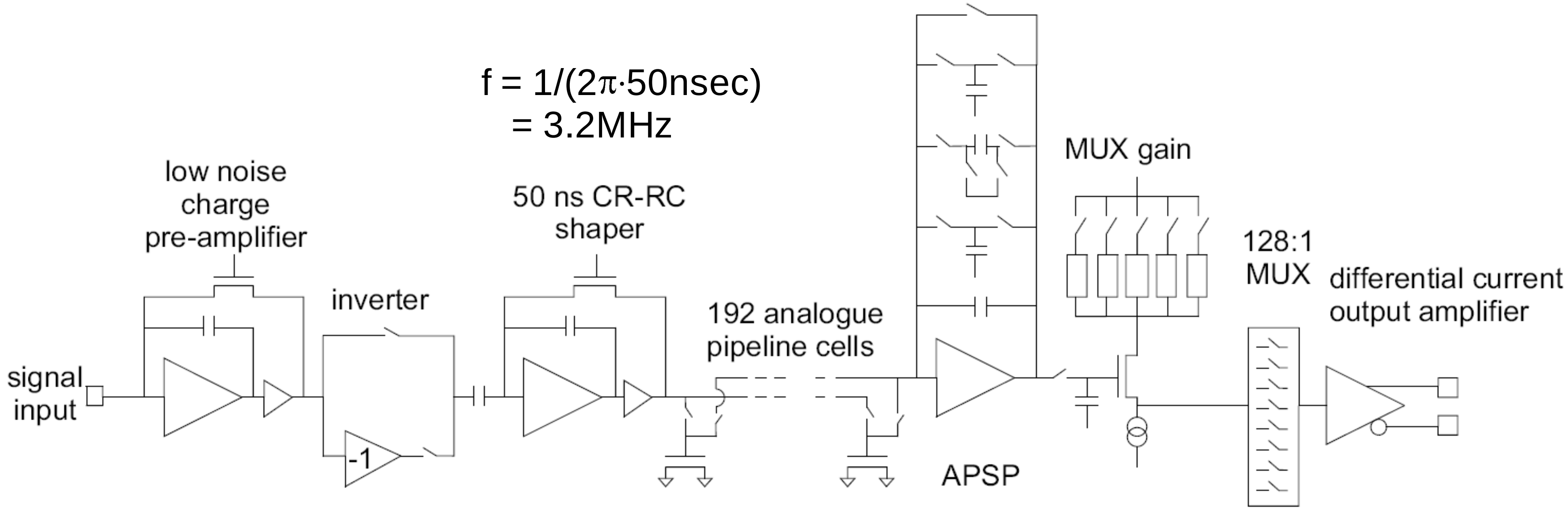
19mm

30mm

Input and output π-filters
L = 12.1nH, C = 22µF

Potentiometer 20kΩ for altering f_S

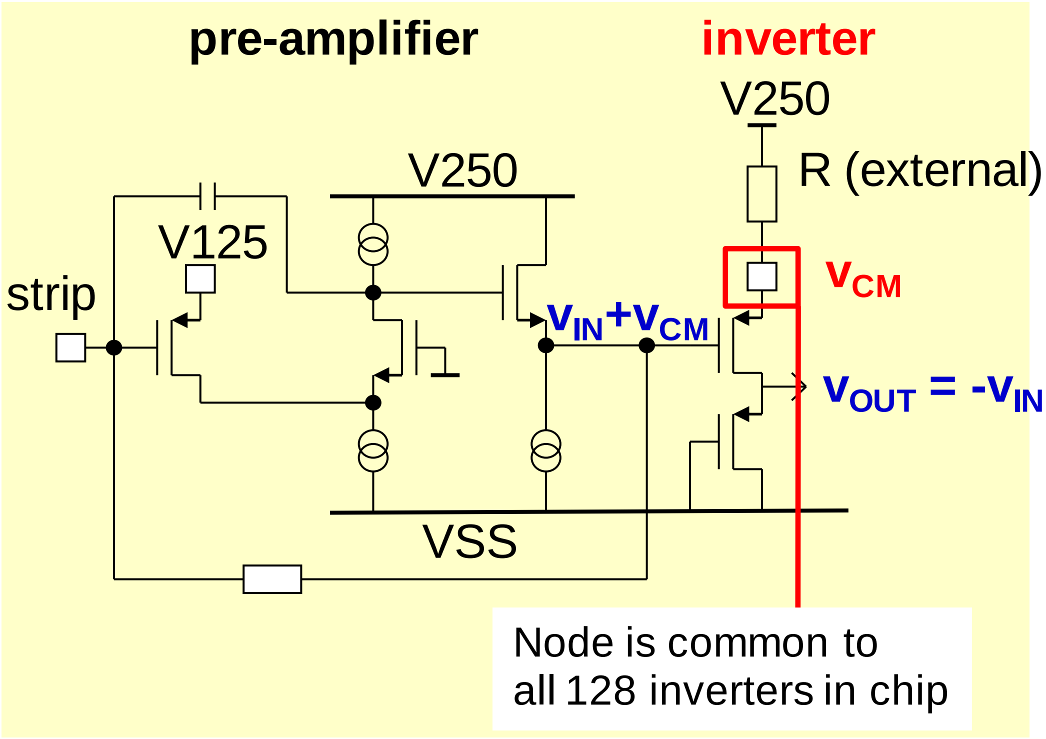
The APV25



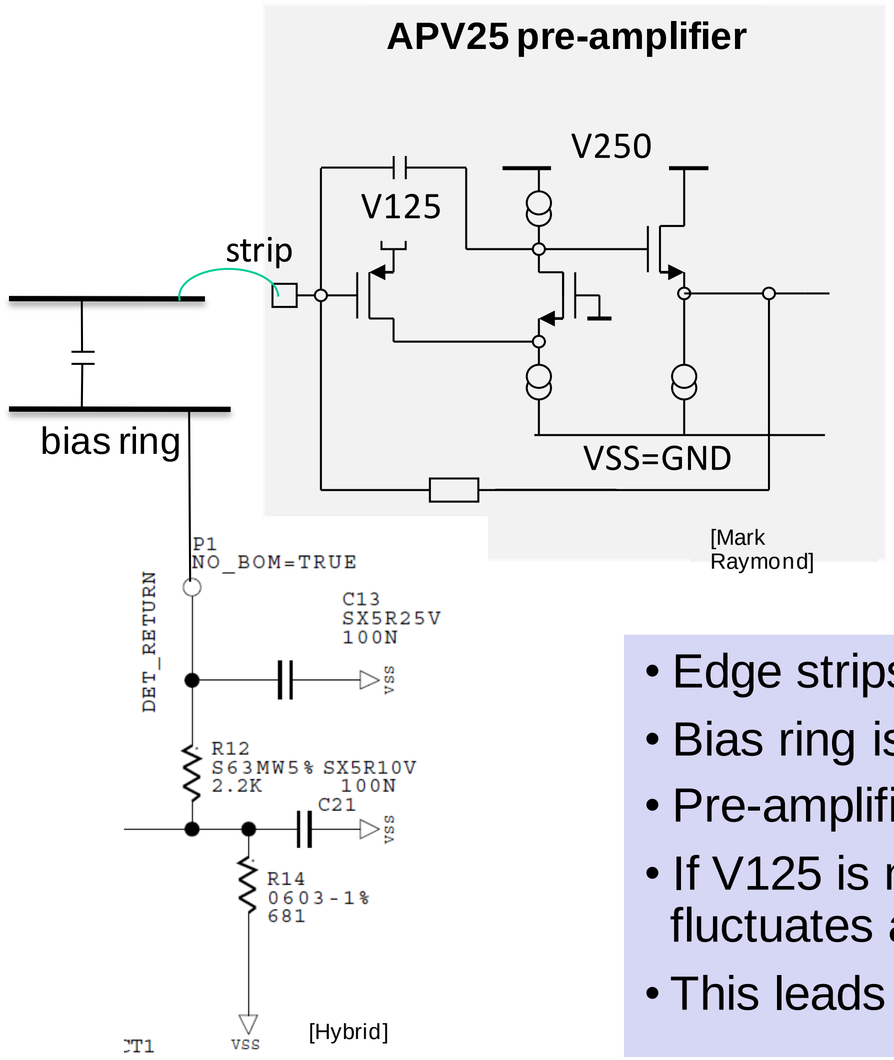
f = 1/(2π·50nsec)
= 3.2MHz
low noise
charge
pre-amplifier
50 ns CR-RC
shaper
MUX gain
128:1
MUX
inverter
192 analogue
pipeline cells
differential current
output amplifier
signal
input
-1
APSP

On-Chip Common Mode Subtraction

- 128 APV inverter stages powered from 2.5V via common resistor (historical reasons)
  ⇒ mean common mode (CM) of all 128 channels is effectively subtracted on-chip
- Works fine for regular channels which see mean CM
- CM appears on open channels which see less CM than regular channels
- CM imperfectly subtracted for channels with increased noise, i.e. edge channels



Module Edge Strips



- Edge strips are capacitively coupled to bias ring
- Bias ring is AC coupled to ground
- Pre-amplifier is referenced to 1.25V
- If V125 is noisy, pre-amp reference voltage fluctuates against input
- This leads to increased noise on edge channels