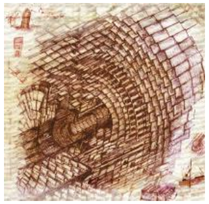


DC-DC Conversion Powering Schemes for the CMS Tracker at Super-LHC

Lutz Feld, Rüdiger Jussen, Waclaw Karpinski,

Katja Klein, Jennifer Merz, Jan Sammet

1. Phys. Institut B, RWTH Aachen University

Workshop on Intelligent Trackers

Lawrence Berkeley National Lab, February 3-5, 2010

Powering a Tracker at SLHC

- Higher detector granularity $\rightarrow$ more readout channels
- More functionality: track trigger to preserve 100kHz trigger rate
- Lower operating voltages (250nm $\rightarrow$ 130nm ...) $\Rightarrow$ larger currents for same power
- Must cope with todays Tracker services, incl. power cables
- Decreasing material budget is the best/only way to improve performance

A novel powering scheme will be needed $\Rightarrow$ **Serial Powering** or **DC-DC conversion**

In a review process, the CMS tracker has chosen **DC-DC conversion as baseline solution**, and maintains Serial Powering as back-up.

Reasons: simpler, closer to todays parallel powering scheme, less system issues

DC-DC Conversion

- Tracker needs kWs of power at a low voltage (1.2V) → I = kAmps
- P = U x I = (rU) x (I/r) ⇒ supply power at higher voltage, but lower current ⇒ lower Ohmic losses $P_{cable} = R_{cable} \cdot (I/r)^2$, and less copper in detector volume
- DC-DC step-down converters transform $V_{in} = rV_{out}$ to V_{out}, with **conversion ratio r**
- Based on inductors or switched capacitors ("charge pump")
- Focus here on **buck converter**: simplest inductor-based step-down converter few components, high r, efficiency ~80%, sev. Amps, regulated by feedback loop via PWM

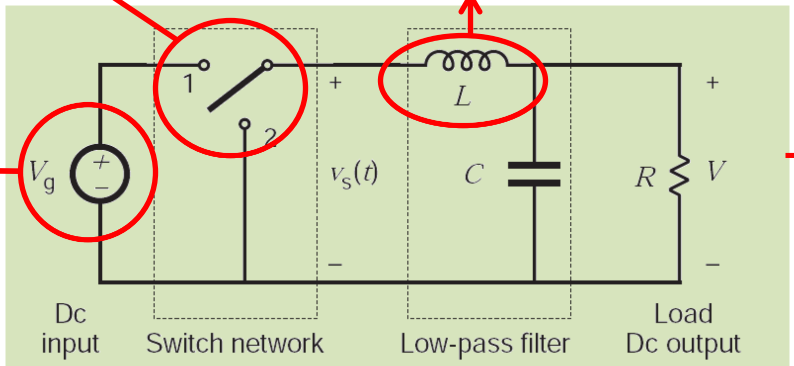
f_s = 1-5MHz
⇒ switching noise

Ferrites saturate for B > ~2T
⇒ air-core inductor needed

bulky

radiates

HV-tolerant
semi-conductor
technology needed
→ radiation-hardness



Efficiency

Material budget

Space constraints

Requirements for CMS Stacked Layers

Quantity	Requirement	Comments
Radiation level	Fast hadron fluence: ~$9\times10^{15}/cm^2$; Dose: ~1.3MGy	For R > 20cm, z < 3m, $5000fb^{-1}$, safety factor of 2
Output voltage	V_{ana} = 1.2V V_{dig} = 0.9V	Assuming 130 or 90nm (+ V_{opto} = 2.5V, 1.5V)
Output current	3-5A	→ 2 converters per double module
Conversion ratio	Up to 10:1, depends on proposal	Max. current in cable channels 15kA Assuming ~100kW & 80% efficiency
Efficiency	70-80%	Losses need to be cooled
Conductive noise (DM, ripple)	Depends on PSRR of the ROC (still to be studied); but f_s well below (or ideally above) system susceptibilty, i.e. ~ 1MHz	Can be filtered
Common mode noise	? As low as possible...	Notoriously hard to control
Radiated noise (magnetic near field)	Ideally none	Minimize with distance, shielding, module design
Material budget	Critical since installed at low R	Expect 1-2g per converter
Real estate	No space on FE-hybrid	$2\text{-}4cm^2$ per converter must be found

Only few aspects really special for double layers. Go now through some of above points.

Radiation Hardness

- Commercial converters are in general not radiation-hard ⇒ custom ASIC
- **Systematic irradiations of candidate technologies by F. Faccio (CERN)**
  Leakage current, R_{on}, $I_{DS} = f(V_{ds})$ vs. TID < 350Mrad & fluence < $10^{16}/cm^2$
  → Best candidate: **IHP SGB25V GOD** 0.25µm SiGe BiCMOS (IHP, Germany)
  → Back-up: **AMIS I3T80** 0.35µm (ON Semiconductor, US)
- **ASIC development in candidate technologies by St. Michelis (CERN)**
  – IHP1 & **IHP2**: 2nd prototype submitted in January 2010
  – AMIS1 & **AMIS2** (May 2009); **used by CMS for system tests etc.**

F. Faccio, CMS/ATLAS Power WG, at TWEPP-09

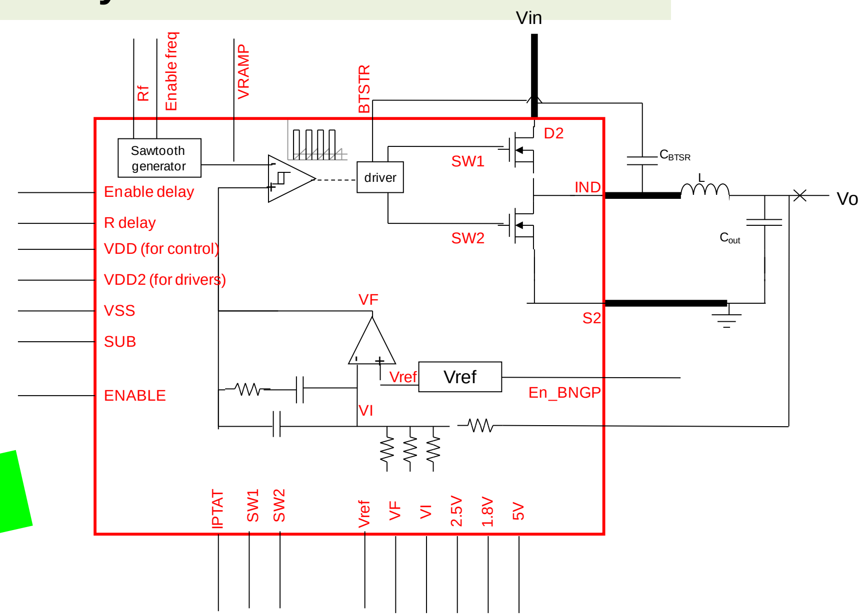
St. Michelis, TWEPP-09

AMIS2 FEATURES (from data sheet)

- VIN and Power Rail Operation from +3.3V to **+12V**
- **Internal oscillator** fixed at **1Mhz, programmable** up to 2.5MHz with external resistor
- **Internal voltage reference**
- **Programmable delay** between gate signals
- **Integrated feedback loop** with bandwidth of 20Khz
- Different Vout can be set: **1.2V, 1.8V, 2.5V, 3V, 5V**
- Lateral HV transistors are used as power switches
- Enable pin

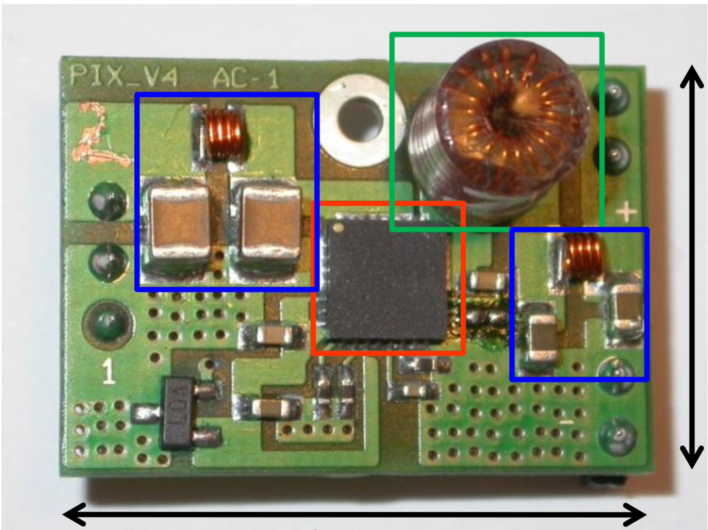
- Some problems with bandgap reference
- Needs extra 3.3V supply
- No safety features yet

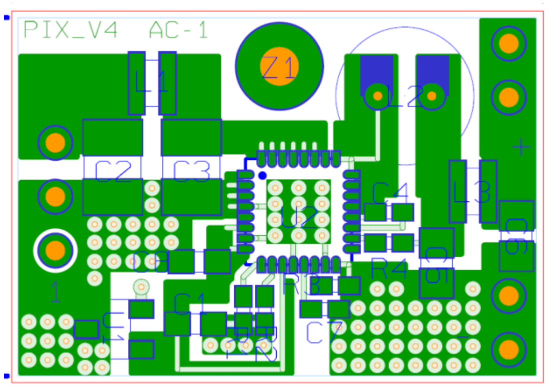
r ≤ 10 and I ≤ 3A!



Aachen Converters with AMIS2 ASIC

Aachen R&D: develop low mass, low noise converters with rad.-hard ASICs for CMS





Schematics in back-up slides.

PCB:
2 copper layers a 35µm
FR4 1mm
A = 18mm x 25mm for QFN32

Chip: AMIS2 by CERN
V_{IN} = 3 - 12V
I_{OUT} < 3A
V_{OUT} = 1.2V, 2.5V or 3.3V
$f_S \approx$ 1.3MHz (**V1**) or
programmable (V2) betw. 600kHz...4MHz

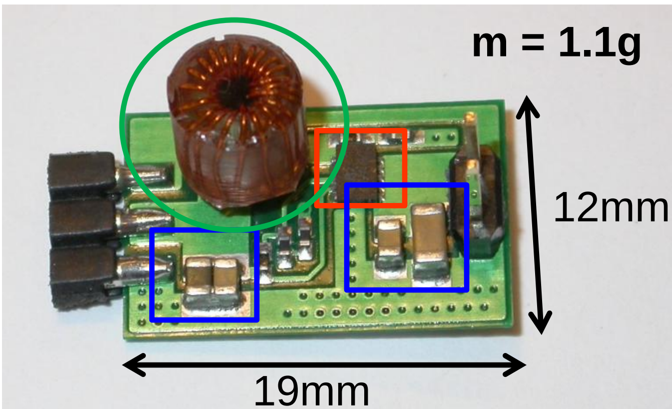
Air-core toroid:
Custom-made toroid, ∅ ≈ 6mm,
height = 7mm, L = 600nH, R_{DC} = 80mΩ

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

"AC2" Buck Converter with Enpirion Chip

The "work horse": buck converter with **non-radiation-hard commercial** chip

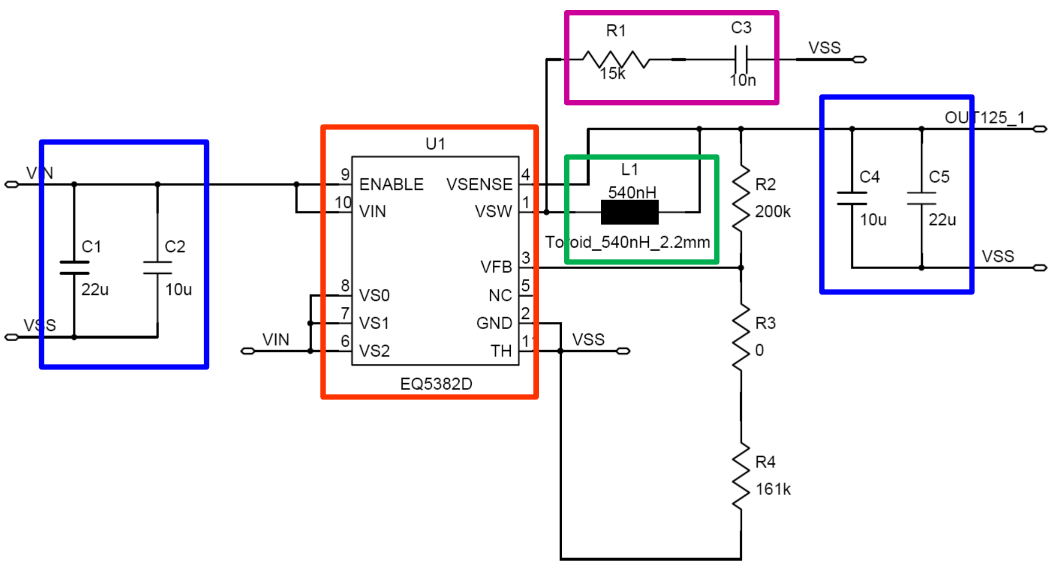
→ useful for comparison, and at pre-AMIS2 times



PCB:
2 copper layers a 35µm
FR4, 200µm
V = 2.3cm^2 x 10mm
m = 1.0g

Chip: **Enpirion EQ5382D**
V_{in} = 2.4-5.5V(rec.)/**7.0V**(max.)
$I_{out} \leq$ 0.8A
$f_s \approx$ 4MHz

Air-core inductor:
Custom-made toroid, ∅ ≈ 6mm
L = 200nH or 600nH



Input/output filters

Snubber to reduce ringing

FE Power / Current / Voltages

Estimates for stacked layers FE power consumption from CMS:

- Power/channel: **0.1mW for 100µm x ~2mm pixel** (cf. tracking: 0.5mW for 5pF)
- Power per unit area: **~100mW/cm^2** (cf. tracking: 10/20 mW/cm^2 for 5.0/2.5 cm strips)
- Power per double module: **2 x 1.0 ... 4.5W** (cf. tracking: 1.5W per module)

More relevant: supply currents

- 130nm or 90nm technology: 1.2V (analogue) or 0.9V (digital)
- Total current at 1.2V: 1.6 ... 8A. Note: buck supply current 3-4A.
- Digital power consumption ~ 50-75% of total; lowering V_{dig} to 0.9V halfes P_{dig}

$\rightarrow$ Need up to **2 x 2A at 1.2V** and **2 x 2A at 0.9V** per double module

$\Rightarrow$ **Two buck converters (1 x 1.2V, 1 x 0.9V) per double module**

   – Currents at 0.9V too large for switched capacitors
   – Linear regulator for 0.9V: efficiency = 0.75%

Link Power

- Power per GBT link: **≈ 2W**
- Power per pixel (50% usage of bandwidth): **150μW**
- 1 GBT per double module for trigger data: **2W**
- Separate GBT links for readout

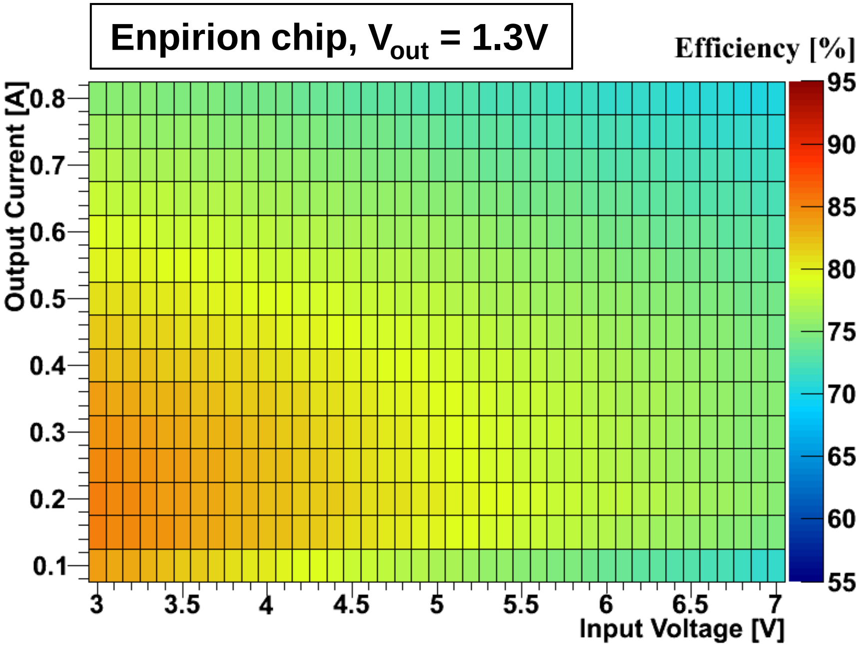
- GBTIA, GB Laser Driver: **≈ 280mA at 2.5V**
- GBTX: **≈ 1.0A at 1.5V**

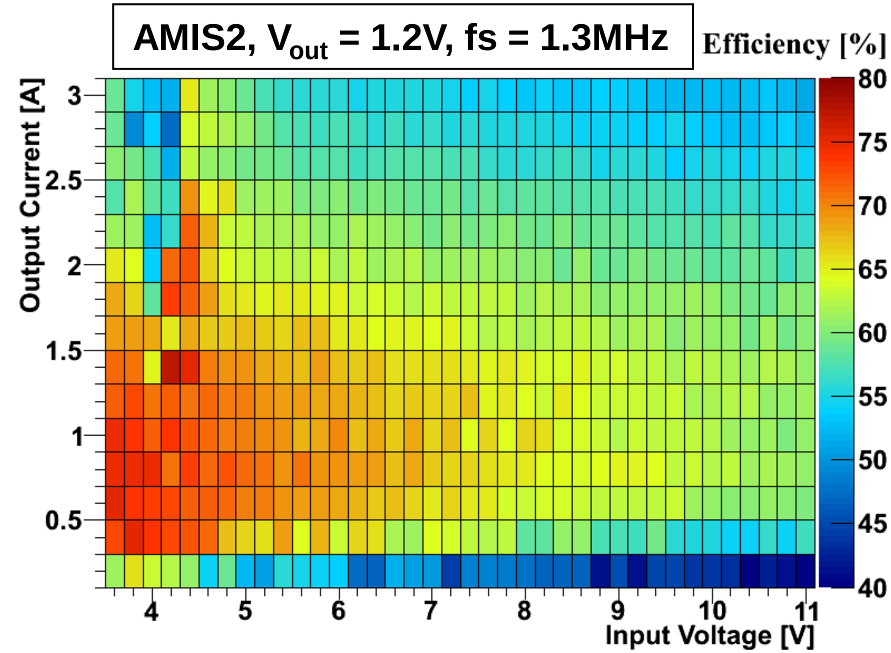
P. Moreira, GBTX SPECIFICATIONS V1.2

Various options:

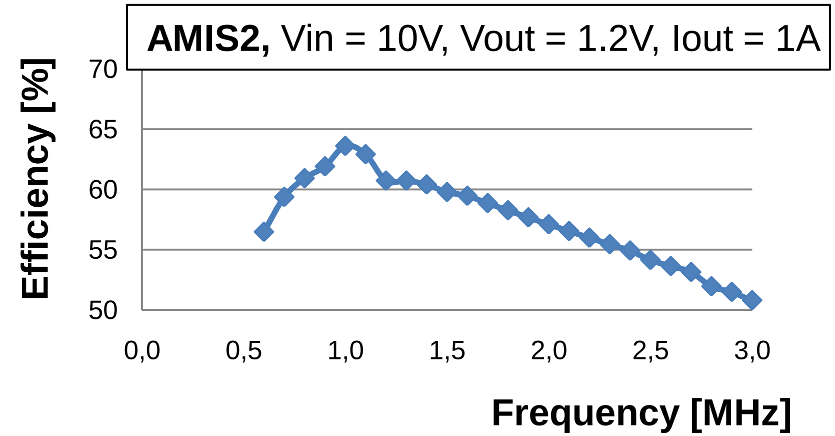
1) One buck (1.5V) plus one step-up switched capacitor conv. (2.5V) per GBT
2) As 1), but 1.5V buck converter delivers in addition V_{ana} to module (25% more P)
3) Two buck converters (1.5V, 2.5V) per 1-3 GBT(s)

Power Efficiency P_{out}/P_{in}

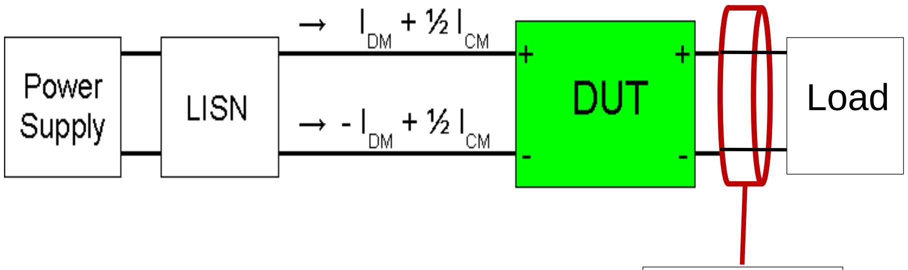




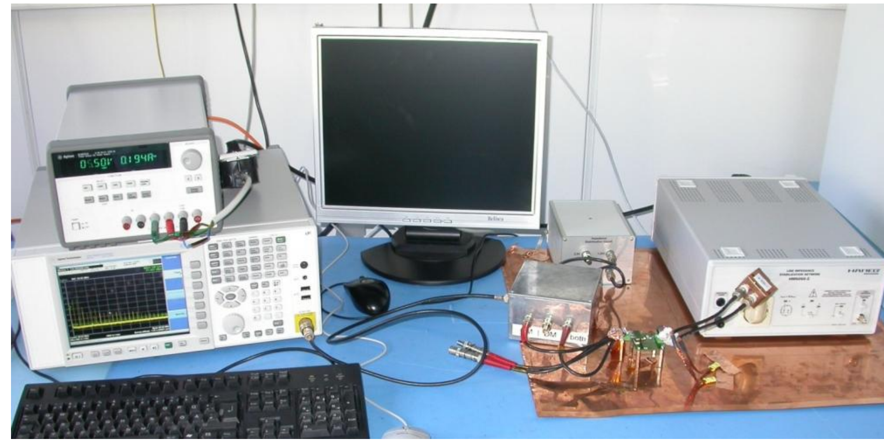
- Efficiency drops with conversion ratio & current
- In practise, efficiencies above 80% hardly reached for any conversion ratio of interest
- Ohmic losses in transistor, wire bonds, PCB, coil; dynamic losses in coil etc.
- Often: higher efficiency ↔ more material



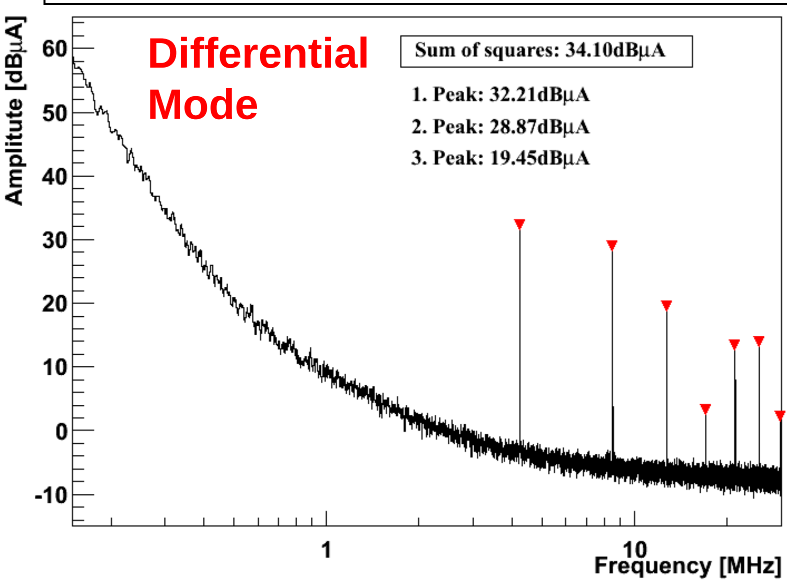
Conductive “Switching“ Noise

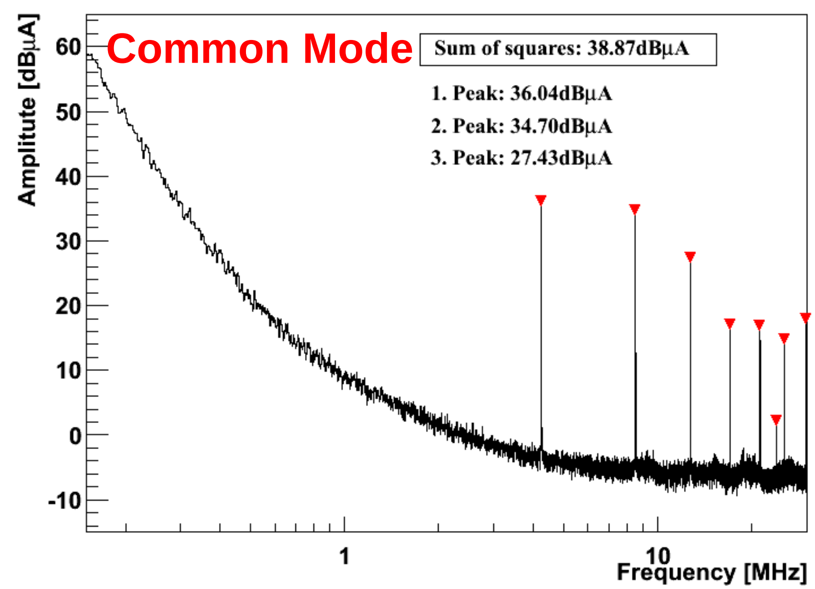


LISN = Line Impedance Stabilization Network



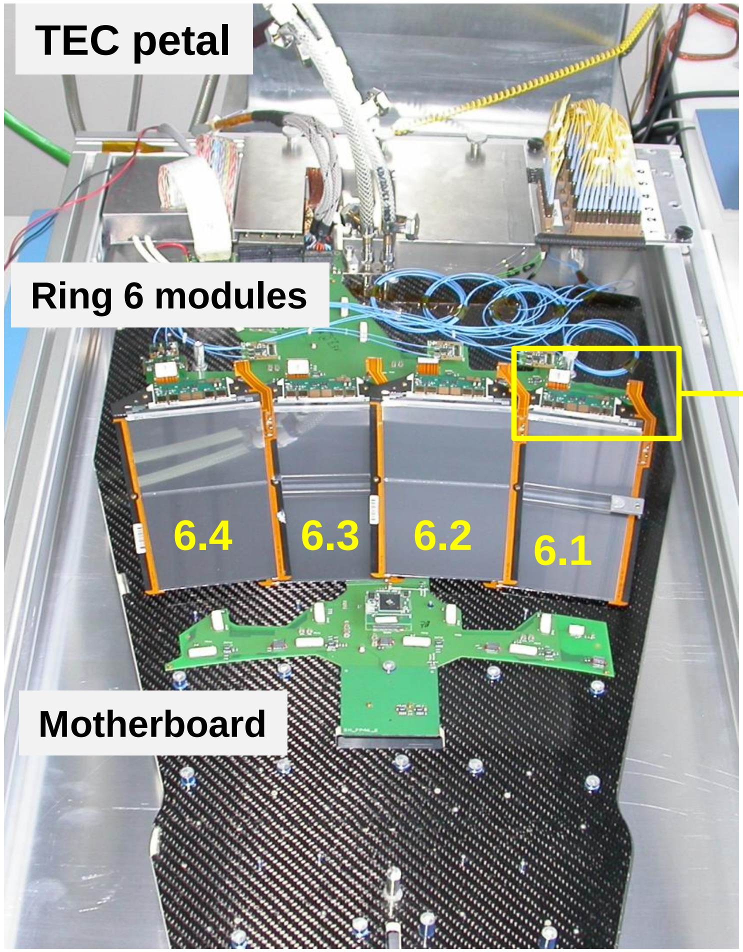
AC2 with Enpirion chip, output noise, V_{in} = 5.5V, V_{out} = 1.3V

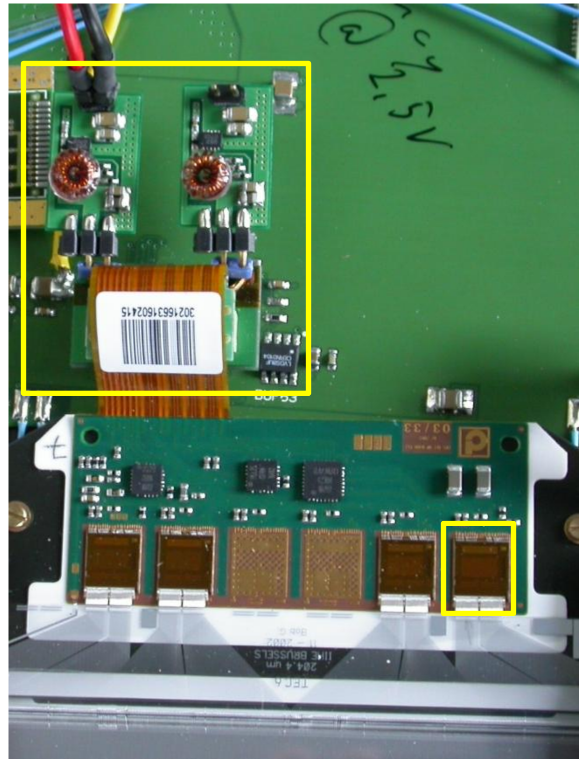




The System Test

SLHC prototype modules not yet available ⇒ existing strip hardware must be used

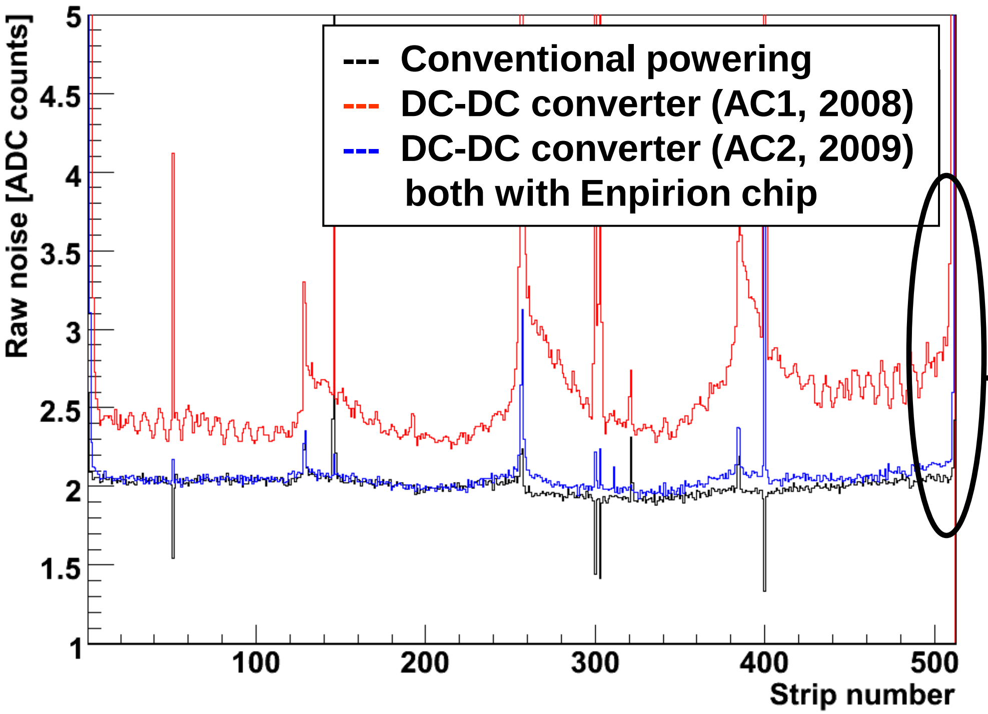


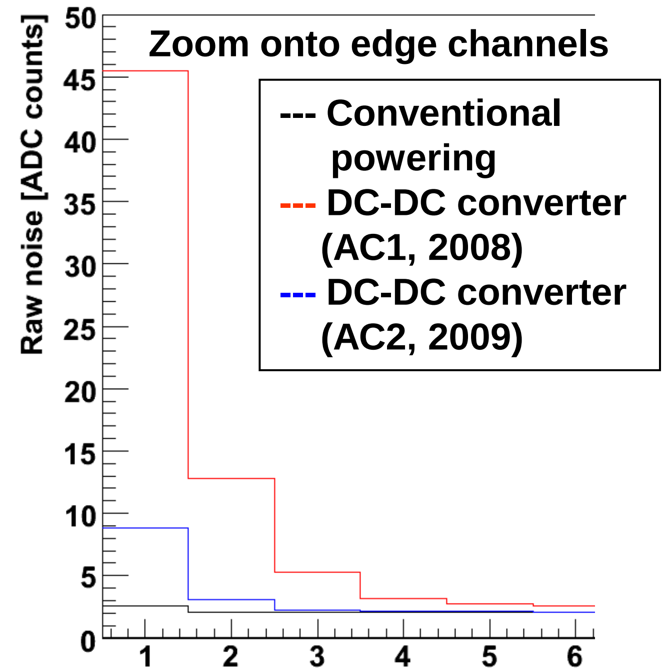


APV25 readout chip:
- 0.25 µm CMOS
-128 channels
- **analogue readout**
- per channel: pre-amp., CR-RC shaper, pipeline
- τ = 50ns
- 1.25V & 2.50V supply
- I_{250} = 0.12A, I_{125} = 0.06A

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

Silicon Strip Module Noise





K. Klein et al., TWEPP-08 & -09

Observations:

- Conductive Differential Mode noise indeed increases module noise, visible mainly on edge strips due to on-chip common mode subtraction in APV25 (details in back-up slides)
- Magnetic radiation from inductor creates "wings"
- Some aspects are special to todays CMS modules
  (e.g. transistor of pre-amp referenced to 1.25V → high sensitivity to ripple on 1.25V)

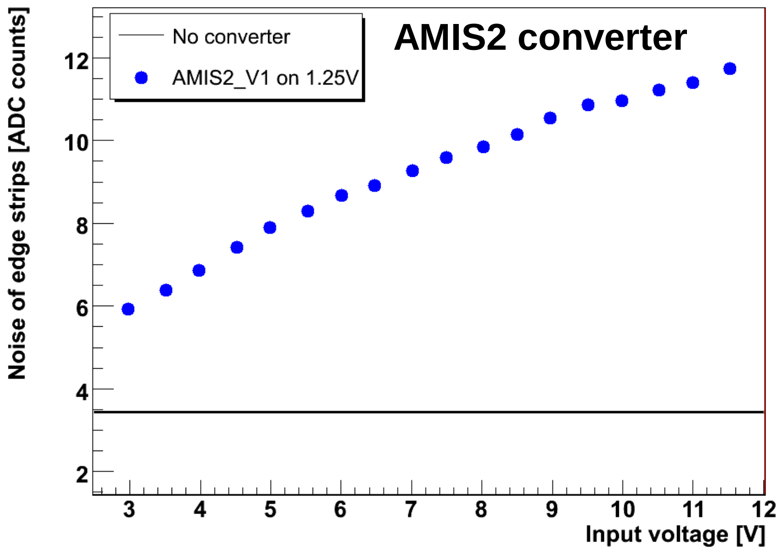
Conductive Noise

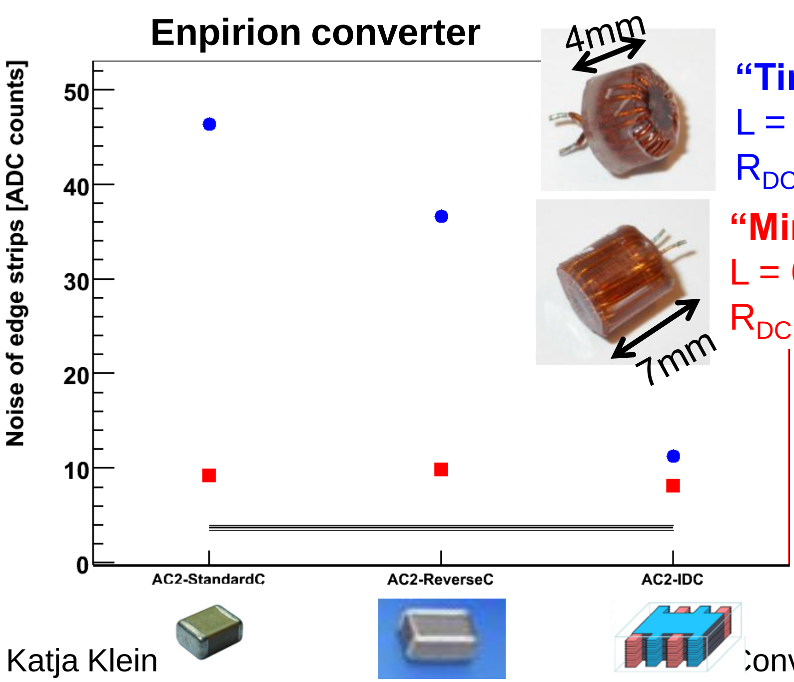
Noise increases for

– **larger conversion ratio**:
  $\delta U_{out}/U_{out} \sim [1 - 1/r] \cdot 1/f_s^2 \cdot 1/LC$

– **lower frequency** - preferred for efficiency; (depends also on module susceptibility)

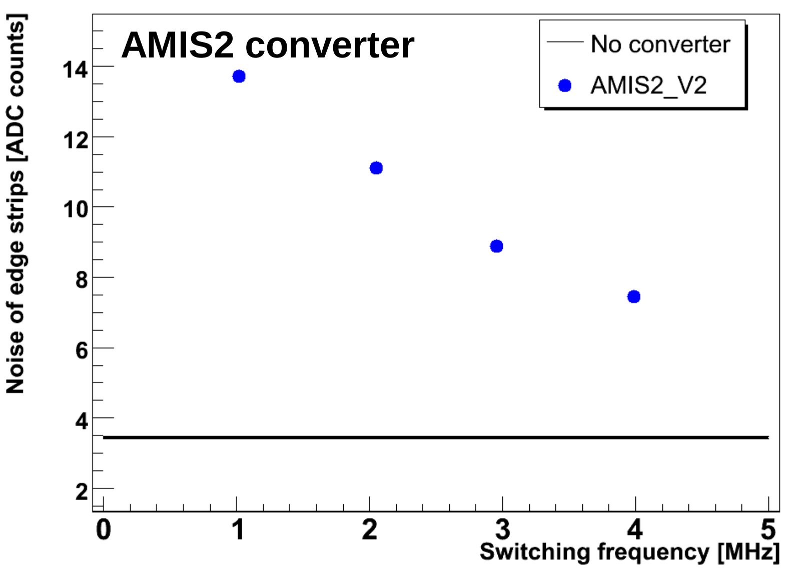
– **lower inductance**: $\delta I_L = V_L \cdot t_{on} / L$





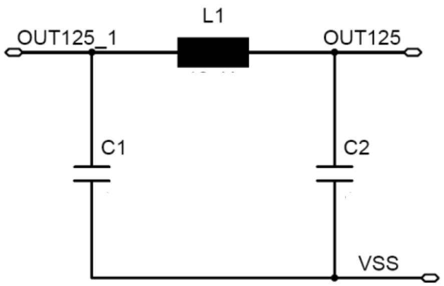
"Tiny Toroid"
L = 200nH
R_{DC} = 40-50mΩ

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



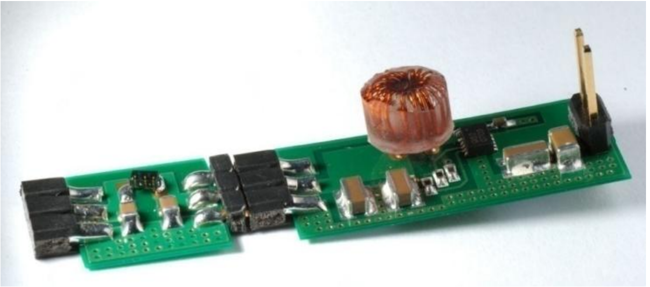
Conductive Noise Filters

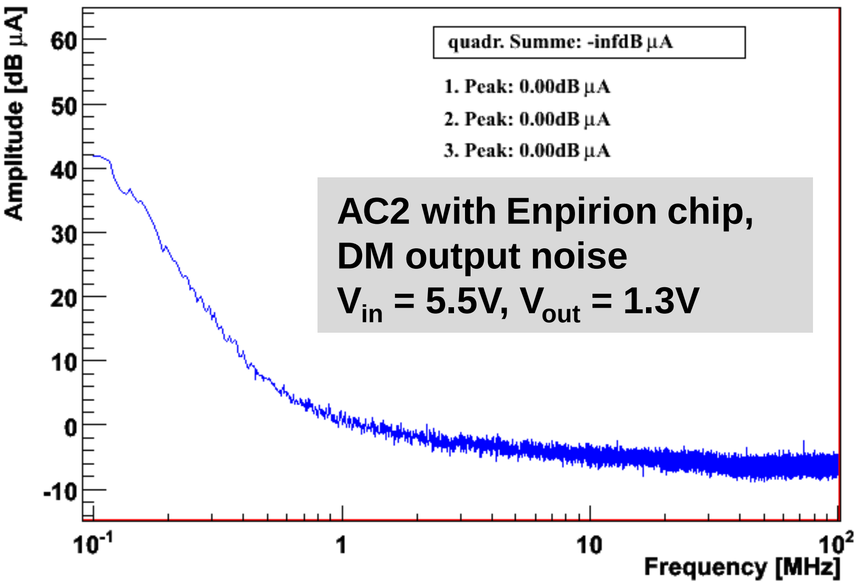
Passive π-filters

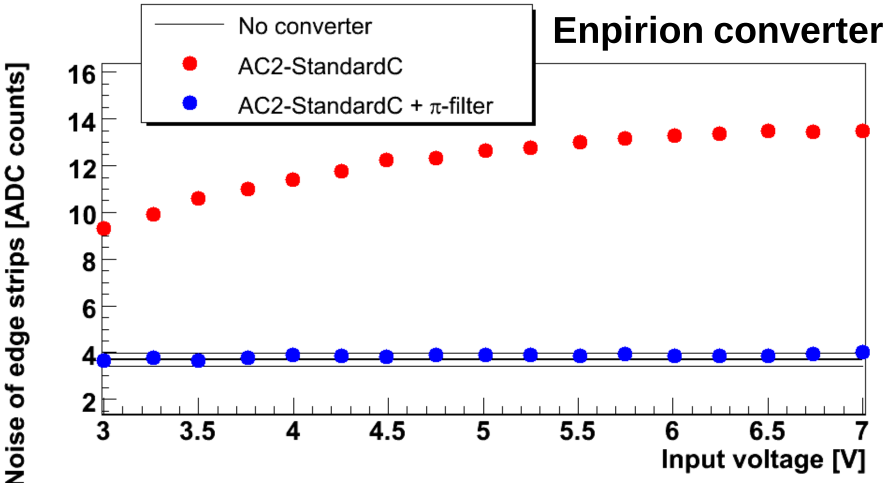


e.g. L1 = 2.55nH ($R_{DC} \leq 5m\Omega$)
C = 2.2µF $\Rightarrow f_{cut} \approx$ 3MHz

Efficiency loss < 1%



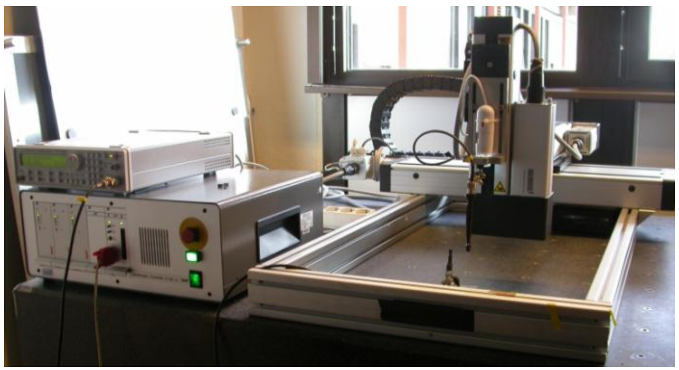


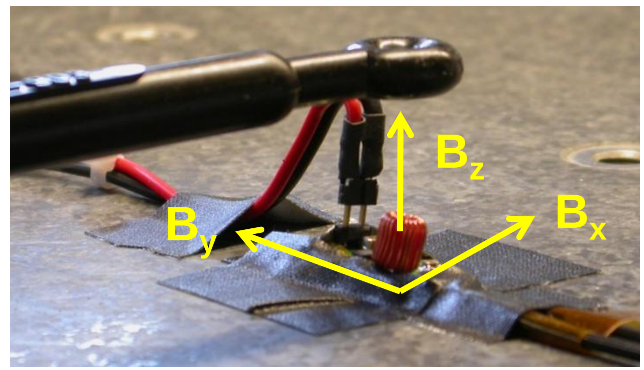


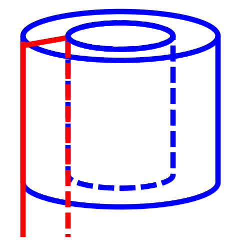
On-board pi-filters of AMIS2 not equally effective
$\Rightarrow$ to be understood

Radiative Noise from Air-Core Inductor

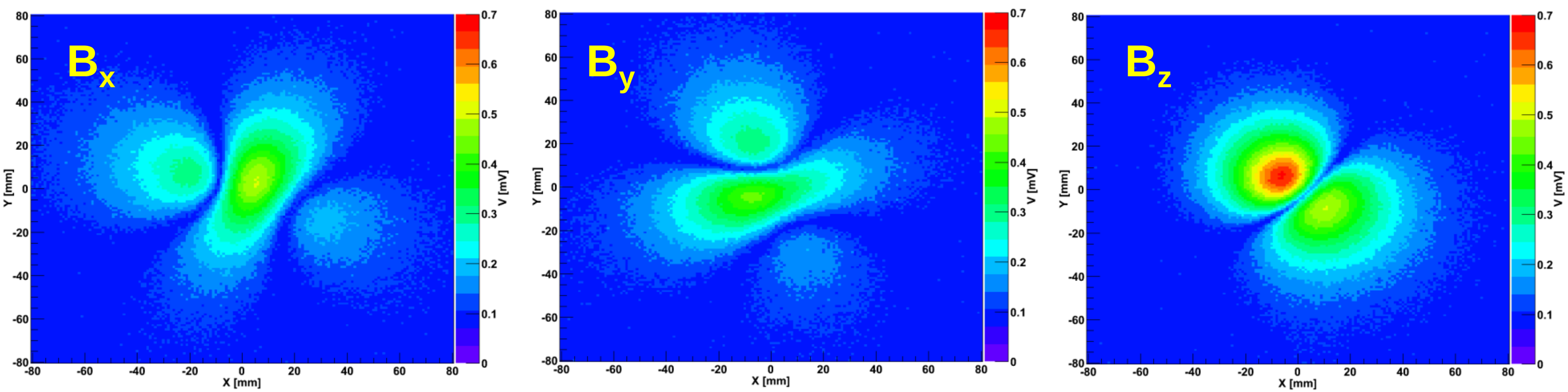
- Large fast changing currents through inductor → magn. near field can induce noise
- Air-core **toroid** field has a multi-polar shape: superposition of toroid + single wire loop
- Confirmed by simulation (COMSOL) and system tests by rotating converter





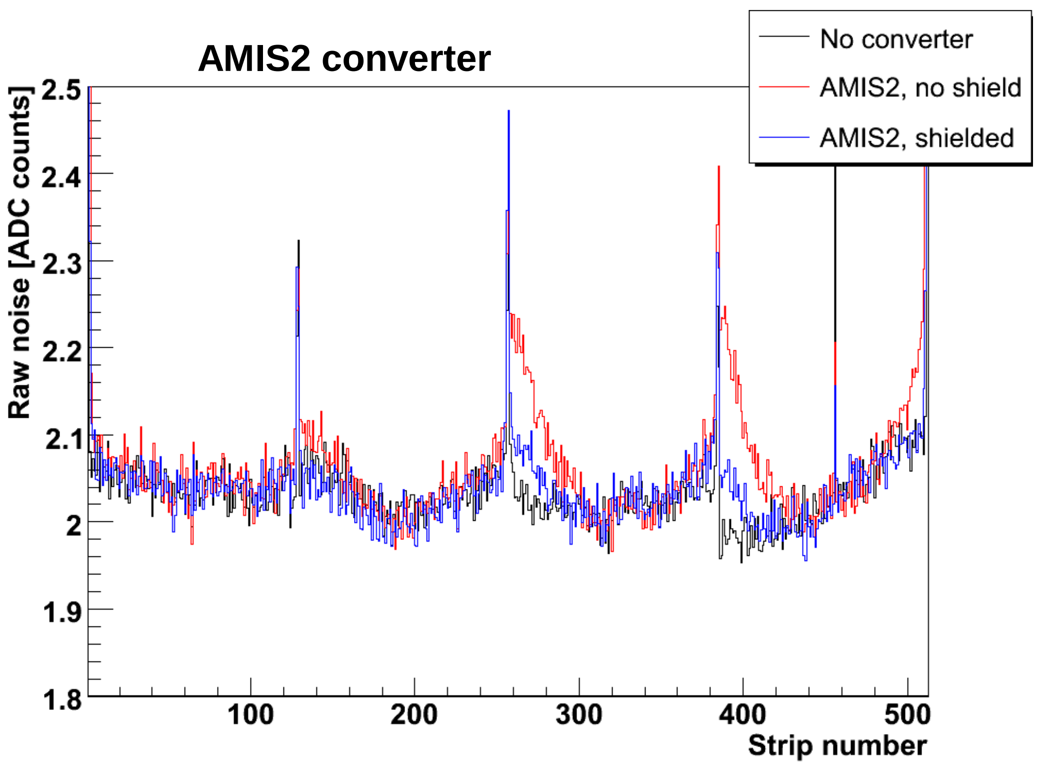


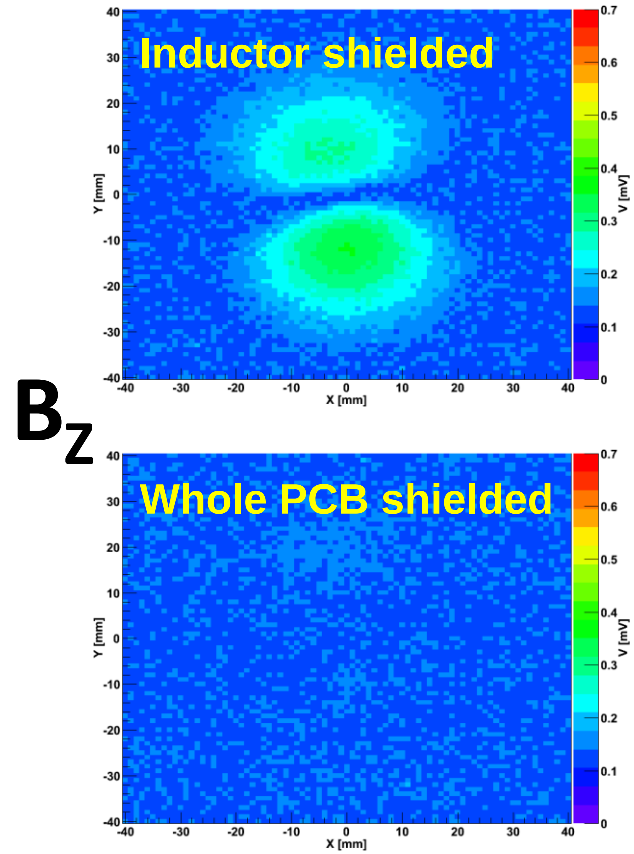
Work in progress!



Shielding

- Amount of radiative noise depends on distance, orientation and other parameters
- A robust solution must be found, cannot rely on “fine-tuning“
- Ungrounded shields (30µm Aluminium) help (eddy currents)
- Shielding only the inductor less effective than shielding PCB



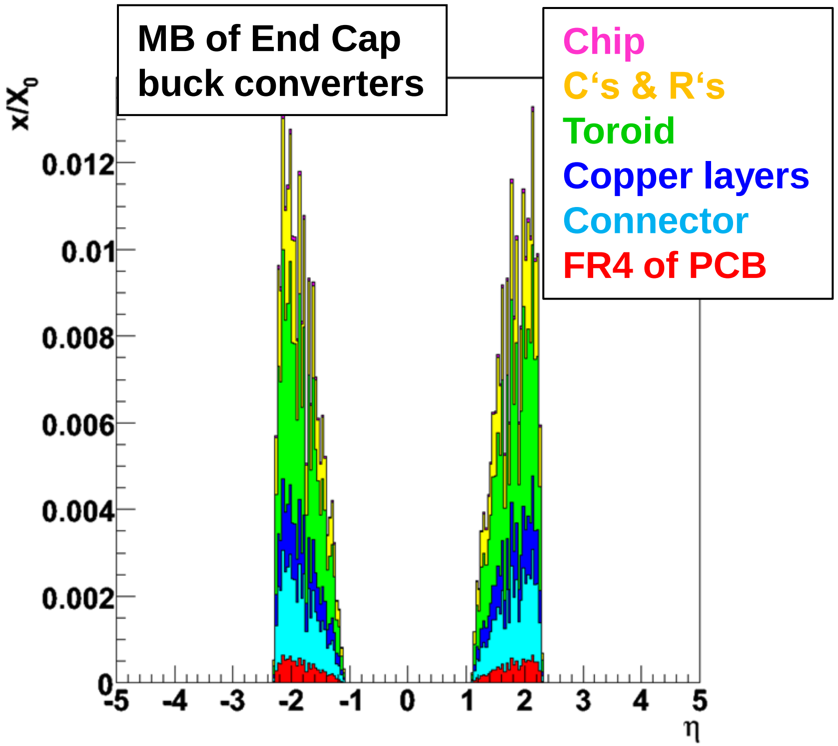


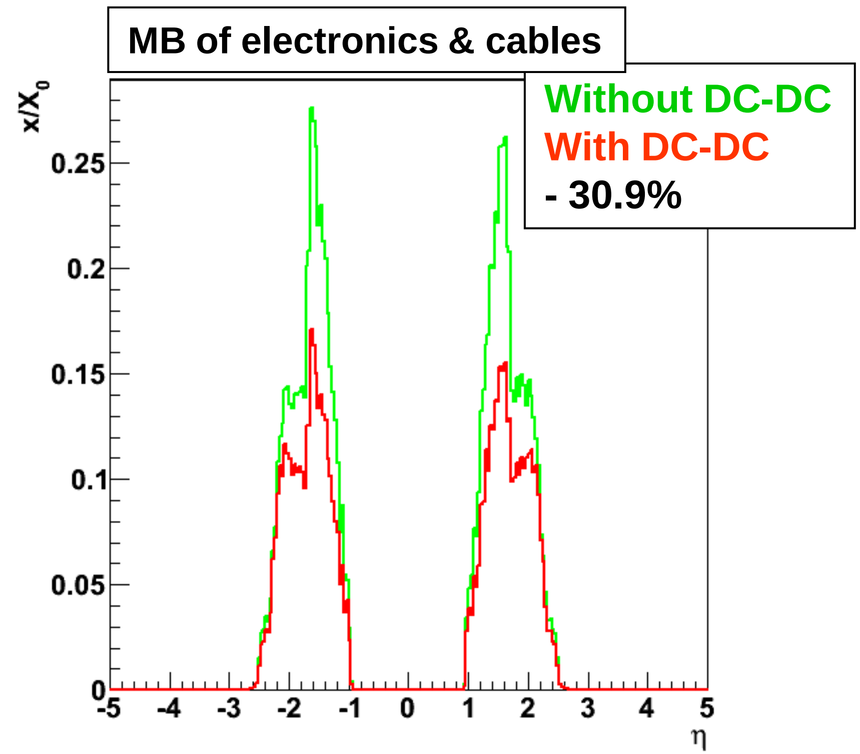
Material Budget (MB)

Motivation for new powering schemes is to save material inside the tracker

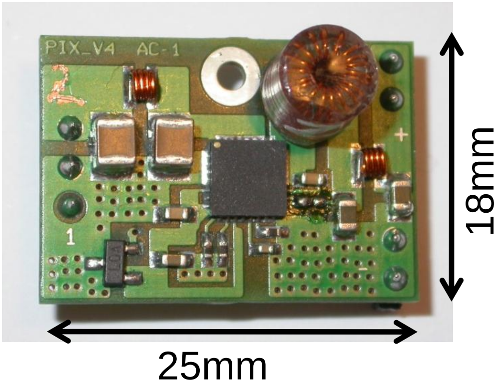
- Detailed study of Enpirion-converter, 1 per Tracker End Cap module, located on FE-hybrid
- Assumptions: 80% efficiency, r = 8, Iout = 2A per module, Uout = 1.2V
- Simulation of current tracker layout with CMS software based on GEANT4

$\Rightarrow$ **Converter adds 10%** of strip module, but still **saves 30% in electronics & cables**





Space Requirements



- **AMIS2 (QFN32)** with input & output pi-filter: **25mm x 18mm**
  ... but LDO for 3.3V and some passives will vanish
- **Enpirion converter**: **19mm x 12mm**
  ... but pi-filter at output desirable
- **Height ~ 10mm**, dominated by inductor (to be optimized)

⇒ Final size will be inbetween

⇒ Will be hard to squeeze below 2cm^2 without compromising performance

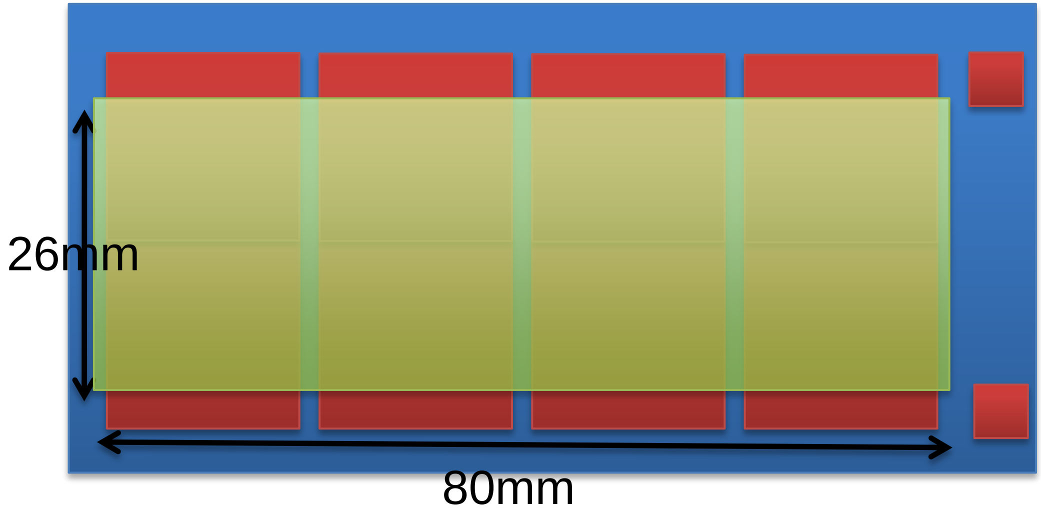
⇒ Trade-off between redundancy and size (e.g. input pi-filter)

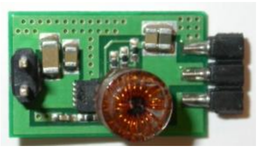
If two converters (1.2V/0.9V) **needed per double module:**

- can of course be installed on one PCB
- size increases by a factor of ≤ 1.5

Space Requirements

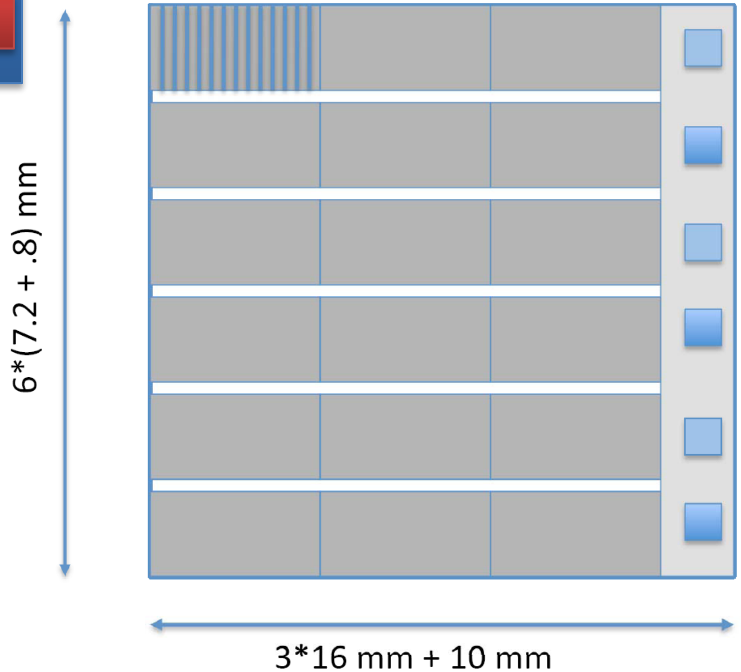
p_T-module by Geoff Hall et al.





Enpirion converter, to scale

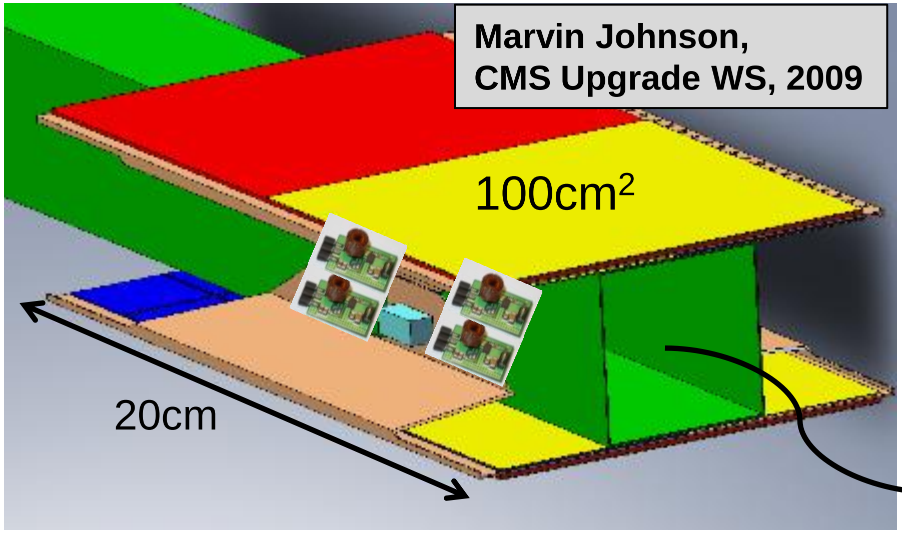
p_T-module by Sandro Marchioro



A Possible Implementation

Converters could be integrated into support structure:

- ✓ no space on hybrid required
- ✓ height/shape of coil no issue
- ✓ larger distance → less magnetic field
- ✓ easier shielding (e.g. by existing Carbon Fibre structures)
- ✓ much easier cooling
- ✓ Kapton bus between converter and modules - needed anyway: GBT, by-pass caps
- ✓ decoupling of module & converter R&D, QA etc.
- ✓ straight-forward in double-stack proposal (less obvious in others)



Per 100cm² double-module:

1 GBT
1 DC-DC a 1.2V for module power
1 DC-DC a 0.9V for module power } 1 PCB
1 DC-DC a 1.5V for GBT
1 DC-DC a 2.5V for GBT } 1 PCB

⇒ 2 PCBs a ≈ 4cm² ~ ok

A lot of space inside – is it usable?

Summary

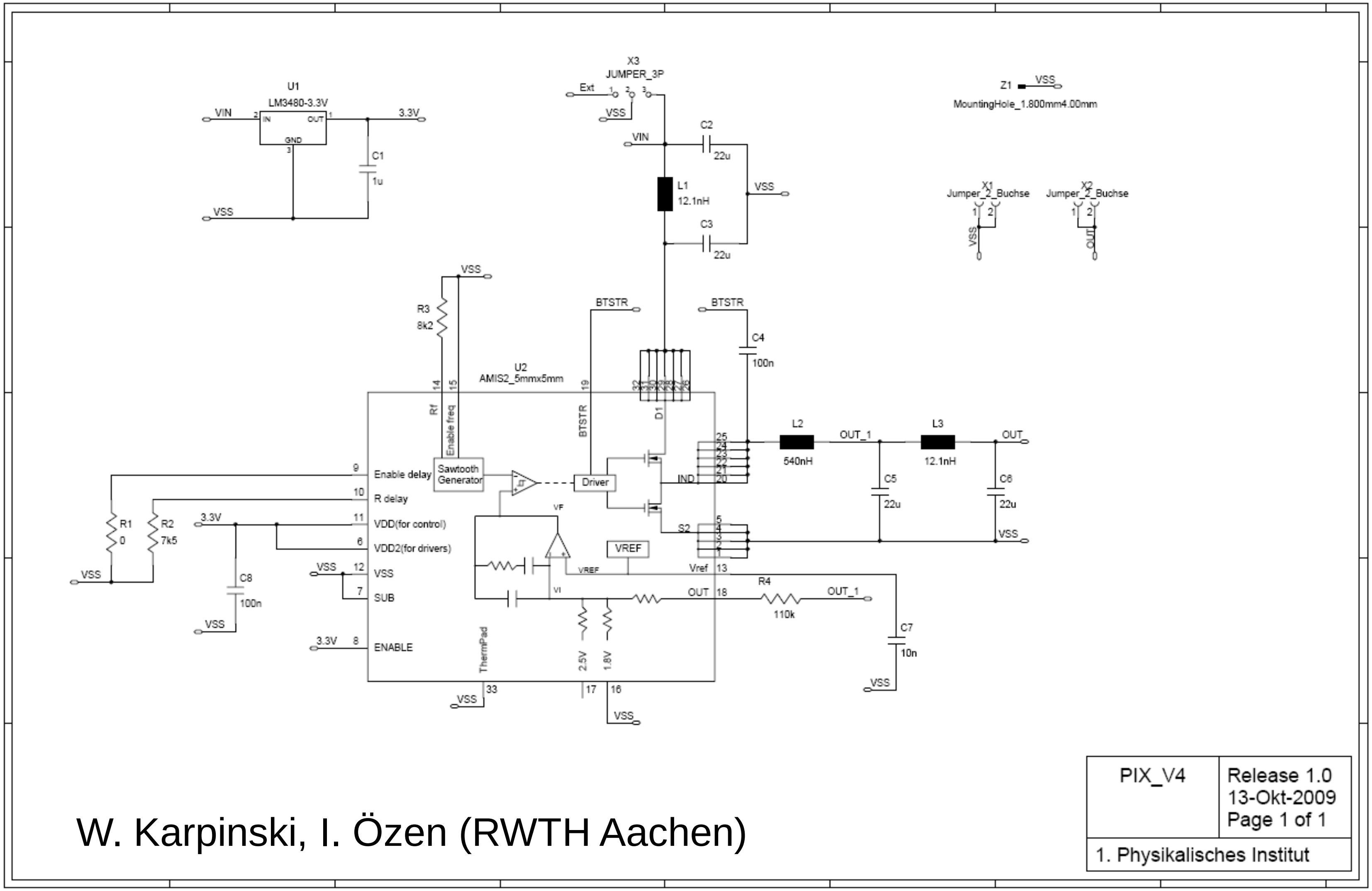
- The CMS tracker upgrade will be powered using DC-DC conversion
- Rad.-had buck converters in two technologies are being developed at CERN
- R&D on noise understanding & mitigation at Aachen, CERN and other places

- Stacked modules require high currents at a high conversion ratio (efficiency!)
- Need to find space and to minimize material

- Converter R&D is still focused on generic aspects
- Once concrete layouts and reliable power estimates are available, DC-DC R&D will become more specific

Back-up Slides

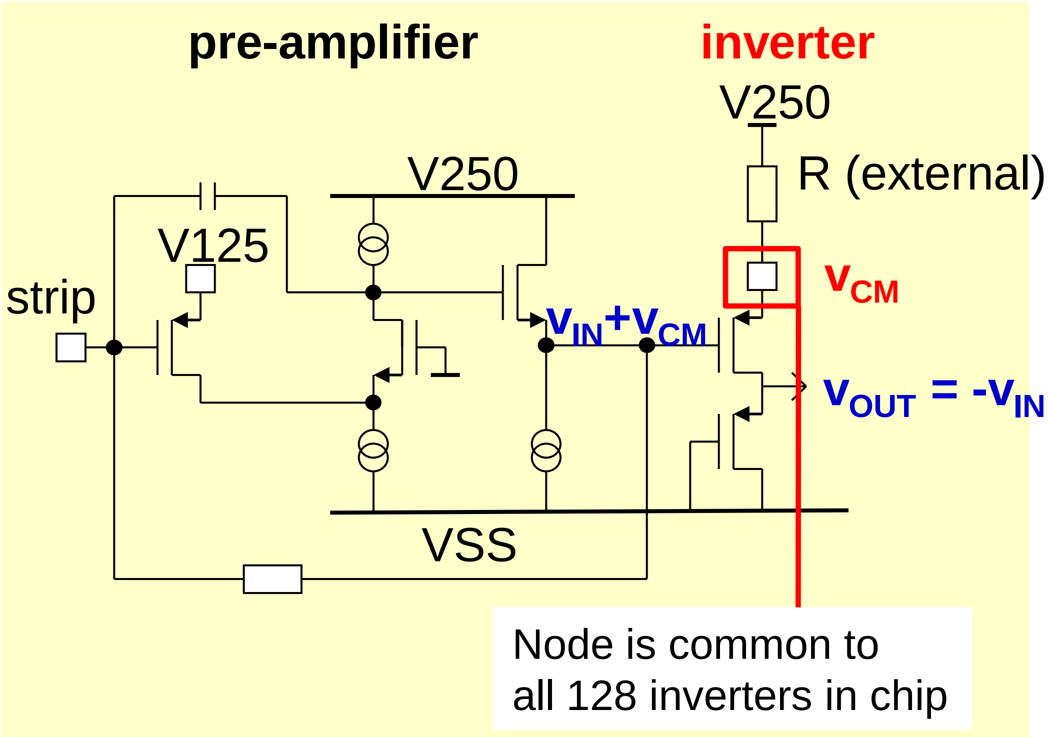
AC_AMIS2 Schematics



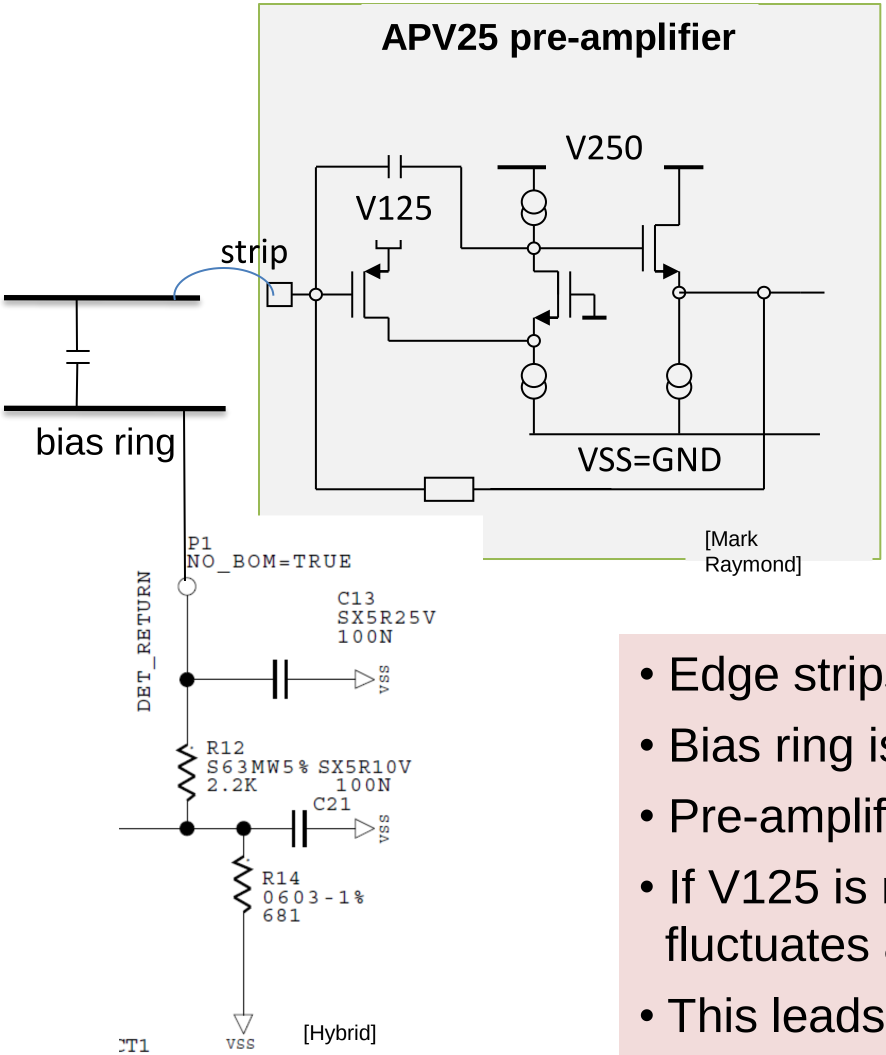
W. Karpinski, I. Özen (RWTH Aachen)

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