DC-DC Conversion Powering for the CMS Tracker at SLHC

Lutz Feld, Rüdiger Jussen, Waclaw Karpinski, Katja Klein, Jennifer Merz, Jan Sammet

RWTH Aachen University

12th Vienna Conference on Instrumentation - VCI 2010

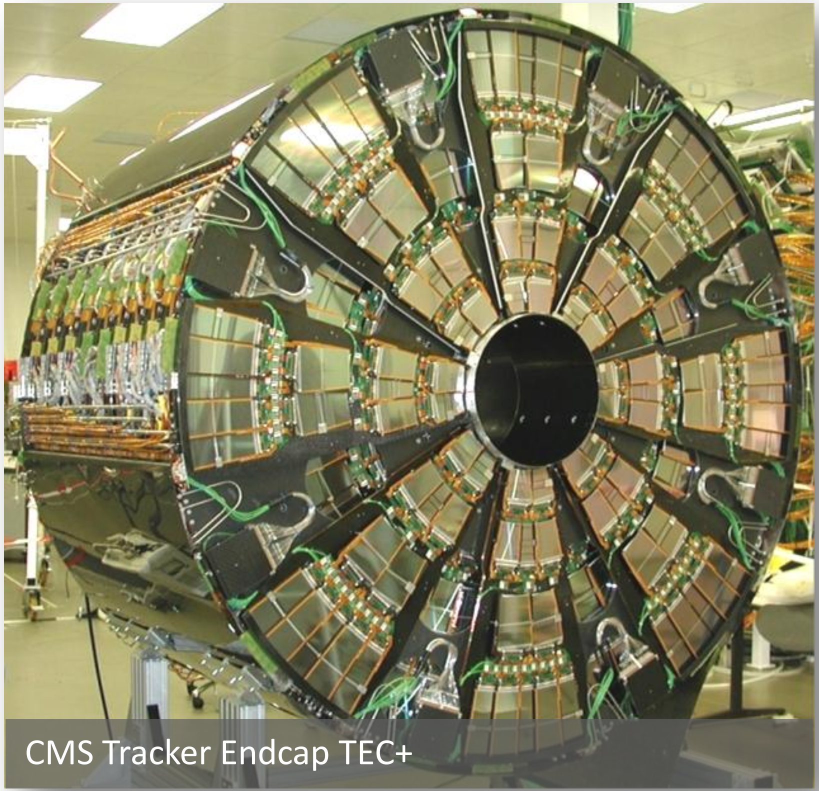
17. 2. 2010

Overview

- Motivation and Strategy
- Powering Scheme with DC-DC Converters
- Problems and Challenges … and how to address them
- R&D with commercial ASICs
- R&D with custom radiation hard ASICs
- Conclusions

Motivation

Tracker before insertion into CMS



CMS Tracker Endcap TEC+

- current CMS and ATLAS trackers burn 50% of their power in supply cables
  CMS: front end 33kW, cables 34kW, total current 15kA

Motivation

- pixel and strip tracker upgrades will likely need more power than current systems:
  - more channels (more pixel layers, higher granularity)
  - more functionality (contribution to L1 trigger)
- …at a lower voltage (smaller ASIC feature size)

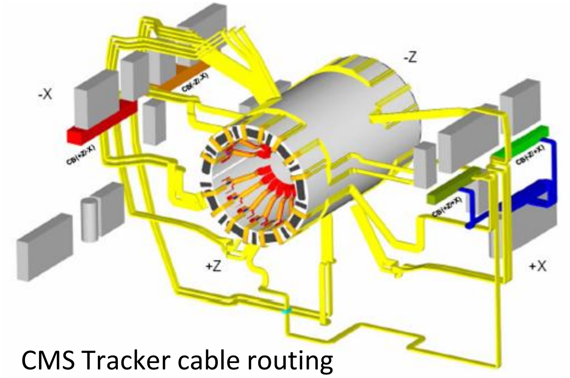
→ **currents will increase substantially**

→ cable losses rise quadratically: $P_{loss}=R \cdot I^2$

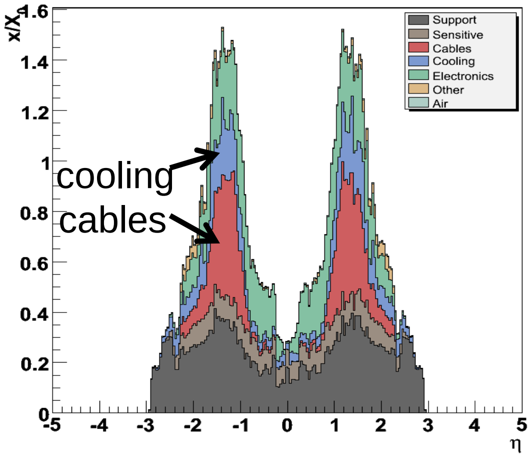
→ increase power cable cross-section … not possible

→ increase copper cross-section inside tracker … not desirable

→ **<u>need an improved powering scheme</u>**



CMS Tracker cable routing



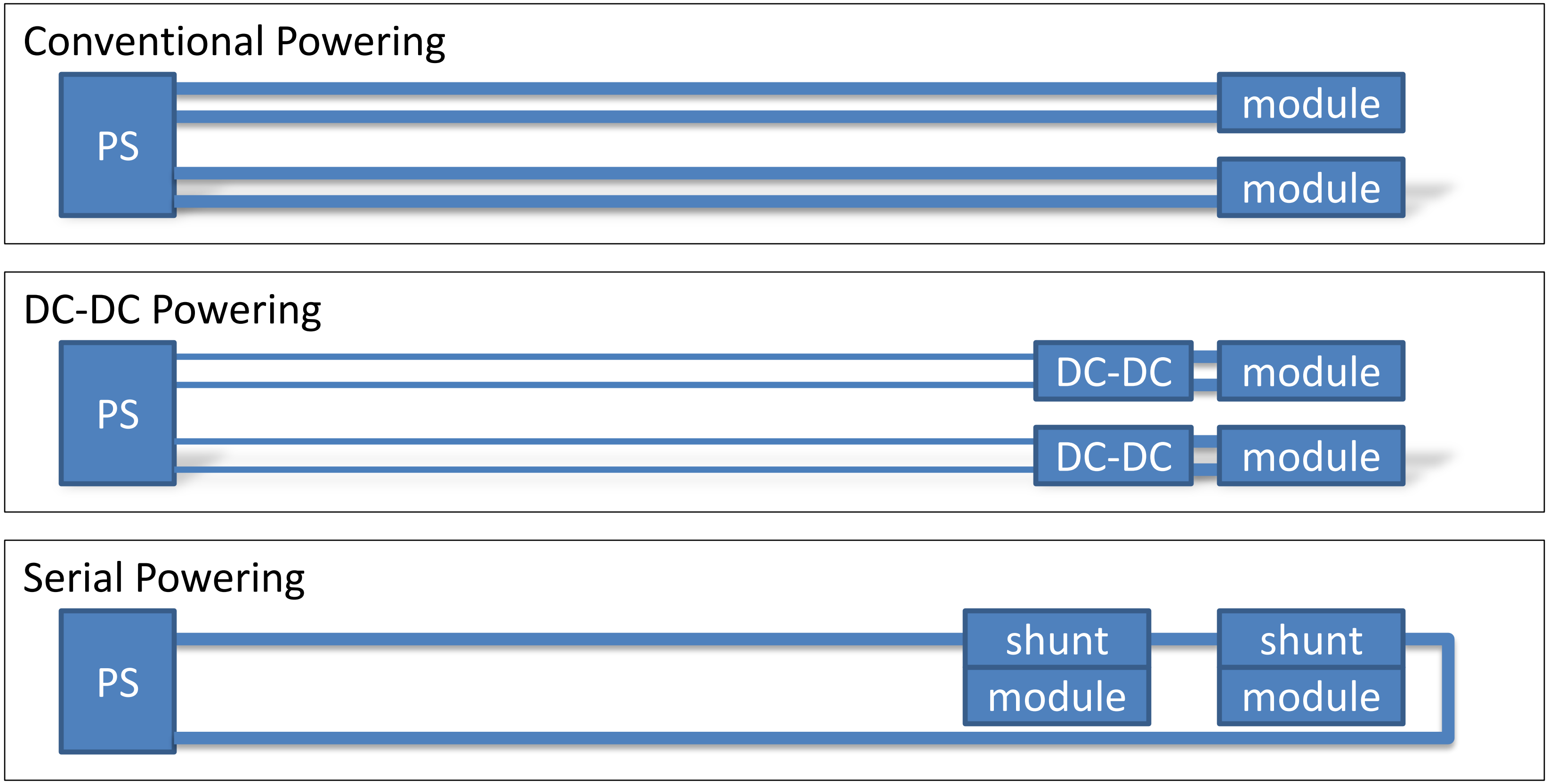
CMS Strip Tracker material budget

Strategy

- **$P = U \cdot I = (rU) \cdot (I/r)$**

  → supply power at higher voltage i.e. lower current

  → cable loss $\mathbf{P_{loss}=R \cdot I^2}$ is reduced by factor $\mathbf{r^2}$!



Choice of Powering Scheme

- both new powering schemes seem feasible

- DC-DC conversion
  - system design is simpler and closer to current systems, less interdependencies
  - only one new component
  - switching noise is a concern

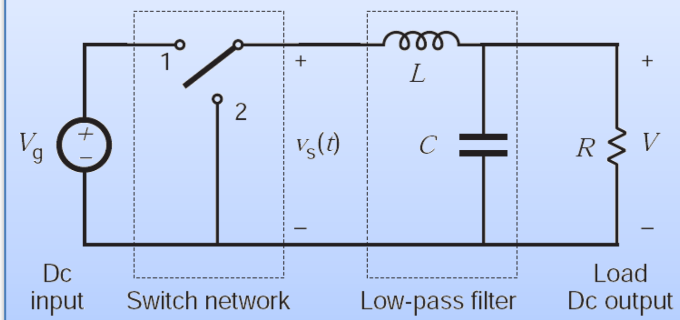
- serial powering
  - no switching
  - each module has different ground potential (AC communication, …)
  - modules in a chain are coupled, need safety features (shunts, …)

- little difference in efficiency and material budget

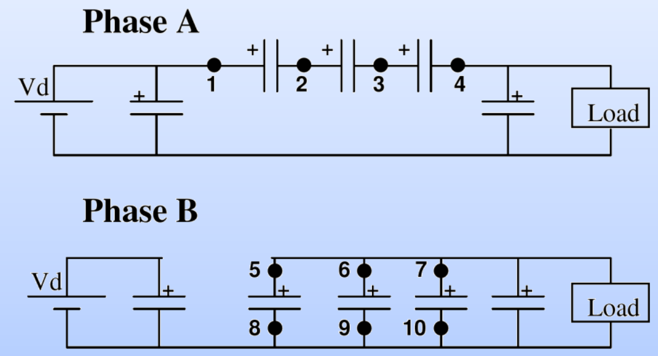
- CMS Tracker has chosen DC-DC conversion as baseline
  - mainly because changes to the system are minimal and factorizable
  - serial powering should be kept as a back-up

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 (external capacitors)
- piezoelectric transformers
- all need rad-hard "high voltage" transistors as switches
- efficiency typically 70 – 90 %
- switching noise is a concern



Inductor Based "Buck Converter"



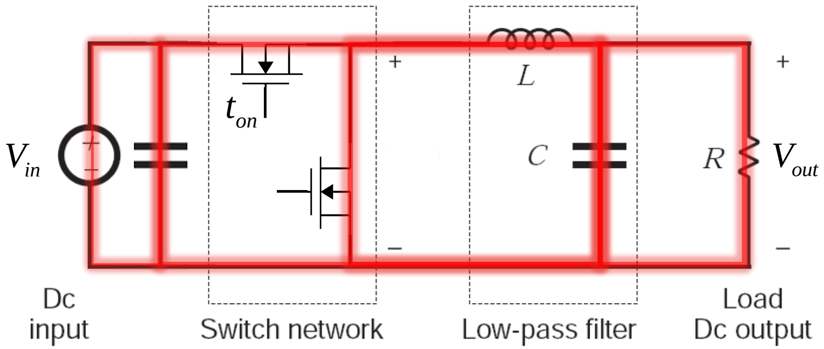
Capacitor Based "Charge Pump" [10]

operation principle

output voltage is regulated via feed-back loop by adjustment of

duty cycle $D = \frac{t_{on}}{T}$:

$$\boxed{V_{out} = D \cdot V_{in}}$$ for lossless converter



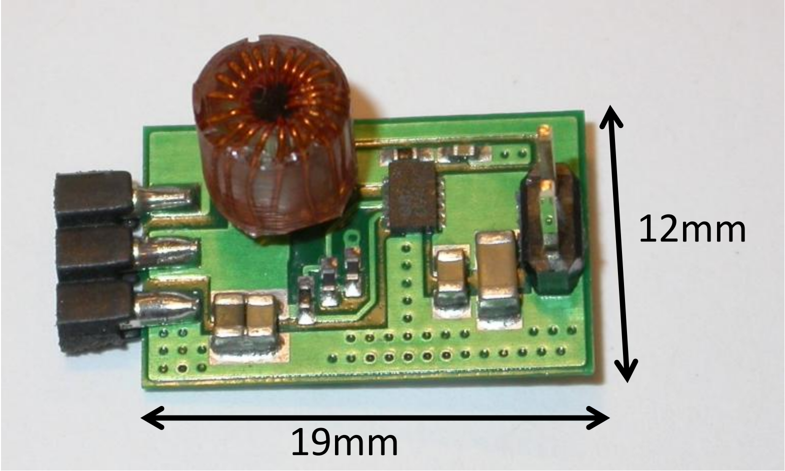
main parameters

conversion ration $r = \frac{V_{in}}{V_{out}} = 2...10$

switching frequency $f = 1...4$ MHz

efficiency $\eta = \frac{P_{out}}{P_{in}} = 60\ldots90\%$

current ripple at inductor $\Delta I_L = \frac{V_{out}(1-D)}{L\ f}$



main loss mechanisms

resistive loss in inductor

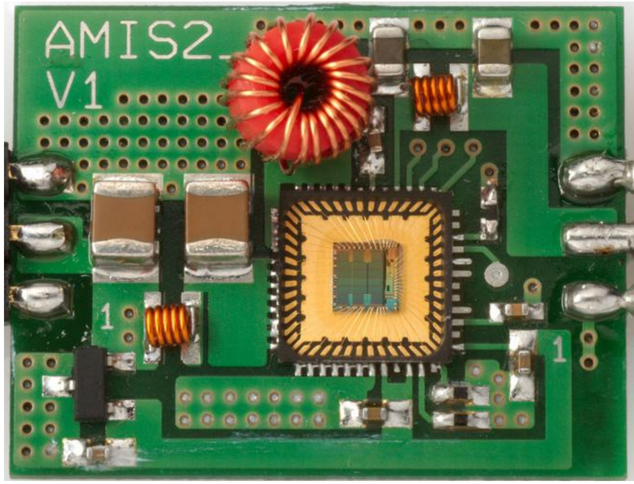
resistive loss in MOSFETs

switching loss in MOSFETs $\left(\sim V_{in}^{2} \cdot I_{out} \cdot f\right)$

input and output capacitor ESR losses

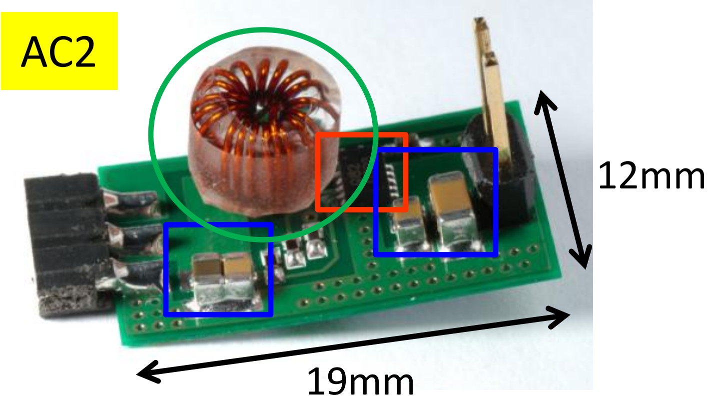
Challenges with DC-DC Buck Converters

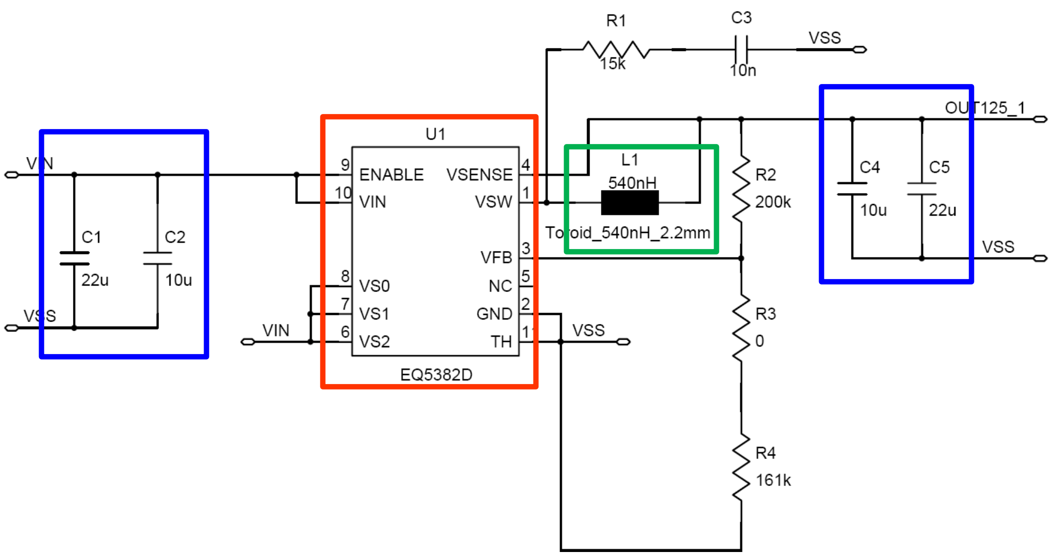
- coupling of switching noise into detector modules
  - conductive
  - radiative
- air core inductors required due to 4 Tesla field
  - bulky
  - radiates noise
- radiation hard ASIC needs to switch rather high voltages (~10V)
  - need special high voltage process
- useful only if efficiency is high
- total material budget should be reduced despite addition of converters
- small size required for integration close to detector modules



R&D with commercial ASICs

- buck converters with **commercial non-radiation-hard** chips
- used to optimize for low mass, low space, low noise, and for studies in system test





PCB:
2 copper layers a 35µm
FR4, 200µm
V = 2.3cm² x 10mm
m = 1.0g

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

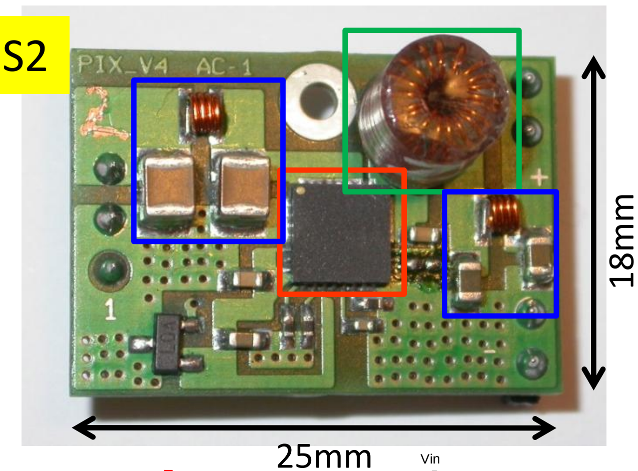
Air-core inductor:
Custom-made toroid, $\varnothing \approx 6mm$
L = 200nH or 600nH

Input/output filters

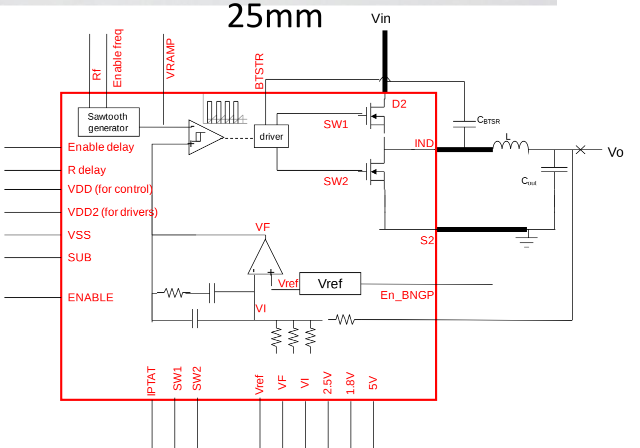
R&D with radiation hard custom ASICs

- radiation levels at 22cm & 3000fb^{-1}: fluence ~ 10^{15}/cm^2 , dose ~ 1MGy
- two candidate technologies identified by F. Faccio, CERN [contrib. to TWEPP 09]
- ASICs developed by S. Michelis, CERN [contrib. to TWEPP 09]

AMIS2



m = 2.7g



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

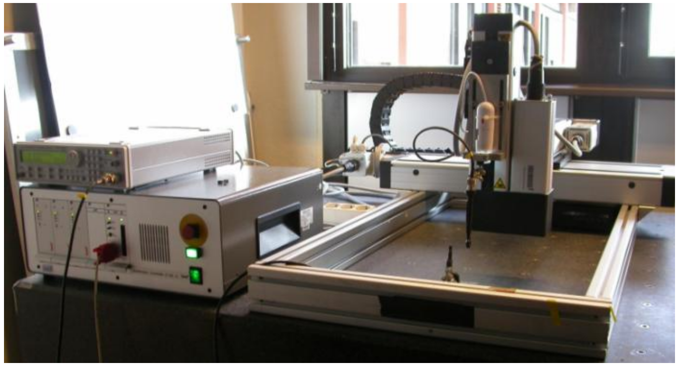
Chip: AMIS2 by CERN
V_{IN} = 3 - 12V
I_{OUT} < 3A
V_{OUT} = 1.2V, 2.5V or 3.3V
$f_S \approx$ 1.3MHz or
programmable betw. 600kHz...4MHz

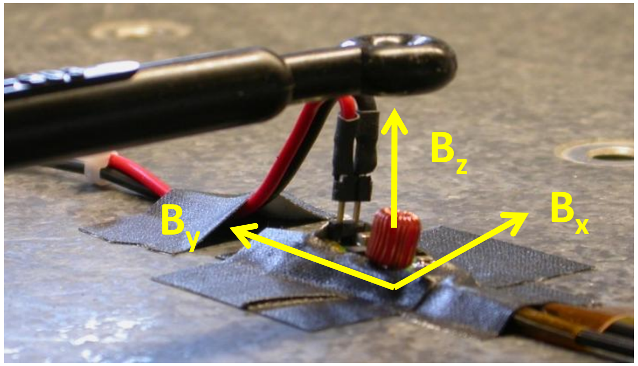
Air-core toroid:
Custom-made toroid, $\varnothing \approx$ 6mm,
height = 7mm, L = 600nH, R_{DC} = 80mΩ

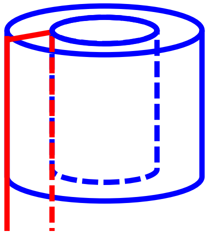
Input and output π-filters
L = 12.1nH, C = 22µF

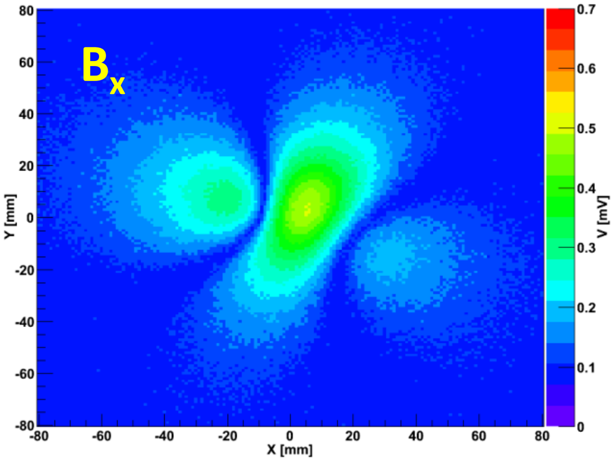
Radiated Switching Noise

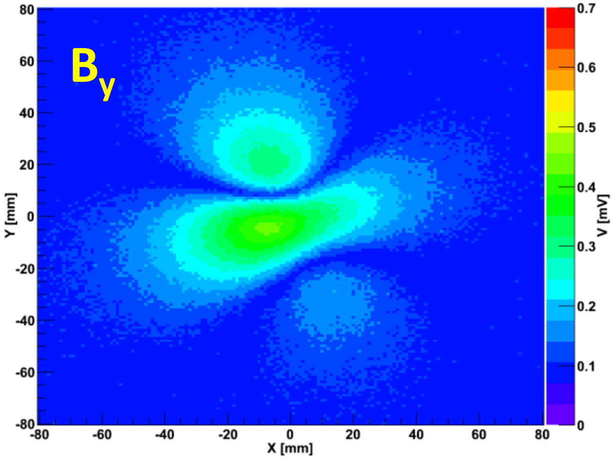
- current ripple in inductor radiates electromagnetic fields (near field)
- even a toroid radiates, dipole characteristics (confirmed by simulation)
- **shielding** with 30µm aluminium works very well and adds little material

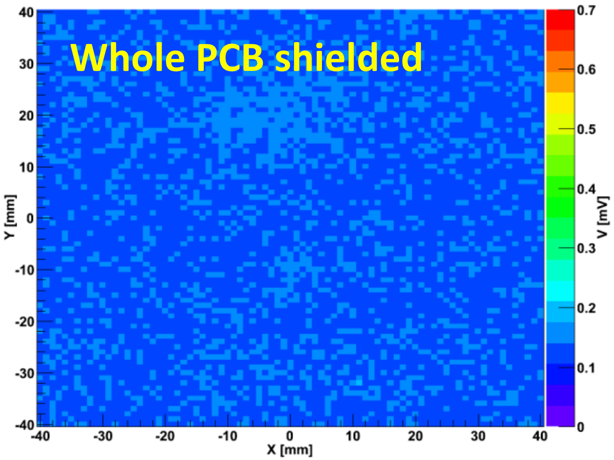




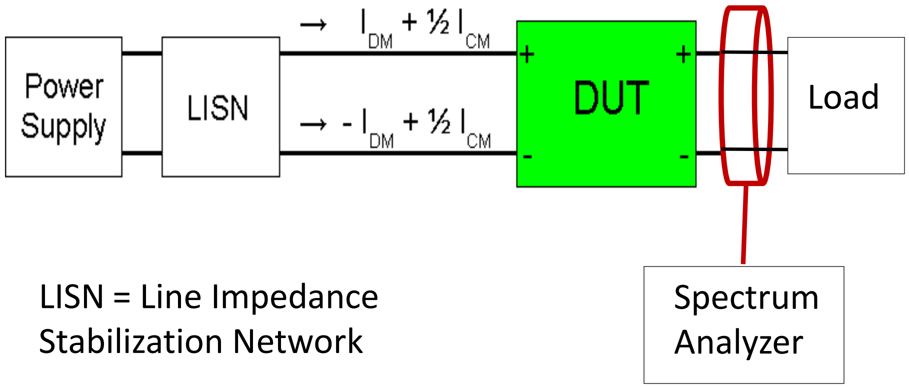




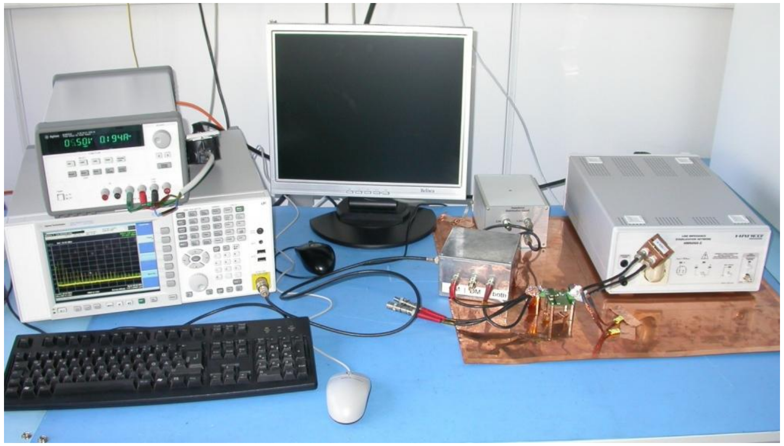


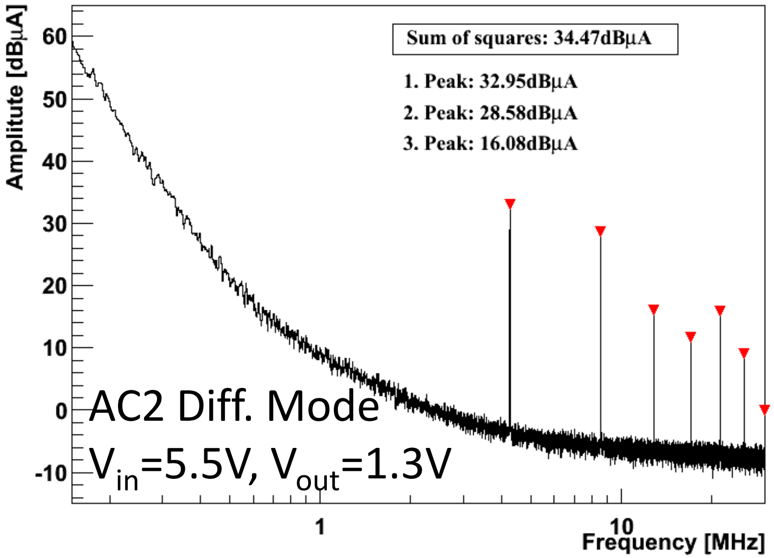


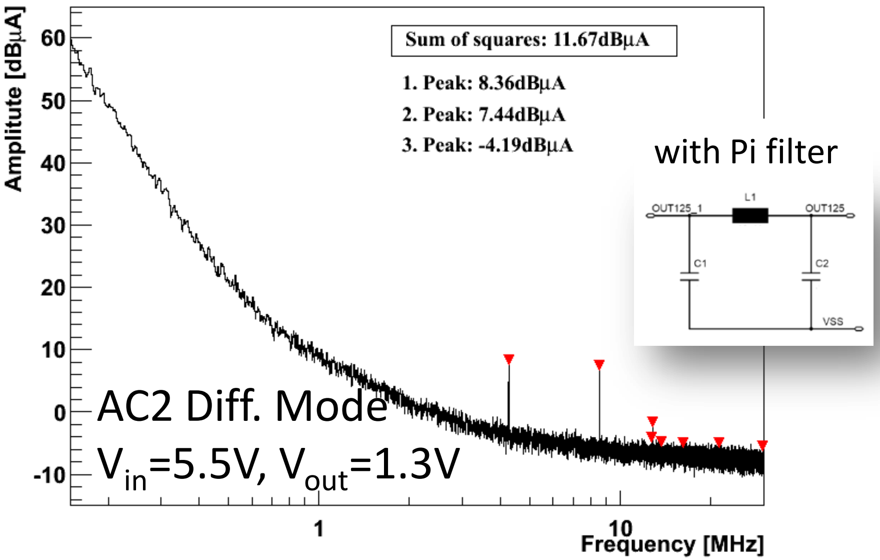
Conducted Switching Noise



LISN = Line Impedance Stabilization Network



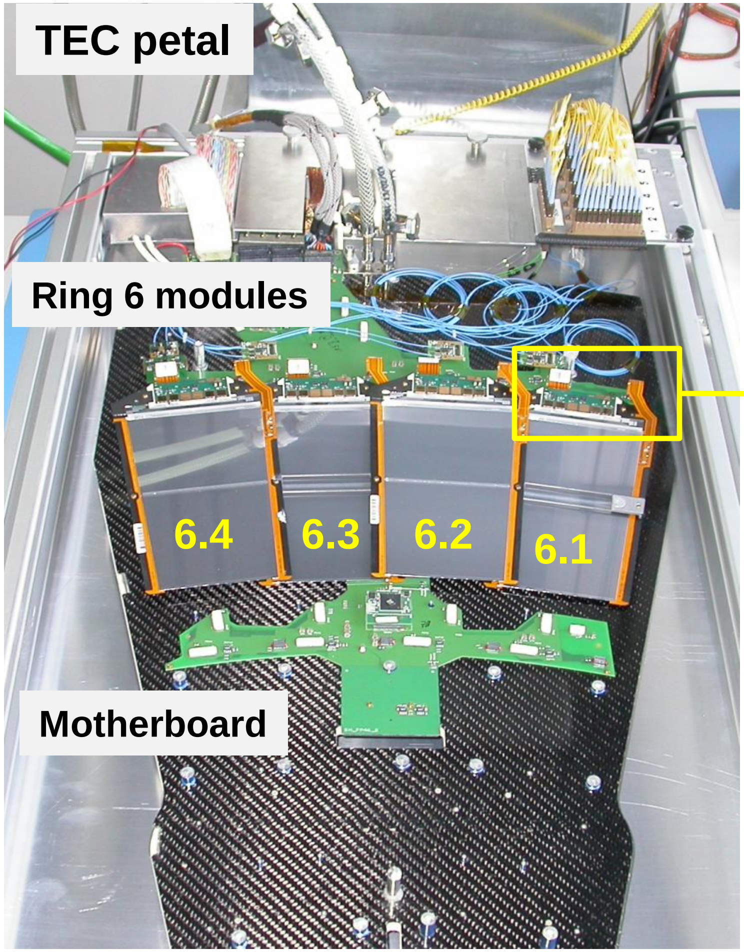


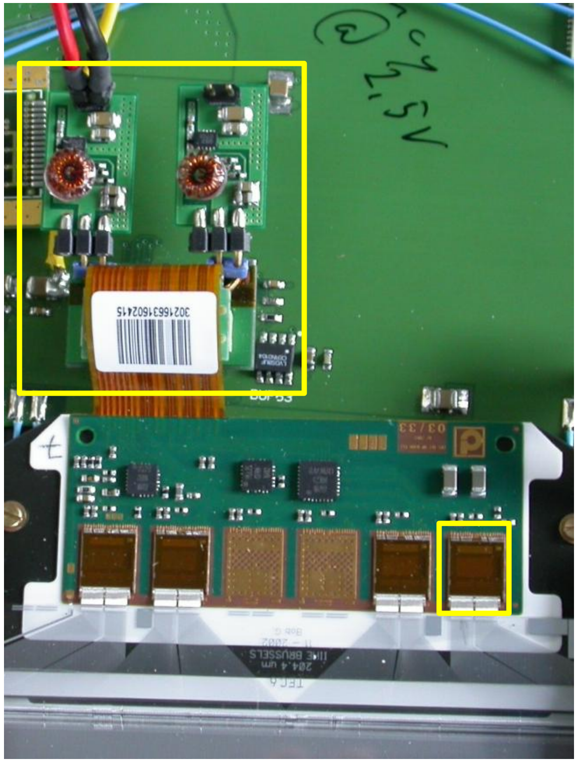


impact on detector system depends on its frequency dependent susceptibility

System Test with CMS Strip Modules

- SLHC readout chips and module prototypes not available before 2011
- use current CMS tracker hardware for system test of DC-DC converters

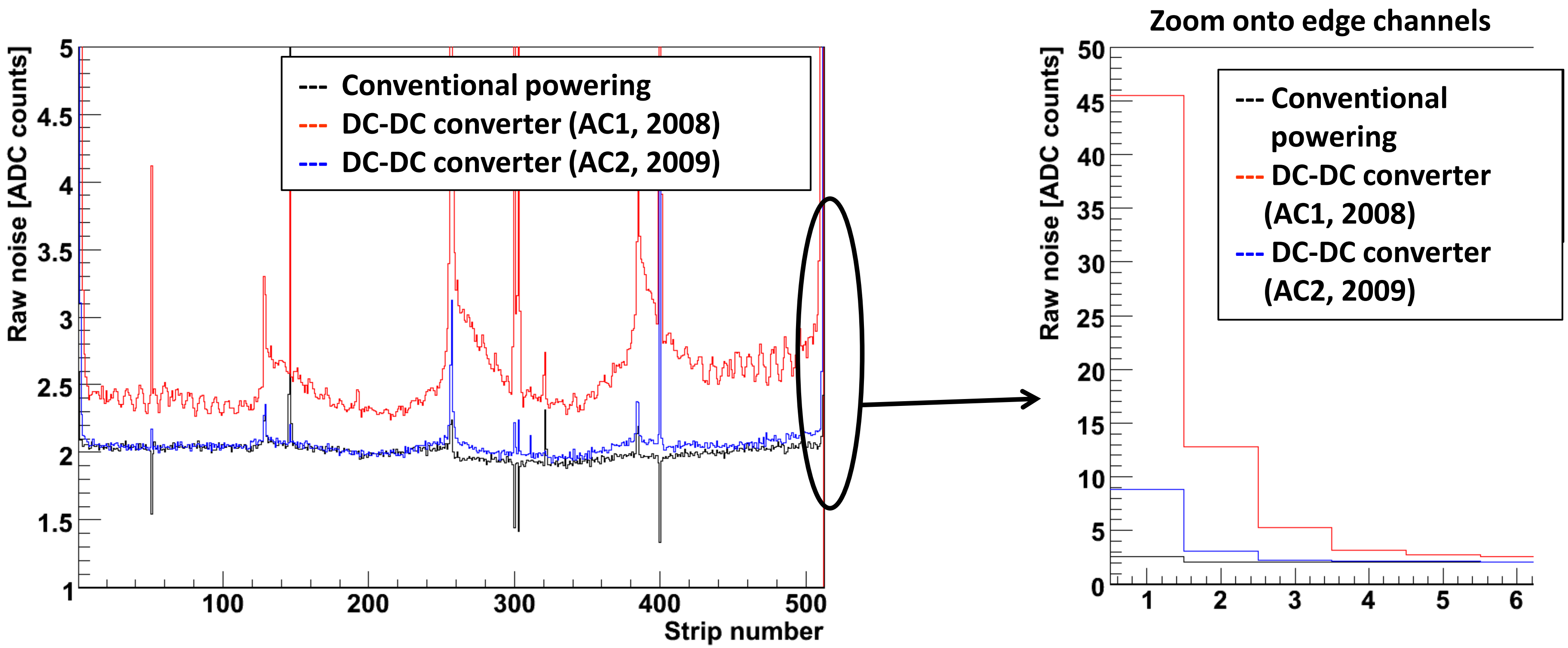




APV25 readout chip:
- 0.25 µm CMOS
-128 channels
- **analogue readout**
- per channel: pre-amp., CR-RC shaper, pipeline
- on-chip common mode subtraction
- τ = 50ns
- 1.25V & 2.50V supply
- I_{250} = 0.12A, I_{125} = 0.06A

- two DC-DC converters per module
- integrated via additional adapter
- V_{in} from external power supply

System Test with CMS Strip Modules

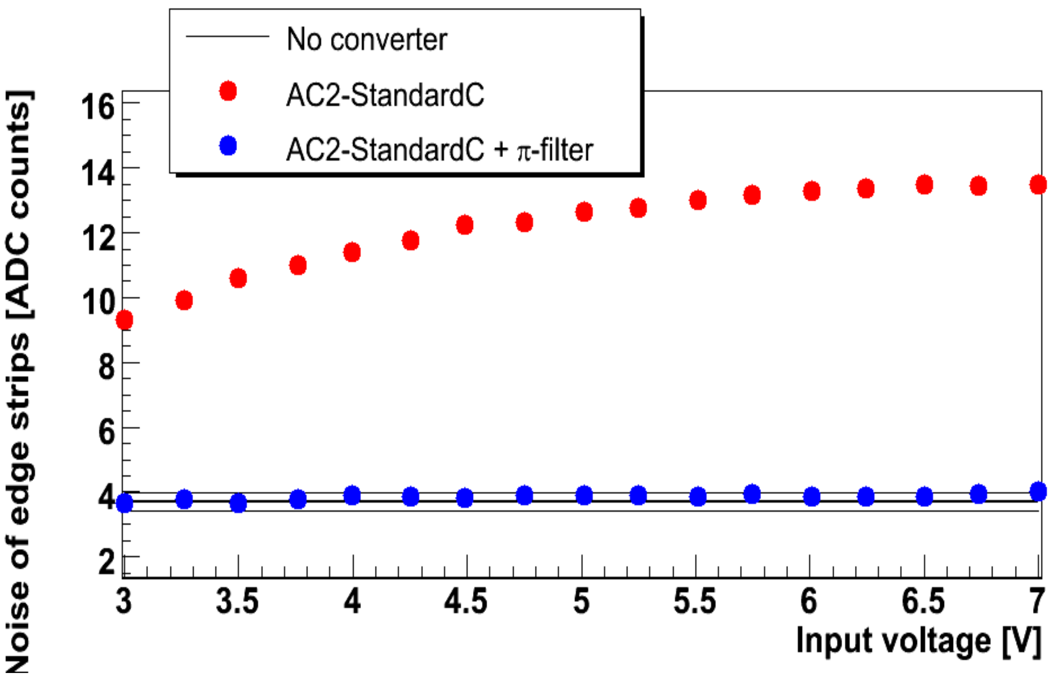


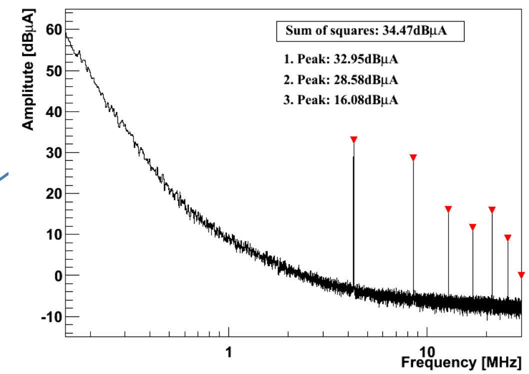
noise of edge strips $= \sqrt{N_1^{\,2} + N_{512}^{\,2}}$

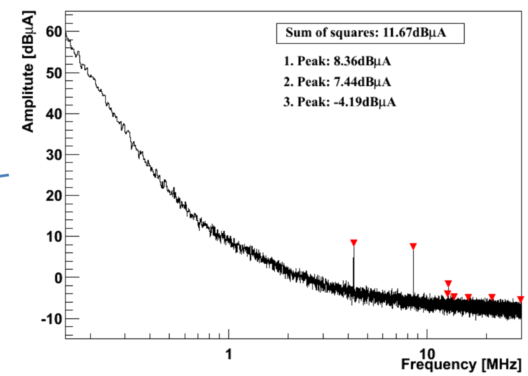
- Raw noise: RMS of fluctuation around pedestal value
- Edge channels are particularly sensitive (due to on-chip common mode subtraction)
- Large increase with previous generation of boards (**AC1**), in particular on edge strips; both conductive (ripple) and radiative (inductor) contributions (TWEPP08)

Results with Commercial Converters

- 4 MHz, conversion ratio up to 5.6, output current ~0.5 A
- no shielding
- simple Pi filter suppresses conductive noise efficiently







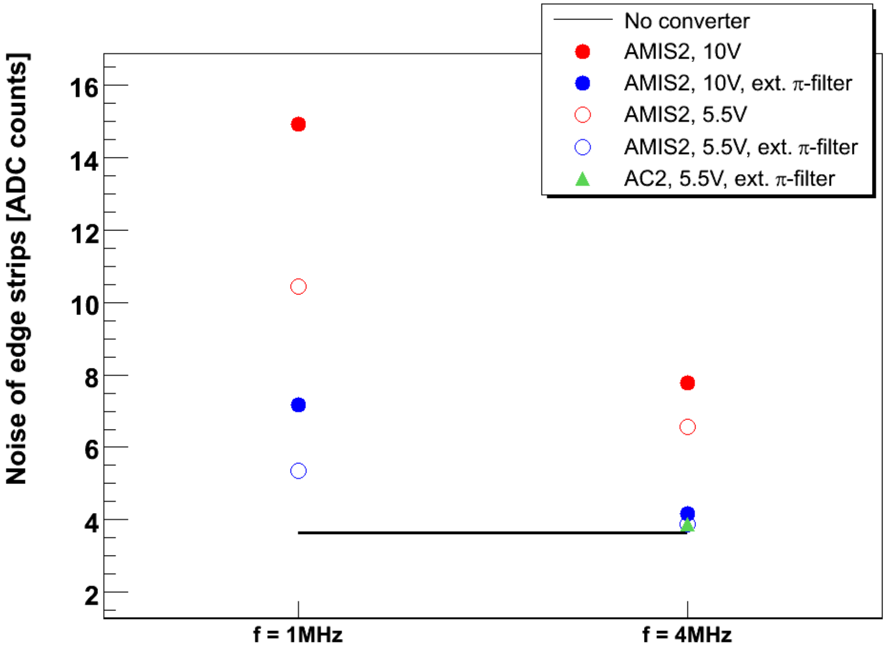
→ DC-DC powering without any noise increase is feasible

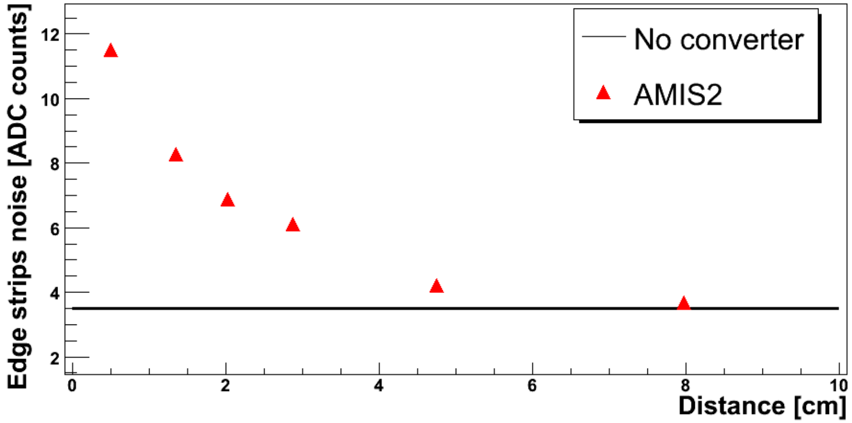
Results with radiation-hard ASIC (AMIS2)

- 1 - 4 MHz
- conversion ratio up to 8
- output current 0.5 A
- no shielding

- at operating conditions similar to commercial converters (4MHz, …)
  - rad-hard ASIC is similarly quiet
  - efficiency is reduced due to switching loss

- at 1MHz switching frequency
  - better efficiency
  - higher ripple leads to conductive and radiative noise
  - can be controlled by filtering, shielding and/or distance to module



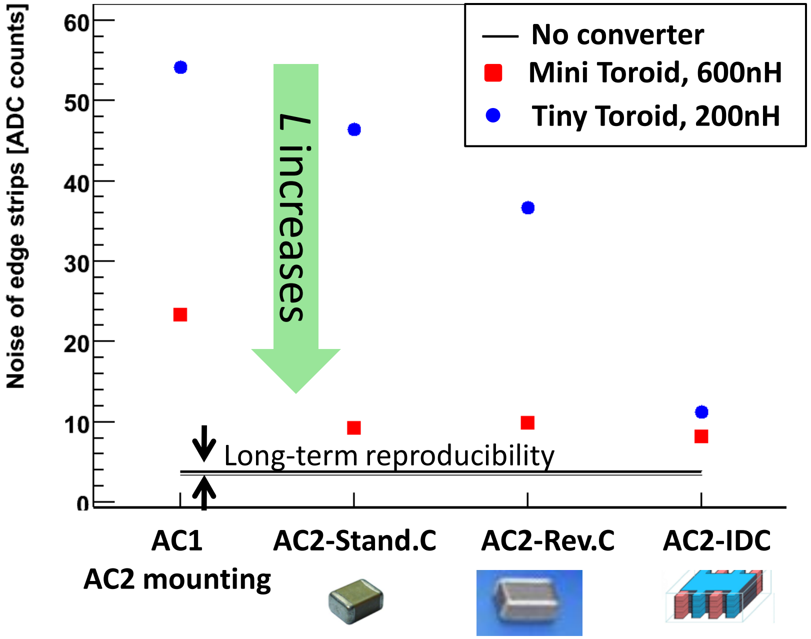


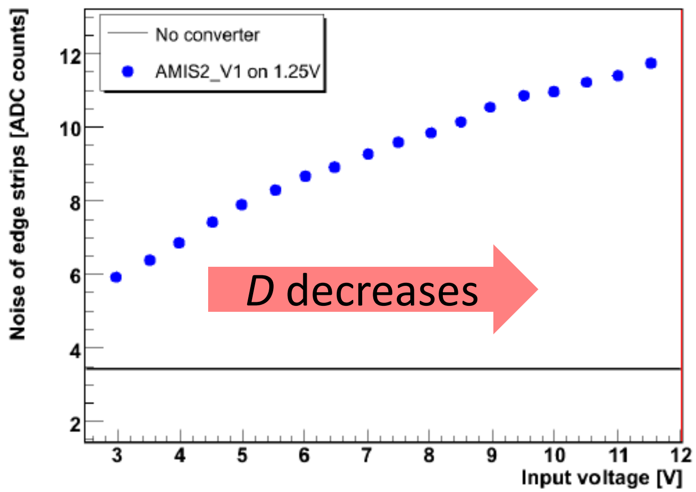
Understanding the Noise

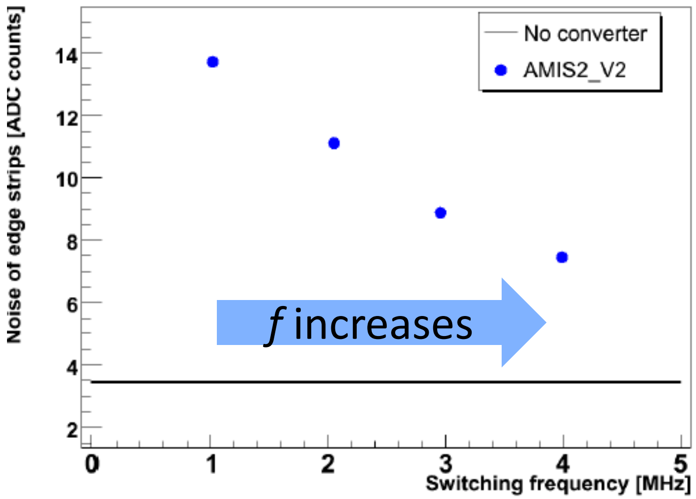
- noise caused by current ripple in inductor

$$\Delta I_L = \frac{V_{out}(1-D)}{L f}$$

- low-ESL in capacitors improve filtering

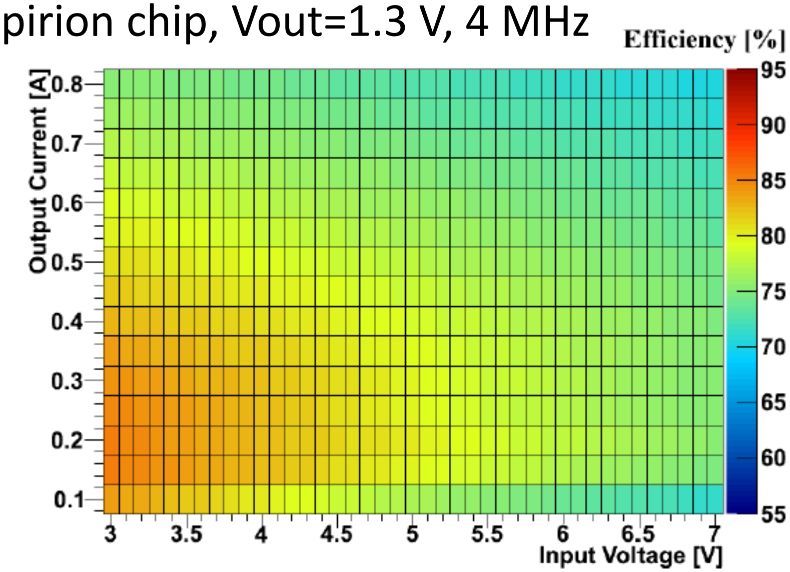




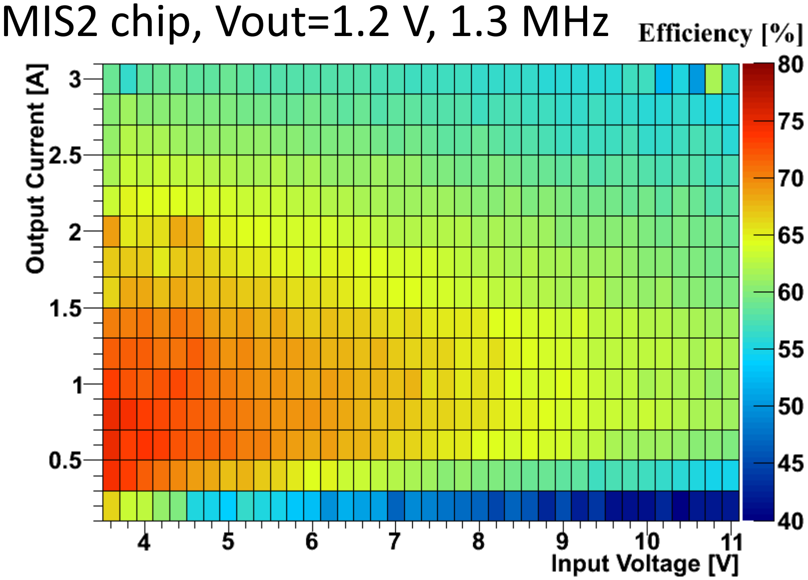


Efficiency

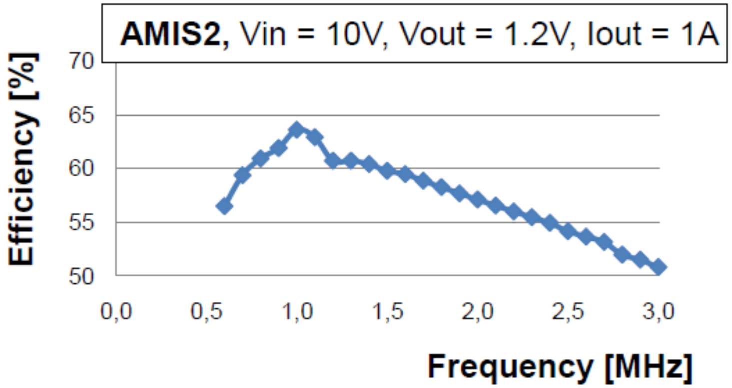
Enpirion chip, Vout=1.3 V, 4 MHz



AMIS2 chip, Vout=1.2 V, 1.3 MHz

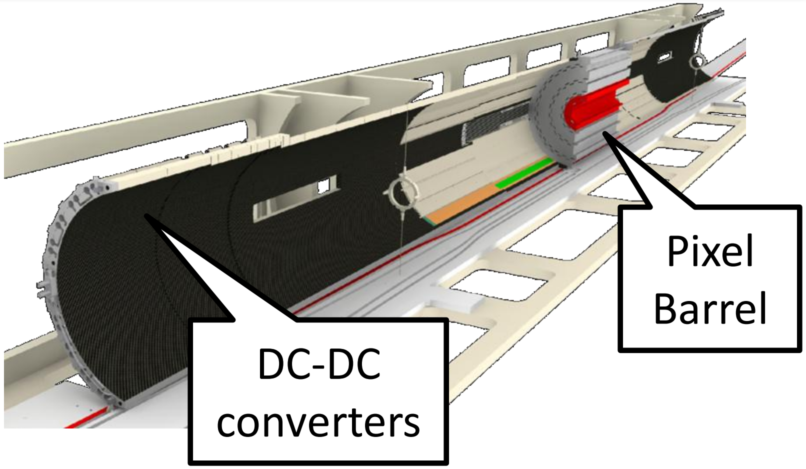


- ohmic losses (inductor, Ron, …) increase with output current
- switching losses increase with frequency and input voltage
- efficiencies of 60 … 80 % reached
- still room for improvement

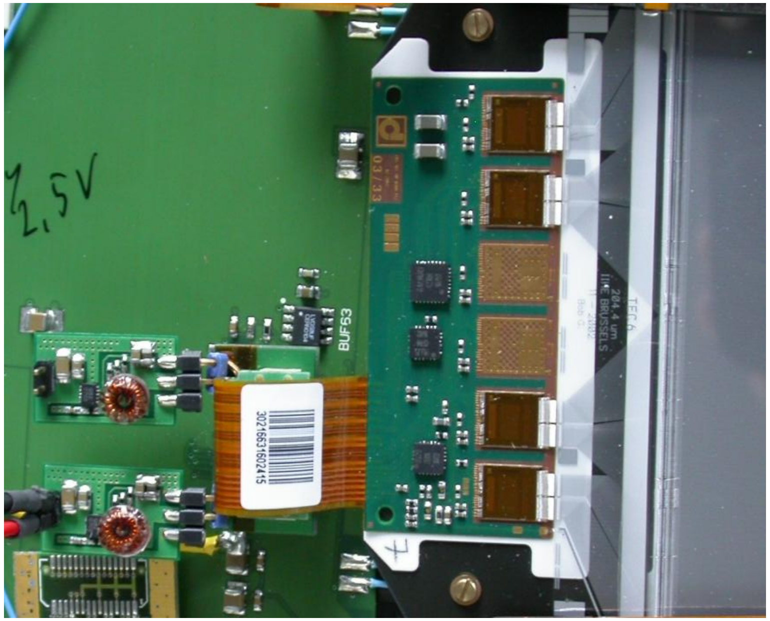


Implementation into a Pixel/Strip System

- CMS plans to employ DC-DC converters in Phase I Pixel upgrade
  - converters will sit on pixel support tube at |eta|~4
    → material budget, size and radiated noise much less critical
  - prototyping is underway



- Phase II upgrade of full tracker will very likely include trigger layers with high power density
  - DC-DC conversion is essential
  - converters should be installed next to modules
  - more R&D needed

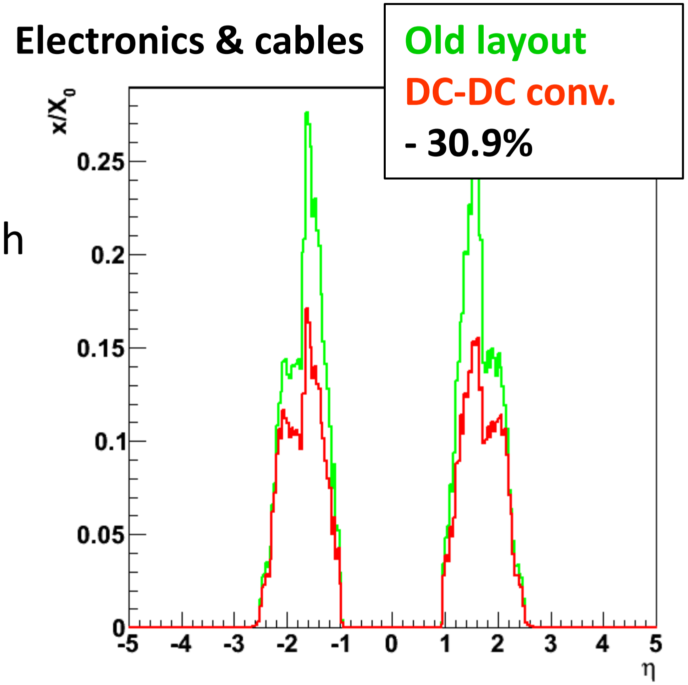


Material Budget

- case study for current CMS Tracker End-Caps
  - full Geant4 simulation
  - typical converter: 10% of module radiation length
  - one converter per module
  - assume conversion ratio of 8 and 80% efficiency
  - re-calculate cable/trace cross sections

  → save 30.9% on ‘electronics & cables’

  → save 8% of total material budget



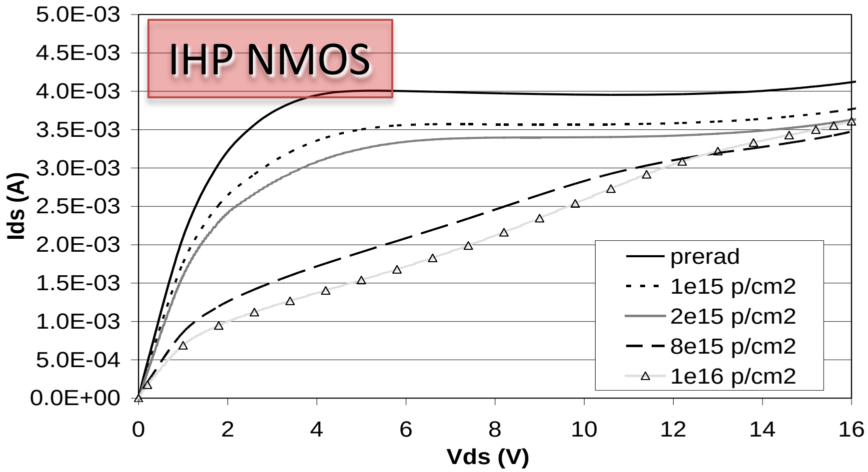
- similar savings for serial powering (7.5%)

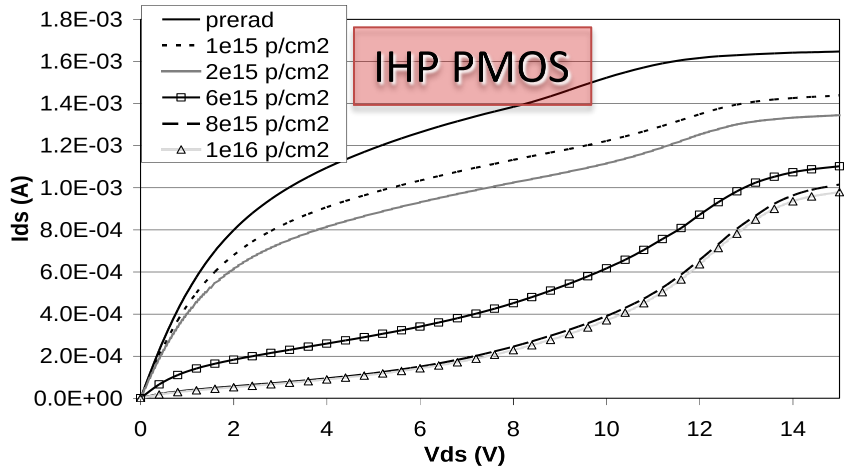
Summary

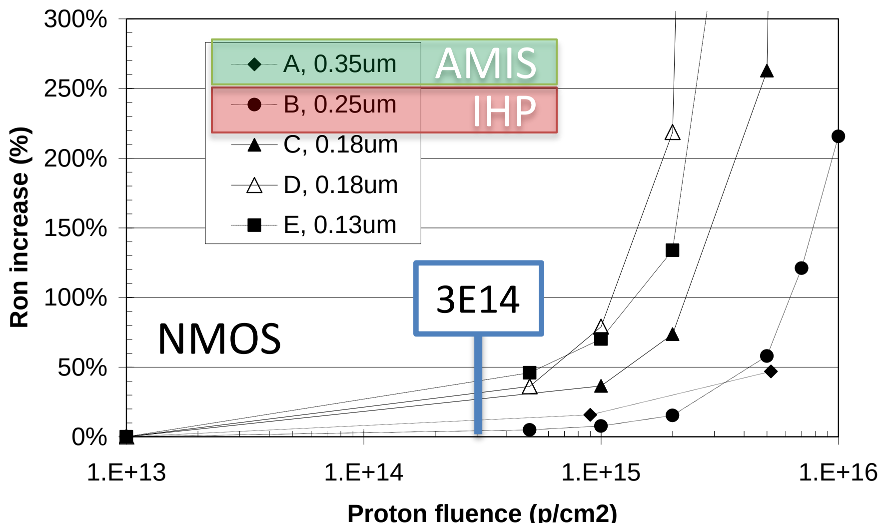
- DC-DC powering can supply the large currents at low voltage which are needed for pixel and strip tracker upgrades
- simulations show that total material budget can be reduced by employing a DC-DC conversion powering scheme
- radiative and conductive noise is an issue, but can be controlled by filtering, board design, shielding, distance, conversion ratio, switching frequency
- non-rad hard converter prototype with commercial components in hand with 75-85% efficiency, I=0.8 A, conversion ration ~4, low mass (~10% of strip module), small size (19x12 mm^2), magnetic field tolerance and no significant impact on system noise
- first rad-hard prototypes under test with promising results

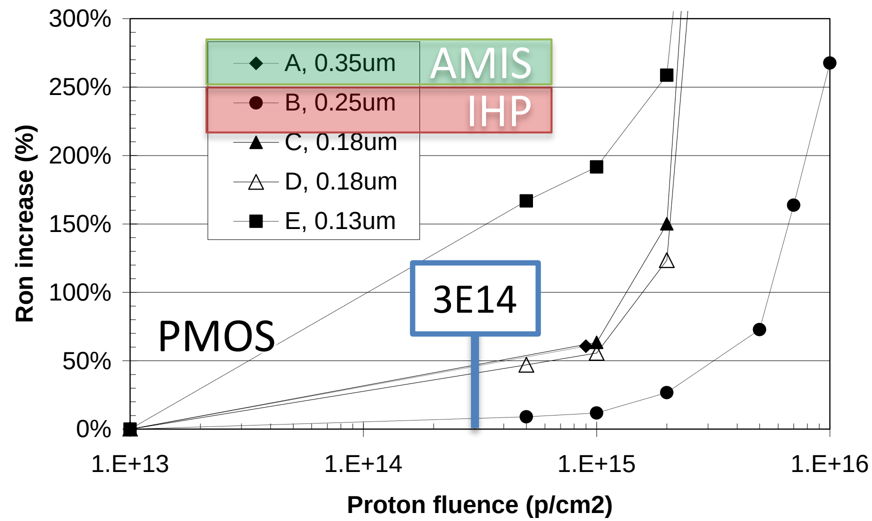
back - up

Irradiation Results for Transistors
[Federico Faccio, TWEPP 2009]





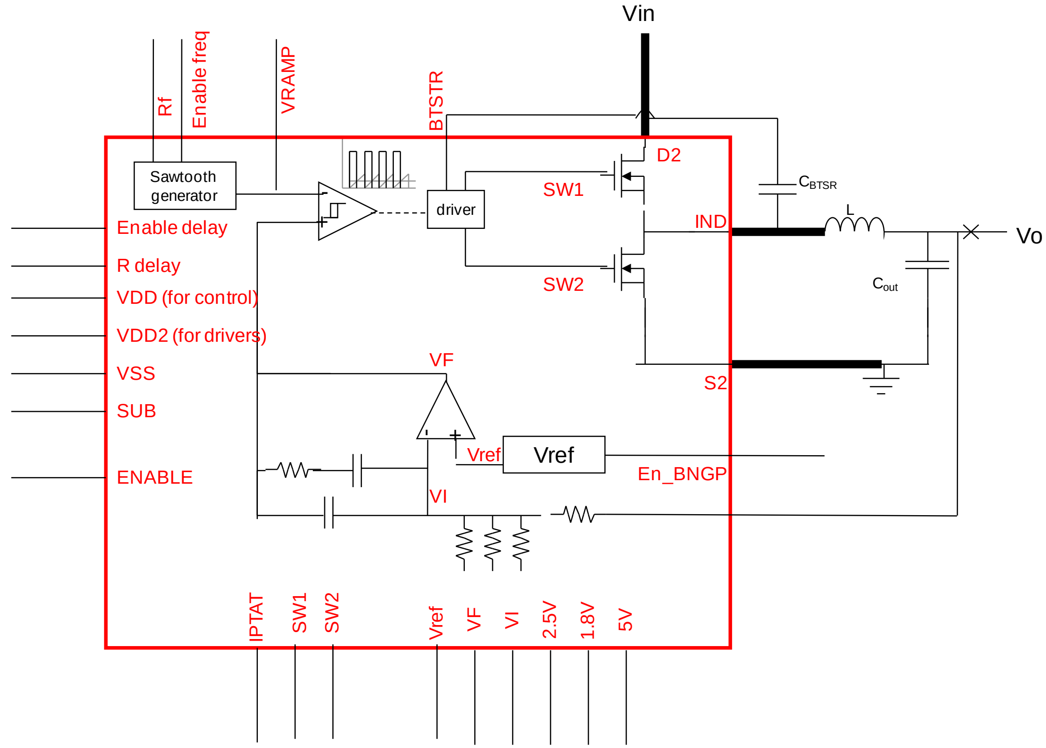




[http://indico.cern.ch/contributionDisplay.py?contribId=163&sessionId=25&confId=49682]

AMIS2 [Stefano Michelis, CERN]

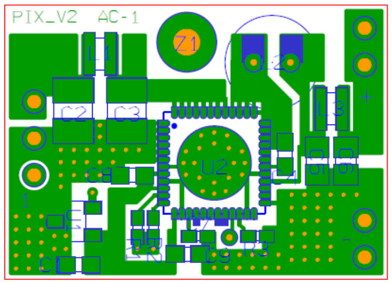
- VIN +3.3V to +12V
- programmable up to 2.5MHz
- internal voltage reference
- integrated feedback loop with bandwidth of 20Khz
- different Vout can be set:
  1.2V, 1.8V, 2.5V, 3V, 5V
  other values by ext. resistor
- lateral HV transistors are used as power switches
- package QFN32



- efficiency measured 70…80%
- tested up to 300 Mrad = 3000 kGy with only 2% efficiency loss (after annealing)
- noise spectra look good (=low)

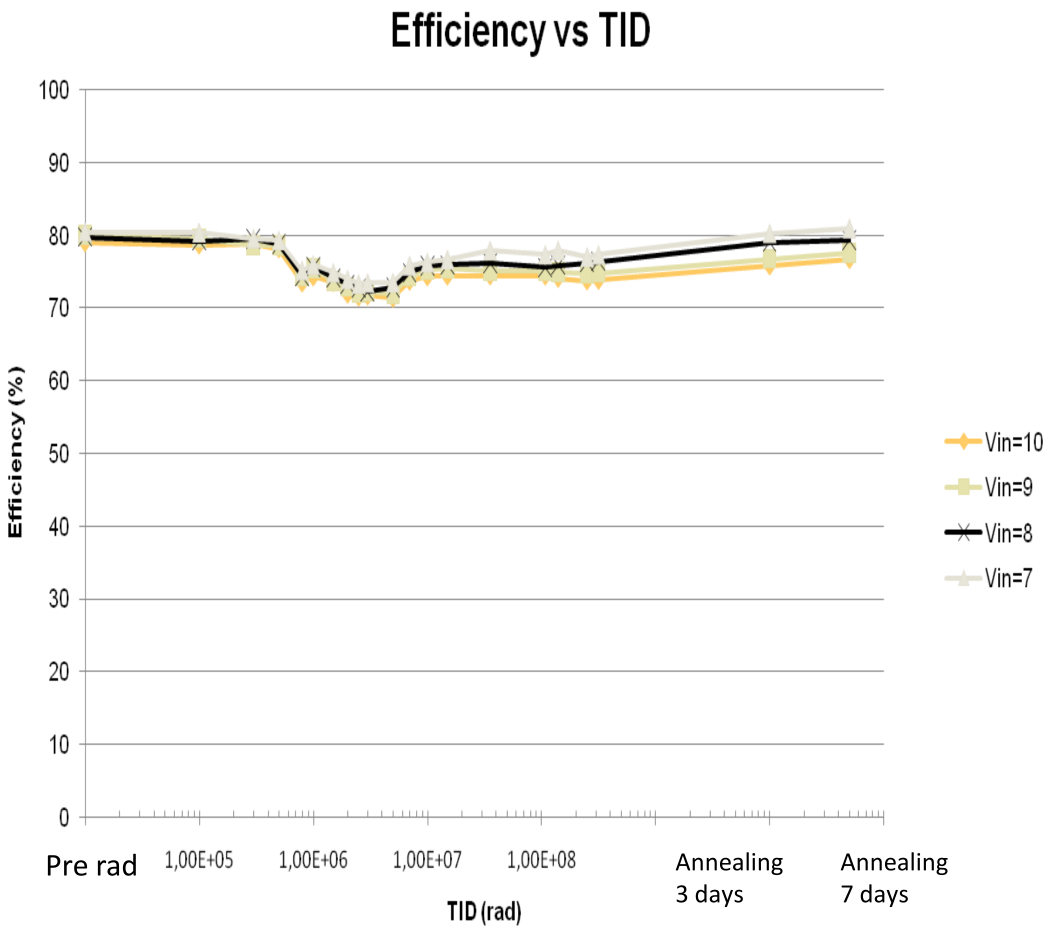
- see Stefano's talk at TWEPP 2009:

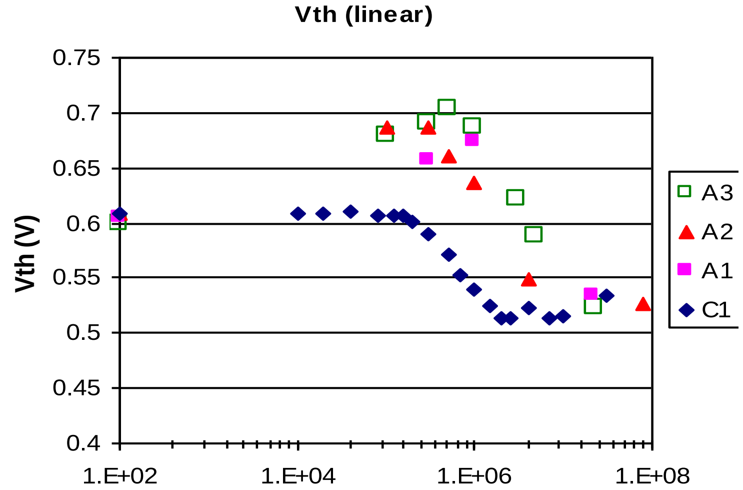
http://indico.cern.ch/contributionDisplay.py?contribId=97&sessionId=42&confId=49682

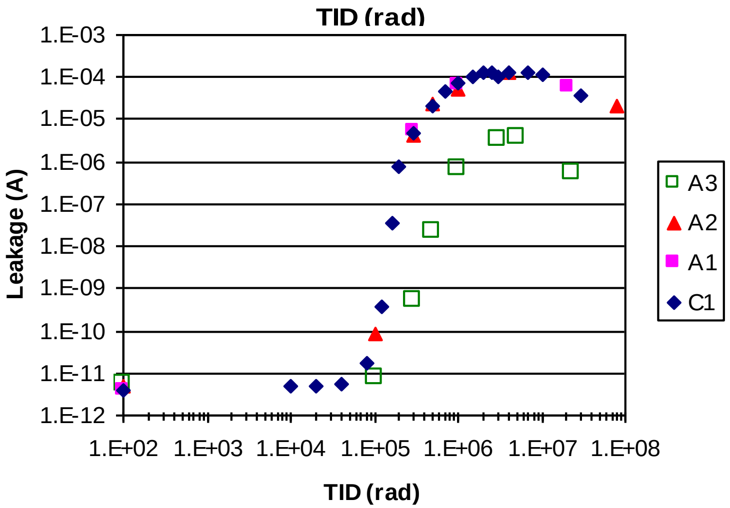


Aachen Converter Board

AMIS 2 Irradiation Results [Stefano Michelis, CERN]



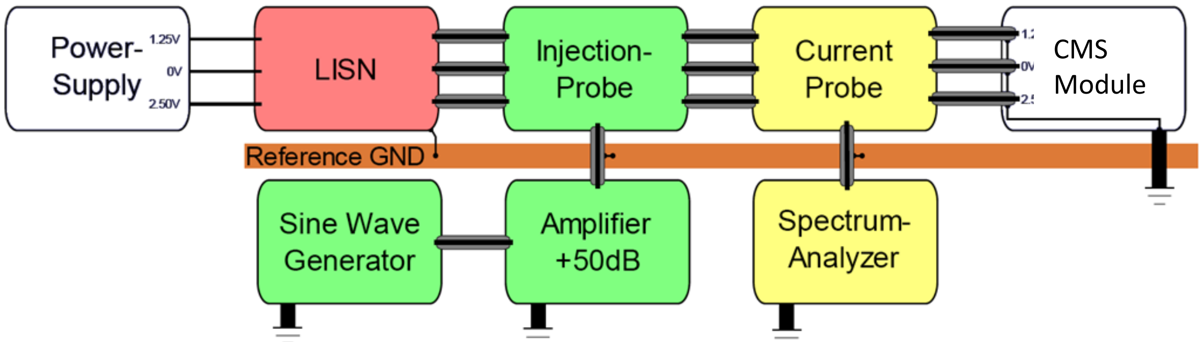


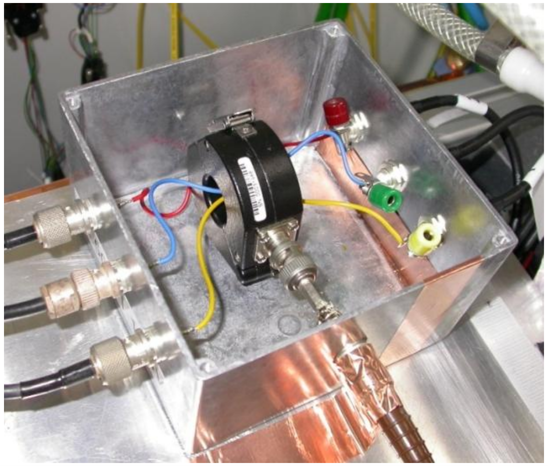


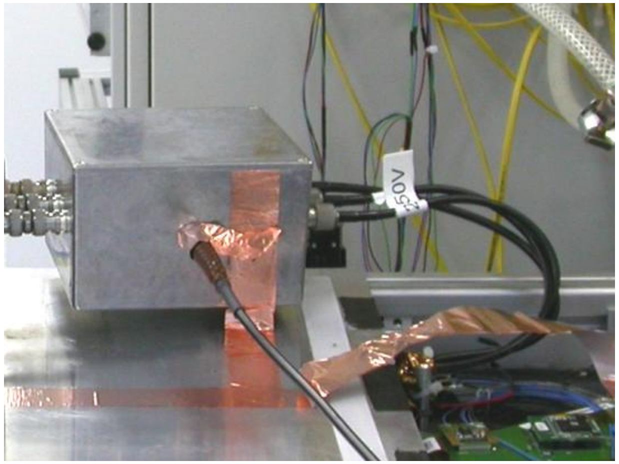
- X-ray radiation tests shows a decrease of the efficiency mostly due to the radiation induced leakage current , compensated by the threshold voltage shift

Noise Susceptibility of APV25 Strip Modules

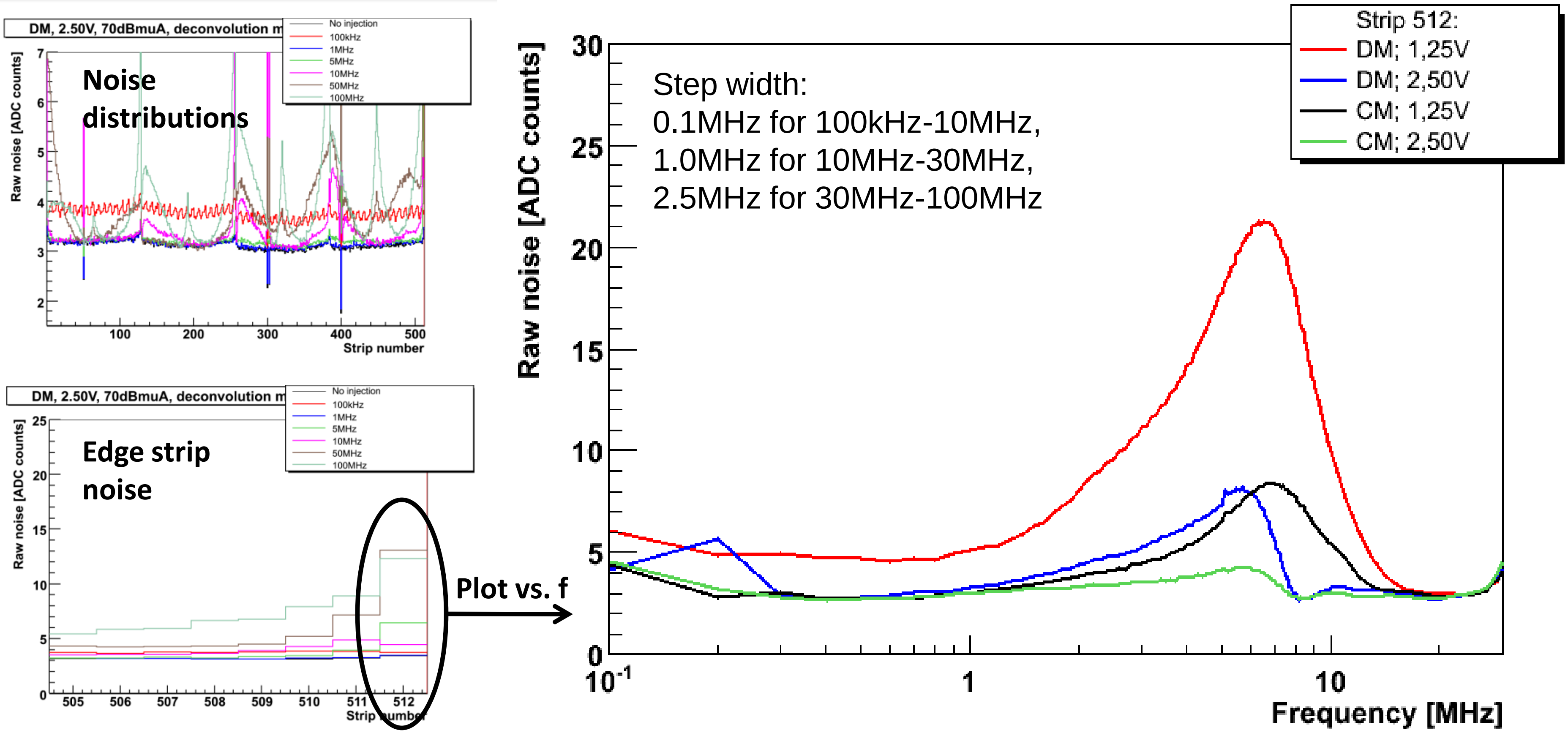
- Goal: identify particularly critical bandwidth(s) for converter switching frequency
- **Bulk current injection (BCI)** method used
- A noise current of 70dBμA (I_{eff} = 3.16mA) is injected into the power lines
  - Differential Mode (DM) and Common Mode (CM) on 2.5V and 1.25V







Noise Susceptibility of APV25 Strip Modules

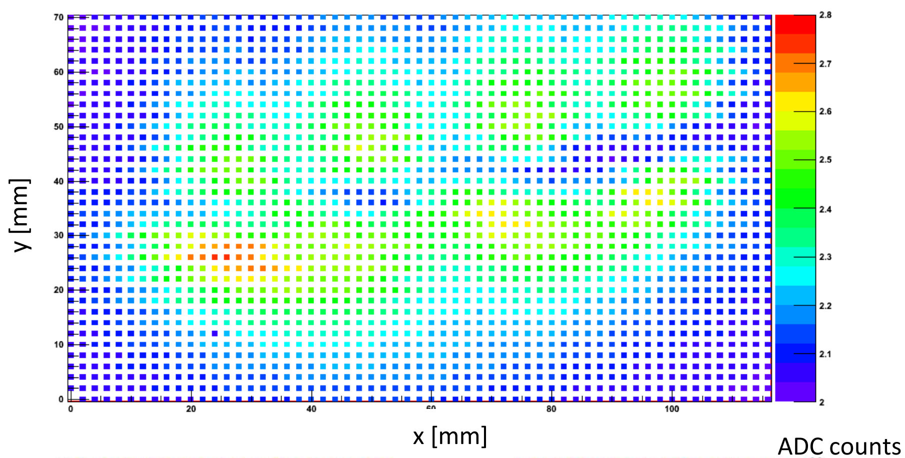


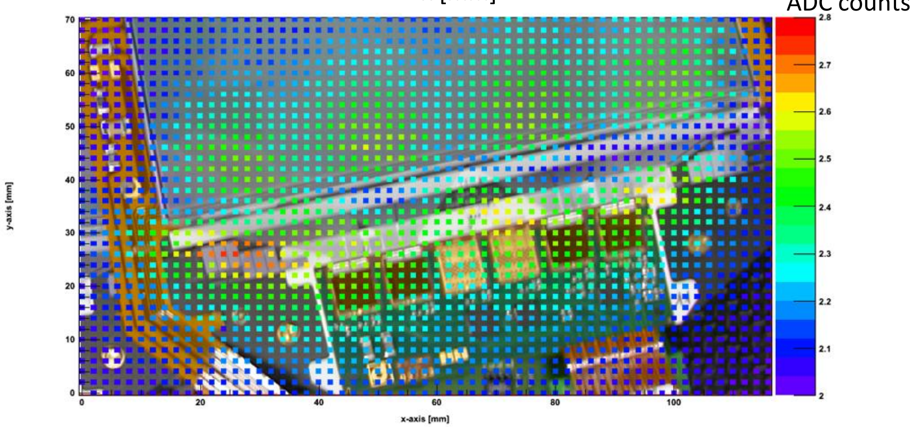
- **Peak at 6-8MHz**, well above future switching frequency (3.2MHz exp. from shaping time)
- Higher susceptibility for DM and 1.25V = pre-amplifier reference voltage
- Set-up will be valuable to characterize future module prototypes

EMI Susceptibility of Strip Modules

- noise injected at 4 MHz
- sender is scanning 10 mm above module
- color code shows average module noise

B-Field injected





E-Field injected