

DC-DC Conversion Powering for the CMS Tracker at SLHC

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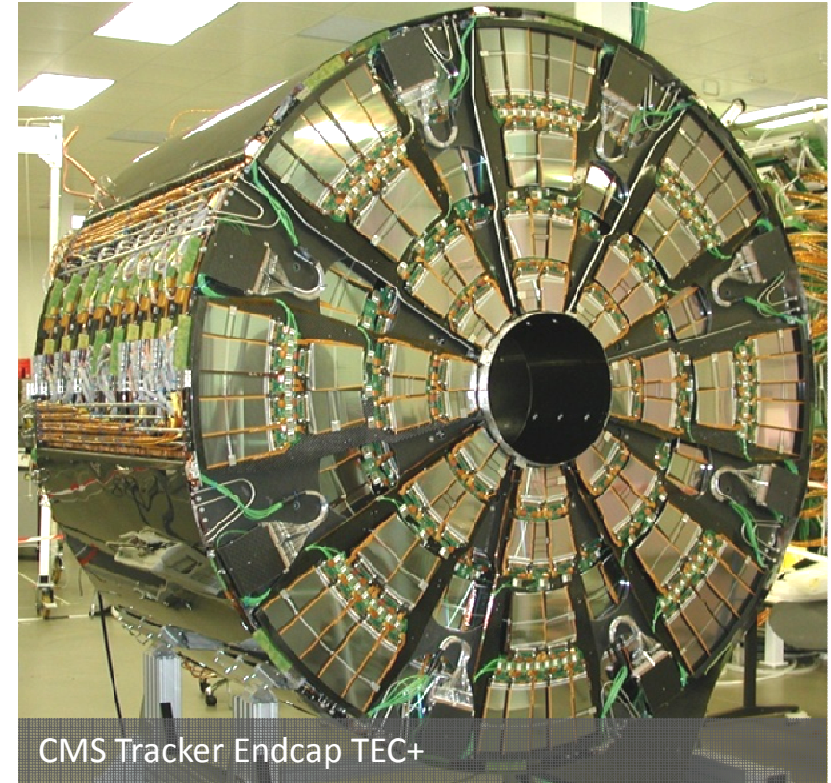
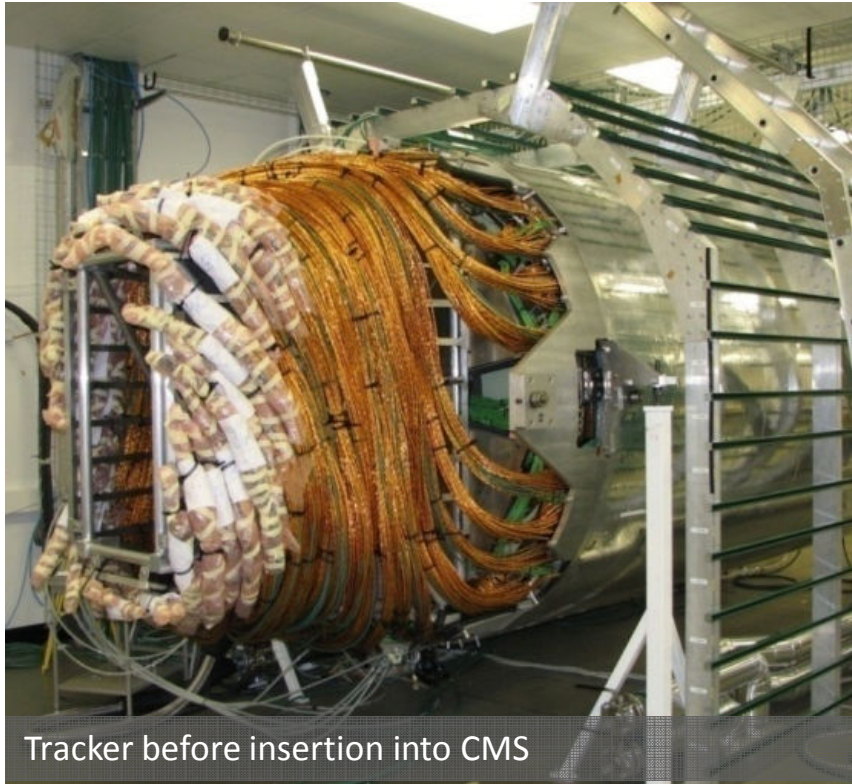
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Overview

- 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



- 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)

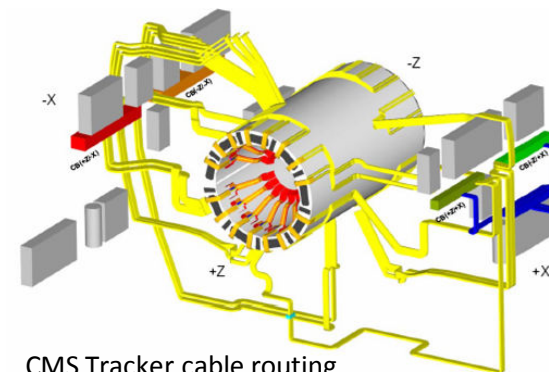
→ **currents will increase substantially**

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

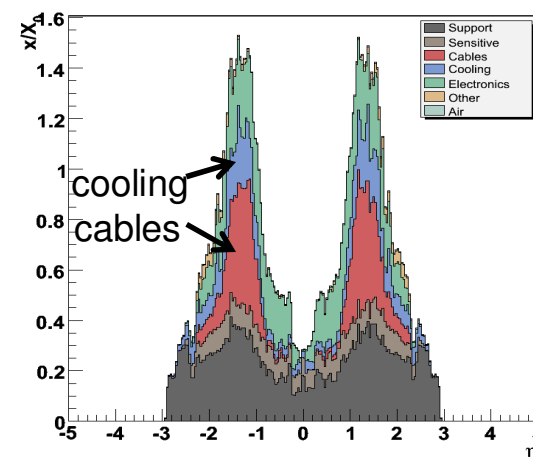
→ increase power cable cross-section ... not possible

→ increase copper cross-section inside tracker ... not desirable

→ **need an improved powering scheme**



CMS Tracker cable routing



CMS Strip Tracker material budget

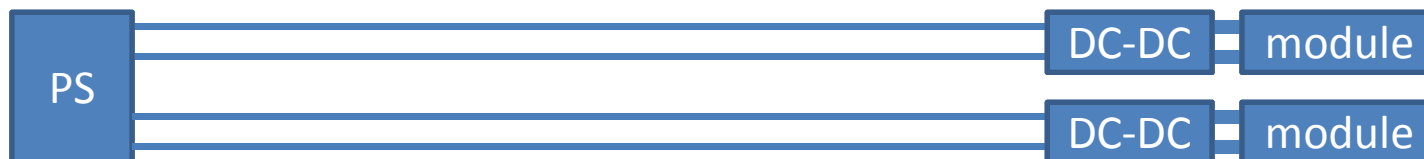
Strategy

- $P = U \cdot I = (rU) \cdot (I/r)$
 → supply power at higher voltage i.e. lower current
 → cable loss $P_{\text{loss}} = R \cdot I^2$ is reduced by factor r^2 !

Conventional Powering



DC-DC Powering



Serial Powering

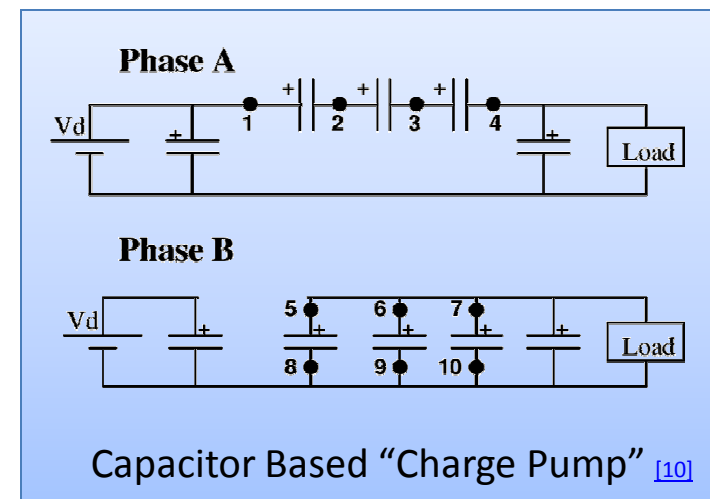
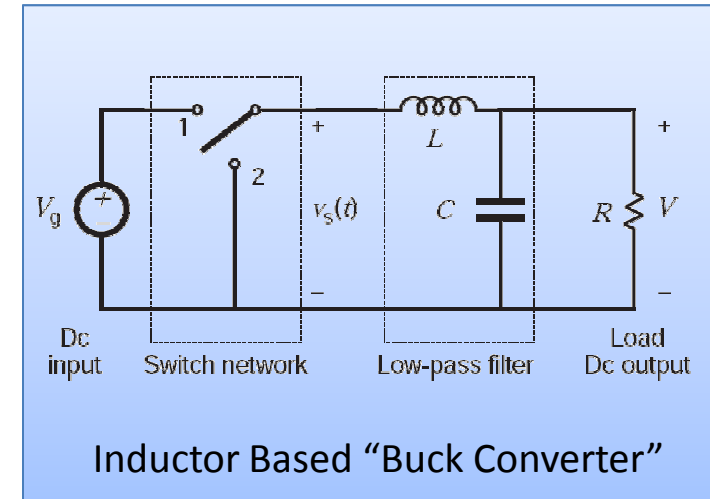


Choice of Powering Scheme

- 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



DC-DC Buck Converters

operation principle

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

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

$$V_{out} = D \cdot V_{in}$$

for lossless converter

main parameters

conversion ration

$$r = \frac{V_{in}}{V_{out}} = 2 \dots 10$$

switching frequency

$$f = 1 \dots 4 \text{ MHz}$$

efficiency

$$\eta = \frac{P_{out}}{P_{in}} = 60 \dots 90\%$$

current ripple at inductor

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

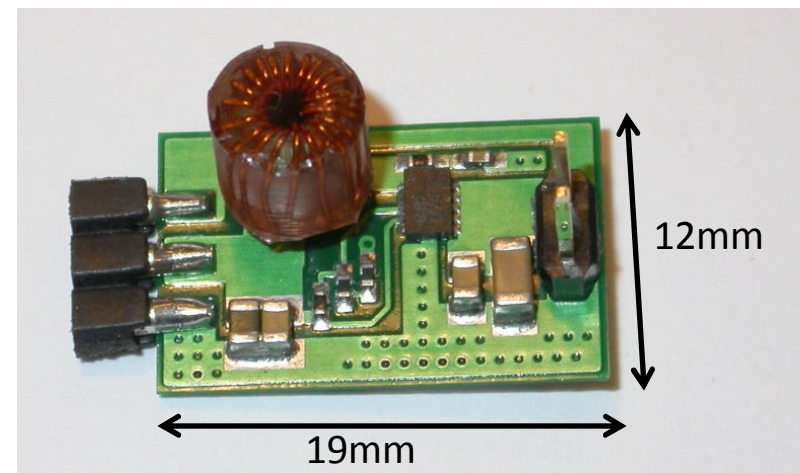
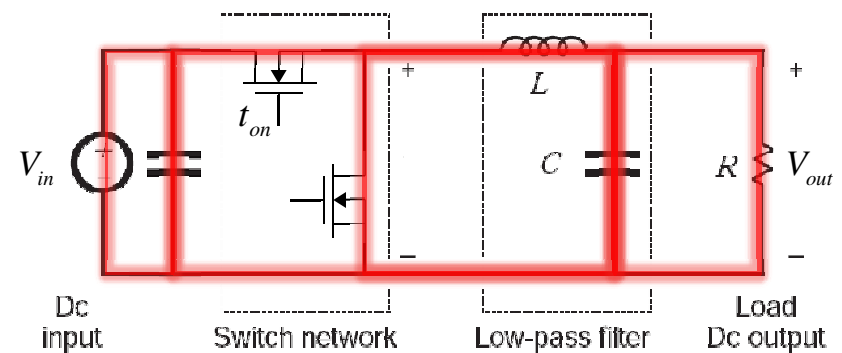
main loss mechanisms

resistive loss in inductor

resistive loss in MOSFETs

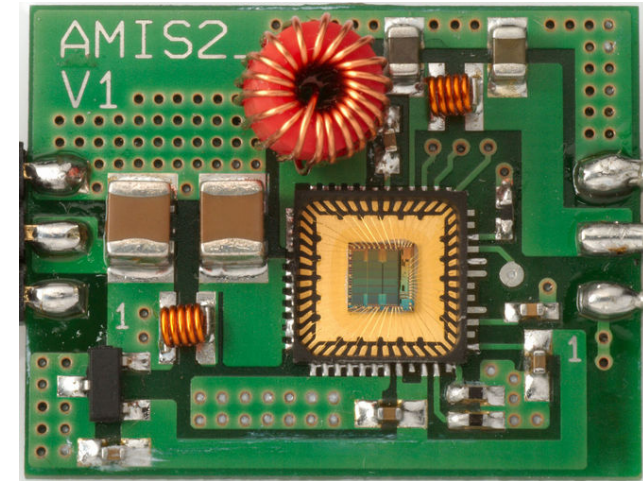
switching loss in MOSFETs ($\sim V_{in}^2 \cdot I_{out} \cdot f$)

input and output capacitor ESR losses



Challenges with DC-DC Buck Converters

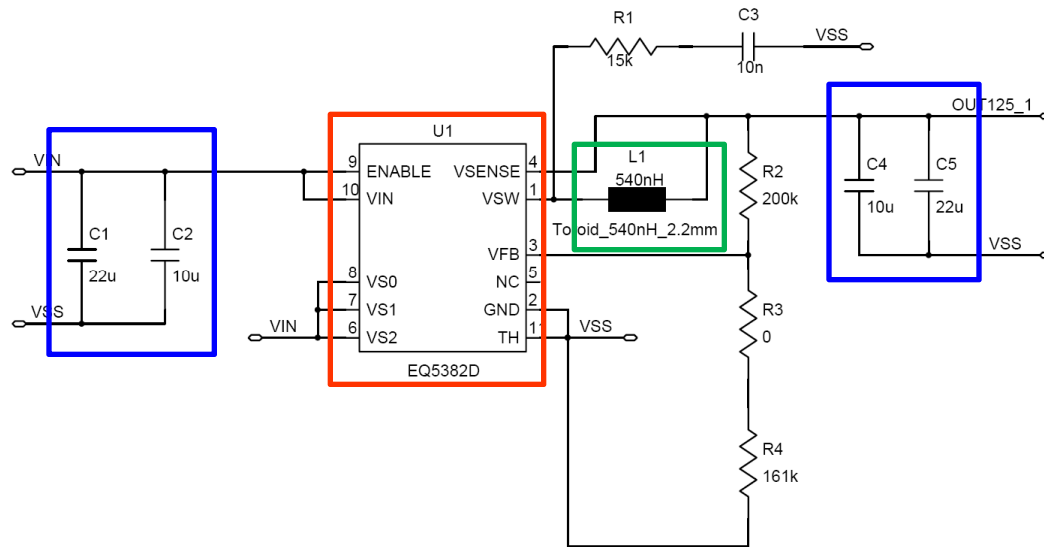
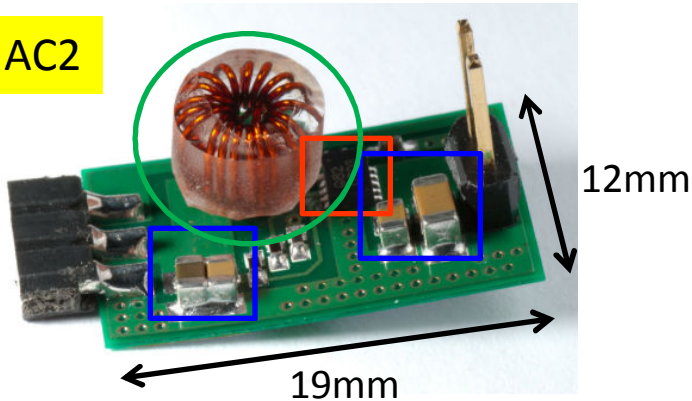
- coupling of switching noise into detector modules
 - conductive
 - radiative
- air core inductors required due to 4 Tesla field
 - bulky
 - radiates noise
- radiation hard ASIC needs to switch rather high voltages ($\sim 10\text{V}$)
 - need special high voltage process
- useful only if efficiency 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

AC2



PCB:

2 copper layers a 35 μ m
FR4, 200 μ m
 $V = 2.3\text{cm}^2 \times 10\text{mm}$
 $m = 1.0\text{g}$

Chip: Enpirion EQ5382D

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

Air-core inductor:

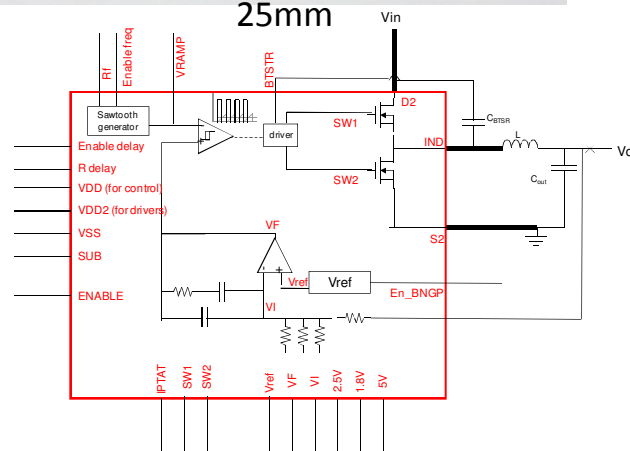
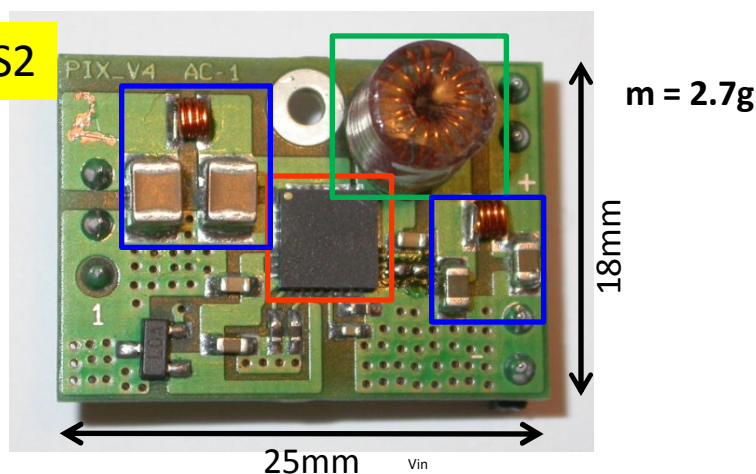
Custom-made toroid, $\varnothing \approx 6\text{mm}$
 $L = 200\text{nH}$ or 600nH

Input/output filters

R&D with radiation hard custom ASICs

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

AMIS2



PCB:

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

Chip: AMIS2 by CERN

$V_{\text{IN}} = 3 - 12\text{V}$

$I_{\text{OUT}} < 3\text{A}$

$V_{\text{OUT}} = 1.2\text{V}, 2.5\text{V}$ or 3.3V

$f_s \approx 1.3\text{MHz}$ or

programmable betw. 600kHz...4MHz

Air-core toroid:

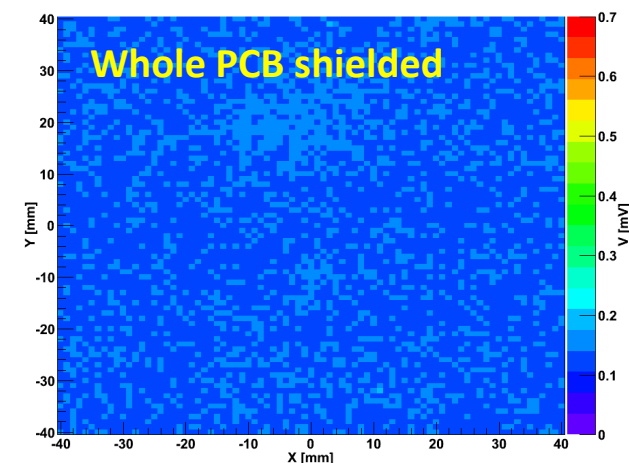
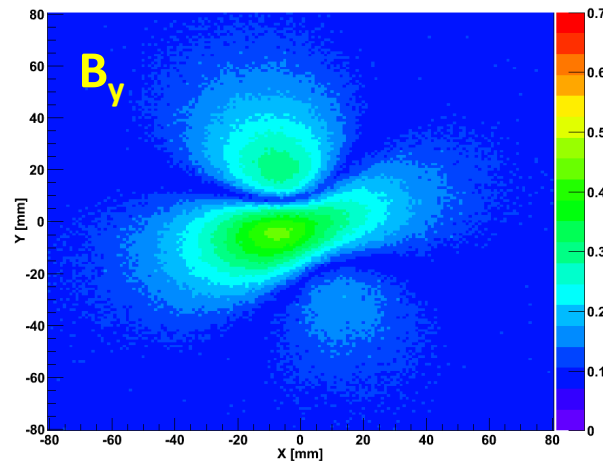
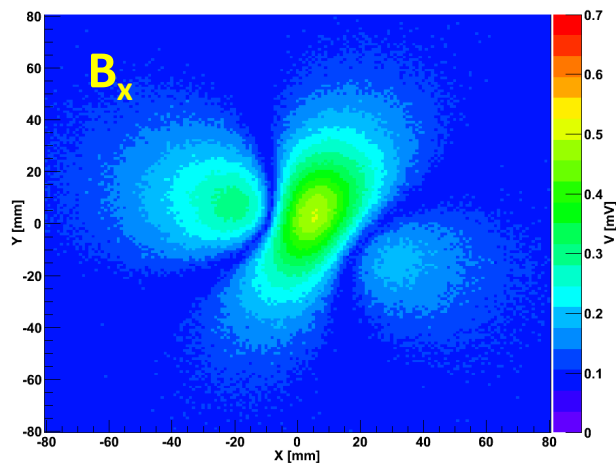
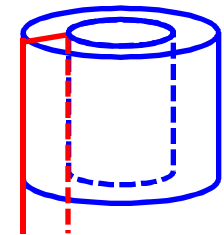
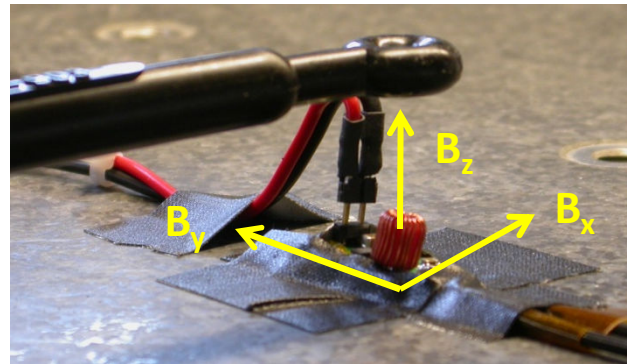
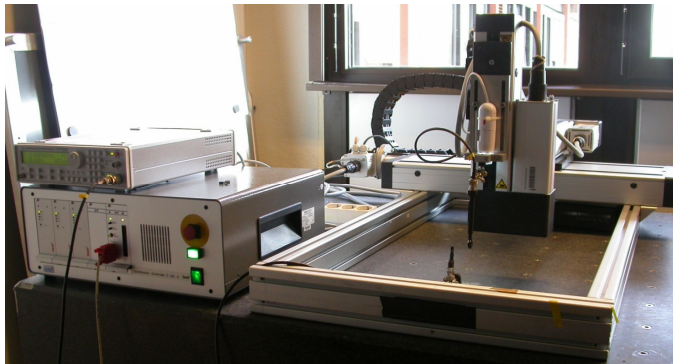
Custom-made toroid, $\varnothing \approx 6\text{mm}$,
height = 7mm, $L = 600\text{nH}$, $R_{\text{DC}} = 80\text{m}\Omega$

Input and output π -filters

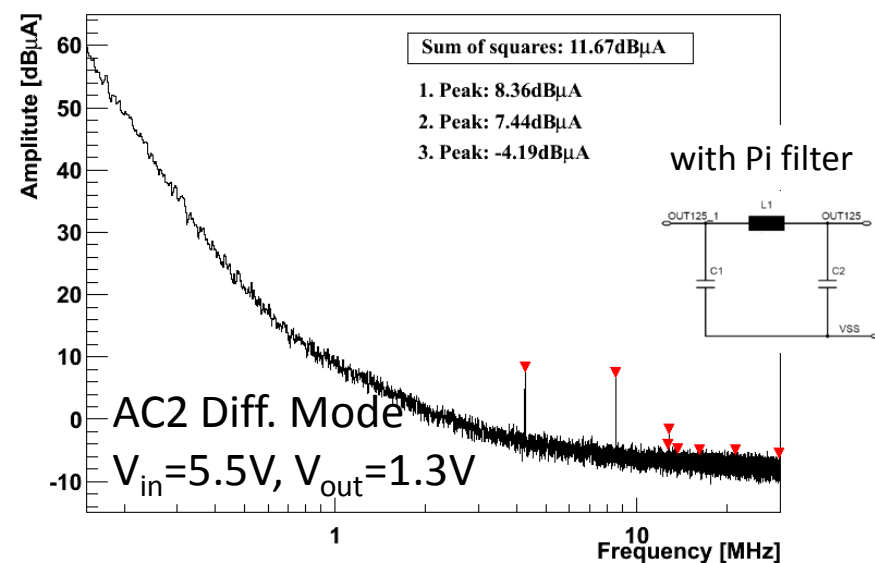
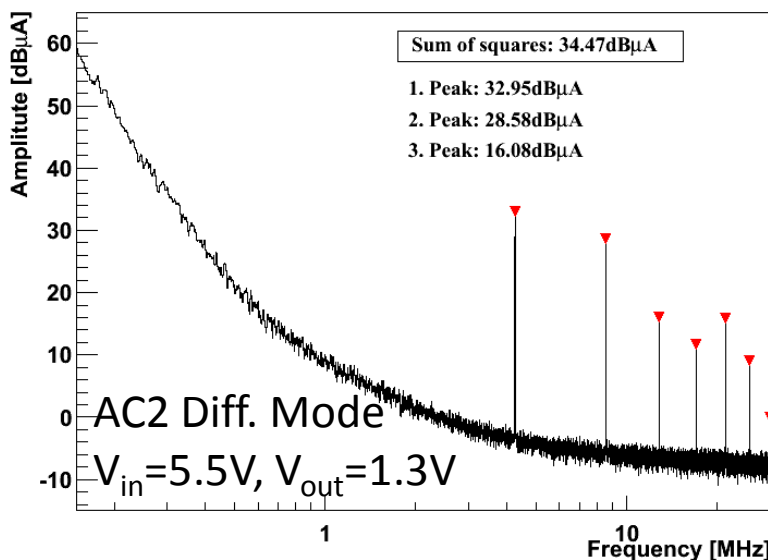
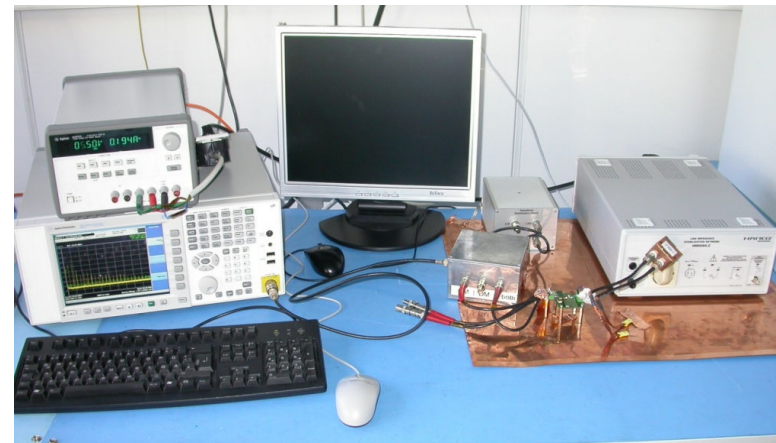
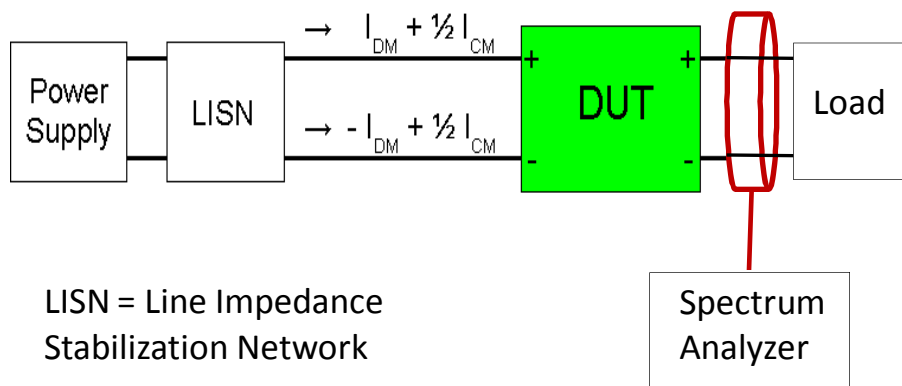
$L = 12.1\text{nH}$, $C = 22\mu\text{F}$

Radiated Switching Noise

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



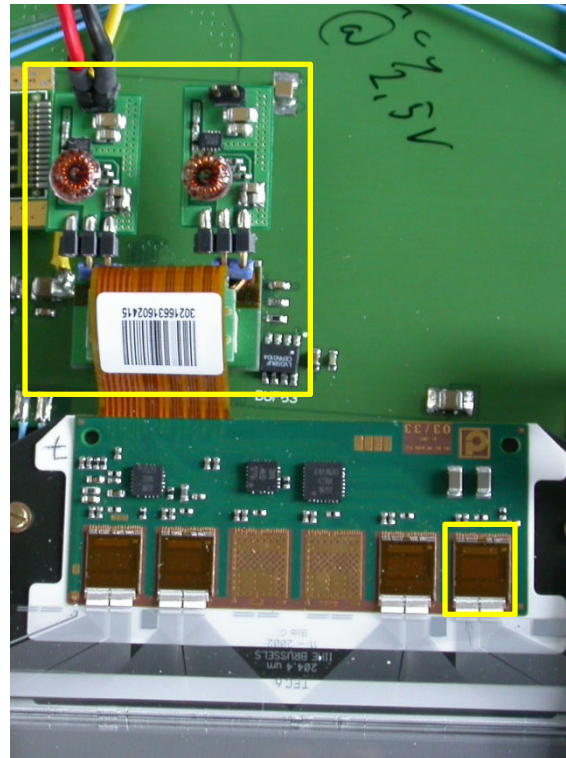
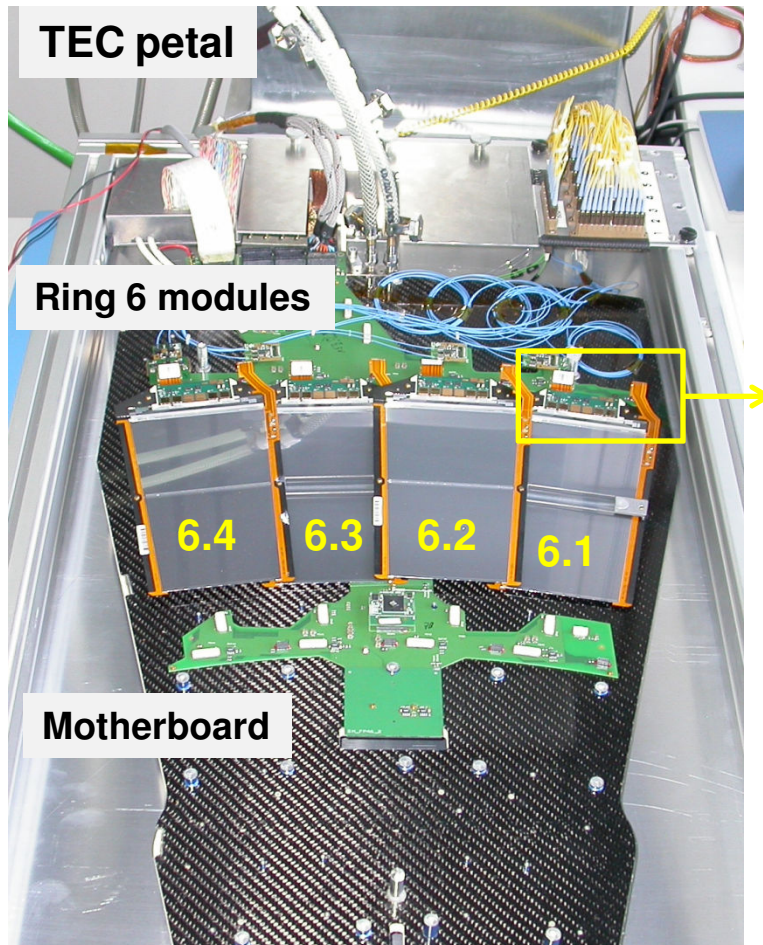
Conducted Switching Noise



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

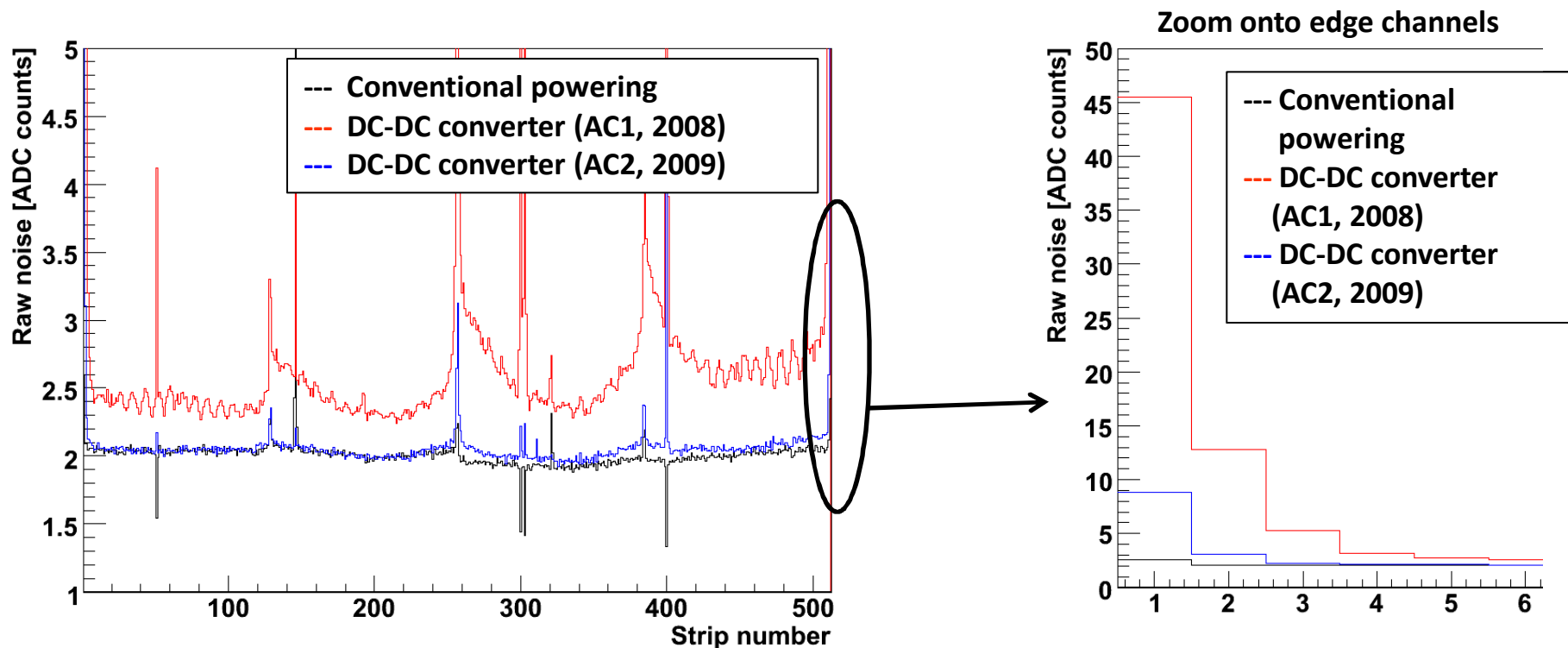


APV25 readout chip:

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

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

System Test with CMS Strip Modules

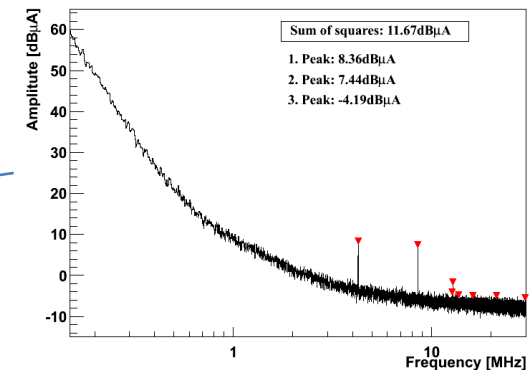
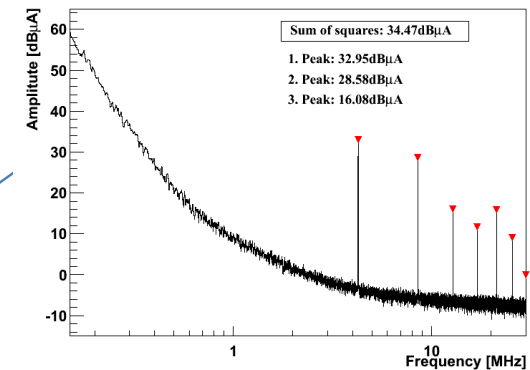
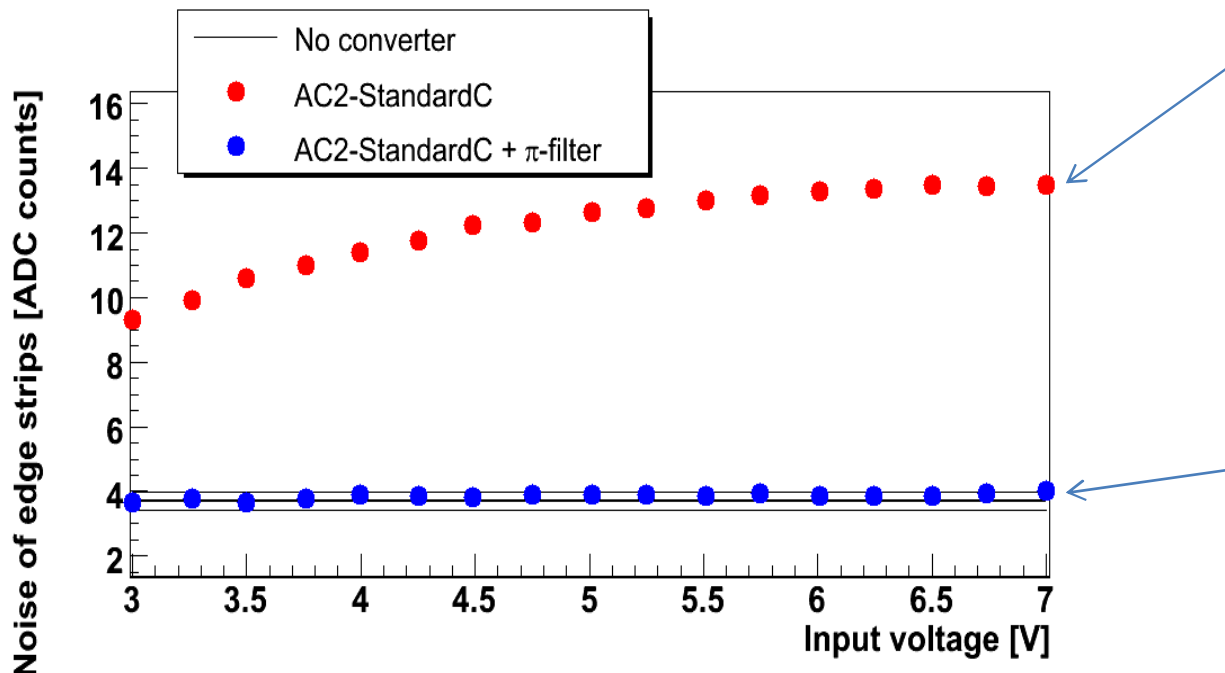


- Raw noise: RMS of fluctuation around pedestal value
- Edge channels are particularly sensitive (due to on-chip common mode subtraction)
- Large increase with previous generation of boards (**AC1**), in particular on edge strips; both conductive (ripple) and radiative (inductor) contributions (TWEPP08)

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

Results with Commercial Converters

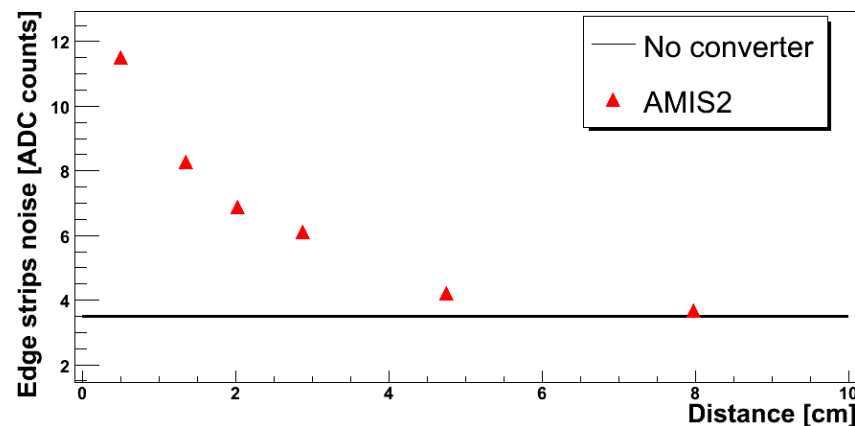
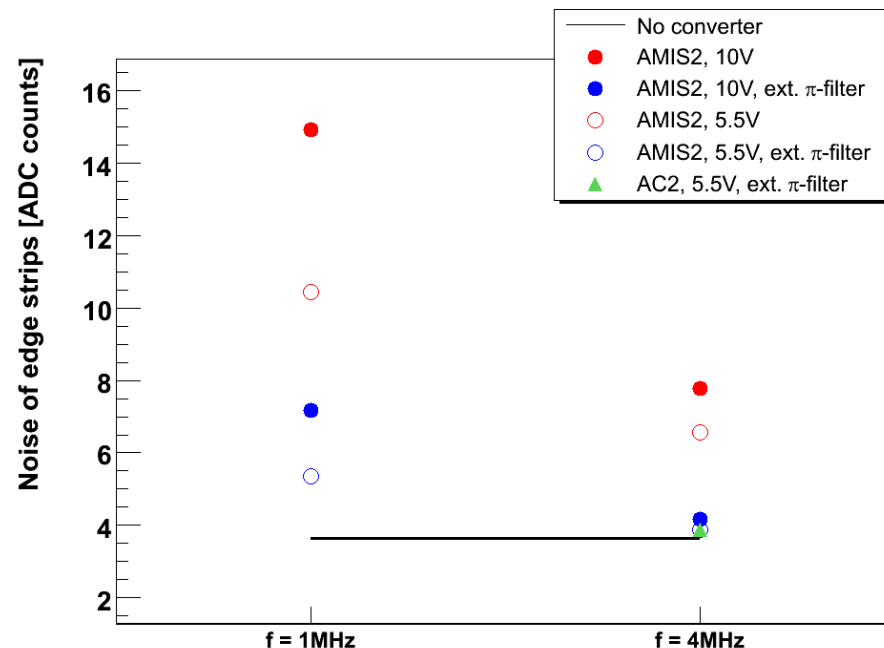
- 4 MHz, conversion ratio up to 5.6, output current ~ 0.5 A
- no shielding
- simple Pi filter suppresses conductive noise efficiently



→ 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

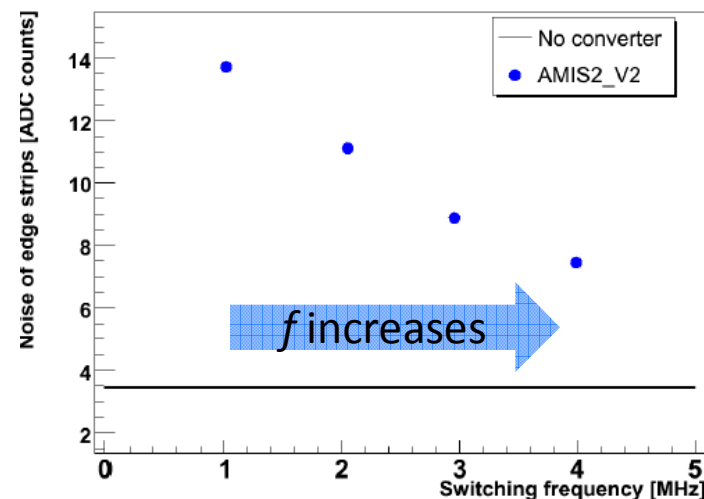
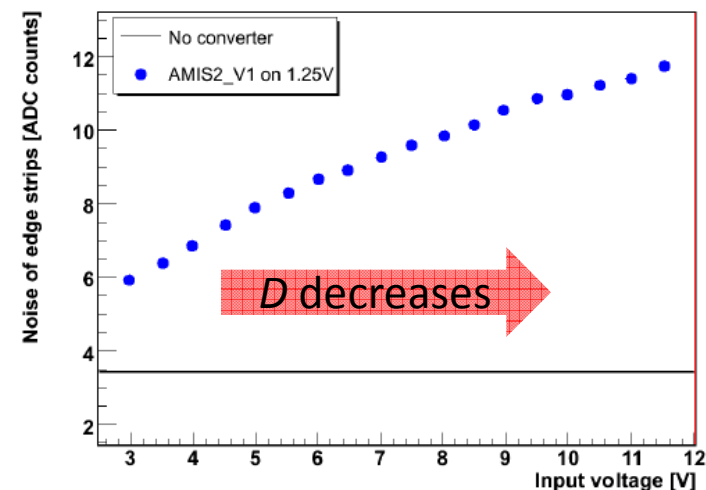
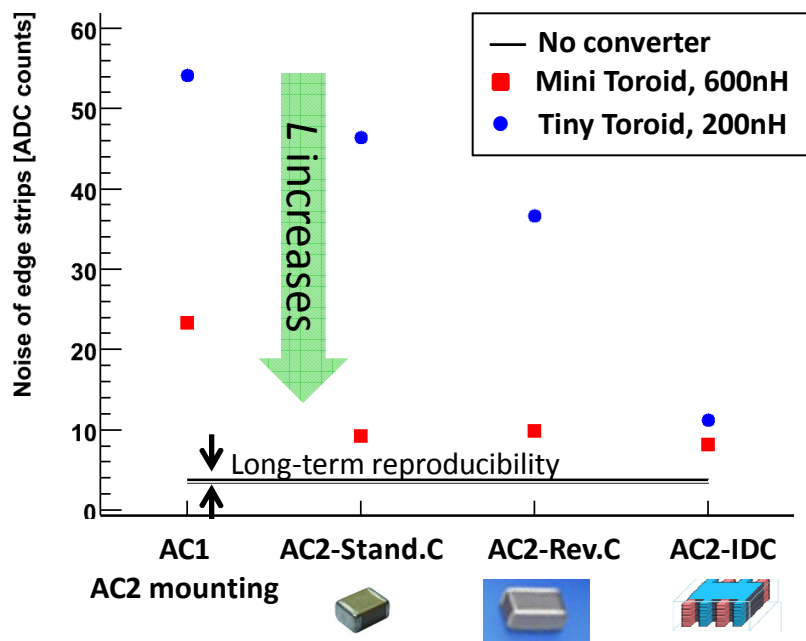


Understanding the Noise

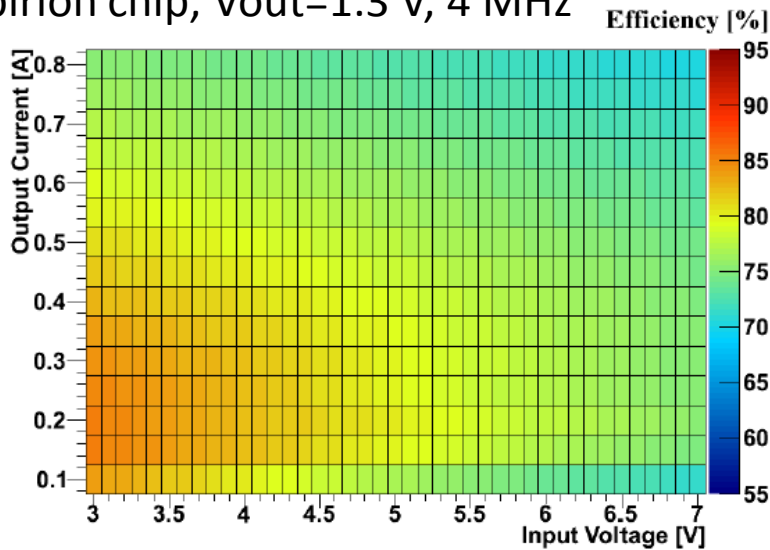
- noise caused by current ripple in inductor

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

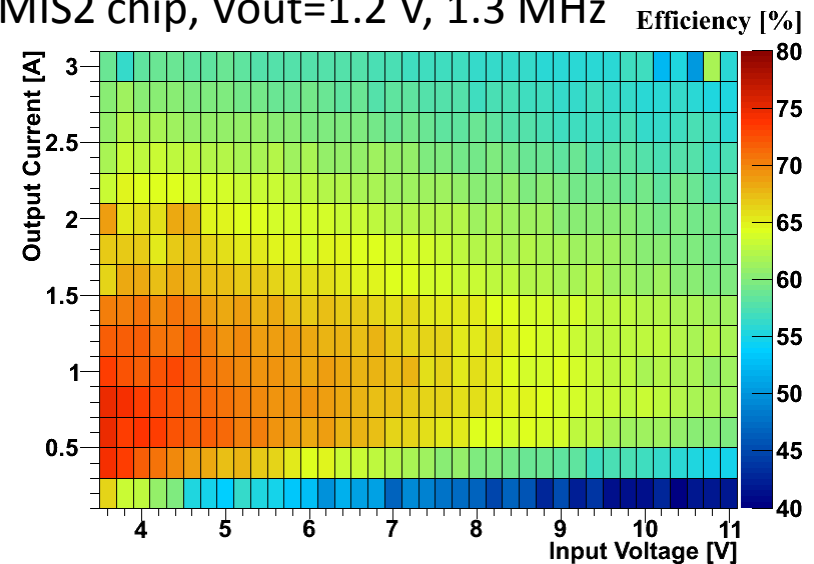
- low-ESL in capacitors improve filtering



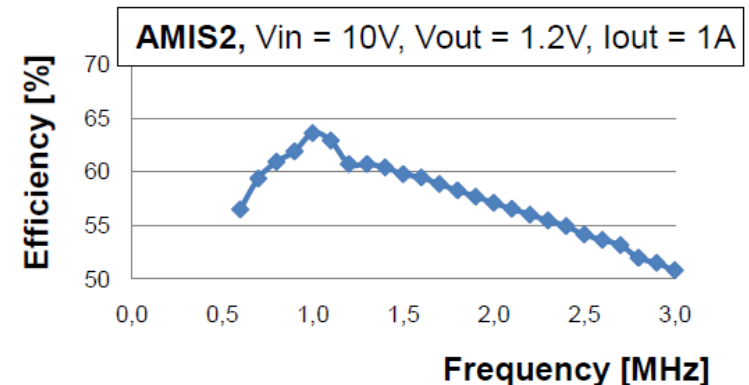
Enpirion chip, $V_{out}=1.3$ V, 4 MHz



AMIS2 chip, $V_{out}=1.2$ V, 1.3 MHz

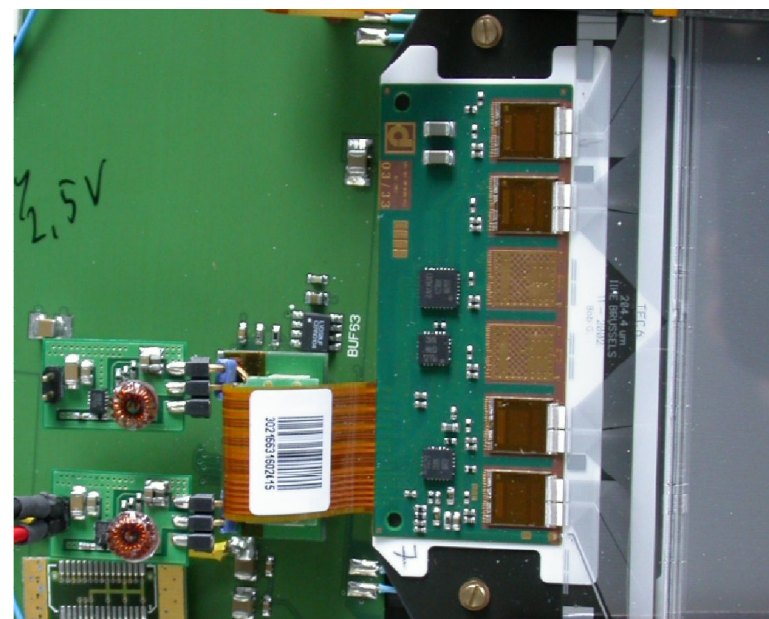
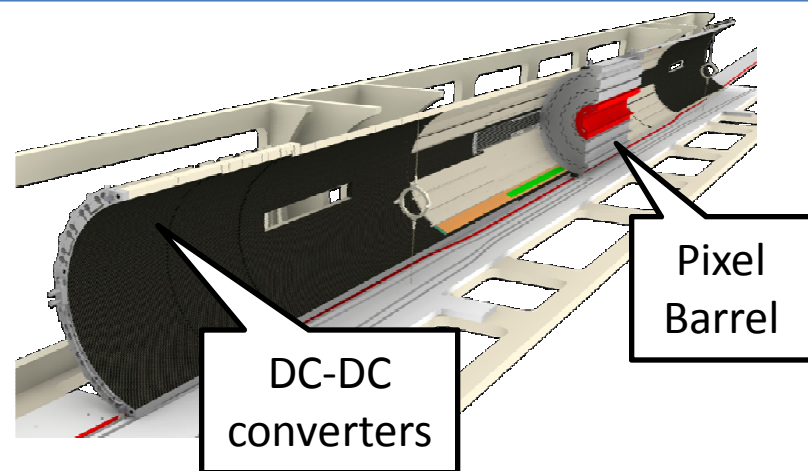


- ohmic losses (inductor, R_{on} , ...) increase with output current
- switching losses increase with frequency and input voltage
- efficiencies of 60 ... 80 % reached
- still room for improvement



Implementation into a Pixel/Strip System

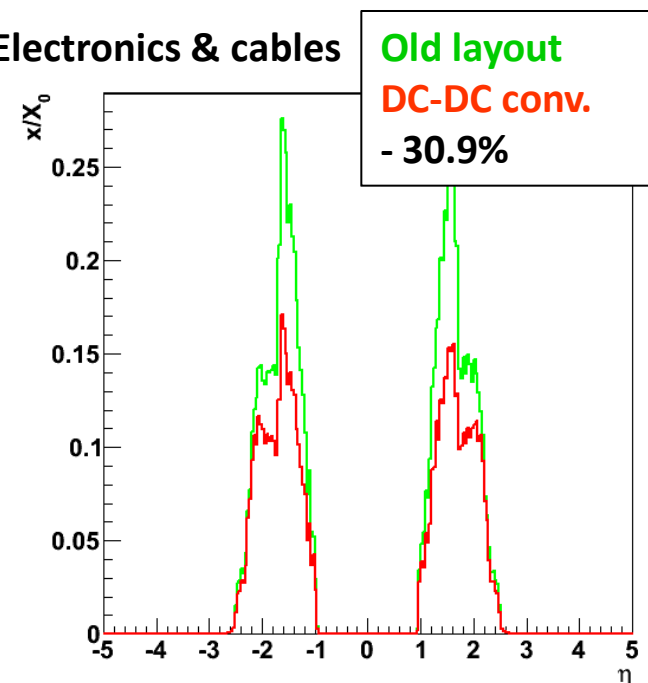
- CMS plans to employ DC-DC converters in Phase I Pixel upgrade
 - converters will sit on pixel support tube at $|\eta| \sim 4$
 - material budget, size and radiated noise much less critical
 - prototyping is underway
- Phase II upgrade of full tracker will very likely include trigger layers with high 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%)

Electronics & cables



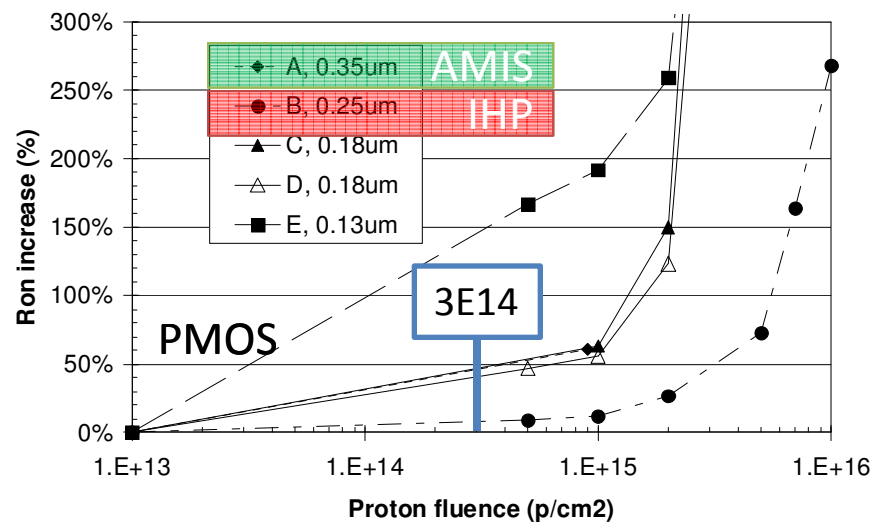
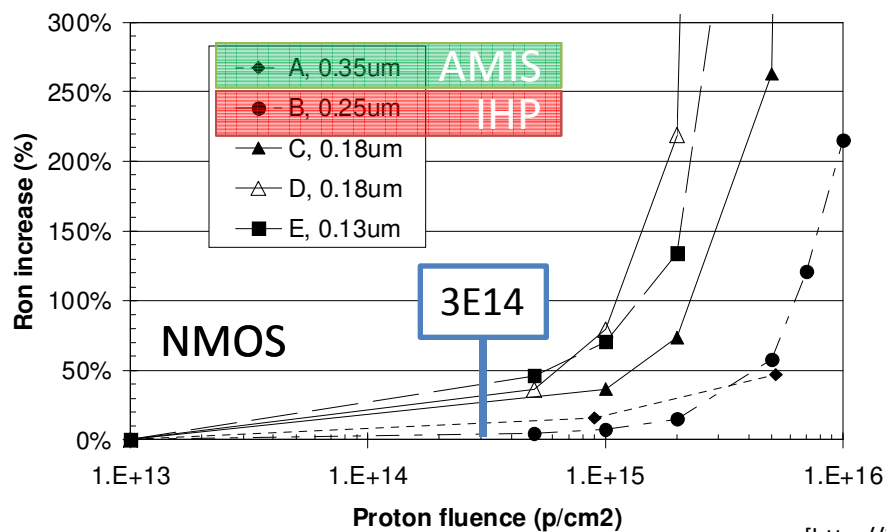
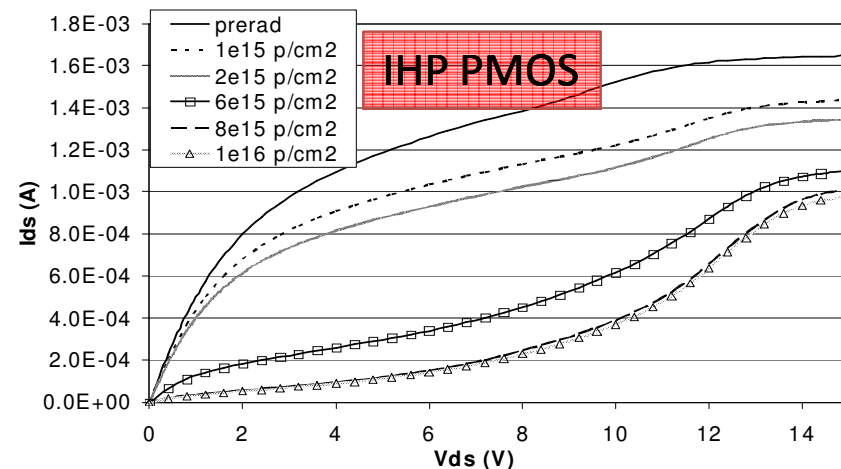
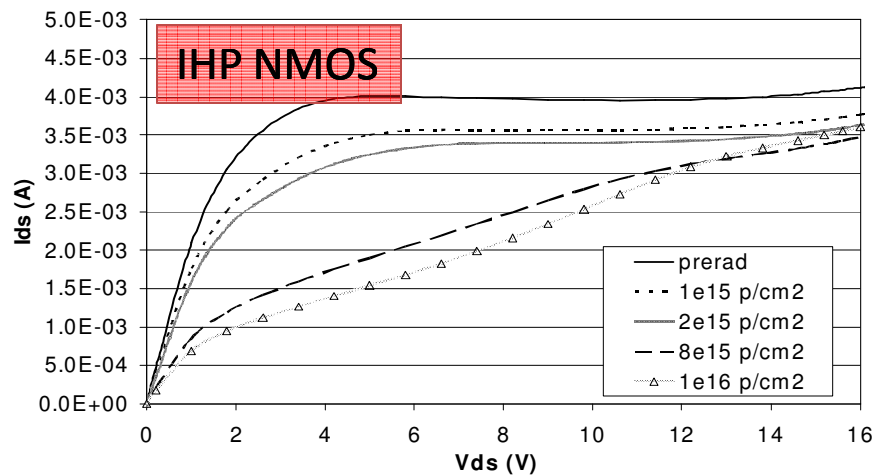
Summary

- 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 ($\sim 10\%$ of strip module), small size (19×12 mm²), 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]

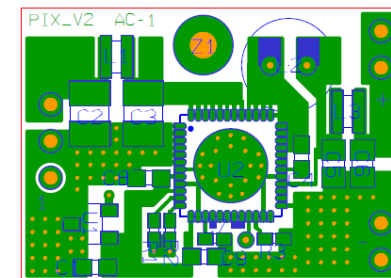
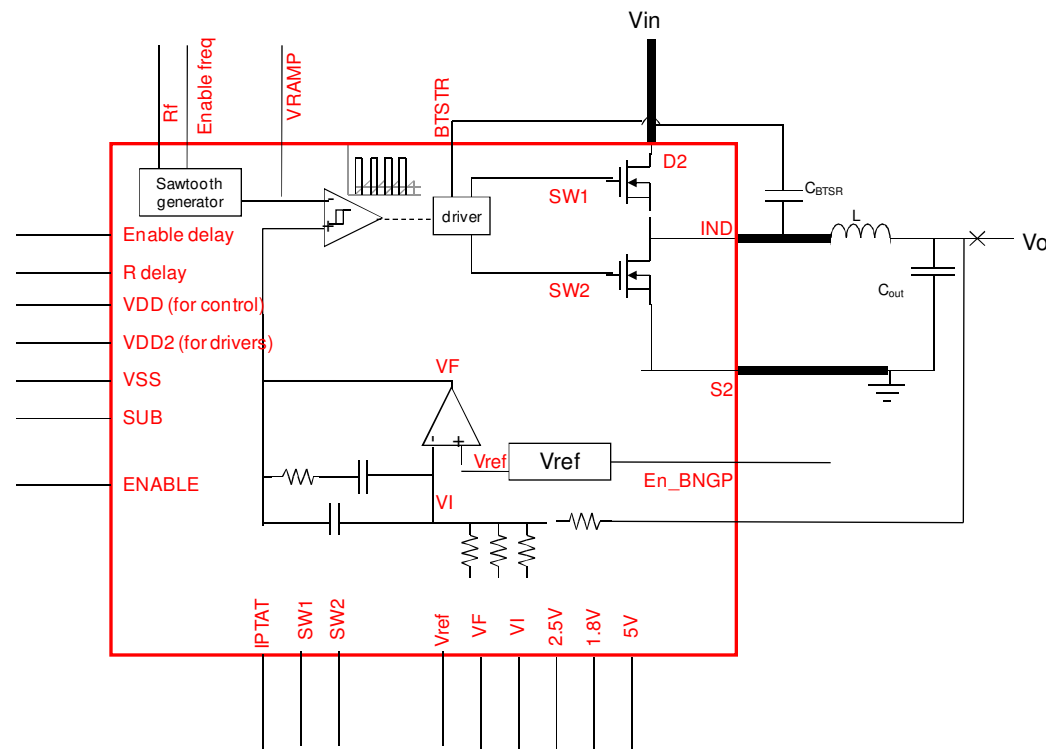


[<http://indico.cern.ch/contributionDisplay.py?contribId=163&sessionId=25&confId=49682>]

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:

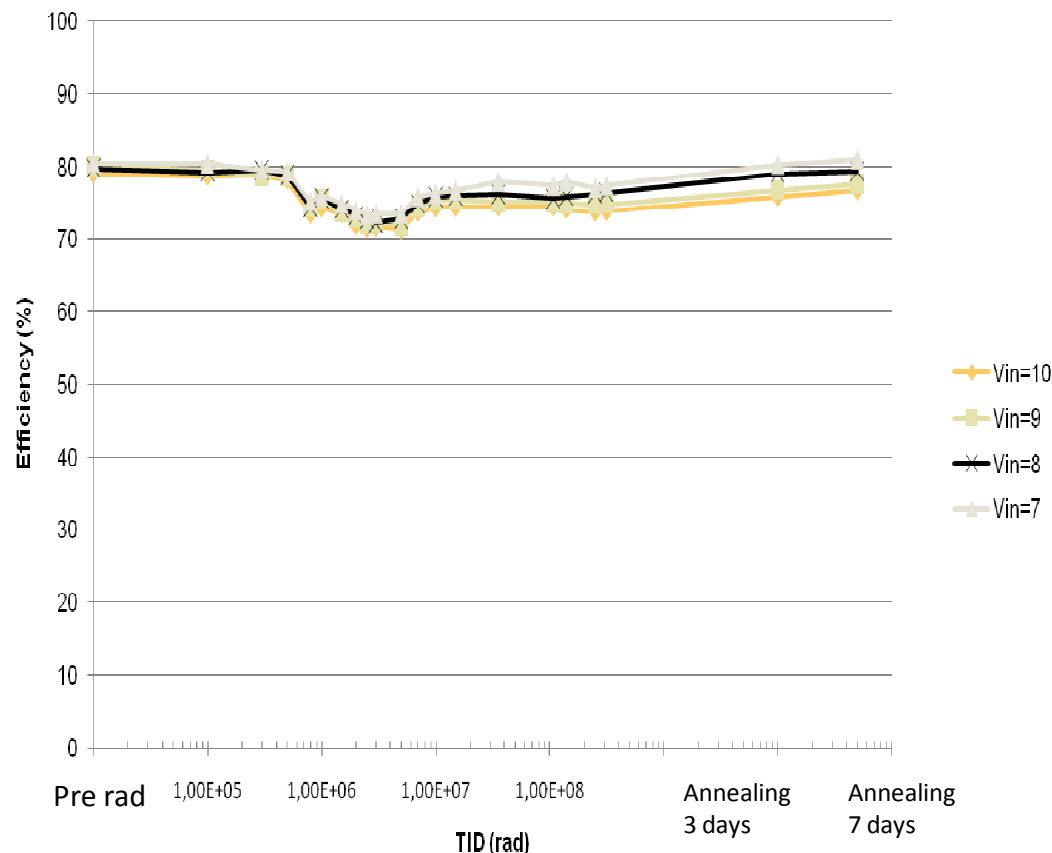
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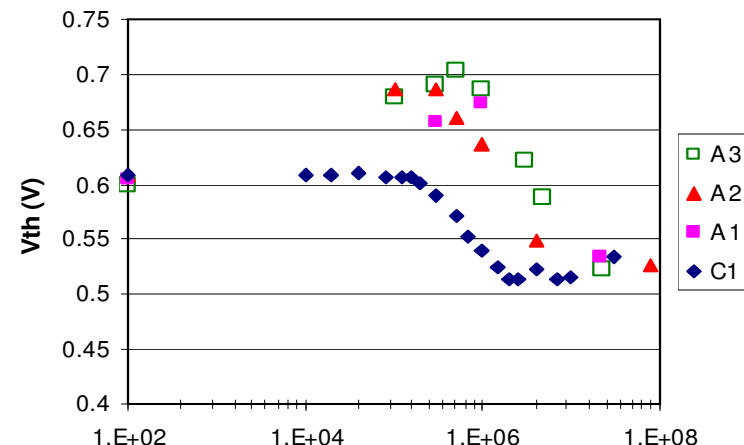
Aachen Converter Board

AMIS 2 Irradiation Results [Stefano Michelis, CERN]

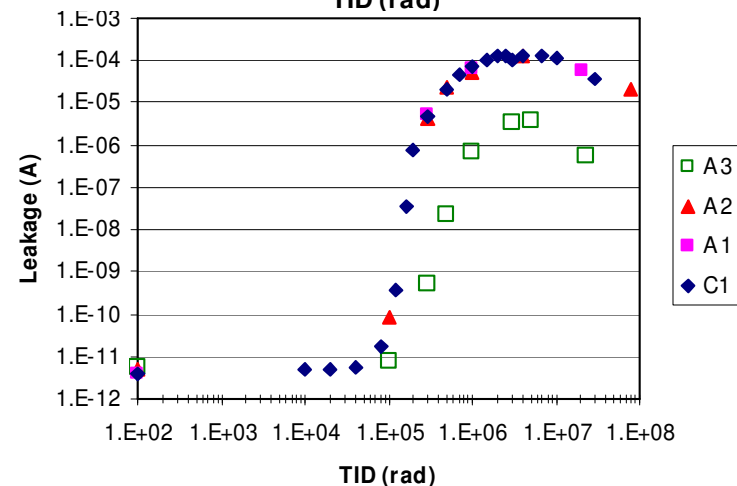
Efficiency vs TID



V_{th} (linear)



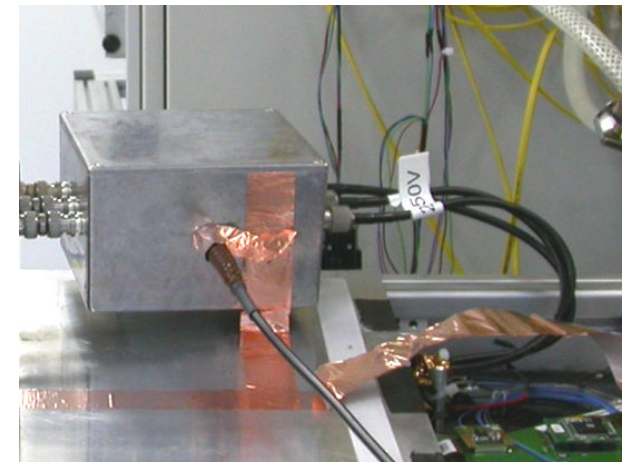
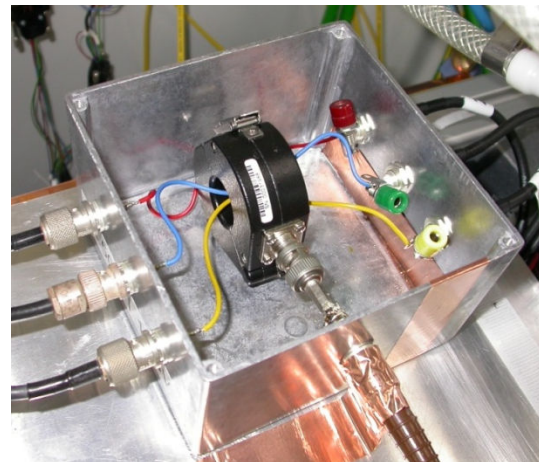
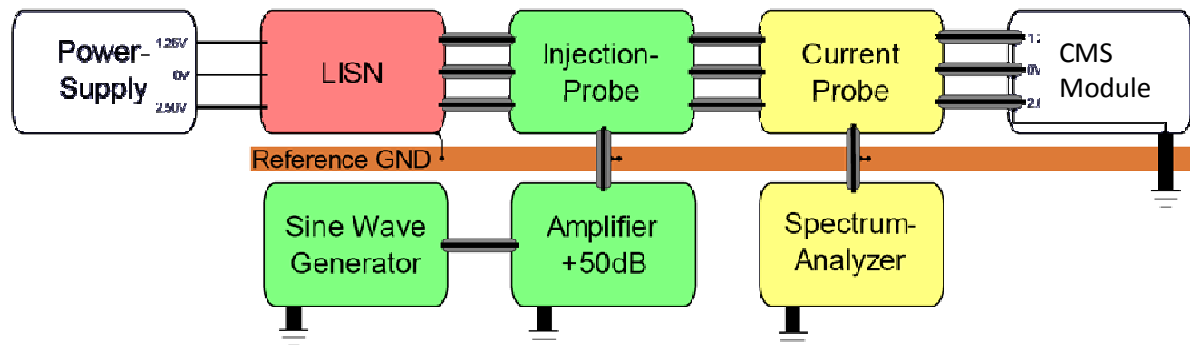
TID (rad)



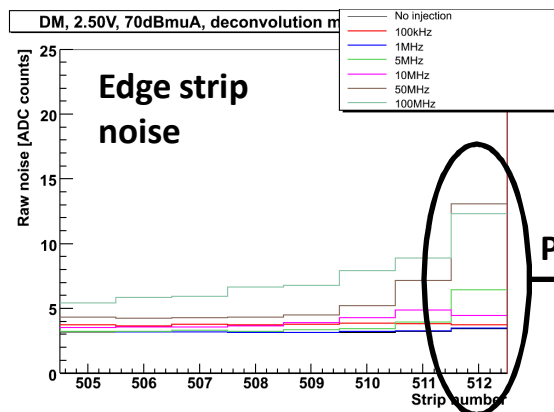
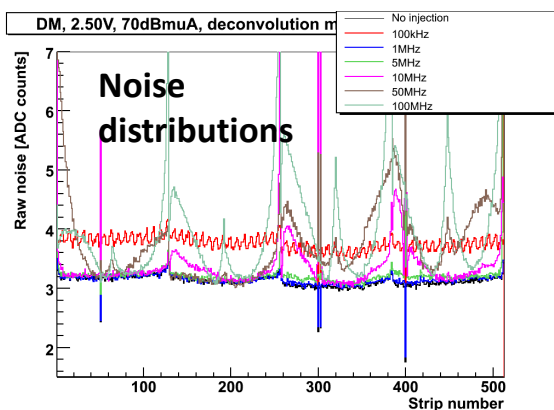
- X-ray radiation tests shows a decrease of the efficiency mostly due to the radiation induced leakage current , compensated by the threshold voltage shift

Noise Susceptibility of APV25 Strip Modules

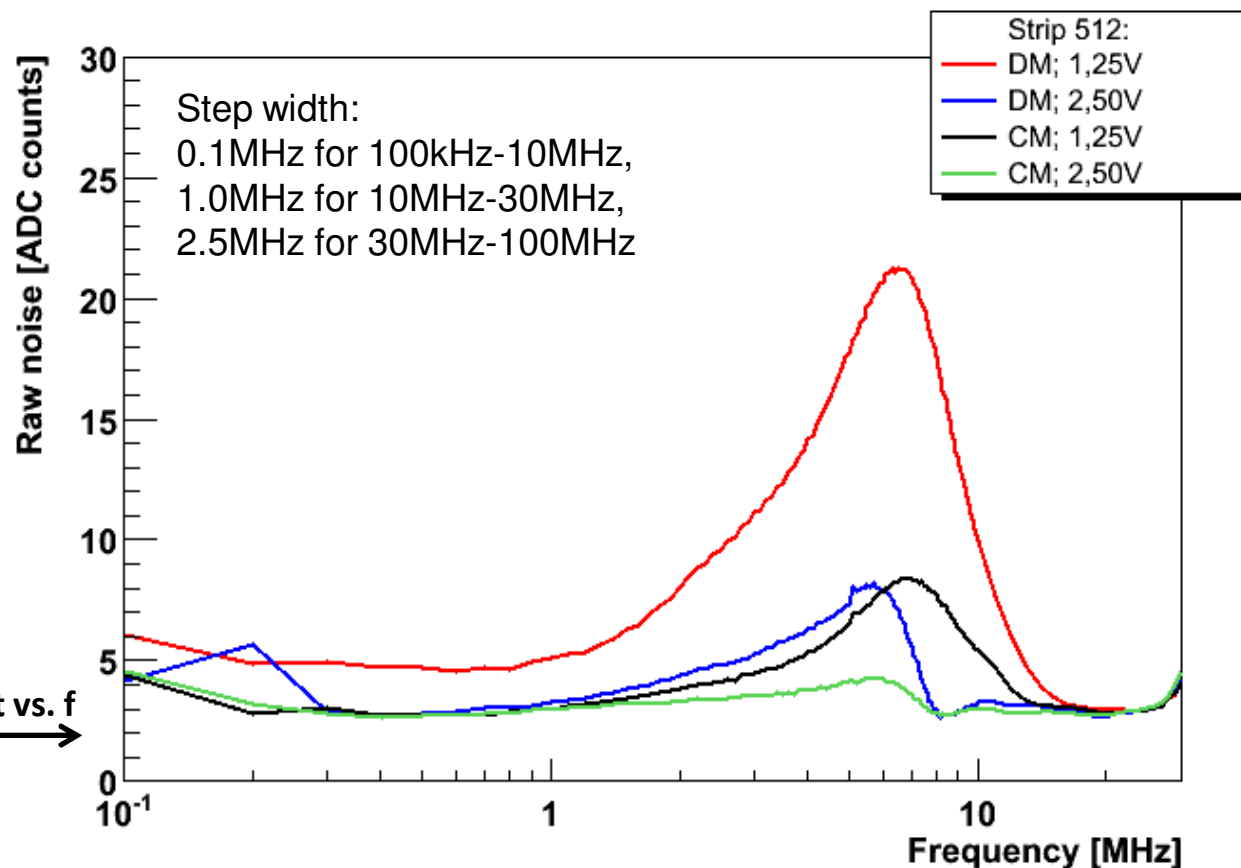
- Goal: identify particularly critical bandwidth(s) for converter switching frequency
- **Bulk current injection (BCI)** method used
- A noise current of $70\text{dB}\mu\text{A}$ ($I_{\text{eff}} = 3.16\text{mA}$) is injected into the power lines
 - Differential Mode (DM) and Common Mode (CM) on 2.5V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



Noise Susceptibility of APV25 Strip Modules



Plot vs. f

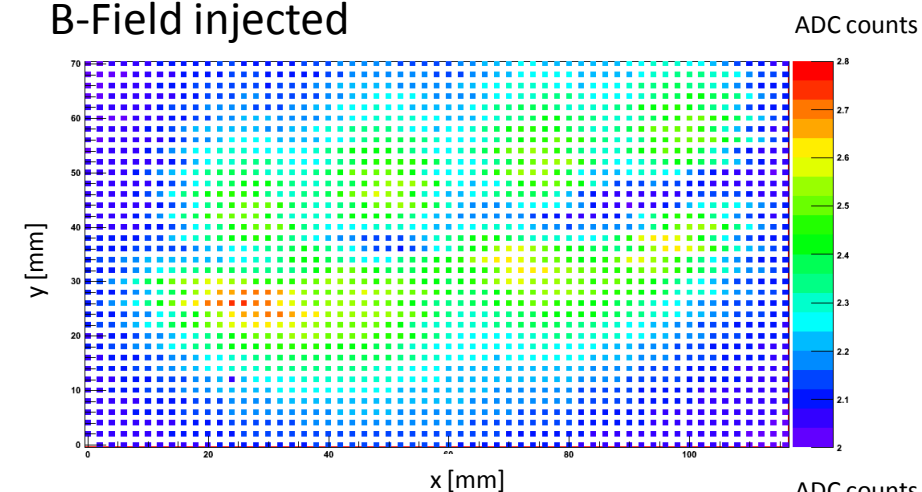


- **Peak at 6-8MHz**, well above future switching frequency (3.2MHz exp. from shaping time)
- Higher susceptibility for DM and 1.25V = pre-amplifier reference voltage
- Set-up will be valuable to characterize future module prototypes

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

