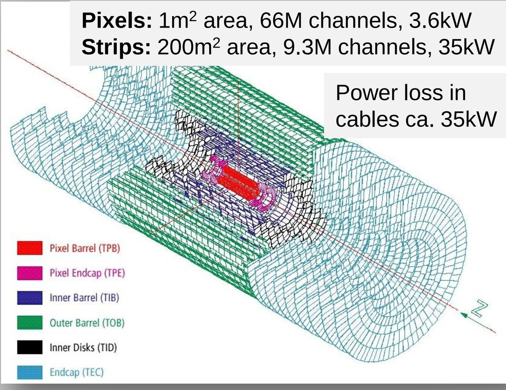
Novel Powering Schemes for the CMS Tracker at the Super-LHC

Katja Klein, HGF Detector Fellow, RWTH Aachen University

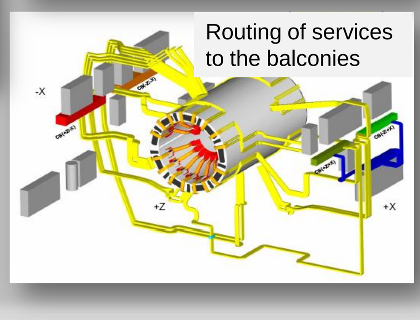
with L. Feld, R. Jussen, W. Karpinski, J. Merz , J. Sammet

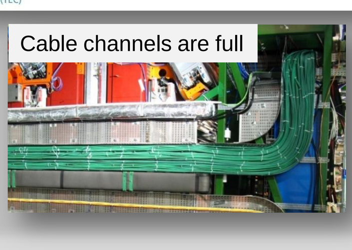
The power distribution problem of the CMS tracker at the Super-LHC

The CMS Tracker and its power distribution




Tracker End Cap with power cables


Routing of services to the balconies


Cable channels are full

	LHC	SLHC Phase-1	SLHC Phase-2
Luminosity	10^{34}cm^{-2}s^{-1}	2 x 10^{34}cm^{-2}s^{-1}	10^{35}cm^{-2}s^{-1}
Particles in tracker	~ 1 000	~ 2 000	~ 15 000 – 20 000 depending on scenario
Start-up	2009 = t_0	t_0 + 5 years	t_0 + 10 years

CMS Tracker power at the Super-LHC (SLHC)

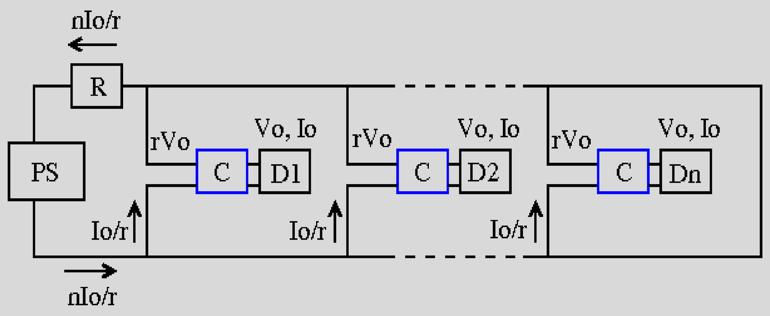
- Higher granularity to keep occupancy at ~ 1% ⇒ shorter strips, more channels
- Track information must be used in the level-1 trigger to preserve trigger rate ⇒ pixellated layers with complex, fast digital electronics
- Smaller feature size front-end electronics: 250nm → 130nm or below ⇒ saves power, but leads to larger currents for same power consumption
- Improvement of detector performance by decreasing tracker material budget
- Services – including power cables – to the tracker cannot be accessed

A new, different Tracker will be built. Its power consumption might be high.

A possible solution: DC-DC conversion

V_{in} (e.g. 12V) → **DC-DC Converter** Conversion ratio r = 2 - 10, r = V_{in}/V_{out} = I_{out}/I_{in} → V_{out} (e.g. 1.2V)

Parallel powering with DC-DC converters:
adopted by the CMS tracker as baseline in January 2009



Resistive losses in cables $P = R_{cable} \cdot I^2$ are reduced by a factor of $1/r^2$, e.g. r = 10 ⇒ losses reduced by 1/100

(Note: in praxis less reduction, since converter efficiency < 100%)

DC-DC converters are currently foreseen for the pixel detector at SLHC phase-1, and the outer tracker at SLHC phase-2.

The DC-DC buck converter

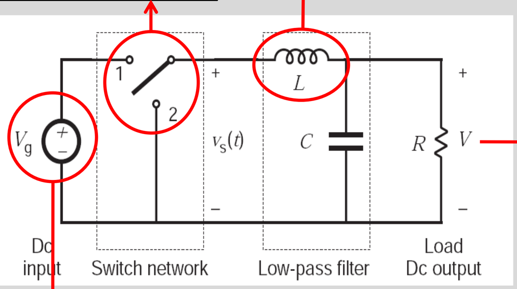
- The simplest inductor-based step-down converter ⇒ few components ⇒ low mass
- Preferred because of its high efficiency (70-80%), the possibility to drive large output currents (several Amperes), and to provide high conversion ratios (r ~ 10)

Switching with MHz frequency → switching noise

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

is bulky

radiates noise



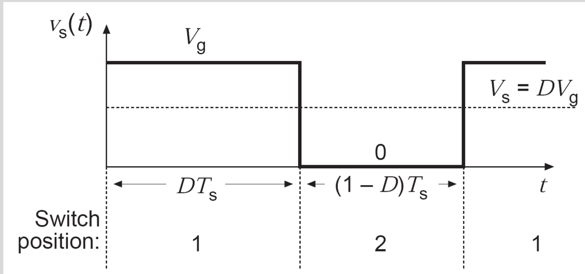
Simplified schematics (feedback loop not shown)

Efficiency

Material budget should be low

Space constraints

Semi-conductor technology must stand V_{in} ≈12V → radiation-hardness

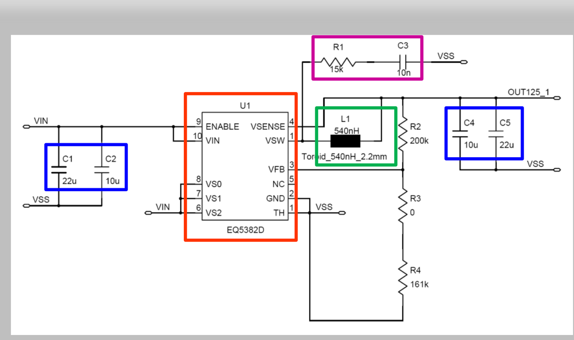


D = Duty cycle, T_s = switching period

- Custom radiation-hard ASIC in non-standard technology is being developed by CERN-PH-ESE group
- Collaboration with CERN group since 2008, prototype chips already received and tested

Aachen DC-DC buck converter development

- Development of converters with commercial, non radiation-hard buck converter ASICs
- Focus on low mass, low noise converter design, and study noise behaviour and integration aspects



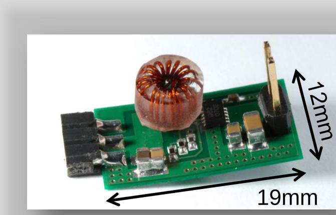
PCB: 2 copper layers a 35µm, FR4, 200µm, V = 2.3cm² x 10mm

Chip: Enpirion EQ5382D V_{in} = 2.4-5.5V(rec.)/7.0V(max.), I_{out} ≤ 0.8A, Switching frequency f_s ≈ 4MHz

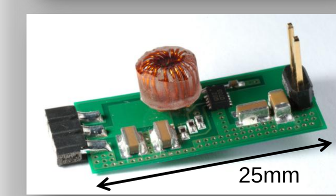
Air-core inductor: Custom-made toroid, ∅ ≈ 6mm, L = 200nH or 600nH

Input/output filters

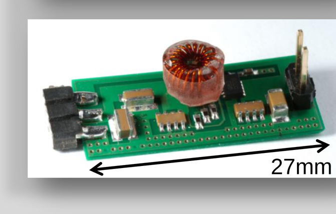
Snubber to reduce ringing



AC2-StandardC: Standard capacitors, m = 1g

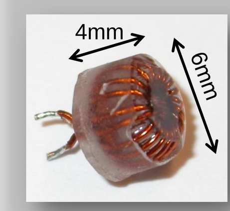


AC2-ReverseC: 3 capacitors in reverse geometry for low Equivalent Series Inductance (ESL)

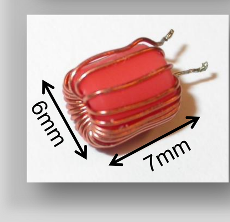


AC2-IDC: 2 Inter-Digitated Capacitors with 8 terminals for low ESL (<100pH)

Two different air-core toroids: custom-made, small, low mass



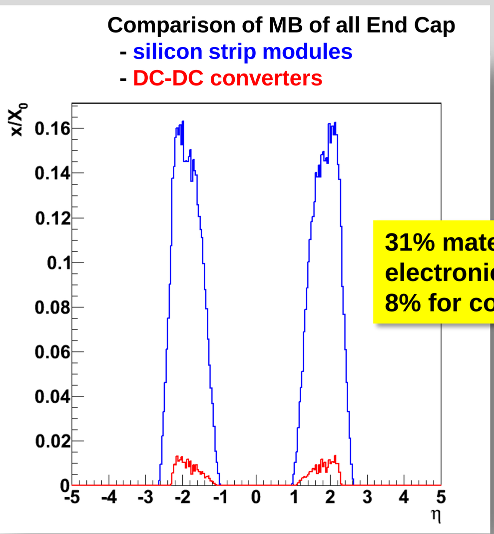
"Tiny Toroid" L = 200nH, R_{DC} ≈ 50mΩ, m = 0.2g

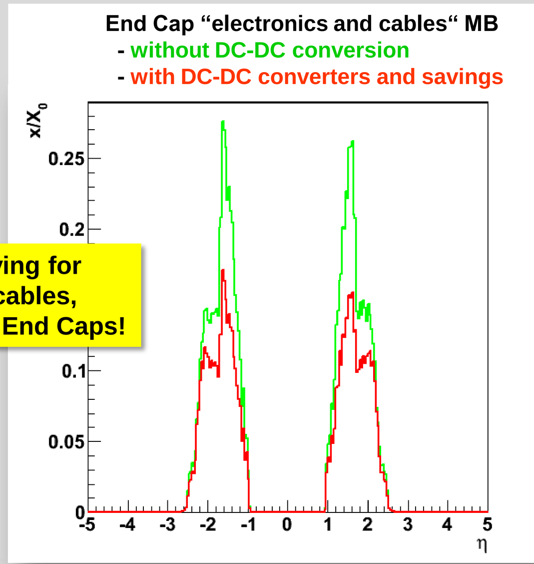


"Mini Toroid" L = 600nH, R_{DC} ≈ 100mΩ, m = 0.3g

Tracker Material Budget with DC-DC conversion

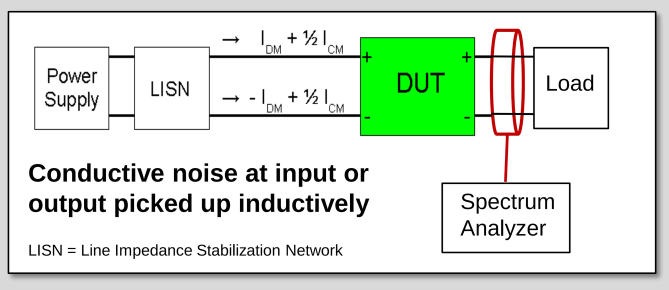
- Simulation of Tracker MB within CMS software (CMSSW), based on GEANT4
- One AC2-StandardC converter simulated per strip module, located on the front-end hybrid
- Assumptions: conversion ratio = 8, efficiency = 80%
- Copper savings in cables and motherboards evaluated based on tolerable voltage drop & power losses





31% material saving for electronics and cables, 8% for complete End Caps!

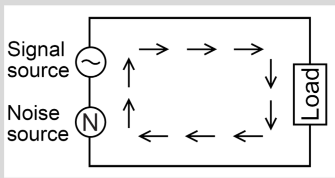
Measurement of converter noise spectra



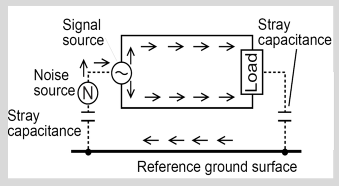
Conductive noise at input or output picked up inductively

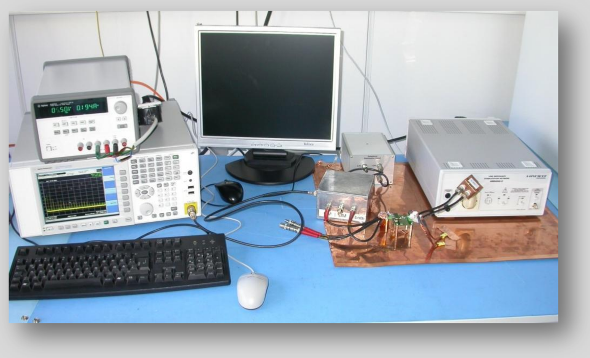
LISN = Line Impedance Stabilization Network

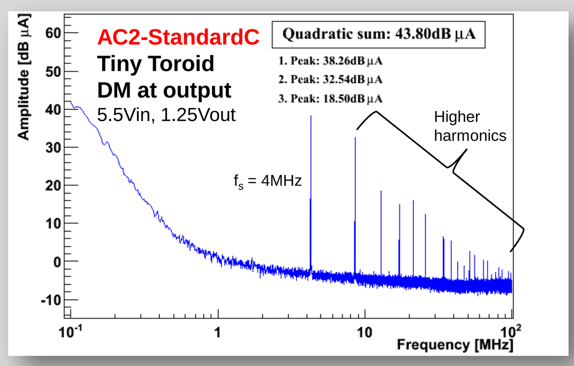
Differential Mode (DM) noise

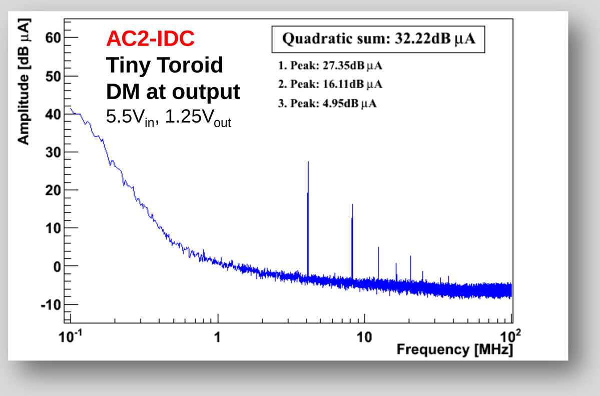


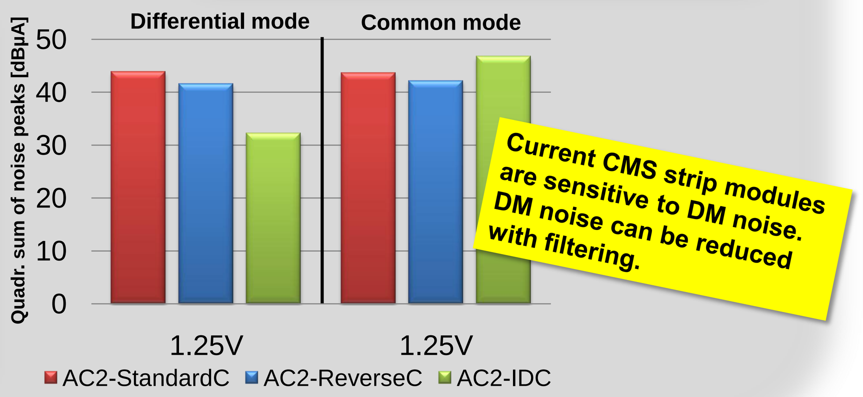
Common Mode (CM) noise







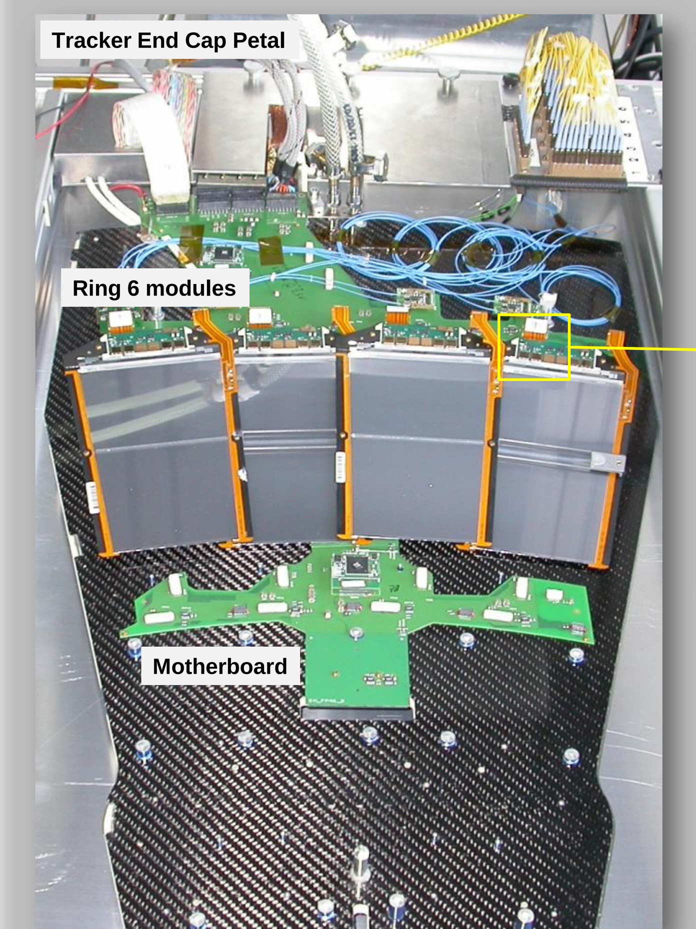


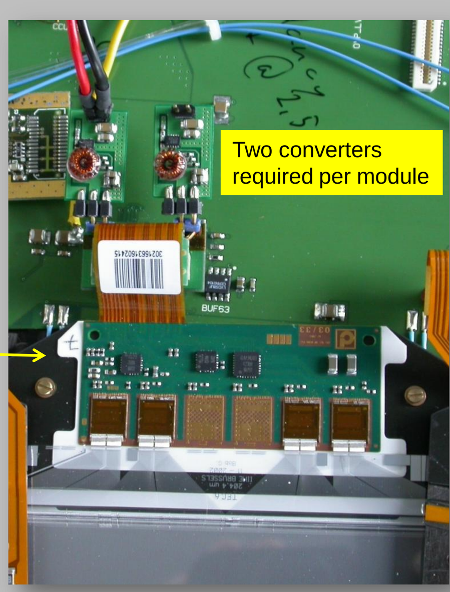


Current CMS strip modules are sensitive to DM noise. DM noise can be reduced with filtering.

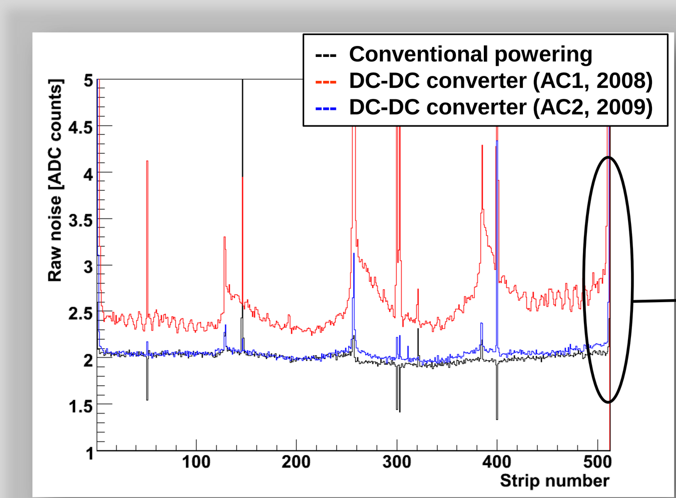
System test measurements

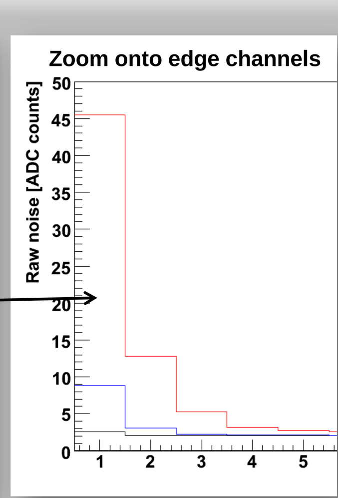
- New readout ASICs and modules prototypes not yet available
- A lot can already be learned from the operation of current tracker hardware with DC-DC converters

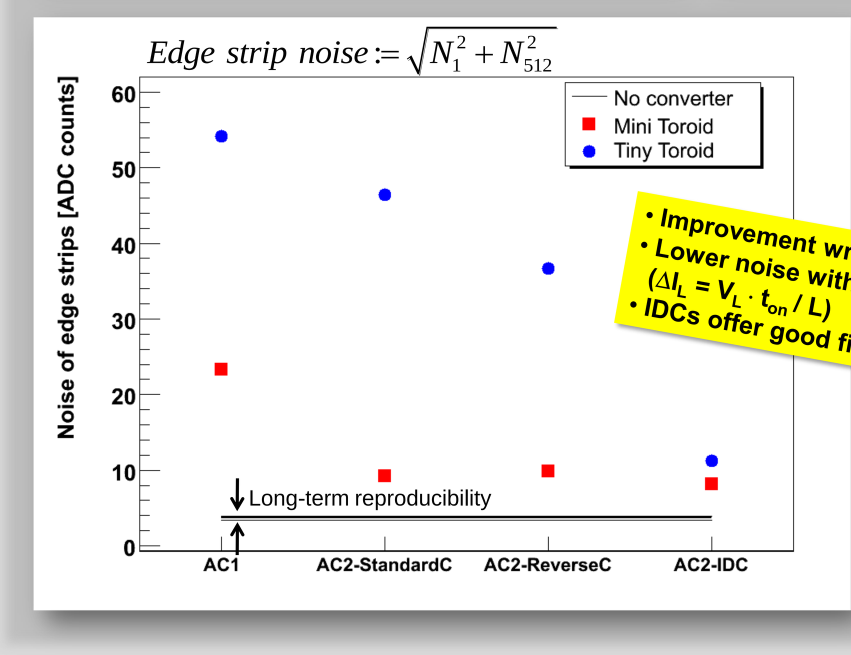




The APV25 readout chip
- 250nm CMOS technology
- **analogue readout**
- 128 channels
- per channel: pre-amplifier, CR-RC shaper, pipeline
- shaping time τ = 50ns
- 1.25V & 2.50V supply voltages
- I_{250} = 0.12A, I_{125} = 0.06A



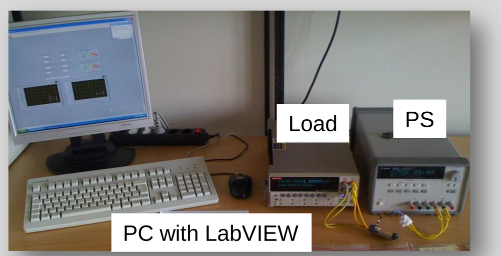


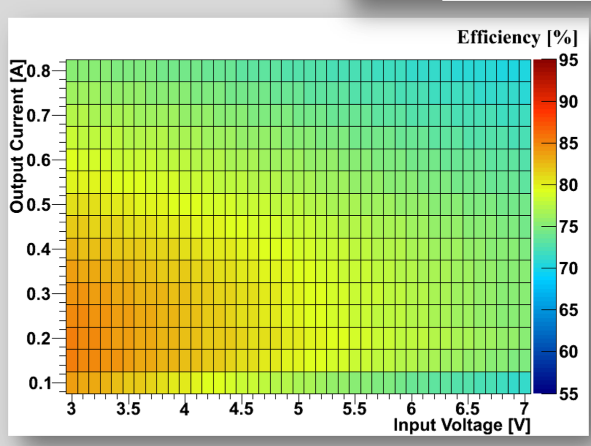


- Improvement wrt. previous prototype
- Lower noise with Mini Toroid ($\Delta I_L = V_L \cdot t_{on}$ / L)
- IDCs offer good filtering performance

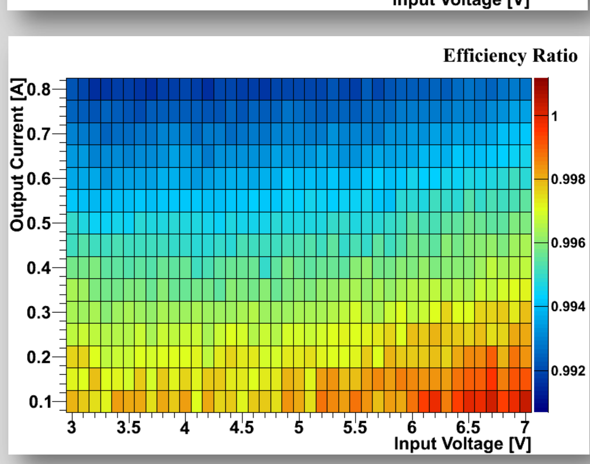
Efficiency

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



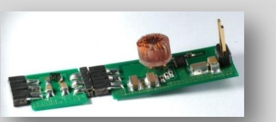


AC2-StandardC with Mini Toroid, V_{out} = 1.3V ⇒ 70-80% efficiency

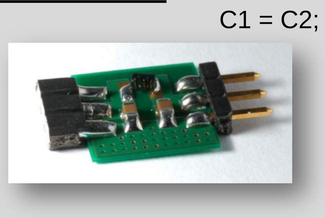


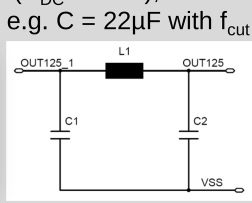
Ratio of efficiency with π-filter to efficiency without filter ⇒ < 1% efficiency loss

Filtering with additional filter boards

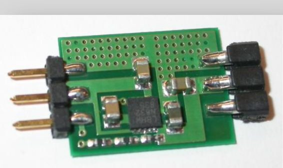


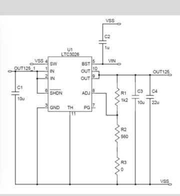
Passive π-filter L = 2.5nH (R_{DC} ≤ 5mΩ), C1 = C2; e.g. C = 22µF with f_{cut} ≈1 MHz

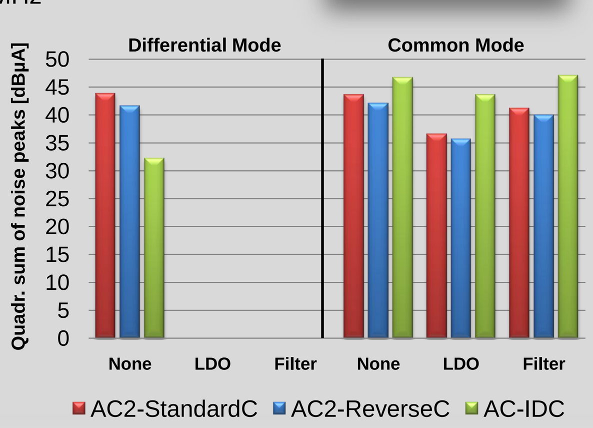


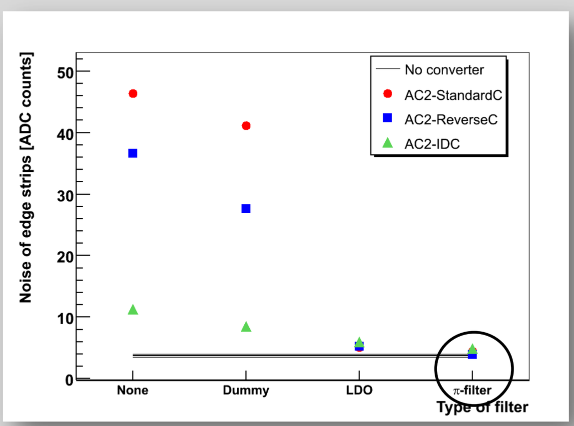


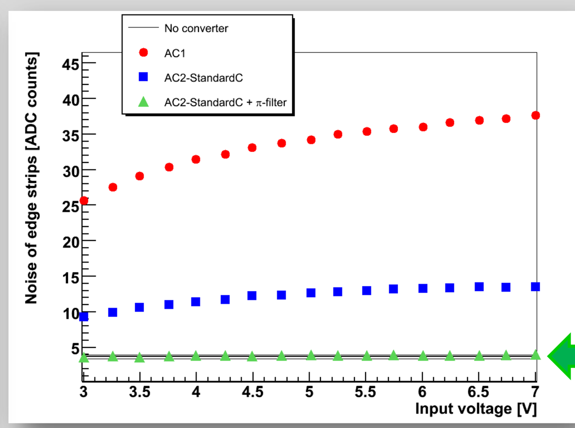
Low DropOut regulator Linear Technology LTC3026







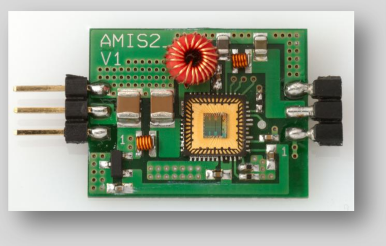




AC2-StandardC with Mini Toroid and π-filter exhibits no significant additional noise, for all accessible conversion ratios

Next steps

- Continue studies of noise coupling mechanisms
- Development of CMS DC-DC converters using radiation-hard ASICs
- System tests with SLHC readout chips and prototype modules
- Converter integration aspects: cooling, space, shielding etc.



Picture from infrared camera