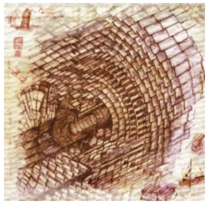


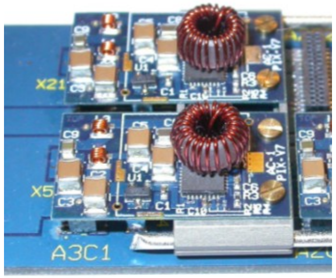
Powering for Future Detectors:
DC-DC Conversion for the CMS Tracker Upgrade

Katja Klein

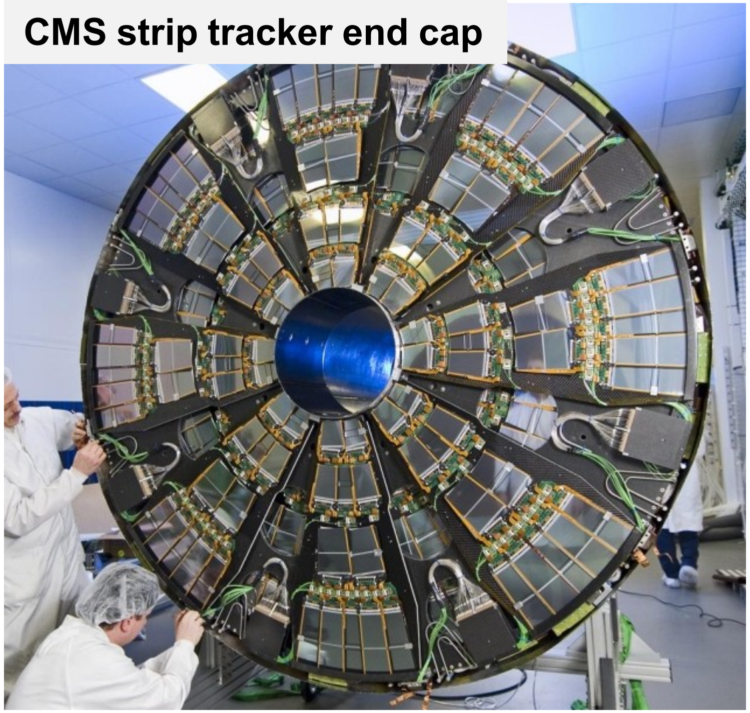
with L. Feld, W. Karpinski, J. Merz, O. Scheibling, J. Sammet, M. Wlochal

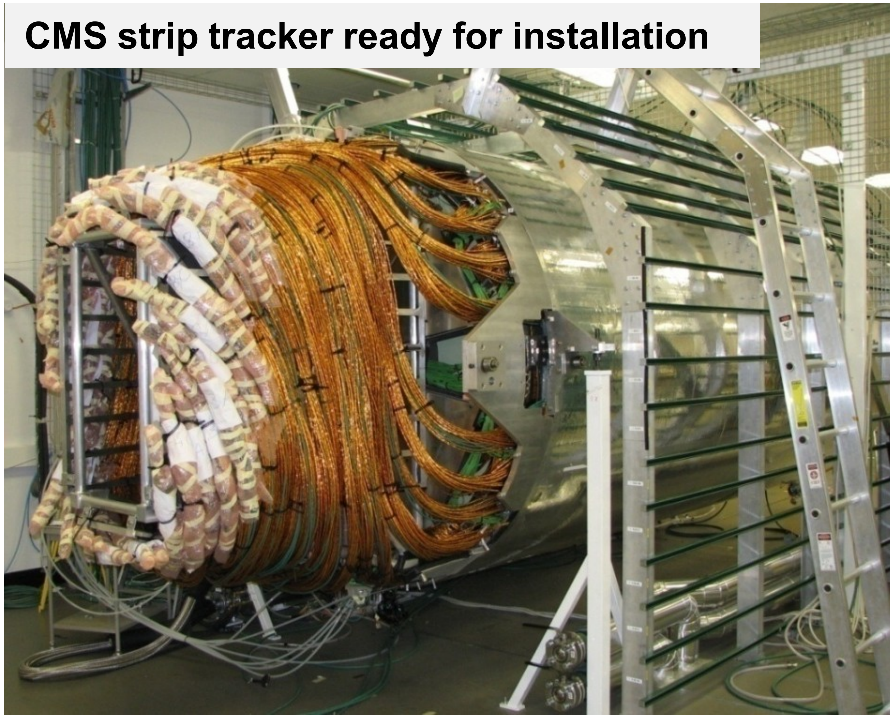
1. Physik. Institut B, RWTH Aachen University

Vertex 2011, Rust, Austria
June 23rd, 2011



Tracker Power Distribution





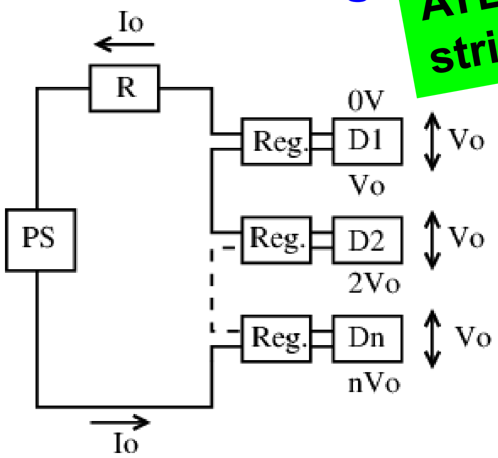
- **Trackers need kilowatts of power:** e.g. CMS strips ~ 33kW
  → power consumption will increase for SLHC: higher granularity, more functionality
- Due to long (50m) cables, power losses are (already today) similar to detector power
- Routing of services complex and nested, cable channels full and total current limited
- Cabling inside tracker volume adds to material budget

→ Novel powering schemes need to be exploited

Powering Schemes

Serial Powering

ATLAS pixels and strips upgrades?



$V_{drop} = R \cdot I_0$

$P_{drop} = R \cdot I_0^2$

- Powered from constant current source
- Shunt regulator and transistor to take excess current and stabilize voltage

\+ Number of modules in chain can be large

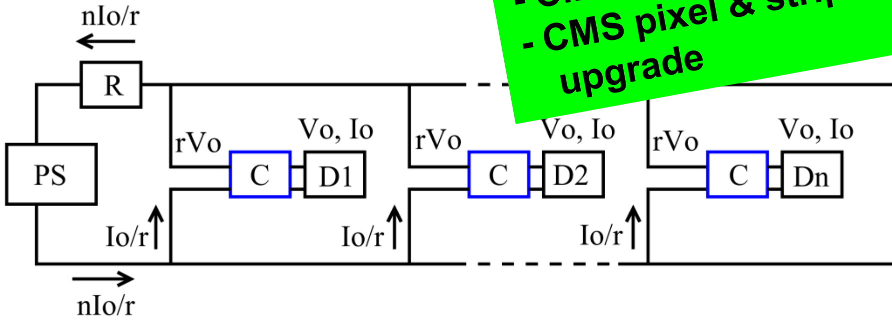
\+ Adds very little extra material

\- No solid system ground → biasing, AC-coupled communication etc.

\- Inefficient if different current consumptions (e.g. end caps)

DC-DC conversion

- ATLAS pixels and strips upgrades?
- CMS HCAL upgrade
- CMS pixel & strips upgrade



$P = U \cdot I = (r \cdot U) \cdot (I/r)$

r = conversion ratio

$P_{drop} = R \cdot (I/r)^2$

- Need radiation-hard magnetic field tolerant DC-DC converter

\+ Standard grounding, biasing, control & communication scheme

\+ Fine for very different current consumption

\- Conversion ratio limited by technology and efficiency

\- Switching devices → switching noise

\- Output current per converter limited

The CMS Tracker Upgrade

As a result of a review process, the CMS tracker has chosen **DC-DC conversion as baseline solution**, and maintains Serial Powering as back-up (January 2009).

Around 2016: Exchange of the CMS pixel detector

- Similar to todays detector, but less material, reduced data losses, CO_2 cooling
- 3 Barrel layers → 4 barrel layers; 2 disks → 3 disks
  → Number of readout chips (ROCs) increases by factor 1.9
  → Unacceptable power losses in cable trays

→ DC-DC buck converters with conversion ratio of 3-4

(Semi-conductor technology limits input voltage to < 12V, and Vout = 2.5 and 3.3V)

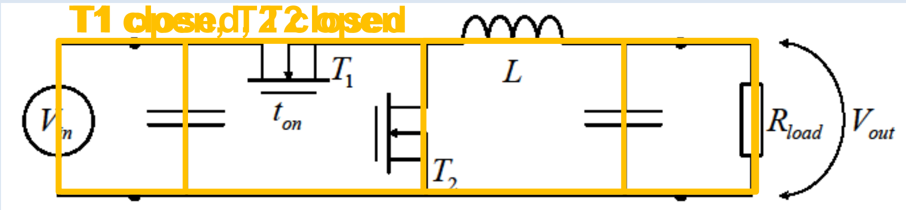
Around 2022: Exchange of the whole CMS tracker

- Higher granularity → more readout channels
- Tracker is supposed to contribute to Level 1 trigger → higher power consumption

→ DC-DC converters with conversion ratio of 8-10

DC-DC Buck Converters

DC-DC converters can be based on many different principles and layouts
→ concentrate here on so-called **buck converters**



Duty cycle $D = t_{1,on}/T$; $1/D = I_{out}/I_{in} = V_{in}/V_{out} = r$

Why buck converters?

- High currents with high efficiency
- Comparably simple & compact
- Output voltage regulation by Pulse Width Modulation (not shown)

Challenges

- Radiation tolerance of high voltage (15V) power transistors
- Switching with MHz frequencies → "switching noise" through cables (conductive)
- Saturation of inductor ferrite cores in magnetic field → air-core inductor
  → radiated noise emissions
- Maximization of efficiency & minimization of material and size

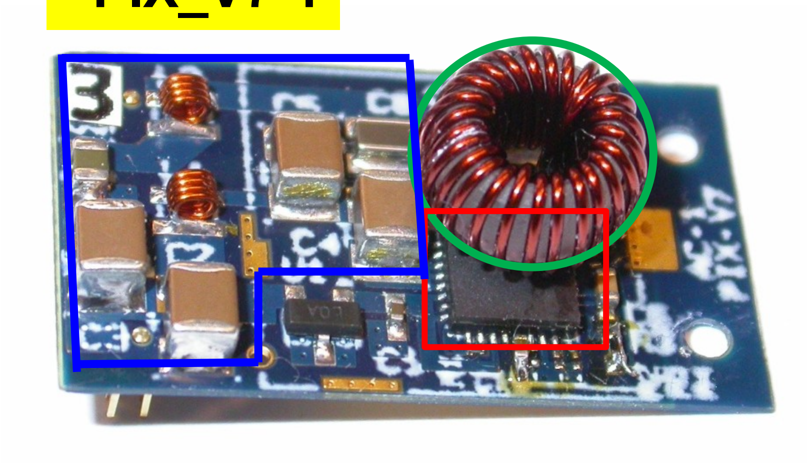
Buck Converter ASICs

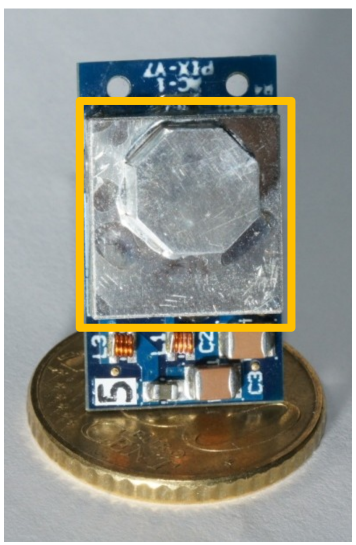
- ASIC includes transistors and voltage regulation circuit
- ASIC is being developed within **CERN electronics group (F. Faccio et al.)**
- Radiation tolerance of many semi-conductor technologies evaluated
  → **AMIS I3T80** 0.35μm (ON Semiconductor, US)
    - functional up to dose of 300Mrad & fluence of $5 \cdot 10^{15}$ p/cm^2
    - no Single Event Burnout effect
- **AMIS prototypes**:
  AMIS1 (2008) → AMIS2 (2009) → AMIS3 (problems)
  → AMIS4 with full functionality (submitted in January 11)
- Work with second supplier (IHP, Germany) to improve radiation tolerance
  - two prototypes in 2010, but ASIC development on-hold due to issues

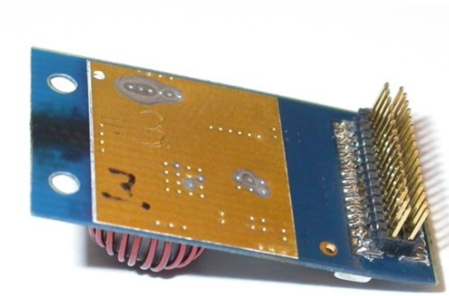
SEB = Single Event Burnout
= ionizing particle in source turns parasitic npn transistor on → destructive current

Aachen DC-DC Converter Development

“PIX_V7“:







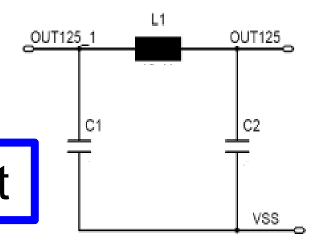
A = 28 x 16 mm^2
M ≈ 2.5g
3.8% of a radiation length

ASIC: AMIS2 by CERN
I_{out} < 3A
V_{in} < 12V
f_s configurable, e.g. 1.3MHz

PCB:
2 copper layers a 35µm
0.3mm thick
Large ground area on bottom for cooling

Toroidal inductor:
L = 450nH
R_{DC} = 40mΩ
Plastic core

Pi-filters at in- and output



Shield

Design guidelines from CERN group have been implemented.

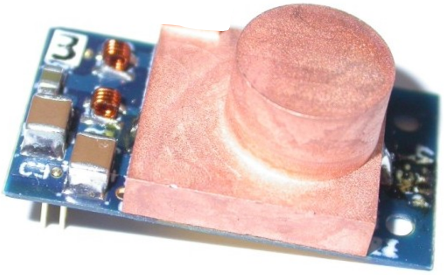
The Shield

The shield has three functions:

1) to shield radiated emissions from inductor
2) to reduce conducted noise by means of segregation between noisy and quiet parts of board (less coupling)
3) to provide cooling contact for coil through its solder connection to PCB, since cooling through contact wires not sufficient

Several technologies are under evaluation:

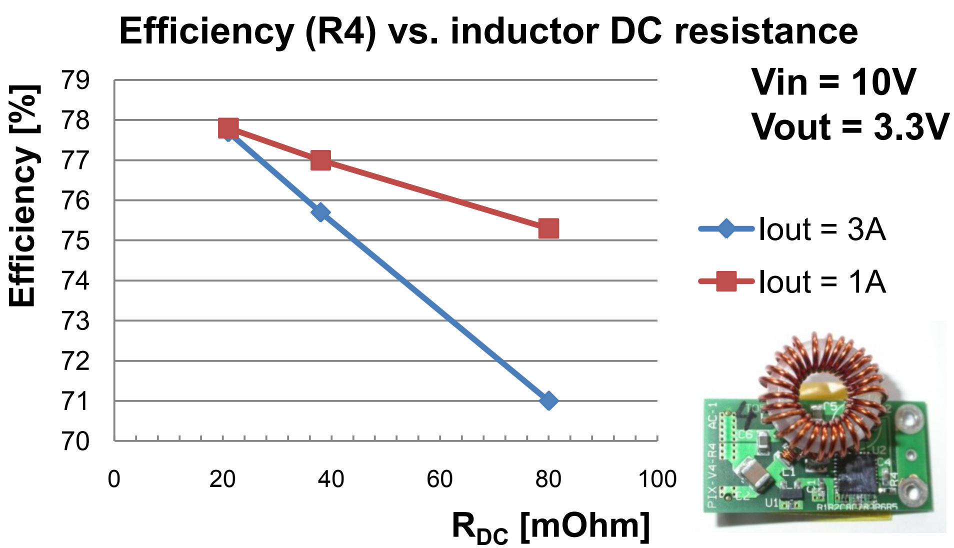
- **Aluminium shields of 90µm thickness (milled in our Workshop)**
- **Plastic shields (PEEK) coated with a metall layer**
  e.g. galvanic deposition of copper (30µm – 60µm)

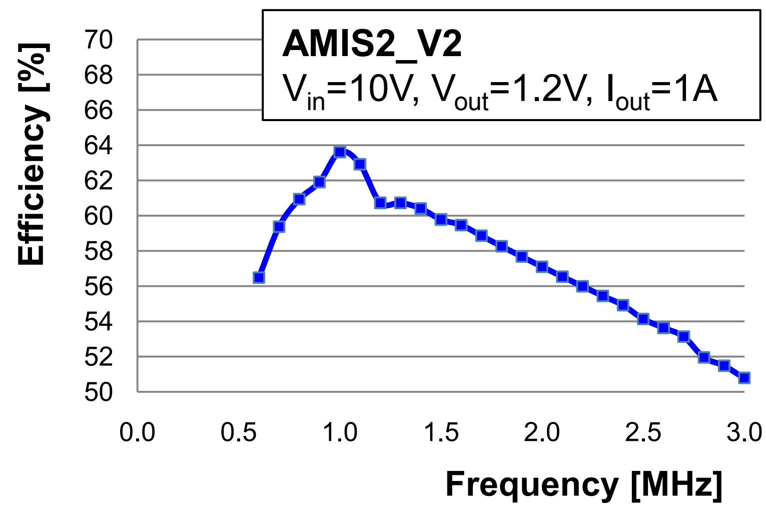


Shape driven by geometrical constraints

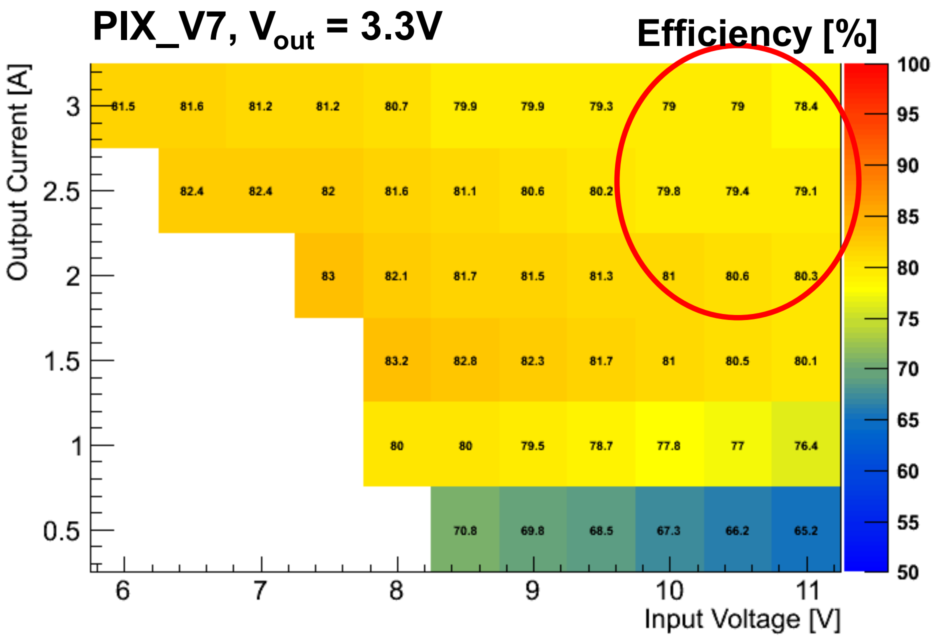
Efficiency

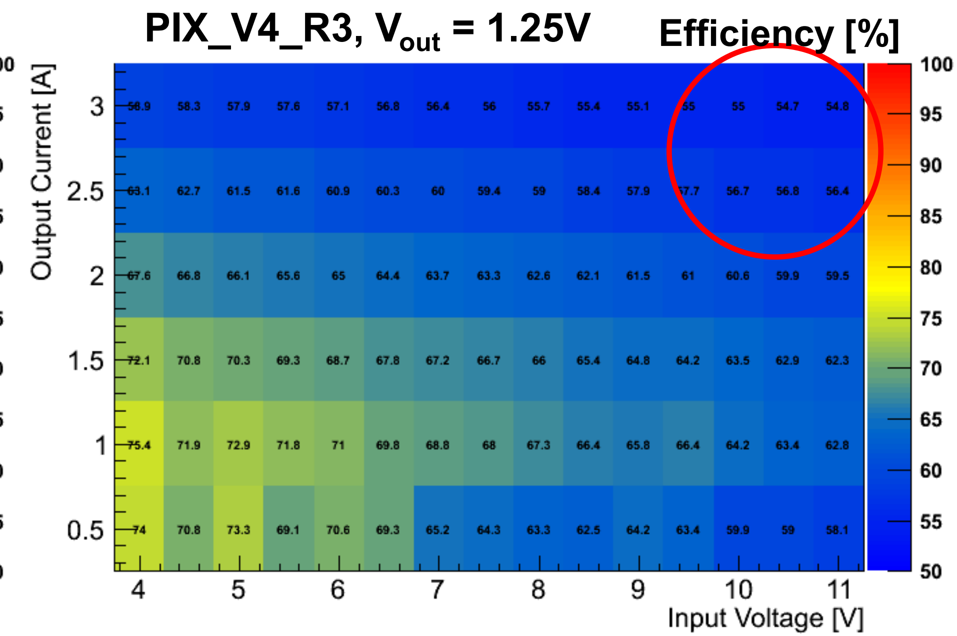
- Efficiency = P_{out} / P_{in}
- Resistive losses from
  - chip (R_{on} of transistors)
  - wire bonds
  - inductor
- Resistive losses ~ $1/f_s$; switching & driving losses ~ f_s
- Need to balance efficiency vs. mass, volume & EMC





Efficiency





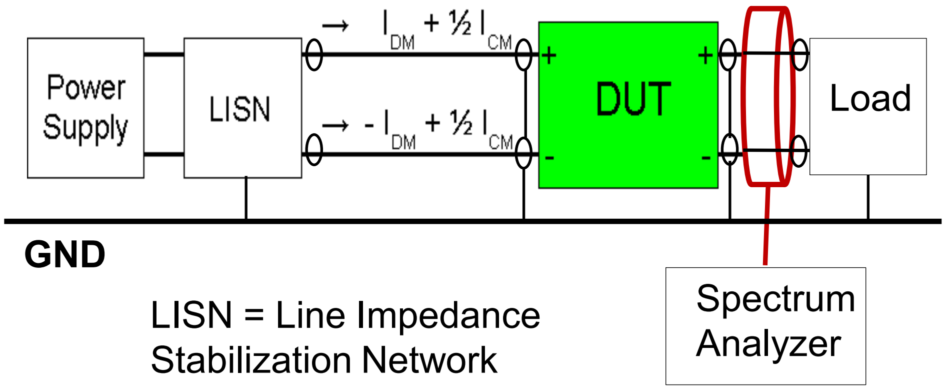
[White regions: regulation not working properly, V_{out} too low]

- **Phase 1 conditions**: V_{out} = 3.3V or 2.5V, I_{out} < 2.8A, conversion ratio of 3-4
  → **75% - 80% efficiency**: ok
- **Phase 2 conditions**: V_{out} = 1.25V, I_{out} = 3A, conversion ratio of 8-10
  → about **55% efficiency**: too low
  Possible solution: combine with a on-chip “switched capacitor“ converter with r = 2

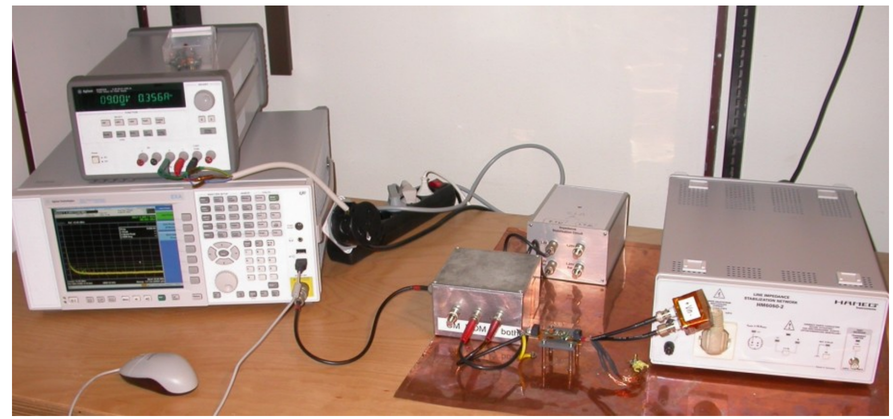
Conductive Noise

Noise through cables (conductive noise) was studied with EMC set-up

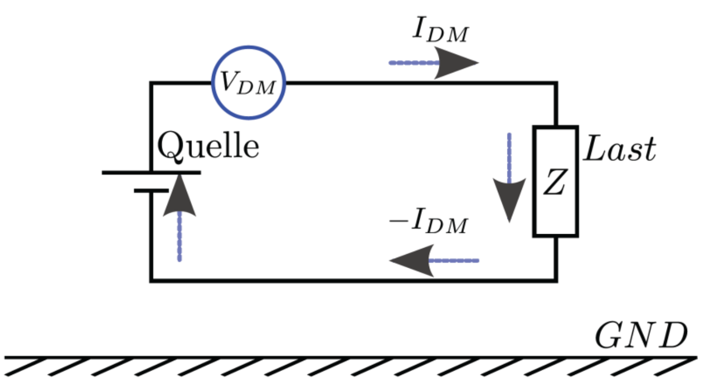
EMC = electromagnetic compatibility



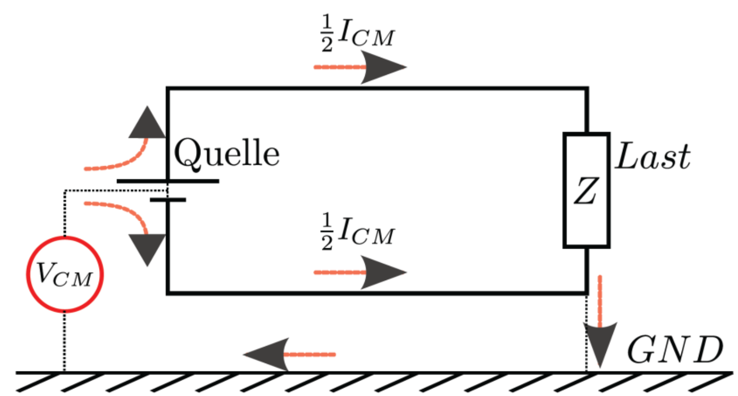
LISN = Line Impedance Stabilization Network



Differential Mode (DM), “ripple“

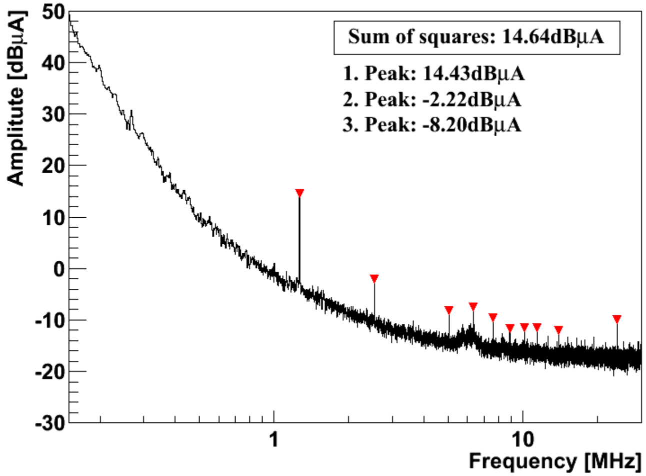


Common Mode (CM)



Conductive Noise

Differential Mode, no shield



PIX_V7 output noise

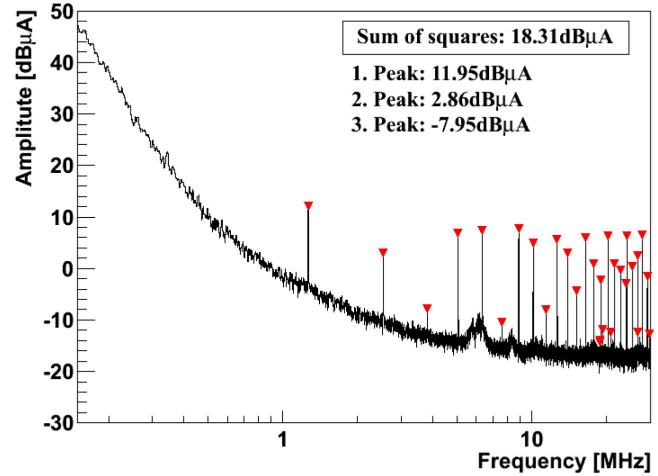
V_{out} = 3.3V

V_{in} = 10V

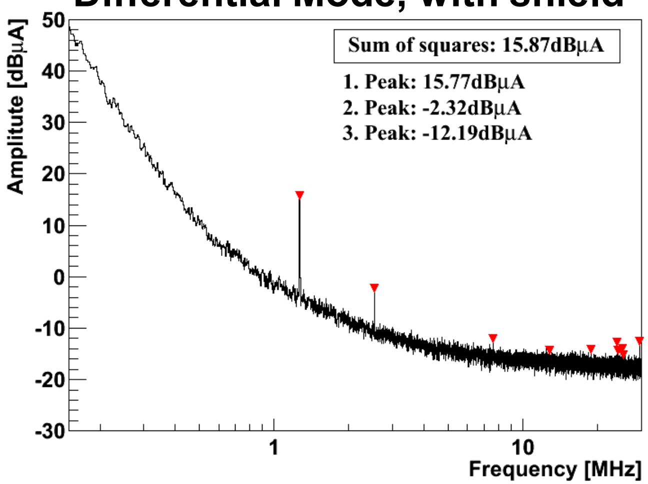
f_s = 1.3MHz

L = 450nH

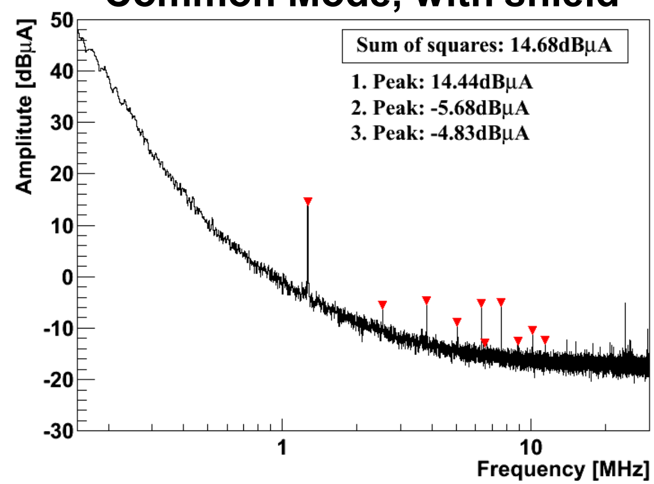
Common Mode, no shield



Differential Mode, with shield



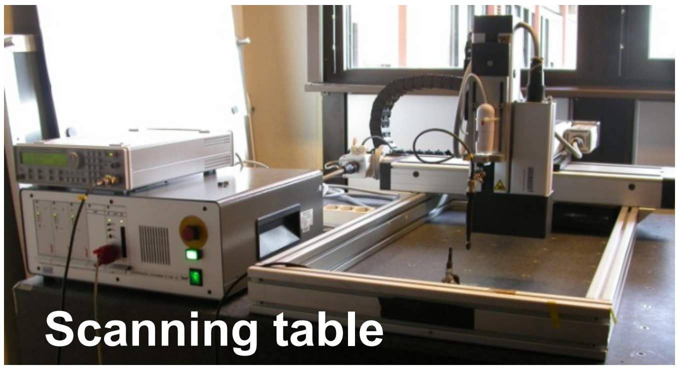
Common Mode, with shield

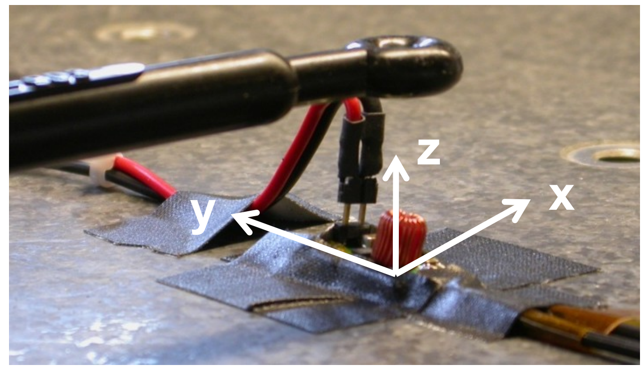


→ **Large reduction of CM above 2 MHz due to shield**

Radiated Noise Emissions

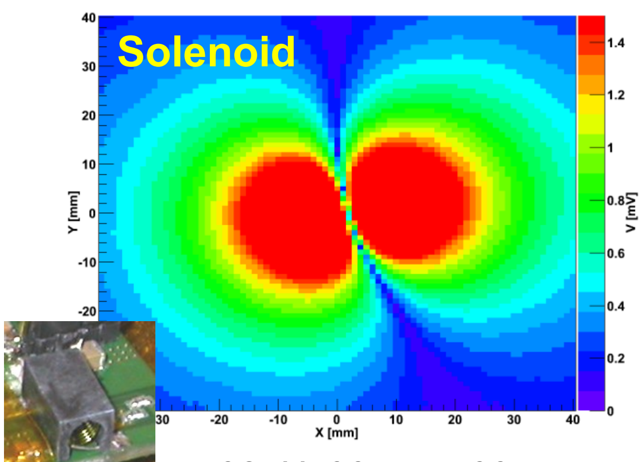
- Large fast changing currents through inductor → magn. near field can induce noise
- Field of air-core **toroid** has been measured and inductor shape optimized



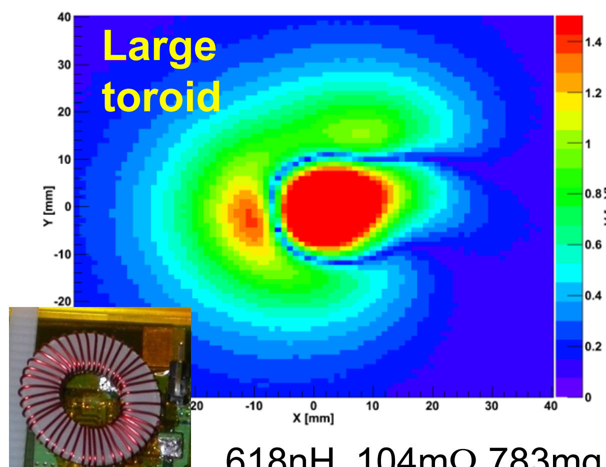


Emitted field is measured with a pick-up probe and spectrum analyzer [height of 1. peak]

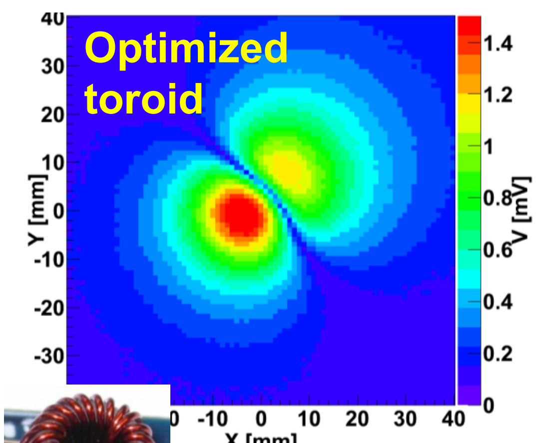
B_z measured in x-y-plane, 1.5 mm above coil:

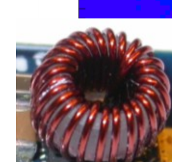


538nH, 90mΩ, 500mg



618nH, 104mΩ,783mg



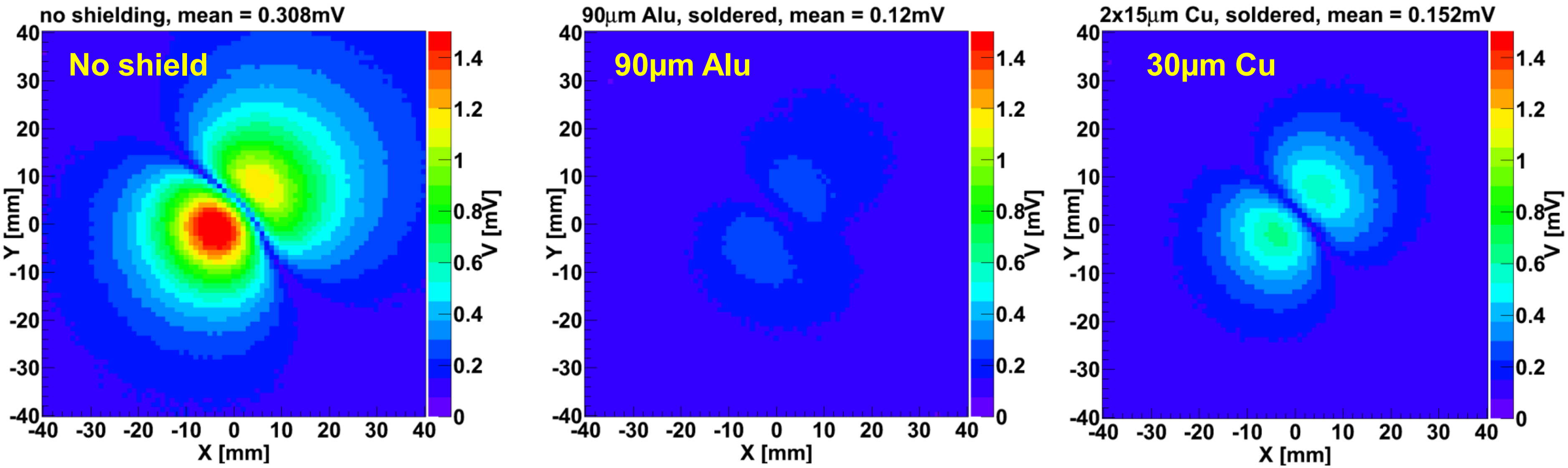


450nH, 40mΩ, 650mg

Shielding from Radiated Noise

Shielding of magnetic field: Eddy currents in metallic shield

- 90µm milled Aluminium shield works fine
- Plastic shield coated with 30µm Cu worse and adds ~ 40% more material (but probably cheaper)



Integration into Phase-1 Pixel Detector

Integration for pixel barrel onto supply tube

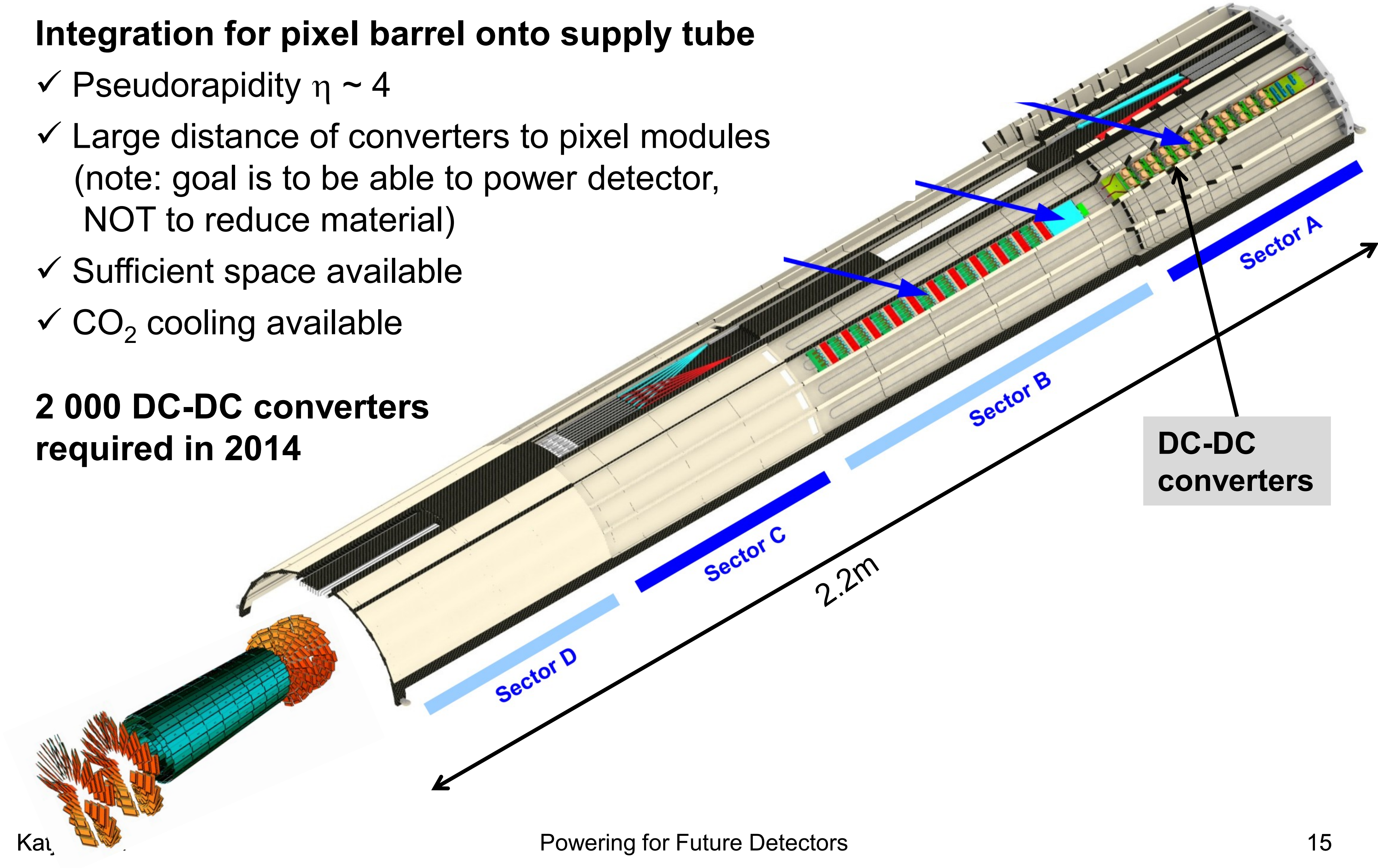
✓ Pseudorapidity $\eta \sim 4$

✓ Large distance of converters to pixel modules (note: goal is to be able to power detector, NOT to reduce material)

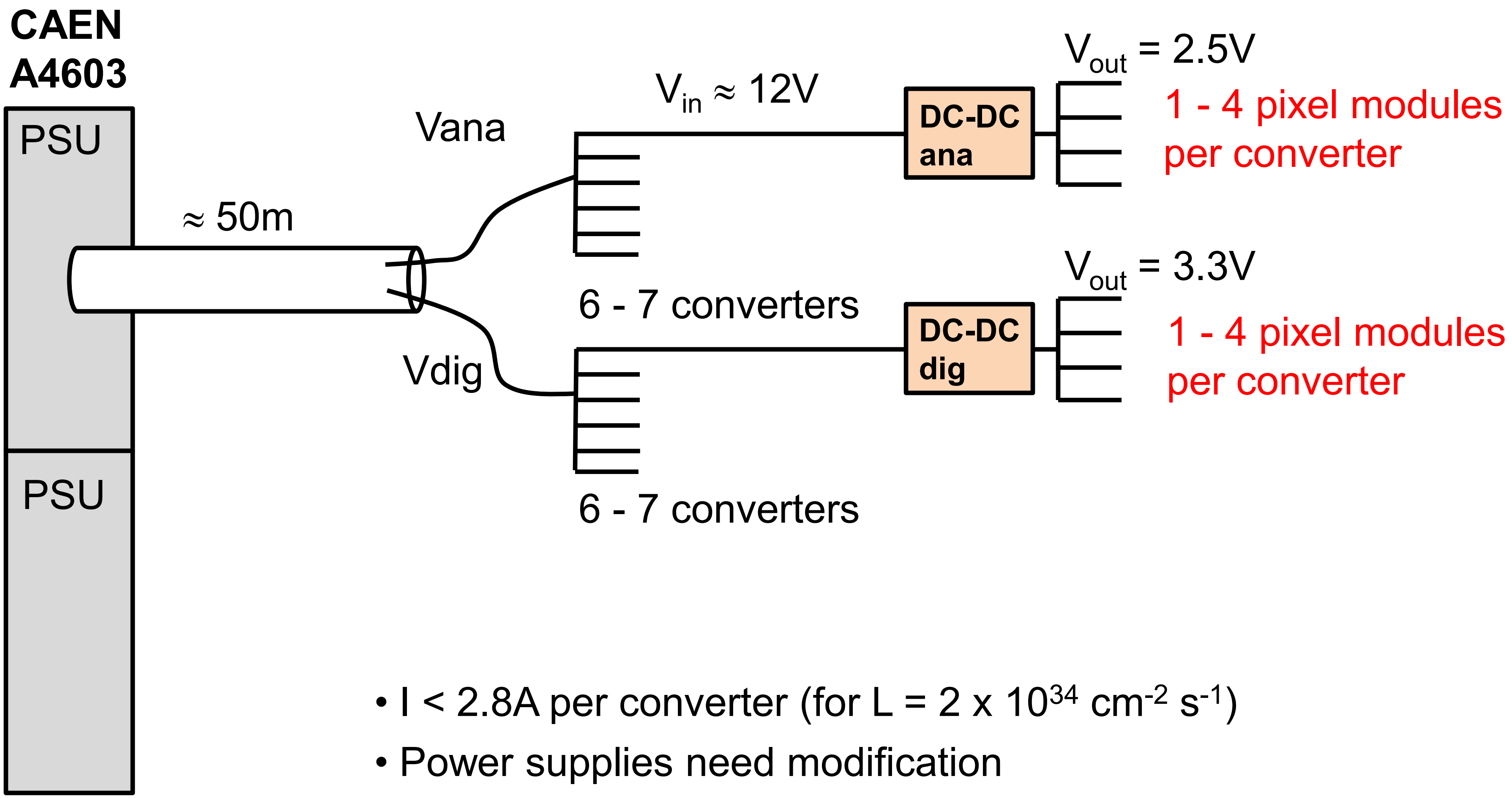
✓ Sufficient space available

✓ CO_2 cooling available

2 000 DC-DC converters required in 2014



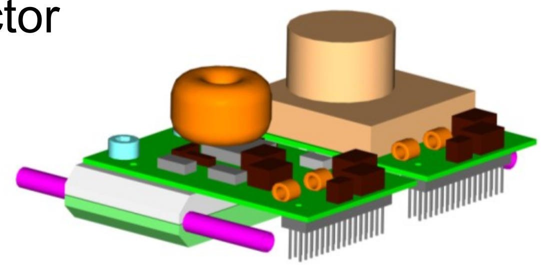
Integration into Phase-1 Pixel Detector

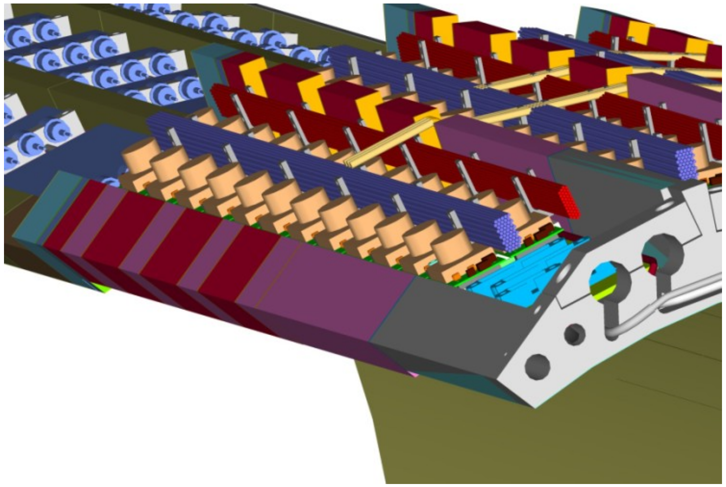


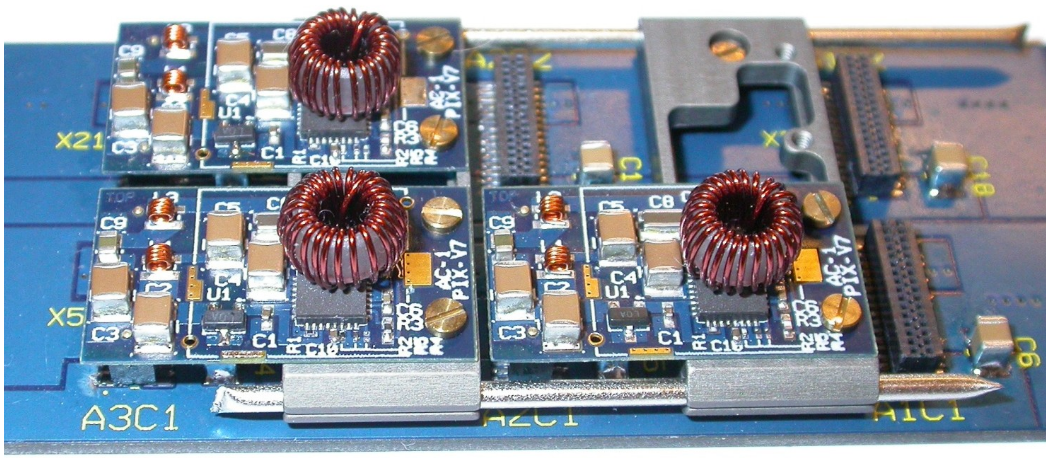
- I < 2.8A per converter (for $L = 2 \times 10^{34}\ cm^{-2}\ s^{-1}$)
- Power supplies need modification
- No remote sensing

Integration into Phase-1 Pixel Detector

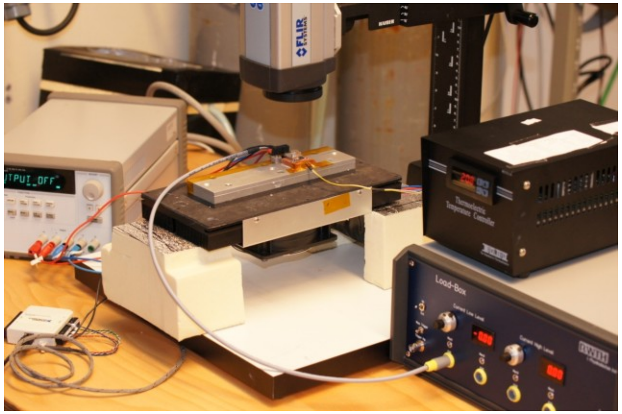
- 26 DC-DC converters per channel
- Power dissipation ~ 50W per channel
- Cooling bridges clamp around CO_2 pipes
- Chip cooled through PCB backside
- Shield (soldered to PCB) acts as cooling contact for inductor

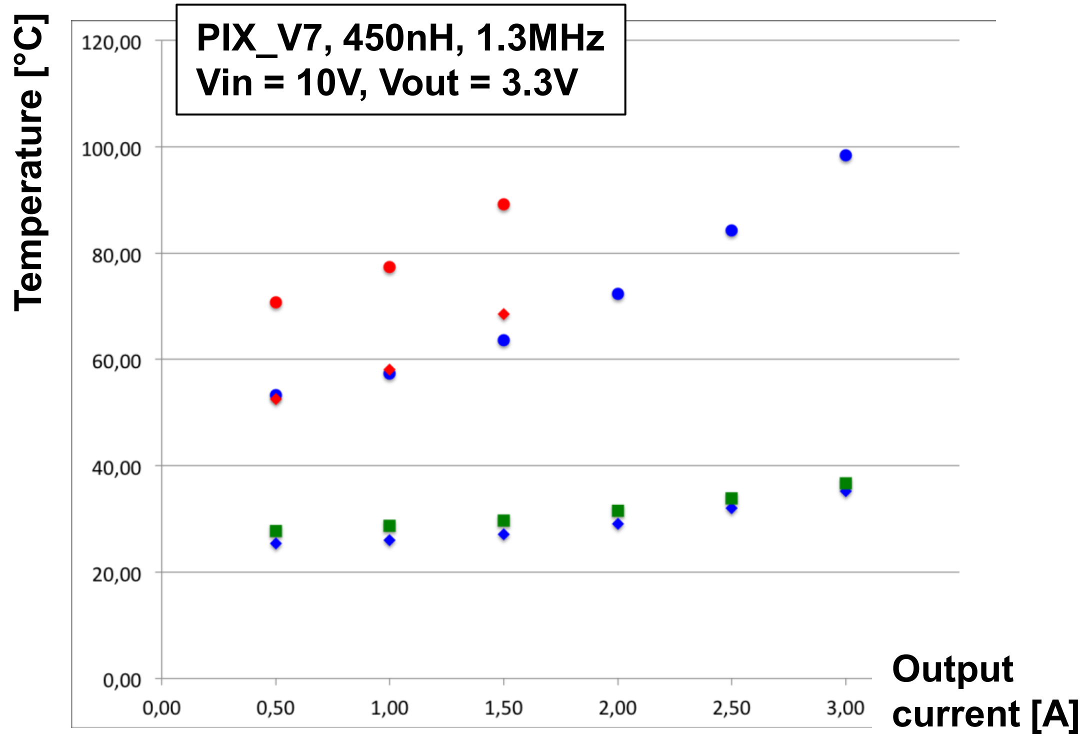






Thermal Measurements





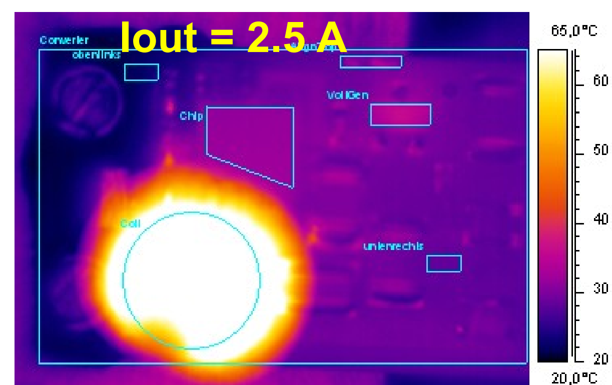
- Coil without cooling
- Chip without cooling
- Coil with cooling, no shield
- Chips with cooling, no shield
- Shield temperature

- Measurements with Flir infrared camera
- Peltier element set to +20°C

→ Cooling of chips via backside of PCB is very effective

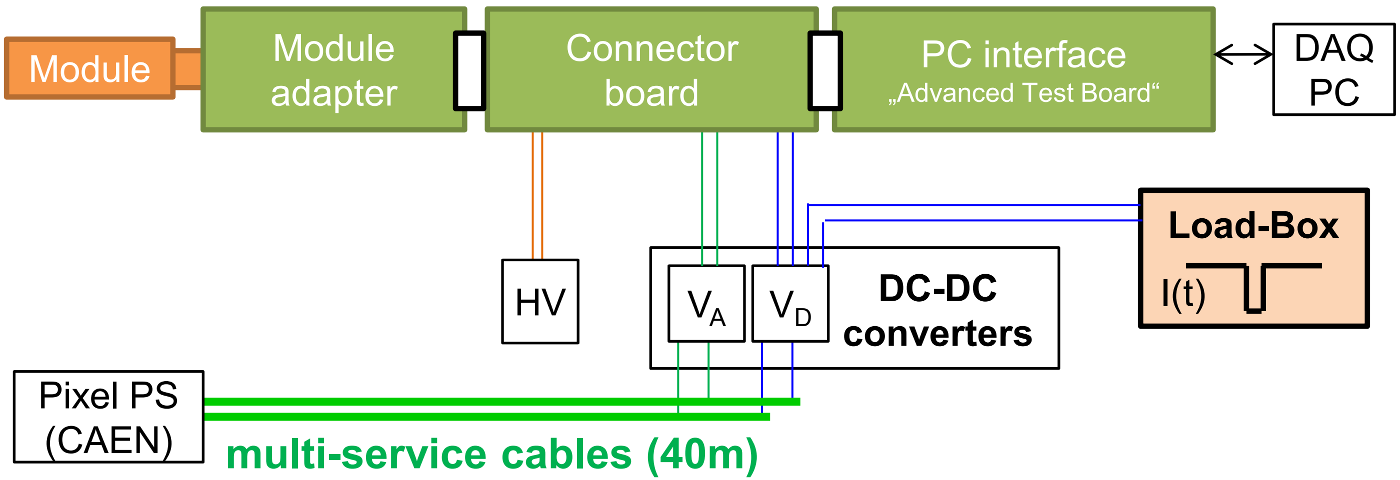
→ Coil needs to be connected to cooling contact (shield)

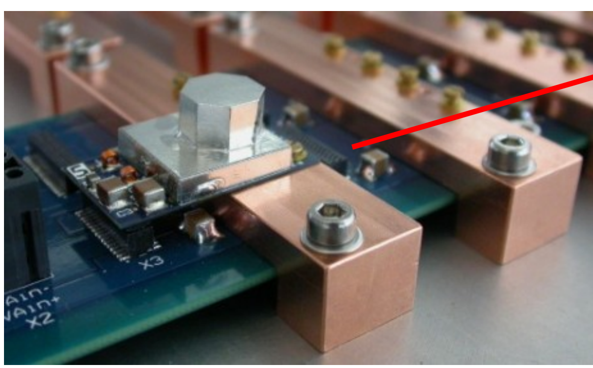
→ Good agreement with Finite Element simulations



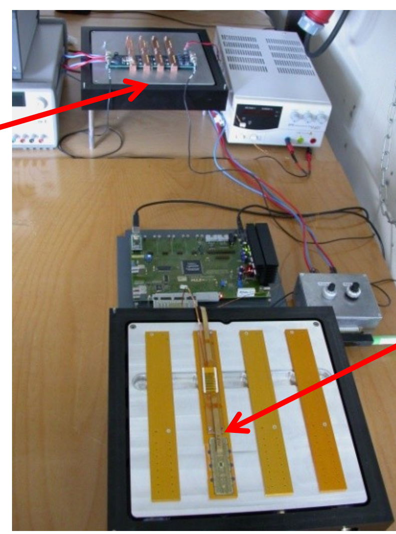
System Tests with Pixel Modules

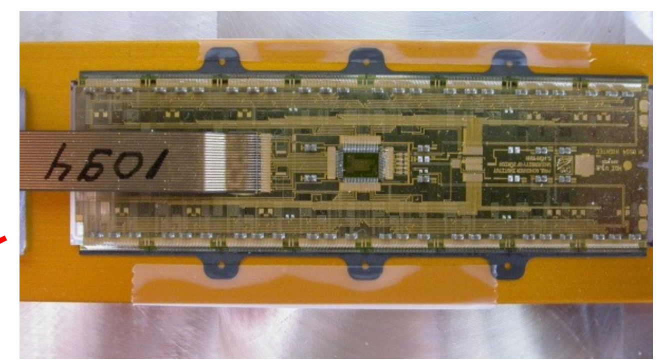
The effect of buck converters on the noise of todays pixel modules has been studied:





DC-DC converter on bus board

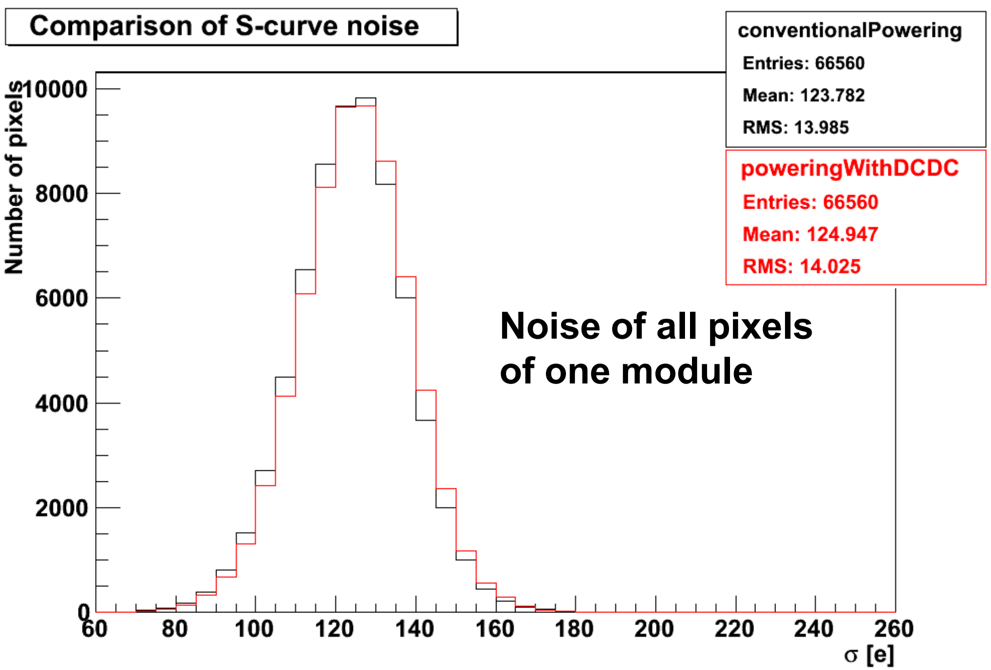


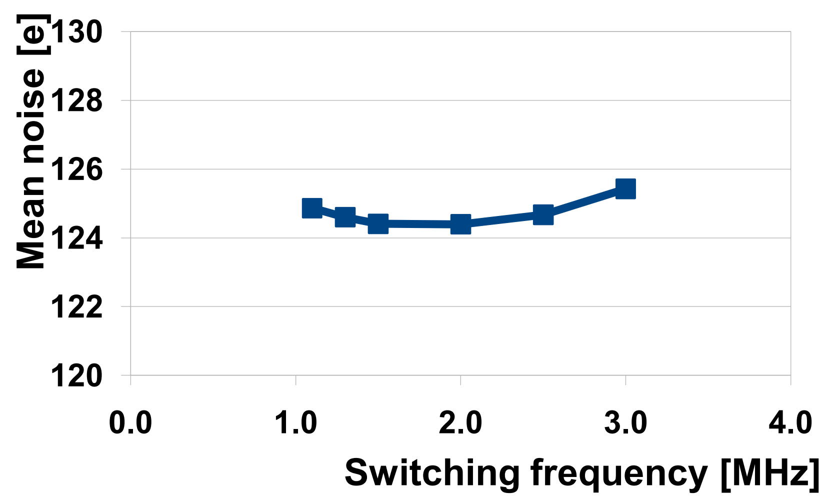


Pixel module

System Tests with Pixel Modules

- **Threshold scan**: efficiency for internal calibration pulse vs its amplitude
- Fit “s-curve“ with error function → width corresponds to noise





→ **Change in noise due to DC-DC converter is below 1%**

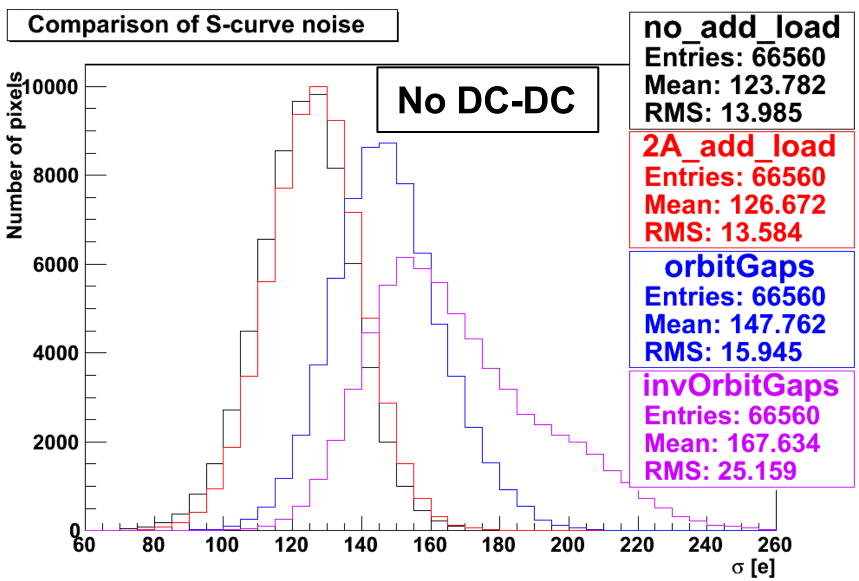
→ **Noise is flat over considered switching frequency range (1-3 MHz)**

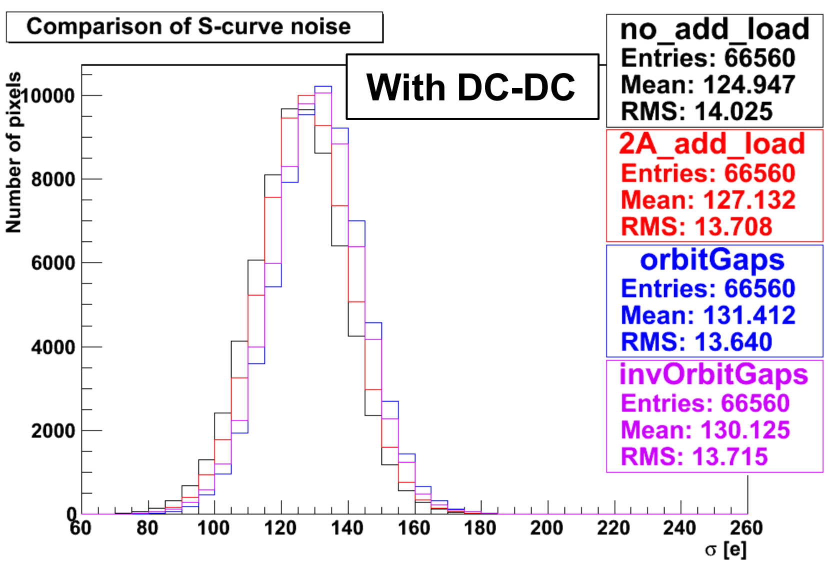
Orbit Gaps

- Sparsified readout → digital power consumption depends on particle fluence
- LHC bunches are not equally distributed: **3µs "abort gap"every 89µs is not filled**
- Digital current per converter drops within ~ 50ns from **2.7A to 1.0A** ($2 \cdot 10^{34} cm^{-2} s^{-1}$)

→ stability of power supply chain for large load variations to be checked

Result: Sensitivity to load changes with DC-DC converters much reduced





Summary

- Novel powering schemes have to be exploited for the LHC upgrades
- CMS tracker has opted for a DC-DC conversion powering scheme
- Prototypes with sufficient efficiency and low noise in hands

- Next big step: AMIS4 ASIC (expected in summer)

- Many more things to be done:
  - More realistic system tests
  - Controls
  - Mass reduction for phase-2 (e.g. aluminium coil)
  - Establish efficient scheme for larger conversion ratios (e.g. 2 stages)