Experience from design, prototyping and production of a DC-DC conversion powering scheme for the CMS Phase-1 Pixel Upgrade

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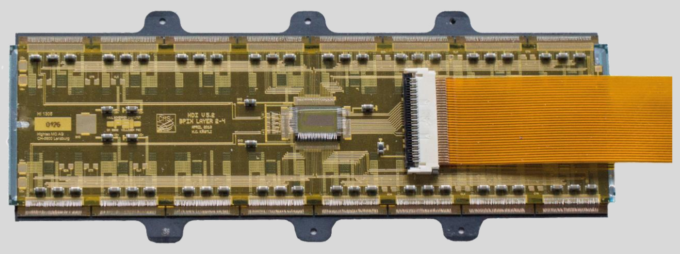
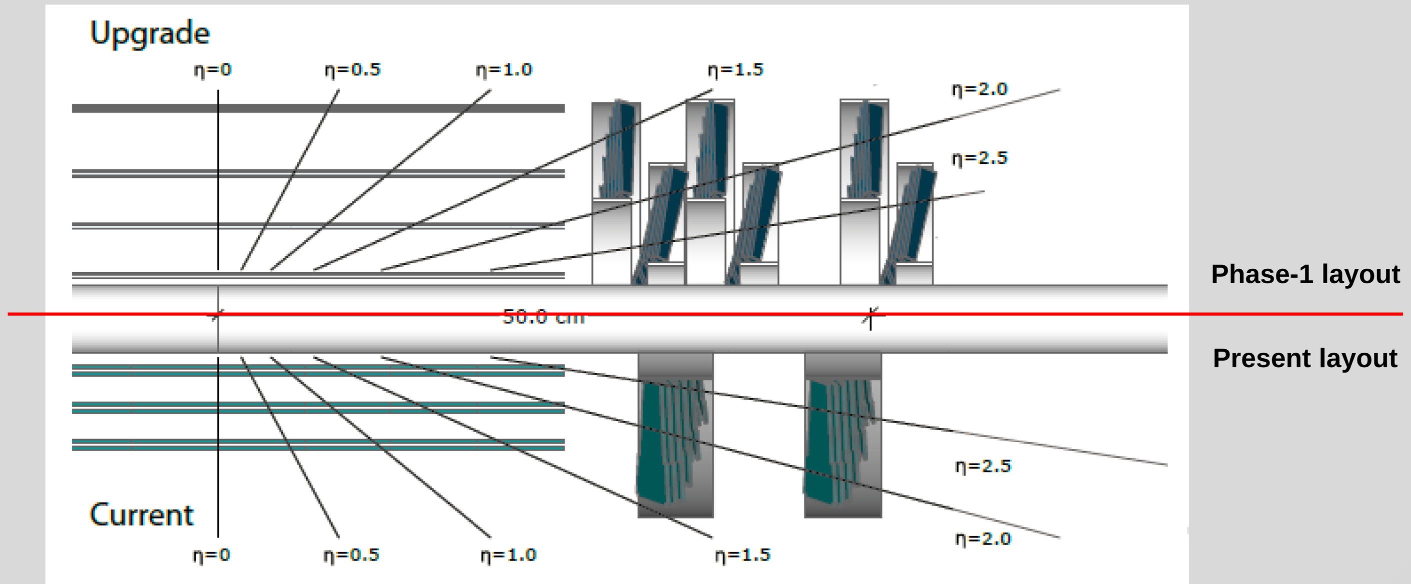
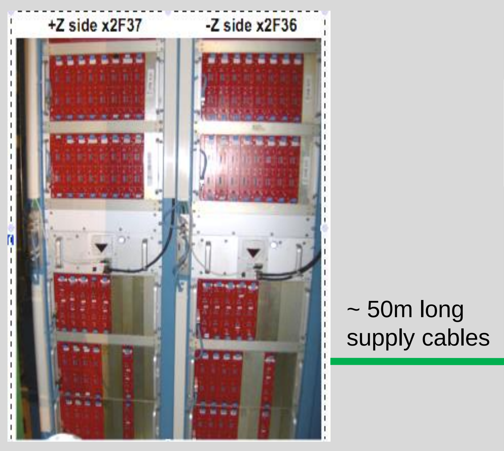
The CMS Phase-1 Pixel Upgrade

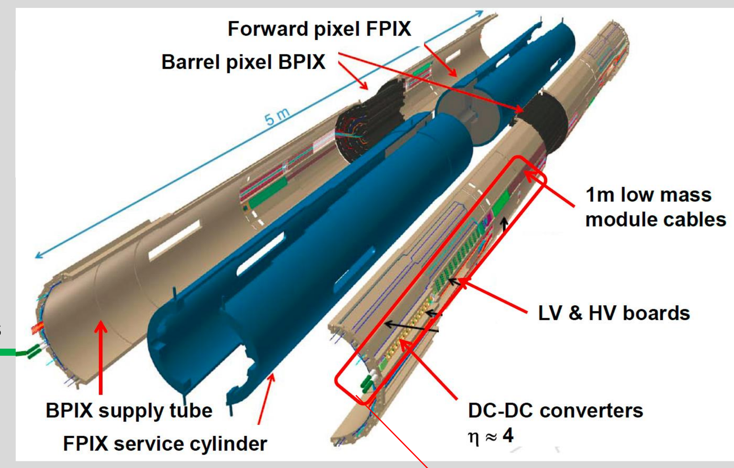
- Present pixel detector was designed for 1.0 x 10^{34} cm^{-2} s^{-1}, would suffer from inefficiency for higher instantaneous luminosities
- Upgrade during an extended technical stop 2016/2017 [1]
- Additional layers → factor 1.9 more channels → factor 1.9 higher currents → factor 3.6 larger losses on supply cables
- A DC-DC conversion powering scheme allows to power the detector with the legacy cable plant and power supplies





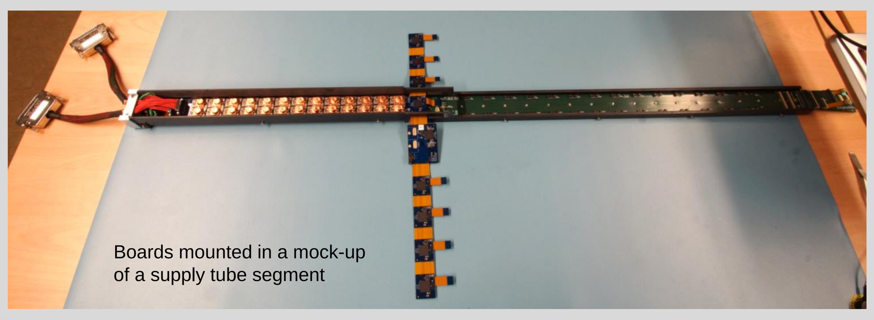
The Powering Scheme and its Implementation

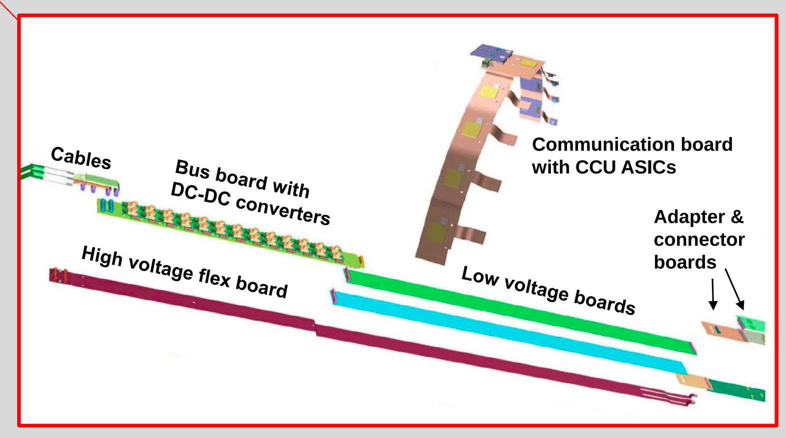




CAEN A4603 legacy pixel power supplies
- Provide 10V to the DC-DC converters
- Fast remote sensing feature removed

- DC-DC converters installed at 1-2m distance of the pixel modules, on support structures
- Pseudorapidity ~ 4, outside tracking volume
- 1200 DC-DC converters in total
- Converters deliver low voltages to the readout chip:
  - 2.4V for the analogue part
  - 3.3V and 3.5V for the digital part
- One pair powers 1 to 4 pixel modules (1-2A)





The DC-DC Buck Converters for the CMS Phase-1 Pixel Detector

- A = 2.8 x 1.7cm^2
- m = 3.0g
- 2-layer PCB

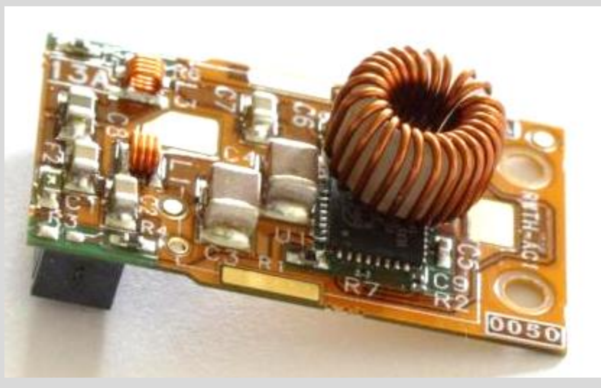
- **Radiation-tolerant FEAST2 ASIC [2] by CERN**
  - Enable feature
  - Status bit "Power good"
  - Protection features
  - Switching frequency set to 1.5MHz

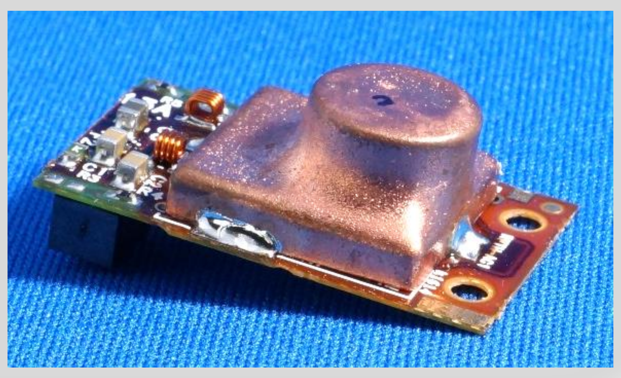
- **Toroidal inductor**
  - L ≈ 430nH
  - To be soldered by hand

- **SMD components** for noise filtering, voltage divider etc.
  - Smallest size: 0201

- **Electro-magnetic shield**: plastic core with 60µm copper outside
  - Filled with thermal grease
  - To be soldered by hand
  - Shorts with SMD components to be avoided

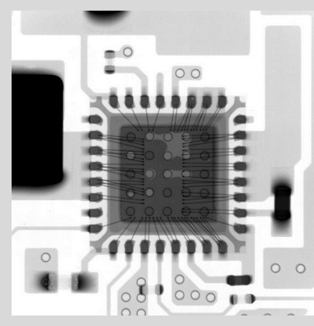
Several years of R&D and prototyping [3].

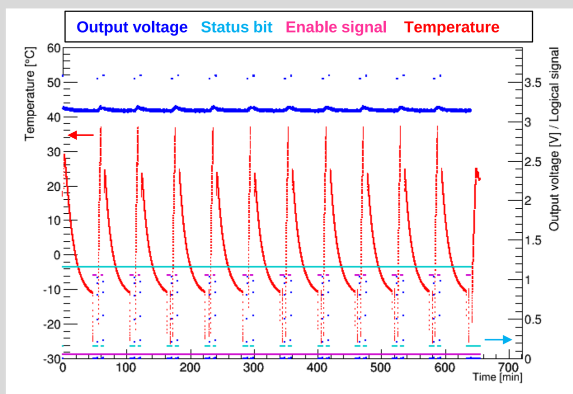


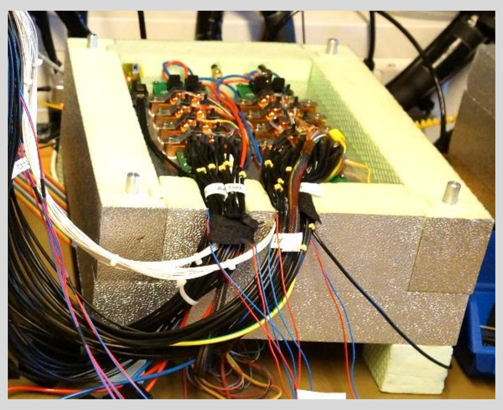


Production Steps, Quality Assurance & Control

- Production of the PCBs → optical inspection
- Production of coils in China; sorted into inductance classes
- Production of shields in Germany
- Assembly at a company, including hand-soldering of the coil and shield
  - Automated Optical Inspection
  - High-resolution X-ray imaging of all samples
  - 10 passive thermal cycles between -30°C and +60°C
- **Electrical test** (output voltage, status bit, enabling)
  - Done twice: before and after shield mounting
- Micrographs of a few samples
- **Thermal cycling**: 10 cycles between -28°C and +20°C
  - Converters are powered and deliver I_{out} = 3A
  - Monitoring of voltage, status bit and temperature
  - 16 DC-DC converters per test, duration ≈ 10 hours
  - Throughput ≈ 80 DC-DC converters per week

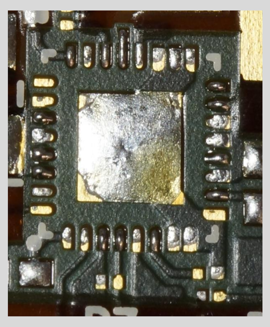






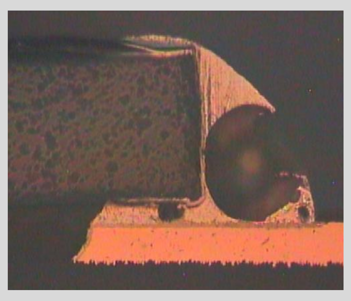
Issues during Pre-Production & Production

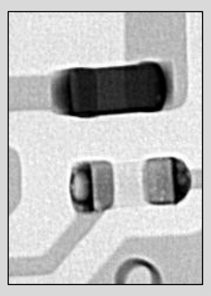
Solder deposition failed during a pre-production run
- Spotted only during thermal cycling, e.g. due to converters switching off after several cycles
- Not spotted by low resolution X-ray test, nor optical inspection → change of assembly company, and assembly of production boards according to IPC-A-610D (Class 3)



Voids in solder of 0201 SMD components
- Spotted in micrographs
- Not spotted in X-ray images, since originally passives only X-rayed in 10% of samples
- Caused by bad resistor quality

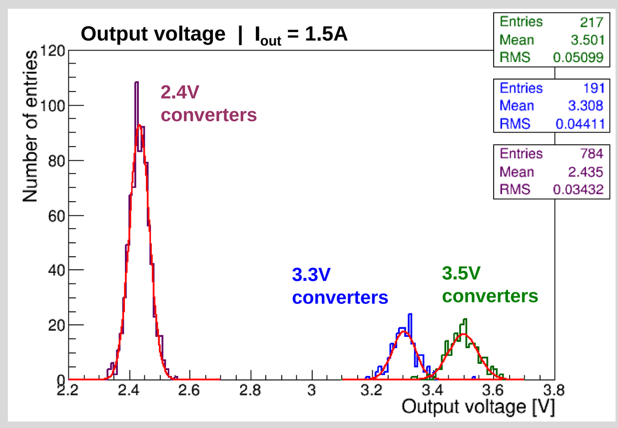
→ Resistor producer changed, and X-ray test of full boards performed on 100% of samples

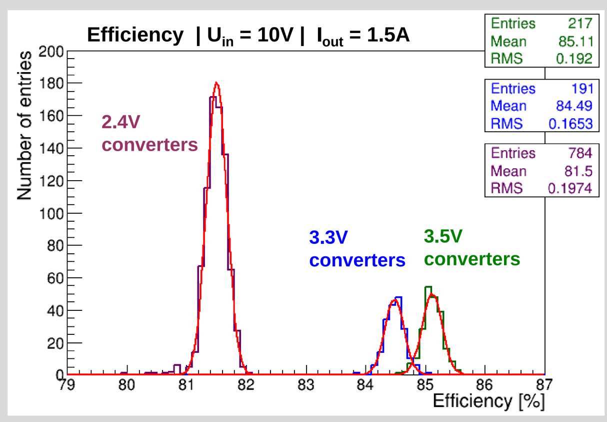


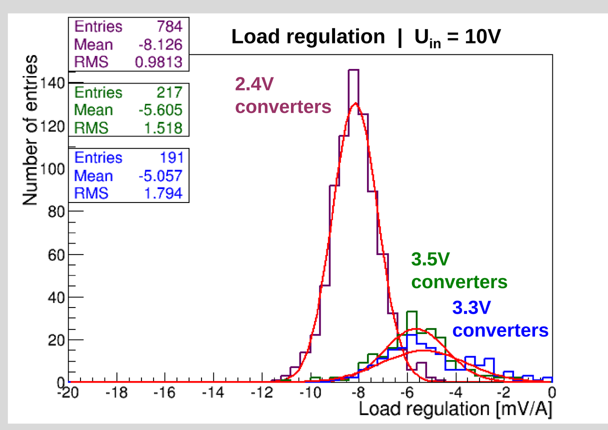


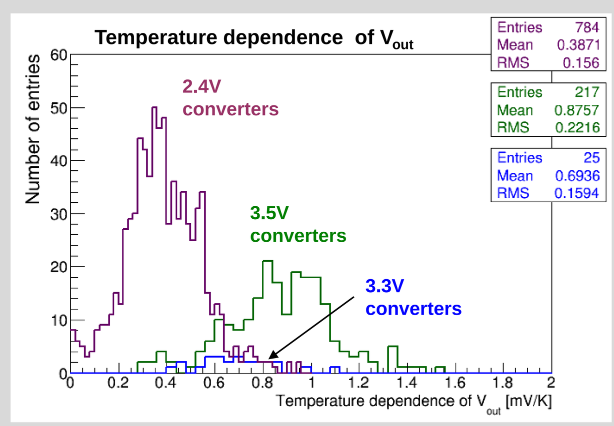
Mass Production: Status and Results

- 1800 DC-DC converters have been produced
- 1200 DC-DC converters fully tested so far - yield is 87%
  - Vast majority: faulty status output of the (non-tested) ASIC
  - Only 8 DC-DC converters with other problems (short in chip, V_{out} very low/zero, very high or unstable)
  - 24% of faults have been found during thermal cycling!
- Efficiency η = P_{out} / P_{in} is high and uniform
- Spread in output voltage is σ ≈ 35-50mV
  → converters are classified by output voltage



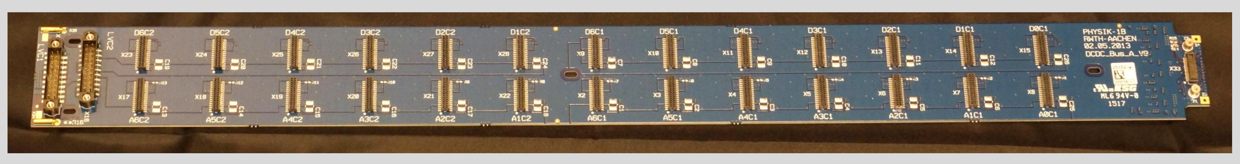






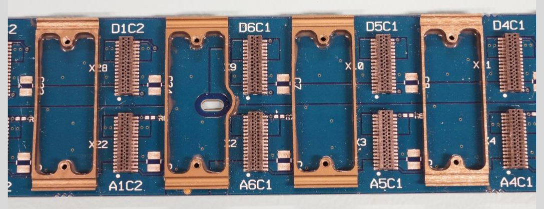
Electro-mechanical Integration: DC-DC Bus Boards

- Distribution of input and output voltages, status and enable signals
- 13 pairs of DC-DC converters per motherboard → dense 8 layer PCB

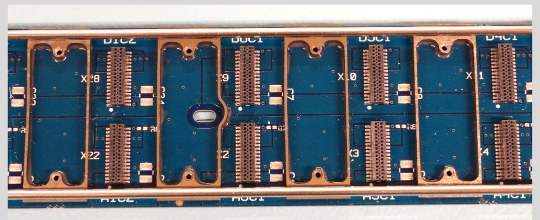


- Up to 2W of heat load per DC-DC converter, to be removed by the CO_2 cooling system
- Two-piece aluminium cooling bridges; lower pieces glued to the DC-DC bus boards (520 pieces)
- Bridges need to be anodized to isolate the converters from the grounded pipes (avoid ground loops)

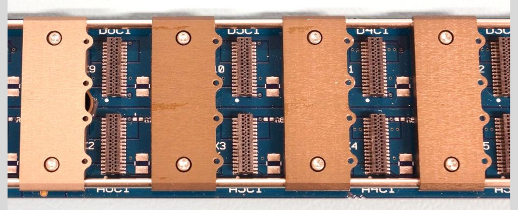
Step 1: Lower pieces are precisely aligned with respect to connectors, and glued to the bus boards



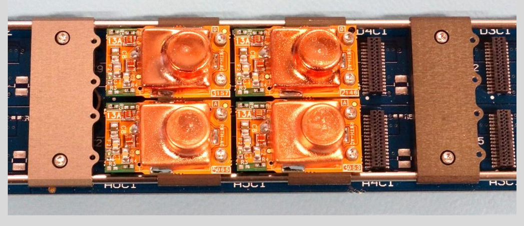
Step 2: During installation, CO_2 pipes are layed in



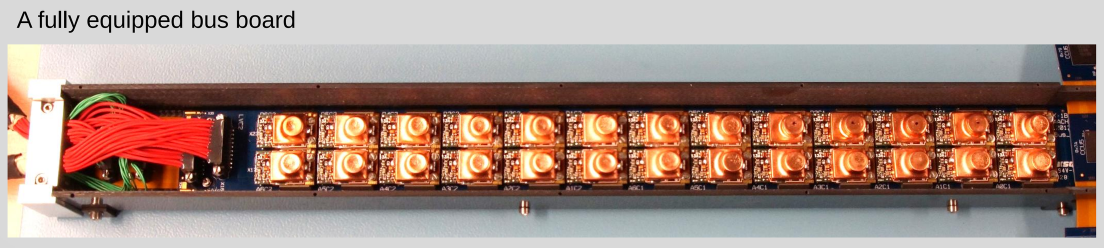
Step 3: Upper pieces are screwed to lower pieces



Step 4: DC-DC converters are screwed onto bridges

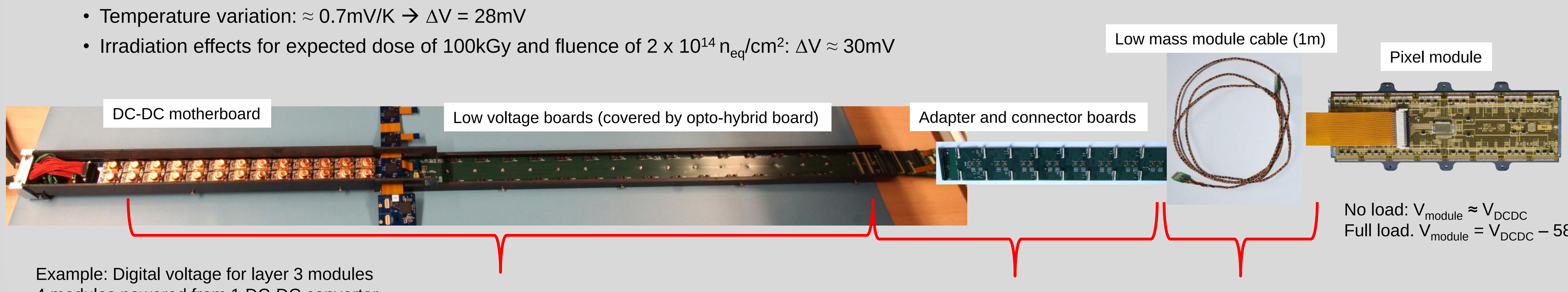


A fully equipped bus board



A Challenging System Feature: Large, Load-dependent Voltage Drops

- DC-DC converters do not feature remote sensing; output voltage is regulated locally, and cannot be adjusted in-situ
- DC-DC output voltages must be carefully chosen: too low → pixel modules will not work; too high → risk of damage for zero load
- Up to 2m distance between DC-DC converters and pixel modules → large, load-dependent voltage drops have to be precisely known and taken into account
- In addition:
  - Spread of output voltage: 1σ ≈ 35-50mV
  - Load regulation: up to -10mV/A
  - Temperature variation: ≈ 0.7mV/K → ΔV = 28mV
  - Irradiation effects for expected dose of 100kGy and fluence of 2 x 10^{14} n_{eq}/cm^2: ΔV ≈ 30mV



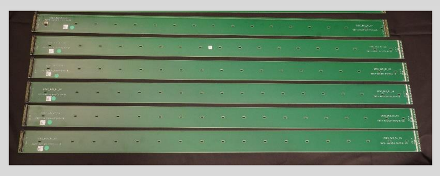
No load: V_{module} ≈ V_{DCDC}
Full load: V_{module} = V_{DCDC} – 580mV !

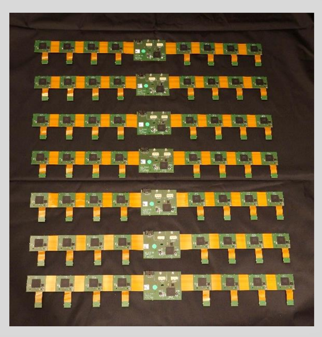
Example: Digital voltage for layer 3 modules
4 modules powered from 1 DC-DC converter
Idig = 2.44A

ΔV = 210mV — ΔV = 148mV — ΔV = 216mV

Next Steps

- Mass production of DC-DC converters until November 2015. Power board production finished.
- Installation of boards and DC-DC converters into the pixel support structures starts December 2015
- Installation in CMS during extended winter technical stop 2016/2017





References

[1] CMS Collaboration, *CMS Technical Design Report for the Pixel Detector Upgrade*, CERN-LHCC-2012-016 (2012).
[2] http://project-dcdc.web.cern.ch/project-dcdc/
[3] L. Feld, W. Karpinski et al., *The DC-DC conversion power system of the CMS Phase-1 pixel upgrade*, 2015 JINST 10 C01052.

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