DEVELOPMENT OF A DC-DC CONVERTER FOR THE MU3E EXPERIMENT

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MU3E COLLABORATION

DPG FRÜHJAHRSTAGUNG

DORTMUNG 2021

3/15/2021

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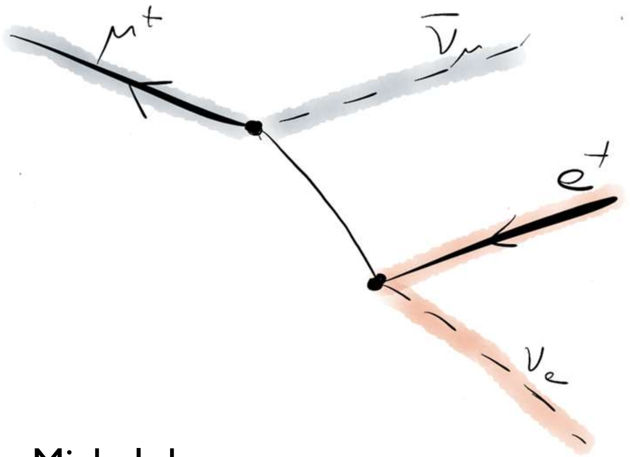
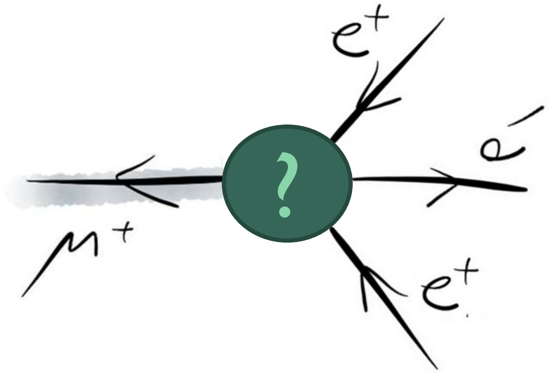
THE MU3E EXPERIMENT

MOTIVATION



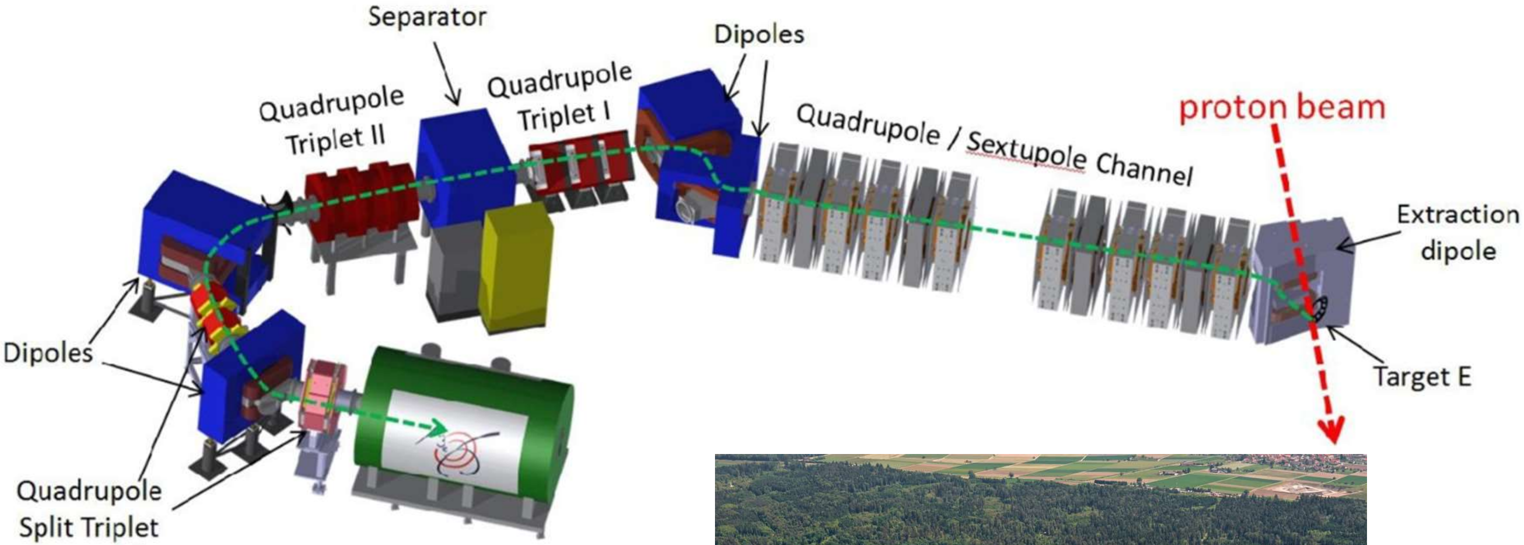
Theories of physics beyond the standard model



Michel decay

- Branching ratio nearly ~100%
- μ → eee suppressed in the standard model
  ⟹ lepton flavour violation

THE EXPERIMENT



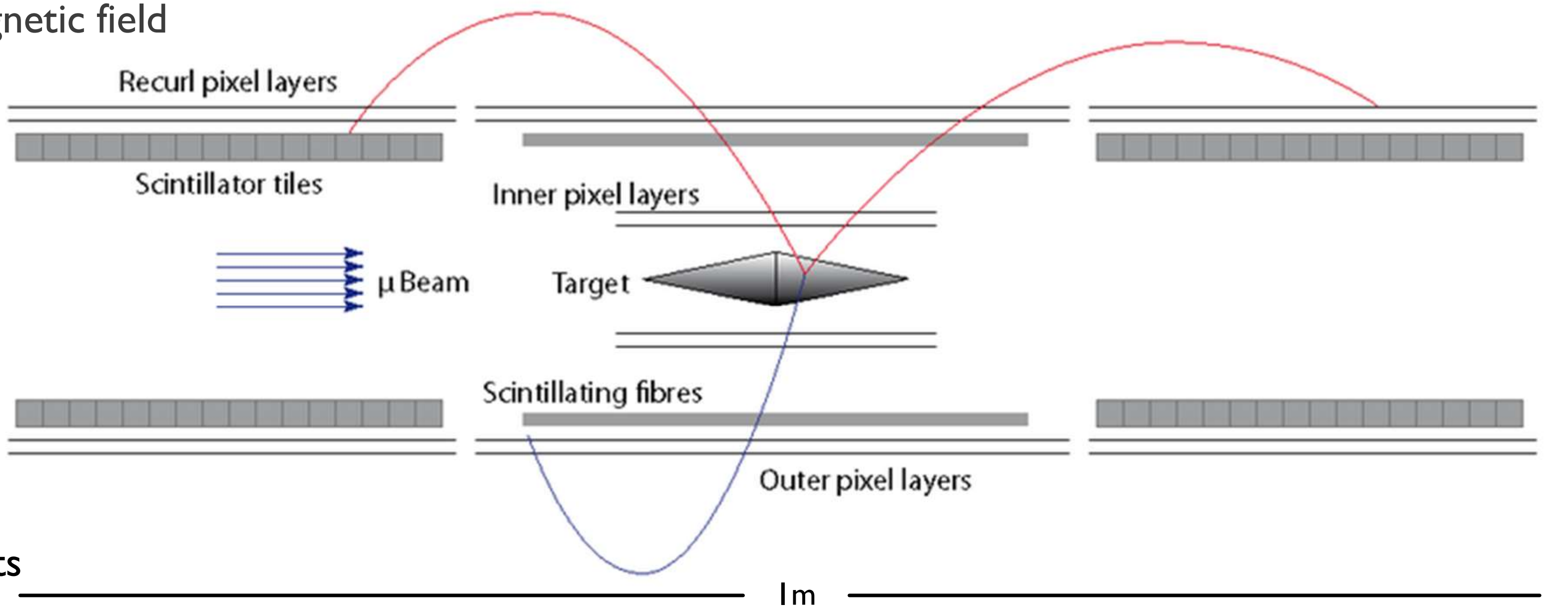
Phase I

- Muon beam: $10^7 - 10^8$ muons/seconds
- Sensitivity goal: B(μ→eee) ≤$2 \cdot 10^{-15}$

Paul Scherrer Institute, Villigen, Switzerland

THE DETECTOR

- Placed inside a 1T strong magnetic field
- Three detector subsystems

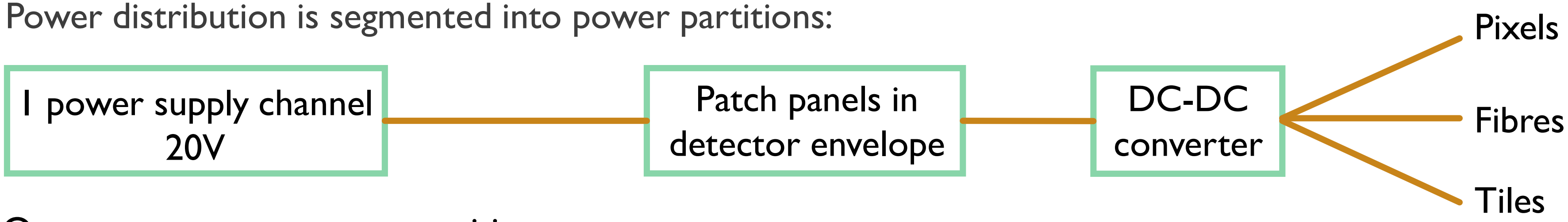


- Pixel detector (MuPix sensors)
  - Accurate track and vertex reconstruction
- Scintillating fibres
- Scintillating tiles

Exact timing measurements (scintillating fibres and tiles)

POWER REQUIREMENTS

- Relatively low voltages required by the detector components (1-3.3V)
- Cables are very long → high losses through the cables
- Thicker cables are not possible according to size
- Solution: DC-DC converters close to the detector parts step a 20V input power down to the required value
- Power distribution is segmented into power partitions:



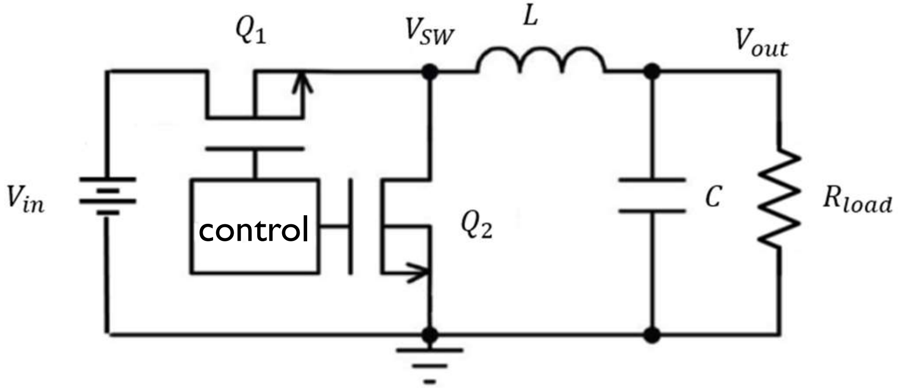
- One converter per power partition
- 126 in total → 10kW in total

Further talk about the mu3e power distribution:
Wed. 16:00 T66.1 Lucas Sebastian Binn

THE MU3E DC-DC CONVERTER

LAB MEASUREMENTS & TEST BEAM RESULTS

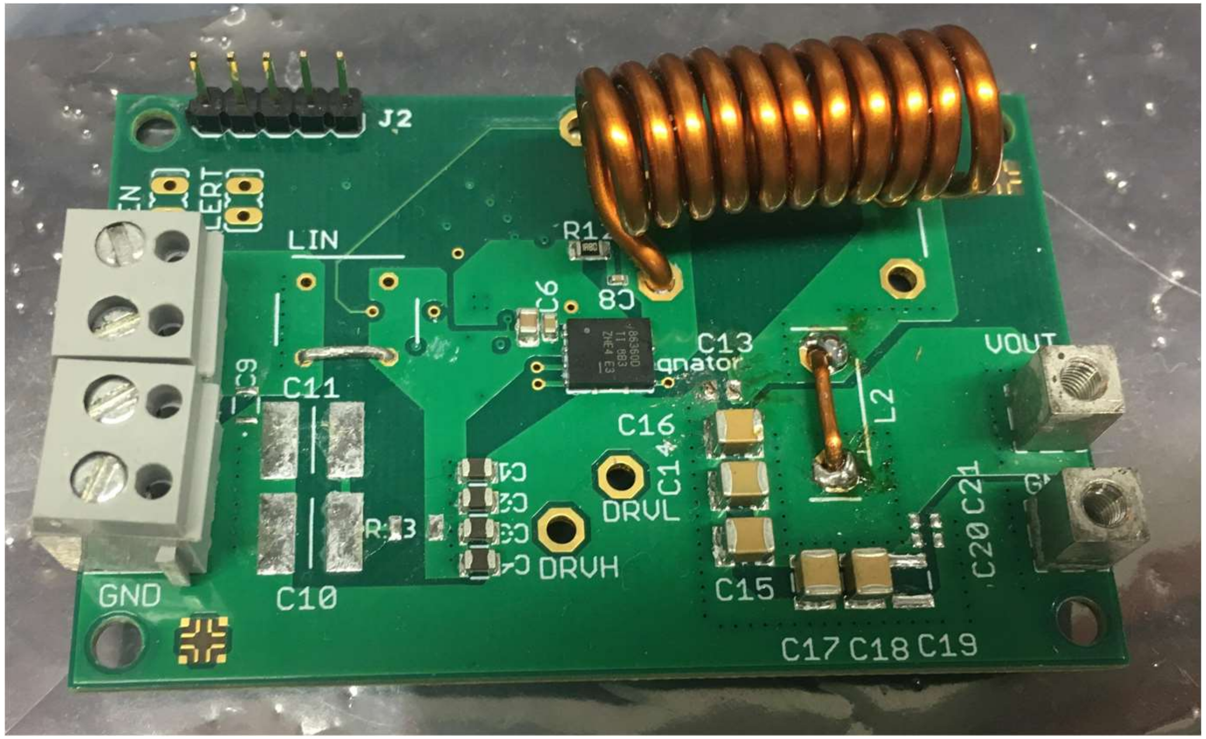
A SYNCHRONOUS BUCK CONVERTER



- Not regulated DC input voltage is converted into a regulated DC output voltage
- Regulation is derived from high-frequency switching of two MOSFETs
  - → Producing a rectangular voltage
- Output signal is smoothed by a coil und capacitors
- Switching behaviour is synchronised to prevent short circuits ➡ **synchronous buck converter**

DC-DC CONVERTER FOR MUPIX & MUTRIG

- Vin = 20V
- Vout = 2.1V
- L = 0.55µH
  - Air coil
- C = 22µF
- fswitch = 1MHz
- Efficiency: 87.0% at 20A



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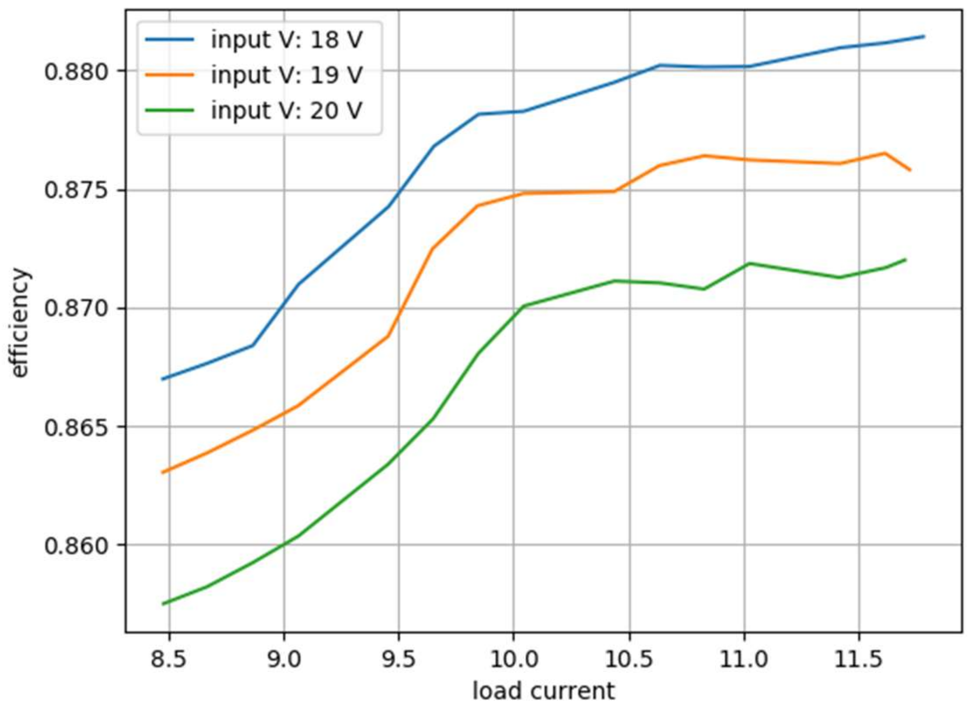
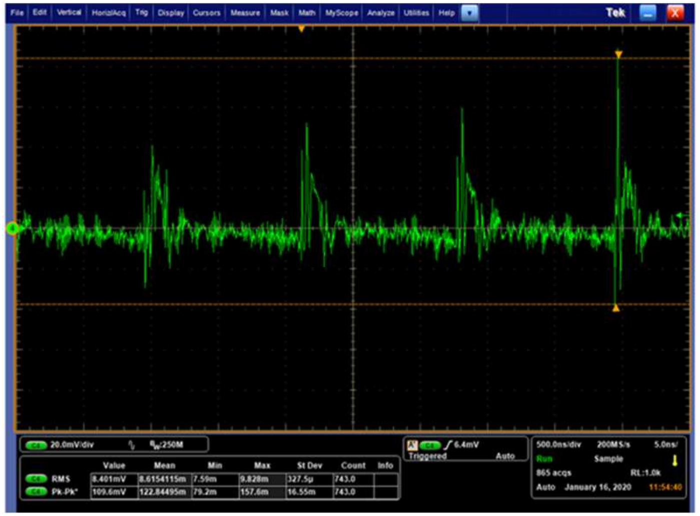


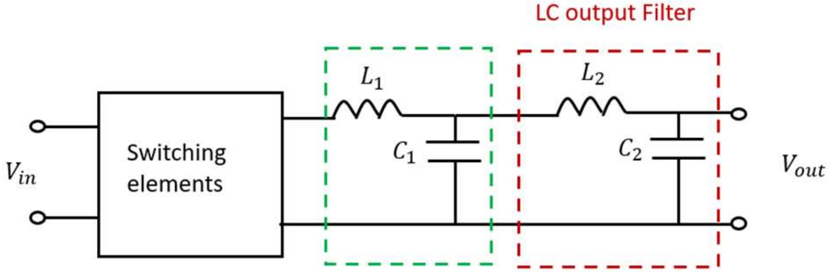
OUTPUT SIGNAL & FILTERING

- V_{in} = 20V
- V_{out} = 2.1V
- I_{out} = 5A
- f_{sw} = 1MHz

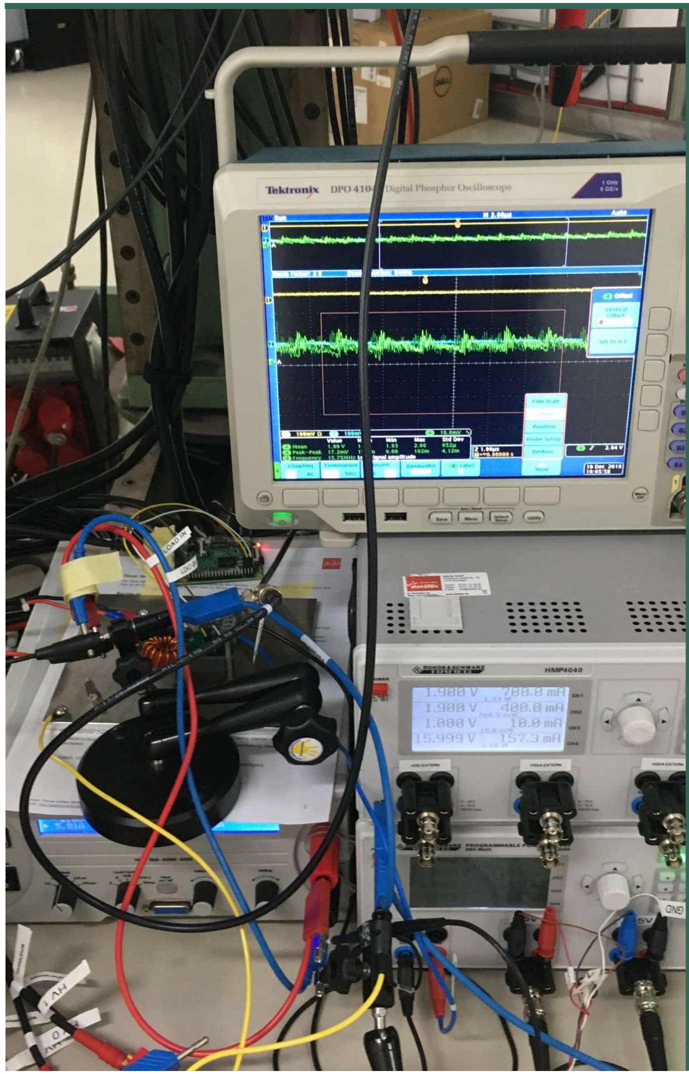


- Ripple height: ~30mV
- Goal: ≤10mV

⟹ Output filter required

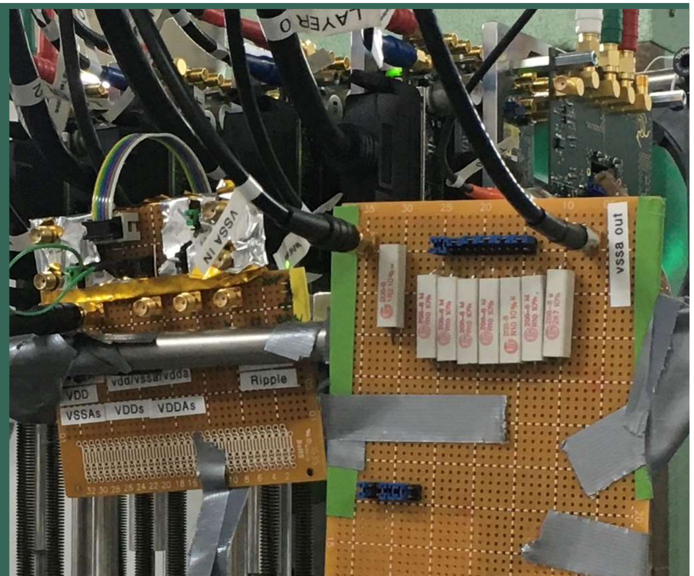


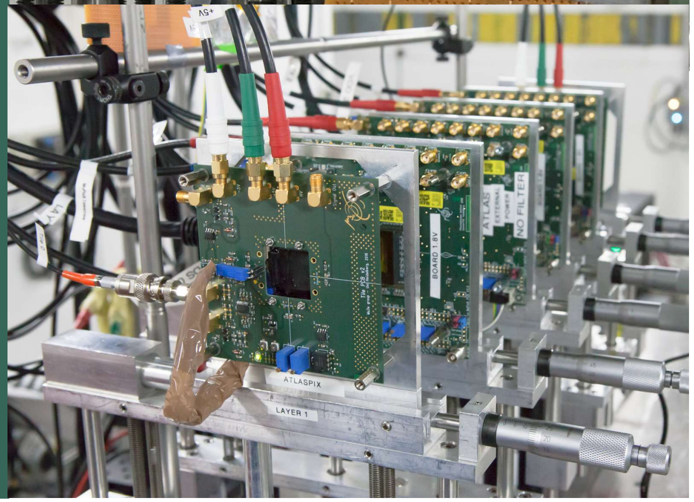
- Ripple height: ~15mV
  ⟹ reduction of 50%

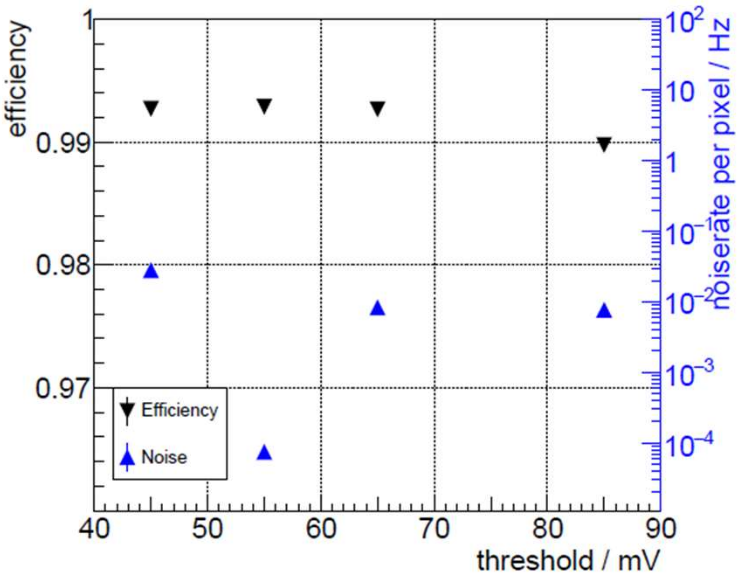


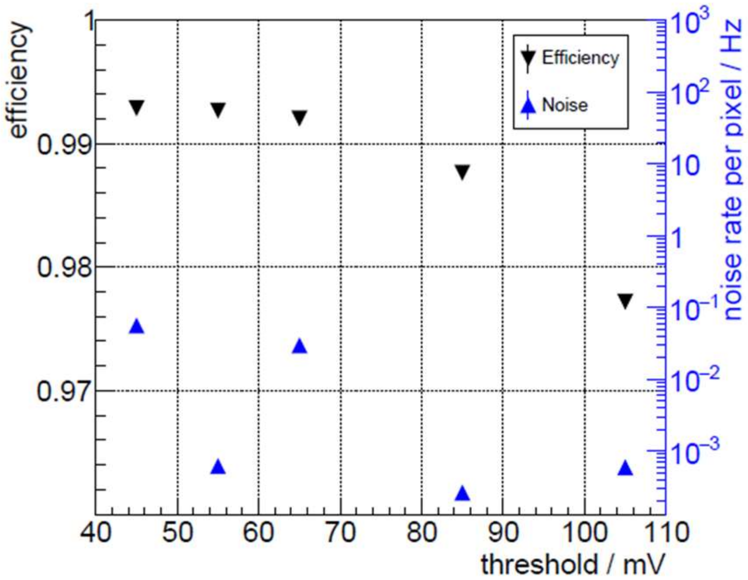
TEST BEAM SET UP

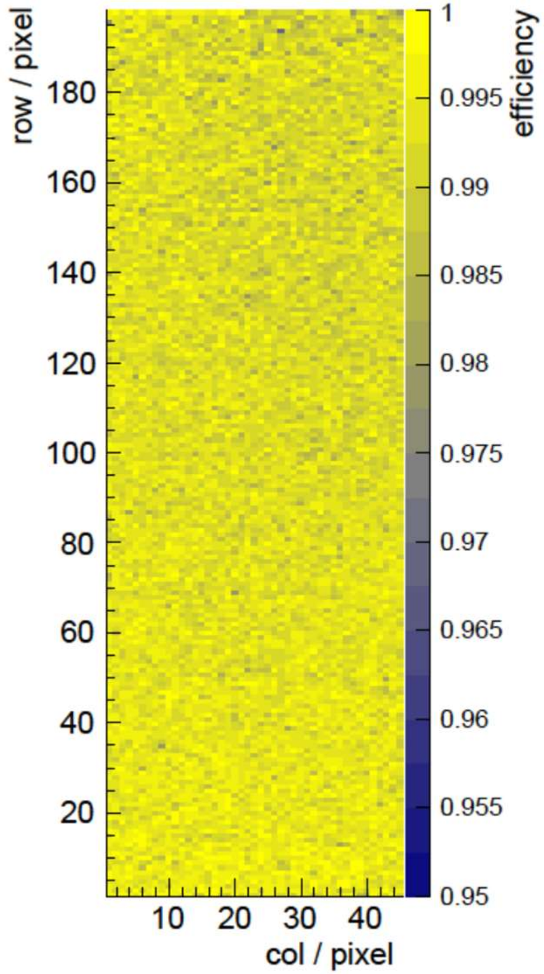
- Powering of a MuPix sensor
- Sensor placed in a MuPix telescope
- Converter supplied with 20V
- Controlled by a Raspberry Pi
- Determine efficiency and noise level
  - Threshold scans
- Signal in a pixel is just registered if its level is above a certain threshold
- Scans with and without a second filter











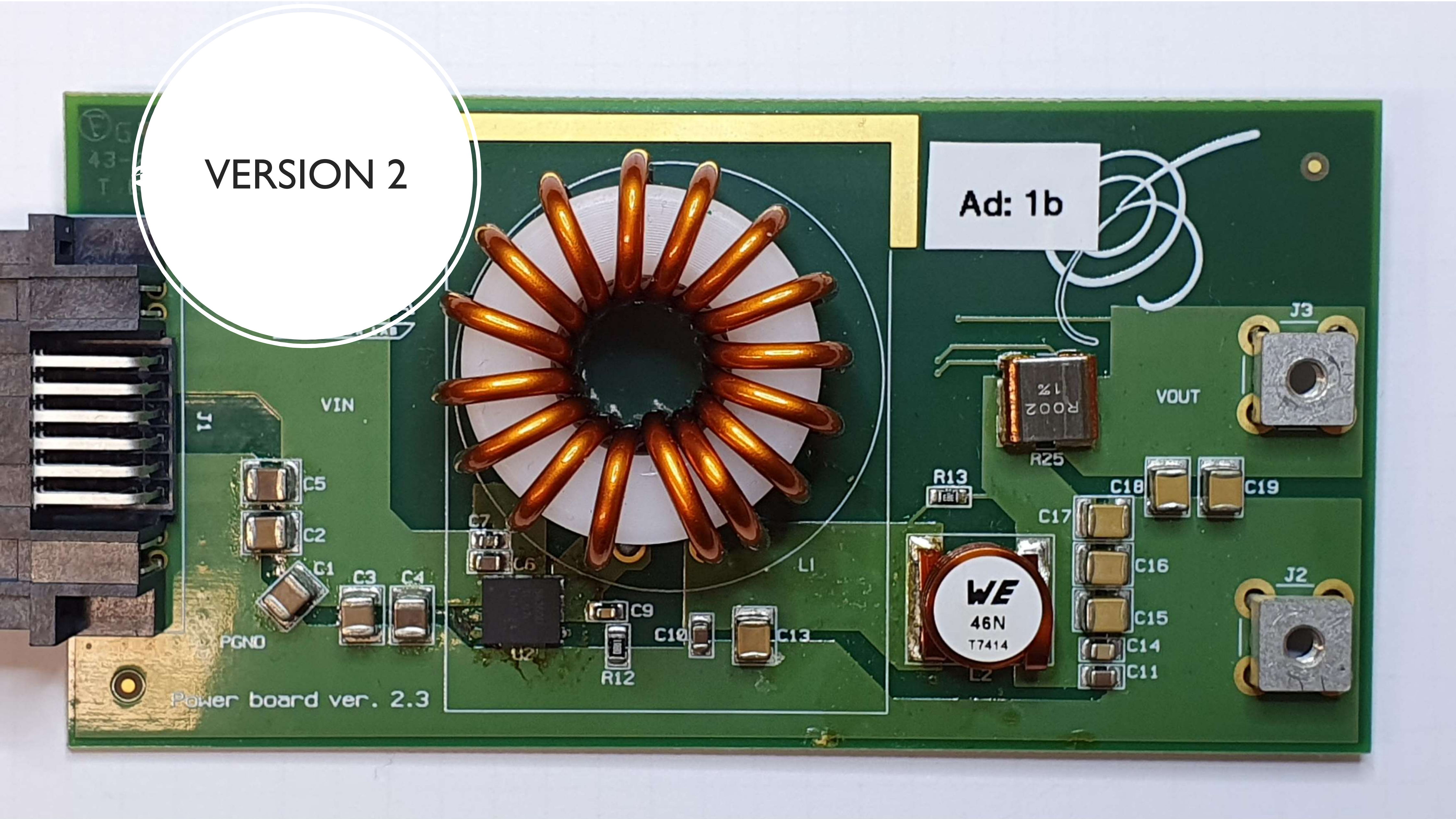
TEST BEAM RESULTS

- Efficiency: 99.3%
- Noise always below 1Hz
- No patterns in the efficiency map
- No difference between the two converters configurations

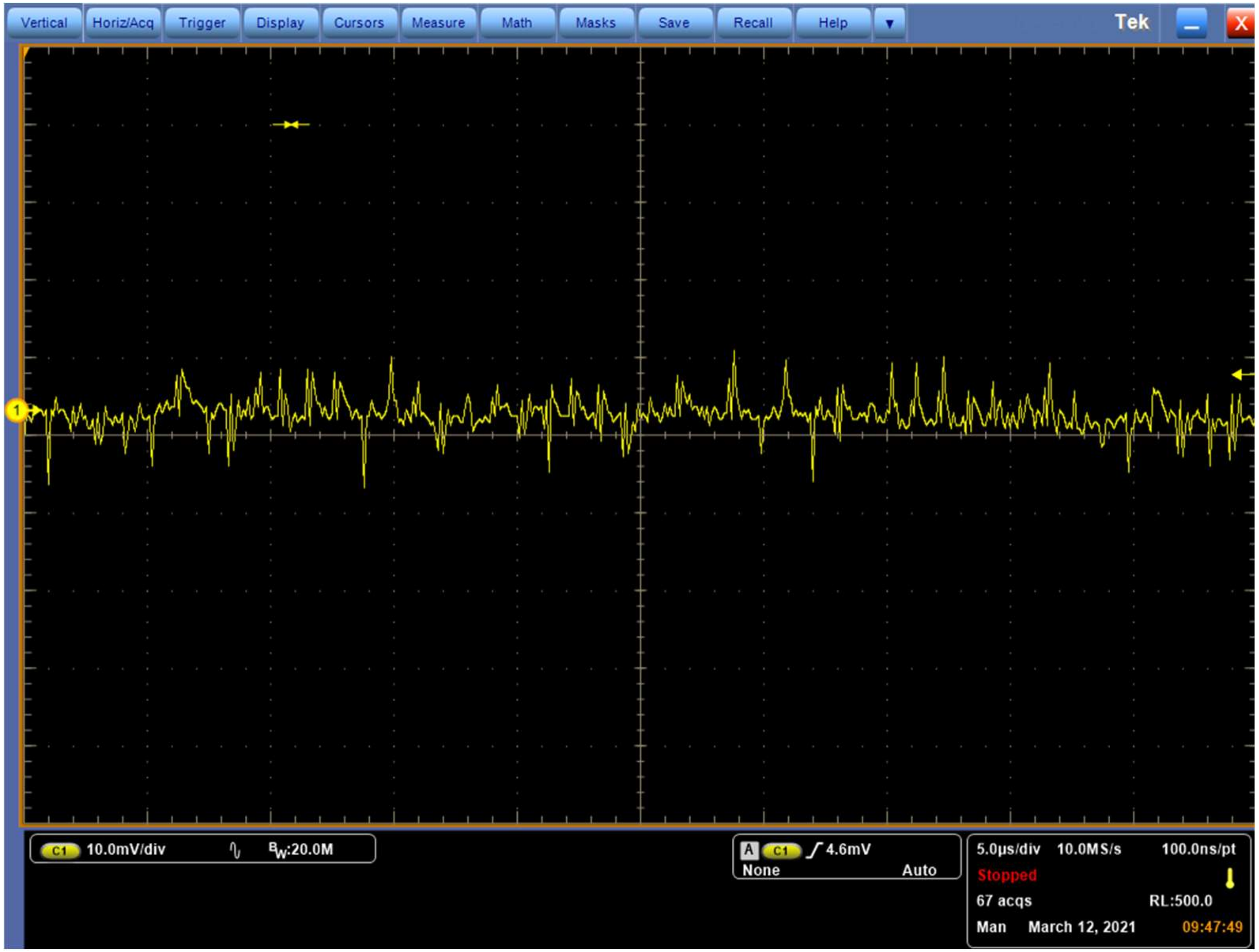
THE SECOND VERSION

IMPROVEMENTS & NEW FEATURES

VERSION 2



Ad: 1b
VIN
VOUT
PGND
J1
J2
J3
L1
L2
C1
C2
C3
C4
C5
C6
C7
C9
C10
C11
C13
C14
C15
C16
C17
C18
C19
R12
R13
R25
R002
1%
WE
46N
T7414
Power board ver. 2.3



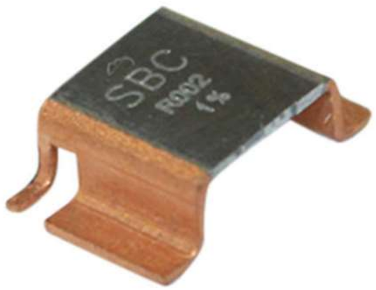
OUTPUT SIGNAL

CURRENT SENSE MEASUREMENT

- Monitoring the current of the converter

  → voltage drop across a shunt resistor is measured

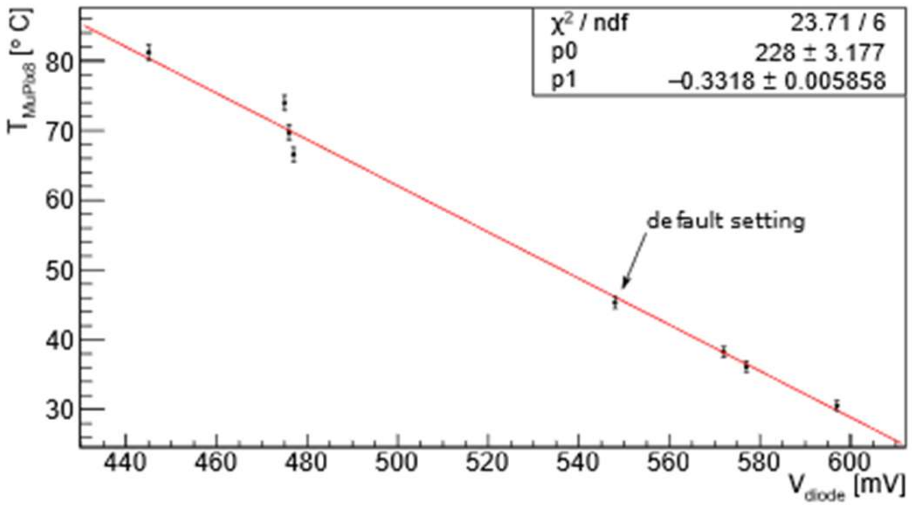
  → the voltage drop can be converted in the corresponding current



- Instrumentation amplifier: INA326, Texas Instruments
- Voltage drop of 50mV selected
- At 20A: 2.5mΩ shunt resistor → 2W power dissipation
- Read out by ADCs
- Tested and working stable

TEMPERATURE INTERLOCK SYSTEM

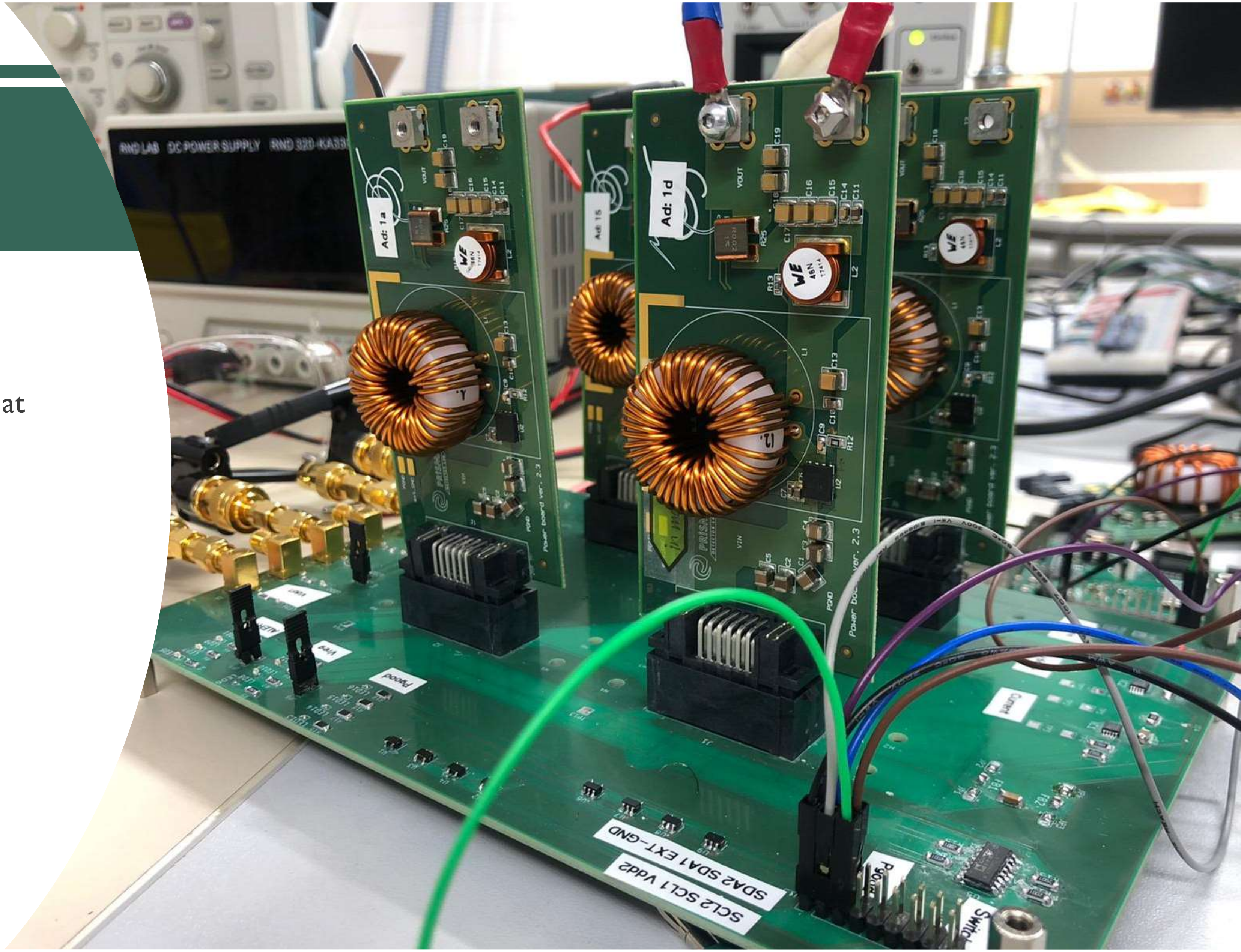
- High power means strong heat development
- Complete detector must be cooled
- System to make sure the detector is running just when the cooling system is on
- Therefore the MuPix temperature diode is used
- Temperature rises → converters are switched off



$$T_{MuPix} = 228.0°C - 0.332°\frac{C}{mV} \cdot V_{bias,diode}$$

BACKPLANE

- Controlling of 4 converters at the same time
- Later 16 boards
- Monitoring of all relevant voltages via ADCs



CONCLUSION & OUTLOOK

The new features of the second version of the mu3e DCDC converter are working

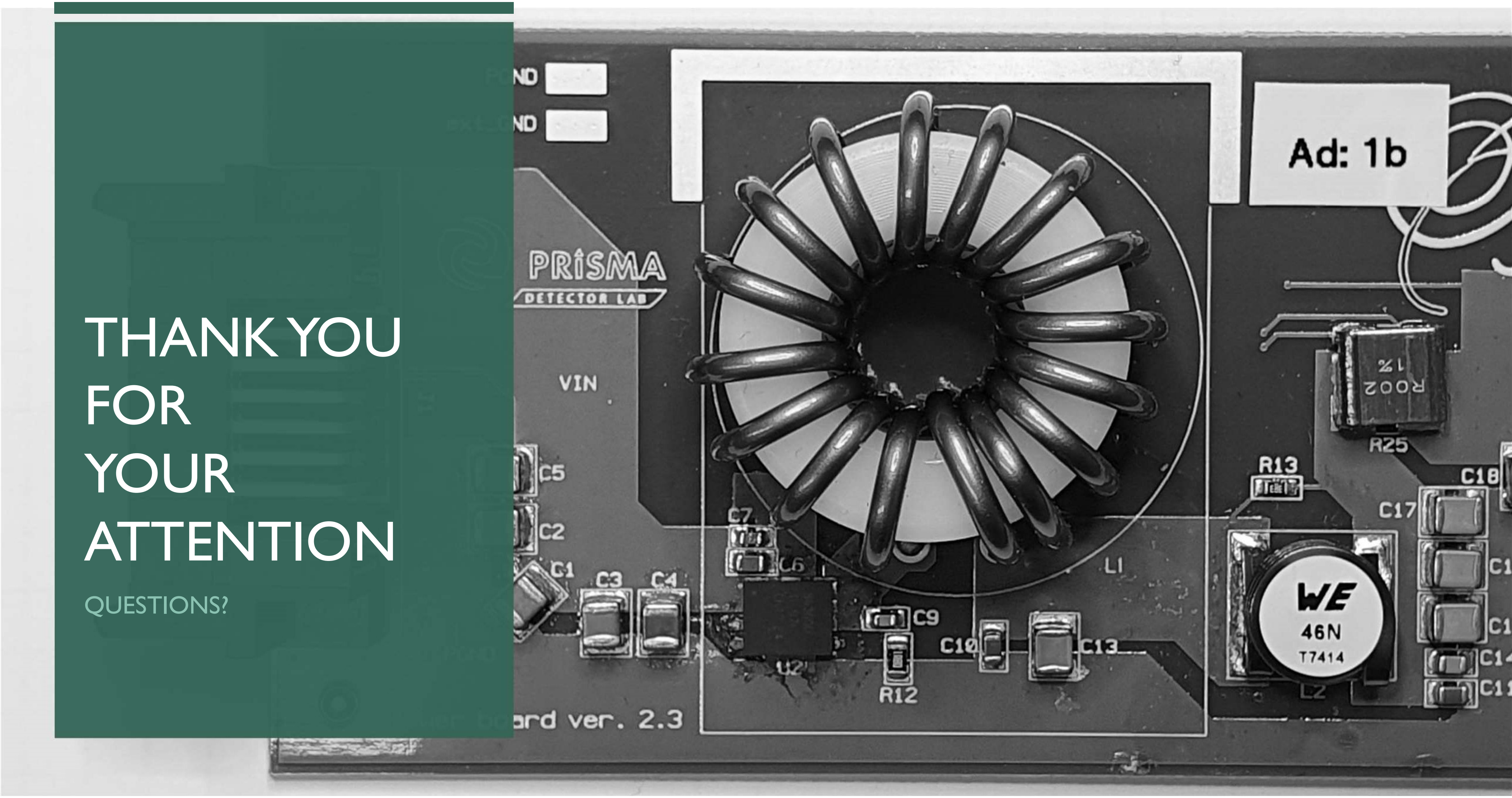
Test beam with several MuPix sensors powered by the converters

Behaviour at full load (20A)

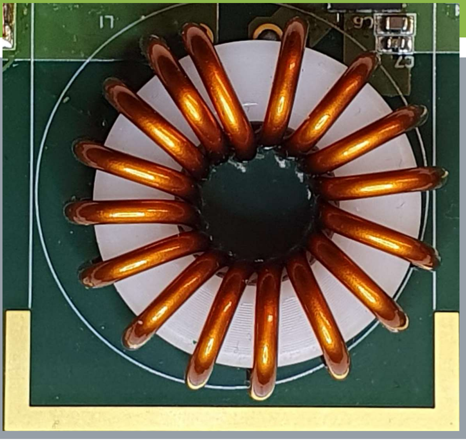
Cooling system needs to be tested (already designed)

THANK YOU FOR YOUR ATTENTION

QUESTIONS?

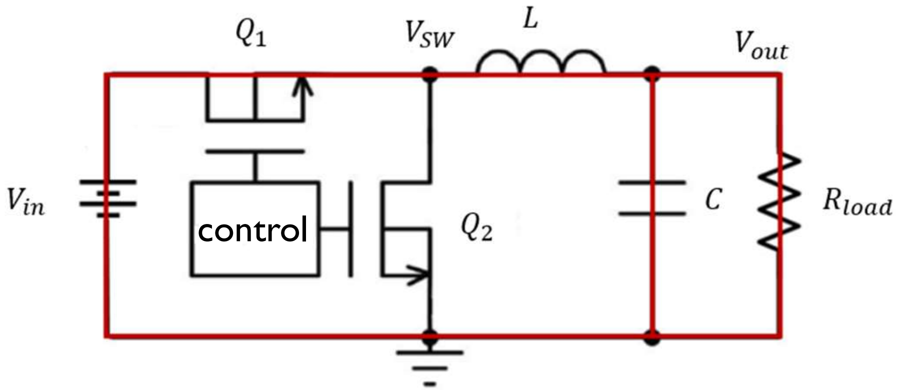


THANK YOU FOR YOUR ATTENTION

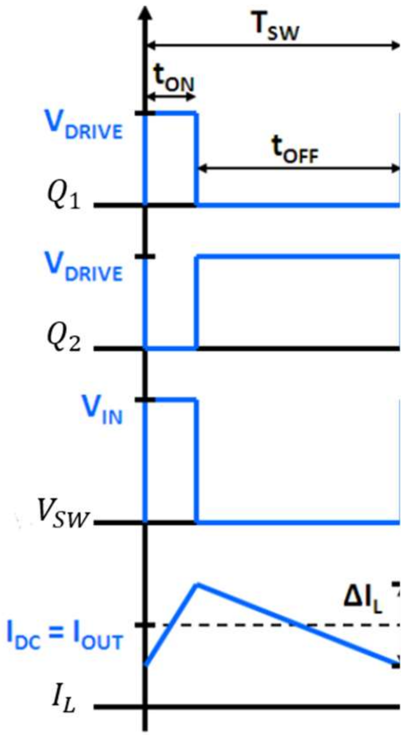


WORKING PRINCIPLE

Phase 1: Q_1 is on and Q_2 is off for a time t_{on}

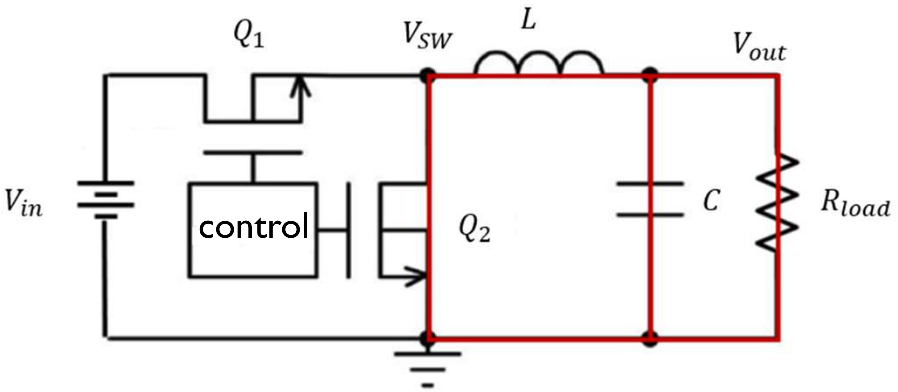


- Current through the coil increases linearly
- The coil provides the current for the load
- The excess current is stored in the capacitor

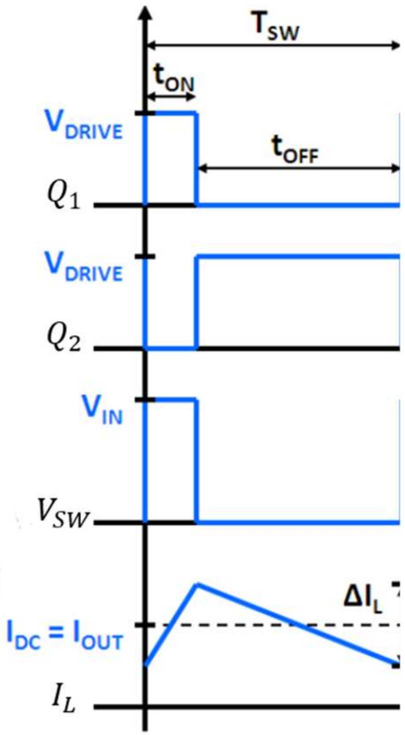


WORKING PRINCIPLE

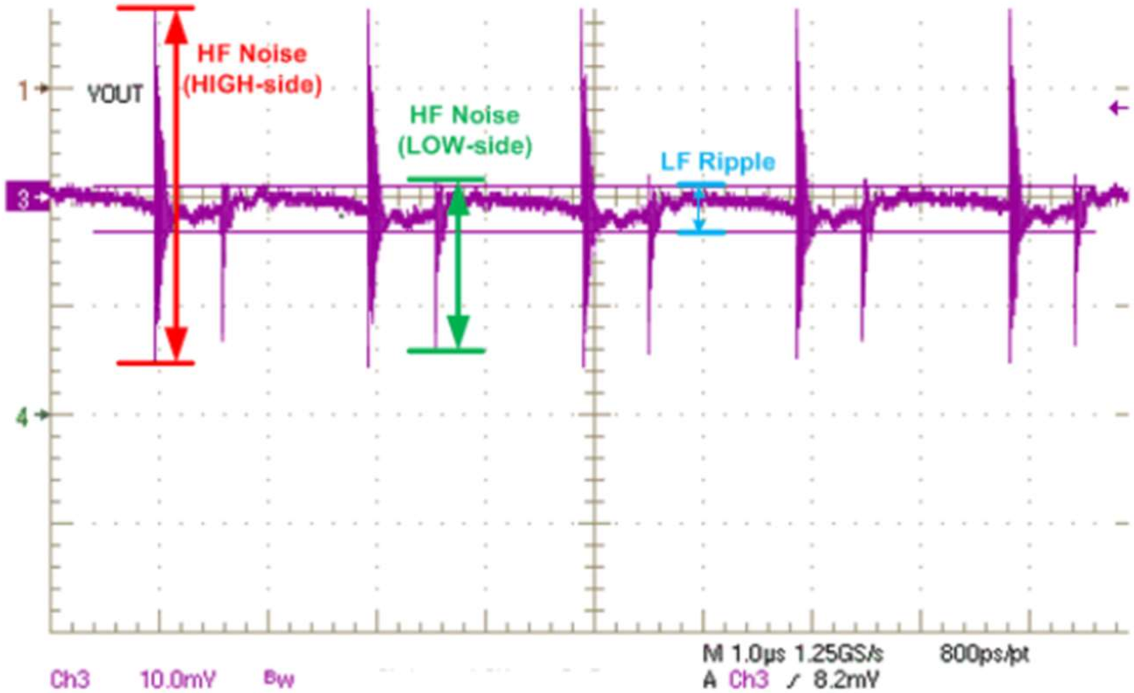
Phase II: Q_1 is off and Q_2 is on for a time t_{off}



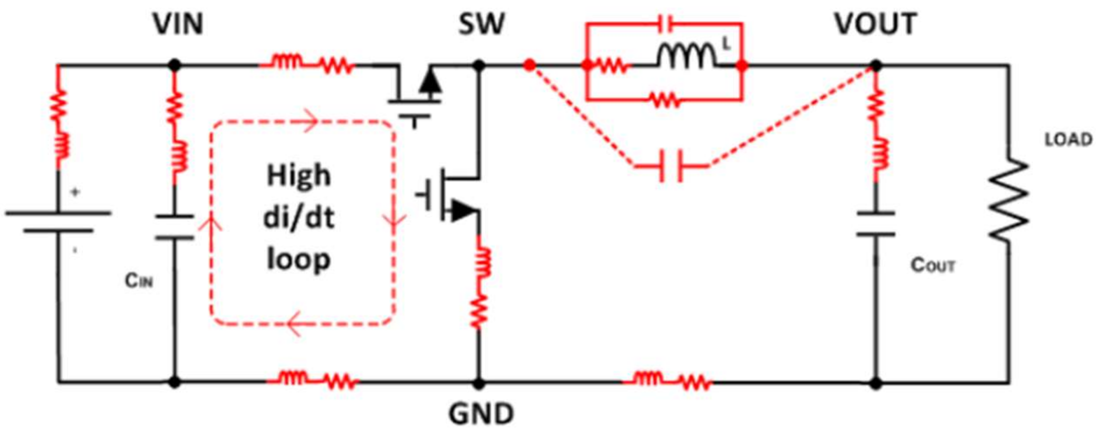
- Voltage source is disconnected
- Current through the coil decreases linearly
- Current from the coil is not sufficient
- Current deficit compensated by the capacitor



NOISE IN A SWITCHING BUCK CONVERTER



HIGH FREQUENCY NOISE



- Main cause for HF noise: current loops
- The changing magnetic field created by the loop produces an inductive voltage:

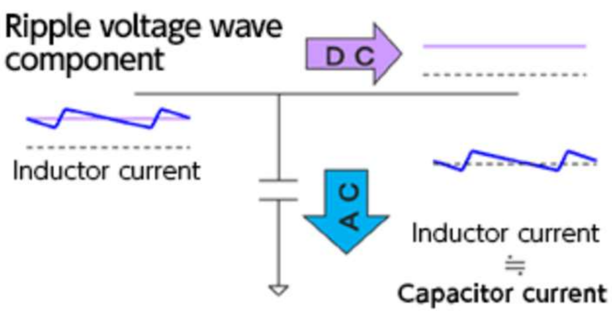
$$V_L = -\frac{d\varphi}{dt} = -L\,\frac{di}{dt},$$

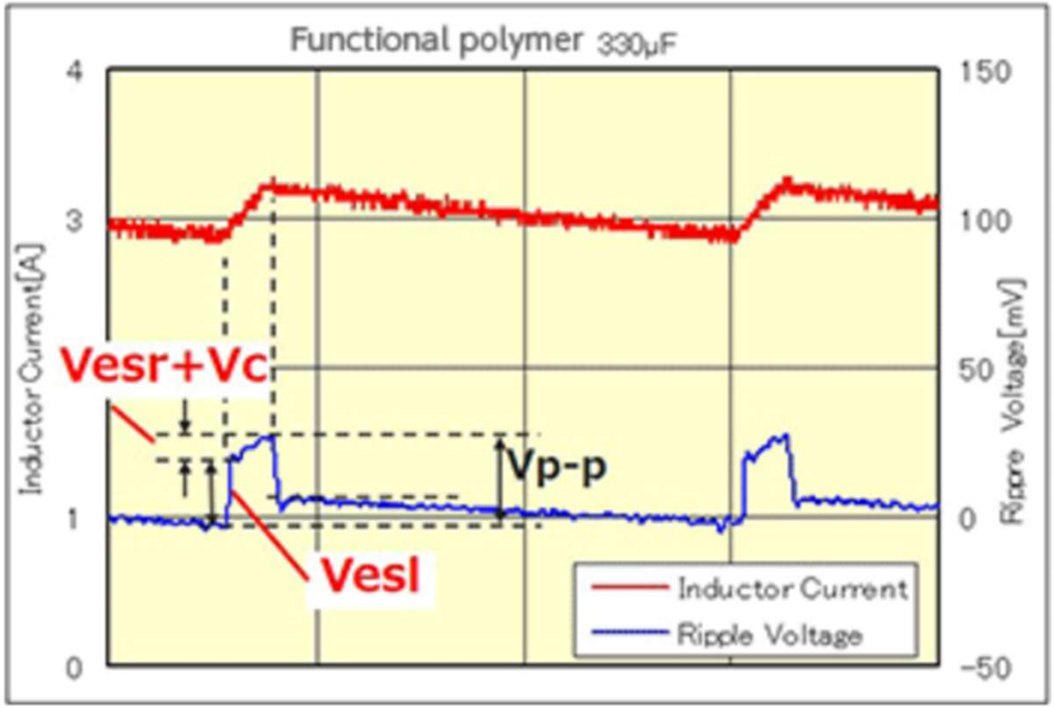
$$\varphi = \int_A B \cdot dA = L \cdot I$$

- Strongly depends on loop geometry
- High di/dt loop must be kept as small as possible
- Noise from the input can couple to the output

LOW FREQUENCY NOISE

- Combination of inductor ripple current and output capacitor impedance
- Different parasitic components have different influence on the output signal

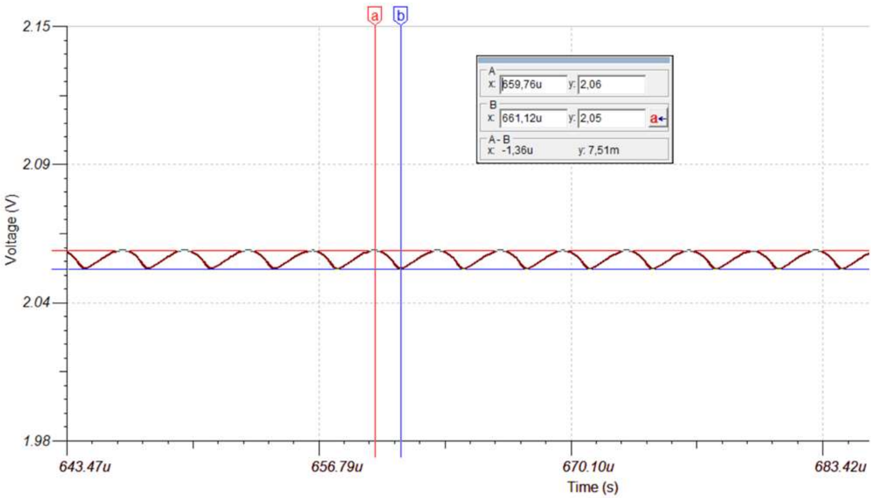




TEST BEAM MEASUREMENTS

- To determine efficiency and noise level threshold scans were performed
  - Signal in a pixel is just registered if its level is above a certain threshold
  - The lower the threshold the higher the efficiency
  - But higher noise level too
- One scan performed with a second LC filter and one scan without
- Short measurement time ➡ low statistics

RE-DESIGNED OUTPUT FILTER



V_{ripple} = 7.51mV

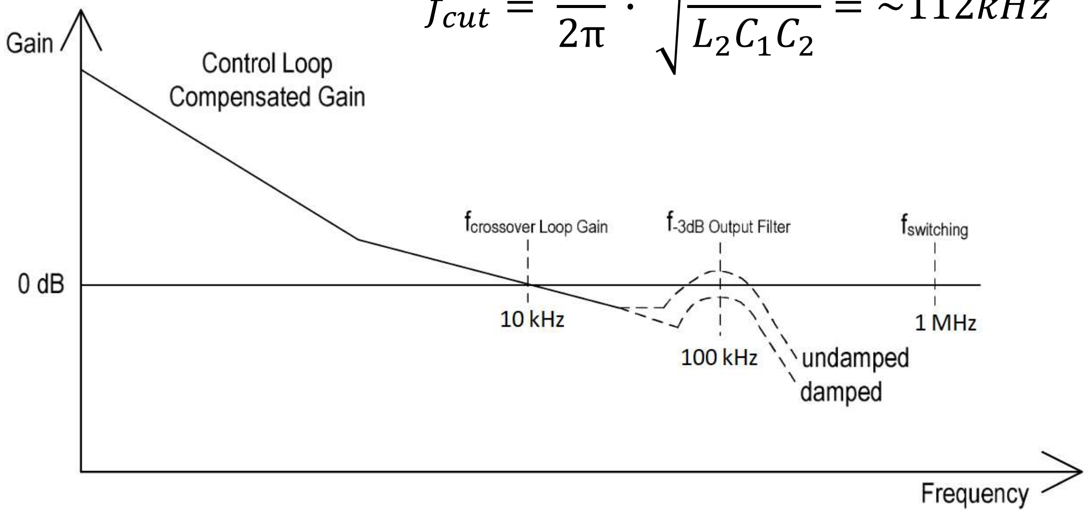
LC FILTER CALCULATIONS

Design rules

- Second coil L_2 should be much smaller than L_1:
  - $L_2 = \frac{1}{10} \cdot L_1 = \frac{1}{10} \cdot 550nH = 55nH$
- Increase of the output capacitor → 541µF
- Second capacitor should be much smaller than the first
  - If not: stability problems can occur
  - C_1 → 47µF

Stability test

$$f_{cut} = \frac{1}{2\pi} \cdot \sqrt{\frac{C_1 + C_2}{L_2 C_1 C_2}} = \sim 112kHz$$



TEMPERATURE INTERLOCK SYSTEM