Piezo Control Device and Piezo Power Supply Module

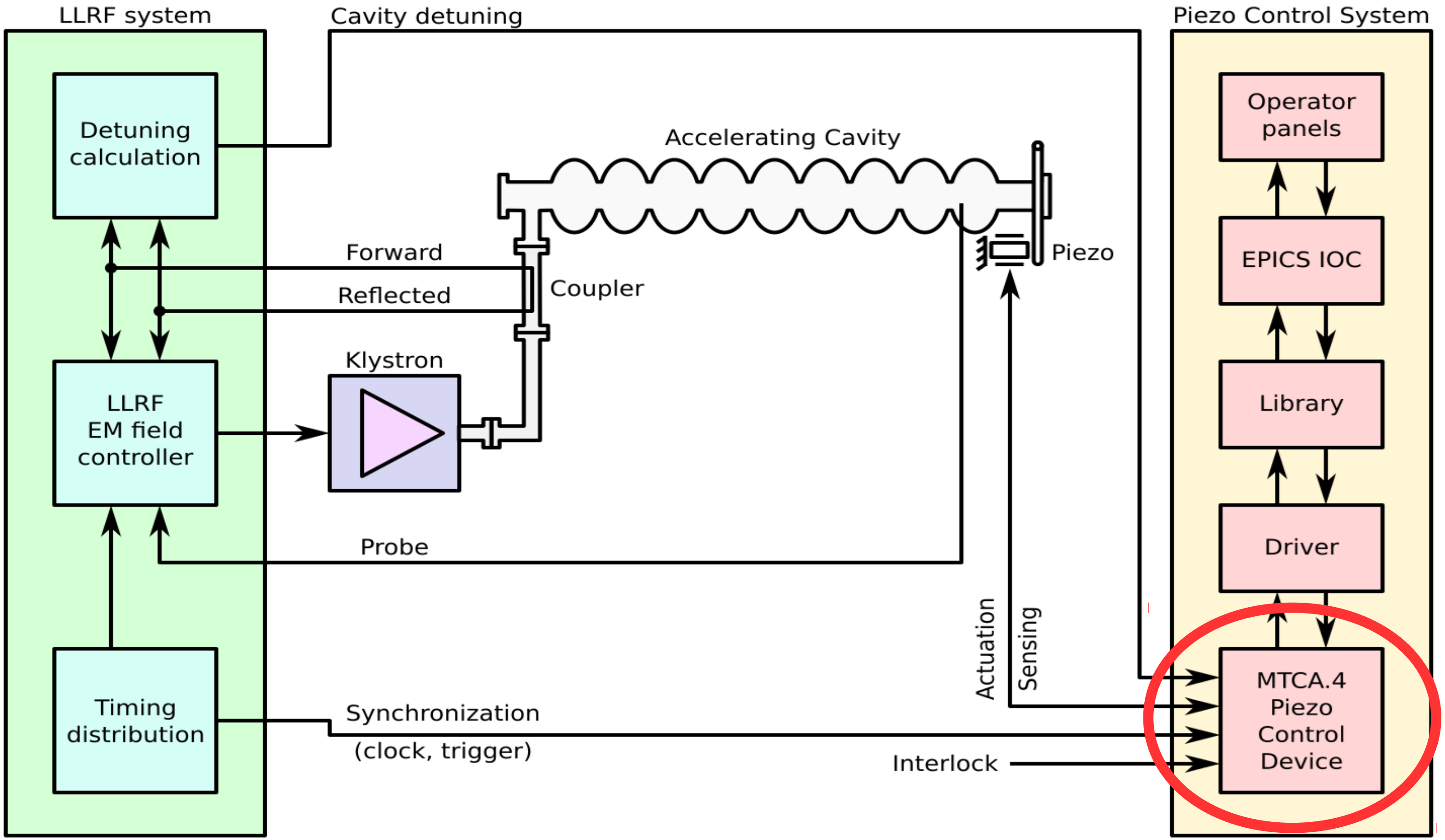
Critical Design Review for the LLRF submodules

Dariusz Makowski

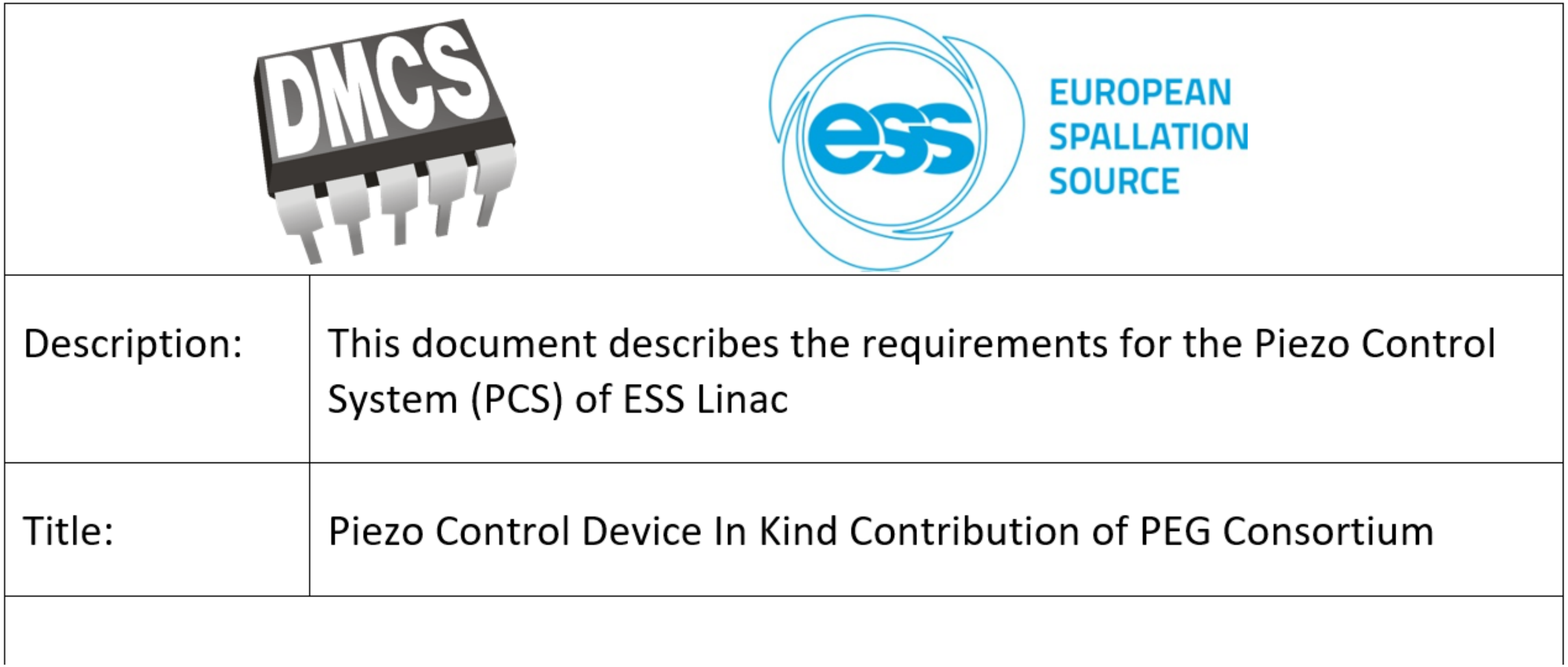
Agenda

- Piezo Compensation System
- Specification for Piezo Control Device
- Second Prototype Optimisation
- Laboratory Measurements
- MMC Development
- Production Schedule
- Risk Analysis
- Summary

Piezo Compensation System



Specification for PCS



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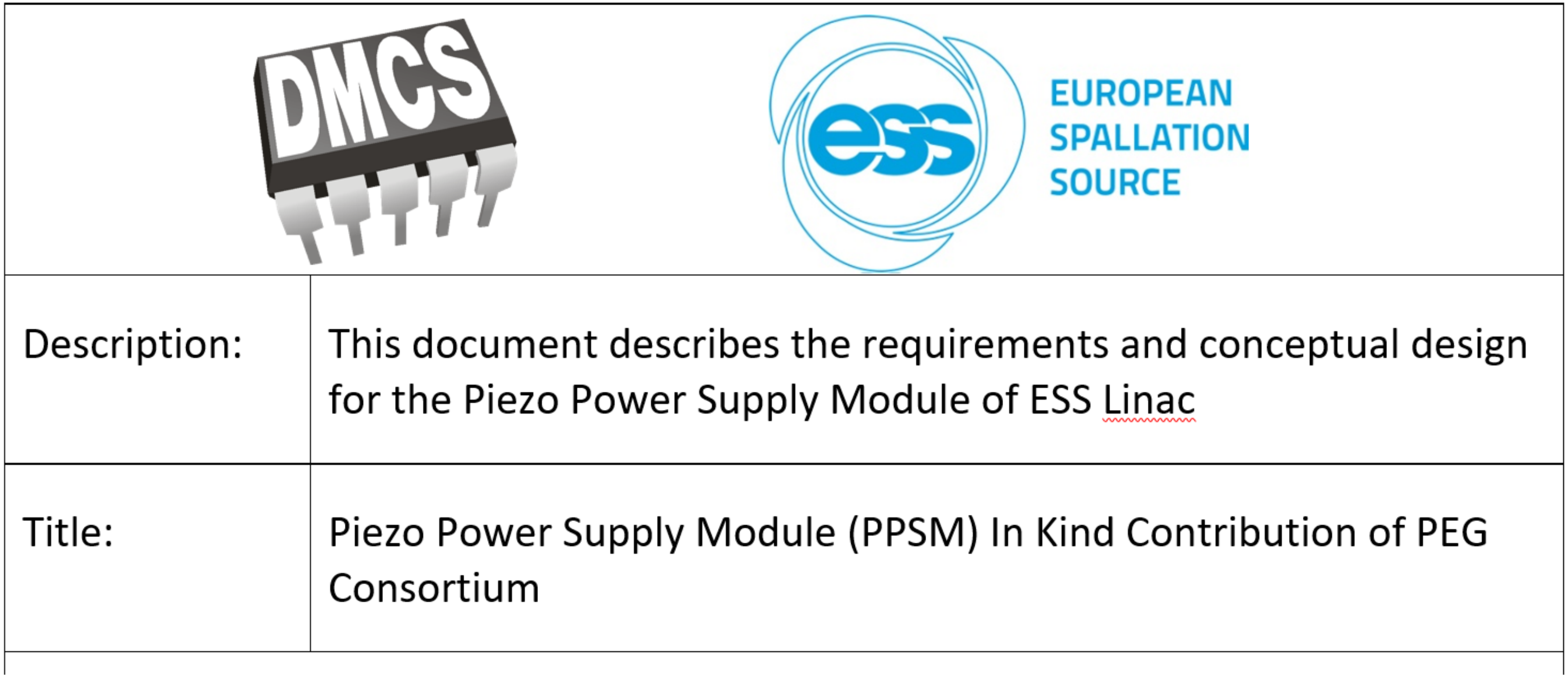
SPALLATION
SOURCE

Description:	This document describes the requirements for the Piezo Control System (PCS) of ESS Linac
Title:	Piezo Control Device In Kind Contribution of PEG Consortium

Specification for PCS



Description:	This document describes the requirements and conceptual design for the Piezo Power Supply Module of ESS Linac
Title:	Piezo Power Supply Module (PPSM) In Kind Contribution of PEG Consortium

Piezo Actuators Planned for ESS Accelerator

Cavity type	Piezo actuator type
Medium Beta cavities	Noliac NAC 2022 H30
High Beta cavities	Noliac NAC 2022 H30
Spoke cavities	Piezo #1: Noliac NAC2022-H90-A01 Piezo #2: PI PICMA P-888.91/51

Piezo type	**Noliac NAC 2022 H30**	**Noliac NAC 2022 H90**	**PI Stack 2x P-888.90 + 1x P-888.50**
Dimensions	10 x 10 x 30 mm	10 x 10 x 90 mm	10 x 10 x 90 mm
Cell material	NCE51F	NCE51F	PIC252
Number of cells	15	45	
Total capacitance (room temp.)	6.6 µF ±15%	17.4 µF ±15%	32 µF ±20%
Total capacitance (cryo, 20 K)	**~2.2 µF**	**~5.8 µF**	**~9.8 µF**
Max. free stroke	**46.2 µm**	**145.2 µm**	**94 µm**
Blocking force	4200 N	4200 N	3600 N
Max. operating voltage	200 V (±100 V)	200 V (±100 V)	-20 to 120 V
Max. operating temperature	200°C	200°C	150°C

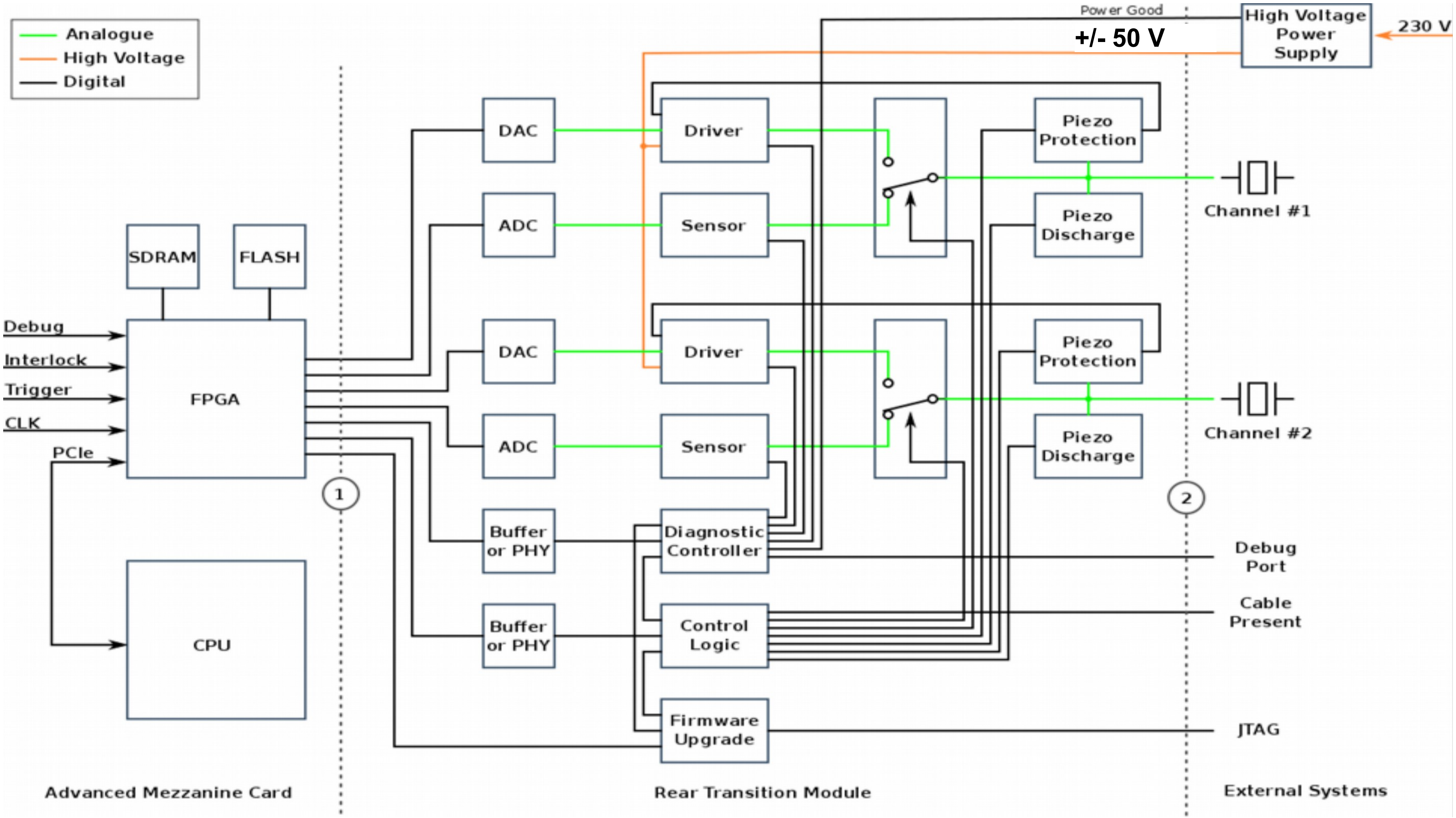
Piezo Control Device - Functional Specification

- Provide a control signal for piezo actuators used for Lorentz Force detuning of Medium and High Beta accelerator cavities.
- Measure cavity deformation using piezo device as sensor element.
- Two independent channels with configurable mode of operation: piezo actuator or sensor.
- Single LLRF synchronization input.
- Single interlock input.
- Digital control and diagnostic interface.
- Compatible with MicroTCA.4 standard.
- Health monitoring and diagnostics.
- Provides firmware upgrade for all programmable devices.
- **Allows to disable external Piezo Power Supply Module.**

Piezo Control Device - Electrical Specification

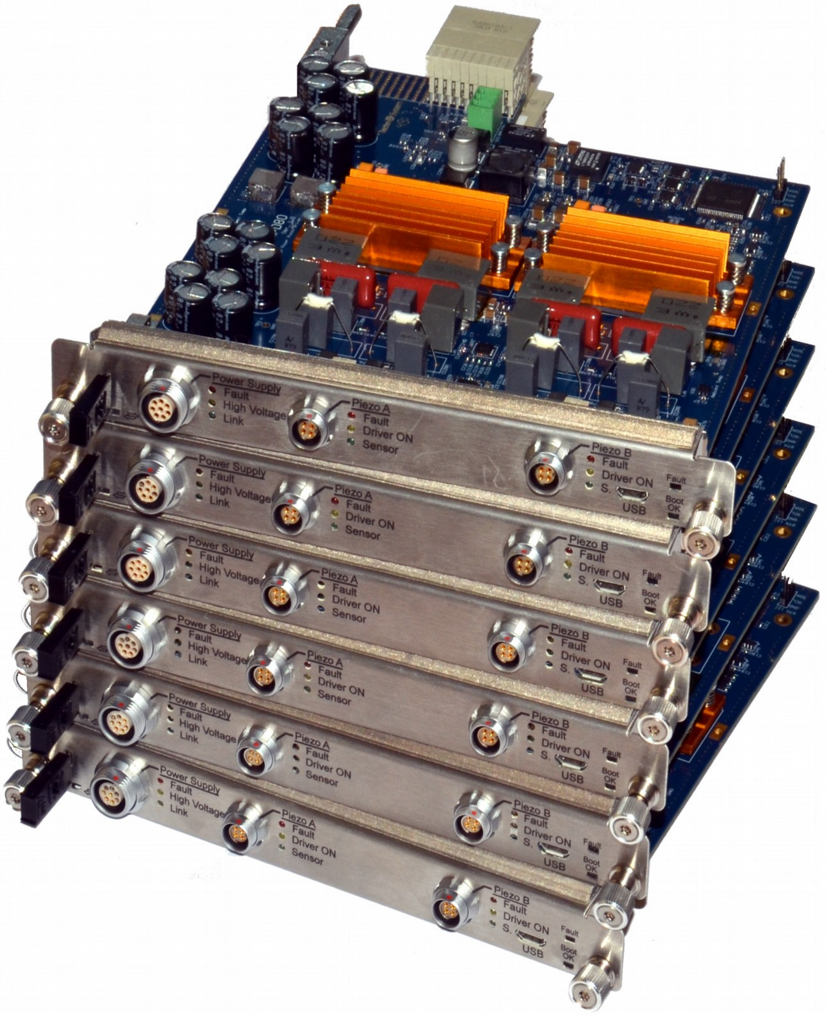
Parameter	Value	Comments
Supported standards	MTCA.0, MTCA.4, AMC.0, AMC.2, IPMI 2.0	
Number of channels	2 bipolar channels with actuator/sensor mode	
Repetition Rate	14 Hz	pulse duration: max. 3.5 ms
Piezo capacitance	6.6 – (9.5 µF) **32 µF** (room temperature)	high and medium beta cavities
Piezo supply voltage	±80 V (160 Vpp)	
Maximum actuator power	(35 W per channel) **100 W per channel**	
Controller Bandwidth	DC – 1 kHz	
Actuator excitation signal	Arbitrary waveform generation Sampling frequency: min. 1 MHz Number of samples: min. 30000 Resolution: 16-bits Output voltage range: ±80 V	
Piezo sensor	Sampling frequency: min. 1 MHz Number of samples: min. 30000 Resolution: 16-bits Input voltage range: ±1 V Input impedance: 10 kΩ	
Protection	Overcurrent, Overvoltage Thermal protection of the driver Maximal control power of piezo	
Cable length	**min. 30 m long, max. 45 m long,** **min. 5 Ω, max. 7 Ω**	**Lapp 0030924 cable, 8x 2x 0.25 mm^2**

Piezo Driver – Block Diagram



Current Status

- 6 PCD modules fabricated and tested
- Design optimised for 2.2 uF piezo and 30-45 m long cables
- Still working on 10 uF solution
- Short-term tests finished successfully
- Need more testing:
  - Long-term reliability tests
  - Corner thermal tests in climatic test chamber
  - EMC/ESD tests and certification
  - Tests with final RTM-Carrier module
  - Test with real cavity and Lorentz force detuning algorithms

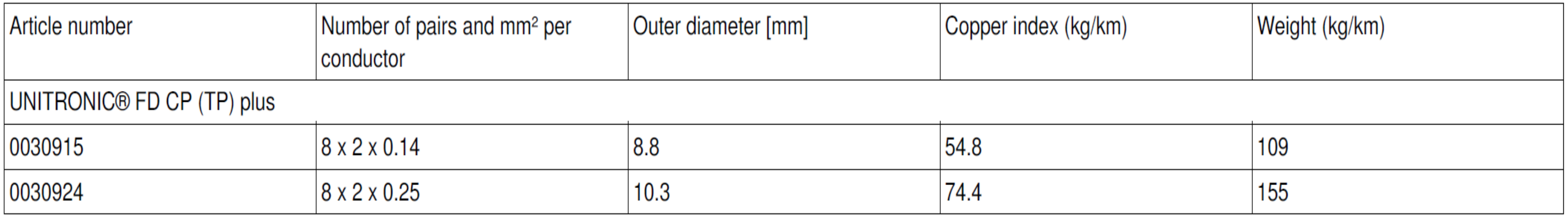


Selected Connectors

- Piezo Connectors
  - 4-pin DBPC 102 A053-130 Fisher connectors with E3 102.248+A clamp
  - Requires confirmation from ESS side
- Power Supply Connectors
  - 8-pin DBPC 103 A058-130 Fisher connector
  - We need to know the length of cable between PCD and PPSM
- All connector signals are described in details in Chapter 3 of "Piezo Control Device and Power Supply Module - Critical Design Review for the LLRF submodules"

Selected Cable for Piezo Actuator

- Estimated cable length from 3D model:
  - Spoke: 42 m
  - Medium-B and High-B: 39 m
  - Maximum distance between LLRF crates in same row is approximately 9 m
- Selected cable: Lapp 0030924 (8x 2x 0.25 mm^2/AWG24)
- Need testing in real conditions, Laboratory, and Freia?



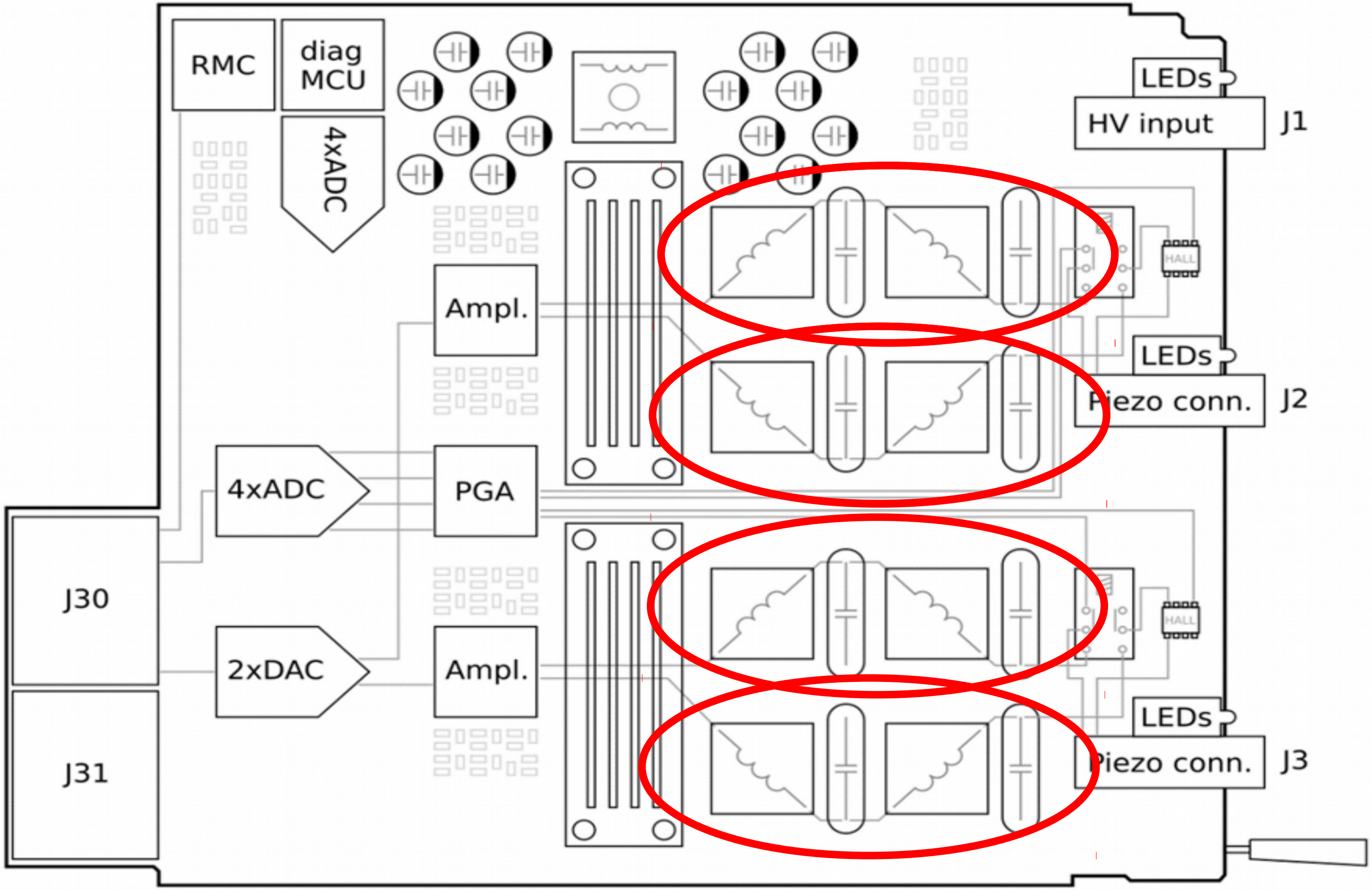
Article number	Number of pairs and mm^2 per conductor	Outer diameter [mm]	Copper index (kg/km)	Weight (kg/km)
UNITRONIC® FD CP (TP) plus				
0030915	8 x 2 x 0.14	8.8	54.8	109
0030924	8 x 2 x 0.25	10.3	74.4	155

7.8 Ω – 11.7 Ω

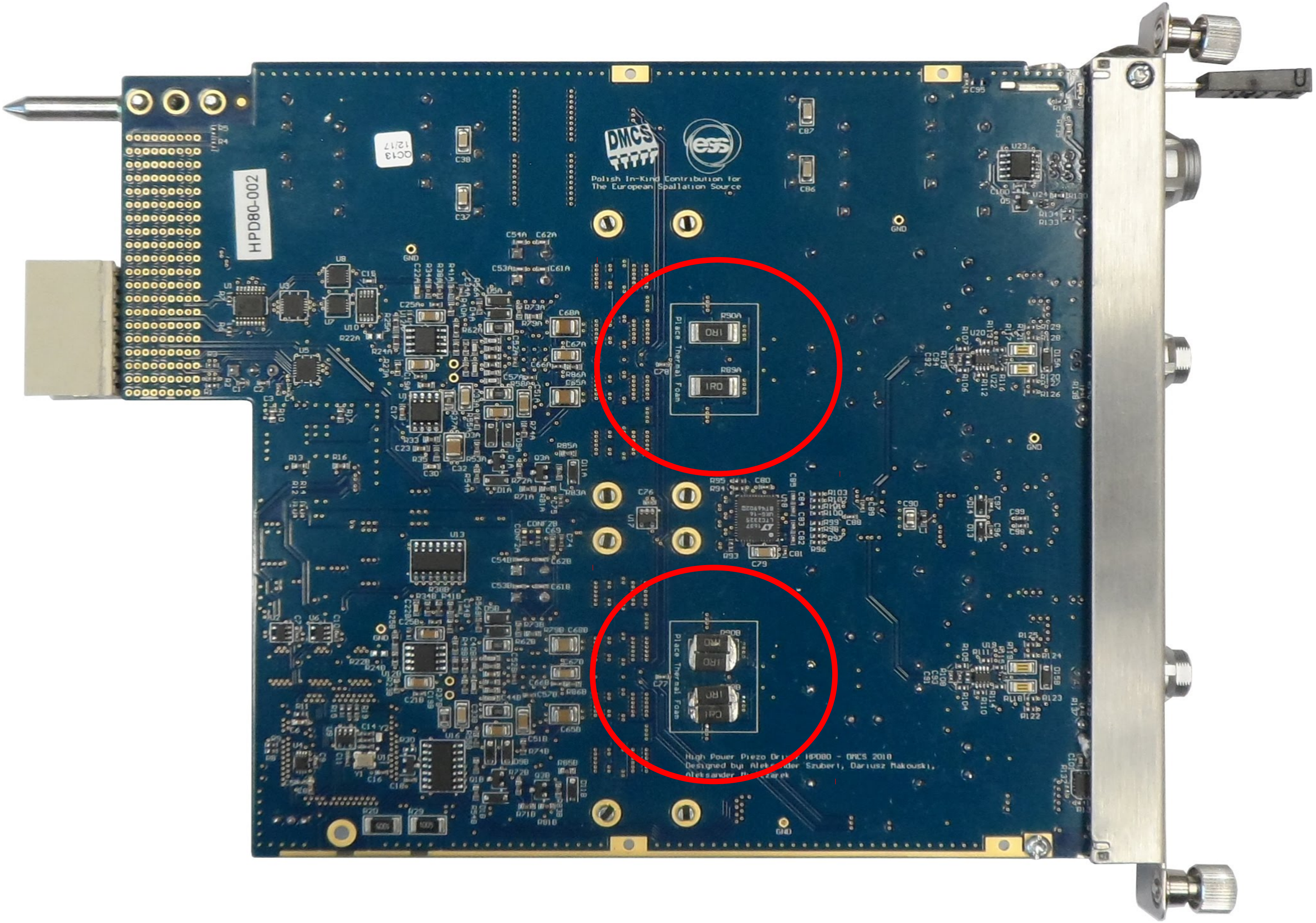
4 Ω – 6 Ω

Piezo Driver Optimisation, Simulations and Measurements

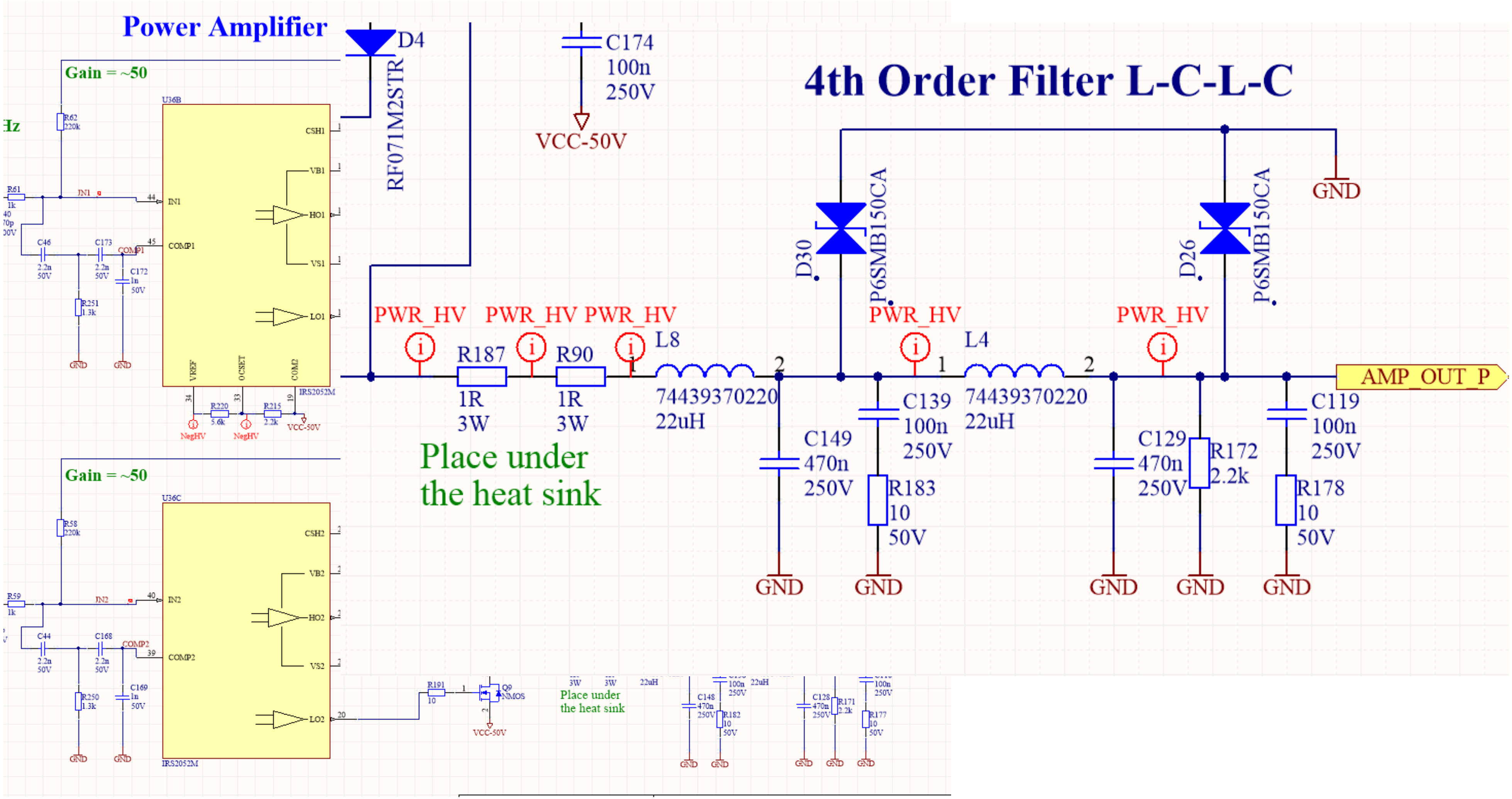
Scope of Optimisation



Series Resistors on PCB

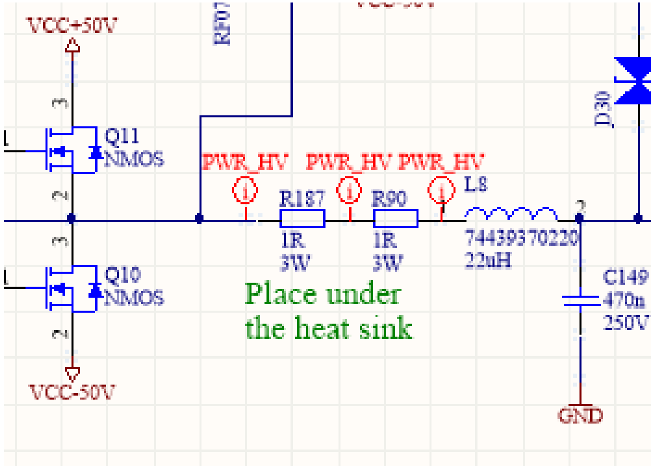


Single Channel PWM High Power Driver

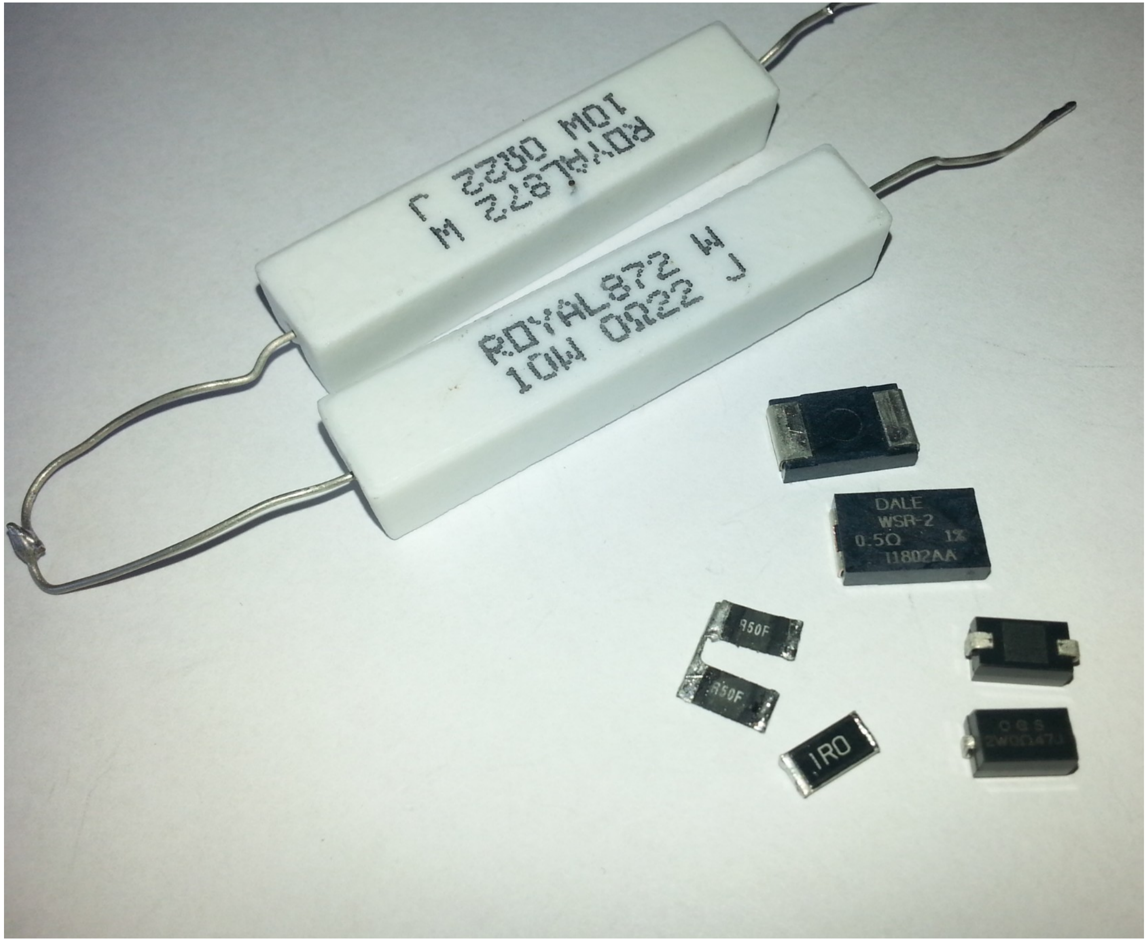


Challenges and Problems

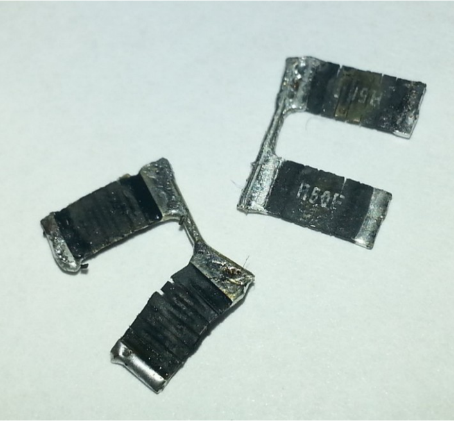
- Series resistance before the L-C-L-C filter required to avoid local resonances and make driver stable
- Capacitive load requires additional series resistance (piezo cables)
- Huge peak power in CW mode: P=28 A * 28 A * 1 Ω = 784 Watts
- Significant RMS power in CW mode: $P_{(rms)}$= 10 A * 10 A * 1 Ω = 100 Watts
- In pulsed mode depends on signal frequency, repetition and signal bandwidth
- We could generate max. 30 Watts per RTM, ~10 Watts for single Piezo driver
- This is the weakest point of the Piezo Driver
- Damaged plenty of various resistors with power from 2 to 50 Watts
- Implemented electronic protections to avoid damage:
  - Measure $U_{(peak)}$, $I_{(peak)}$, $U_{(rms)}$, $I_{(rms)}$ and calculate Energy dissipated in resistance and disable driver when malfunction detected
  - Measure max. load current and disable driver
  - Limit max. voltages to +/- 50 V



Tested High-Power Resistors

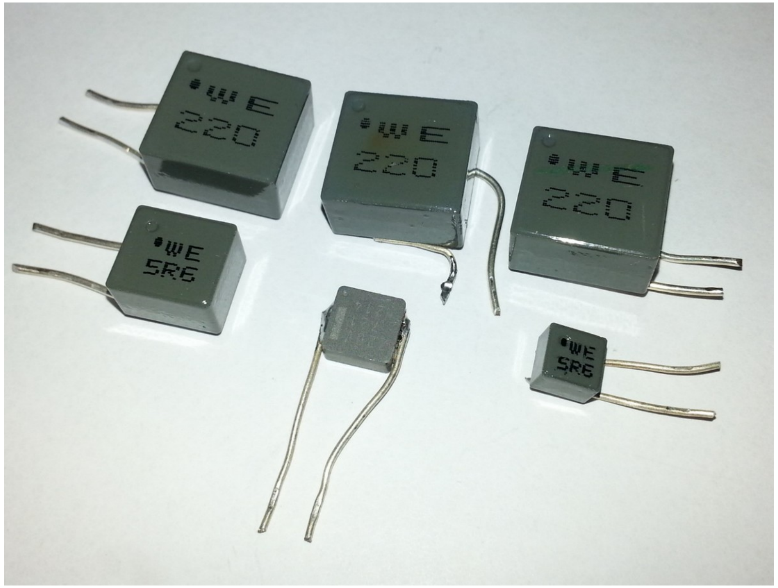


SMD 1.0 ohm 25W 1% D-Pak

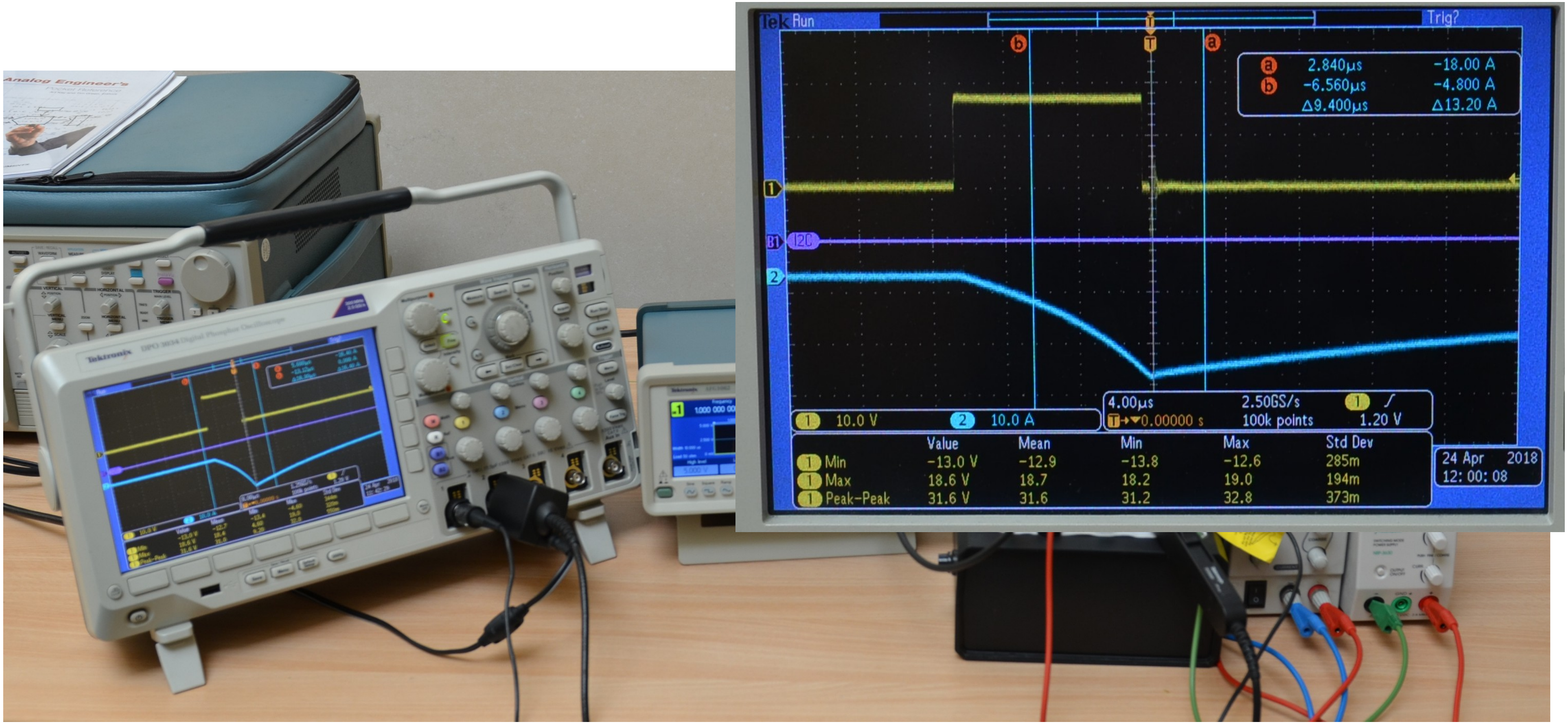


L-C-L-C Filter Coils

- Problem:
  - High-voltage (>80 VDC) and large saturation current (>13 A) is difficult to find on market
  - Additional restriction is a small size (>12 mm height), shielded coil, etc.
  - Need to use 2 coils connected in series to increase the operation voltage
  - Saturation current measured for selected coils



Coil Saturation Current Measurements



Tek Run

Trig?

ⓐ	2.840µs	-18.00 A
ⓑ	-6.560µs	-4.800 A
	Δ9.400µs	Δ13.20 A

① 10.0 V ② 10.0 A

4.00µs T→▼0.00000 s

2.50GS/s 100k points

① ∫ 1.20 V

	Value	Mean	Min	Max	Std Dev
① Min	-13.0 V	-12.9	-13.8	-12.6	285m
① Max	18.6 V	18.7	18.2	19.0	194m
① Peak-Peak	31.6 V	31.6	31.2	32.8	373m

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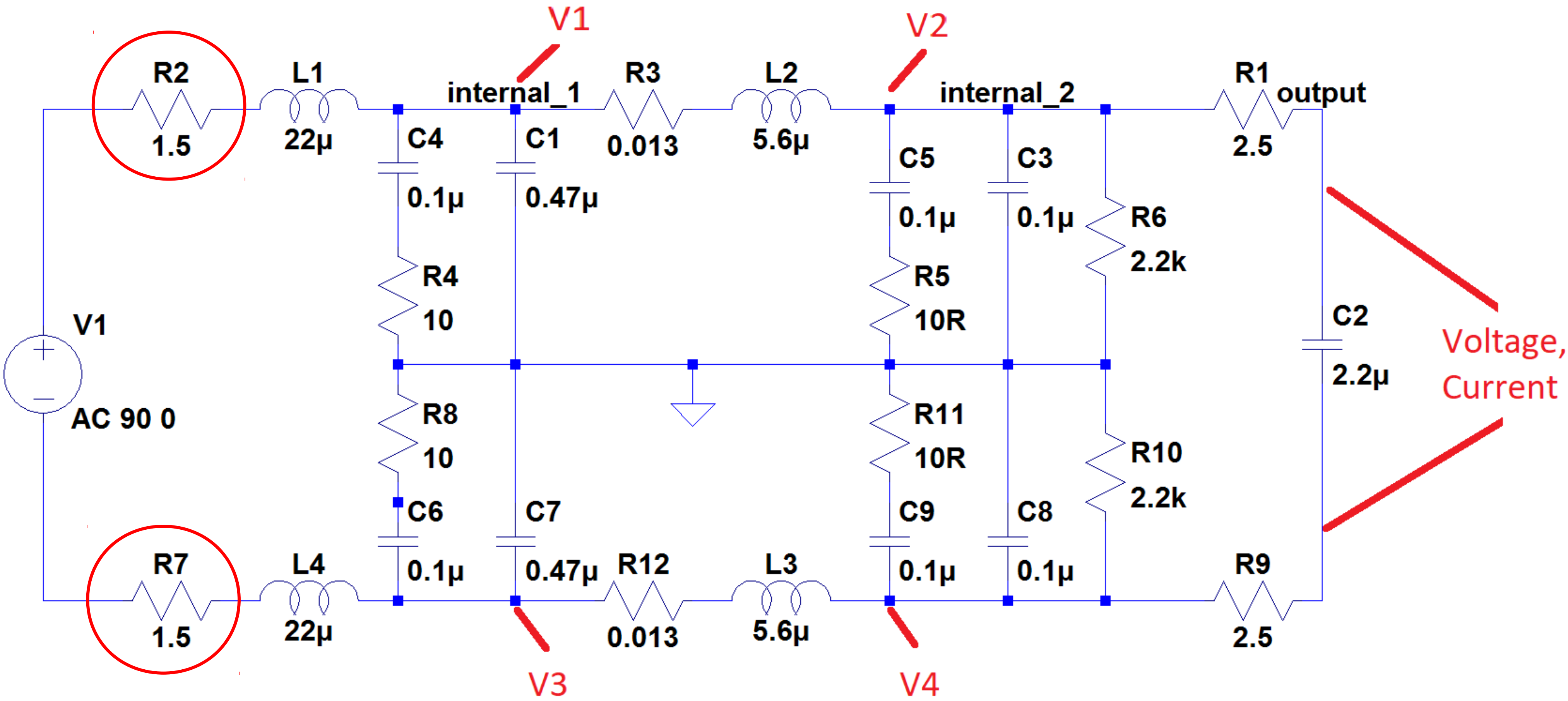
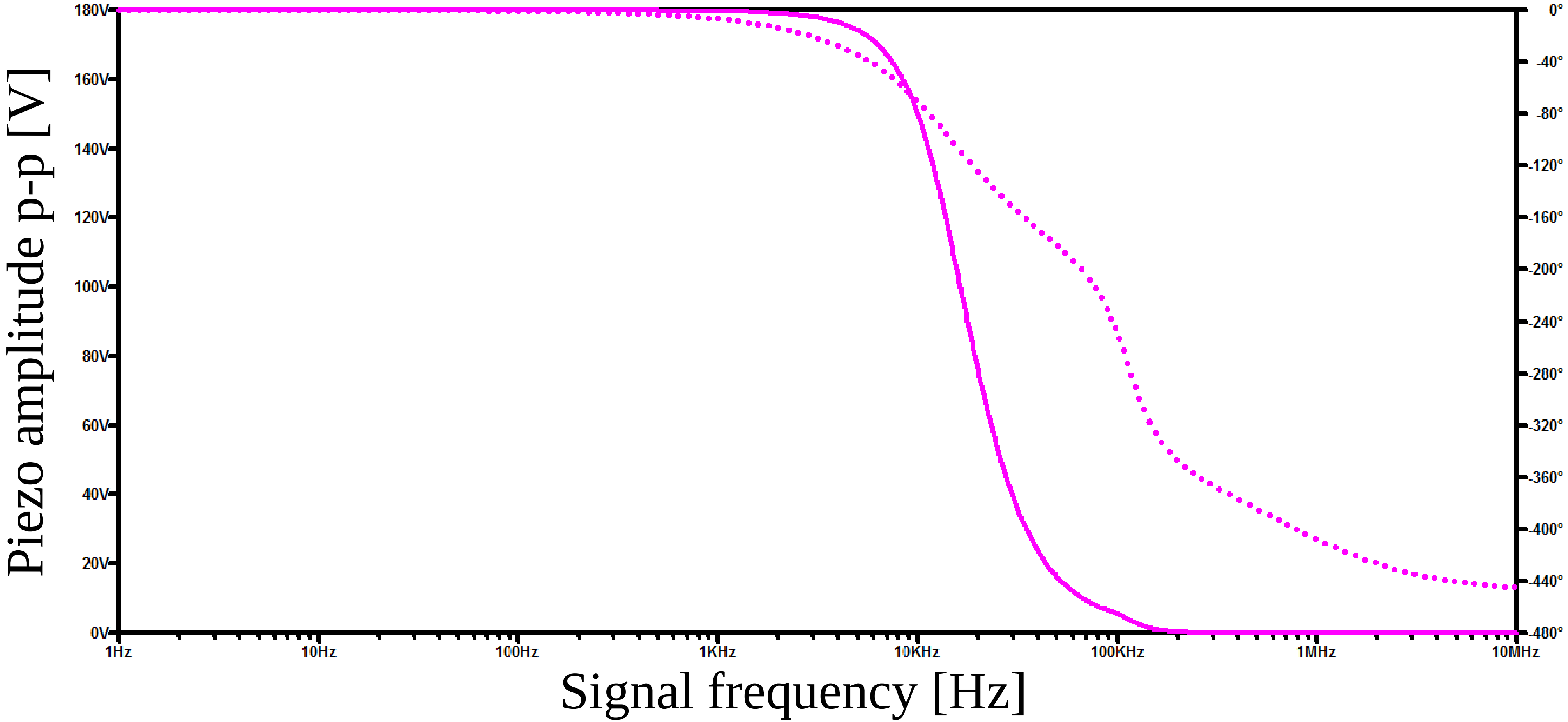
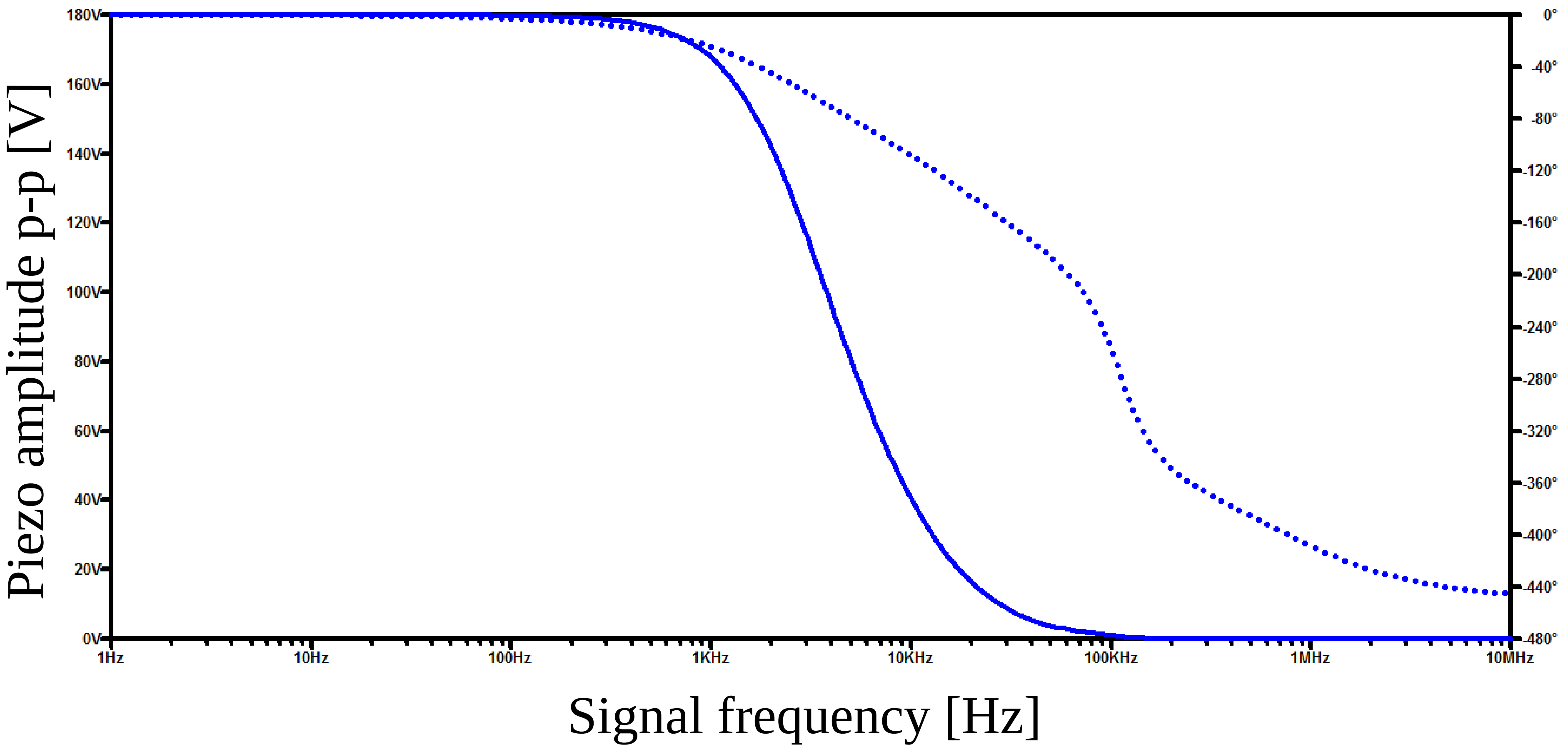
Simulation Environment, C=2.2 µF, R=1.5 Ω



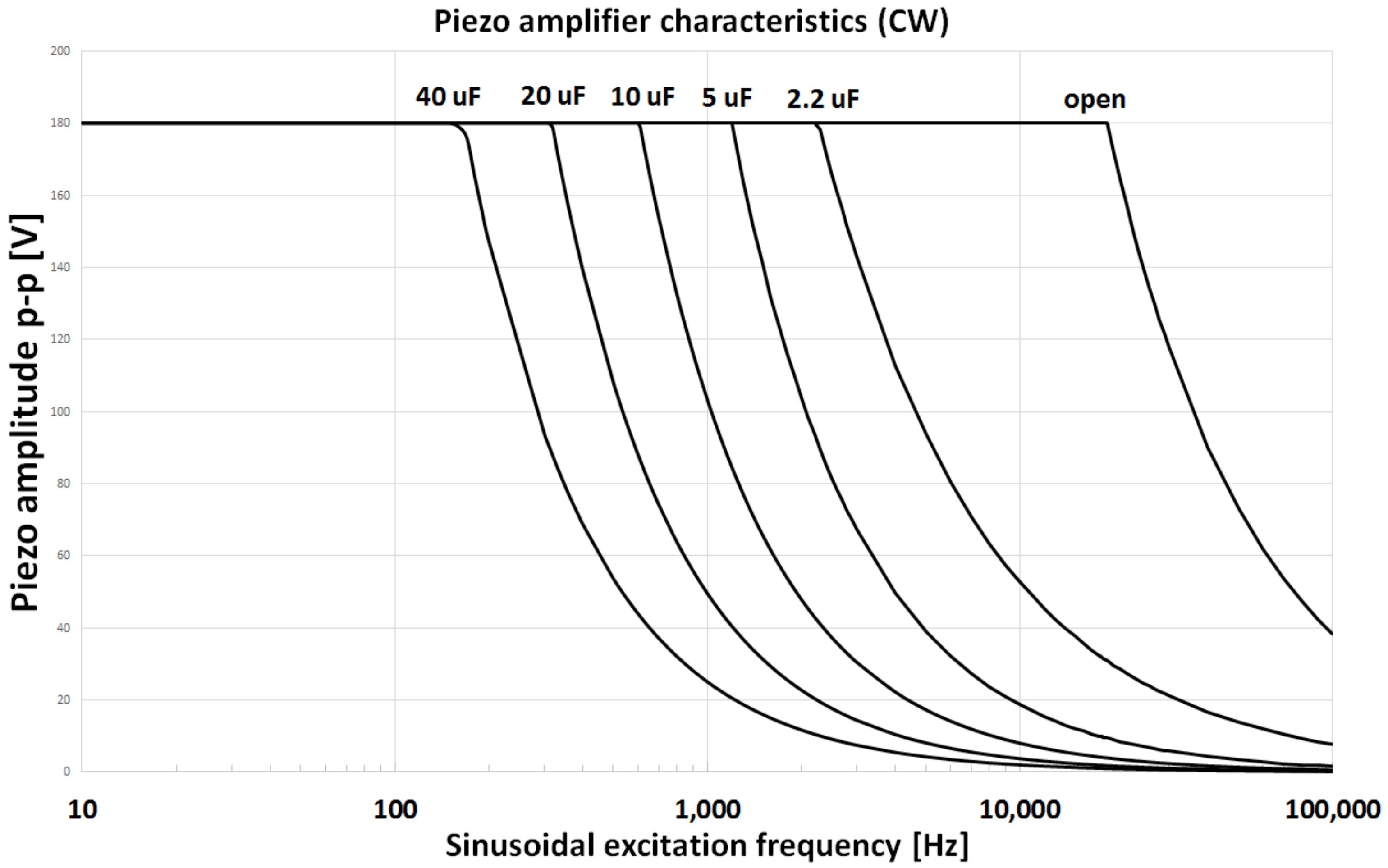
Simulation with C=2.2 µF, R=1.5 Ω Series Resistance



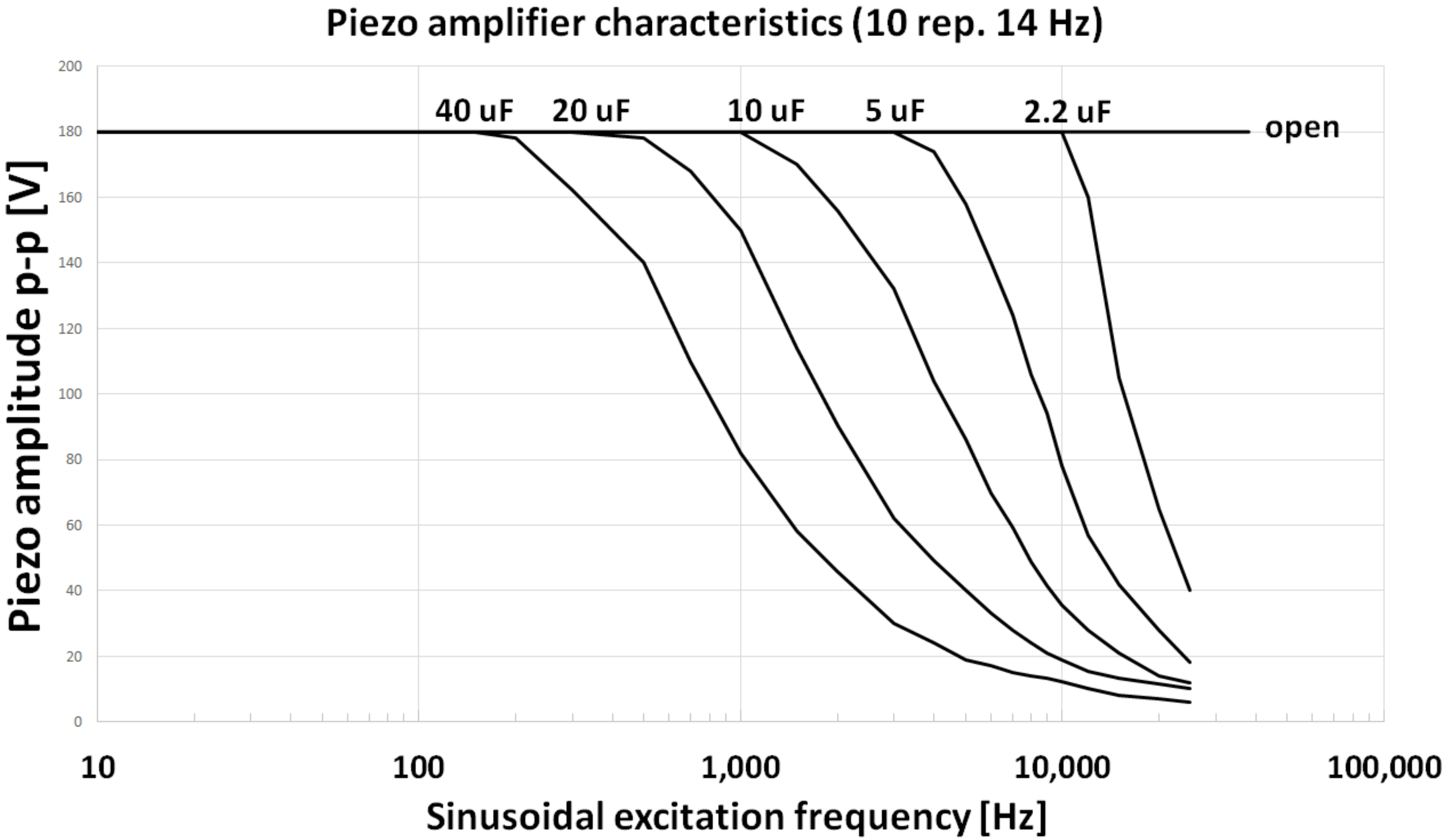
Simulation with C=10 µF, R=1 Ω Series Resistance



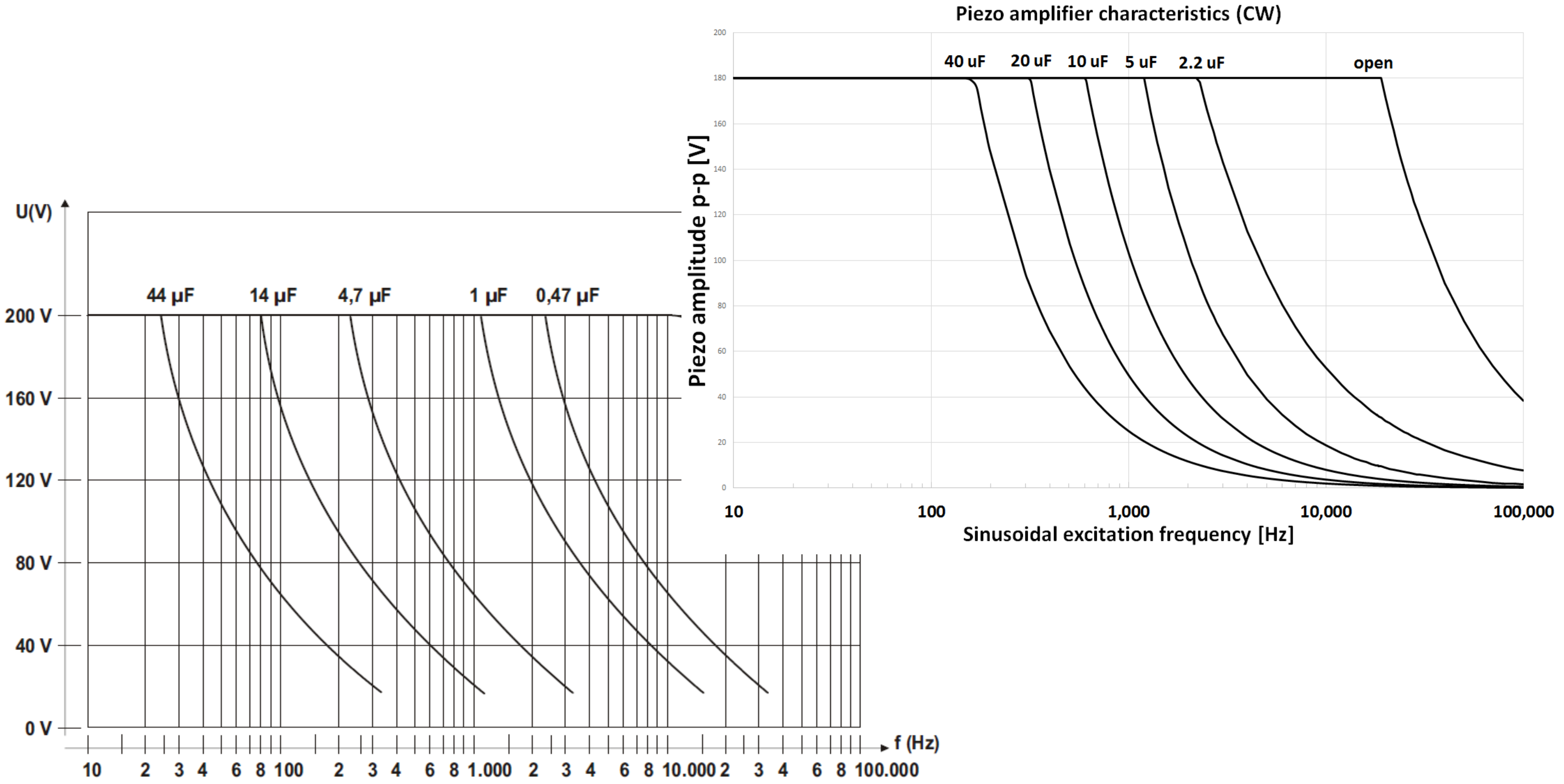
CW Mode: 22 uH/470 nF/5.6 uH/100 nF, 1 R series resistance



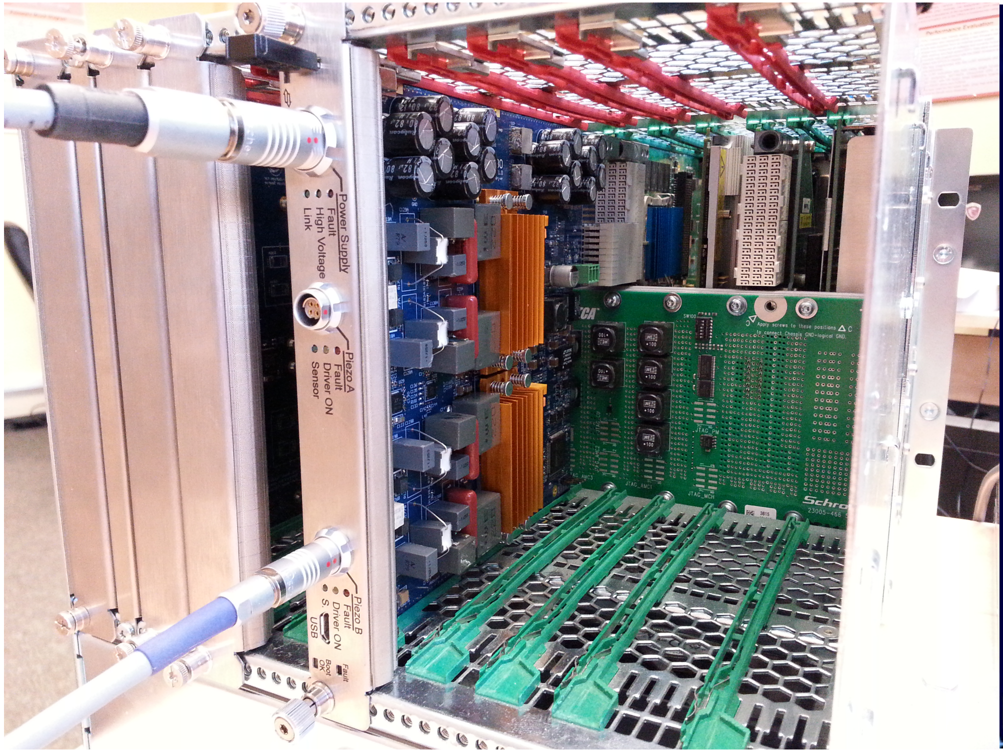
Pulsed Mode: 22 uH/470 nF/5.6 uH/100 nF, 1 R series resistance

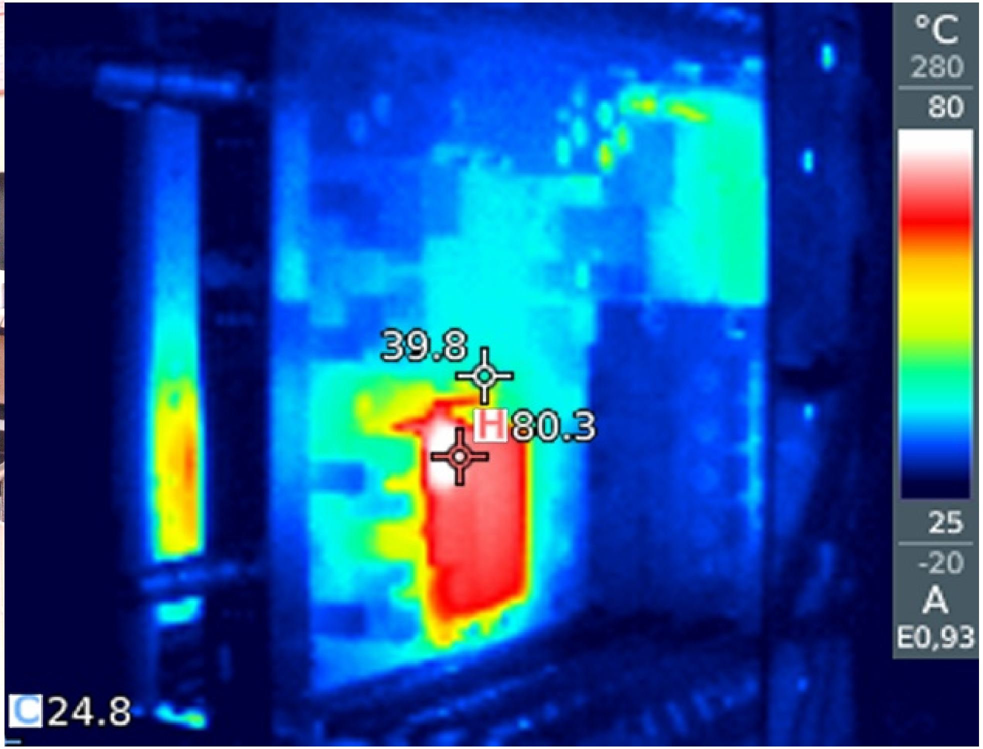


SOA Characteristics for Commercial Driver LE200/070 EBW - Comparison



Thermal Measurements





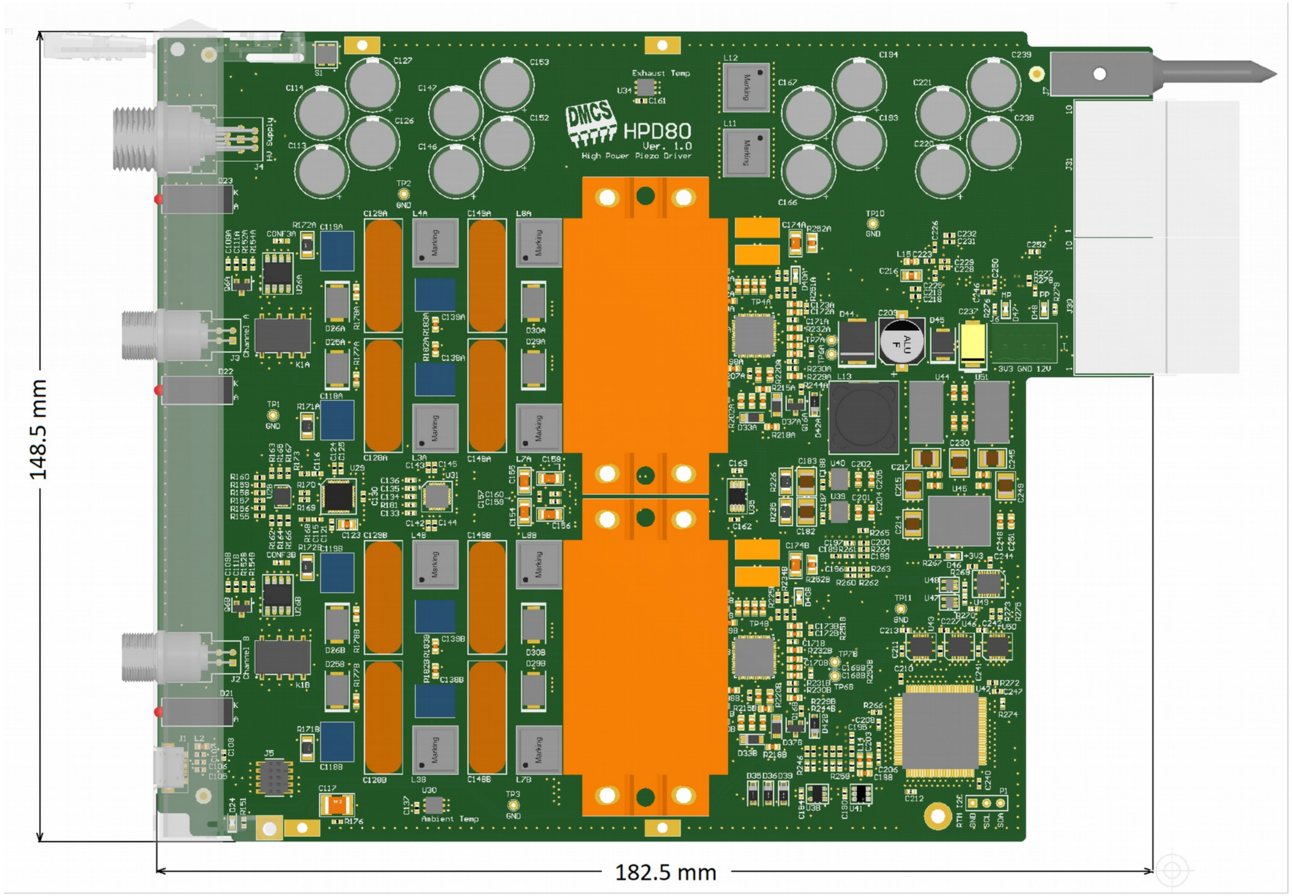
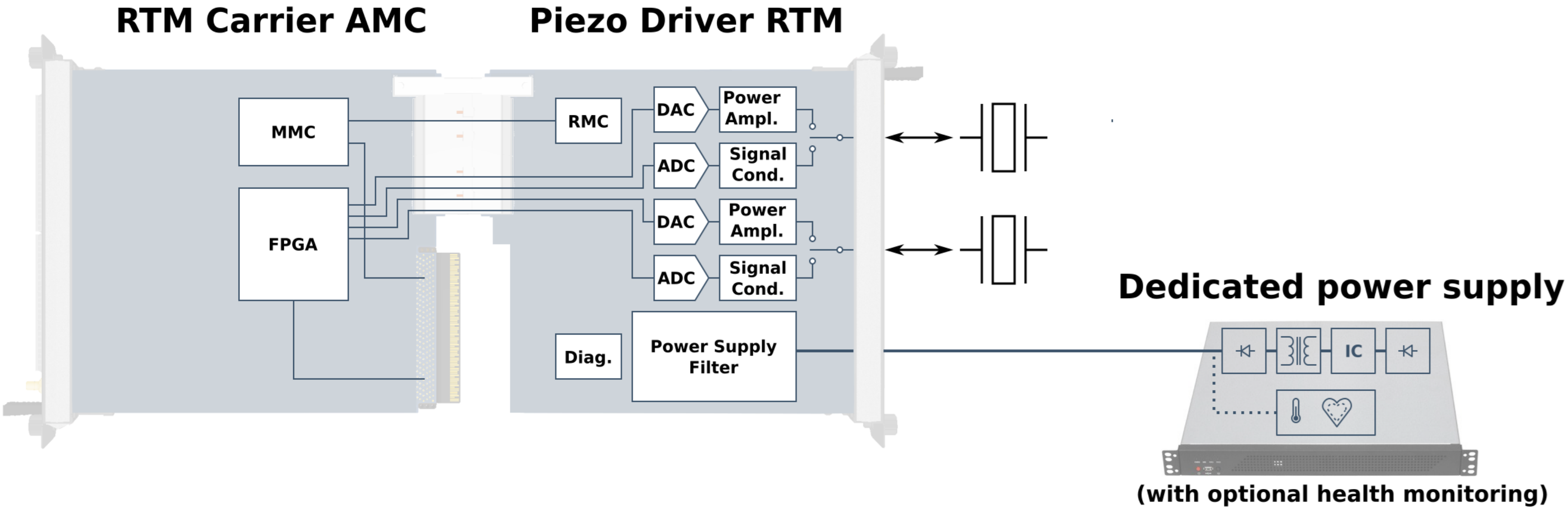


Figure 1 Piezo Control Device - Top-view.

External Piezo Power Supply Module

- Finaly selected power supply modules:
  - TDK Lambda HWS100A-48/AR
- Prototype built without health monitoring module.
- Design needs to be modified – power control function required.
- Planned to manufacture 6 power supply devices. Health monitoring module redesign. Plan for production in May.



Comparison of selected AC Power Supply Modules

Manufacturer	PSM model	Nominal output voltage (tuned voltage range)	Maximum output current	Output power	Ripple [mV]	MTBF [hours]	Failure Rate (FPMH)
TDK Lambda	CSS65A-48	48 V ±2%, (48 V - 54 V)	1.36 A	65 Watts	200 mV	209,440 (at 30 °C)	4.774634
TDK Lambda	HWS100A-48/A	48 V ±2%, (38.4 V - 52.8 V)	2.1 A	100 Watts	200 mV	2,963,512 (at 25 °C)	0,337437
TDK Lambda	HWS100A-48/RA	48 V ±2%, (38.4 V - 52.8 V)	2.1 A	100 Watts	200 mV	2,963,512 (at 25 °C)	0,337437
TDK Lambda	ZMS100-48	48 V ±2%, (45.6 V -52.8 V)	1.67 A	80.2 Watts	480 mV	430,000 (at 30 °C)	2.318214

External Piezo Power Supply Module

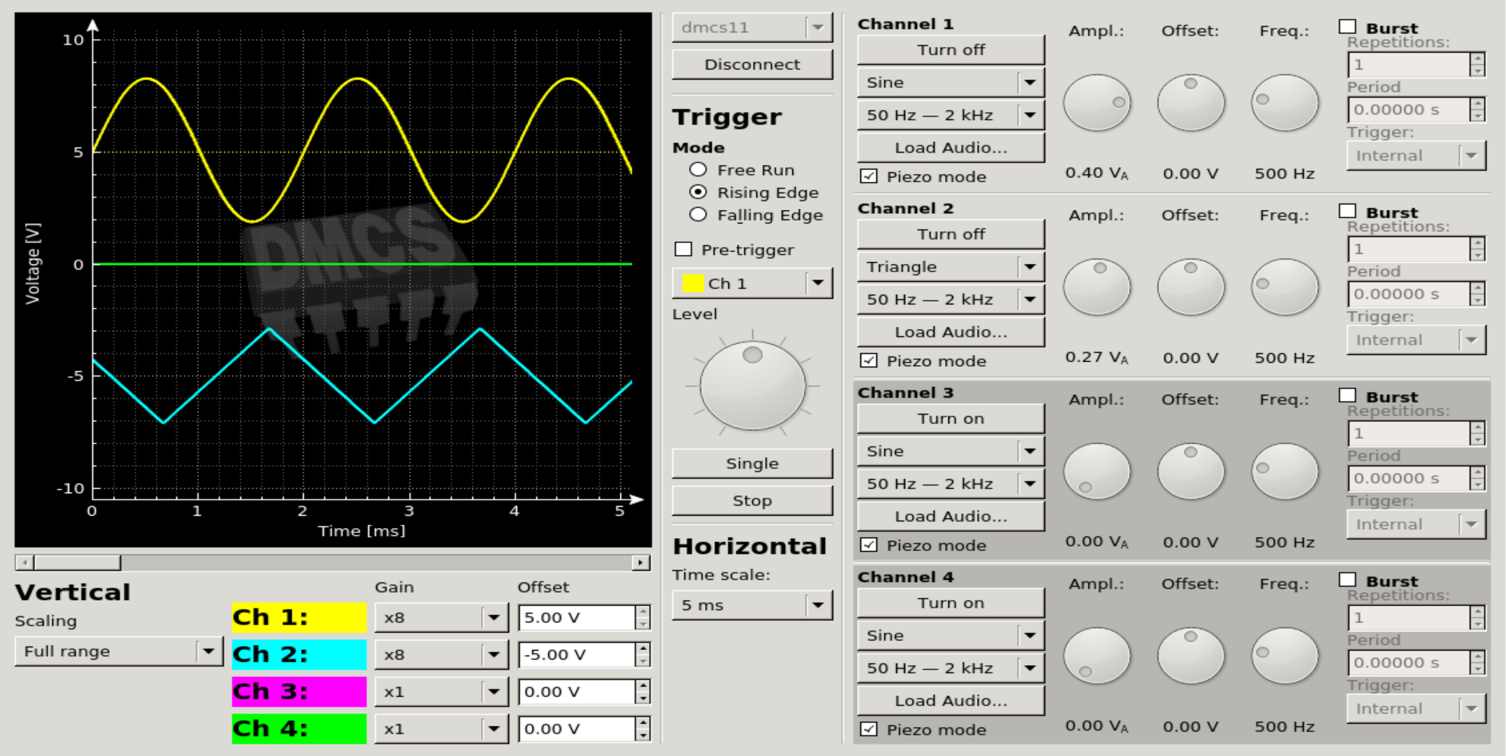
Piezo Power Supply Module (PPSM) should fulfil the following functional specification:

- Provide high-voltage power supply for PCD.
- Provide power good indicators.
- Provide AC power supply indicator.
- Provide EMI filtering.
- Compatible with 19” standard.
- Provide basic health monitoring and diagnostics.
- Allow for power control from RTM-piezo card.

EU Electromagnetic Compatibility and Certification

- Piezo Control Device RTM (PCD) is a MicroTCA.4 component and does not fall within the scope of the EMC directive. Compliance with the EMC directive must be considered in the final installation
  - It is not possible to test and certify the PCD component separately
  - Need the whole MicroTCA.4 infrastructure and installation including suitable connectors, cabling and load
  - Many small and not easily visible aspects have a direct and significant influence on the final results
- Piezo power Supply Module (PSM) is a separate component and it requires a compliance testing
  - Triggered collaboration with Department of Transformers and Electromagnetic Compatibility, Łódź University of Technology
  - We need to prepare the final hardware and deliver specification
    - What should be tested
    - In which conditions

Firmware and Operator Panels



Trigger

Mode

○ Free Run
● Rising Edge
○ Falling Edge

☐ Pre-trigger

Ch 1

Level

Horizontal

Time scale: 5 ms

Vertical

Scaling: Full range

	Gain	Offset
Ch 1:	x8	5.00 V
Ch 2:	x8	-5.00 V
Ch 3:	x1	0.00 V
Ch 4:	x1	0.00 V

Channel 1: Turn off; Sine; 50 Hz — 2 kHz; ☑ Piezo mode; Ampl.: 0.40 V$_A$; Offset: 0.00 V; Freq.: 500 Hz; ☐ Burst; Repetitions: 1; Period 0.00000 s; Trigger: Internal

Channel 2: Turn off; Triangle; 50 Hz — 2 kHz; ☑ Piezo mode; Ampl.: 0.27 V$_A$; Offset: 0.00 V; Freq.: 500 Hz; ☐ Burst; Repetitions: 1; Period 0.00000 s; Trigger: Internal

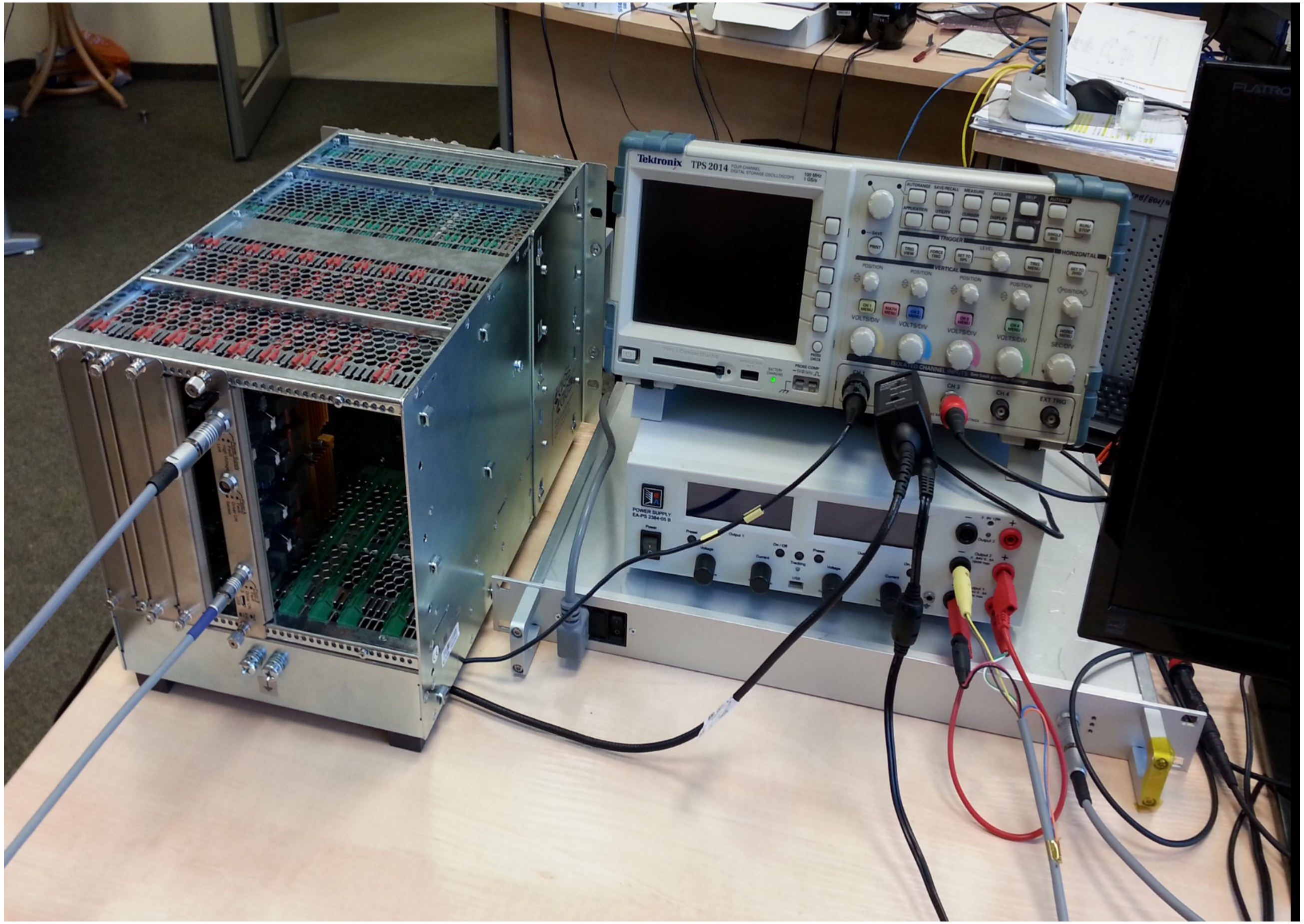
Channel 3: Turn on; Sine; 50 Hz — 2 kHz; ☑ Piezo mode; Ampl.: 0.00 V$_A$; Offset: 0.00 V; Freq.: 500 Hz; ☐ Burst; Repetitions: 1; Period 0.00000 s; Trigger: Internal

Channel 4: Turn on; Sine; 50 Hz — 2 kHz; ☑ Piezo mode; Ampl.: 0.00 V$_A$; Offset: 0.00 V; Freq.: 500 Hz; ☐ Burst; Repetitions: 1; Period 0.00000 s; Trigger: Internal

Operator interface:

- on the left – an oscilloscope inspired design
- on the right – a four-channel generator

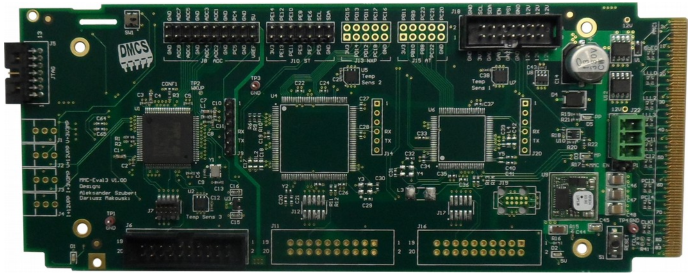
Development Area



Only One AMC Card Available

More Test-stands

Module Management Controller (MMC) – Firmware Development



- Initial prototype version of the firmware developed using MMC-Eval3 board
  - Board equipped with the same microcontroller as RTM Carrier: NXP MK26FN2M0VLQ18
  - Firmware supports:
    - Communication with MCH over IPMI protocol
    - Module identification using FRU Information
    - Module activation/deactivation
    - Sensors identification (SDR information) and monitoring
    - Power Supply and Payload (e.g. FPGA) control and monitoring
  - **Firmware does not support RTM control and monitoring**
- RTM Carrier
  - Board delivered to Łódź on 09.04.2018
  - Current activities:
    - Testing of particular components of the MMC
    - Development of drivers for MMC firmware

RTM Carrier - Module Management Controller (MMC)

- Microcontroller – NXP MK26FN2M0VLQ18
    - Core: ARM Cortex-M4
    - Operating frequency: max. 180 MHz
    - Memory: 256 kB SRAM, 2048 kB FLASH
    - Interfaces: 100 GPIO, 4 x I^2C, 6 x UART, 3 x SPI, USB, 16-bit ADC
- I2C buses:
    - IPMB-L – for communication with MCH
    - SENS – for peripheral devices e.g. sensors
    - RTM – for communication with RTM
- Sensors:
    - Temperature sensors: 3 + 1 (connected to FPGA)
    - Voltage sensors: 10 voltages connected to ADC
- Other components:
    - RTM Hot Swap Controller
    - Digital signature / EEPROM memory

RTM Carrier MMC – Tested Components

Finished tests:

- AMC Handle + LEDs
- Digital signature / EEPROM
- Temperature sensors: 2x MAX6626 + 1x SA56004 (local + FPGA)
- Power sequencer
- ADC for voltage monitoring (10 channels)
- RTM Power Supply Controller
- RTM I2C Communication

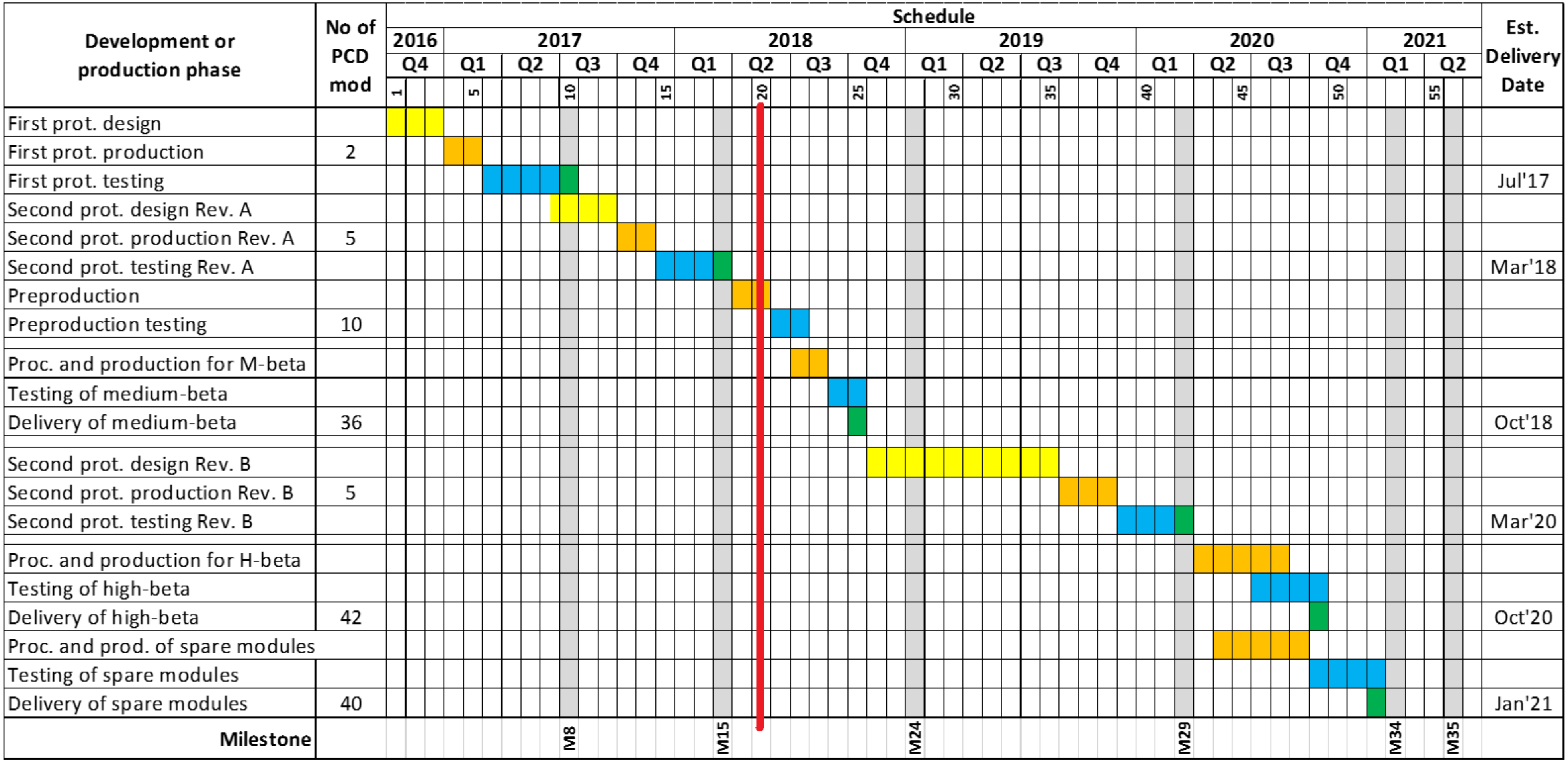
In progress:

- Communication with MCH over IPMB-L bus using IPMI protocol

Issues:

- Bugs in I2C driver from NXP
- Duplicated signals ENABLE for DC/DC converters
- Misleading labels on the schematics e.g. for ADC converters

PDC Development - Manufacture Schedule



Development or production phase	No of PCD mod	Est. Delivery Date
First prot. design		
First prot. production	2	
First prot. testing		Jul'17
Second prot. design Rev. A		
Second prot. production Rev. A	5	
Second prot. testing Rev. A		Mar'18
Preproduction		
Preproduction testing	10	
Proc. and production for M-beta		
Testing of medium-beta		
Delivery of medium-beta	36	Oct'18
Second prot. design Rev. B		
Second prot. production Rev. B	5	
Second prot. testing Rev. B		Mar'20
Proc. and production for H-beta		
Testing of high-beta		
Delivery of high-beta	42	Oct'20
Proc. and prod. of spare modules		
Testing of spare modules		
Delivery of spare modules	40	Jan'21
Milestone		

Testing before Preproduction

- Before the preproduction we be started the following tests need to be finished:
  - Long term reliability tests (min. 30 days).
  - Corner thermal tests in climatic test chamber.
  - EMC/ESD tests for PZD and PPSM, certification for PPSM.
  - Tests with the final RTM-Carrier module.
  - Test with real cavity and Lorentz force detuning algorithms.
- We need more RTM-Carrier modules to perform the required tests.
  - The RTM-Carrier must be in final version.
- At this stage we are not ready for final production.
- We plan the preproduction of next 4 PZD modules as soon as tests above will be succeeded.

QA - Risk Analysis – Old Risks

- Three main risks were identified
  - Undefined or imprecise requirements for piezo driver (piezo capacitance, operation conditions, i.e. piezo temperature, cable length)
    - Problem: Difficult to estimate driver power
    - Countermeasure: Collect and clarify precise requirements, overestimate driver parameters, test with in real conditions in cryostat
    - Clarified and agreed for piezo cable and length
  - Unknown excitation signal and piezo control algorithm (signal shape, frequency, energy)
    - Problem: Difficult to estimate driver power
    - Countermeasure: Overestimate driver parameters, test with various excitation signals, use higher number of pulses for the signal
  - Lack of cooling in rear side of MicroTCA.4 chassis (RTM device)
    - Problem: max. power dissipated on RTM in MicroTCA.4 limited to 30 W
    - Countermeasure: Change PCS architecture (external power supply), high efficiency design, high quality component
    - PWM driver and external PSM allows to control 2.2 – 10 uF piezos

QA - Risk Analysis – New Risks

- Lack of RTM-carrier module prevents to make the required tests:
    - Long term reliability tests (min. 30 days)
    - Corner thermal tests in climatic test chamber
    - EMC/ESD tests and certification
    - Tests with final RTM-Carrier module
- Lack of test with real cavity and Lorentz force detuning algorithms
- High risk of project delay - at this stage we are not ready for final production
- Long-delivery time or unavailability of components required to manufacture PCD or PPSM
- Limited resources assigned for the project

PCD - Reliability Prediction

- Method is known
- The Failure Rate will be calculated using the
  Telcordia Reliability Prediction Procedure SR-332 (part of FR-796)

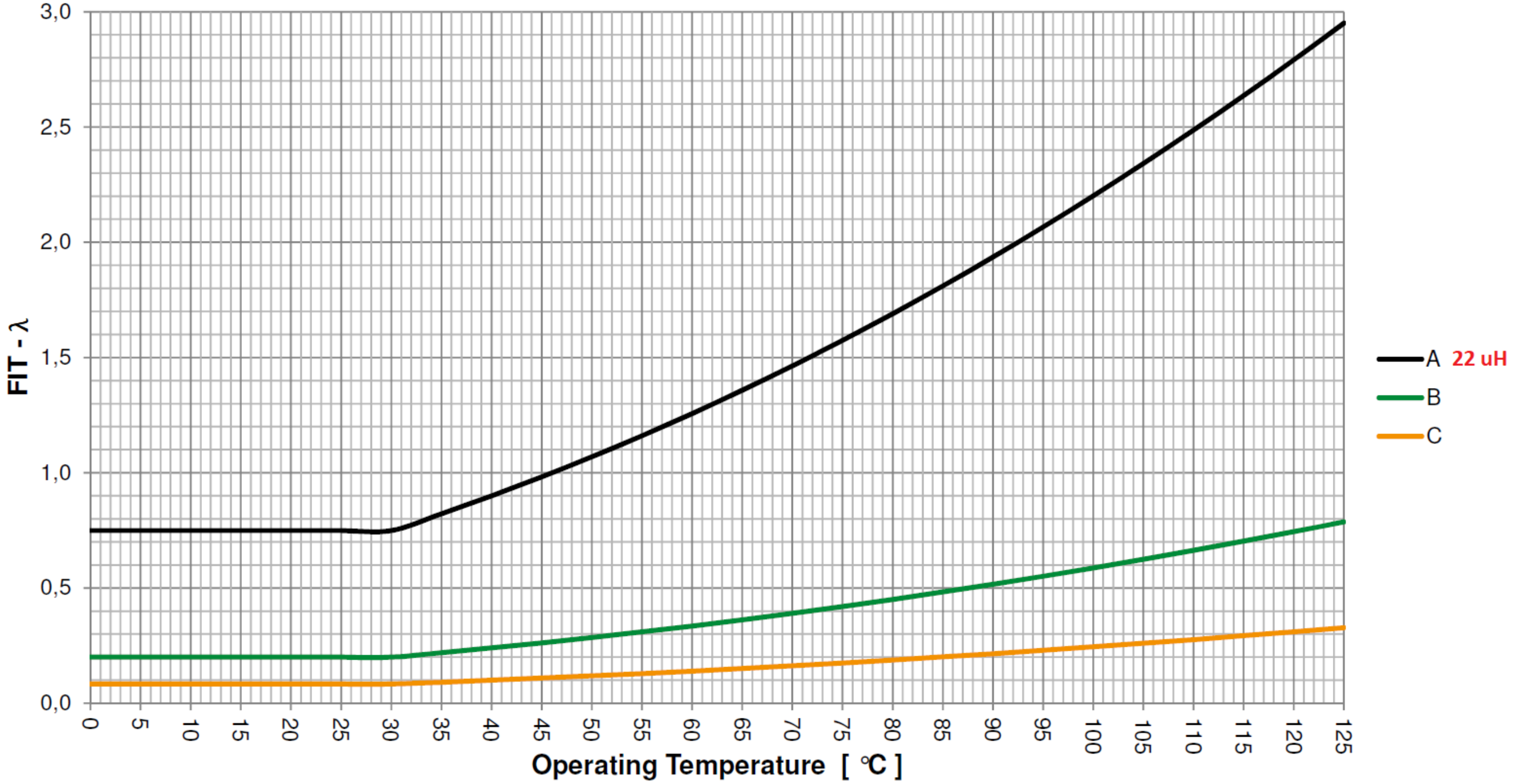
$$MTBF = \frac{1}{\lambda_{equip}} = \frac{1}{\pi_E \sum_{i=1}^{m} (N_i \cdot \lambda_{ssi})} \times 10^9 \text{ (Hours)}$$

$$\lambda_{ssi} = \lambda_{Gi} \cdot \pi_{Qi} \cdot \pi_{Si} \cdot \pi_{Ti}$$

- λ_{equip} is total equipment failure rate (FITs = Failures in10^9 hours)
- We need to have the final and fix BOM for PCD and PPSM
- We need to know the failure rates for all components of both devices
- Military handbook with predicted failure rates for various components could be used
- MTBF will be calculated when all tests will be succeeded and we will know the final BOM
- Question: which temperature will be in cubicle or MTCA.4 chassis?

Example – 10^9 FIT for 22 uH Coil

5.1 Table λ-Values



Summary

- 6 Piezo Driver modules fabricated
  - Both piezo channels (A and B) are in operation
  - Tests carried with capacitors succeed (2.2 uF - 40 uF)
  - Tests carried with Noliac NAC 2022 H30 piezos
- Piezo Power Supply Module Prototype built and tested
  - Need power control function
- The board is not ready for final production
  - Next revision is expected
- More tests required
  - Not tested with the final RTM-carrier
  - We need to schedule tests in cryogenic conditions with suitable cable and connectors
- Need final approval for Fisher connectors
- Need rack drawing including piezo cabling and length of cables

Thank you for your attention