High-power Piezo Driver for Fast Cavity Tuning

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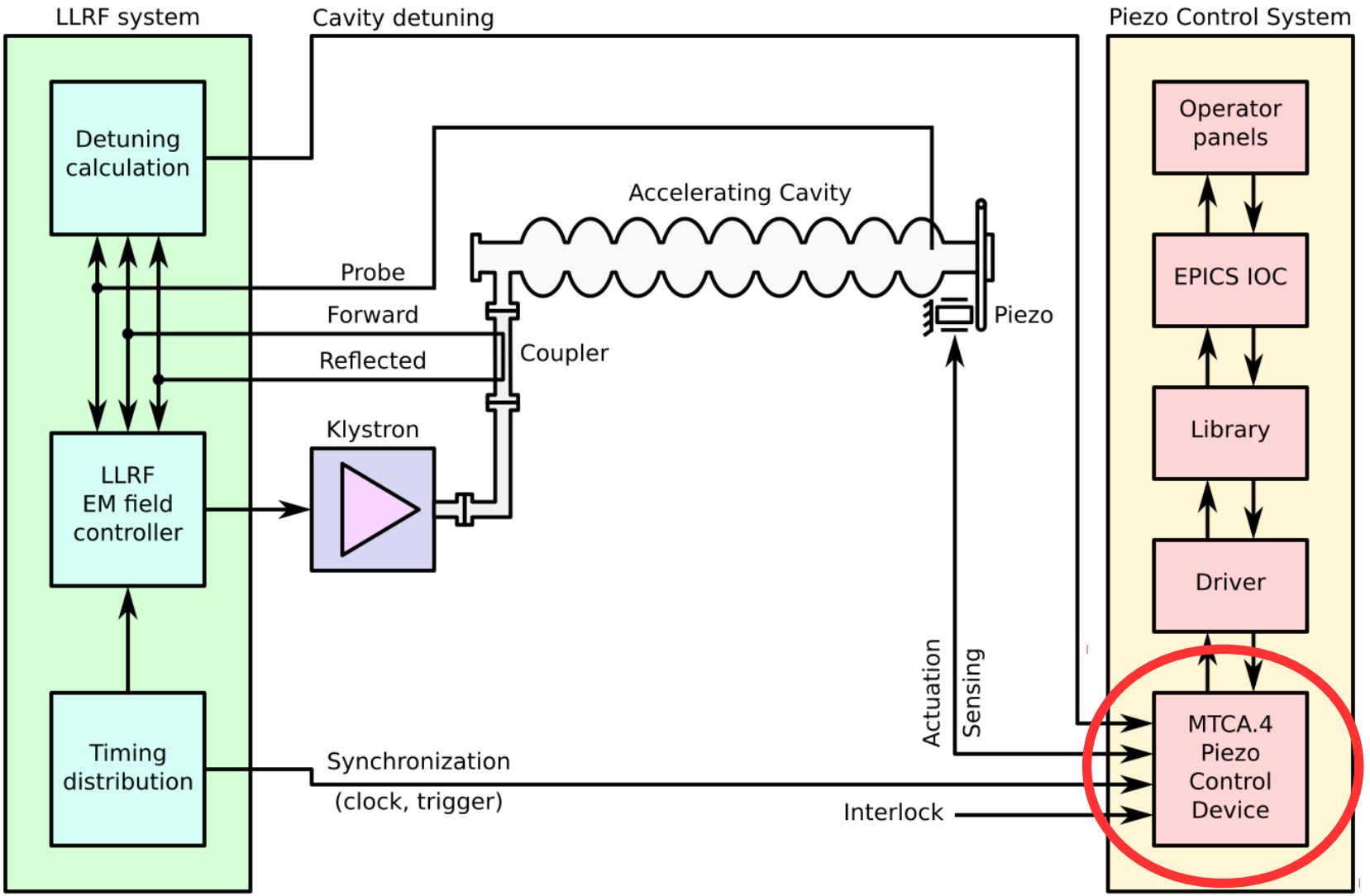
Agenda

- High Power Piezo Driver - Motivation
- Limitations of MicroTCA.4 Technology
- Possible Implementations
- First Prototype
- Initial Results
- Conclusions

High Power Piezo Driver - Motivation

- This work is being done in frame of the Polish in-kind delivered by the Polish Electronic Group (PEG) within in-kind agreement signed between PEG and ESS on 2016-11-08, (together with Schedule AIK 8.2, signed 09.2017, ESS-0060409)
- Department of Microelectronics and Computer Science, Lodz University of Technology as a member of PEG consortium is responsible for piezo driver system delivery for elliptical cavities of ESS linac.

Piezo Compensation System



Functional Specification for Piezo Control System at ESS

- Provide a control signal for piezo actuators of medium-, high-beta and spoke cavities of ESS accelerator operating in cryogenic temperatures
- Measure cavity deformation using piezo device as sensor element
- Support two independent channels with configurable mode of operation:
  - Piezo actuator and/or
  - Piezo sensor
- Compatible with MicroTCA.4 standard
- Provide health monitoring and diagnostics
- Assure safe operation of piezo actuator

Piezo Actuators selected for ESS

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

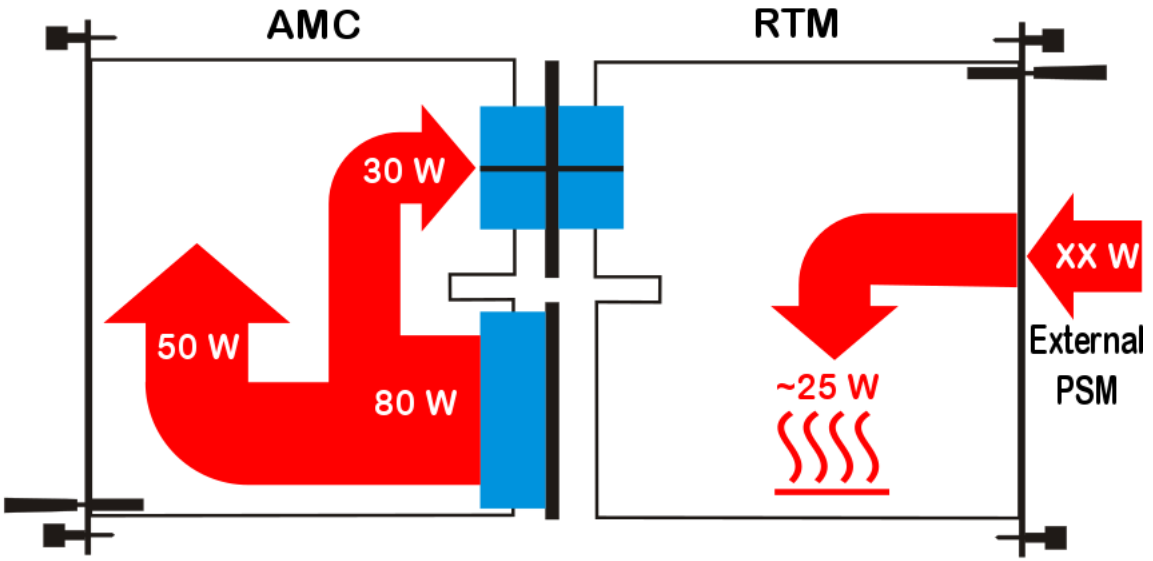
Piezo Control Device - Electrical Specification

Parameter	Value
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
Piezo capacitance	6.6 – (9.5 µF) 32 µF (room temperature)
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

Possible Solution of Piezo Driver MicroTCA.4 Implementation

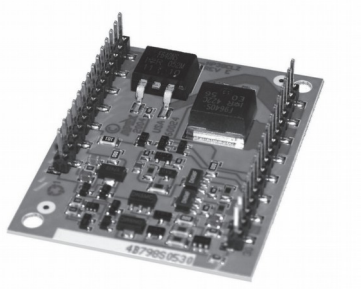
AMC + RTM card + External PSM

1. 5-10 Watts for Payload (from AMC)
2. Unlimited power for Piezo Driver from external power supply
3. Limited piezo power by cooling capability to ~20-25 Watts



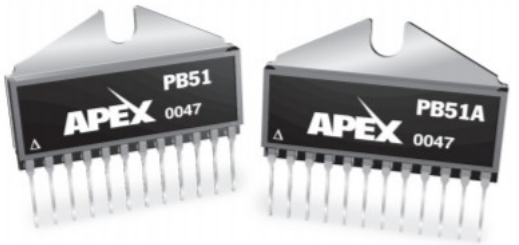
Piezo Driver - Linear Amplifier

Linear Class AB power booster amplifiers could be applied to design piezo driver



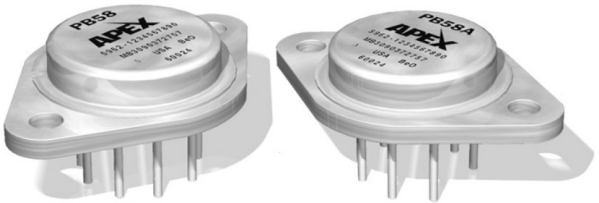
Advantages

- Simple design – preamplifier and booster
- Wide supply range: ±15V to ±150V
- High power amplifiers available



Disadvantages

- Poor efficiency of Class AB booster (reaching 50%) limits the total driver power in MicroTCA.4
  - AMC module: ~30 Watts
  - RTM module: ~10 Watts
  - RTM module + PSM: ~40-50 Watts



Problems

- Lack of power and limited cooling in AMC and RTM slots
- Usage of external power supply does not solve the problem

Piezo Driver – Class-D Amplifier

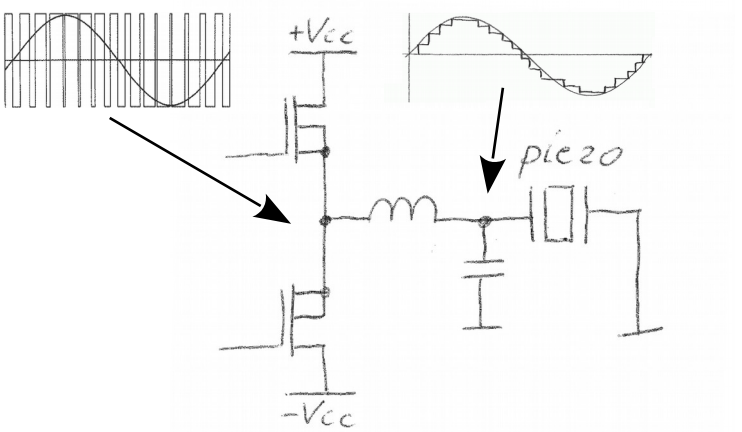
High efficiency Class-D amplifier (PWM) could be applied to drive piezo actuators

Advantages

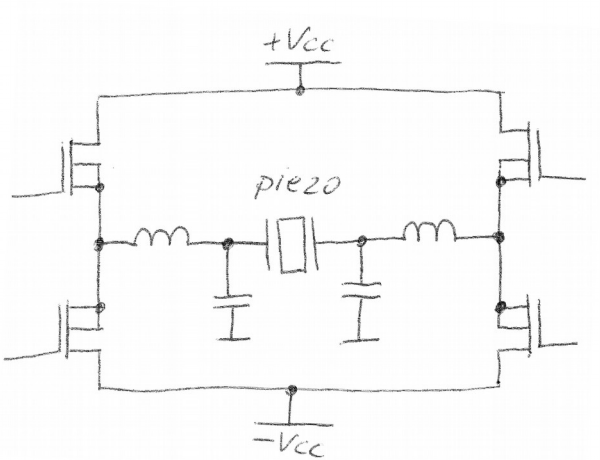
- High efficiency reaching 90-95%
- Wide supply range: ±15 V to ±200 V
- Full H-bridge solution could be applied to lower the power supply voltage, e.g. ±50 V gives ±100 V
- High power amplifiers easily available (100-500 W)

Disadvantages

- More complex design
- Need more space on PCB
- Requires careful filtering and PCB design to remove PWM carrier frequency and control EMI distortions



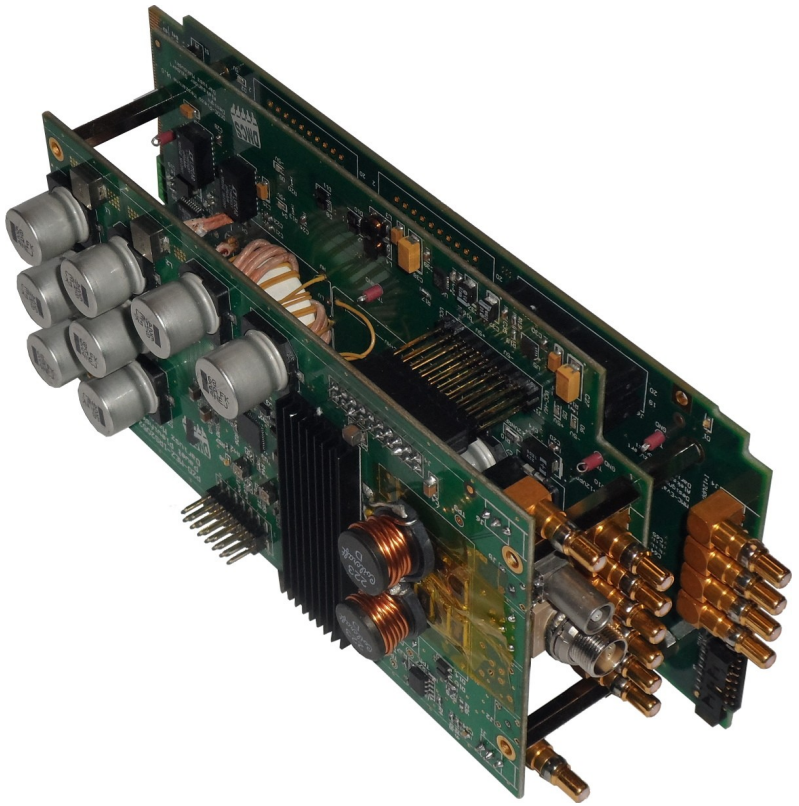
Half-Bridge solution

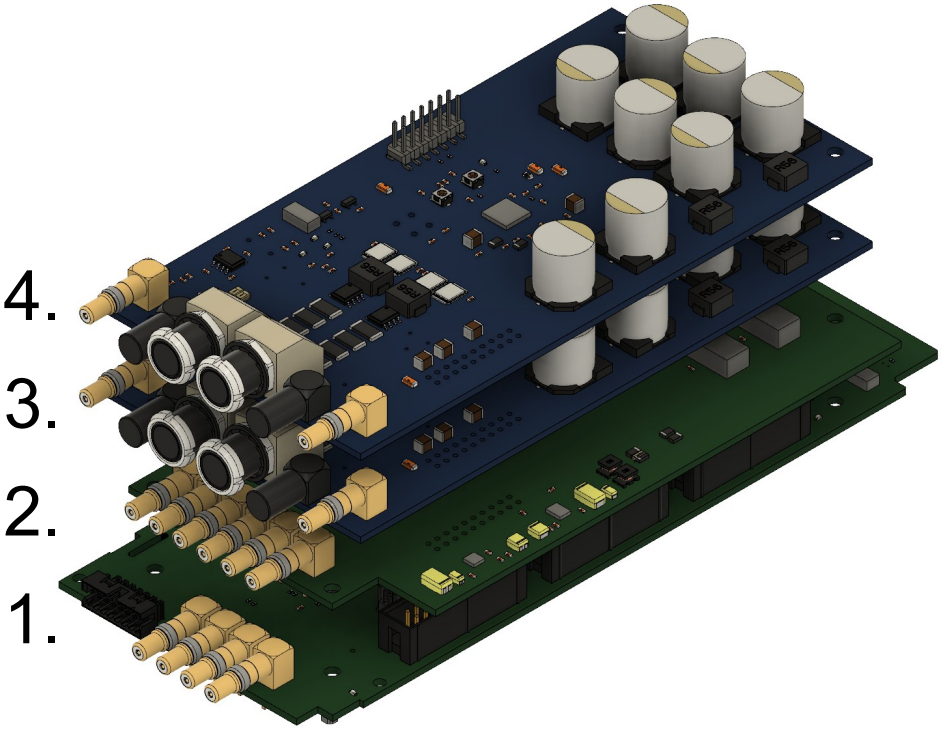


Full-Bridge solution

PCS – First Prototype

4. Piezo Driver module #1
3. Piezo Driver module #2
2. DC/DC Boost converter
1. AMC Carrier Module with MMC

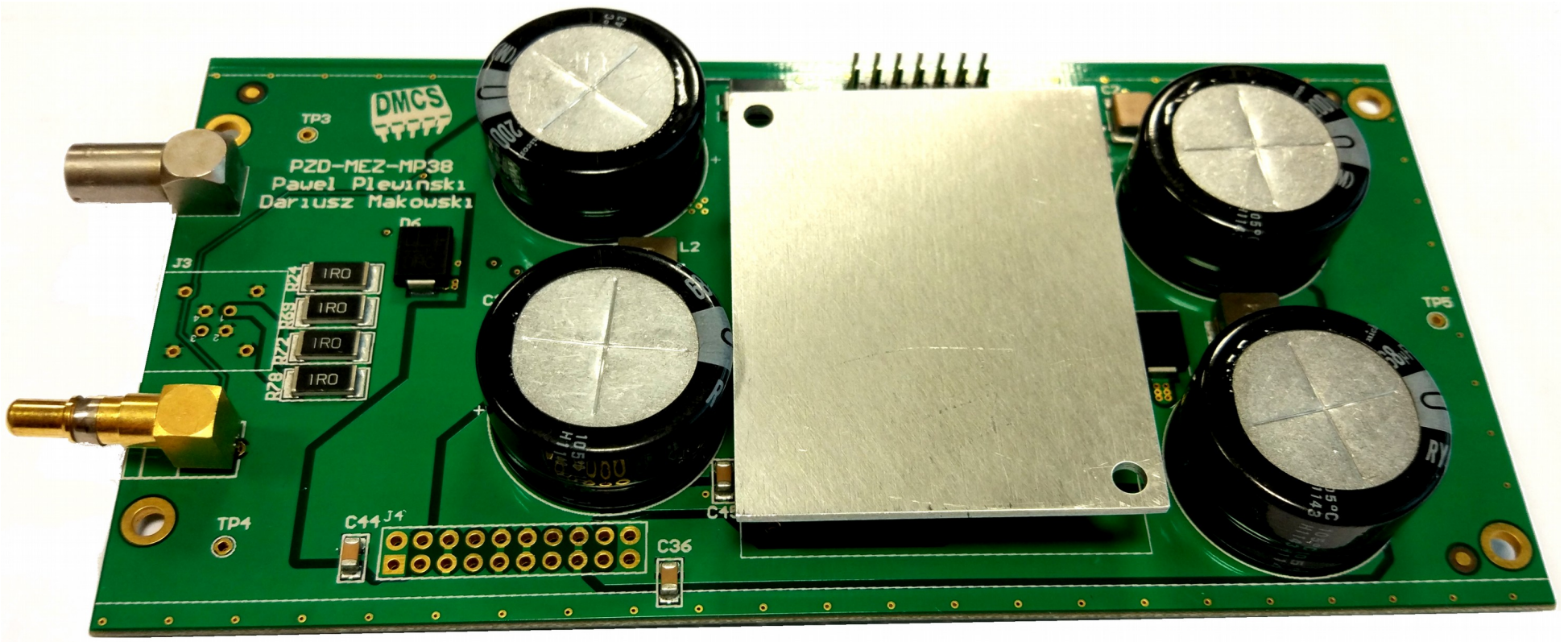




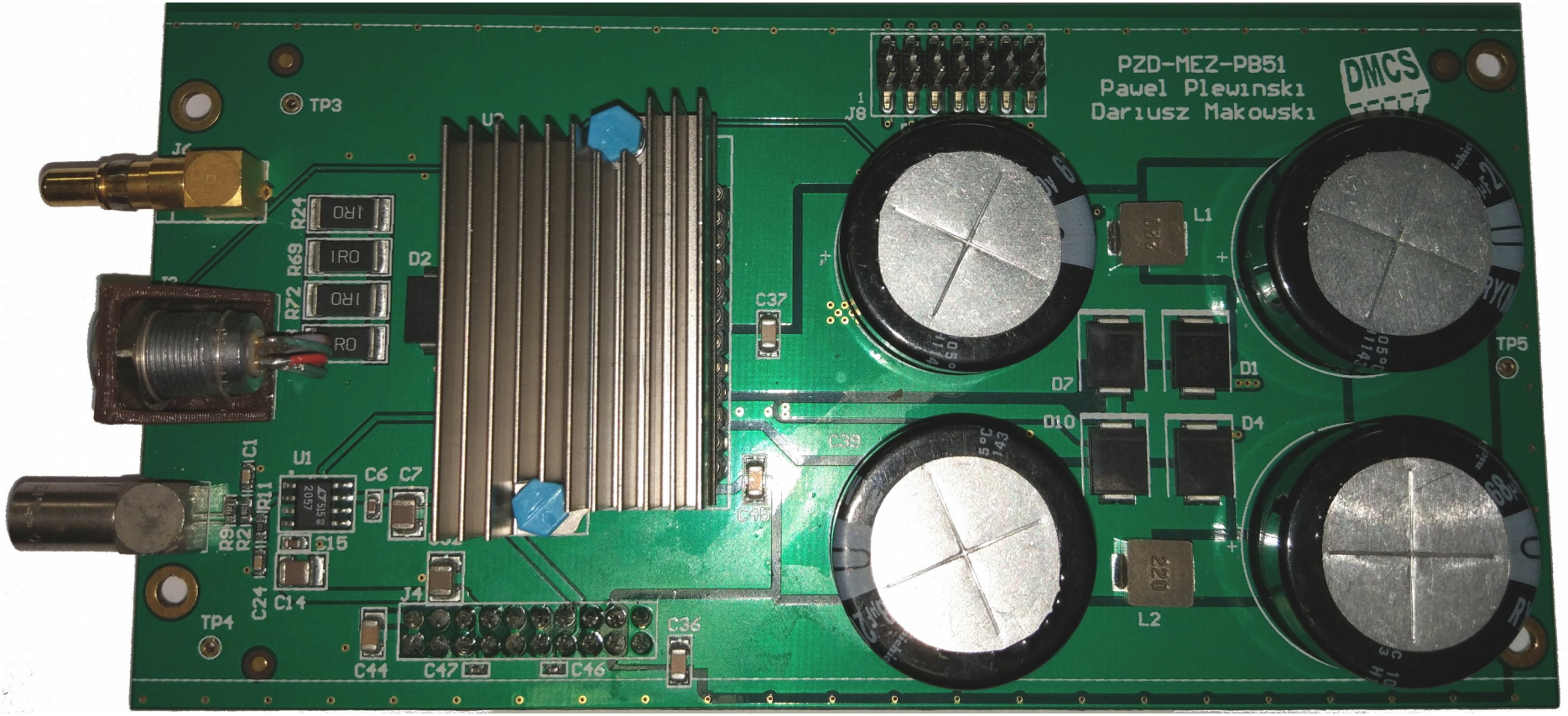
A few amplifier boards were designed:

- Apex PB 51 Class-AB amplifier
- Apex MP38 Class-AB amplifier
- International Rectifier Class-D amplifier

Class-AB Piezo Driver – Version 1



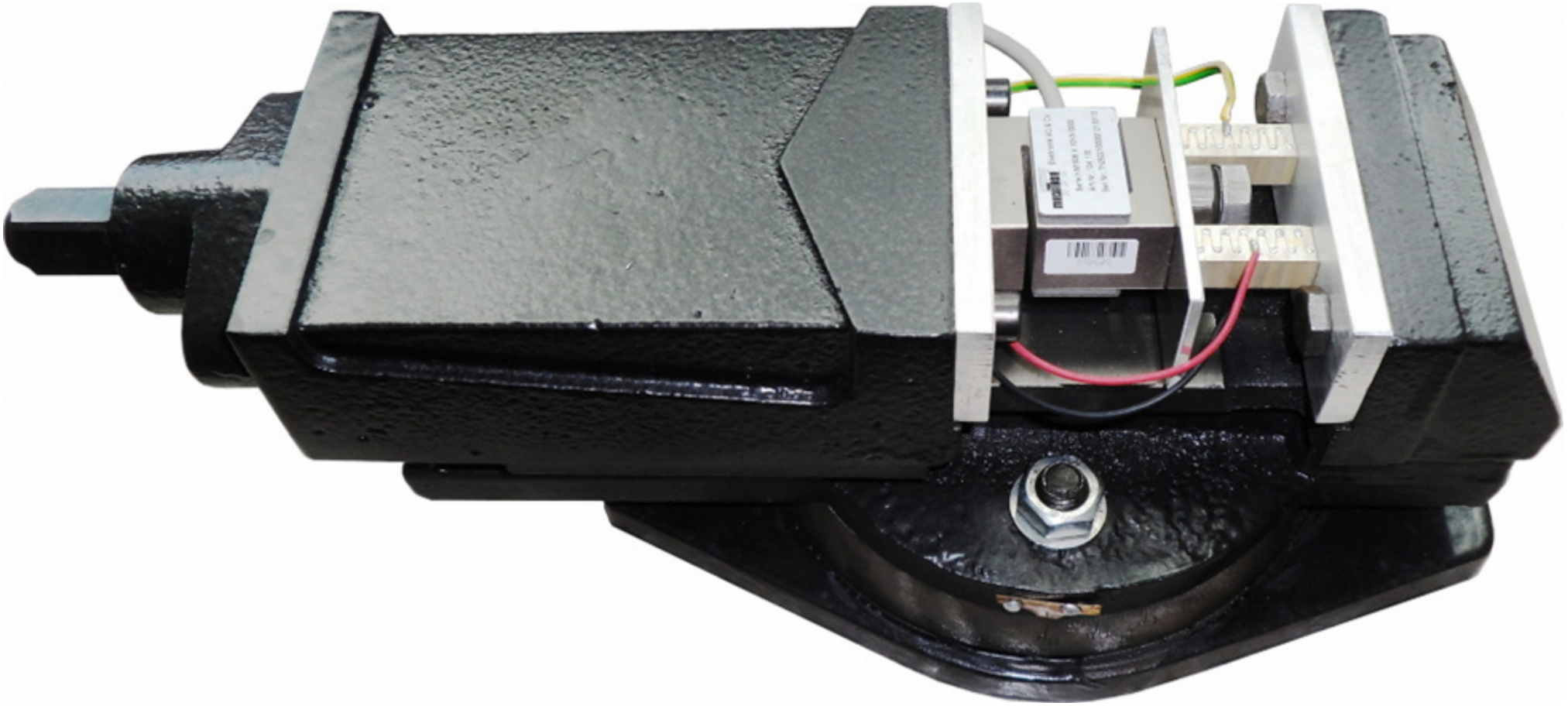
Class-AB Piezo Driver – Version 2



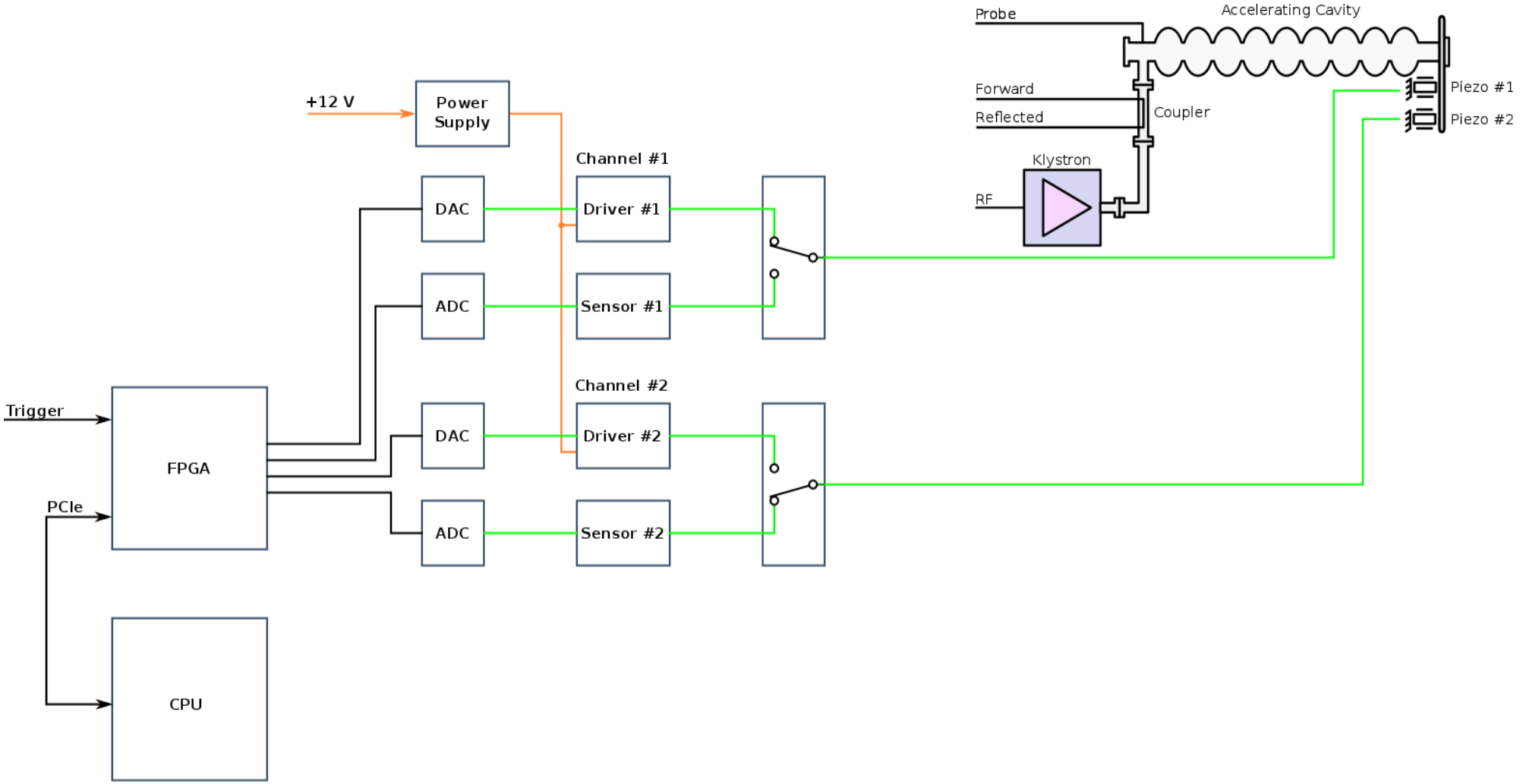
Piezo Controller and Piezo Monitor

PCS Development and Testing at TUL-DMCS

Piezo Actuator, Sensor, and Tensometer installed in Machine Vice



Tests at Freia Facility, Sweden - Evaluation of Piezo Driver in Open Loop



Piezo Actuators used During the Freia Tests

Piezo type	Noliac NAC 2022 H50-C01	PI PICMA P-888.91
Dimensions	10 x 10 x 50 mm	10 x 10 x 36 mm
Cell material	NCE51F	PIC252
Number of cells	25	
Capacitance (room temperature)	9.5 µF ±15%	13 µF ±20%
Capacitance (cryo temperature, 20 K)	3.14 µF	5.18 µF
Max. free stroke	79.2 µm	32 µm
Blocking stroke in cryo temp.	5 µm	TBD
Blocking force max.	4200 N	3800 N
Max. operating voltage	200 V	-20 to 120 V
Unloaded resonance frequency	248 kHz – 11 kHz	40 kHz

Summary of Freia Tests

Continuous wave operation (1 kHz sine wave)

- Both piezos connected in parallel to a single driver
  - output voltage amplitude 132 Vpp before reaching the protection limit
- Two drivers driving separate piezos
  - output voltage amplitude of 128 Vpp before reaching the current limit in case of Noliac NAC 2022 H50-C01
  - output voltage amplitude of 120 Vpp before reaching the current limit in case of PI PICMA P-888.91.

Pulsed-mode operation (10 pulses, 1 kHz sine, 14 Hz repetition rate)

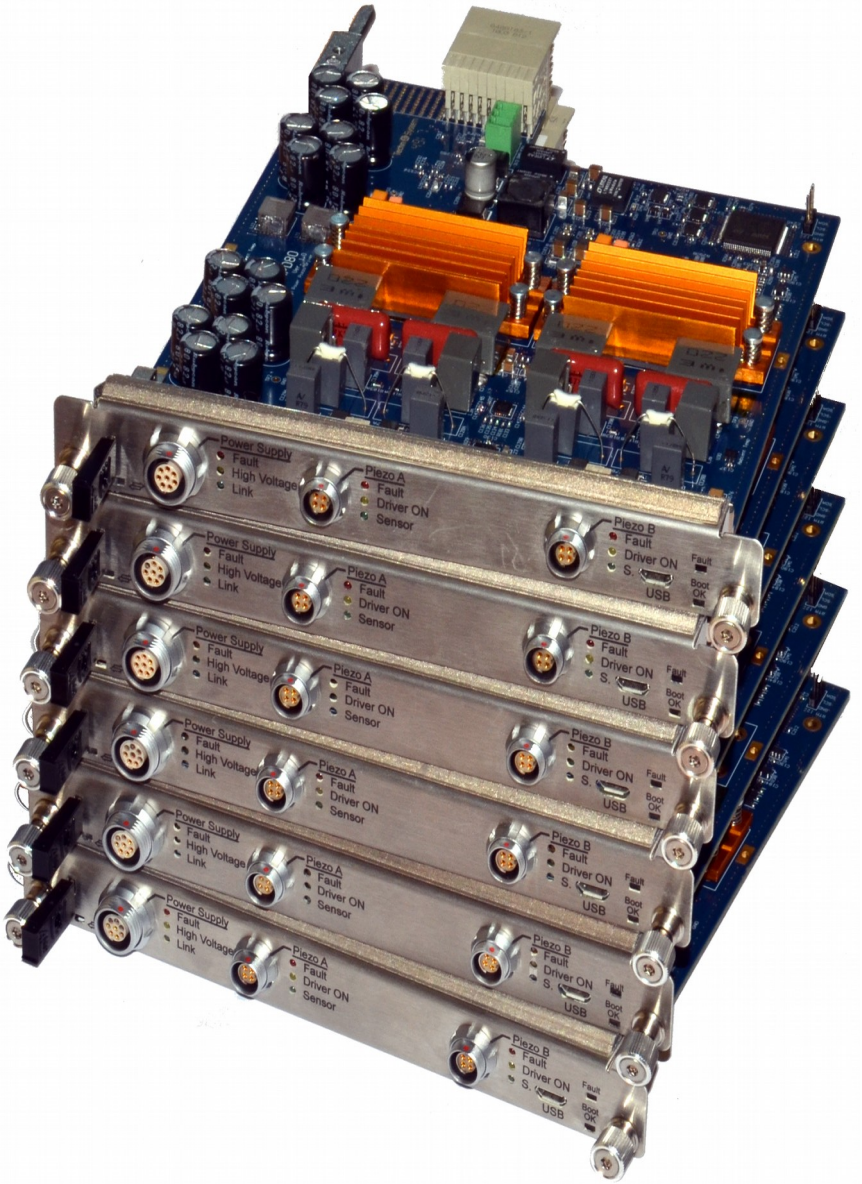
- Both piezos connected in parallel to a single driver
  - maximum of 180 Vpp amplitude; the driver was not disabled by protection circuit.
- Both piezos connected to two piezo driver modules
  - maximum of 180 Vpp amplitude on both piezo actuators; none of the drivers was disabled by protection circuit

Piezo Driver RTM Module – Second Prototype

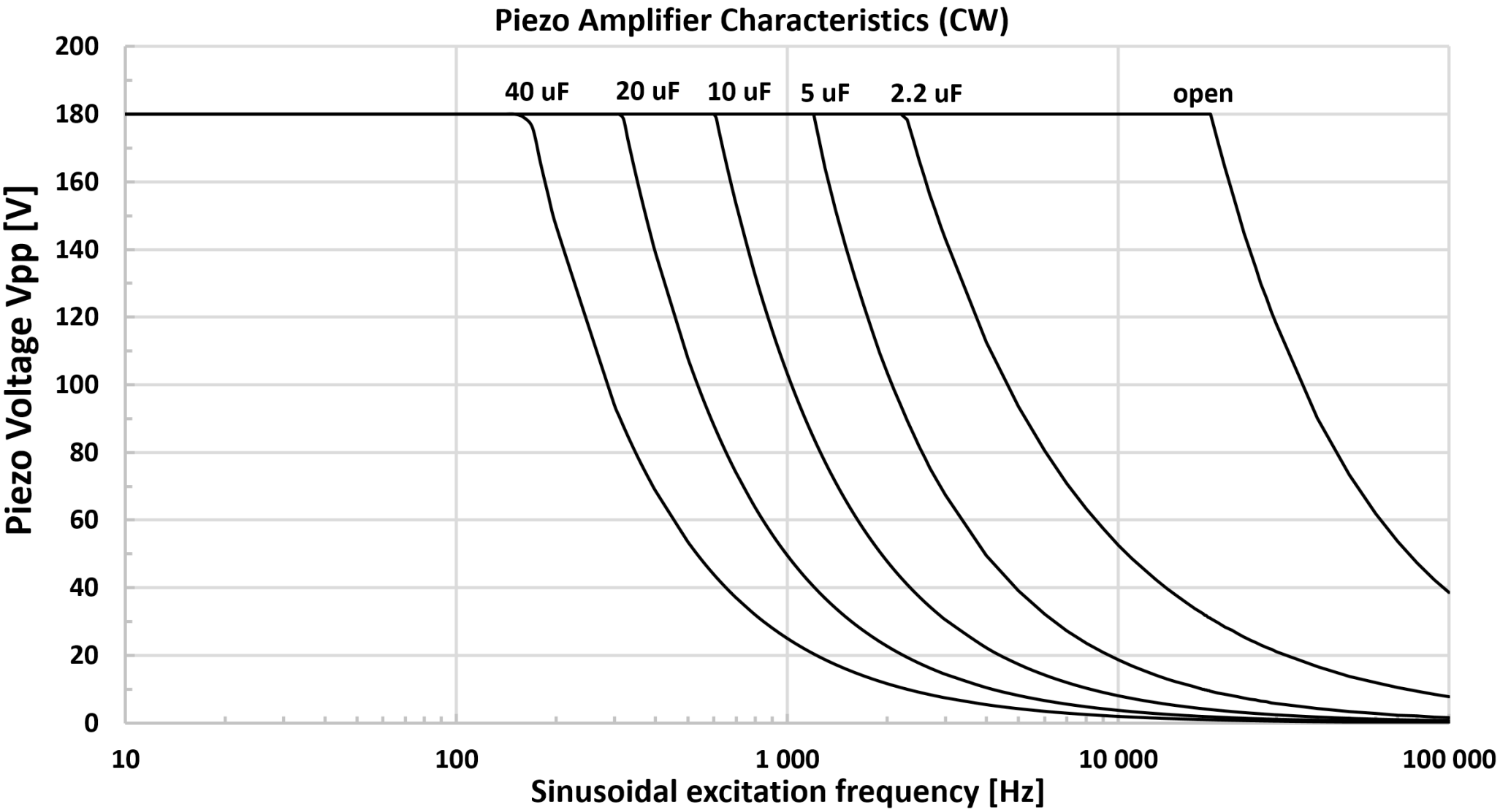
- 2 channels of high power piezo driver
  - 2x 35 Watts (MTCA.4 power supply)
  - 2x 100 Watts (external power supply)
- Piezo driver and piezo sensor mode
- Build-in diagnostics (advanced implementation of RMC)
- Various protection mechanisms for both Piezo channels to protect driver itself and piezo actuator
- Proposed new digital high-voltage class D1.2-HV (±50 V) on Zone 3 (MTCA.4 power supply)

Current Status

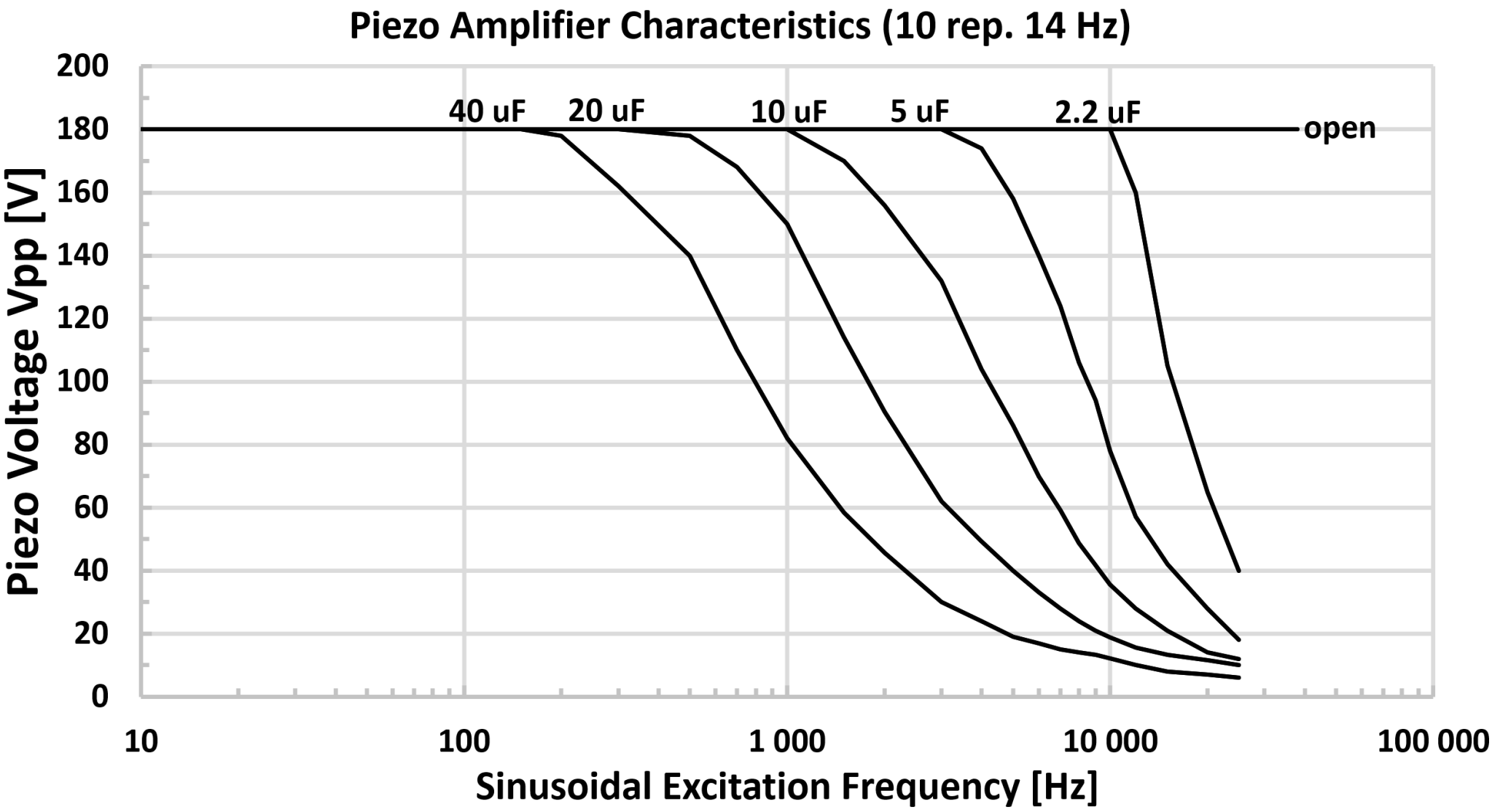
- 6 PCD modules fabricated and tested
- Design optimised for 2.2 uF piezo and 30-45 m long cables
- Short-term tests finished successfully
- More tests in progress:
  - Long-term reliability tests
  - Corner thermal tests in climatic test chamber
  - EMC/ESD tests and certification
  - Tests with final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



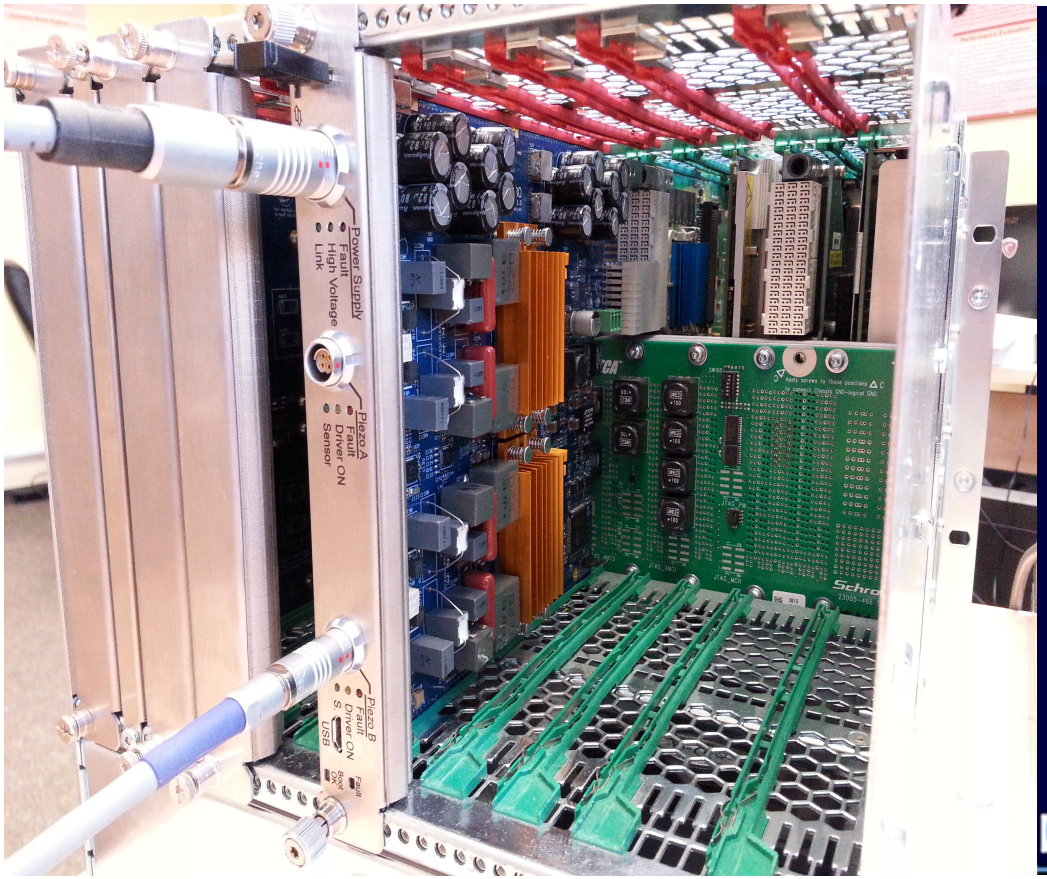
Piezo Control Device – SOA Characteristics in CW Mode

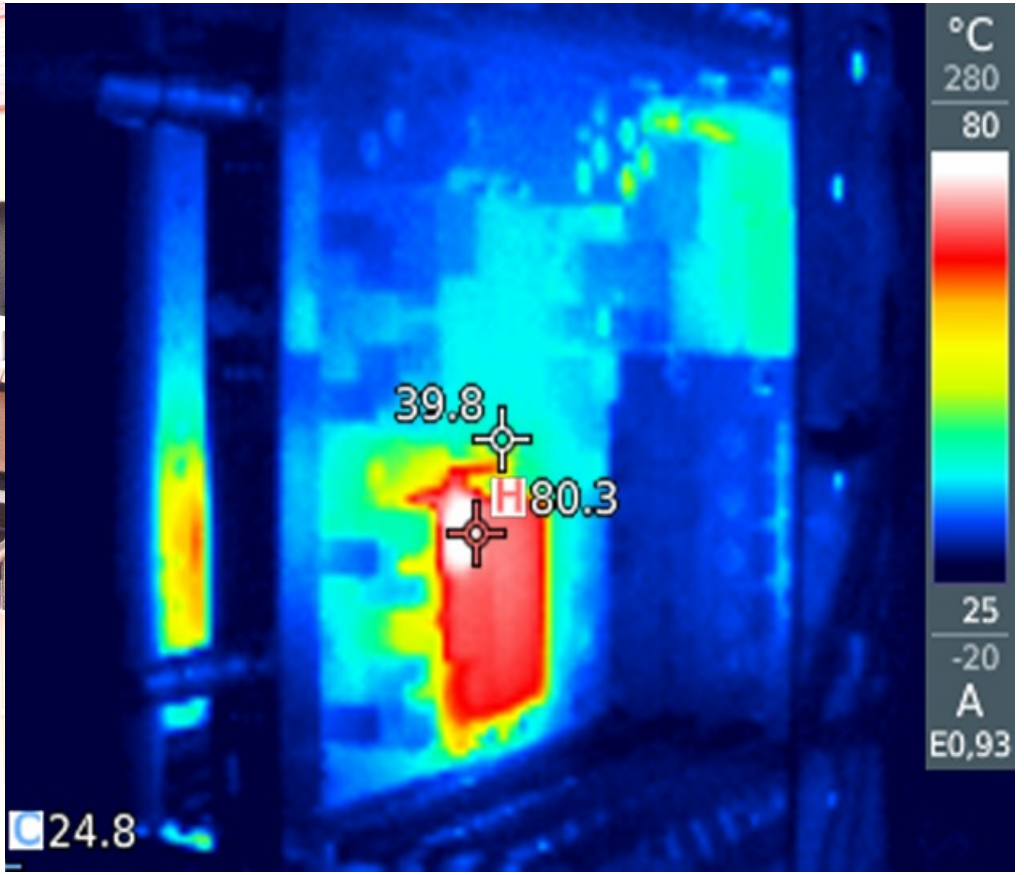


Piezo Control Device – SOA Characteristics in Pulsed Mode



Thermal Measurements





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.

Summary

- Various MicroTCA.4 piezo driver solutions analysed and tested
- Designed a two channel 40 Watts PWM piezo driver prototype (HPD80)
- Two solutions available:
  - Internal MicroTCA.4 and,
  - External power supply
- Suitable for driving large piezo actuators (room temperature capacitance >30 µF)
- Prototype successfully tested in laboratory and cryo-conditions
- Design optimised for long-term accelerator operation (MTBF ~120 000 h @ 25ºC)
- Carefully designed for both conducted and radiated EMI
- More tests planned with second prototype

Thank you for your attention