Design of preamplifier cards for multipad PICOSEC detector

Marinko Kovacic

University of Zagreb, Faculty of electrical engineering and computing
Department of Electric Machines, Drives and Automation

VISC at CERN SY-EPC-HPM

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UNIVERSITY OF ZAGREB
Faculty of Electrical Engineering and Computing

CERN

Home institution

- University of Zagreb, **Faculty of electrical engineering and computing**
- **Department of Electric Machines, Drives and Automation**
- Founded in 1925
- Head of the department:
  - Assoc. prof. Igor Erceg, Ph.D.
- Address:
  - Unska 3, HR-10000 Zagreb, Croatia
- Department staff
  - 5 full professors
  - 2 associate professors
  - 6 assistant professors
  - 18 PhD students (teaching assistants + researchers)
- Students
  - around 70 mentored undergraduate students (study years 3 to 5)

- Technical and scientific areas:
  - **Electrical machines**
  - Electrical drives
  - **Power electronics**
  - **Control of electrical drives**
  - Industrial automation
  - Interactive simulations and virtual reality (defense technology)

Few facts about me

Education:

- 2010 – 2017: **PhD**, Thesis title: *Design optimization method of three level inverter for auxiliary power supplies in railway vehicles,* University of Zagreb
- 2004 – 2009: **Dipl. Ing. Electrical Engineering**, University of Zagreb

Areas of interest:

- Power electronics, magnetics and **EMC**
- Electrical machines
- **Instrumentation**, metrology and embedded
- RF – hobby level

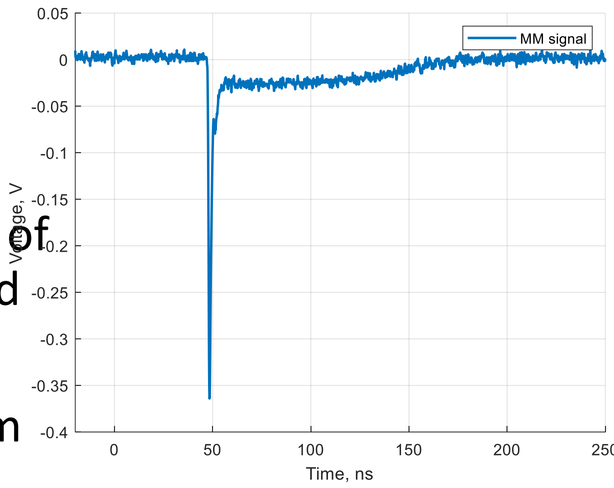
Employment:

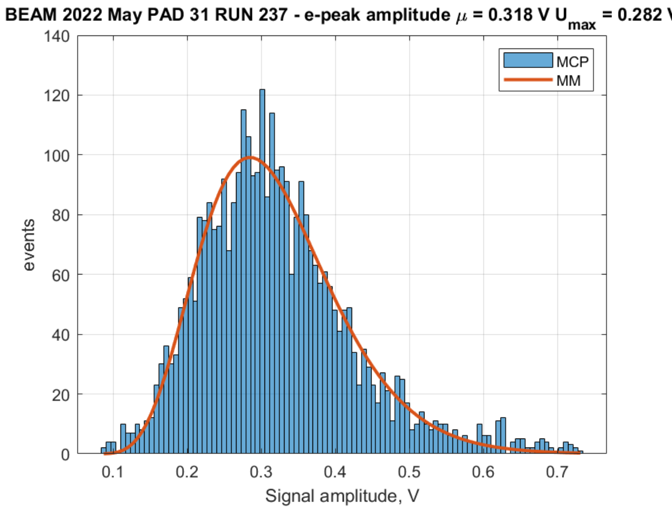
- 2020 – : **Visiting Scientist**, CERN SY-EPC-HPM, Geneva
- 2019 – : **Assistant professor**, University of Zagreb
- 2017 – 2019: **Postdoctoral researcher**, *University of Zagreb*
- 2012 – 2017: **Teaching assistant**, *University of Zagreb*
- 2011 – 2012: **Intern**, *UTRC, Hartford CT, USA*
- 2009 – 2011: **Junior Researcher**, *University of Zagreb*

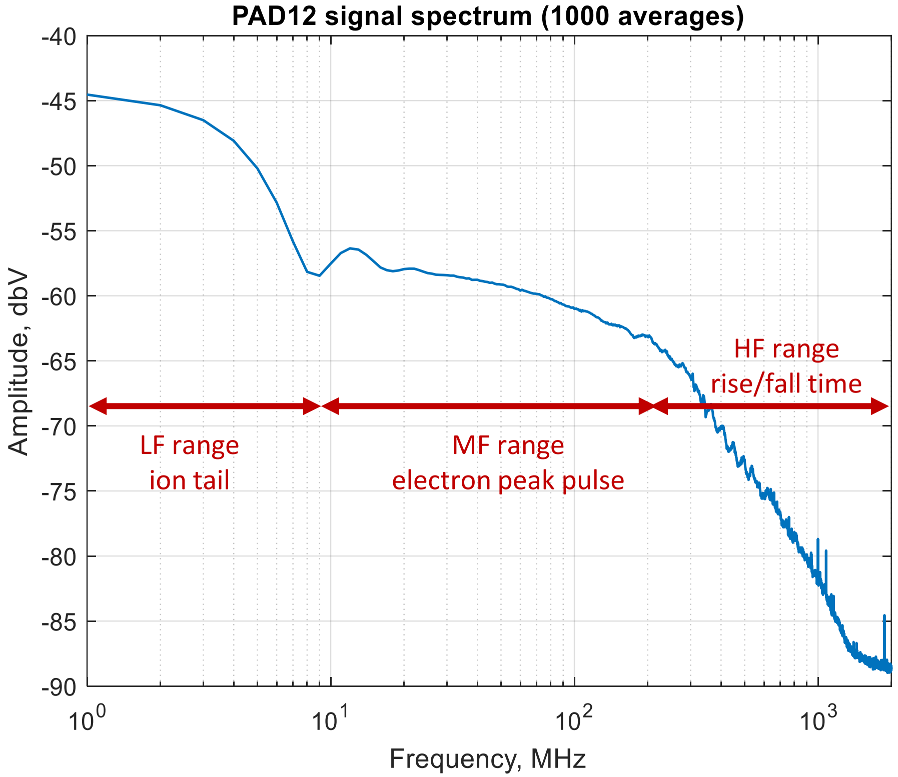
https://www.fer.unizg.hr/en/marinko.kovacic

Introduction

- The signal of PICOSEC micromegas detector is composed of two **negative** pulse components with different lenght and amplitude (electron peak and ion tail).
- Fast Fourier transformation was made on the signals from the 100 ch multipad PICOSEC (with CIVIDEC).
- Representative spectrum of signal was obtained by averageing 1000 pulses.
- Three distinctive regions can be observed in the spectrum
  - First one is from 1M Hz to 10 MHz. It most likely corresponds to the ion tail that is pulse whith duration of cca. 100 ns – 10 MHz.
  - Second one is from 10 MHz to 200 MHz and most likely corresponds to the electron peak pulse.
  - Third region from 200 MHz to 2 GHz is related to the risetime of the signal.
- To ensure signal integrity, the amplifier should be very fast with a bandwith of arround **1 GHz.**
- Largest signals observed with CIVIDEC in order of **700 mV.**

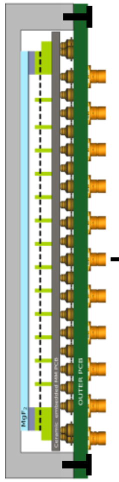






Standard PICOSEC readout

- Currently used Picosec FE and Data Acquisition:



OR

Amplification: CIVIDEC C2 (40 dB, 2 GHz), https://cividec.at

Digitization 1: LECROY WR8104 oscilloscopes operated at 1.0 GHz, 10 GSps.)

Digitization 2: SAMPIC (1.0 GHz analogue bandwidth, 6.4 / 8.5 GSps, 1 V dynamic range)

More details A. Utrobicic VCI 2022 https://indico.cern.ch/event/1044975/contributions/4663685/

Requirements for the preamplifier

- **Gain** – Wideband, around 40 dB,
- **Bandwidth**: 5MHz - 1000MHz
- **Low noise** – timestamping of low amplitude pulses.
- **Linear** for the output pulses up to -1V – to comply with SAMPIC.
- **Spark protection** – non-resistive detector.
- **Small footprint** – 7x10mm to fit to multipad grid.
- **Minimal crosstalk** between channels.
- **Low power** consumption – CFD simulations needed to determine max.
- **Single supply** if possible – simplicity.
- **Good immunity** to external interferences.
- **Low cost.**

S parameters

- Amplifier is considered as an active two port network.
- S parameters (scattering) of a two-port network
  - **S11** – input reflection coefficient (can be used to calculate **input impedance of the amplifier**)
  - **S21** – forward transmission coefficient (**transfer function of the amplifier**)
  - S12 – reverse transmission coefficient
  - S22 – output reflection coefficient
- S parameters are measured having in mind certain referent impedance(e.g., 50 Ohm) and are frequency dependant.
- To measure S parameters, it is most convinient to use calibrated VNA (Vector Network Analyzer).

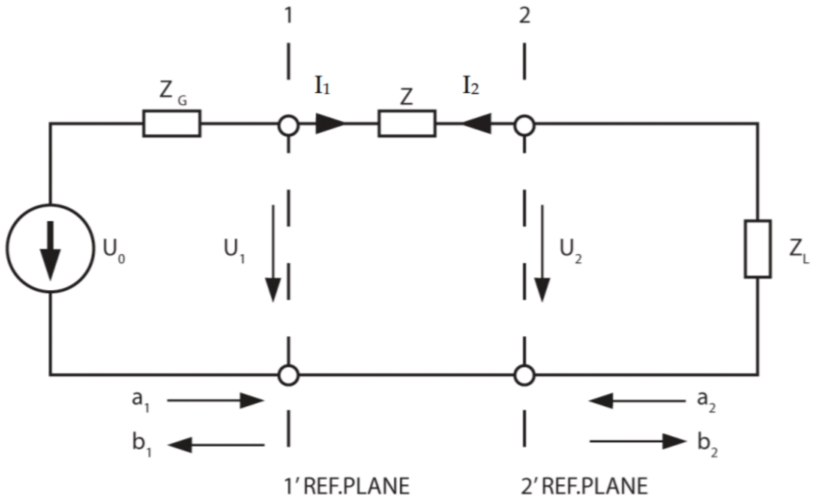


Fig. 1: Example for a 2-port network: a series impedance Z

$$b_1 = S_{11}a_1 + S_{12}a_2$$
$$b_2 = S_{21}a_1 + S_{22}a_2$$

or, in matrix formulation

$$\mathbf{b} = \mathbf{S}\,\mathbf{a}$$

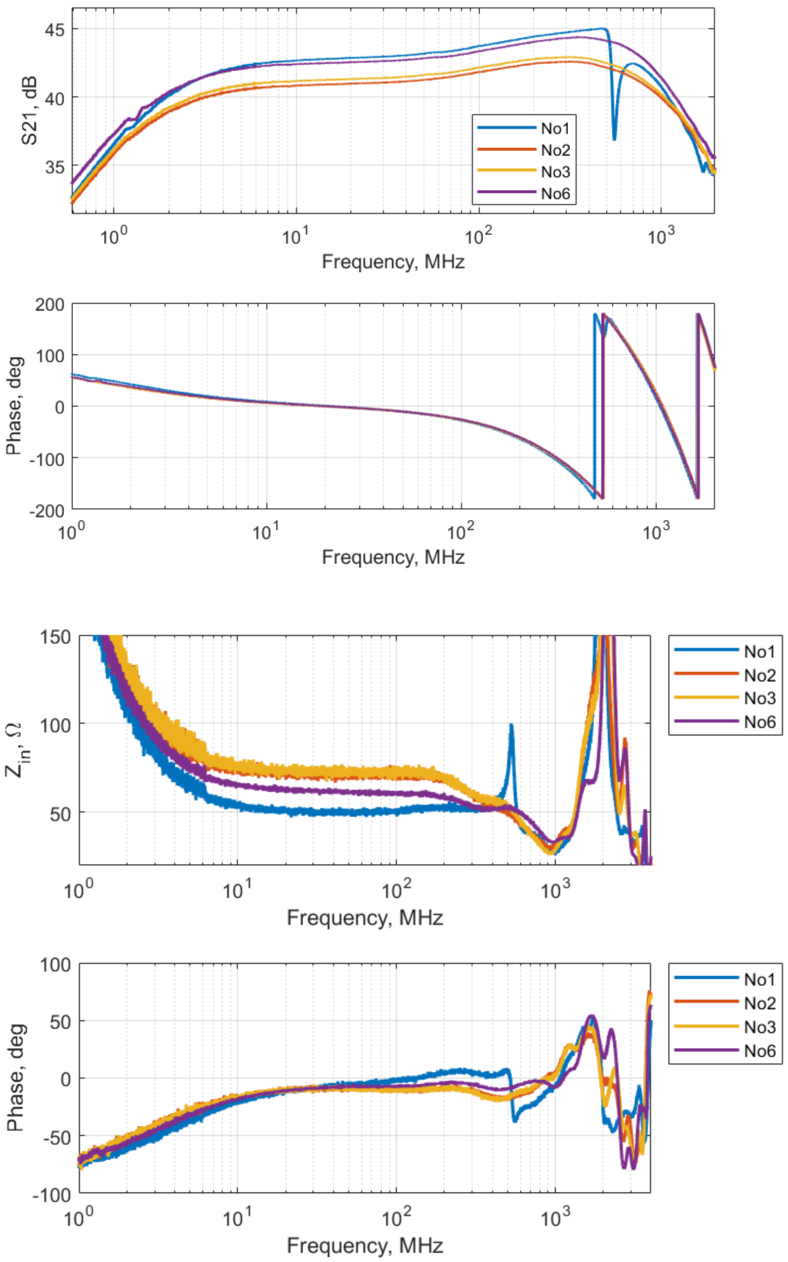
If we want to calculate input impednce:

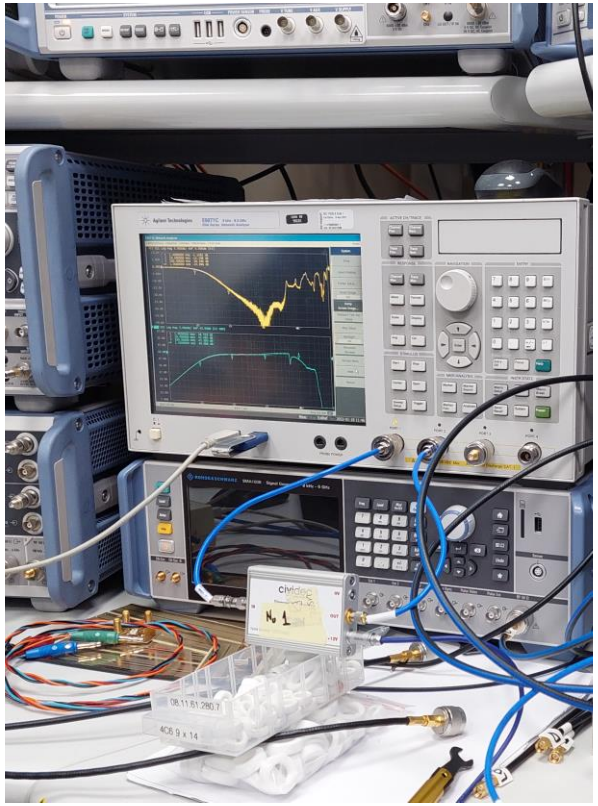
$$Z_{in} = Z_0 \frac{1 + S_{11}}{1 - S_{11}}$$
$$Z_0 = 50\Omega$$

For more details see: https://cds.cern.ch/record/1415639/files/p67.pdf

First VNA measurements CIVIDEC

- Measurements were performed to obtain baseline for design of custom preamplifiers.
- Agilent E5071C VNA was used to perform the measurements (by Daniel Valuch RF group).
- Before each of the measurements VNA was calibrated with SMA standards (open, short, through, 50Ω)
- Performed on 4 CIVIDEC amplifiers.
- Measurements were performed in the linear region (well below 1 dB compression point).
- Measurements show variations in gain (S21) and input impedances of the CIVIDEC amplifiers
- Amplifiers achieve claimed gain of 43 dB, but the bandwidth is lower than 2 GHz.





Important finding – RF pulse amplifier for CVD diamond detectors

- **RF pulse amplifier** for CVD diamond particle detectors (C. Hoarau et al 2021 JINST 16 T04005)
  - **Benefits**: low power, low noise, single polarity supply, high gain, fast rise time, low price, standard components, small dimensions…
  - Performance very promising, but there no discharge protection and the time resolution stated in the paper in range of 40 – 100 ps (no details about the measuring method).
  - This was motivation for development of custom-made amplifier for PICOSEC detector with integrated discharge protection:
    - 2 original preamp ordered from LPSC
    - Development of 10 channel preamplifier boards started.

RF pulse amplifier for CVD-diamond particle detectors

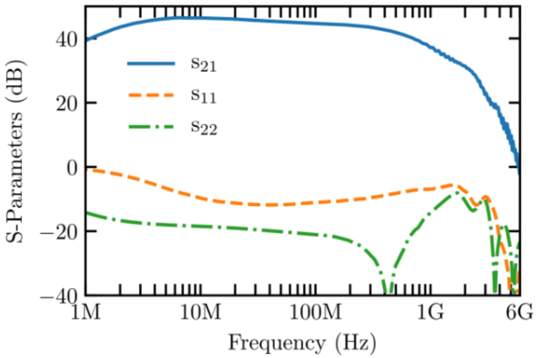
C. Hoarau, G. Bosson, J.-L. Bouly, S. Curtoni, D. Dauvergne, P. Everaere, M.-L. Gallin-Martel, S. Marcatili, J.-F. Muraz, A. Portier and N. Rosuel.

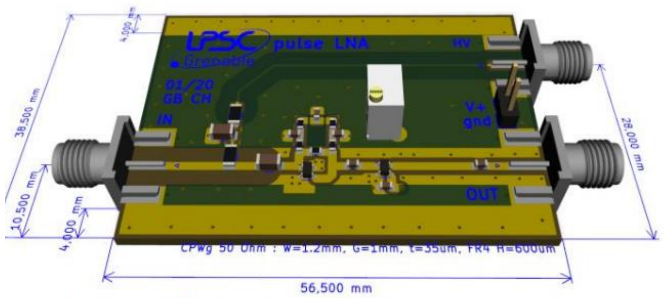
Univ. Grenoble Alpes, Laboratoire de Physique Subatomique et Cosmologie – CNRS, 53 av. des Martyrs, 38000 Grenoble, France

Abstract – This article introduces a design of a Low Noise Amplifier (LNA), for the field of diamond particle detectors. This amplifier is described from simulation to measurements, which include pulses from α particles detection. In hadron therapy, with high-frequency pulsed particle beams, the diamond detector is a promising candidate for beam monitoring and time-stamping, with prerequisite of fast electronics. The LNA is designed with surface mounted components and RF layout techniques to control costs and to allow timing performance suitable for sub-nanosecond edges of pulses. Also this amplifier offers the possibility of high voltage biasing, a characteristic essential for driving diamond detectors. Finally the greatest asset of this study is certainly the minimization of the power consumption, which allows us to consider designs with multiple amplifiers, in limited space, for striped diamond detectors.

Table 1 : Performance comparison. (a) Estimated, (b) from M. Fisher-Levine [19].

Ref.	Gain	Rise time	FWHM	ENC	SNR	Power
G. Bertuccio [14]	31.5 dB (a)	2.8 ns (b)	~38 ns (a)	139 e⁻	n/a	0.7 W (a)
DBA II [16]	42 dB	>0.5 ns	n/a	n/a	n/a	1.44 W
CIVIDEC [17]	60 dB	350 ps	1.38 ns	1000 e⁻	MIP : 6.07:1	5.4 W (a)
DBA IV [21]	50 dB	n/a	10 ns	n/a	n/a	1.8 W
M. Fisher-Levine [19]	146 mV/fC	2.12 ns	3.75 ns	293 e⁻	n/a	1 W (a)
This work	43 dB	350 ps	1.25 ns	230 e⁻ (a)	MIP : 4.3:1	75 mW

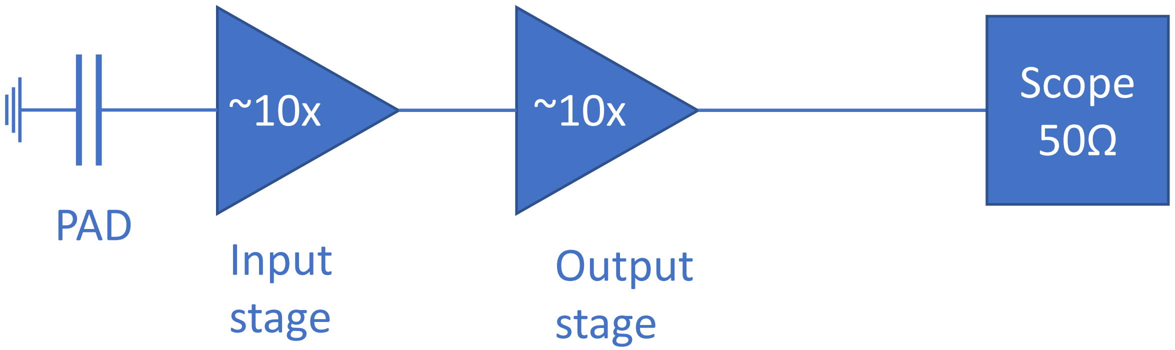




gure 6: Layout 3D drawing of LNA.

How it works

- Amplifier is designed with two stages.
- It is important that first stage is designed for low noise and second stage for high power output.
- Noise from input stage is amplified by output stage.
- Input stage is designed using HBT (Heterojunction bipolar transistor) in reverse biased common emitter circuit.
- Usage of HBT results in high bandwidth and low noise behavior.
- HBT is biased with 6 mA what is optimal current regarding the noise and offers 20 dB amplification
- Output stage is made around BGA427 MMIC gain block which gives additional amplification of around 23 dB.



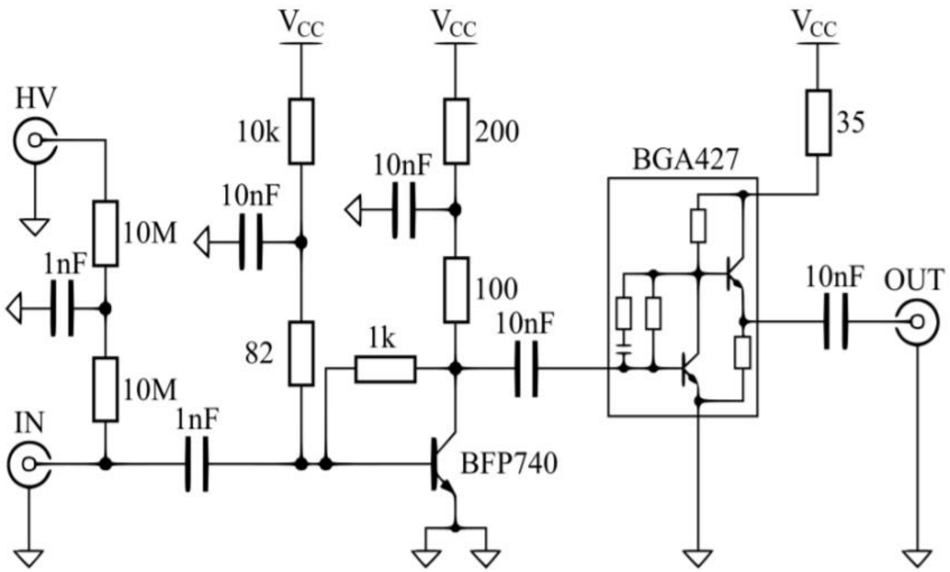
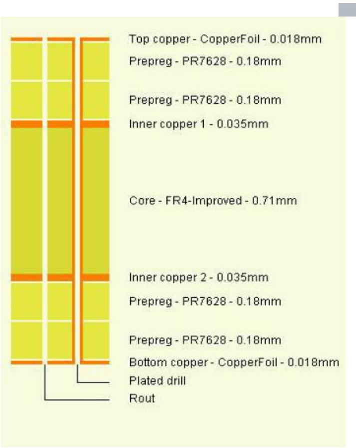
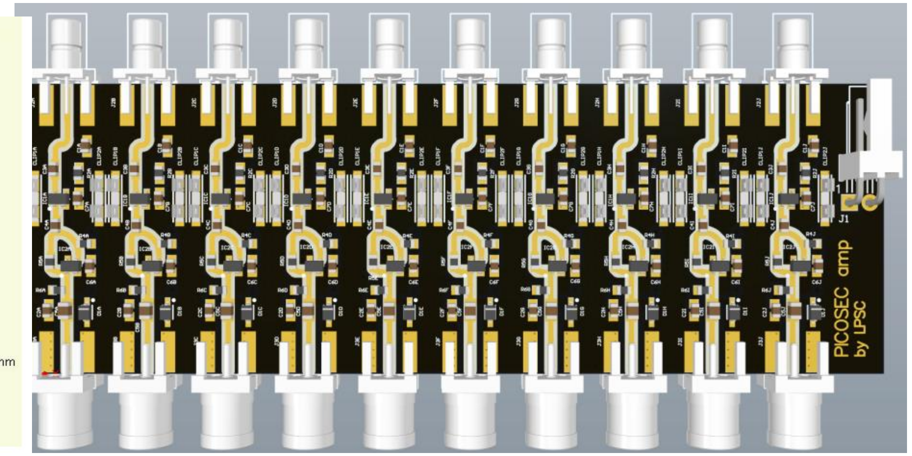


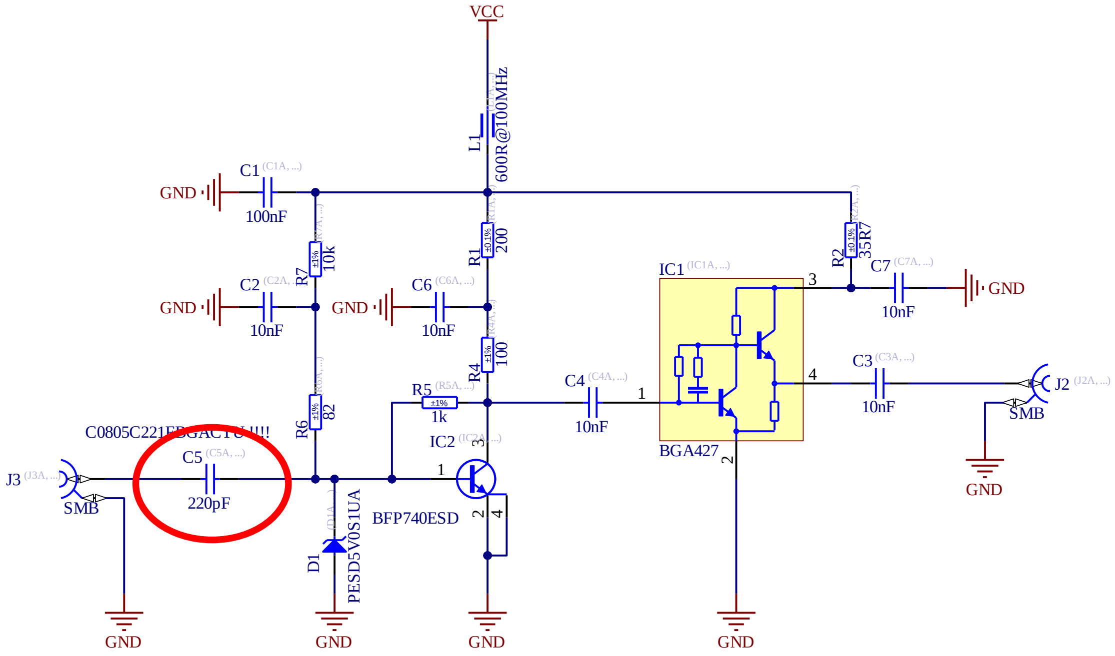
Figure 3: Electronic schematic diagram of the LNA.

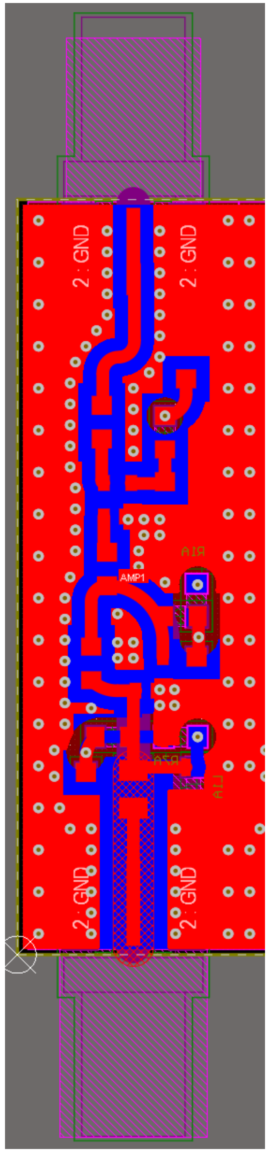
Building the first amplifier card

- Motivation was to replicate the design from C.Hoarau with different layout that fits the multipad SMB connector raster (10.02mm)
- Only changes were reduced input capacitance to 220 pF and placeholder for protection diode D1.
- Four-layer board was used with two-layer PR7628 prepreg (0.36mm total).
- This enabled usage of wider traces to achieve 50Ohm impedance (0.6 mm) – good for prototyping.
- Many vias along the signal path were placed to connect ground planes in all layers (coplanar waveguide).
- Stitching vias were placed between the channels to reduce possible crosstalk.
- Components that are not part of HF circuit are placed on back of the board to save space.
- THT SMB connectors were misused as the SMT edge mount ☺



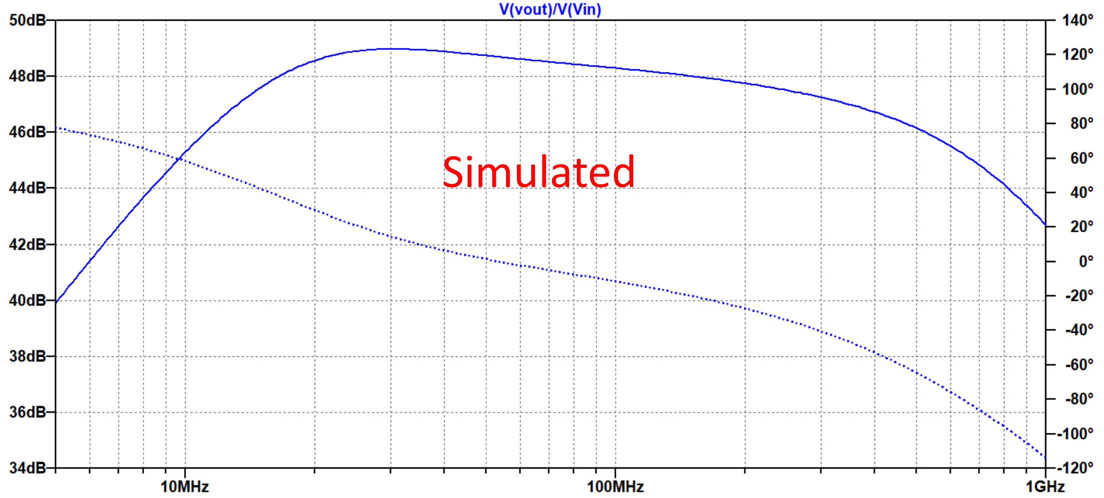


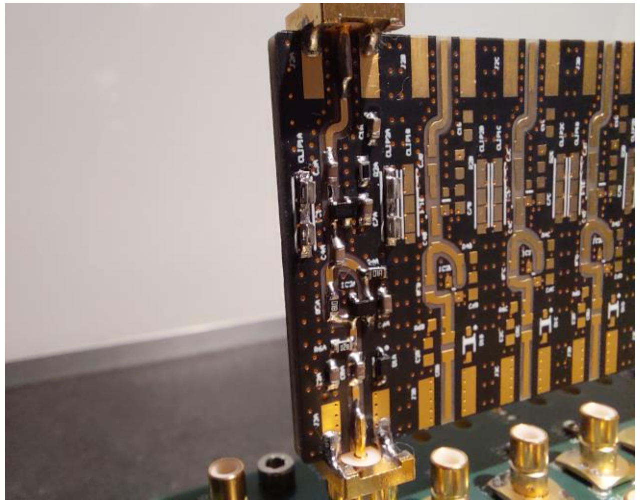


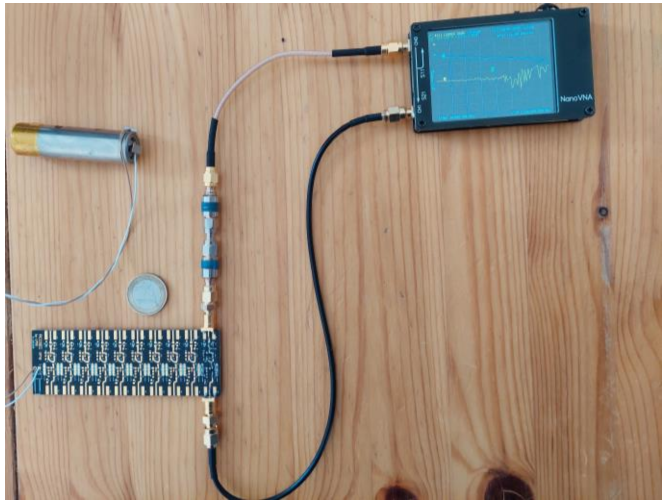


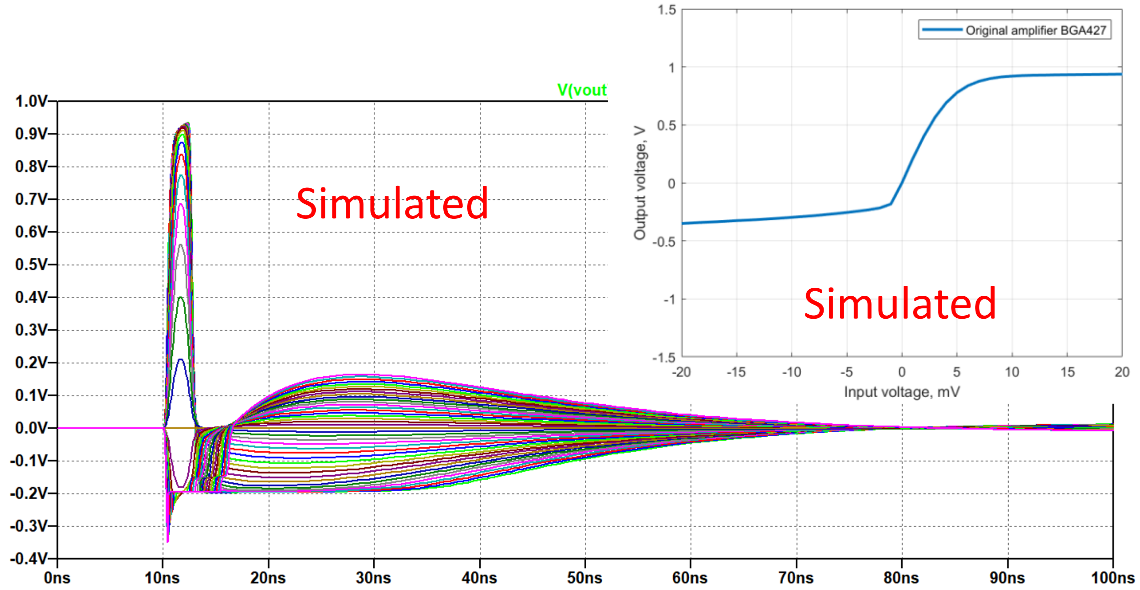
First amplifier built (BGA427 version)

- One channel was populated with the original components.
- The gain that was observed was around 48 dB.
- Regarding the noise, power consumption the amplifier was within the specs from the paper.
- However, this configuration seems to have very limited ability to amplify negative pulses. It works linearly to -200 mV peak.
- This in combination with high gain will limit the performance on the detector as the amplifier will work in compression most of the time and will not use the dynamic range of digitizer.
- The output transistor is DC biased to 800 mV limiting the performance.
- Multiple modifications to the circuit were made (external biasing, compensation networks with limited success).



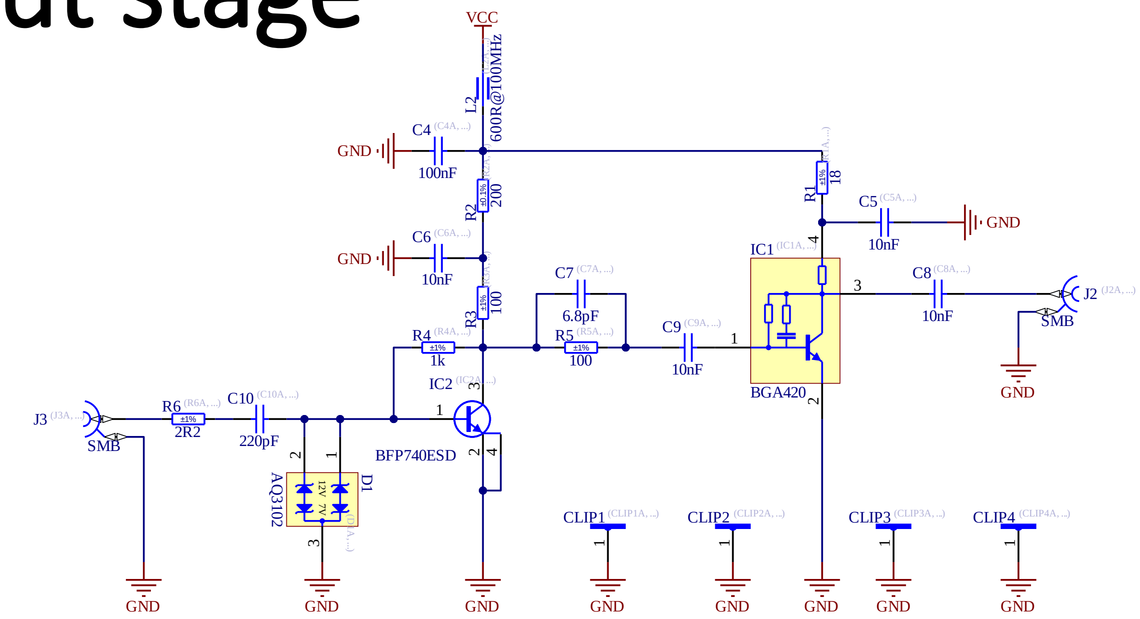


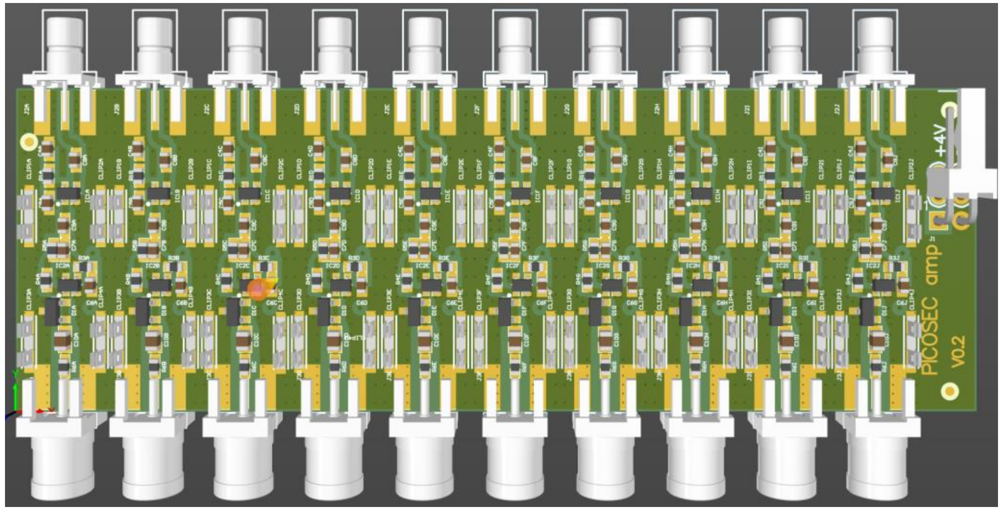


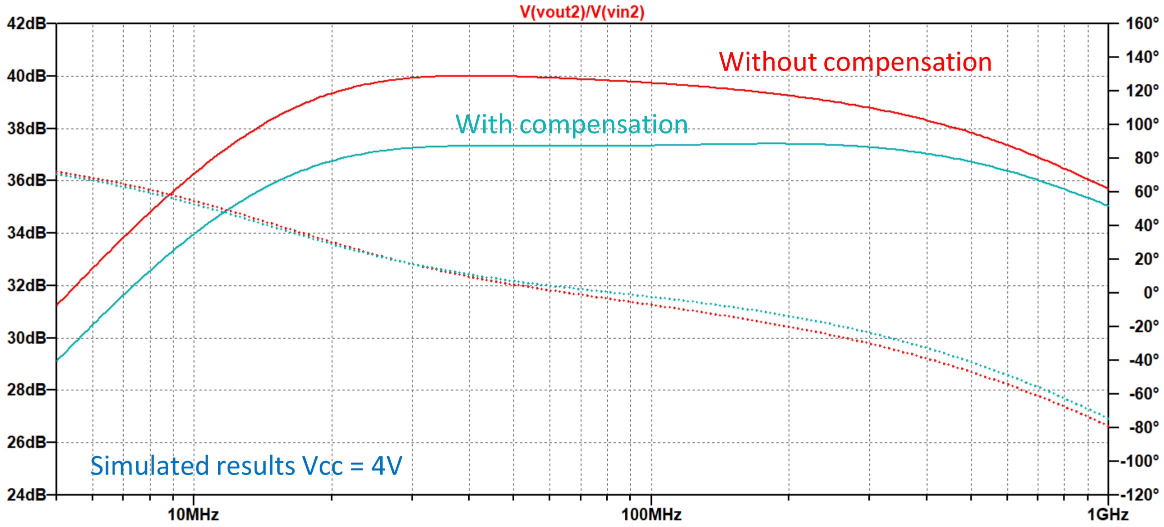


Redesign to BGA420 output stage

- Topology of the input stage remained the same as in the original paper.
- **Modifications**
  - output stage replaced with BGA420 MMIC amplifier to reduce gain to around 38.5 dB.
  - compensation network (C7 & R5) added to flatten the frequency response
  - Two AQ3102 diodes added for spark protection together with R6 current limiting resistor
  - Additional pair of RF shield clips added to each amplifier.

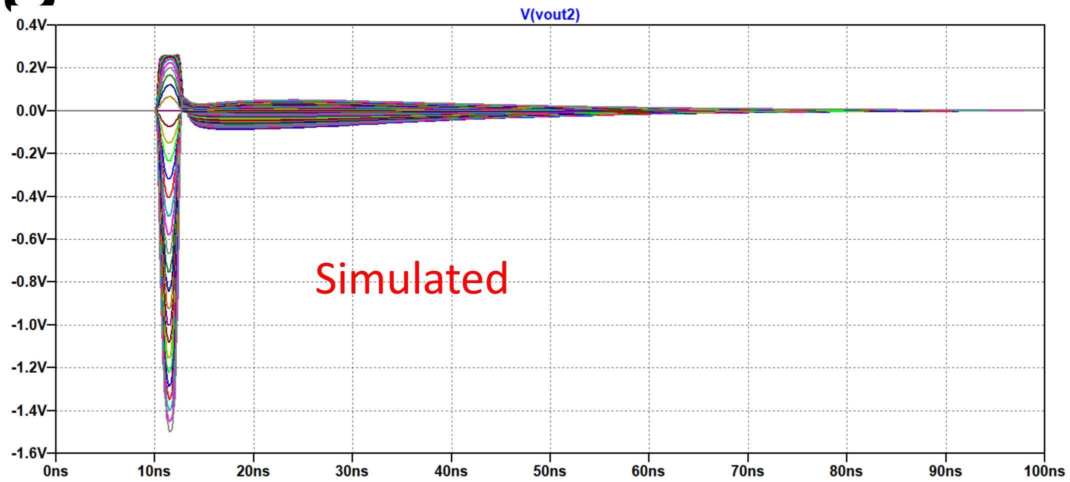


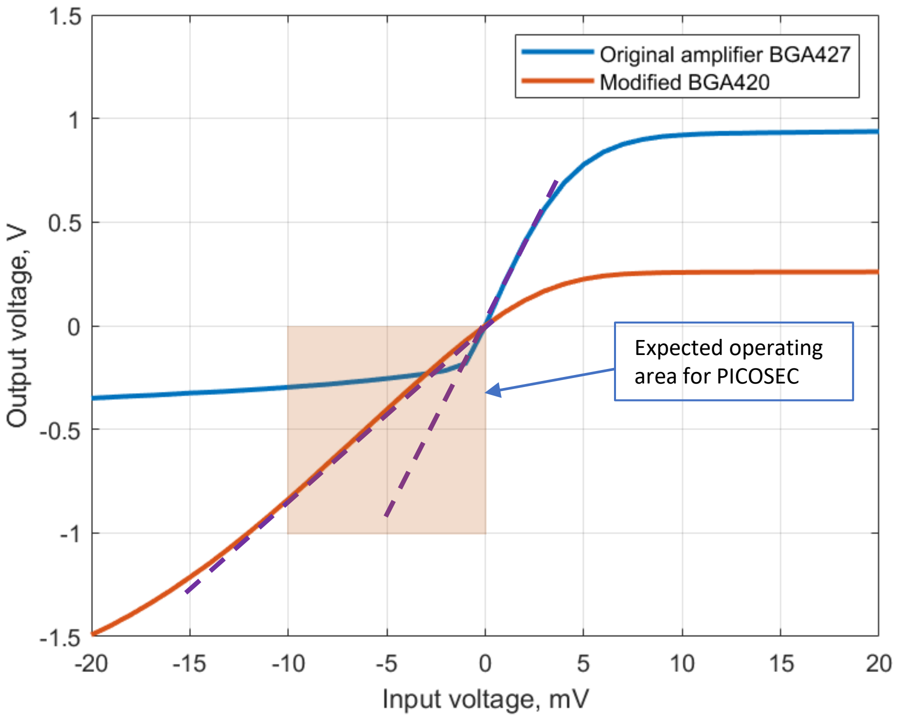




Redesign to BGA420 output stage

- Both, simulations and measurements confirmed superior performance when handling the negative pulses.
- The “almost” linear range of the operation is extended to -1 V peak of output voltage and covers entire expected operating area for PICOSEC detector.
- If the amplifier is used for positive pulses or as regular RF amplifier, the output is limited to 220 mV peak before entering compression.
- The bandwidth of the amplifier is affected by the heavy-duty protection diode that was required to meet the spark protection.
- The power dissipation remained at 78 mW per channel – forced cooling still needed for 100 ch detector (7.8 W total).





Result: not so good RF amplifier, but very good for pulse applications...

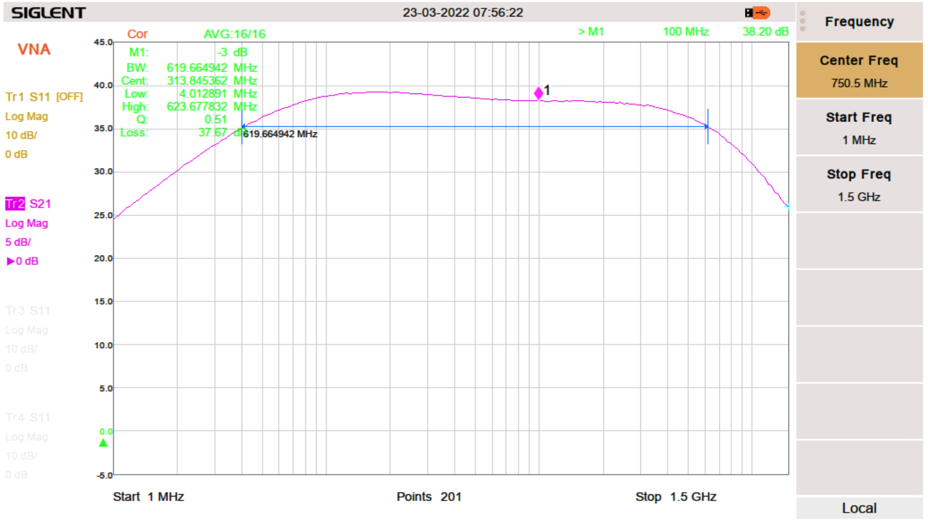
VNA tests

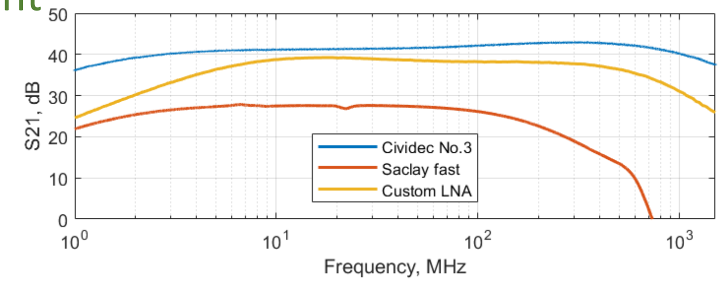
- Gain **38.5dB** @100MHz
- HF -3dB cut-off **625 MHz**
- LF -3dB cut-off 4 MHz
- Input impedance 44 Ohm
- Gain relatively flat over the frequency range
- -34 dBm input -1dB compression point.

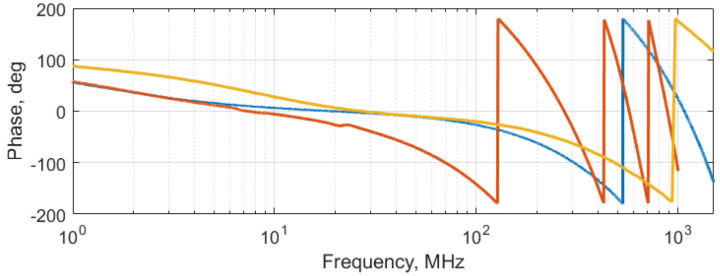
- LF cut-off higher than in Cividec and Saclay due to 220pF dec. capacitor.

- Output noise power spectral density arround **~ 32 nV√Hz**. Consistent with measured noise (800 uVrms).

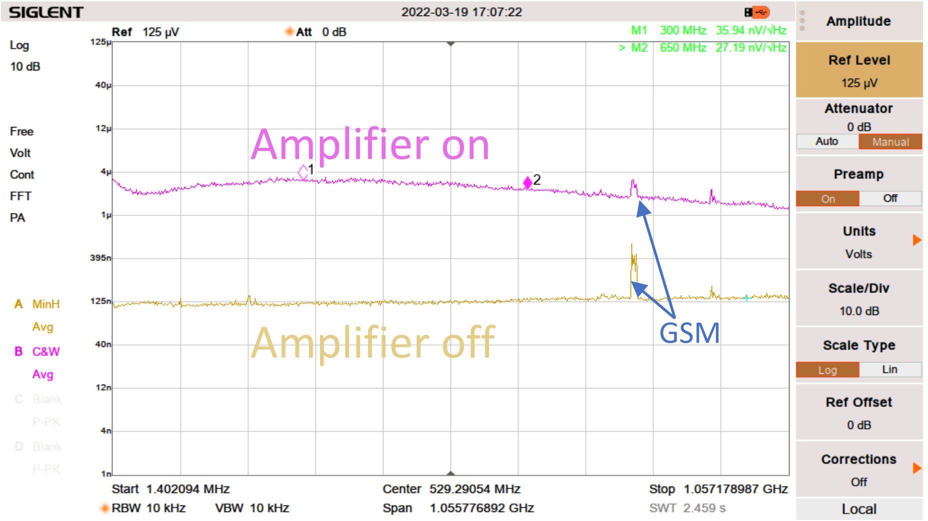
Siglent SVA1032X – VNA mode S21 measurement

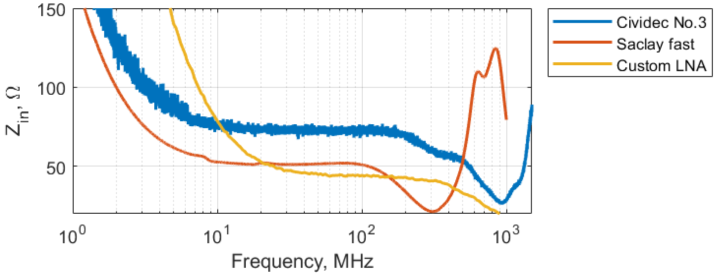


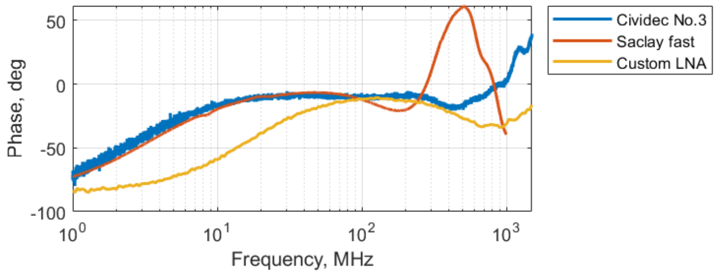




Siglent SVA1032X – Spectrum analyzer mode noise measurement



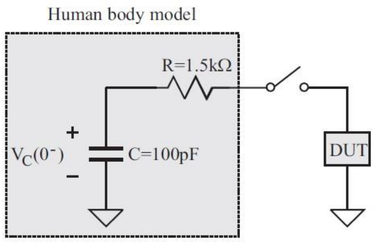


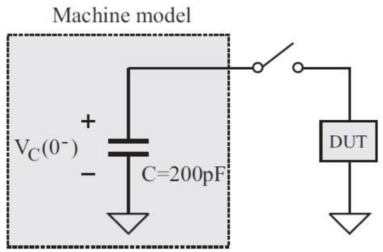


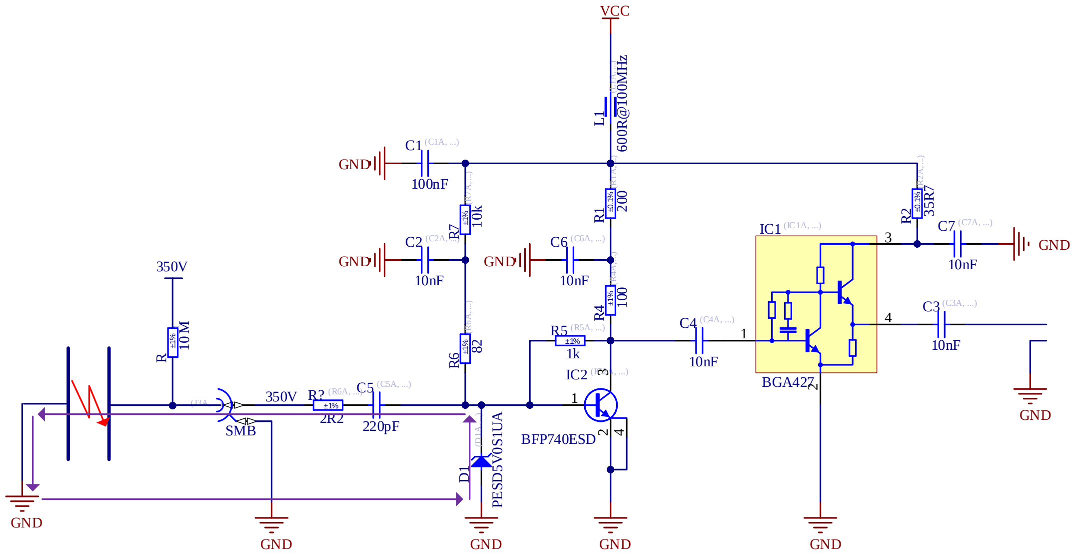
Spark protection

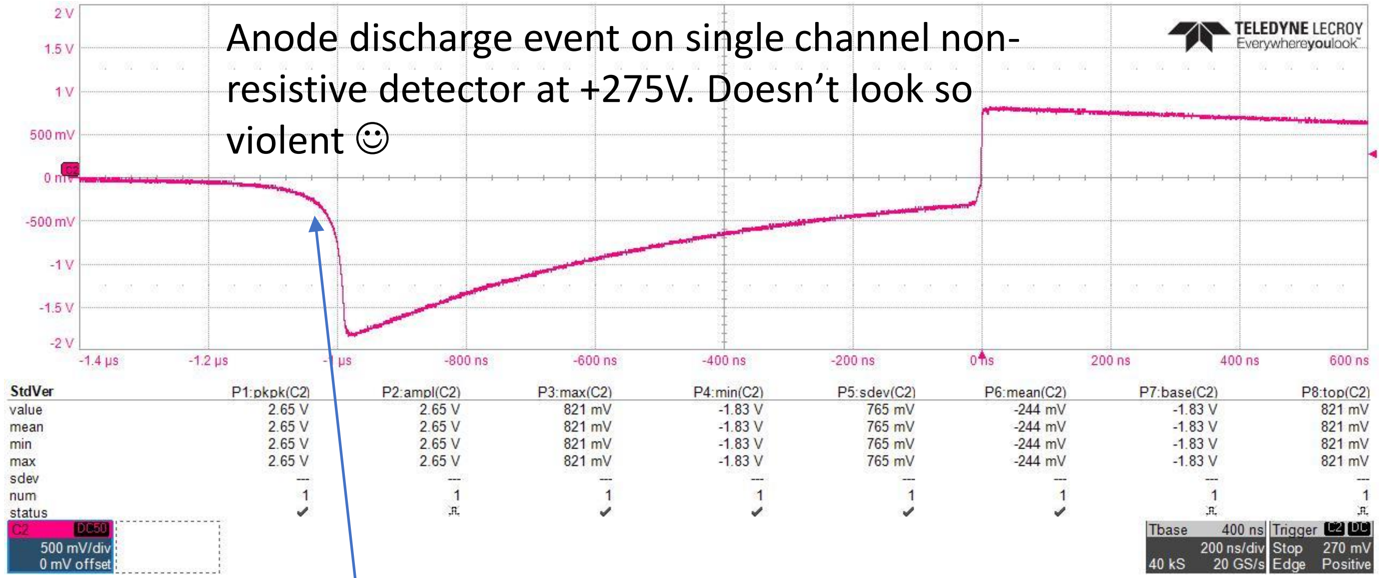
- The input transistor has internal ESD protection up to +/- 2kV HBM (human body model)
- Human body model implies the discharge over the resistance of 1.5kOhm.
- The amplifier needs to be protected against direct discharge with low impedance, so called machine model?

- The additional diode needs to be added to protect BFP740ESD.
- The amplifier was tested to direct discharges on the input connector with the bias voltages up to 350 V.
- Several ultra low capacitance diodes have been tried out, and the AQ3102 was the winner (lot of burned BF740 ☹).
- **The amplifier is fully protected only for positive bias voltages!**





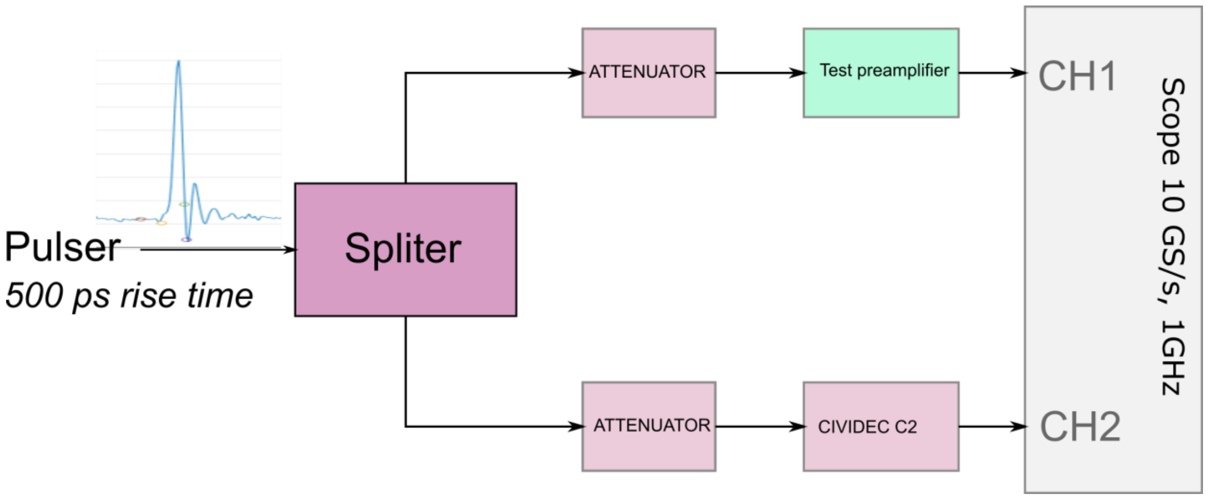


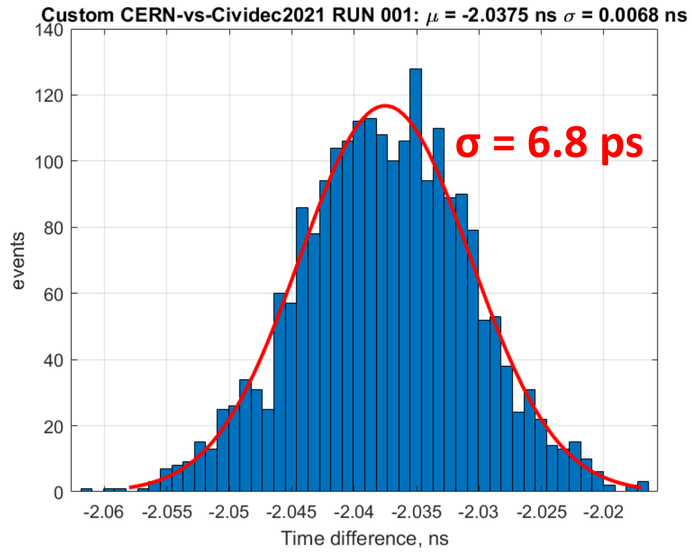


Antonija will have to look at this ☺

Pulser test (CIVIDEC vs. custom amp)

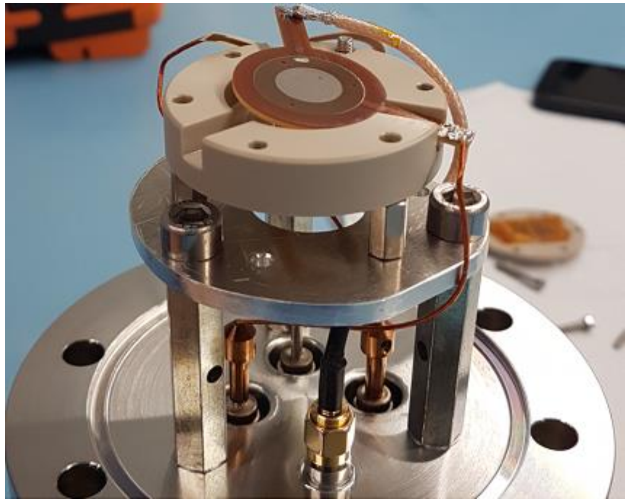
- Pulser test was performed to evaluate the timing performance of new amplifier.
- Signal from pulser was splitted and injected to amplifiers over the attenuators.
- Attenuators were chosen so that the amplifier doesn’t operate in compression mode.
- The limitation was the positive pulse from the amplifier which is not optimal for the custom amplifier.

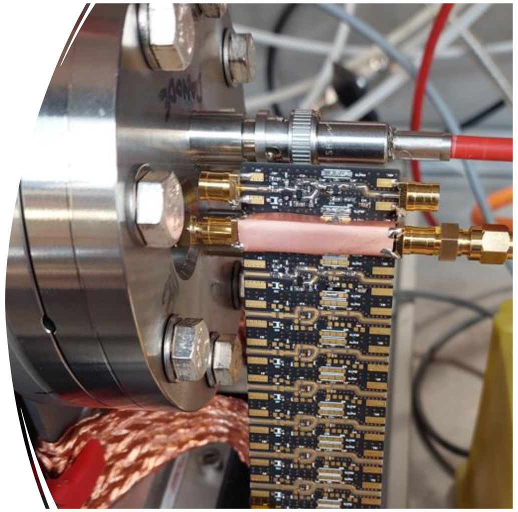


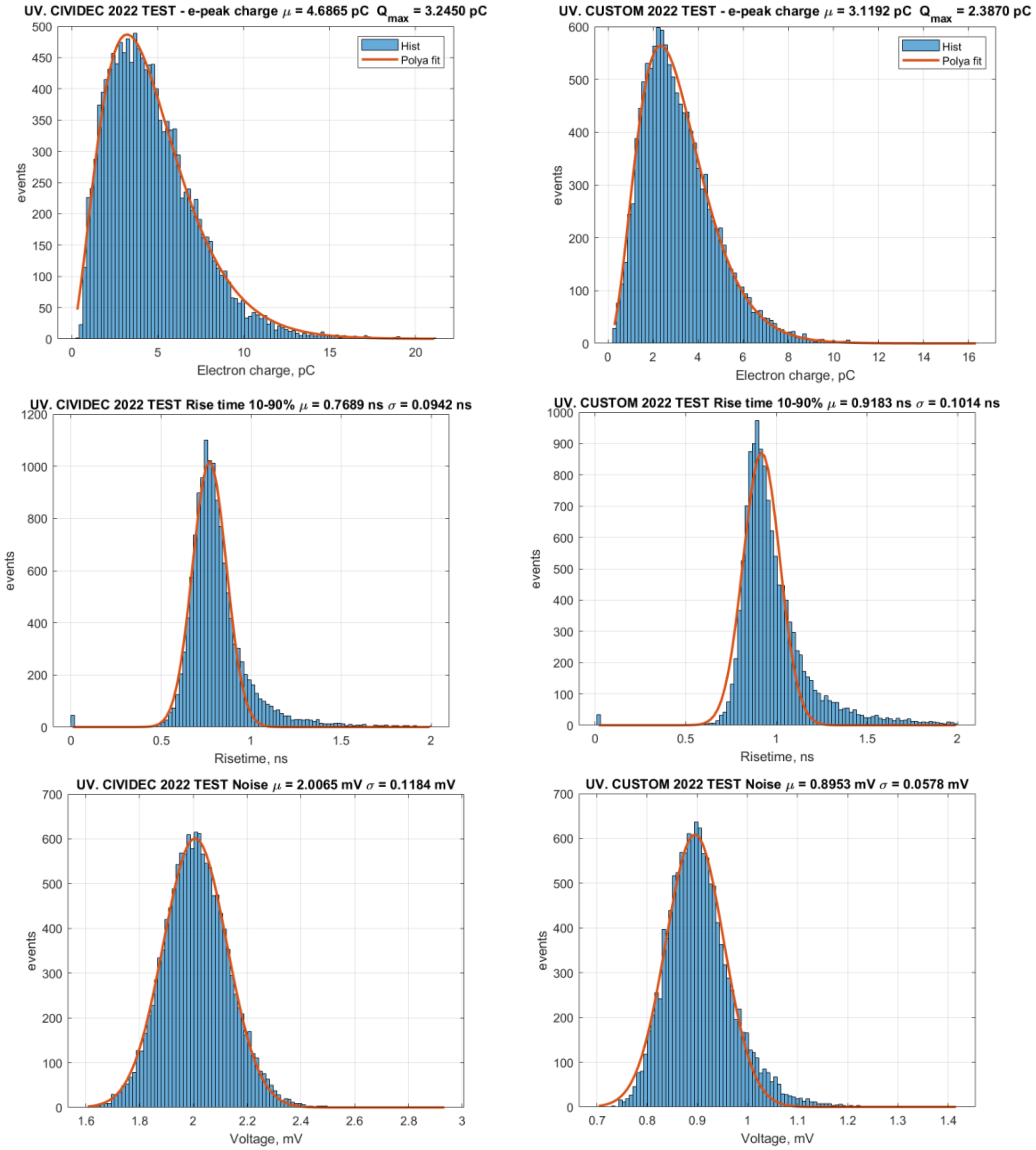


Test on detector with UV LED

- Measurements of single p.e response with **UV LED** (250 nm)
- Detector: Single channel resistive (340 kΩ/sq)
- Photocathode: B4C with metallic layer below.
- Reference amplifier: CIVIDEC C2 (40 dB, 2 GHz), https://cividec.at
- **Amplifier under test:** custom made 10 ch board (BGA420 version)
- Detector voltages: +275 V on anode and -540 V on cathode.





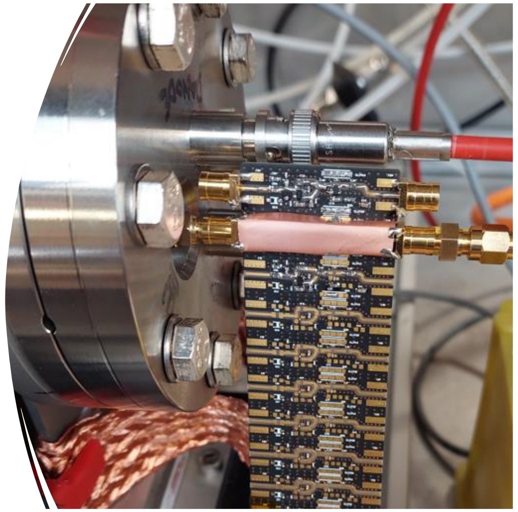


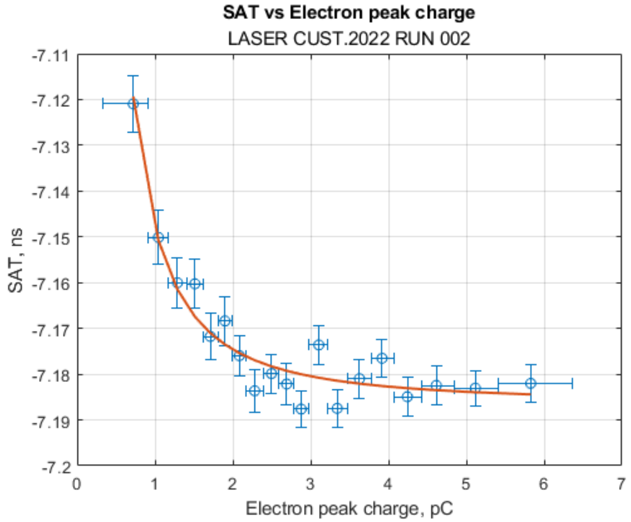
Comparison with CIVIDEC:

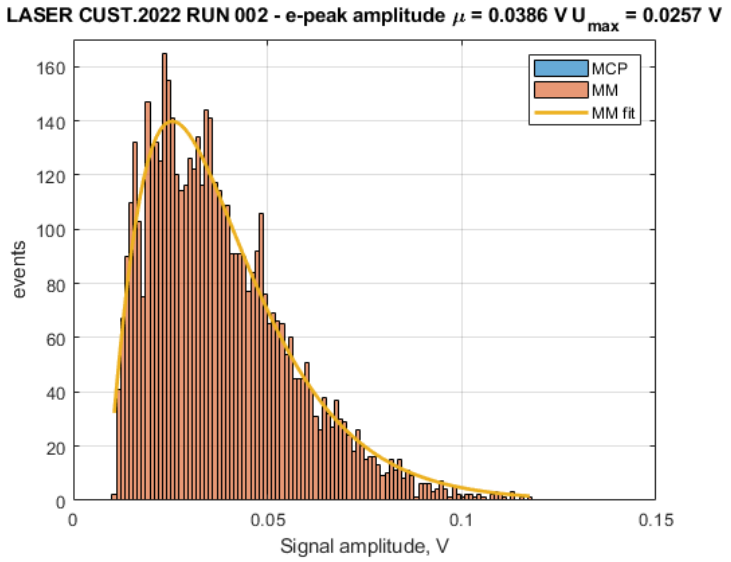
- 1.5x lower gain (3.5dB)
- 1.2x lower rise time
- 2.3x lower noise
- 1.53x better SNR

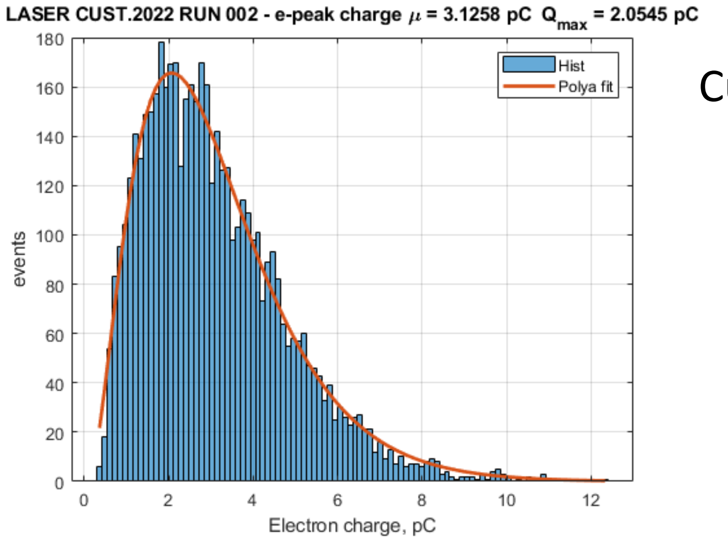
Laser test on resistive single pad detector

- Measurements of **single p.e** response with **fs laser.**
- Detector: Single channel resistive (340 kΩ/sq).
- Photocathode: B4C with metallic layer below.
- Preamplifier: custom made preamplifier (BGA420 version) board directly mounted to the chamber.
- Source: Laser (515 nm, pulse duration < 200 fs).
- Rate: 3Hz.
- Detector voltages: +275 V on anode and -540 V on cathode.

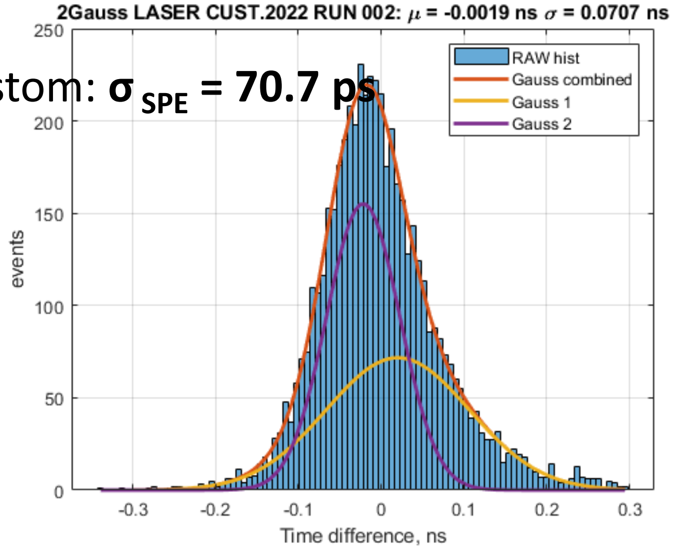






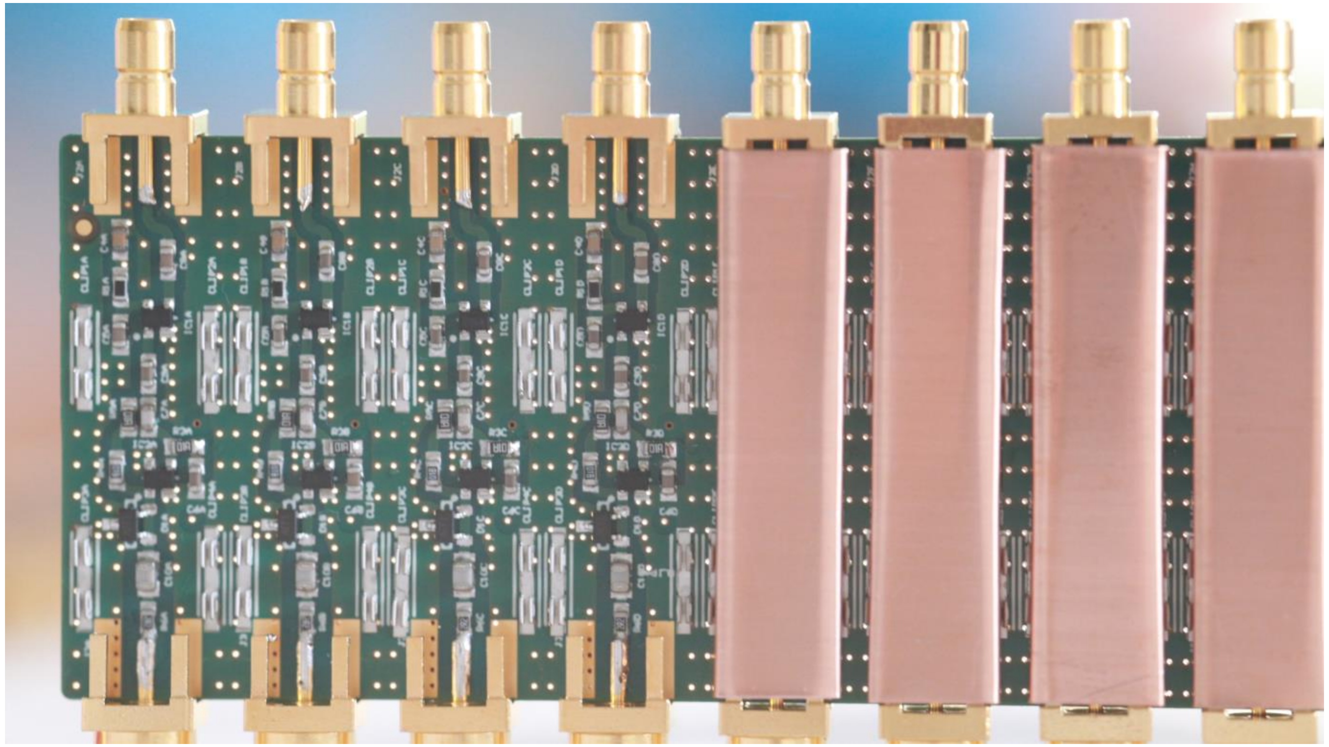


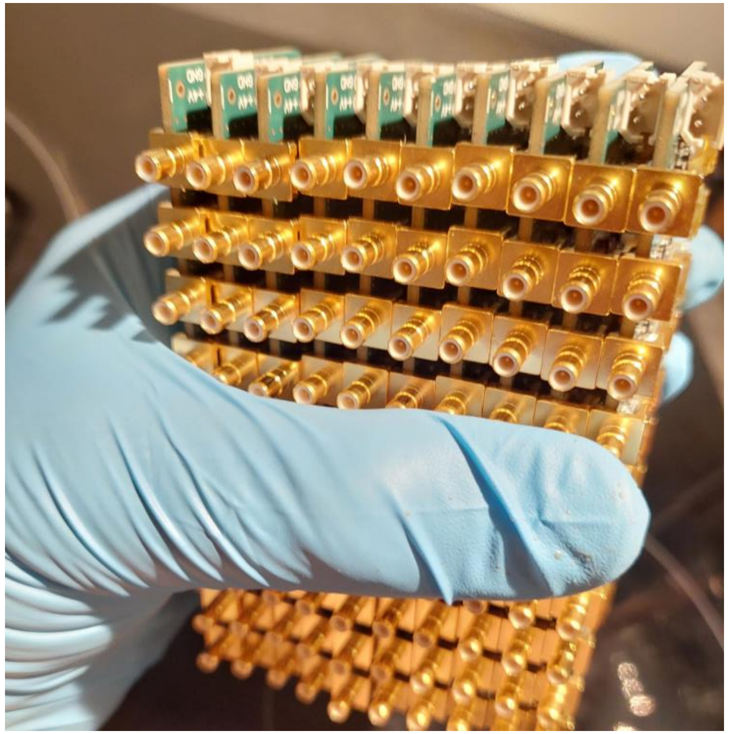
Custom: **σ_{SPE} = 70.7 ps**

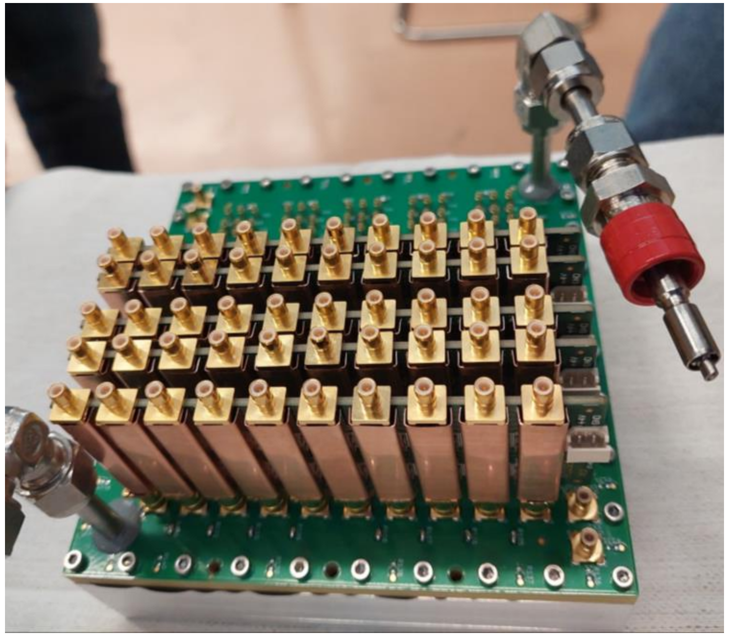


Production

- New PCB with all the modifications was designed.
- In total 11 boards with 10 channel were manufactured.
- SMD components were machine mounted while connectors were soldered manually on mockup detector to ensure correct spacing.
- Individual shields were shaped from 0.2 mm thick Beryllium-Copper sheet to C-shape manually – very time-consuming procedure.

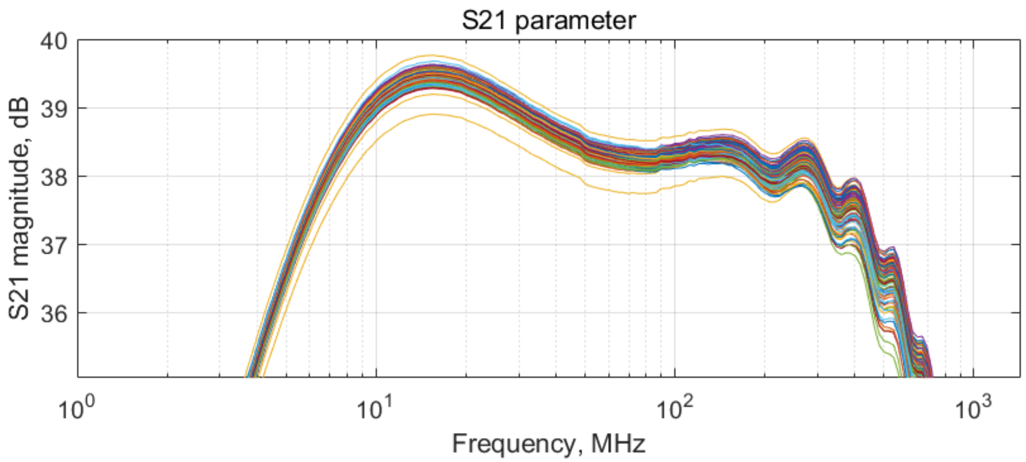






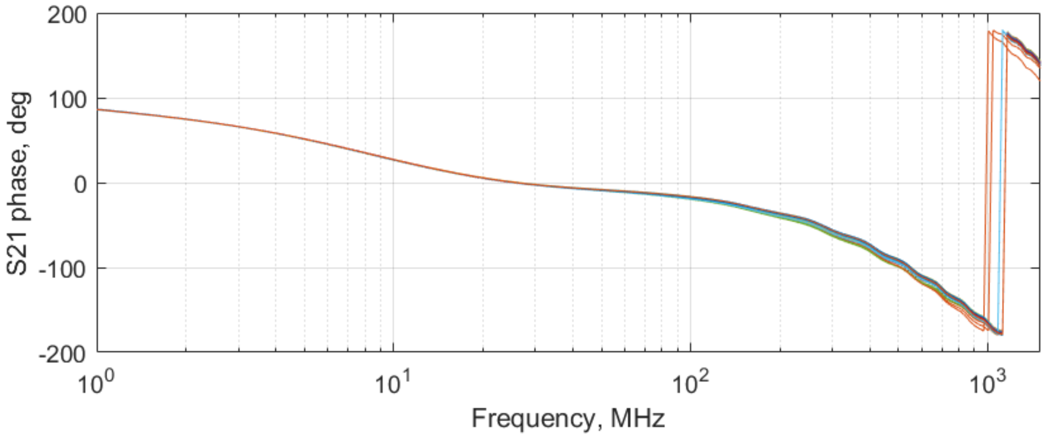
Production test - uniformity

- All of the 110 produced channels were tested using VNA to evaluate the uniformity.
- Measured gain is within 0.8dB for all of the produced amplifiers.
- Board No 4. ch B has biggest deviation – to be checked.
- Considering simplicity of the design the gain uniformity is very good.
- Measured data can be used for further corrections.



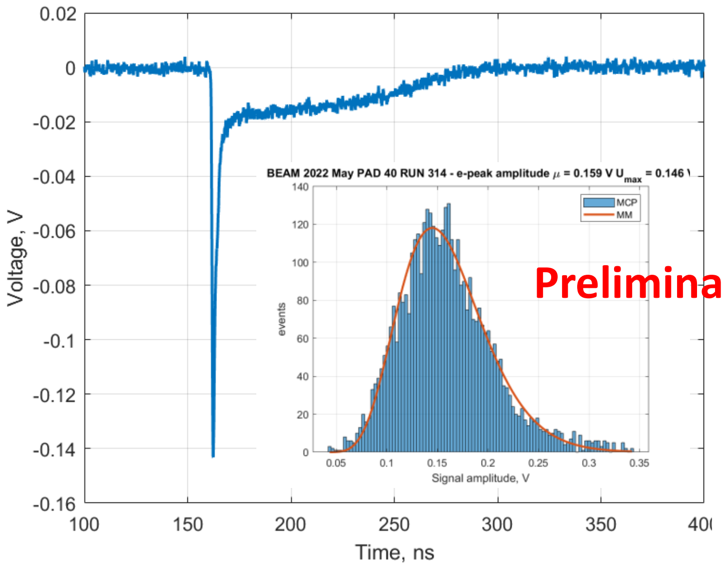
Board level uniformity

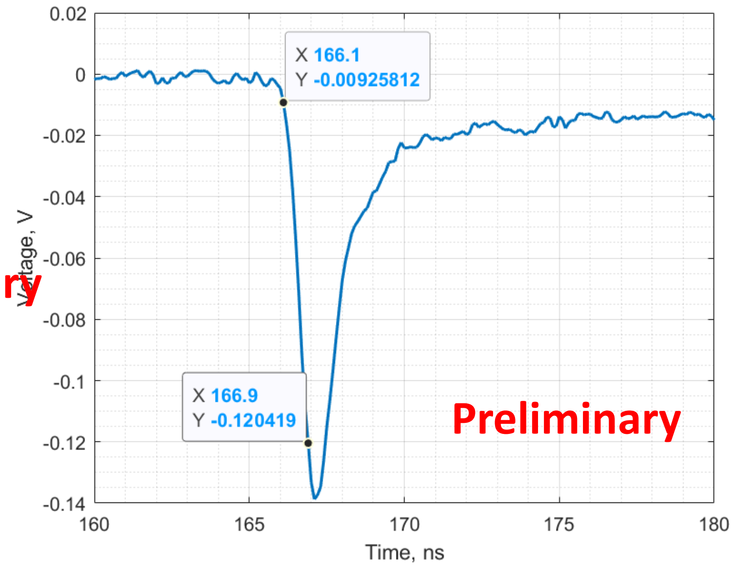
Board number	Gain σ	Gain µ	Gain max-min
'Board No. 0'	1.09	82.11	2.88
'Board No. 1'	0.89	82.09	2.67
'Board No. 2'	0.96	82.27	2.59
'Board No. 3'	0.88	82.18	2.74
'Board No. 4'	1.28	81.44	4.35
'Board No. 5'	0.87	82.69	2.62
'Board No. 6'	0.73	82.01	2.31
'Board No. 7'	0.78	82.03	2.08
'Board No. 8'	1.04	82.43	2.87
'Board No. 9'	0.95	82.30	3.53
'Board No. 10'	1.04	82.45	3.41



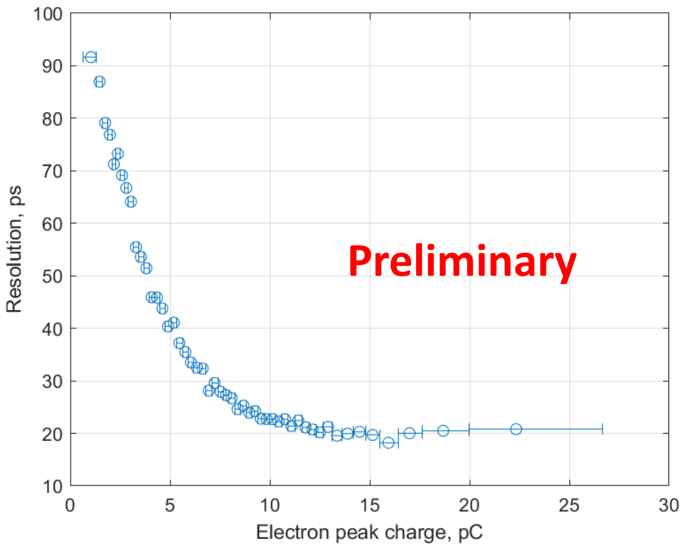
Preamplifier test with MIPs

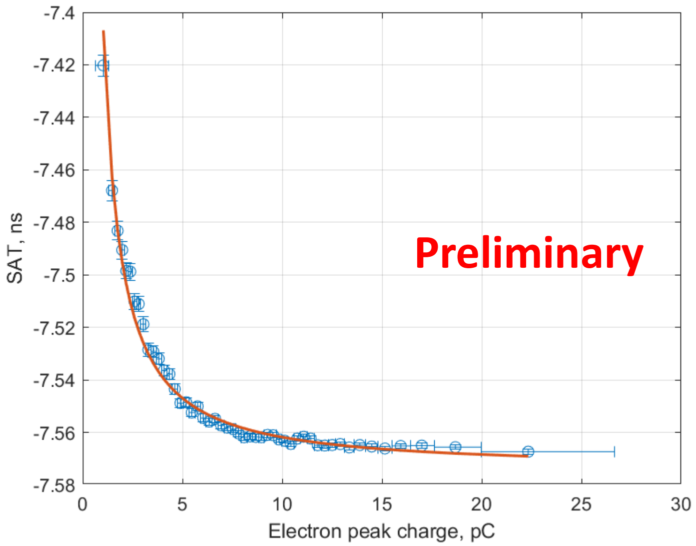
- Small area (11 mm dia) MCP (Hamamatsu R3809U-50) reference.
- Functionality of the preamps tested.
- Low noise confirmed at beam < 800 μVrms.
- Risetime in order of 800 ps.
- No visible reflections or oscillations in waveforms (cables to PADs eliminated).
- Obtained expected shape of SAT and time resolution vs. Q E-peak.
- Time resolution in order of 20 ps achieved (amplifiers do not dominate the jitter).

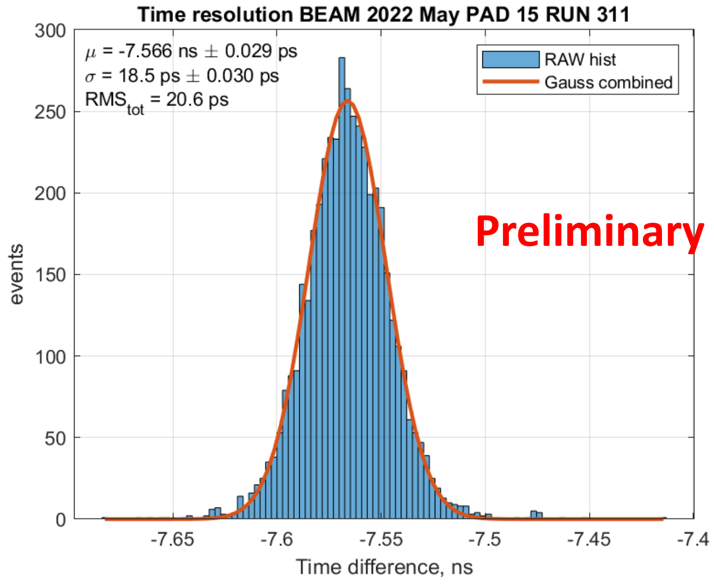




More details RD51 Coll. Meeting A. Utrobicic https://indico.cern.ch/event/1138814/contributions/4915978/

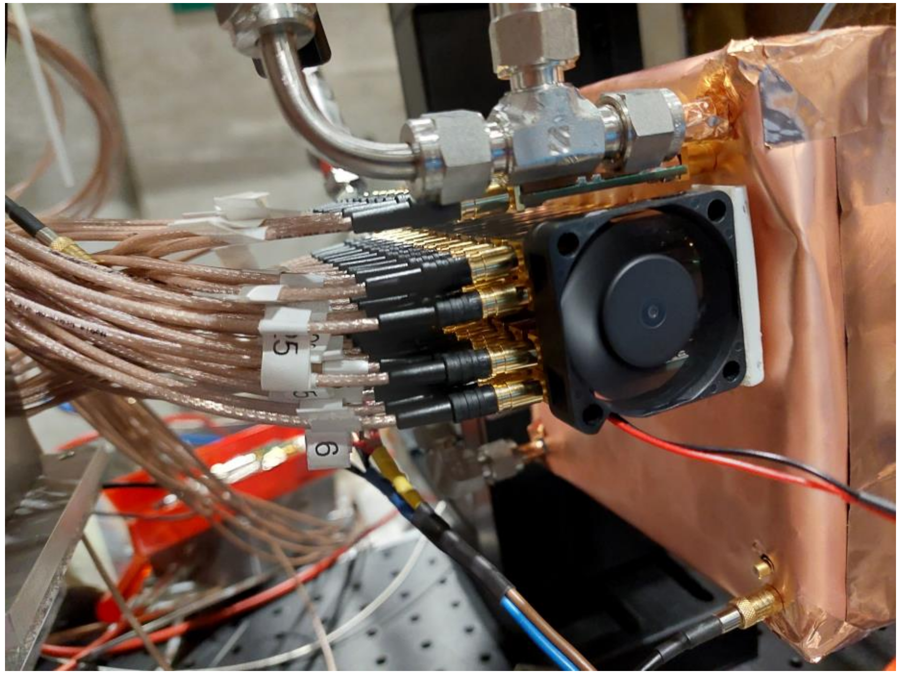


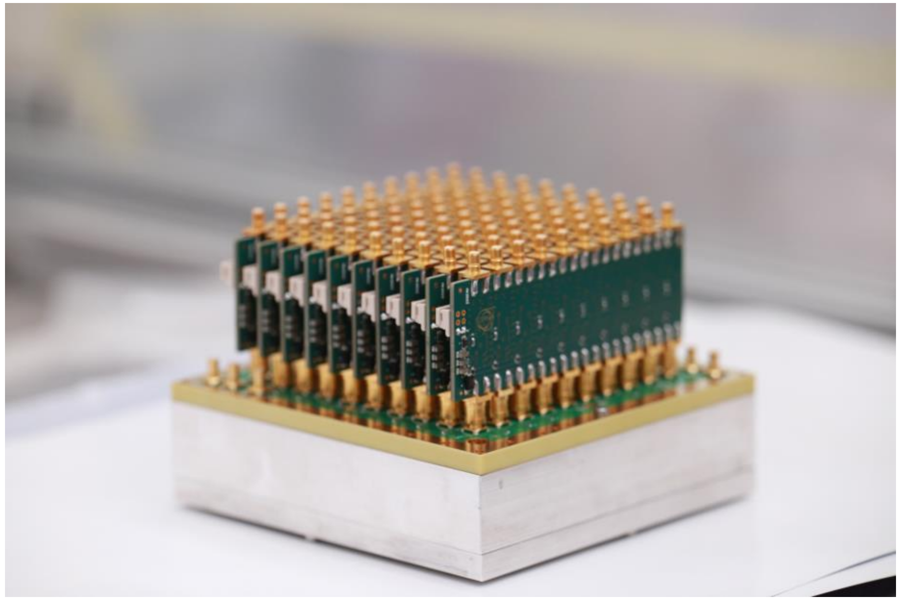




Conclusion and outlook

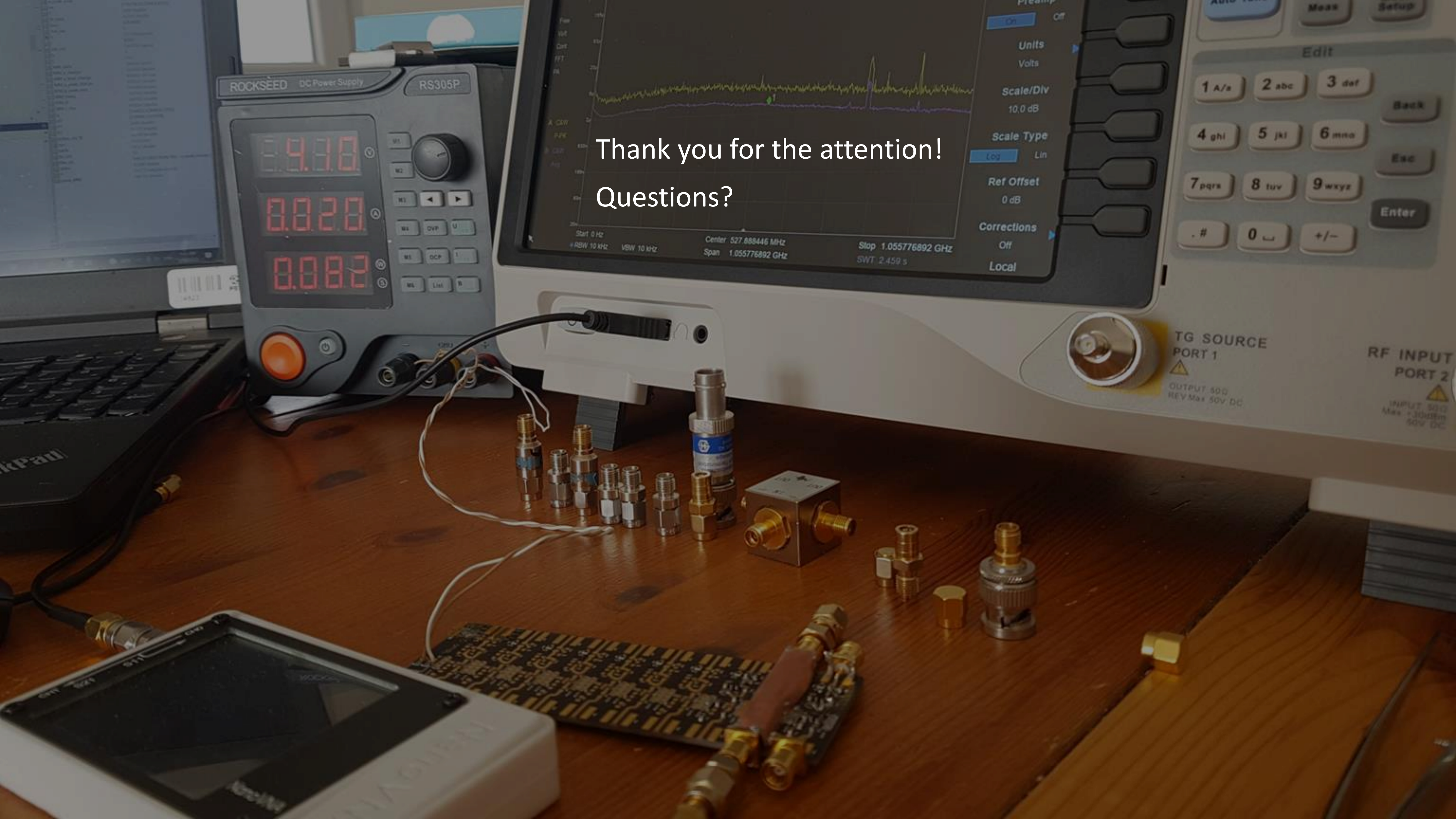
- The original design from C.Hoarau was sucsessfuly transfered to a compact footprint in form of 10 channel boards.
- The design was optimized and made amplifier suitable for 100 ch PICOSEC multipad detector.
- Amplifiers showed excelent results in the operation with pulser, UV laser and MIP.
- Still some improvments need to be done, mostly related to increase of gain to fit the dynamic range of SAMPIC (less robust spark protection, rethink need for compensation network...)
- Connectors are expensive – think of more economical method for connection to the detector.





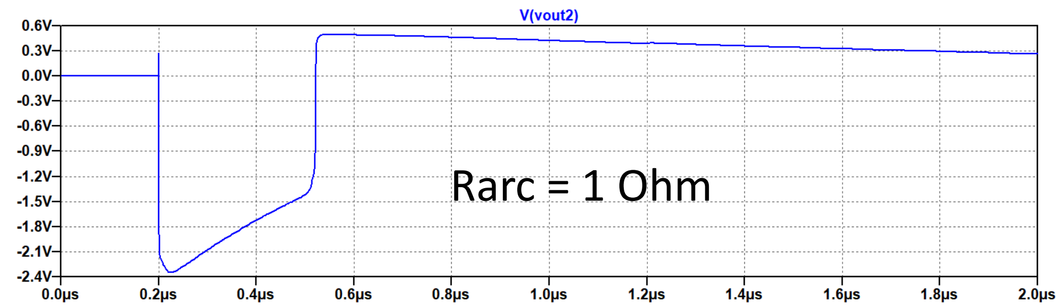
Thank you for the attention!

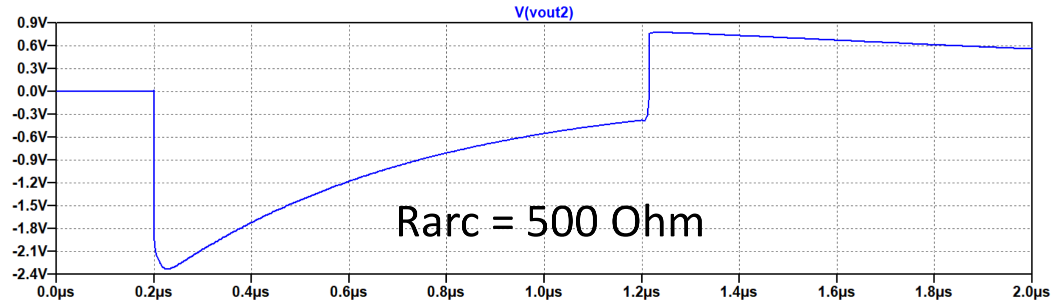
Questions?

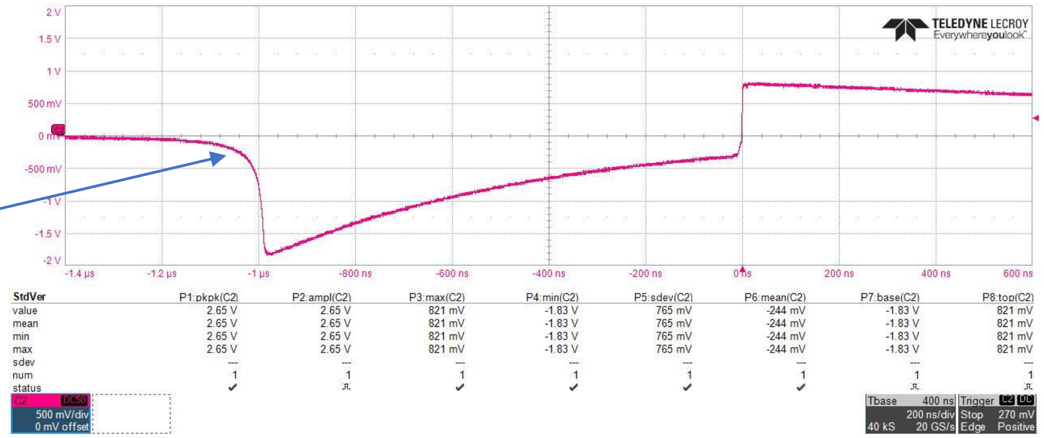


Backup – spark simulaiton

- Simulation with 500 Ohm arc reisitance.
- Looks very similar.
- Probably, most of the energy is dissipated within the arc/detector.
- Spark protection could be ligher – more bandwidth







Discharge is not abrupt, we can see formation