Universität Zürich[UZH]
PAUL SCHERRER INSTITUT
PSI
ATLAS Forward Proton Time-of-Flight Detector
results, experiences, and plans
Tomáš Sýkora
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Faculty of Mathematics and Physics
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on behalf of the ATLAS Roman Pot Detectors
ATLAS
EXPERIMENT
MATHEMATICA PHYSICAQUE
FACULTAS

message

The Time-of-Flight (ToF) detectors of the ATLAS Forward Proton (AFP) system are designed to measure the primary vertex z-position of the pp → pXp processes by comparing the arrival times measured in the ToF of the two intact protons in the final state.

We present the results obtained from a performance study of the **AFP ToF detector operation in 2017** and **discuss plans for LHC Run 3** as well as for **an eventual future upgrade** of the ToF detectors.

In 2017, time resolutions of individual channels ranging between 20 ps and 40 ps were extracted. Even though the AFP ToF efficiency is below 10%, **the overall time resolution of each ToF detector** is found to be **20(26) ± 4(5) ps for side A(C)**. This represents a superb time resolution for a detector operating at few millimeters from the LHC beams... …The difference of the primary **vertex z-position measured by ATLAS and the value obtained by the AFP ToFs is studied**. The fits performed to the distribution of the reconstructed time difference yield the vertex position resolution (of about 6 mm ± 1 mm at best) that is in agreement with the expectation based on single-ToF channel resolutions.

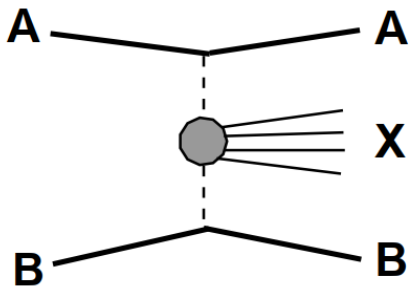
Description and functionality of **new detector components**, especially of a **R2D2 based MCP-PMT** with the modified back-end electronics, of the **Out-of-Vacuum construction** introduced to overcome problems with operating MCP-PMT in vacuum, of the new, **single-channel pre-amplifiers** and **trigger**, **trigger decoder** and **pulser** modules is given.

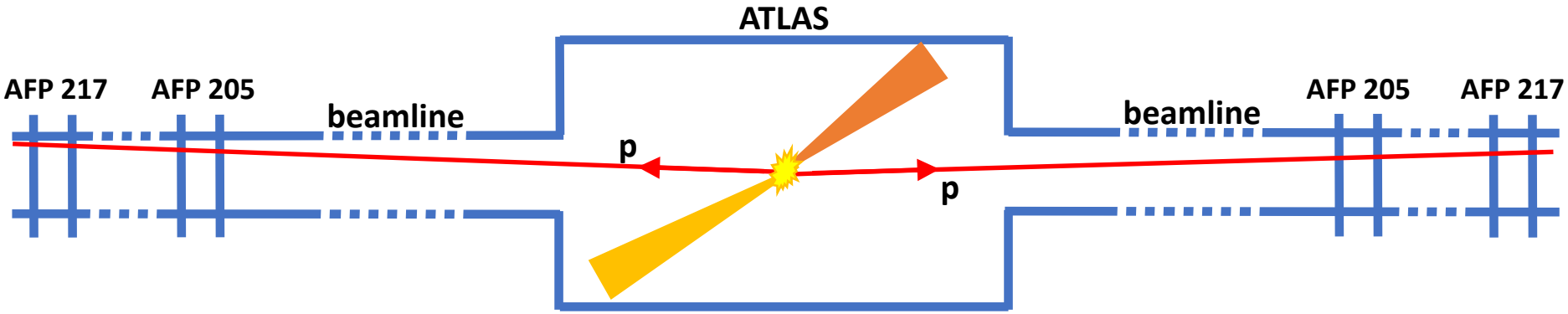
outline

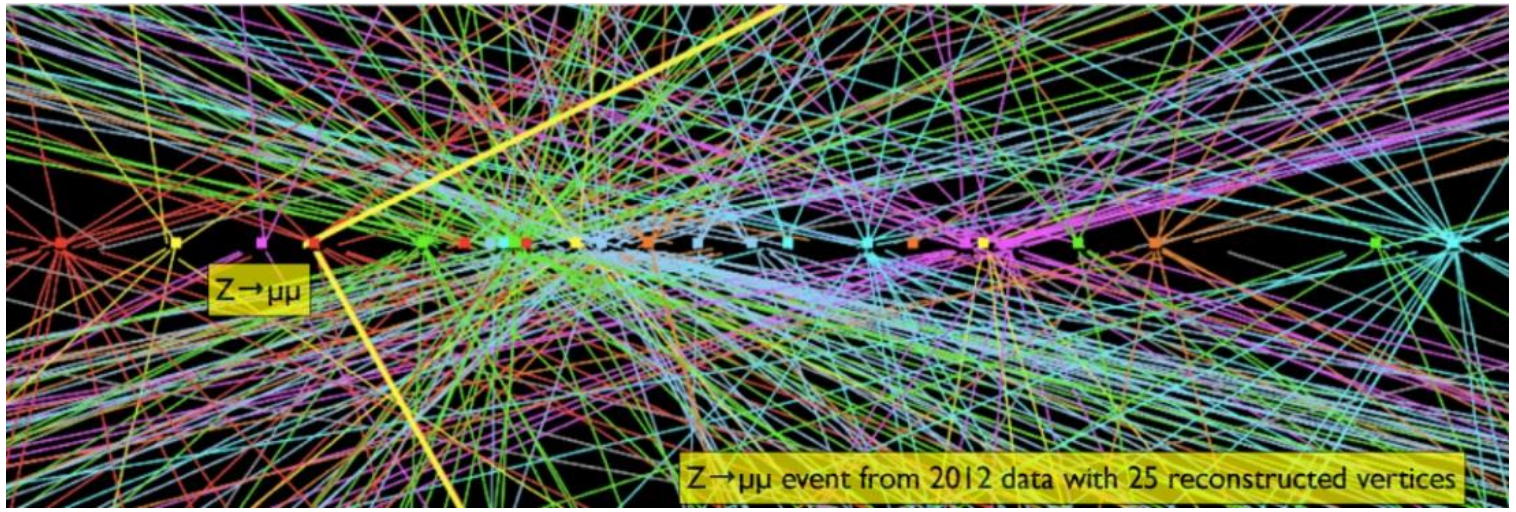
- AFP – physics and ToF subdetector
- AFP ToF design in 2017
- AFP ToF – expected performance
- AFP ToF – results based on 2017 data
  - timing
  - z-vertex reconstruction
- AFP ToF – operational experience in 2017
  - MCP-PMT in vacuum
  - crosstalk
  - high rates
- AFP ToF – new design
  - Out-of-Vacuum solution
  - R2D2 MCP-PMT
  - LQBars
  - PAa preamplifiers, 3 stages
  - picoTDC (x)
  - trigger module & trigger decoder
  - pulser

- ATLAS-AFP Collaboration: *Technical Design Report for the ATLAS Forward Proton Detector*, CERN-LHCC-2015-009; ATLAS-TDR-024-2015
- LANGE, J. et al., *Beam tests of an integrated prototype of the ATLAS Forward Proton detector*, JINST 11 (2016), no. 09, P09005
- NOZKA, L. et al., *Design of Cherenkov bars for the optical part of the time-of-flight detector in Geant4*, Optics Express, 2014, vol 22(23), pp 28984-28996
- NOZKA, L. et al. *Construction of the optical part of a time-of-light detector prototype for the AFP detector*, Optics Express, 2016, vol 24(24), pp 27951-27960
- CHYTKA, L. et al., *Timing resolution studies ofthe optical part of the AFP Time-of-flight detector,* Opt. Express. 2018, vol. 26, no. 7, pp. 8028–8039
- CHYTKA, L. et al., *Time resolution of the SiPM-NUV3S*, NIM A, Volume 935, 11 August 2019
- ČERNÝ, K., *The ATLAS Forward Proton Time-of-Flight Detector System*, International Workshop on Vertex Detectors 2019, Croatia
- MELIKYAN, Y. at al., *Load capacity and recovery behaviour of ALD-coated MCP-PMTs*, NIM A, Volume 949, 1 January 2020, 162854
- KOMÁREK, T. at al., *Timing resolution and rate capability of Photonis miniPlanacon XPM85212/A1-S MCP-PMT*, submitted to NIM A
- ATLAS Collaboration, *Performance of the ATLAS Forward Proton Time-of-Flight Detector in 2017*, ATL-FWD-PUB-2021-002
- CERNY, K. at al., *Performance studies of Time-of-Flight detectors at LHC*, 2021 JINST 16 P01030

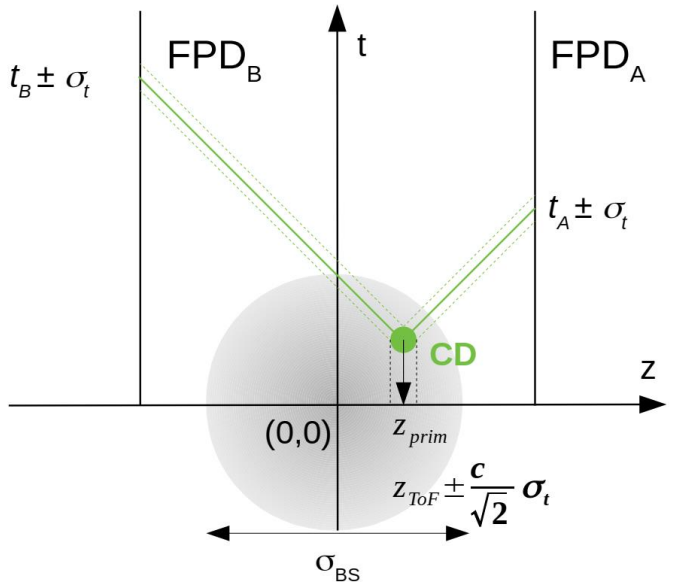
AFP – physics and ToF subdetector







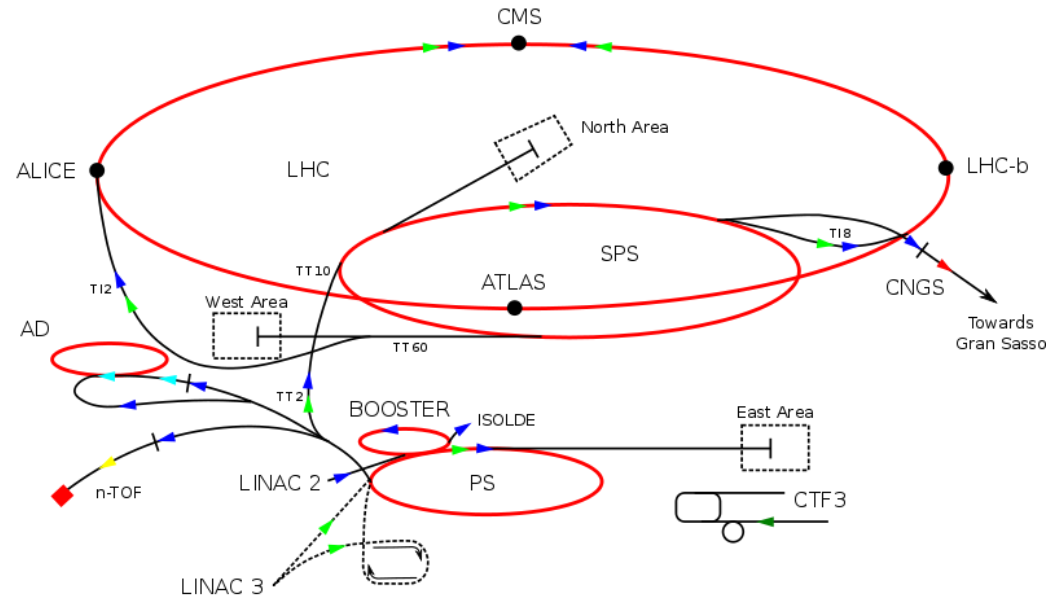
$$z_{\mathrm{ToF}} = \frac{c}{2}(t_{FAR-C} - t_{FAR-A})$$

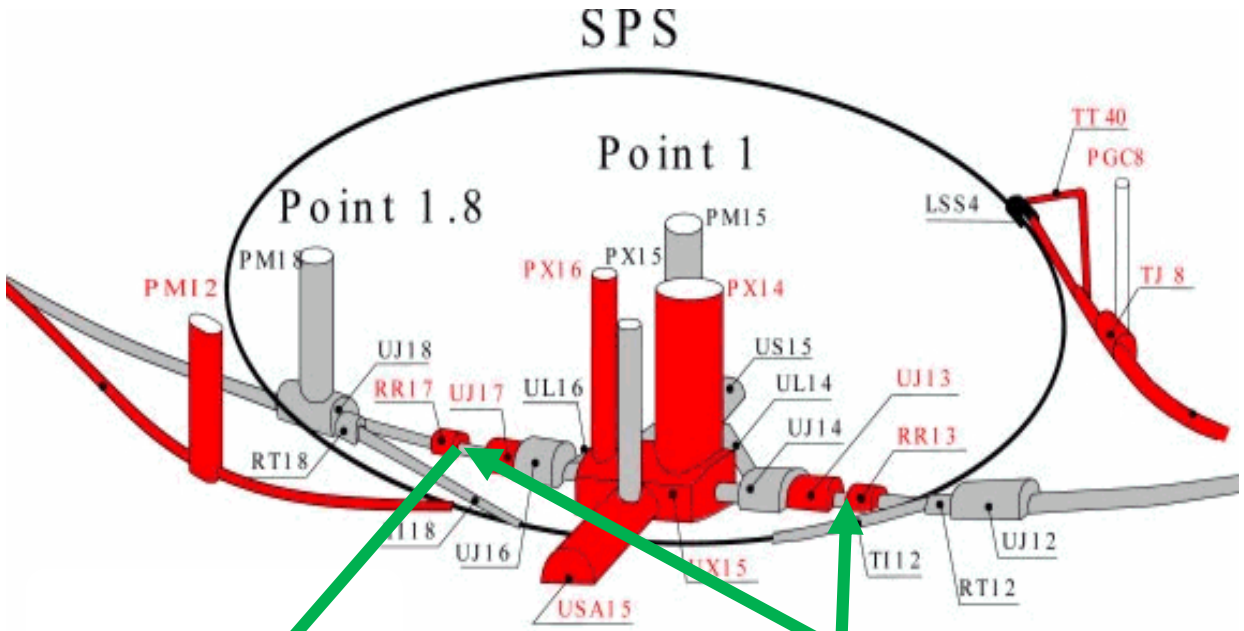


ToF main goal – pileup suppression; possibility for a dedicated trigger

a combination of AFP ToF information with e.g. HGTD…

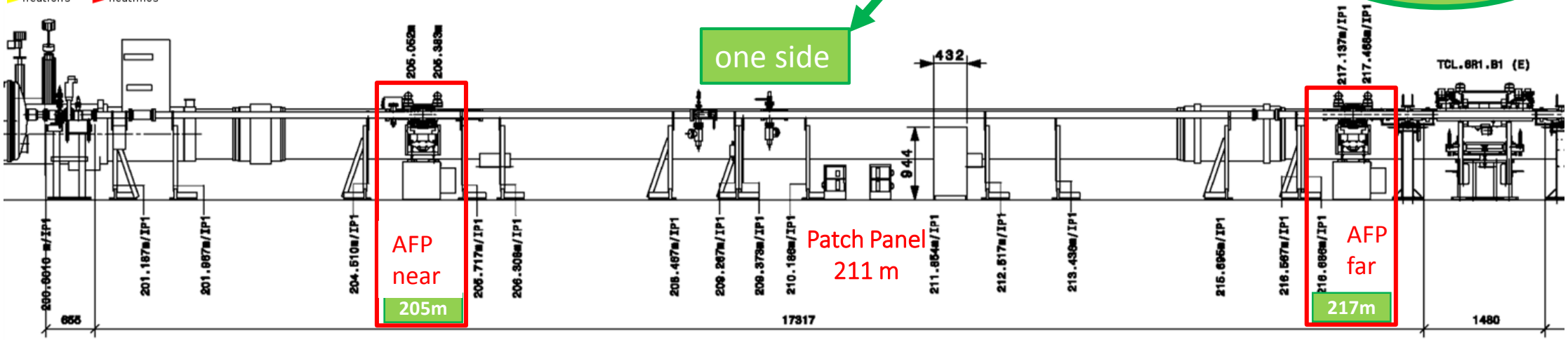
AFP – location



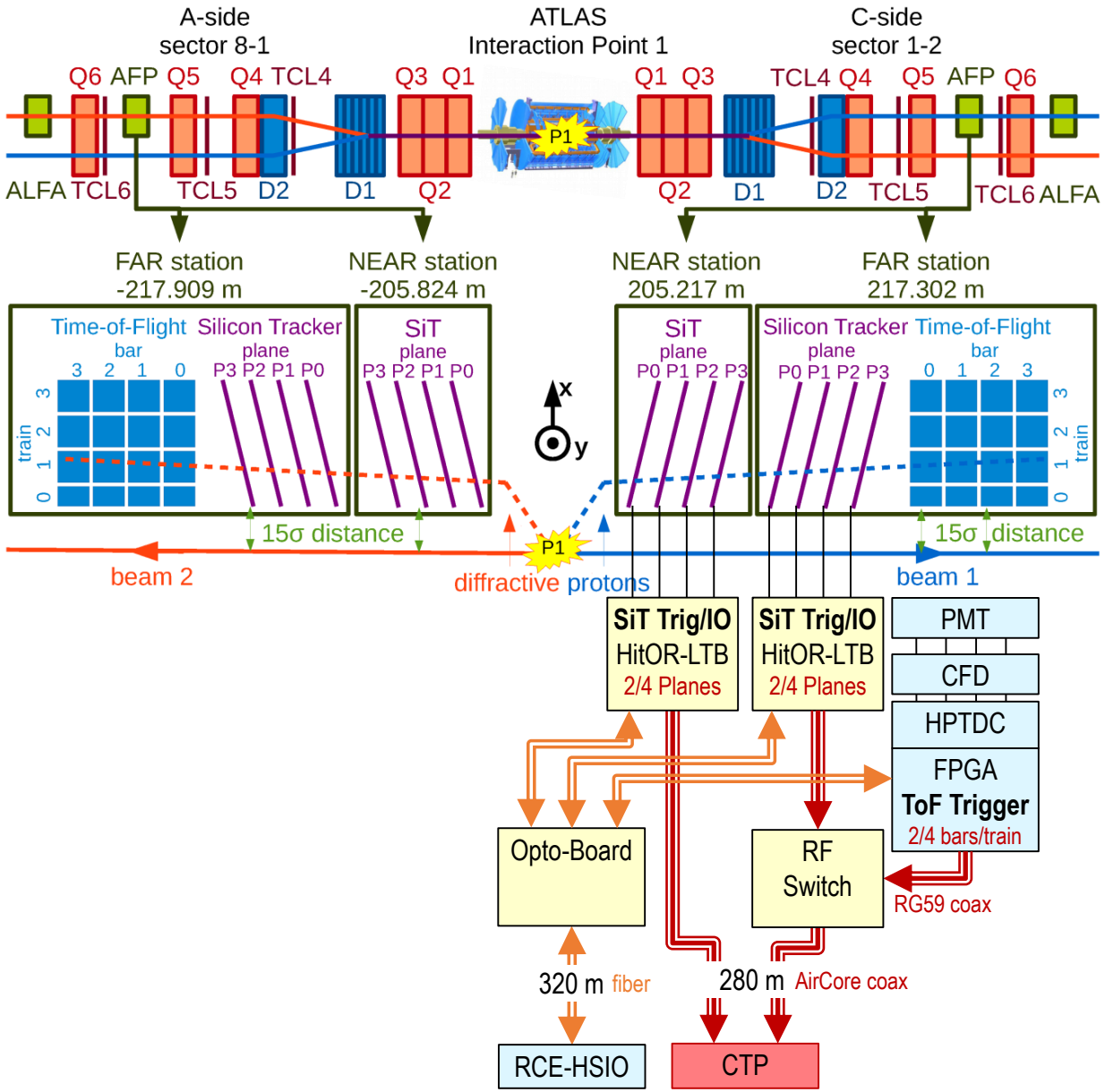


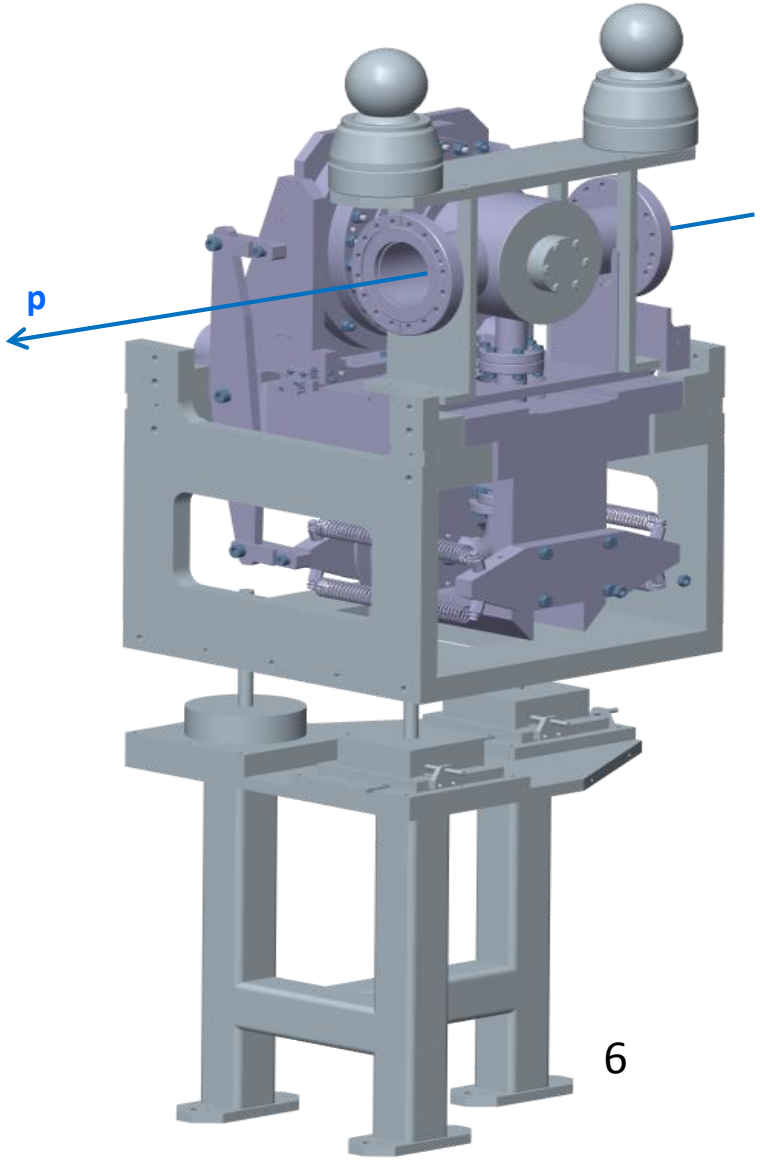
AFP stations left-right (IP)

one side



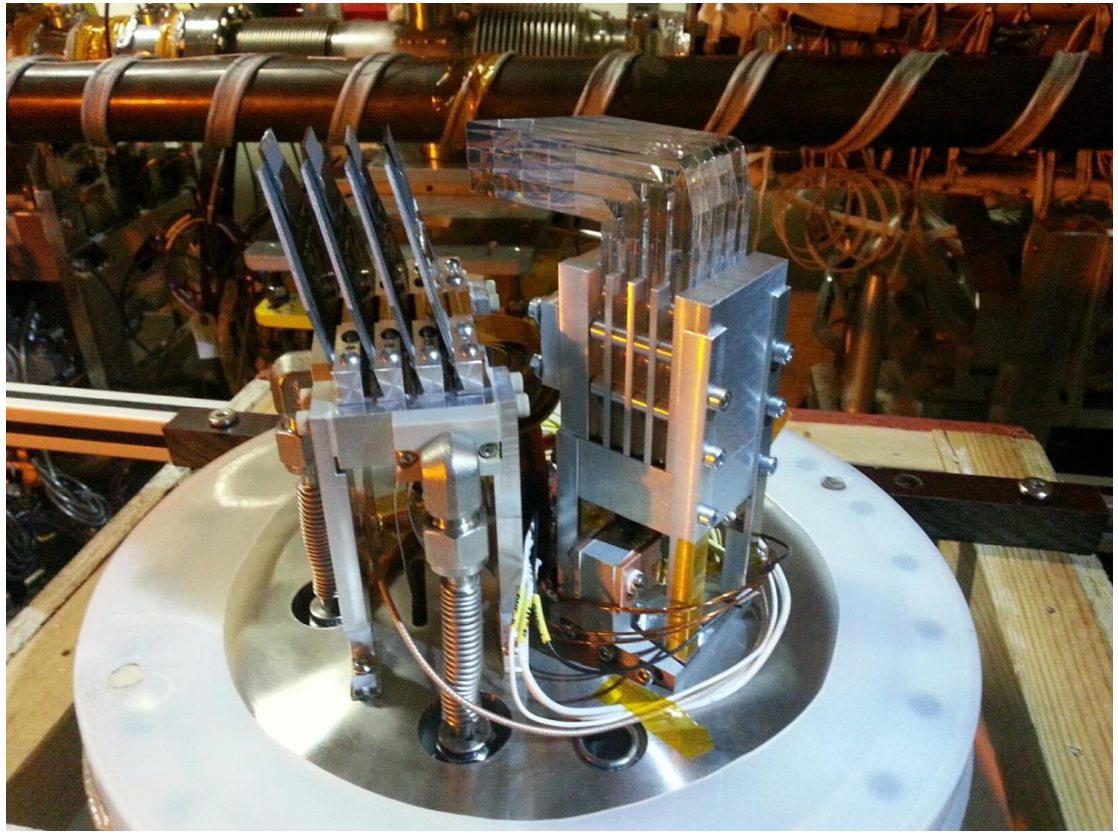
AFP – design

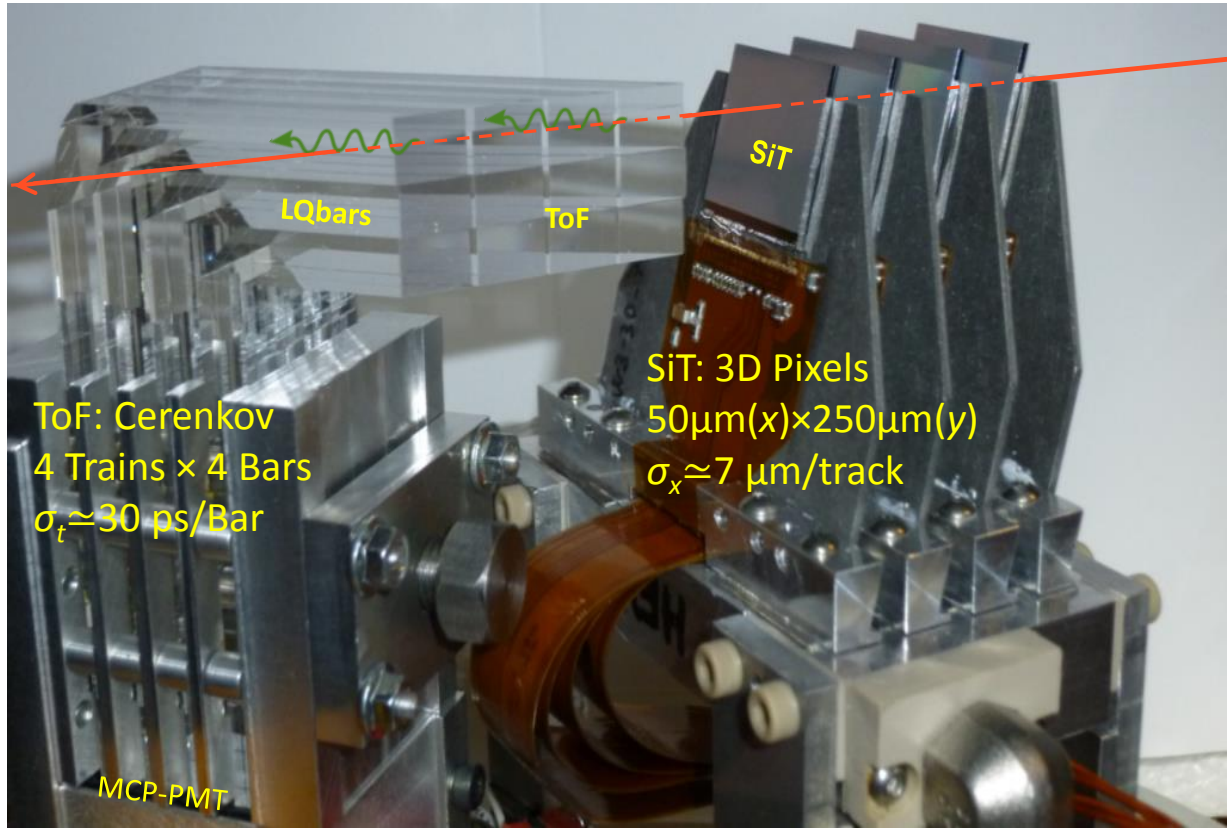




AFP station with passing proton **p**

AFP ToF design in 2017





original requirements on ToF system:

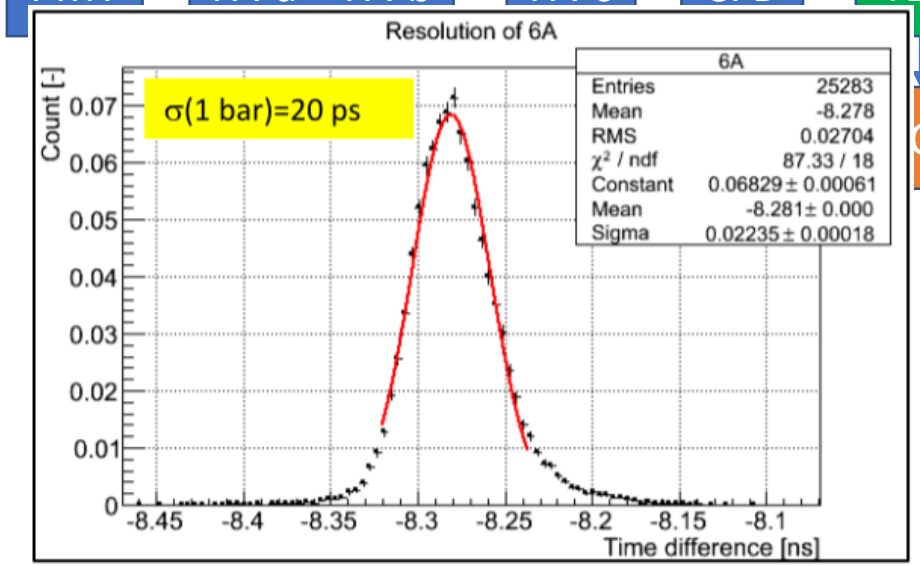
- resolution 10 ps or better for higher pileup
  30 ps for 1-st phase
- acceptance over full range of tracker
- near 100% efficiency

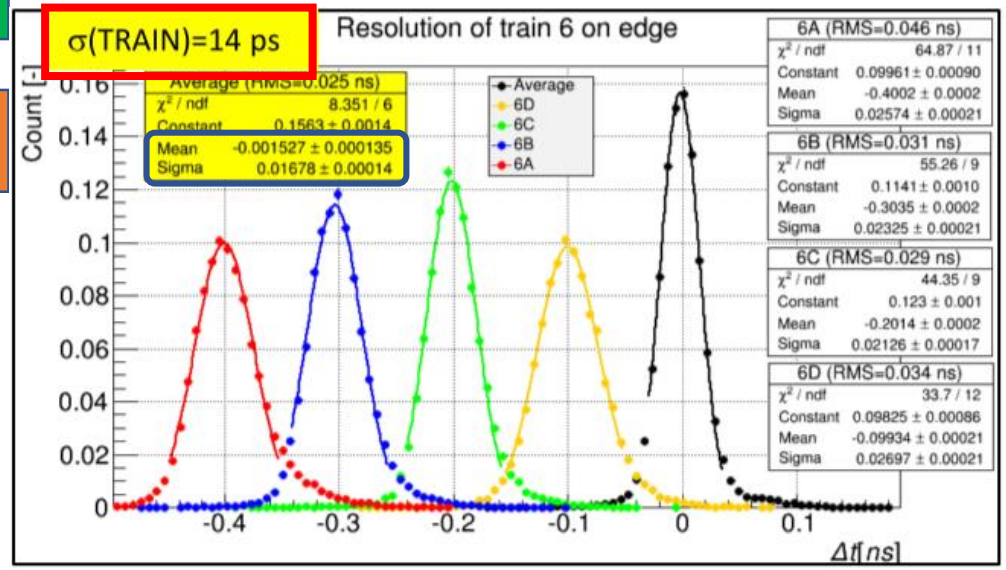
- segmentation for multi-proton timing
- high rate capability, ~ 5 MHz/segment
- L1 trigger capability
- radiation hardness

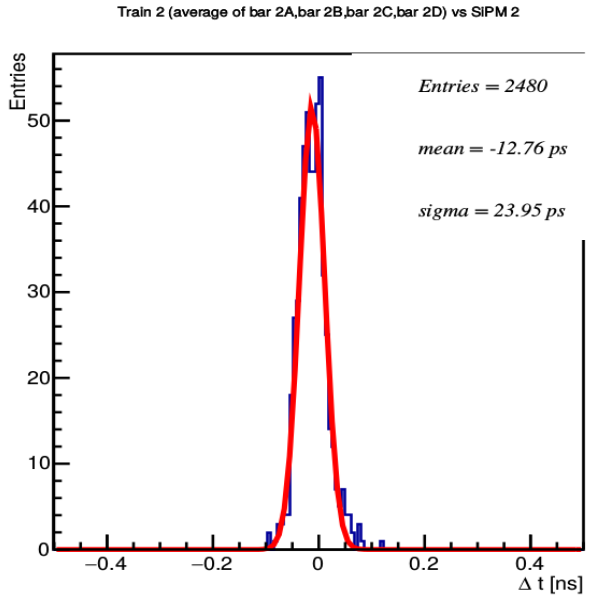
ToF performance as measured in beam tests <= 2017

T. Sykora, AFP ToF detector: results, experiences and plans Workshop on picosecond timing detector for Physics, Zurich,

oscilloscope measurements





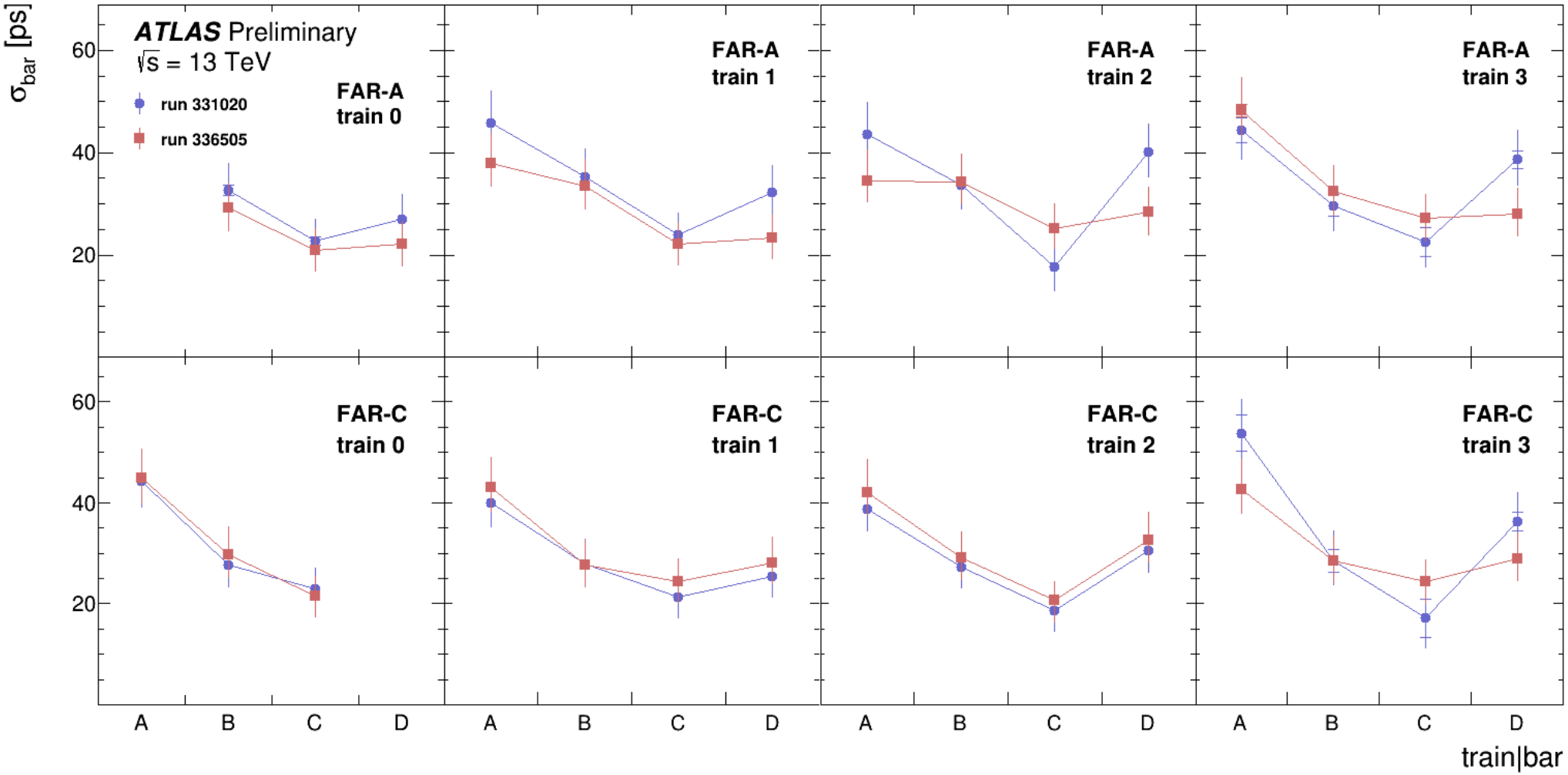


HPTDC included (RCE), trigger included

final resolution after trigger subtraction – **20.6 ps**

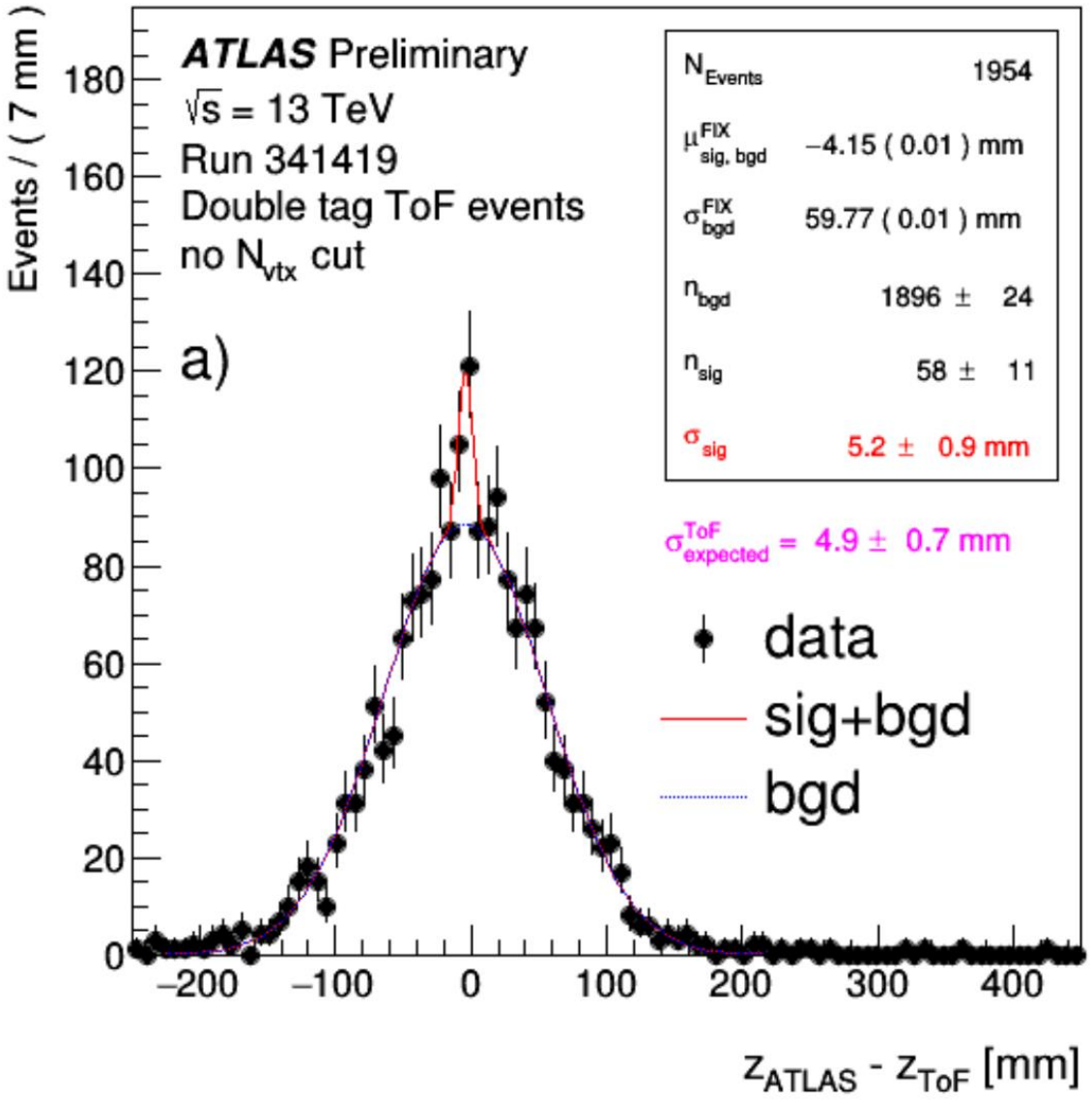
test beam, not tunnel!

ToF in 2017 – timing



resolution of each bar within train and station, fully consistent with beam tests; no effect of synchronization clock

ToF in 2017 – z-vertex reconstruction



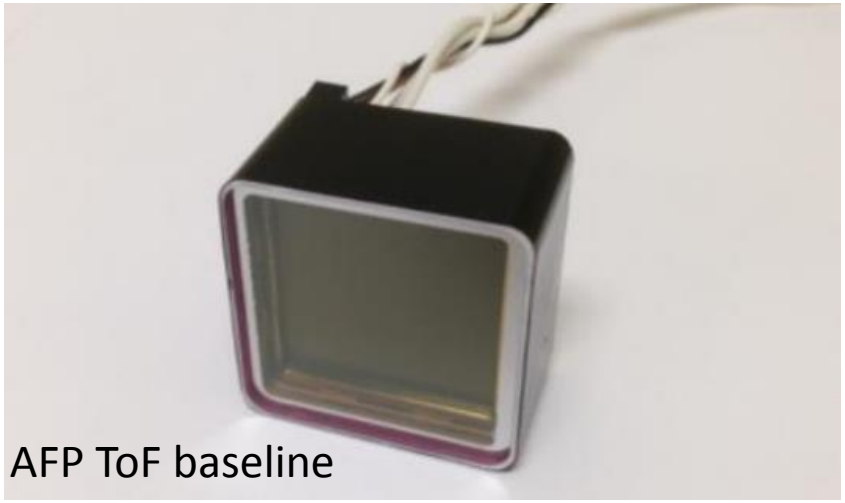
z_{ATLAS} - z_{ToF} distribution: obtained by random mixing of times measured by the AFP To detector in either station and the z_{ATLAS} values which do not originate in the same collision event.

the expected resolution of the ToF detector, $\sigma^{ToF}_{expected}$ is obtained from the known single-channel resolutions convoluted with the actual channel-hit-patterns observed in the data in the 'no N_vtx cut' scenario

the shape of the distribution (narrow peak) provides a hint of presence of the (central diffraction) signal pp → pXp

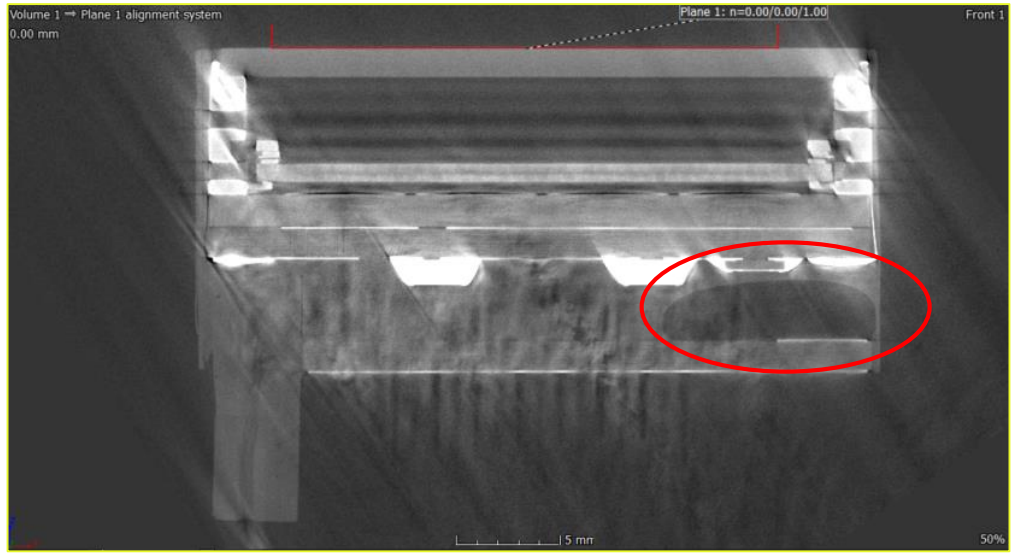
for more detailed analysis see
CERNY, K. at al., *Performance studies of Time-of-Flight detectors at LHC*, 2021 JINST 16 P01030

MCP-PMT – operability in vacuum

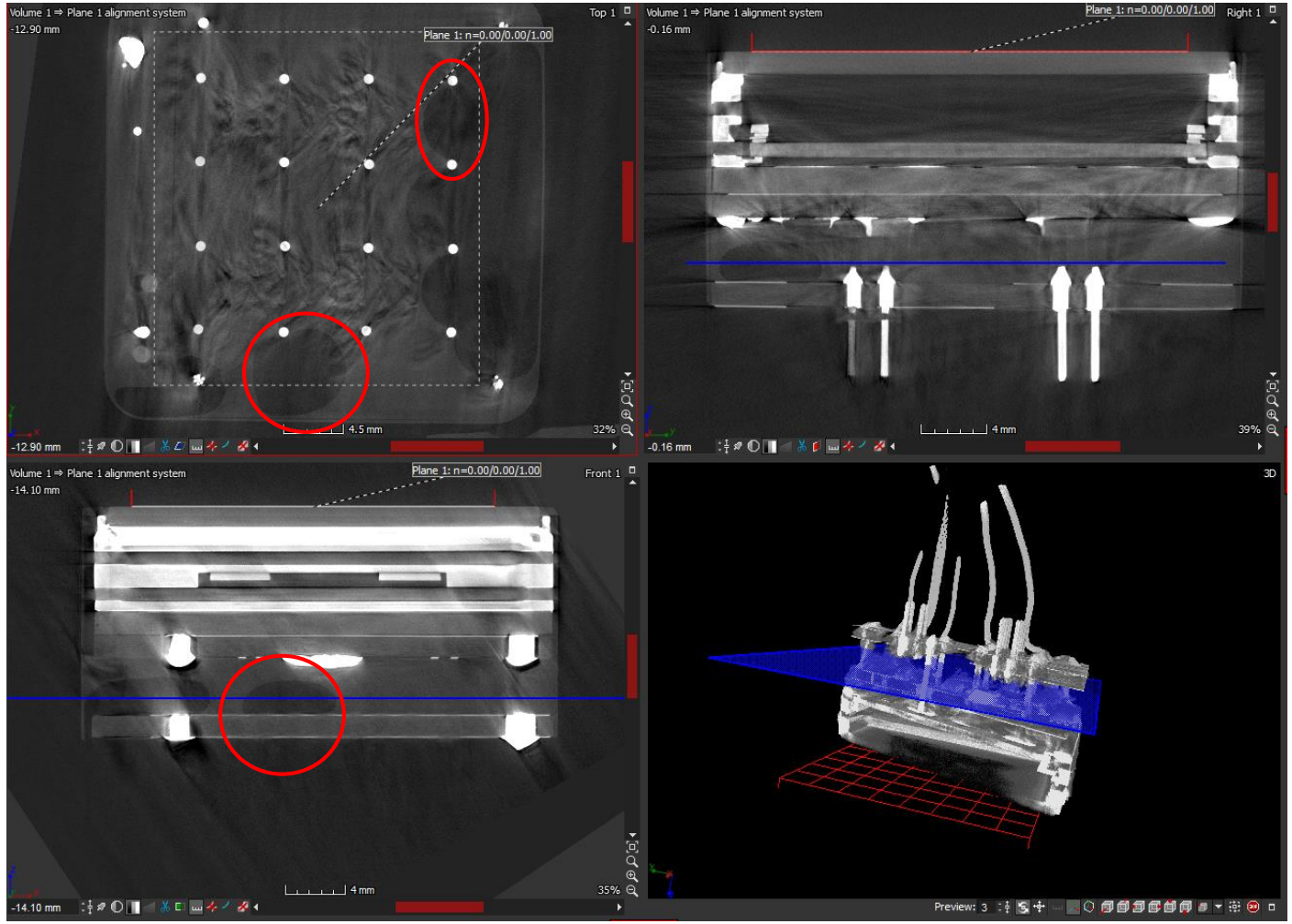


AFP ToF baseline

miniPLANACON® XPM85112



repeated failures during HV tests in vacuum



originally we thought about air bubbles…

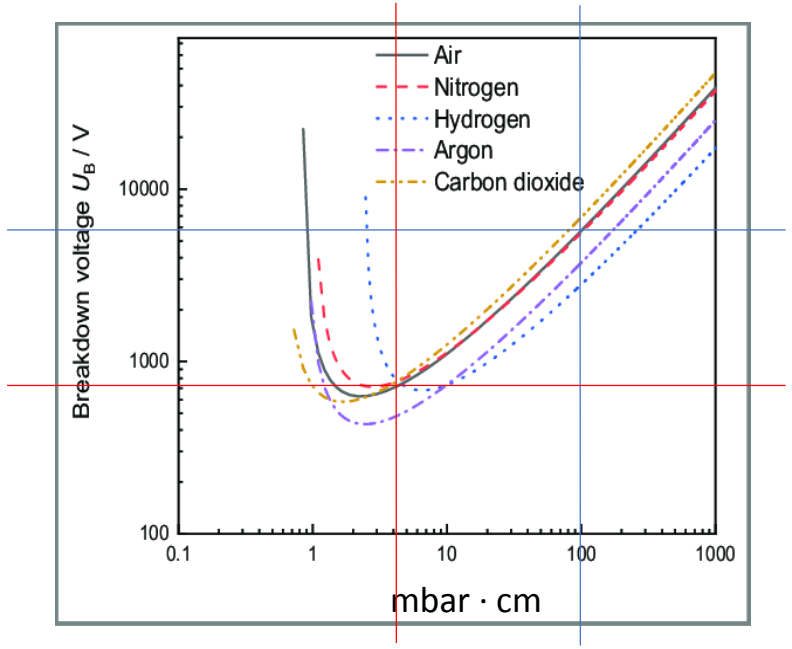
⇨ change of the detector design

removal of MCP-PMTs from the vacuum: advantages

1. safe regime Paschen's curve
2. no feedthroughs needed
    1. for signal
    2. for HV
3. better cooling
4. easier to replace PMT if needed

standard pressure: 1013.25 mbar
typical pressure in pot: 30 mbar

typical distance: 1 mm

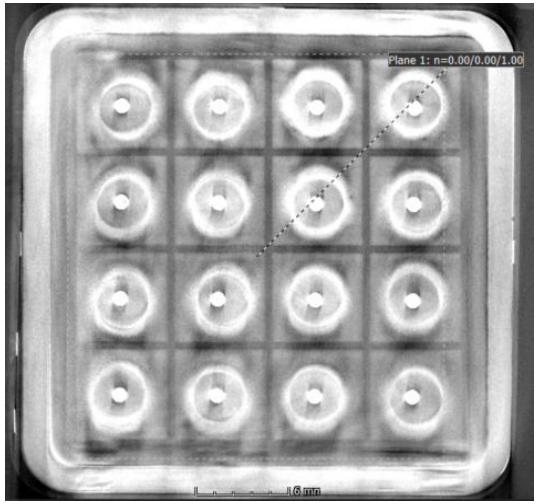


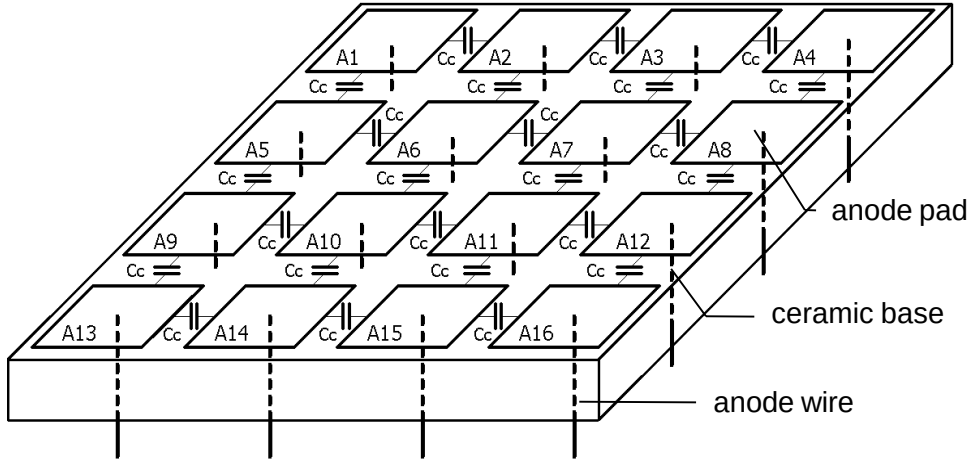
MCP-PMT – crosstalk ($\sqrt{N}$)

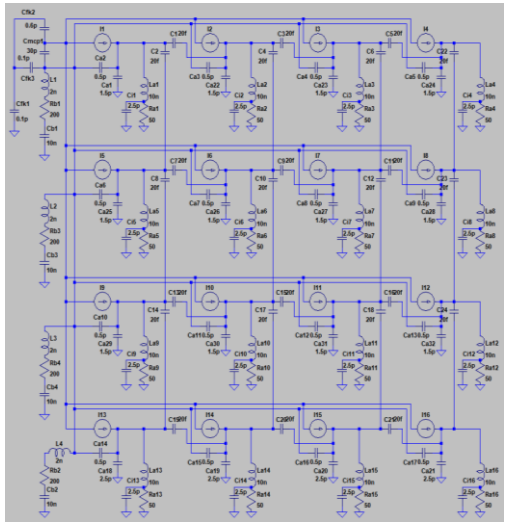
observed crosstalk, depending on the MCP-PMT model (e.g. reduced anode gap): 20-40 %

motivated (also) by ALICE – change of back-end electronics design

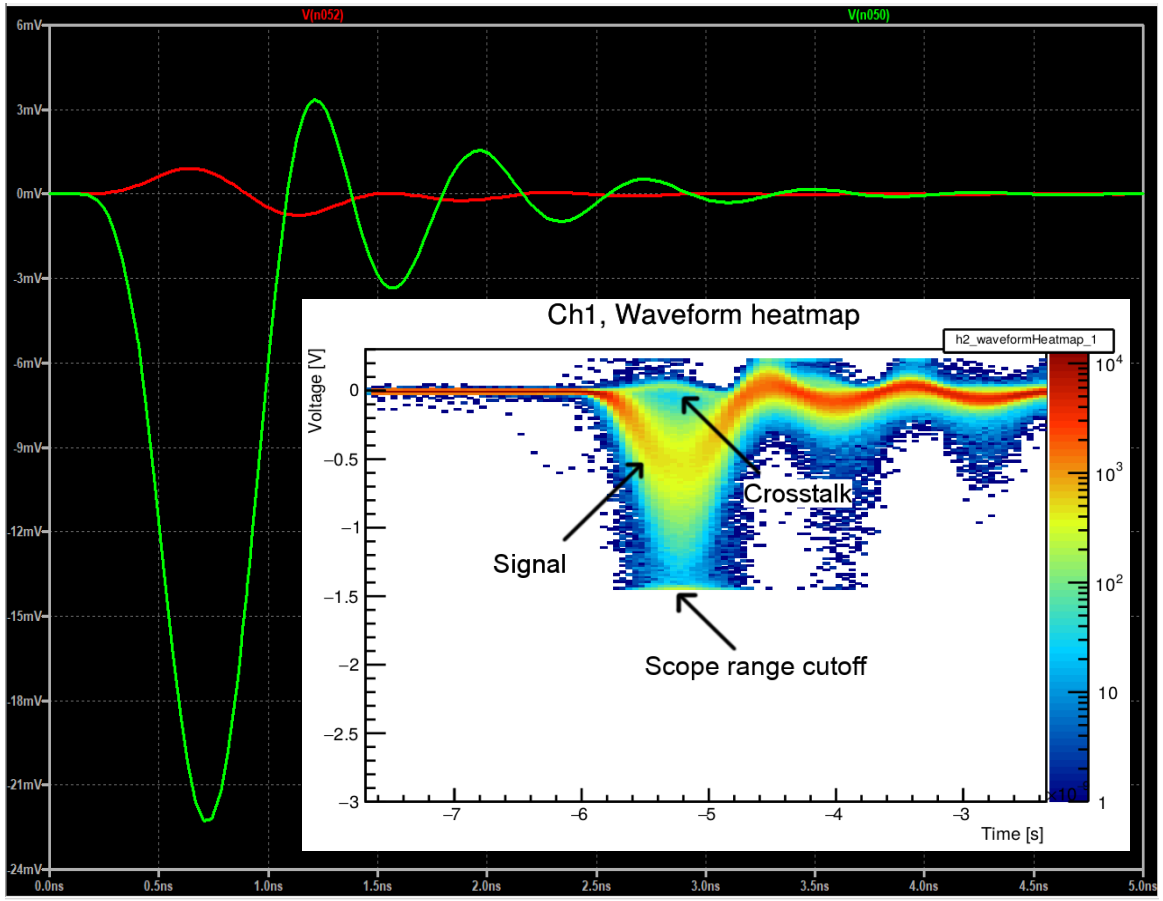
modelling and simulations





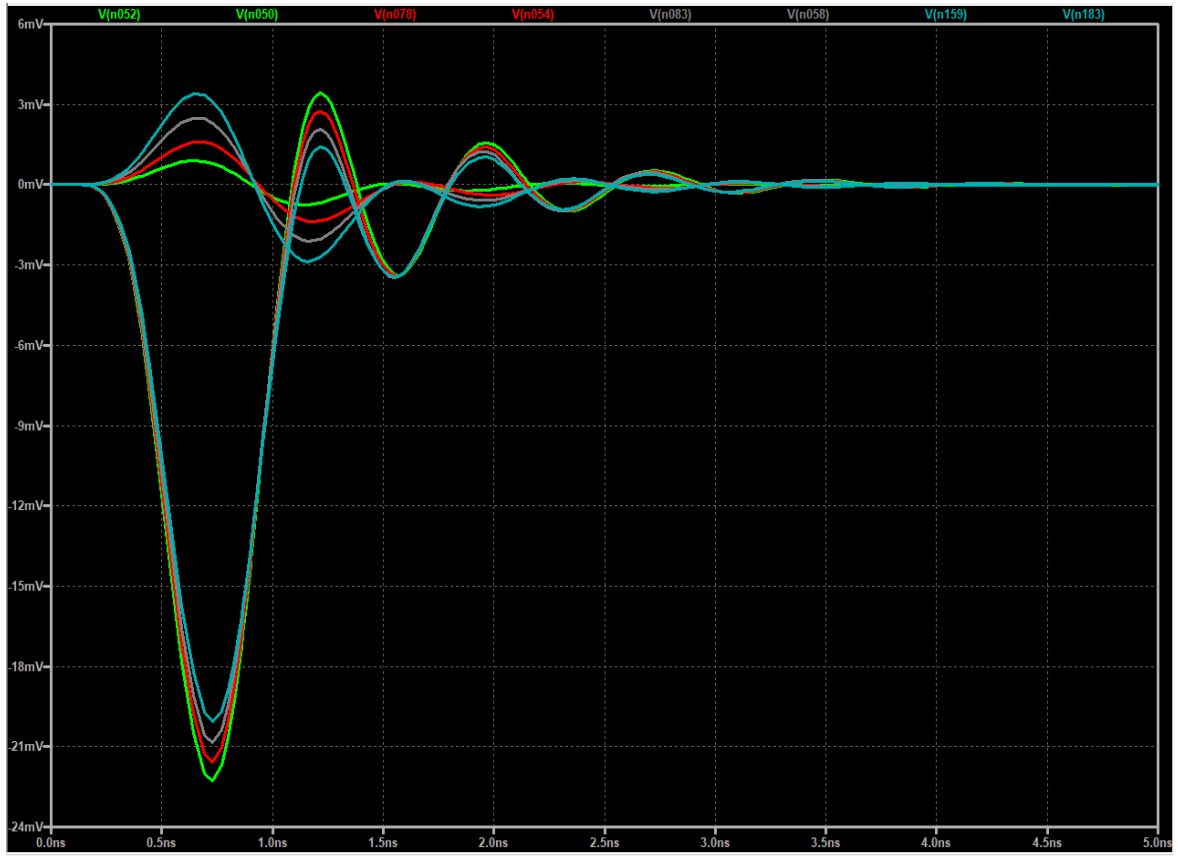


MCP-PMT – crosstalk modelling



signal and crosstalk – active 1 channel MCP-PMT

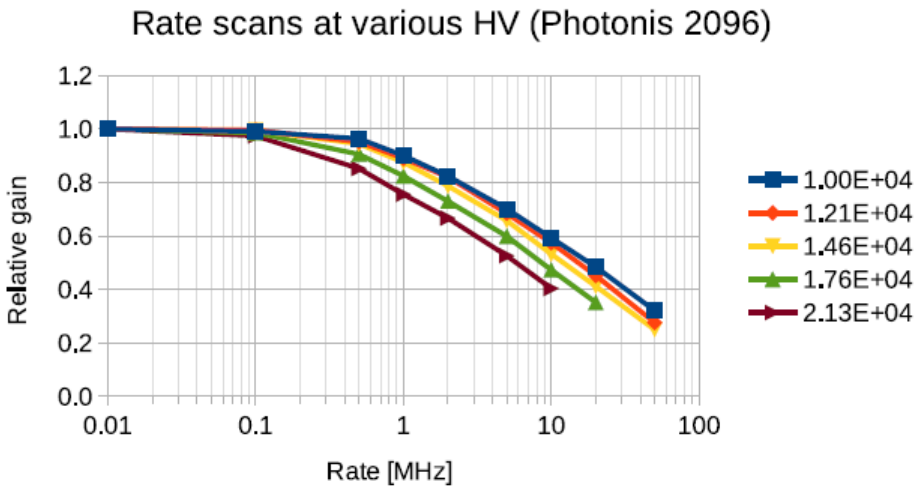
good agreement of simulation with measurement

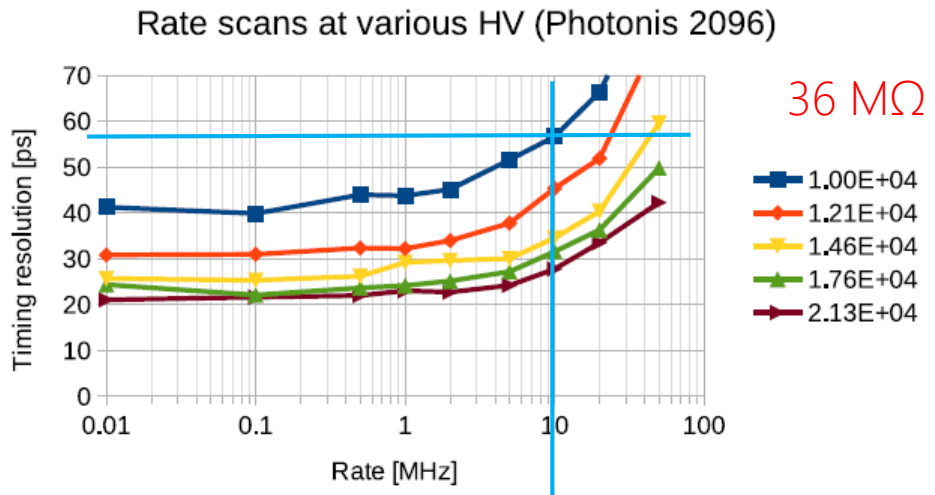


signal and crosstalk – signal in 1-4 channels

new design, crosstalk: < 13 % for reduced anode gap

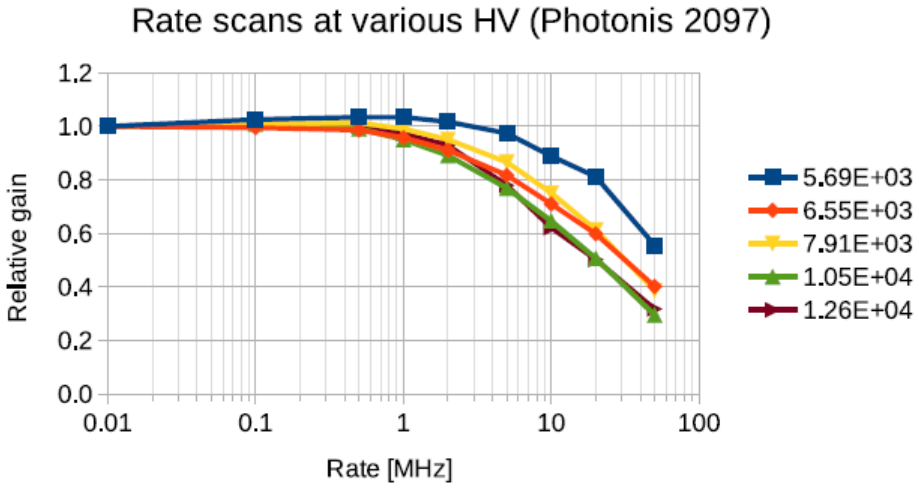
rate behaviour measurement, at the UTA, 2018

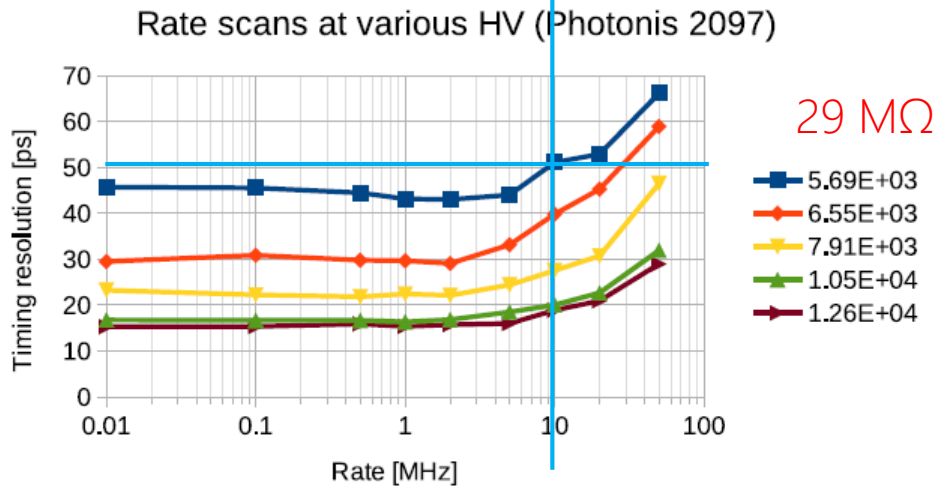




36 MΩ

four channels illuminated with 20 p.e. pulses each

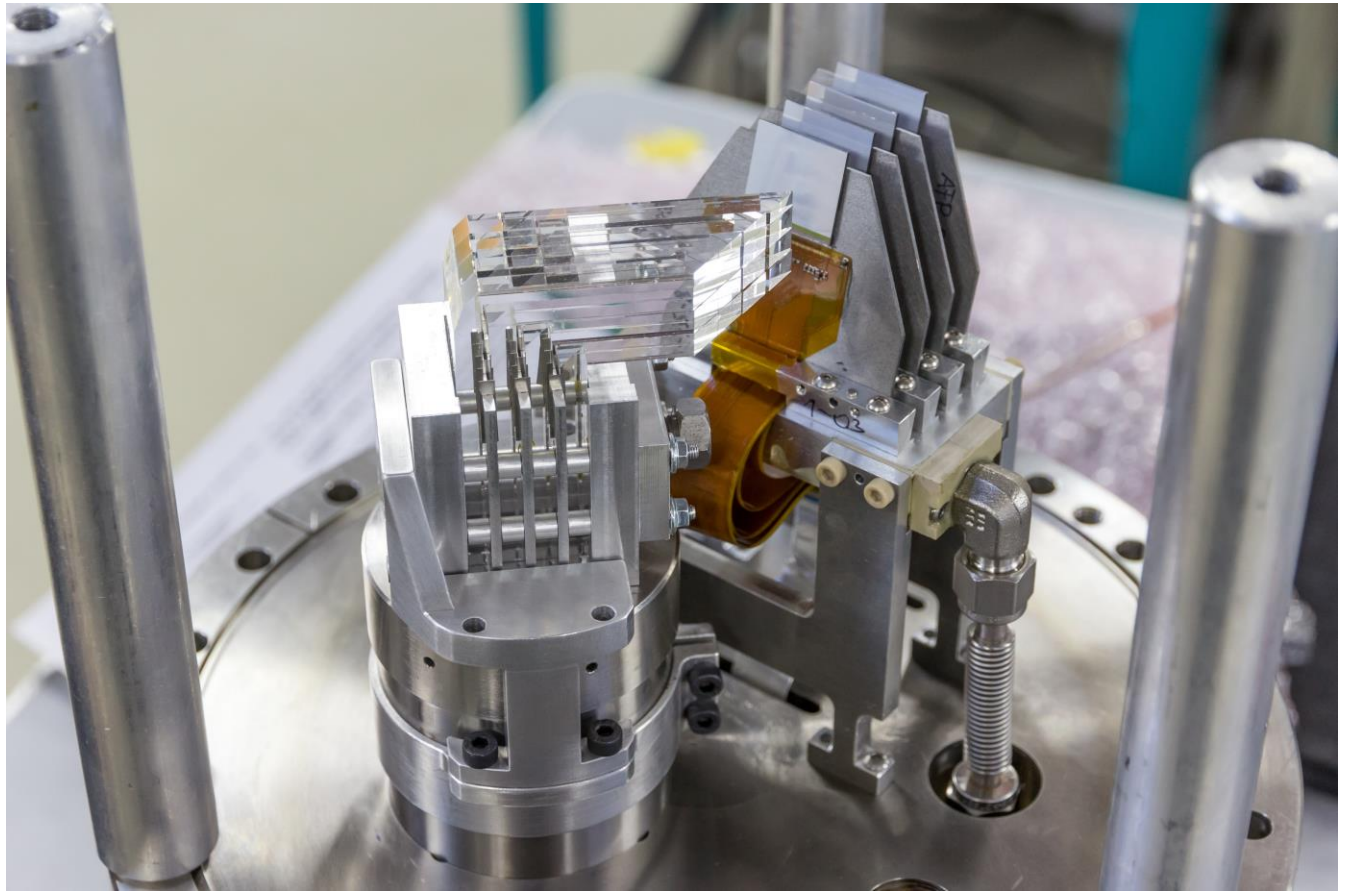




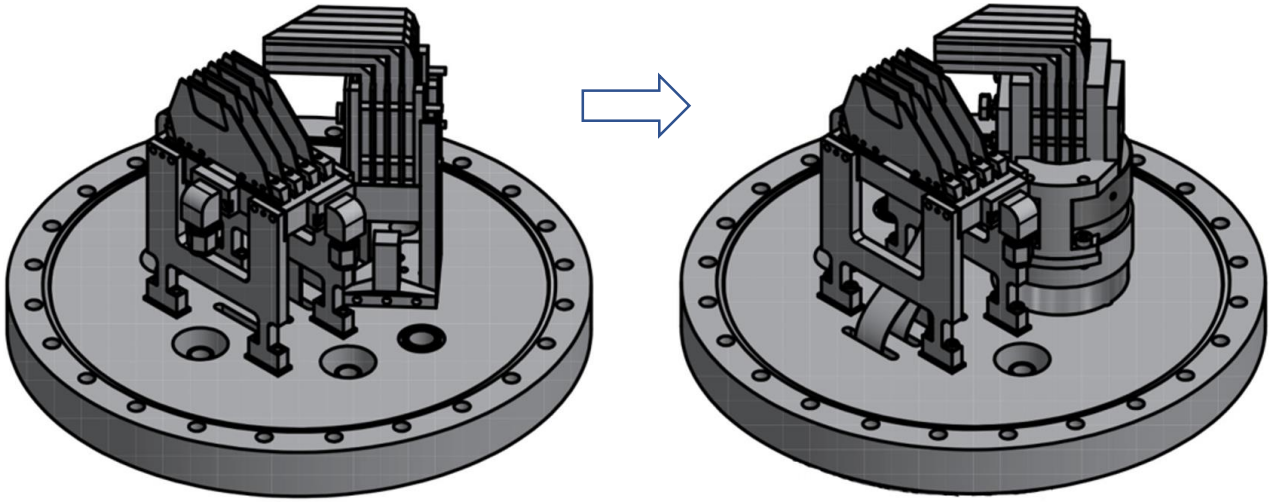
29 MΩ

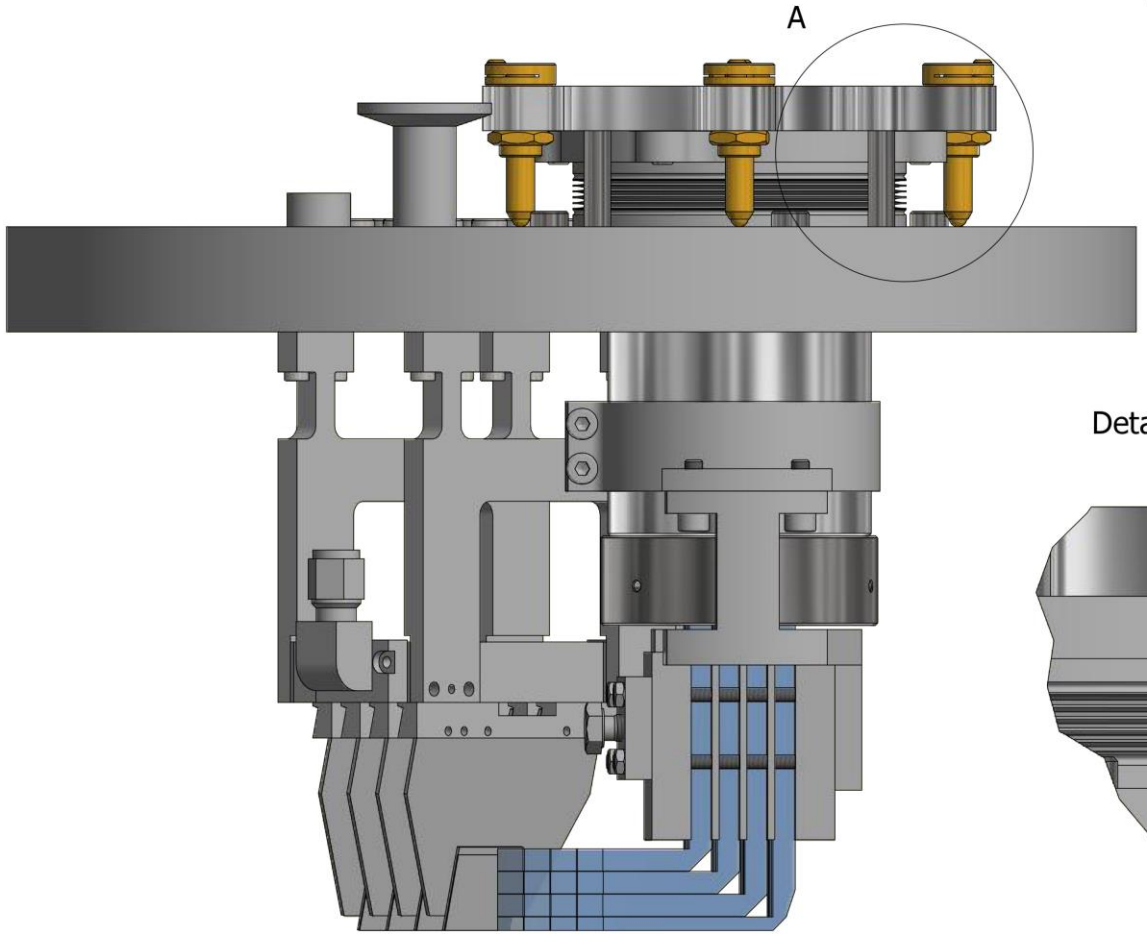
rate NOT per cm^2, spot with **Ø = 4.8 mm**

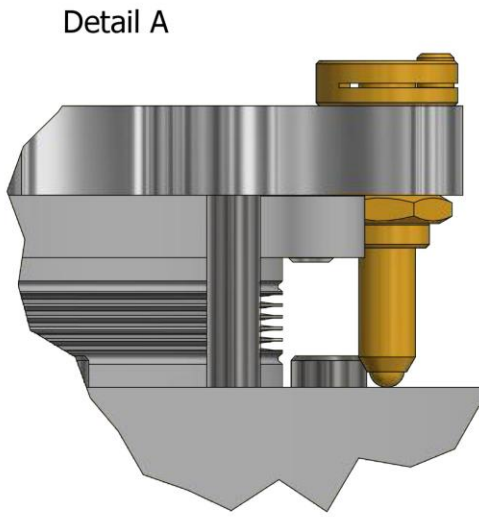
towards Run3

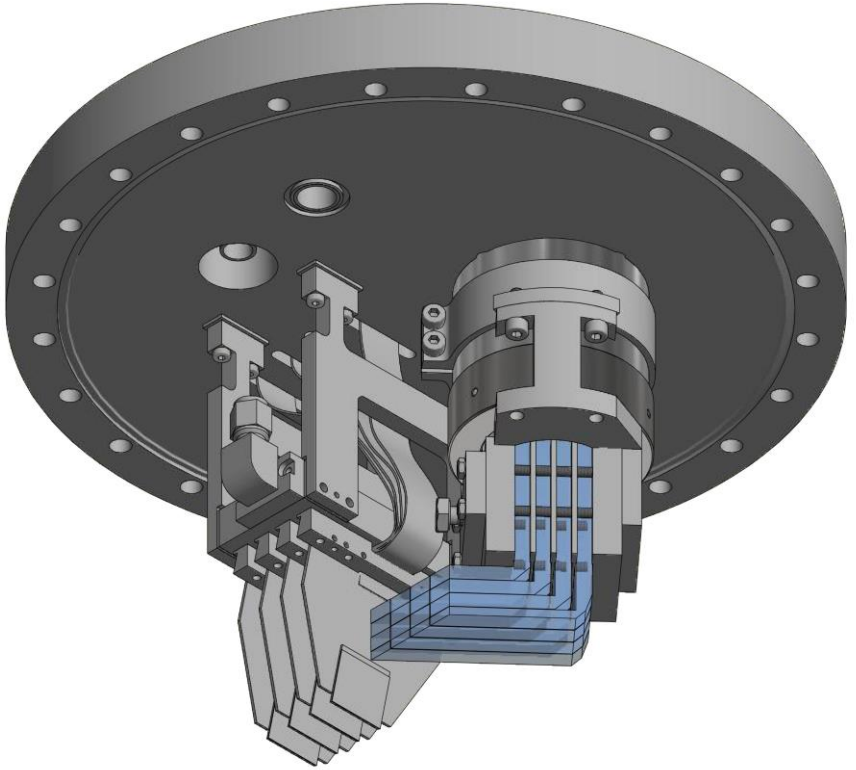


detector new design









Out-of-Vacuum solution (OoV)

no guaranteed operability of MCP-PMT in vacuum -> we put MCP-PMT in air

after MC studies (effect of separation window)*, test bench studies*, vacuum and overpressure tests*, beam tests*

the new design was approved by the LMC at April 1st 2020

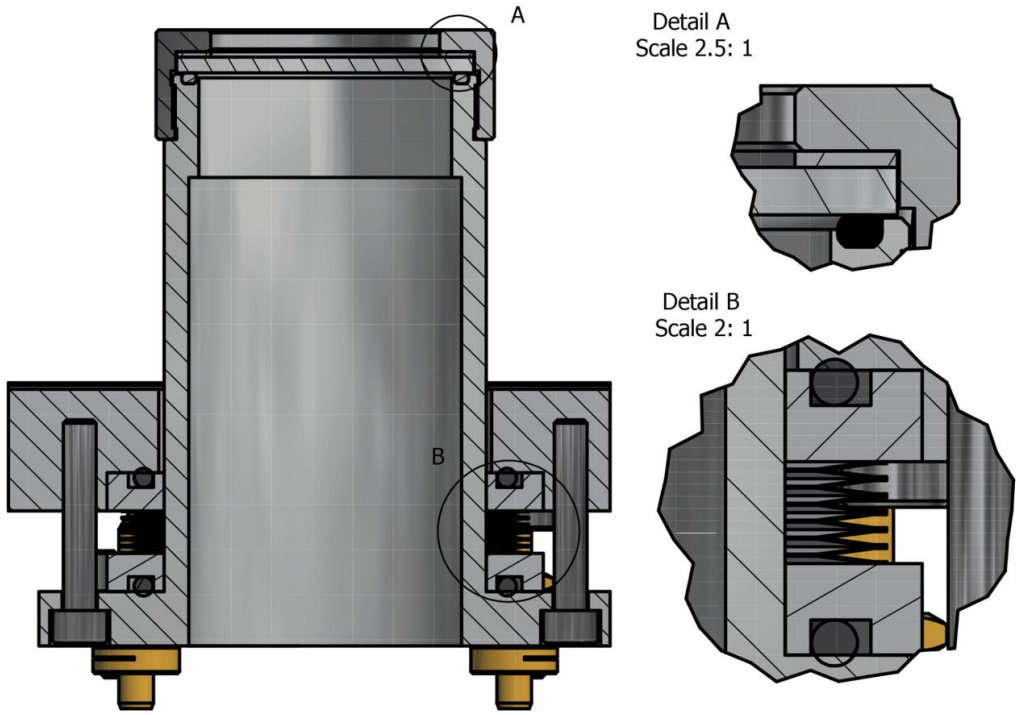
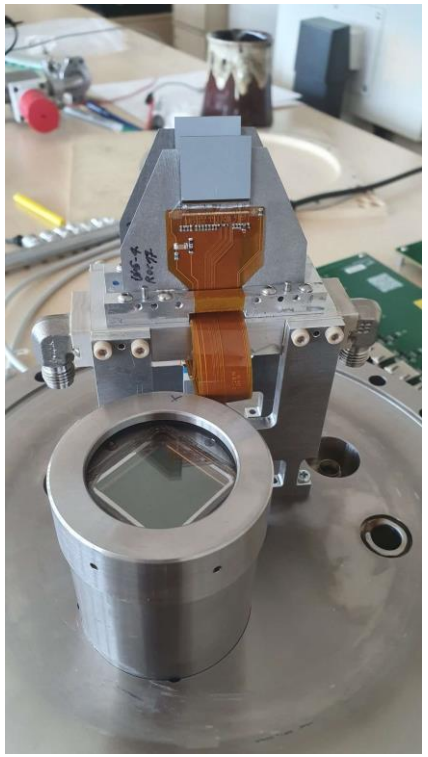
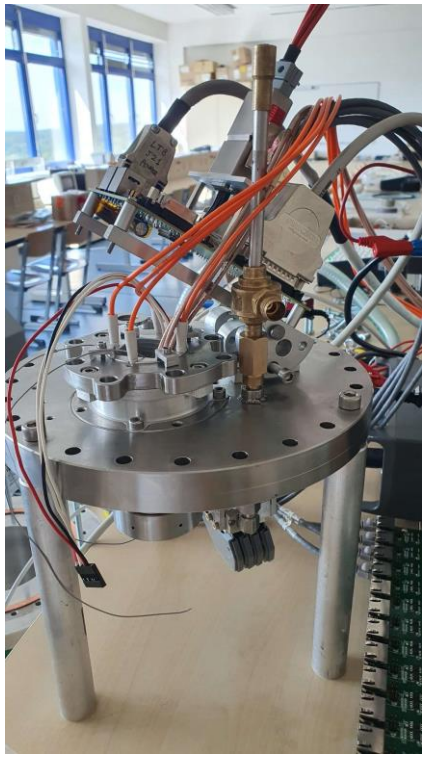
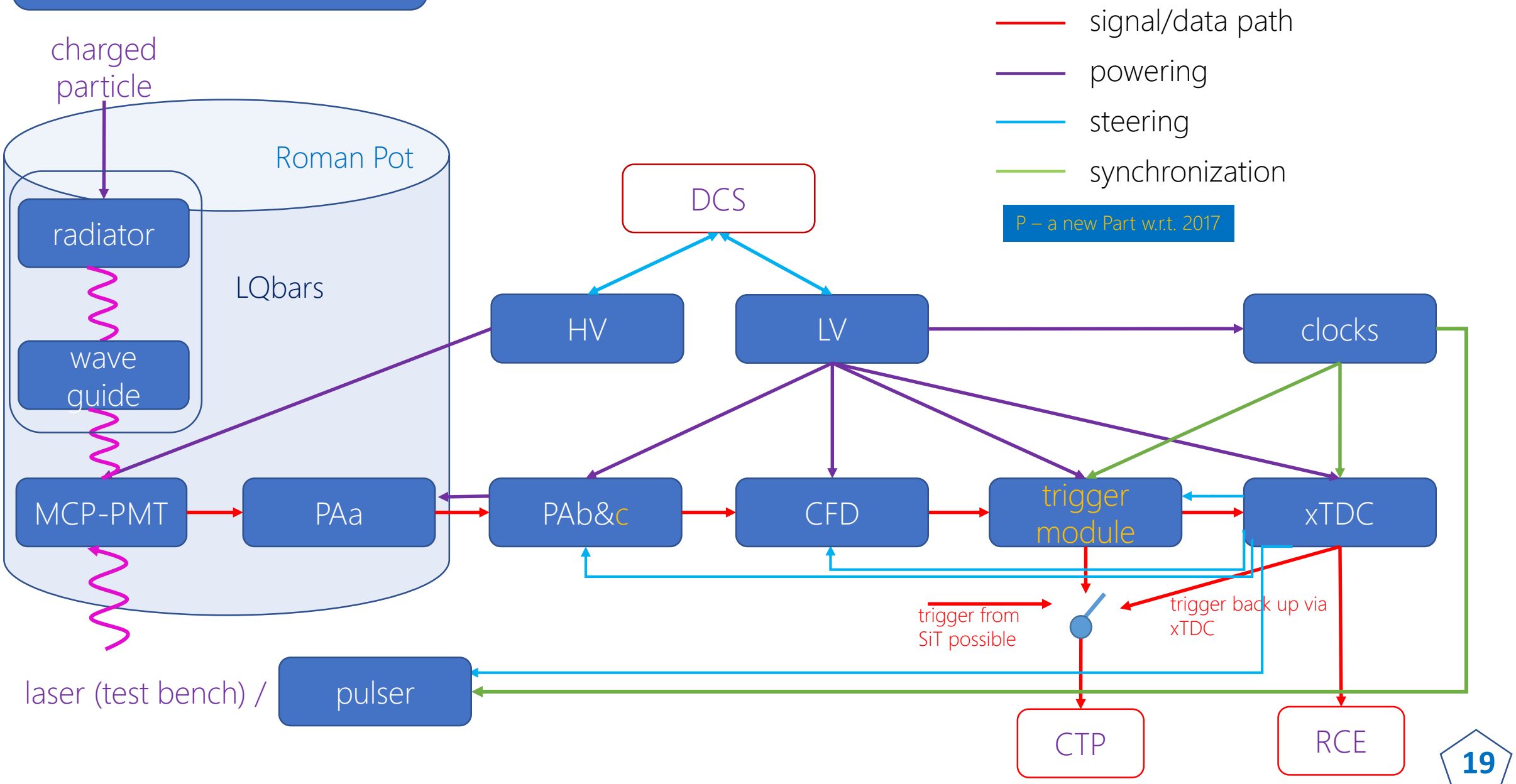


Figure 4 - The three new O-rings in the new design. One is shown in the detail A, another two in the detail B.





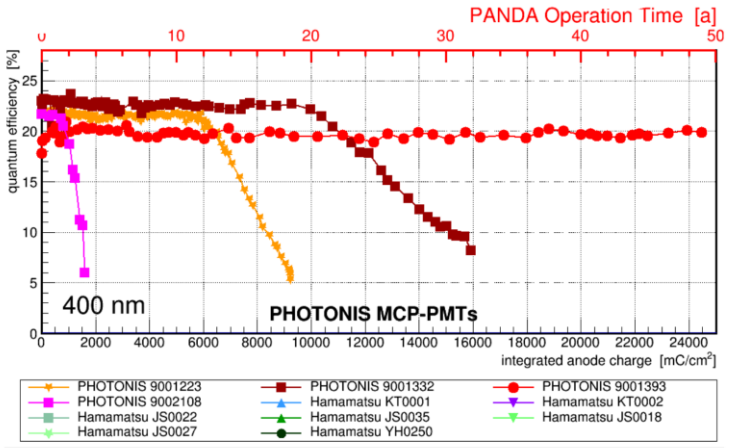
hardware components of the AFP ToF detector in 2021



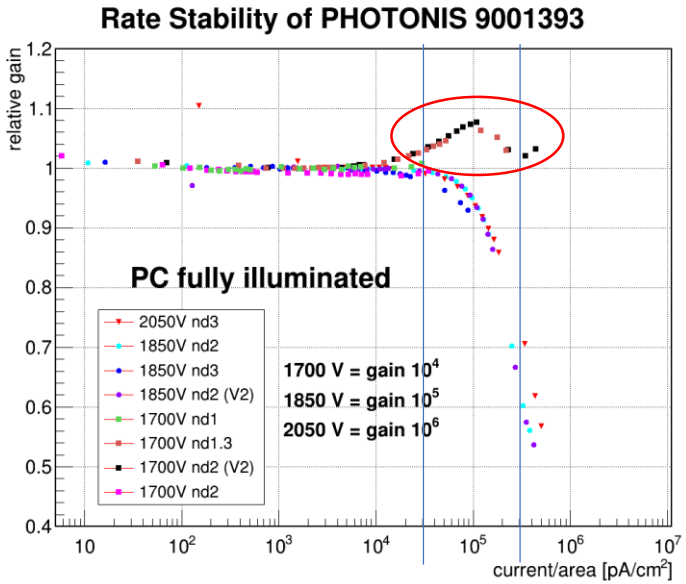
MCP-PMT and high rates, Photonis, XPM85112-S-R2D2

we need to deal with high rates – search for a solution

suggested by A. Brandt and motivated by A. Lehmann's group measurement



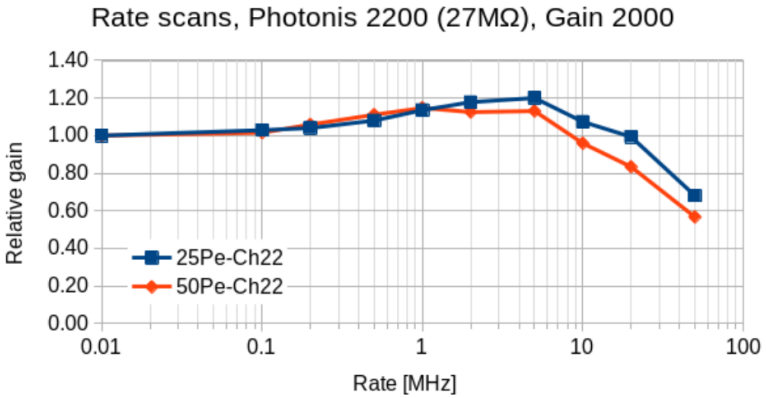
superb lifetime, > 20 C/cm²

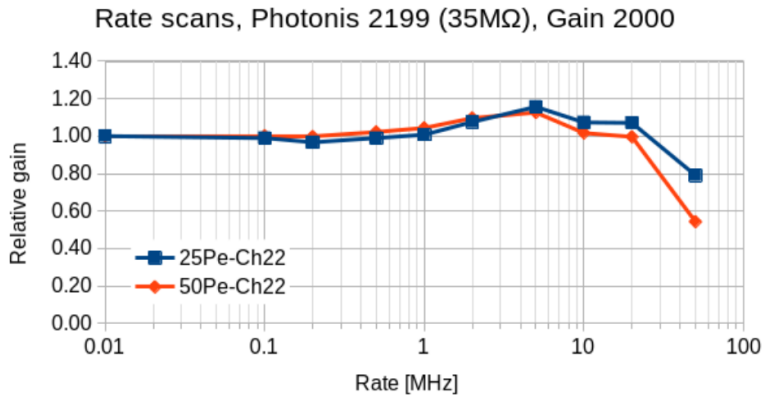


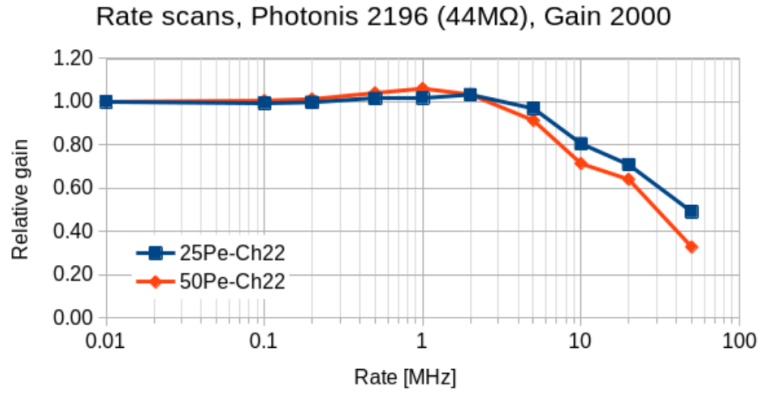
100 kHz 1 MHz

our geometry, 80 p.e./ cm², at gain 5 x 10⁴

produced by Photonis and Arradiance (R2D2)

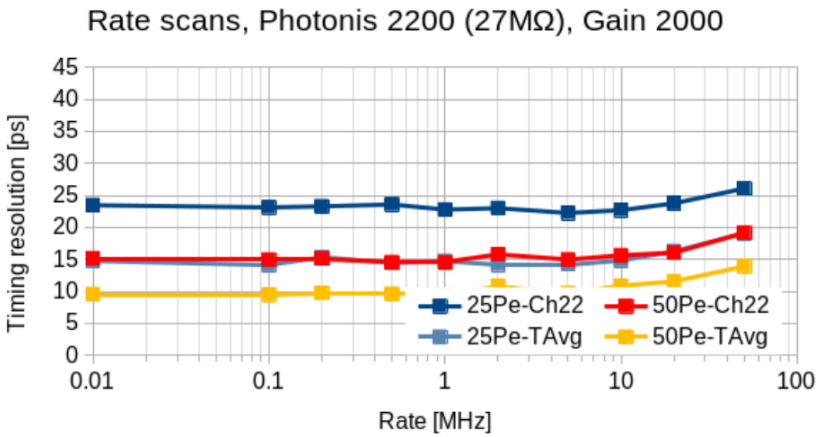


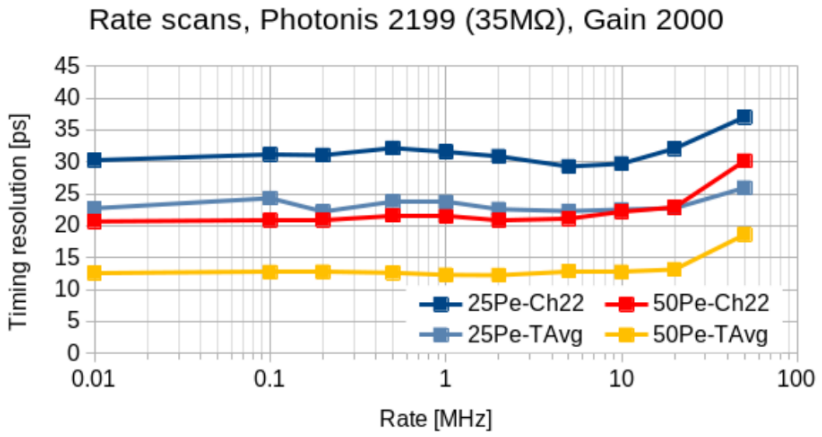


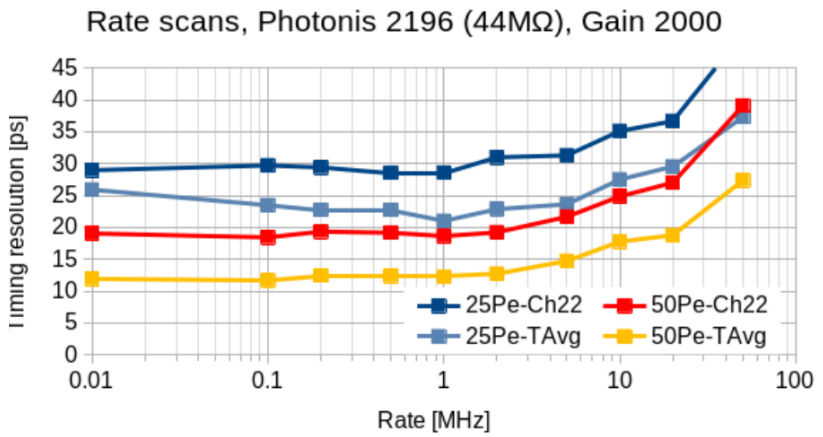


timing - lab results (R2D2 tubes)

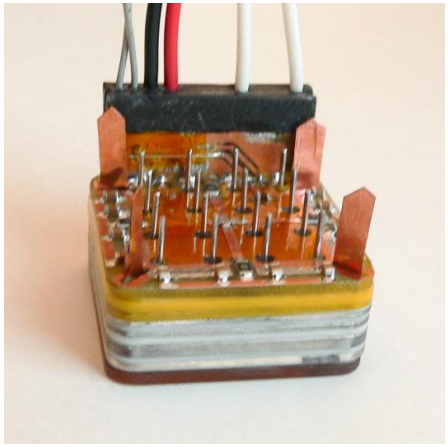
direct light into MCP-PMT channels

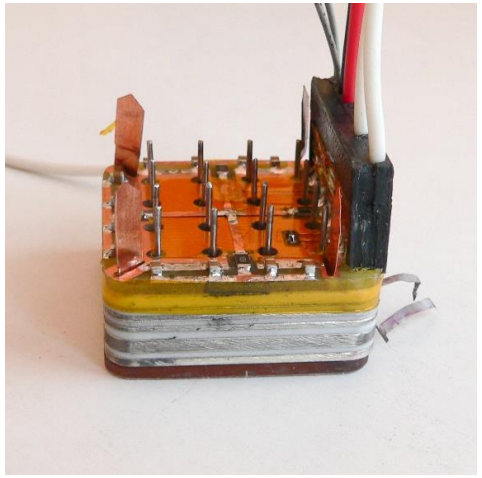


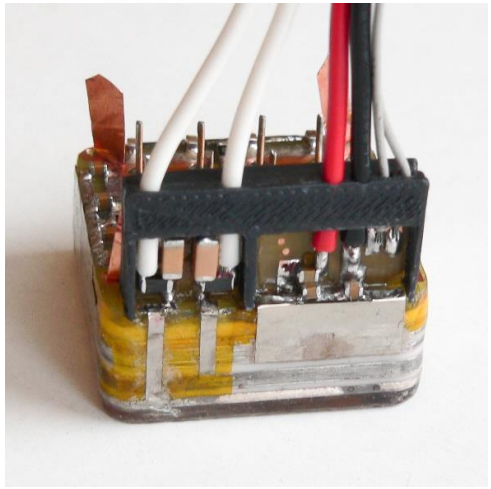


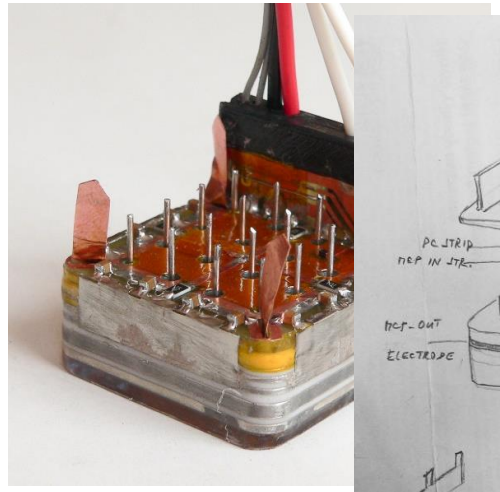


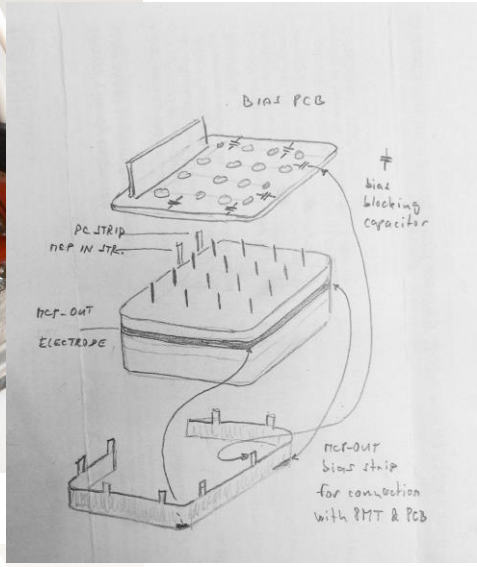
new back-end electronics (for R2D2 tubes)

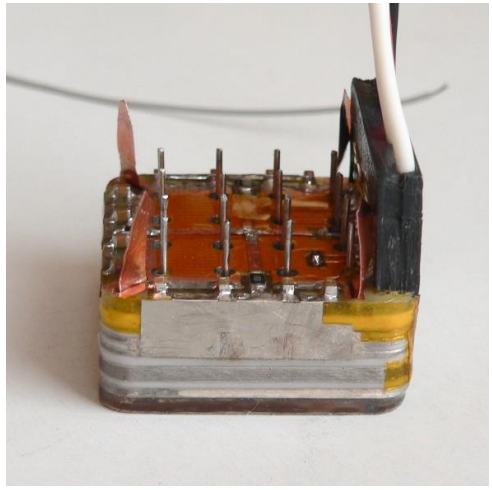


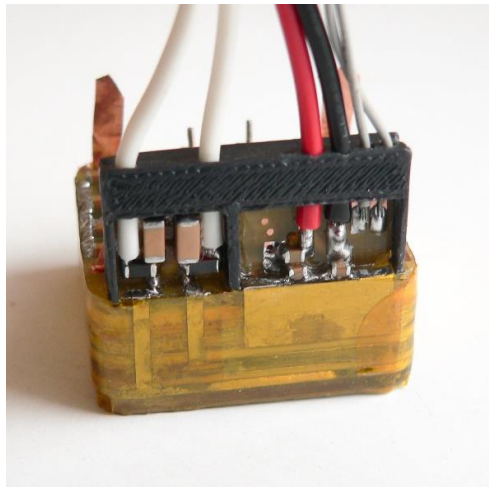


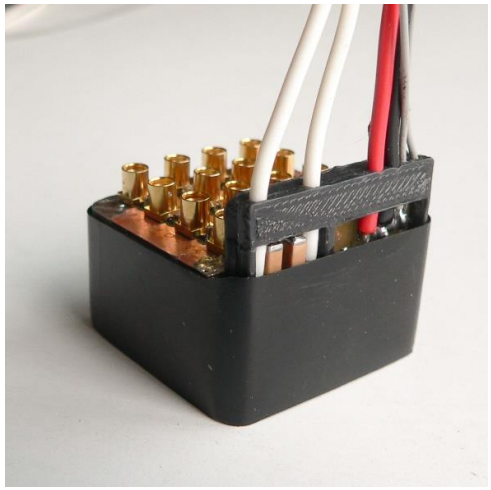


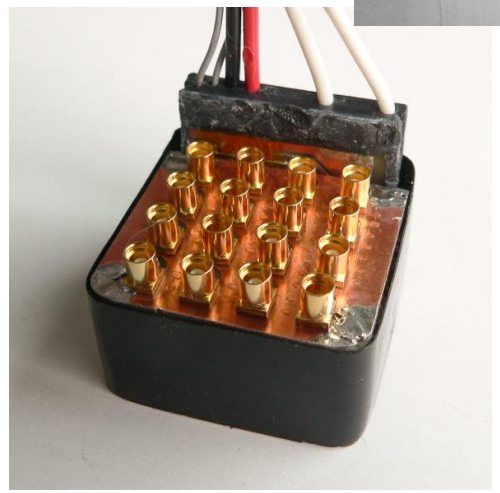






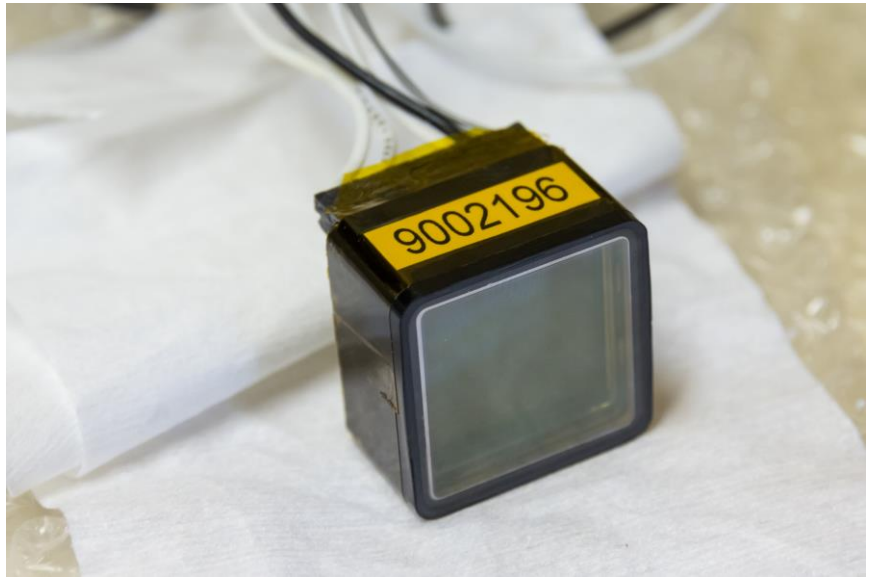


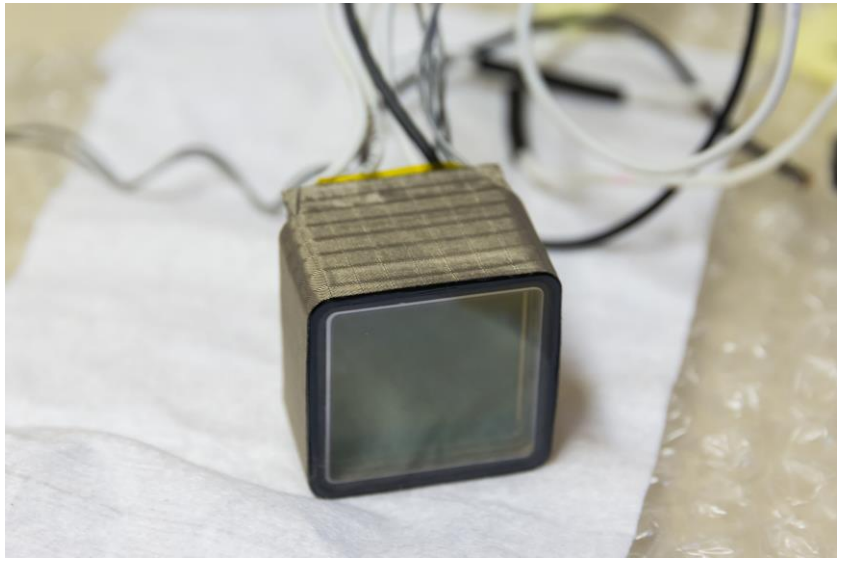


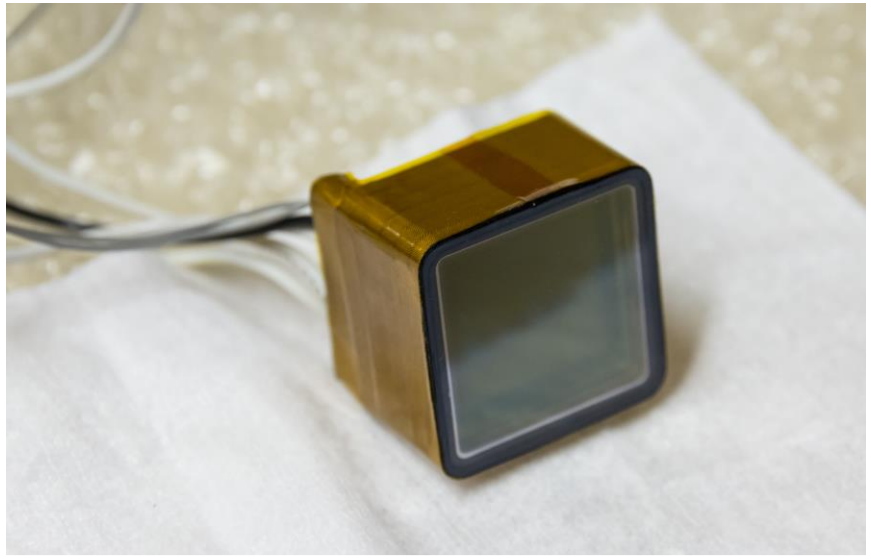


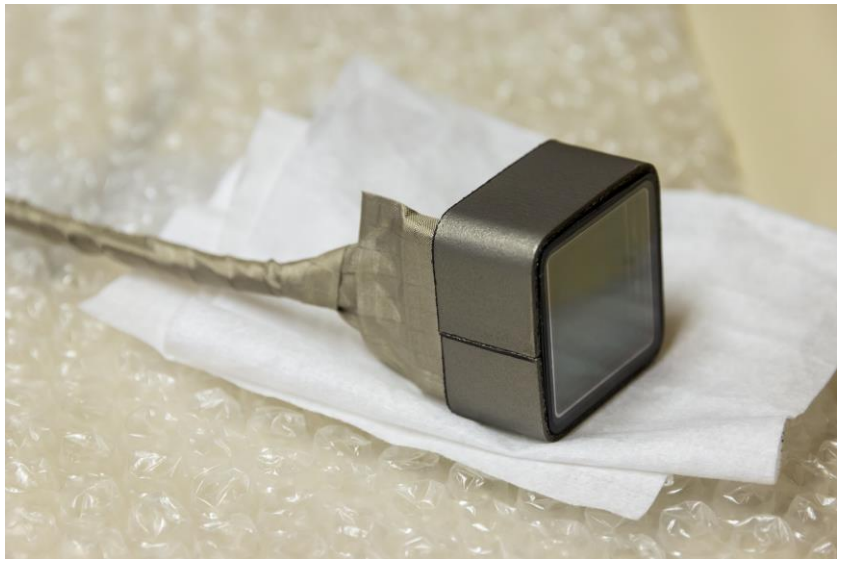
after simulations, construction and testing 4 sets of back-end electronics were sent to Photonis for the production of new tubes

shielding of MCP-PMT (example)

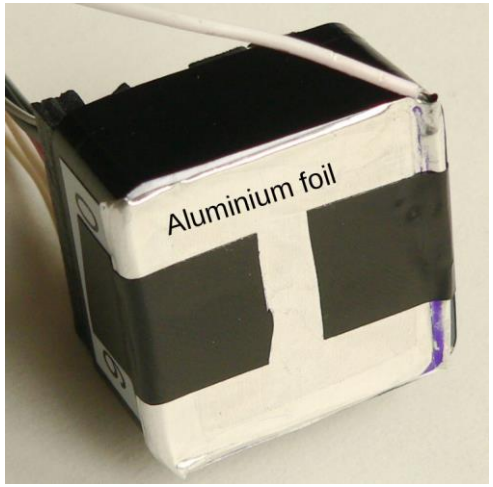


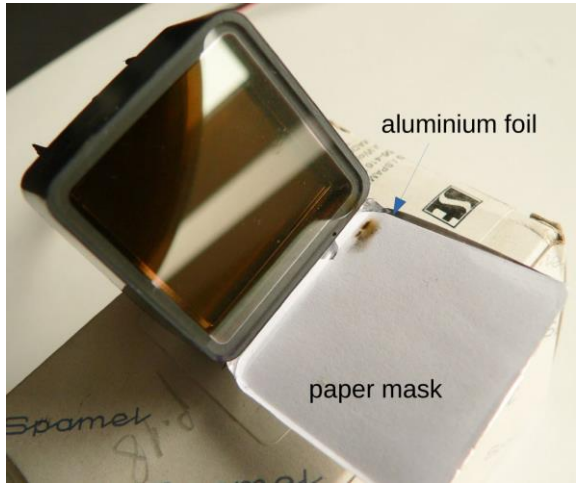


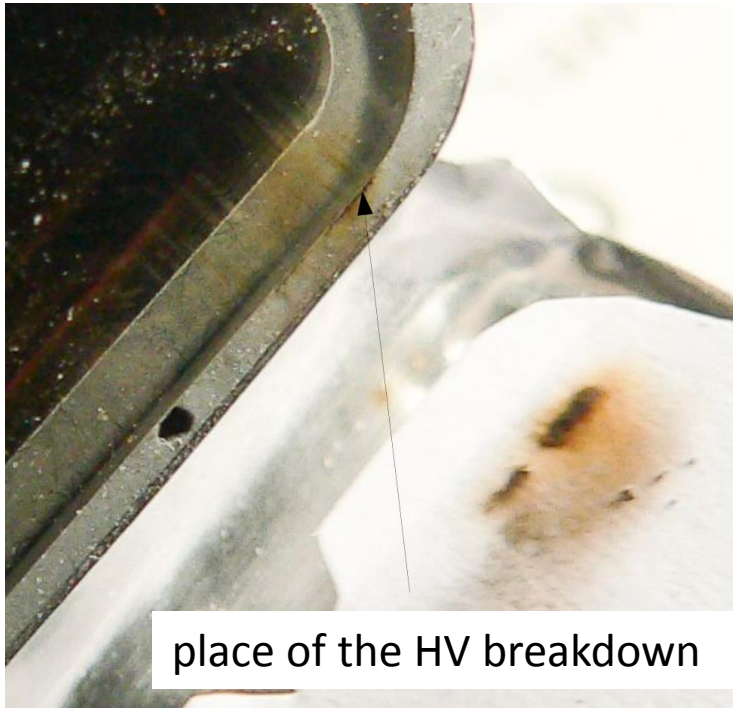


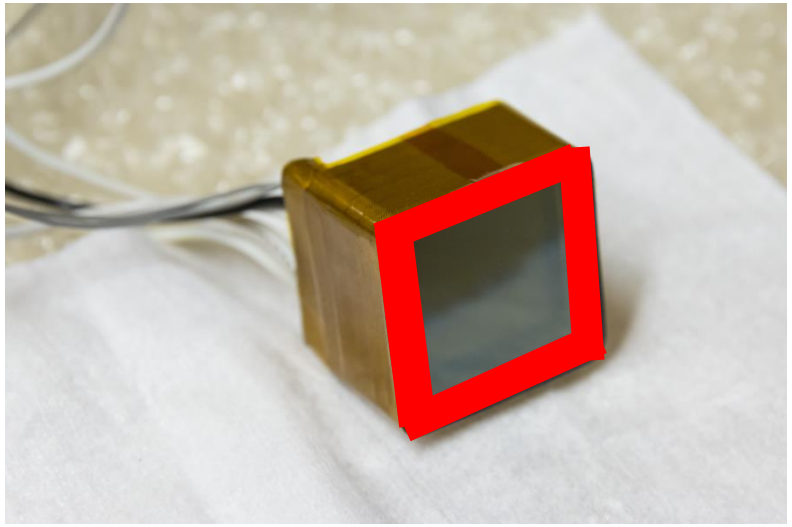


MCP-PMT – HV issue



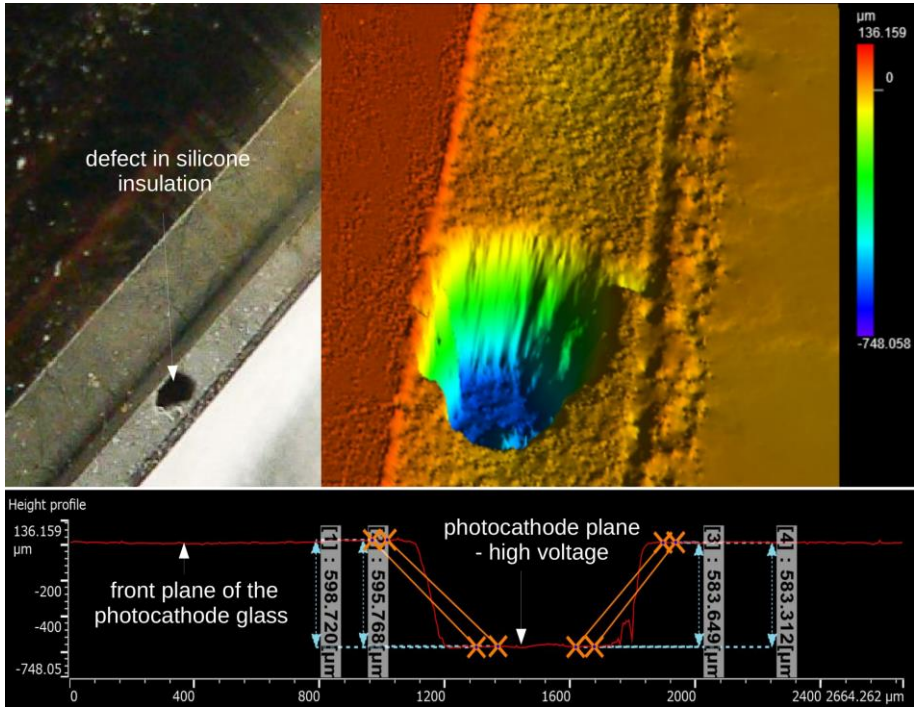






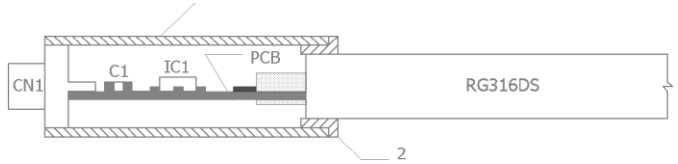
kapton tape
(schematically,
in red colour)

tested up to 3 kV



preamplifiers: PAa

due to the change of the mechanical design, new pre amplifiers were produced; 16-channel and single channel solutions considered

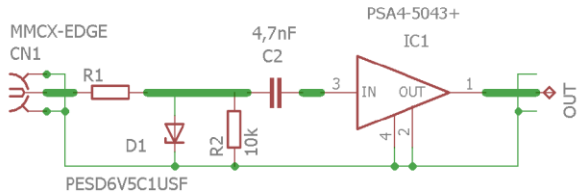


1 - preamplifier case
2 - brass nut

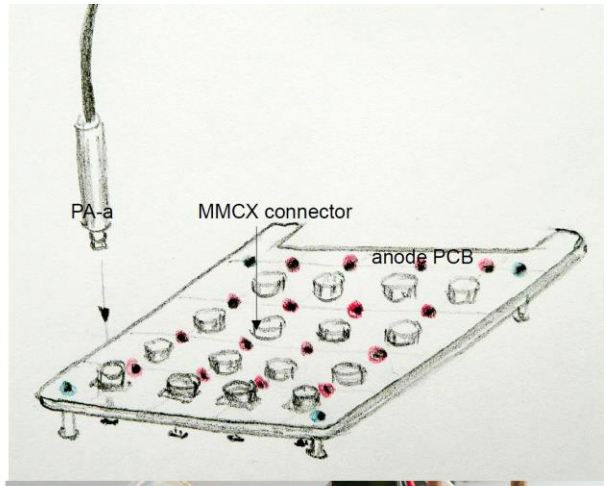
outer/inner diameter 5mm , material brass

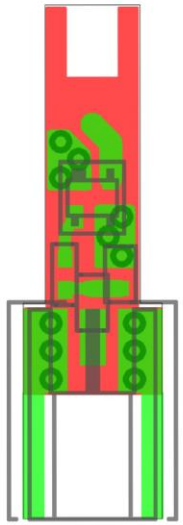
chosen single channel solution [in case of a preamplifier failure just one preamplifier will be replaced]

the new solution allowed to improve signal paths (one coaxial cable between MCP-PMT & PAbc)

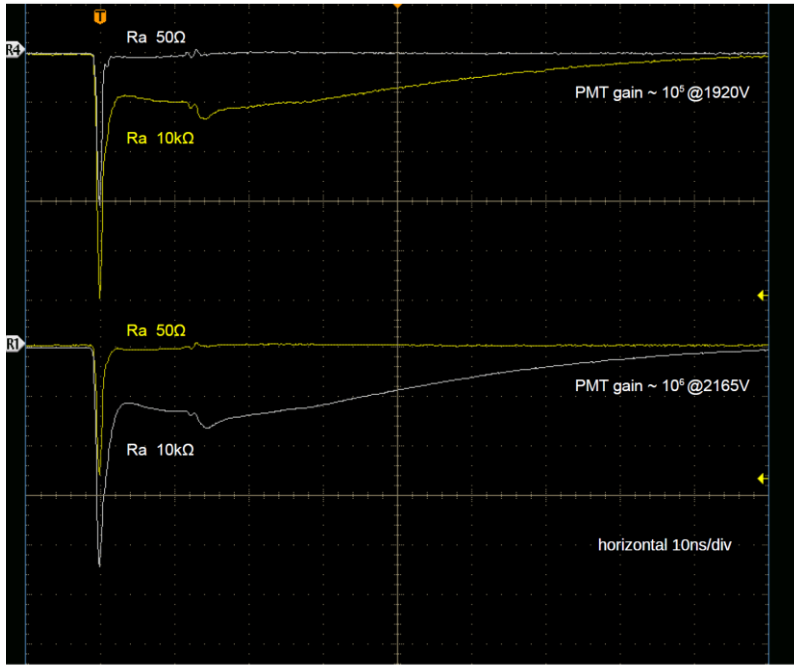


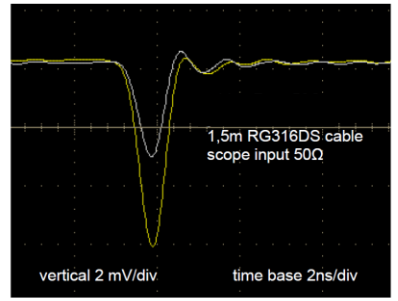
versions with R2(=Ra) = 10 kΩ and 50 Ω



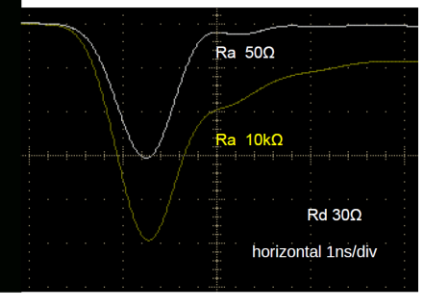


single-channel module located directly on the MCP-PMT anode MMCX connector



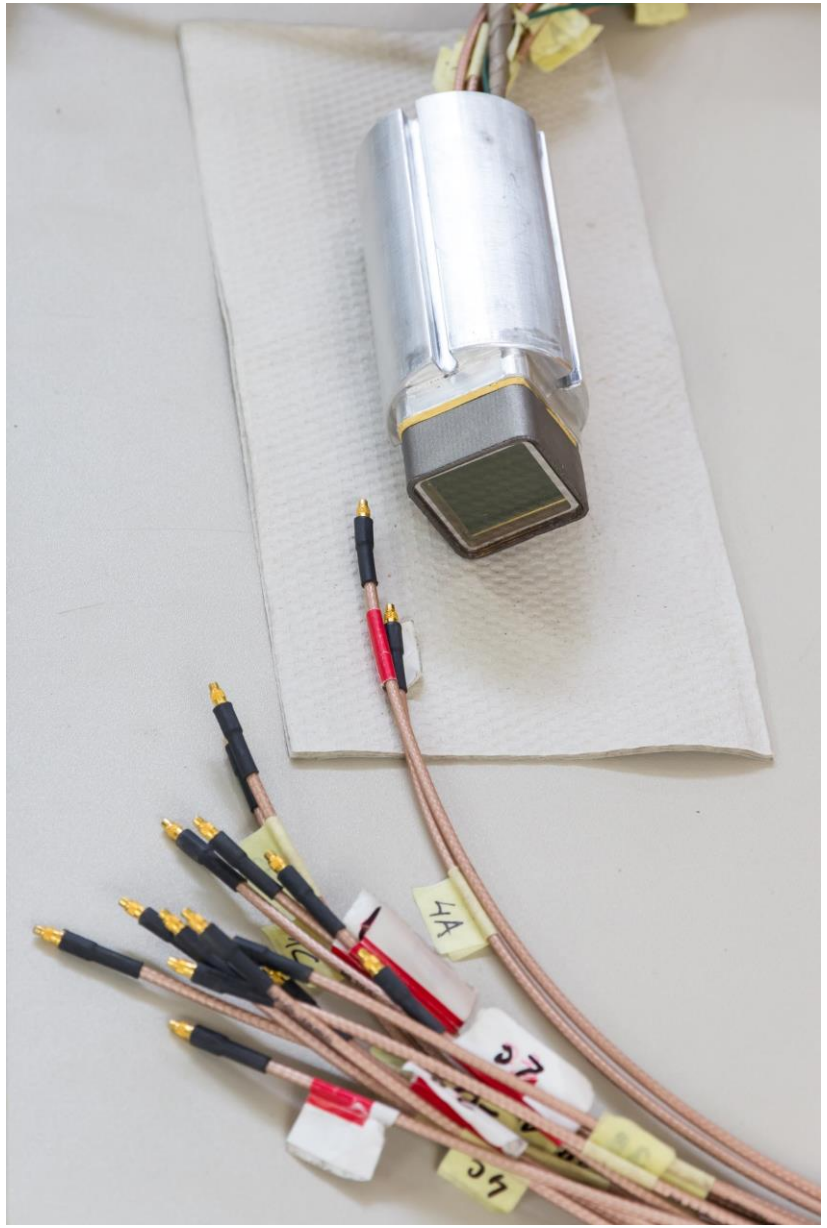


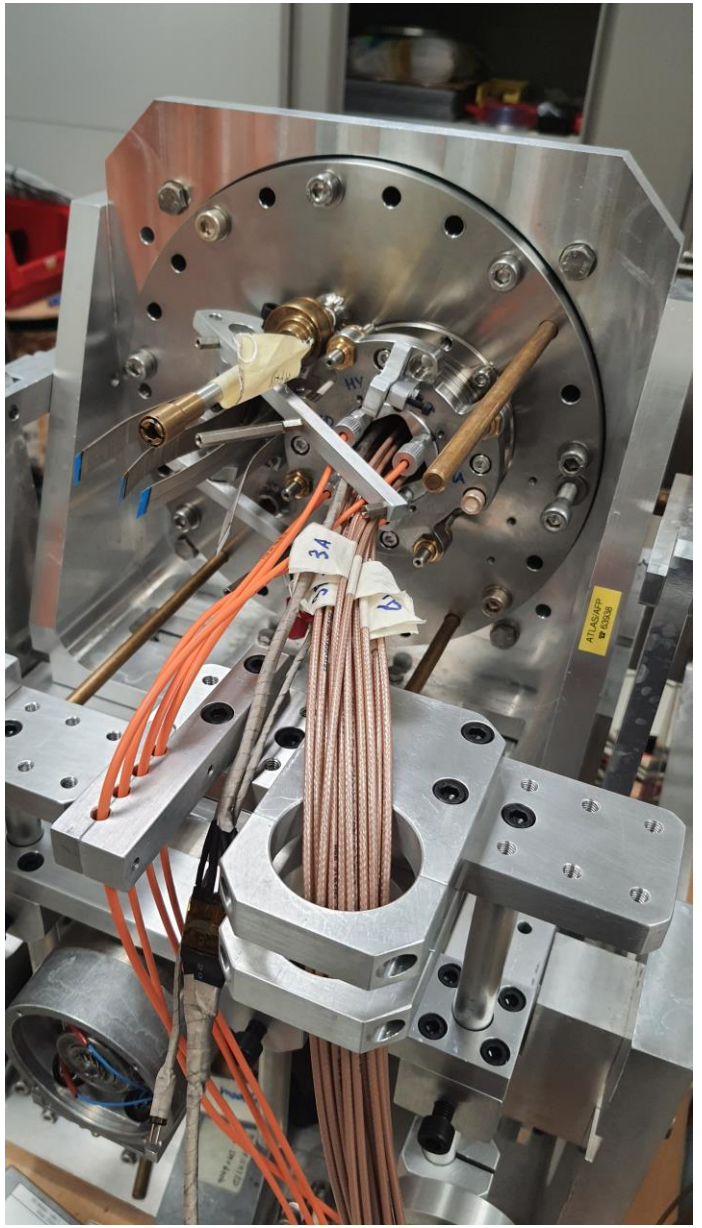
dark pulse XPM85112 s.n.9002010 at 1900V wo PAa



dark pulse XPM85112 s.n.9002010 at gain 10^5 (10^6) with PAa

PAa





LQBars – glued vs monolithic solution

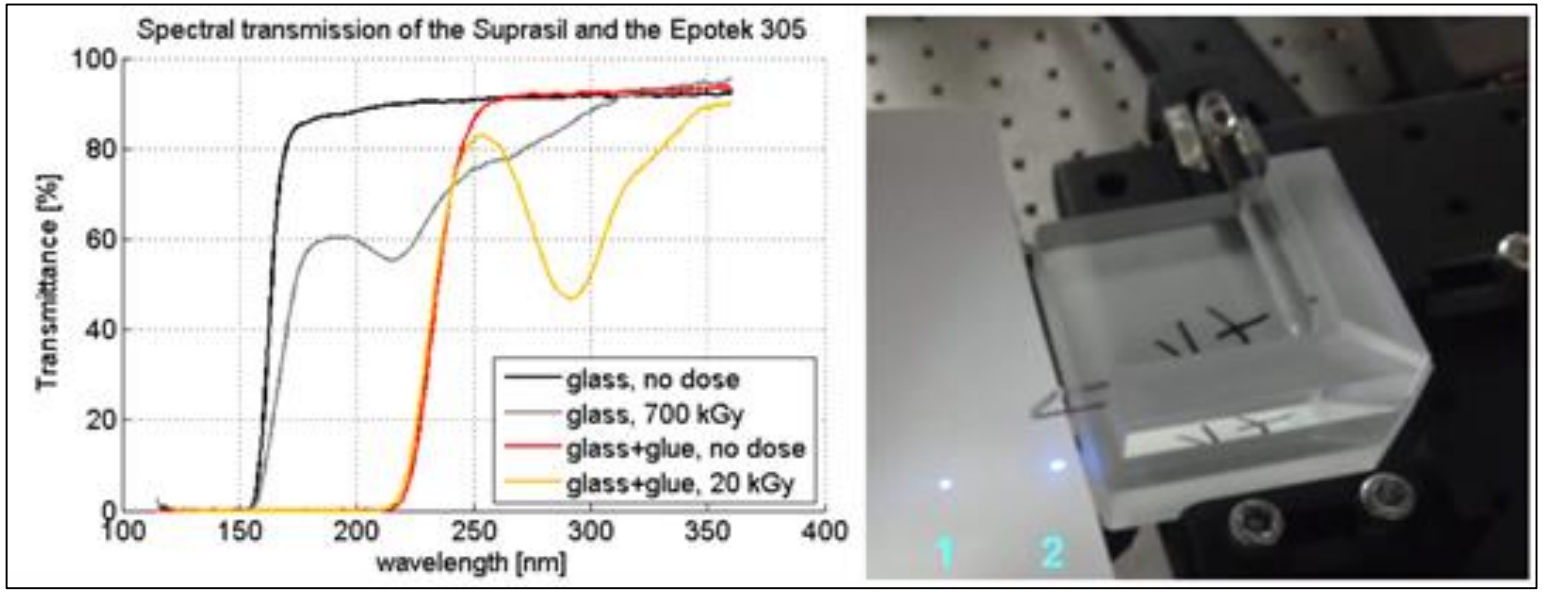
glued bars

– advantages

- **simpler and cheaper** production – less groundwork (preparation phase, auxiliary elements), better machining (grinding, polishing)
- **excellent polishing quality** up to 1 interference ring (peak-to-valey = 320 nm) on all surfaces

– disadvantages

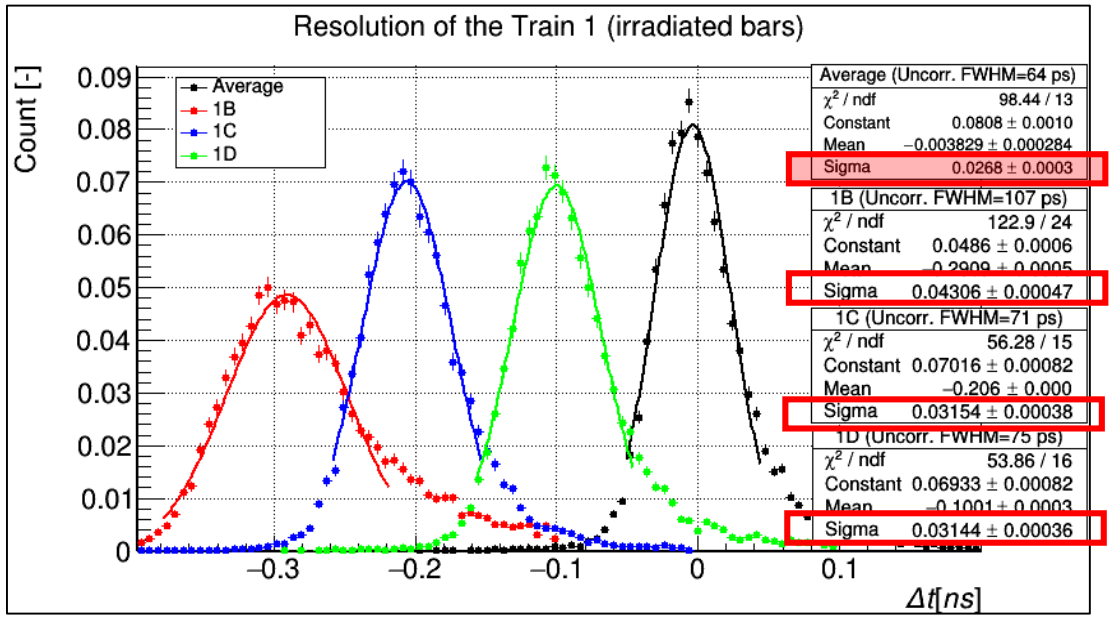
- glue – **wavelength cut** (235 nm) [?], additional tilt between arms, **less radiation hard** than used glass, fragility (small joint area, for bars with 2 mm radiator excessively small 2x5 mm^2)

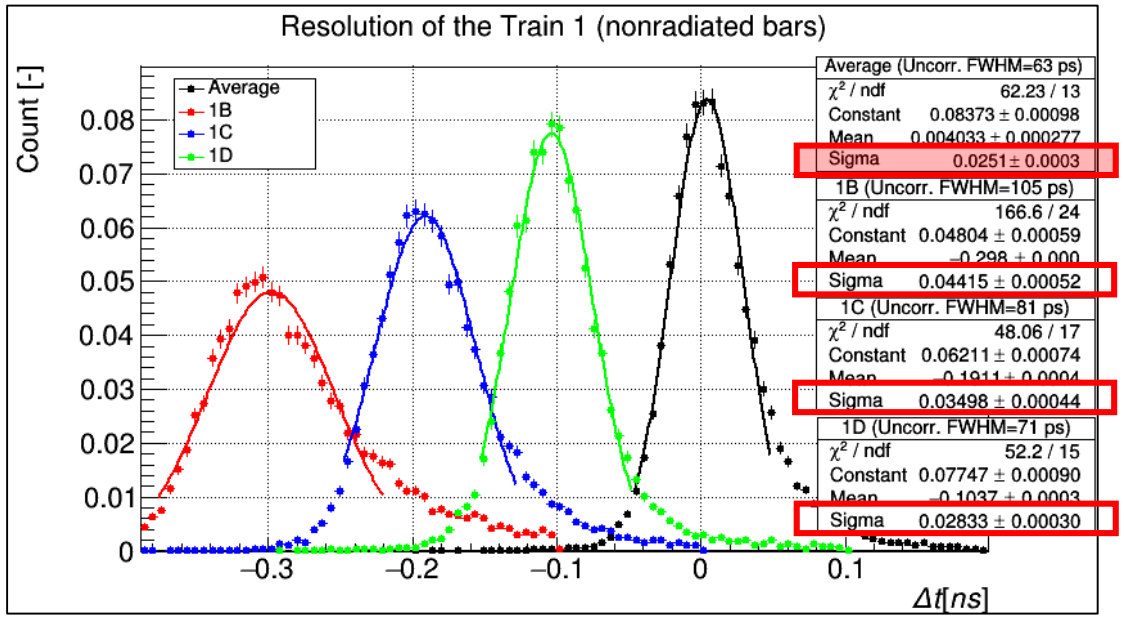


700 kGy ~ 100 fb^{-1}
at 5 mm from beam

20 kGy ~ 100 fb^{-1}
at 5 cm from beam

LQBars – irradiated vs non irradiated, timing





bars irradiated by ~ 50.4 fb^{-1}

bars measured during the AFP beam test in DESY 2019

no significant difference

irradiated vs non-irradiated – efficiencies

non-irradiated bars

```
Processing data 1/4
Channel empty (ID=1):
 Threshold=-100 mV: efficiency=4.2%
 Threshold=-150 mV: efficiency=0.2%
 Threshold=-200 mV: efficiency=0.1%

Processing data 2/4
Channel 1B (ID=2):
 Threshold=-100 mV: efficiency=90.4%
 Threshold=-150 mV: efficiency=73.2%
 Threshold=-200 mV: efficiency=50.9%

Processing data 3/4
Channel 1C (ID=3):
 Threshold=-100 mV: efficiency=95.5%
 Threshold=-150 mV: efficiency=87.8%
 Threshold=-200 mV: efficiency=74.7%

Processing data 4/4
Channel 1D (ID=4):
 Threshold=-100 mV: efficiency=95.5%
 Threshold=-150 mV: efficiency=91.8%
 Threshold=-200 mV: efficiency=86.4%
```

empty

1B

1C

1D

irradiated bars

```
Processing data 1/4
Channel empty (ID=1):
 Threshold=-100 mV: efficiency=5.0%
 Threshold=-150 mV: efficiency=0.6%
 Threshold=-200 mV: efficiency=0.1%

Processing data 2/4
Channel 1B (ID=2):
 Threshold=-100 mV: efficiency=89.4%
 Threshold=-150 mV: efficiency=72.1%
 Threshold=-200 mV: efficiency=50.7%

Processing data 3/4
Channel 1C (ID=3):
 Threshold=-100 mV: efficiency=94.1%
 Threshold=-150 mV: efficiency=88.4%
 Threshold=-200 mV: efficiency=79.6%

Processing data 4/4
Channel 1D (ID=4):
 Threshold=-100 mV: efficiency=94.0%
 Threshold=-150 mV: efficiency=87.8%
 Threshold=-200 mV: efficiency=78.3%
```

empty

1B

1C

1D

no significant difference

LQBars – glued vs monolithic - timing

Timing resolution of single bars in [ps] (uncertainty ±2 ps) for the amplitude threshold of -150 mV at the distance of 5 mm from the edge.

	Glued bars			Solid bars		
Bar	gain $5.4 \cdot 10^4$ (HV 2100 V)	gain $7.6 \cdot 10^4$ (HV 2150 V)	gain $1.1 \cdot 10^5$ (HV 2200 V)	gain $3.8 \cdot 10^4$ (HV 2050 V)	gain $5.4 \cdot 10^4$ (HV 2100 V)	gain $7.6 \cdot 10^4$ (HV 2150 V)
2A	40	**39**	35	49	**46**	42
2B	40	**38**	36	47	**43**	40
2C	39	**36**	32	45	**43**	40
2D	38	**36**	34	44	**41**	38

Timing resolution of the Train 2 in [ps] composed of glued and solid bars for the amplitude threshold of -150 mV at the distance of 5 mm from the edge.

		Glued bars			Solid bars		
HV [V]	Gain [-]	edge	5 mm	9 mm	edge	5 mm	9 mm
2050	3.8E+4	-	-	-	24±2	26±2	26±2
2100	5.4E+4	21±2	24±2	25±2	**24±2**	**26±2**	**26±2**
2150	7.6E+4	**24±2**	**24±2**	**26±2**	24±2	26±2	26±2
2200	1.1E+5	20±2	25±2	27±2	-	-	-

monolithic bars give worse resolution!

BUT

xTDC

the **pico**TDC group has encountered issues getting the chips wire bonded as they are getting package warping

waiting on a generic packaged version

the timeline for the final packed version is the end of the year

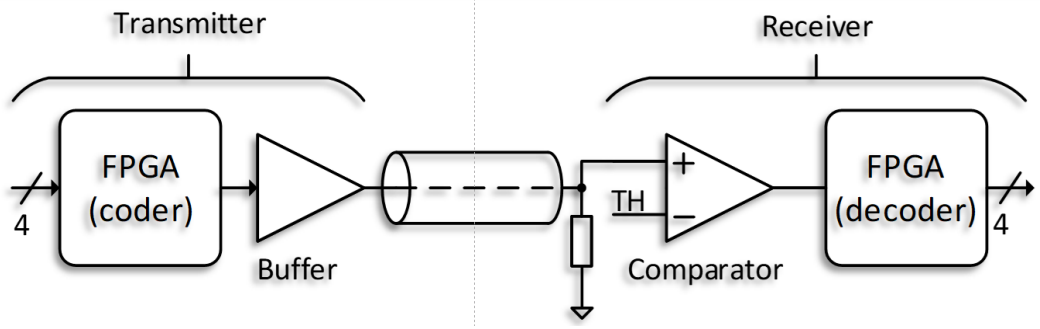
the delay of picoTDC should not be an issue as the main contribution to the timing comes from MCP-PMT (but this can change…)

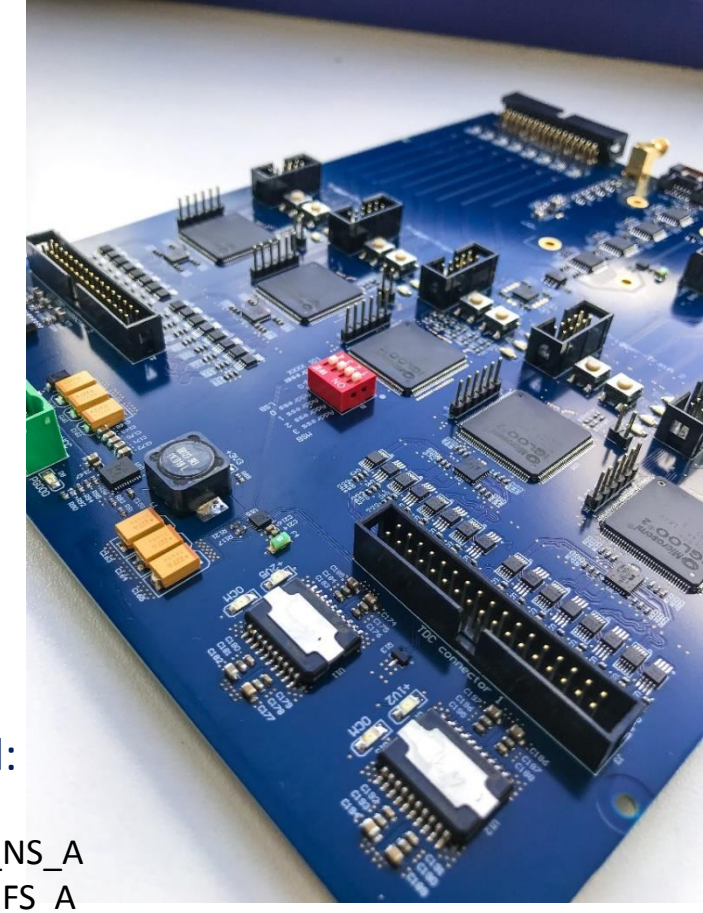
back-up: new, rad-hard, **HP**TDCs are ready (6 pieces)

HPTDC limits:

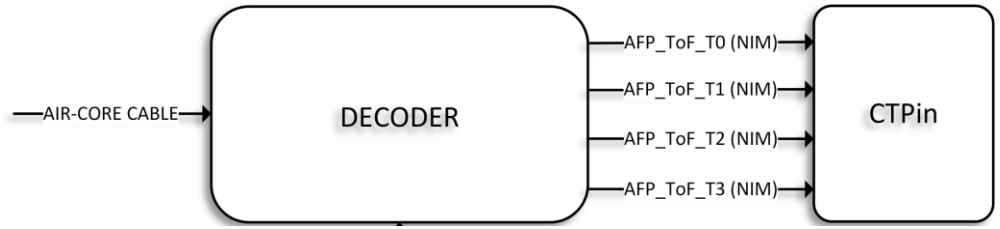
a) maximally 8MHz signal capability -> **the need for the trigger module** to reduce the rate
b) channel cross talk, need for the adjustment during data reprocessing

trigger & decoder modules





1. ready
2. trigger module efficiency close 100%
3. radiation hardness on the same level as of the rad hard TDC (the same FPGA used)
4. its starting functionality will be logical OR but later the following schema will be applied:



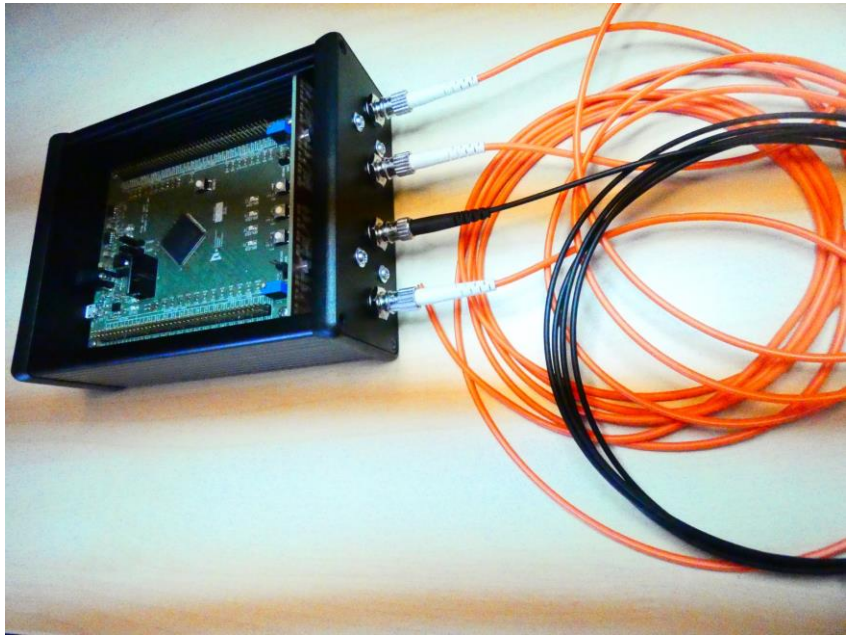
5. decoder in prototype stage – production (NIM module) September 2021

AFP_NS_A
AFP_FS_A
AFP_ToF_T0_A
AFP_ToF_T1_A
AFP_ToF_T2_A
AFP_ToF_T3_A
AFP_NS_C
AFP_FS_C
AFP_ToF_T0_C
AFP_ToF_T1_C
AFP_ToF_T2_C
AFP_ToF_T3_C

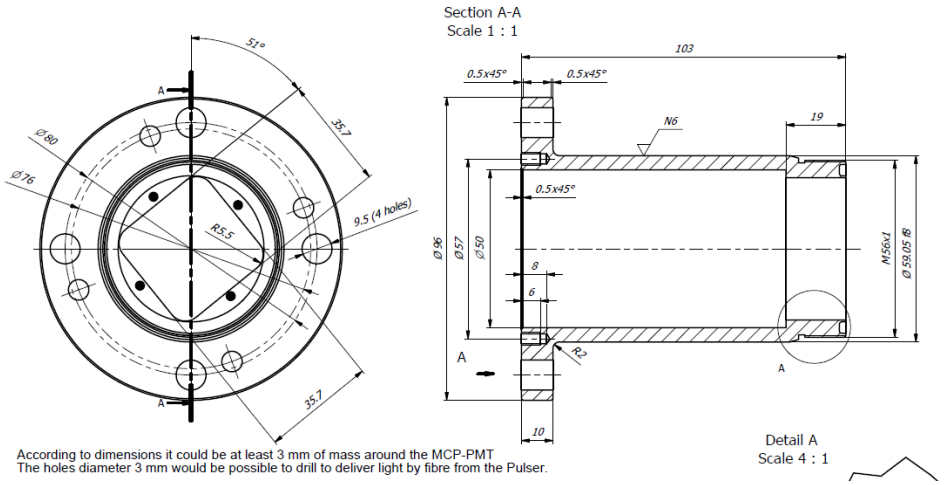
pulser

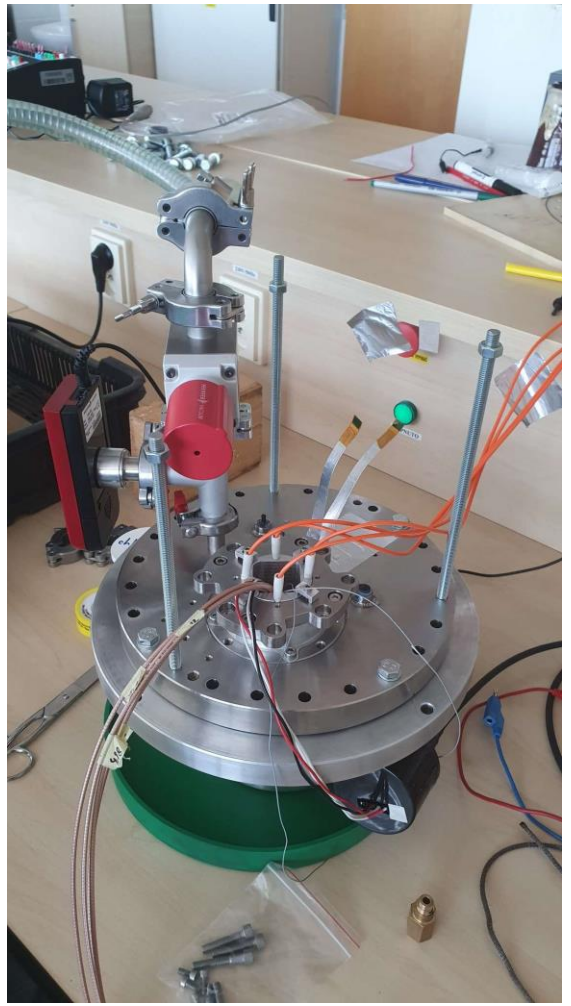
purpose: full signal path cross check after installation & between runs

constructed & tested, communication protocol for I2C prepared

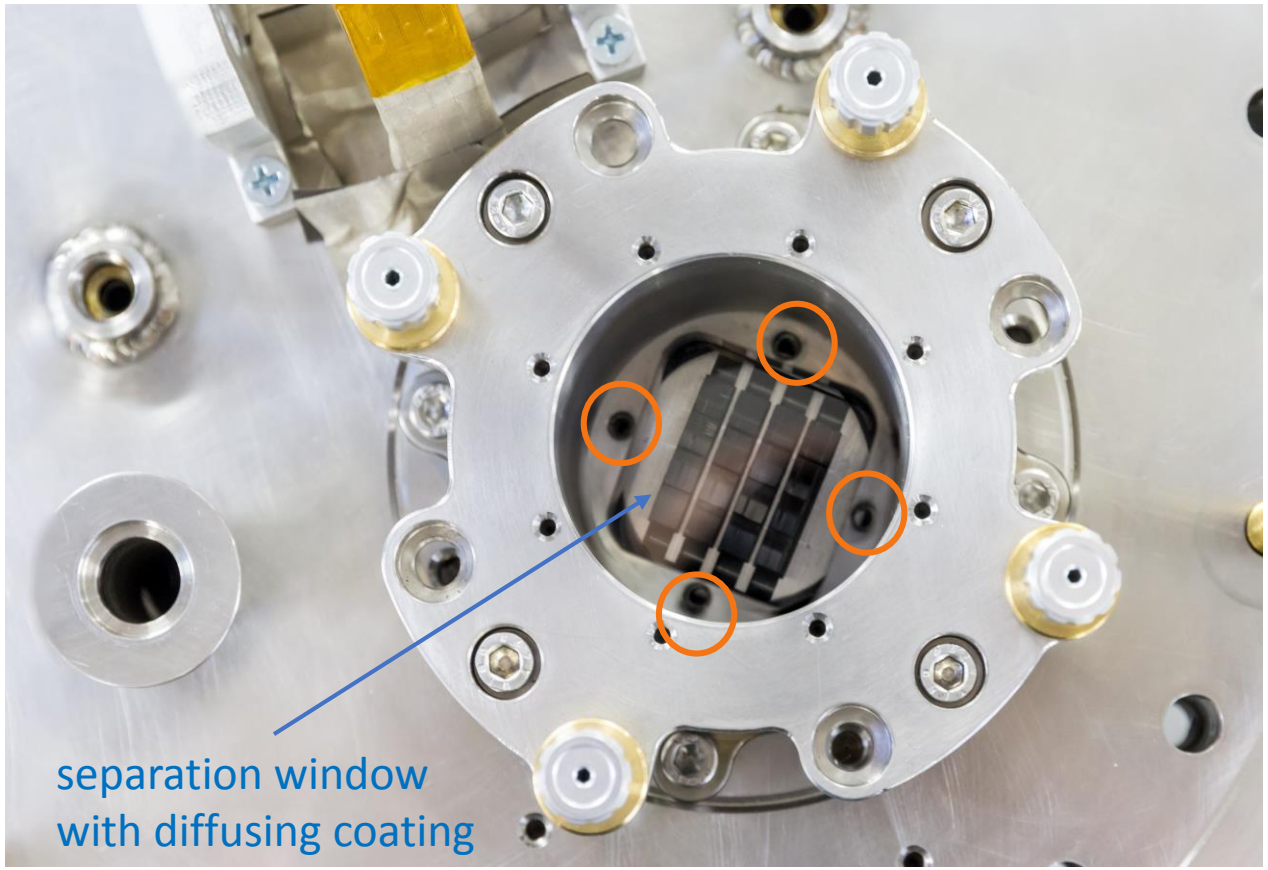


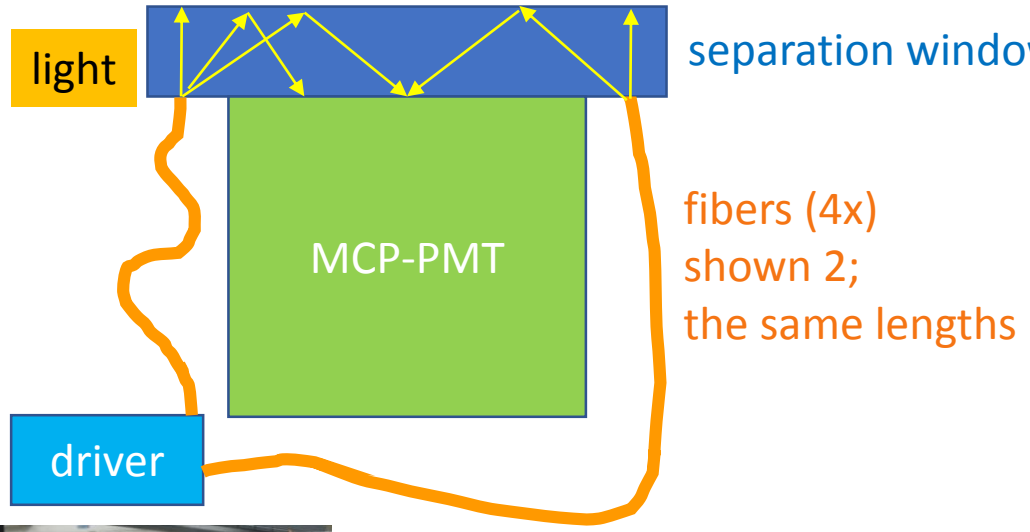
prototype

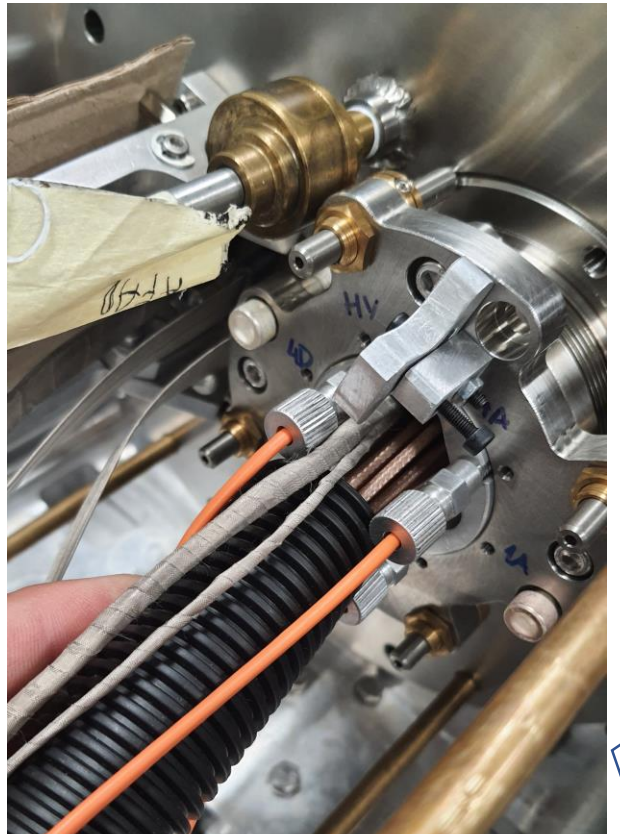




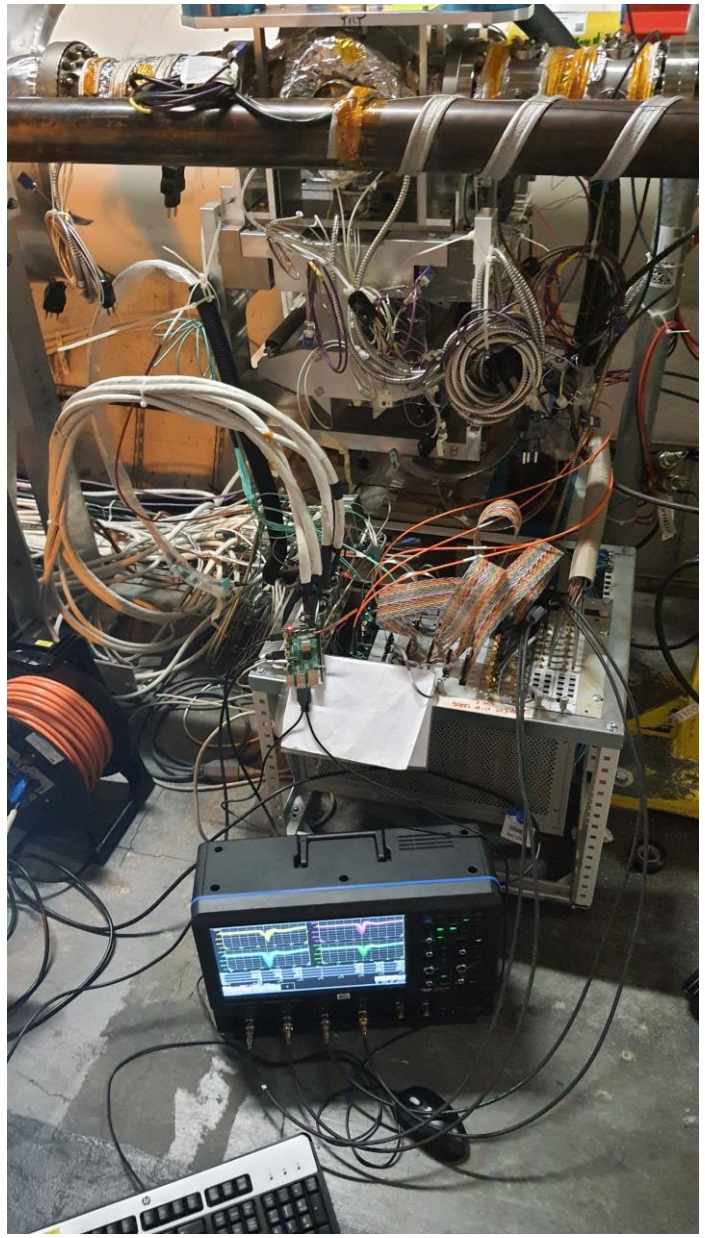
pulser module

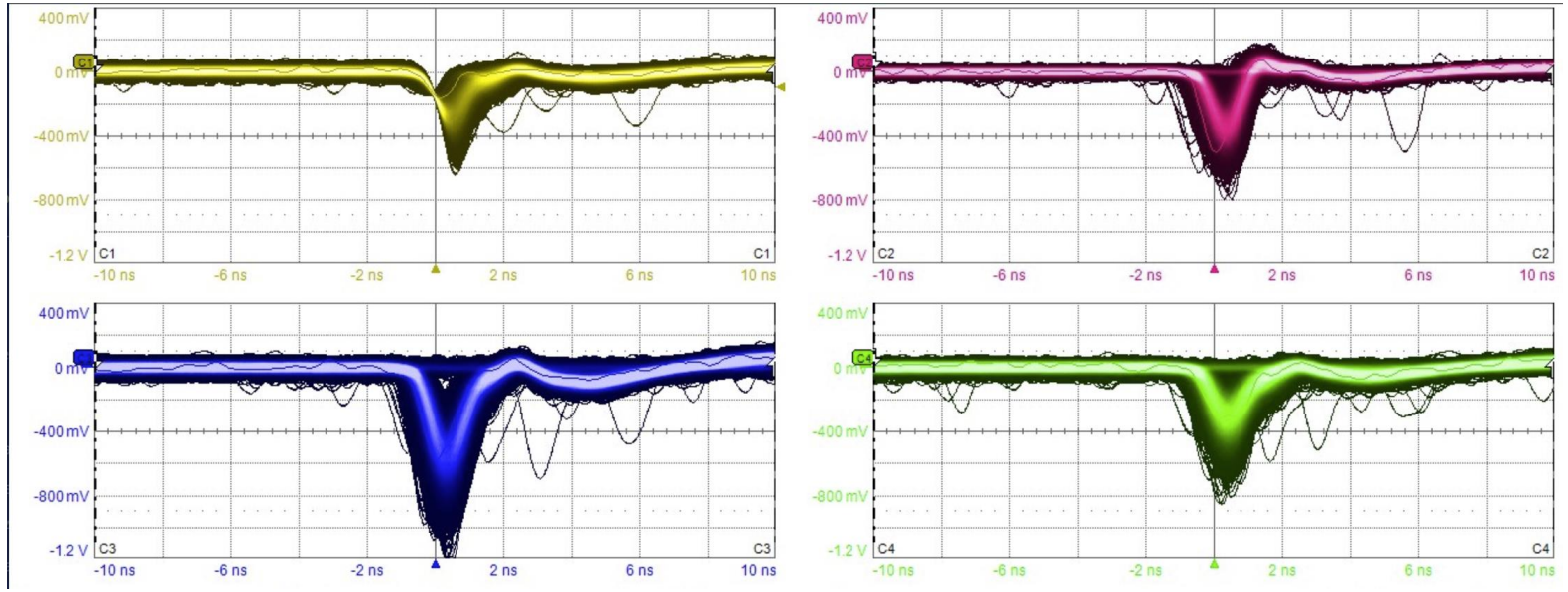






pulser module in the tunnel - installation





PAbc output for train 1, channels A, B, C, D

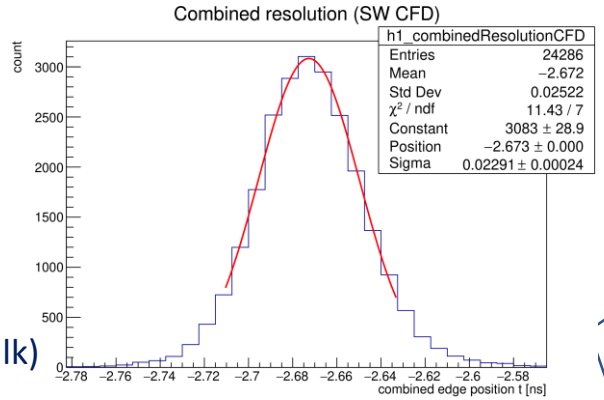
beam tests 2021 results - timing

MCP-PMT # 2199, train 2, gain 2000	bar A, amplitude [mV]	bar C, amplitude [mV]	$\langle\sigma_t\rangle$, any # of bars used weighed, [ps]	$\langle\sigma_t\rangle$, all bars used not weighted, [ps]	$\langle\sigma_t\rangle$, all bars used not weighted, [ps]
distance for edge: 0 mm					
glued	-300	-400	24	24	27
monolithic	-500	-700	20	20	21
distance for edge: 5 mm					
glued	-250	-350	27	27	27
monolithic	-400	-600	22	22	25
distance for edge: 9 mm					
glued	-250	-300	28	28	32
monolithic	-400	-500	24	24	26

different result w.r.t. the DESY BT - monolithic bars better now

higher time resolution σ_t per channel expected – new R2D2 MCP-PMTs have higher TTS
(typical values 38-45 w.r.t. previously < 30 ps)

although higher σ_t per channel, combined time resolution $\langle\sigma_t\rangle$ is comparable (smaller cross talk)



contributions of ToF components to the detector overall timing resolution

based on subtraction of MCP-PMT contribution from scope measurement

- LQbars ~ 17 ps
- MCP-PMT >(!) 17 ps (at high signal rates) depends on MCP-PMT

if properly tuned; proper HV, proper divider & properly shielded

- PAa 3-4 ps
- PAb, PAc (old) / PAb & PAc 5 ps each / < 5 ps (FWHM 10 ps)
- CFD 5 ps <
- HPTDC / picoTDC 15-17 ps / < 6 ps, ideally < 2 ps

after calibration!

- reference clock 2 ps

time resolution limited by

1) MCP-PMT & its gain dependency on rates
2) LQbar design
3) HPTDC

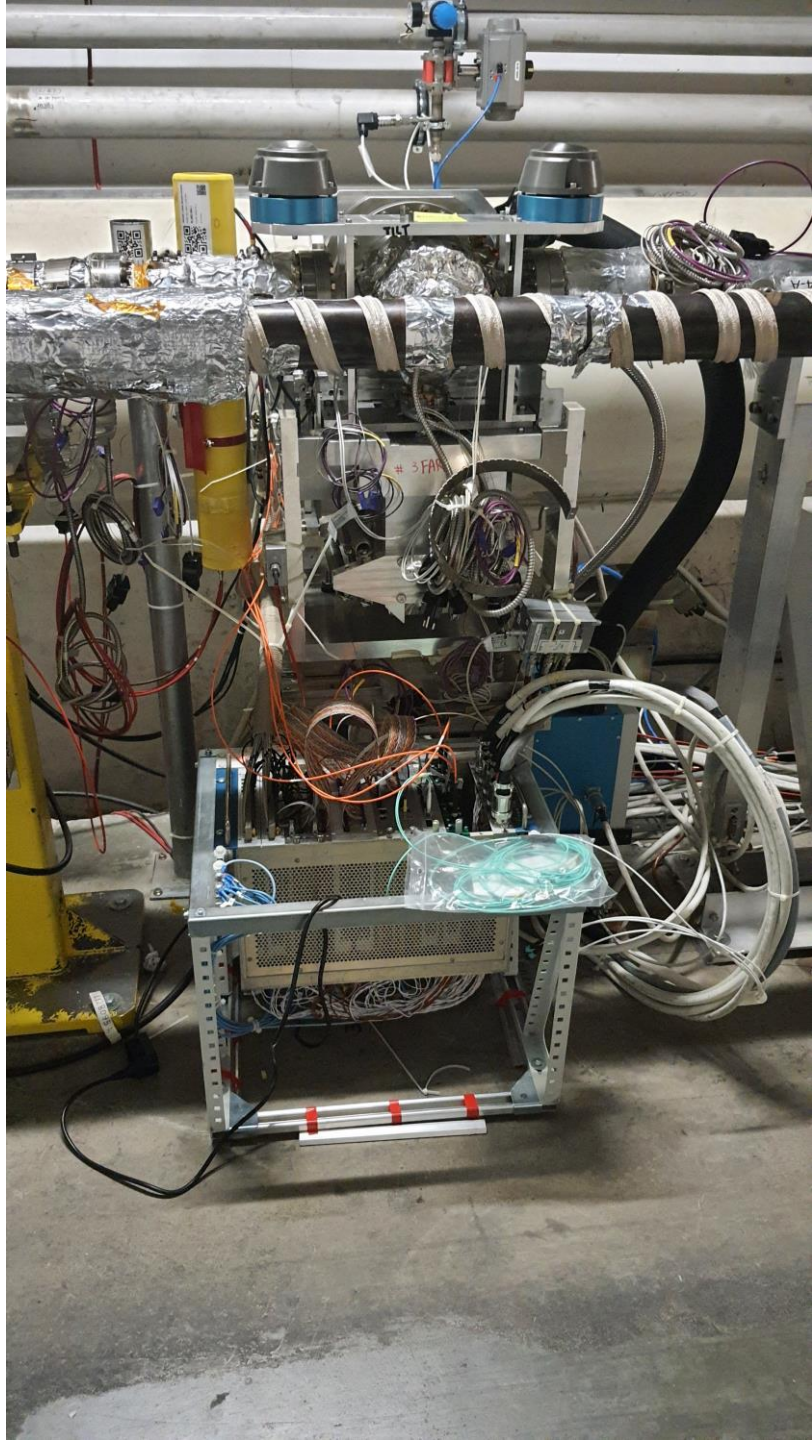
] bar resolution (based on beam test and MCP high rates lab measurements): $\sqrt{\sigma_{\mathrm{LQ}}{}^2 + \sigma_{\mathrm{MCP}}{}^2 + \sigma_{\mathrm{PAa}}{}^2 + \sigma_{\mathrm{PAb+c}}{}^2} = \sigma_{\mathrm{scope}} \sim 35$ ps (conservative)

naïvely calculated resolution per channel: $\sqrt{\sigma_{\mathrm{scope}}{}^2 + \sigma_{\mathrm{xTDX}}{}^2 + \sigma_{\mathrm{clock}}{}^2} = \begin{cases} 39 \text{ ps} & \text{HPTDC} \\ 36 \text{ ps} & \text{picoTDC} \end{cases}$

assuming channel correlations ~ 1.5 (conservative) -> train resolution ~ 26 / 24 ps

summary

- AFP ToF detector was installed and took data in 2017 (July-September)
- achieved timing performance was very good, despite of detector very low efficiency (which affected timing), in agreement with beam tests results
- due to repeated failures of MCP-PMTs in vacuum, the detector was not installed in 2018
- **new design of detector ready**
  - MCP-PMT Out-of-Vacuum solution, tested in 2019 & 2020 & 2021, approved by LHCC in April 2020
  - new MCP-PMT back-end electronics to suppress cross-talk, tested in 2020 & 2021; used for the production
  - new sets of monolithic, glue-less, bars produced
  - simplified signal and powering paths, tested in 2020 & 2021 beam tests
  - prototype of picoTDC tested in 2019, not finalized yet
  - new trigger module produced; tested in 2020 & 2021 beam tests; trigger decoder prototype tested
- **detector recently installed for LHC Run 3** (see the photo)
- analysis of the 2017 data shown the good agreement with beam tests results -> the new version of the AFP ToF detector has a potential to achieve resolution **25 ps in LHC Run 3 running**, **with efficiency above 80%** (conservative estimates)



plans

- bars/light optimization [assuming limited space, i.e. no Hamburg beampipe available]

- MCP-PMT development:
  - improvement to reach higher rates gain stability
  - improvement of TTS
  - further development of MCP-PMT back-end electronics

- further improvement of signal preamplification

- direct signal sampling (more particles in the train)

backup slides