Performance of Planacon MCP-PMT photosensors under extreme working conditions

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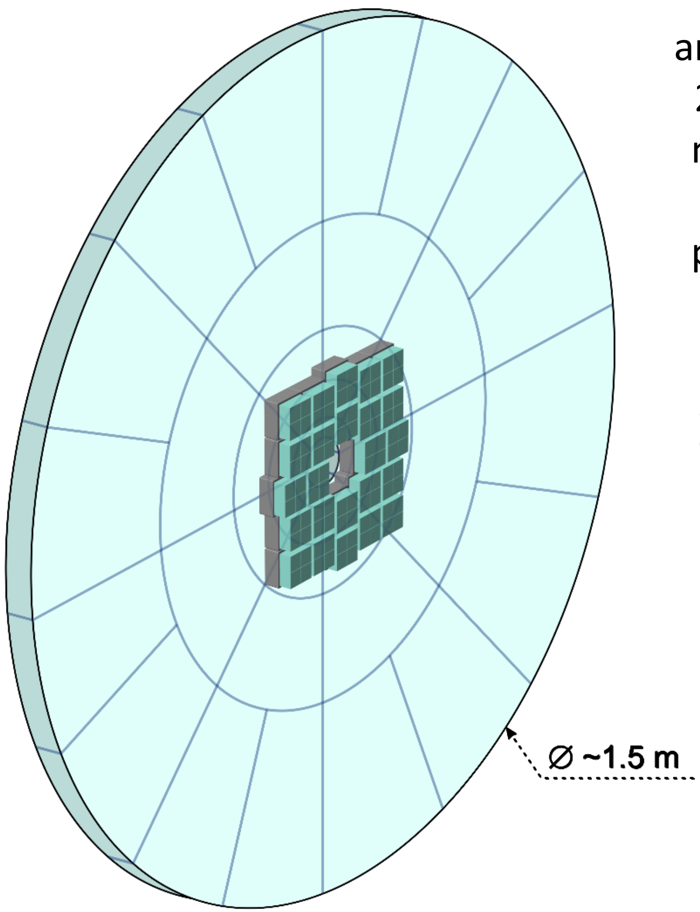
National Research Nuclear University MEPhI
(Moscow Engineering Physics Institute)

RICH2018

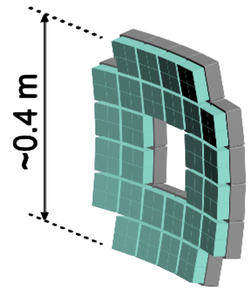
10th International Workshop on Ring Imaging Cherenkov Detectors,
29 July - 4 August 2018, Russian Academy of Sciences, Moscow

Fast Interaction Trigger (FIT) detector for the upgraded ALICE experiment at LHC

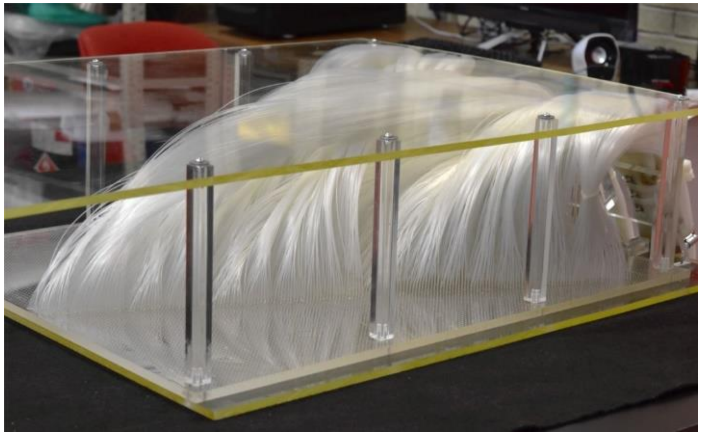
FIT V0+: fragmented scintillation detector for precise multiplicity measurements (48 independent readout channels)



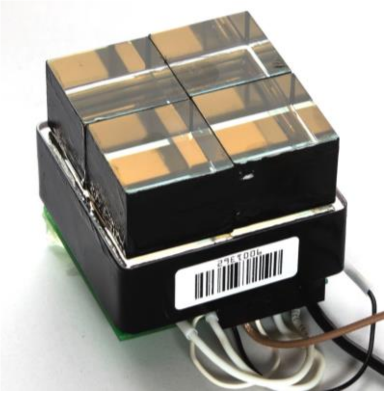
FIT T0+: two arrays of 24 and 28 Cherenkov modules - fast trigger with precise timing



Each V0+ sector is based on EJ-204 plastic scintillator + clear Asahi fibers with recessed ends + 2” Hamamatsu R5924-70 fine-mesh PMTs.



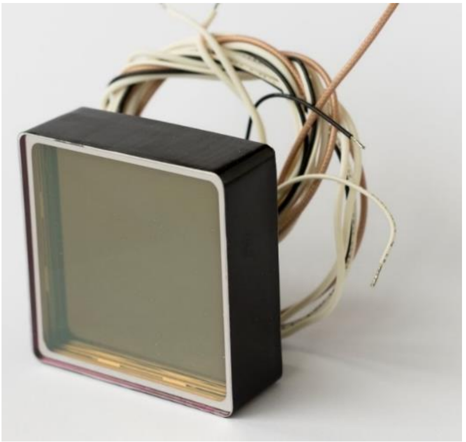
Each T0+ module is based on four quartz radiators + MCP-PMT photosensors + Dow Corning 200 optical grease.



Photosensor selection for the Cherenkov subsystem

*Not a simple task due to the following **list of requirements:***

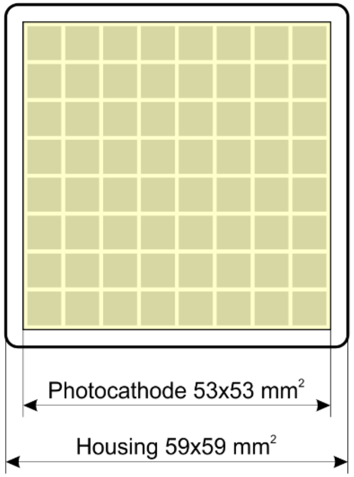
- **Radiation hardness** (46 krad and $1.3*10^{12}$ 1-MeV-neq/cm^2 + safety factor);
- **Magnetic field immunity** up to 0.5 T;
- **Precise timing**;
- Form factor enabling the possibility of nearly **hermetic design**;
- **Linear operation** for extended anode currents (average up to ~10 uA, pulsed – up to 20 mA);
- **Total thickness up to ~3 cm**



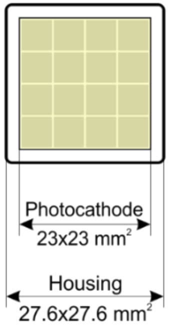
PLANACON® **XP85012**
or XP85112

Back in 2013-2015 only **Planacon** photosensors by Photonis and **R10754-07-M16** by Hamamatsu Photonics K.K. were suitable for such application.

Planacon has higher geometry efficiency (80% vs 70%) and we've been offered significantly lower price (per 1 cm^2 of photocathode).



Planacon XP85012 layout



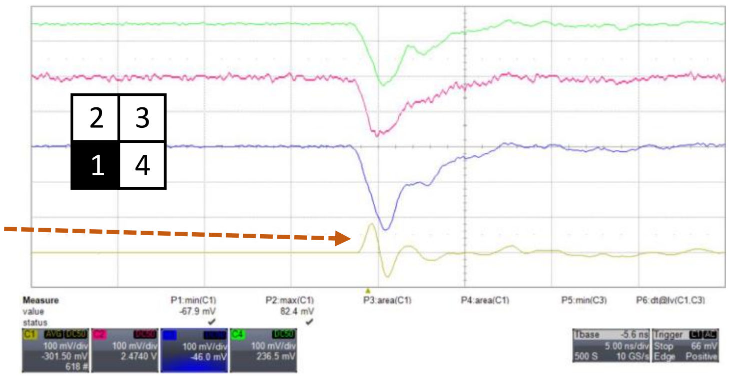
Hamamatsu R10754-07-M16 layout

Peculiarities of the standard Planacons

- Circuitry of standard Planacons features **64 anode outputs + common output of positive polarity**.

- Large capacitance between MCP out and anode planes creates **positive crosstalk at all anodes (even unfired)**. We prefer to group anodes in 4 equal quadrants – for this case, bipolar cross-talk of 45% amplitude is seen at the shaded quadrant when three others are fired.

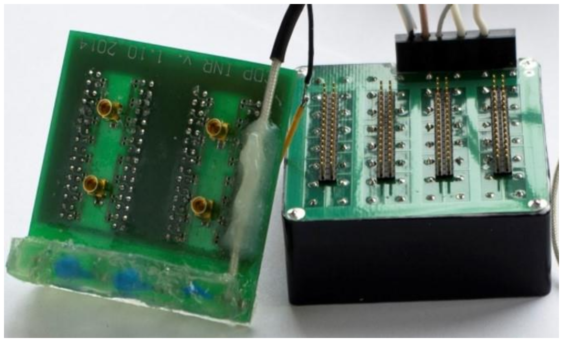
  Such cross-talk significantly **distorts rising edge of each signal** when two or more channels are fired, **which deteriorates time resolution of the device**.

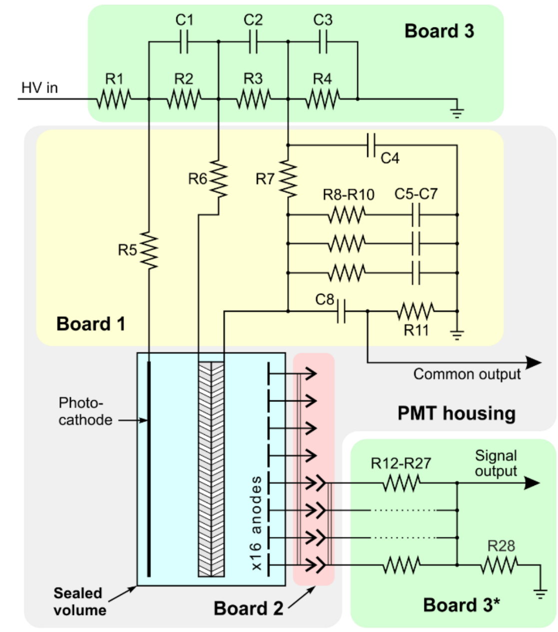


- **Length of traces from individual anodes to the four multi-pin jacks is unequal,** which also worsens the timing.

- Anode grouping could be done at an external PCB only: 21 mm housing → 36 mm total thickness.

  The external PCB increase L and C of the traces and **distorts the signal shape** making it XY-dependent.





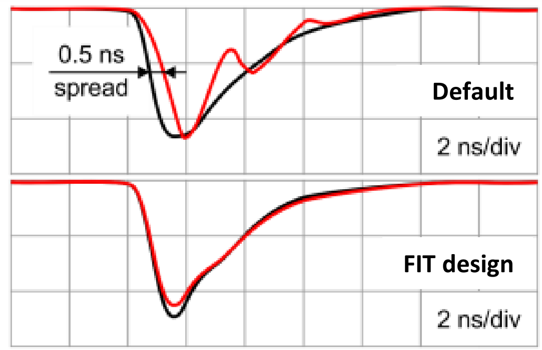
*only 16 out of 64 channels shown.

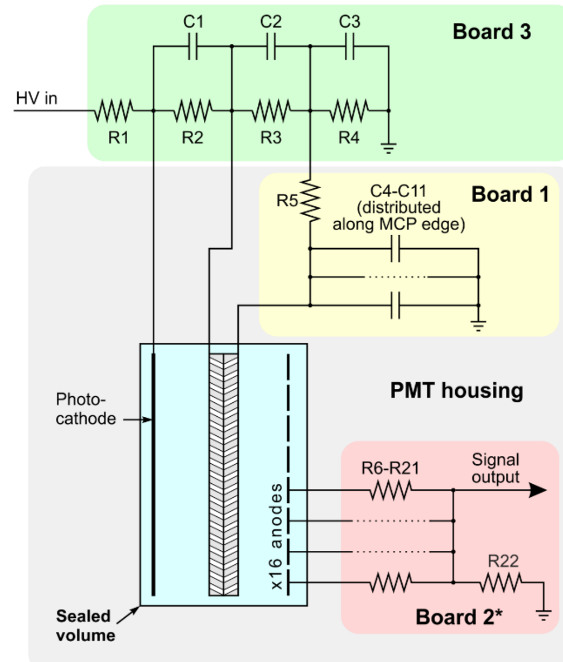
- R5 and R6 resistors are glued inside the HV port and **determine its height, while they are not needed** when a divider circuit is used.

FIT solution for Planacon modification

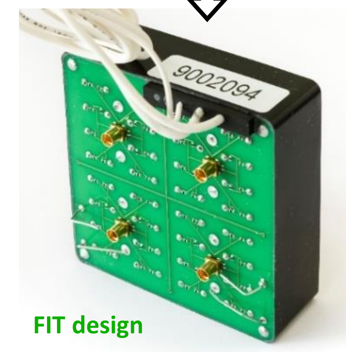
We have designed custom internal PCBs for Planacons – they were installed to FIT devices by the manufacturer:

- Common output and its load resistance are eliminated → no positive cross-talk → **rising edge is never distorted**;
- Signals from 16 individual outputs go directly to the MMCX jack for quadrant signal output → **no additional PCB for signal collection**;
- Equalized connection length → **better time resolution** when wide light spots are detected;
- Optimized traces length and ground plane location at the most inner PCB → twice smaller anode capacitance → **smaller cross-talks between anodes, higher amplitude-to-charge ratio**;
- No resistors inside HV port → **unit thickness reduced to 27 (23) mm**;
- In-line 75 Ω resistors to **reduce Q-factor of anodes LC-circuit.**



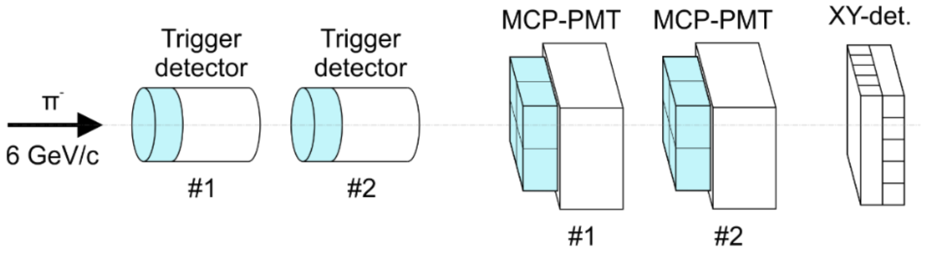


*only 16 out of 64 channels shown.



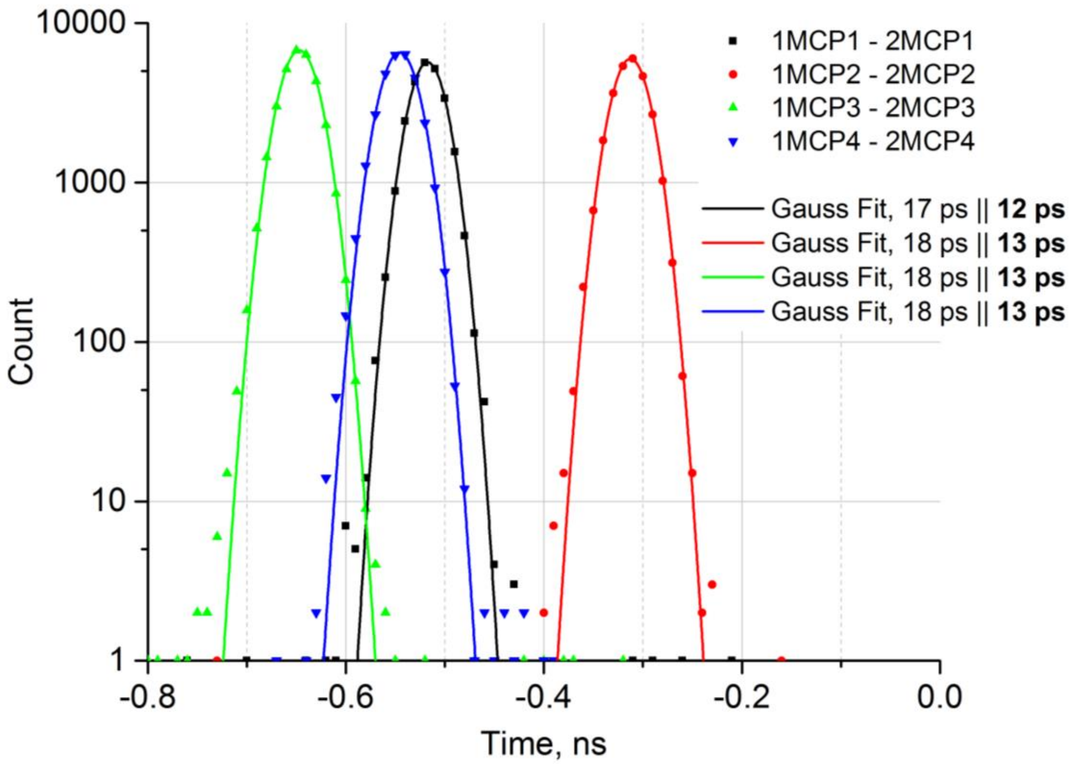
FIT Cherenkov module characteristics

The modified Planacon XP85012/A1-Q MCP-PMTs + 2 cm-thick fused silica radiators were irradiated at CERN PS pion beam.



Time resolution of σ=13 ps is confirmed for single MIPs detection **(1 MIP ≈ 300 p.e.)**

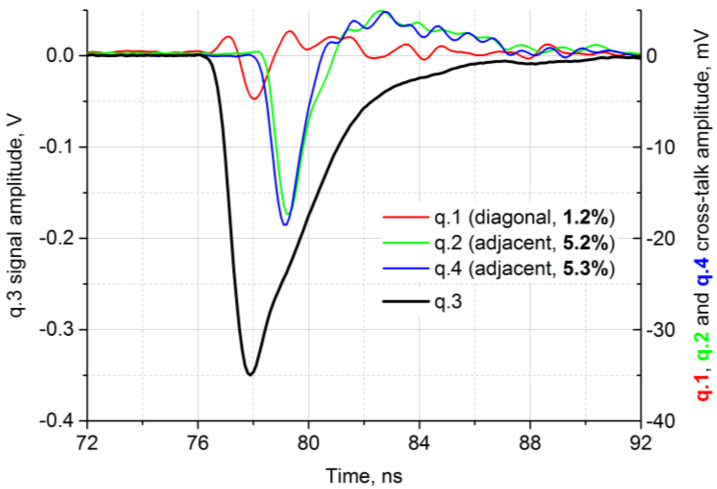
Time resolution of the whole system (Cherenkov module + 40 m cables + analog readout electronic) is **σ=33 ps**.



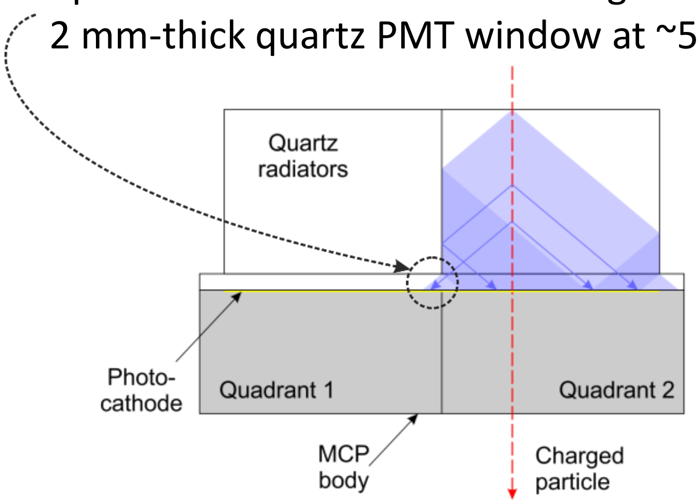
FIT Cherenkov module characteristics

The modified Planacon features cross-talks, but only of the negative polarity:

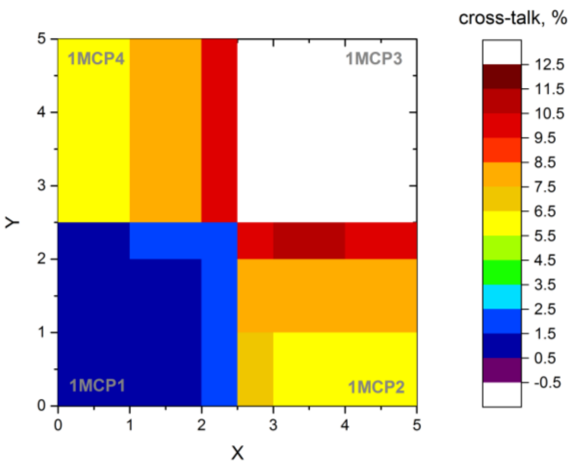
- electrical cross-talks between anodes



- optical cross-talk of Cherenkov light emitted in 2 mm-thick quartz PMT window at ~50° angle



Influence of the combined cross-talk from those signals occurred in different areas of the module to quadrant 3:



So, each MCP-PMTs in FIT act as four independent sensors with zero dead space and minor cross-talks between the sensors:

	Adjacent	Diagonal
Amplitude	8%	1.2%
Charge	4%	0

Planacon anode current linearity

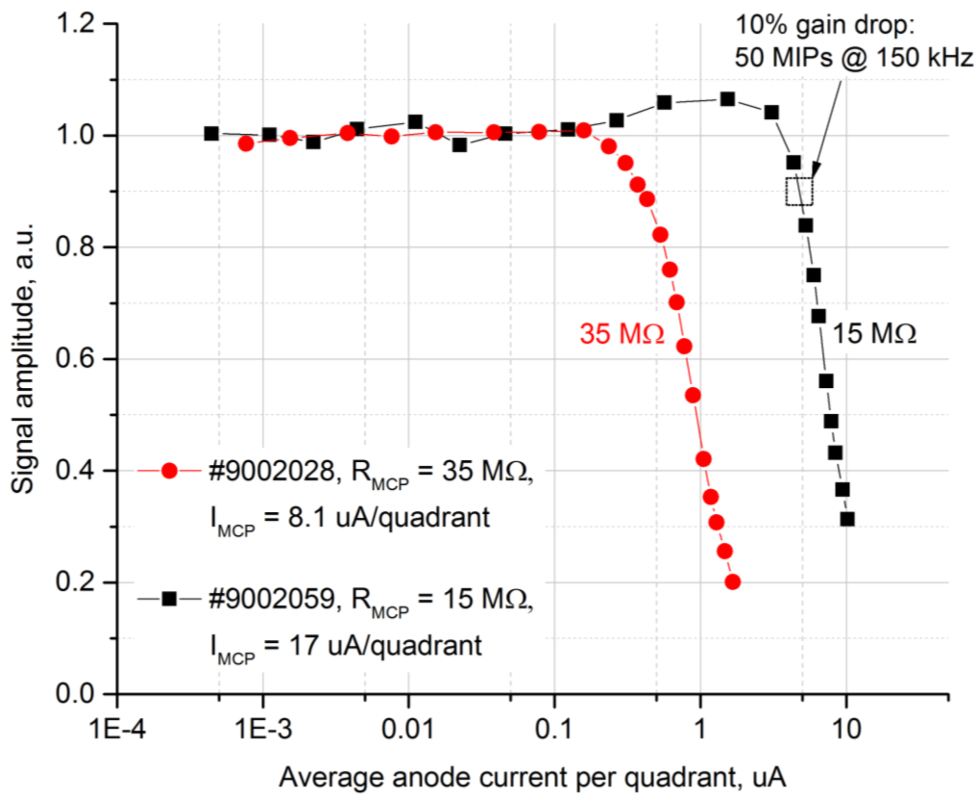
Even though we'll operate MCP-PMTs at $1.5*10^4$ gain only, heavy ion collisions at top LHC energies result in **~2 uA/quadrant average anode current (AAC)** for the most inner FIT modules. The declared limit for stock Planacons is lower – **3 uA/device**.

Anode current saturation limit of MCP-PMTs depends on the MCP parameters (R, C), so devices of the proper parameters should be purchased.

Usually, Planacons have ~35 MΩ MCP stack resistance, and their dynamic range is insufficient for the central pixels of FIT:

Although, the specially requested **15 MΩ devices have high enough anode current saturation limit**.

For the batch purchase, tubes within 12-22 MΩ MCP resistance range would be selected for an additional charge.



Planacon ageing

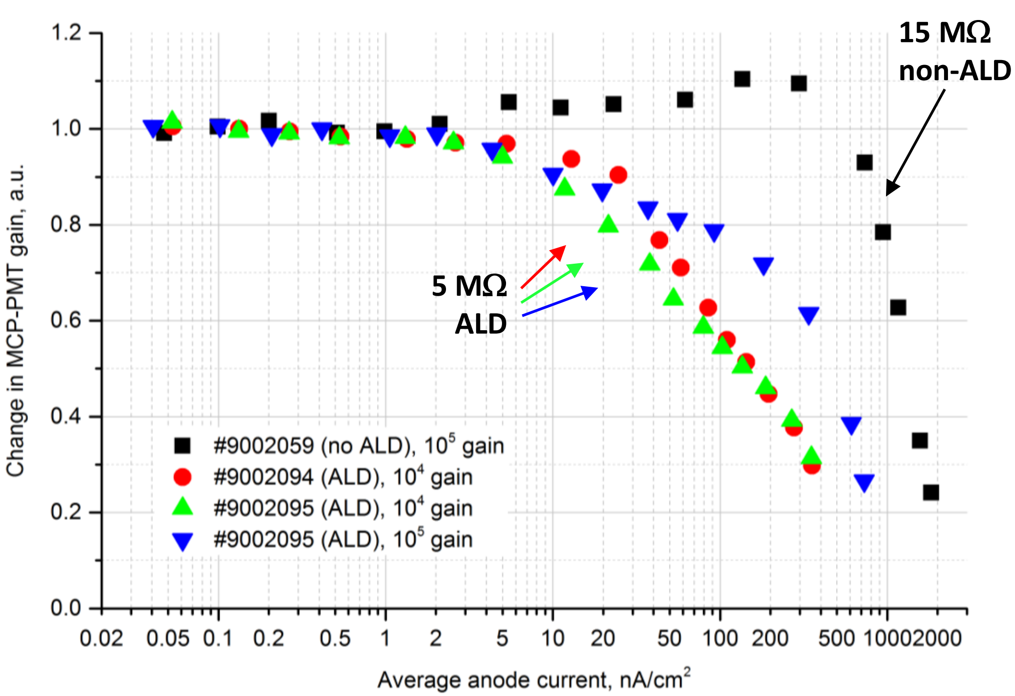
Planacons in FIT would operate at high average anode current for ≳6 years, which results in **≳0.6 C/cm² integrated anode charge** (IAC) collected at the most central quadrants.

Back in 2011 Planacon XP85012 and XP85112/A1-Q lifetime was limited **by 0.1 C/cm² only** according to *[2011 JINST 6 C10001]*. Although, Planacon manufacturing process has been **improved since then (better electron scrubbing, vacuum and electropolishing).**

ALD-coated Planacons were proven to have lifetime up to 10 C/cm² [NIM A 845 (2017) 570–574].

Two **Planacon XP85112/A1-Q-ALD** samples were tested by us. They are **unsuitable for FIT due to very low anode current saturation limit** (50 times lower than for non-ALD samples) and unstable gain after the saturation was achieved.

Further reading:
https://arxiv.org/abs/1807.03804

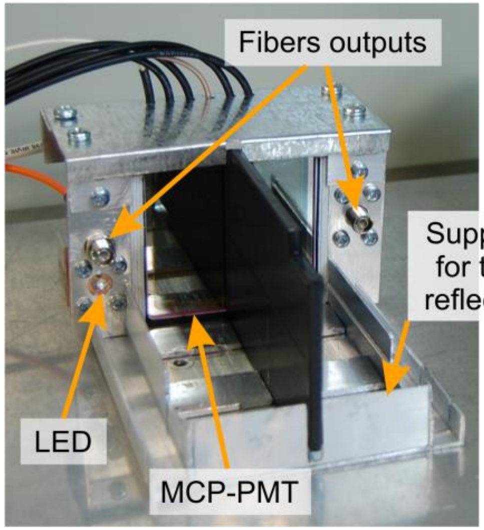


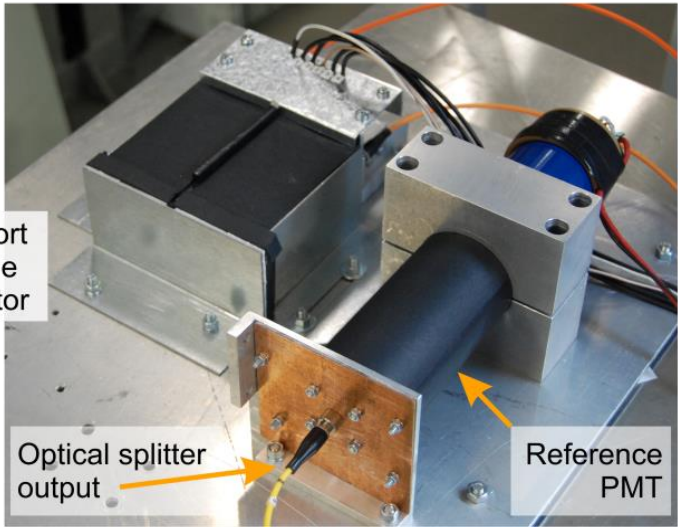
Planacon ageing study

Lifetime of a sample non-ALD Planacon MCP-PMT was tested in a dedicated setup at NRNU MEPhI in April-October 2017.

The tested MCP-PMT was manufactured in 2015 and was not optimized for its use in FIT: high resistance (35 MΩ), old PCB (serial #9002028).

IAC was collected at two quadrants by illuminating them with 470 nm LED in pulsed mode round the clock from April to October 2017 in non-saturated mode (AAC≈30 nA/cm^2). As a result, **~0.5 C/cm^2 IAC was collected at q.1**.





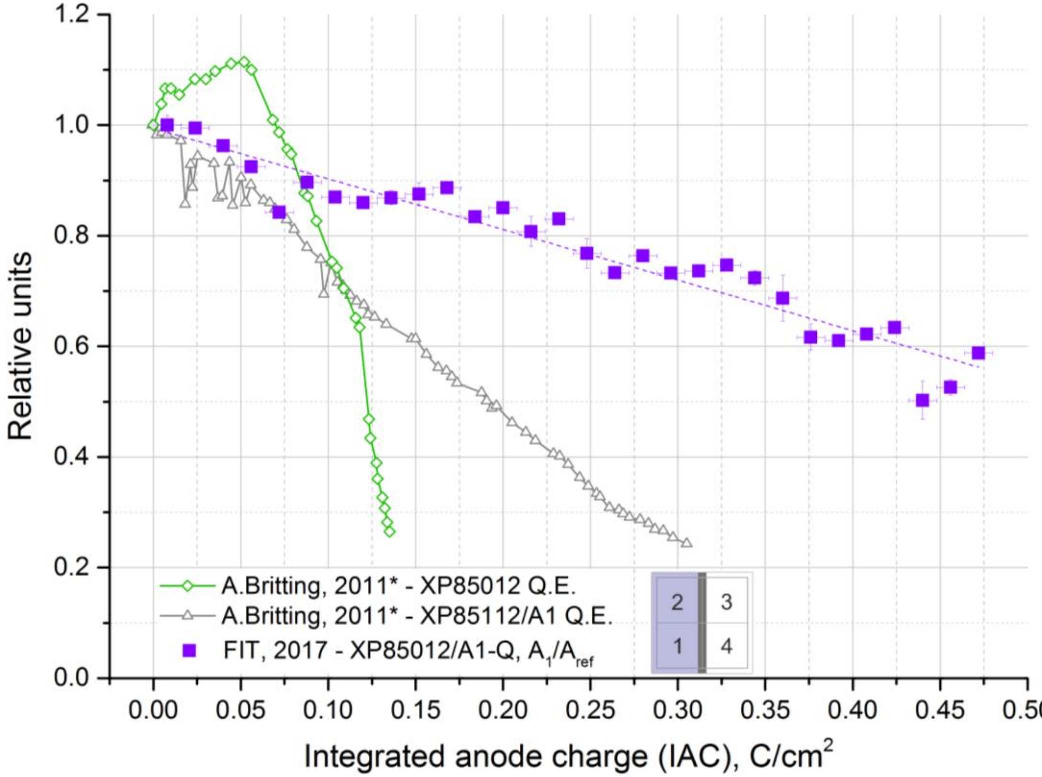
Results of the ageing test

Since the test was performed at low gain ($4*10^4$), ageing was monitored by illuminating the two MCP-PMT halves and the reference PMT by 405 nm laser and measuring signal amplitude in relative values.

As a result, **44% drop in pulse amplitude** was revealed relatively to the reference PMT - could be both due to Q.E. and/or gain deterioration.

The obtained trends (violet) compared to the only data published by *A. Britting et al.* in 2011:

At the same time, **only 27% decrease in pulse amplitude was seen for the illuminated quadrant relatively to the shaded one.**



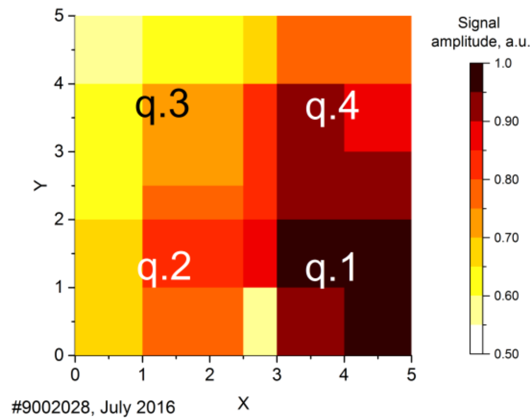
* Data taken from: A. Britting et al. Lifetime-issues of MCP-PMTs, 2011 JINST 6 C10001

Results of the ageing test for the actual wavelength

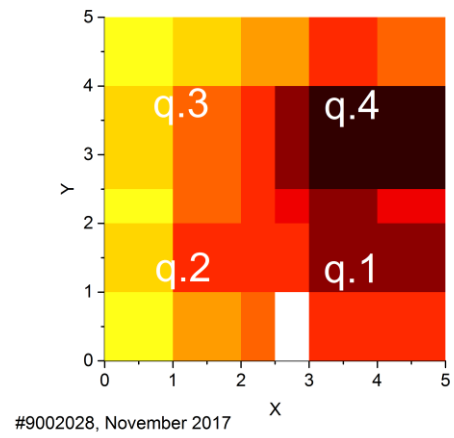
To check ageing influence for the Cherenkov light (160…300 nm), the tested MCP-PMT was irradiated in a wide beam at CERN PS before and after IAC collection.

Cherenkov light was generated in the 2 mm-thick quartz window of Planacon – pulse amplitude distribution across the MCP-PMT area could be compared.

Before:



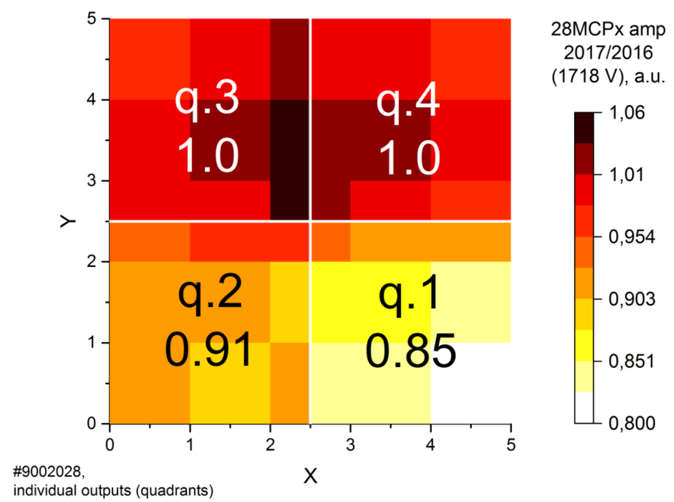
After:



15% (instead of 27%) decrease is seen in q.1 relatively q.3 and q.4, which were shaded during the ageing test → **only ½ of the detected drop in pulse amplitude is expected for the actual Cherenkov pulses.**

So, ~25% combined decrease in Q.E. and gain is expected for Planacon XP85012/A1-Q after collecting 0.5 C/cm² IAC.

Their ratio:



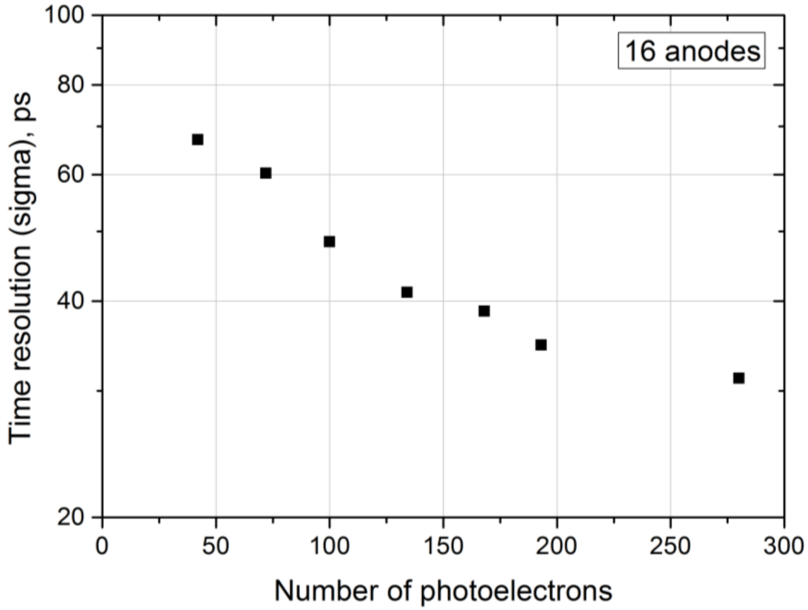
Results of the ageing test for the actual wavelength

~150 p.e./MIP is sufficient for precise timing – so, we have x2 margin in Q.E.

All Planacons could reach 10^6 gain, while we use $1.5*10^4$ – so, we have x70 margin in gain.

The observed ~25% drop in signal amplitude could be easily recovered by increase in HV with negligible loss in timing precision.

Fast ageing test of one MCP-PMT sample from the batch purchase is planned in October-November 2018.



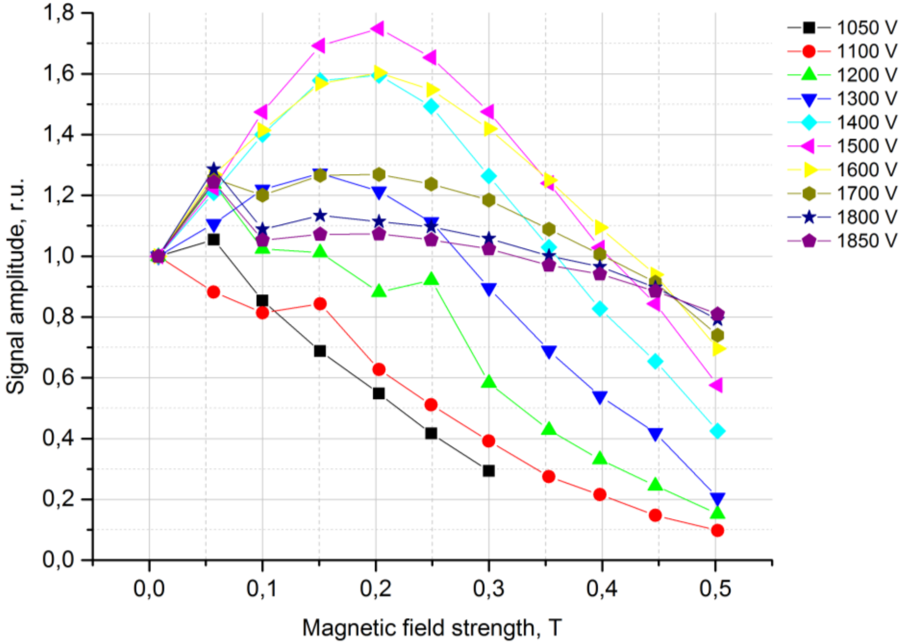
Planacon behaviour in magnetic field

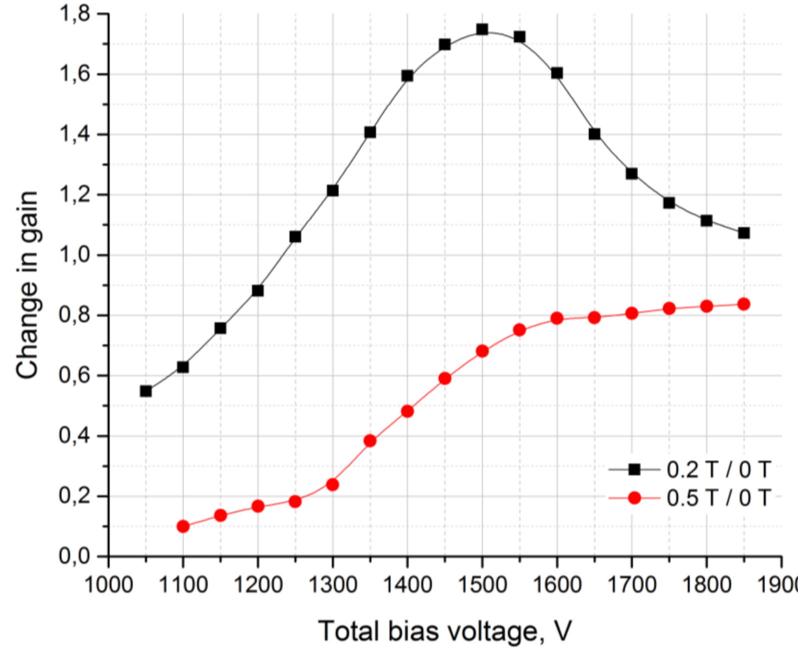
- 1.5*10^4 gain is needed for Planacons in FIT. Typically, it requires 1300…1500 V bias voltage (~1330 V for the sample used in the B-field test);
- No published data on Planacon behaviour in B-field was found for such low voltage values;
- We have performed gain scanning of 25 um-pore Planacon XP85012/A1-Q in magnetic field with inductance up to 0.5 T.

We are grateful to the **Department for Nuclear Research of the Lebedev Physical Institute RAS** for providing the possibility of using the SP57A1 magnet at the Troitsk accelerator site.

Personal gratitude to A.I. Lvov and V.A. Baskov!

Planacon behaviour in magnetic field



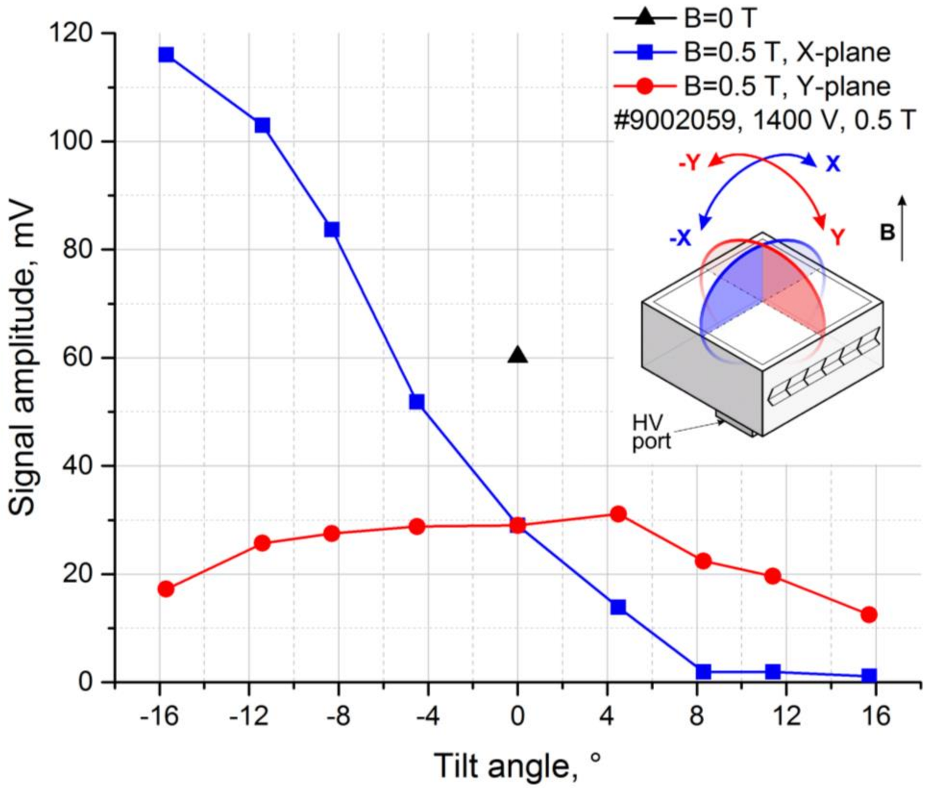


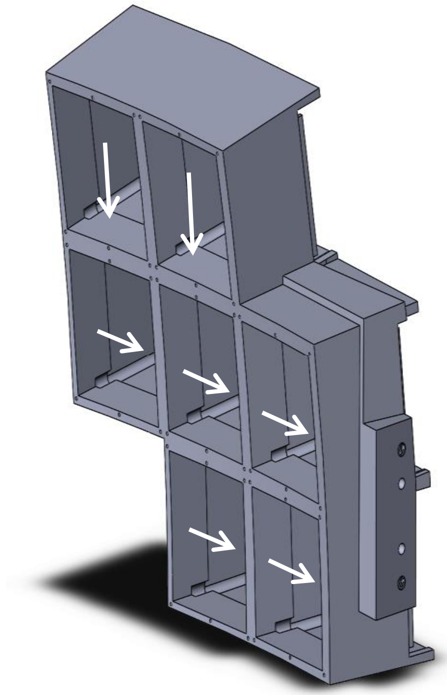
- 1.5*10^4 gain is needed for Planacons in FIT. Typically, it requires 1300…1500 V bias voltage (~1330 V for the sample used in the B-field test).
- We've observed **x3 drop in gain at 0.5 T for 1330 V bias voltage** – could easily be compensated by ~50 V increase in U_b.
- Gain decrease is dependent on the absolute voltage value: x10 drop in gain is observed at $U_b \leq 1100$ V. To rule out any MCP-PMT outliers, for the batch purchase **we've specified the minimal HV for 10^5 gain to be 1250 V.**

Planacon behaviour in magnetic field

Also, we've observed that Planacon gain in B-field is highly dependent on the tilt angle in the chevron angle plane. Gain is maximal when B-field direction coincides with microchannels of the first MCP (due to the avalanche nature of electron multiplication).

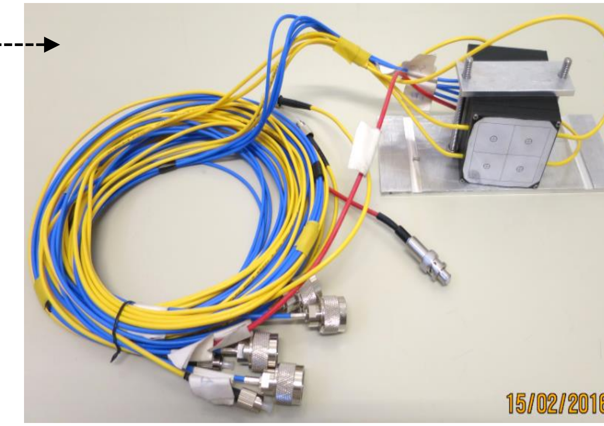
We are planning to install MCP-PMTs to FIT-C array in the way to achieve minimal inclination angles in X-plane.



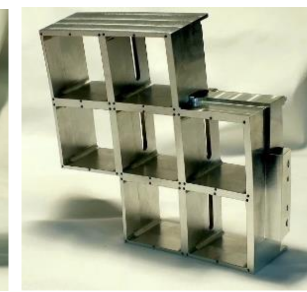


FIT detector status

- **Test Cherenkov module** has been installed in the ALICE cavern 2.5 years ago. Its behaviour conforms well with the R&D results:
  - Timing resolution better than 40 ps for single MIPs;
  - 3-fold gain decrease at 0.5 T;
  - No signs of ageing.



- **T0+:** R&D and design phase finished, hardware production is underway;
- **V0+:** final prototype to be tested at CERN PS this September, designing of hardware components is underway;



- **Electronics:** design phase finished, production underway;
- **Photosensors:** first 25 items to be shipped in three batches from 15 October to 15 December 2018, other 35 - in January-April 2019;

  Each MCP-PMT batch of 10 samples to be scrutinized in a dedicated test bench;

- **FIT-C** to be assembled in May 2019, installed – in April 2020;
- **FIT-A** to be assembled in November 2019, installed in August 2020;
- **Detector commissioning:** November 2020 – December 2021.

Conclusions

- Cherenkov subsystem of the FIT detector for the ALICE upgrade requires compact and rad-hard photosensors of superior timing performance and high geometry efficiency, capable of working in high B-field;
- Non-ALD Planacon MCP-PMTs match these requirements in the best way;
- Cross-talk related drawbacks of the off-the-shelf Planacons were eliminated by modifying the signal readout PCBs of Planacon XP85012/A1-Q, incorporated to the sensor;
- Additional parameters (linearity, B-field immunity at low gain etc.) are fixed by setting the selection criteria (for some extra charge);
- 0.5 C/cm^2 integrated anode charge collection leads to 25% only decrease in Q.E. and/or gain for a modern non-ALD Planacons (for Cherenkov light);
- Currently, FIT project is well on track: FIT-A should be assembled already in 9 month, final FIT commissioning – in two years from now.

Thank you for your attention!

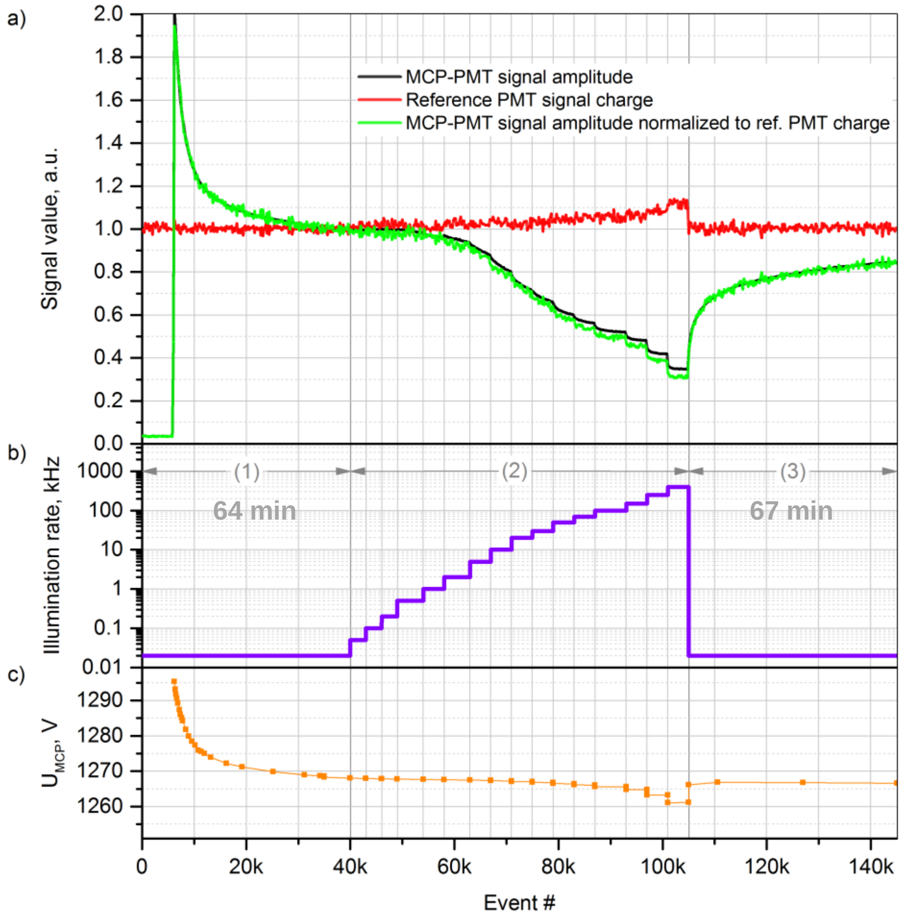
See more details on FIT electronics in the poster (#19)

"Fully digital readout and trigger for fast Cherenkov counters"

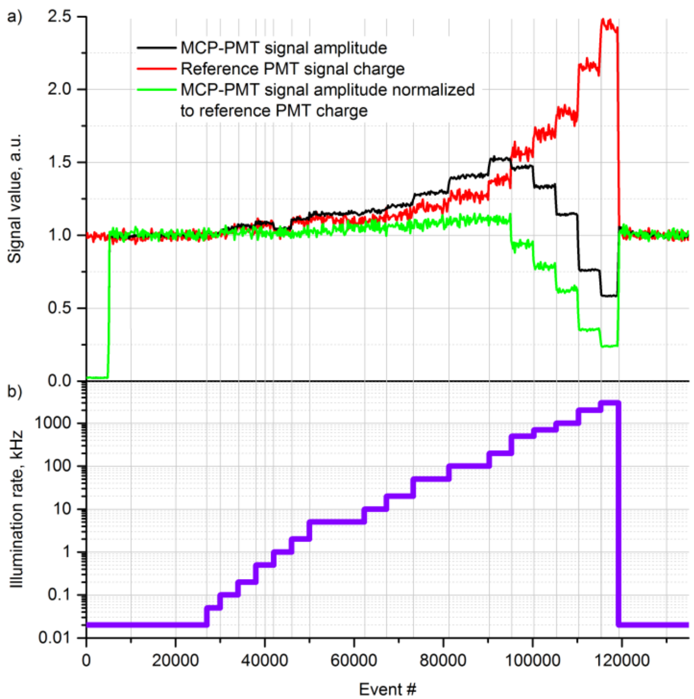
by D.A. Finogeev!

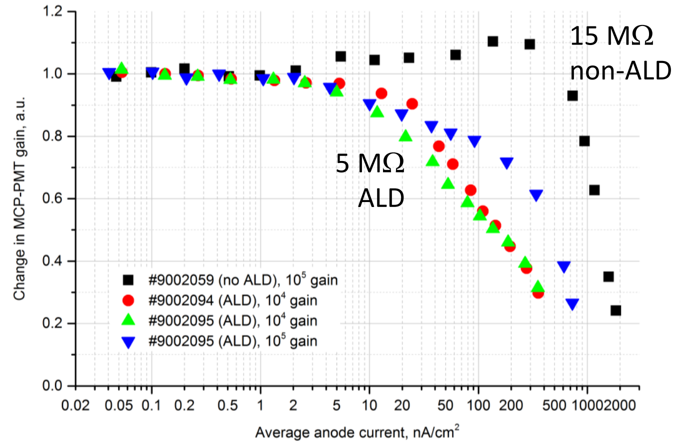
Back-up slides

Planacon XP85112/A1-Q-ALD, #9002095



Planacon XP85012/A1-Q, #9002059



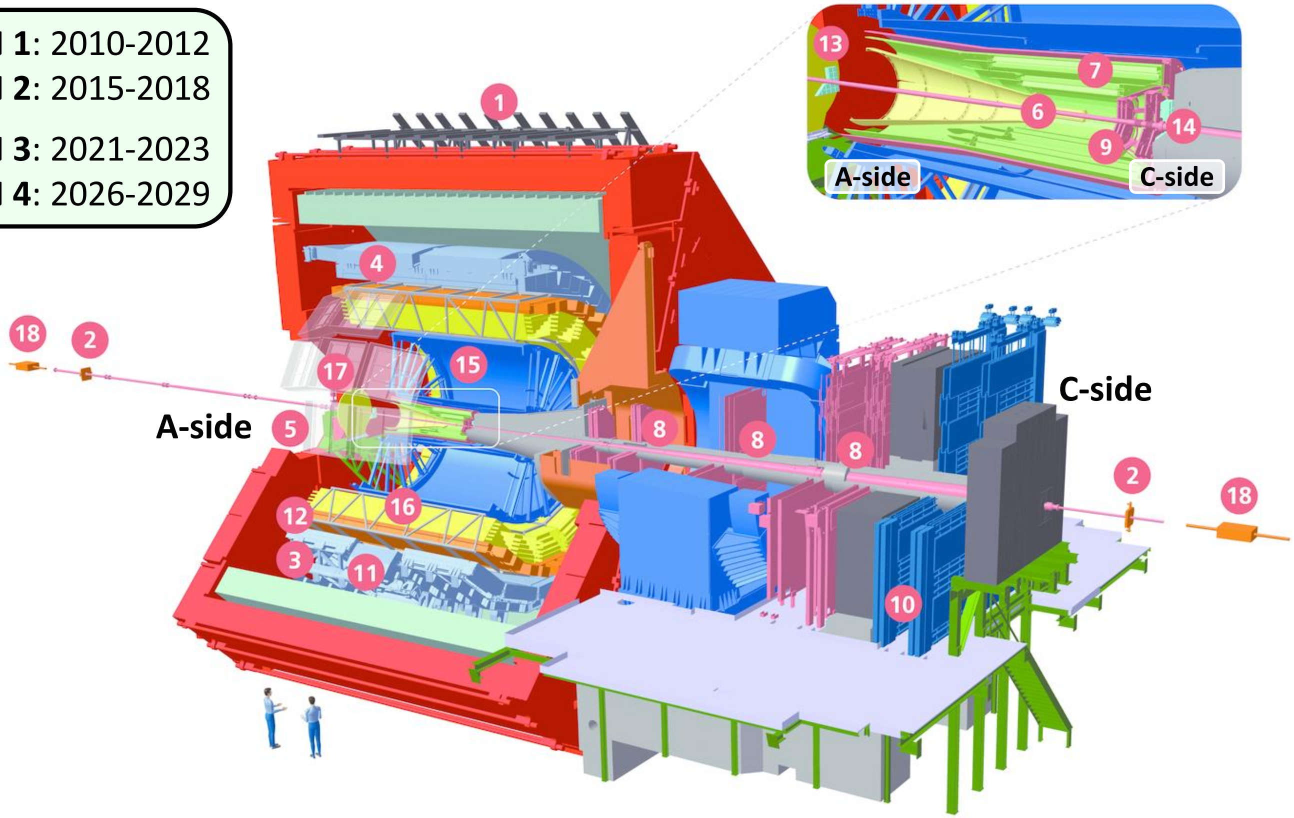


https://arxiv.org/abs/1807.03804

ALICE - A Large Ion Collider Experiment

A dedicated heavy-ion detector to study nucleus-nucleus interactions at LHC energies.

RUN 1: 2010-2012
RUN 2: 2015-2018
RUN 3: 2021-2023
RUN 4: 2026-2029



1. **ACORDE** | ALICE Cosmic Rays Detector
2. **AD** | ALICE Diffractive Detector
3. **DCal** | Di-jet Calorimeter
4. **EMCal** | Electromagnetic Calorimeter
5. **HMPID** | High Momentum Particle Identification Detector
6. **ITS-IB** | Inner Tracking System - Inner Barrel
7. **ITS-OB** | Inner Tracking System - Outer Barrel
8. **MCH** | Muon Tracking Chambers
9. **MFT** | Muon Forward Tracker
10. **MID** | Muon Identifier
11. **PHOS / CPV** | Photon Spectrometer
12. **TOF** | Time Of Flight
13. **T0+A** | Tzero + A
14. **T0+C** | Tzero + C
15. **TPC** | Time Projection Chamber
16. **TRD** | Transition Radiation Detector
17. **V0+** | Vzero + Detector
18. **ZDC** | Zero Degree Calorimeter

New detectors to be installed before RUN3 for even better particle identification and tracking (especially at low p_T) and capability of matching 50 kHz Pb-Pb interaction rate (current limit ~1 kHz)

Fast Interaction Trigger (FIT) detector for the upgraded ALICE

Replaces several current forward and trigger detectors.

Main limitations:

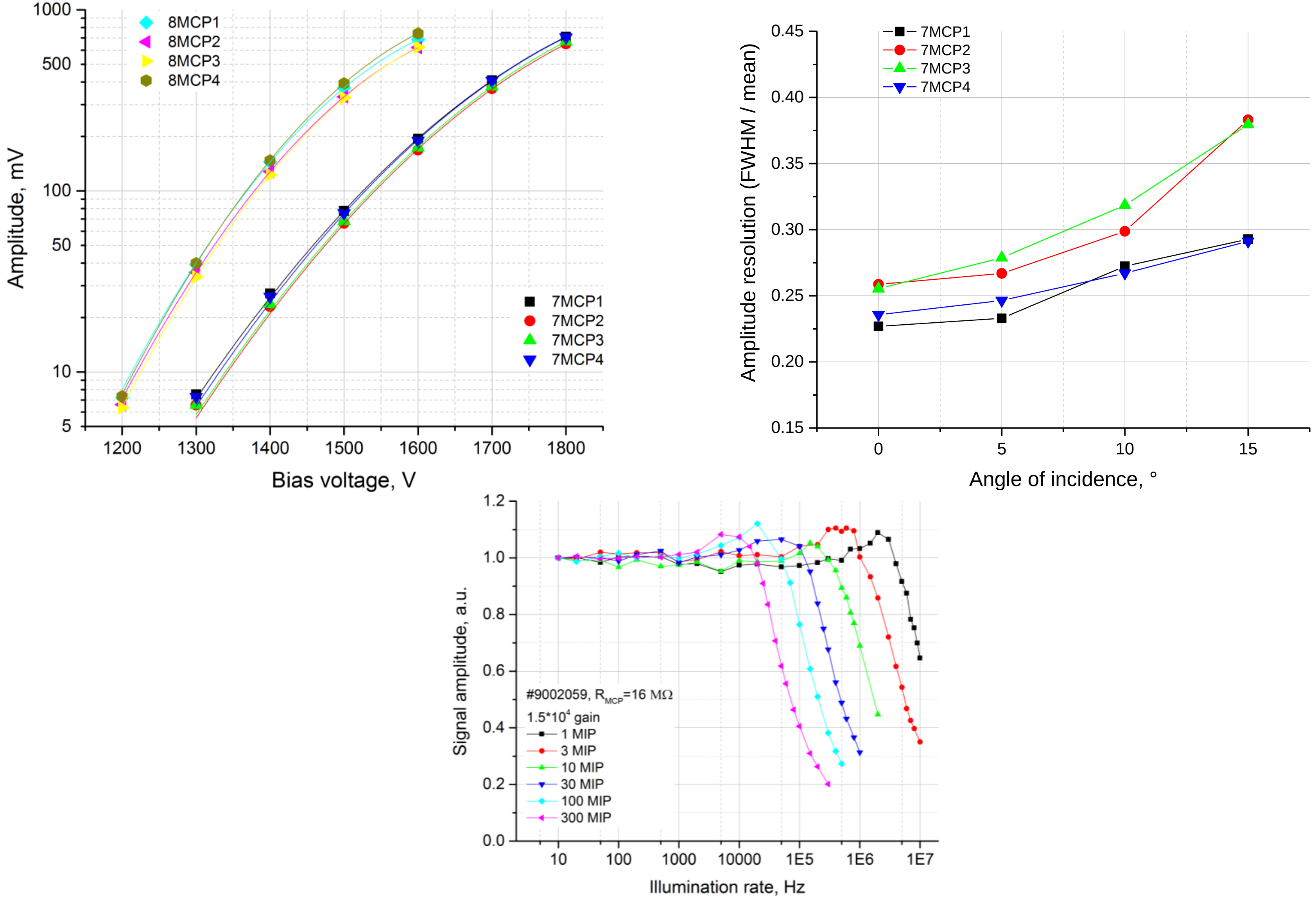
- *Very limited space from the C-side* due to the MFT introduction (92 mm along the beam pipe);
- Smooth operation at *higher collision rates* required (50 kHz Pb-Pb, 0.2 or 1 MHz in p-p and p-Pb, bunch spacing as low as 25 ns);
- Immunity to *higher radiation doses*: 46 krad and $1.3*10^{12}$ 1-MeV-neq/cm^2 expected (+ safety factor);
- Capability to operate at *0.5 T magnetic field*;
- *Hermetic design and precise collision time detection.*

Required functionality:

- Event trigger with *minimal latency (<425 ns)*, including vertex determination, centrality selection, background and ultra peripheral collisions rejection;
- Collision time for Time-Of-Flight particle ID: *σ<50 ps required* (LHC clock precision $\sigma \approx 250$ ps)
- Centrality and Event Plane determination basing on the measured multiplicity;
- On-line luminosity monitoring.

Trigger Latency	Input to CTP [ns]	Contributing detectors
LM	425	FIT
L0	1200	ACO,EMC,PHOS,TOF, ZDC
L1	6100	EMC, ZDC

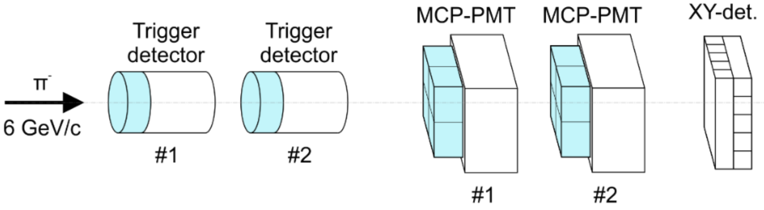
- **Fast Interaction Trigger (FIT)**
  - Minimum bias (MB) used by most of detector
  - TRD wake-up
- **FIT Trigger Input latency**
  - 425 ns from interaction to signal at detector CTP input
- **Continuous readout** **(rare processes do not exhibit signatures that can be selected by hardware triggers, they can only be collected by a zero bias triggers)**

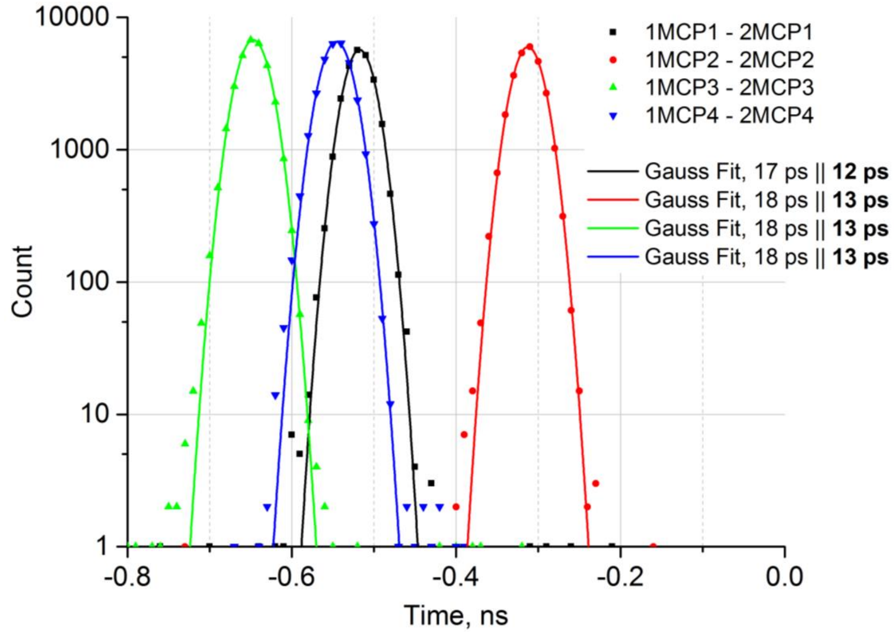

8MCP1
8MCP2
8MCP3
8MCP4
7MCP1
7MCP2
7MCP3
7MCP4
Amplitude, mV
Bias voltage, V
Amplitude resolution (FWHM / mean)
Angle of incidence, °
#9002059, R_{MCP}=16 MΩ
1.5*10^4 gain
1 MIP
3 MIP
10 MIP
30 MIP
100 MIP
300 MIP
Signal amplitude, a.u.
Illumination rate, Hz

FIT Cherenkov module characteristics

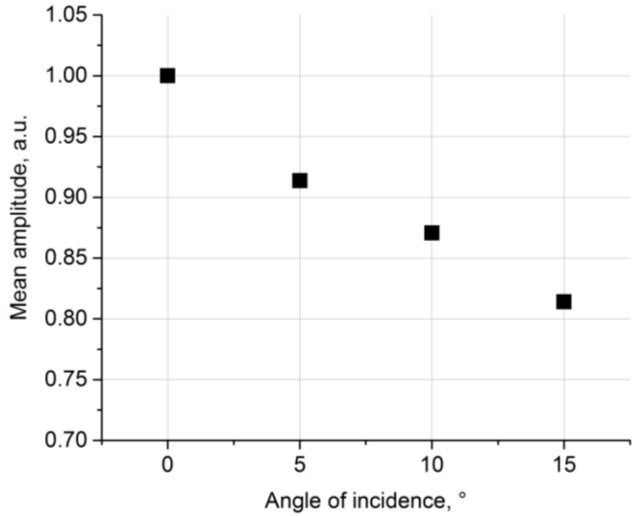
The modified Planacon XP85012/A1-Q MCP-PMTs + 2 cm-thick fused silica radiators were irradiated at CERN PS pion beam.

Time resolution of σ=13 ps is confirmed for single MIPs detection **(1 MIP ≈ 300 p.e.)**





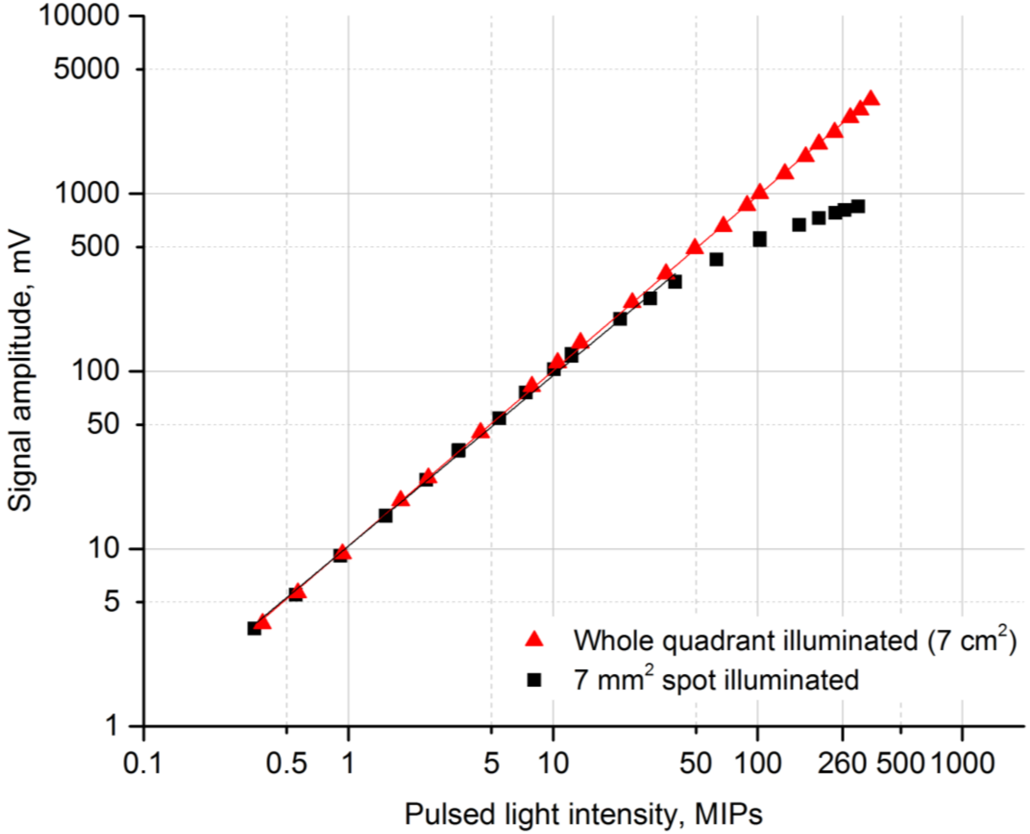
Time resolution of the whole system (Cherenkov module + 40 m cables + analog readout electronic) is **σ=33 ps**.



1 MIP signal amplitude is **dependent on the angle of particle incidence** → FIT array in 0.8 m from the interaction point would be **concave**.

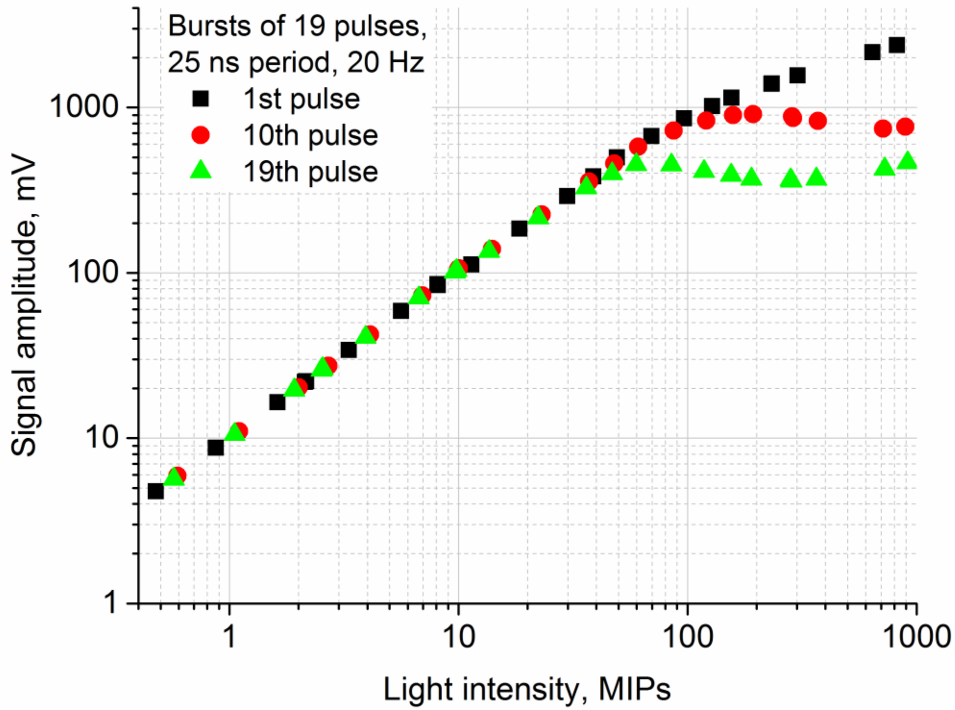
Planacon amplitude linearity

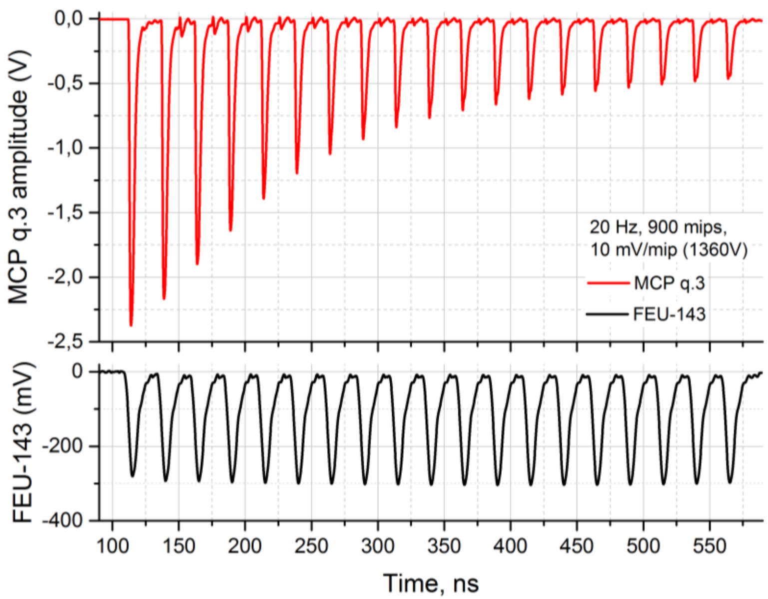
In the pulsed mode, Planacons routinely achieve 20 mA/quadrant anode currents required for FIT at the default gain (~260 MIPs or 7.5*10^4 p.e.).



Planacon charge saturation

Bursts of 19 pulses with 25 ns period, 20 Hz repetition rate, illuminated ∅1 cm





Saturation due to the charge depletion at the microchannels ends inside the illuminated area (450 ns illumination periode << τ≈1 ms).

So, charge limitation within the microchannels dead time is:

19 pulses * 40 MIP/pulse / 0.785 cm^2 = 970 MIP/cm^2, or ~6800 MIP/quadrant – within the FIT requirements.

Calculating the lifetime needed for T0+ modules:

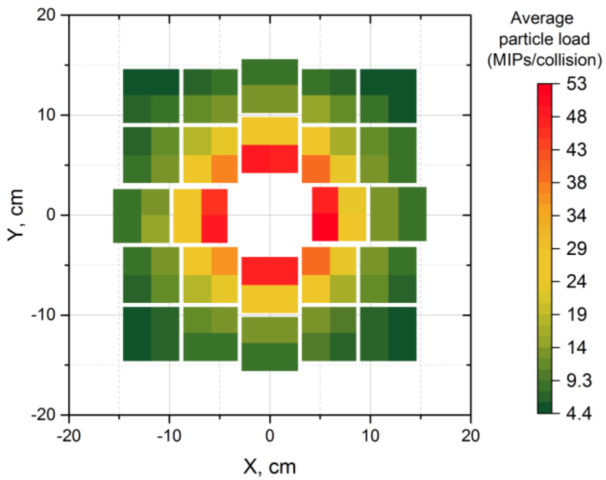
Expected integral number of collisions in ALICE after LS2 [2-4]:

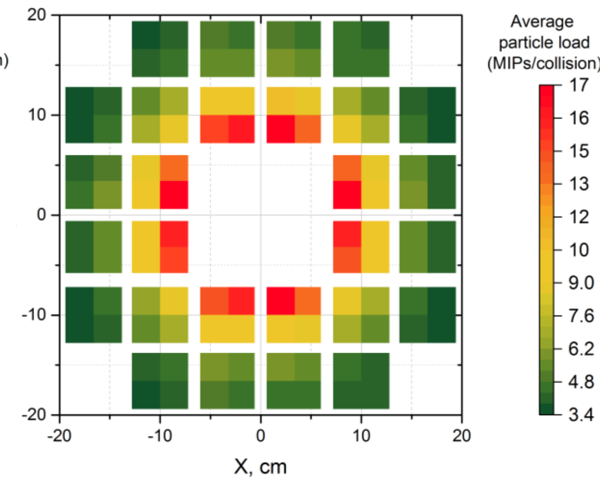
	p-p	p-Pb	Pb-Pb
Standard scenario	**5.6*10¹¹** (8.4 pb⁻¹)	**10¹¹** (50 nb⁻¹)	**1.1*10¹¹** (13 nb⁻¹)
Alternative scenario	**1.7*10¹³** (250 pb⁻¹)	**2*10¹²** (1 pb⁻¹)	**1.1*10¹¹** (13 nb⁻¹)

Average particle load of the most central **T0+A** quadrants (MC simulations):

p-p 14 TeV	p-Pb 8.8 TeV	Pb-Pb 5.5 TeV
0.84 MIP/q.	**3.3 MIP/q.**	**52 MIP/q.**

Particle load for the most central T0+C and outer T0+A modules is ≳3 times lower (Pb-Pb distribution example):





10 mV/MIP signals correspond to 0.63 pC/MIP charge – known from beam tests (290 p.e./MIP, 10^4 gain)

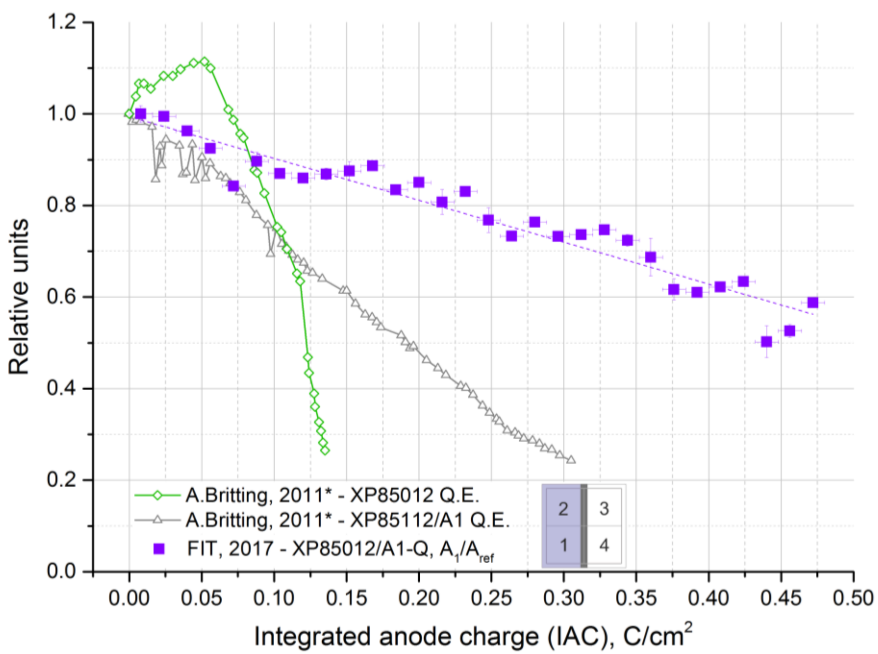
[2] Upgrade of the ALICE Experiment: Letter Of Intent.J. Phys. G: Nucl. Part. Phys. 41 (2014) 087001.
[3] Radiation Dose and Fluence in ALICE after LS2, ALICE-PUBLIC-2017, 30.11.2017.
[4] Technical Design Report for the Upgrade of the Online–Offline computing system.CERN-LHCC-2015-006.

Results of the ageing test

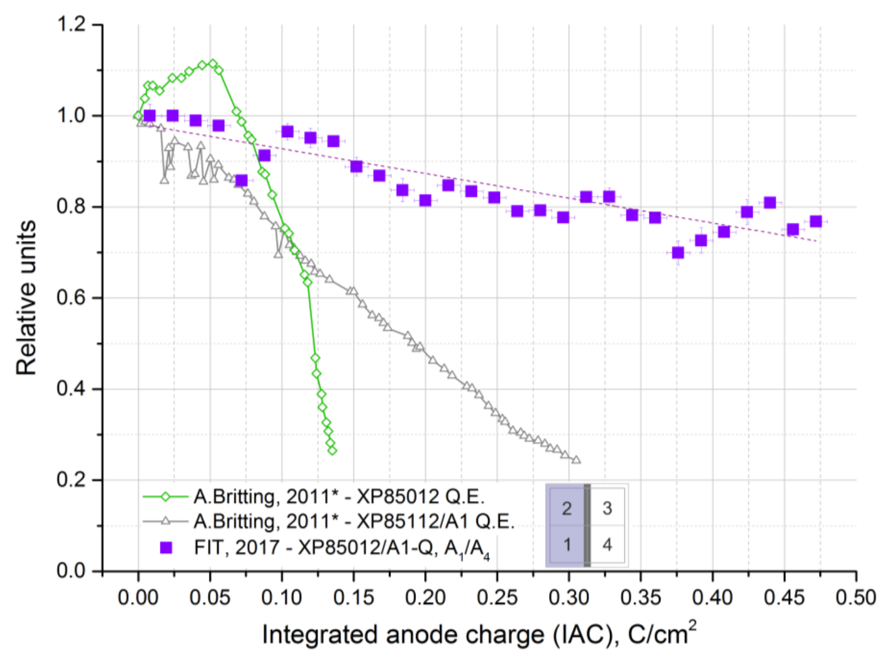
Since the test was performed at low gain ($4*10^4$), ageing was monitored by illuminating the two MCP-PMT halves and the reference PMT by 405 nm laser and measuring signal amplitude in relative values.

As a result, **44% drop in pulse amplitude** revealed relatively to the reference PMT and **27% relatively to the two halves** (illuminated/shaded). It could be both due to Q.E. and/or gain deterioration.

The obtained trends (violet) compared to the only data published by *A. Britting et al.* in 2011:



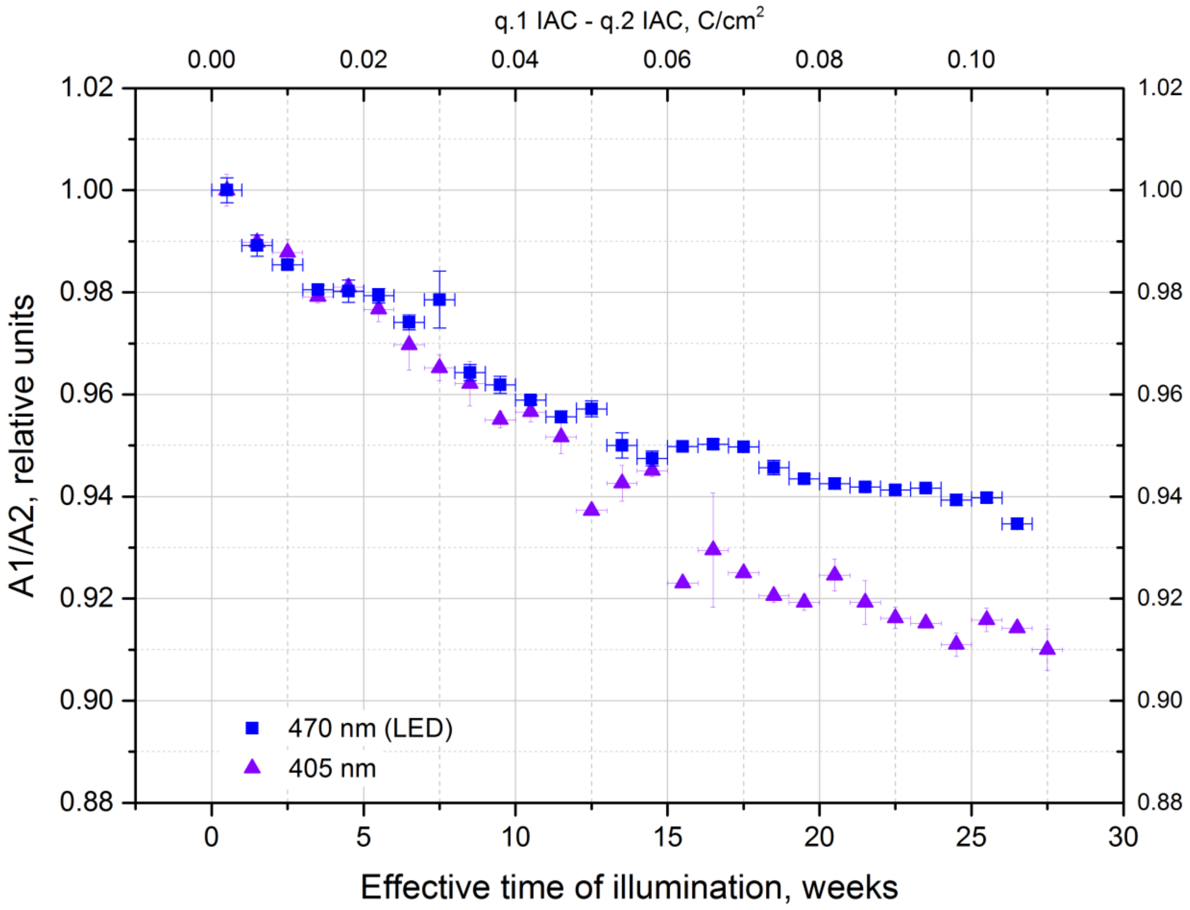
* Data taken from: A. Britting et al. Lifetime-issues of MCP-PMTs, 2011 JINST 6 C10001



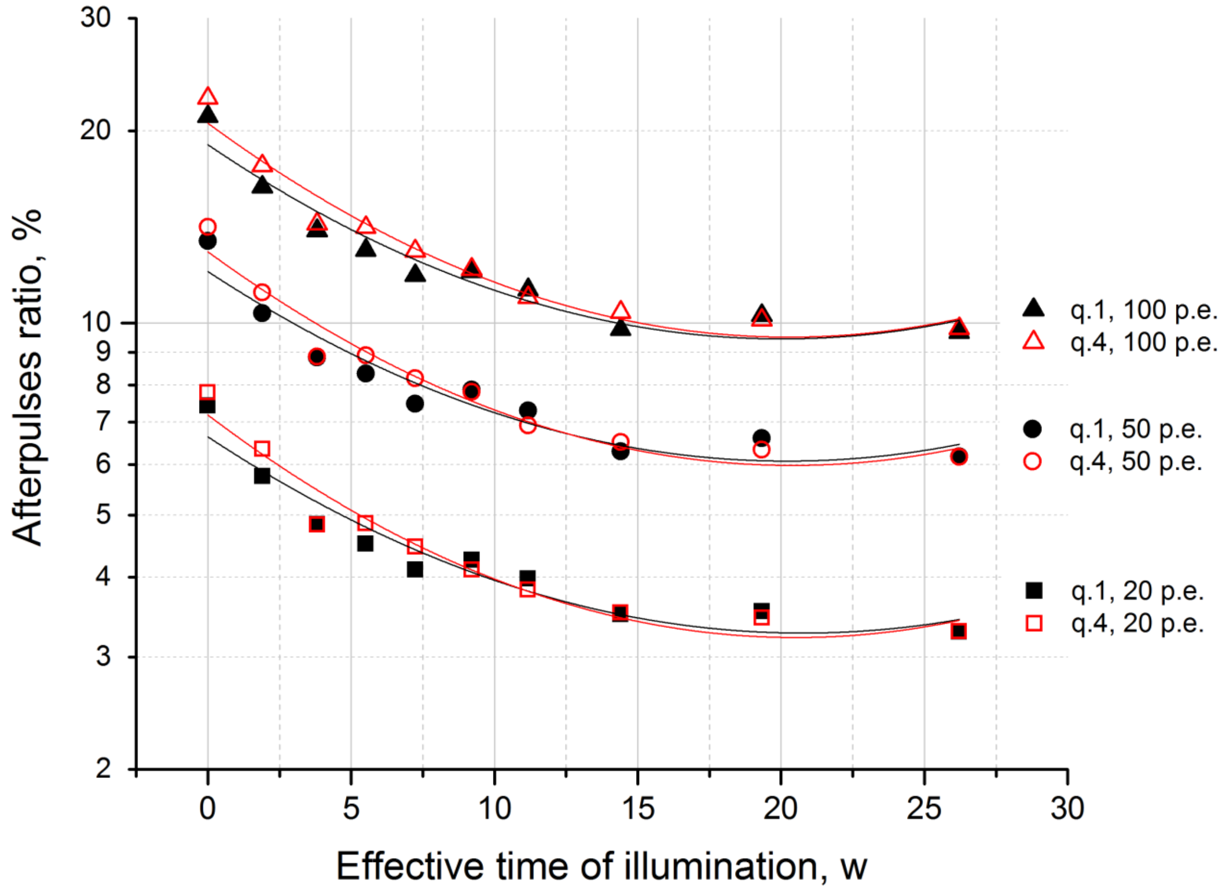
* Data taken from: A. Britting et al. Lifetime-issues of MCP-PMTs, 2011 JINST 6 C10001

q.2 gain was ~20% lower, than q.1. It led to 0.11 C/cm^2 difference in IAC, which resulted in 9% difference in signal amplitude decrease.

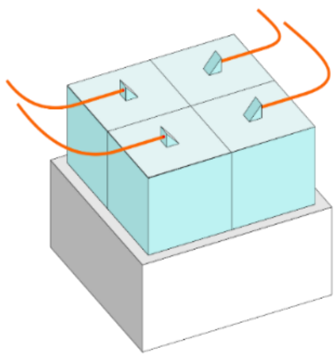
Linear extrapolation of this value for 0.47 C/cm^2 results in ~40% average amplitude decrease, which confirm the basic ageing test result.

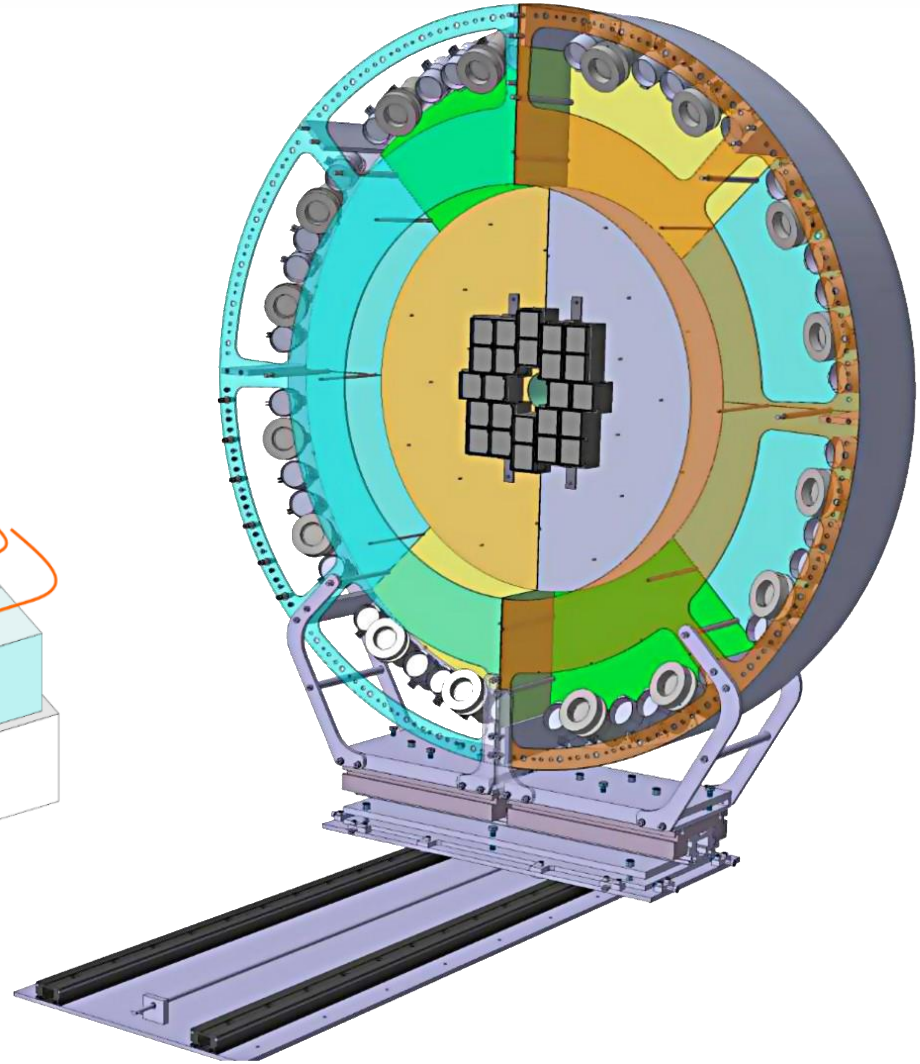


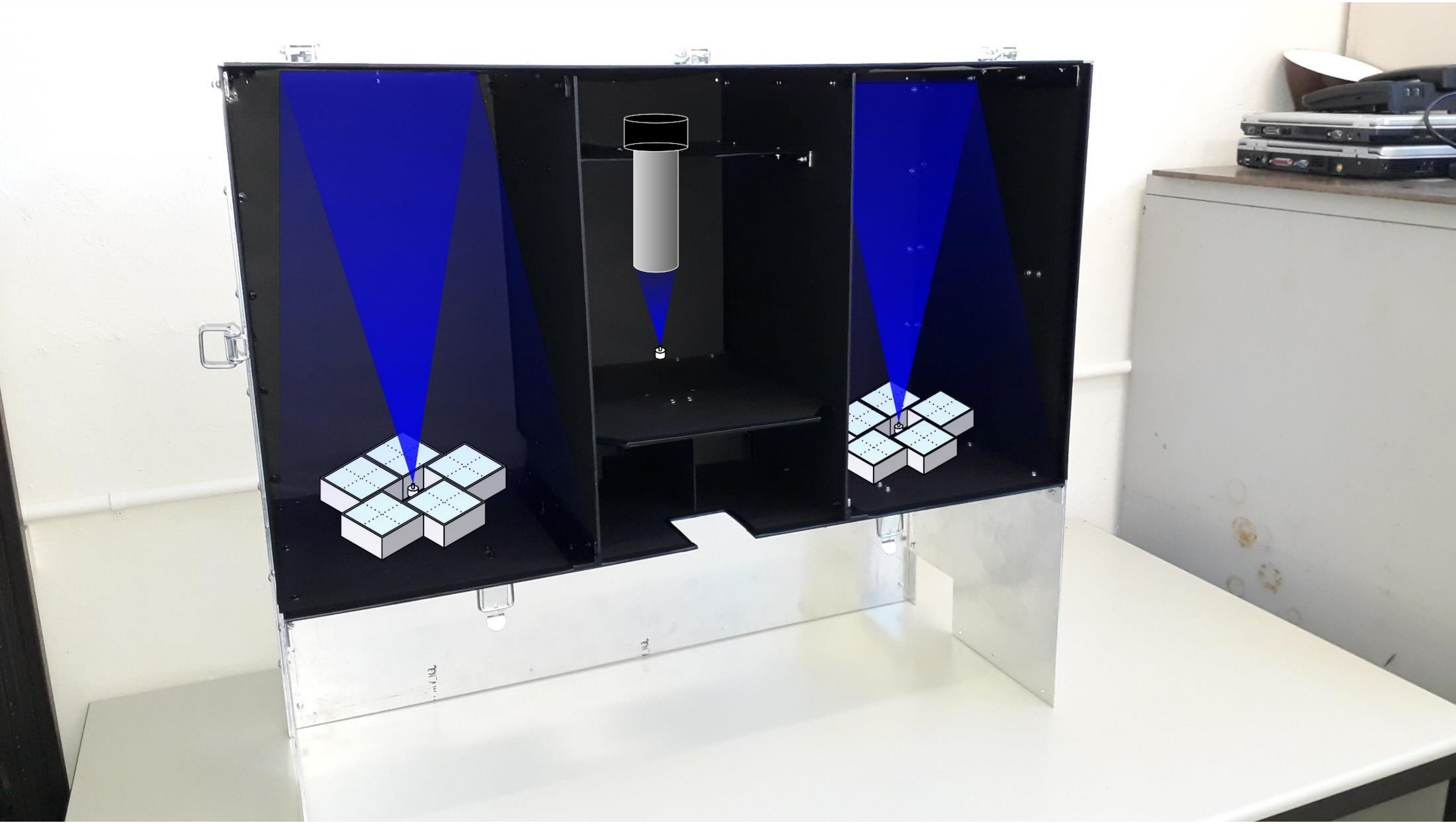
Ageing does not deteriorate Planacon quality in terms of afterpulsing – afterpulses ratio drops with the test time.

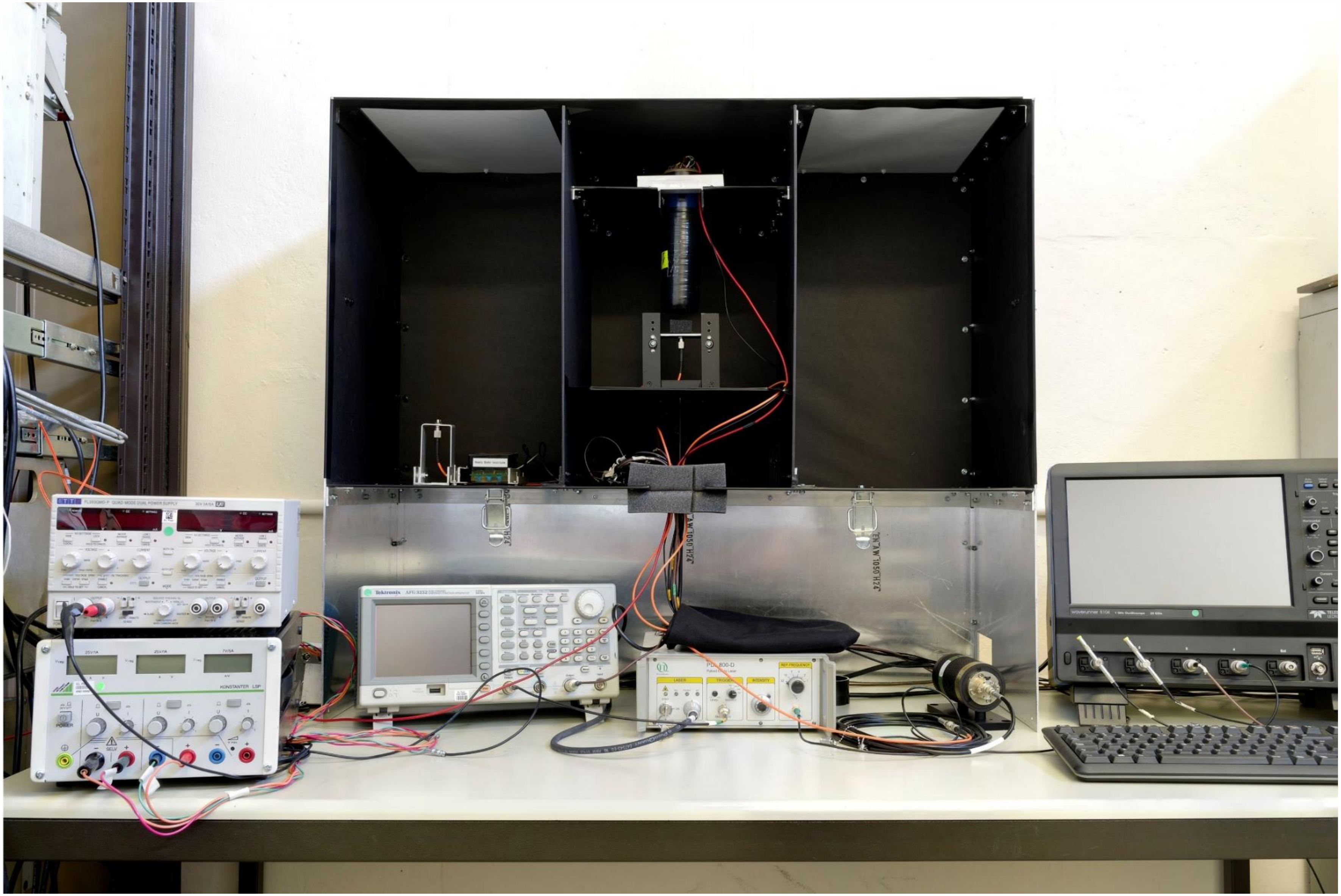



19/10/2017

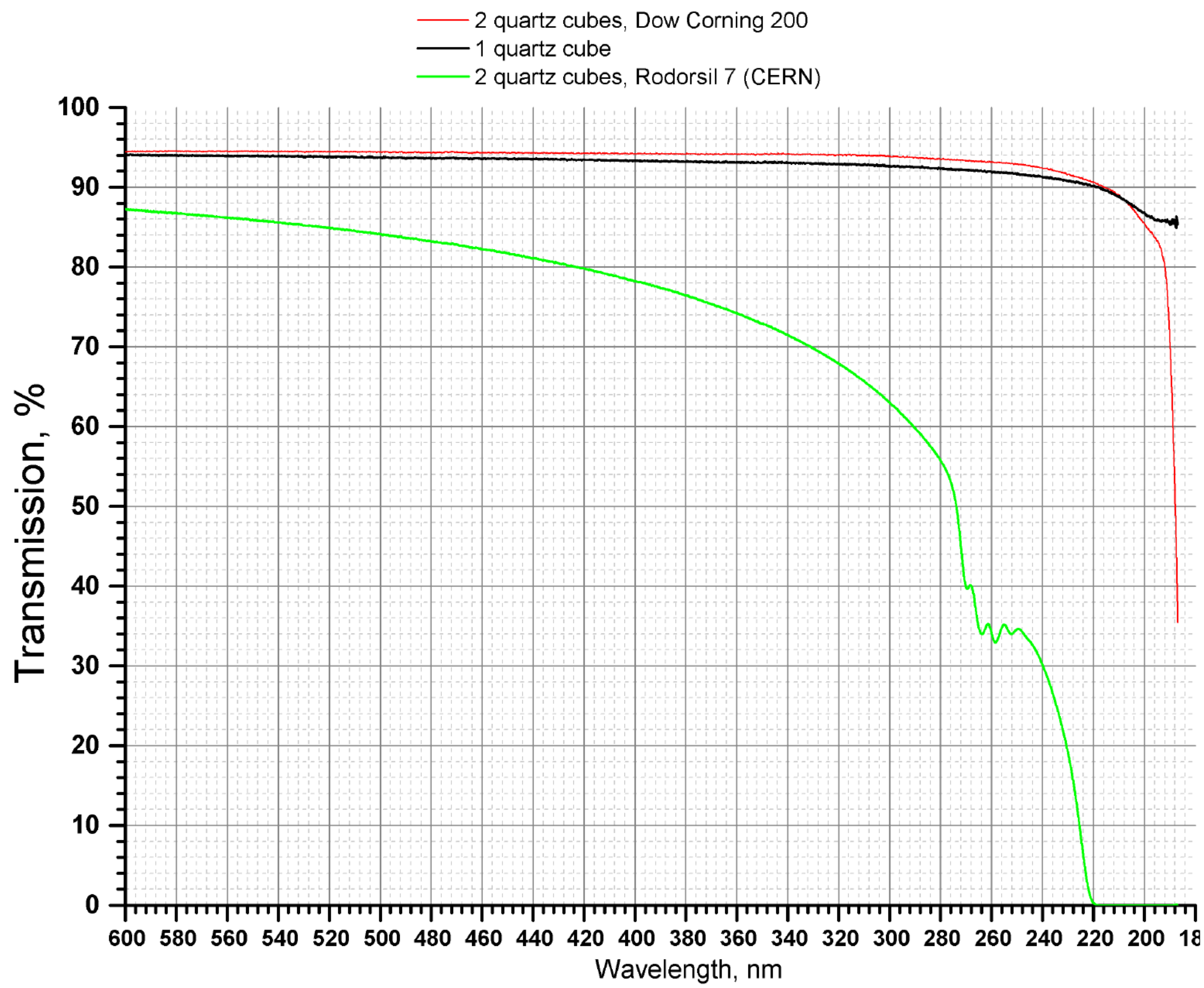


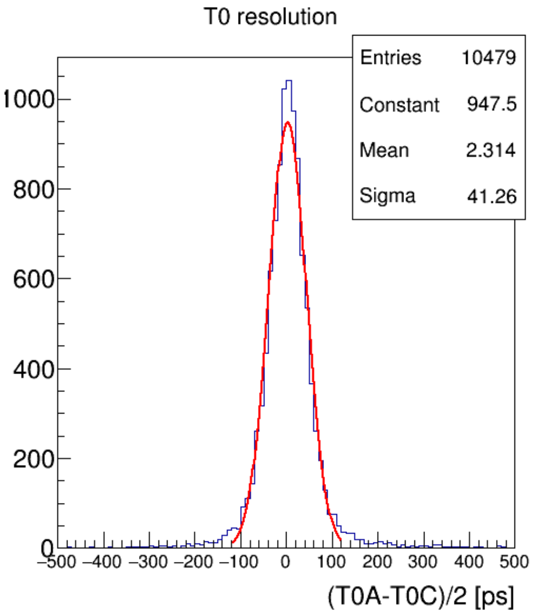


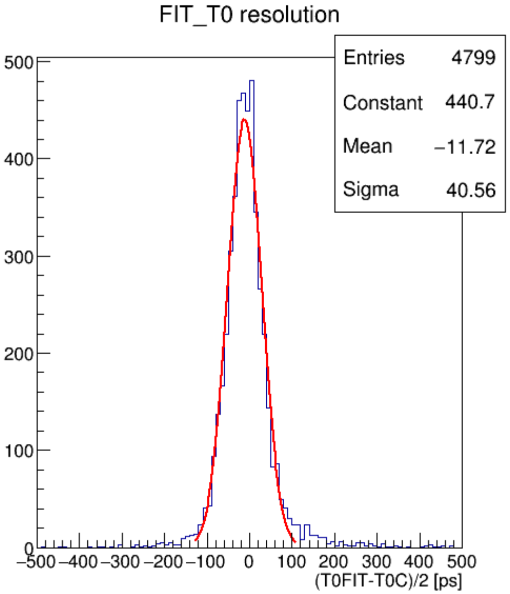


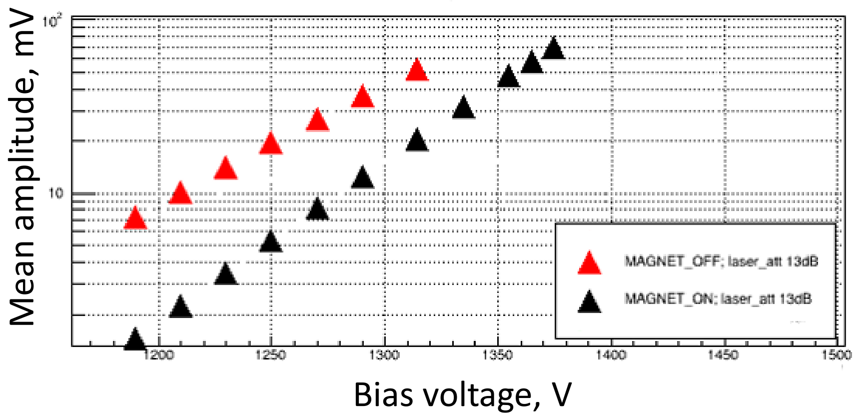


Transmission spectra for our quartz cubes, Rhodorsil 7 grease and chemically pure dimethylsiloxane (Dow Corning).




T0 resolution
Entries 10479
Constant 947.5
Mean 2.314
Sigma 41.26
1000
800
600
400
200
0
−500 −400 −300 −200 −100 0 100 200 300 400 500
(T0A-T0C)/2 [ps]


FIT_T0 resolution
Entries 4799
Constant 440.7
Mean −11.72
Sigma 40.56
500
400
300
200
100
0
−500 −400 −300 −200 −100 0 100 200 300 400 500
(T0FIT-T0C)/2 [ps]


Mean amplitude, mV
10^2
10
1200
1250
1300
1350
1400
1450
1500
MAGNET_OFF; laser_att 13dB
MAGNET_ON; laser_att 13dB
Bias voltage, V