Centre of Excellence
in Quark Matter

HELSINKI INSTITUTE OF PHYSICS

ALICE

Long-term performance of non-ALD MCP-PMTs in the high-radiation environment of ALICE

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on behalf of the ALICE Collaboration

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XII International Workshop
on Ring Imaging Cherenkov Detectors

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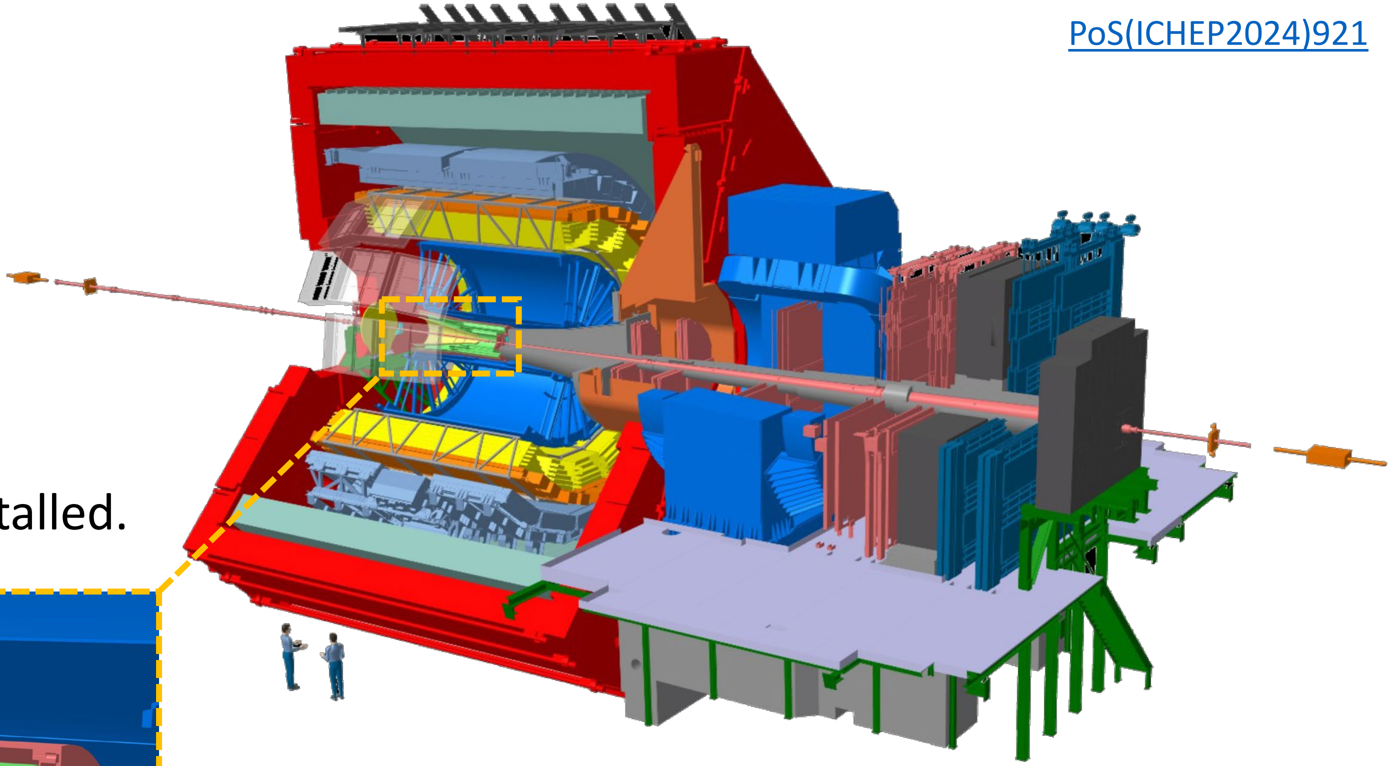
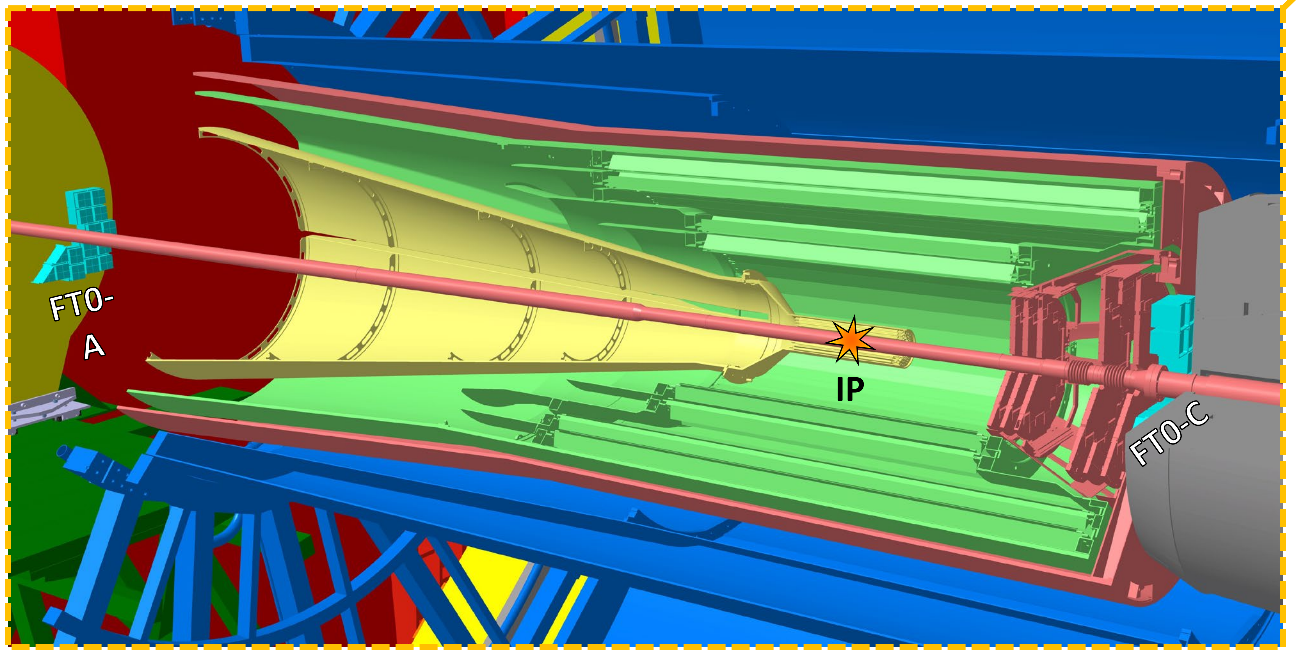
ALICE and FIT

Further reading on the ALICE FIT: PoS(ICHEP2024)921

A Large Ion Collider Experiment (ALICE):

- One of the four large LHC apparatus;
- Fine-tuned to study heavy-ion collisions;
- Undergone a major upgrade in 2018-2021: the **Fast Interaction Trigger (FIT)** detectors (including the **FT0 Cherenkov** detector) were installed.





FT0 physics purpose:

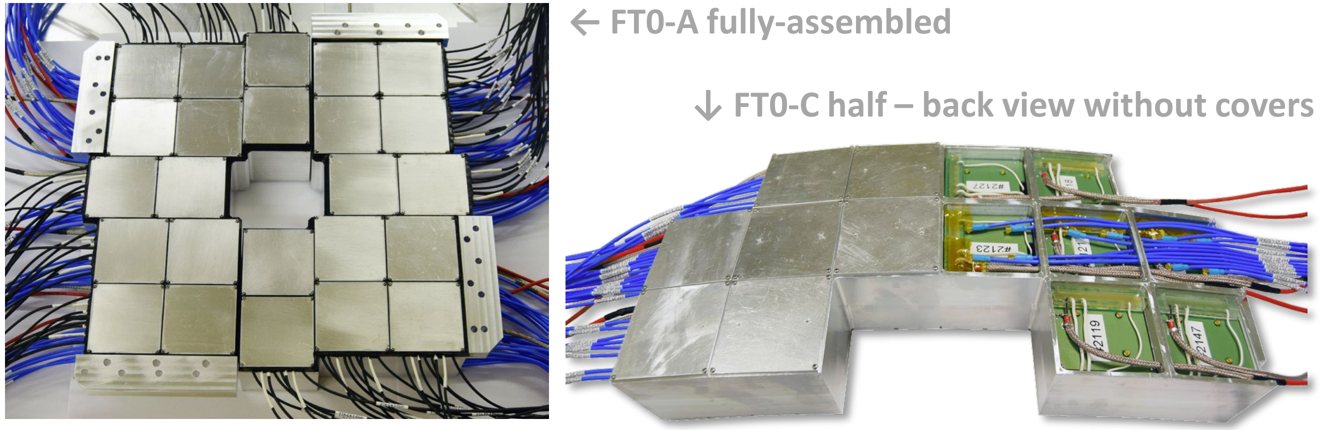
- On-line trigger;
- Precise time-zero detector for TOF;
- Main luminometer & background monitor;
- Centrality & multiplicity measurements.

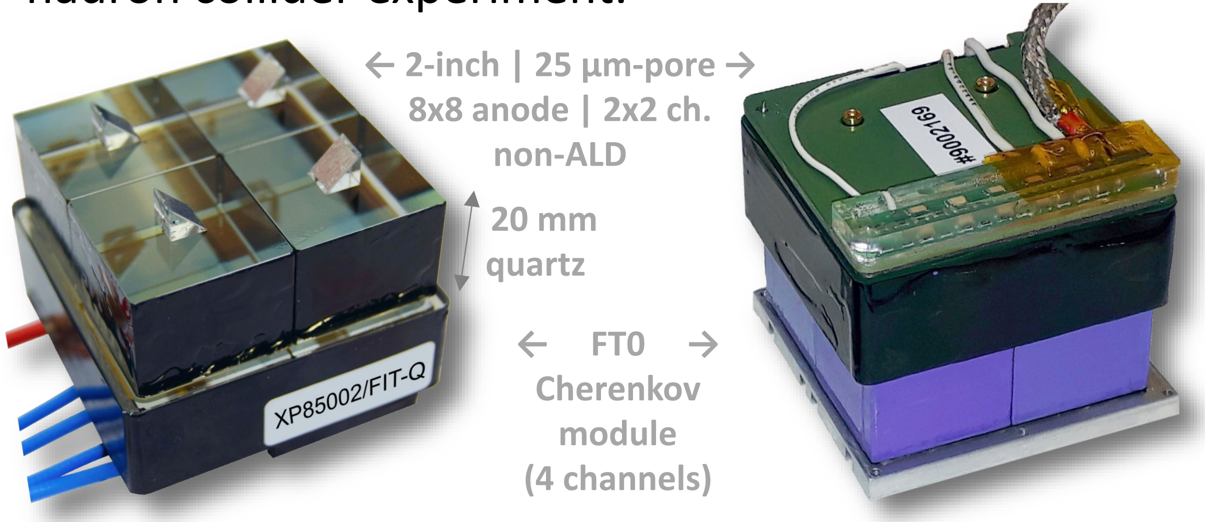
FT0 Cherenkov detector

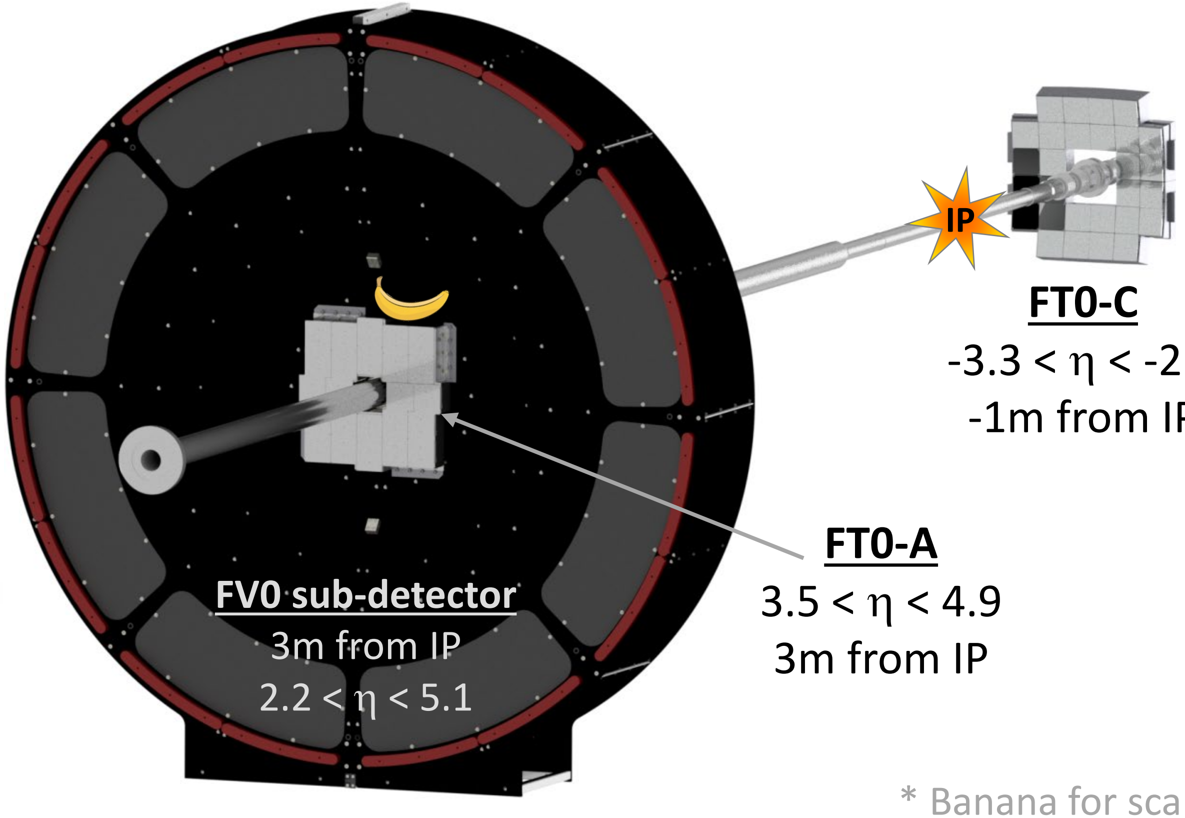
Two arrays of Cherenkov counters: 96 & 112 fused silica radiators coupled to 52 multianode Planacon XP85002/ FIT-Q MCP-PMTs (custom backplane).

Now completing its 4th year in operation:

- First large-scale deployment of the Planacons in HEP;
- First large-scale deployment of MCP-PMTs in a hadron collider experiment.





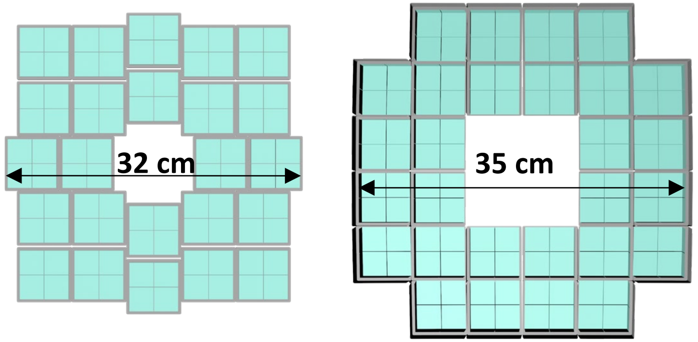


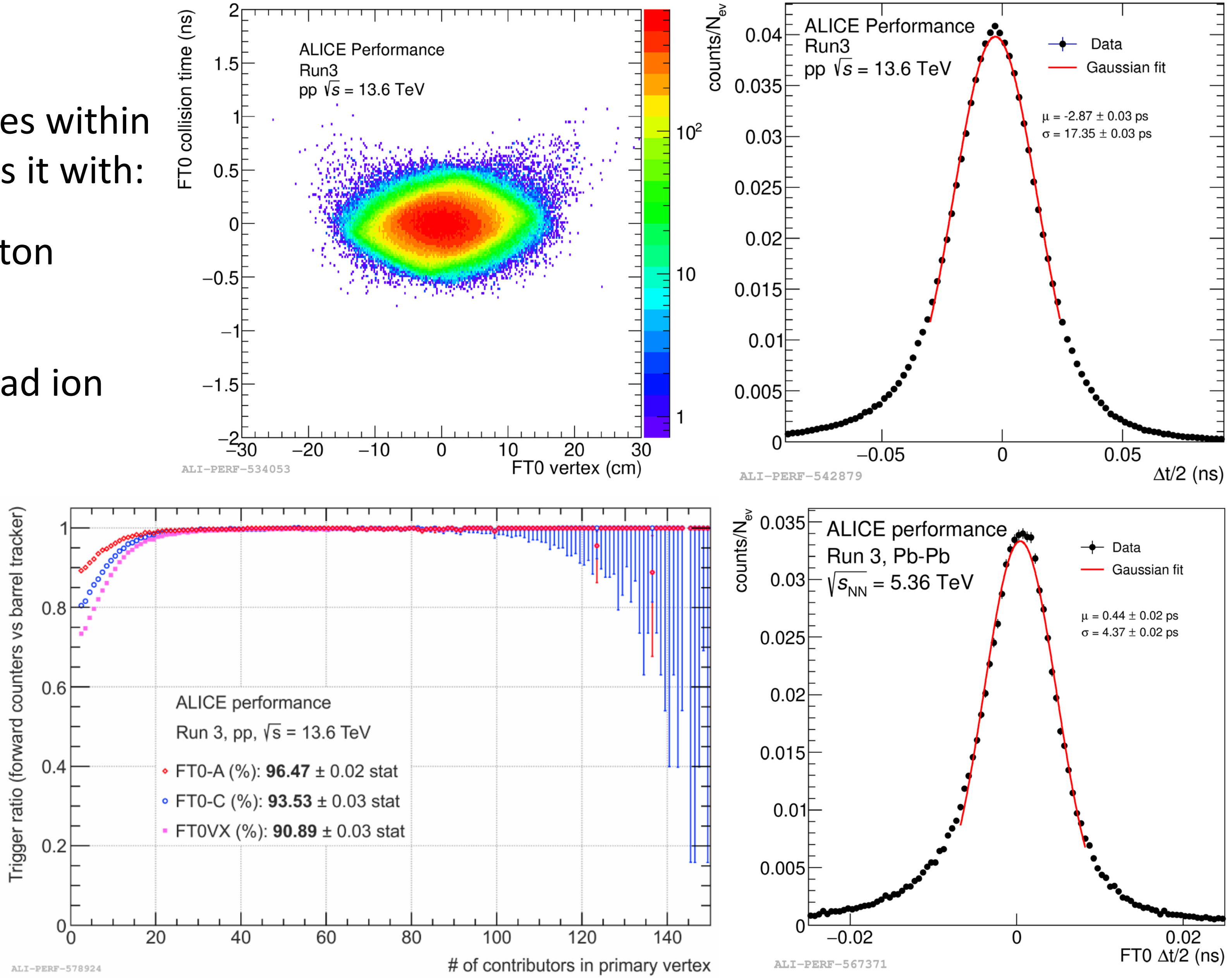
Planacon upgrade for ALICE FIT – NIM A 952 (2020) 161689 (RICH-2018 proceedings)
Bench testing of the ALICE FIT Planacons – JINST 16 (2021) P12032

FT0 detector performance

Collision point of the LHC beams fluctuates within **±10 cm along the beam axis**. FT0 resolves it with:

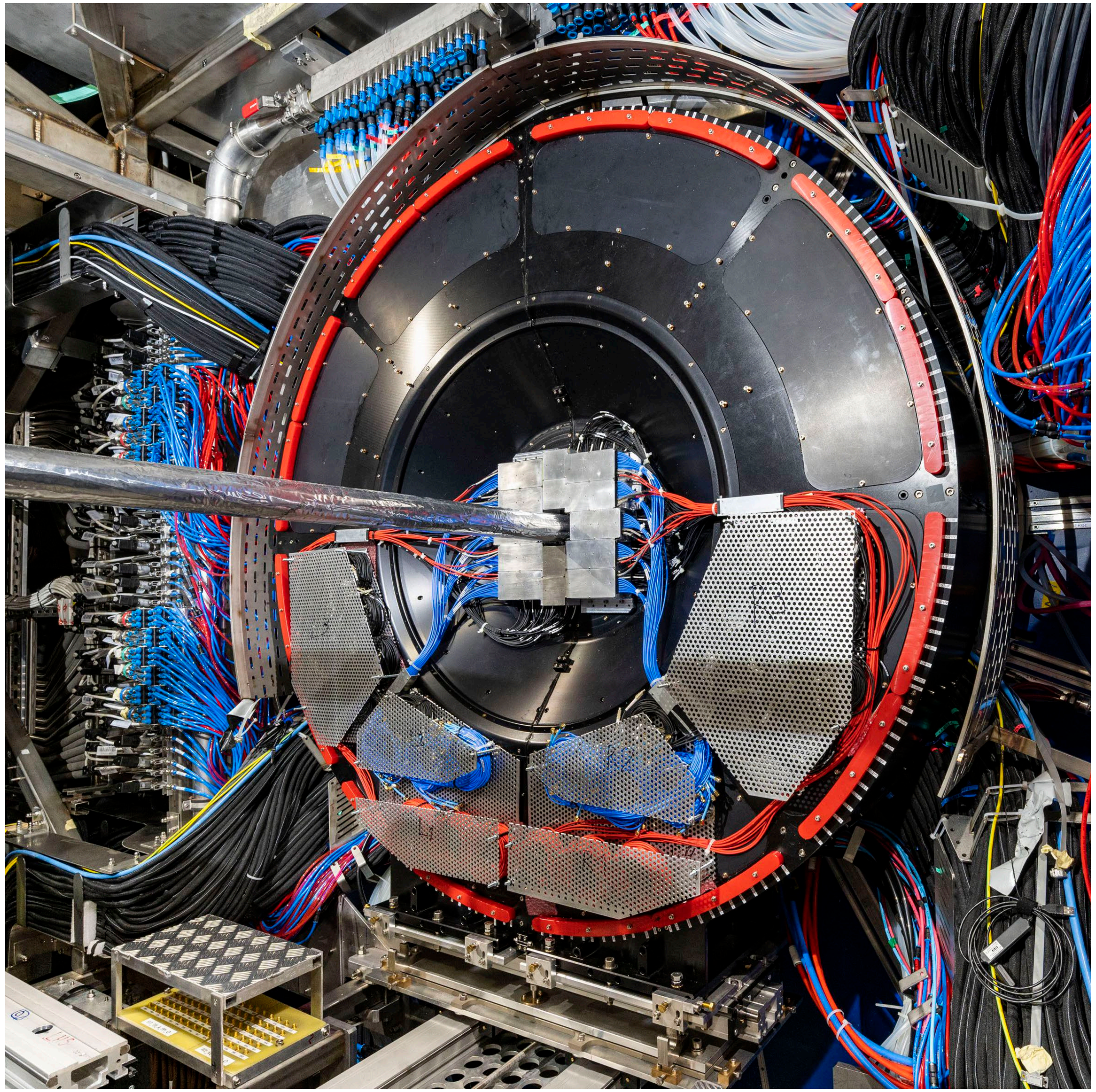
- **σ = 17 ps ≡ ±5.1 mm** – precision in proton collisions (twice worse online);
- **σ = 4.4 ps ≡ ± 1.3 mm** – precision for lead ion collisions (twice worse online);
- FT0 trigger efficiency exceeds **90%** in top-energy pp collisions – limited by the inter-PMT radiator gaps.





FT0 design constraints

- Single-MIP time resolution **≲50 ps** (the lower – the better);
- BC*-per-BC readout capability **(dead time ~15 ns);**

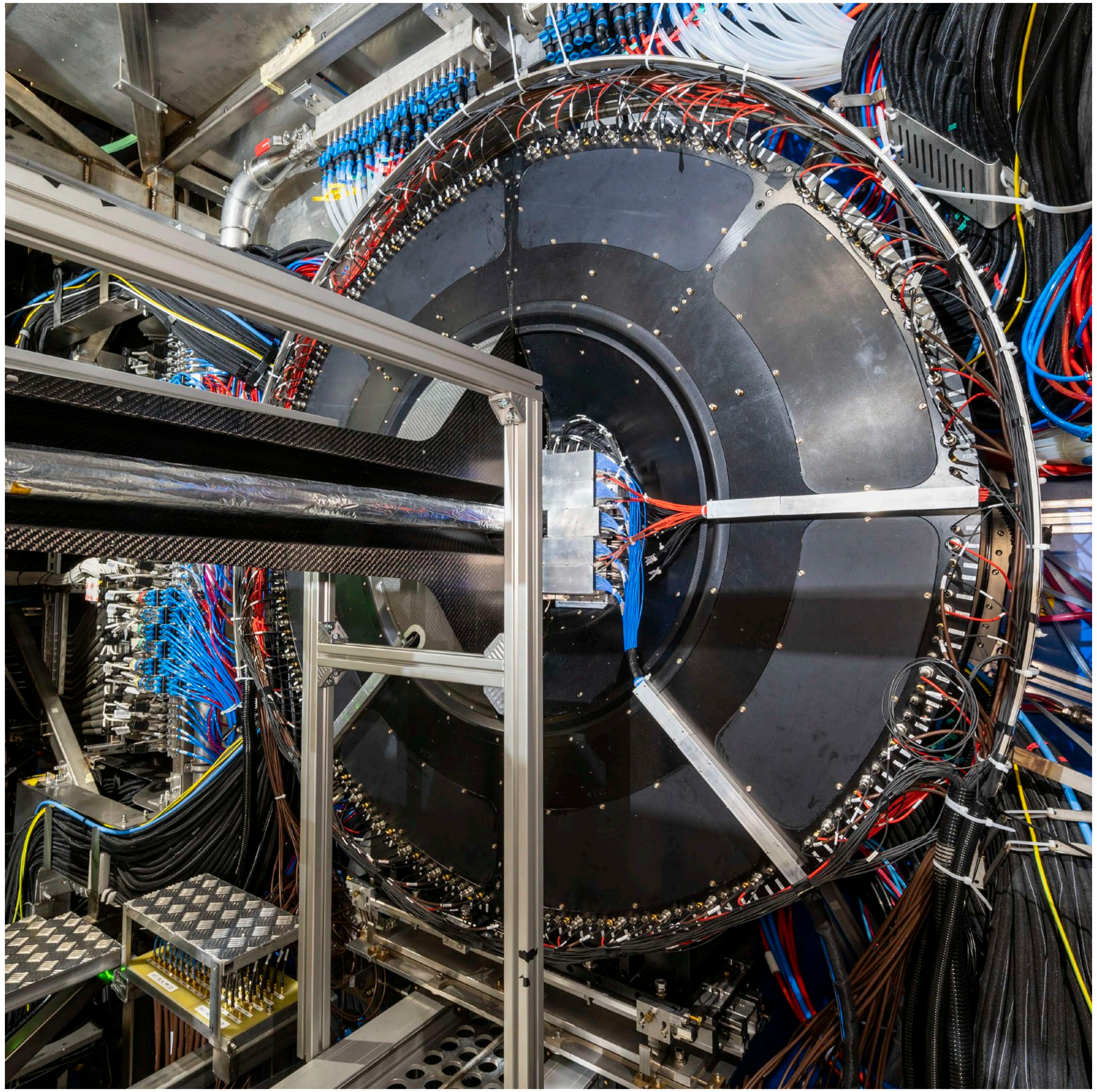


FT0+FV0 just after the installation in the cavern →

*BC – Bunch Crossing interval (25 ns)

FT0 design constraints

- Single-MIP time resolution ≲50 ps (the lower – the better);
- BC*-per-BC readout capability (dead time ~15 ns);
- Harsh radiation conditions:
  - **~3*10^{10} n$_{eqv}$ / cm^{2} / month** (full program ≲ **3*10^{12}**)**;
  - **~4 kRad / month** (full program ≲ **0.5 MRad**);
- Non-axial magnetic field **≤ B = 0.5 T**;



No make-up view of FT0+FV0 (all cables connected) →

**NIEL equivalent converted for 1 MeV neutrons as for silicon detectors

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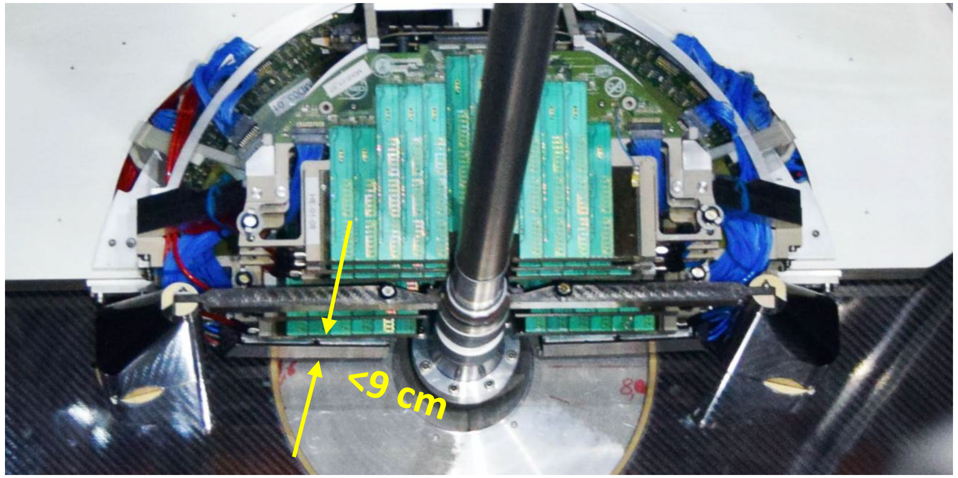
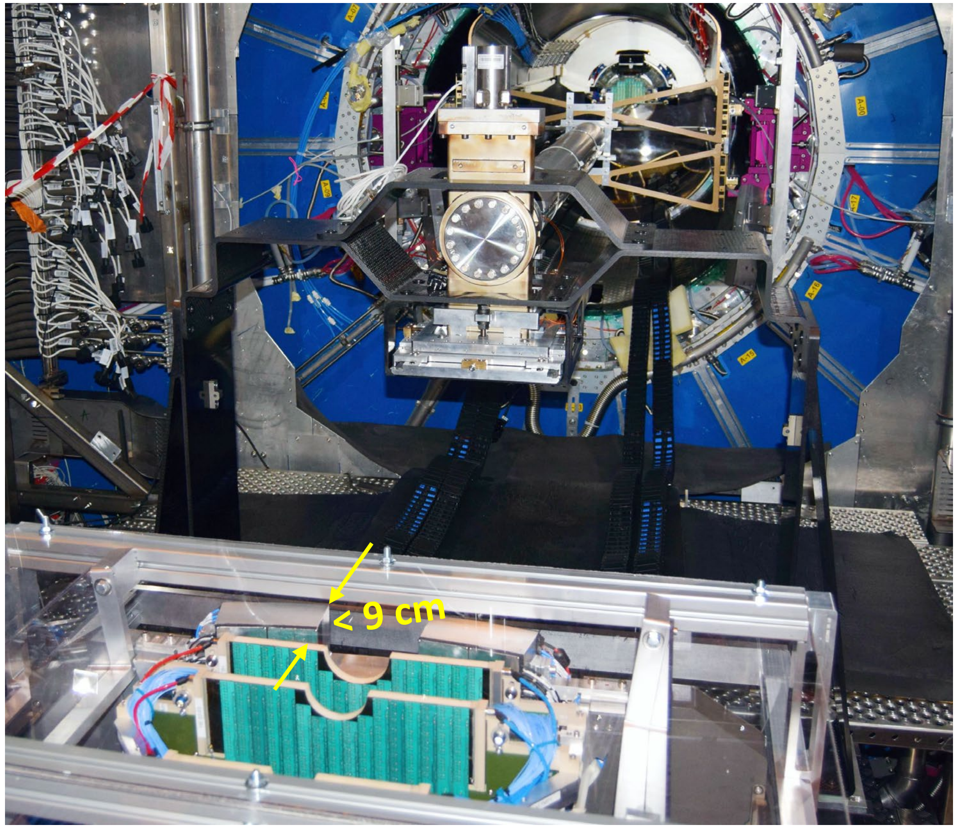
  - **~4 kRad / month** (full program **≲ 0.5 MRad**);
- Non-axial magnetic field **≤ B = 0.5 T;**
- Total thickness of the C-side array **≤ 9 cm.**
- Efficient running at nominal collision rates:
  (0.5 MHz for pp, 30-50 kHz for Pb-Pb) **≤ 10^6 MIPs / cm^2 / s;**

Why we can't use ALD-coated MCP-PMTs





Congested spacing of FT0-C →

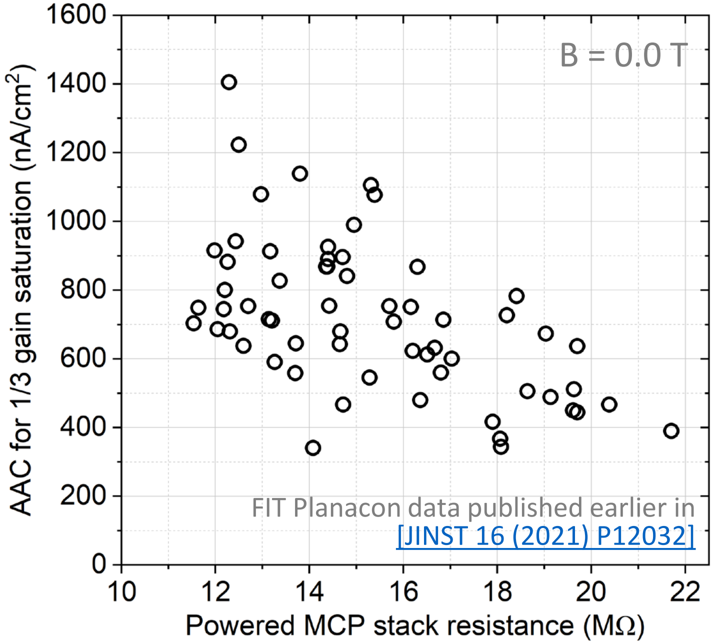
*BC – Bunch Crossing interval (25 ns)
**NIEL equivalent converted for 1 MeV neutrons as for silicon detectors

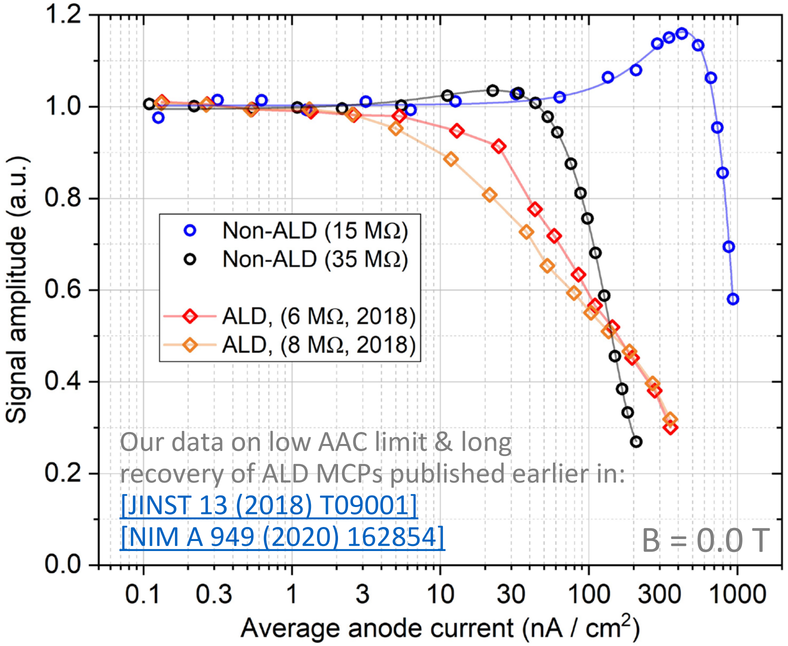
Average anode current saturation

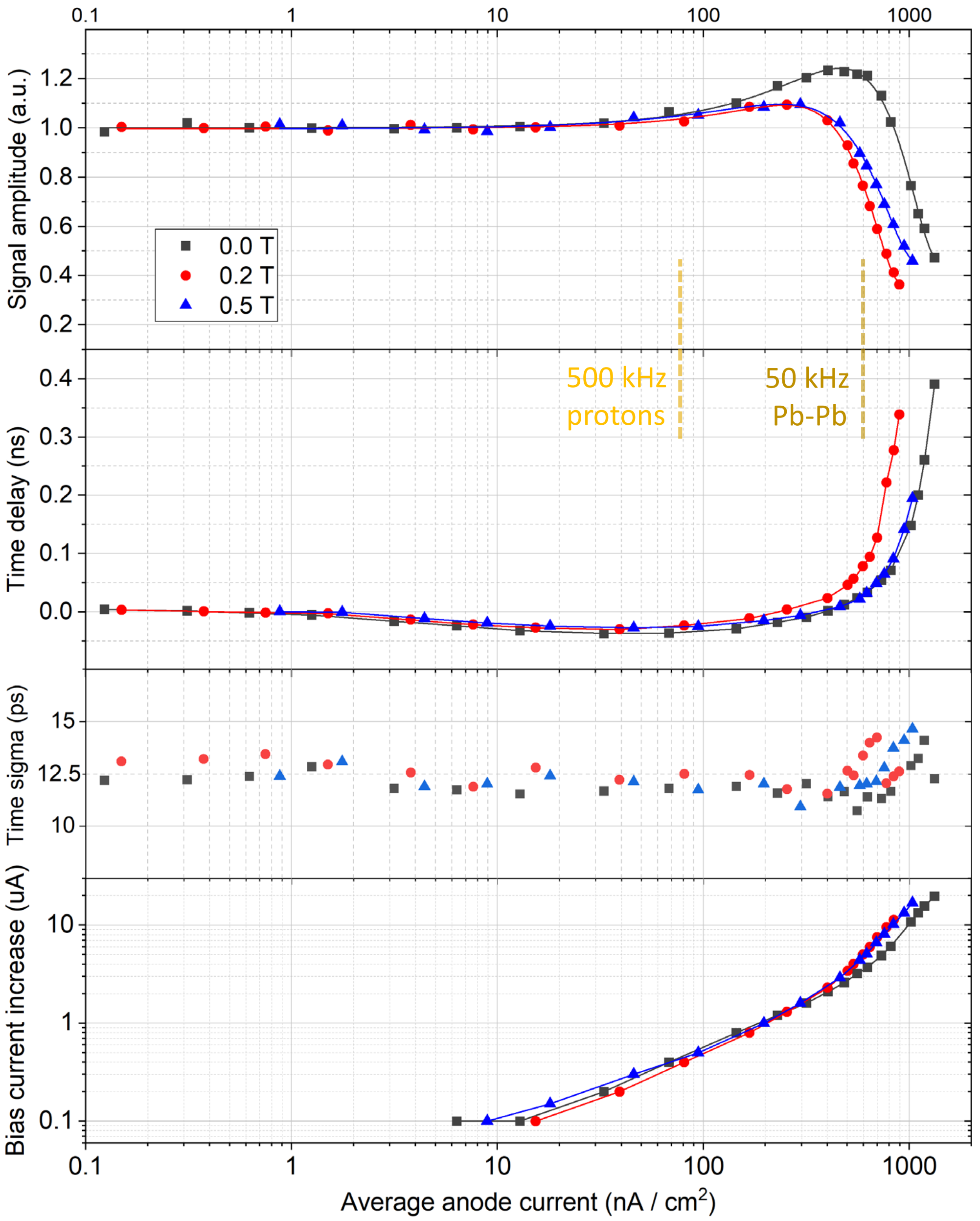
- Rate capability is naturally limited by the MCP RC:
  - **~100 nA/cm²** for standard non-ALD Planacons;
  - **~800 nA/cm²** for the low-resistance non-ALD Planacons;

  (↑ gets further suppressed in 0.5 T B-field ↑)
  - **~50 nA/cm²** for the low-resistance ALD Planacons (in 2018).

Innermost FIT Planacons see **~3x10⁸ p.e. / cm² / s ≈ 600 nA/cm².**

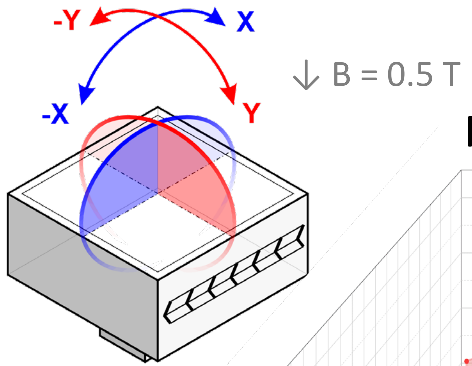




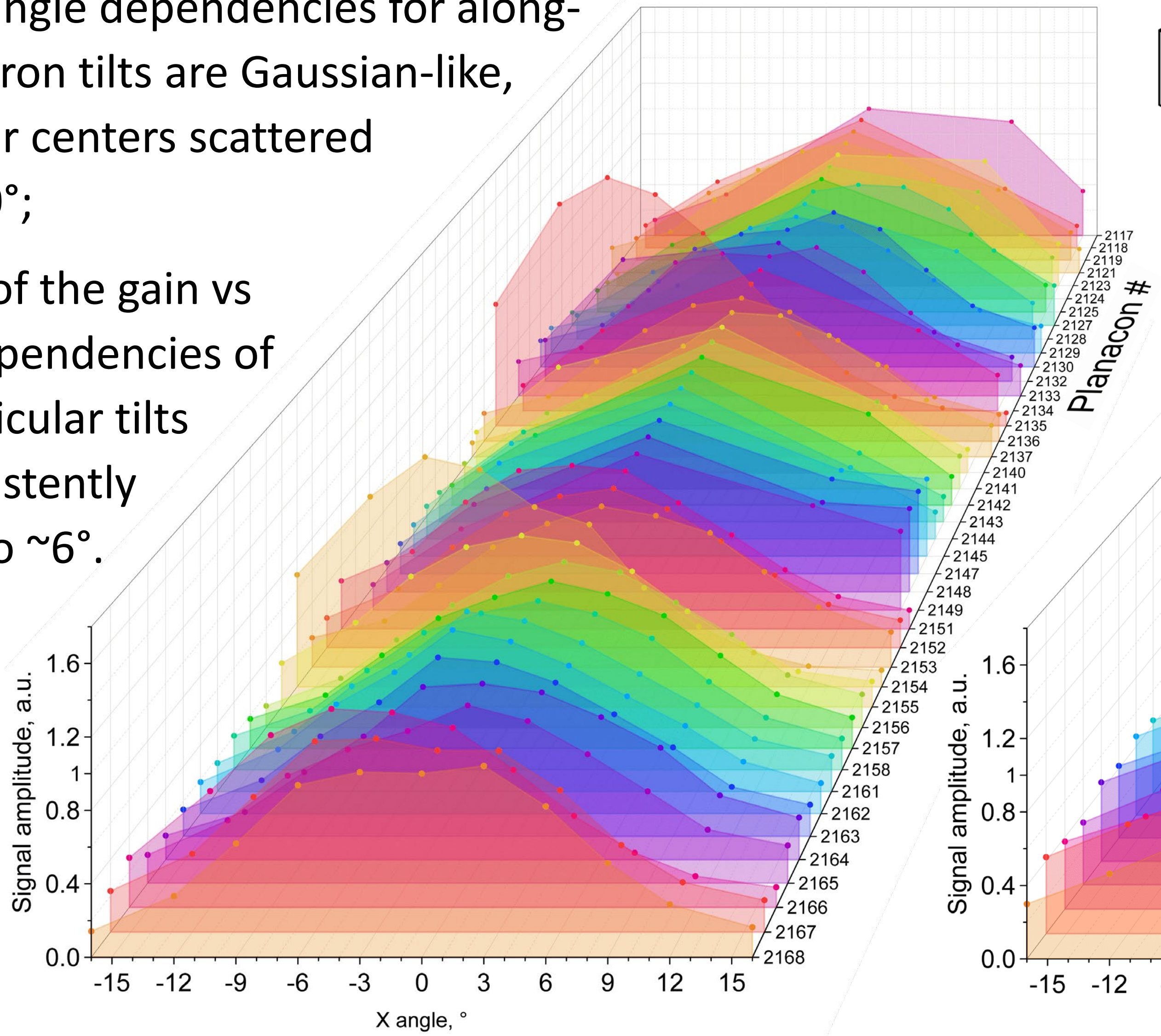


Effect of non-axial B-field

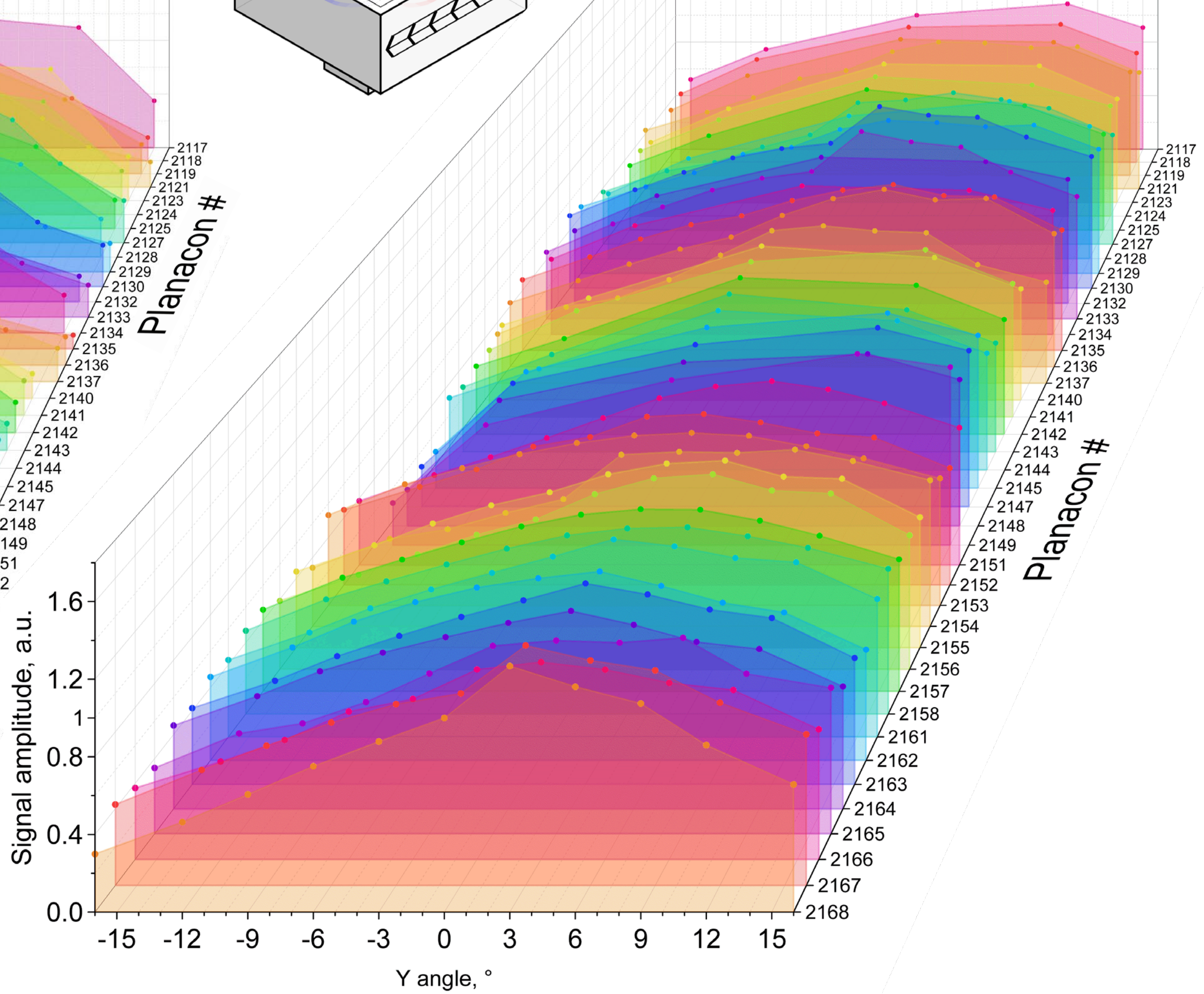
- Gain vs angle dependencies for along-the-chevron tilts are Gaussian-like, with their centers scattered around 0°;
- Centers of the gain vs angle dependencies of perpendicular tilts are consistently shifted to ~6°.



Along the chevron:

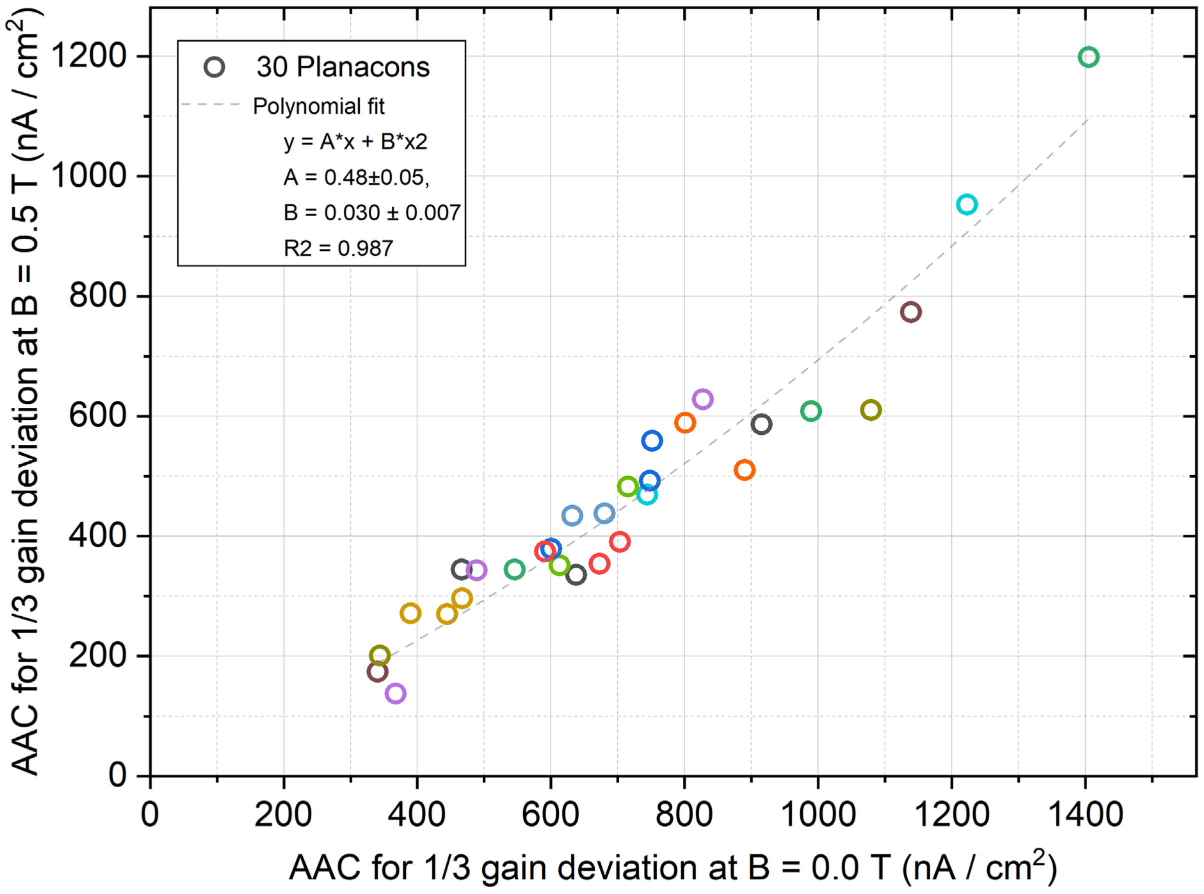


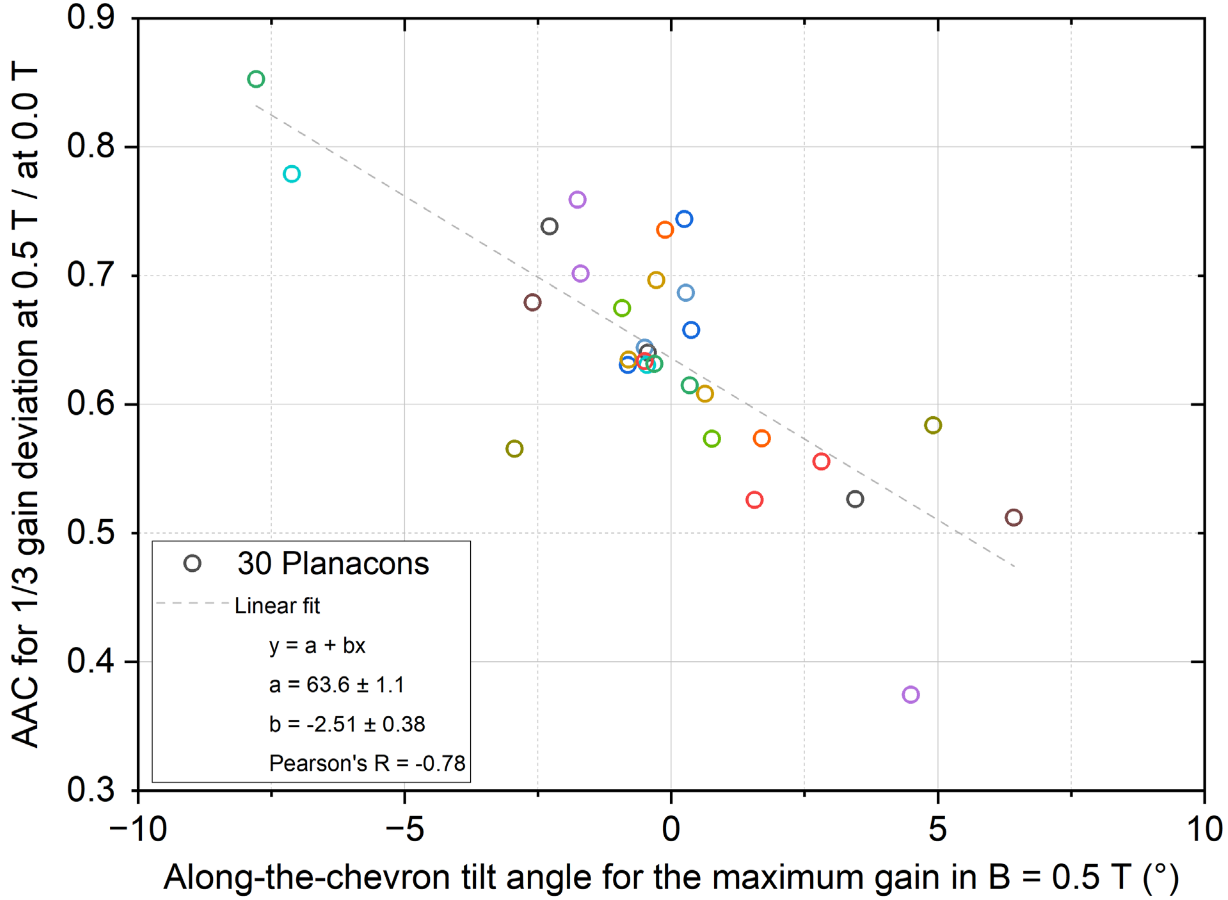
Perpendicular to chevron:



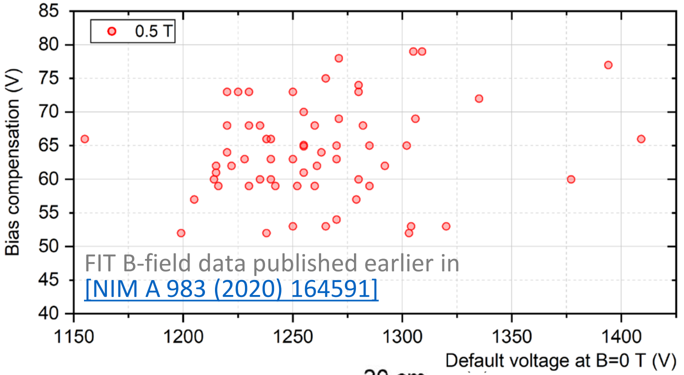
AAC limit in B-field

- In B = 0.5 T AAC limit reduce to **0.4 … 0.9** of its value outside the magnetic field.
- The reduction factor somehow looks correlated with the along-the-chevron tilt angle for maximum gain.

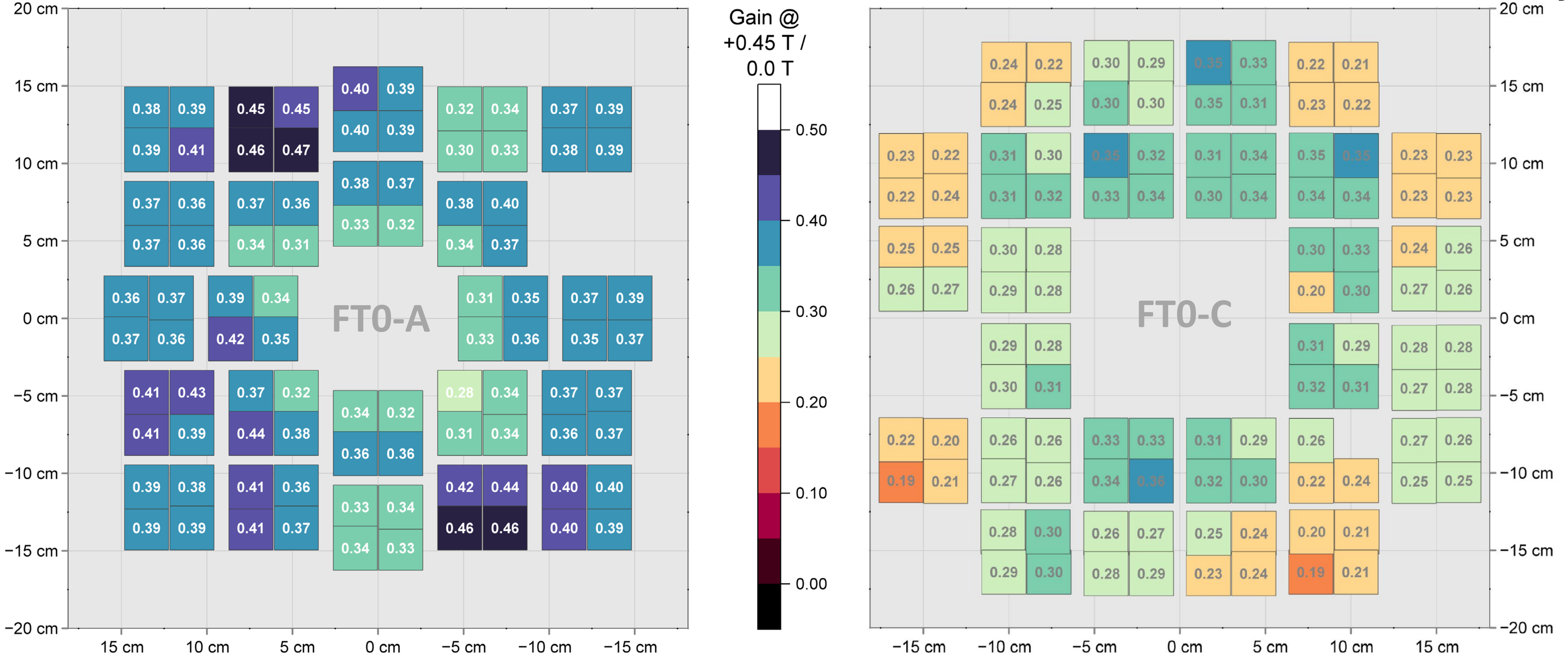




B-field effect on the detector



- 0.45 T B-field reduce gain x3 for the (flat) A-side, x5-x3 – for the (concave) C-side;
- Easily compensated by + ~60 V; still average V_{bias} < 1.4 kV (<< V_{max} = 2.0 kV).

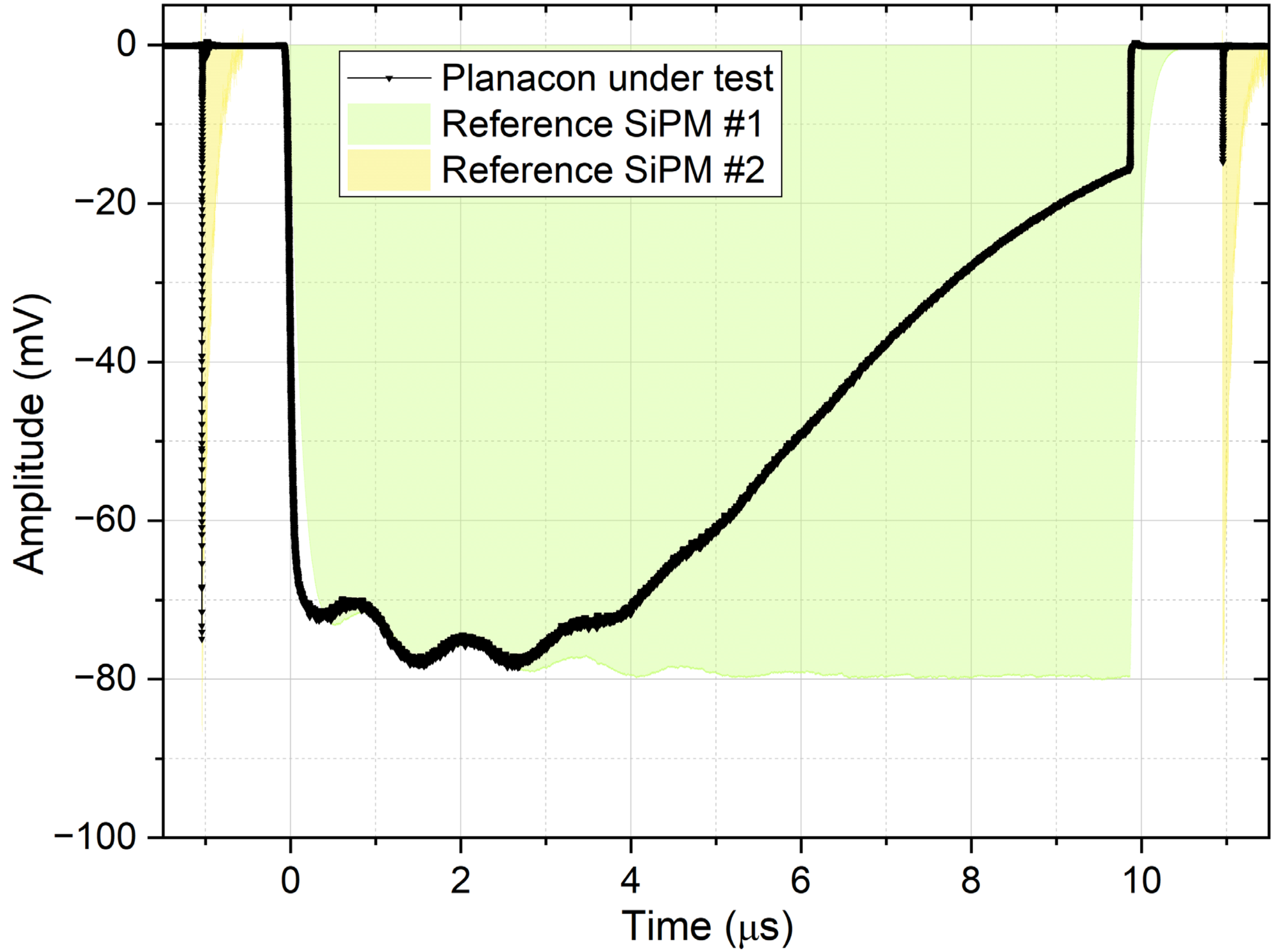


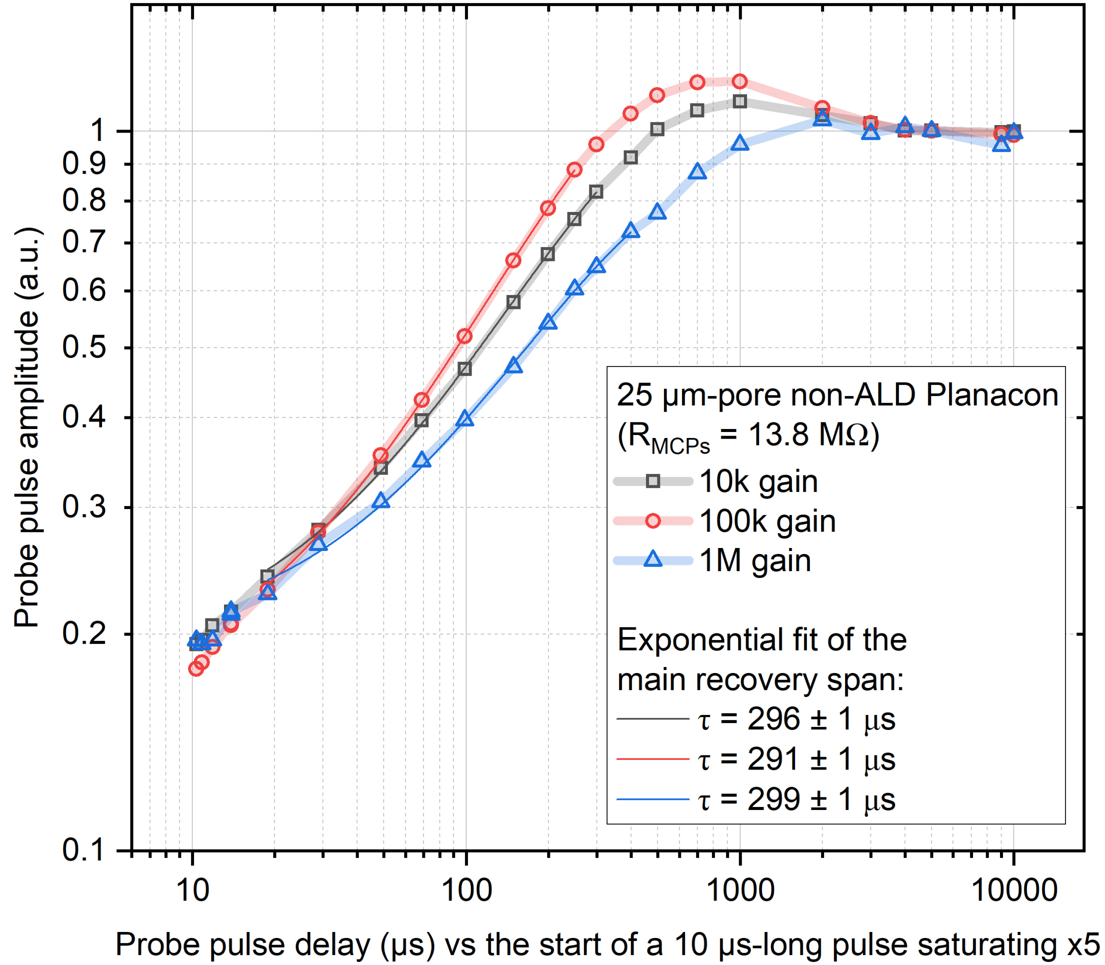
Characteristic MCP recovery time

Shape of the recovery curve is gain-dependent, but the typical τ = 300 μs (with $R_{MCP\ stack}$ = 14 MΩ).

Saturation is reached once 10 nC (~$1.7*10^4$ MIPs) is detected within a time period notably shorter than that.

Illustration of the measurement technique and saturation conditions:





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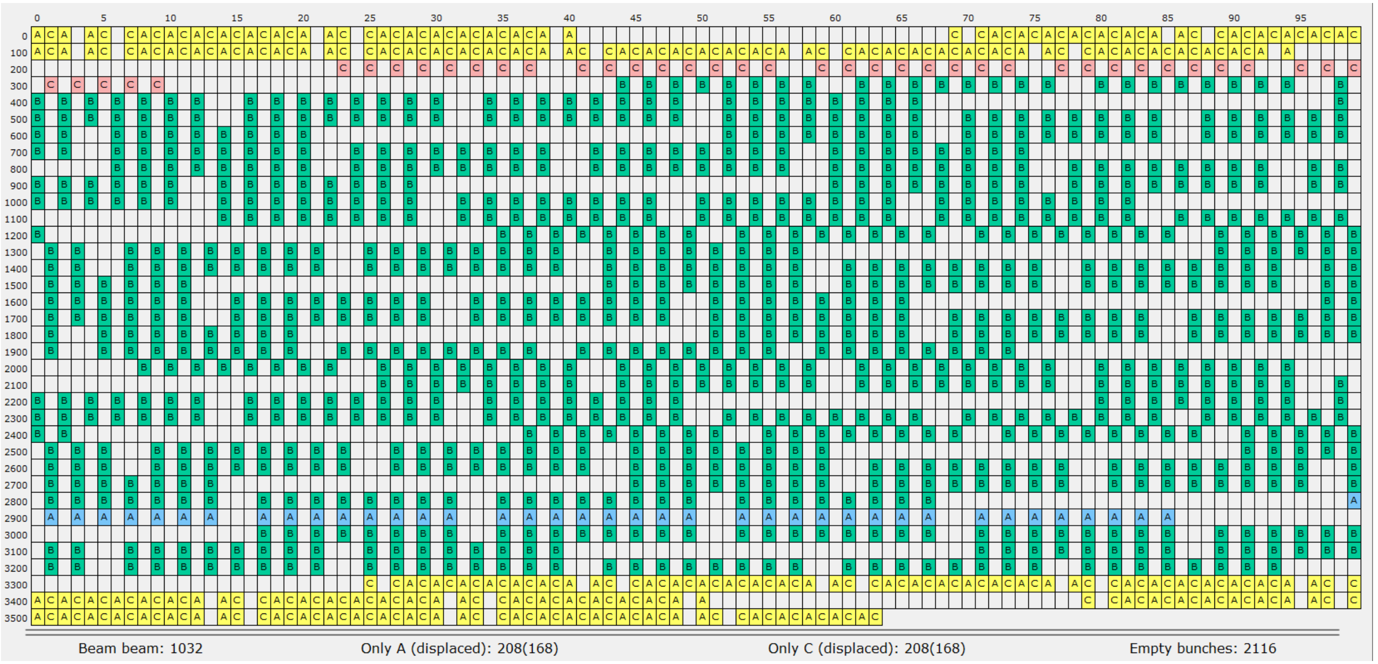
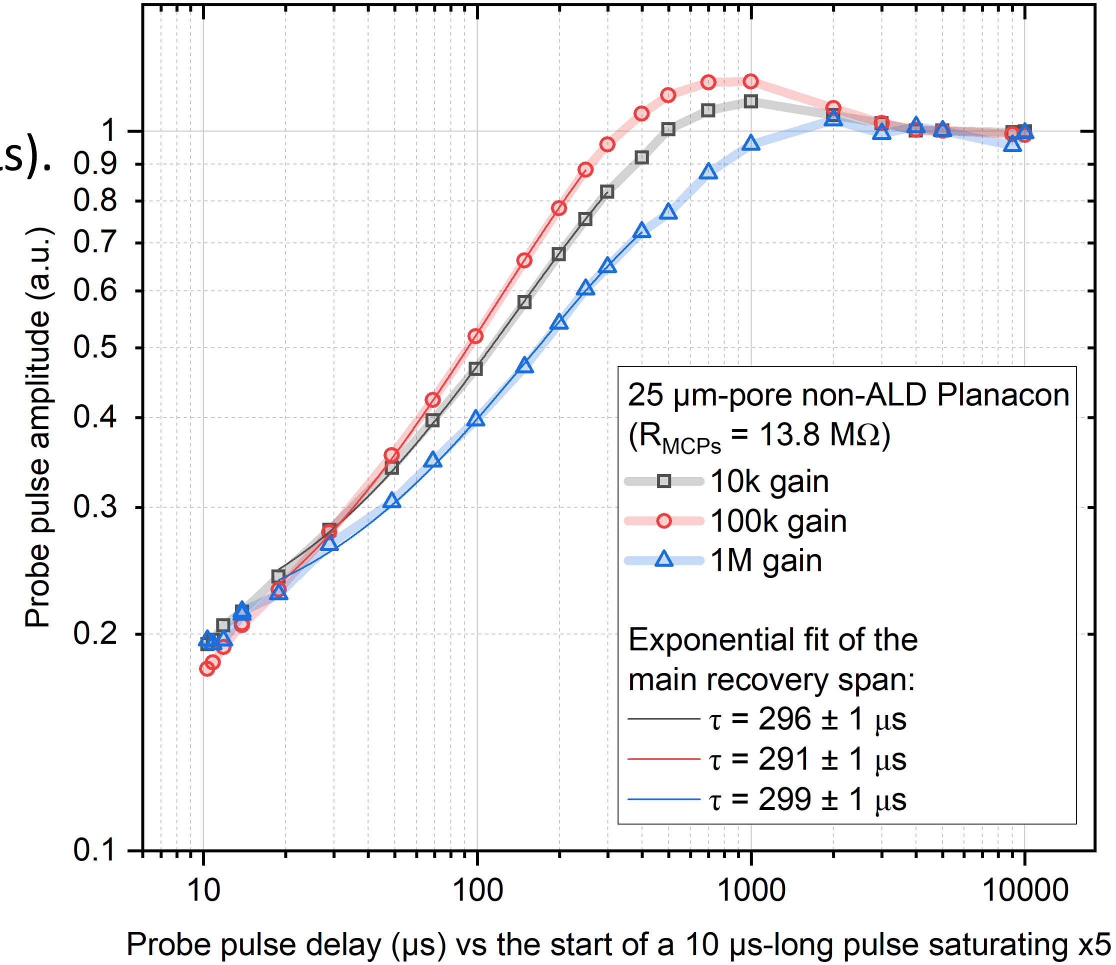
Load from the LHC collisions is distributed ~uniformly:

- typical period < 2 µs in pp and <30 µs in Pb-Pb.
- longest gap – 140 BC in pp (= 3.5 µs), 600 BC in Pb-Pb (=15 µs).

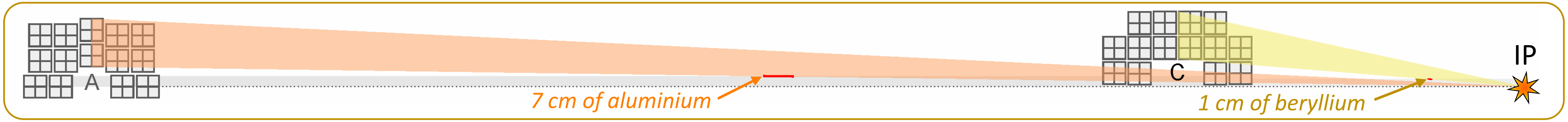


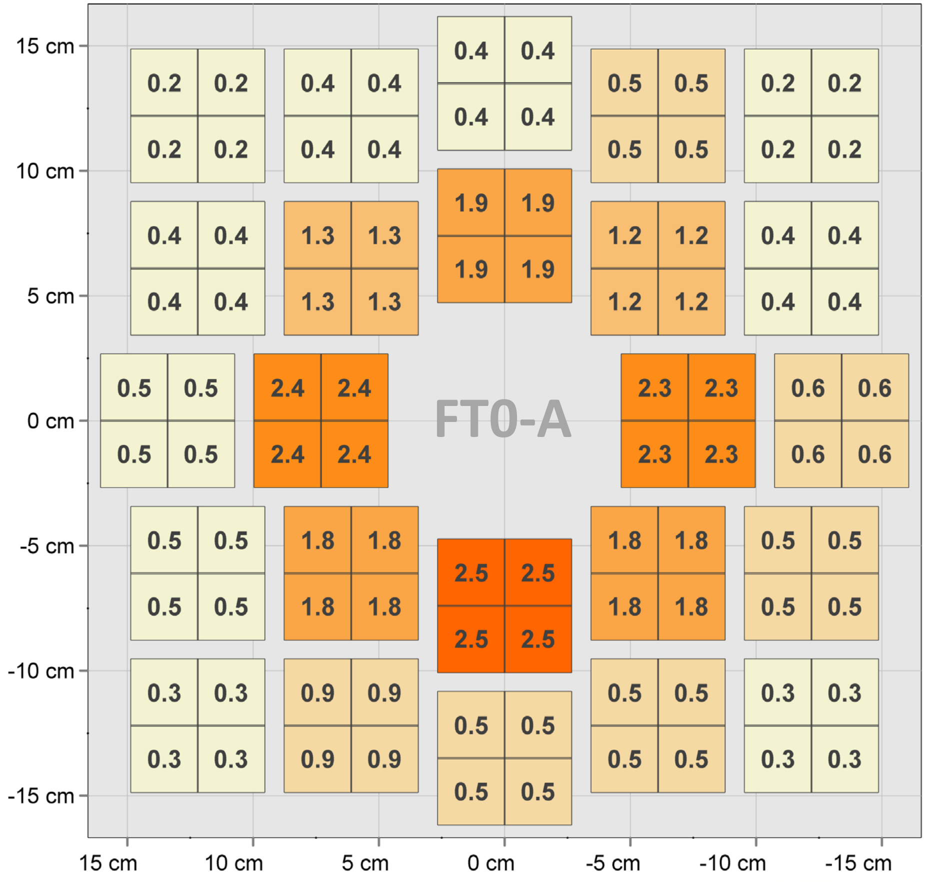
Visualization of a fully-packed LHC orbit. **Green cells = colliding BCs.**
Number of cells = 3600 (27 km / 25 ns at the speed of light).

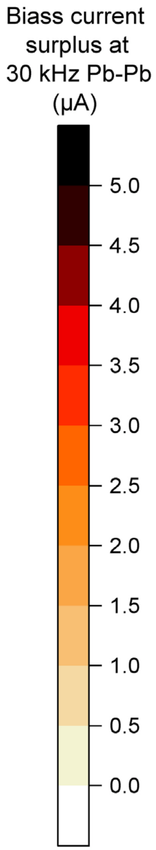


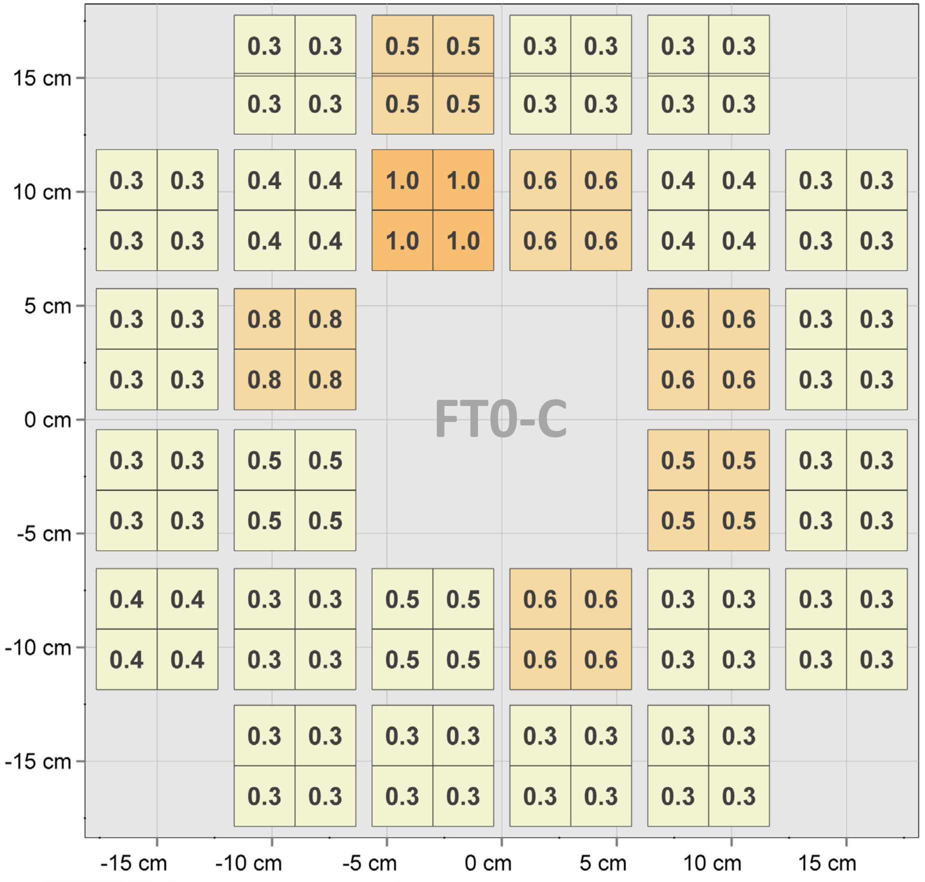
AAC saturation effect on the FT0 performance

Innermost FT0-A load is ~x6 of that for FT0-C (different pseudorapidity and material budget):



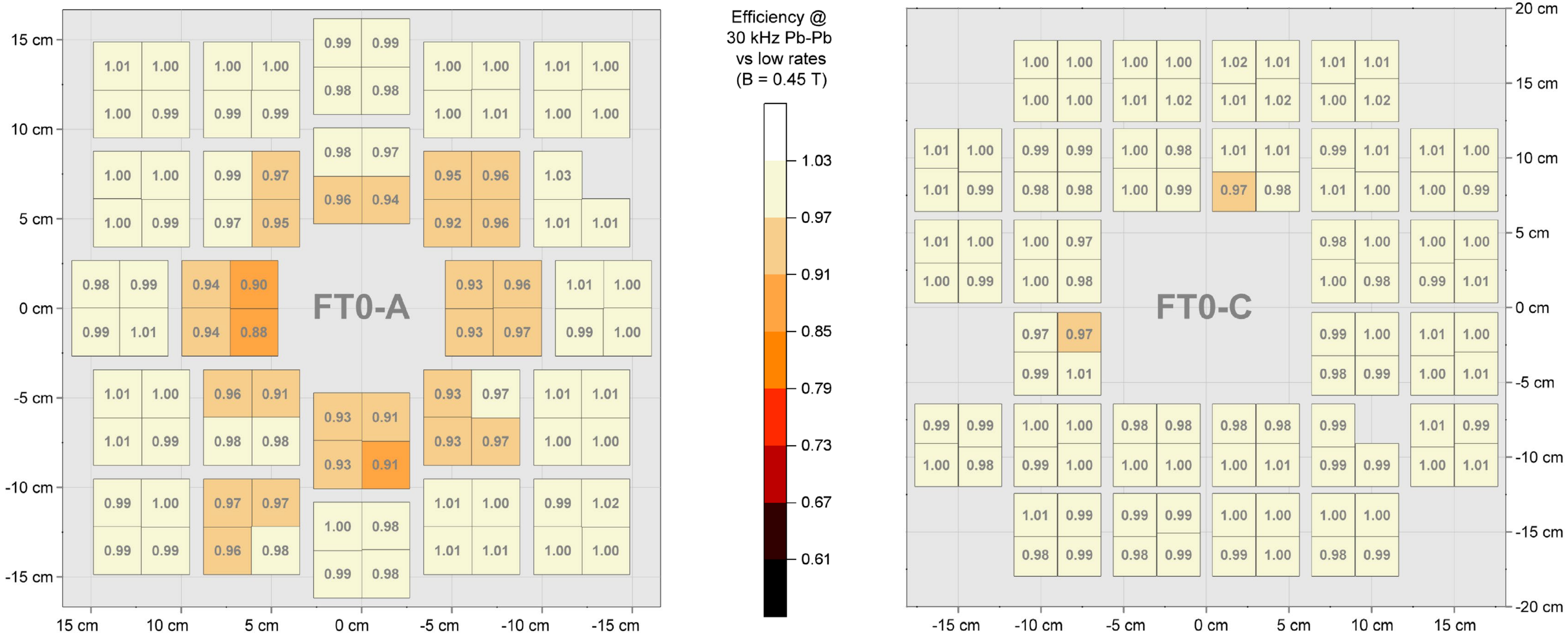






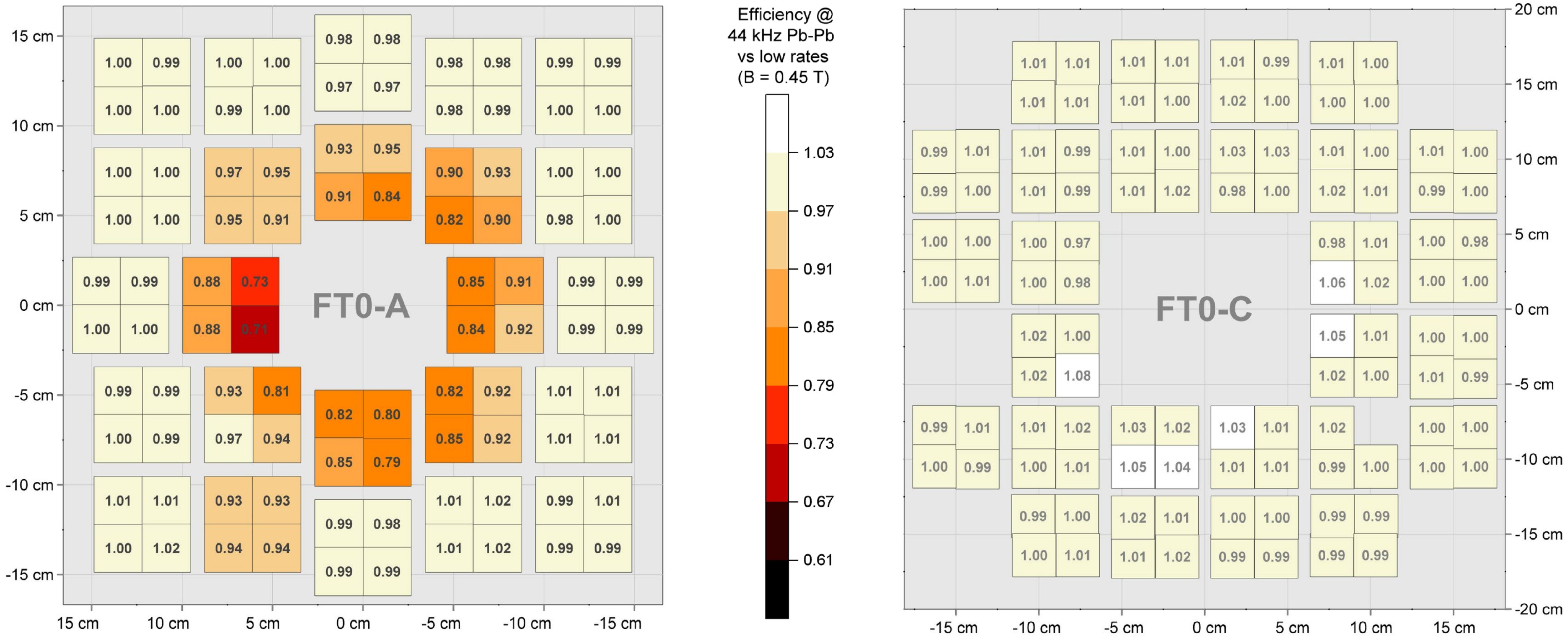
AAC saturation effect on the FT0 performance

- So far LHC can run without a visible beam burnout at Pb-Pb rates ≤30 kHz;
- 30 kHz is also the preferred rate by ALICE to maximize the data taking efficiency;
- Good stability of the FT0 Planacons' response seen.



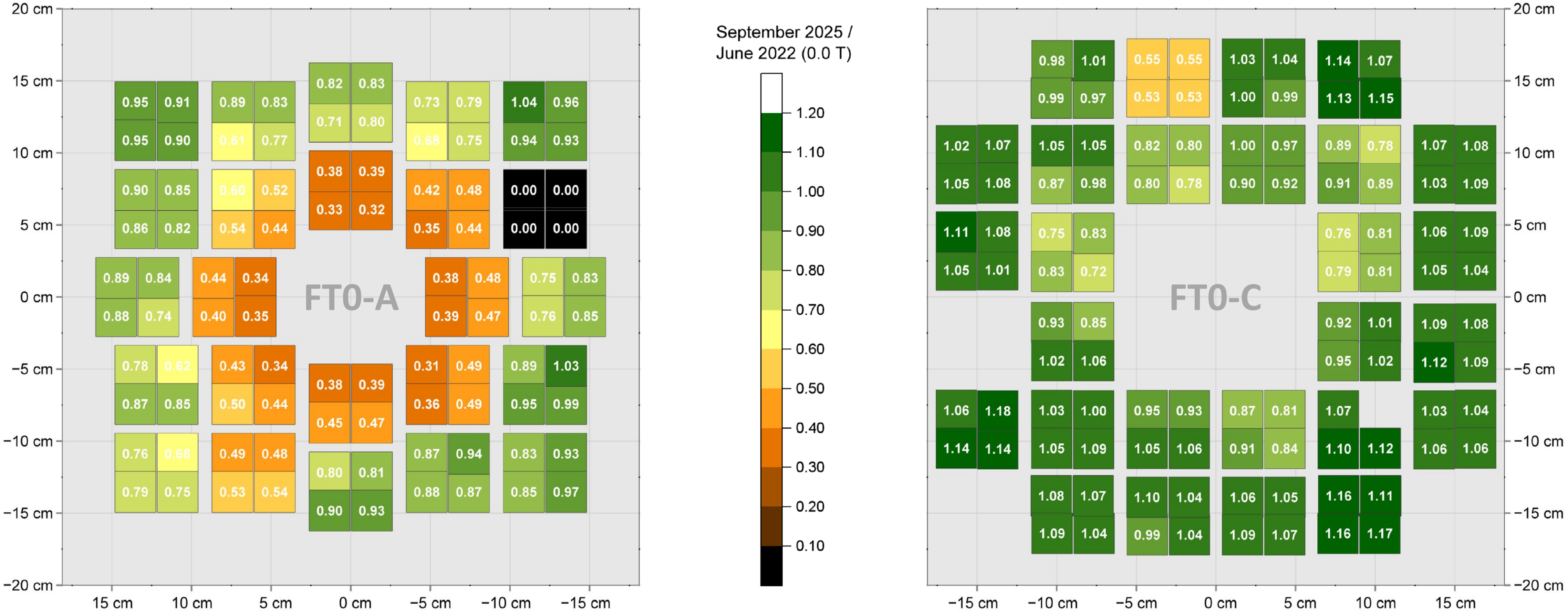
AAC saturation effect on the FT0 performance (worst case)

- Stable response at highest rates, except the inner FT0-A ring (treated separately in the Pb-Pb data processing).
- AAC saturation is correlated with an increased bias current consumption – can be corrected offline.



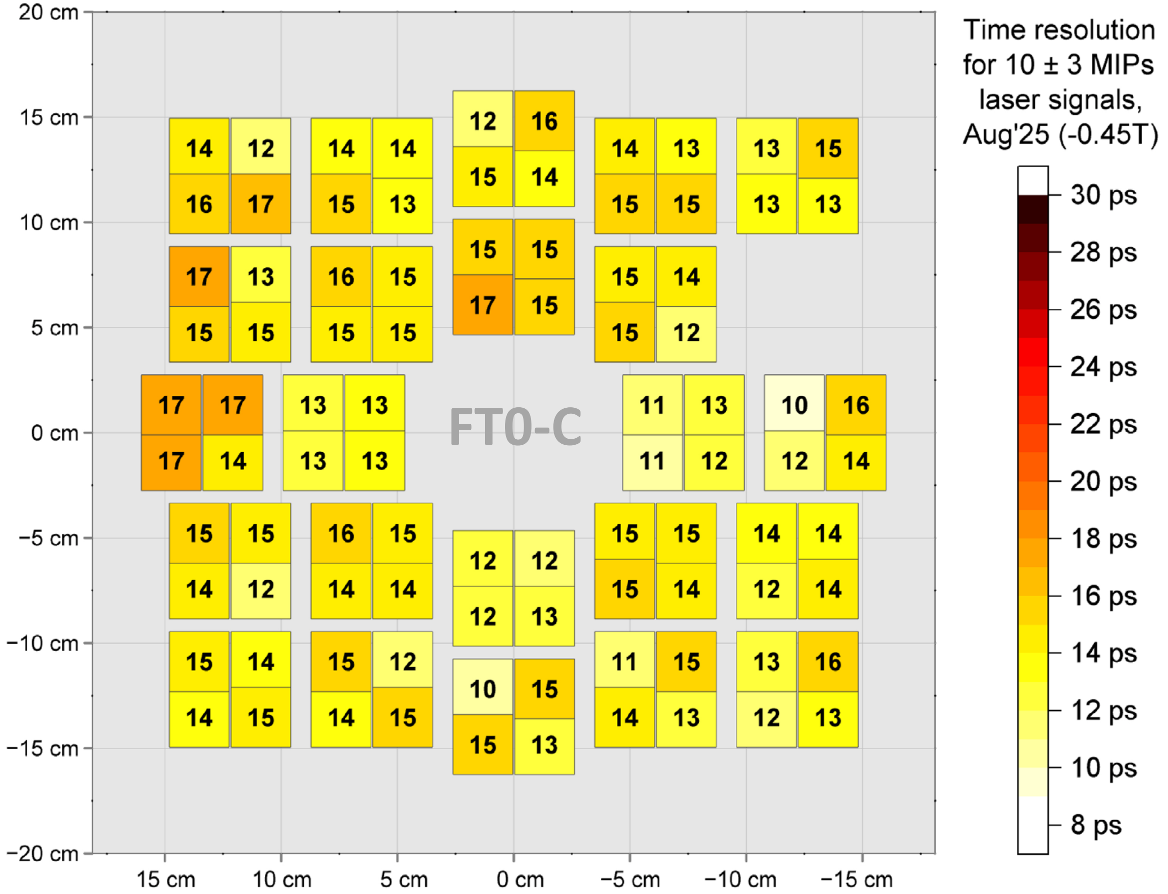
Ageing of the non-ALD Planacons

- By September 2025, response of the inner FT0-A ring dropped by **~2/3** – compensated with HV increase;
- **< 100 V used, ~400 V of margin left** – profit of the high yield / low gain strategy (~15 k gain @ ~1.3 kV typ.).



Ageing of the non-ALD Planacons

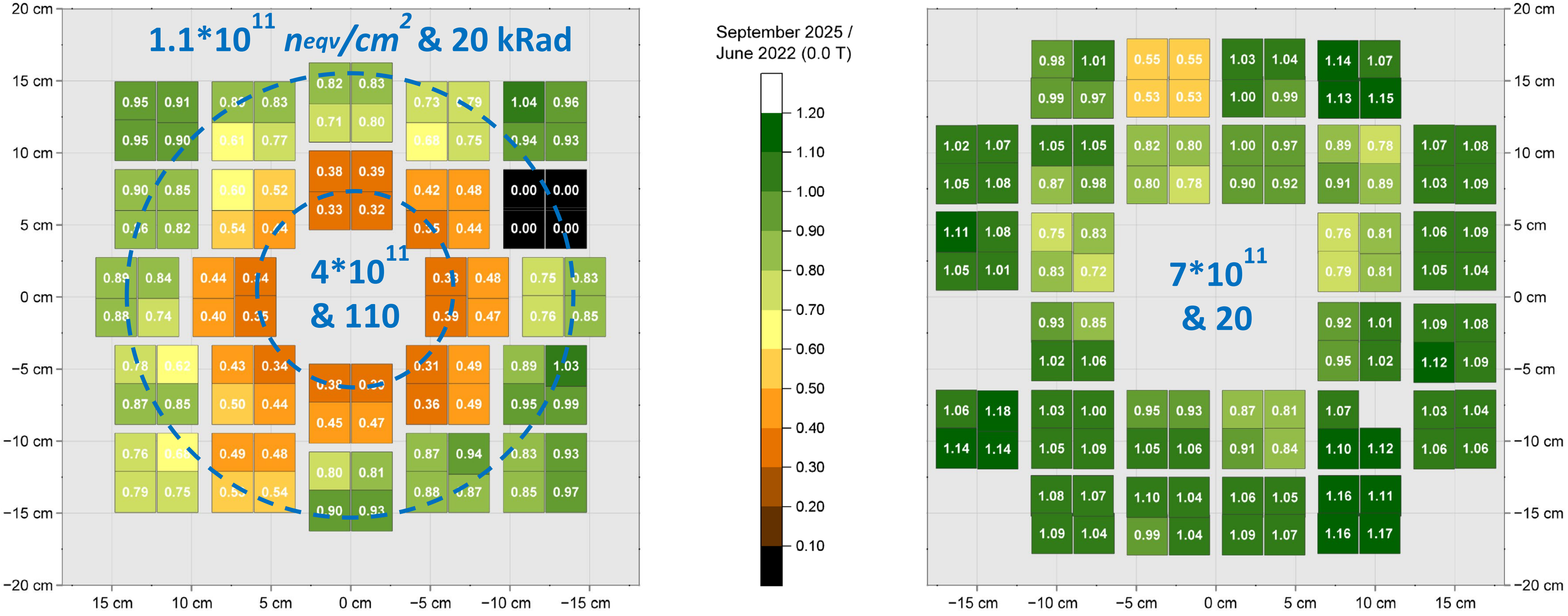
No visible deterioration of the (excellent) time resolution – **no real side effects of ageing seen so far.**



Ageing of the non-ALD Planacons

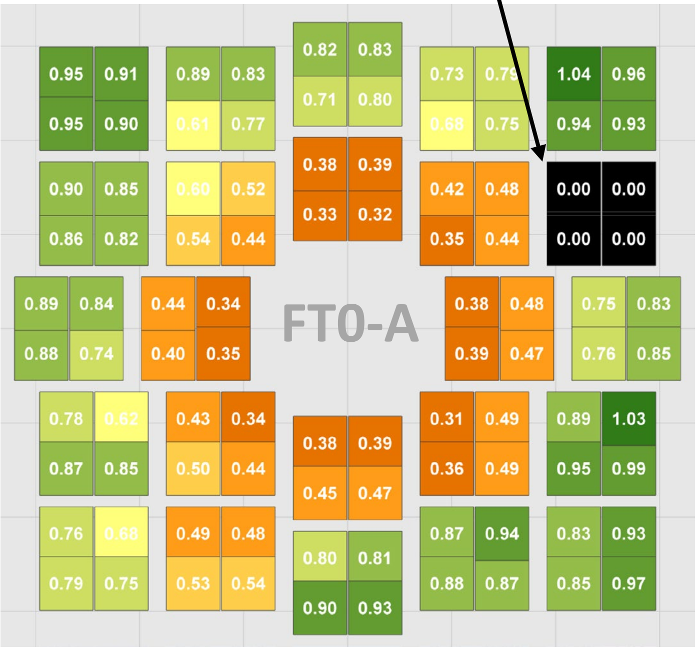
MCP-PMTs are (deservedly) considered rad-hard photosensors: FIT Planacons have been exposed to **>100 kRad and ~7*10^{11} *1-MeV-n$_{eqv}$/cm^{2}*** *without any clear correlation to ageing nor other effects.*

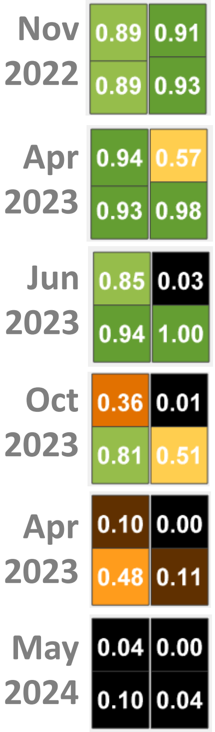
Radiation conditions indicated in blue: NIEL (equivalent for silicon, 1-MeV-n$_{eqv}$/cm^{2}) & TID (kRad):

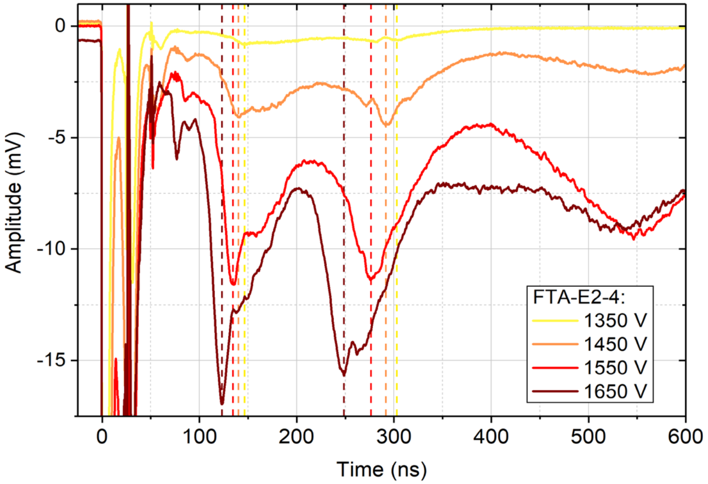


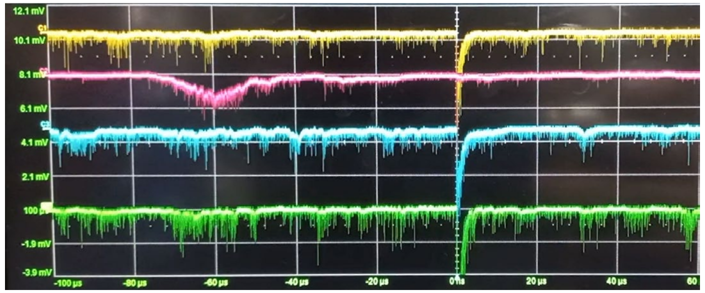
The blind spots

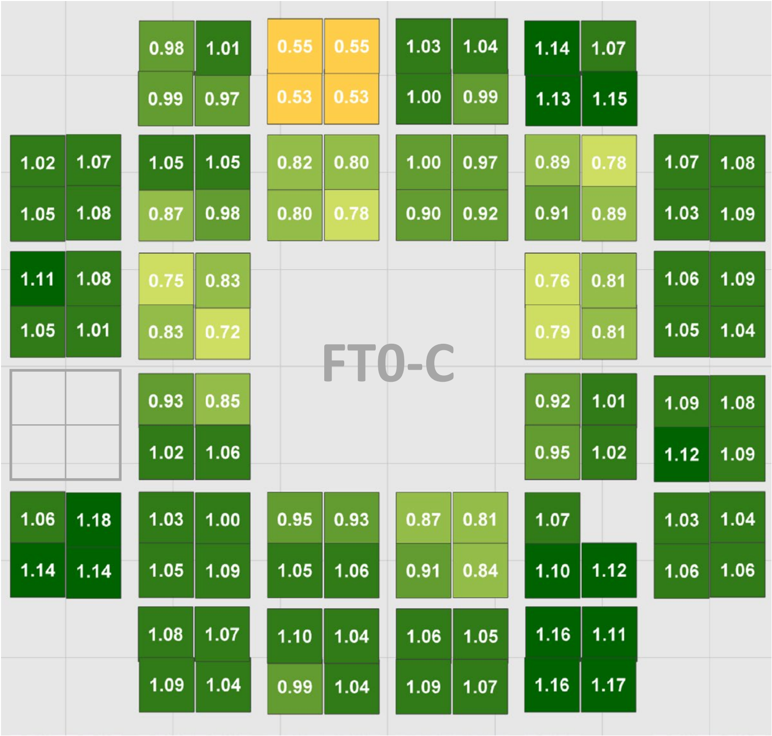
- The only blind PMT suffered from a proven **vacuum microleak.**





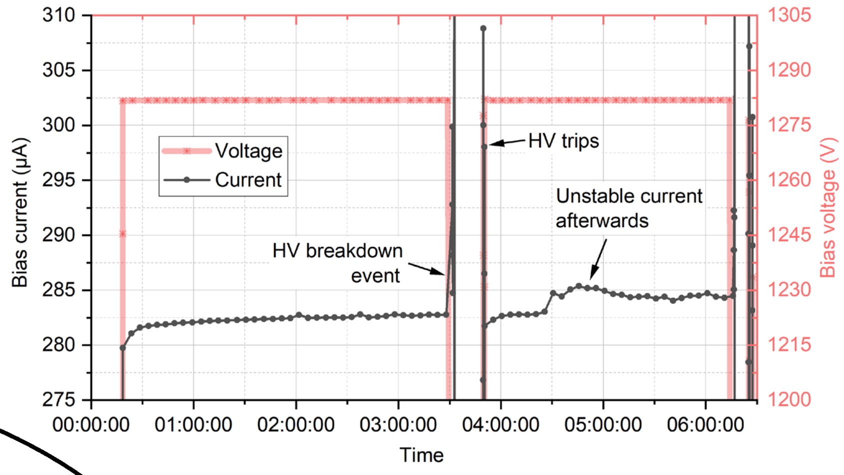


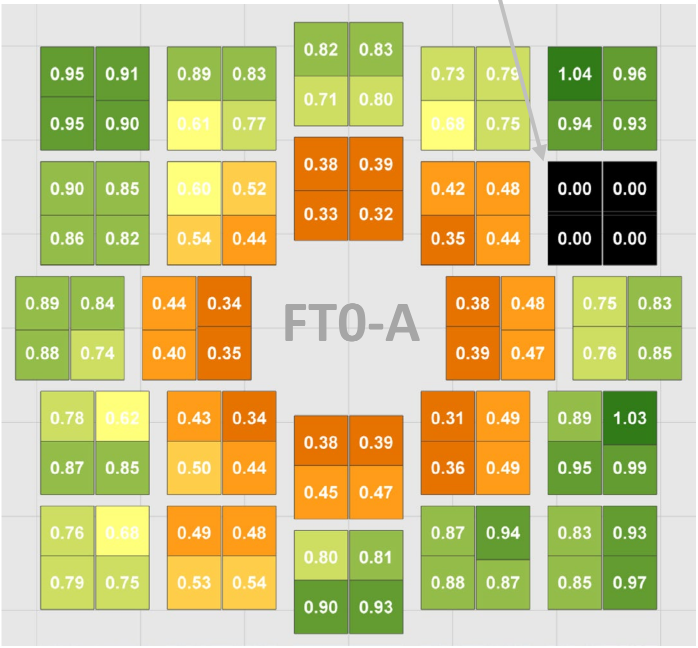


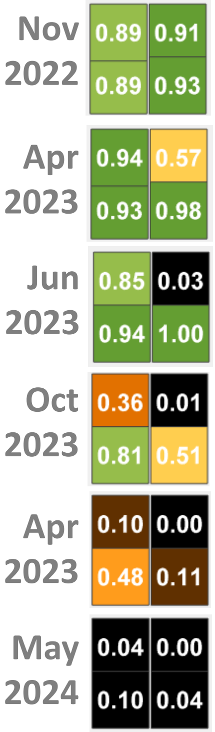


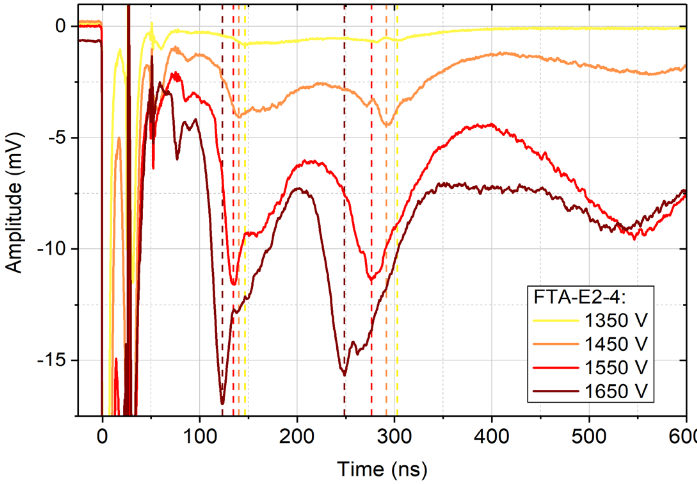
The blind spots

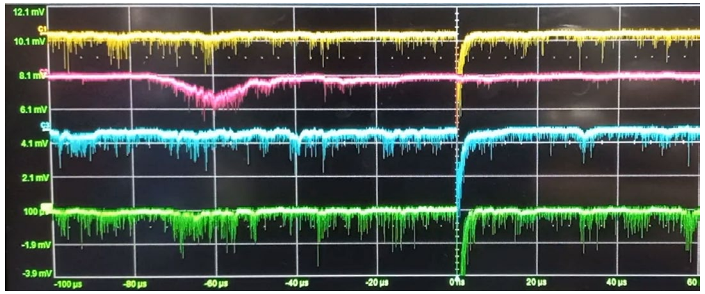
- The only blind PMT suffered from a proven **vacuum microleak.**
- HV breakdowns across the MCP:
  four cases over four years – three repairable, one ultimate

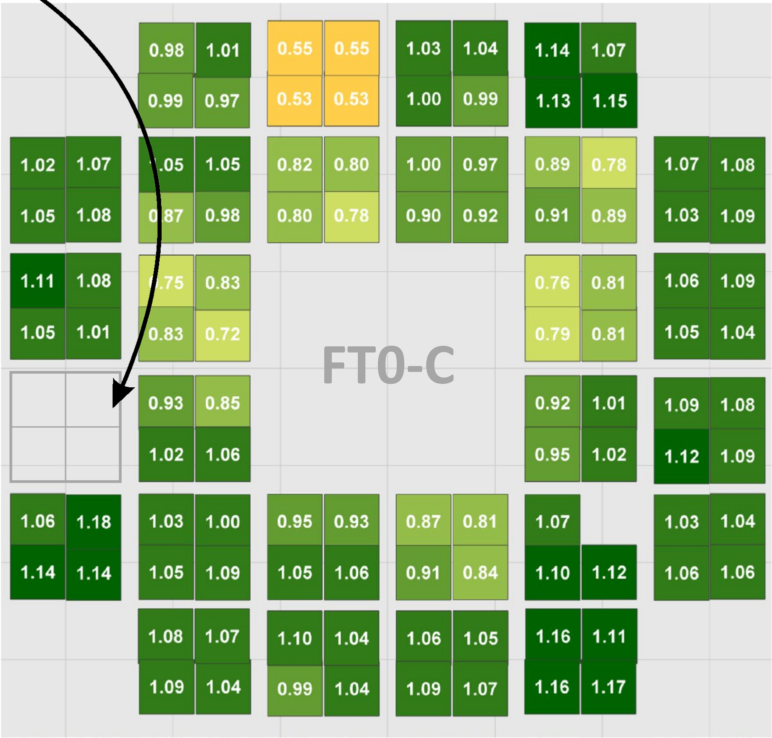






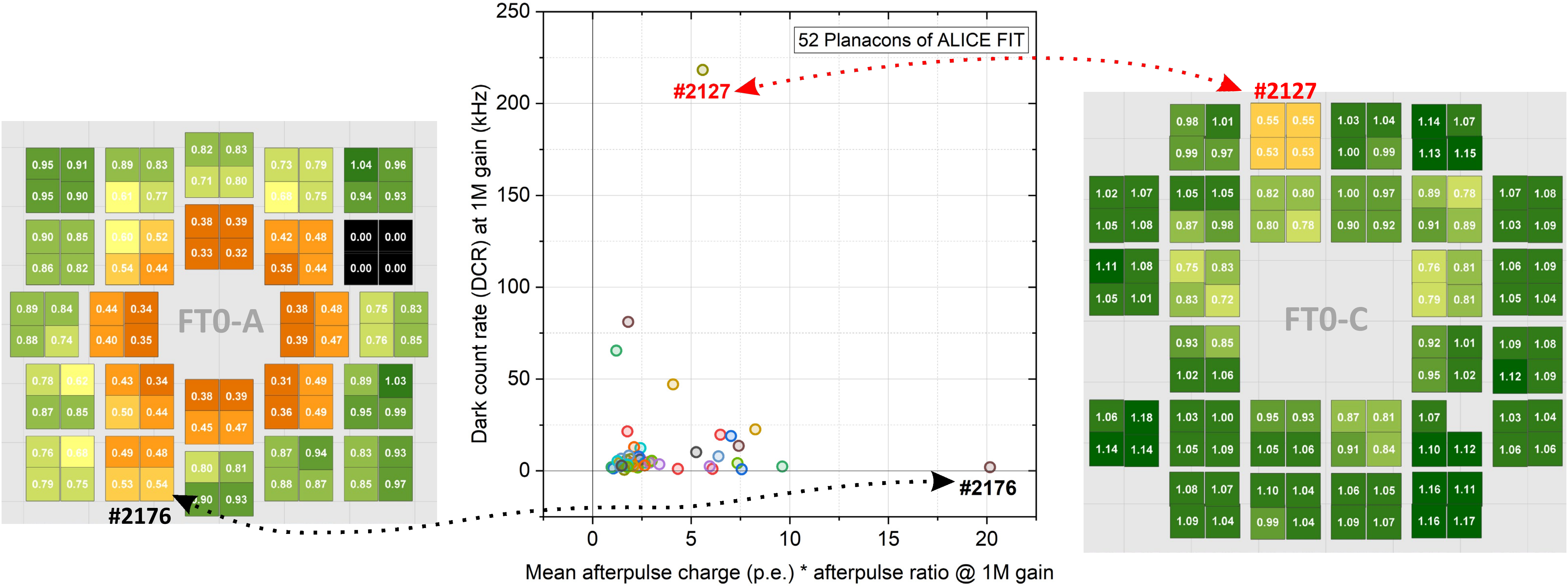






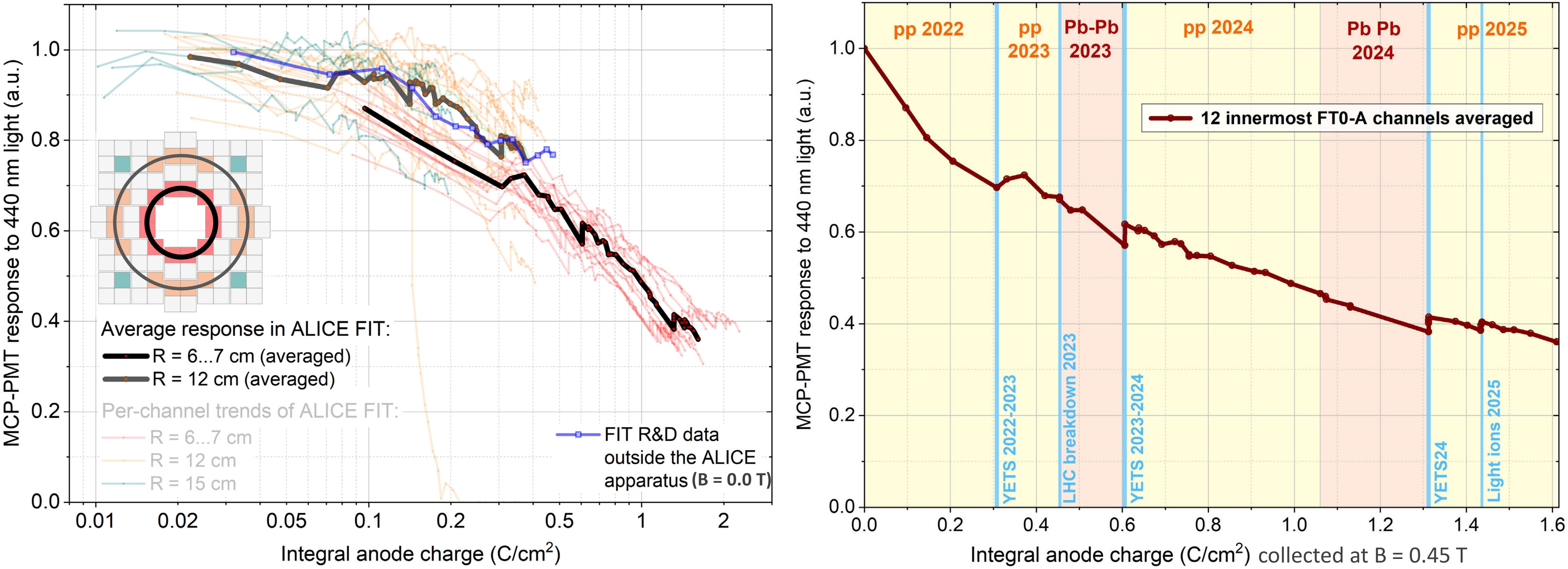
The ageing outliers

The only two outliers in terms of ageing speed are the only two outliers in terms of the intrinsic noise characteristics **(DCR & afterpulsing)**.



Ageing development

- Trends' shapes ~repeatable across different MCP-PMTs;
- Moderately-loaded Planacons age as fast as in the dedicated ageing test in lab (outside ALICE);
- Ageing of the most loaded channels is slow enough to avoid any FT0 performance deterioration in LHC Run 3.



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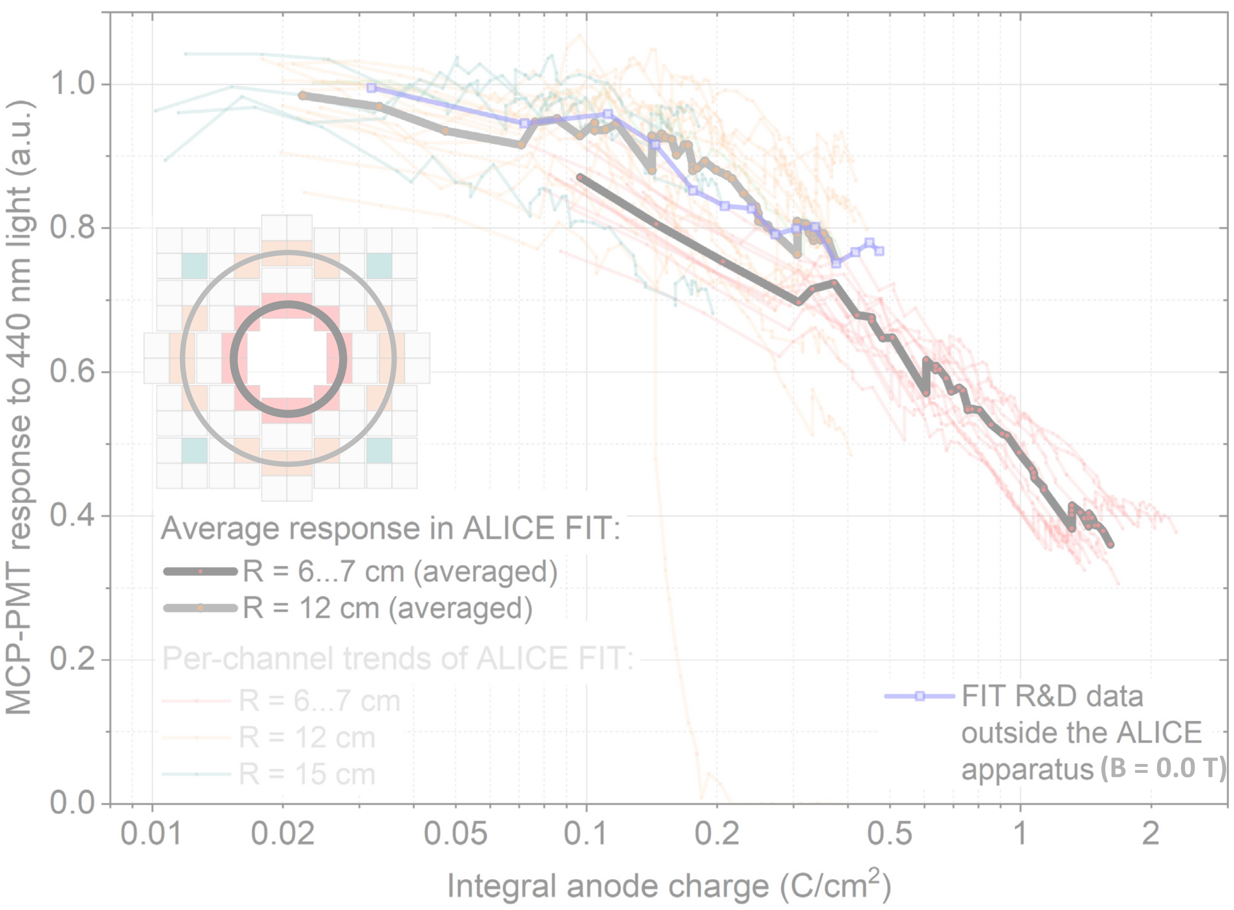
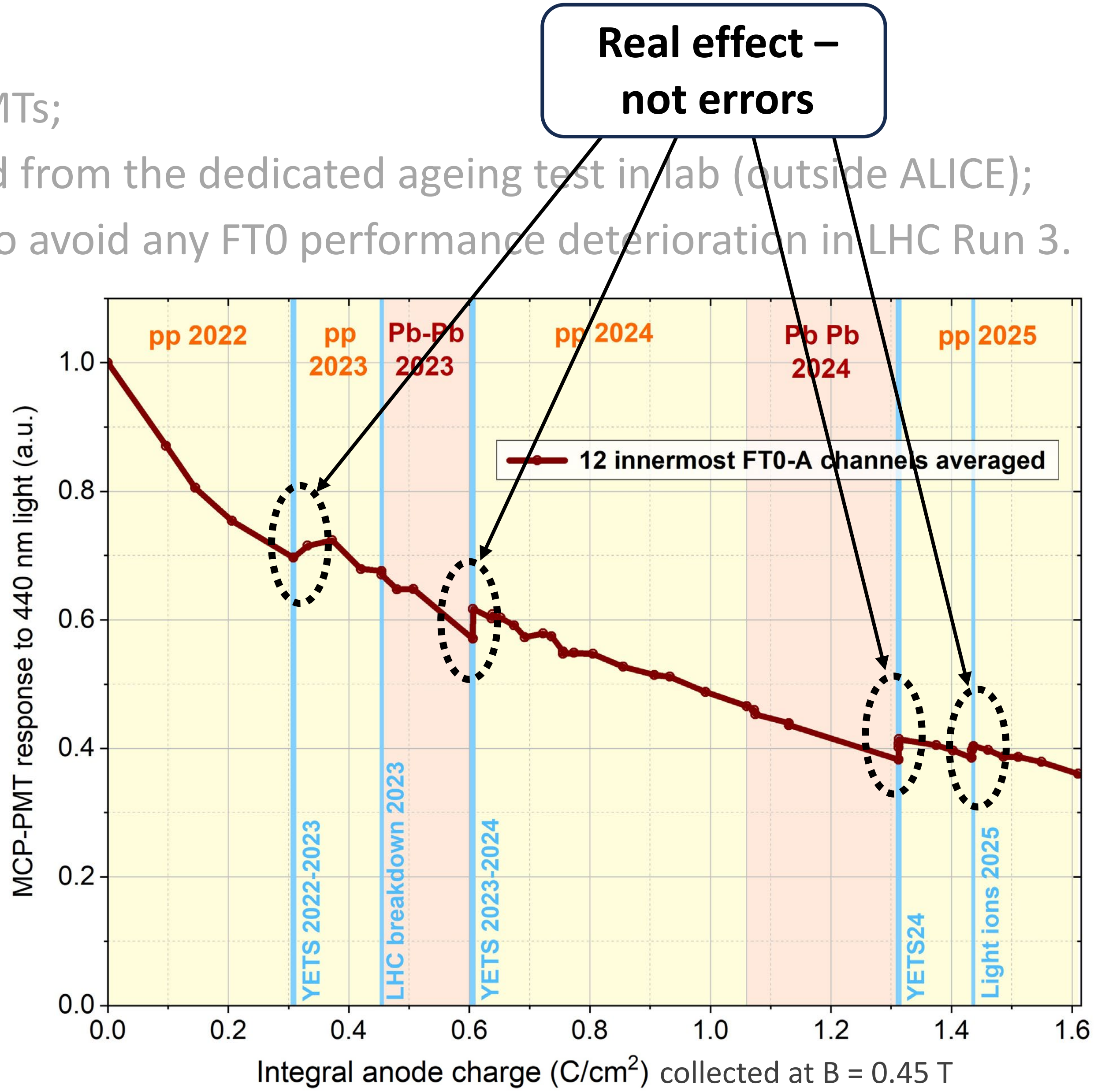
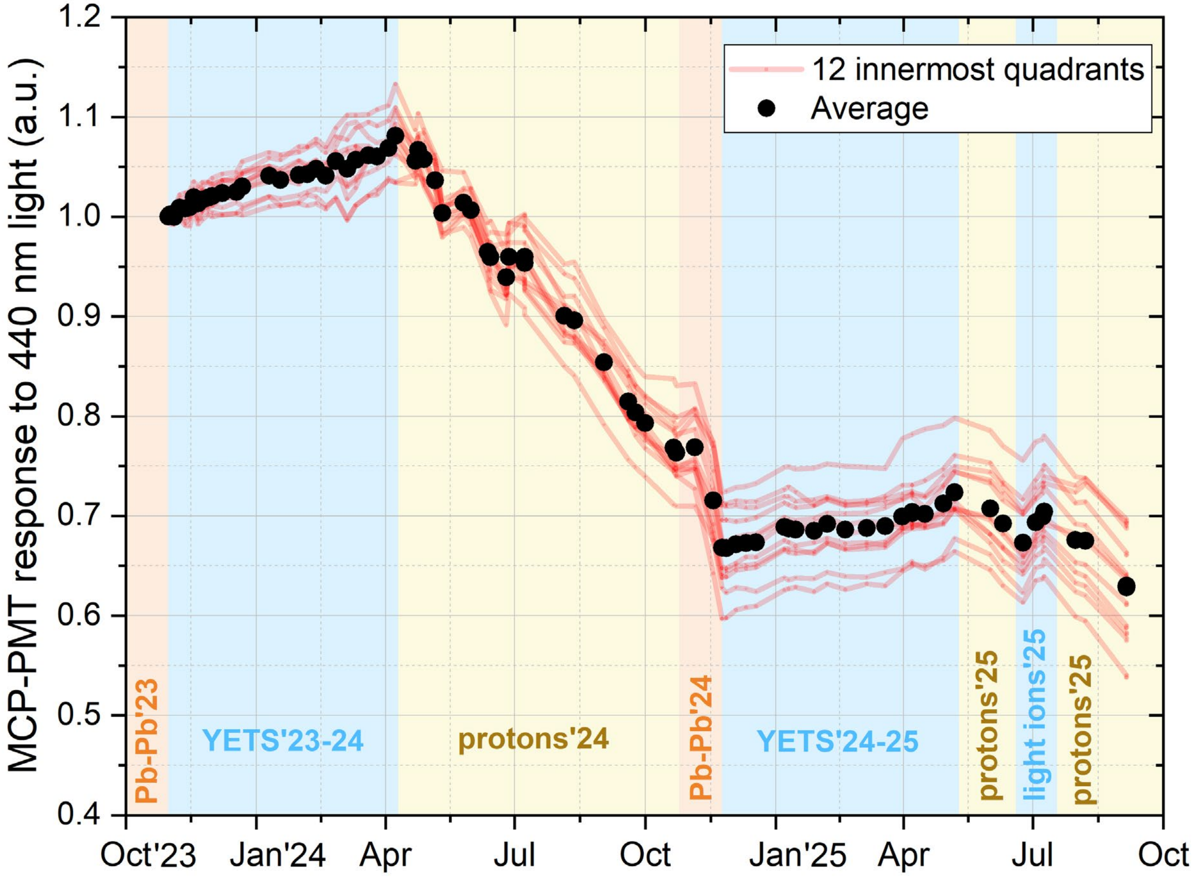
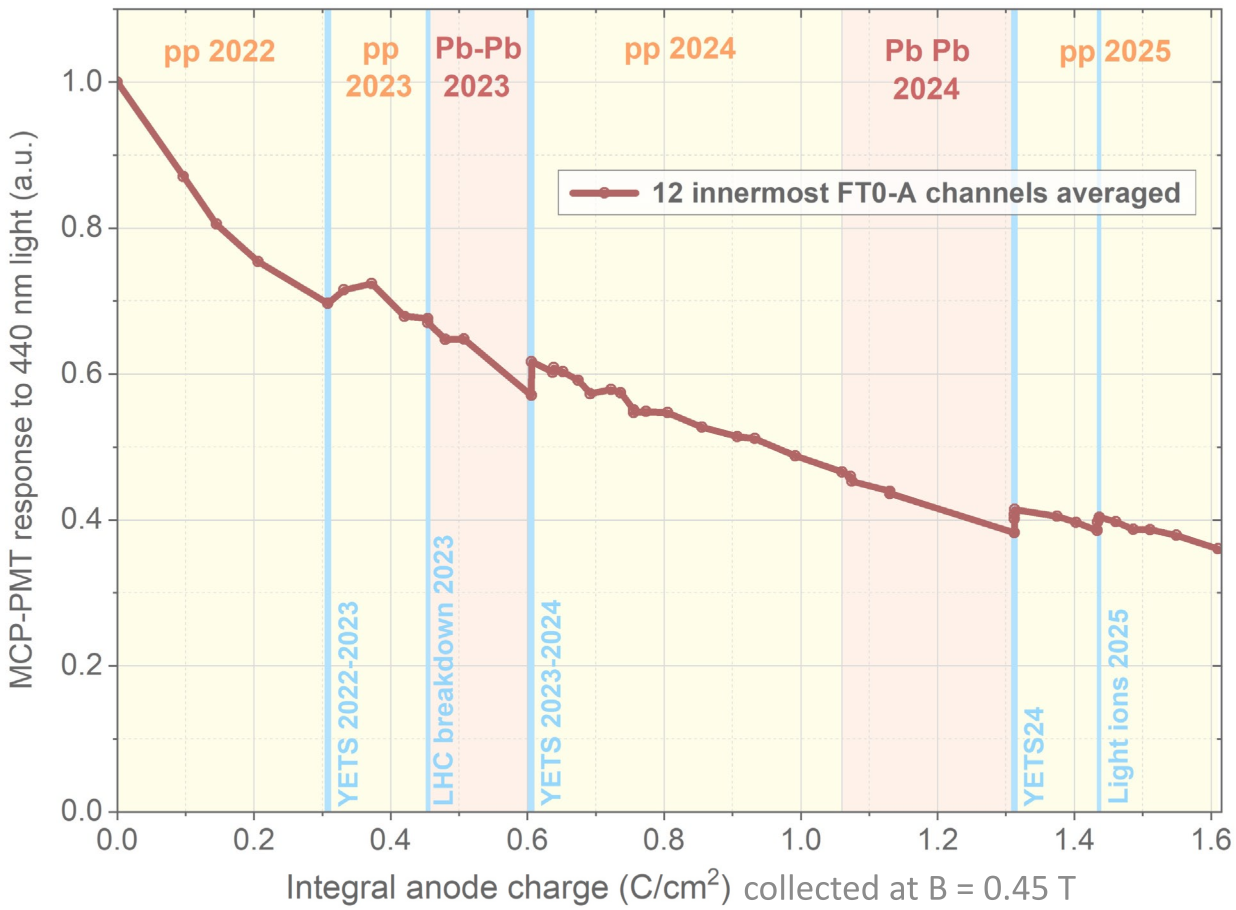




Self-recovery of the ageing effect

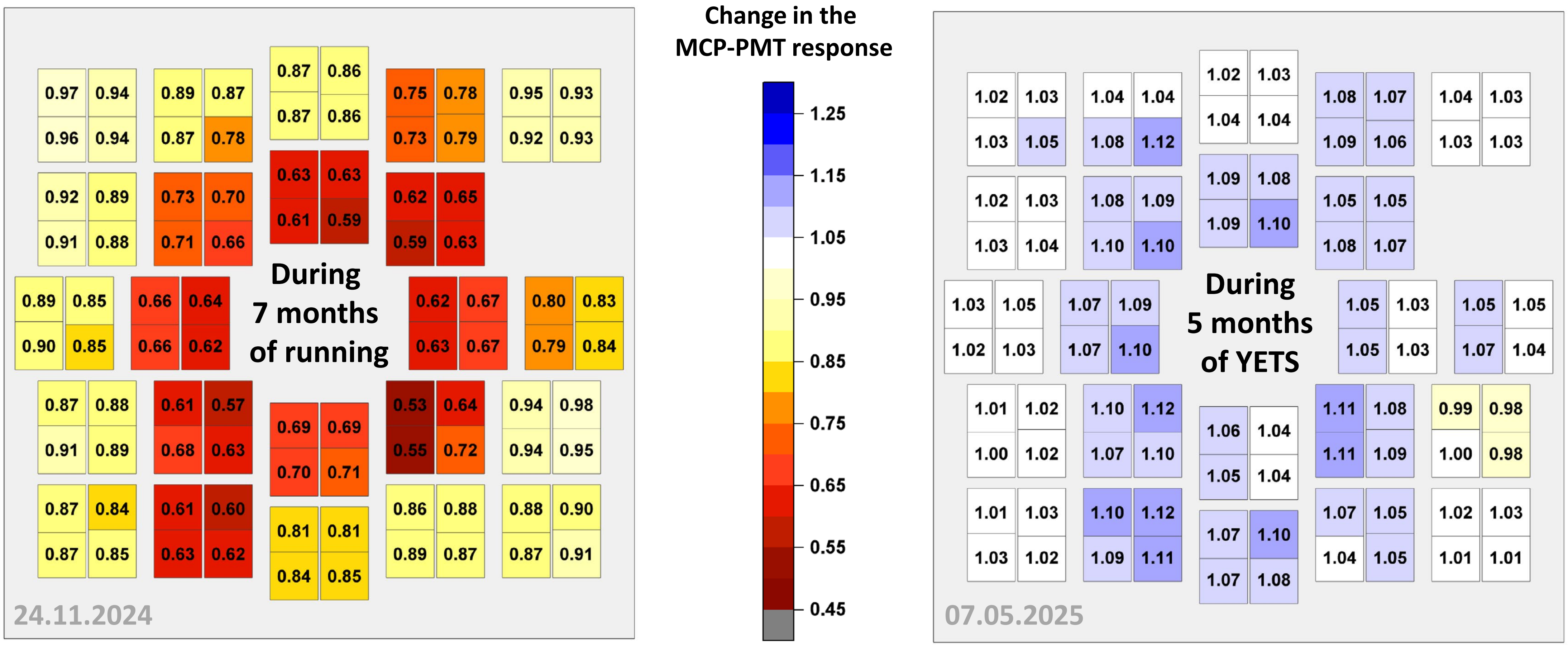
- LHC normally runs for ~7 months in a row – then no collisions for ~5 month (“YETS” period);
- Heavy-ion running results in faster ageing (x6 proton load) – proportional to IAC;
- Notable self-recovery of the aged MCP-PMTs is observed throughout YETS (at room temperature).





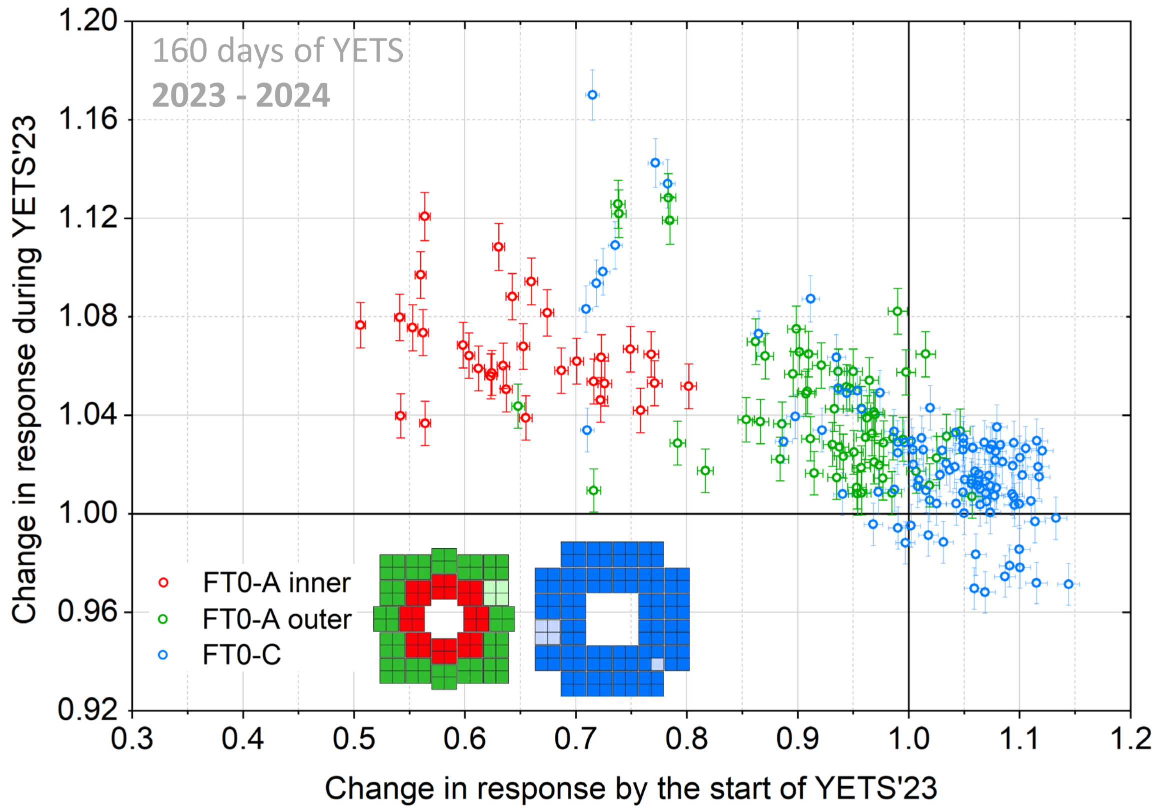
Self-recovery of the ageing effect

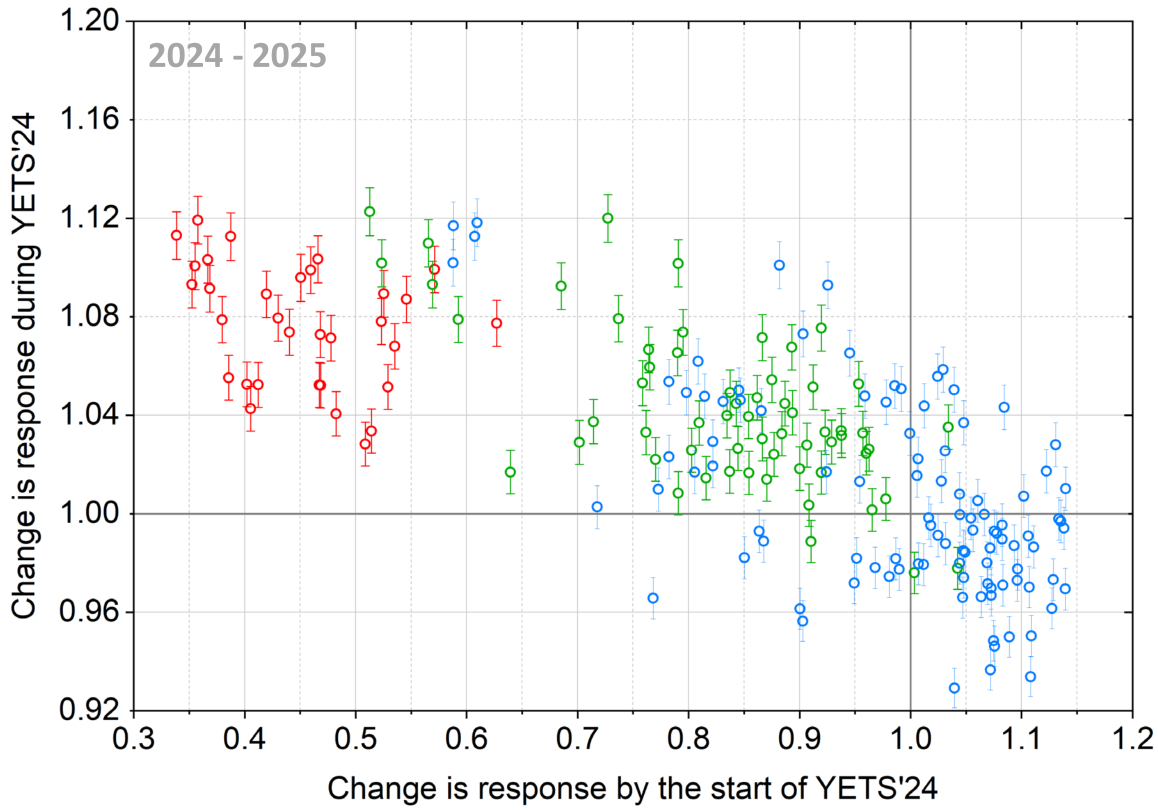
- Stronger ageing → stronger self-recovery



Self-recovery of the ageing effect

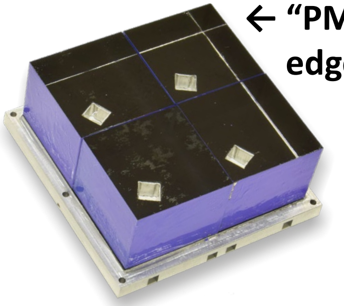
- Stronger ageing → stronger self-recovery (true at moderate ageing);
- No ageing → no recovery;
- Very strong ageing → notable recovery.



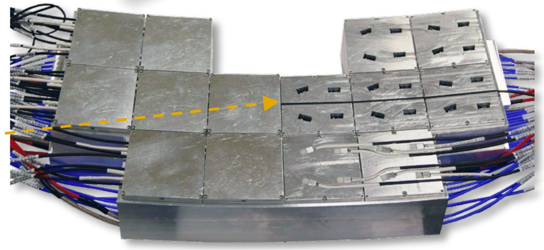


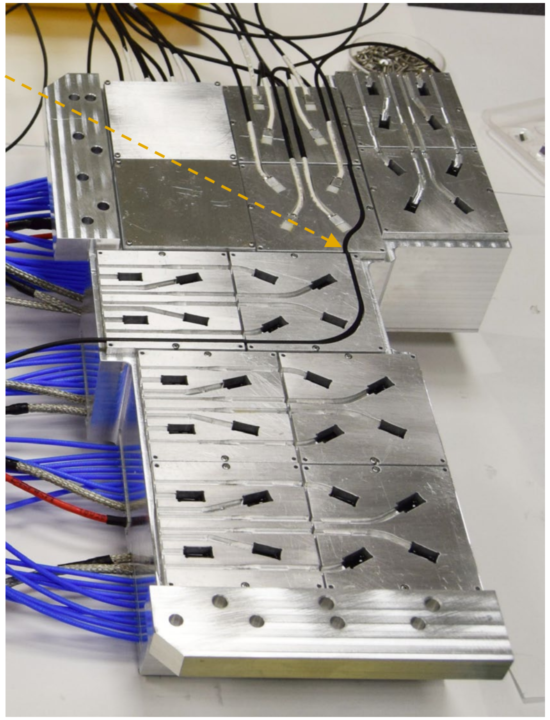
FT0 laser calibration system

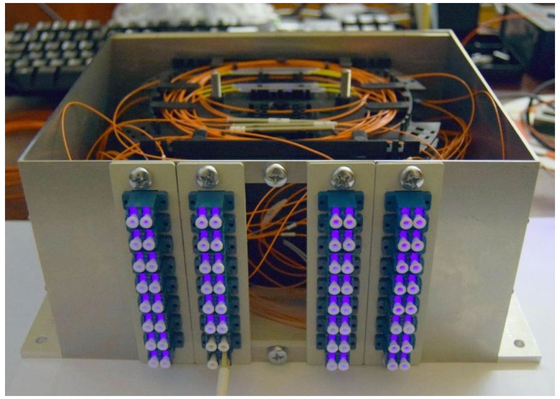
- Essential tool to calibrate the detector and monitor the MCP-PMT response;
- Light from a single laser delivered to 208 channels;
- Dedicated fibers traced through both detectors to monitor for possible radiation damage;
- "Non-invasive" solution to monitor and correct for laser light instability with the photon leakage via fiber walls.



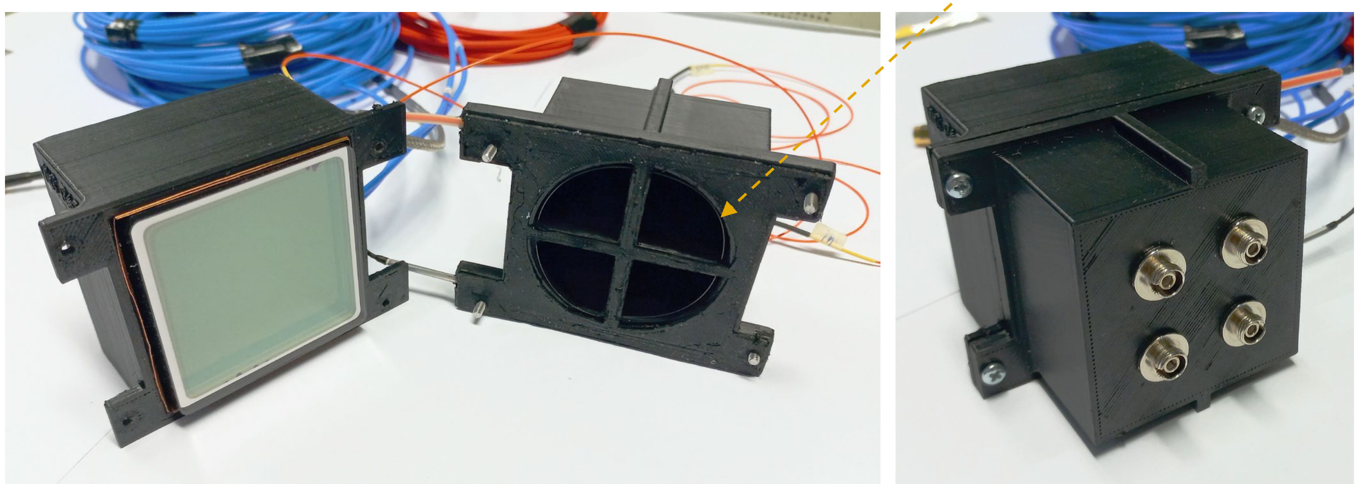
← "PMT view" of the radiators – black edge to suppress backward signals (> x20).







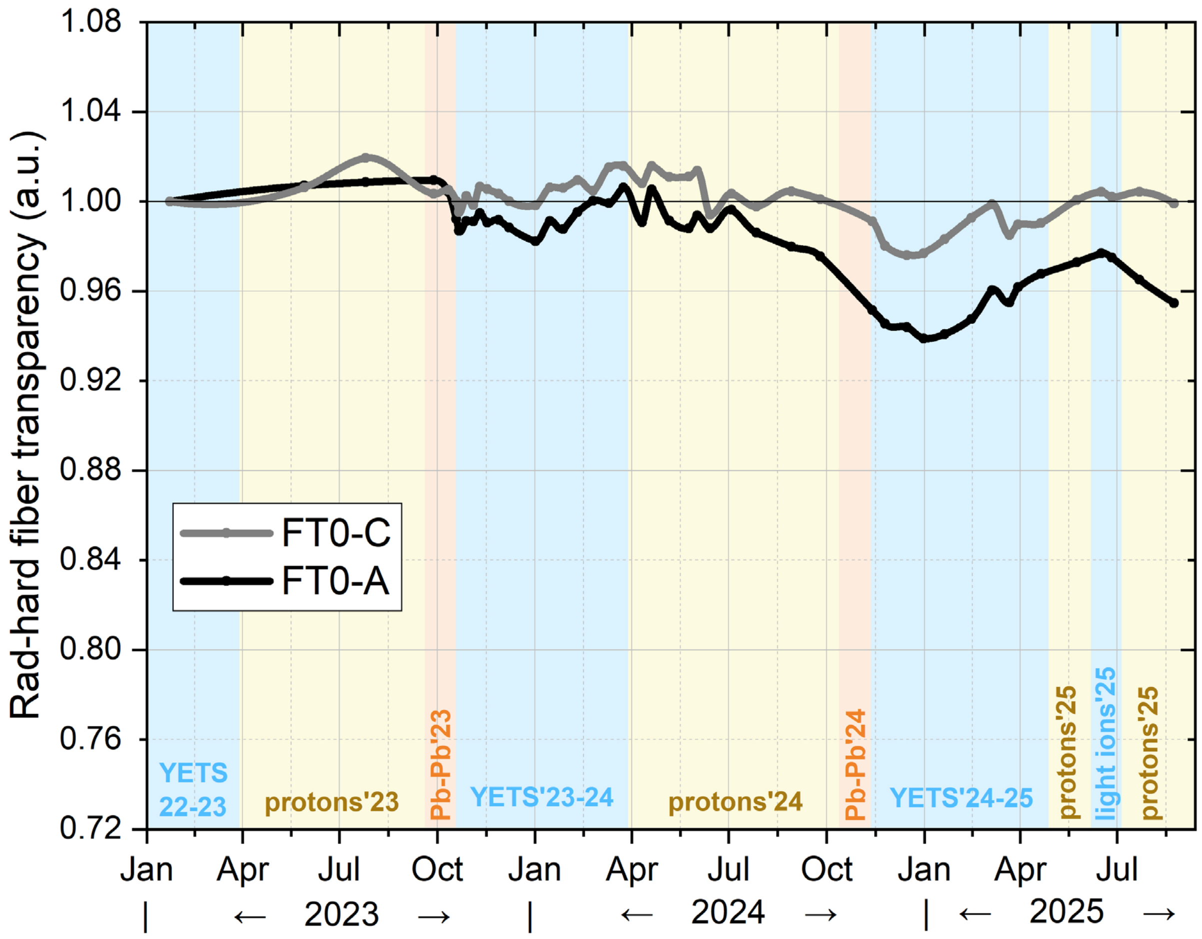
↑ 1-to-64 optical splitter boxes custom-made to deliver 440 nm light from a single laser to 208 detector channels

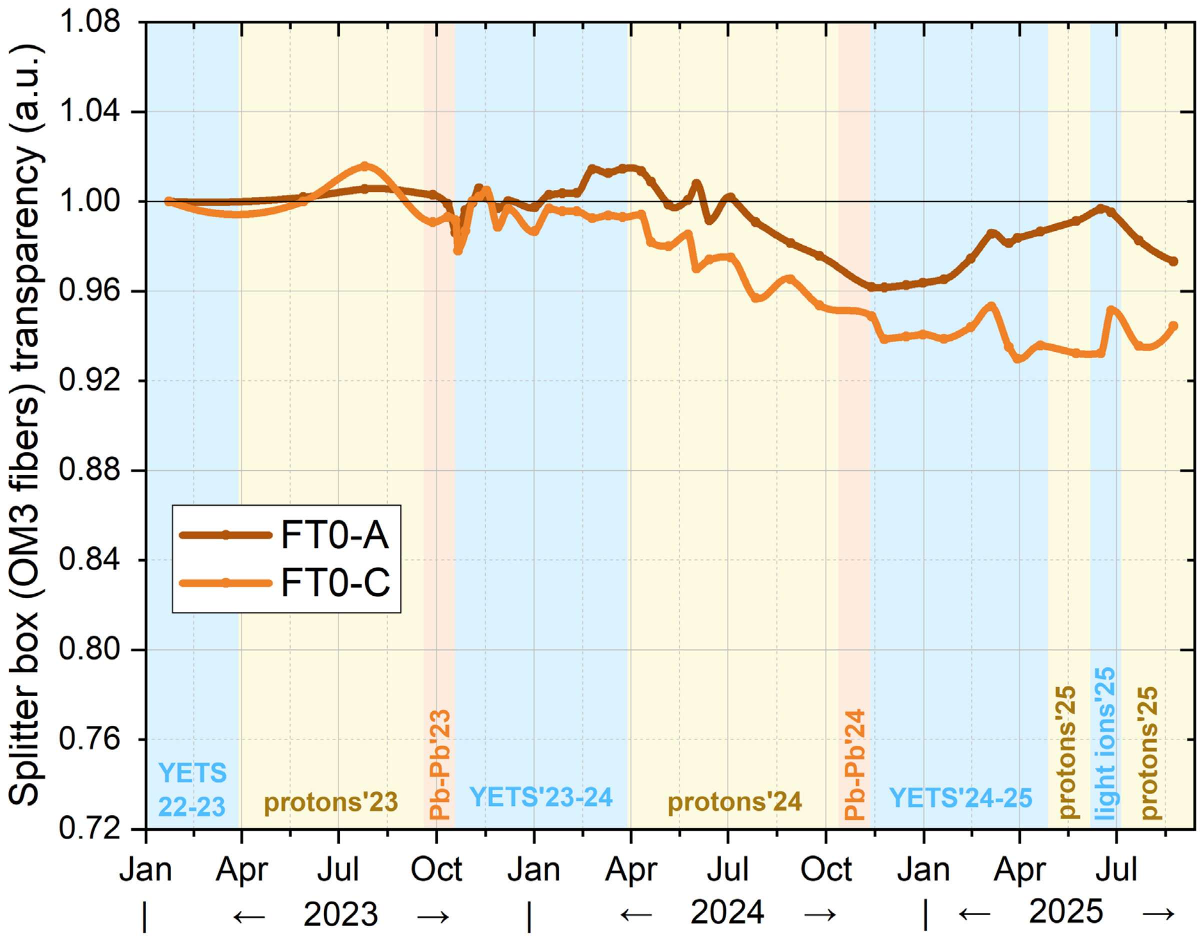


↑ FT0 reference PMT module with a laser intensity monitoring loop and return inputs ↑

Stability of the laser calibration system

- Fiber transparency is stable within ±1% over the 5 months-long YETS periods;
- Sample rad-hard fiber degrades by <5% after *4*10*^{12} *n_{eqv}/cm fluence*, but on-detector fibers get ~x10 less.





Conclusions

The first large-scale Planacon application in HEP!

ALICE FIT-FT0 – success story of the using the cost-effective* MCP-PMTs

- Key contributor to the **remarkable time resolution** for Pb-Pb collisions σ = 4.4 ps;
- **Handling high photon fluxes & AAC**: ~10^8 p.e./cm^2/s | 600 nA/cm^2
  - Profit of the low-resistance MCPs with τ = 0.3 ms;
  - **AAC limit is B-field dependent**, and peculiarly correlated to the tilt angle for the maximum gain.
- Beyond 1.5 C/cm^2 IAC the **strong ageing is balanced by HV increase without timing deterioration**
  - Profit of the large Cherenkov yield (2 cm of quartz + VUV-sensitivity);
  - **Outliers in terms of DCR and afterpulsing age notably faster;**
  - **Self-recovery of the aged MCP-PMTs** – newly observed effect (to be scrutinized during the LS3).
- Among the unpleasant surprises:
  - Vacuum microleak (1 case), non-repairable HV breakdown across the MCP (1 case).

(*25 µm pore size, non-ALD)

Thanks a lot for your attention!

More on the

[ALICE FIT](#)

[on YouTube](#)

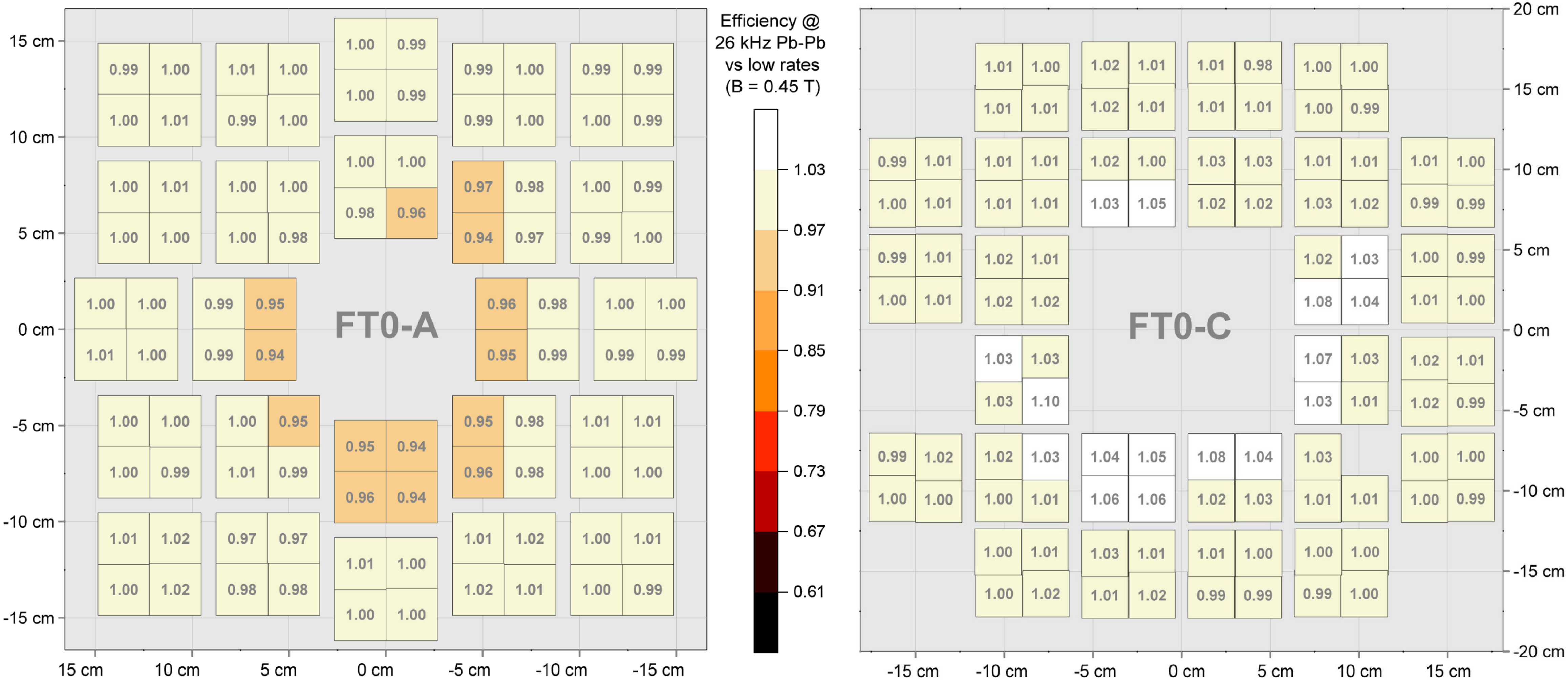
Back-up slides

Our publications on the relevant topic

1. Yu. Melikyan, on behalf of ALICE. **Status and performance of the ALICE Fast Interaction Trigger**, PoS(ICHEP2024)921
2. Yu.A. Melikyan et al. **Characteristic properties of Planacon MCP-PMTs**, JINST 16 (2021) P12032
3. Yu. Melikyan et al. **Load capacity and recovery behaviour of ALD-coated MCP-PMTs**. NIM A 949 (2020)162854
4. Yu.A. Melikyan et al. **Performance of the cost-effective Planacon® MCP-PMTs in strong magnetic fields**, NIM A 983 (2020) 164591
5. Yu.A. Melikyan, on behalf of ALICE. **Performance of Planacon MCP-PMT photosensors under extreme working conditions**, NIM A 952 (2020) 161689
6. Yu. Melikyan, PhD thesis (2019) in Russian: Development of the Fast Interaction Trigger detecting system for the upgraded ALICE
7. E.V. Antamanova, et al. **Anode current saturation of ALD-coated Planacon® MCP-PMTs**. JINST 13 (2018) T09001
8. V.A. Grigoryev et al. **Fast timing and trigger Cherenkov detector for collider experiments**. J. Phys. Conf. Ser. (2016) 675(4):042015
9. V.A. Grigoryev et al., **Study of the Planacon XP85012 photomultiplier characteristics for its use in a Cherenkov detector**. J. Phys. Conf. Ser. (2016) 675 (042015)

Effective AAC saturation

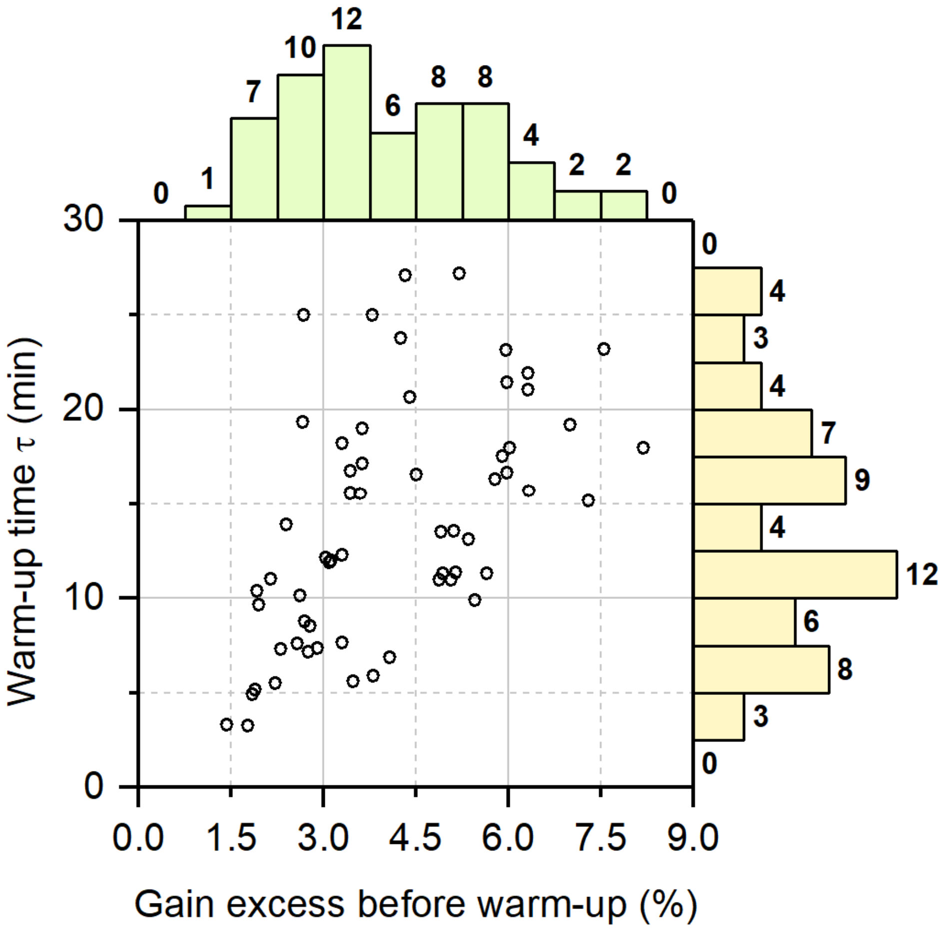
- Sufficient rate capability of all FT0 channels at 26 kHz.

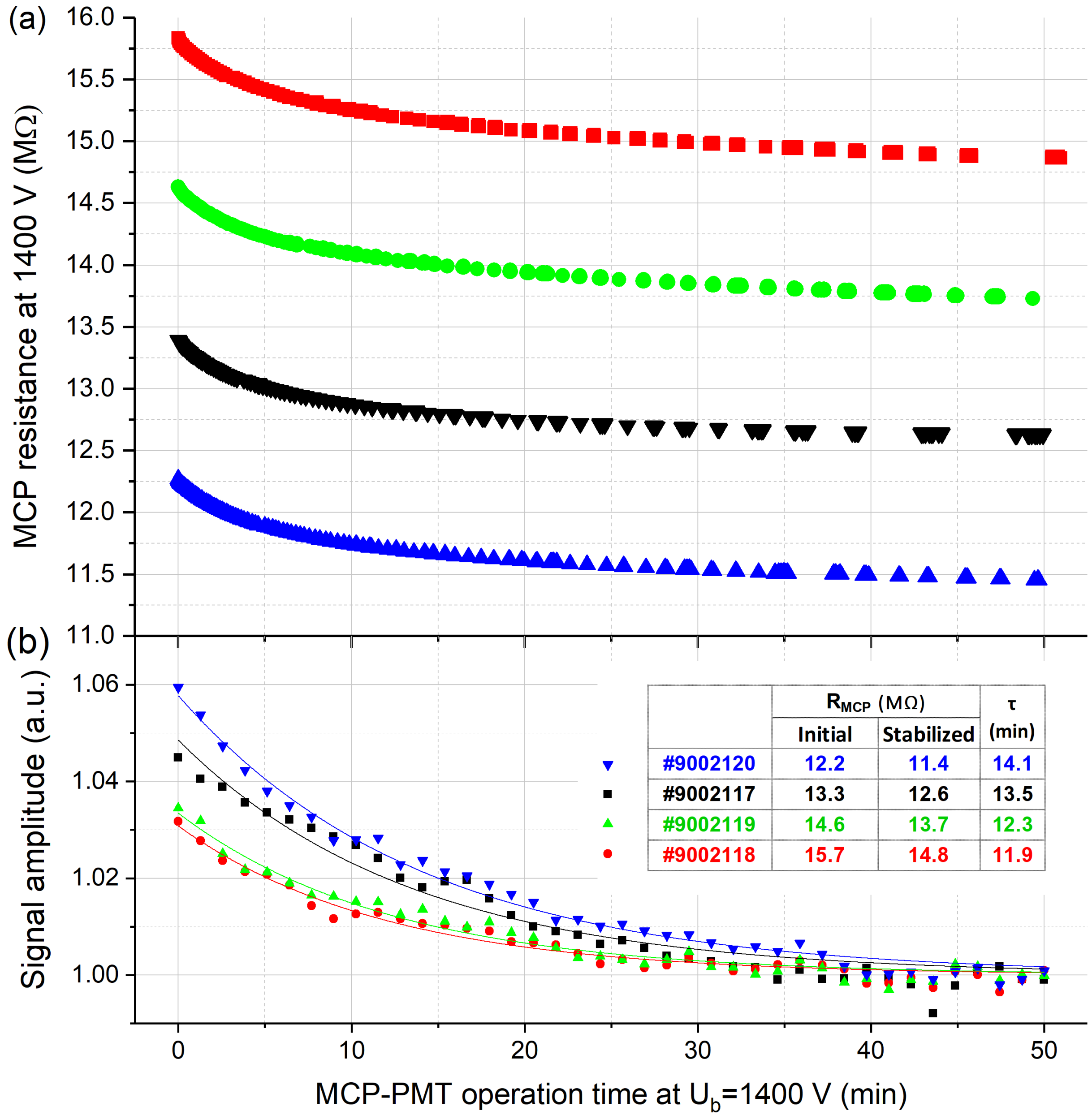


Warm-up trends

(11 MΩ ≤ $R_{MCP\ stack}$ ≤ 20 MΩ)

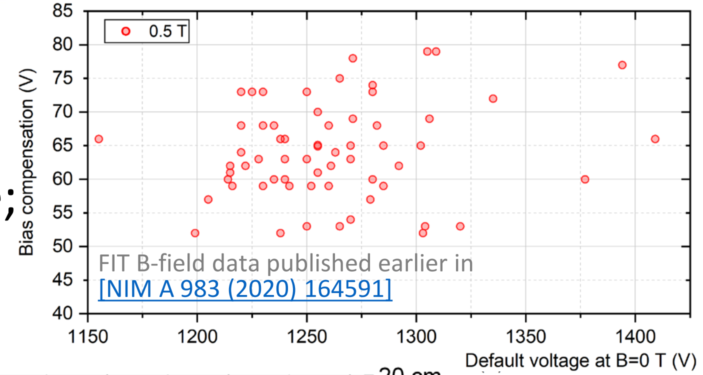
FIT Planacon data published earlier in [JINST 16 (2021) P12032]

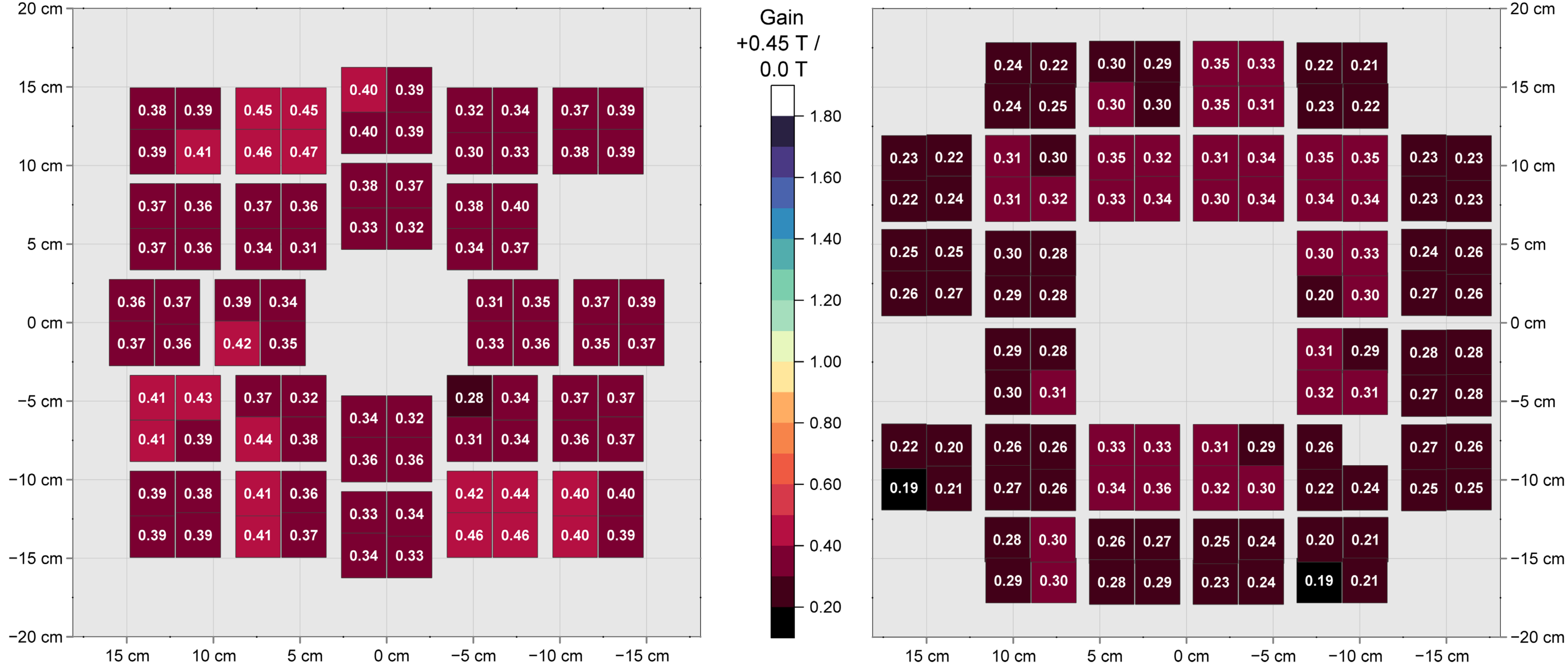




B-field effect on the detector

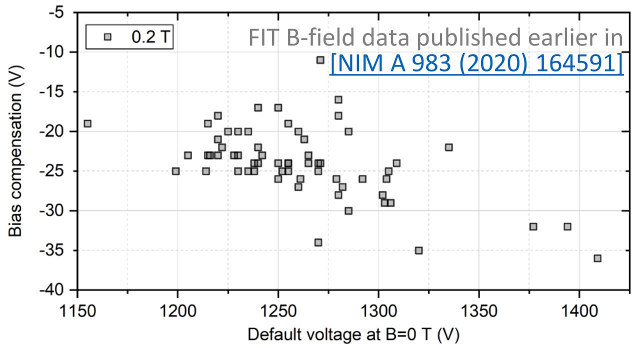
- 0.45 T B-field reduce gain x3 for the (flat) A-side, x5-x3 – for the (concave) C-side;
- Easily compensated by + ~60 V; still average V_{bias} < 1.4 kV (<< V_{max} = 2.0 kV).

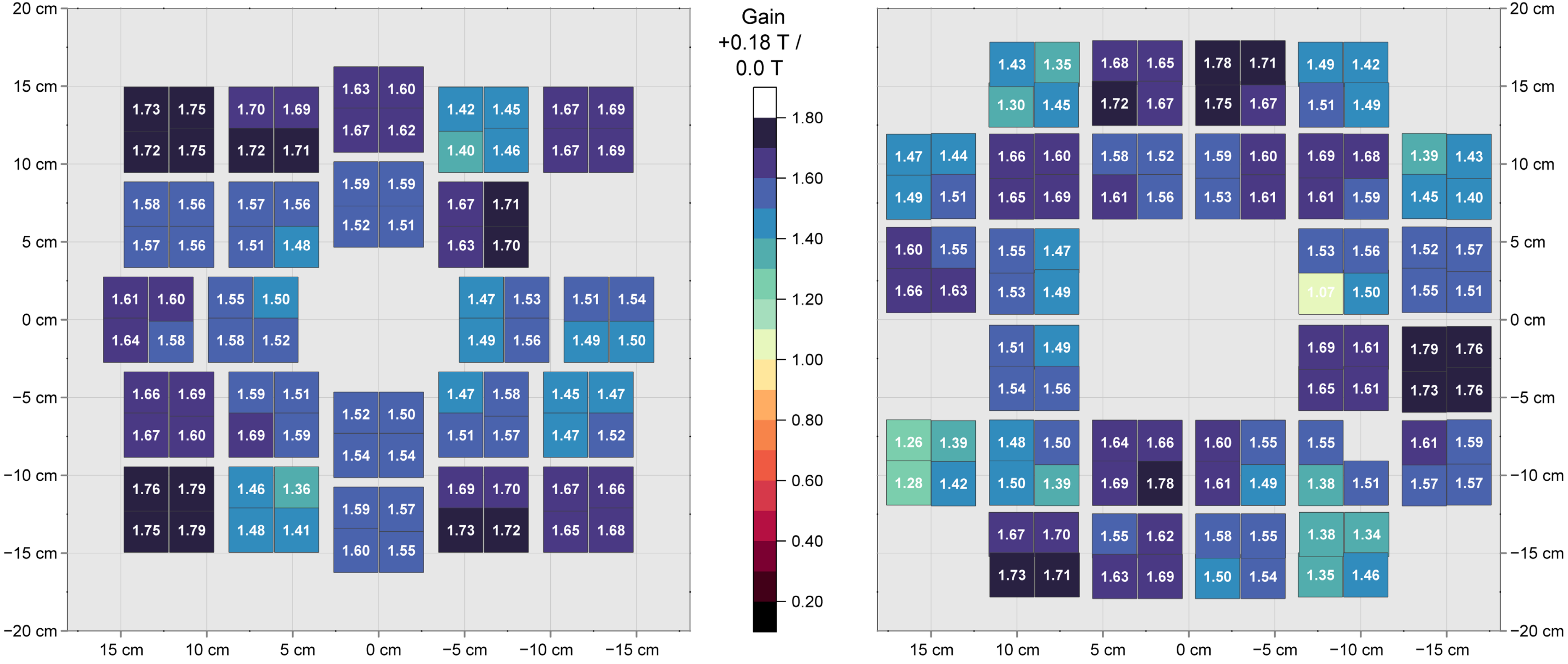




B-field effect on the detector

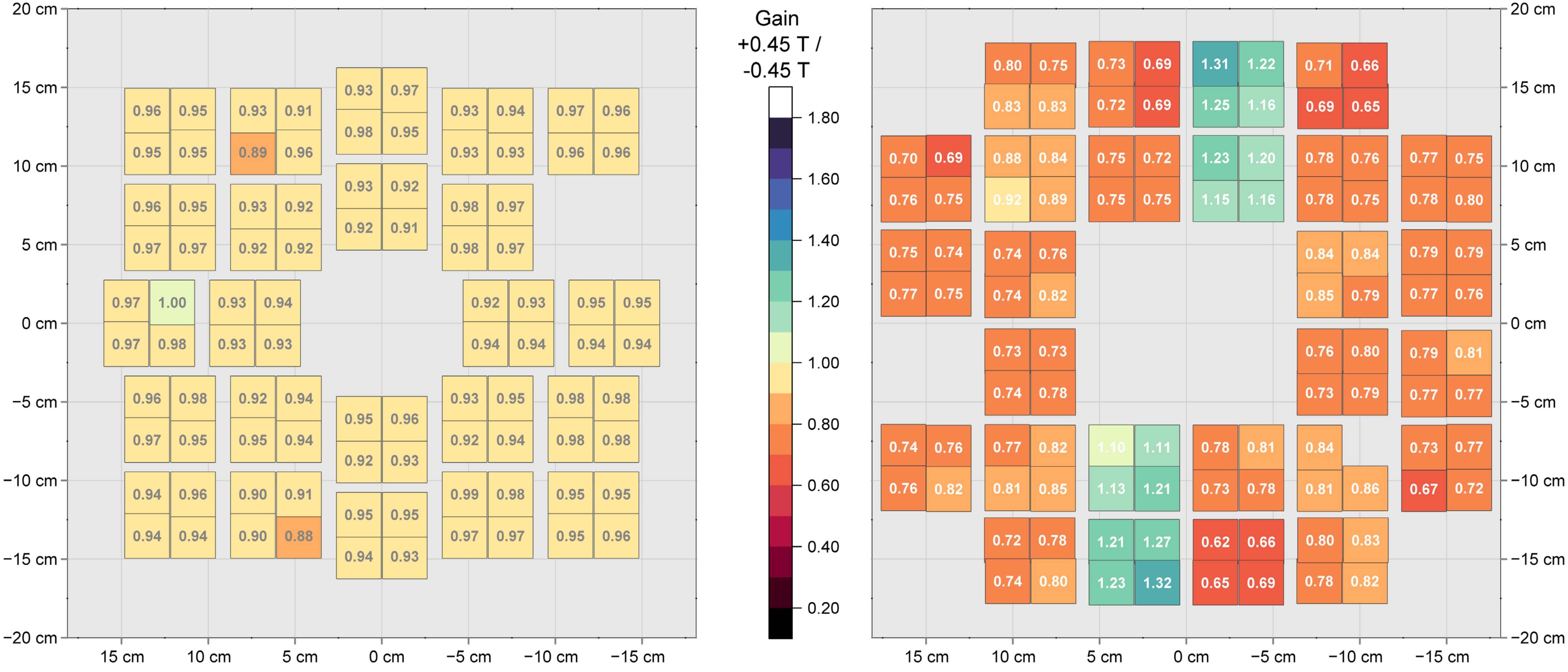
- Reduced field vs no field



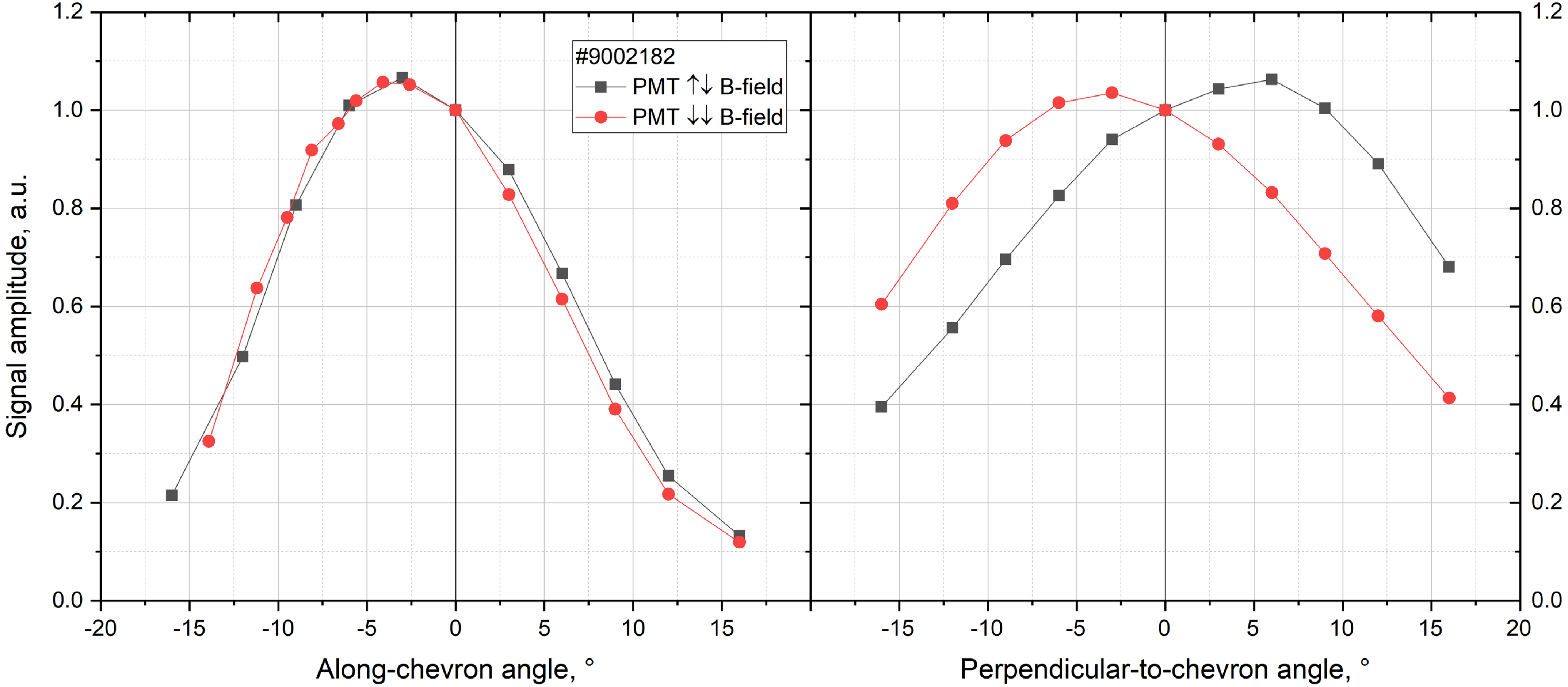


B-field effect on the detector

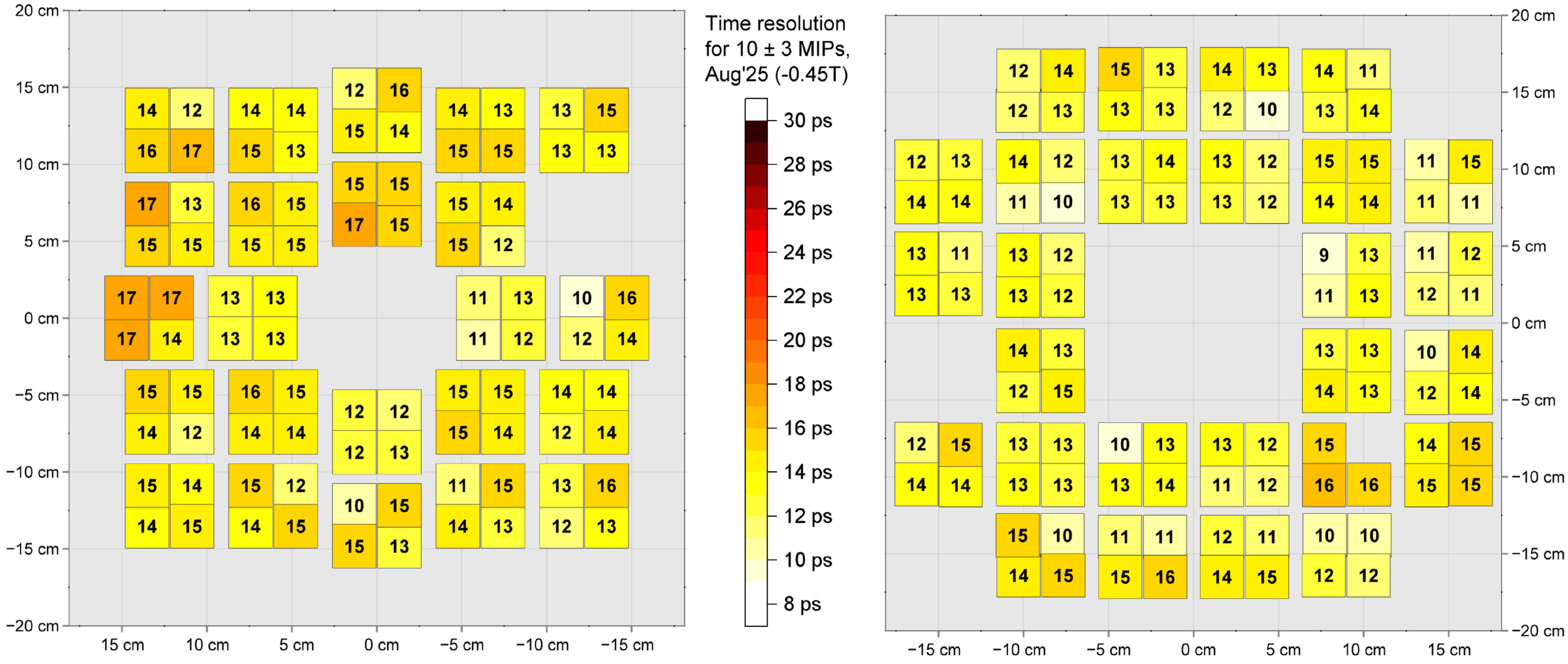
- Full field – positive vs negative



Gain change vs tilt

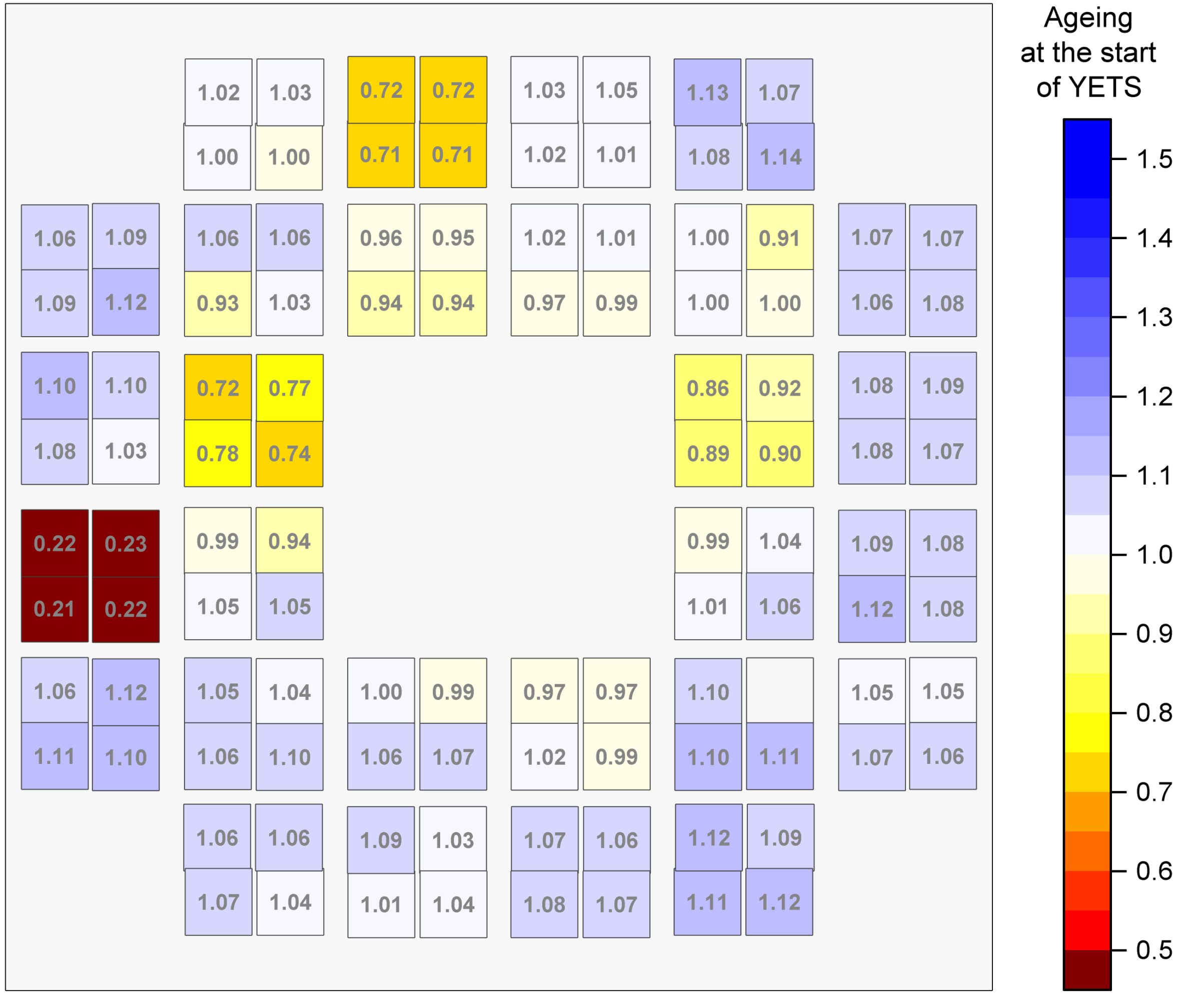


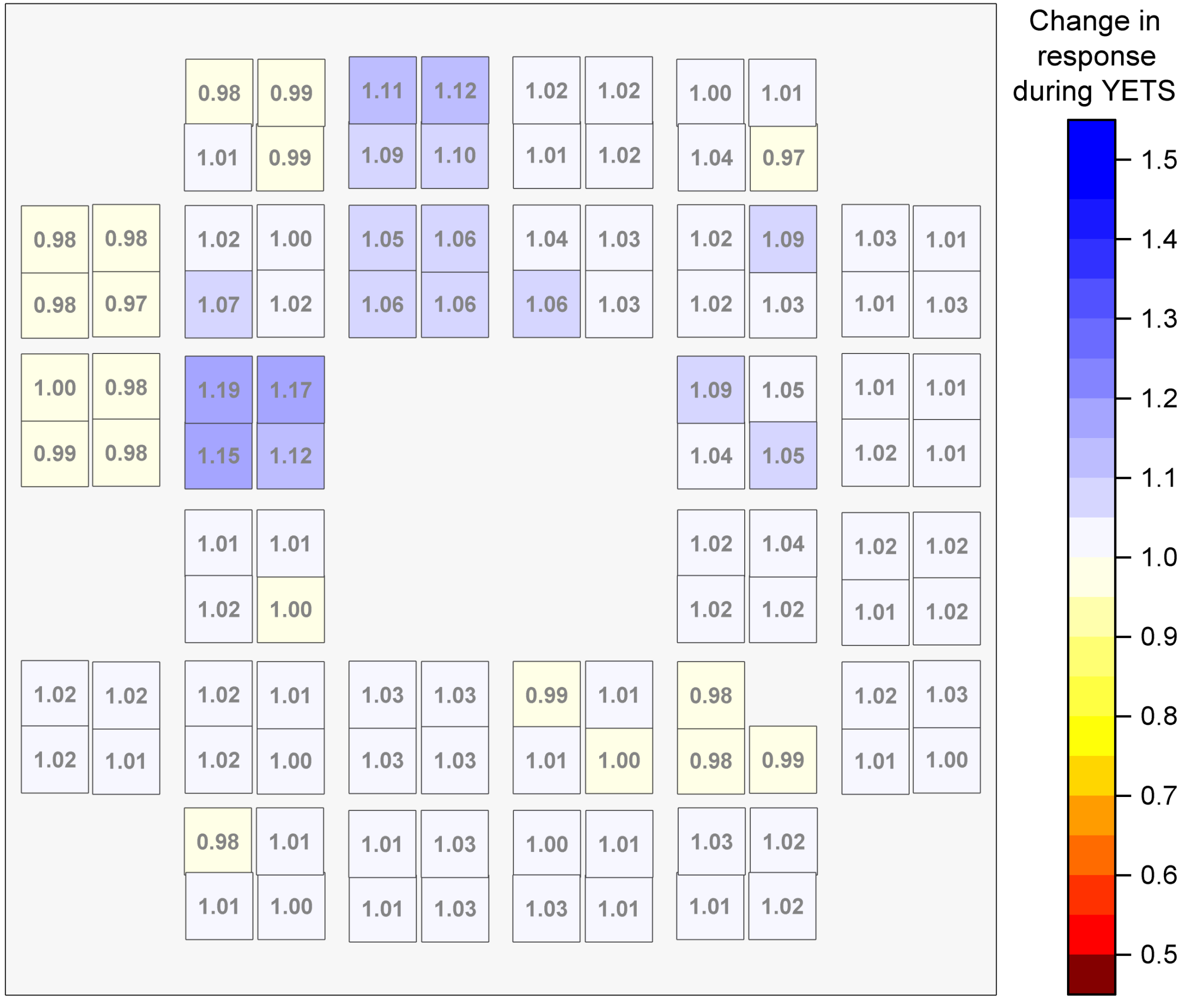
Ageing of the non-ALD Planacons

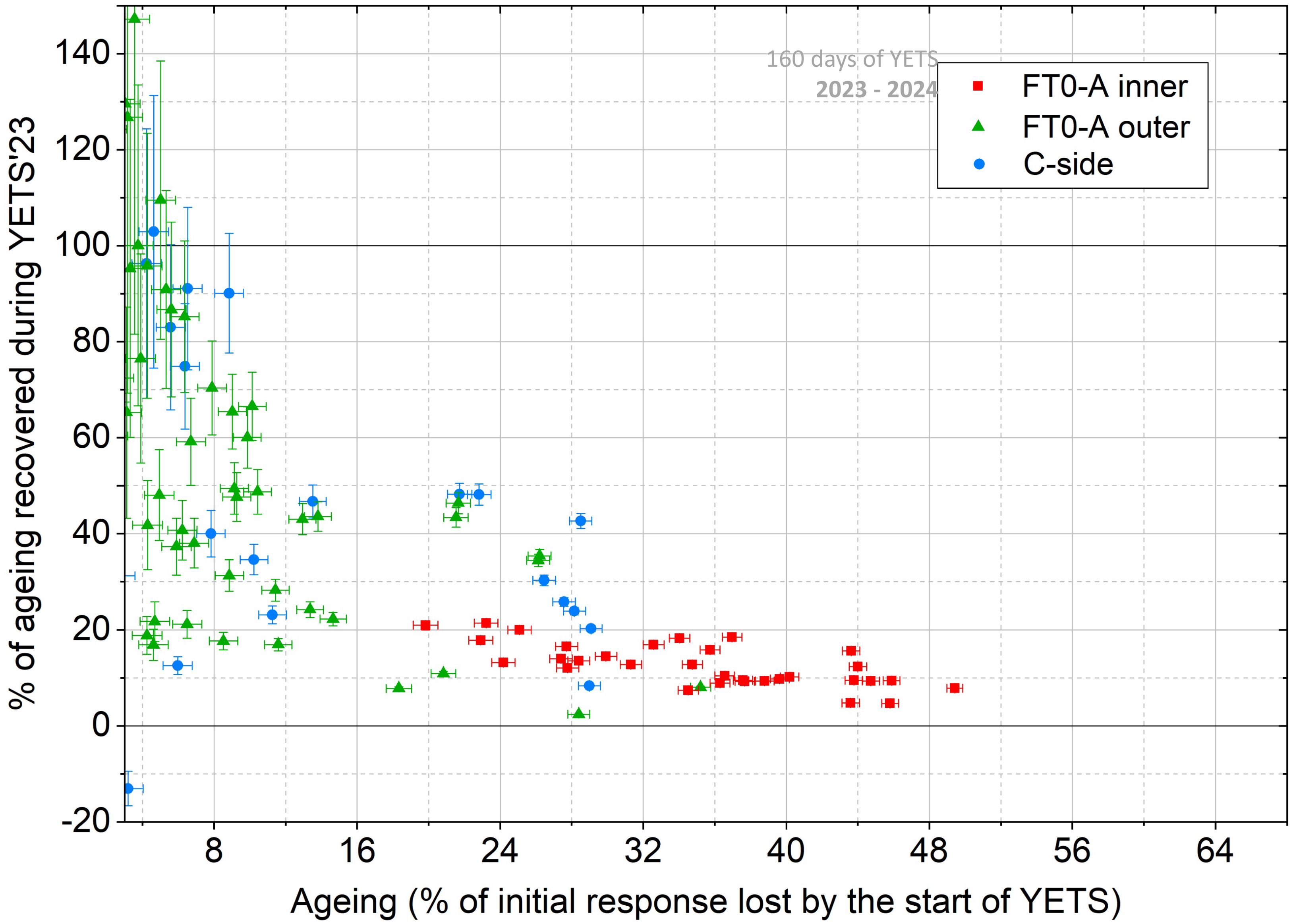


C-side ageing & annealing maps

- Partial ageing recovery during the year-end technical stops (160 days of no-lumi);






160 days of YETS
2023 - 2024
FT0-A inner
FT0-A outer
C-side
% of ageing recovered during YETS'23
Ageing (% of initial response lost by the start of YETS)
140
120
100
80
60
40
20
0
-20
8
16
24
32
40
48
56
64