The ATLAS Forward Proton Time-of-Flight Detector System

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on behalf of ATLAS Forward Detectors

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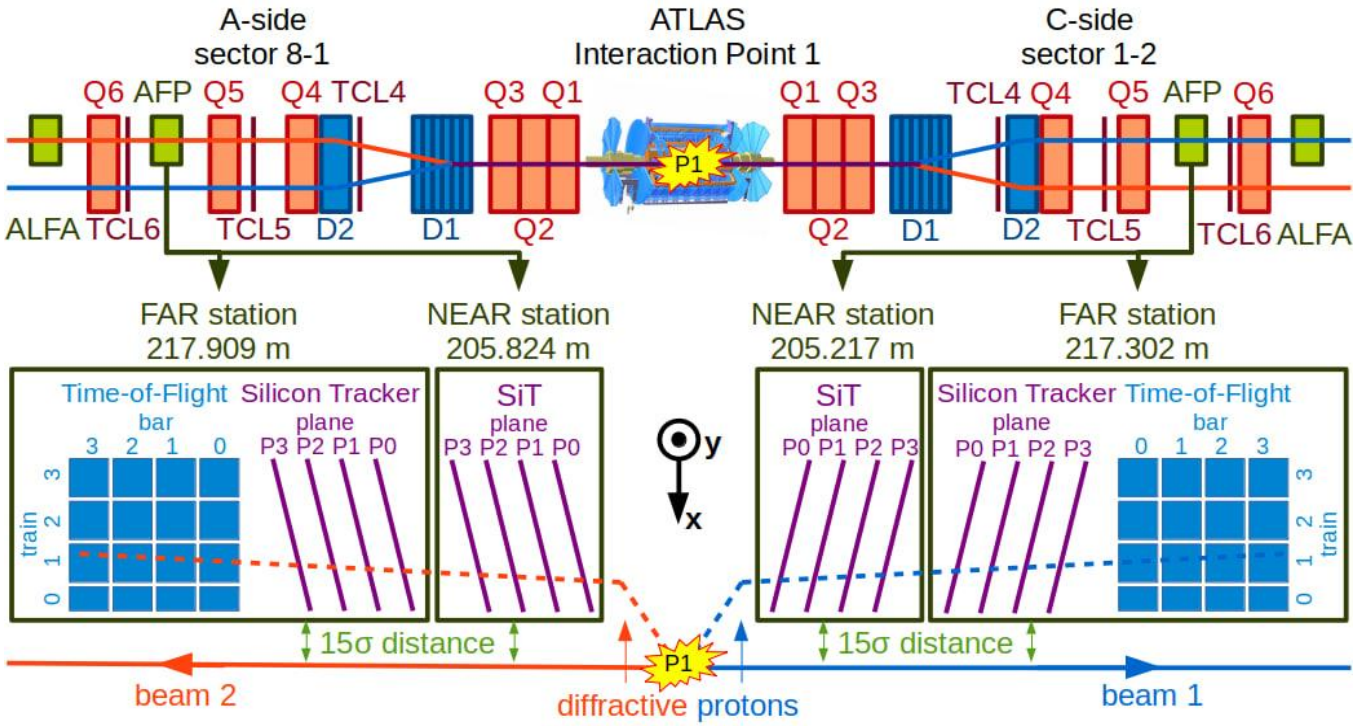
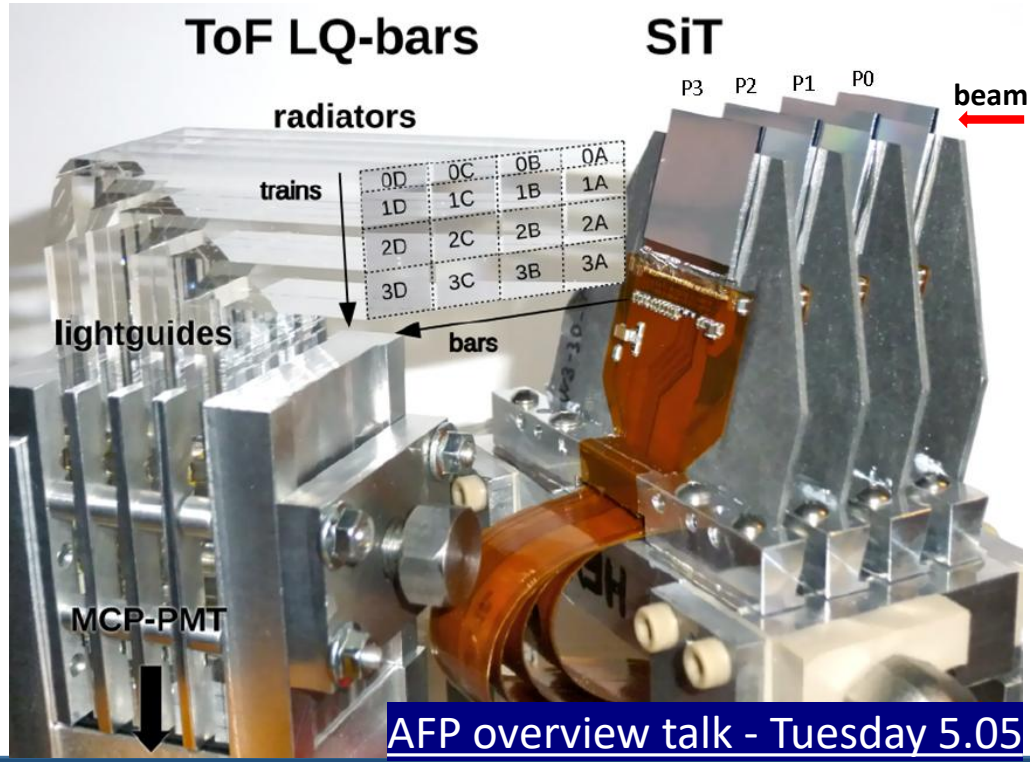
ATLAS Forward Proton (AFP) detector

- ATLAS Forward Proton (AFP) is a forward detector of ATLAS, designed to detect protons undergoing small or zero angle scattering at the interaction point (IP)
- AFP is a Roman Pot detector system, located at ~ 210 m in the LHC tunnel outside of ATLAS cavern on both sides of the ATLAS IP (side A and C). Pots are moving close to the beam (1-3 mm) once Stable Beams are declared
- For tracking, each station uses Silicon Tracker (SiT), which consists of four layers of silicon pixel detectors
- FAR stations are additionally equipped with Time-of-Flight (ToF) detectors



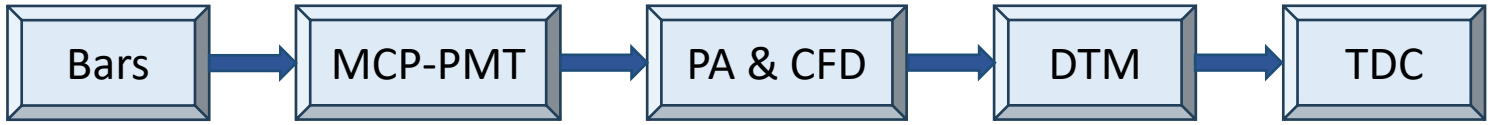


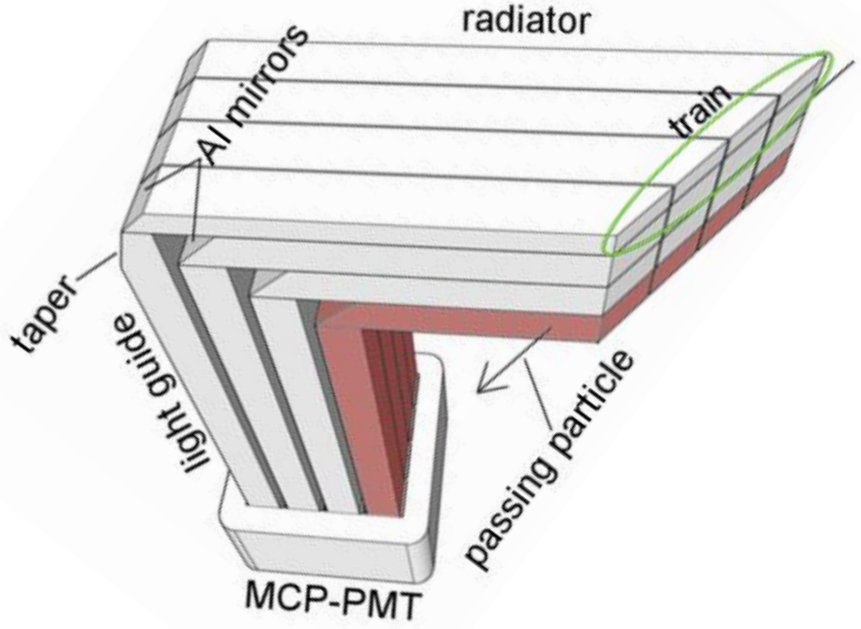
AFP overview talk - Tuesday 5.05

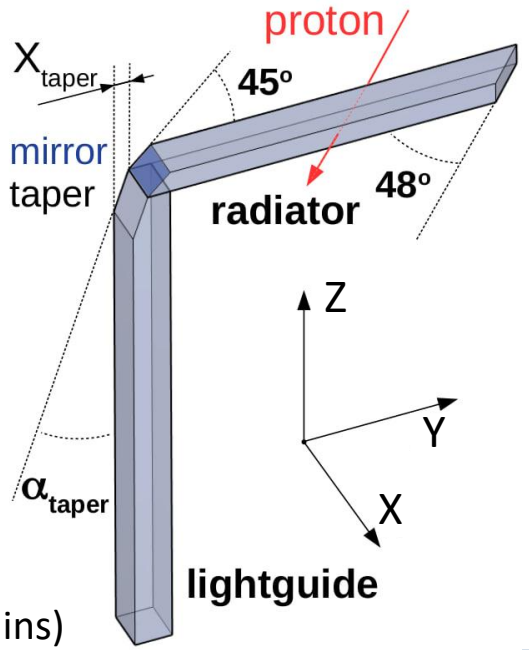
Time-of-Flight (ToF) detector

- A fast Cherenkov timing detector
- 4x4 channel matrix, 4 bars form a train
- Purpose:
  - reduce background by matching vertex reconstructed by central ATLAS detector with the one computed from the difference of protons' arrival times
  - provide fast trigger
- L-shaped silica bars (LQ-bars) send Cherenkov signal to a microchannel plate photomultiplier tube (MCP-PMT)
- Amplified by 3-stages of Pulse Amplifiers (PAa and PAbc)
- Processed by Constant Fraction Discriminator (CFD)
- Passed through Digital Trigger Module (DTM)
- Processed by Time-to-Digital Converter (TDC)*
- Double PAbc, CFD, and TDC*; each for 2 trains

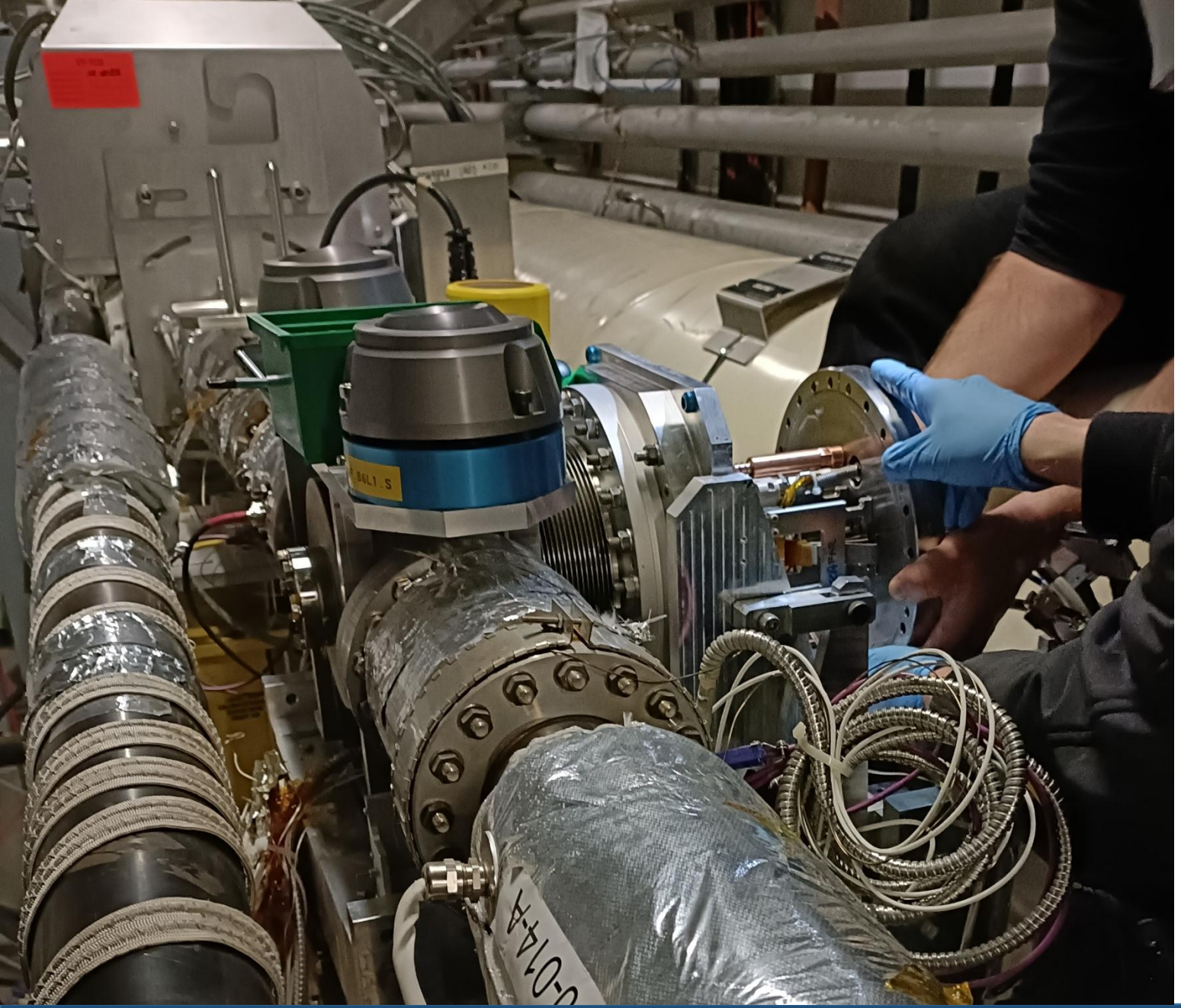
Whole system was developed entirely within the AFP collaboration, every component was designed specifically for ToF

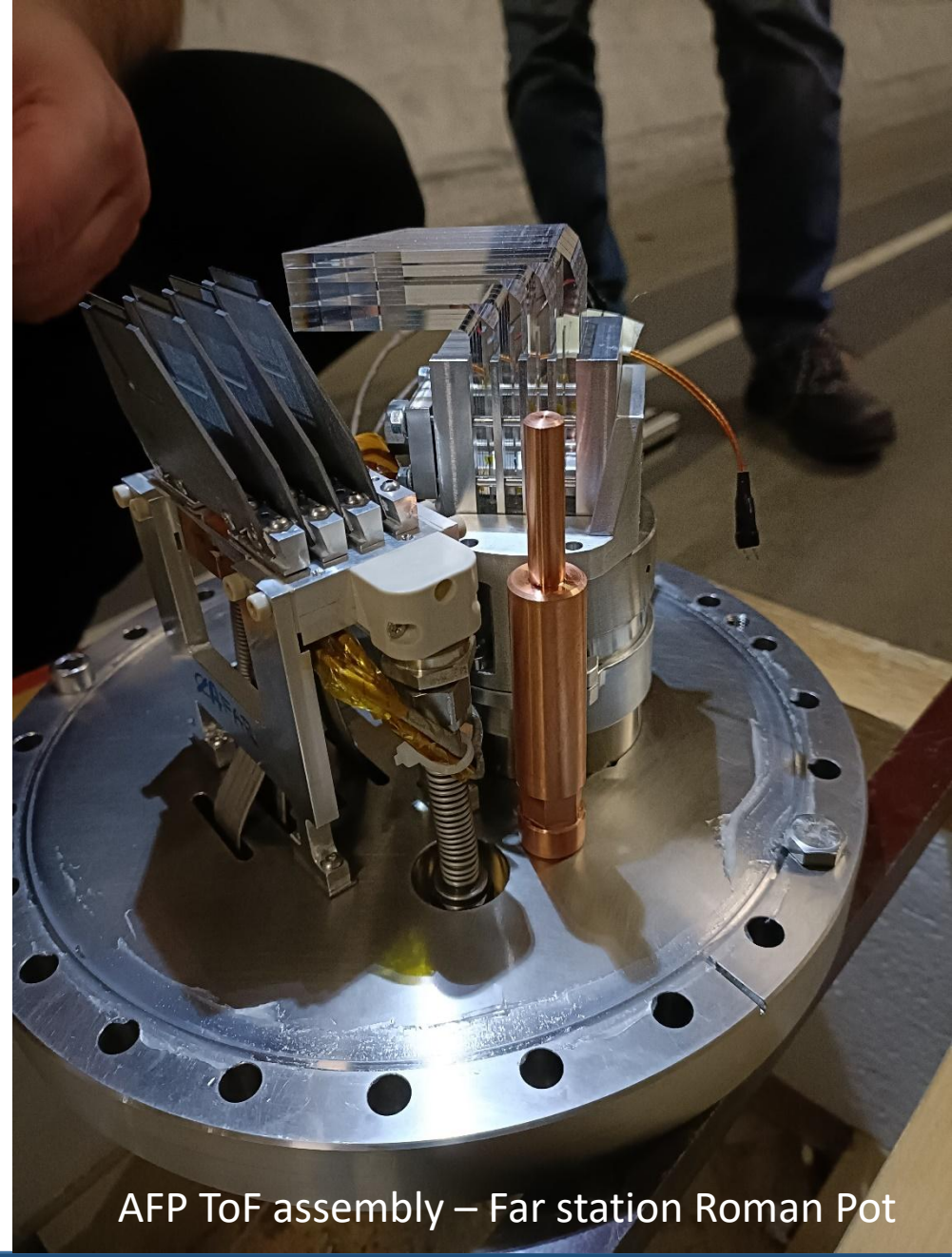






* During YETS 2025/2026 TDC was upgraded: from HPTDC (1 module 2 trains) to pico-TDC (1 module 4 trains)

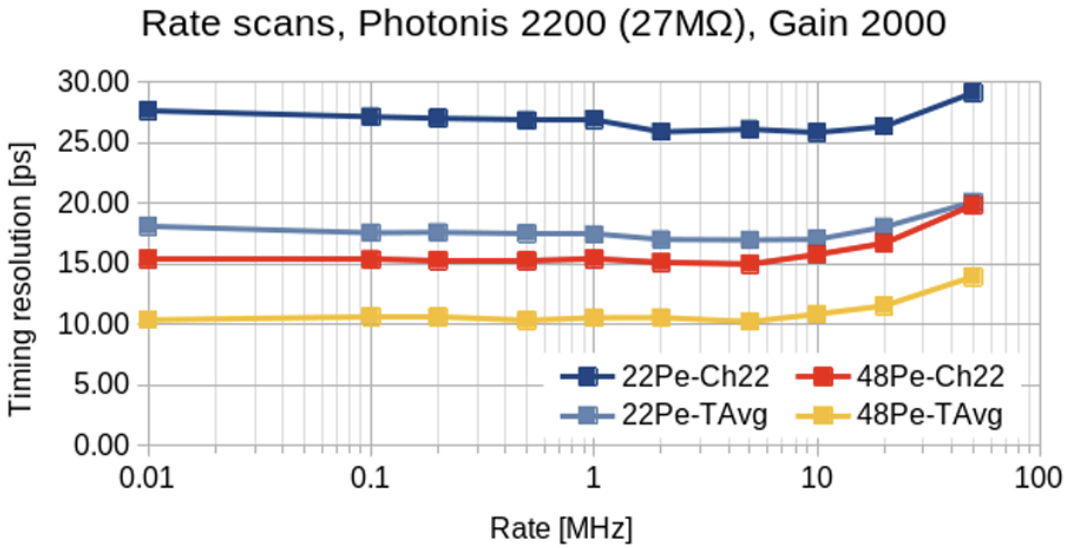


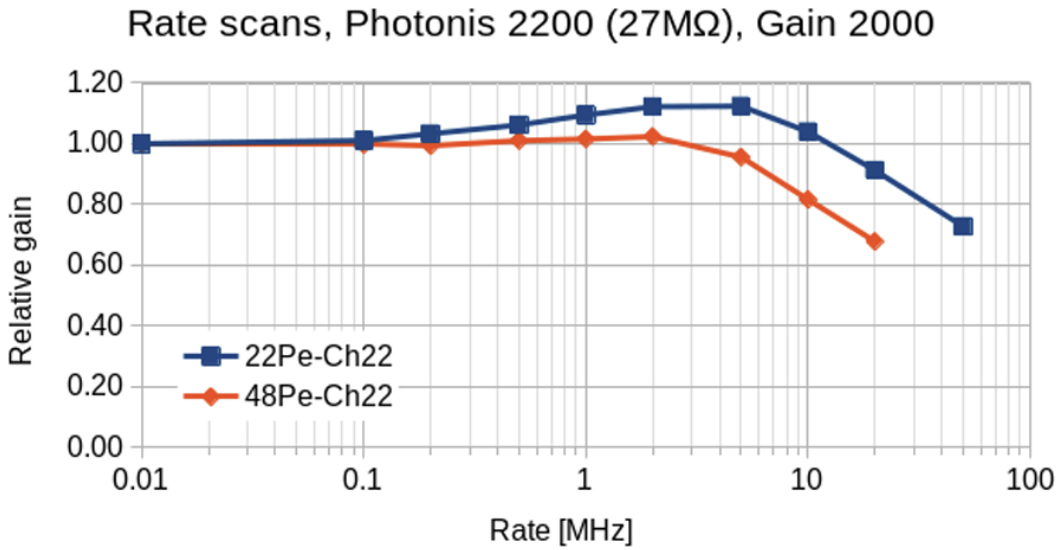


AFP ToF assembly – Far station Roman Pot

Photomultiplier (MCP-PMT)

- Need for long-life tubes with relatively low MCP resistance (~ 20–30MΩ)
- Need to deal with high rates
- Solution*: XPM85112-S-R2D2— low-resistance MCP (27 MΩ), selected for long lifetime at LHC radiation levels — operating at low gain (×2000) to maximize rate capability (R2D2 tubes)
- Gain depletes at very high rates, influencing timing and efficiency above ~15 MHz
- Out of vacuum design – PMT out of the pot, major serviceability upgrade
- **PMT is working in the tunnel whole Run-3 – never changed**
  - Radiation level at Far station is around **1000 µSv** after beam dump





* A. Lehmann et al 2018 JINST 13 C02010, A. Lehmann et al 2017 NIM A 876, 4–24, Brandt et al. 2021 NIM A 985, 164705, Komárek et al. NIM A 1041, 167330, 2022

Time-to-Digital Converter (TDC)

Used throughout Run 3 (2022–2025) High Performance TDC (HPTDC):

- Rate limit 8MHz
- Train resolution after trigger subtraction 20.6 ps
- 2 modules per side (module handles 2 trains)
- Radiation-tolerant

Resolution – test beam results

Installed during YETS 2025/2026 picoTDC:

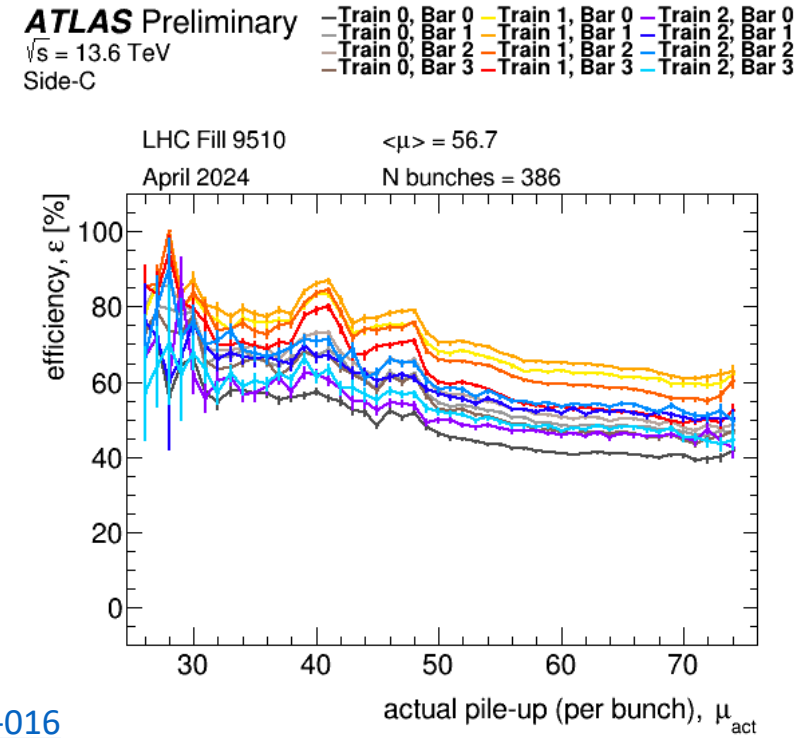
- Performs perfectly at 60MHz
- Theoretical rate limit 79MHz (260BX latency), no limit found with lower latency (40BX) – up to 200MHz
- Train resolution after trigger subtraction 13.4 ps
- 1 module per side (module handles all 4 trains)
- Radiation-hardened

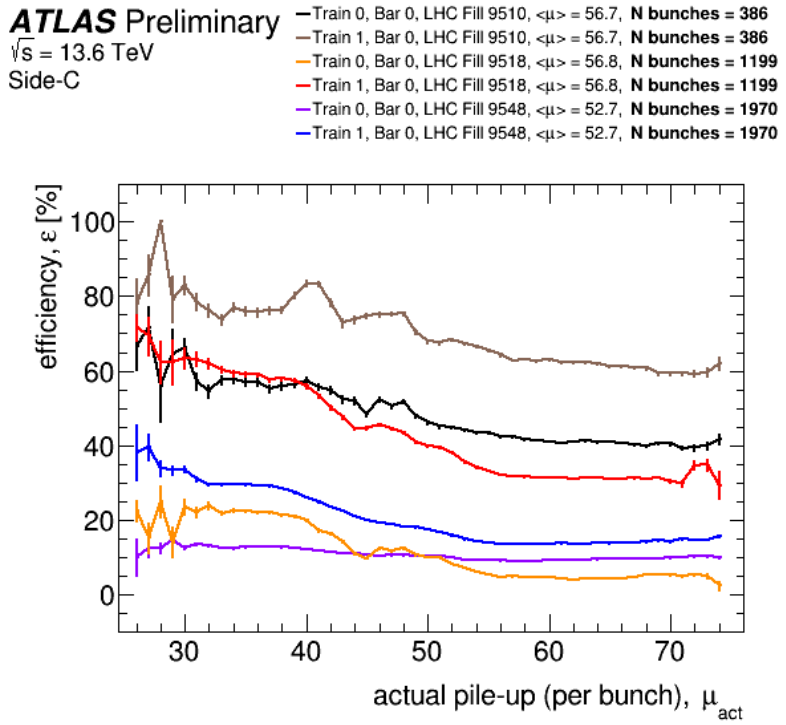
ToF challenges

The following dependencies were found after analysis of ToF data in 2024-2025 (using HPTDC):

- ToF efficiency depends on number of interaction per bunch crossing (μ)
- ToF efficiency depends on a filling scheme of LHC (number of bunches)

New pico-TDC was developed and installed for 2026 operation

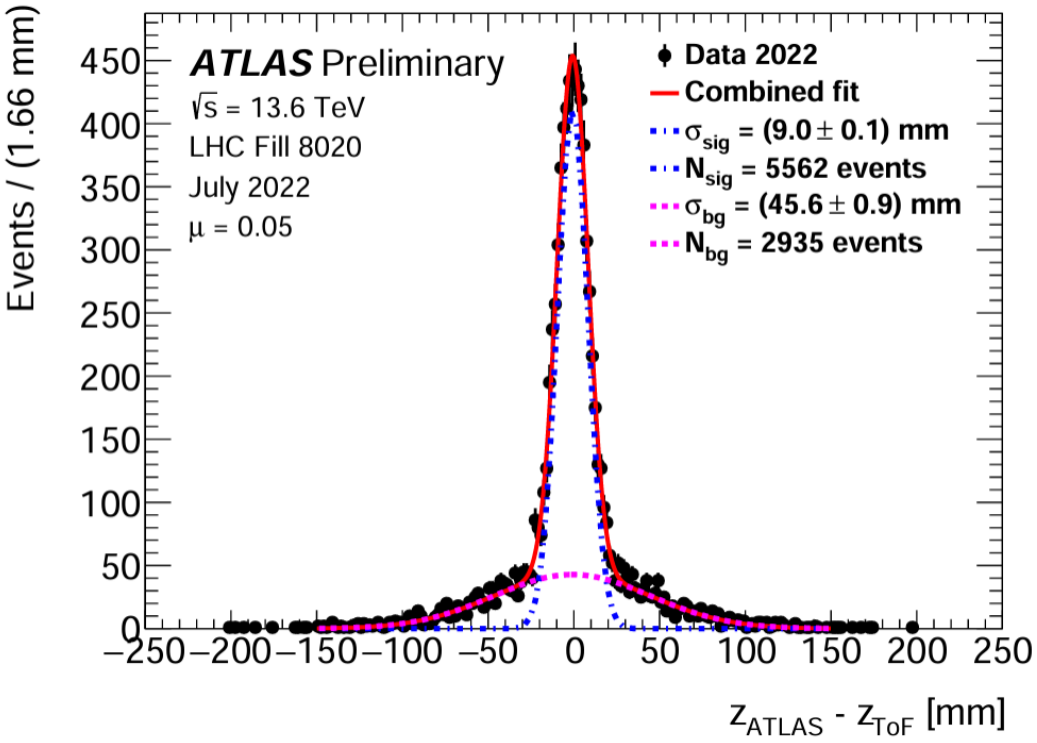




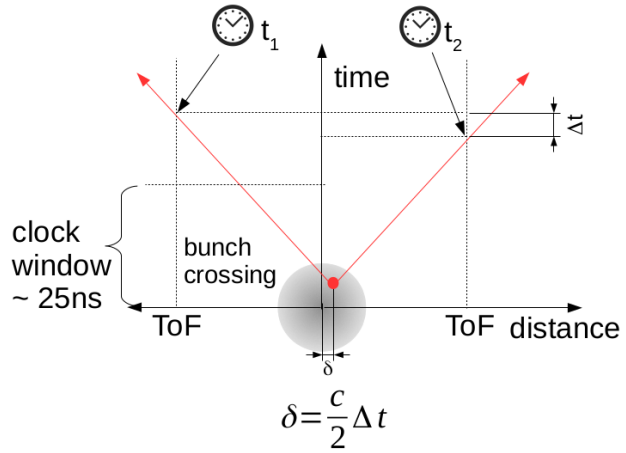
ATL-COM-FWD-2025-016

Di-proton ToF vertex reconstruction: vertex matching

- The ToF detector reconstructs the primary vertex in the case of finding two leading protons under the proper conditions.
- However, it can reconstruct fake vertices caused by a fake double-tag of two leading protons from two unrelated interactions in the same event.



- If z_{ToF} happens to be measured from protons that truly are coming from the primary ATLAS vertex, a narrow peak is observed in the otherwise wide $z_{\mathrm{ATLAS}} - z_{\mathrm{ToF}}$ distribution.

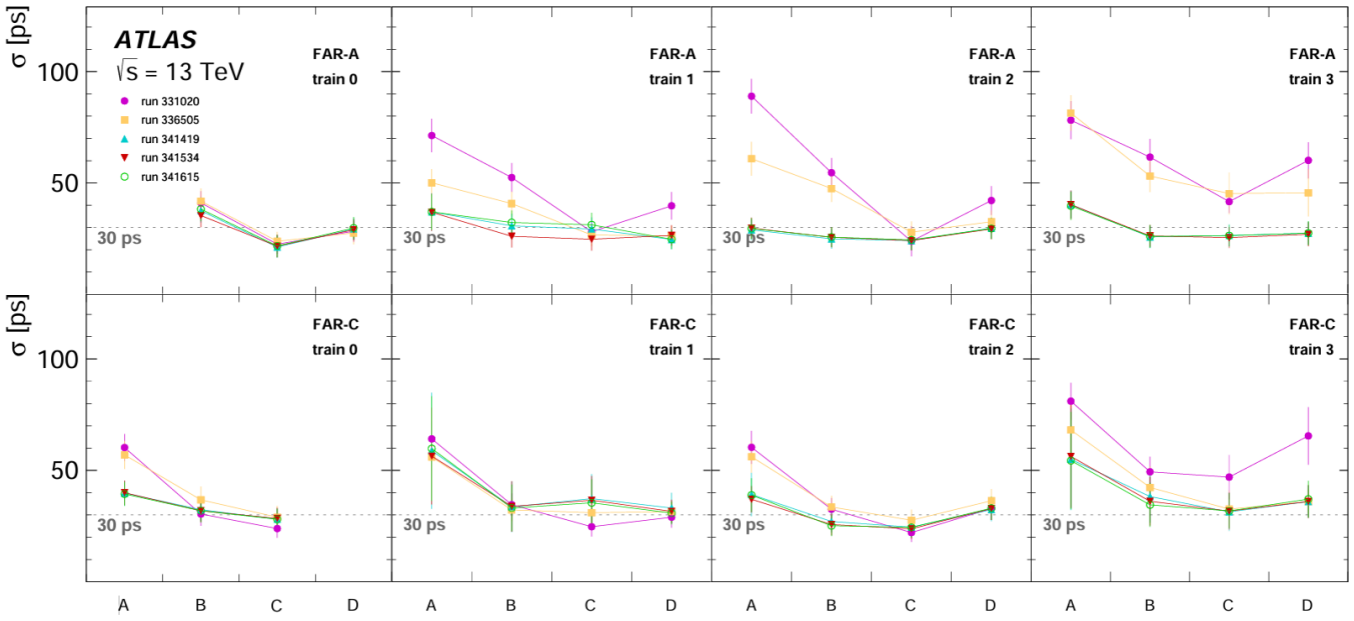


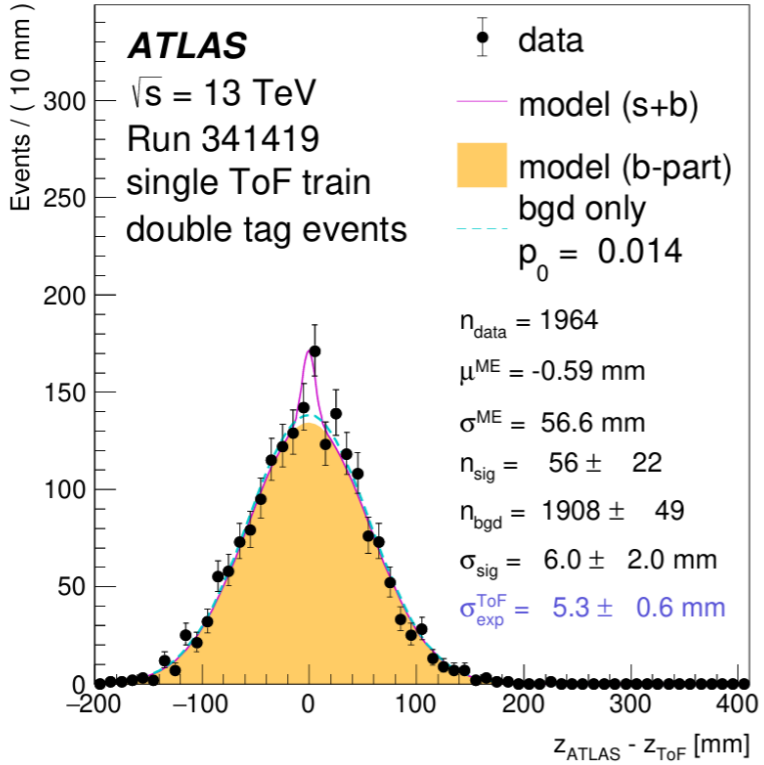
- Resolution σ = 9 mm ≈ 42.4 ps

ATL-COM-FWD-2024-019

ToF performance analysis 2017

- Performance analysis of 2017 data shows efficiencies of just a few percent
- Nonetheless good timing resolution, consistent with beam tests





2024 JINST 19 P05054

Summary

Upgrades before/during Run-3

- Monolithic glueless LQ-bars
- MCP PMT – new long-lifetime R2D2 tubes + out-of-vacuum design
- Third amplification stage (PAbc)
- Trigger module (DTM) added
- Laser Diode Pulser – new testing infrastructure added
- YETS 2025/2026: pico-TDC

ToF analysis with Run-3 data

- Efficiency dependencies
- Resolution in vertex matching analysis: 9 mm
- New pico-TDC 2026 data are being analyzed

Backup

MCP-PMT: 3 generations from 2017

The original XPM85112/A1-Q tubes (10 µm pores)

- completely unsuitable for long-term operation. Degrade after as little as 0.5 C/cm² of integrated charge —needed to be replaced multiple times per year

Generation 2 — XPM85212/A1-S (single ALD pore treatment)

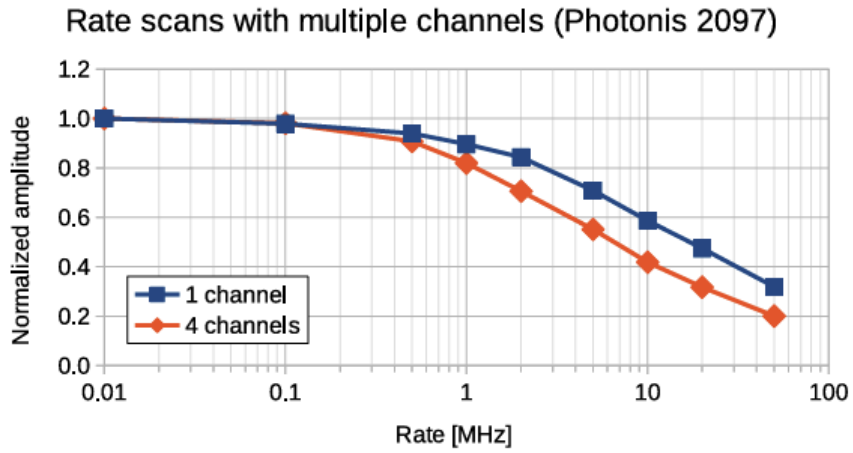
- 6.5 µm pores with single ALD (Atomic Layer Deposition) pore treatment reaching lifetimes of ~10 C/cm². However, they suffered from severe problems:
  - Extreme crosstalk when multiple channels were hit simultaneously
  - Long gain recovery after high-rate exposure

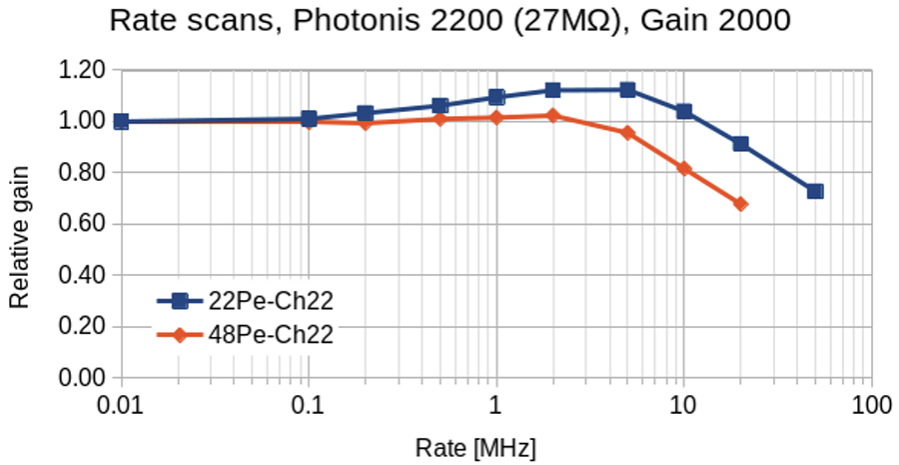
Generation 3 — XPM85112-S-R2D2 (double ALD treatment)

- 10 µm pores (proven technology) with a modified double ALD procedure
- No signs of degradation above 16 C/cm² — a 100× improvement over the original generation and a ~30× improvement over non-ALD types

Other improvements:

- Custom backend electronics
- HV divider redesign
- Out-of-vacuum redesign





MCP-PMT: Out-of-vacuum redesign

Complete mechanical redesign of how the PMT is housed relative to the Roman Pot vacuum. In the original design, the PMT and PAa preamplifiers were inside the Roman Pot secondary vacuum, requiring complex HV vacuum feedthroughs, flex cables routed through tight spaces, and laborious alignment procedures. Problems included:

- HV supply on the vacuum side was unreliable and caused operational issues
- PAa and PAbc channels sometimes failed during handling
- The PMT was not replaceable without opening the vacuum system
- Alignment was extremely tedious and prone to accidentally damaging the SiT silicon tracker planes

The OOV solution placed the PMT outside the vacuum, separated from the bar matrix by a glass separation window with anti-reflection coating. The PAa coaxial cables now plug directly onto the back of the PMT via MMCX connectors, and all cabling runs through an external mounting tube. Benefits:

- PMT is now field-replaceable without breaking vacuum
- No more complex HV vacuum feedthroughs
- Alignment is done with precision screws from the outside, not with internal shims
- Cleaner signal path, easier shielding

Other improvements for Run-3 ToF

Cherenkov Radiator Bars — Glueless Design

- The original 2017 bars were glued together from two pieces using epoxy at the L-joint. This was the weakest point of the optical system:
  - The glued joint was mechanically fragile and prone to breaking during handling or transport
  - The epoxy blocked UV wavelengths below 250 nm, cutting off a significant portion of the Cherenkov spectrum
  - The epoxy's optical transmission degraded further with radiation exposure at levels far lower than what the quartz glass itself could withstand (as shown in spectral transmission vs. irradiation tests)
- The solution – manufacture the bars as a single monolithic piece, a labour-intensive process developed by the Joint Laboratory of Optics in Olomouc.
  - Signal amplitude increased by a factor of 1.6–1.9
  - Timing resolution improved by 15–20%
  - The only geometric compromise was a slightly rounded inner corner at the L-joint, replacing the former clean 90° angle

Third Amplification Stage (PAbc Upgrade)

- The original design used two amplification stages (PAa and PAbc). Operating at lower PMT gain to improve rate capability required stronger downstream amplification. A third stage was added via modifications to the PAbc module.

Digital Trigger Module (DTM) — New Addition

- Serves two functions: signal pass-through and generation of a trigger output based on coincidence conditions (e.g. 2/4 or 3/4 bars firing in a train). It enables the fast-trigger capability of the ToF system

Laser Diode Pulser — New Testing Infrastructure

- A dedicated laser diode pulser (Hamamatsu C10196) was introduced as an in-site calibration and testing tool. It delivers light pulses through optical fibres directly into each bar channel and allows verification of all 16 channels without needing a particle beam.

Electromagnetic Shielding Improvements

- Nickel shielding tape was applied to all HV lines, HV dividers, and ToF coax cables
- SiT flex cables (which were inducing noise into ToF signal lines) were wrapped in nickel tape
- PMT bodies were wrapped in thick shielding material
- Ferrite beads were added to the HV line near the PMT

ToF Efficiency

Method

- First sample: events passing main selection criteria and in addition inside a specific region of SiT
  - 4 numbers for each ToF train
- Second sample: defined for each ToF channel
  - 16 numbers for each ToF channel
- Final efficiency: the ratio of the number of events in sample two (each channel) and number of events in sample one (each train).

Following requirements were imposed on the data:

- One track in the SiT Far per event.
- One hit per channel in ToF per event.

The regions for the x-value of the SiT, corresponding to the ToF train were defined experimentally for each side (A and C).

Train №	A-side (mm)	C-side (mm)
0	-4.9 to -2.0	-5.3 to -2.0
1	-8.0 to -5.0	-8.4 to -5.4
2	-13.0 to -8.1	-13.4 to -8.5
3	-15.0 to -13.1	-15.0 to -13.5

Di-proton ToF vertex reconstruction: time delays

- The time measured in one ToF channel is made up from several components, one of them is constant time delay, individual for each channel.
- Method, proposed by Karel Cerny: $z_{ToF} = \frac{c}{2}(t_C - t_A)$ value in its mean value copy the z-position of the luminous ATLAS beamspot.
- Requirements on data:
  - One track in SiT per event
  - One hit per channel in ToF per event
  - One active train in the ToF per event
    - Gives the most clean signal

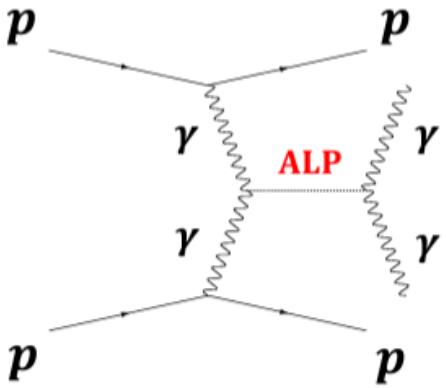
Channel delays and ToF positions are absorbed into correction factors “D”:

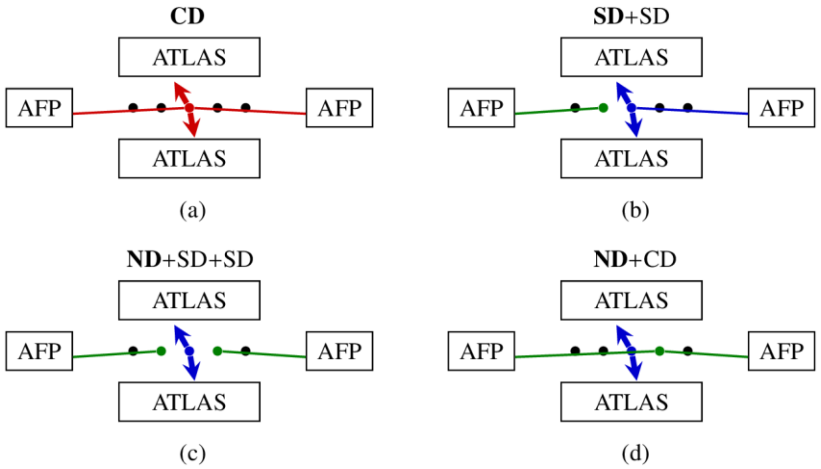
$$< \sum_{LB} z_{\mathrm{ToF}}^{(ij)} - z_{\mathrm{BS}} >= D_C^j - D_A^i$$

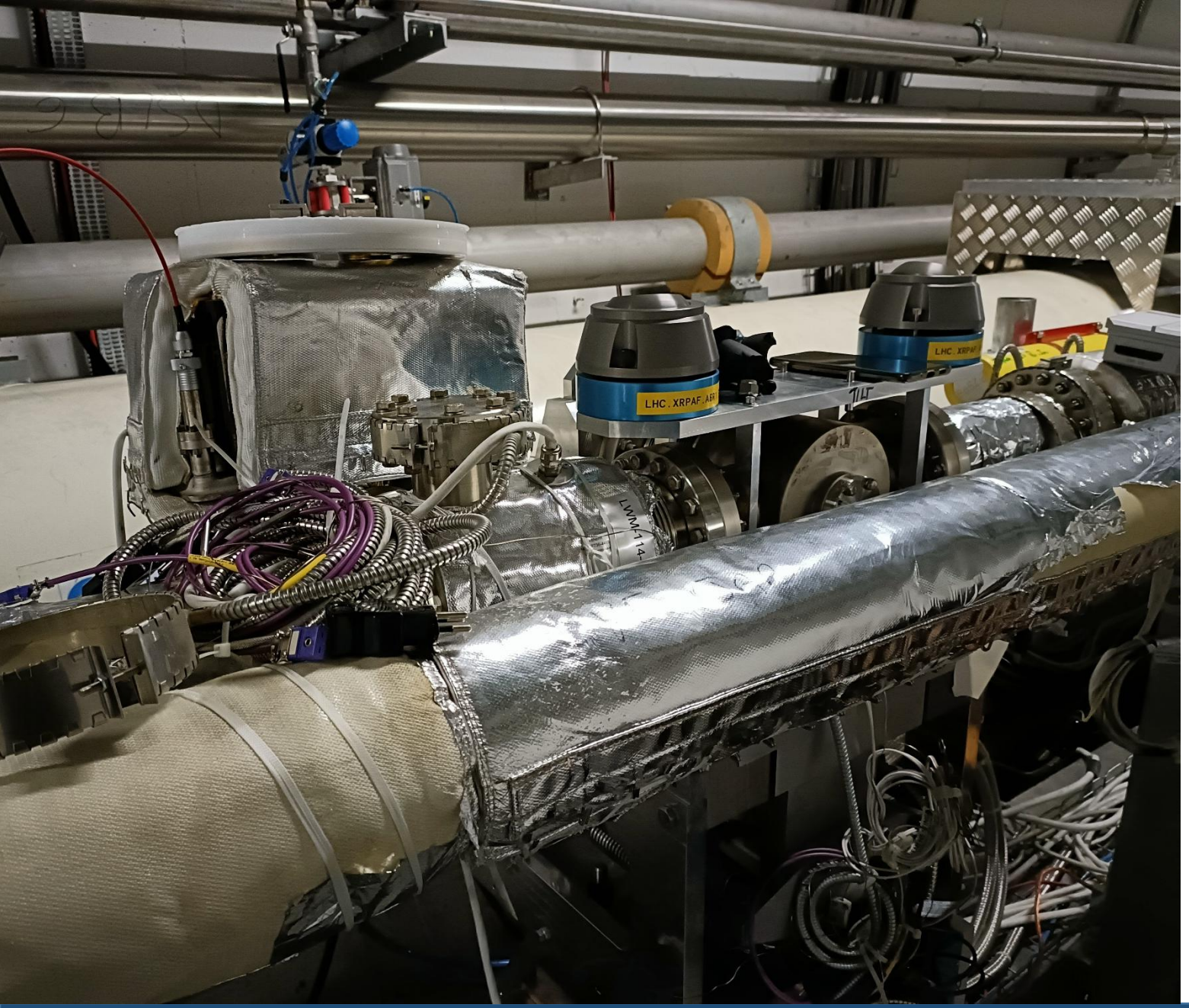
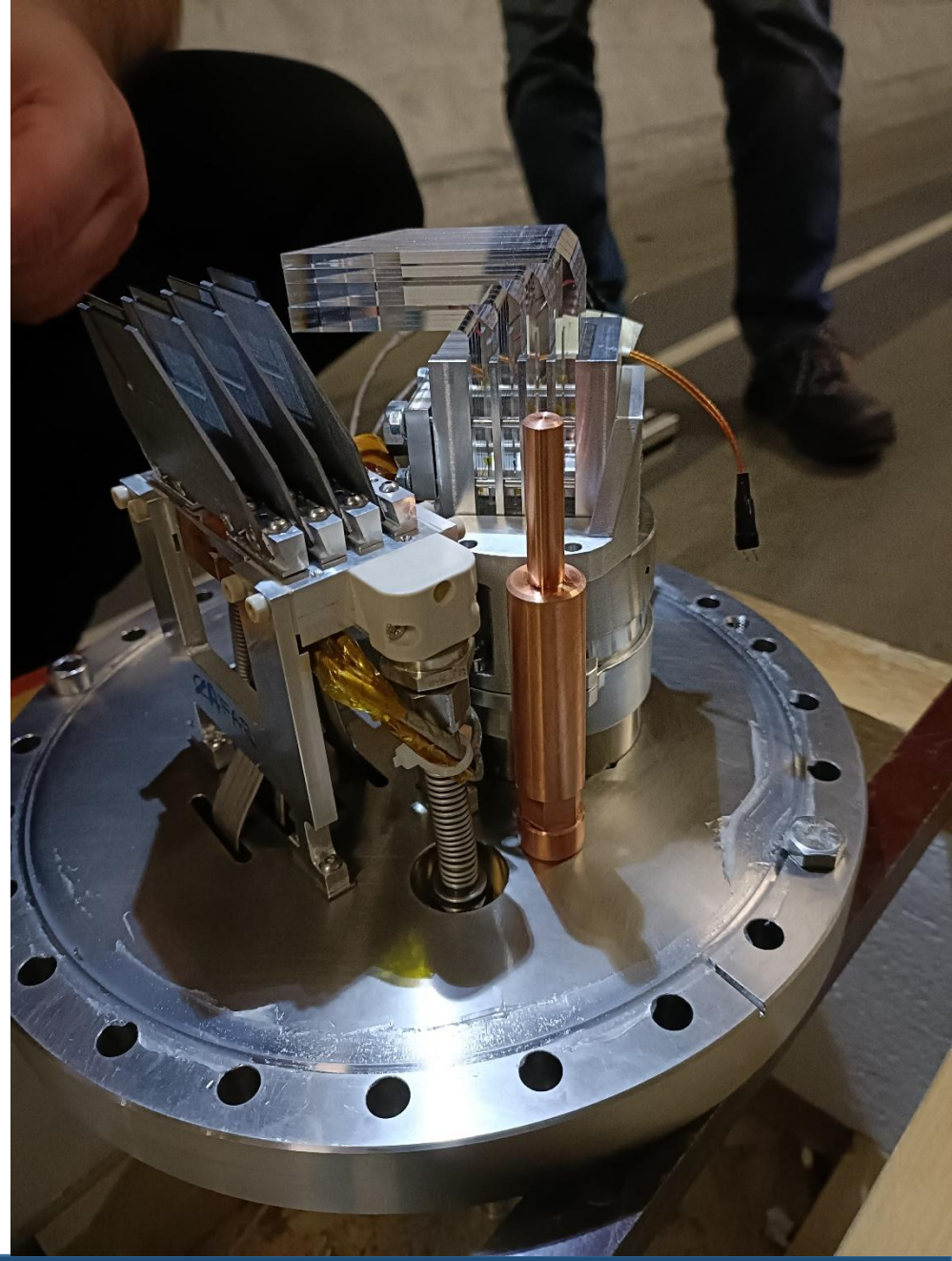
- ToF z-position is obtained within one lumiblock, using mixed events technique.
- Using chi-squared minimization fit 32 correction factors are obtained from 256 time delays.

ToF usage: ALP motivation

- Many extensions of the Standard Model use Axions and Axion-like particles (ALP), which are considered as candidates for particles that make up dark matter.
- Vertex position of di-photons are used as a criteria to separate di-photon events coming from the expected ALP signal from such events produced in background processes.
- Photons events from process of central exclusive di-photons production $pp \rightarrow p(\gamma\gamma)p$ are recorded with the ATLAS central detector. Protons are recorded with AFP.
- The ToF detector will provide data to improve the vertex reconstruction.






LHC . XRPAF . AR
LHC . XRPAF