ATLAS Forward Proton

Summary of Data-taking + Plans for 2024/2025

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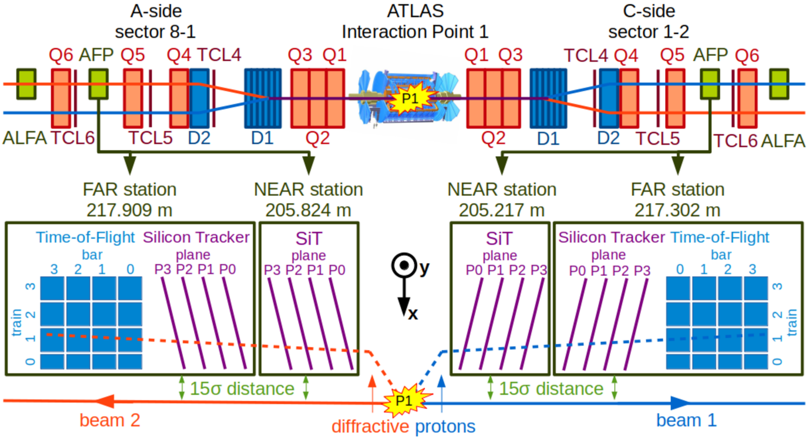
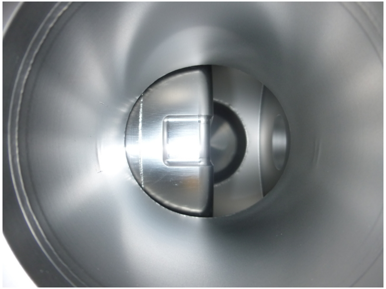
ATLAS Forward Proton (AFP) Detector

- 4 Roman Pot stations at $\pm$ 205 and 217 m from ATLAS collision point.
- Near stations: Silicon Tracker (SiT) for precise proton position measurement.
- Far stations: SiT + Time-of-Flight (ToF) detectors for pile-up background reduction.

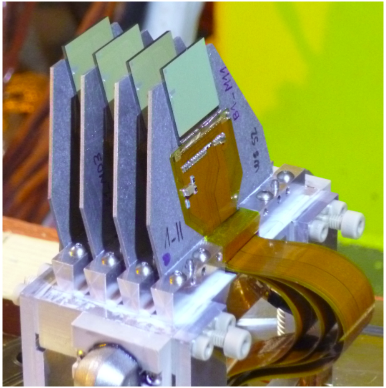


AFP Silicon Tracker

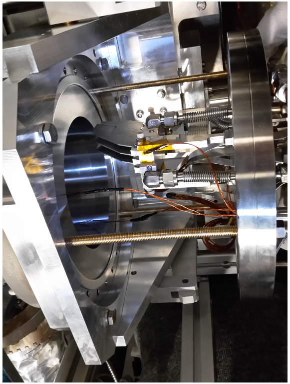
Roman pot as "seen" by proton beam, thin window of RP is visible:



4 layers of SiT modules mounted on heat exchanger:



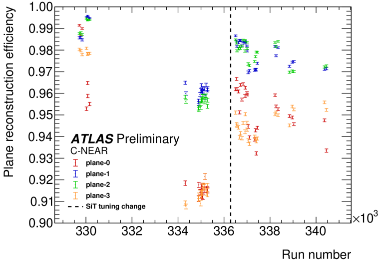
Installation of detector package:

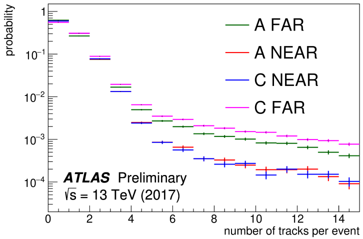


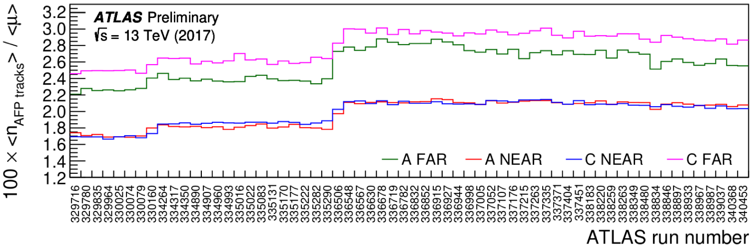
- **4 Silicon Tracker (SiT) planes** are present in each RP station to measure proton position.
- Slim-edge 3D ATLAS IBL pixel sensors bonded with FE-I4 readout chips.
- 336×80 array of 50×250 μm^2 pixels per plane.
- 14° **tilt** to improve resolution in x, staggering of layers to improve resolution in y.
- Resolution (measured): 5.5 ± 0.5 μm in x and ≈ 30 μm in y [JINST 11 (2016) P09005].

Run 2 Performance Highlights: Silicon Tracker

- Hit reconstruction efficiency between 95 and 98% (single plane; top plot).
- Track reconstruction efficiency on the level of 99%.
- No major issues with multiple-track reconstruction (showers; bottom left).
- Change of detector-beam distance nicely reflected by change of the average track multiplicity (bottom right).

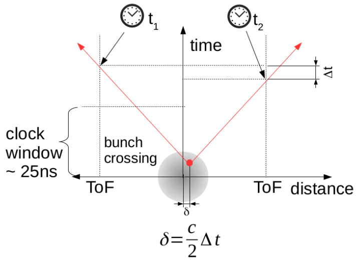




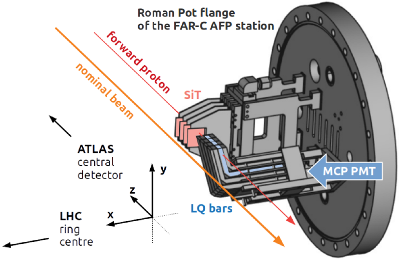


AFP Time-of-Flight Detectors

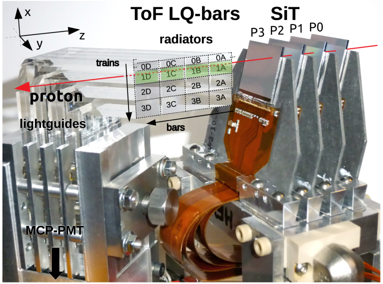
Concept of ToF measurement:



Sketch of mounting SiT and ToF (Run 2 design):

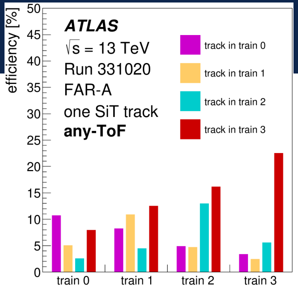


Detector package before installation (Run 2 design):

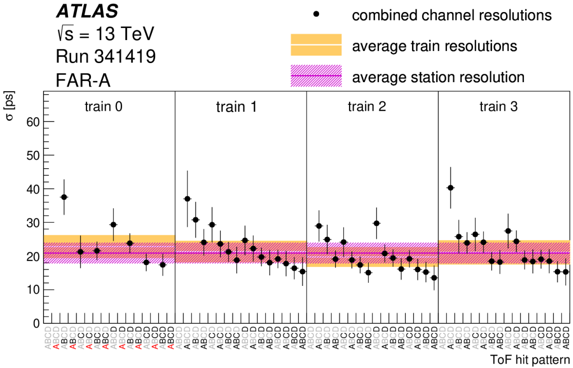


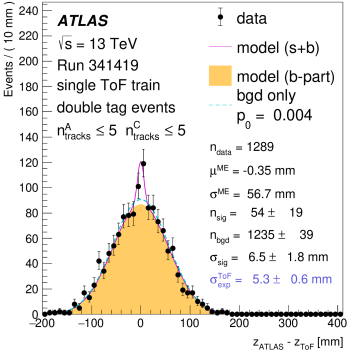
- **Purpose:** Assign protons to individual collisions in IP1 (reducing background due to pile-up).
- **Concept:**
  - measure ToF difference: $\Delta t = (t_A - t_C)/2$,
  - calculate vertex position: $z_{ToF} = c\Delta t$,
  - compare vertex z position reconstructed by ATLAS and AFP ToF.
- Detectors: 4×4 matrix of quartz bars, L-shaped and rotated 48° w.r.t. LHC beam (Cherenkov angle).
- **Timing:** aim for 20 ps [Opt. Express] resolution for Run 3, 30 ps at the beginning (in Run 2) [JINST 11 (2016) P09005].

Run 2 Performance Highlights: Time-of-Flight



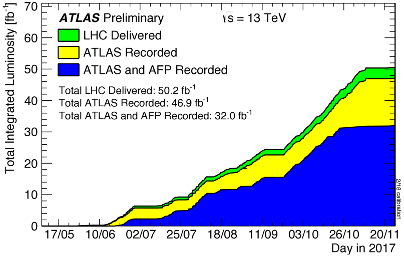
- Low data-taking efficiency, later understood to be due to non-radiation hard PMT (top plot).
- Very good timing reconstruction resolution:
  - 20 – 40 ps within a station (between ToF bars; bottom left),
  - translating to $\sim$ 5 mm of vertex reconstruction resolution (bottom right).

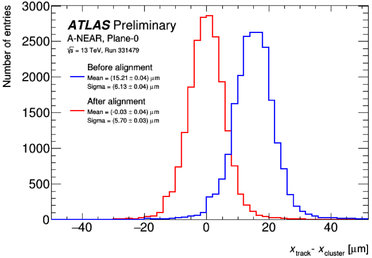


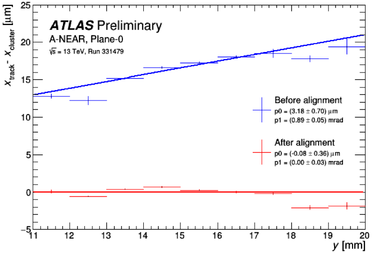


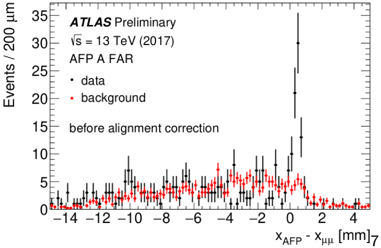
Run 2 Performance Highlights

- Around 32 fb^{-1} of high-μ data recorded (top right plot), from which 19.2 fb^{-1} used for analyses after data quality requirements.
- Few special, low pile-up runs ($\mu \sim 0.04, 1$ and 2).
- Detector alignment well understood:
  - between SiT planes (bottom left),
  - SiT plane rotation (bottom middle),
  - wrt. proton beam (bottom right).
- Run 2 performance studies published:
  - SiT: ATL-FWD-PUB-2024-001,
  - ToF: JINST 19 (2024) P05054.



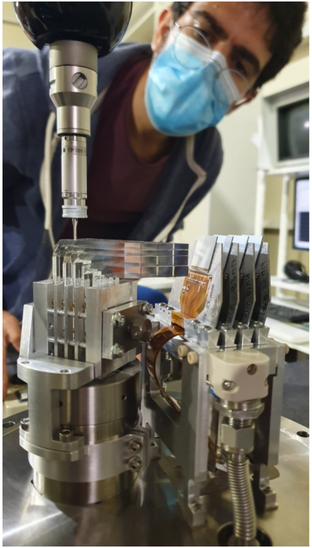


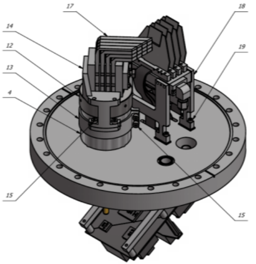


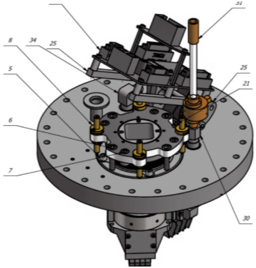


AFP Upgrades for Run 3

- Improvement in silicon detector cooling (new heat exchangers).
- Production of new SiT modules.
- New design of detector flange: Out-of-Vacuum solution for ToF detectors.
- New trigger module: possibility to trigger on single train.
- New photo-multipliers: address inefficiency issues from Run2 data-taking.
- Upgraded readout chain.
- Above items were successfully tested at DESY in 2020.
- Both NEAR and FAR station have been successfully installed in the LHC tunnel before 2022 data-taking campaign.

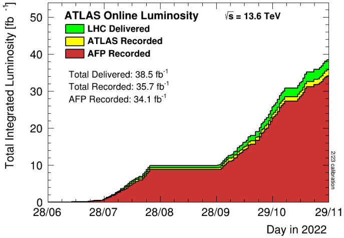


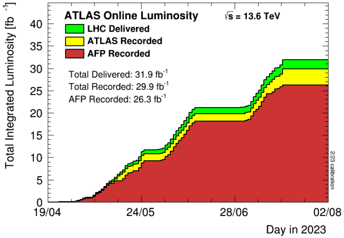


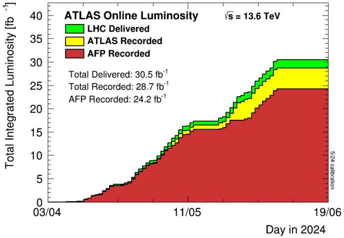


Run 3 Data-taking

- Continuous data-taking with other ATLAS sub-systems in high pile-up runs:





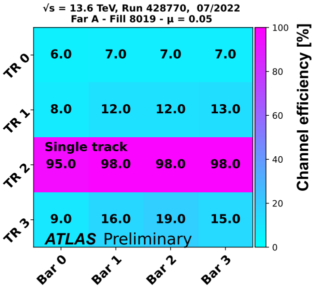


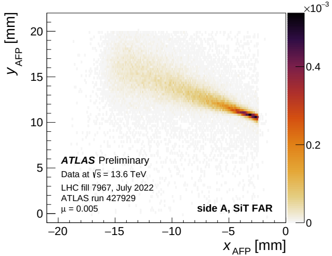
- Several dedicated, low-μ data-taking campaigns:

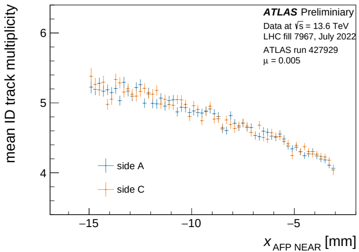
2022		2023		2024	
pile-up	recorded lumi	pile-up	recorded lumi	pile-up	recorded lumi
1	630 nb^{-1}	1	230 nb^{-1}	1	12.5 pb^{-1}
0.25	73 nb^{-1}	0.2	35 nb^{-1}		
0.05	63.6 nb^{-1}	0.05	63 nb^{-1}		
0.02	170 nb^{-1}	0.005	1.76 nb^{-1}		
0.005	0.46 nb^{-1}				

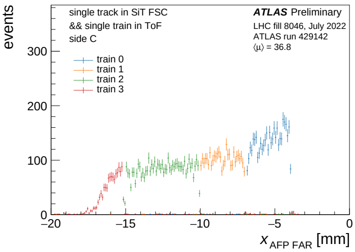
Run 3 Performance Highlights

- Well understood inter-plane alignment; studies of global alignment ongoing.
- High SiT hit reconstruction efficiency.
- Good ToF efficiency during low-μ runs (top right); inefficiency at high-μ under investigation.
- Correlations between AFP and 'central" ATLAS objects (bottom middle).
- Link to additional performance plots.





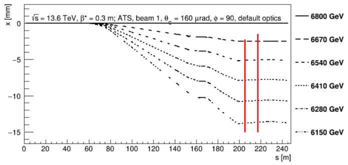




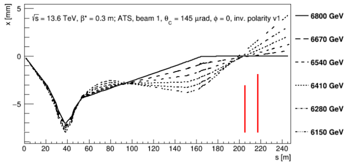
Concern: Inversion of Triplet Polarity

- In 2023 a concern about LHC magnets in vicinity of IP1 and IP5 was raised by some of LHC experts: elements may not survive until the end of Run 3.
- In order to mitigate the effect, an idea to re-cable the inner triplets and change the plane of the crossing angle (horizontal $\leftrightarrow$ vertical) was proposed.
- The AFP acceptance is highly dependent on the LHC optics settings:
  - unfortunately the "full inversion" (reversing magnet polarity and changing IP1 crossing planes) resulted in no protons in the AFP $\rightarrow$ end of data-taking!
  - for 2024 "partial inversion" (reversin triplet polarity followed by optics adaptation) was introduced:
    - acceptance comparable to 2022–2023 one,
    - worse energy reconstruction resolution (proton trajectories closer to each other),
    - increased radiation in vicinity of TCL6 collimator $\rightarrow$ negative, destructive effect on the AFP electronics in the tunnel.
  - for 2025+ the decision abut optics is not made yet $\rightarrow$ major uncertainty regarding the AFP data-taking plans.

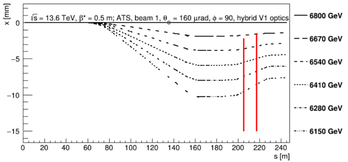
optics before inversion: 2022–2023



"full inversion" $\rightarrow$ zero acceptance



"partial inversion": 2024 (and possibly 2025)



Plans for Data-taking

2024:

- Continue data-taking as efficiently as possible:
  - use short accesses to promptly replace electronics damaged due to radiation,
  - refurbish damaged parts & produce spares,
  - mitigate the SiT radiation damage (especially in the peak of the "diffractive pattern") by increasing high voltage as long as possible,
  - understand and address ToF inefficiency at high-μ.
- Take part in the 2024 "pp reference" run (Beam Based Alignment required).
- Participate in all special, low-μ runs once they will happen.

2025 (and 2026?):

- High-μ plans contingent on inner triplet radiation dose mitigation strategies:
  - if triplet polarity as in 2024 $\rightarrow$ AFP in all standard high-μ runs,
  - if crossing angle changes from vertical to horizontal at IP1 $\rightarrow$ AFP limited to special runs only.
- Participation in 2025 proton-oxygen and oxygen-oxygen runs:
  - insertion possible on both proton and oxygen sides,
  - additional beam-based alignment required.

HL-LHC:

- Run 4 (HL-LHC, from 2029): no ATLAS Roman Pots,
- Run 5+: possibility of re-installation (space reservation maintained); recently, some discussions on the physics programme and detector technology started.

Summary

- **Run 2** performance:
  - SiT: high efficiency (95-98%), alignment understood,
  - ToF: good timing resolution (20-40 ps), but faced efficiency issues,
  - general: good understanding of global alignment and proton reconstruction,
  - $\sim$32 fb^{-1} of high-μ data recorded; analyses ongoing.
- **Run 3** upgrades and data-taking:
  - improved cooling, new modules (SiT, ToF, readout electronics), out-of-vacuum ToF solution,
  - continuous data-taking in high pile-up runs: $\sim 84.6 fb^{-1}$ of high-μ data recorded so far (2.6 times more than in Run 2),
  - several dedicated low-μ campaigns,
  - detector performance studies ongoing,
  - first analyses of Run 3 data started.
- Challenges and **future plans**:
  - concerns about radiation damage of LHC magnets leading to optics changes,
  - 2024: continue data-taking, address radiation damage of AFP electronics,
  - 2025+ plans are driven by the decisions on the LHC (change of crossing plane),
  - HL-LHC: no AFP in Run 4, possibility for re-installation in Run 5+.

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