The ATLAS Forward Proton (AFP) sub-detector and the adverse effects of radiation from Large Hadron Collider (LHC) collimators during pp-collisions at 13.6 TeV

ATLAS EXPERIMENT

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1. Introduction & Motivation

AFP stations are installed at ~205 and ~218 m on both sides of the **ATLAS Interaction Point (IP1)**.

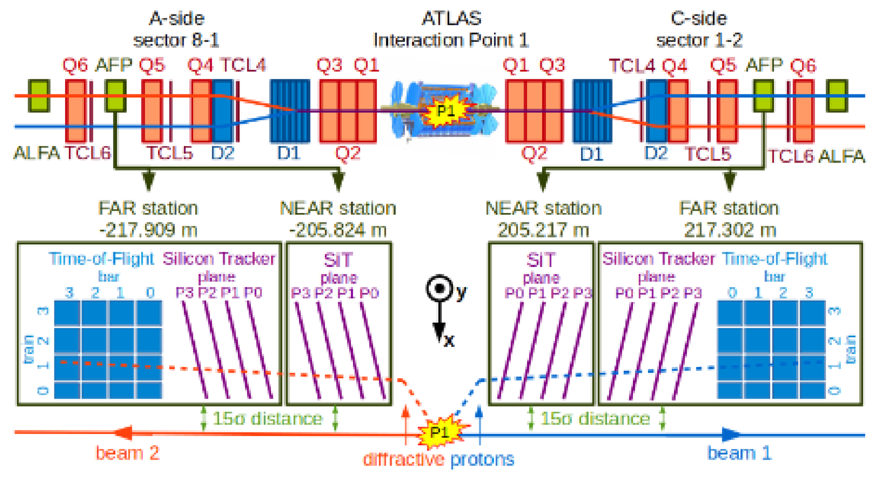
The "**NEAR**" stations located closer to the interaction point contain **Silicon Tracking** detectors (**SiT**), while "**FAR**" ones at **218 m** are also equipped with **Time-of-Flight** (**ToF**) devices.

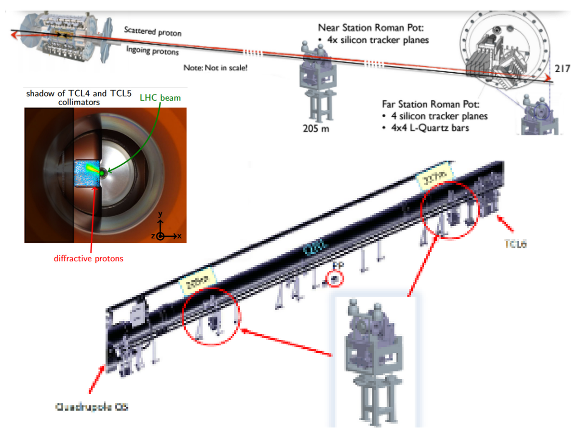
At **212 m** there is a **patch-panel (PP)** installed housing electronics services for module voltage regulation and data acquisition.

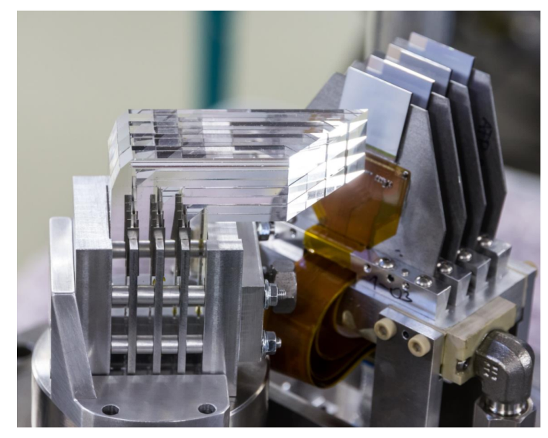
Each station's detectors are mounted on a flange, housed inside a "**Roman Pot**", which moves closer to the beam upon declaration of Stable Beams.

The purpose of the AFP tracking system is to **measure the trajectory of protons** deflected during a proton-proton interaction & collect data as much as possible for physics analysis.

During Run-3 collisions at **13.6 TeV**, severe radiation conditions emerged due to **increasing luminosity** and **collimator-induced particle showers.** These conditions pose challenges both for detector reliability and for safe hands-on access during short technical stops.







2. AFP Environment and Radiation Conditions

AFP FAR station located ~1 m upstream of the TCL6 collimator

→ small TCL6 aperture generates high local radiation levels

TCL6 absorbs secondary particles from IP1/IP5:

- protects downstream magnets and detectors
- reduces heat load on superconducting magnets
- prevents quenches

AFP exposed to a mixed radiation field dominated by:

- secondary hadrons
- neutrons
- electromagnetic showers

Run-3 operation revealed dose rates significantly higher than expected

Consequences:

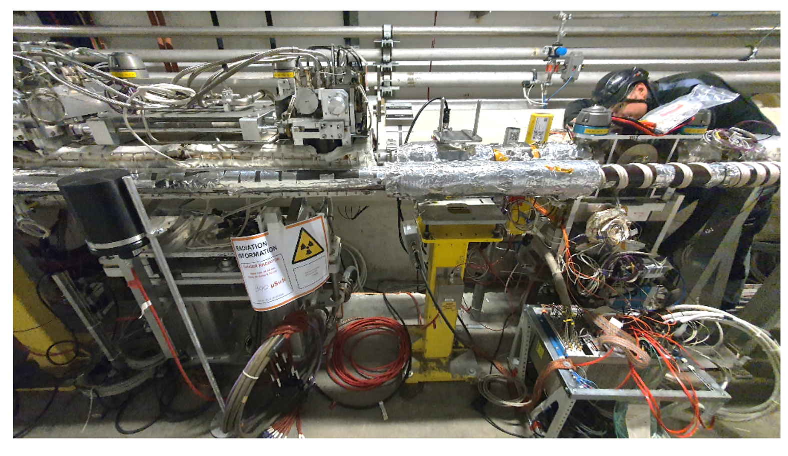
- reassessment of shielding
- revised access procedures
- evaluation of long-term operation scenarios

Radiation characterization based on:

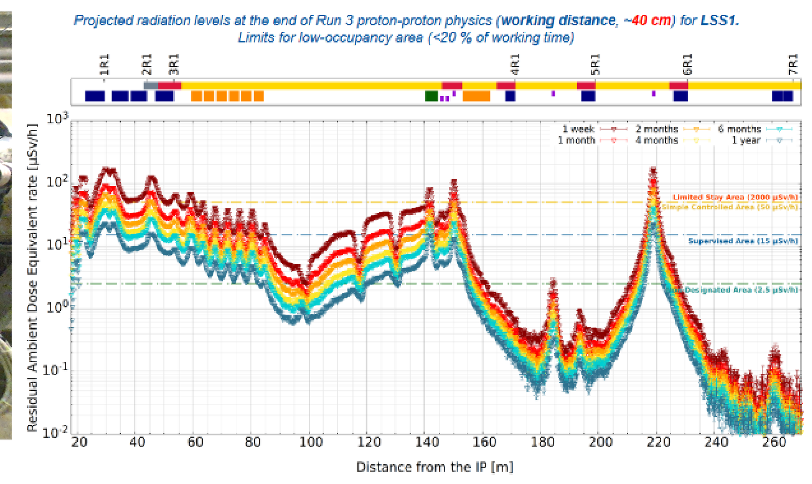
- active/passive monitors
- active/passive dosimeters
- FLUKA simulations

Used to evaluate:

- accumulated dose to electronics
- occupational exposure of tunnel personnel



LSS1L: 900 µSv/h (dose rate at 40cm)



3. Observed Radiation Effects on AFP and Operational Procedures

Radiation-induced effects observed in all AFP tunnel subsystems

Single-Event Upsets (SEUs)

- failures in control systems and electrical components
- observed in both SiT and ToF modules

Silicon tracker degradation

- increased leakage current and electronic noise
- growing number of bad pixels
- loss of detector efficiency

Calibration and electronics effects

- diffractive pattern burnout
- increasing difficulty of calibration and re-tuning
- long-term degradation of:
  - Local Trigger Boards (LTBs)
  - power supplies
  - front-end electronics

Operational impact

- intervention frequency increases with delivered luminosity
- repair / replacement campaigns affect:
  - detector availability
  - data-taking efficiency

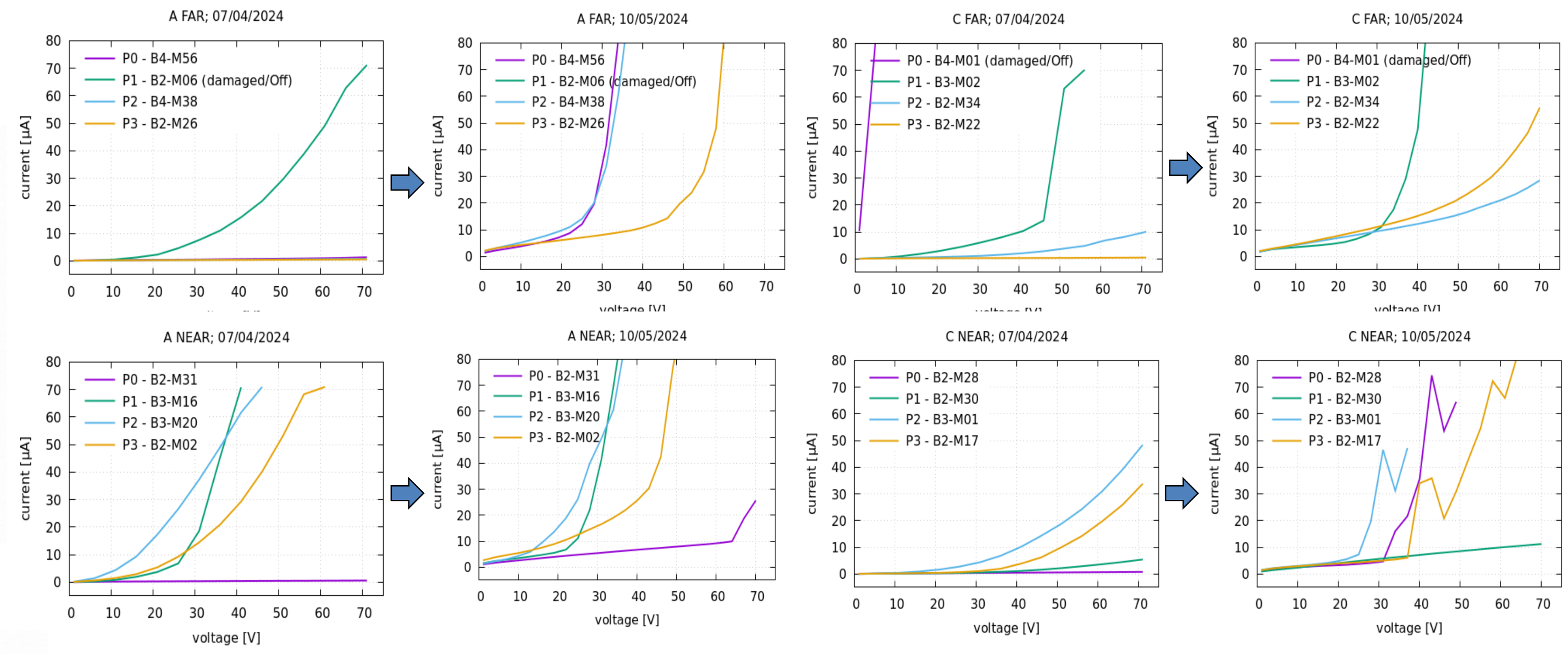
Radiation protection constraints

elevated AFP dose rates limit:

- intervention duration
- intervention frequency

maintenance activities optimized to:

- minimise individual dose
- minimise collective dose
- preserve detector performance



4. Impact on Personnel and Work Dose Planning

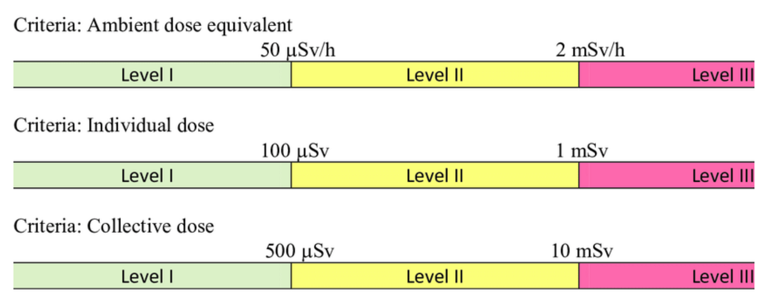
As LHC luminosity increased throughout Run 3, **tunnel interventions became progressively more constrained**, particularly at the FAR stations, where radiation levels reached up to **~2 mSv/h**.
Under CERN's default **ALARA** (As Low As Reasonably Achievable) **Level 1 criteria**, the maximum allowed individual dose is limited to **50–100 µSv** per person per day!

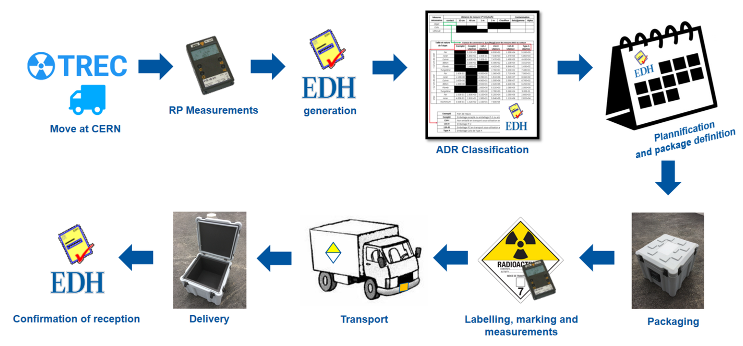
At the same time, the preparation of DIMRs (Dossiers of Intervention in Radiation areas) became increasingly complex due to the growing number of **IMPACTs** (Intervention Management Planning and Activity Coordination Tool entries) required throughout the year. In parallel, **Work Dose Planning (WDP) became mandatory**, requiring tunnel interventions to be carefully **optimised** in order to **minimise** occupational exposure.

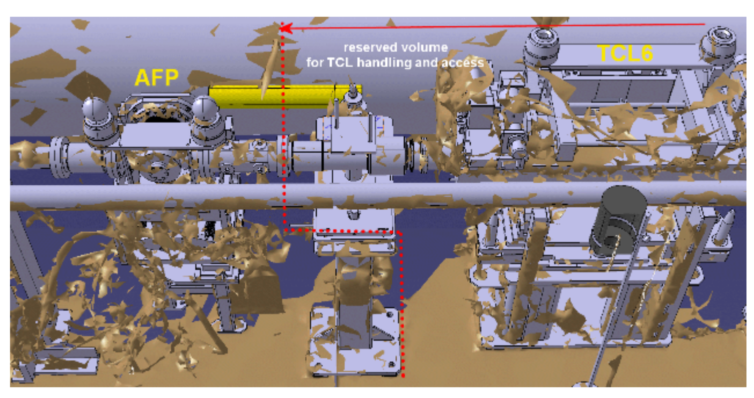
Both **individual** and **collective radiation doses** must remain within **regulatory limits**, while AFP interventions represent a significant contribution to the exposure of the personnel performing them. This has led to a more systematic approach to WDP, including **detailed job preparation**, **task consolidation**, **personnel rotation**, and the use of **additional local shielding** whenever feasible.

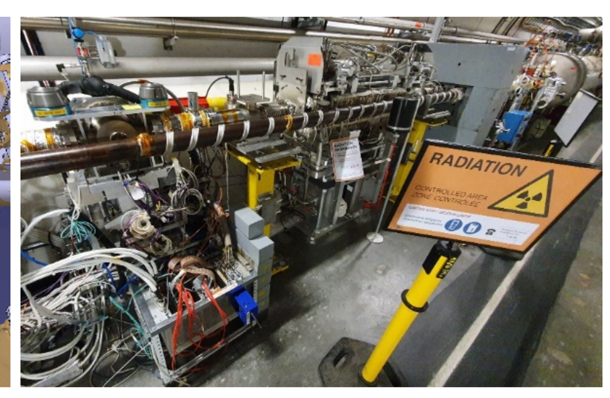
Furthermore, **self-transport of radioactive material was discontinued** during Run 3, making urgent interventions involving irradiated spare parts significantly more challenging and time-consuming.

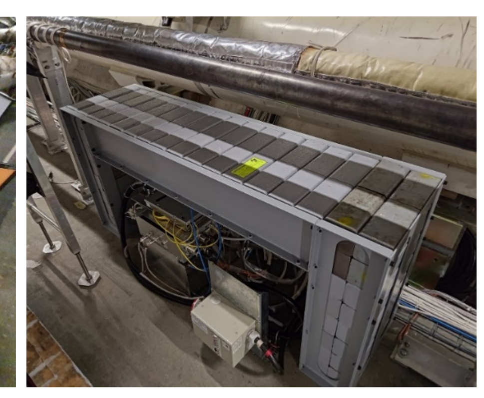
Careful work planning, strict dose management and the application of ALARA principles are essential to ensure the safety of personnel while maintaining detector performance.











5. Mitigation Strategies

Several mitigation strategies have been investigated and implemented to reduce the adverse impact of the collimator-generated radiation field on AFP and its personnel.

1 Collimator settings

- Relaxed TCL6 settings to favourable conditions agreed in 2023
- Reduced AFP radiation exposure
- Not available in 2024 due to conflicting R2E constraints
- Extensive equipment refurbishment during YETS 23/24

2 Shielding

- FAR stations: shielding severely constrained by geometry/vacuum layout
- Small local shielding wall installed in 2024 with no substantial impact
- **PP: shielding wall designed and installed during YETS 2024/2025**
- FLUKA simulations indicate:
  - dose reduction by a factor of ~3
  - particle fluence reduction by a factor of ~2

3 ALARA & WDP

- FAR stations: average dose rates up to ~400 µSv/h
- CERN Radiation Protection unit suggested to increase the default implemented ALARA Level 1 to Level 2 (up to 1 mSv) for AFP interventions in order to relax time constraints.
- Permanent/yearly IMPACT introduced
- Work Dose Planning (WDP) became mandatory
- Interventions carefully optimised to minimise occupational exposure

4 Radiation monitoring

- Battery-powered **BatMons** deployed near racks and patch panels on both sides of IP1
- Measurements indicate:
  - TID: ~100 – ~200 Gy
  - HEH fluence: 10^{11} – 10^{12} HEH/cm^2
- Radiation-induced failures deemed critical: very high probability of SEEs (*Single Event Effects*)

5 Transport & logistics

- Buffer-zone storage not available
- Radiation supervised lab nearby (SR1) used for this purpose
- Removed **ToF** crates in 2025 reached:
  - 8 µSv/h (Side-C)
  - 10 µSv/h (Side-A)

  at 40 cm distance

6 SiT damage mitigation

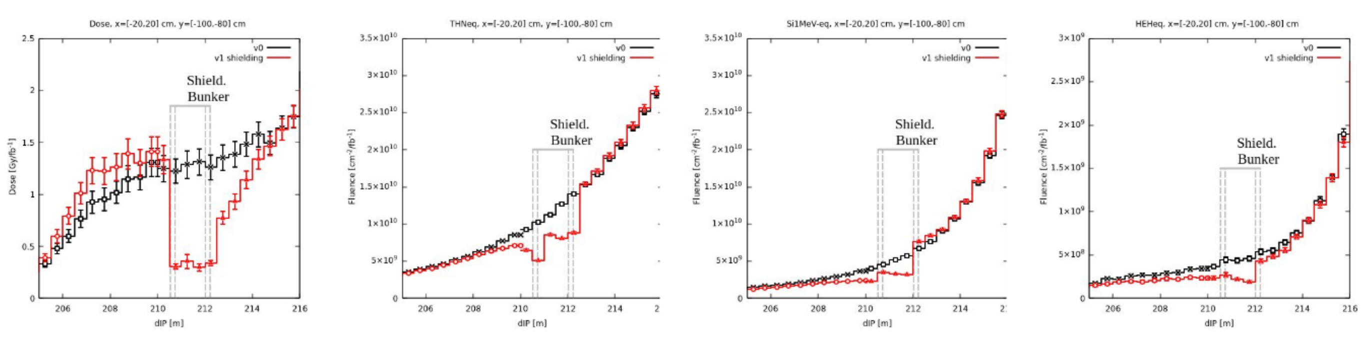
- 3D silicon sensors bump-bonded to **FE-I4B ASIC** improve radiation tolerance
- Thermal annealing during TS/MD:
  - lowers leakage current
  - partially restores depletion voltage
- Irradiation degradation remains unavoidable
- SEU in PP cards may require keeping Roman Pots retracted

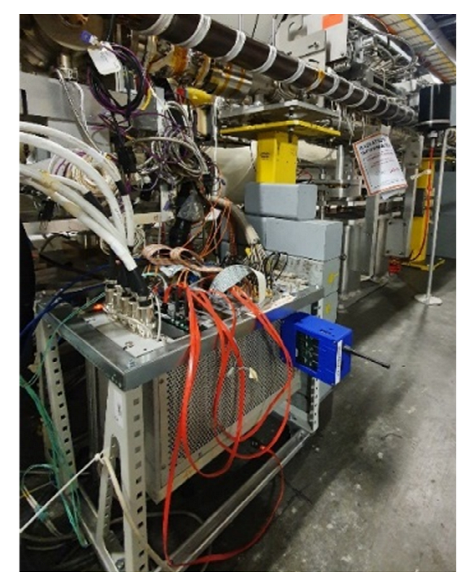
Lessons learned / Outlook

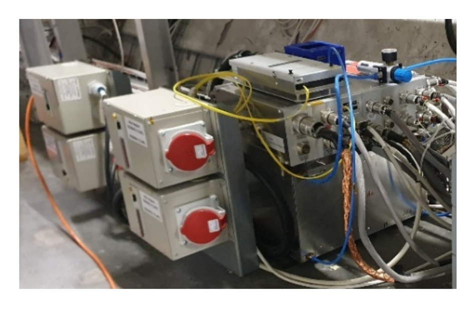
Mitigation strategies successfully reduced radiation exposure of AFP components and improved operational stability.

Use of radiation-tolerant components and optimized procedures remains essential for future upgrades.

Experience from AFP is highly relevant for the design and placement of forward detectors in the HL-LHC era and beyond.





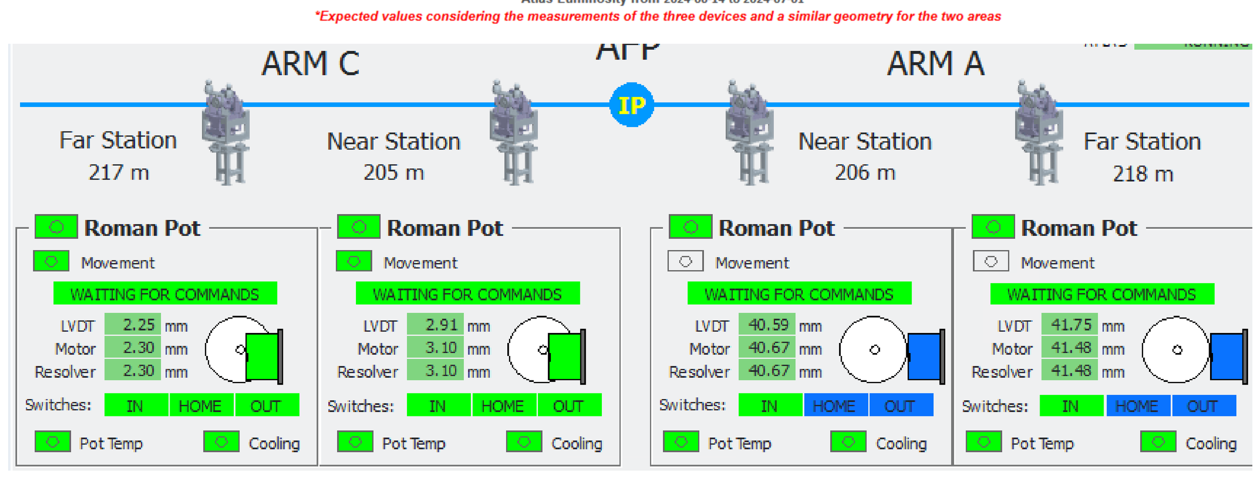


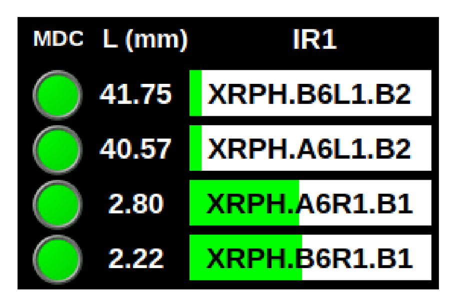
Summary and Normalized Measurements for IR1-AFP racks

		P1 Left Side			P1 Right Side		
Position	**Magnitude**	****5.7 fb-1**	**1 fb-1**	**120 fb-1**	****5.7 fb-1**	**1 fb-1**	**120 fb-1**
CRATE	TID	8.27	1.45	174	5.6*	0.98*	117.6*
CRATE	Φ_{HEH} [pp/cm^2]	3.99×10^{10}	7×10^{9}	8.4×10^{11}	3.12×10^{10}*	5.4×10^{9}*	6.5×10^{11}*
CRATE	Φ_{ThN} [pp/cm^2]	1.96×10^{11}	3.44×10^{10}	4.13×10^{12}	1.80×10^{11}*	3.16×10^{10}*	3.8×10^{12}*
PATCH PANEL	TID	9.03	1.58	190	6.12	1.07	128.4
PATCH PANEL	Φ_{HEH} [pp/cm^2]	5.91×10^{9}	1.03×10^{9}	1.24×10^{11}	4.62×10^{9}	8.11×10^{8}	9.73×10^{10}
PATCH PANEL	Φ_{ThN} [pp/cm^2]	3.30×10^{10}	5.79×10^{9}	6.95×10^{11}	3.05×10^{10}	5.35×10^{9}	6.42×10^{11}

**Atlas Luminosity from 2024-06-14 to 2024-07-01

*Expected values considering the measurements of the three devices and a similar geometry for the two areas





6. Conclusions

AFP is exposed to **extreme radiation** due to proximity to LHC collimator TCL6, leading to **severe operational challenges.**

Refurbishment efforts and shielding during YETS brought **partial improvements**, but **limitations in space and design** prevent full protection, especially at FAR stations.

Residual ambient dose equivalent rates decrease significantly with cooling time after beam stop, with **the most pronounced reduction occurring during the first days and weeks.** Nevertheless, even after two months of cooling, **localized high-radiation regions remain** around the FAR stations and collimation areas, continuing to impose strong constraints on tunnel interventions and occupational exposure management.

Radiation monitoring with BatMons confirms **high TID and HEH fluences**, underlining **unsuitability** of tunnel areas for long-term electronics operation.

Thermal annealing, retuning and insertion control help **mitigate SiT degradation** but it does not prevent it. Change of SiT modules is **mandatory** every few years.

AFP operation close to LHC collimators remains **feasible** but requires **substantial maintenance effort**, **radiation mitigation** and **operational planning**.
Lessons learned are **highly relevant for HL-LHC forward detector projects.**

AFP's unique position near LHC collimators provides both an **opportunity for forward physics** and a **demanding radiation environment.** Run-3 experience demonstrates that radiation from collimation can significantly affect detector hardware and constrain maintenance activities, even when regulatory dose limits are respected. **A comprehensive radiation impact assessment**, combined with targeted mitigation measures and careful work planning, is essential to ensure the **long-term operability of AFP** and **similar forward detectors.**

The experience gained with AFP highlights the importance of **integrating radiation protection** considerations into the life cycle of forward detectors, from design and integration to operation and maintenance.
It also provides **valuable input for future projects** that aim to exploit very forward regions of the LHC for physics measurements.

LS3: LSS1 Residual H*(10)