ATLAS Forward Proton

Experience from Run 2

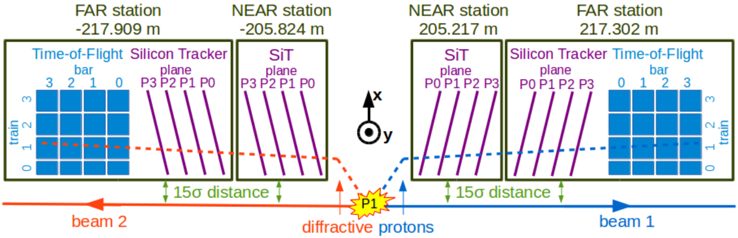
Maciej Trzebiński

Institute of Nuclear Physics
Polish Academy of Sciences

LHC Working Group on Forward Physics and Diffraction

CERN, 18th December 2018

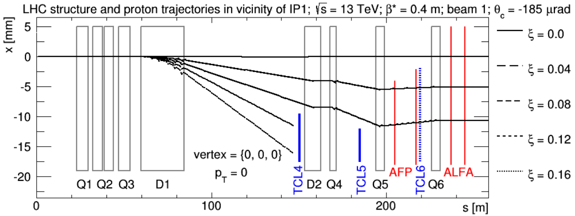
AFP Detector



- Two Roman pot stations on each side of ATLAS.
- Located around 210 m from ATLAS Interaction Point (IP).
- Horizontally inserted into LHC beam-pipe up to few mm from the beam.
- Each station consists of four Silicon Trackers (SiT).
- Position reconstruction resolution: $\sim$6 μm in x and $\sim$30 μm in y.
- Far stations host also Time of Flight (ToF) detectors.
- Expected timing resolution: $\sim$25 ps.

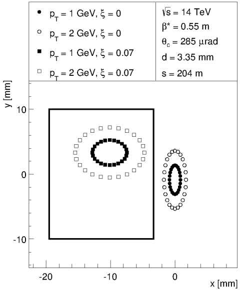
LHC Optics and Proton Trajectories

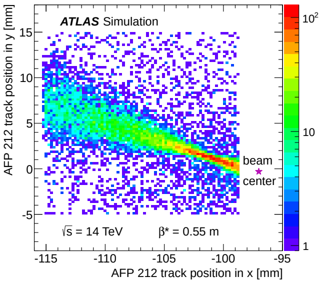
- Proton trajectories between IP and AFP detectors are not straight lines.
- Several LHC elements influence proton trajectory before AFP:
  - two dipole magnets (D1-D2) for beam separation (bending),
  - five quadrupole magnets (Q1-Q5) for beam focusing,
  - two collimators (TCL4, TCL5) for magnet protection.
- Settings of these elements, called optics, are due to requirement of experiments in terms of luminosity and LHC machine protection.
- Typical situation ($\beta^* = 0.4$ m optics[1]) for the high-luminosity ATLAS data taking:



- Assuming proton transverse momentum $p_T = 0$, protons are bent accordingly to the energy lost during the collision: $\xi = 1 - \frac{E_{proton}}{E_{beam}}$:
  - protons with too small energy loss are too close to the beam to be detected,
  - protons with too high energy loss are filtered by collimators.

[1] From https://doi.org/10.1117/12.2074647.

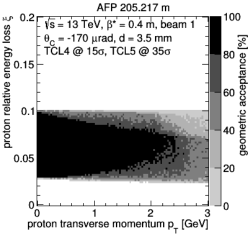




- **Left figure:**
  - Simple simulation: artificial protons with given ξ and p_T, MAD-X proton transport.
  - Protons with higher energy loss are further away from the beam.
  - Presence of non-zero transverse momentum makes additional shift in x-y, accordingly to azimuthal angle.
  - Crossing angle moves protons with non-zero ξ towards higher values of y.
  - Source: `https://doi.org/10.1117/12.2074647`.
- **Right figure:**
  - ATLAS simulation: diffractive protons generated by Pythia 8, Geant4 transport, simulation of detector response and track reconstruction.
  - Protons shape up in characteristic shape – so-called diffractive pattern.
  - Source: `https://twiki.cern.ch/twiki/bin/view/AtlasPublic/ForwardDetPublicResults`

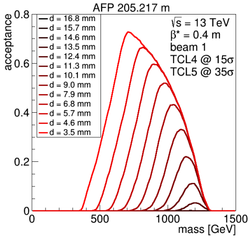
Geometric acceptance:

- ratio of number of protons of a given relative energy loss (ξ) and transverse momentum (p_T) that reached the AFP detector to the total number of scattered protons having such (ξ) and (p_T),
- black region: >80% of protons hitting AFP,
- acceptance limit for:
  - small ξ is due to beam-detector distance,
  - large ξ is due to collimator settings.

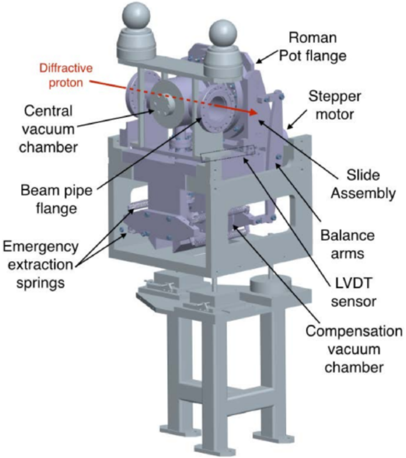


Mass acceptance:

- probability that central system of a given mass will visible in AFP (double proton tag),
- example: if a hypothetical particle of mass of 700 GeV will be exclusively produced in the proton-proton collision, there is a 70% chance to observe scattered protons in the AFP detector if they are inserted 3.5 mm from the beam,
- exclusivity means that no other particles will be created.

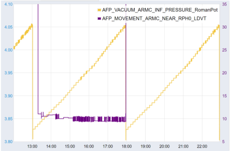


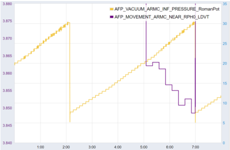
- Beam size and position depends on the LHC optics.
- LHC beam can be unstable $\rightarrow$ detectors should be protected, *i.e.* be far away from the beam.
- Need to adjust the position of detectors in relation to the LHC beam.
- Roman pot technology – detector movement:
  - non-stable beams: detectors are in garage (40 mm from the beam),
  - stable beams: detectors move 2-3 mm close to beam centre,
  - precise movement control: 5 μm accuracy.
- Motor position is cross-checked with the LVDT readout.

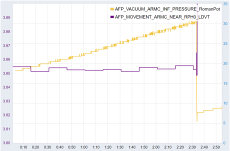


Pot Self Extraction Problem

- First self-extraction happened on 1/05/2018; 2 more before TS1: on 1/06 and 2/06.
- Self extraction is triggered when warning limits are reached. These are:
  - set to 150 μm from working position,
  - based on LVDT readout,
- **Action taken during TS1**: LVDT exchange.
- After TS1 4 more extraction happened: 19/07, 8/08, 31/08 and 6/09.
- A strong correlation was observed between self-extraction and vacuum pump cycle – extraction happen always when the pump was switching off (note that not all switching-offs caused extractions):

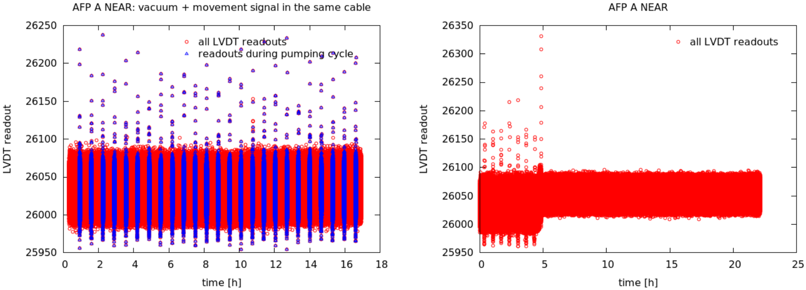






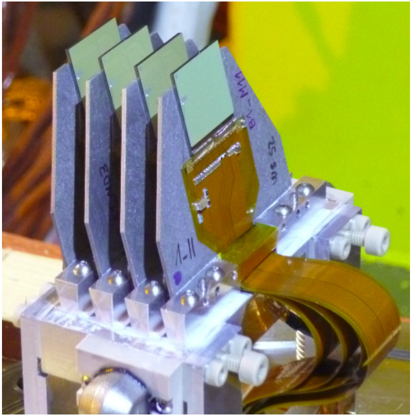
- **Action taken during TS2**: crate-LVDT cable (tunnel, few meters) exchange to a better shielded one.
- Two more extractions were observed after TS2: 29/09 and 30/09.
- The last one caused a beam dump, *i.e.* LVDT gave value above 200 μm from working position.
- The nature of such 'glitches' was always extremely fast (few ms) – not visible in DCS.

- Special, extended monitoring of PXI revealed a clear correlation between the pump cycle and increase of LVDT fluctuations (left plot):

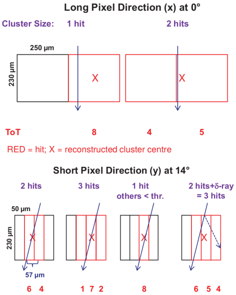


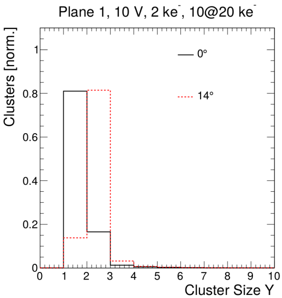
- Cause: LVDT signals were sent to USA15 through the same cable as pump signals.
- Fortunately, there was a spare cable which was used to spilt motor and pump signals.
- After the fix situation improved by a lot – all spikes disappeared and readout was more stable (see right plot).

- Four **Si**licon **T**rackers in each AFP station.
- 336×80 pixels with a pixel size of 50×250 μm^2.
- Total active area: 1.68×2.00 cm^2.
- Edgeless: dead edge (beam side) of only $\sim$100 μm.
- Read-out: FE-I4B front-end chip.
- Radiation hardness: non-uniform radiation with the fluence of $3 \cdot 10^{15}$ n_{eq}/cm^2 per 100 fb^{-1}.
- Trigger capabilities.



- Diffractive protons are almost perpendicular to the beam – trajectory slope is of about 20 μrad.
- SiT planes perpendicular to the beam would have resolution of $50/\sqrt{12}$ μm. Only close to the edge, charge will be shared with neighbouring pixel and resolution will be improved (top left plot).
- Tilt allow charge sharing (bottom left plot).
- For AFP, 14^0 tilt was chosen in order to increase the probability of hitting two or more pixels while keeping effective detection area large (above 16 mm in x) – right plot.





Figures from JINST **11** (2016) P09005

Test-beam studies:

- method:
    - measure the average per-plane resolution of three identical planes without a track fit,
    - residual variable res_{trip} from the hit position x_i of three successive equidistant planes ($i = 1, 2, 3$): $res_{trip} = 0.5 \cdot (x_1 + x_3) - x_2$,
    - effective average single-plane (SP) resolution: $\sigma_{SP,trip} = \sqrt{2/3} \cdot \sigma_{trip}$.
- settings:
    - default operational parameters: 10 V, 2ke$^-$, 10@20 ke$^-$,
    - charge-weighted cluster centre,
    - one track and one cluster per plane (to eliminate combinatorial background),
- **reconstruction resolution for single plane: 6.0 μm.**

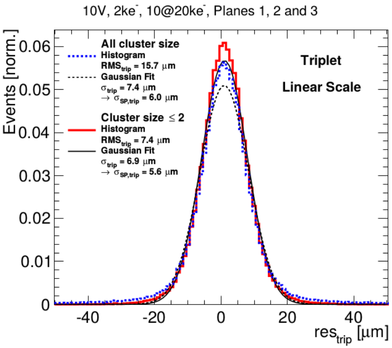
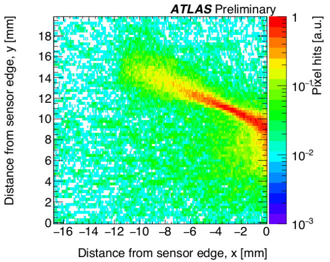
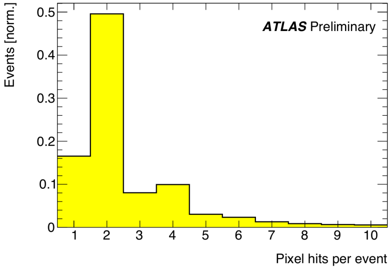
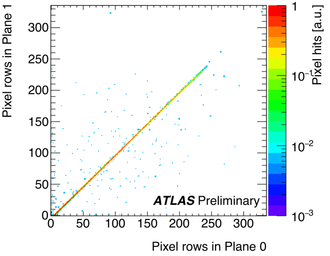


Figure from JINST **11** (2016) P09005



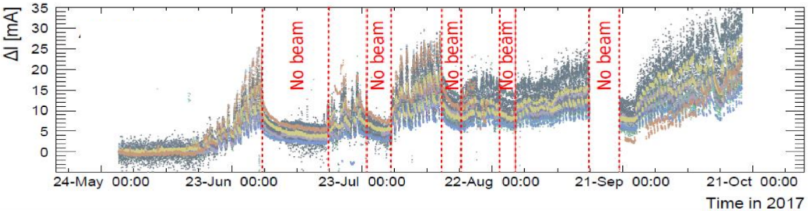




- AFP successfully takes data since 2016.
- Top left: diffractive pattern + beam halo visible in AFP FAR satation during the Beam-Based-Alignment procedure.
- Top right: pixel multiplicity during high 300 bunches LHC intensity ramp-up in May 2016.
- Bottom: correlation of raw unclustered pixel hits between two consecutive tracker planes in events with maximally 2 hits per plane.

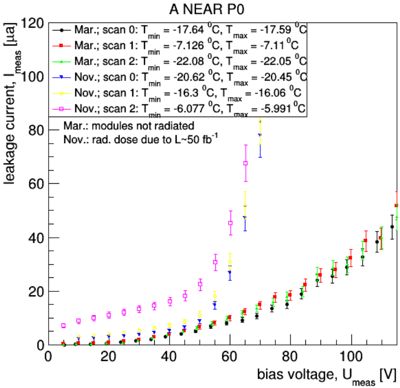
Figures from

- In 2016 AFP was only inserted during special, low luminosity runs.
- Since 2017 AFP takes data in all fills:
  - 2017: 32.0 fb^{-1} of raw data collected,
  - 2018: 49.3 fb^{-1} of raw data collected so far.
- Operation in high-luminosity environment causes a radiation damage to the sensors.
- Damage is proportional to the integrated luminosity and visible *e.g.* in the increase of Low Voltage (LV) current w.r.t. irradiated modules (bottom plot).
- In the absence of the beams, the so-called annealing phenomena appear – the SiT modules recover which results in drop of the LV current.

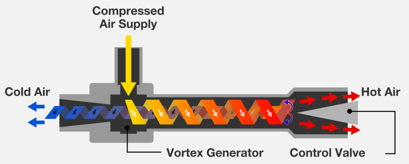


Figures from https://twiki.cern.ch/twiki/bin/view/AtlasPublic/ForwardDetPublicResults

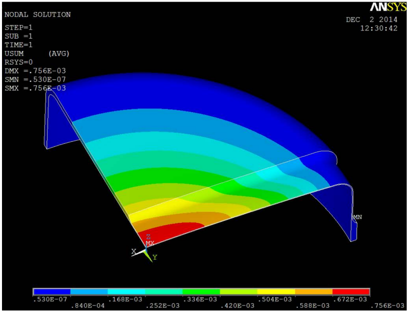
- Performance of irradiated modules strongly depends on temperature on the chip due to the High Voltage leakage current.
- Leakage current depend on the temperature – in the first approximation it doubles every 8 ^{0}C.
- The chosen working temperature for AFP SiT modules is around -20 ^{0}C.



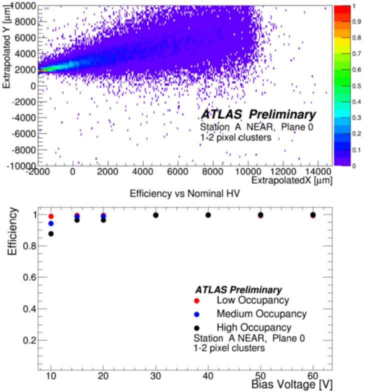
- AFP cooling system is based on the Vortex Tube technology.
- Efficient cooling down to -25 ^{0}C with detectors powered on.
- Online temperature regulation with Proportional-Integral-Derivative (PID) algorithm.



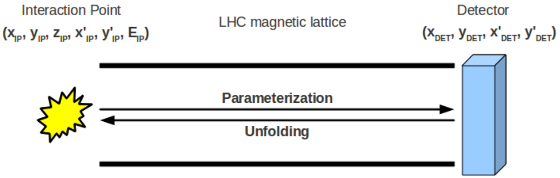
- Operation at -20 ^{0}C increases risk of icing.
- To decrease dew point, secondary vacuum system was installed.
- Inside of the Roman pot is kept in secondary vacuum, under the pressure between 5 and 30 mbar.
- Presence of secondary vacuum reduces the stress on the thin window and floor of Roman pot:
  - at 1 atm the maximal bulge is of about 700 μm towards the beam,
  - at $\sim$ 10 mbar it is reduced to below 100 μm,
  - **pot (detectors) can be much closer to the beam** $\rightarrow$ increased low-ξ acceptance.



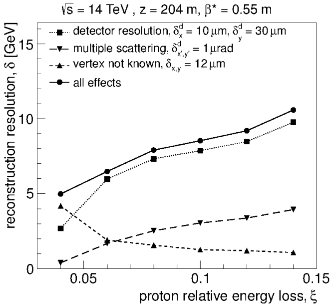
- Studies were done at the end of 2017 data taking, after $\sim$30 fb^{-1} data was collected.
- Tracks reconstructed with 3 planes and extrapolated to forth one.
- Track reconstruction requirements:
  - single cluster per plane,
  - no more than two pixels in plane.
- **Top:** extrapolated track position to Plane 0 in A NEAR station at 60V.
- **Bottom:** efficiency for the three different occupancy regions as a function of the bias voltage.
- Efficiency regions:
  - high: above 70%,
  - medium: between 30 and 70%,
  - low: below 30%.
- Full efficiency is reached for a bias voltage larger than 30V.



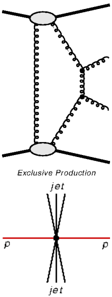
Figures from https://twiki.cern.ch/twiki/bin/view/AtlasPublic/ForwardDetPublicResults



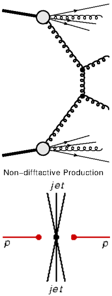
- At the interaction point proton (IP) is fully described by six variables: position (x_{IP}, y_{IP}, z_{IP}), angles (x'_{IP}, y'_{IP}) and energy (E_{IP}).
- They translate to unique position at the forward detector (x_{DET}, y_{DET}, x'_{DET}, y'_{DET}).
- Idea: get information about proton kinematics at the IP from their position in the AFP detector.
- Exclusivity: kinematics of scattered protons is strictly connected to kinematics of central system.
- Detector resolution play important role in precision of such method.



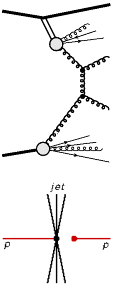
signal



background



background



Idea:

- measure difference of time of flight of scattered protons, $(t_A - t_C)/2$
- compare to vertex reconstructed by ATLAS, $(t_A - t_C) \cdot c/2 - z_{ATLAS}$

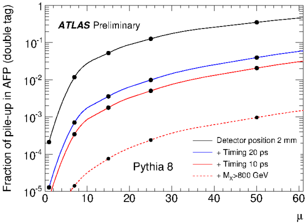
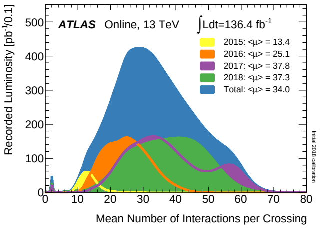
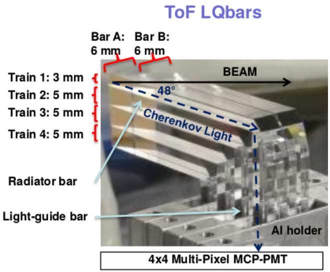


Figure from ATLAS-TDR-024

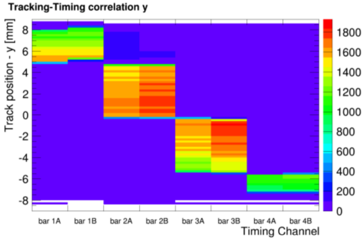
- Several proton-proton interactions in single bunch-crossing are expected during regular ATLAS data-taking (see top plot).
- Probability of combinatorial background is high.
- AFP Time-of-Flight detector was designed to reduce such background by factor of few.
- ToF components (bottom plot):
  - 16 L-shaped quartz bars to guide Cherenkov light created by protons,
  - radiated photons are detected by a Micro-Channel Plate Photo-Multiplier (MCP-PMT),
  - after amplification, readout is done by radiation hard electronics.
- Expected resolution: $\sim$20 ps.

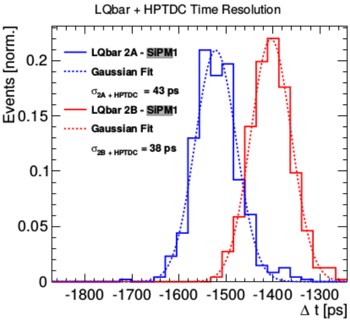




Figures from ATLAS-TDR-024 and
https://twiki.cern.ch/twiki/bin/view/AtlasPublic/LuminosityPublicResultsRun2

- Top plot: spatial correlation between reconstructed track position and ToF channels.
- Bottom plot: the time differences between the LQbars of the second train (2A and 2B) and Silicon Photomultipliers (SiPM).
- The time resolutions of the full ToF including the readout contributions were measured to be (at 1900 V) between:
  - 38 ± 6 ps and 46 ± 5 ps per LQbar,
  - 35 ± 6 ps and 37 ± 6 ps per train.





Results from JINST **11** (2016) P09005

Summary

AFP detector was installed ...

AFP detector was installed ...

... commissioned to operate at the LHC ...

AFP detector was installed ...

... commissioned to operate at the LHC ...

... successfully took data in years 2016–2018 during standard and special runs ...

AFP detector was installed ...

... commissioned to operate at the LHC ...

... successfully took data in years 2016–2018 during standard and special runs ...

... and is ready for the future data-taking!