ATLAS Forward Proton Detectors

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CERN Detector Seminar

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Usual situation at the LHC:

Proton(s) remain intact when exchanged objects do not change quantum numbers:
- electromagnetic force: photon
- strong force: Pomeron (QCD = two gluons + higher-order terms)
Usual situation at the LHC:

- Can proton(s) remain intact? Yes!
- But exchanged object must not change quantum numbers of proton(s):
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Physics Processes

■ **hard** – perturbative approach is valid; small cross-sections:

- **non-diffractive**

  ![Diagram of non-diffractive interaction]

- **diffractive**

  ![Diagram of diffractive interaction]

■ **soft** – large cross-sections:

- **non-diffractive**:

  ![Diagram of non-diffractive interaction]

- **diffractive**:

  ![Diagram of diffractive interaction]

**Diffraction:**

- colour singlet exchanged,
- Pomeron (QCD = two gluons + ...).

**Natural ways to seek for diffraction:**

- rapidity gaps,
- forward protons.
Assumption: one would like to measure diffractive interactions at the LHC.
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Measurement Methods

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Method 1 (rapidity gap):

+ usual method of diffractive pattern recognition
+ no need to install additional detectors
- gap may be killed by e.g. particles from pile-up
- gap may be outside acceptance of central detector

Method 2 (forward protons):

+ protons are directly measured
+ can be used in pile-up environment
- protons are scattered at small angles (few µrad)
- additional “forward” detectors are needed far away from the interaction point
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Forward Detectors
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**ALFA**

- **Absolute Luminosity For ATLAS**
- 240 m from ATLAS IP
- **soft diffraction** (elastic scattering)
- special runs (high $\beta^*$ optics)
- vertically inserted Roman Pots
- tracking detectors, resolution:
  \[ \sigma_x = \sigma_y = 30 \, \mu m \]
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### AFP
- **ATLAS Forward Proton**
- 210 m from ATLAS IP
- hard diffraction
- nominal runs (collision optics)
- horizontally inserted Roman Pots
- tracking detectors, resolution: $\sigma_x = 6 \ \mu m, \sigma_y = 30 \ \mu m$
- timing detectors, resolution: $\sigma_t \sim 20 \ \text{ps}$
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**Similar devices @ IP5:** CMS-TOTEM.
**Phase-1: AFP0+2 (2016)**

- 2 horizontal **Roman Pot** stations at 205 (NEAR) and 217 m (FAR) in ATLAS C side – installed!
- study beam background in low and high intensity runs
- measure diffractive and exclusive events with one tag in a special low-$\mu$ runs (AFP triggers ATLAS)
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Phase-2: **AFP2+2 (2017+)**
- 2 horizontal RPs on A side – installed!
- time-of-flight detectors in far stations on both sides were installed
- measure double tagged diffractive and exclusive events
- deliver diffractive triggers to ATLAS during:
  - special (low pile-up) and standard (high pile-up) runs

**AFP TDR: CERN-LHCC-2015-009, ATLAS-TDR-024**
**ECR: LHC-XAFP-EC-0002, LHC-XAFP-EC-0003**
Advantages of Roman Pot Technology

LHC beam
Advantages of Roman Pot Technology

LHC beam

M. Trzebiński AFP Detectors
Advantages of Roman Pot Technology

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LHC beam

thin window and floor (300 µm)
Advantages of Roman Pot Technology

shadow of TCL4 and TCL5 collimators

thin window and floor (300 \mu m)

Geometric acceptance:

```
\begin{align*}
\gamma_s &= 13 \text{ TeV}, \beta^* = 0.4 \text{ m, beam 1} \\
\theta_0 &= -170 \text{ \mu rad, } d = 16.8 \text{ mm} \\
\text{TCL4 } @ 15\sigma, \text{TCL5 } @ 35\sigma
\end{align*}
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Advantages of Roman Pot Technology

- Geometric acceptance:
  - Thin window and floor (300 µm)
  - Shadow of TCL4 and TCL5 collimators

- Mass acceptance:
  - Diffractive protons
  - LHC beam

- Geometric acceptance plot:
  - \( y_s = 13 \text{ TeV}, \beta^* = 0.4 \text{ m}, \text{beam 1} \)
  - \( \theta_c = -170 \mu \text{rad}, d = 15.7 \text{ mm} \)
  - TCL4 @ 15\( \sigma \), TCL5 @ 35\( \sigma \)

- Mass acceptance plot:
  - \( d = 16.8 \text{ mm} \), \( d = 15.7 \text{ mm} \)
  - \( y_s = 13 \text{ TeV} \)
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  - Beam 1
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  - $\sqrt{s} = 13 \text{ TeV}$, $\beta^* = 0.4 \text{ m}$, beam 1
  - $\theta_0 = -170 \mu \text{rad}$, $d = 12.4 \text{ mm}$
  - TCL4 @ 15σ, TCL5 @ 35σ

- Mass acceptance:
  - $d = 16.8 \text{ mm}$
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  - $d = 14.6 \text{ mm}$
  - $d = 13.5 \text{ mm}$
  - $d = 12.4 \text{ mm}$
  - $\sqrt{s} = 13 \text{ TeV}$
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thin window and floor (300 $\mu$m)
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  - \( \sqrt{s} = 13 \text{ TeV}, \beta^* = 0.4 \text{ m}, \text{beam 1} \)
  - \( \theta_0 = -170 \mu \text{rad}, d = 11.3 \text{ mm} \)
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thin window and floor (300 \( \mu \text{m} \))

diffractive protons

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LHC beam
Advantages of Roman Pot Technology

Geometric acceptance:

- \( \sqrt{s} = 13 \text{ TeV}, \beta^* = 0.4 \text{ m}, \) beam 1
- \( \theta_0 = -170 \mu\text{rad}, d = 10.1 \text{ mm} \)
- TCL4 @ 15\( \sigma \), TCL5 @ 35\( \sigma \)

Mass acceptance:

- \( d = 16.8 \text{ mm} \)
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shadow of TCL4 and TCL5 collimators

diffractive protons

thin window and floor (300 \( \mu \text{m} \))
Advantages of Roman Pot Technology

Geometric acceptance:

Mass acceptance:

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thin window and floor (300 µm)
Advantages of Roman Pot Technology

Geometric acceptance:

- Geometric acceptance of diffractive protons with respect to the LHC beam.
- Thin window and floor (300 µm).

Mass acceptance:

- Acceptance curves for different values of d (d = 16.8 mm, 15.7 mm, 14.6 mm, 13.5 mm, 12.4 mm, 11.3 mm, 10.1 mm, 9.0 mm, 7.9 mm).
- Constraints on the interaction region: √s = 13 TeV, β⋆ = 0.4 m, beam 1, TCL4 @ 15σ, TCL5 @ 35σ.
Advantages of Roman Pot Technology

**Geometric acceptance:**
- Shadow of TCL4 and TCL5 collimators
- Diffractive protons
- Thin window and floor (300 µm)

**Mass acceptance:**
- \( \sqrt{s} = 13 \text{ TeV}, \beta^* = 0.4 \text{ m}, \) beam 1
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diffractive protons

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LHC beam

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Optics
Luminosity: \( L = \frac{N_1 \cdot N_2 \cdot n \cdot f \cdot \gamma}{4 \cdot \pi \cdot \varepsilon \cdot \beta^*} F \)

- \( N_1 \) and \( N_2 \) – number of protons per bunch in beam 1 and 2,
- \( n \) – number of bunches per beam,
- \( f \) – revolution frequency,
- \( \gamma \) – beam Lorentz factor,
- \( \varepsilon \) – beam emittance,
- \( \beta^* \) – betatron function at the IP,
- \( F \) – luminosity reduction factor due to the crossing angle at the IP.
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Data collecting strategies
LHC Optics

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Data collecting strategies

hard processes, potential discoveries
↓
small cross sections
↓
rare events
↓
much luminosity needed
↓
maximise \( N_1, N_2, n, \frac{1}{\beta^*} \)

forward protons: access to wide range of relative energy loss (\( \xi \))
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maximise \( N_1, N_2, n, 1/\beta^* \)

soft processes, elastic scattering
\[ \downarrow \]
large cross sections
\[ \downarrow \]
clean environment needed
\[ \downarrow \]
minimise pile-up, pp interactions within a beam and beam divergence
\[ \downarrow \]
optimise \( N_1, N_2, n, \beta^* \)

forward protons: access to wide range of relative energy loss (\( \xi \))

forward protons: access to as low \(|t|\) values as possible
Proton trajectory is determined by the LHC magnetic field.
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collision optics, ALFA and AFP: trajectory due to $\xi$

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collision optics, ALFA and AFP: trajectory due to $p_y$
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**collision optics, ALFA and AFP:**
trajectory due to $\xi$

$\xi = 1 - \frac{E_{\text{proton}}}{E_{\text{beam}}}$

**special high-$\beta^*$ optics, ALFA:**
improve acceptance in

$p_T = \sqrt{px^2 + py^2}$
Geometric Acceptance for Various Optics

\[ \beta^* = 0.55 \text{ m} \]
nominal (collision)

\[ \beta^* = 90 \text{ m} \]
special (high-\(\beta^*\))

\[ \beta^* = 1000 \text{ m} \]
special (high-\(\beta^*\))

Simulation: distance from the beam was set to \(10\sigma (\beta^* = 0.55 \text{ m})\) or \(15\sigma (\beta^* = 90 \text{ and 1000 m})\).

AFP Components
Two stations on each side of ATLAS:
- NEAR: $\sim 205$ m,
- FAR: $\sim 217$ m.

Design based on the CMS-PPS/TOTEM horizontal stations.

NEAR stations contain silicon trackers (SiT).

FAR stations are equipped with SiT and Time-of-Flight detectors.
Proton Tagging or Position Measurement?

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 \((E_{IP})\).
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- Exclusivity: kinematics of scattered protons is strictly connected to kinematics of central system.

From ISRN High Energy Physics (2012) 491460; ATLAS-TDR-024
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- Detector resolution play important role in precision of such method.

From ISRN High Energy Physics (2012) 491460; ATLAS-TDR-024
- Four detectors in each station.
- Technology: slim-edge 3D ATLAS IBL pixel sensors bonded with FE-I4 readout chips.
- Pixel size: \(50 \times 250 \, \mu m^2\).
- Tilted by 14° to improve resolution in \(x\).
- Resolution: \(\sim 6 \, \mu m\) in \(x\) and \(\sim 30 \, \mu m\) in \(y\).
- Trigger: majority vote (2 out of 3; two chips in FAR station are paired and vote as one).

How to Reduce Physics Background?

Idea:

Measure difference of time of flight of scattered protons,

\[
\frac{t_A - t_C}{2}
\]

compare to vertex reconstructed by ATLAS,

\[
\frac{(t_A - t_C) \cdot c}{2} - z_{\text{ATLAS}}
\]
How to Reduce Physics Background?

**Idea:**
- Measure difference of time of flight of scattered protons, \((t_A - t_C)/2\)
- Compare to vertex reconstructed by ATLAS, \((t_A - t_C) \cdot c/2 - z_{ATLAS}\)

- 4x4 quartz bars oriented at the Cherenkov angle with respect to the beam trajectory.
- Light is directed to Photonis MCP-PMT.
- Expected resolution: \( \sim 25 \text{ ps} \).
- Installed in both FAR stations.
Cooling System

- **Technology:** Vortex Tube.
- **Staged approach:**
  - precooling of input air in AirCooler box,
  - cooling with Vortex tube installed on RP.
- **Efficient cooling:** temp. down to -30 °C with detectors powered on.
- **Operational requirements:** -10 °C.
- **Online temperature regulation with PID algorithm.**
Vacuum System

- Each RP is kept under secondary vacuum:
  - reduce stress and limit "bulge" of thin window,
  - allows cooling below 0 deg. (prevents icing of detectors).

- Two vacuum pumps (P1, P2) are located in alcoves on both sides (RR13 and RR17).

- Four operating modes:
  - mode 1: alternating between P1 and P2,
  - mode 2: use P1, if problem switch to P2,
  - mode 3: use P2, if problem switch to P1,
  - mode 4: use both pumps.

- Overall leak rate below 0.3 mbar / min.
Positions of IN, OUT, and HOME switch and Electrical Stop were set according to the laser measurements.

Pot position is precisely calibrated (few µm) before every insertion w.r.t. electrical switch.

In case of emergency (i.e. loss of power) – retraction with springs to the HOME position.

Mechanical stops installed to prevent damage of fragile electrical stop.
Temperature sensors (NTC):

- each station:
  - each SiT detector (on flex),
  - ToF (on amplifiers),
  - heat exchanger (NTC + PT1000),
  - pot wall (up + under second thin window),
  - flange (cold output of Vortex tube + HV for ToF),
  - LTB.

- VReg. crate.

- AirCooler box:
  - hot output of VT,
  - cold output of VT,
  - output of box.

Radiation sensors:

- bottom of each pot,
- VReg. crate,
- far station LTB,
- RR17 alcove.
Detector Control System

DCS is responsible for coherent and safe operation of the detector:

- provides tools for bringing the detector into desired operational state, monitors its parameters, signals any abnormal behaviour and performs actions,
- defined subset of detector parameters is stored in data bases for later inspections,
- graphical user interfaces allow overall detector operation and visualisation.

AFP is fully integrated with ATLAS DCS system.
**Architecture of AFP TDAQ:**
- **High Speed Input Output board (HSIO):** DAQ board with many high-speed and low-speed I/O channels, Xilinx Artix 200 FPGA, mezzanines with ATLAS TTC and RCE (Reconfigurable Cluster Element),
- frontends are configured at 40 Mbps, the data are readout at 160 Mbps.

**AFP is fully integrated with ATLAS TDAQ system:**
- AFP trigger signals are generated, combined (OR, AND, majority vote logics), synchronized with LHC clock and send to ATLAS Central Trigger Processor,
- trigger signals are sent via fast air-core cables and reach CTP within the standard ATLAS latency (85 BCXs).
Operation and Data-taking
Copy of ALFA BIS.

Hardware commissioning tests related to the position control of the AFP Roman Pots:

- correct mapping and signal distribution of the LHC flags between the AFP Interlock and AFP position control system,
- signal integrity of the HOME SWITCH signal from RP station to AFP interlock and the transmission of the COPY HOME switch back to the PXI,
- EXTRACTION RP SWITCH and OVERRIDE signals from the ATLAS control room,
- HOLIDAY MODE KEY.

**Status:** system is fully commissioned
**BBA procedure:**

- **scraping:** close collimator to trim the beam,
- **approach the beam with detector,**
- **monitor rates in BLMs and AFP** – sudden increase marks the beam position.
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**Loss maps procedure:**
- move detectors to the operational position \((e.g. \, 20\sigma)\),
- distort beam trajectory,
- observe rates in BLMs and AFP – beam should not touch the Roman pot.
2016

2017

Conditions:

$\sqrt{s} = 13$ TeV, $\beta^* = 0.4$ m.

Only two stations installed (ATLAS side C).

Only single tagged events.

Data taken during BBA: two runs, closer to the beam than during standard collisions, very useful for alignment and optics studies.

Data taken during special runs:

$\mu \sim 0.03$: int. lumi. $\sim 40$ nb$^{-1}$, AFP triggers $\sim 2$ kHz stored, main goal: soft diffraction.

$\mu \sim 0.3$: int. lumi. $\sim 500$ nb$^{-1}$, AFP triggers $\sim 2$ kHz stored, main goal: low- $p_T$ jets.

Data taken during standard runs: AFP was inserted only when number of bunches was not greater than 600 (ramp-up).

$\sqrt{s} = 13$ TeV, $\beta^* = 0.3$ and 0.4 m.

Full system ready.

Single and double tagged events.

Data taken during BBA: two runs.

Data taken during special runs:

$\mu \sim 1$: int. lumi. $\sim 640$ nb$^{-1}$, AFP triggers $\sim 2$ kHz stored, main goal: low- $p_T$ jets.

$\mu \sim 2$: int. lumi. $\sim 150$ pb$^{-1}$, AFP triggers $\sim 300$ Hz stored, goals: medium- $p_T$ jets, W/Z.
<table>
<thead>
<tr>
<th>Year</th>
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2016
- Conditions: $\sqrt{s} = 13$ TeV, $\beta^* = 0.4$ m
- Only two stations installed (ATLAS side C).
- Only single tagged events.
- Data taken during BBA:
  - two runs,
  - closer to the beam than during standard collisions,
  - very useful for alignment and optics studies.
- Data taken during special runs:
  - $\mu \sim 0.03$:
    - int. lumi.: $\sim 40$ nb$^{-1}$,
    - AFP triggers: $\sim 2$ kHz stored,
    - main goal: soft diffraction.
  - $\mu \sim 0.3$:
    - int. lumi.: $\sim 500$ nb$^{-1}$,
    - AFP triggers: $\sim 2$ kHz stored,
    - main goal: low-$p_T$ jets.

2017
- $\sqrt{s} = 13$ TeV, $\beta^* = 0.3$ and 0.4 m
- Full system ready.
- Single and double tagged events.
- Data taken during BBA:
  - two runs.
- Data taken during special runs:
  - $\mu \sim 0.05$:
    - int. lumi.: $\sim 65$ nb$^{-1}$,
    - AFP triggers: $\sim 2$ kHz stored,
    - main goal: soft diffraction.
  - $\mu \sim 1$:
    - int. lumi.: $\sim 640$ nb$^{-1}$,
    - AFP triggers: $\sim 2$ kHz stored,
    - main goal: low-$p_T$ jets.
  - $\mu \sim 2$:
    - int. lumi.: $\sim 150$ pb$^{-1}$,
    - AFP triggers: $\sim 300$ Hz stored,
### 2016
- **Conditions:** $\sqrt{s} = 13$ TeV, $\beta^* = 0.4$ m
- Only two stations installed (ATLAS side C).
- Only single tagged events.
- **Data taken during BBA:**
  - two runs,
  - closer to the beam than during standard collisions,
  - very useful for alignment and optics studies.
- **Data taken during special runs:**
  - $\mu \sim 0.03$:
    - int. lumi.: $\sim 40$ nb$^{-1}$, 
    - AFP triggers: $\sim 2$ kHz stored, 
    - main goal: soft diffraction.
  - $\mu \sim 0.3$:
    - int. lumi.: $\sim 500$ nb$^{-1}$, 
    - AFP triggers: $\sim 2$ kHz stored, 
    - main goal: low-$p_T$ jets.
- **Data taken during standard runs:**
  - AFP was inserted only when number of bunches was not greater than 600 (ramp-up).

### 2017
- $\sqrt{s} = 13$ TeV, $\beta^* = 0.3$ and 0.4 m
- Full system ready.
- Single and double tagged events.
- **Data taken during BBA:**
  - two runs.
- **Data taken during special runs:**
  - $\mu \sim 0.05$:
    - int. lumi.: $\sim 65$ nb$^{-1}$, 
    - AFP triggers: $\sim 2$ kHz stored, 
    - main goal: soft diffraction.
  - $\mu \sim 1$:
    - int. lumi.: $\sim 640$ nb$^{-1}$, 
    - AFP triggers: $\sim 2$ kHz stored, 
    - main goal: low-$p_T$ jets.
  - $\mu \sim 2$:
    - int. lumi.: $\sim 150$ pb$^{-1}$, 
    - AFP triggers: $\sim 300$ Hz stored, 
- **Data taken during standard runs:**
  - AFP was inserted on regular basis, usually few minutes after stable beams.
Plans for YETS and LS2

- **Standard maintenance:**
  - take out detector packages,
  - pull new optics cables,
  - change readout technology (HSIO → ATCA),
  - replace broken/not efficient parts,
  - follow general ATLAS upgrades of DCS and DAQ.

- Improve cooling system – active cooling of ToF, better heat distribution inside RP.

- Install new ToF readout – more rad-hard (e.g. picoTDC).
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 2016 and 2017 during standard and special runs ...
AFP detector was installed ... 

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

... successfully took data in 2016 and 2017 during standard and special runs ... 

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

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