3D Silicon Tracker for AFP: From Qualification to Operation

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On behalf of the ATLAS Forward Proton Detector (AFP) Collaboration

VERTEX 2017 - 11th September 2017
Las Caldas, Asturias, Spain

1) Introduction

2) Qualification

3) Installation

4) Running

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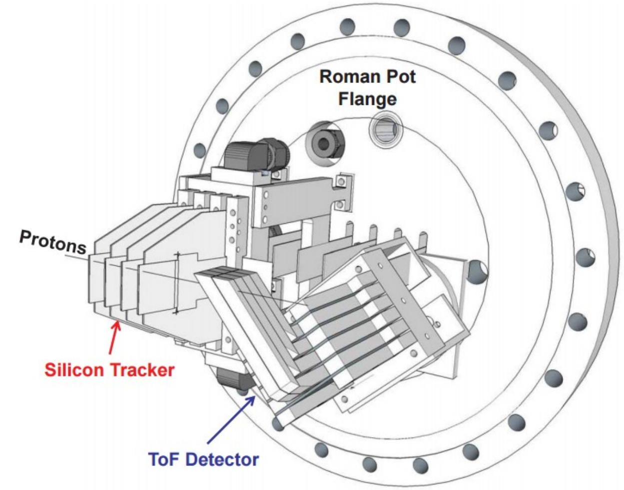
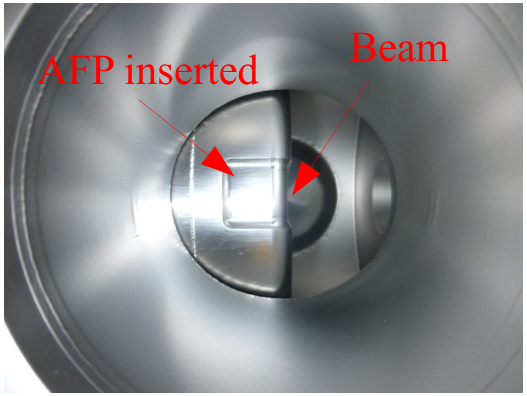
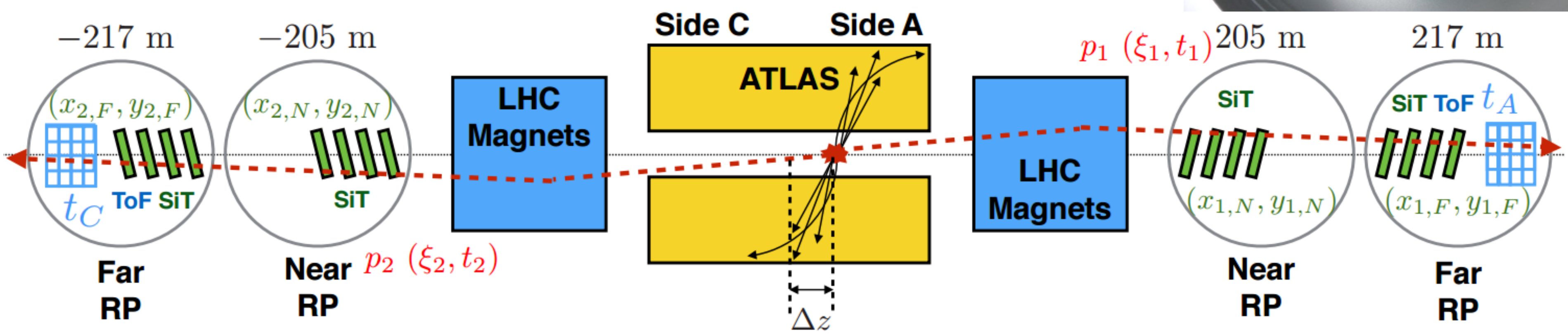
ATLAS Forward Proton (AFP)

AFP TDR: CERN-LHCC-2015-009



- AFP measures protons emerging intact from ATLAS inelastic collisions
  - → forward tagging
  - → gamma-gamma interactions, ...
- Detectors in AFP:
  - Silicon Tracker: to determine particle momentum
  - Time-Of-Flight: Quartz bars to reduce pileup
- Detectors are placed in Roman Pots to approach beam up to 2 mm





Brief History of AFP

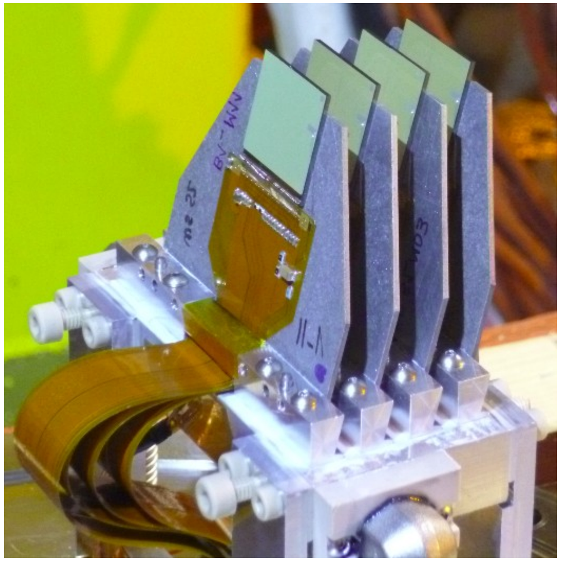
- ATLAS and CMS collaborated in the FP420 project, which was not realized, but served as cornerstone for AFP
  - originally envisioned to install forward detectors at 420m from IP, but proved too difficult
  → more feasible at 200m!

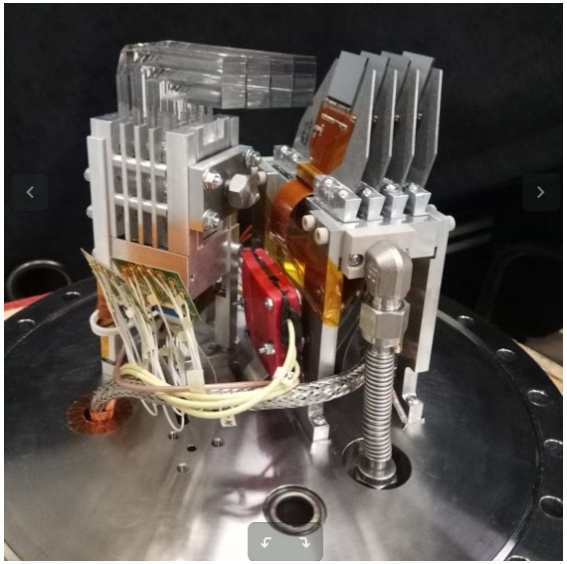
- AFP collaboration proposed detector to ATLAS (2009)

- AFP approved by LHCC (June 2015) following intensive qualification progress

- First AFP arm installation (YETS 2015-2016)
  - Only tracker installed
  - Intended for commissioning and low luminosity data tacking

- Second AFP arm installation (EYETS 2016-2017)
  - Full AFP detector operational, capable of data taking at nominal luminosity





3D Silicon Detectors

- Requirements:
  - slim edge to approach beam as close as possible
  - withstand non-uniform radiation (up to 3E15 n_{eq}/cm^2 in 3 years)
  - 10 (30) µm resolution in short (long) pixel direction to determine p_T

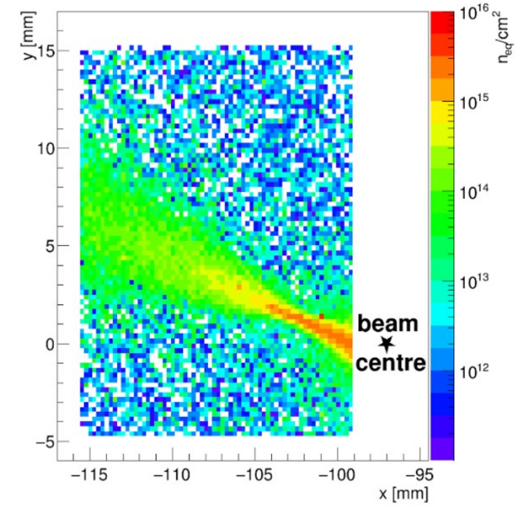
  M. Kocian talk, today 9:00

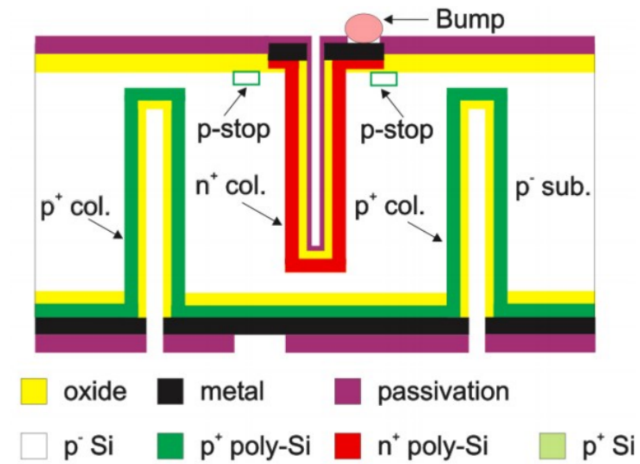
  → will show IBL 3D fulfills these!

- Column-like electrodes: (50x250 µm² pixel size, 336x80 pixels)
  - Decoupled electrode distance (~ 67 µm) from detector thickness (230 µm)

    → Lower depletion voltage and radiation hardness

- FE-I4 readout chip
  - Tunable threshold, charge measurement (via ToT)
  - Provides trigger signal





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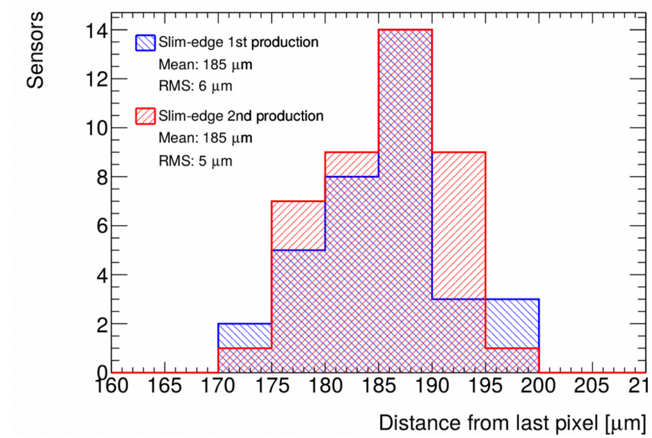
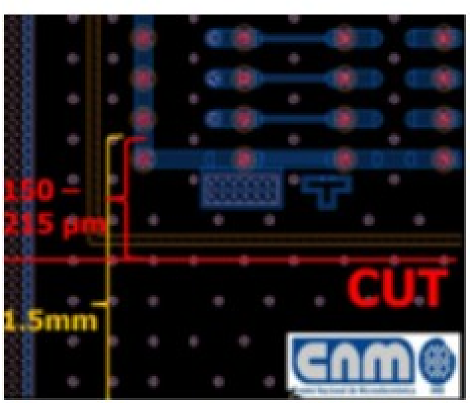
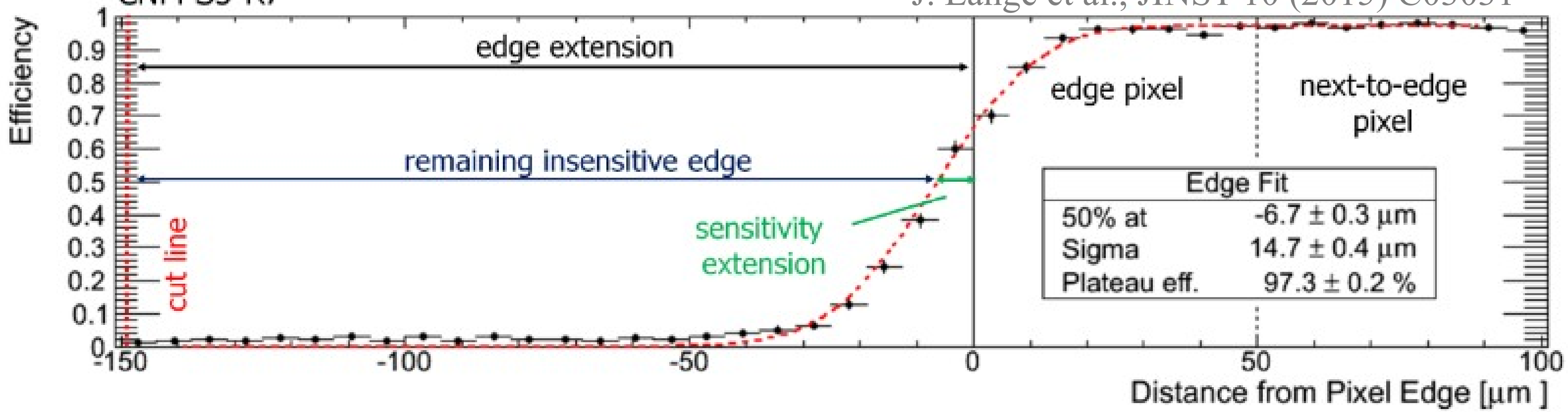
Qualification: Slim Edge

- **Requirement:** Slim edge to approach proton beam as much as possible
  → ~ 200 μm insensitive edge can be done in tight schedule of AFP
- **CNM** (3D guard ring design): Fully sensitive up to last pixel
  → **Fulfills slim edge requirement!**



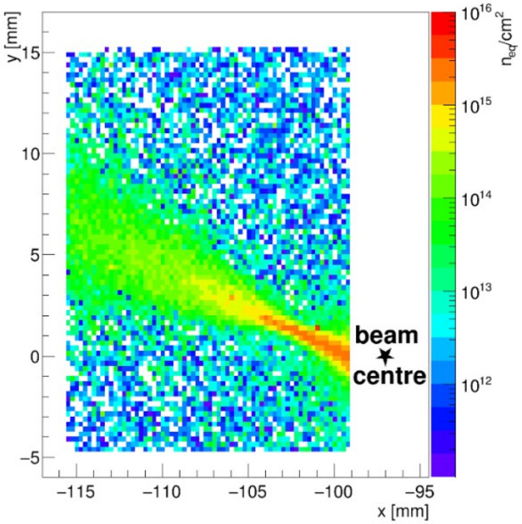




J. Lange et al., JINST 10 (2015) C03031

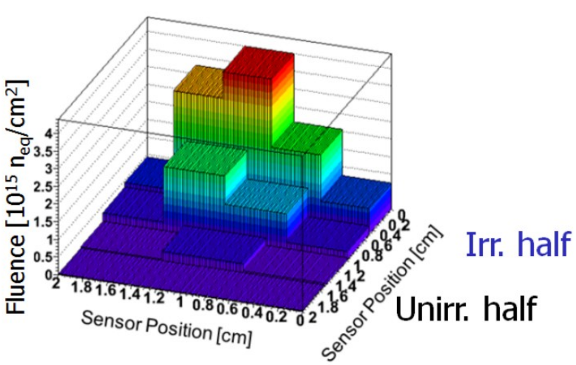
Qualification: Non-uniform irradiation

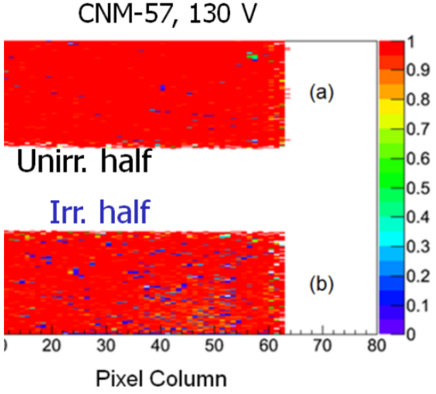
- Expect **highly non-uniform fluence** from diffractive protons:
  - 3×10^{15} n_{eq}/cm^2 in a small area over 3 years
  - Orders of magnitude lower nearby
- 2 irradiation campaigns with different **non-uniform** irradiations:

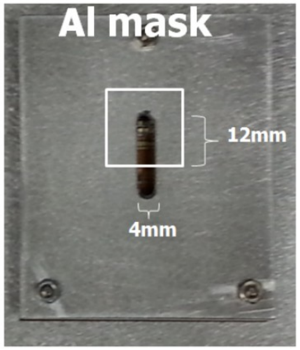


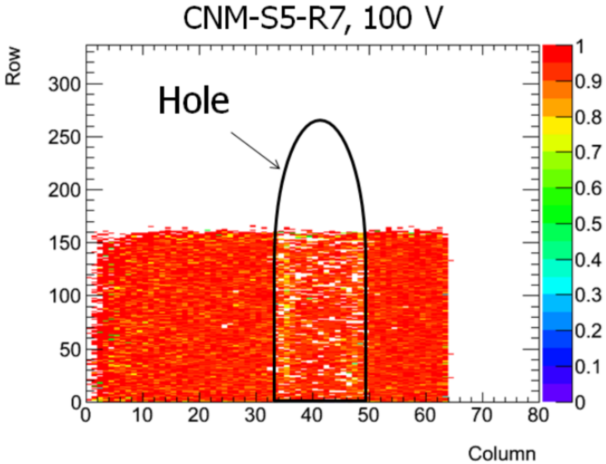
Focused 23 GeV p irradiation (CERN-PS)
→ Large fluence spread (max 4×10^{15} n_{eq}/cm^2)

23 MeV p through hole in 5 mm Al plate (KIT)
→ Localized fluence (max 3.6×10^{15} n_{eq}/cm^2) with abrupt transition









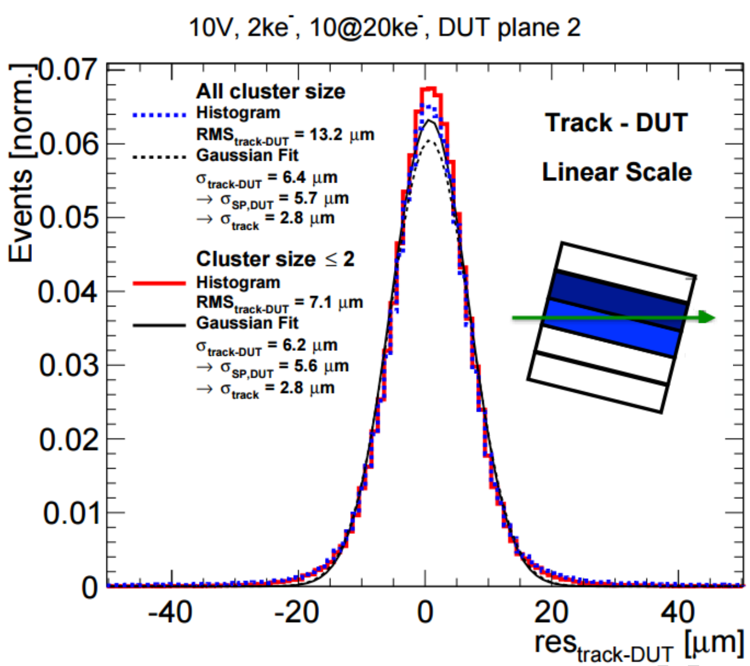
S. Grinstein et al., NIM A730 (2013) 28
J. Lange et al., JINST 10 (2015) C03031

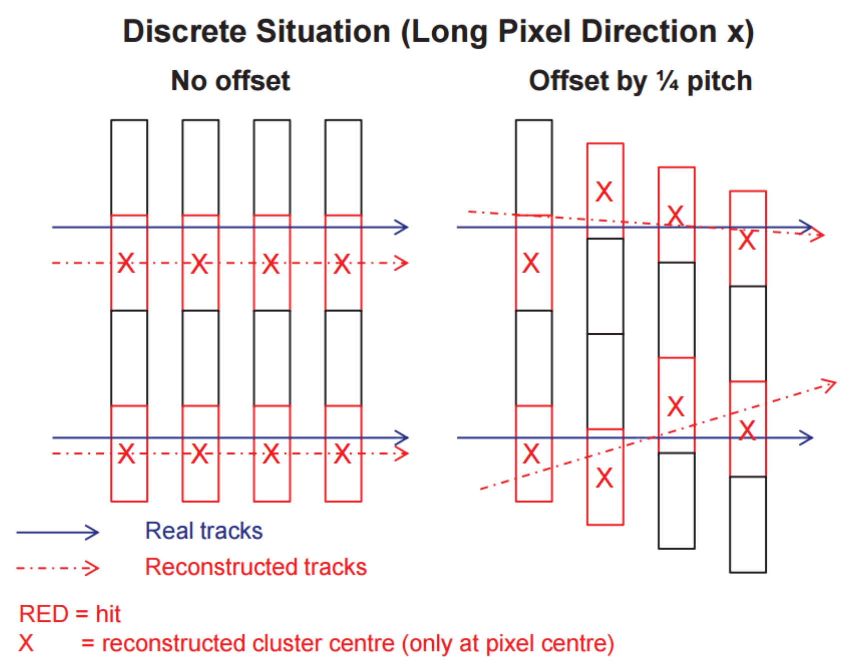
Efficiency 96-99% in all regions
→ Requirements in radiation hardness for AFP fulfilled!

Qualification: Position Resolution

- **Short pixel direction**
- **Requirement:** 10 μm resolution
- 50 μm pixel size → 14 μm digital resolution
- **But:** detectors placed at 14° angle to maximize 2-hit events → Use 4 bit ToT of FEI4 for cluster determination
- **Testbeam result:** 6 μm resolution per plane → 3 μm per station

- **Long pixel direction**
- **Requirement:** 30 μm resolution
  - 250 μm pixel size →72 μm digital resolution
- Staggered planes by 60 μm each → Improve resolution to up to 19 μm per station



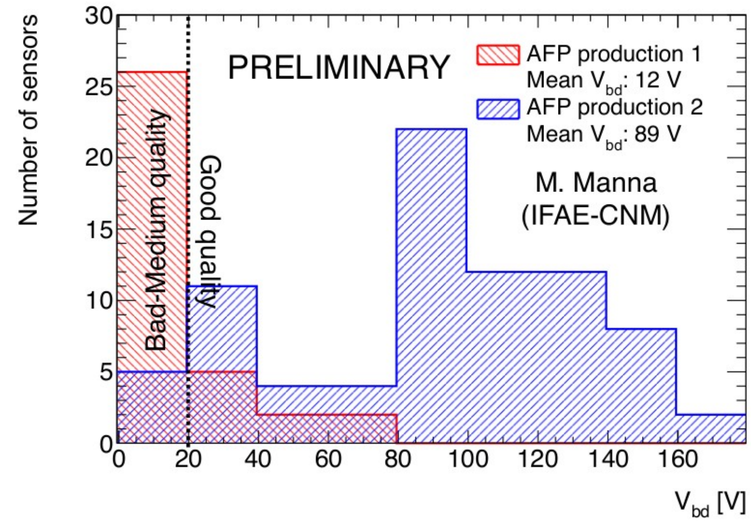


J. Lange et al., JINST 11 (2016) P09005

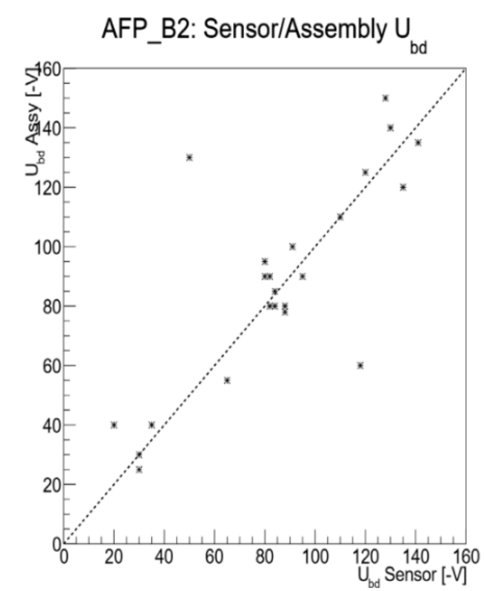
Sensor Productions

Production	Wafer Yield	Good Wafers	Sensor Yield	Good Sensors
First	38 %	5	23 %	9
Second	83 %	10	94 %	75

- **First CNM production** (January 2015):
  - For the one-arm AFP (2016)
    - → YETS 2015-2016 installation
  - Production had poor yield
    - → Only 9 Sensors with $V_{bd} > 20V$
  - Before irradiation at 14° 3D sensors are >99% efficient already at 1V
    - → Sufficient for first installation (YETS 2015-2016)



- **Second CNM production** (April 2016):
  - For full AFP detector (2017)
    - → EYETS 2016-2017 installation
  - Optimization of column-etching at CNM improved yield
    - → 75 Sensors with $V_{bd} > 20V$

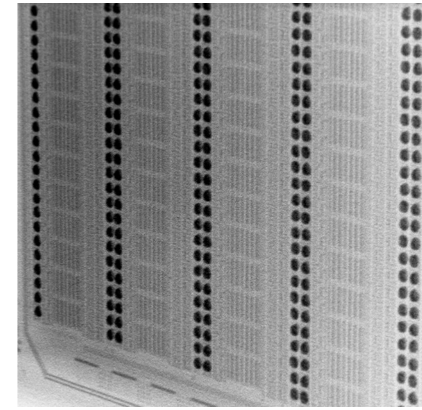


Module Production

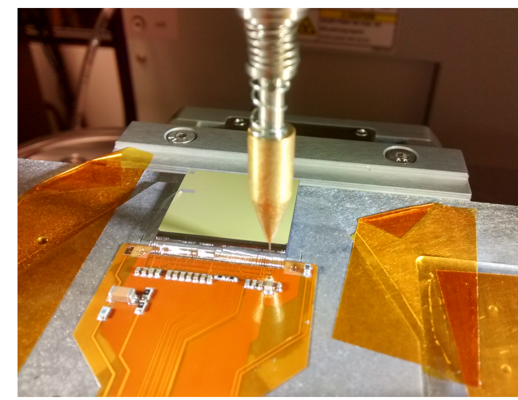
- **Bare Assembly:** Flip-chipped sensor on FE-I4
  - good sensor selected based on IV-behavior on Wafer-level
  - Bump-bonding followed by X-ray inspection before module assembly

- **Tracker Module:** Bare Assembly + Carrier card + Flex
  - Bare Assembly is glued onto the carrier card with alignment mark
  - Flex is glued as well on carrier card
  - Chip is wire-bonded to Flex

Bump-bonding and X-ray inspection (IFAE)



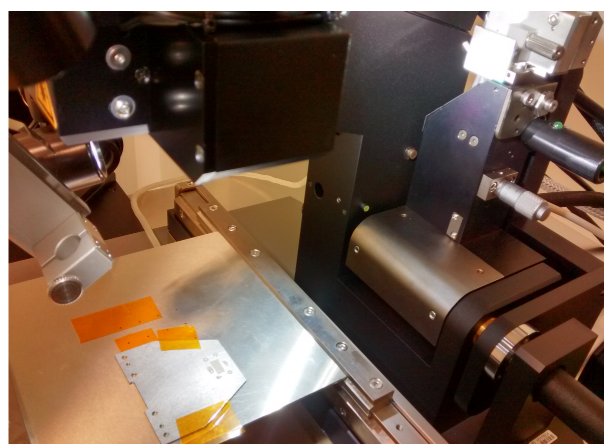
Wire bond and pull test (IFAE)

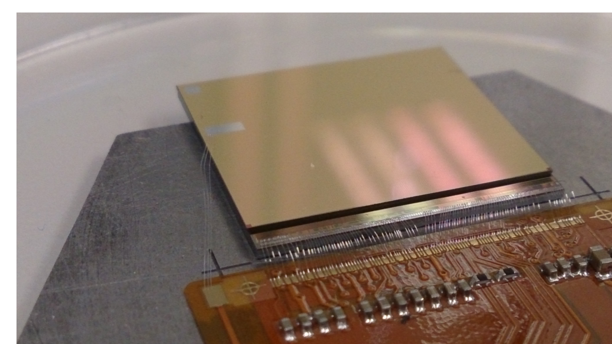


Carrier card (SUNY)

Flex (Oslo)

Assembly with Pick and Place machine (IFAE)

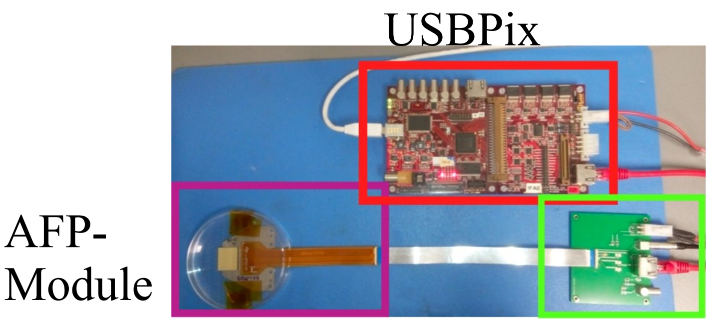


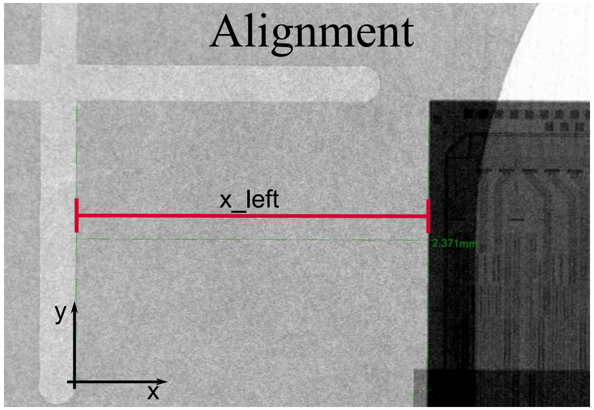


S. Grinstein et al., JINST 12 (2017) C01086

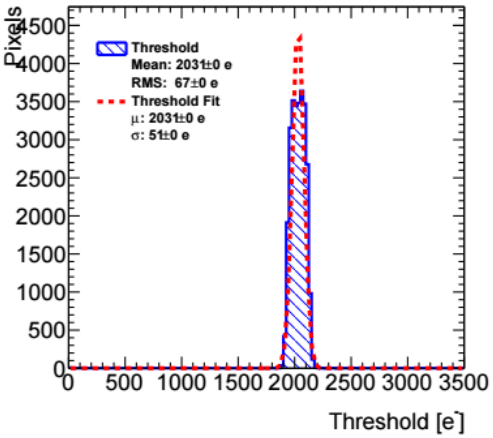
Quality Assurance

- **Electrical characterization** (IFAE and CERN):
  - Tuning
  - Source scan (bump bonds)
  - IV behavior
- **Alignment measurement** with X-ray machine
- **Temperature cycling ('Burn-In Test'):**
  - powered FEI4
  - from -20°C to 40°C, 1 hour at each peak for a total of 24 hrs

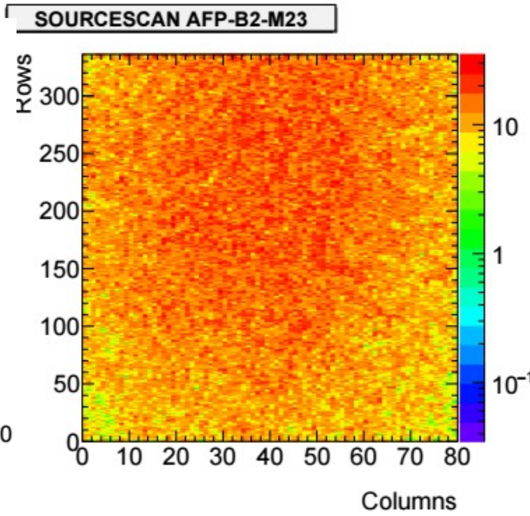




Threshold scan



Source scan



Production Step	Production	Total	Good	Yield
BB	1	22	21	95%
	2	31	30	97%
Assembly	1	17	17	100%
	2	29	29	100%
QA	1	17	14	82%
	2	27	26	96%

Time-of-Flight detectors

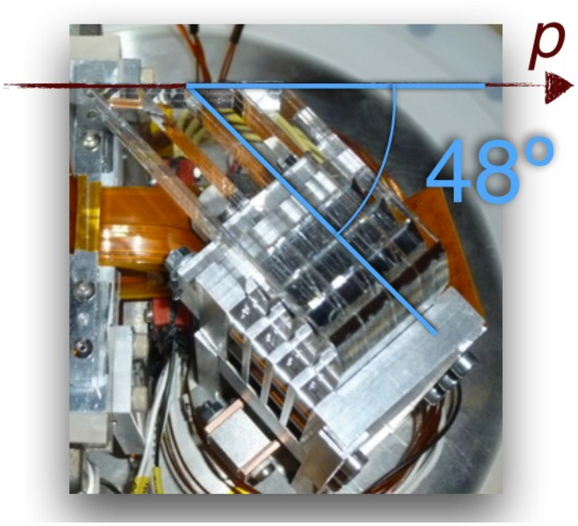
Cherenkov Quartz bars

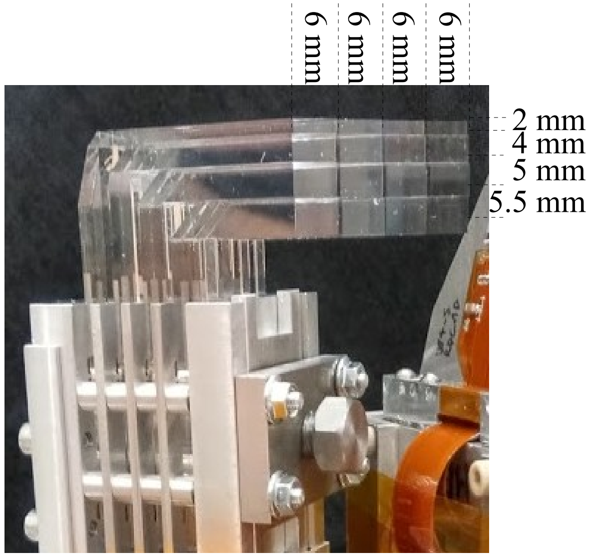
- Placed at Cherenkov angle (48°) with respect to proton direction to synchronize photon detection
- Photons are collected in a Micro-Channel-Plate Photomultiplier (MCP-PMT) at the end of the bars

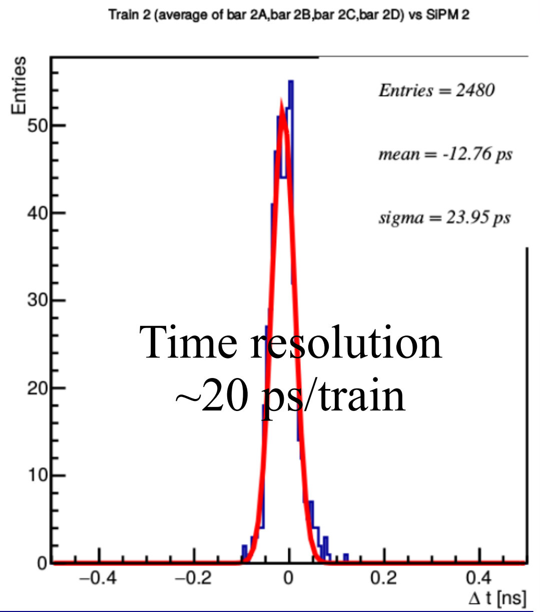
- **ToF requirement:** Time resolution 10 - 30 ps
- Performance evaluated in various test-beams:
- Full train (4 bars) time resolution: ~20 ps

→ ~4 mm z-resolution of the primary vertex in the central detector

L. Nozka et al., Opt Express 2016 Nov 28; 24(24): 27951-27960







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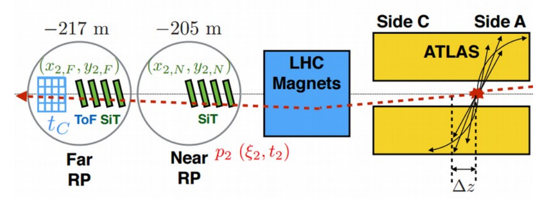
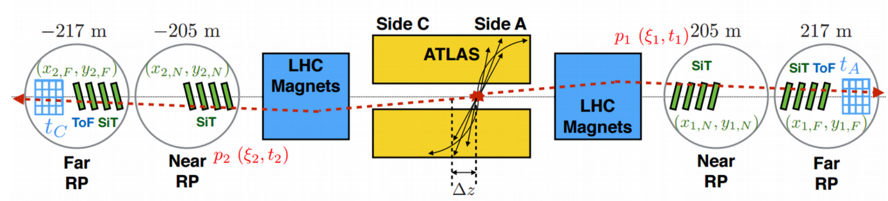
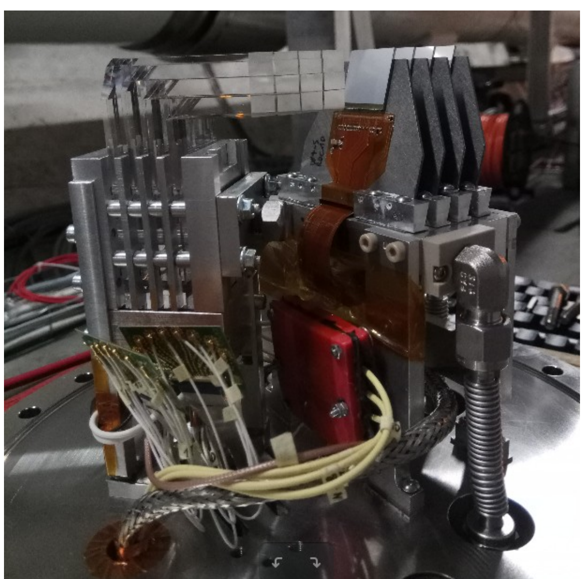
AFP Installations

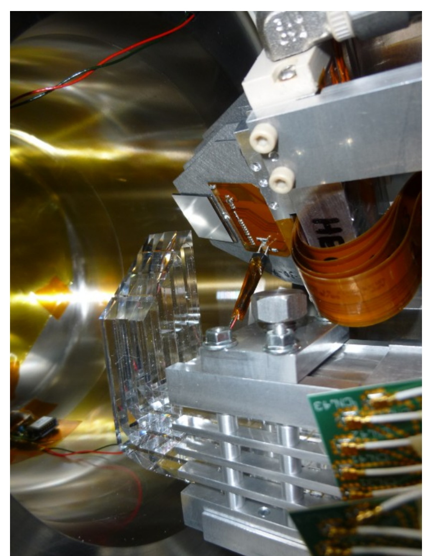
- **One-Arm installation** (YETS 2015-2016):
  - One day for installation (26.02.16)
  - On one side with only tracker:
    - proof of principle and commissioning
    - Physics data at low pile-up

- **Two-Arm installation** (EYETS 2016-2017):
  - Several weeks for installation (13.03 – 04.04.17)
  - Both sides with tracker and ToF:
    - Physics data at low and high pile-up!

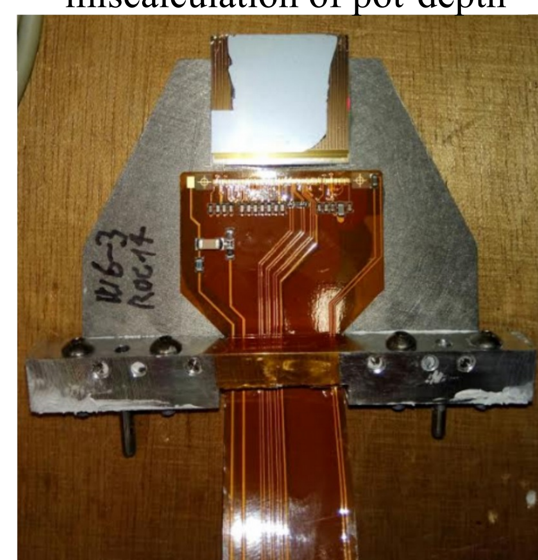








Crushed tracker after miscalculation of pot-depth




LHC GENERAL
RADIATION
ZONE SURVEILLÉE
SUPERVISED AREA
RADIATION
ZONE SURVEILLÉE
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YCA01
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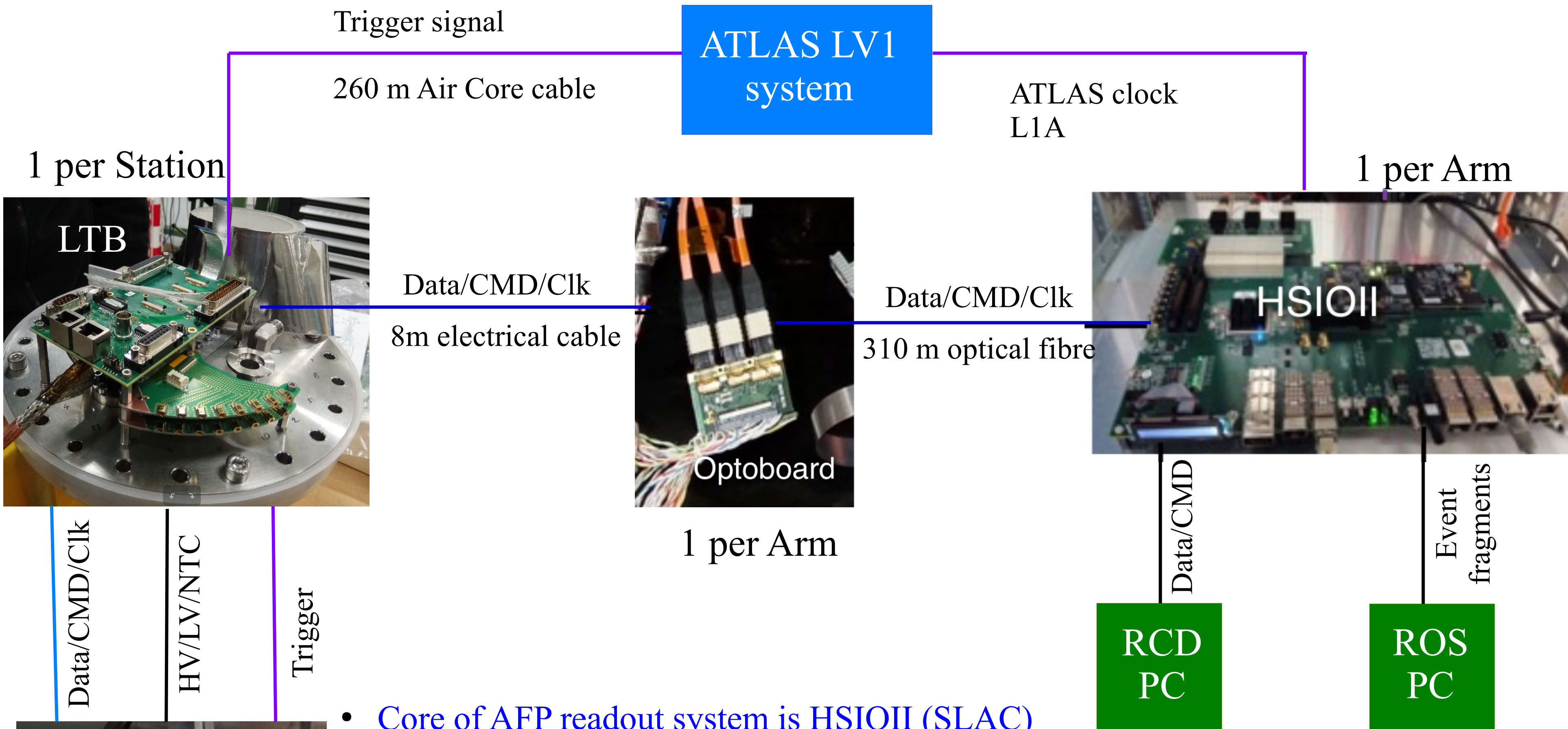
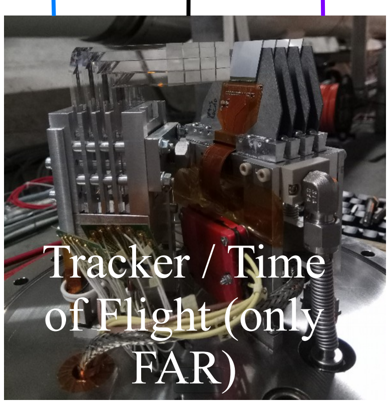
Read-out and trigger chain





- Core of AFP readout system is HSIOII (SLAC)
  - Clock and commands sent from HSIOII to the frontend through optical cable
  - Commands are sent from RCD to HSIOII, ROS receives the events from HSIOII
- Trigger from Tracker sent to HitBus chip (DBM) which performs station-wise trigger logic
  - 3 planes per station participate in trigger: Majority vote
  - Each station sends a trigger signal to the ATLAS LV1 system
- FAR stations also have ToF trigger, which is required for pile-up
  - However: currently small trigger efficiency

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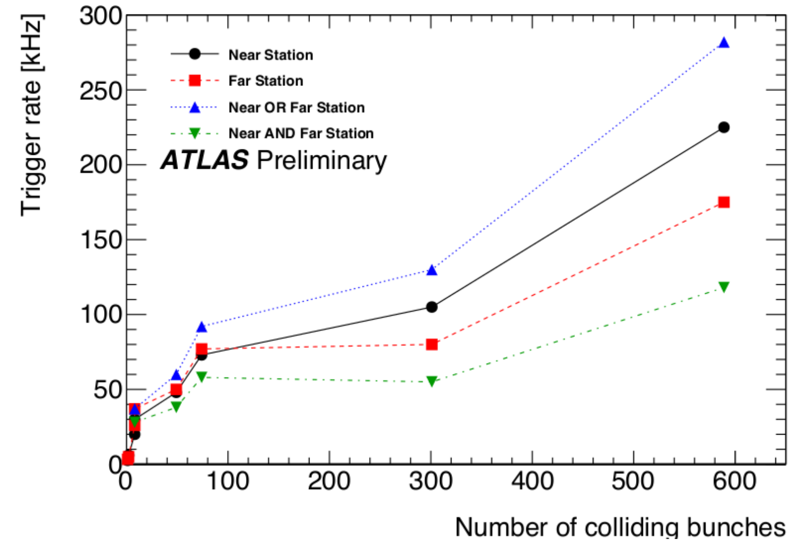
2016 Operation

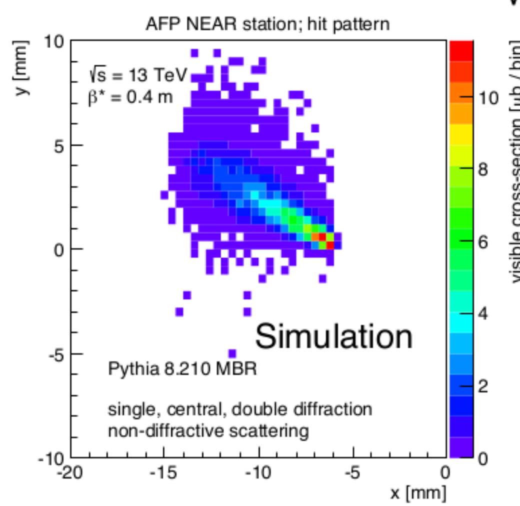
- **Standard pile-up:** AFP was inserted in beam position during intensity rampup in each intensity step up to 600 colliding bunches
- Study detector performance and alignment
- Understand beam background and AFP trigger
- Time-in detector to read-out 1BC and to send triggers inside ATLAS latency

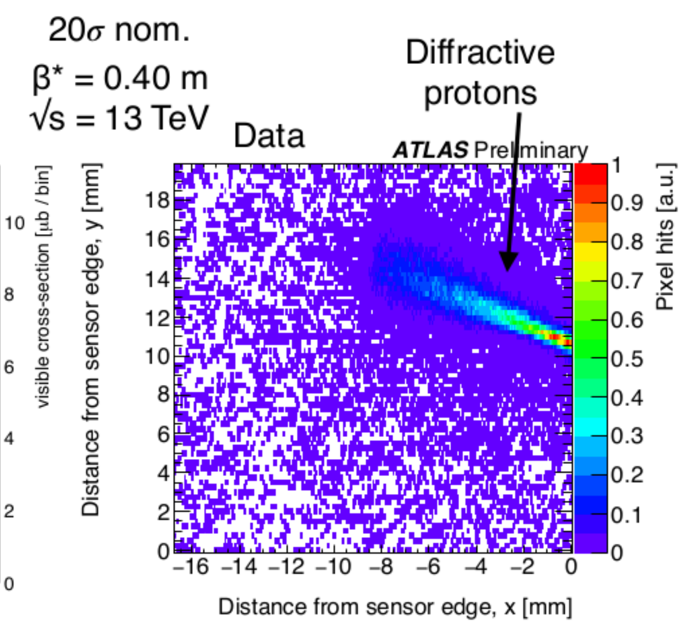
Low pile-up → Physics

- Problems with Tracker:
  - 1 module with HV short (operated at 0V, still 97% efficient before irradiation)



Date	Fills with AFP inserted	TDAQ Mode
19 - 22.04	Alignment and Loss Maps	AFP Only
29.04 – 05.05	TDAQ integration (LHC power cut)	
23.04 – 14.10	3 – 600 bunches	After 05.05: with ATLAS
31.07 & 8.10	**600 b. low-μ physics run**	**with ATLAS**



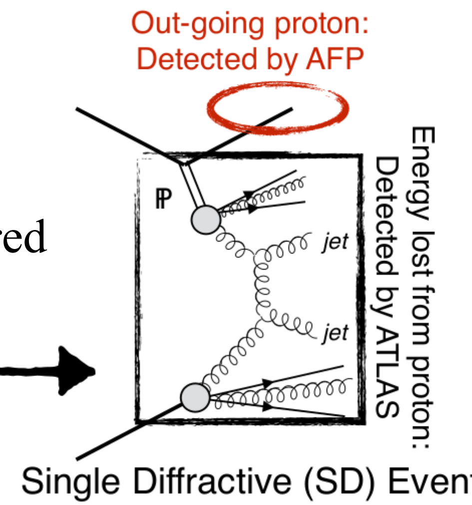


First 2016 results: Proton tagged SD+jets

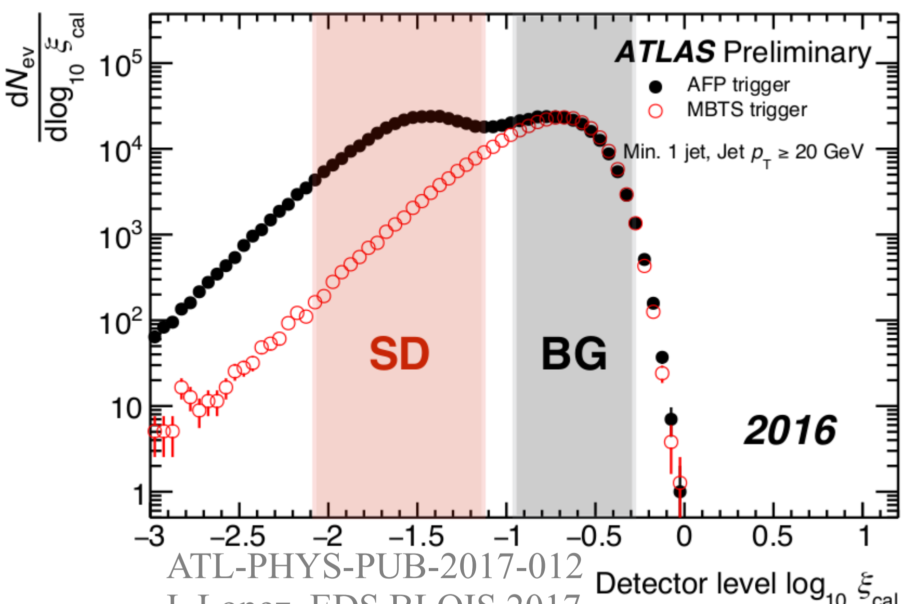
- **Validate AFP proton tagging:**
  - Tag protons to select single diffractive events with jets in the final state
  - Proton kinematic reconstruction of AFP not yet available

    → Correlate AFP triggered events to ξ (proton energy lost) measured at the calorimeter

$$\xi^{CAL} = \frac{1}{\sqrt{s}} \sum_{CalClus} p_T e^{-\eta}$$



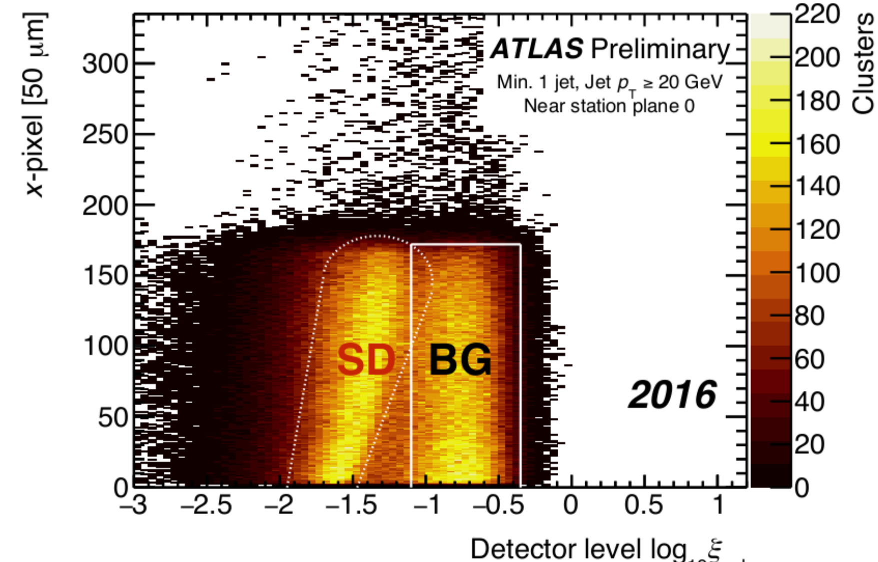
Excess in low ξ indicates presence of proton tagged diffractive events



ATL-PHYS-PUB-2017-012

I. Lopez, EDS BLOIS 2017

Low ξ excess correlates with x position measured in AFP (trajectory of diffractive proton in LHC magnetic field depends on it's energy)



2017 Operation

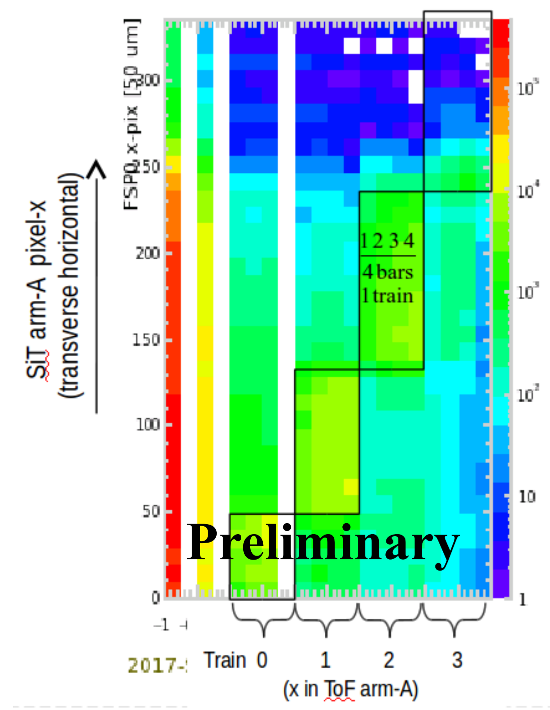
- **Standard pile-up:** AFP was inserted in beam position during intensity ramp-up in each intensity step up to 2544 bunches
  - Study detector performance and alignment
  - Understand beam background and new ToF-based AFP-trigger
  - Time-in-detector to read-out 1BC and to send triggers inside ATLAS latency
  - ToF detector commissioning

    → ToF-Tracker correlation visible, but more signal cleaning required

- **Low and high (standard) pile-up physics runs:**
  - AFP is inserted during stable beams all the time for physics
  - First low pile-up runs

- **Problems with Tracker:**
  - 1 plane has broken LV wirebond (only shunt circuit visible)
  - 2 planes with HV short
  - Radiation damage increases FEI4 current drastically and requires retuning (next slide)

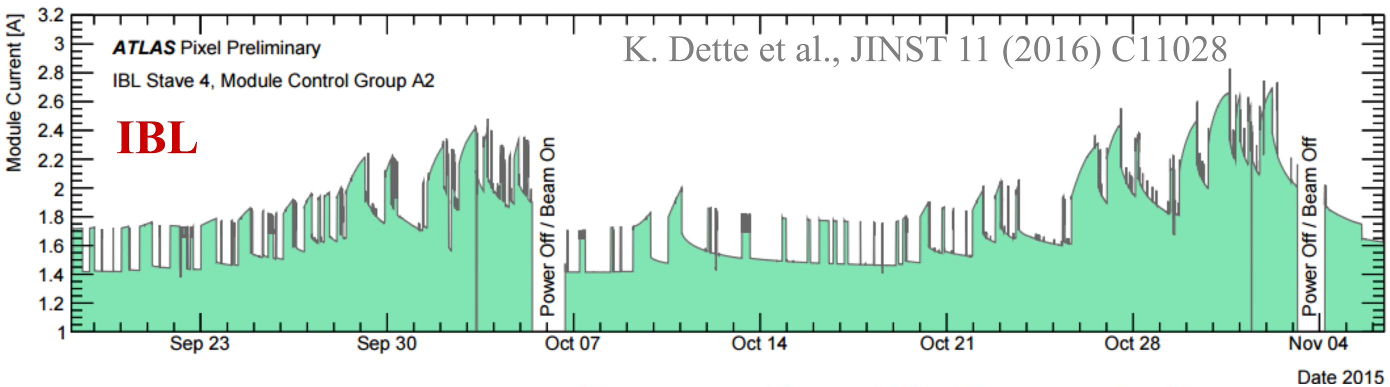
ToF-Tracker correlation

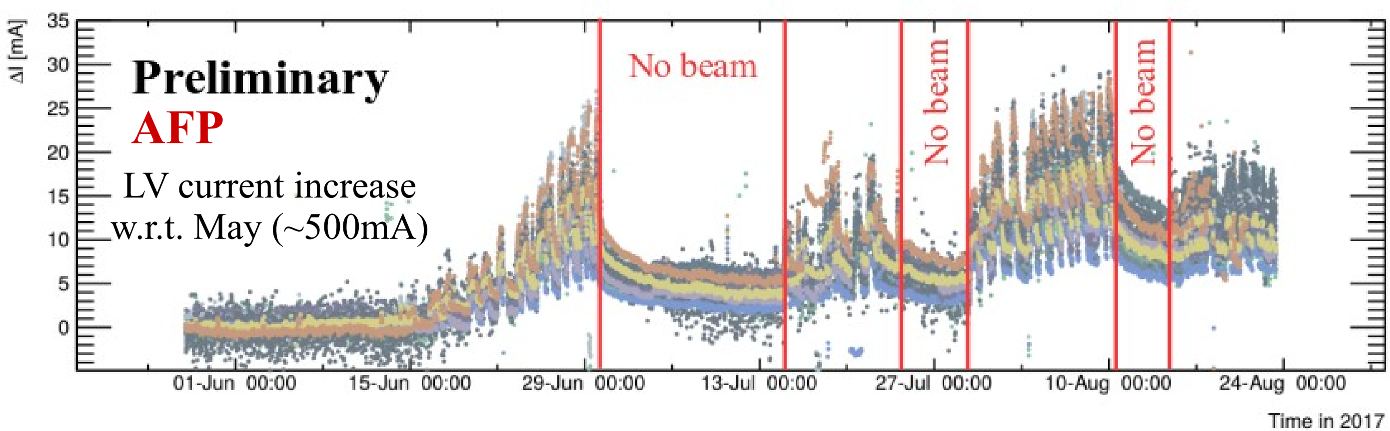


Radiation Damage: FEI4

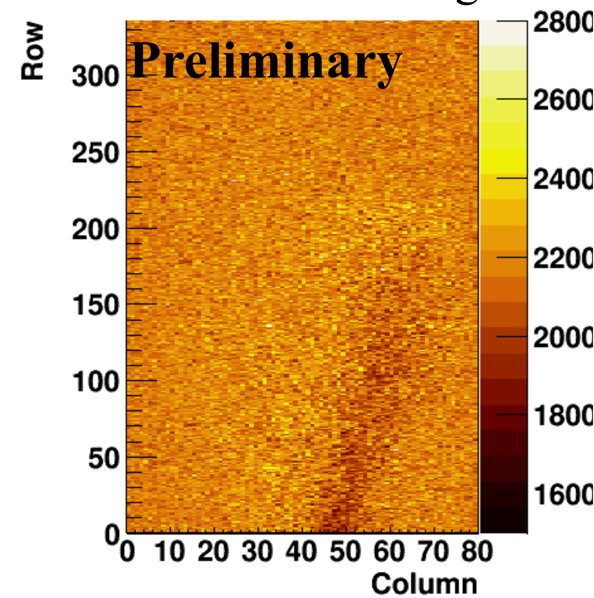
- As seen and studied in IBL: Low dose (<10 Mrad) in NMOS transistors of FEI4 causes defects
  - Increased power consumption of transistors and thus LV current
    → have to be careful to not burn LV wirebonds
    → Higher temperature helps annealing and returning to lower current

  - Also changes behavior of transistors and thus tuning
    → Threshold/ToT of irradiated area gets higher/lower
    → Frequent retuning required!





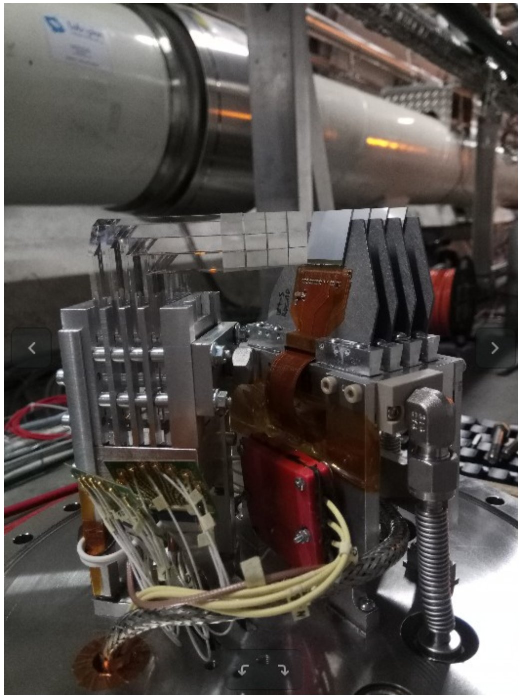
Threshold map after 2 weeks of running



Summary

- **3D sensors successfully qualified** for AFP
- Established production and QA of tracker modules for AFP
- **The AFP detector was installed in two phases in 2016 and 2017:**
  - 2016: 2 Roman Pot stations with silicon trackers in one side (z<0) of ATLAS
    - Commissioned and took data for physics and analysis
    - Single proton tag and **low luminosity** (no ToF → no pileup removal):

      → First analysis showing AFP is able to tag diffractive events
  - 2017: 4 Roman Pot stations with silicon trackers and Time-of-Flight detectors (only FAR) on both sides of ATLAS
    - Detector commissioning ongoing
    - Radiation visible in FEI4 current increase
    - Double proton tag and **low to high luminosity** (ToF available for pileup removal)

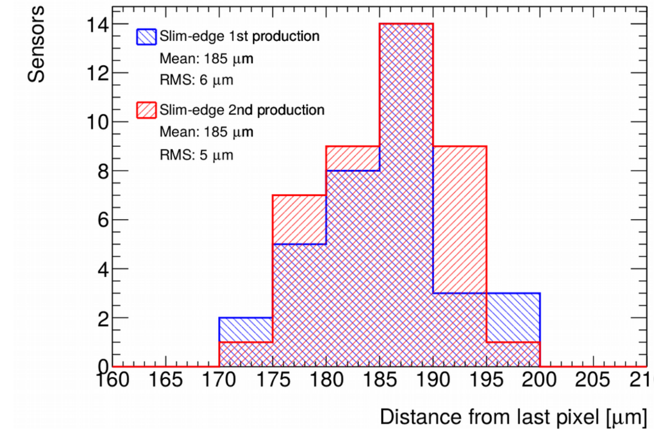


Backup

Qualification: Slim Edge

- **Requirement:** < 200 μm insensitive edge
- **CNM** (3D guard ring design): Fully sensitive up to last pixel
- **FBK** (no guard ring): Sensitive ~75 μm beyond last pixel

  → **Both productions fulfill slim edge requirement!**



- At time of production FBK changed production from 4” to 6” wafer → chose CNM

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