AFP Beam Tests – Integration and Tracker

Jörn Lange
on behalf of the AFP Test Beam Group

LHC Working Group on Forward Physics and Diffraction,
16 March 2016

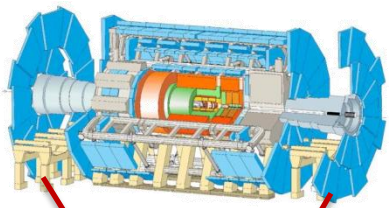
Institut de Física d'Altes Energies

EXCELENCIA SEVERO OCHOA

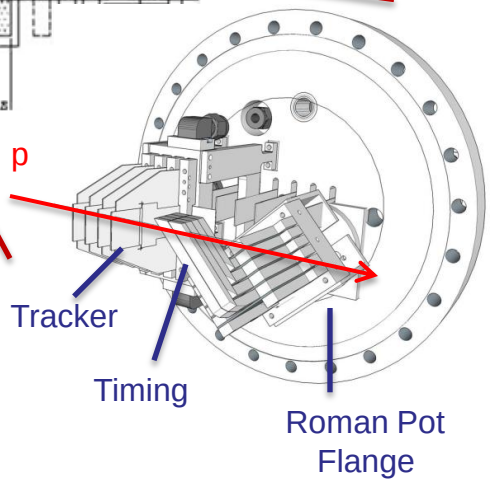
BIST Barcelona Institute of Science and Technology

ATLAS

AFP Detector



AFP
210 m
Horizontal
Stations



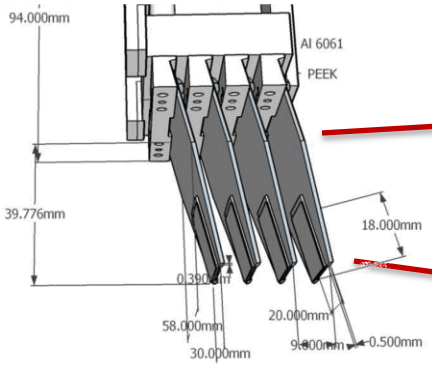
- ATLAS Forward Proton (AFP): measure forward protons
- Combination of tracker and timing detector for pile-up removal in Roman Pots
  - 2 stations at ~210 m at both sides of ATLAS IP
  - Only 2-3 mm away from beam
- Staged approach:
  - One arm (0+2) in winter shutdown 2015/16
    → **Installed!!**
  - Second arm (2+2) in shutdown 2016/17

AFP TDR: ATLAS-TDR-024; LHCC-2015-009
http://cds.cern.ch/record/2017378

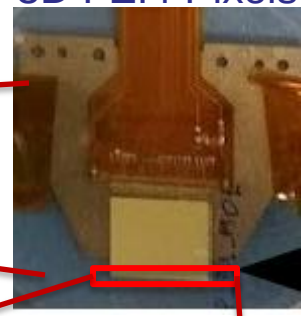
AFP Tracking Detector

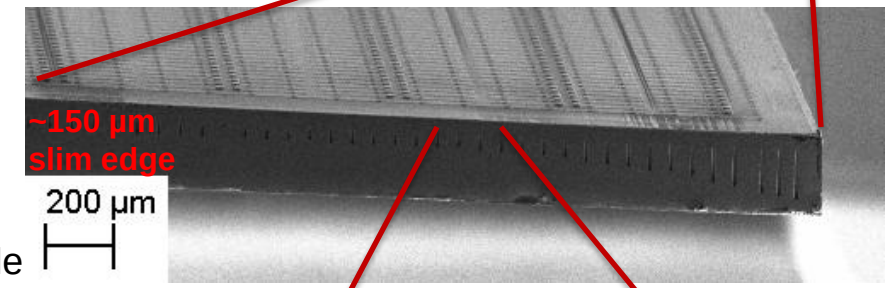
See talk by Ivan Lopez

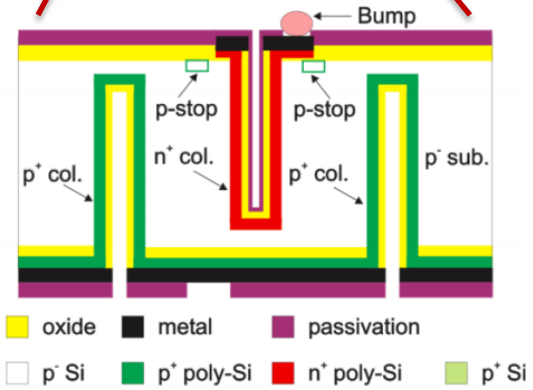
- Task
  - Tag p and measure its momentum (together with LHC magnets)
- Requirements
  - 10 (30) µm resolution in x (y)
  - Slim edge 100-200 µm
  - Radiation hard (non-uniform irradiation)
- Solution
  - 4 planes of **3D CNM FE-I4** Si pixel sensors (ATLAS-IBL proven)
    → **like a telescope**
  - 14° tilt in x for efficiency and resolution improvement
  - FE-I4 chip
    - 336x80 pixels with 50x250 µm²
    - 1.68x2.00 cm² active area → single-chip module
    - Threshold 1.5-3 ke tunable
    - Charge information from Time Over Threshold (ToT, 4 bit)
  - Sensors
    - Double-sided 3D sensors by CNM (Barcelona)
    - 230 µm thick, p-type substrate, 2E
    - Edge termination with 3D guard rings
    - Edge slimmed at side facing the beam (100-200 µm)
  - Module assembly at IFAE Barcelona



3D FEI4 Pixels







AFP Beam Tests

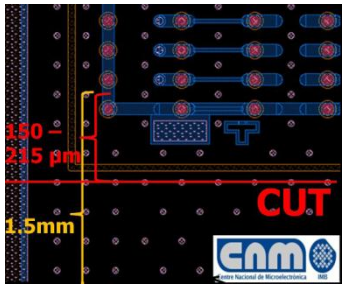
- 2012-2014:
  3D Sensor qualification beam tests
  - Slim edge of 15 µm – 200 µm possible
  - Good efficiency after non-uniform irradiation

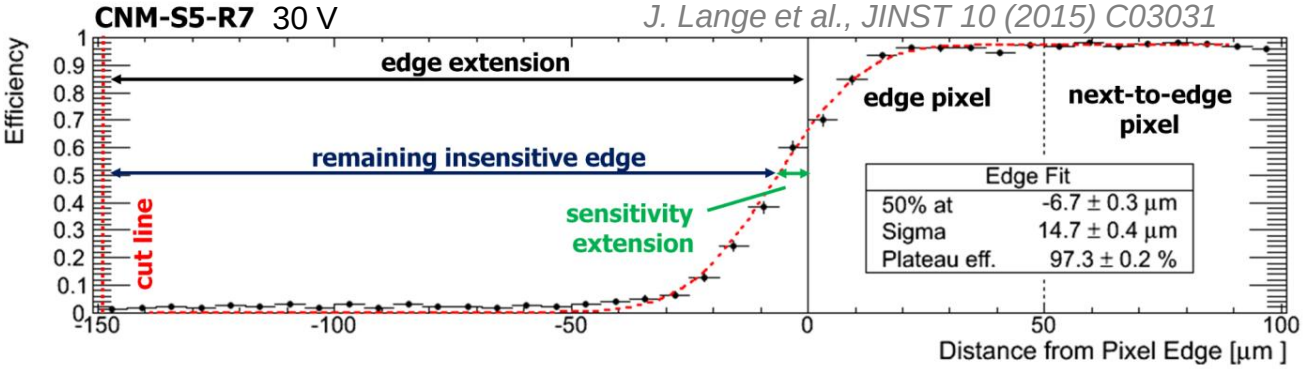
J. Lange et al., JINST 10 (2015) C03031

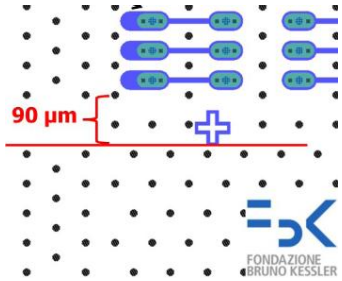
- 2014-2015:
  AFP integration beam tests at CERN SPS H6A/B (120 GeV pions)
  - Tracking+Timing+Readout Integration
  - Detector Performance
- Results
  - 2015 analysis on-going
  - Preliminary 2014 results documented in AFP TDR, ATLAS-TDR-024 (2015)
  - Publication in preparation

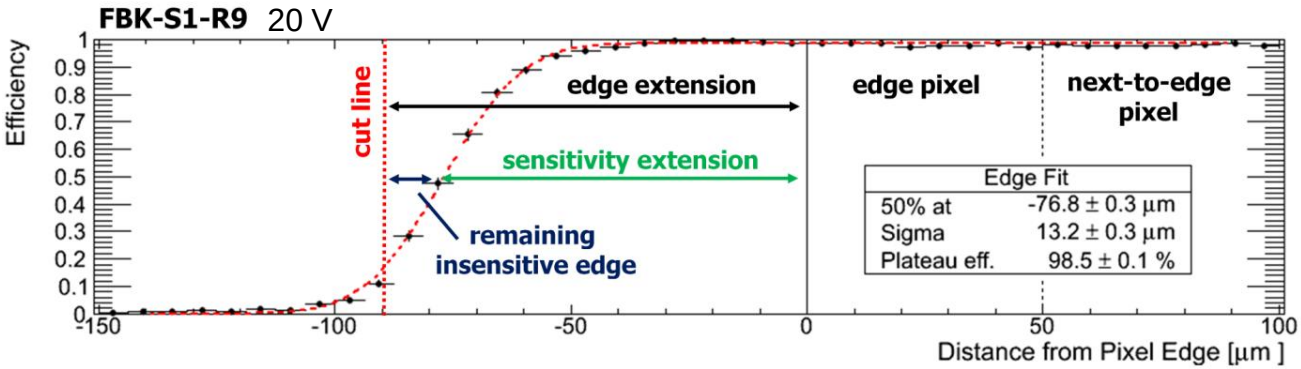
AFP Sensor I – Slim Edge

Slim-edged 3D FE-I4







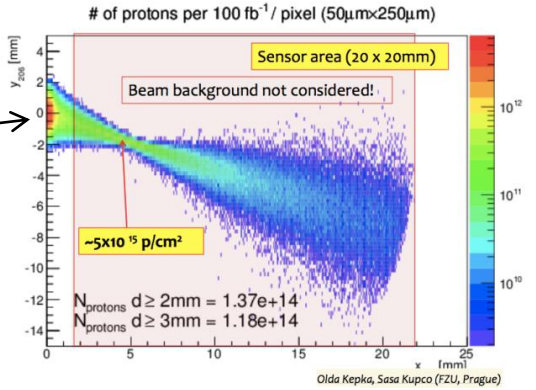


- **CNM (3D guard ring design):** Fully sensitive up to last pixel
- **FBK (no guard ring):** Sensitivity extends ~75 µm beyond last pixel
  → <15 µm insensitive edge: slimmest edge apart from fully active edge
- For both CNM and FBK: ≤150 µm insensitive edge possible

→ AFP slim-edge requirements fulfilled

AFP Sensor II – Radiation Hardness

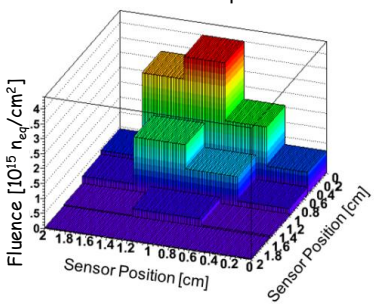
- Radiation hardness for uniform radiation to 5x10^{15} n_{eq}/cm^2 known from IBL
- AFP: Highly non-uniform fluence from diffractive p
  - 3x10^{15} n_{eq}/cm^2 in max. (~7 TeV p), orders of magnitudes less nearby
- 2 irradiation campaigns with different non-uniformity scenarios



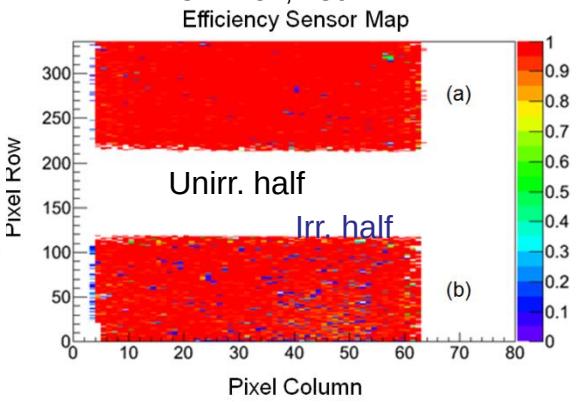
1) Focussed 23 GeV p irradiation (CERN-PS)
   → fluence spread large

2) 23 MeV p (KIT) through hole in 5mm Al plate
   → very localised fluence with abrupt transition

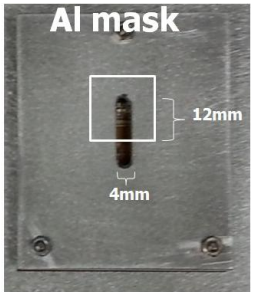
max. 4x10^{15} n_{eq}/cm^2



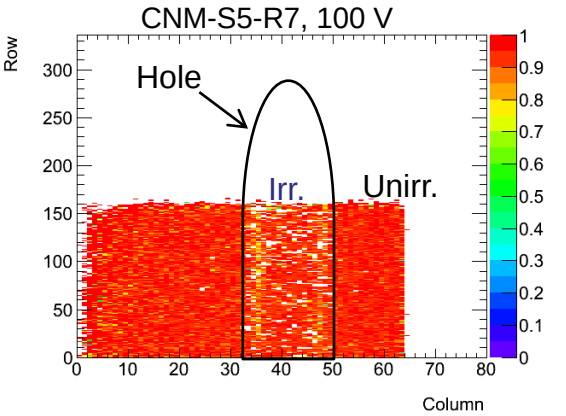
CNM-57, 130 V



3.6x10^{15} n_{eq}/cm^2



CNM-S5-R7, 100 V

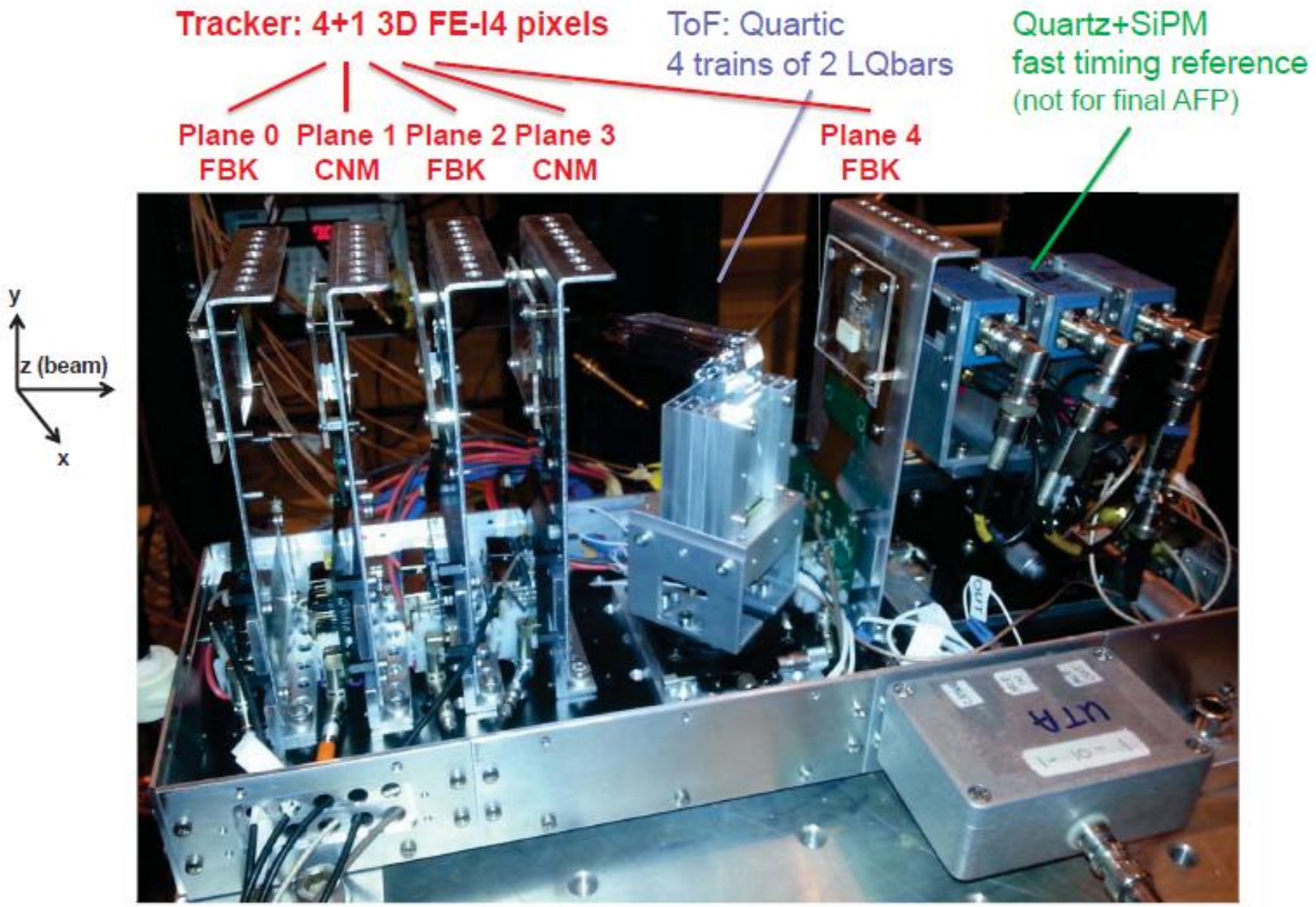


Efficiency 96-99% in all regions

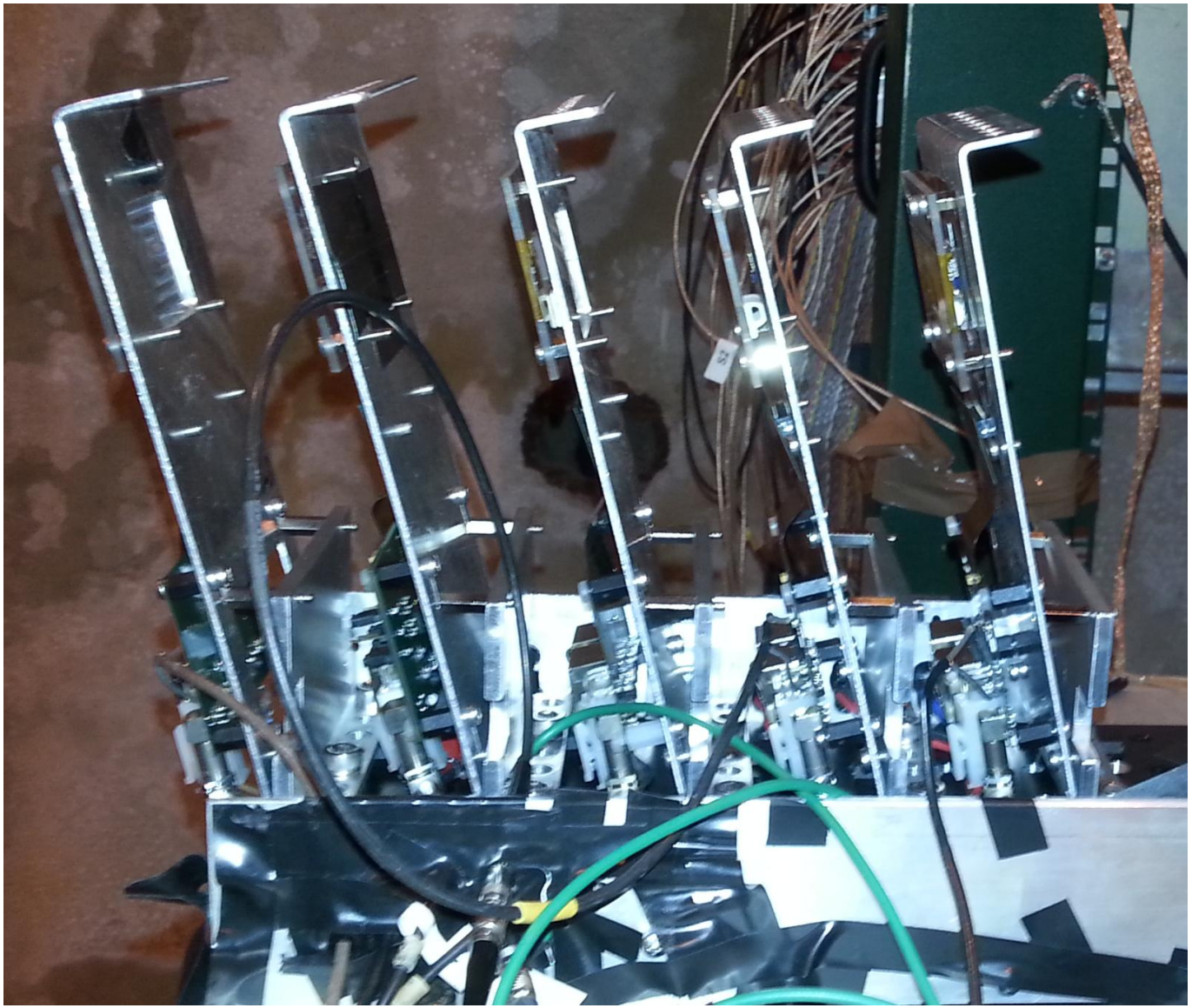
→ AFP radiation-hardness requirements fulfilled

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

Integrated AFP Prototype



Tracker-Only at 14°

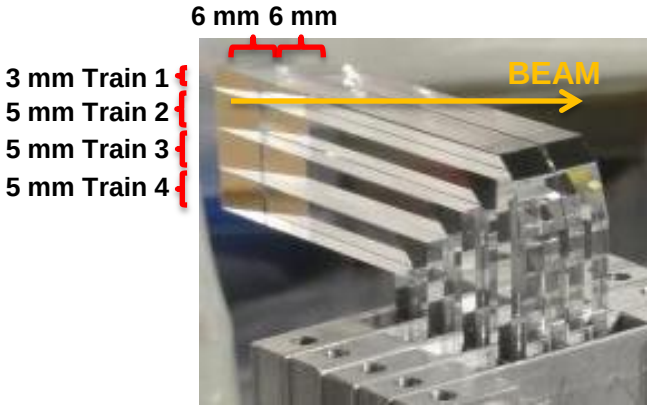


System Components

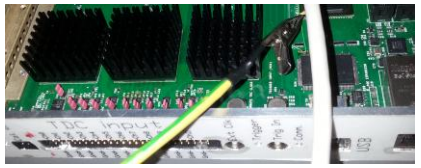
TRACKING: 5 FE-I4 3D Pixel Detectors
- IBL style (by CNM/FBK), IBL spares (not best quality)
- Bias voltage typically 10 V
- HitOr triggering output of all pixels

TIMING: 4 rows of trains of 2 LQbars
- Oriented at Cherenkov angle of 48°

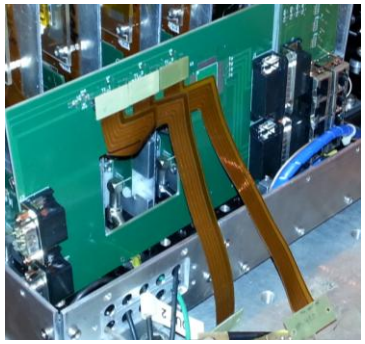
See talk by Tom Sykora



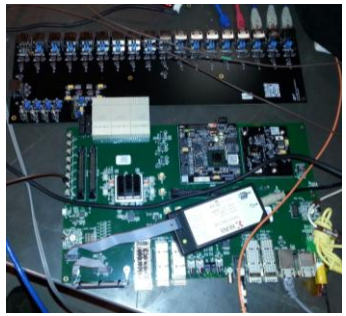
Signal chain
→ 4x4-pixel MCP-PMT
→ PreAmp
→ Constant Fraction Discriminators (CFD)
→ High-Precision Time-to-Digital (HPTDC)



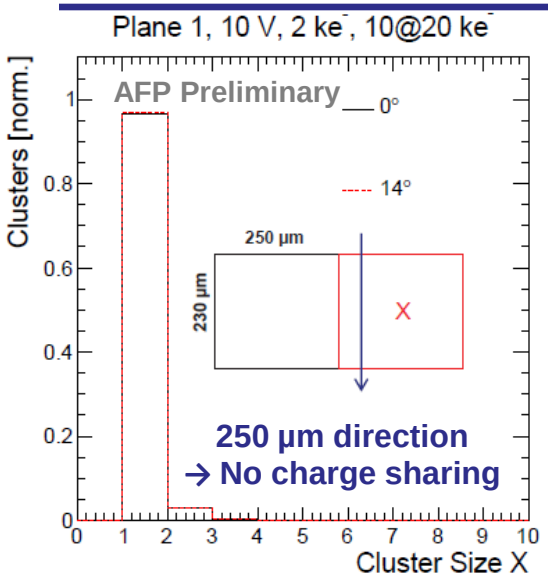
Trigger: Pixel Plane Coincidence
- Logic by HitBus chip developed for ATLAS-DBM

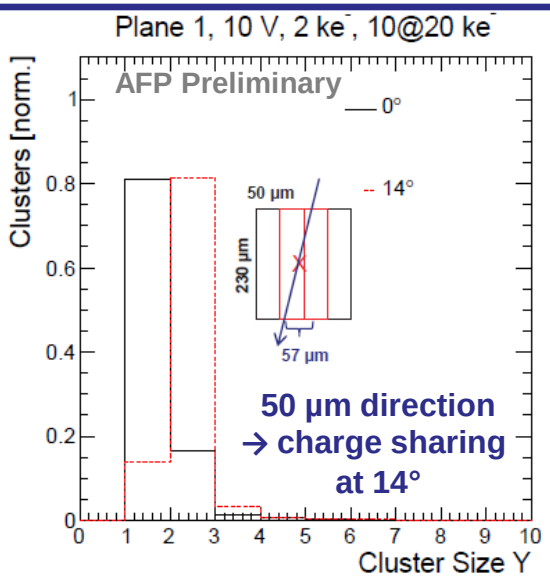


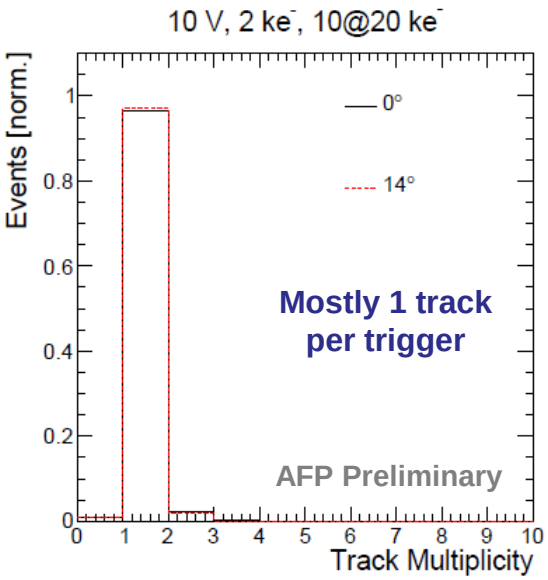
READOUT: RCE

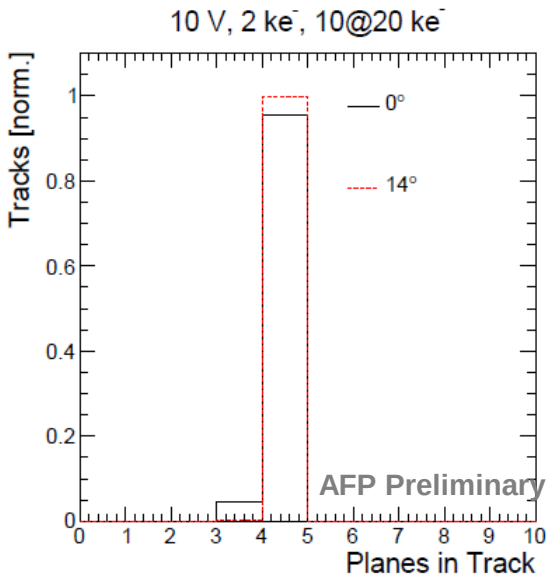


Tracker Reco. + Performance





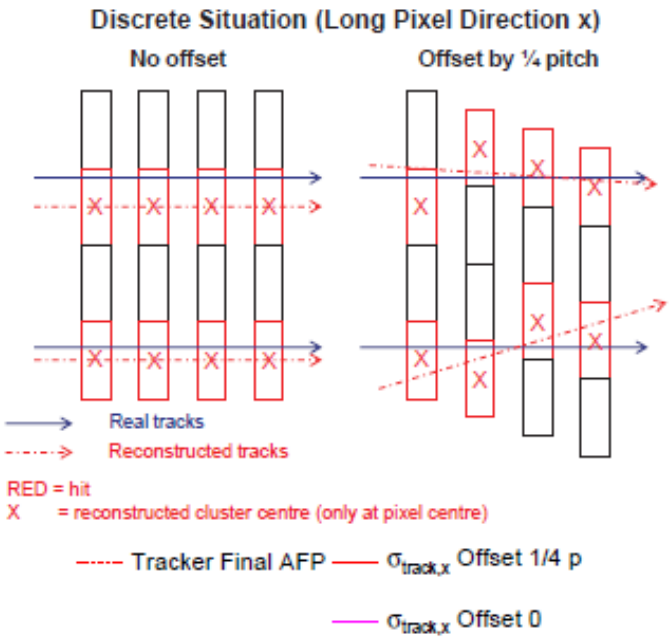


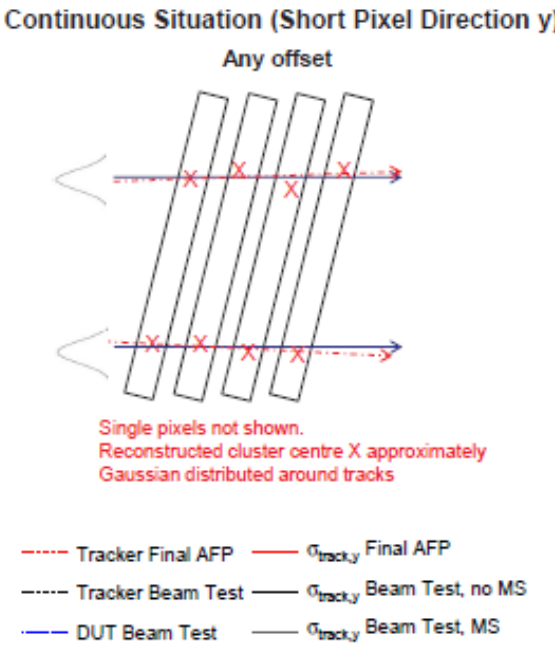


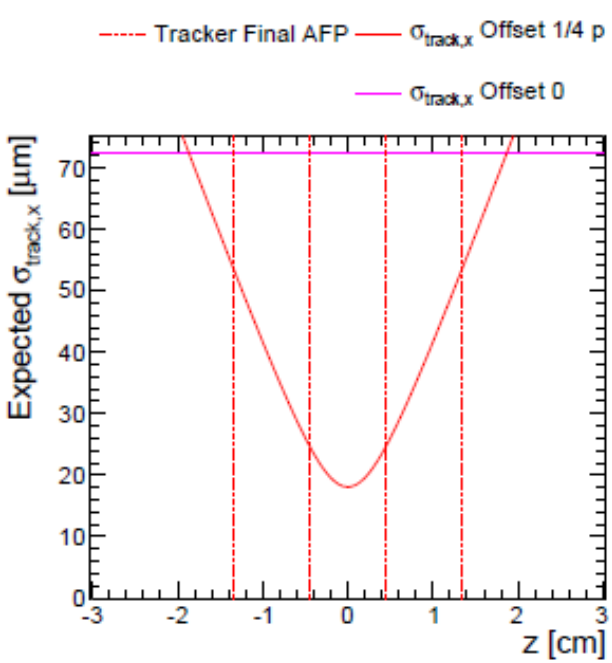
- RCE stores track+timing data in common data format (root tree)
- Tracks reconstructed with software framework Judith
  G. McGoldrick al., NIM A765 (2014) 140
  - Grouping pixel hits into clusters
  - Straight line fit
- Compared data at
  - 0° (beam test standard)
  - 14° (final AFP condition)
    → qualitatively different!

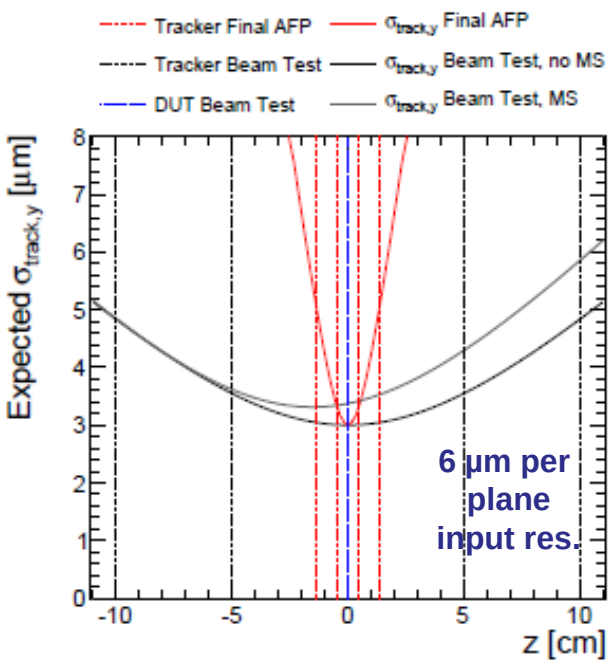
→ almost always all planes included in track (reco for first 4 planes) → good efficiency

Position Resolution – Basic Considerations



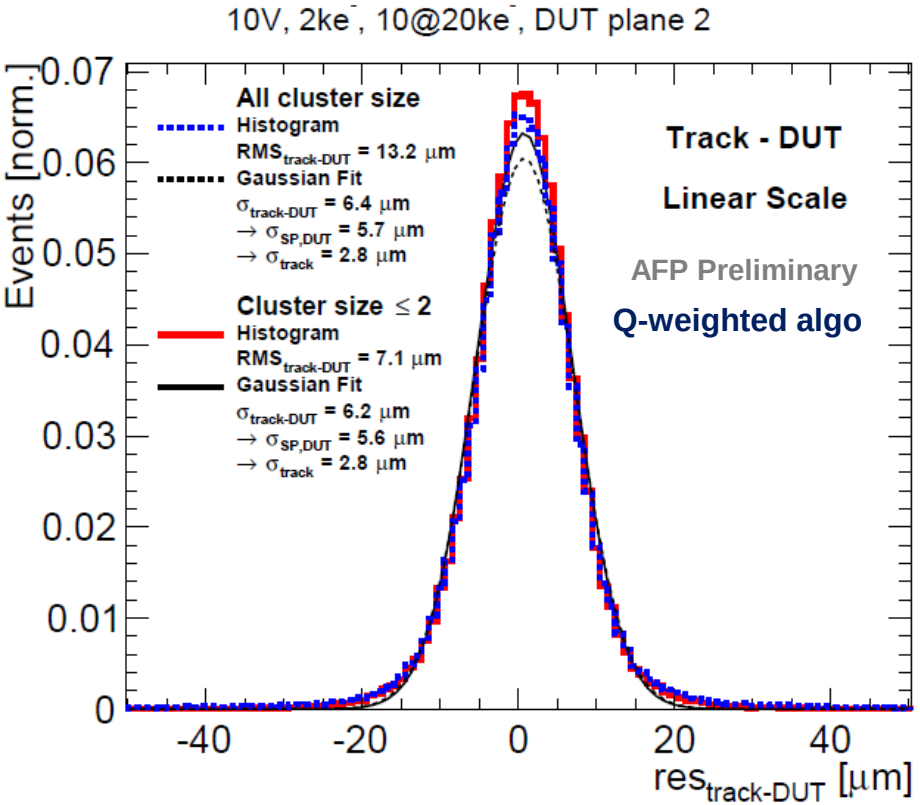


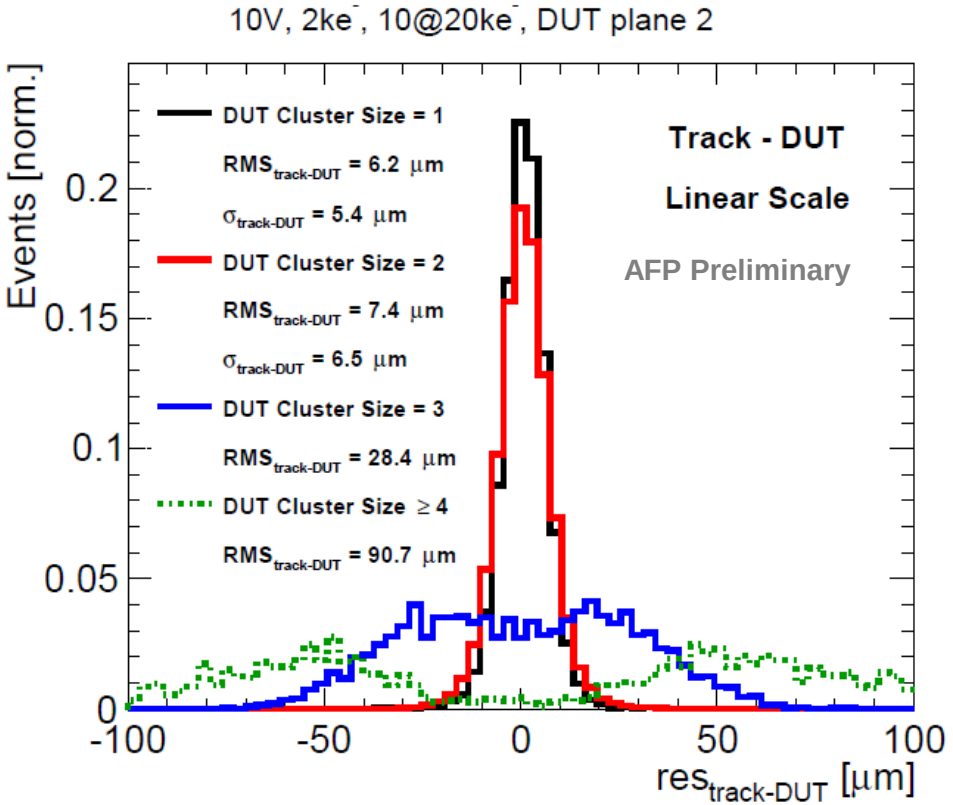




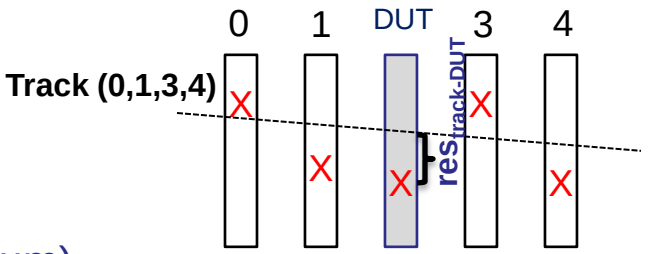
- Qualitatively different in short+long pixel direction
- Long pixel direction 250µm
  - Discrete (only 1 pixel hit)
  - Cluster position only in pixel centre
  - 4-plane resolution depends on offset → down to 18 µm for offset by ¼ pitch
  - Cannot measure resolution from residuals in identical planes (bias!)
- Short pixel direction 50µm
  - Continuous/analog (Q-weighted algo)
  - 4-planes improve to $1/\sqrt{N_{planes}}$ in tracker centre (neglecting mult. scattering (MS))
  - 0.4 µm worse due to MS in beam test; MS in AFP negligible
  - Can measure resolution from residuals in identical planes

Position Resolution

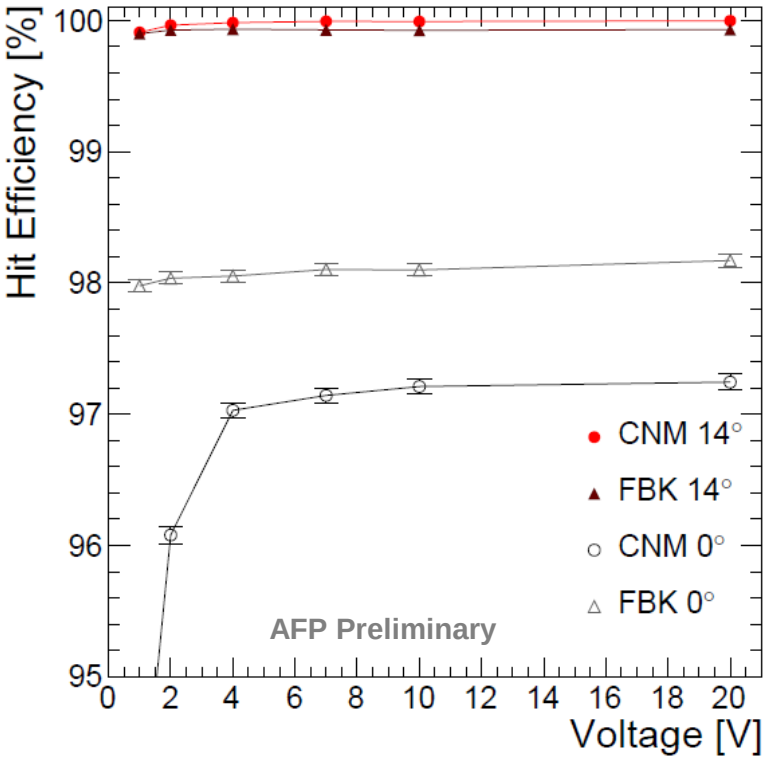


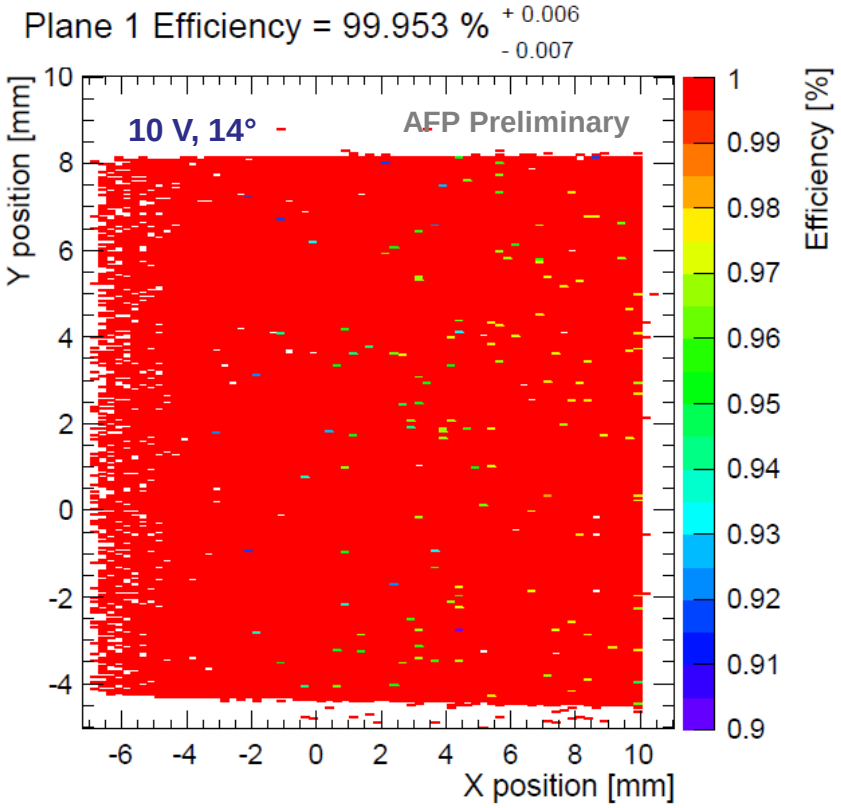


- Residual track-DUT (central plane)
  - Gives convolution of single-plane DUT resolution and 4-plane track resolution at position of DUT
- Non-Gaussian tails from cluster size>2 (delta rays etc.)
  - Highly reduce when cutting on cluster size<=2 (96% cut eff.)
- Disentangling track and DUT resolution when assuming $\sigma_{track} = ½\ \sigma_{SP,DUT}$ (neglecting MS, absorbed in syst. unc. ~0.5 µm)
- **6 µm single plane resolution, 3 µm track resolution**



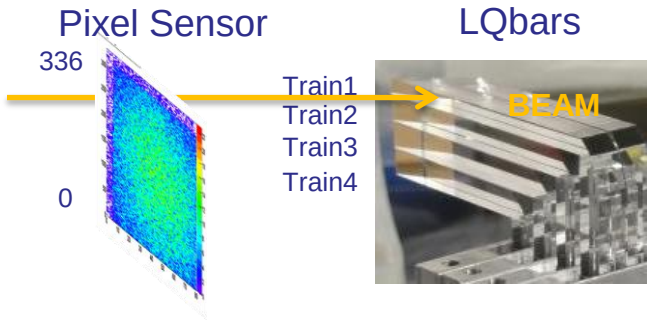
Tracker Hit Efficiency



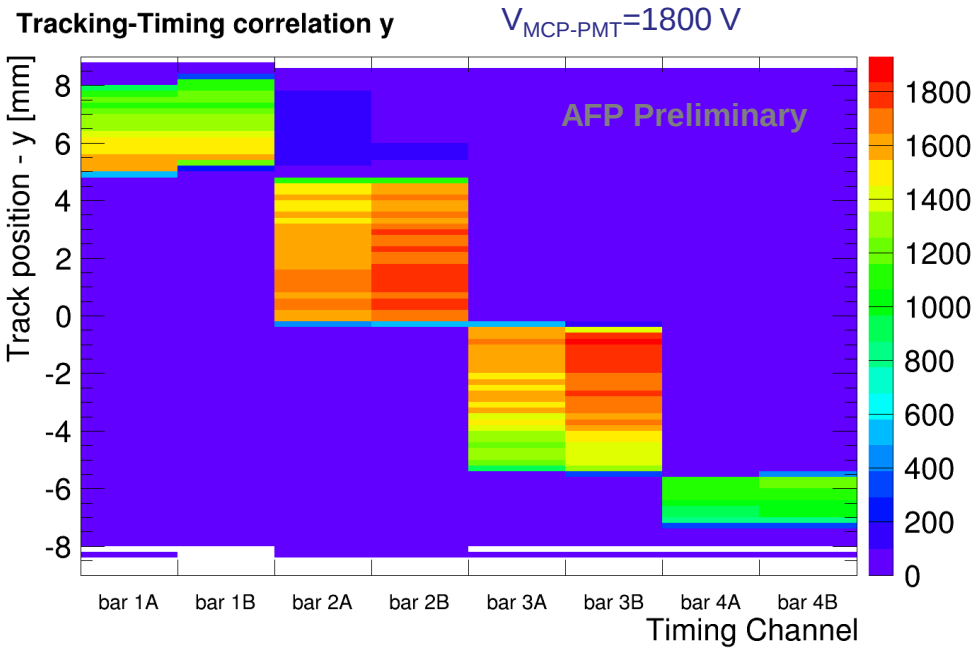


- Excluded DUT from track fit
- 97-98% at 0° for IBL spare quality class (inefficient 3D columns+local low-field regions)
- Improves to **>99.9% at 14°** due to spreading out charge
- Already from 1V!

Tracking-Timing Correlations



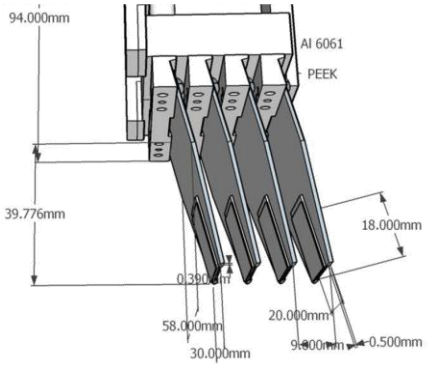
- Principle:
  Track position and LQbar train numbers are correlated in space (for parallel tracks):
  Upper pixels fire → upper LQbar trains fire



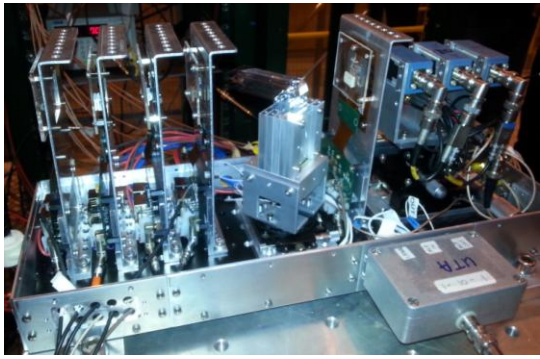
- Good spatial correlations between pixels and LQbars

→ **Tracking-timing integration works!**

Conclusions

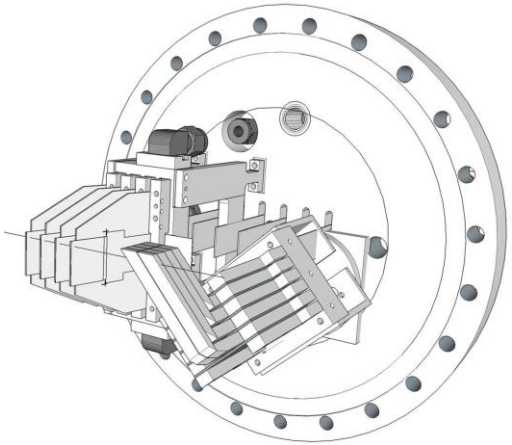


- AFP tracker
  - Pixel module prototypes extensively qualified
    → **Fulfill AFP requirements** of slim edge, non-uniform radiation hardness and resolution
  - First pixel modules produced and installed



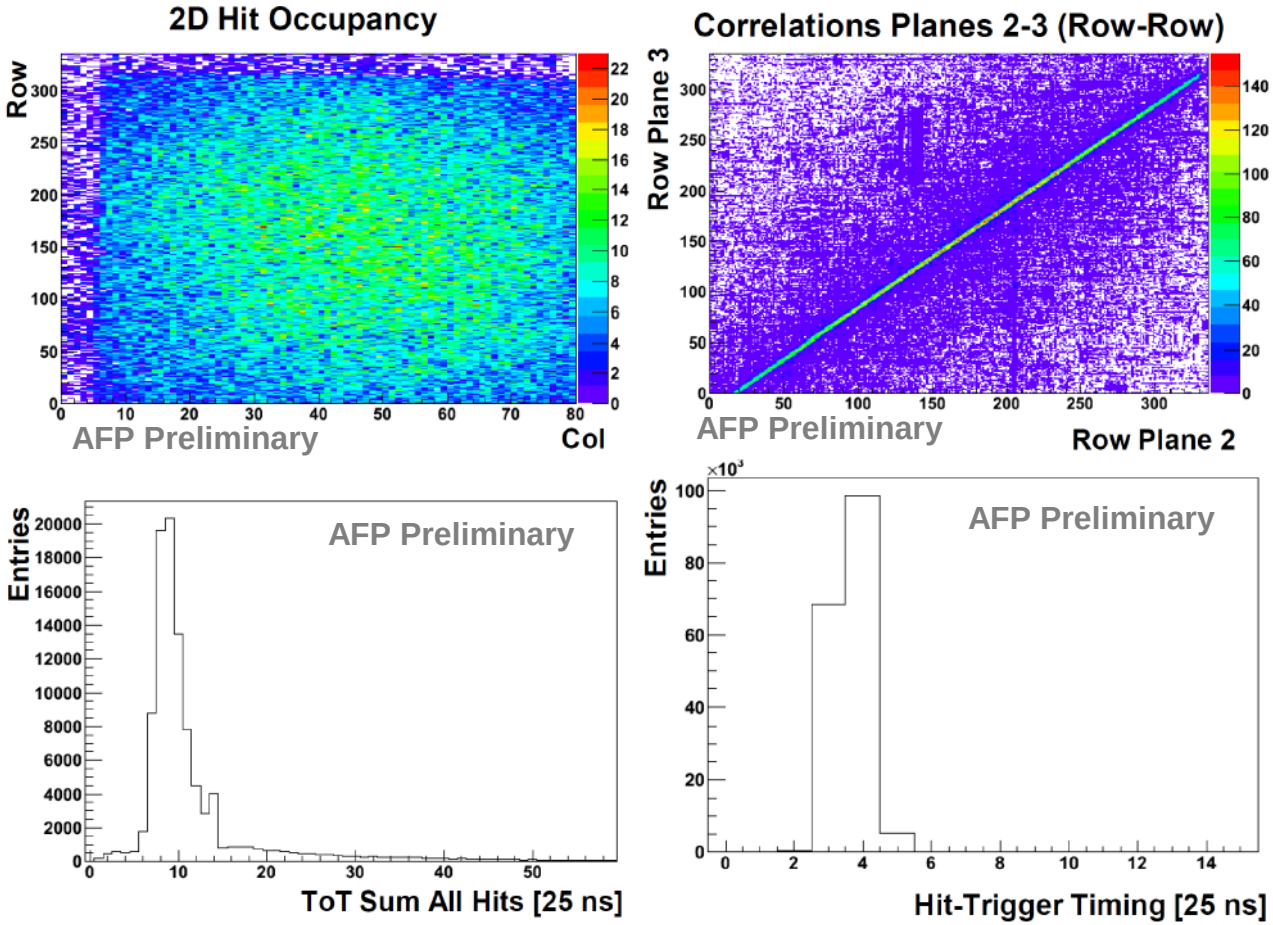
- AFP beam tests 2014+15 with first AFP prototype successfully finished
  - Tracking + timing **integrated** into RCE readout
  - Integration into ATLAS TDAQ system tested
  - **Good performance** of pixel tracker and LQbar timing detectors
    - >99% hit efficiency
    - 3 µm track resolution (3-4 times better than required)

- Outlook:
  - Analysis efforts of 2015 data on-going
  - 3 more beam tests for final integration and ToF development in 2016
  - …. and LHC data from real AFP!



BACKUP

Online Monitoring



- Integrated in RCE data taking GUI
- **Good online control on main tracking parameters**
- Also one ToF plot available per HPTDC channel