AFP Tracker and Beam Tests

Jörn Lange

on behalf of the AFP Group

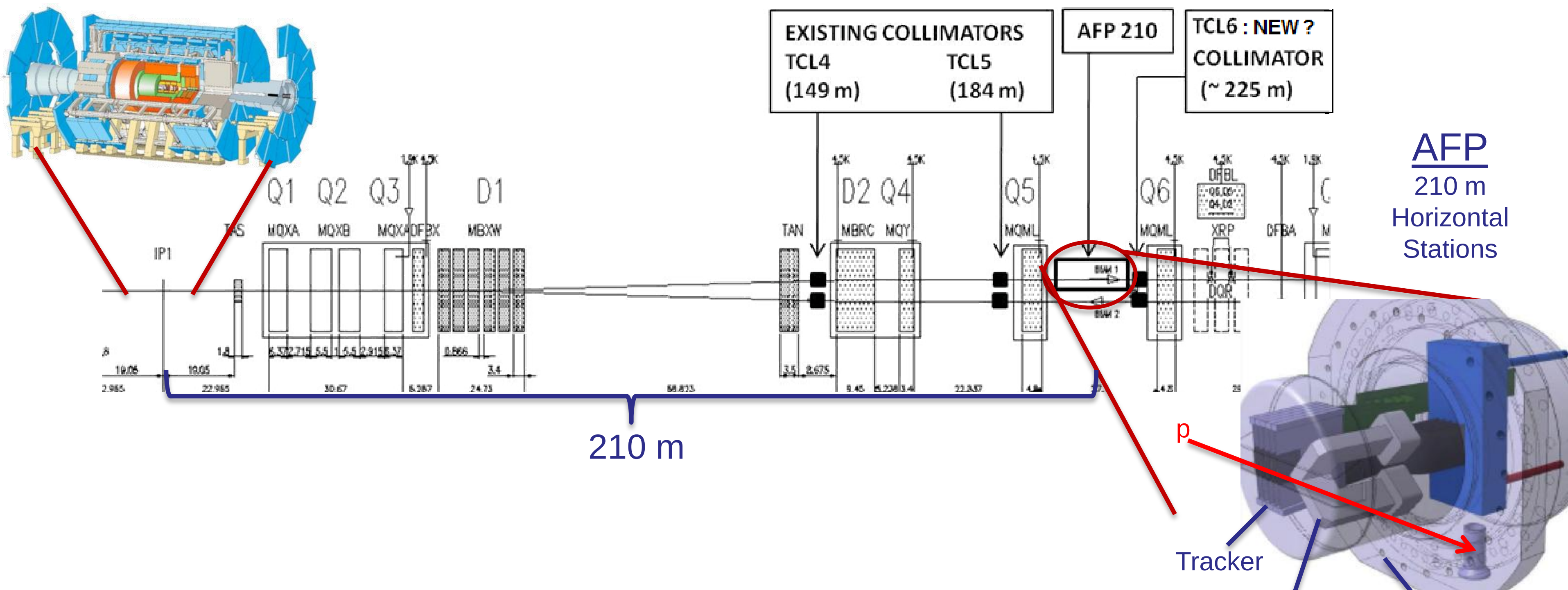
LHC Working Group on Forward Physics and Diffraction, 27 Oct 2015

IFAE

EXCELENCIA SEVERO OCHOA

ATLAS

AFP Status

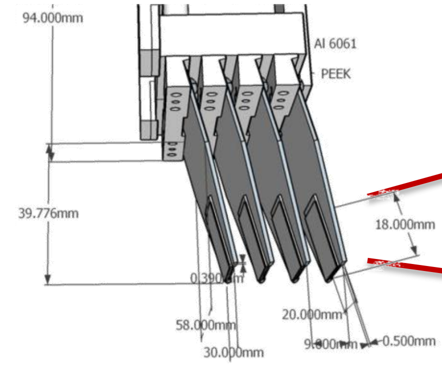


- ATLAS Forward Proton (AFP) approved by ATLAS June 2015
- AFP TDR: ATLAS-TDR-024; LHCC-2015-009
  - http://cds.cern.ch/record/2017378
- Engineering Change Request
  - Accepted at LMC meeting Aug 26
- Staged approach:
  - One arm (0+2) in winter shutdown 2015/16
  - Second arm (2+2) in shutdown 2016/17

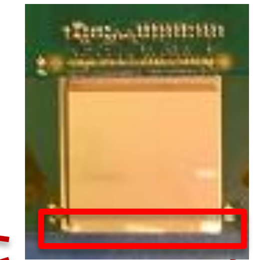
Other AFP talks tomorrow:
AFP Physics by R. Staszewski
AFP TDAQ by K. Korcyl
AFP installation by P. Sicho

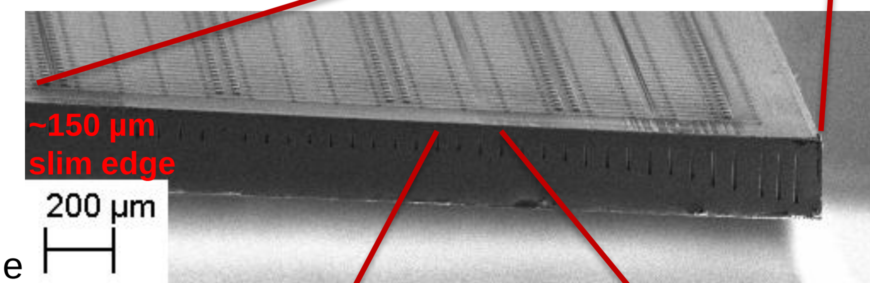
AFP Tracking Detector

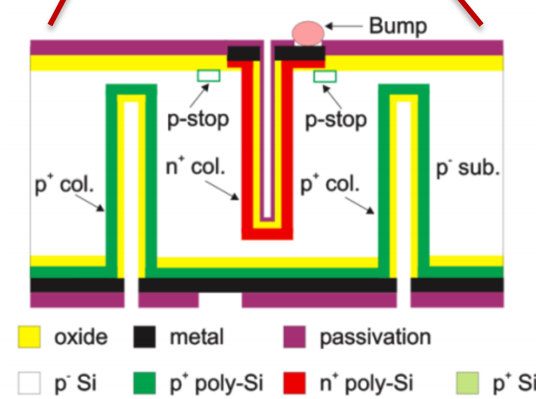
- Task
  - Tag p and measure its momentum (together with LHC magnets)
- Requirements
  - 1 µrad angular resolution
  - 10 (30) µm resolution in x (y)
  - Slim edge 100-200 µm
  - Radiation hard (non-uniform irradiation)
- Solution
  - 4 planes of **3D CNM FE-I4** Si pixel sensors (ATLAS-IBL proven)
  - 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)
  - Tracker Cards
    - Aluminium or Al-Carbon-Fibre (NOVAPACK)



3D FEI4 Pixels

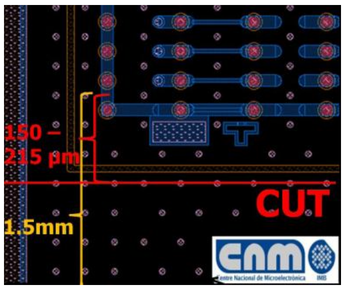


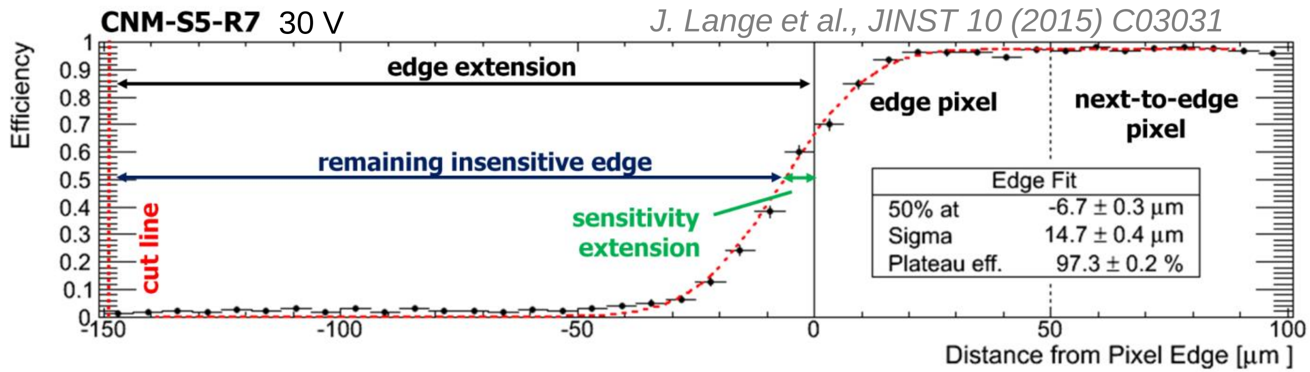


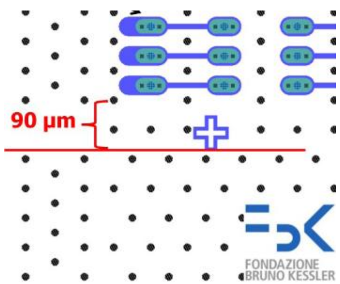


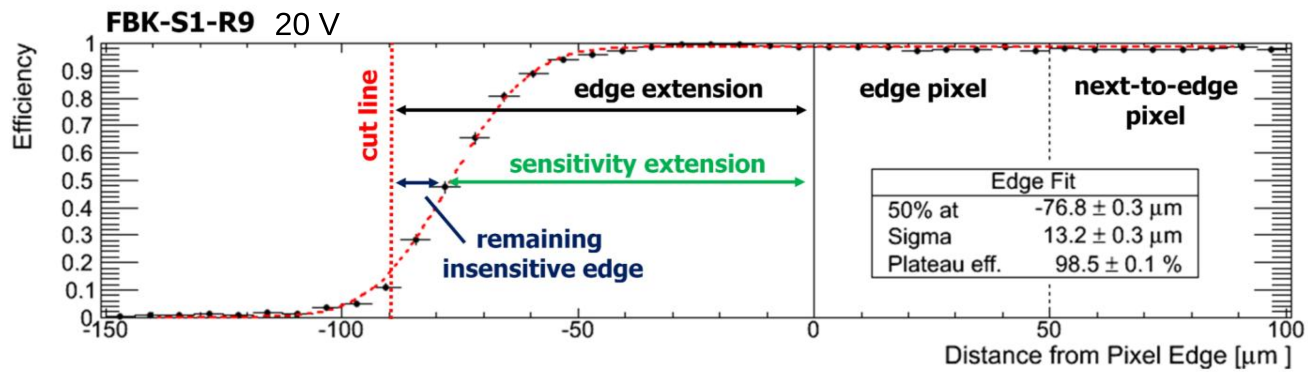
AFP Sensor I – Slim Edge

Slim-edged 3D FE-I4







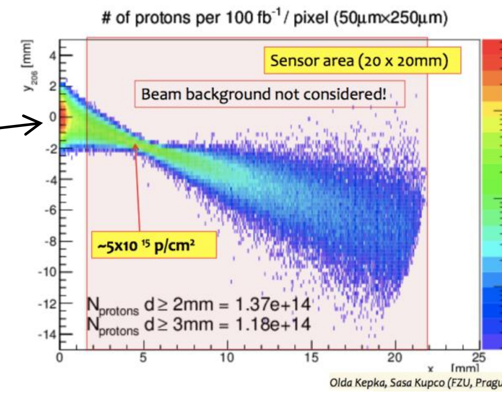


- **CNM:** Fully sensitive up to last pixel (3D guard ring design)
- **FBK:** Sensitivity extends ~75 µm beyond last pixel (no guard ring)
  → <15 µm insensitive edge: slimmest edge apart from fully active edge
- For both CNM and FBK: ≤150 µm insensitive edge possible

→ AFP slim-edge requirements fulfilled

AFP Sensor II – Radiation Hardness

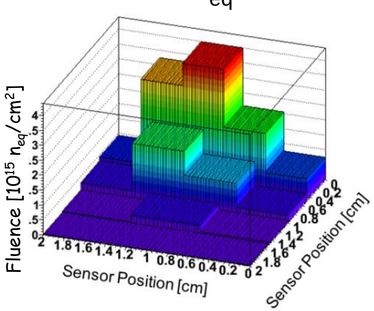
- Radiation hardness for uniform radiation to 5x10^{15} n_{eq}/cm^2 known from IBL
- AFP: Highly non-uniform fluence from diffractive p
  - 3x10^{15} n_{eq}/cm^2 in max. (~7 TeV p), orders of magnitudes less nearby
- 2 irradiation campaigns with different non-uniformity scenarios

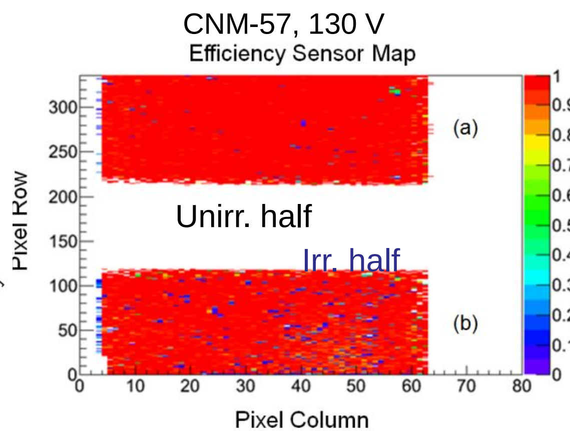


1) Focussed 23 GeV p irradiation (CERN-PS)
→ fluence spread large

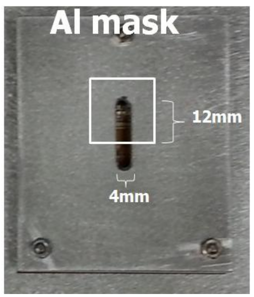
2) 23 MeV p (KIT) through hole in 5mm Al plate
→ very localised fluence with abrupt transition

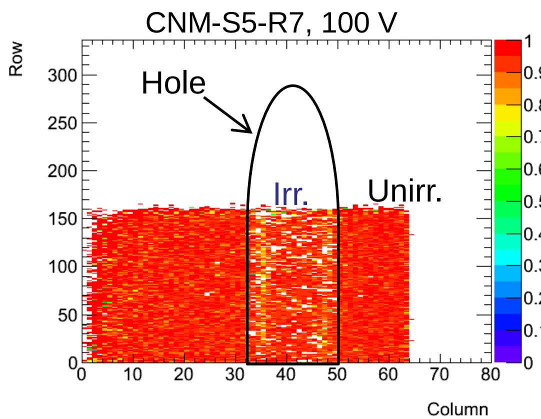
max. 4x10^{15} n_{eq}/cm^2





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





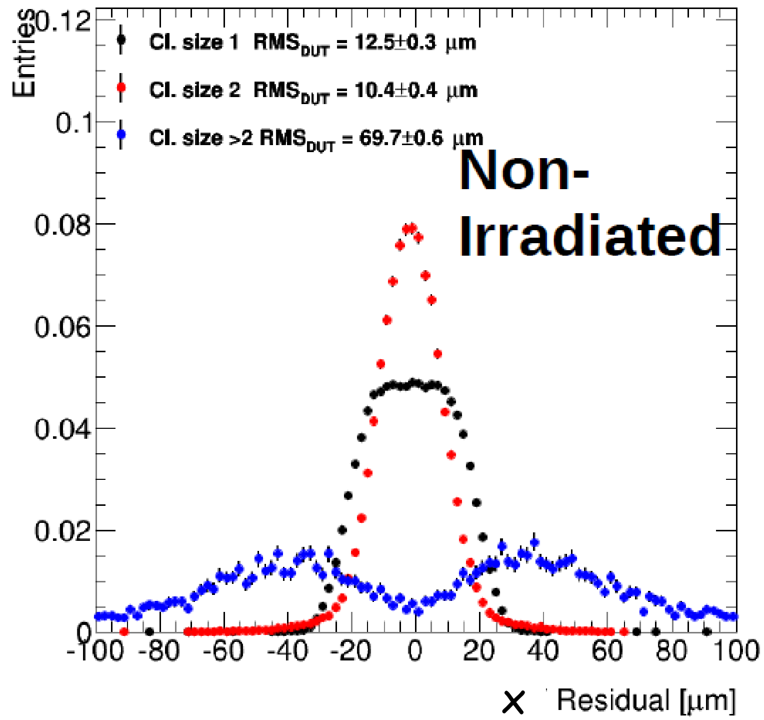
Efficiency 96-99% in all regions

→ AFP radiation-hardness requirements fulfilled

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

AFP Sensor III – Resolution

- At 0° tilt extensively studied in beam tests
- Depends on cluster size, algorithm, tuning, …
  - Per-plane resolution for events with 1 or 2 pixels/cluster (98-99% of the events, simple ToT weighting)
    - RMS = 12 µm in 50 µm pixel direction (AFP x)
    - RMS = 72 µm in 250 µm pixel direction (AFP y)
  - Degraded for larger cluster size due to delta rays
  - Only slight degradation (~1 µm) after $4x10^{15}$ n_{eq}/cm^2 irradiation
- Expect improvement in x to <10 µm per plane from 14° tilt
  - Enhanced charge sharing
  - Under study
- 4-plane telescope expected to improve over single plane
  - In x direction by roughly √4 (continuous distribution from charge sharing)
  - In y direction with the help of staggering planes (discrete one-hit distribution) → e.g. staggering by 80 µm expected to give ~25 µm RMS



I. Lopez et al., ANIMMA Conference 2015, Lisbon

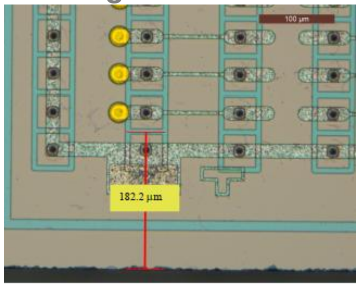
→ AFP resolution requirements fulfilled

AFP Pixel Module Production

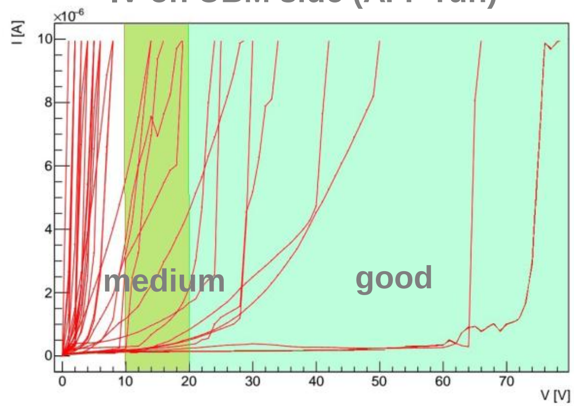
- 3D sensor production run at CNM
  - Finished in July 2014
  - 8 lost wafers due to machine malfunctions, 5 wafers successfully finished (40 sensors)
  - Slim-edged to 180 µm
  - 9 good + 5 medium quality-IV sensors
    → Low yield due to etching problems with DRIE
    → Identified and solved for next runs
    - Reliable IV only after bump-bonding
      → Final yield might change
      (2 bad IVs shifted to medium)
  - New AFP run started at CNM in February 2015, to finish in December
- Tracker cards (Al) produced by Bergen
- Flexible Circuit Board production by Oslo to finish soon
- Module assembly incl. bump- and wirebonding and QA to be done at IFAE Barcelona
  - Full assembly line in house incl. bump- and wire-bonding machines
  - Already many successful tests performed on prototypes

→ AFP tracker production proceeding well

Slim-edged AFP sensor

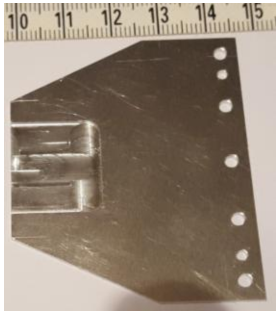


IV on UBM side (AFP run)



M. Baselga, CNM

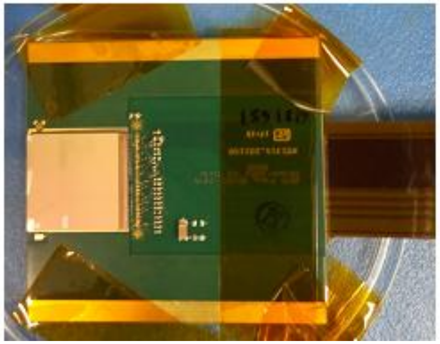
Al Tracker Card



Bump-Bonding

Assembled prototype

AFP_6181_W6_S1



AFP Beam Tests

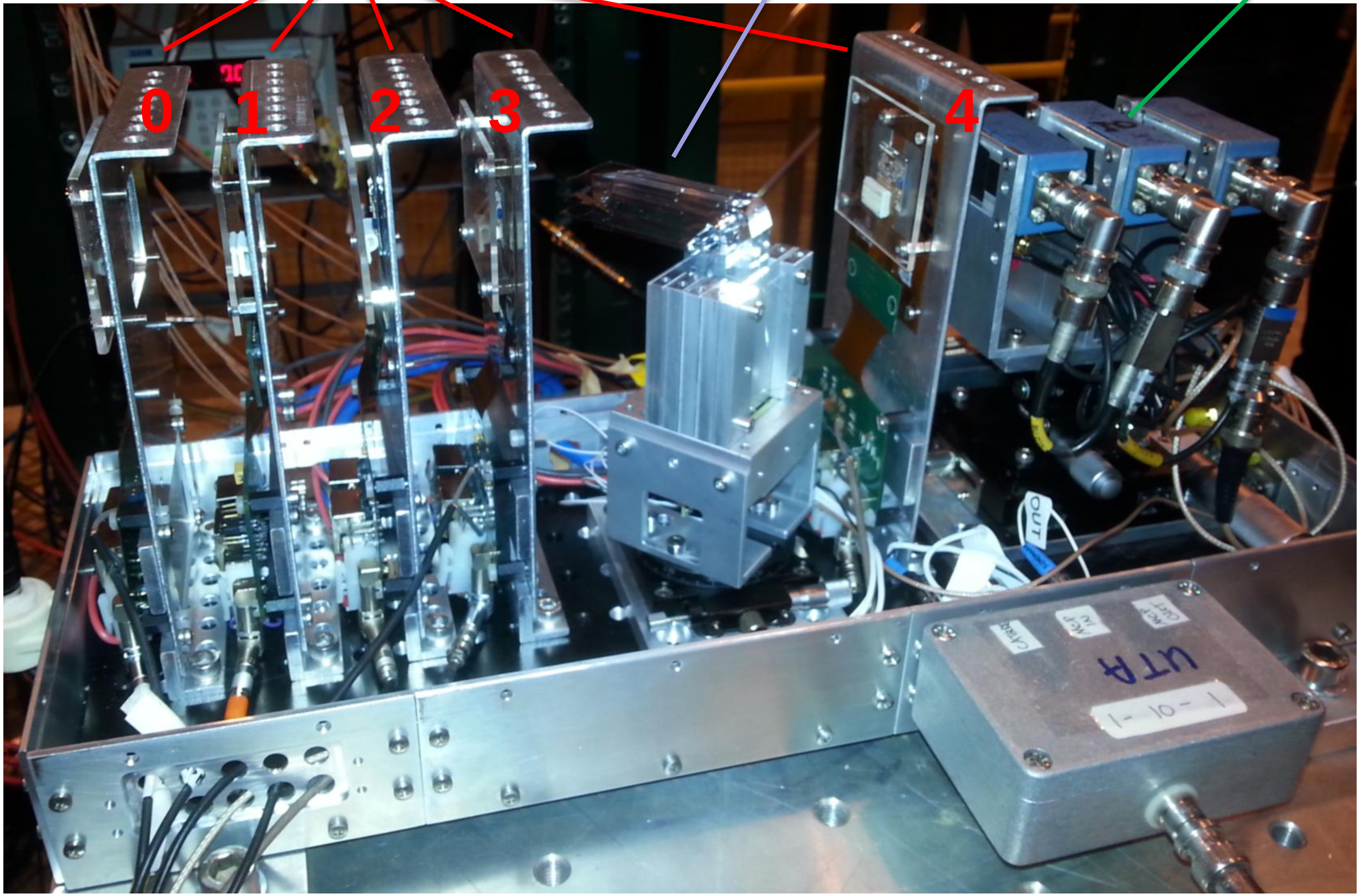
- AFP beam tests at CERN SPS H6A/B
  - 120 GeV pions
- November 2014 (1 week)
  - Tracking+Timing Integration
  - Detector Performance
- September 2015 (2 weeks)
  - Further ATLAS TDAQ Integration
  - Detector Performance
- Typically 20 participants
  - Overlap with ALFA group
  - In 2014 also some CMS/TOTEM participants
- Results
  - In the following almost only from 2014 beam test
  - Documented in AFP TDR, ATLAS-TDR-024 (2015)
  - 2015 analysis on-going
  - Publication in preparation

Integrated AFP Prototype

Tracker: 4+1 3D FEI4 pixels
→ trigger: 0 & 3 & 4

Timing: Quartic
4 trains of 2 LQbars

Quartz+SiPM
fast timing reference
(not for final AFP detector)



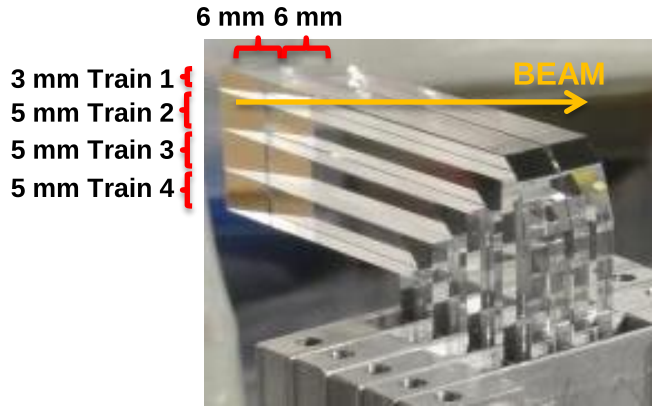
System Components

TRACKING: 5 FE-I4 3D Pixel Detectors

- IBL style (by CNM/FBK), IBL spares (not best quality)
- 2 of them with AFP slim edge
- Bias voltage typically 10 V
- HitOr triggering output of all pixels

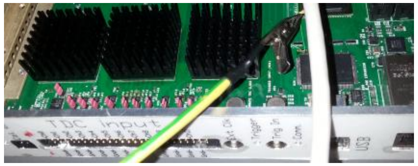
TIMING: 4 rows of trains of 2 LQbars

- Oriented at Cherenkov angle of 48°
- Standard: transparent LQbars, 2 adjacent LQbars/train
- Also different LQbars in 2015 (transparent/matt)
- Also different bar configurations in 2015 (e.g. with gap)



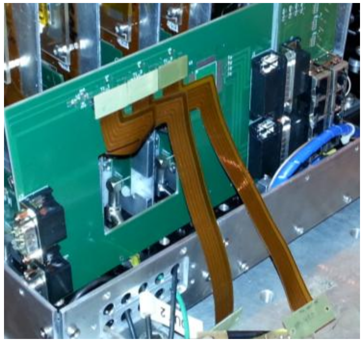
Signal chain

→ 4x4-pixel MCP-PMT
→ 2 10x Amp.
→ Constant Fraction Discriminators (CFD)
→ High-Precision Time-to-Digital (HPTDC)



Trigger: Pixel Plane Coincidence

- Track trigger for initial AFP runs at low μ (later ToF)
- Logic by HitBus chip developed for ATLAS-DBM
- ATLAS TDAQ chain tested: LTP + TTC in VME crate

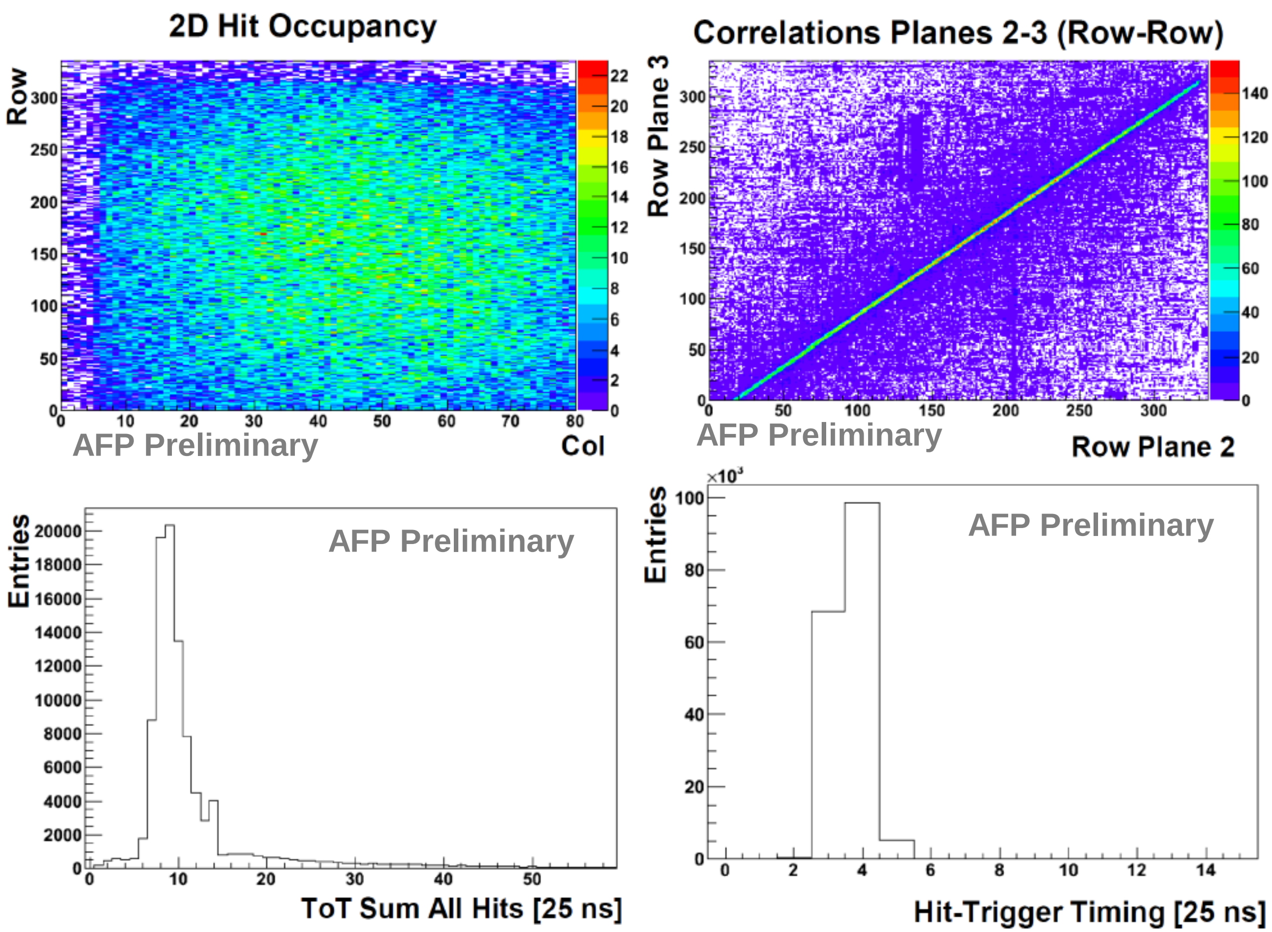


See talk by K. Korcyl

READOUT: RCE

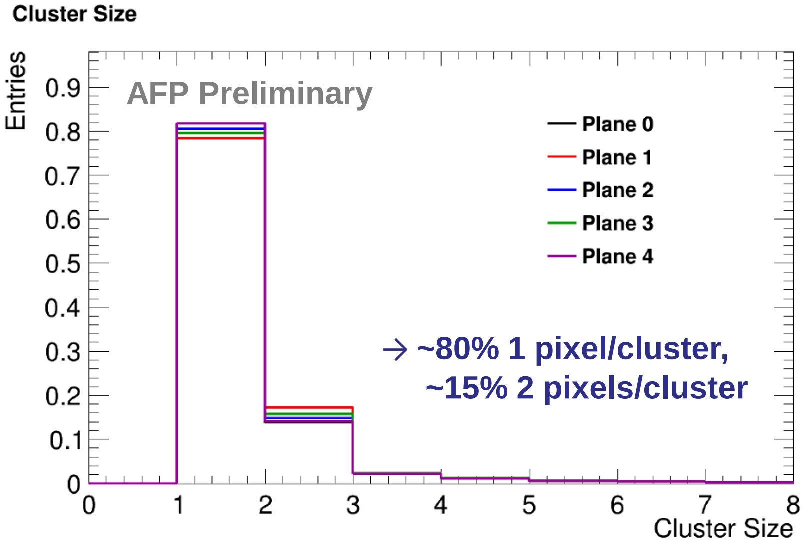
- Extensively proven in IBL stave testing
- HSIO board with 8-16 input channels (here: 5 pixels + 1 HPTDC)

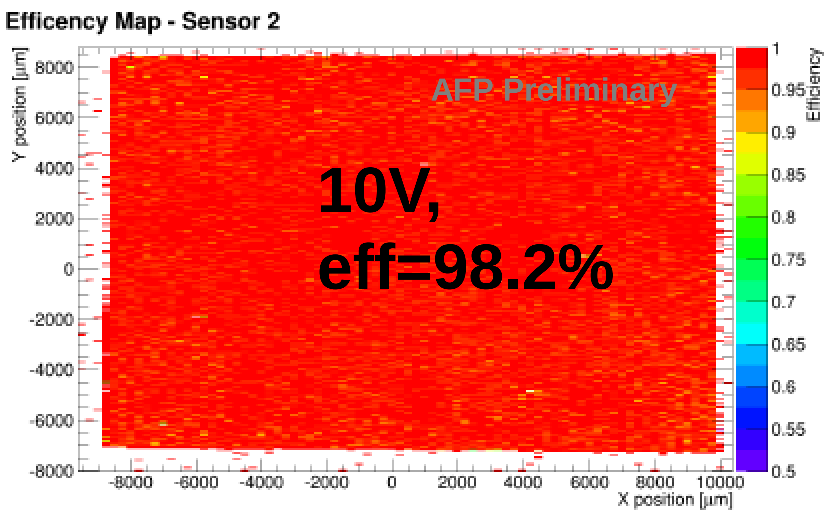
Online Monitoring



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

Tracker Reco. + Performance





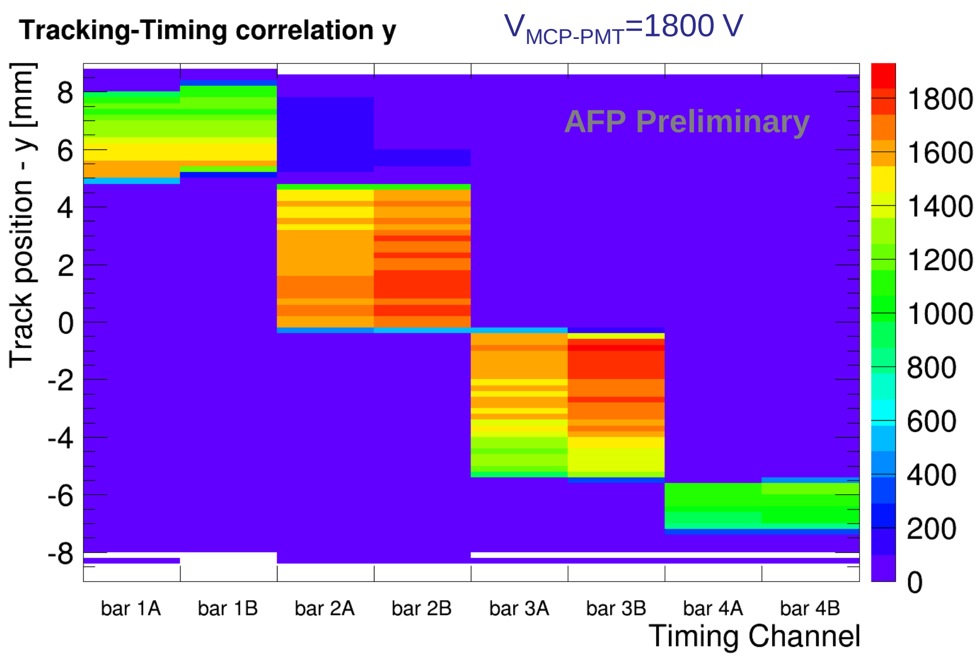
- Tracks reconstructed with software framework Judith G. McGoldrick al., NIM A765 (2014) 140
- 2014 data at 0° analysed
  - Mostly 1 cluster per plane and 1 track per trigger reconstructed (98%)
  - Mostly 1 pixel/cluster (80%)
    - Dominantly digital/binary behaviour at 0°
  - Efficiency per plane >98% at only 10 V
  - Track resolution in x of ~10 µm at 0°
- In 2015 also at AFP tilt of 14° measured
  - Still under study
  - Expect efficiency improvement
  - Expect enhanced charge sharing: mostly 2 pixels/cluster
    → expect resolution improvement (<10 µm per plane)

→ **Good tracker performance**

(despite IBL-spare quality)

Tracking-Timing Correlations

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



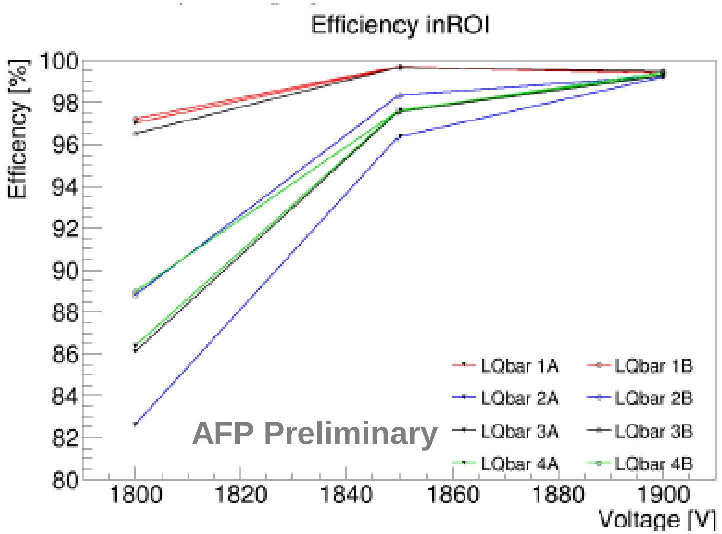
- Good spatial correlations between pixels and LQbars

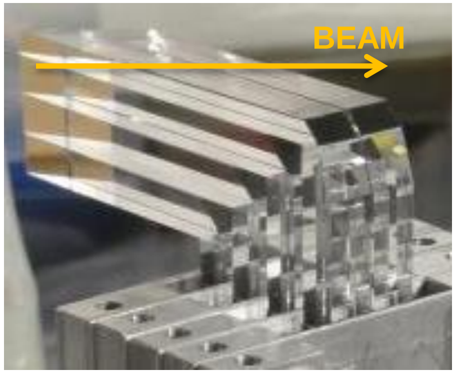
→ **Tracking-timing integration works!**

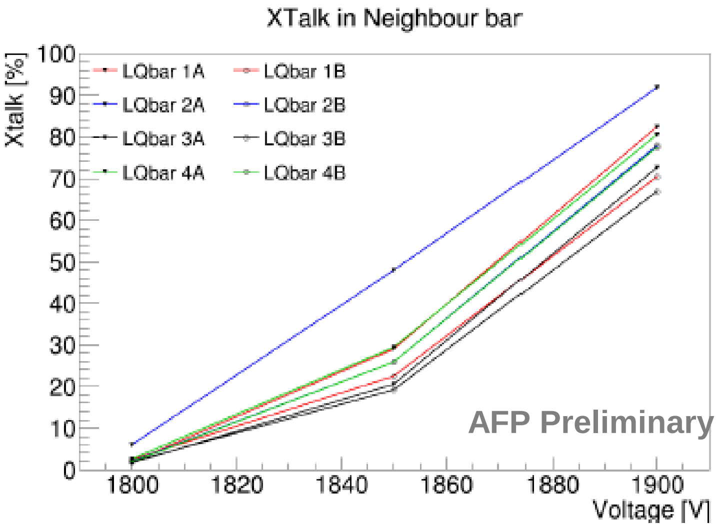
LQbar Efficiencies + X Talk

2014 data, Standard LQbars

- Track info very useful to determine if LQbars hit or not → can determine LQbars efficiencies and cross talk
- Efficiency increasing with $V_{MCP-PMT}$, eff.>99% at 1900 V
- Cross talk between trains increasing with $V_{MCP-PMT}$, few % at 1800 V, 60-90% at 1900 V
  - Disadvantageous if LQbars intended for use as position-resolved trigger, but no problem for time resolution



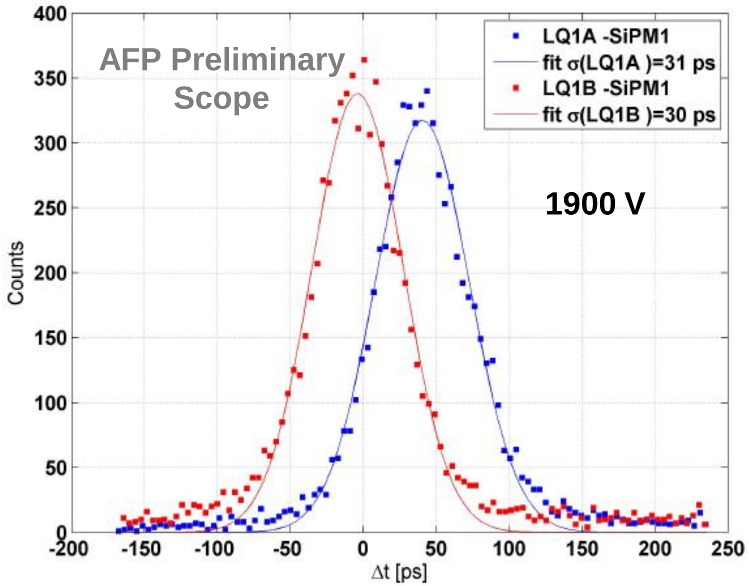


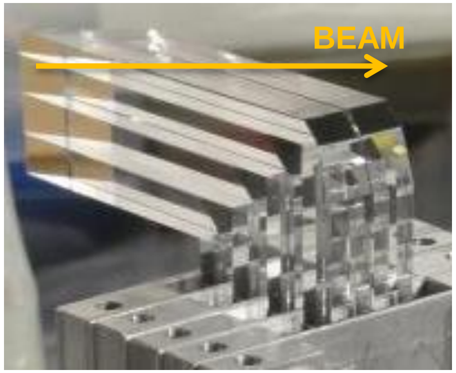


Time Resolutions

- Time resolutions from time difference with fast SiPM references
  - With oscilloscope or full readout system (HPTDC+RCE)
- SiPM resolution: 11 ps (scope), 18 ps (HPTDC+RCE) → HPTDC contribution in SiPM channels ~ 14 ps
- LQbar resolution improves with $V_{MCP\text{-}PMT}$
  - At 1900 V (reference contribution subtracted): 30 ps/bar (scope), ~40 ps/bar (HPTDC+RCE)
- 2-LQbar-train average improves over single bar
  - At 1900 V (reference contribution subtracted): 25 ps/train (scope), ~35 ps/train (HPTDC+RCE)
  - But not by √2 → correlations between bars of same train present (50-60%)
- Optimisation of time resolution has not been focus of 2014 beam test
  - More systematic studies done in 2015 (analysis on-going), more planned for 2016
  - HPTDC contribution still under study
  - Final AFP ToF system will have more LQbars per train

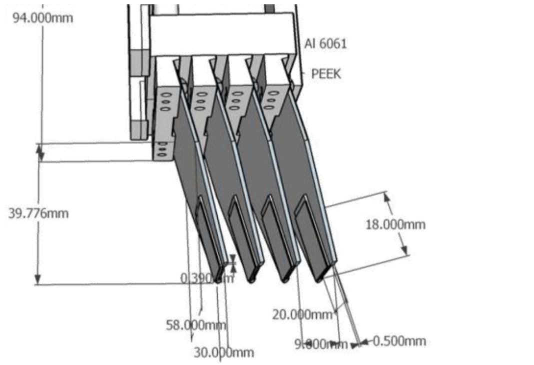
2014 data, Standard LQbars



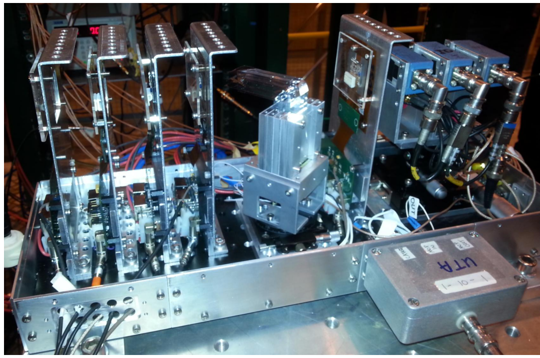


→ Already meets requirements of initial AFP runs at low μ

Conclusions



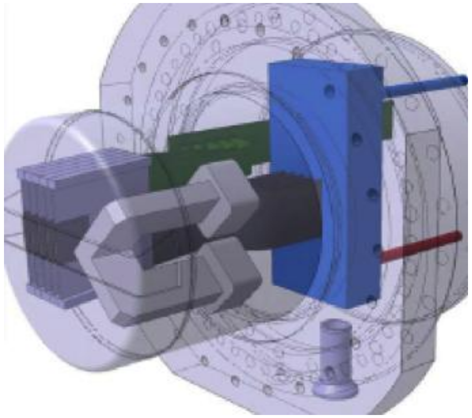
- AFP tracker
  - Pixel module prototypes extensively qualified
    → **Fulfill AFP requirements** of slim edge, non-uniform radiation hardness and resolution
  - Pixel module production on-going



- 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

- Outlook:
  - Analysis efforts of 2015 data on-going
  - Preparing for installation

Other AFP talks tomorrow:
AFP Physics by R. Staszewski
AFP TDAQ by K. Korcyl
AFP installation by P. Sicho

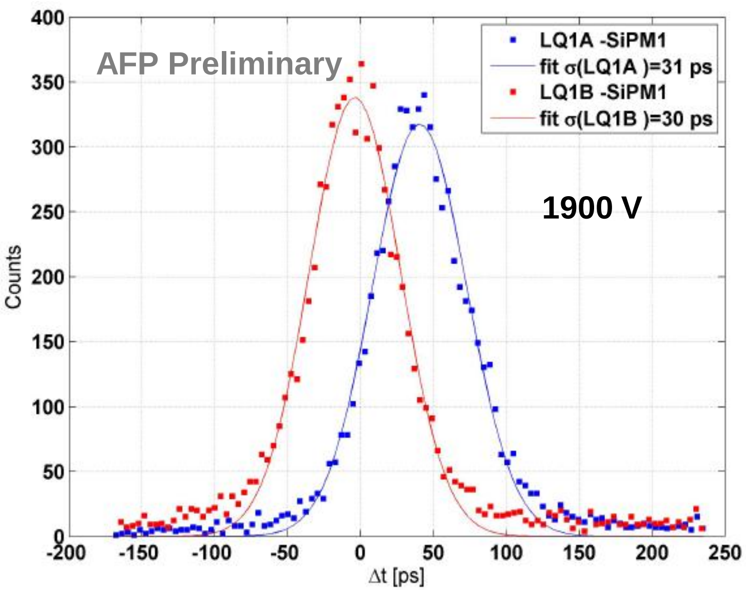


BACKUP

LQbar Time Resolution (Scope)

2014 data, Standard LQbars

- Time resolutions from time difference with fast SiPM references
  - With oscilloscope or full readout system (HPTDC+RCE)
- Oscilloscope measurements
  - SiPM resolution: 11 ps
  - LQbar resolution improves with $V_{MCP-PMT}$:
    30 ps/bar at 1900 V (SiPM contribution subtracted)
  - Train average improves over single bar:
    25 ps/train at 1900 V
    - But not by √2 → correlations between bars of same train present (50-60%)
  - Optimisation of time resolution has not been focus of 2014 beam test
    - More systematic studies done in 2015 (analysis on-going), more planned for 2016
    - Final AFP ToF system will have more LQbars per train



AFP Preliminary

$V_{MCP-PMT}$ [V]	1750	1800	1850	1900
LQbar	Time resolution [ps]			
1A	63 ± 5	45 ± 5	36 ± 5	31 ± 5
1B	85 ± 5	52 ± 5	37 ± 5	30 ± 5
Average Train 1	64 ± 5	44 ± 5	31 ± 5	25 ± 5
2A	-	48 ± 5	36 ± 5	32 ± 5
2B	-	42 ± 5	31 ± 5	30 ± 4
Average Train 2	-	42 ± 5	29 ± 5	25 ± 4

LQbar Time Resolution (HPTDC)

2014 data, Standard LQbars

- HPTDC+RCE measurements (FULL AFP SYSTEM)
  - SiPM+HPTDC resolution: 18 ps
    → HPTDC contribution in SiPM channels ~ 14 ps
  - LQbar+HPTDC resolution improves with $V_{MCP\text{-}PMT}$:
    ~40 ps/bar at 1900 V (SiPM+HPTDC contribution subtracted)
  - Train average improves over single bar:
    ~35 ps/train at 1900 V
    - Also here not by √2 due to correlations between bars of same train
    - **Meets requirements of initial AFP runs at low μ**
  - LQbar resolutions with HPTDC and scope cannot be compared 1:1 to extract HPTDC contribution of each LQbar channel since data taken under different conditions
    - More systematic studies in 2015 beam test (analysis on-going)
    - Indications that HPTDC contribution depends on channel (especially if on different HPTDC chips)

AFP Preliminary

$V_{MCP-PMT}$ [V]	1750	1800	1850	1900
LQbar	Time resolution [ps]			
1A	78 ± 5	61 ± 6	52 ± 6	46 ± 5
1B	85 ± 6	60 ± 6	47 ± 6	41 ± 6
Average Train 1	67 ± 7	54 ± 12	44 ± 6	37 ± 6
2A	94 ± 5	80 ± 10	50 ± 6	43 ± 7
2B	94 ± 8	64 ± 5	45 ± 6	38 ± 6
Average Train 2	77 ± 7	63 ± 7	41 ± 6	35 ± 6