

Experience with the AFP 3D Silicon Pixel Tracker

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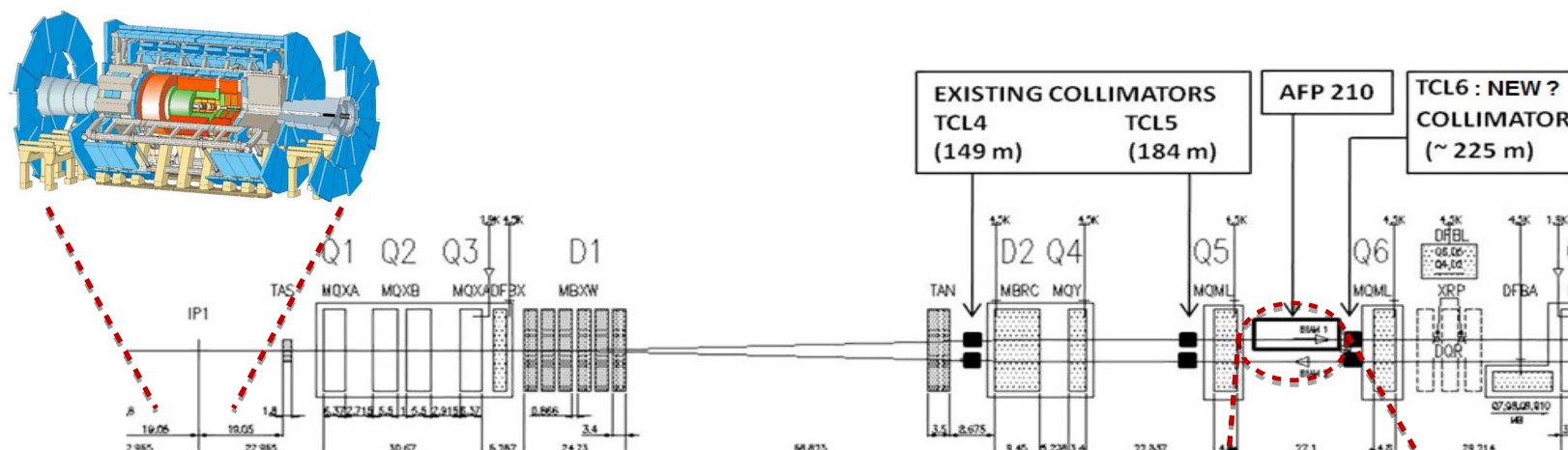
***8th International Workshop on
Semiconductor Pixel Detectors for
Particles and Imaging (Pixel 2016)***



*Sestri Levante (Italy),
5th-9th September*

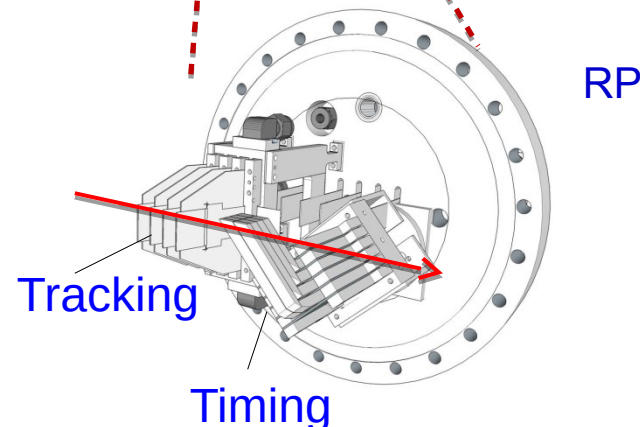
ATLAS Forward Proton (AFP)

- AFP is studying events in which intact protons emerge from ATLAS collisions, with detectors close to the LHC beam at ~210 m from the IP



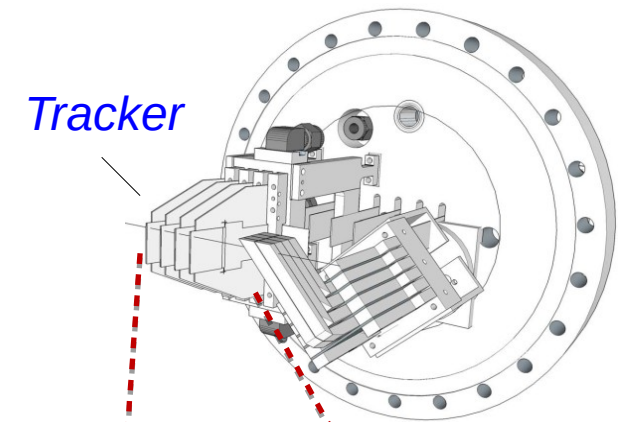
Study scattering processes characterized by protons emitted at very low angles

- **Roman Pots** for acceptance of diffractive protons
 - Horizontal RP needed (LHC optics)
- **ToF** to reduce background (at high luminosity)
 - System based on quartz radiators
- **Tracker** for momentum measurements

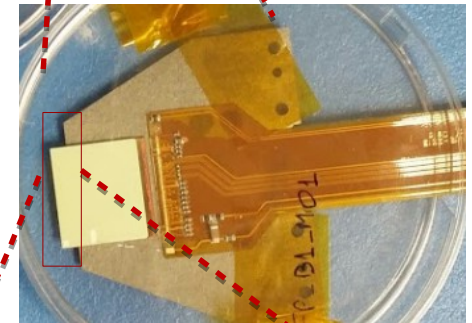


AFP Tracker

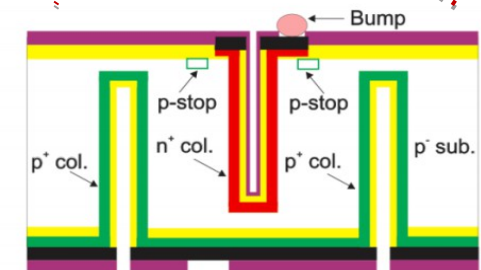
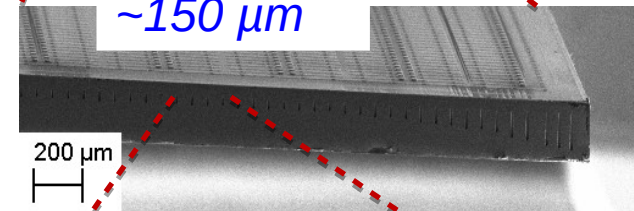
- **Requirements**
 - Slim edge 100-200 μm
 - Radiation hard after non-uniform irradiation
 - 10 (30) μm resolution in x (y)
- **3D CNM FE-I4 3D Si pixel sensors**
 - Mask of IBL production
 - 230 μm thick n-on-p
 - 50 μm x 250 μm pixels
- **Tracker Station**
 - Four planes of single 3D FE-I4 modules
 - 14° tilt to improve resolution and efficiency
 - Trigger based on FEI4 HitOr signal
 - Two stations at each side of ATLAS
- **AFP Installation**
 - One arm (0+2 stations) installed in YETS 2015/16
 - *Tracker modules planned for summer 2016*
 - Second arm (2+2) planned for EYETS 2016/17



3D FEI4 module



Slim-edge
~150 μm

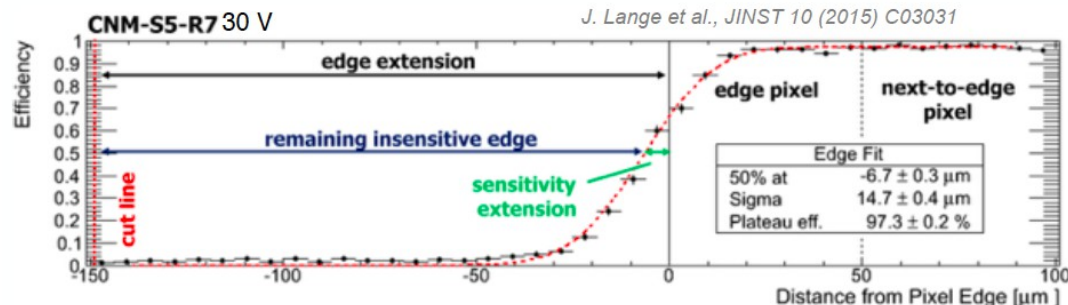


■ oxide ■ metal ■ passivation
 □ p⁺ Si ■ p⁺ poly-Si ■ n⁺ poly-Si ■ p⁺ Si

3D Qualification for AFP

- Slim edge**

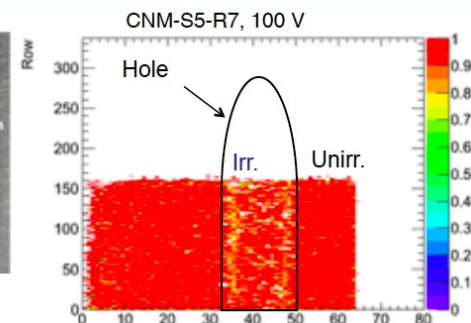
- CNM and FBK devices slim-edged with diamond saw
- Shown to have high efficiency up to 15-150 μm



- Radiation hardness**

- Non uniform irradiation at PS (CERN) and KiT
- Efficiency > 97% after peak of $4 \times 10^{15} \text{ n}_{\text{eq}}/\text{cm}^2$

$3.6 \times 10^{15} \text{ n}_{\text{eq}}/\text{cm}^2$



- Position resolution**

- 3 μm resolution in x (20-70 μm in y, staggering dependent)

Irradiations and beam tests supported by AIDA/AIDA2020

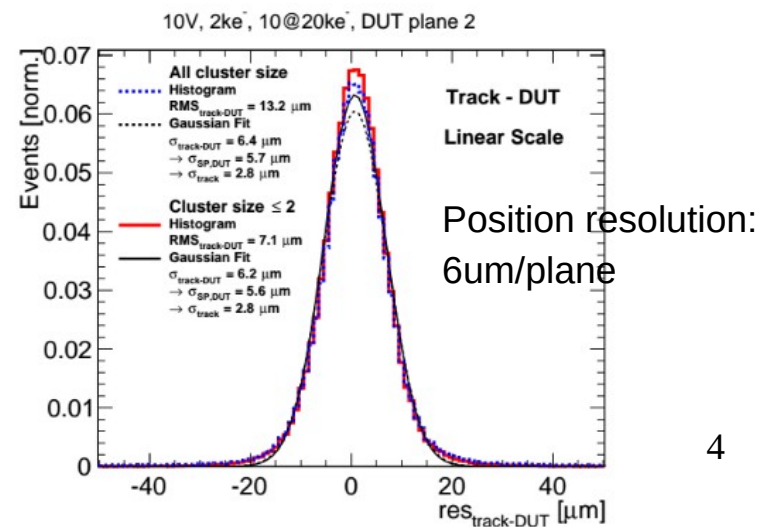
AFP 3D qualification:

S. Grinstein et al., NIM A730 (2013) 28

J. Lange et al., JINST 10 (2015) C03031 (PIXEL 2014)

J. Lange et al, <http://arxiv.org/abs/1608.01485>, submitted to JINST

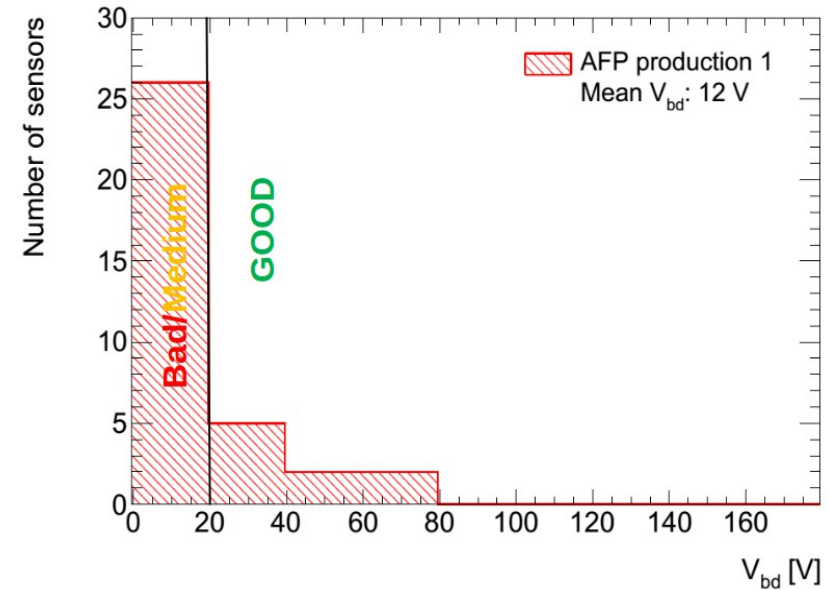
S. Grinstein - Pixel 2016



AFP Sensor Production

- 1st CNM AFP production run 6682 (July 2014)
 - 5 wafers with 40 sensors finished, 8 wafers lost
 - Slim-edged to $\sim 180\ \mu\text{m}$ (diamond saw cut)
 - 9 good-quality sensors: low yield

First AFP arm fabrication for 2015 YETS installation had only 9 good sensors!
(need excellent assembly yield).



Production Run	Wafer Yield	Good Wafers	Sensor Yield	Good Sensors
AFP 1 (6682)	38%	5	23%	9

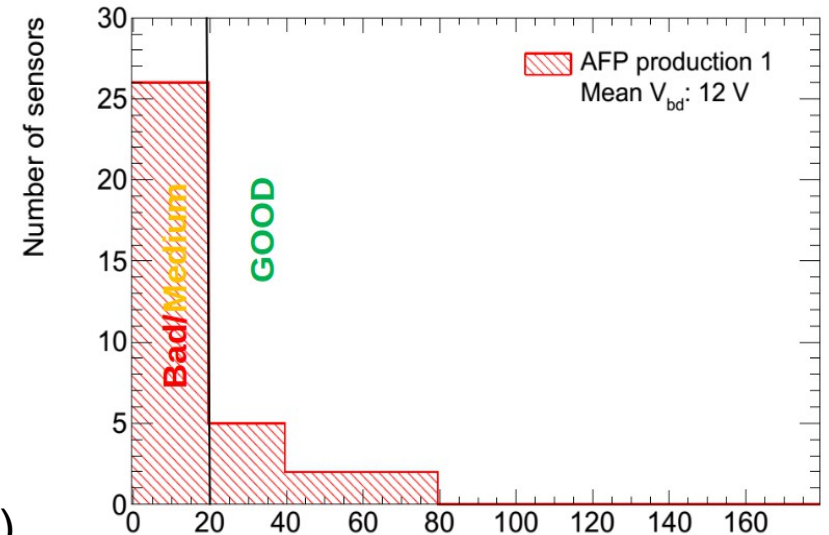
Good sensor: $V_{BD} > 20\ \text{V}$

Sensor yield based on good wafers

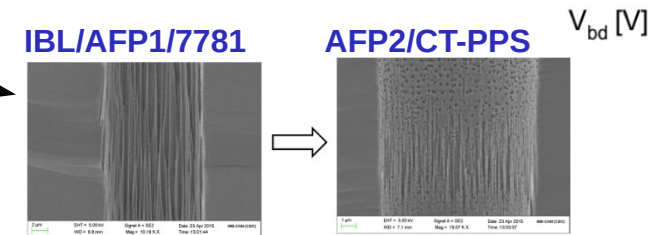
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- Investigation and improvement of CNM process (2015)
 - DRIE optimization: less column side wall defects
 - Wafer edge protection: less broken wafers



G. Pellegrini, D. Quirion (CNM)

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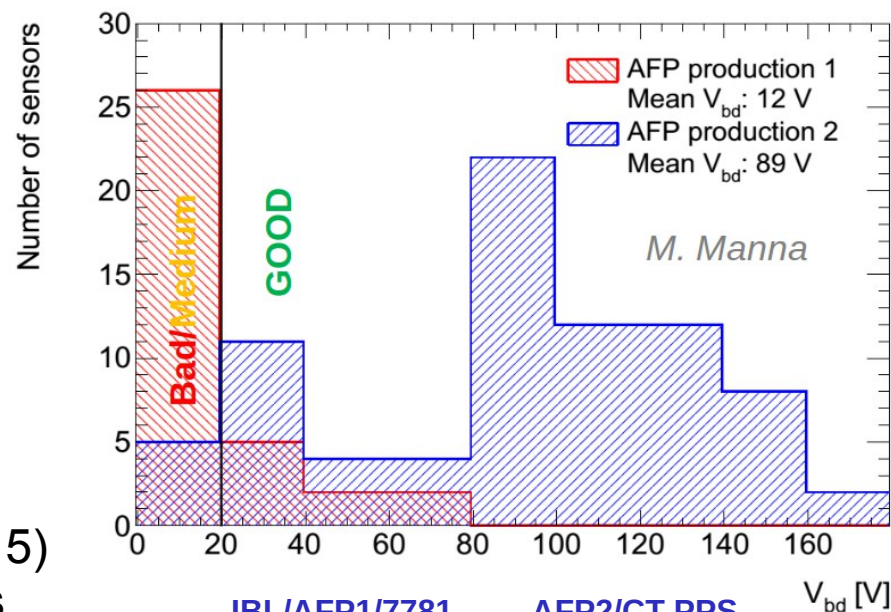
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AFP Sensor Production

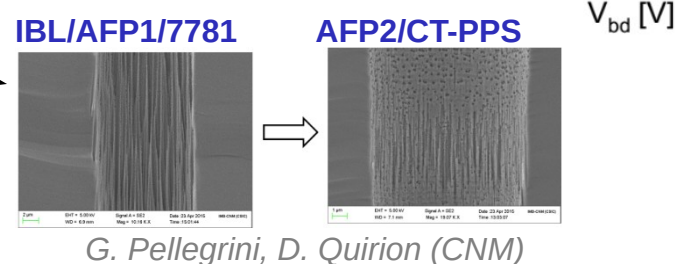
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- Investigation and improvement of CNM process (2015)
 - DRIE optimization: less column side wall defects
 - Wafer edge protection: less broken wafers

- 2nd CNM AFP production run 7984 (March 2016)
 - 10 wafers with 80 sensors finished, 2 wafers lost
 - 73 good quality sensors!
 - UBM done at IZM
 - Being slim-edged to $\sim 150 \mu\text{m}$ at CNM



Production Run	Wafer Yield	Good Wafers	Sensor Yield	Good Sensors
AFP 1 (6682)	38%	5	23%	9
AFP 2 (7945)	83%	10	94%	73

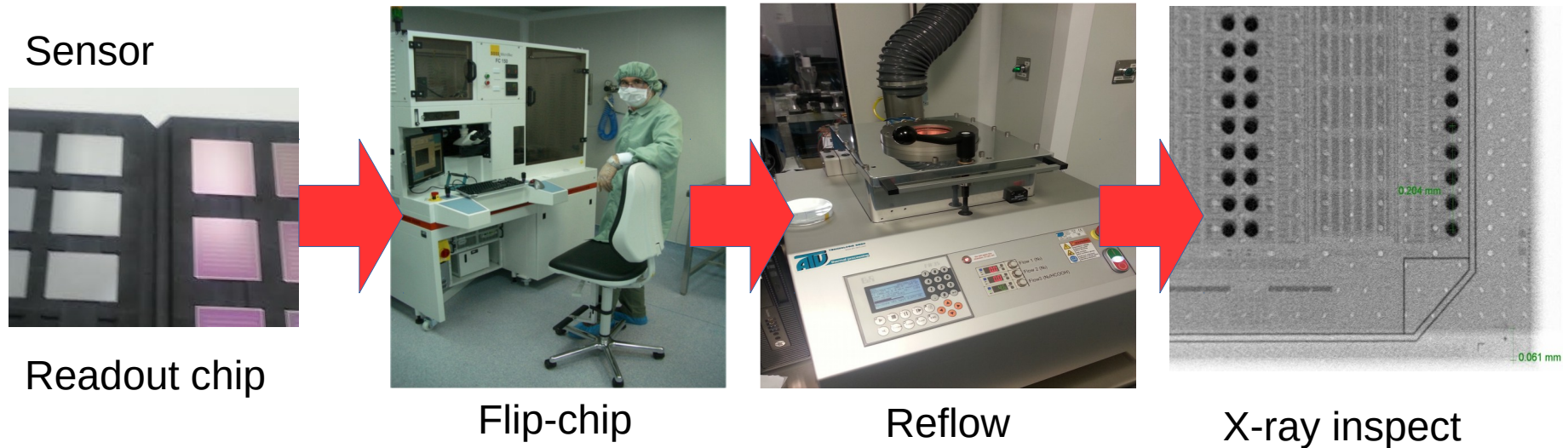
Huge yield and IV improvement!

Promising for 2nd AFP arm (and HL-LHC productions)

Good sensor: $V_{BD} > 20 \text{ V}$

Sensor yield based on good wafers

AFP Tracker Production



- Bump-bonding and assembly performed at IFAE

- In-house solder flip-chip

- Inspect disconnected bumps with X-ray

Almost no problems observed
due to 700 μm -thick FEI4 chips

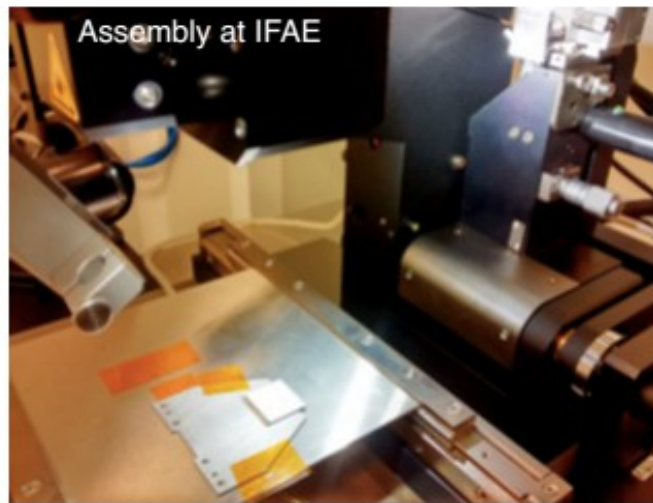
AFP Tracker Production



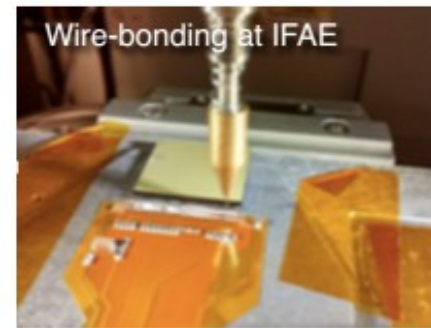
Carrier card



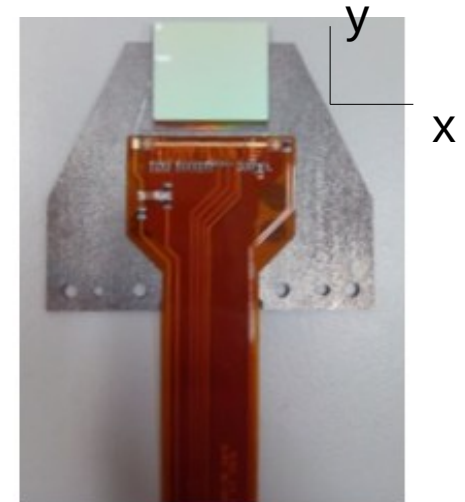
Flex



Pick and Place machine



Wire-bond machine



Tracker module

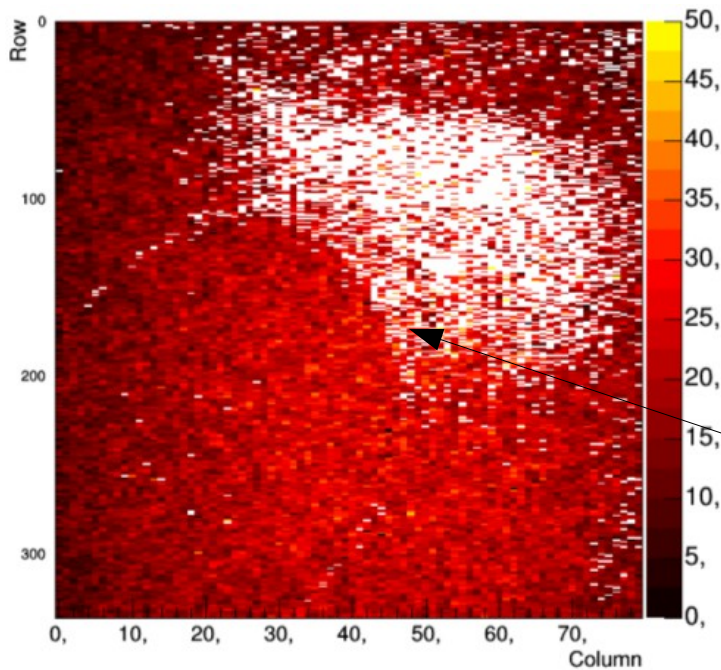
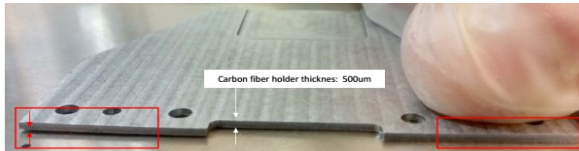
- **Bump-bonding and assembly performed at IFAE**
 - In-house solder flip-chip
 - Inspect disconnected bumps with X-ray
 - Hybrid pick-and-placed and glued with Araldite 2011 + Tesa onto NOVAPACK Al+CF carrier card
 - Flex (produced by Oslo) also glued onto card
 - Wire-bond chip to flex (pull-test check)
- **Quality assurance (QA) at IFAE before shipping and at CERN after receiving**

Excellent assembly yield achieved

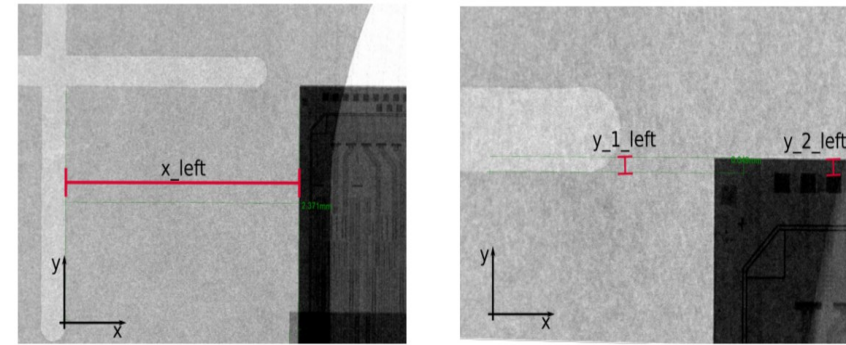
Production Step	Total	Good	Yield
Bump Bonding	22	21	95%
Assembly	17	17	100%

AFP Tracker Production: Issues

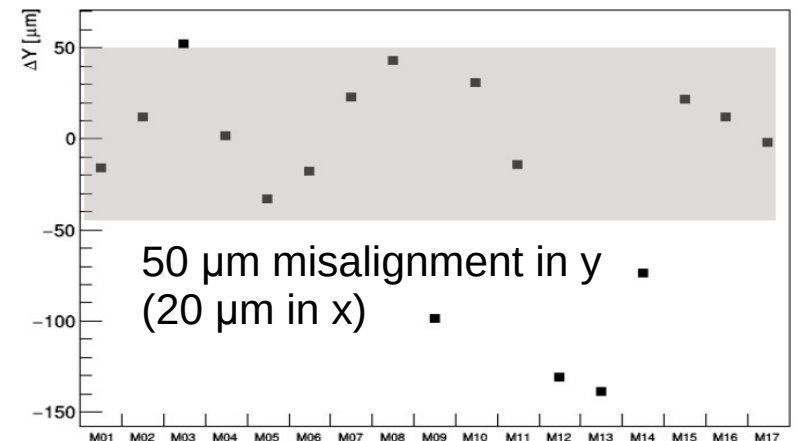
- **Alignment of hybrid**
 - Good alignment problematic to achieve
 - Due to poorly placed alignment marks and bending of Al+CF card
 - Thicker tesa-tape yield better results
 - New production with better marks



AFP_B1_M07



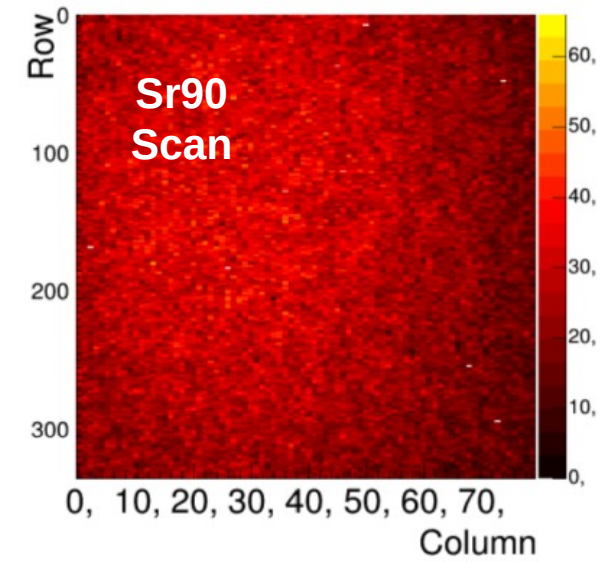
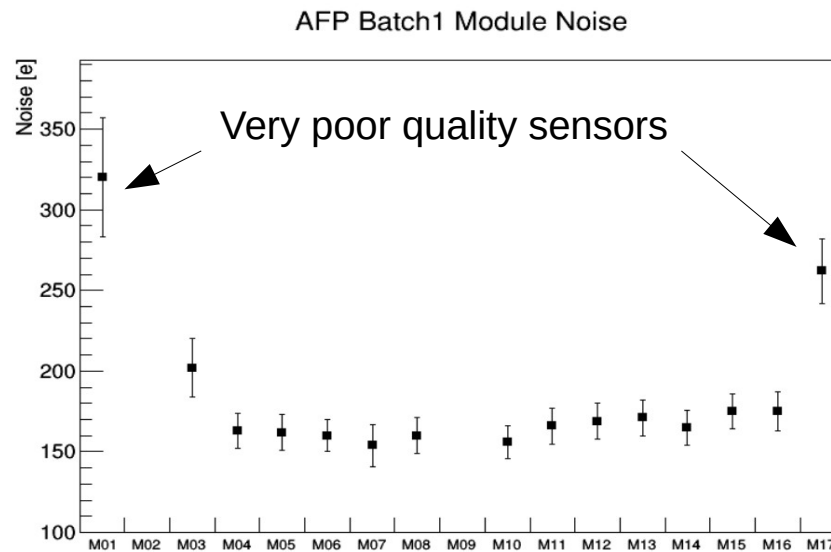
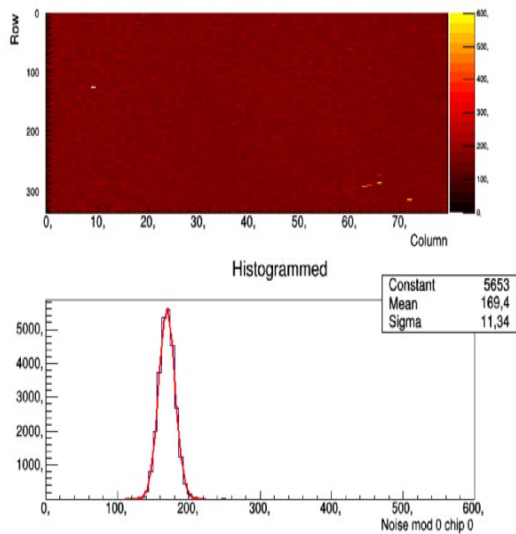
AFP Batch1 Modules Y_left - Y_right alignment



- Only assembly with **bump-bonding** problem probably due to handling

AFP Module QA

- All assembled modules tested at IFAE and CERN
 - Different readout system, USBPix test stand at IFAE, RCE (HSIO-2) DAQ at CERN
 - Analog/digital, tuning, Sr90 source scans, HltOR triggering



Compatible with IBL noise level

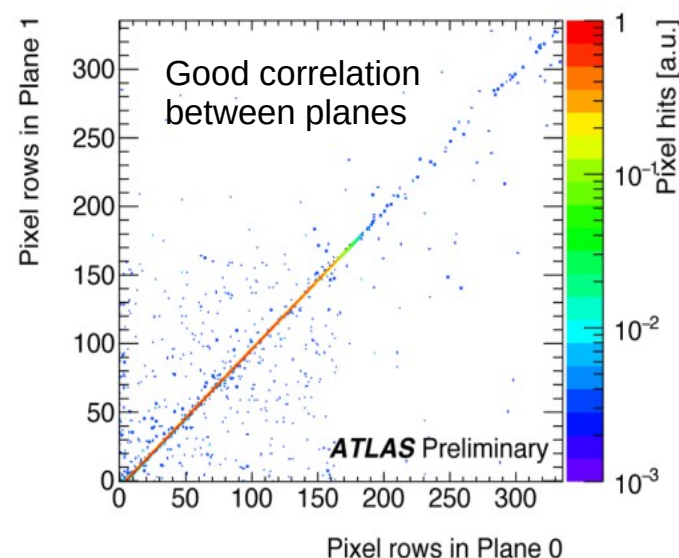
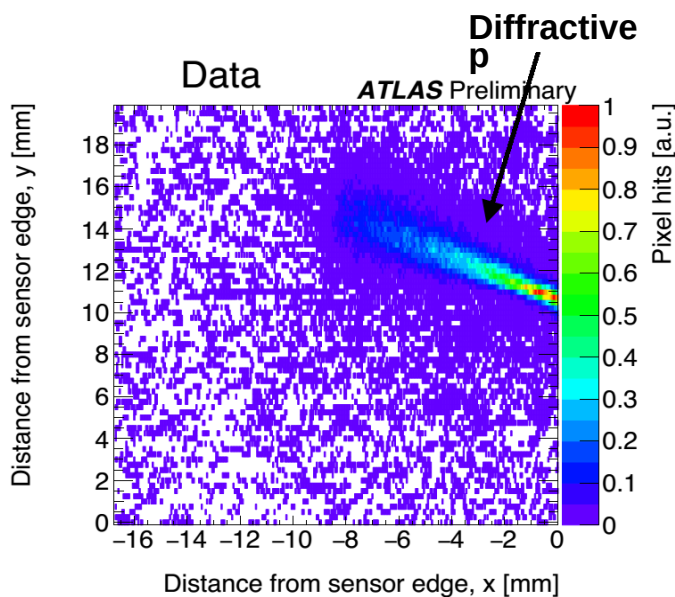
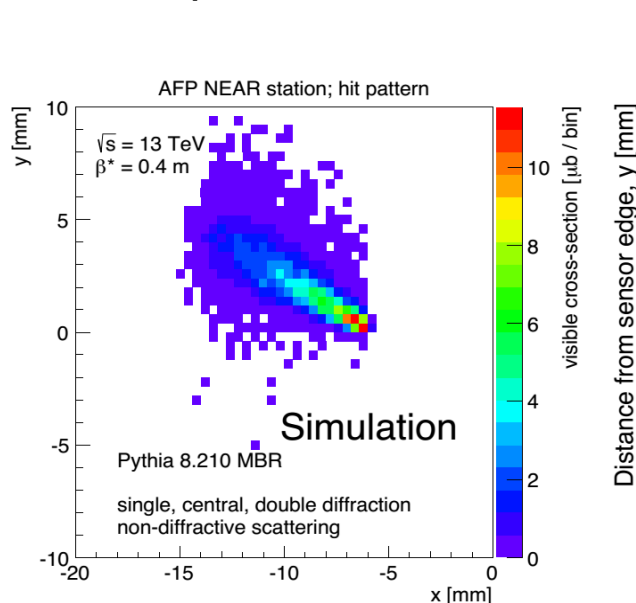
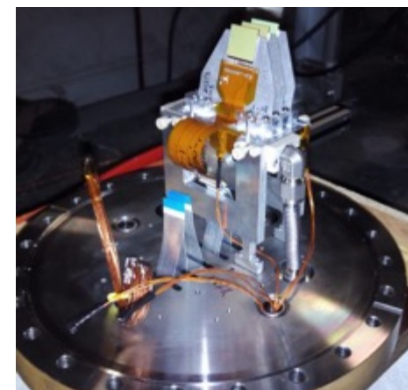
- Three devices did not pass QA
 - One lost FE communication during connectivity test at CERN
 - Two could never communicate with FE

Overall, excellent assembly process, 7 modules delivered to CERN for installation (ahead of original plan).

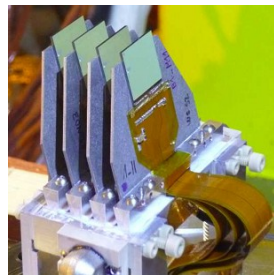
Production Step	Total	Good	Yield
Bump Bonding	22	21	95%
Assembly	17	17	100%
QA	17	14	82%

AFP Tracker Installation and Running

- *Tracker assembled and installed in 2 Roman Pots in Feb 2016*
 - Near station: 3 modules with $V_{op} = 5-10$ V (only available at the time)
 - Far station: 4 modules with $V_{op} = 0-30$ V (one HV short, but 3D at 0 V is quite efficient)
- *Running from start-up of LHC in March 2016*
 - Stand-alone and integrated with ATLAS, up to 600 bunches
 - Successful dedicated low mu (0.03) run in Aug 2016
 - Good quality LHC data!
- *About to launch second production phase for AFP 2+2 to be installed in EYETS 2016/17*
 - Expect further improvements due to sensor quality and experience



Summary

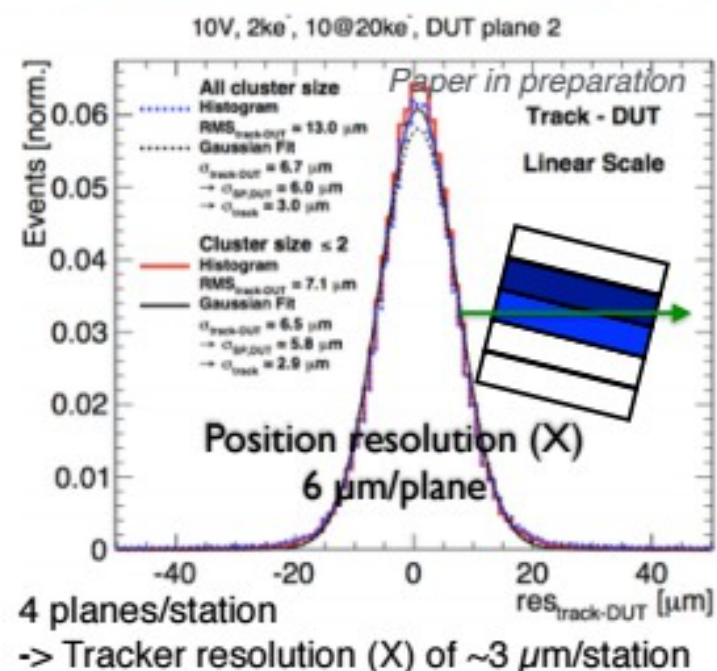
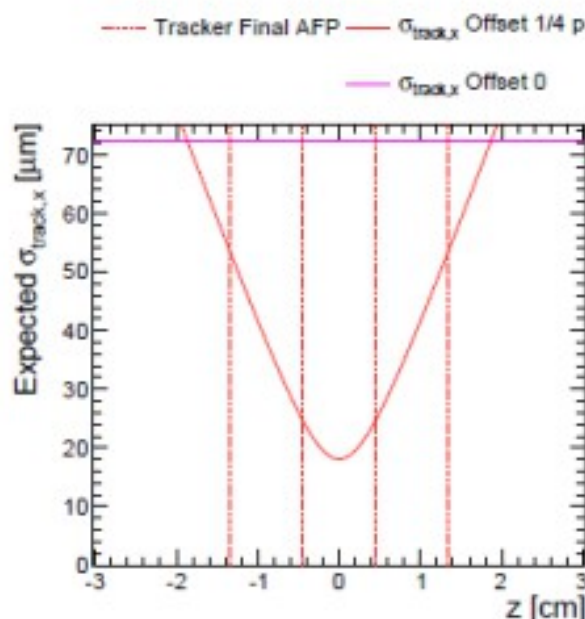
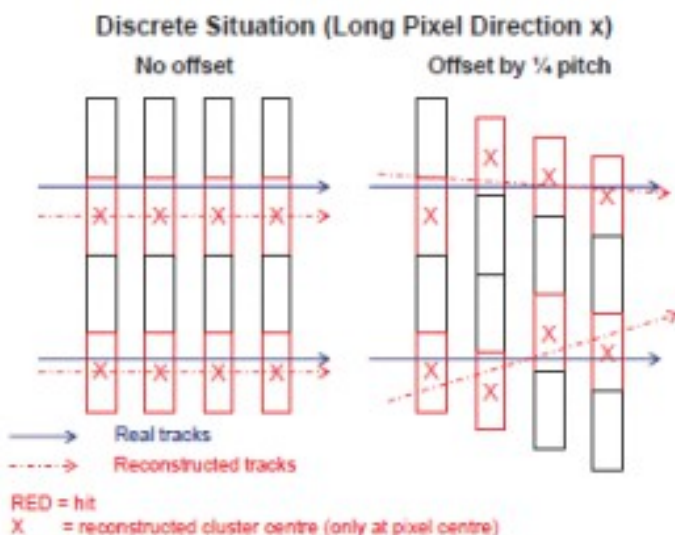


- With forward proton tagging, AFP aims to enhance ATLAS physics program
- AFP Tracker needed for mass and momentum resolution
 - 3D sensor modules showed to satisfy AFP requirements
- First 3D sensor production at CNM had low yield
 - Thus was critical to achieve high bump-bonding and assembly yield
- AFP 0+2 (first AFP tracker-only arm): with relatively low quality sensors were able to produce and installed a tracker that is performing very well
 - Data analyses on-going
- Huge yield improvement in second production (AFP 2+2) due to process optimization at CNM
- Production of modules for second arm just started

Backup Slides

Position resolution

- Measure position resolution
 - Digital resolution per plane for a $50 \times 250 \mu\text{m}^2$ pixel is $\sim 14 \times 72 \mu\text{m}^2$ (i.e. $\text{pitch}/\sqrt{12}$)
 - But** FE-I4 has 4-bit Time-over-Threshold measurement (\sim Charge collected)
 - Maximize 2-hits events by adding 14° tilt along the short pixel direction and measure plane resolution on test beam
- Introduce staggering in y-direction (long pixel direction) to improve resolution



With staggering
→ Tracker resolution (Y) of $\sim 20 \mu\text{m}/\text{station}$

3D FE-I4 detectors proven suitable for AFP

I. López, on behalf of the AFP collaboration
3rd Elba Workshop on Forward Physics @ LHC Energy
31st of May 2016