Characterization and Test Beam Analysis of 3D Silicon Sensors for the ATLAS IBL Upgrade

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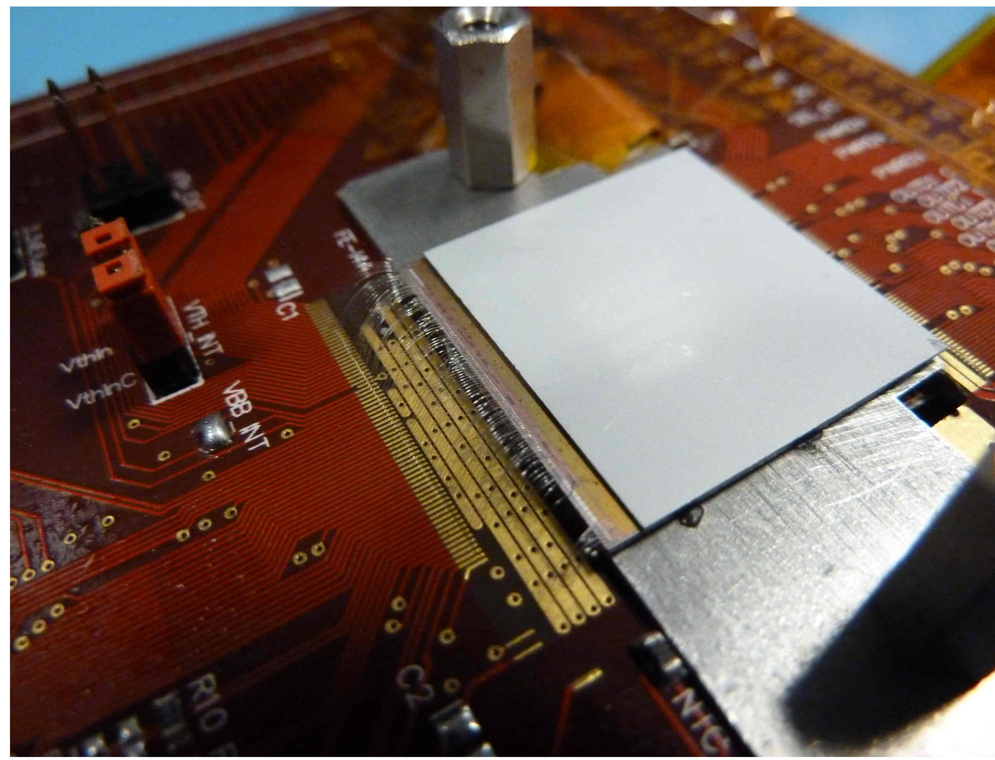
Outline

- Motivation
- Insertable B-Layer (IBL)
- 3D Silicon Sensors
- Analysis Steps
  - Characterization
  - Reconstruction
  - Data Analysis
- Summary



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Current ATLAS Pixel Detector

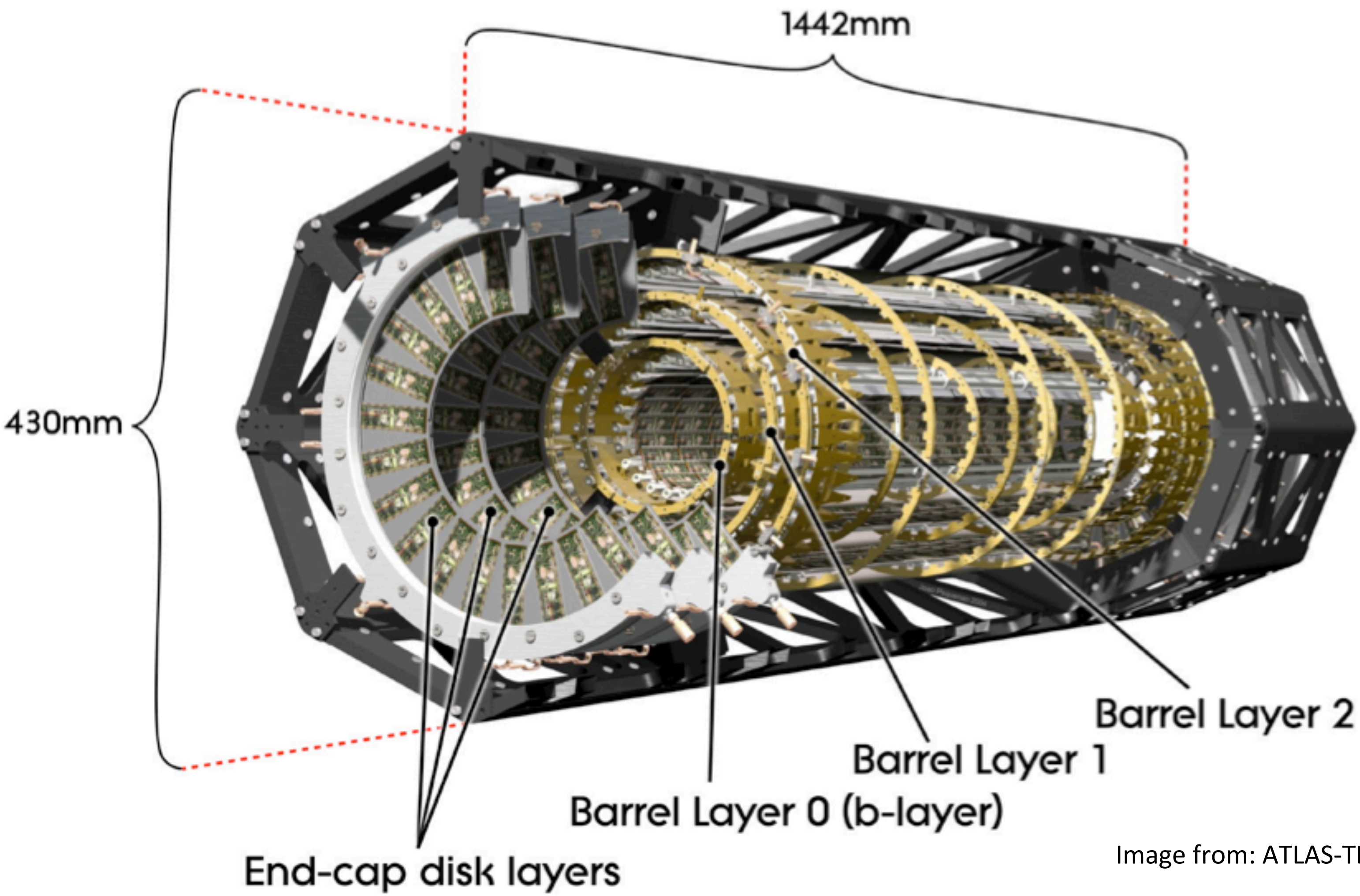
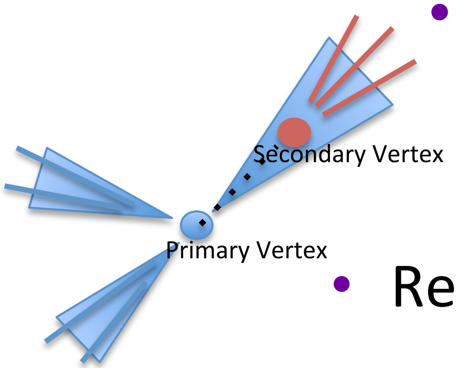


Image from: ATLAS-TDR-019

Motivation

- The Pixel Detector is at the very centre of ATLAS and hence subjected to the greatest amount of radiation.
- Due to timing and feasibility issues, it's not possible to replace the whole Pixel Detector => new layer (IBL)
  - ➢ Requires new/improved detector technology and read-out electronics.



- Extra layer will provide an additional point in space.
  - Improved vertex resolution and location for primary and secondary vertices.
    - ➢ Improved b-tagging.
    - ➢ Helps with pile-up (can ignore tracks from unwanted primary vertex).
- Redundancy in case of failure in one layer.

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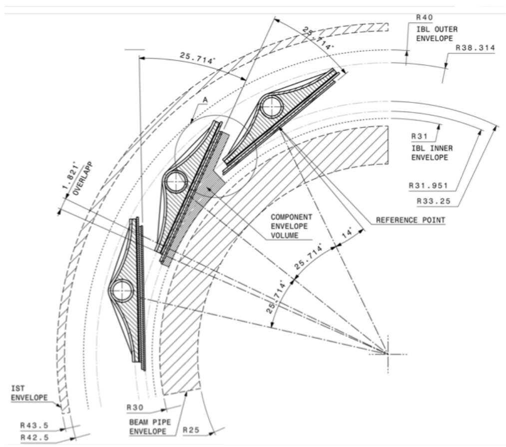
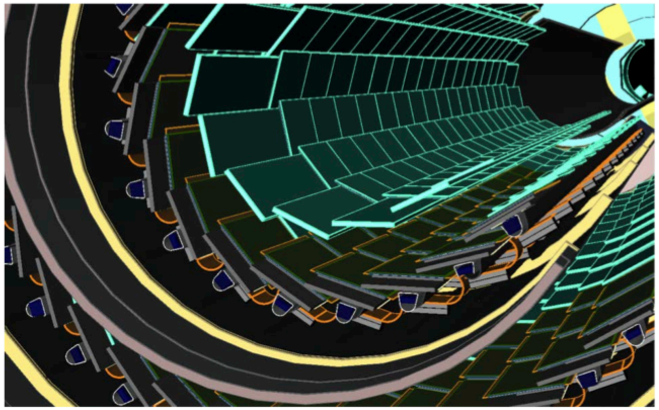
Insertable B-Layer (IBL)

- Phase 0 upgrade (2013).
- New layer to be mounted onto a smaller (26.5 mm (R_{min})) beam pipe.
- 14 staves with 32 chips on each.
- Sensor specifications:
  - Have a hit efficiency > 97%
  - Qualify to $5x10^{15}$ n_{eq} cm^{-2}
  - Maximum power dissipation of 200 mW/cm^2 at -15 oC
- Two technologies:
  - 25% 3D silicon sensors (single chip),
  - 75% Planar silicon sensors (double chip).





Images from: ATLAS-TDR-019

3D Silicon Community for the Insertable B-Layer

Community: B. Stugu, H. Sandaker, K. Helle, (1), M. Backhaus, M. Barbero, J. Janssen, F. Hügging, M. Karagounis, V. Kostyukhin, H. Krüger, D-L Pohl, J-W Tsung, N. Wermes (2), M. Capua; S. Fazio, A. Mastroberardino; R. Mendicino, G. Susinno (3), C. Gallrapp, B. Di Girolamo; D. Dobos, A. La Rosa, H. Pernegger, S. Roe (4), T. Slavicek, S. Pospisil (5), K. Jakobs, M. Köhler, U. Parzefall (6), G. Darbo, G. Gariano, C. Gemme, A. Rovani, E. Ruscino (7), C. Butter, R. Bates, V. Oshea (8), S. Parker (9), M. Cavalli-Sforza, S. Grinstein, I. Korokolov, K. Shota Tsiskaridze C. Padilla (10), K. Einsweiler, M. Garcia- Sciveres (11), M. Borri, C. Da Vià, J. Freestone, C. Lai, C. Nellist, J. Pater, R. Thompson, S.J. Watts (12), M. Hoeferkamp, S. Seidel (13), E. Bolle, H. Gjersdal, K-N Sjoebaek, S. Stapnes, O. Rohne, (14) D. Su, C. Young, P. Hansson, P. Grenier, J. Hasi, C. Kenney, M. Kocian, P. Jackson, D. Silverstein (15), H. Davetak, B. DeWilde, D. Tsybychev (16). G-F Dalla Betta, M. Povoli (17), M. Cobal, M-P Giordani, L. Selmi, A. Cristofoli, D. Esseni, A. Micelli, P. Palestri (18)

Institutions (18): 1 - Bergen University, 2 - Bonn University, 3 - Calabria University, 4 – CERN, 5 - Czech Technical University, 6 - Freiburg University, 7 - University and INFN of Genova, 8 - Glasgow University, 9 - The University of Hawaii, 10 - IFAE Barcelona, 11 - Lawrence Berkeley National Laboratory, 12 - The University of Manchester, 13 - The University of New Mexico, 14 - Oslo University, 15 – SLAC, 16 - Stony Brook University, 17 - University and INFN of Trento, 18 - University of Udine

Processing Facilities (4+1): C. Fleta, M. Lozano G. Pellegrini, D.Quirion (CNM Barcelona, Spain); M. Boscardin, A. Bagolini, G. Giacomini, F. Mattedi, C. Piemonte, S. Ronchin, E. Vianello, N. Zorzi (FBK-Trento, Italy) , T-E. Hansen, T. Hansen, A. Kok, N. Lietaer (SINTEF Norway), J. Hasi, C. Kenney (Stanford). J. Kalliopuska, A. Oja (VTT , Finland)

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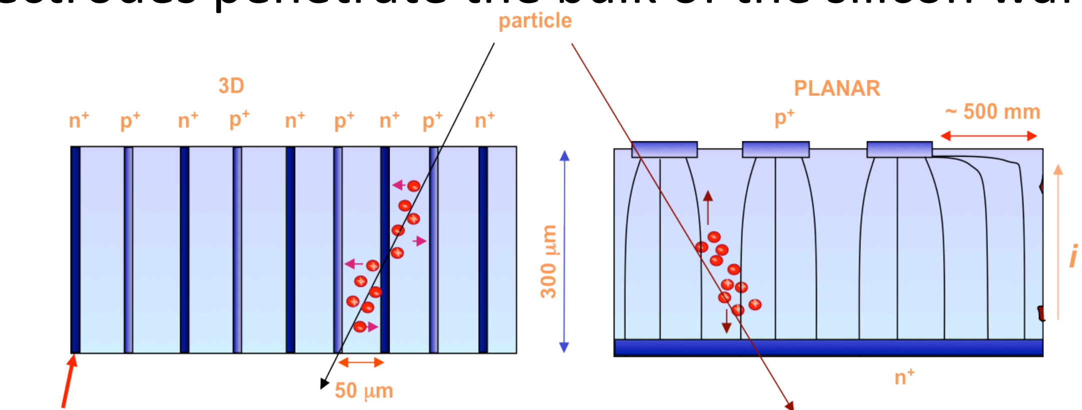
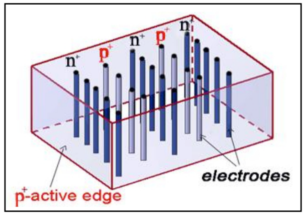
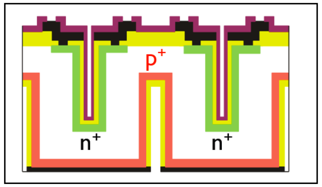
3D Silicon Sensors

- Electrodes penetrate the bulk of the silicon wafer.





Full 3D proposed by S. Parker, et. al. in NIMA 395 (1997), 328

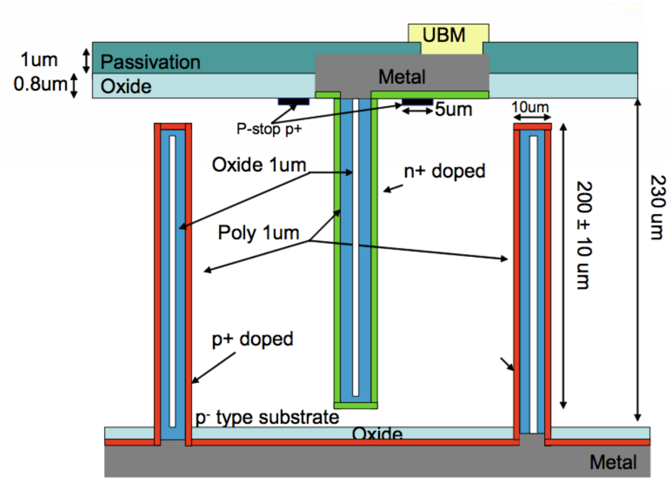


Two 3D Silicon layouts
- Full 3D (above)
- Double-side double-type

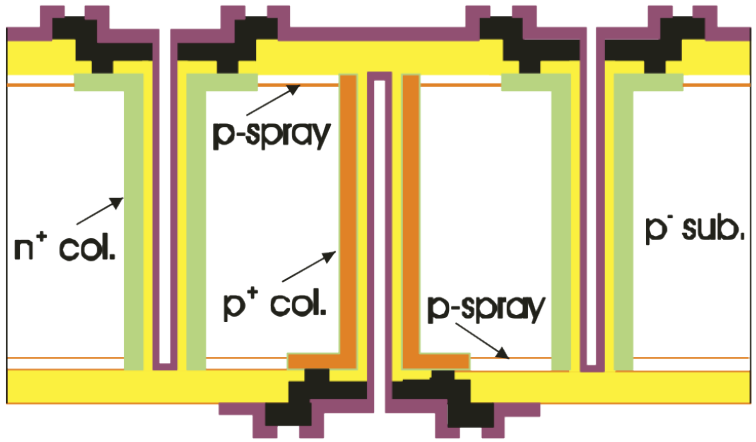
- Two layouts – Full 3D and DDTC.
- **Advantages**:
  - Electrode distance is decoupled from the active wafer.
  - ➢ Shorter inter-electrode distance,
    - Greater radiation hardness,
    - Faster response time,
    - Low Bias Voltage
      - Low power dissipation
      - More stable at higher temperatures
- Active edges (~170um or less) => much smaller dead area
- **Disadvantages**:
  - Complicated fabrication process.
  - Higher capacitance and hence a lower signal / noise.

3D Silicon Sensors for IBL

- Simplified manufacturing methods – used for the IBL 3D sensors.



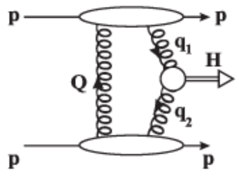
CNM
G. Pellegrinia, et al., 2008, doi:10.1016/j.nima.2008.03.119



FBK
G-F. Dalla Betta, et al., 2010 IEEE NSS Conference record, paper N15-3

- Manufacturing is easier because:
  - Do not require a support wafer.
  - Empty electrodes.
- Do not have active edge, but slim edge (~200um).
- Two electrodes per pixel.

- R&D ongoing for future upgrades
  - New pixel layer for HL-LHC.
  - ATLAS Forward Physics.



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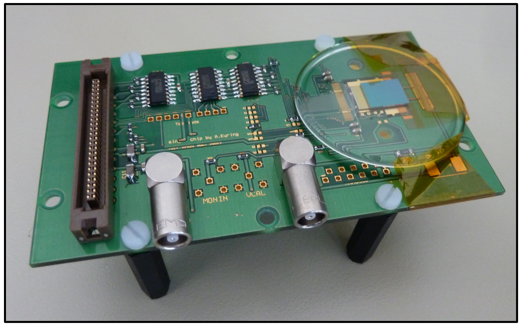
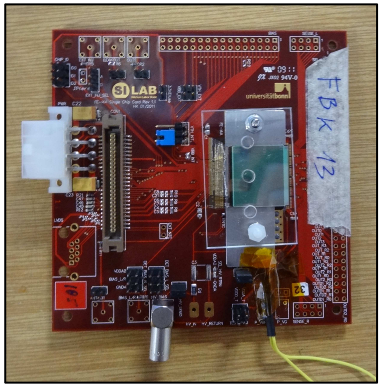
Analysis Steps

Characterization → Test Beam → Reconstruction → Data Analysis





3D sensors on FE-I3 (above) FE-I4 (right) boards.

FE-I4 sensors in test beam at DESY.

Laboratory Setup, CERN

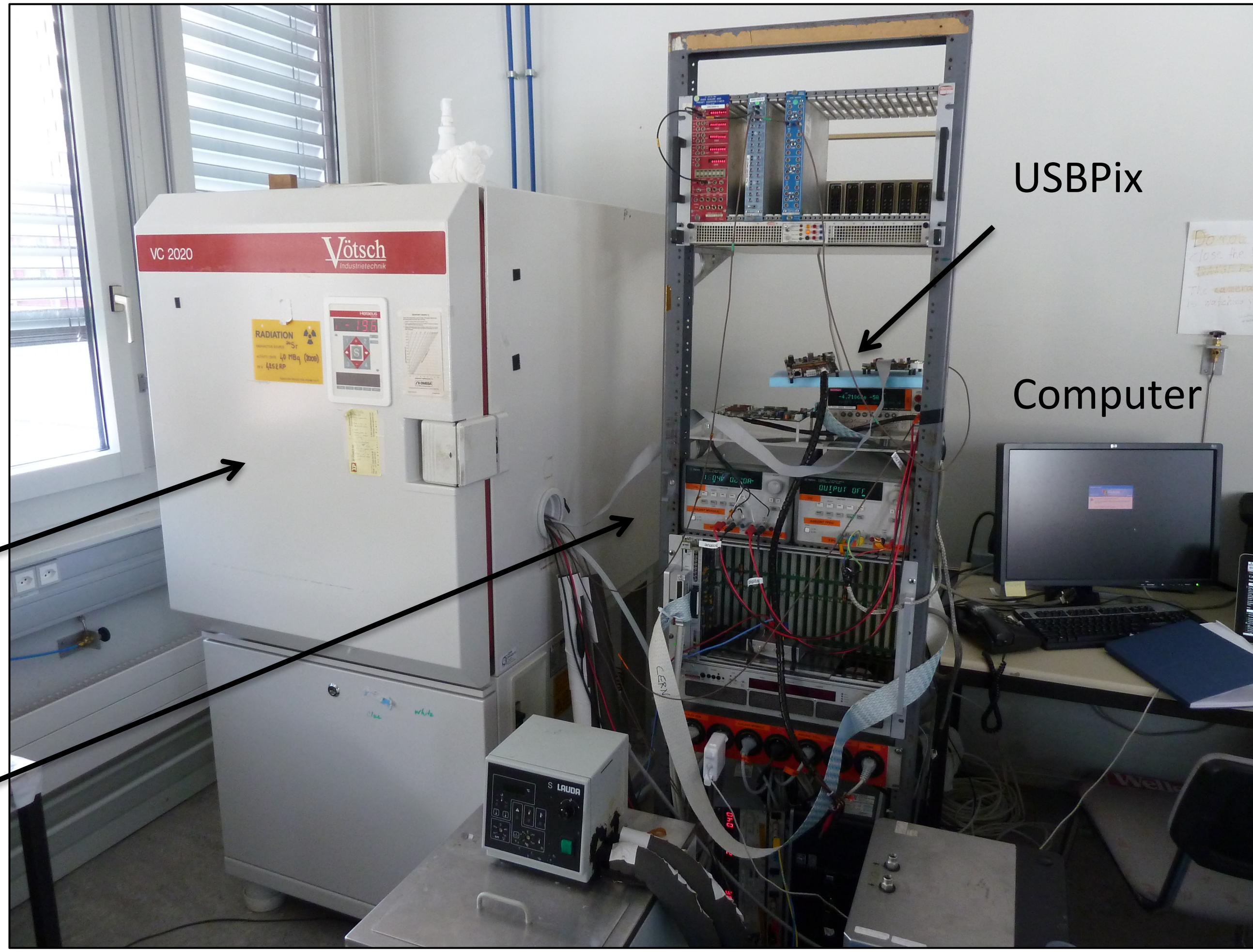
Setup for irradiated sensors.

Sample inside Climate Chamber

Power Supplies

USBPix

Computer



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Characterization

- It’s important to determine how well a sensor functions before it can be irradiated, or tested in a test beam. Characterization involves tuning the device and taking measurements (for various bias voltages and temperatures) of the
    - Current
    - Noise output
    - Charge
- Due to intrinsic differences in the electronics of each pixel, tuning is required to ensure a uniform output of the sensor.
- Results can be used to perform a comparison of different devices, or the same device before and after irradiation (radiation hardness).

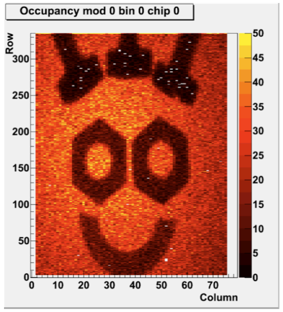
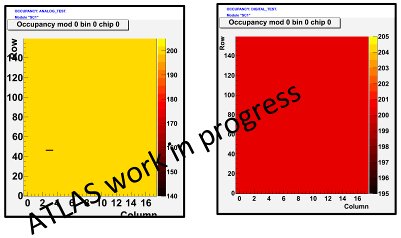
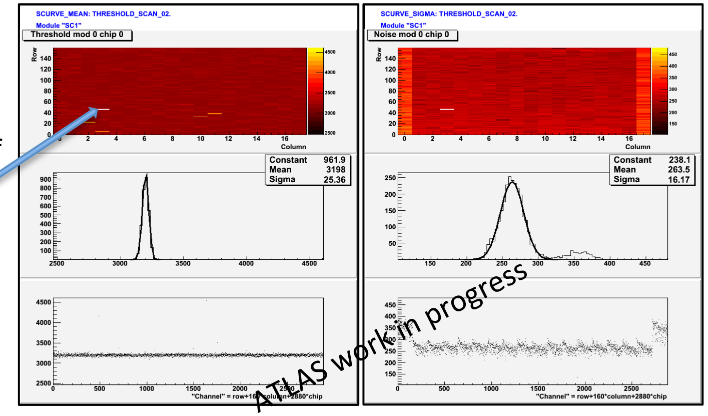


Image by A. Micelli

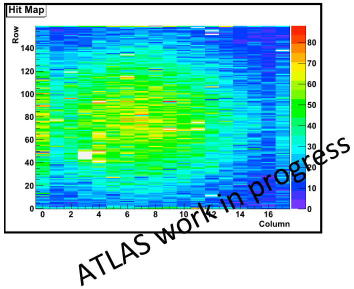


Analog and digital scans

Turned off pixel



Threshold and noise scans after tuning to threshold of 3200e. For a SINTEF FE-I3 non-irradiated sensor.



Hit map from source scan using Strontium 90 (left).

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Test Beams

- 3D Sensors have been tested at CERN (Geneva, Switzerland) and DESY (Hamburg, Germany) in 2011.

- DESY (Feb & April)
  - 4 GeV electrons

- CERN (June & Sept)
  - 180 GeV pions

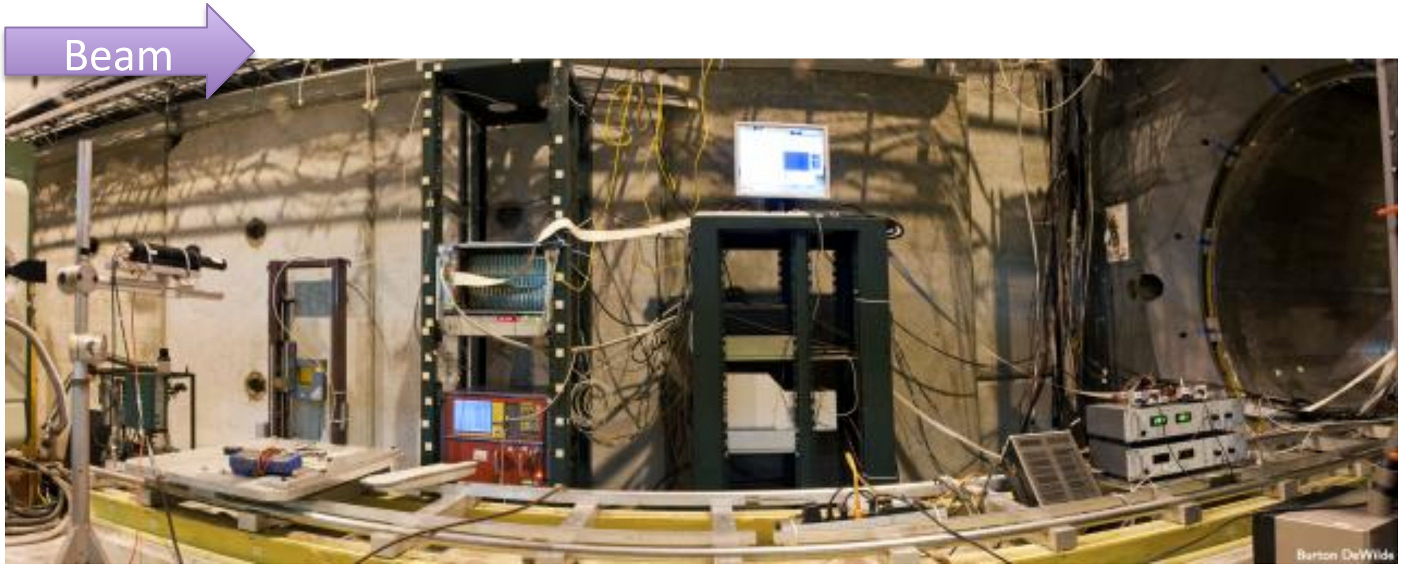
Sensor	Front End?	Irradiated?	Angle?	B- Field?
SINTEF	FE-I3	No	0^o & 15^o	Off
FBK	FE-I3	No	0^o & 15^o	Off
FBK	FE-I4	No	0^o & 15^o	Off
FBK	FE-I4	$2x10^{15}$ (P)	0^o & 15^o	Off

P = proton irradiated
N = neutron irradiated

Sensor	Front End?	Irradiated?	Angle?	B-Field?
CNM	FE-I4	No	0^o & 15^o	Off & On
CNM	FE-I4	$5x10^{15}$ (P)	15^o	Off & On
CNM	FE-I4	$5x10^{15}$ (P)	15^o	Off
CNM	FE-I4	$5x10^{15}$ (N)	0^o & 15^o	Off
CNM	FE-I4	$5x10^{15}$ (N)	15^o	OFF
FBK	FE-I4	$2x10^{15}$ (P)	15^o	Off
FBK	FE-I4	$5x10^{15}$ (P)	15^o	Off
FBK	FE-I4	No	0^o	Off

Test Beam Halls

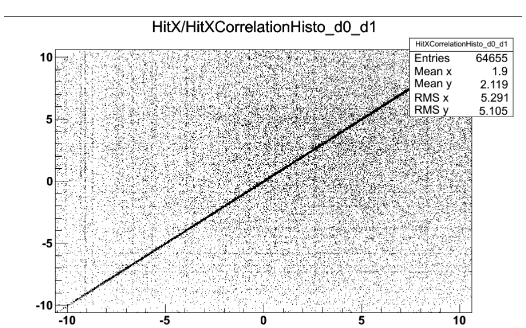
CERN (right)



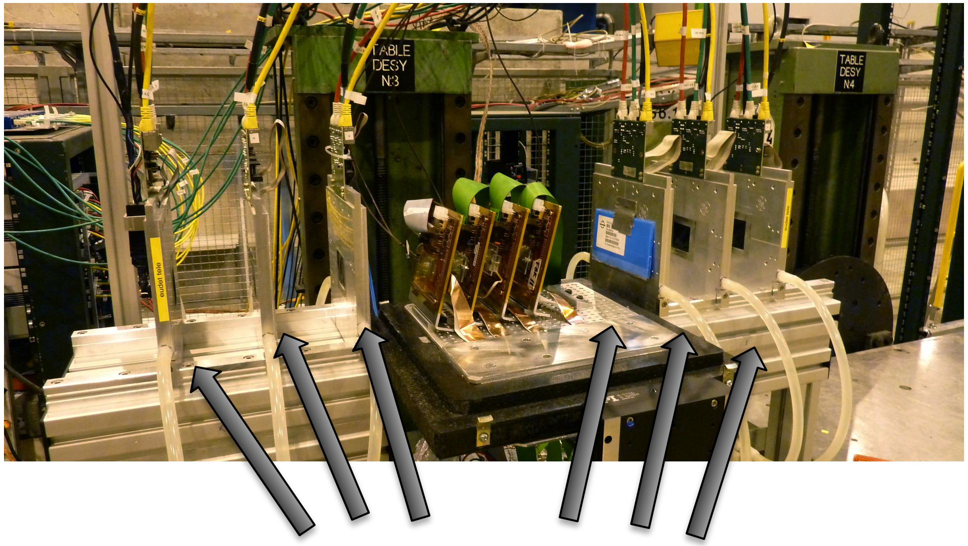
DESY (below)

Reconstruction

- Data taken in a test beam setup has to be reconstructed before it can be analysed.
- The Eudet telescope used in recent test beams
  - Consists of six planes of Monolithic Active Pixel Sensors (MAPS). Three on either side of the devices under test
  - Has a resolution of ~3 um.



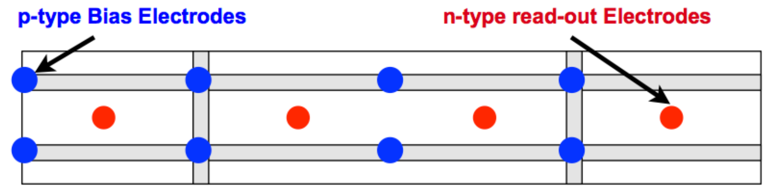
Correlation between two telescope planes.

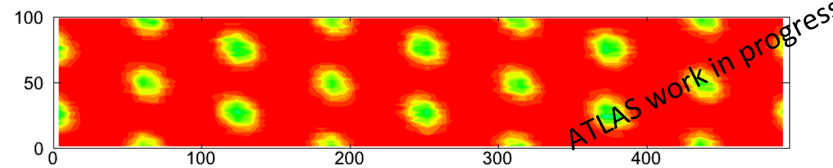


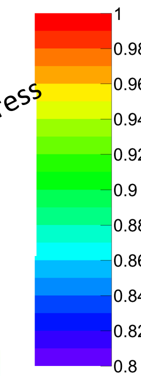
Telescope Planes

Test Beam Data Analysis

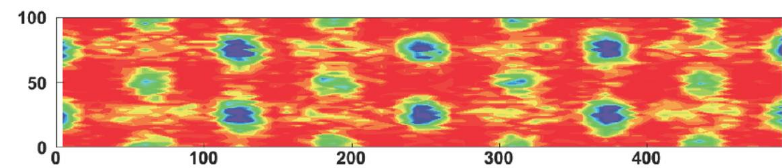
- Efficiency
  - H_{eff} = # hits detected / # hits expected
  - Lower efficiency at electrodes, but this is recovered to ~100% when the sensor is tilted > 10º.
- Charge Sharing
  - The higher the charge sharing between pixels
    - Greater resolution
    - But higher chance that some pixels will not be above threshold.
  - Need to find an optimum balance.





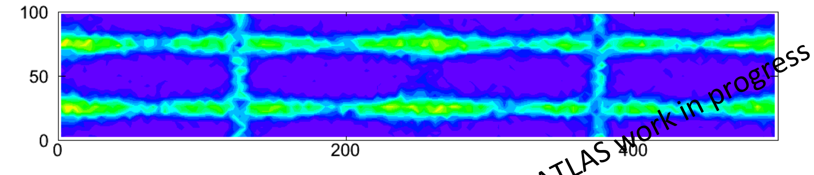


FBK non-irradiated sensor bonded to FE-I4.
At normal incidence to the beam.
Efficiency (match): 98.8 %



CNM proton irradiated 5x10[15] sensor bonded to FE-I4.
At normal incidence to the beam.
Efficiency (match): 97.5 %

J .Weingarten, *ATLAS IBL Sensor Qualification*. PSD09 Conference



CNM non-irradiated sensor bonded to FE-I4.
At normal incidence to the beam.
Charge Sharing: 13.6%

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Summary

- Laboratory tests and data from test beams are important tools for determining the suitability of new sensor technology for use in ATLAS.
- 3D Silicon technology has already been accepted for the ATLAS IBL and has proven to be a very strong candidate for future upgrade projects.

Thank you for your attention!