Steve McMahon
RAL

Towards Phase II tracking at ATLAS

International Workshop on Future High Energy Circular Colliders
December 16-17 2013
Beijing China

Introduction
ATLAS nomenclature information

- **ID:** Current detector up to Phase II (to 2023)
- **ITk**: Next generation detector beyond 2023

The *Current* ATLAS Inner Detector (ID)
Initial Specifications & Limitations

Current Inner Detector

3 layers of Pixels (PIX), 4 layers of Si micro-strips (SCT), straw tracker (TRT)
Additional PIX-layer (IBL) to be inserted in Long Shut-Down 1 (LS1 - 2014)
ID designed for **10 years** of operation, peak luminosity of **1×10^{34} cm^{-2}s^{-1}**
The assumed pile up (μ) was **23**, bunch crossing frequency **25ns**
and the L1 trigger rate of **100kHz. 2 Tesla Magnetic field**

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IBL: desi
SCT: desi
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Bandwidth Limitation

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Occupancy limits

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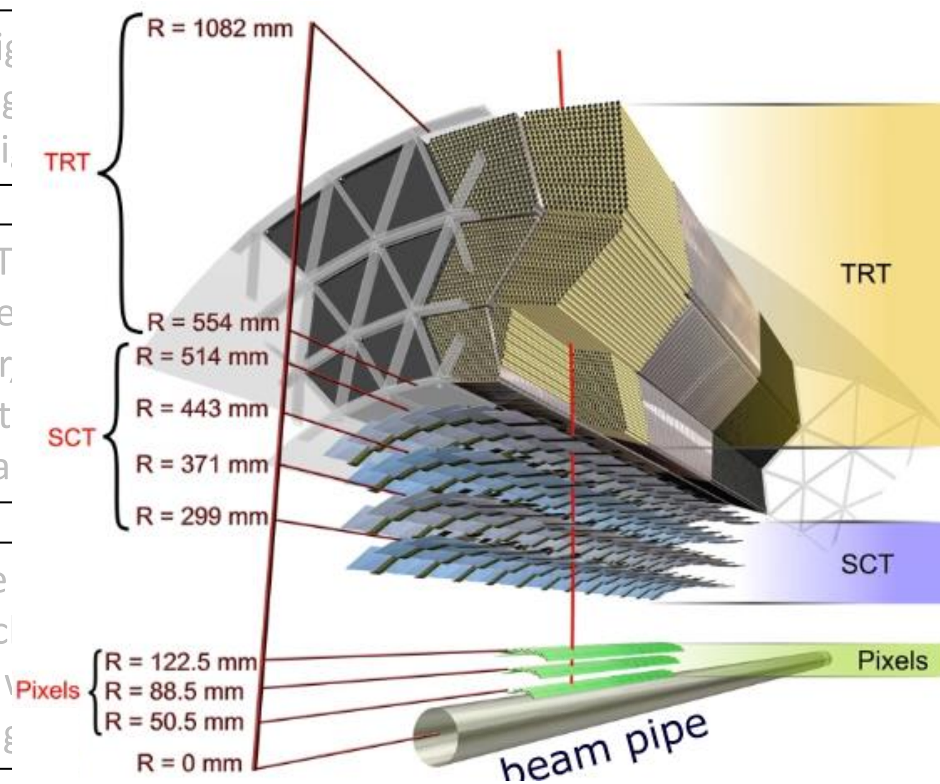

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PIX: designed to withstand 10^{15} 1MeV neq/cm^2 or about 400fb^{-1}
IBL: designed to about 850fb^{-1}
SCT: designed to withstand 2×10^{14} 1MeV neq/cm^2 or about 700fb^{-1}

Bandwidth Limitation

Both SCT and PIX apply zero suppression to accommodate $\langle\mu\rangle$ up to 50
This is being expanded in LS1 to get bveyond 75 (**3×10^{34} cm^{-2}s^{-1} @ 25ns)**
However, there are "hard wired" limitations which mean one cannot go beyond this. PIX-Limits 0.2-0.4 pixels per 25ns. For SCT data rate between FE chip and ReadOut Driver (ROD) limit us to **3×10^{34} cm^{-2}s^{-1}**

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With the occupancy expected at the HL-LHC the SCT would not be able to resolve close-by tracks in the core of High P_T jets
The TRT will approach 100% occupancy and tracking efficiency will suffer accordingly

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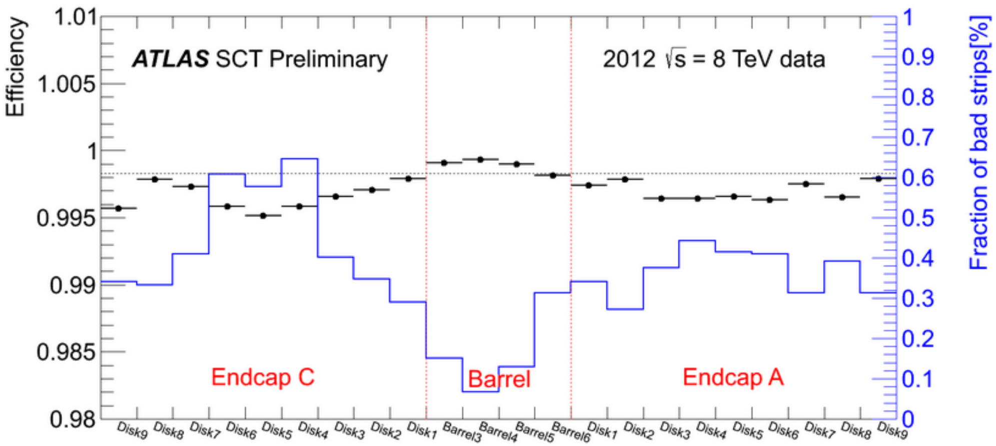
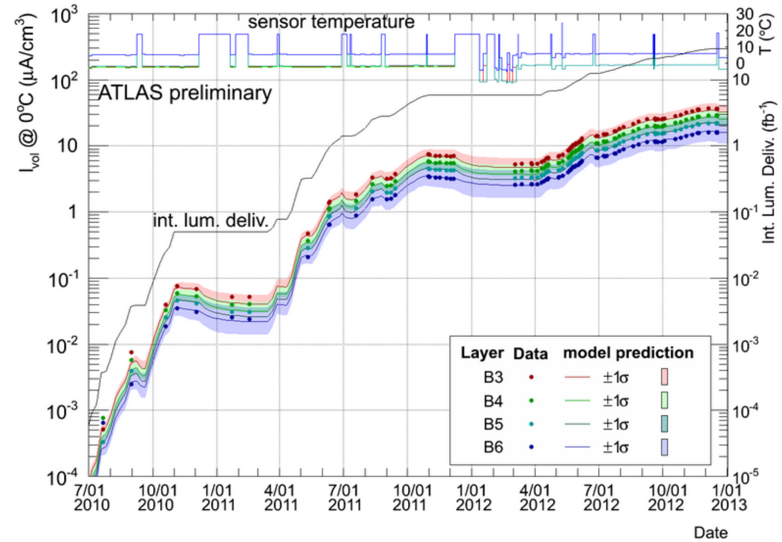
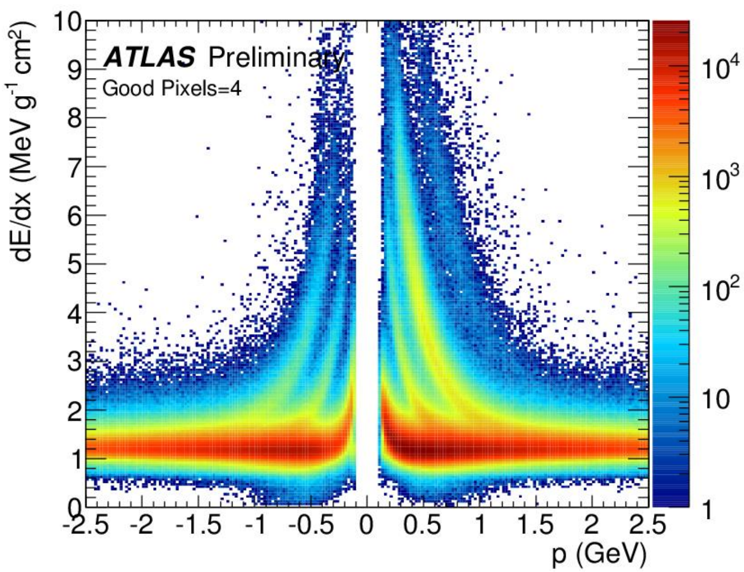
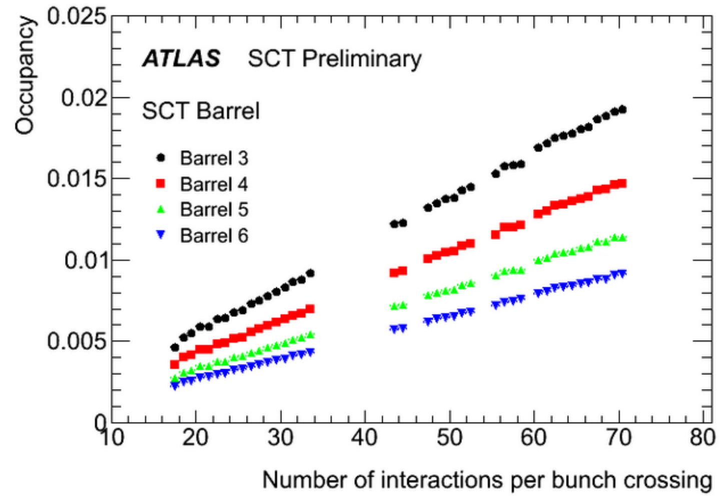
The Current ATLAS Inner Detector

A few selected silicon highlights (with personal bias)









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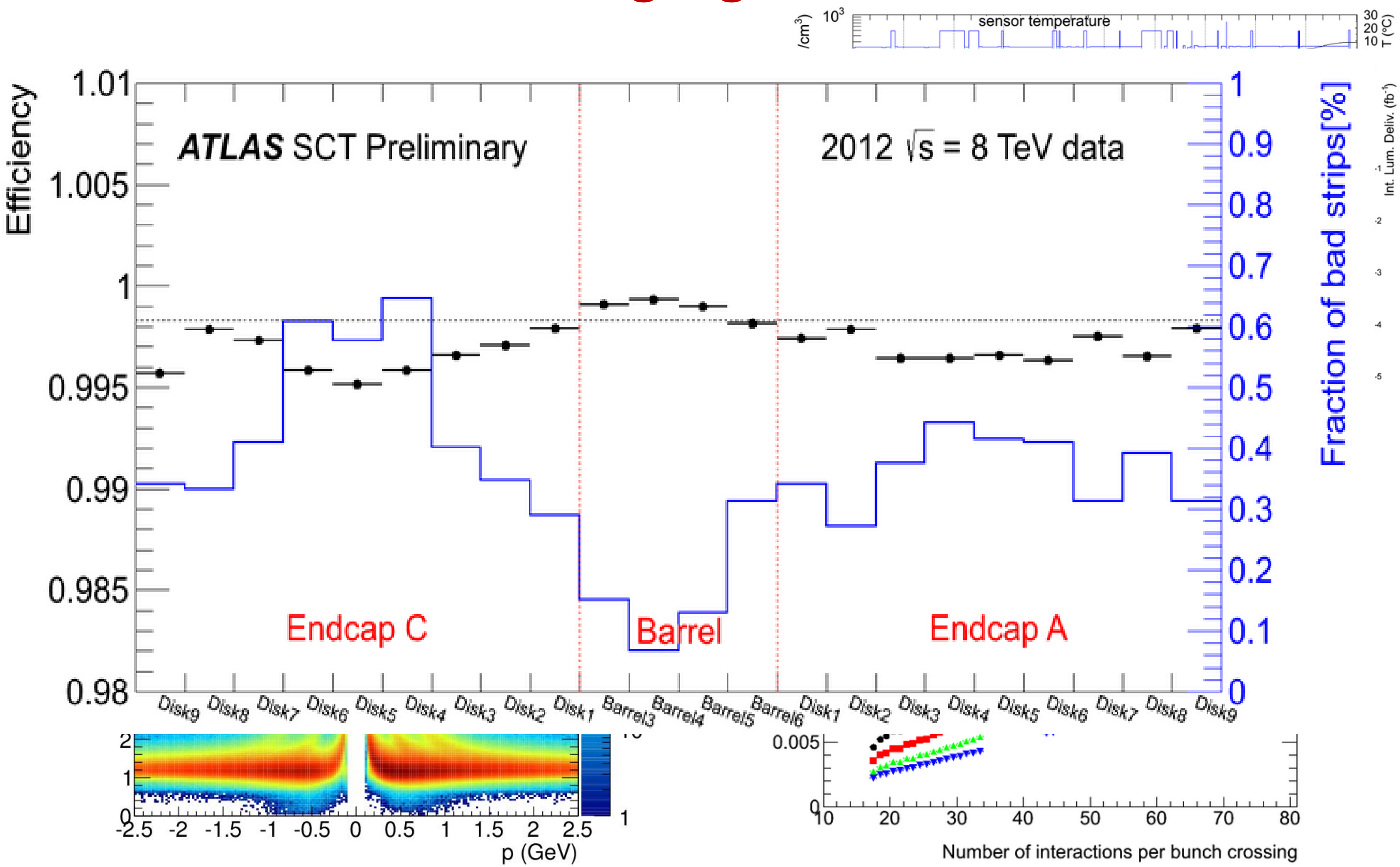

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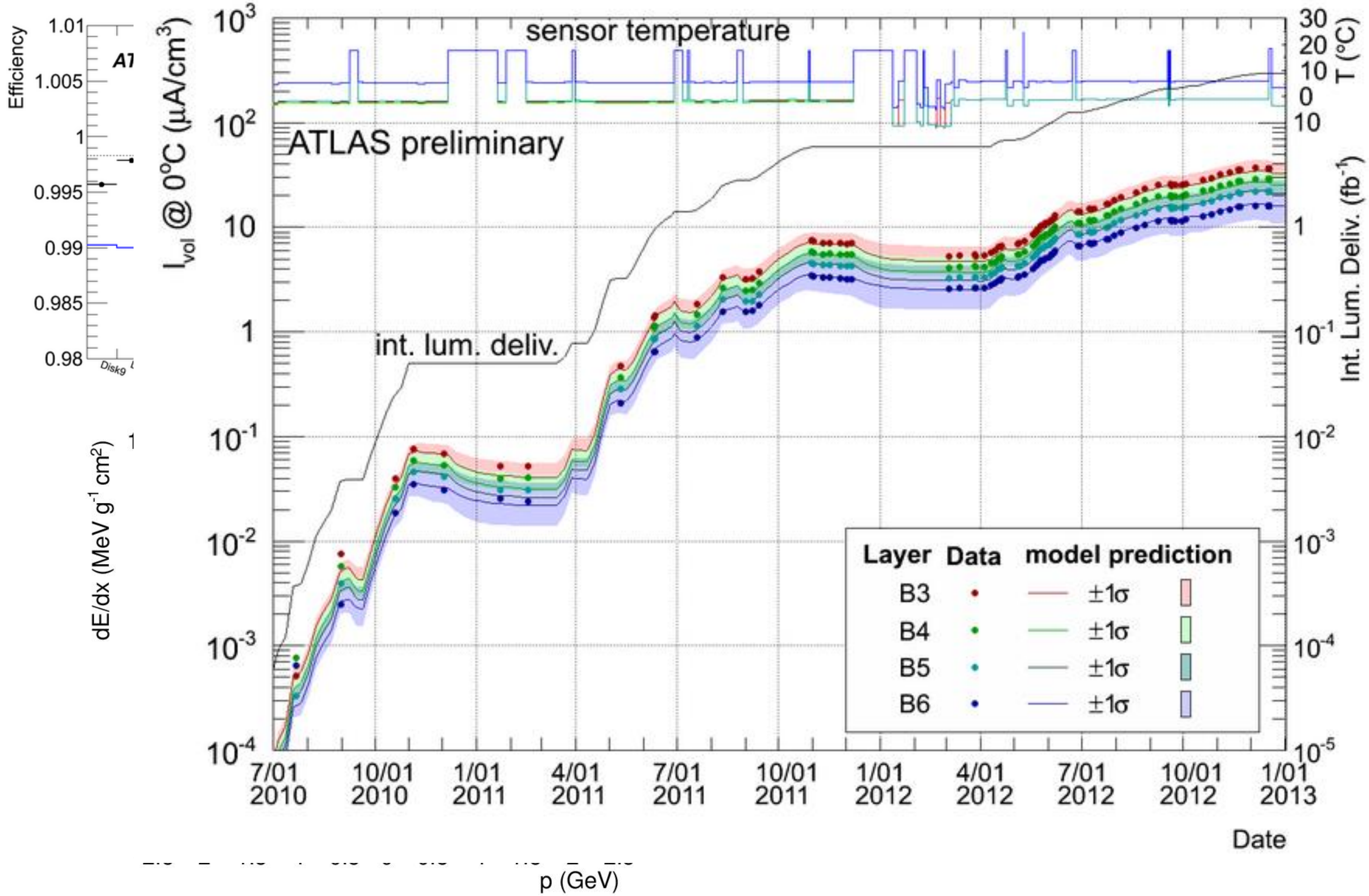

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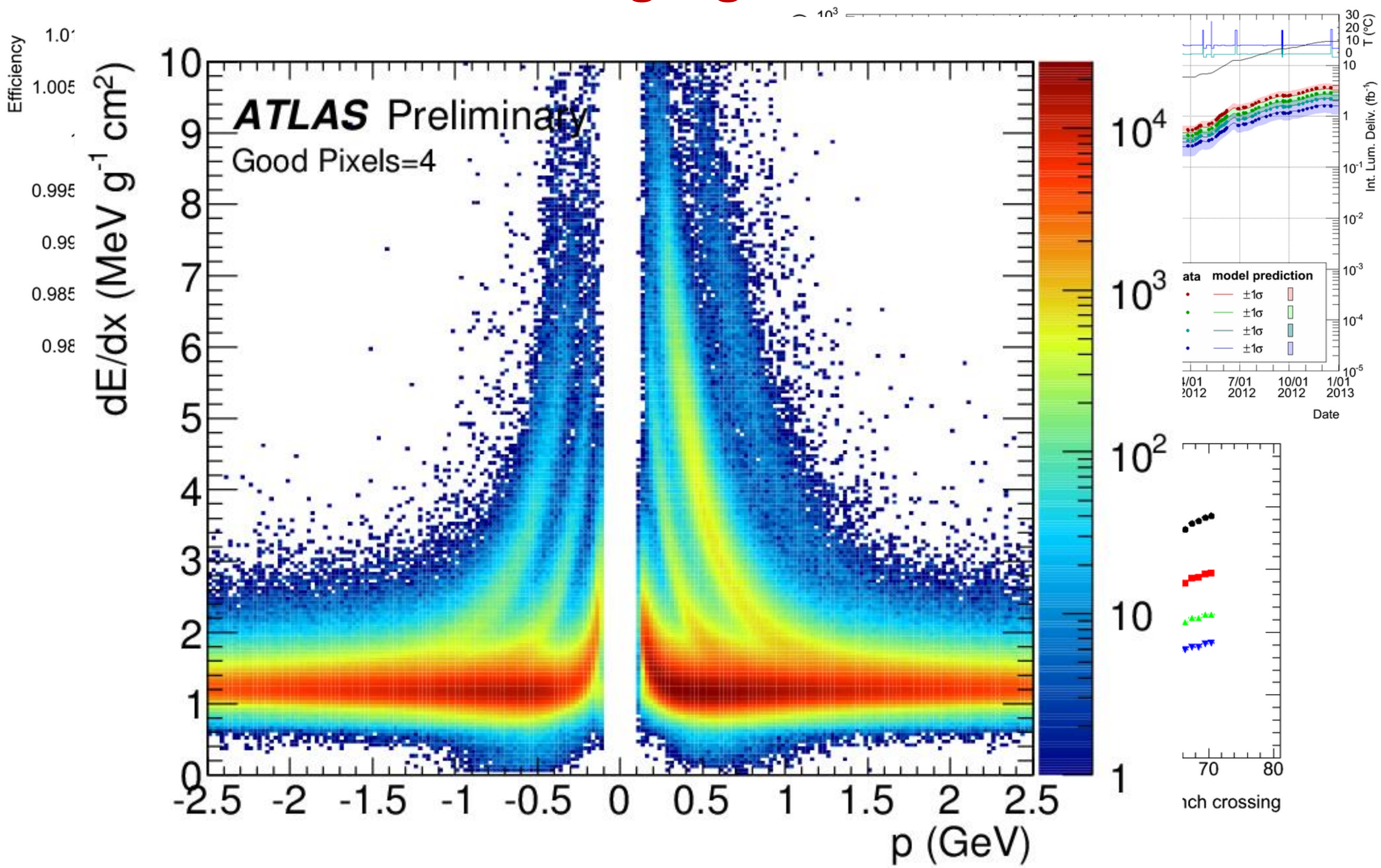

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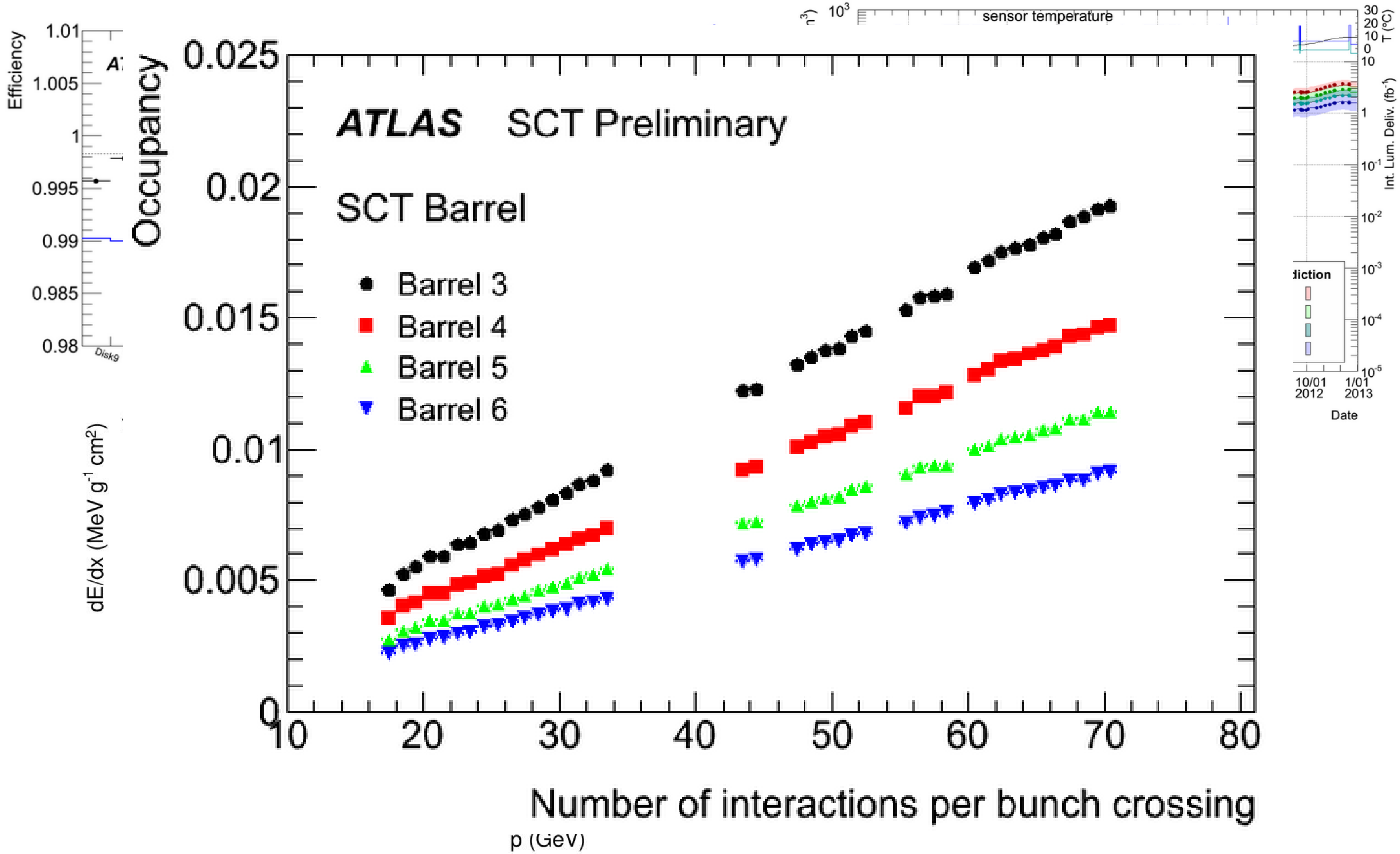
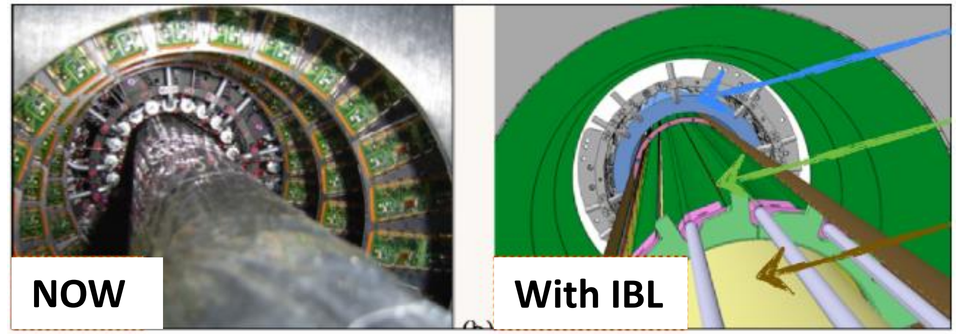
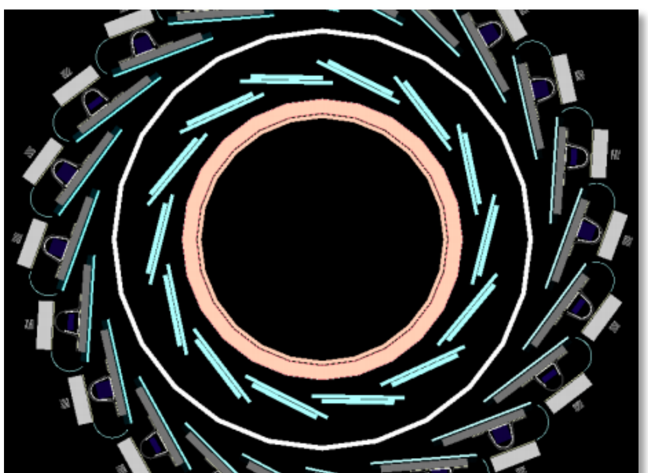


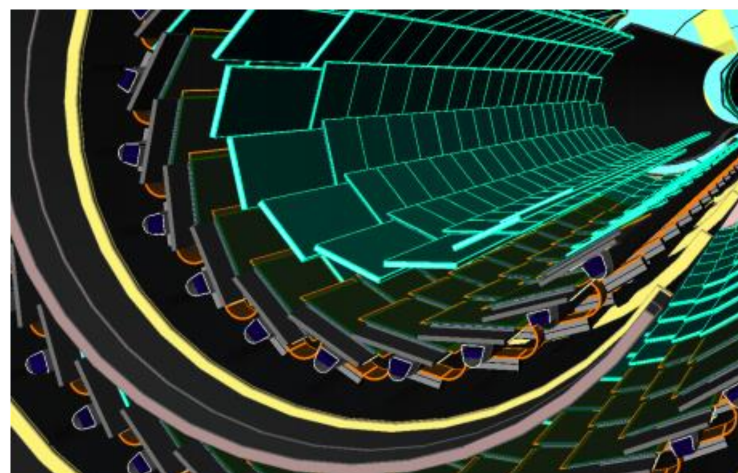
IBL : Phase-0 upgrades (LS-1)



Insertable B Layer (IBL)

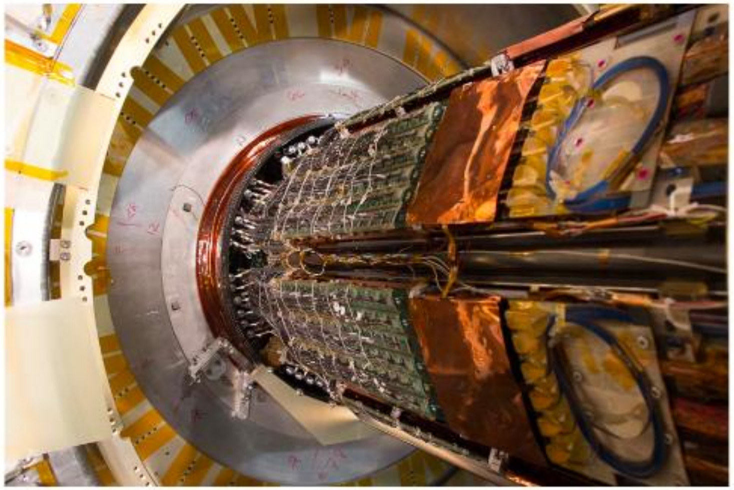
- ✓ Inserted at small radius (see insert)
- ✓ Closest measurement 3.3cm from IP
- ✓ Significantly improves light jet rejection
- ✓ 3→ 4 layer pixel device
- ✓ n-in-n planar & 3D sensors
- ✓ Installation scheduled for March 2014
- ✓ Production and integration are on schedule
- ✓ Uses the 2cm x 2cm FEI4 rad hard chip produced in 130nm CMOS
- ✓ IBL stays in place to Phase II

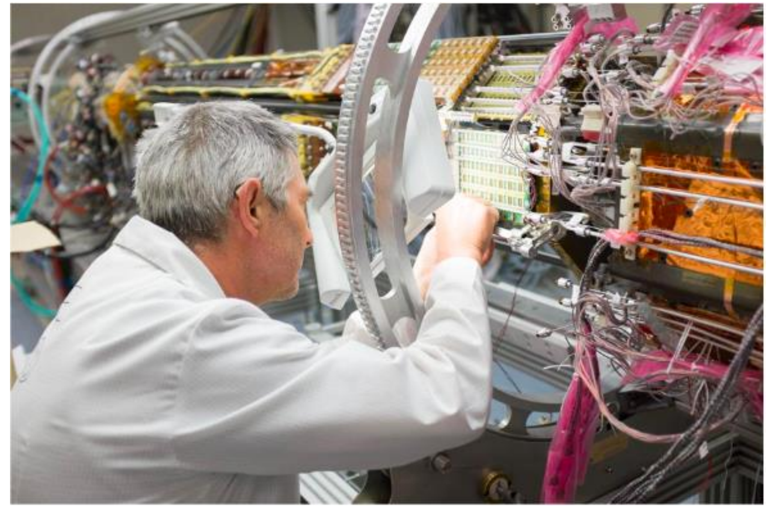




ID Pixel : Phase-0 consolidation (LS-1)

Extraction April 2013



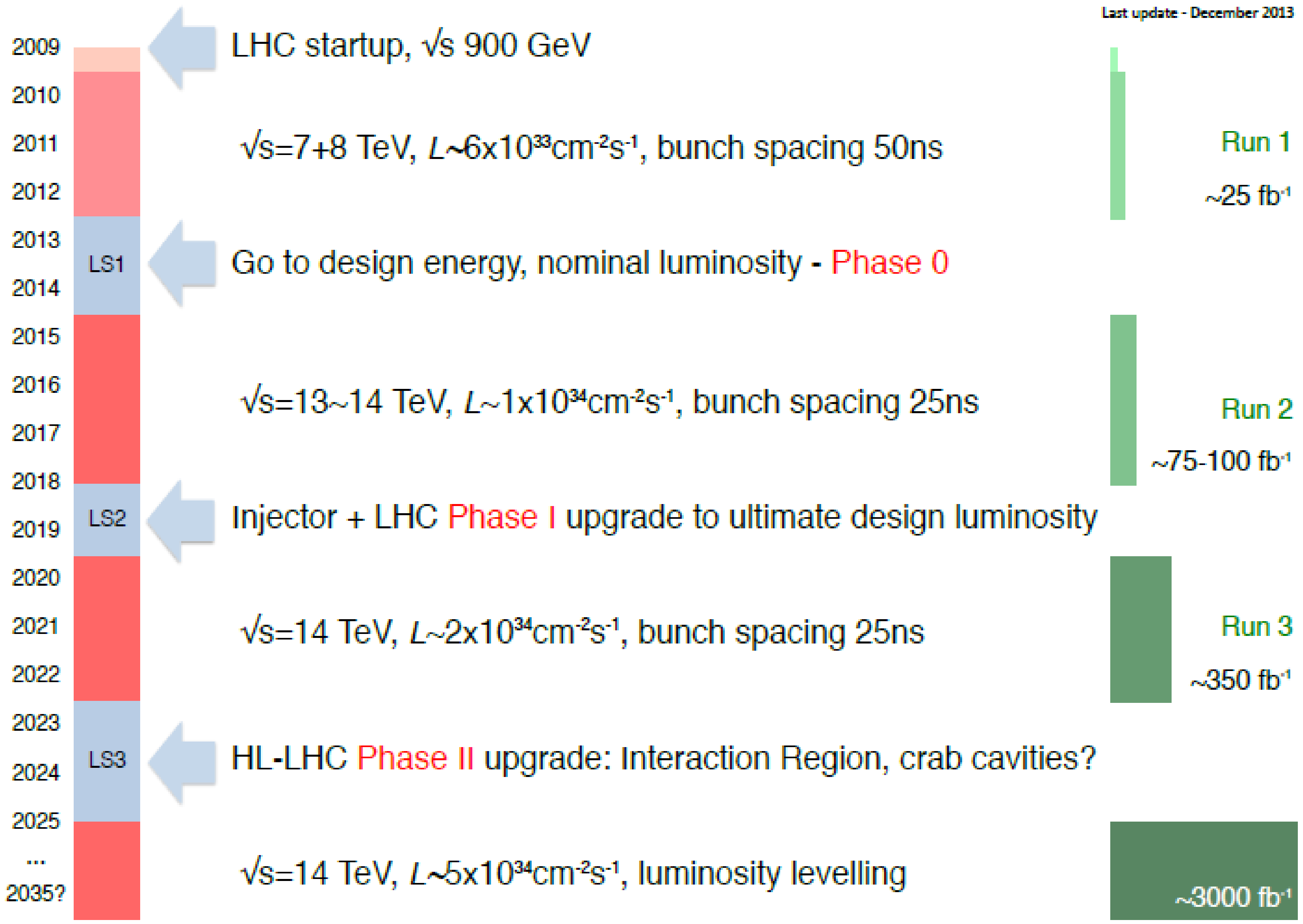


Improvements to the
Existing pixel services
The so –called NSQP

Surface Clean Room

Return December 3rd 2013

The LHC roadmap (updated December 2013)



The Future Phase II ATLAS Tracker Requirements

General ITk Requirements

Guided by the physics requirements (see talk by Takanori Kono Monday)
Maintain and improve performance of existing ATLAS - ID to 3,000fb^{-1}

- ✓ Tracking to $<\mu>$ ~ *160–200*, expect 1000 tracks per unit of rapidity
- ✓ Measure P_T and direction of isolated particles (e and μ),
- ✓ reconstruct vertices of pile-up events
- ✓ identify vertex of hard scatter
- ✓ Identify secondary vertices in b-jets with high efficiency and purity
- ✓ Measure tracks in the core of dense jets with good resolution
- ✓ Identify the decays of τ leptons, including impact parameter resolution
- ✓ Reconstruct tracks associated with converted photons
- ✓ The tracking must be robust against minor losses of acceptance
- ✓ Tracking at first level of triggering

Pixel

ITk Pixels.

- ✓ Fluences up to 2x10^{16} 1MeV neq/cm^2
- ✓ Low mass to reduce multiple scattering (<1.5%X_o Inner, < 2.0%X_o Outer)
- ✓ Inner layers removable/replaceable in a short LHC stop (clam shell)
- ✓ Approximately 10m^2 of pixels

Strip Detector

ITk Strips.

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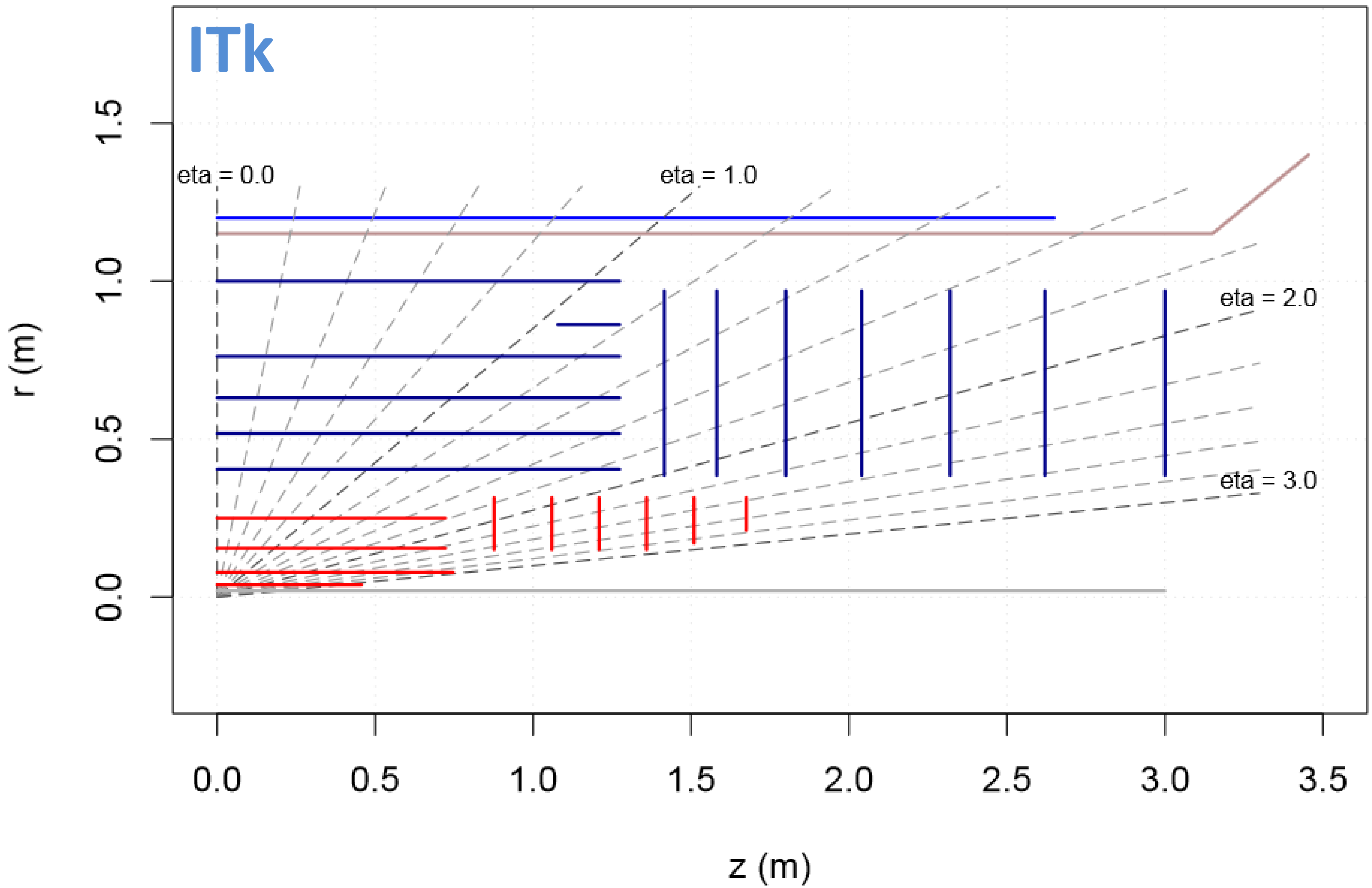
Baseline (LoI) Layout

http://cds.cern.ch/record/1502664?ln=en



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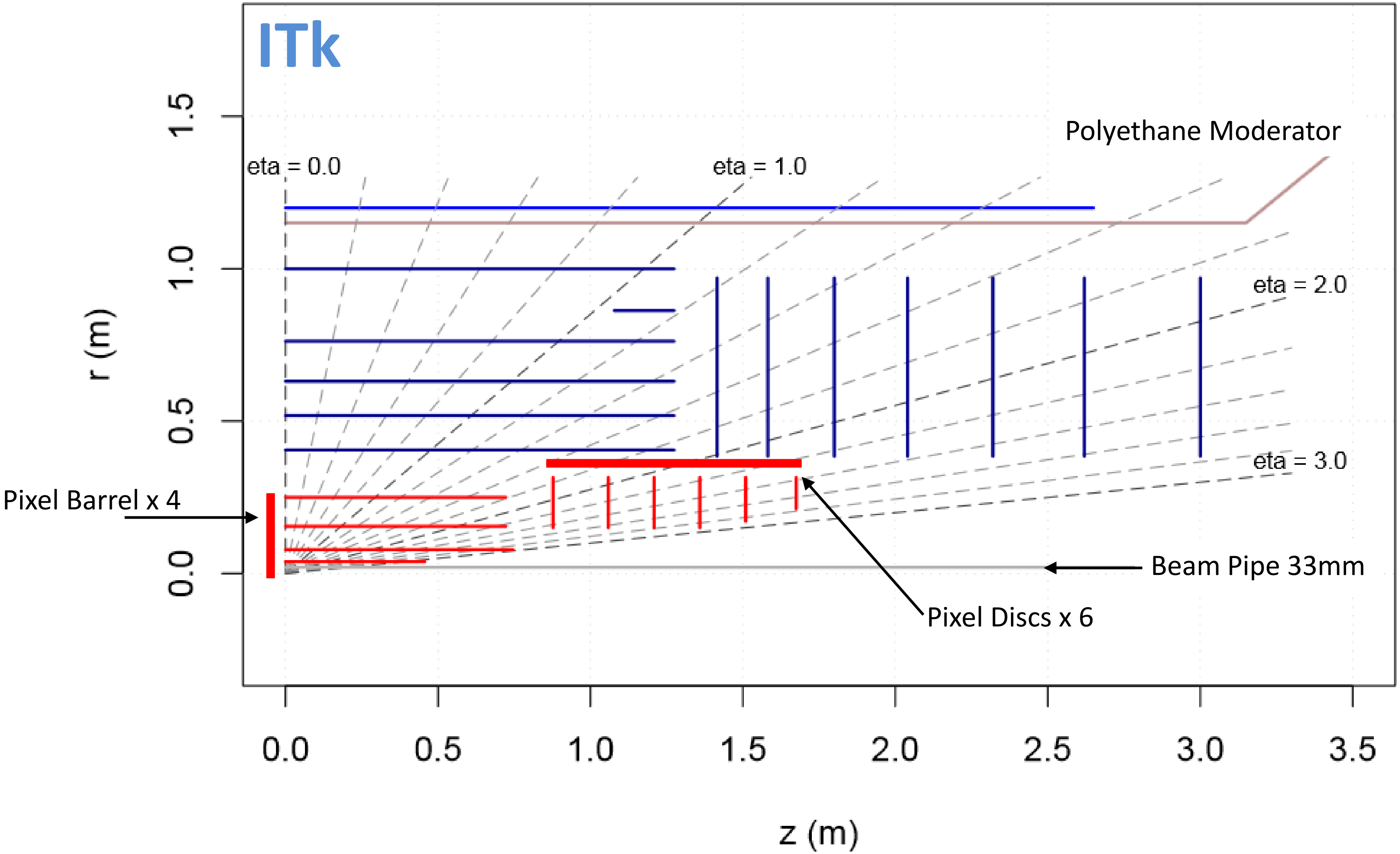
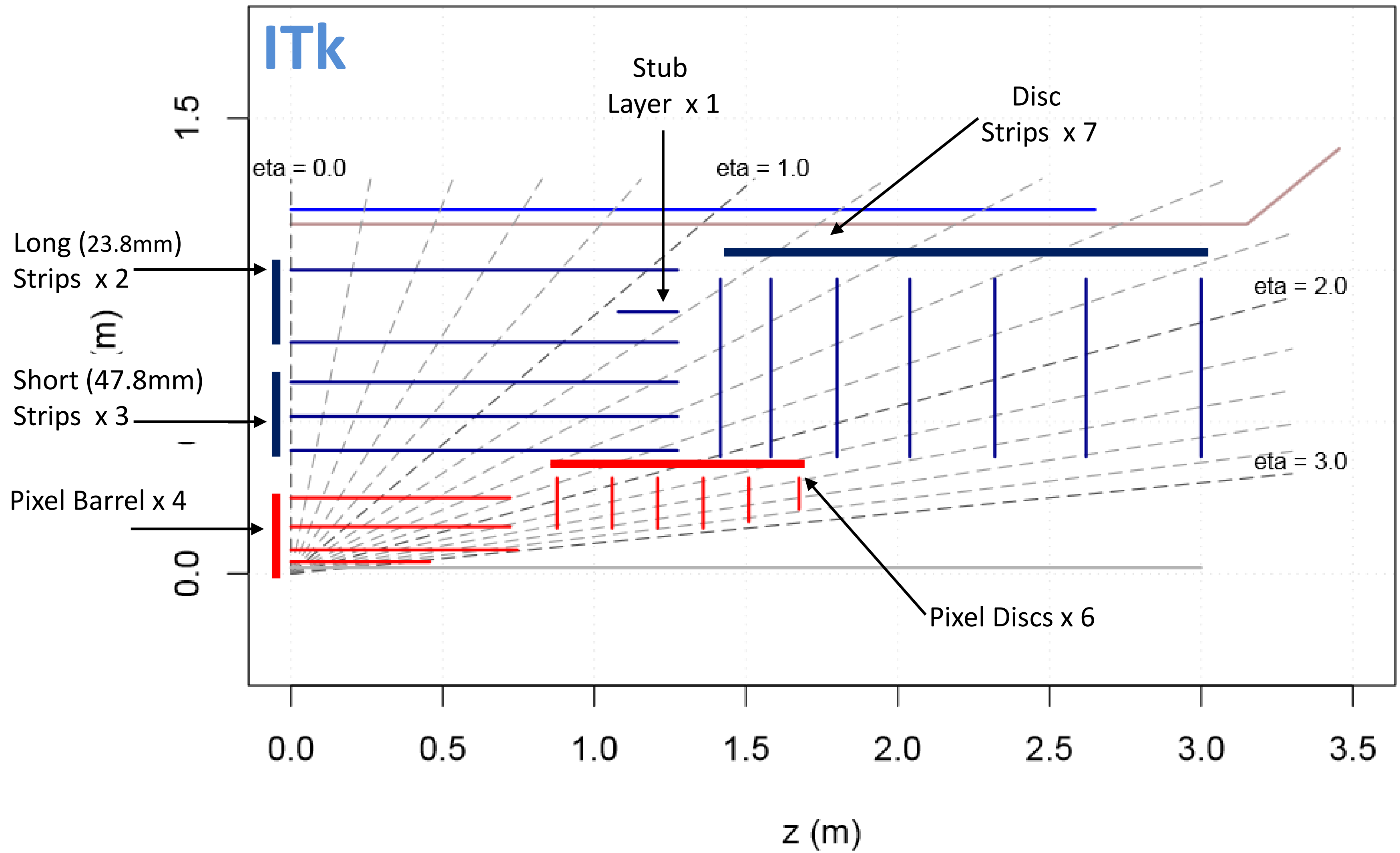


PIXELS
8.2 m²
638x10⁶ channels

Baseline (LoI) Layout

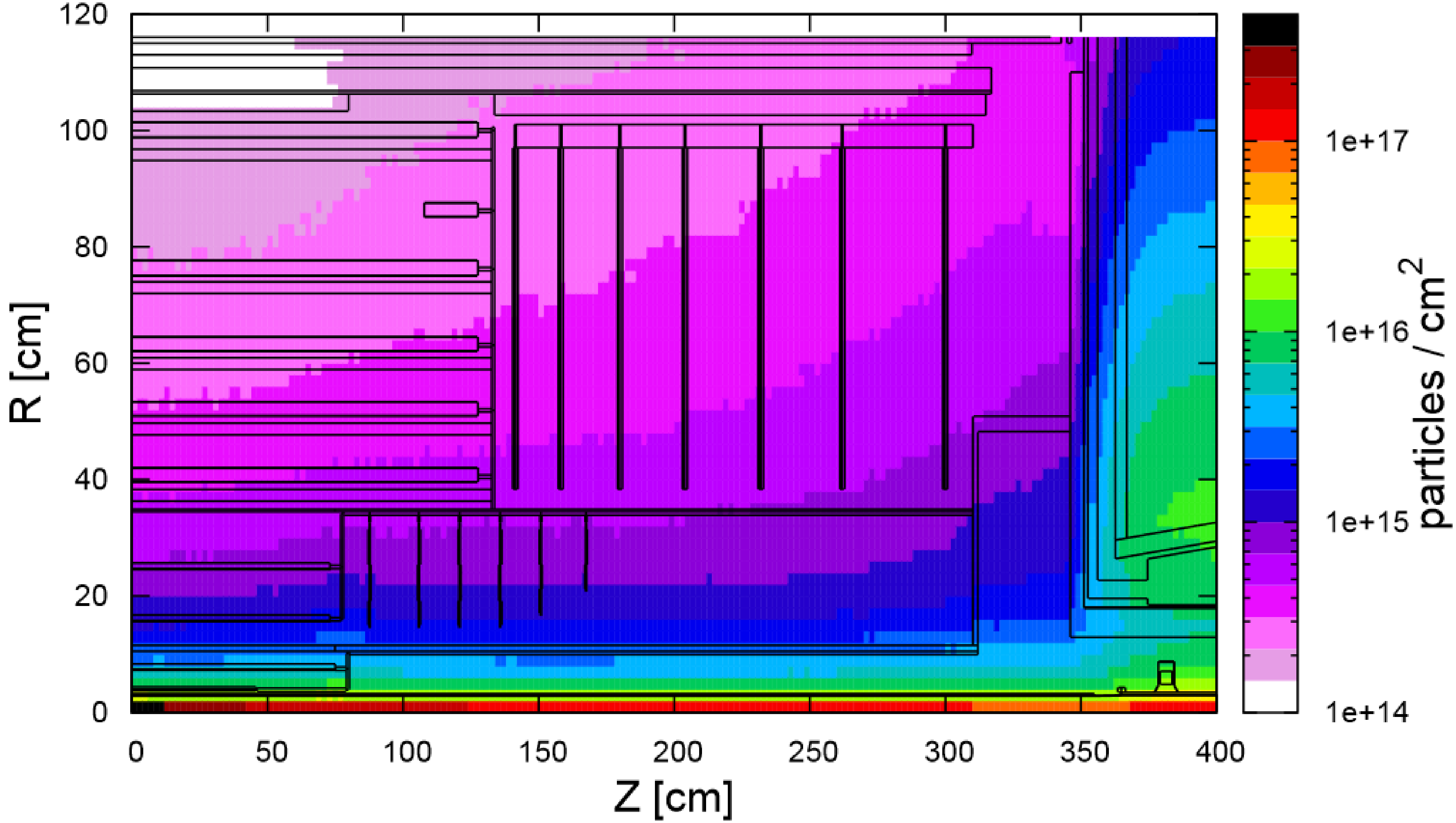
http://cds.cern.ch/record/1502664?ln=en

STRIPS
193 m²
74x10⁶ channels



ITk - Radiation Fluences : 1 MeV $n_{eq}.cm^{-2}$

Small radius dominated by flux from IP, larger radius significant contributions from cascades in Calorimeter. Factor of flux at large radius with and without polymoderator



Simulations with FLUKA, for integrated luminositiy to $3{,}000 fb^{-1}$

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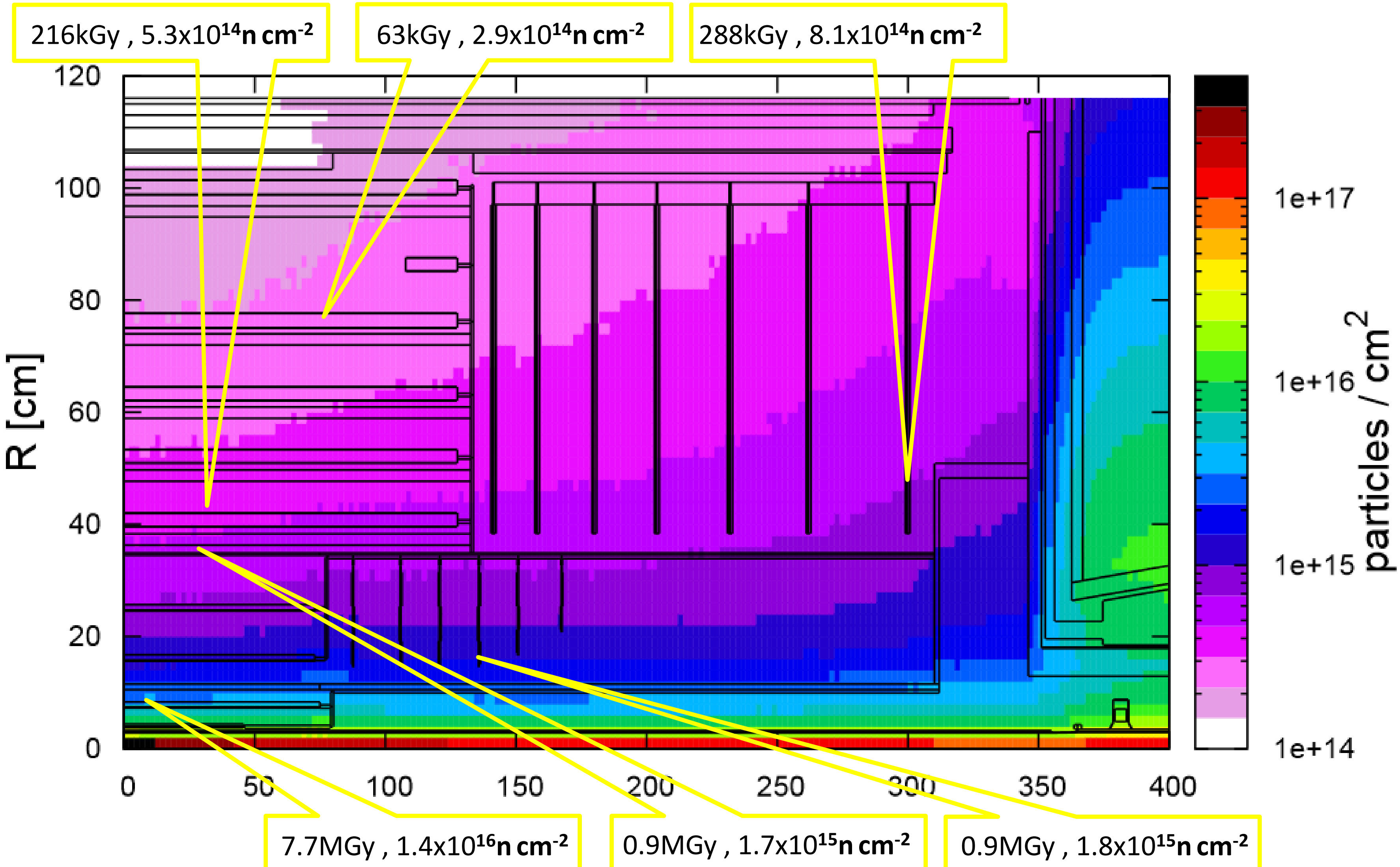


Simulations with FLUKA to 3,000 fb^{-1}

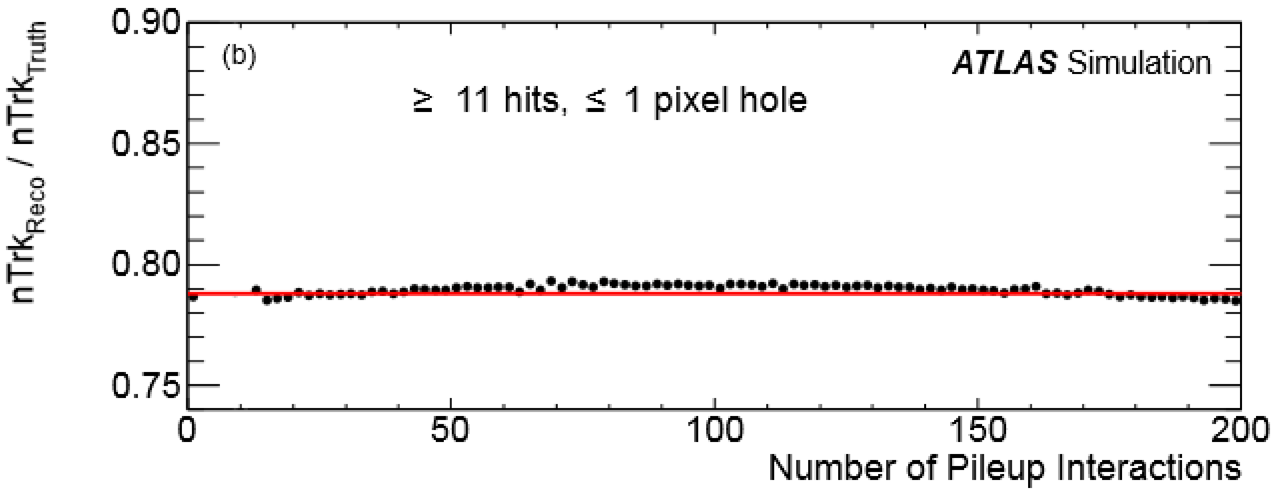
Performance of the ATLAS Phase II Tracker Compared with the existing ID + IBL

Track parameter $\|\eta\| < 0.5$	Existing ID with IBL no pile-up $\sigma_x(\infty)$	Phase-II tracker 200 events pile-up $\sigma_x(\infty)$
Inverse transverse momentum (q/p_T) [/TeV]	0.3	0.2
Transverse impact parameter (d_0) [μm]	8	8
Longitudinal impact parameter (z_0) [μm]	65	50

The expected performance of the ATLAS Phase II tracker compared to the performance of the existing ID with the addition of the IBL.
$\sigma x(\infty)$ refers to σx for $P_T \rightarrow \infty$ which allows one to remove the effect of material.

Performance parameters extracted from full ATLAS simulation including realistic service routing and appropriate engineering considerations.

Performance of the ATLAS Phase II Tracker
Number of hits on Track



Sample of $t\bar{t}$ events

Performance of the ATLAS Phase II Tracker
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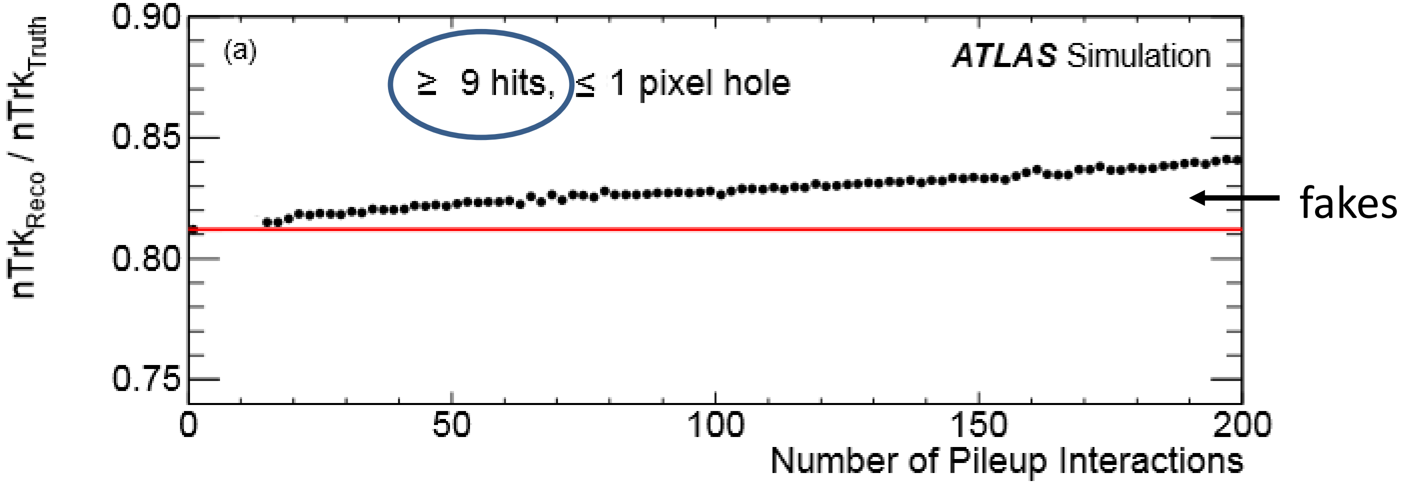

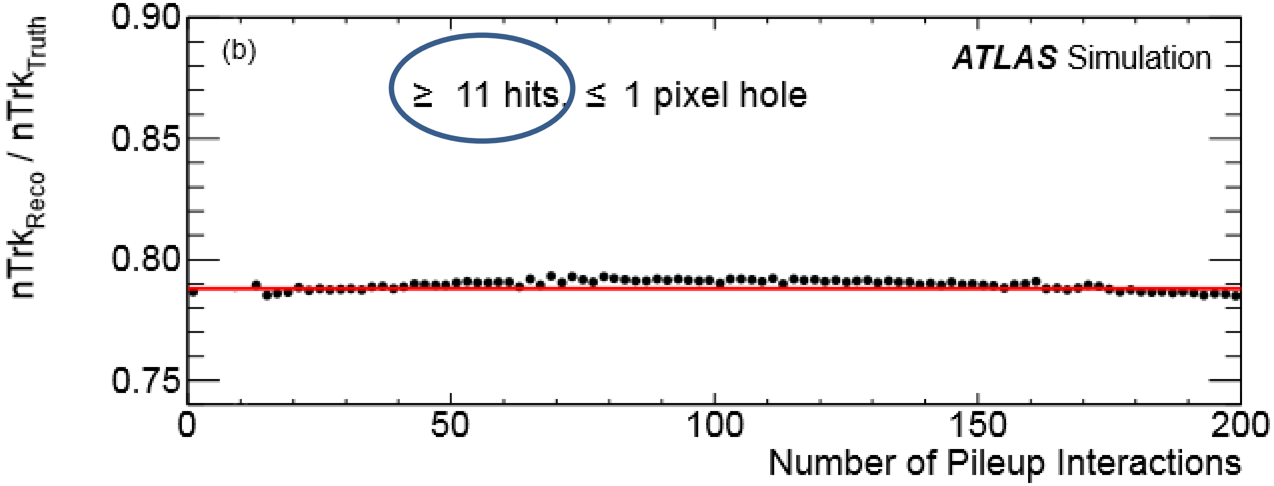

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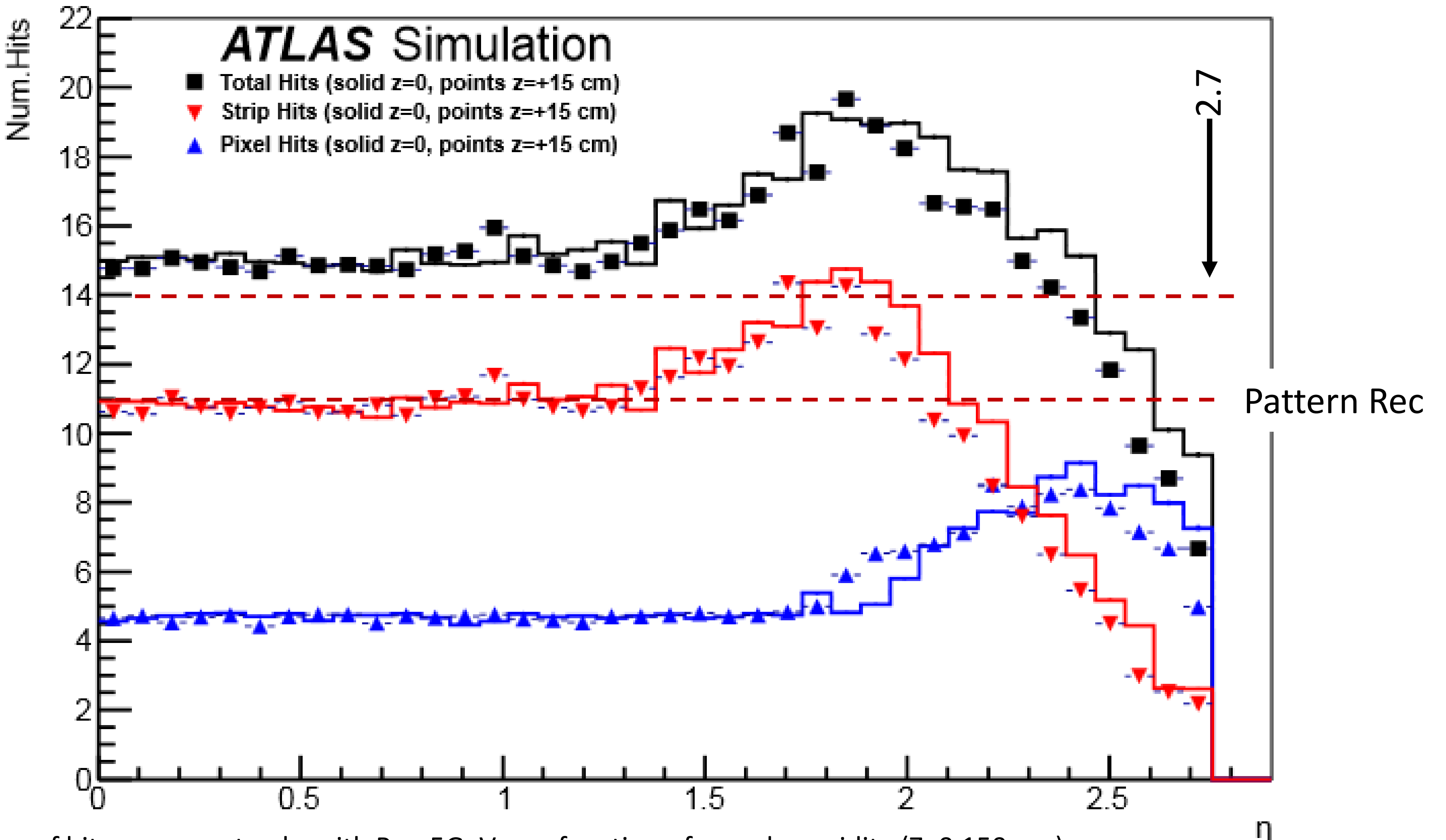
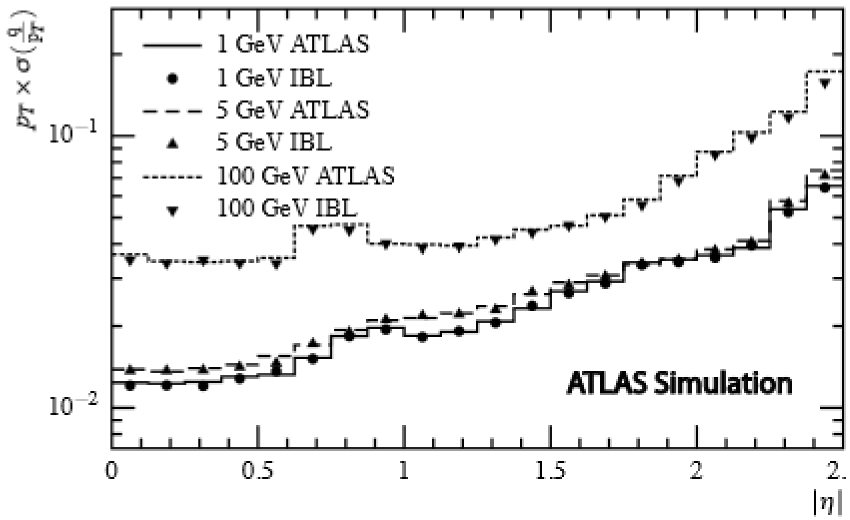


Number of hits on muon tracks with P_T > 5GeV as a function of pseudo-rapidity (Z=0,150mm)
Optimization in progress

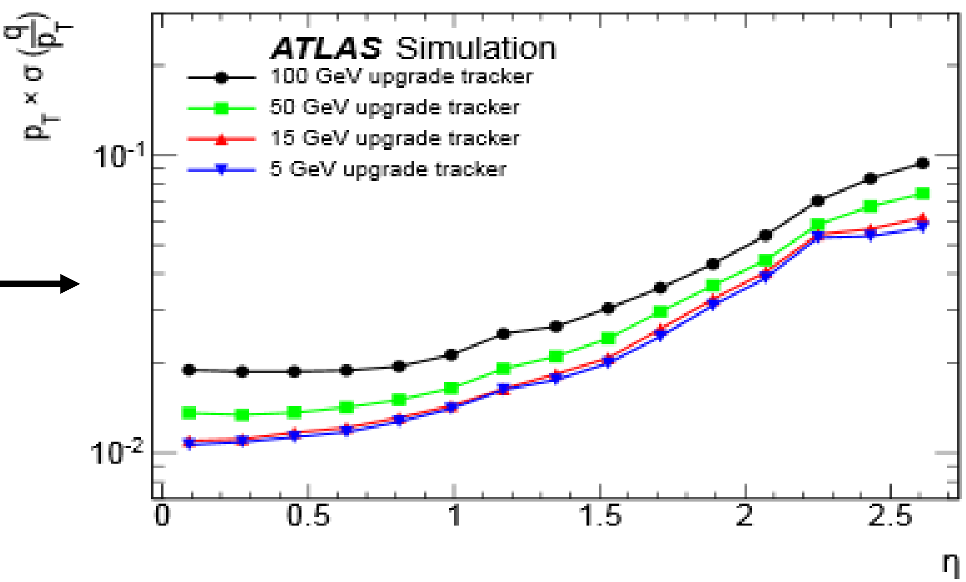
Performance of the ATLAS Phase II Tracker
Transverse momentum resolution

Current ID



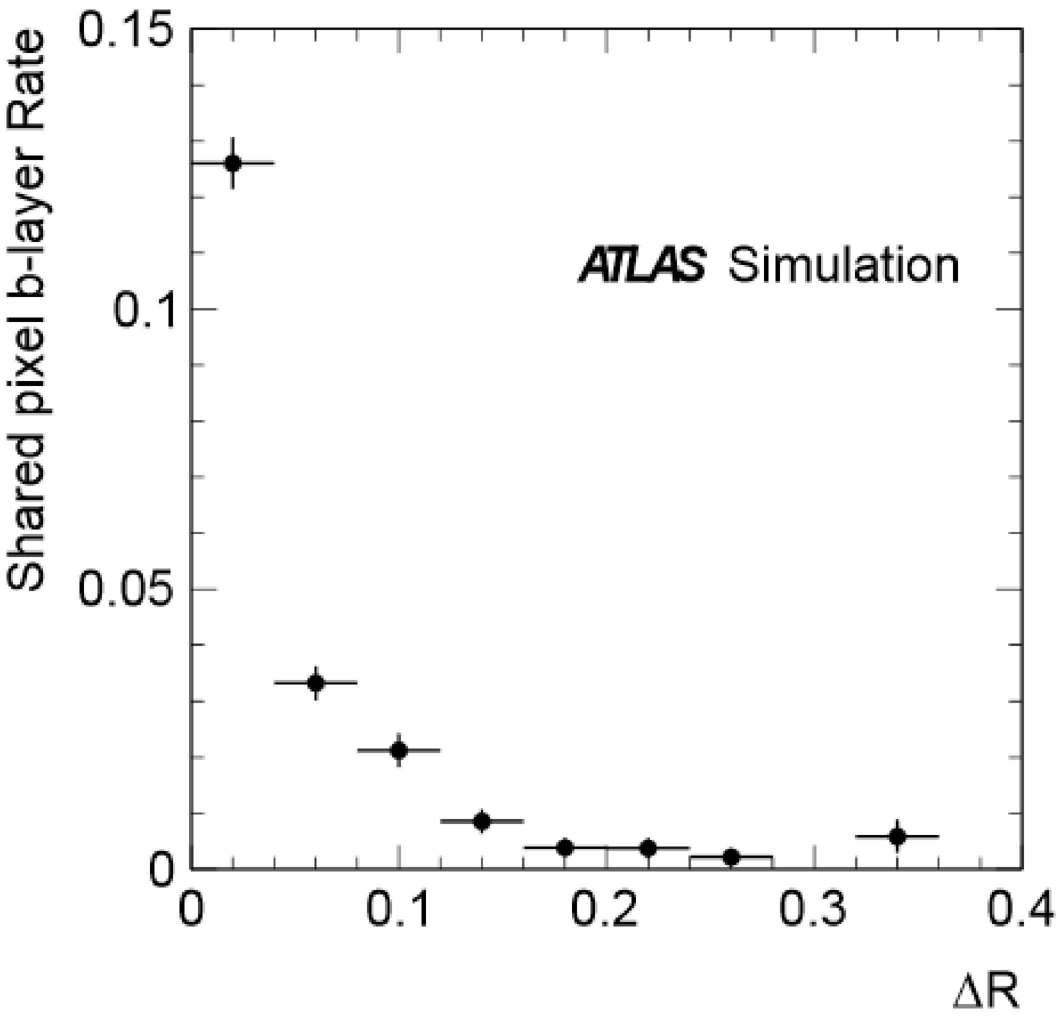
P_T resolution as a function of η for different particle momentum
Comparison of current ID with & without the IBL

Phase II ITk



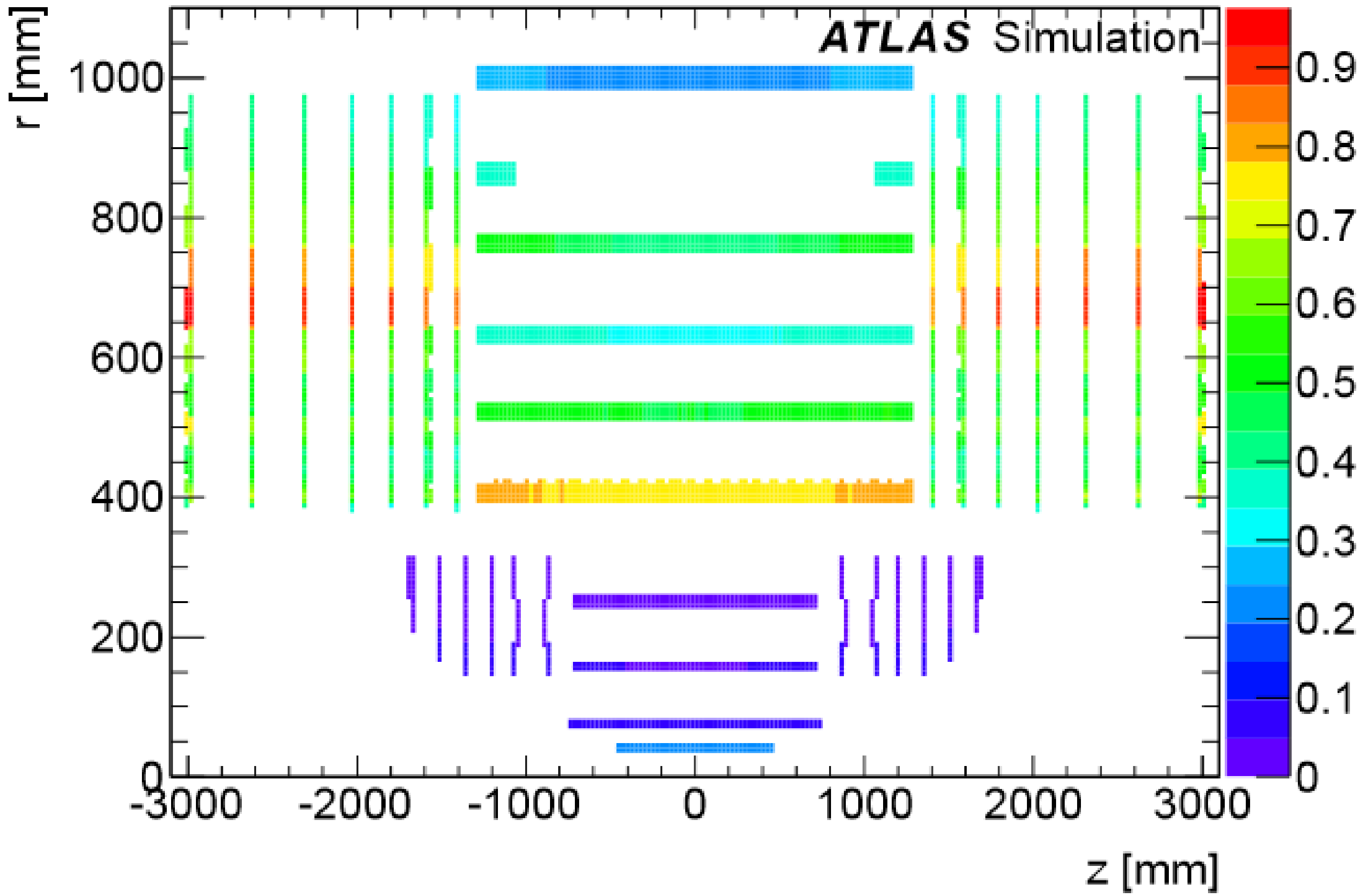
P_T resolution as a function of η
For Upgrade tracker for different momenta

Performance of the ATLAS Phase II Tracker
Separation of close by tracks



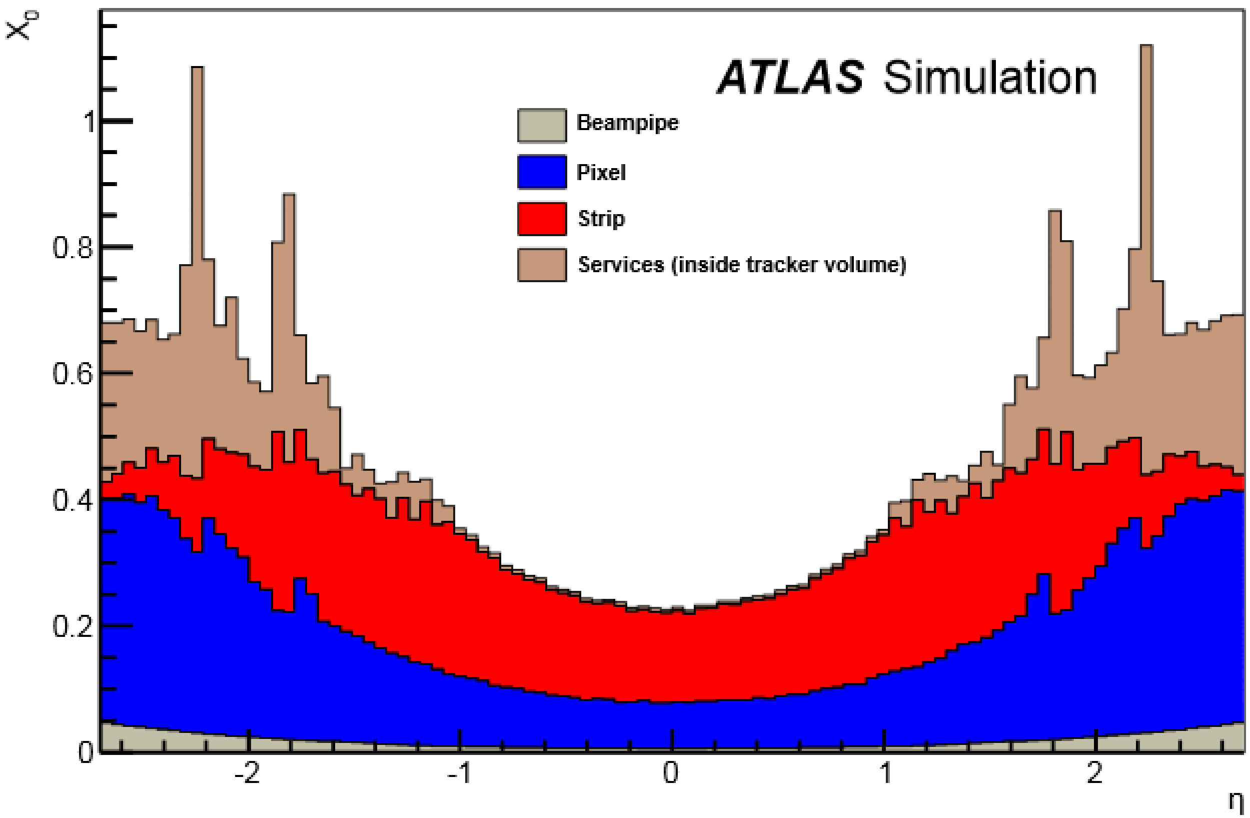
Good particle separation
Inside jets achieved with
Small pixel size
2 innermost pixels: 25x 150μm^2
2 outer pixels: 50 x 250μm^2

Construction of the ATLAS Phase II Tracker
Detector Occupancies



Hit occupancies in different sub-detectors in the presence of <u>200 pile up events</u> (peak around 0.9)

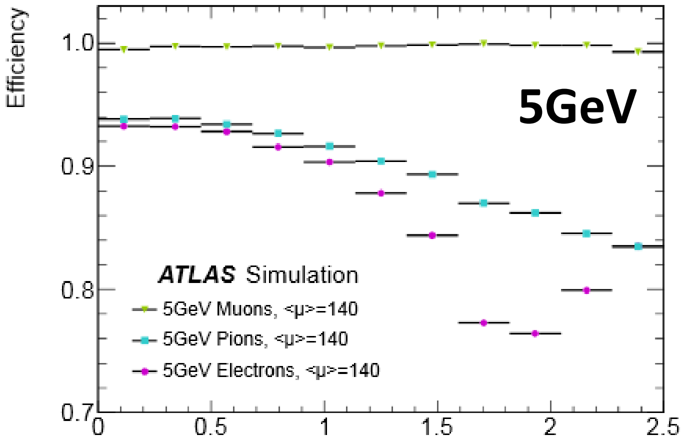
Construction of the ATLAS Phase II Tracker
ITk Material

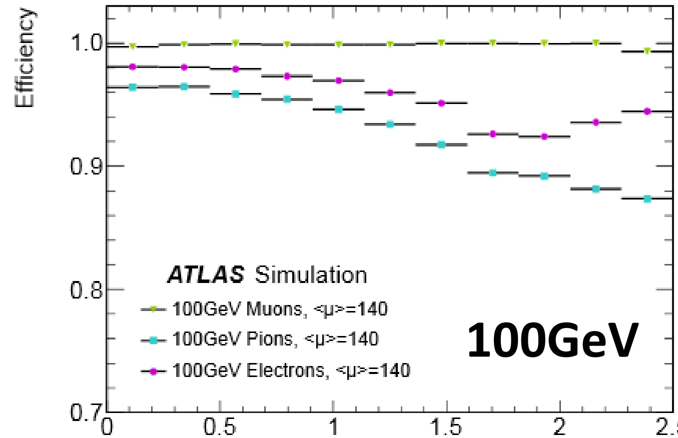


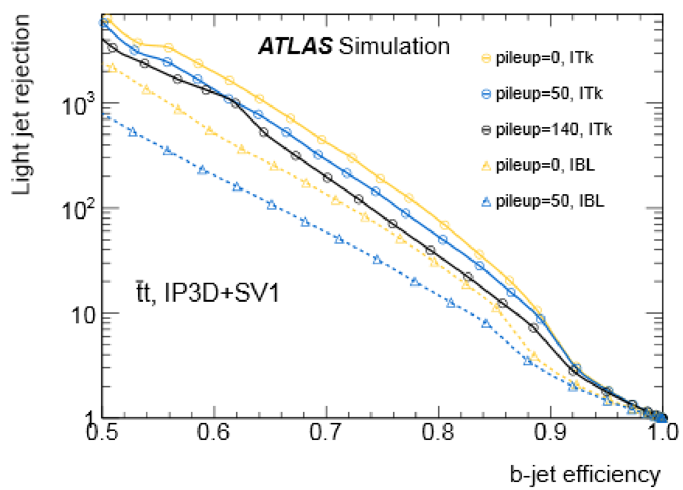
Particular attention put into reducing the material in the tracker volume
Note that everywhere less than 0.7Xo while in ID (+IBL) ~1.2%
Achieved through carful choice of materials, service routing etc

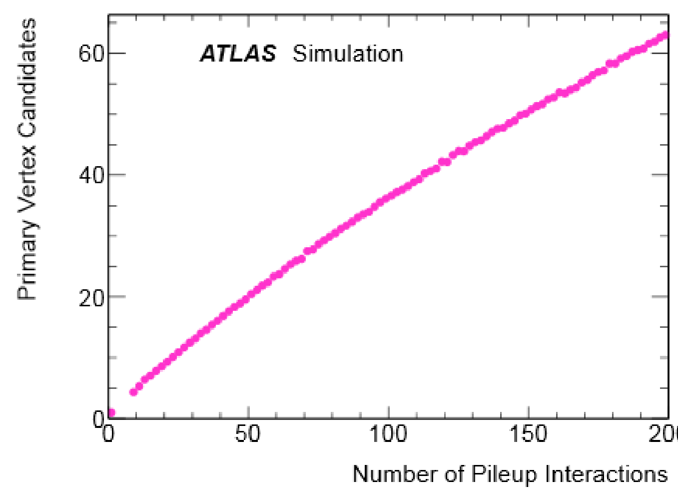
Performance of ATLAS Phase II Tracker Efficiencies b-tagging and vertex reco

NB Brem recovery used



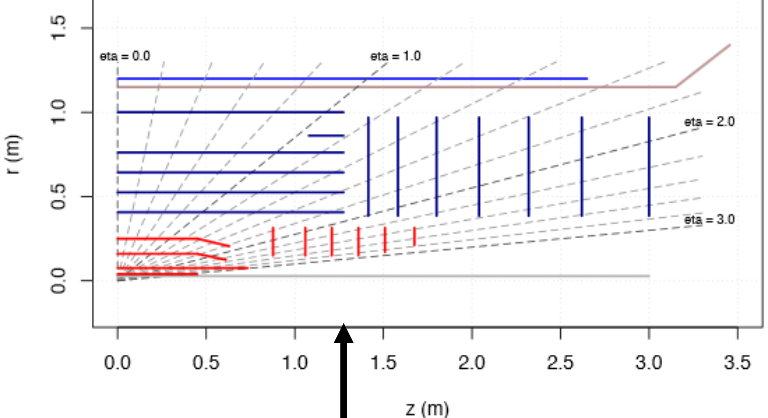




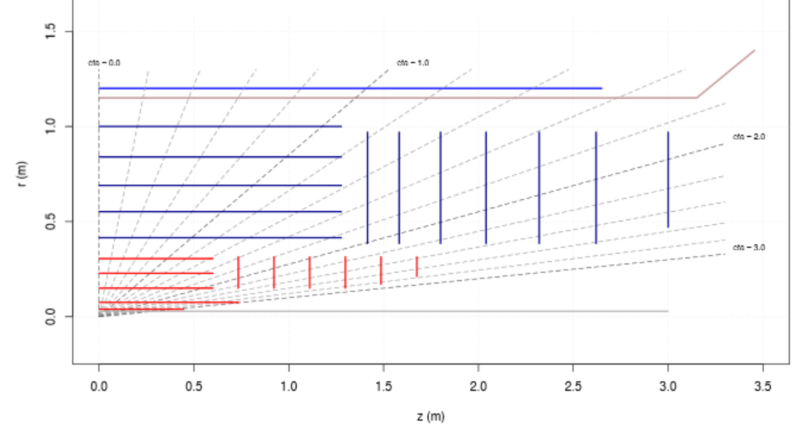


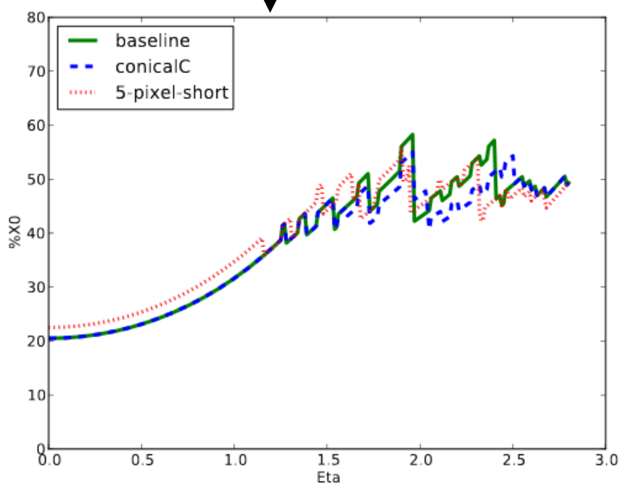
Alternate Layouts of Phase II Pixels

Conical (Barrel area 5.1 → 4.6 m²)

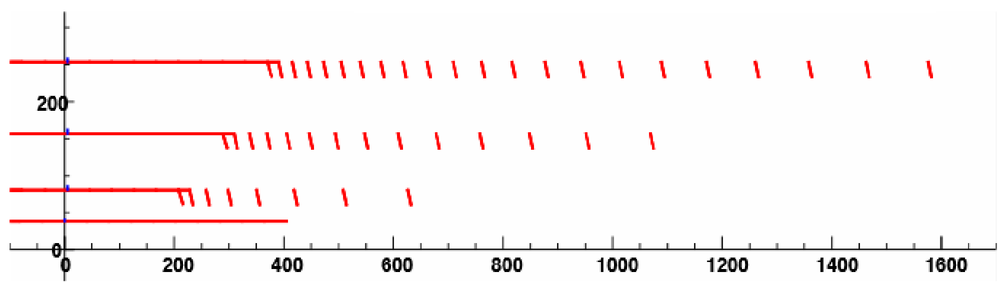


Fifth Pixel (optimized pattern rec)





Alpine (reduced area ∟ modules)



Work also ongoing with coverage out to a pseudorapidity of 4

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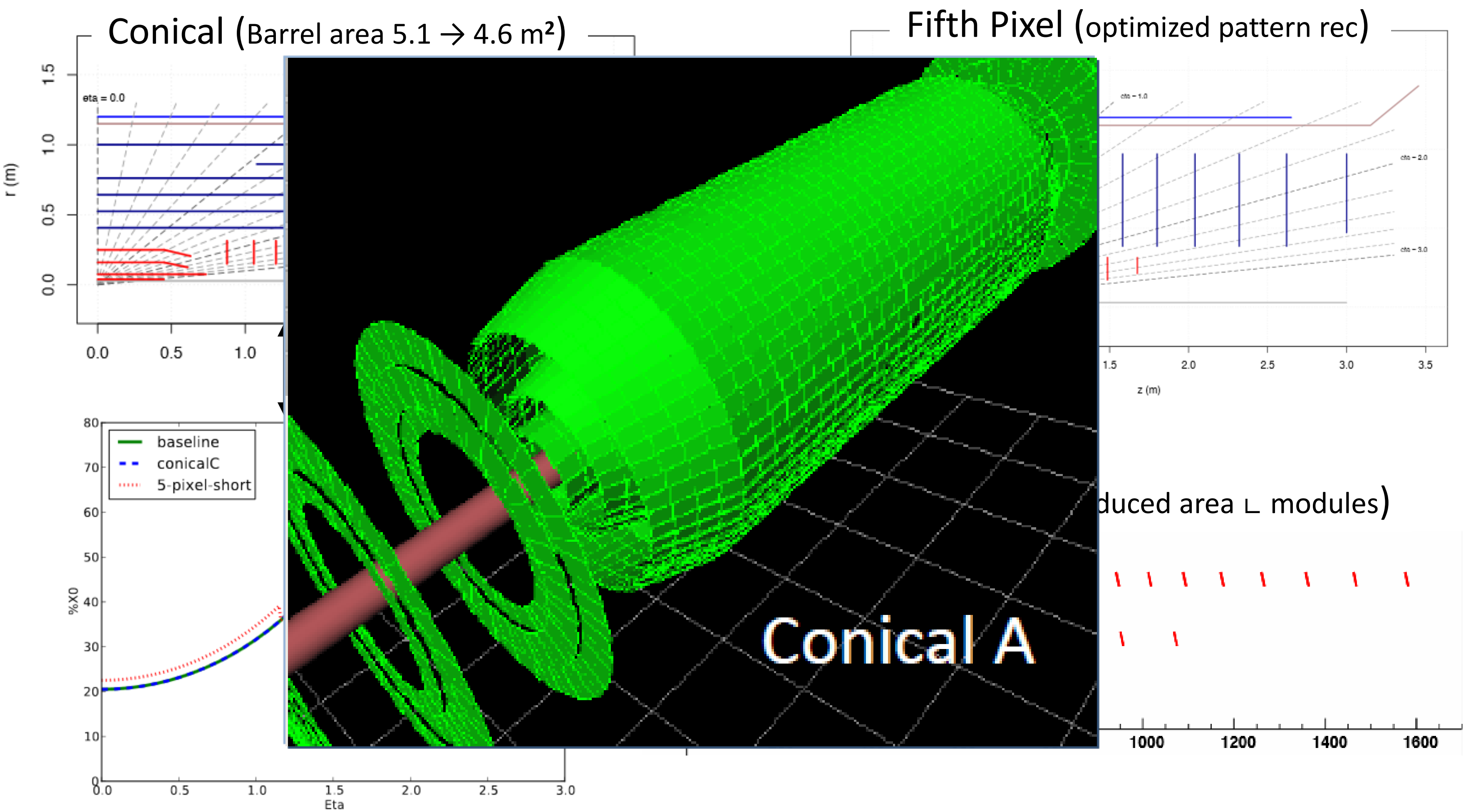

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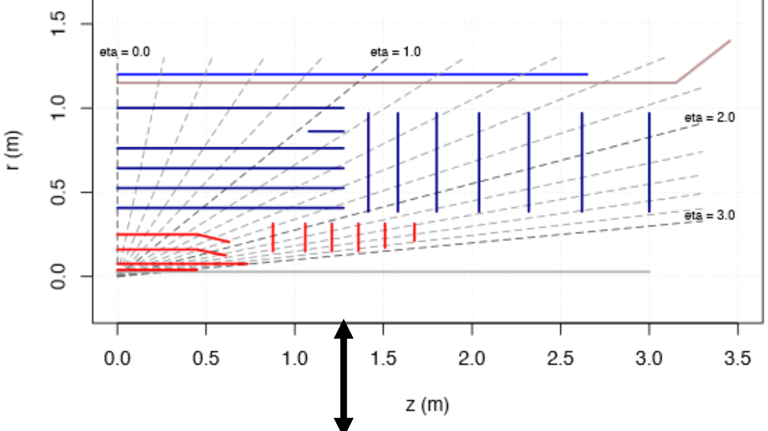
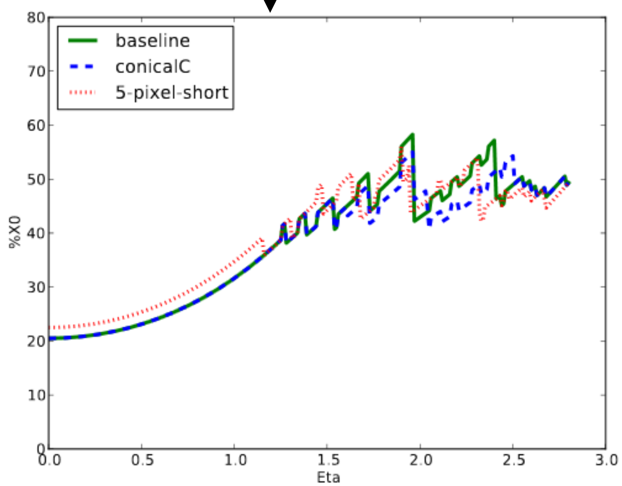
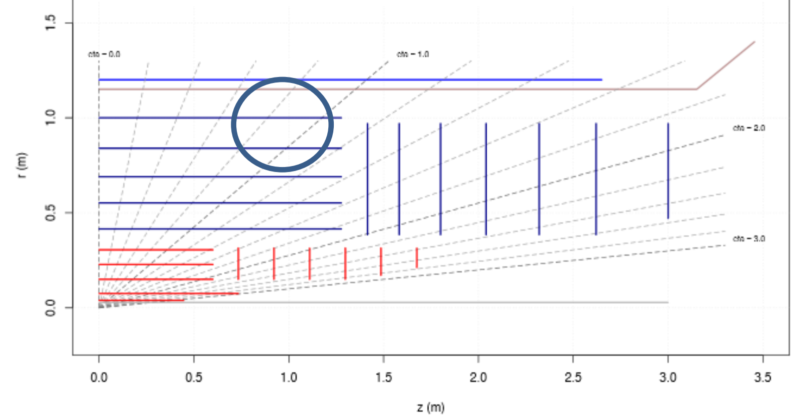
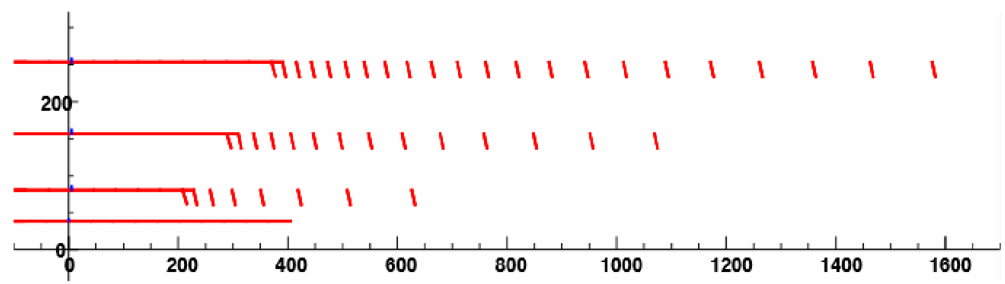




Fifth Pixel (optimized pattern rec)



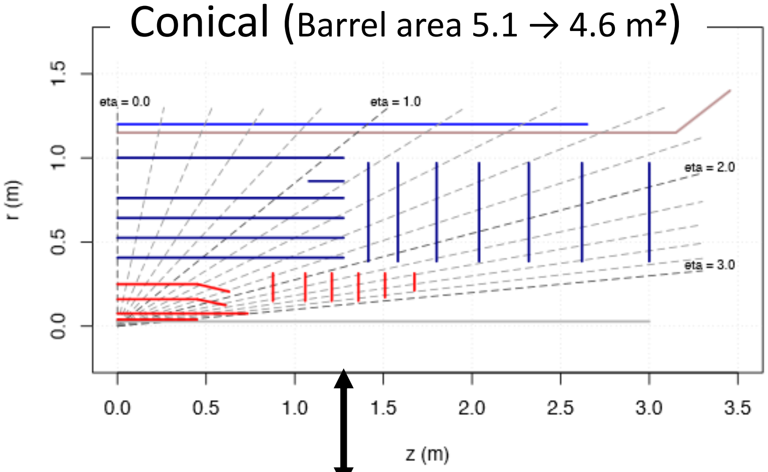
Alpine (reduced area ⊾ modules)



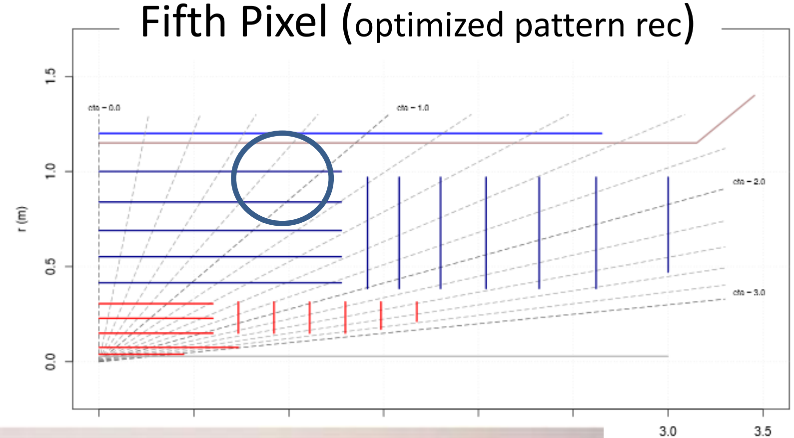
Work also ongoing with coverage out to a pseudorapidity of 4

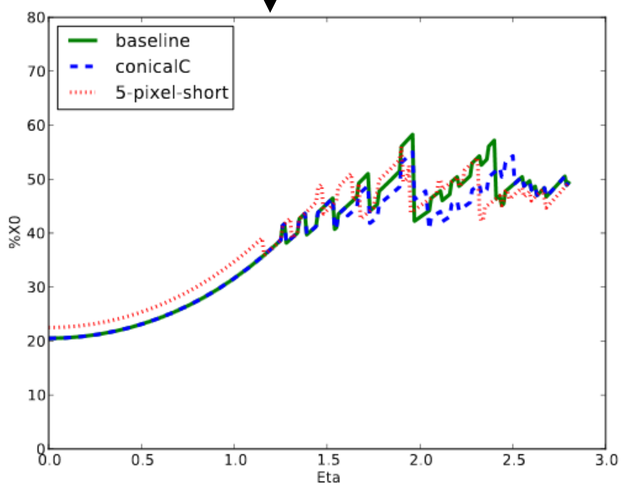
Alternate Layouts of Phase II Pixels

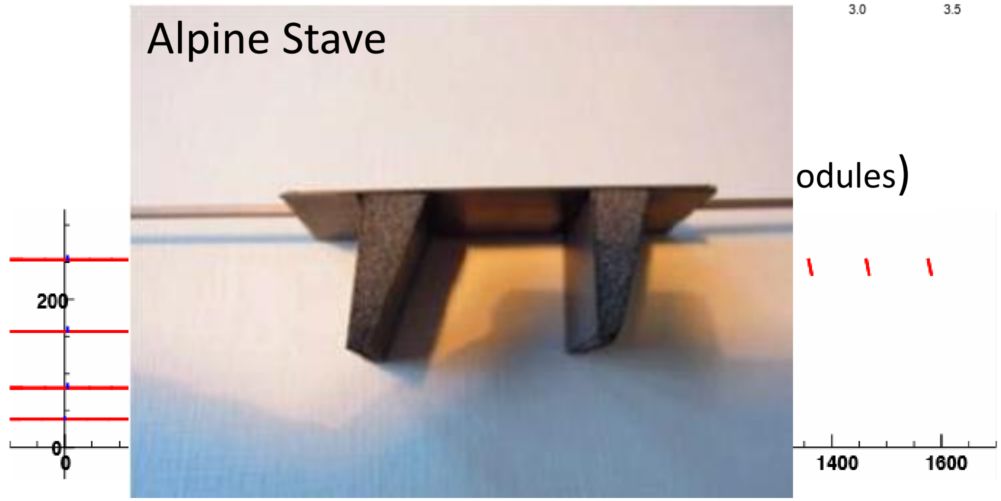
Conical (Barrel area 5.1 → 4.6 m²)



Fifth Pixel (optimized pattern rec)





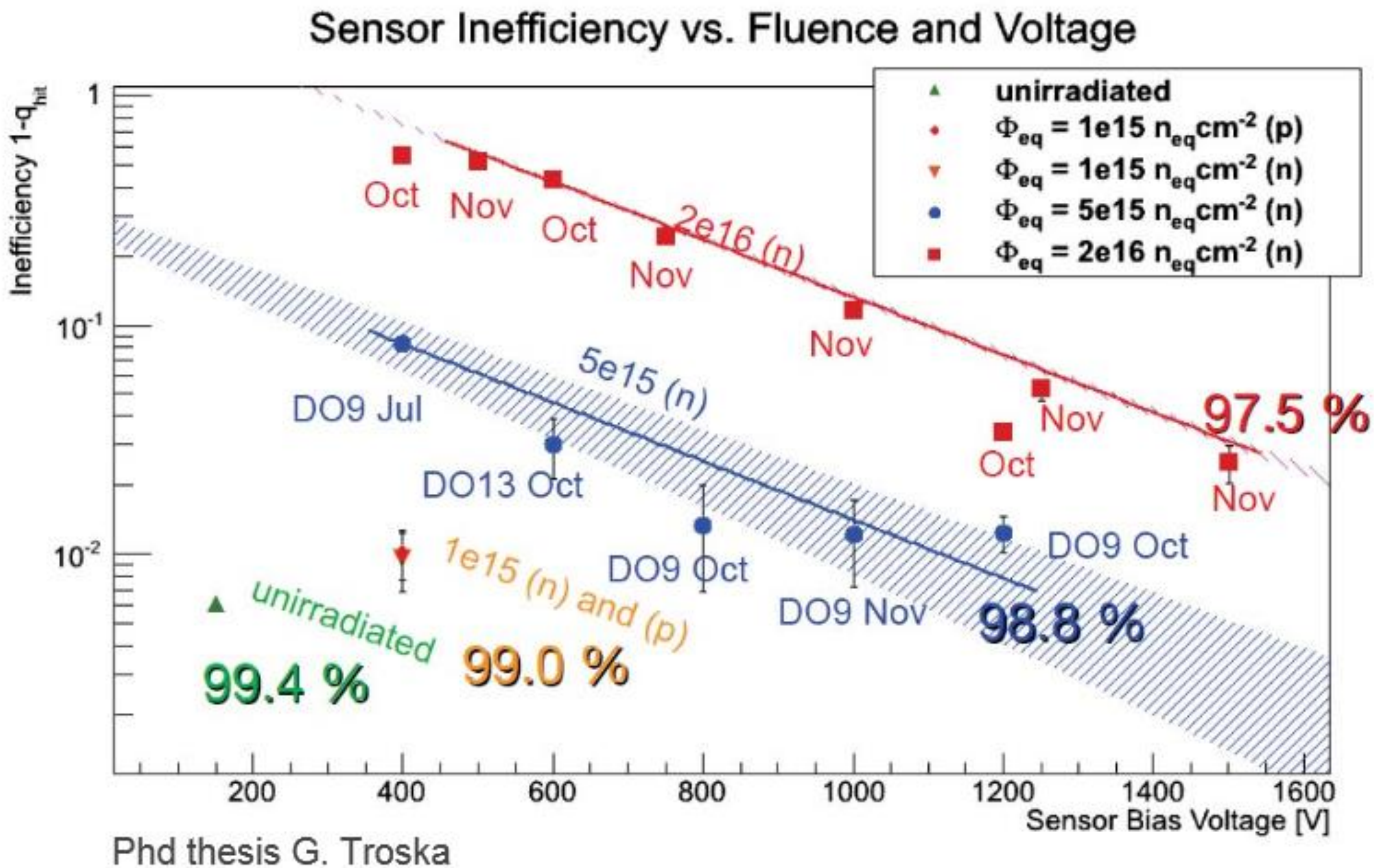


Work also ongoing with coverage out to a pseudorapidity of 4

ATLAS Phase II Pixels

- **Candidate Sensor Technologies**
  - **Choices largely driven by radiation tolerance requirements.**
    - *Standard Planar Sensors*
      - Thin (150μm) High Resistivity Silicon [n-in-n (*inner layers*) or n-in-p (outer)]
      - Demonstrated to HL-LHC fluxes, Lots of experience and known vendors, mass production understood.
    - *3D sensors*
      - *Used in the IBL, Low depletion voltage after irradiation, radiation tolerant*
    - *Diamond Sensors*
      - *Good radiation tolerance , Low capacitance (noise), no cooling, BUT expensive*
      - *Used in ATLAS beam monitoring, current and replacement in 2014*
    - *CMOS*
      - *Emergent technology (used on STAR and baseline for ALICE ITS), low power, varying degrees of sensor-hybrid integration (move away from standard implementation) to a more MAPS like approach, <u>Cheap</u>, Need to demonstrate radiation tolerance and readout speed.*
  - **Developments & Choices**
    - *Extensive R&D in progress, wait for appropriate time to make decisions*

ATLAS Phase II Pixels : Planar sensors



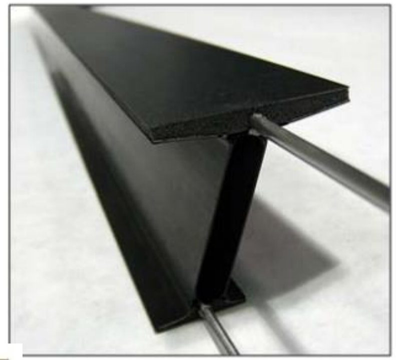
Hit inefficiency for n-in-n sensors (IBL) as a function of bias voltage for different fluences.

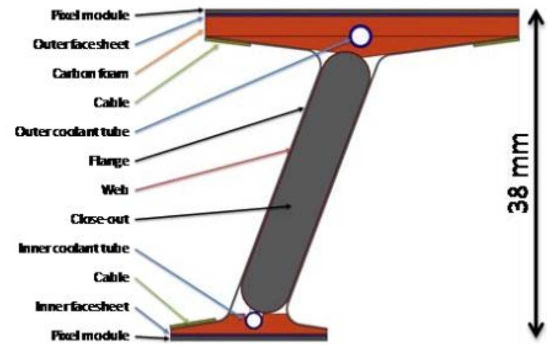
ATLAS Phase II Pixels

- **Electronics Technologies & Challenges**
  - **Specifications and Challenges.**
    - Radiation tolerance, Low power consumption per channel, Low noise
    - High density of channels -> interconnects (TSV, bump-bonding=cost)
    - Move towards deep(er) sub-micron technologies 65nm. CERN - RD53 now established and operational.
    - On detector power conversion (DC-DC (baseline) and Serial Power under consideration)
  - **FEI4**
    - *Currently being used for IBL, requirement well matched to outer layers of ITk pixel detector. To limit cooling requirements chip plus sensor power should not exceed 450mW/cm².*
    - *RD65 to develop the next generation of chips*
  - **Choices**
    - Note that we do not necessarily need the same technologies at large and small r
    - *Extensive R&D in progress, wait for appropriate time to make decisions, cost is a driver*

ATLAS Phase II Pixels: Modules and Structures

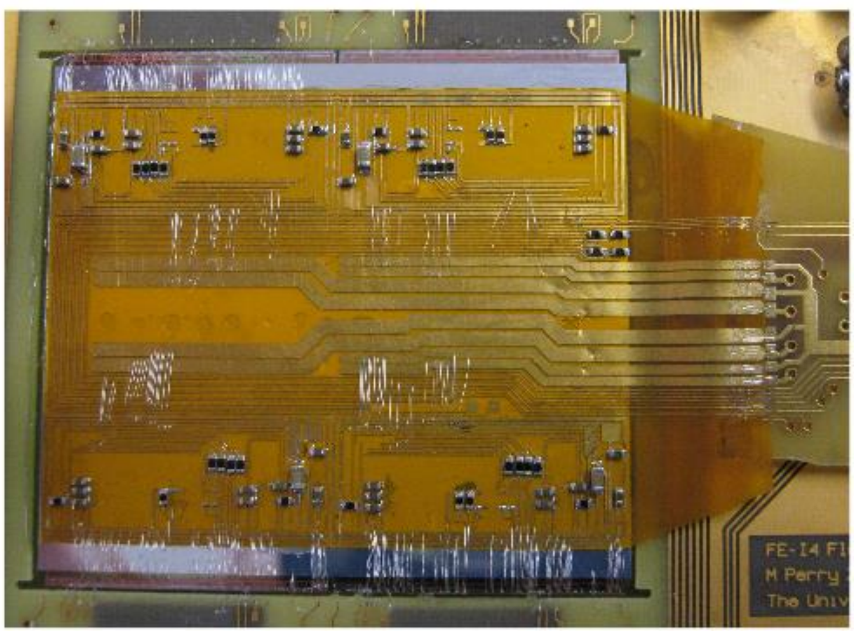
0.43%/layer

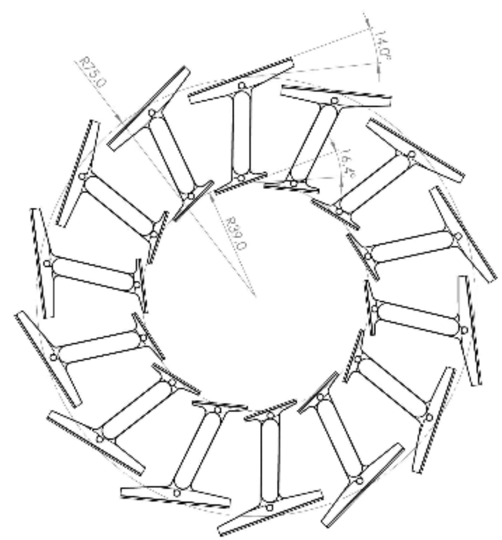




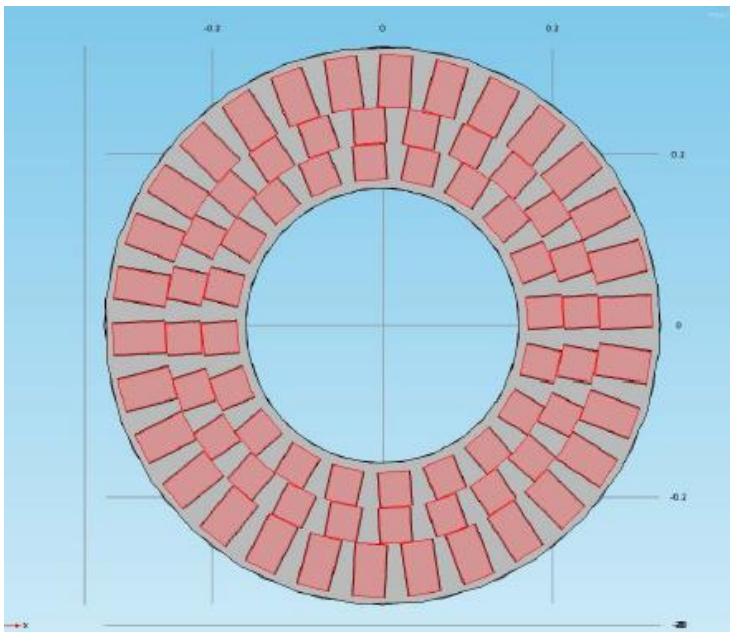
Multi-chip modules will be important

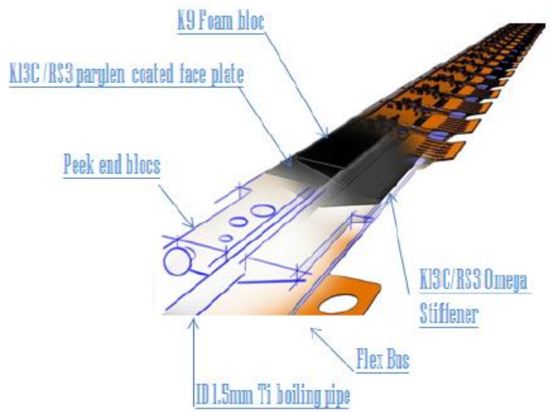
A prototype of a Quad Module
This has 4 FEI4 chips

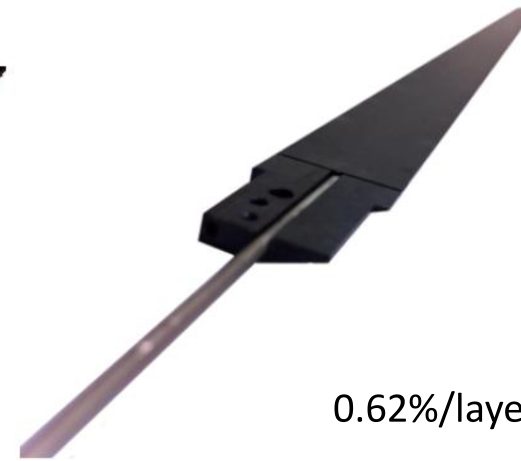




ATLAS Phase II Pixels:
Discs & Outer Layers (IBL like structures)





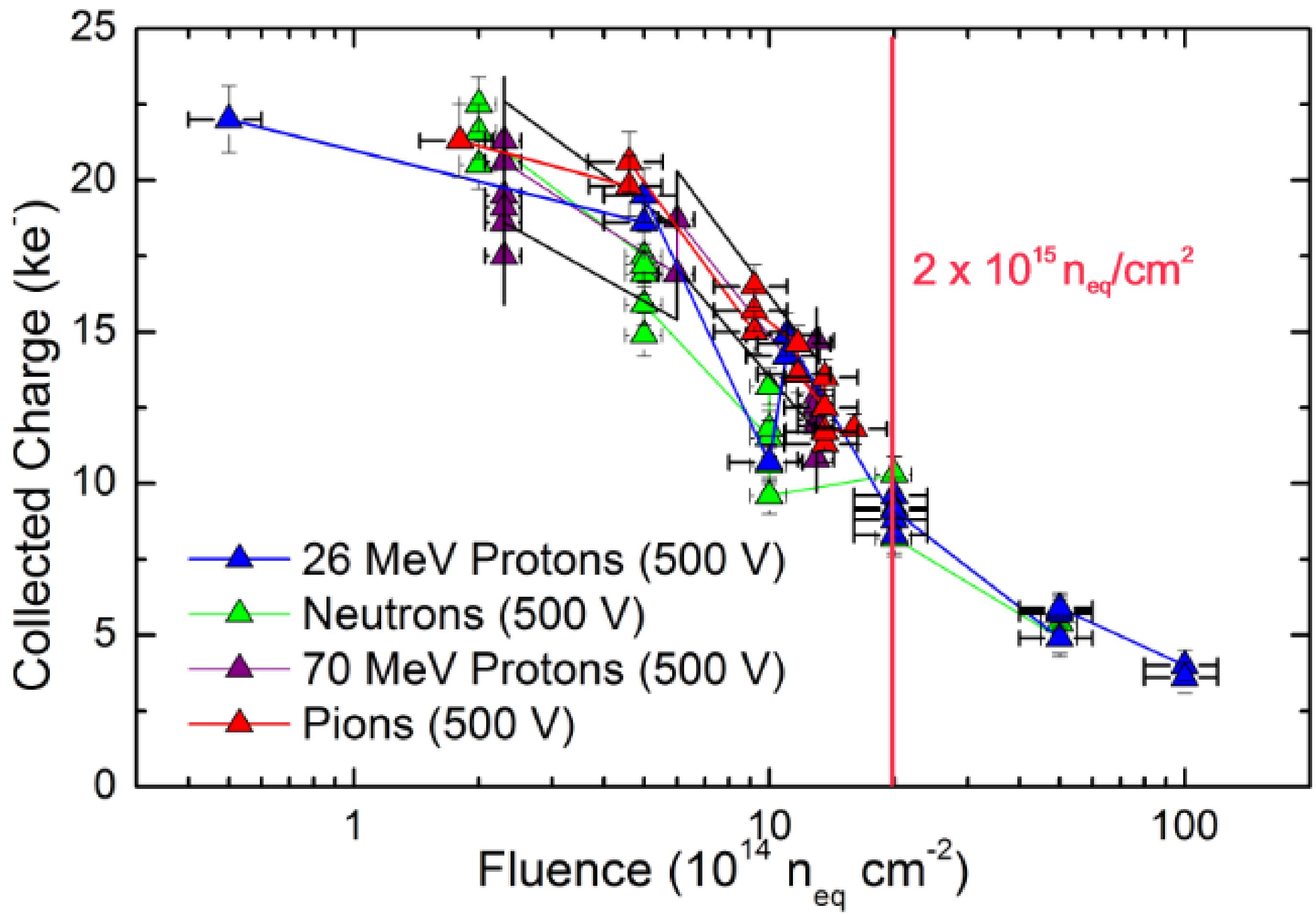


0.62%/layer

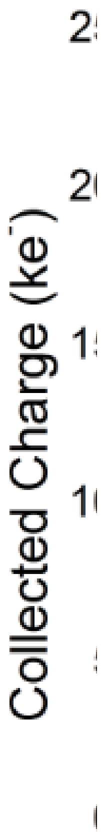
ATLAS Phase II Strips

- **Sensors**
  - Need to withstand 8.1×10^{14} neq $\mathbf{cm^{-2}}$ (no safety factor) and operate up to 500V. Including a safety factor takes us to 2×10^{15} neq $\mathbf{cm^{-2}}$
  - Current baseline is n-in-p FZ , 320 μm thick, 97.54 x 97.54mm^2
  - 1280 strips, AC coupled to FE chip, pitch 74.5μm
  - On stave/petal, sensors axial on one side, small angle stereo on the other
  - 2 lengths of strips: short = 23.82mm, long=47.75 (match track density)
  - The petal sensors use pointing strips (to beam-line) and so sensors are wedge shaped. Ideally sizes would minimize number of wafers (currently assuming 6")
- **FE electronics**
  - ABCN is an evolution of the binary chip used for the SCT (binary readout)
  - Prototypes based on 250nm CMOS area already in use
  - New 130nm currently under evaluation
  - See slide

ATLAS Phase II Strips

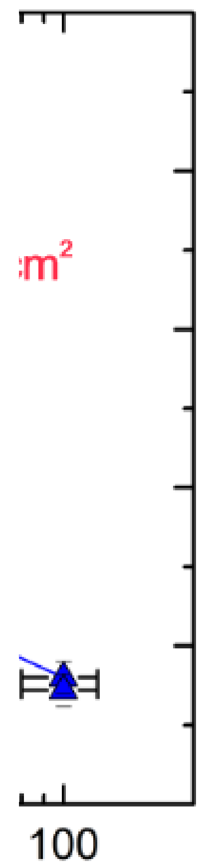


Collected signal charge at 500Vbias voltage for minimum ionising particles as a function of 1MeV neq/cm2 fluence for different particle species. S/N at end of life > 23 (17) for barrel (EndCap)
Need S/N >10 for efficient tracking.



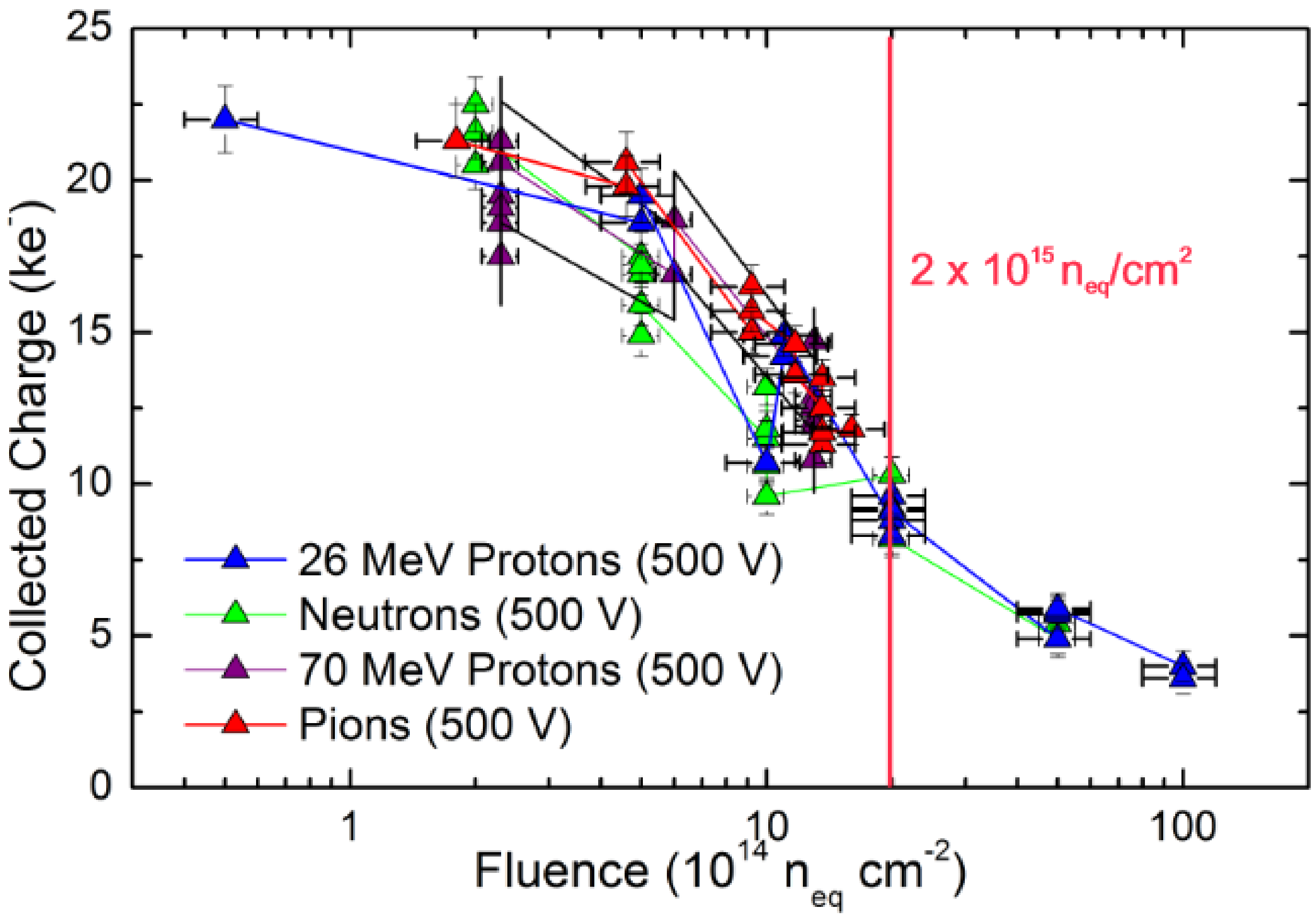
Upgrades	Area	Baseline sensor type
ALICE ITS	10.3 m^2	CMOS
ATLAS Pixel	8.2 m^2	*tbd*
ATLAS Strips	193 m^2	n-in-p
CMS Pixel	4.6 m^2	*tbd*
CMS Strips	218 m^2	n-in-p
LHCb VELO	0.15 m^2	*tbd*
LHCb UT	5 m^2	n-in-p

S



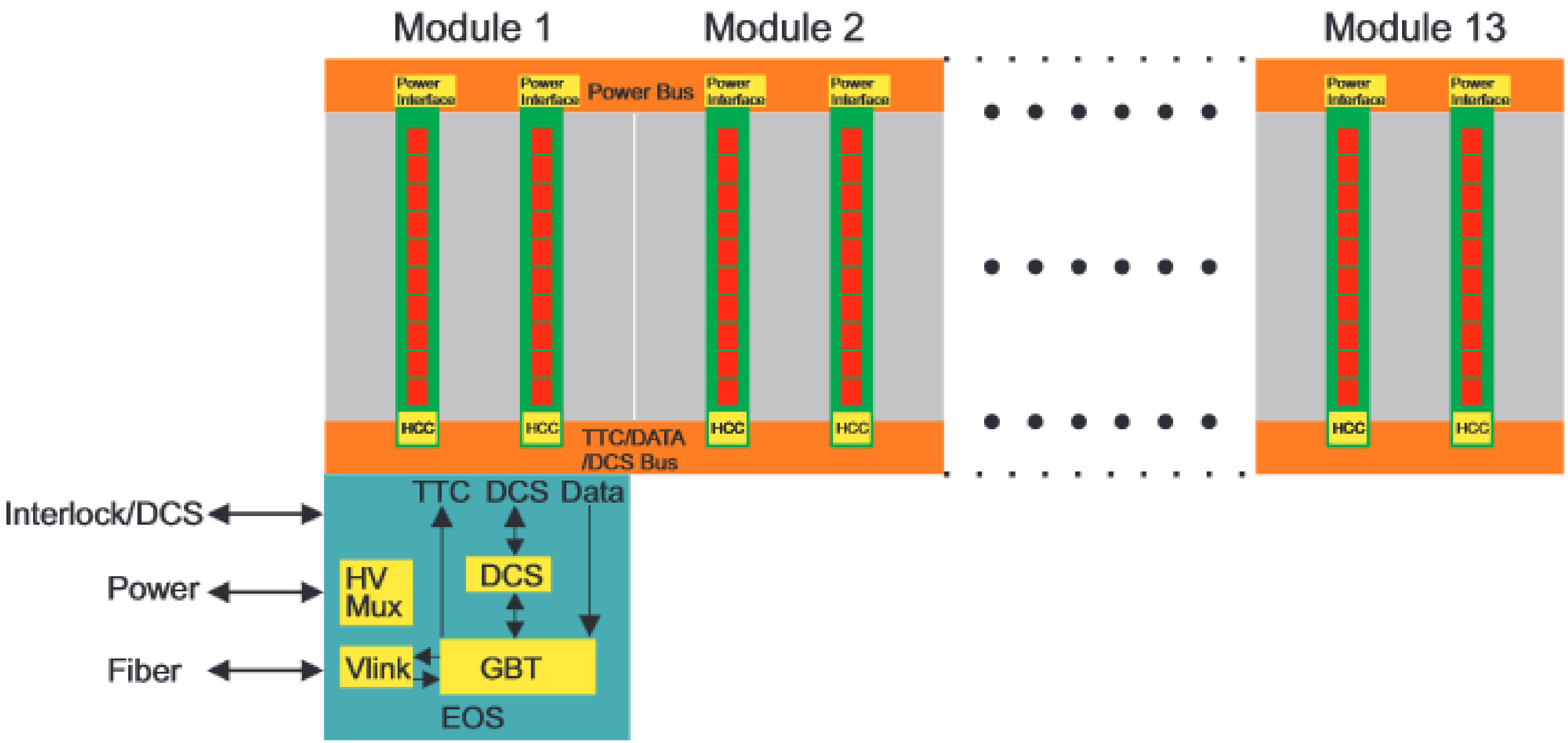
Collected signa *Taken from talk of P. Rieder in Aix Les Bain (Oct 2013)* function
of 1MeV neq/c (17) for barrel (EndCap)
Need S/N >10 for efficient tracking.

ATLAS Phase II Strips



Collected signal charge at 500Vbias voltage for minimum ionising particles as a function of 1MeV neq/cm2 fluence for different particle species. S/N at end of life > 23 (17) for barrel (EndCap) Need S/N >10 for efficient tracking.

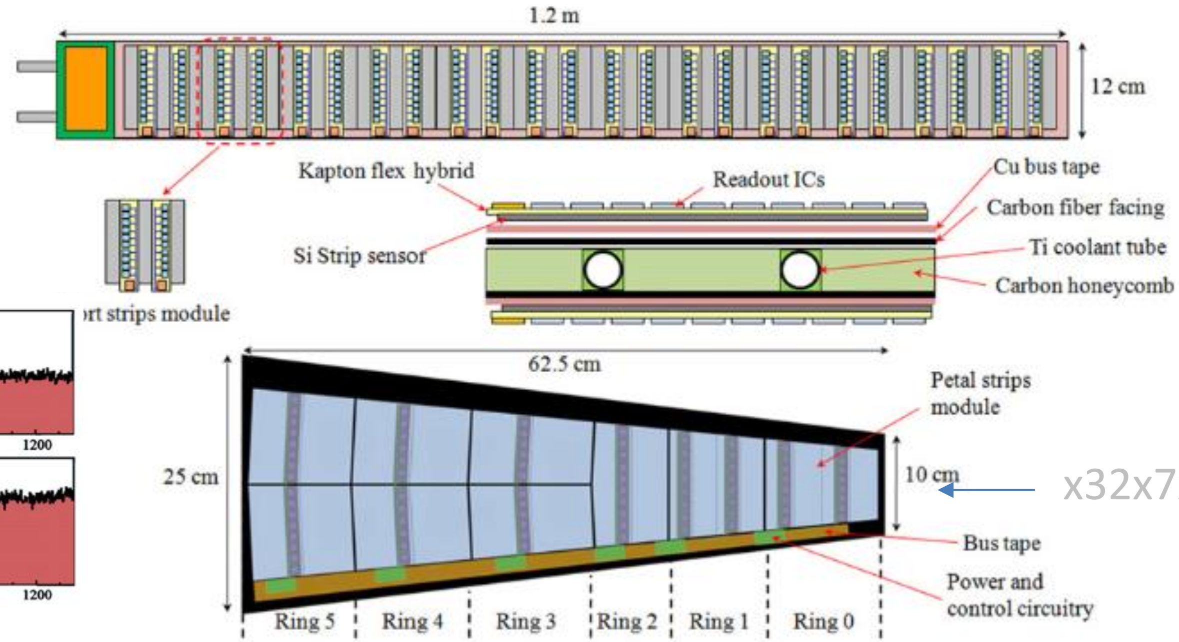
ATLAS Phase II Strips



VLink is a cross-experiment development of a family of on detector RAD hard optical transmitters and receivers. Unlike ID where we have individual power (HV & LV) for Each module in Itk we will have HV multiplexing and for LV (DC-DC or SP)

ATLAS Phase II Strips : Staves/Petals

x 472



x32x7x2

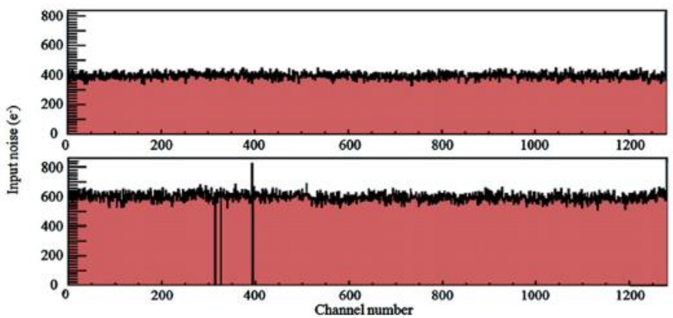
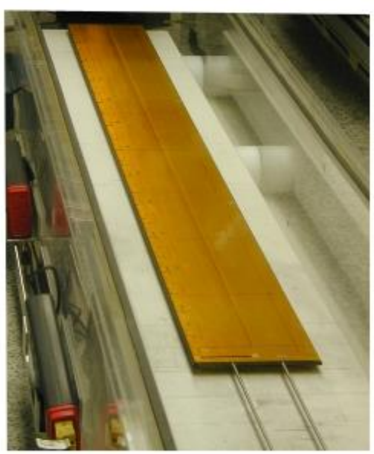
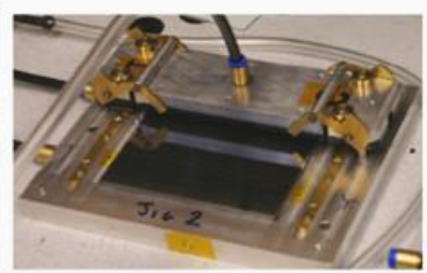
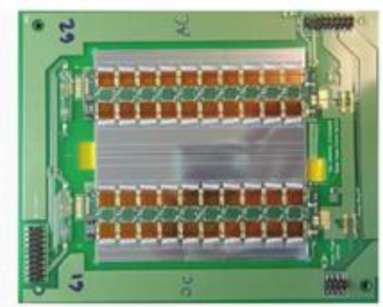


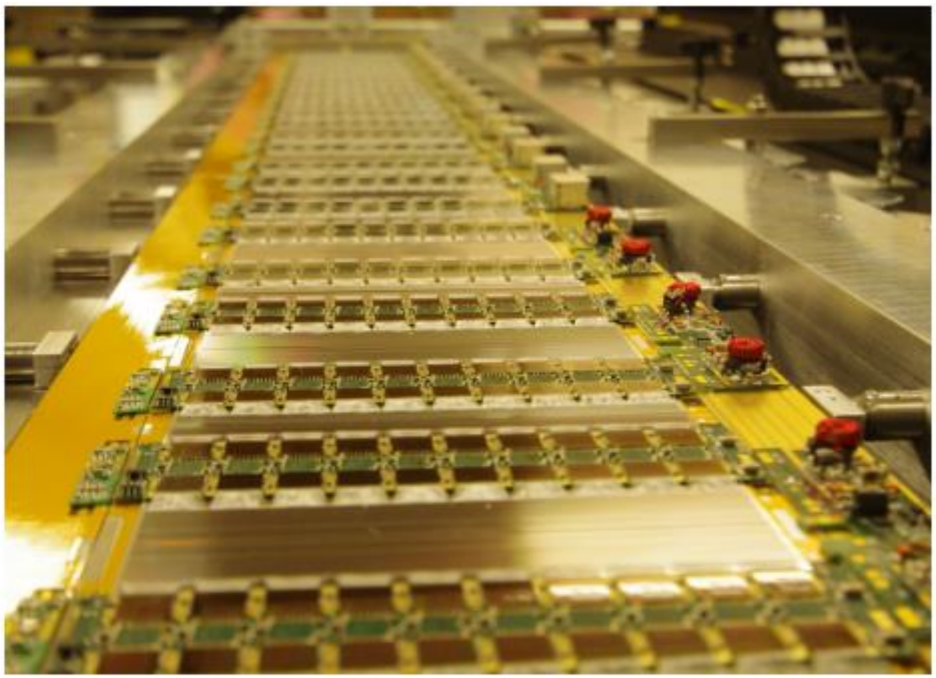
Fig. 1. Sketch of a barrel short strip stave and its cross-section (top); sketch of an end-cap petal (bottom).

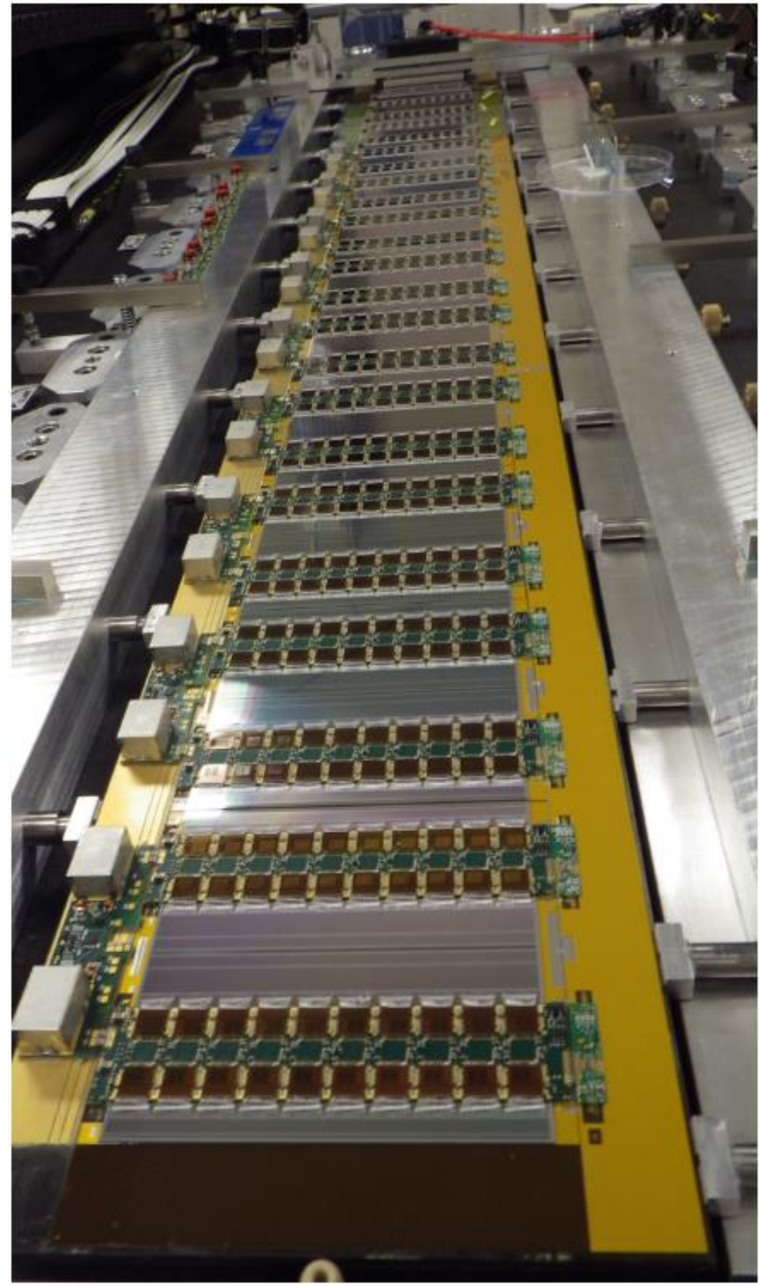






Fully populated DC-DC powered 250nm stave in December 2013





ATLAS Phase II Strips : End-Caps

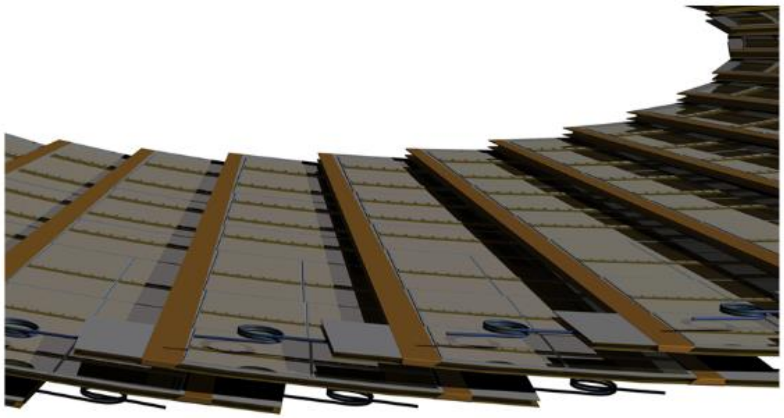
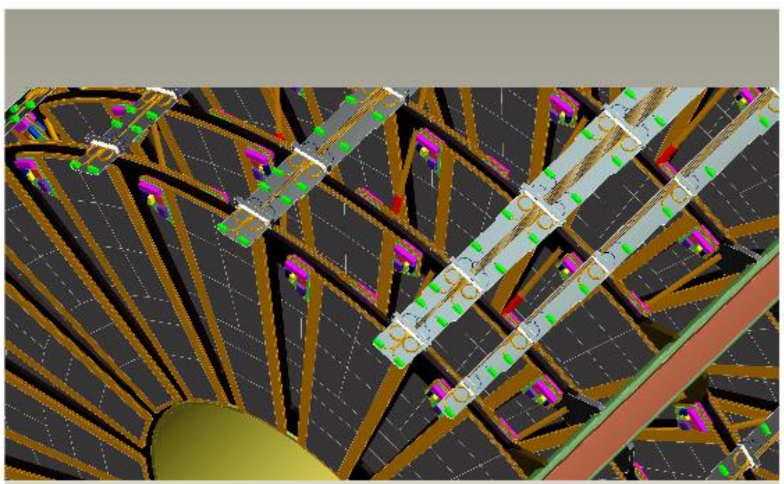
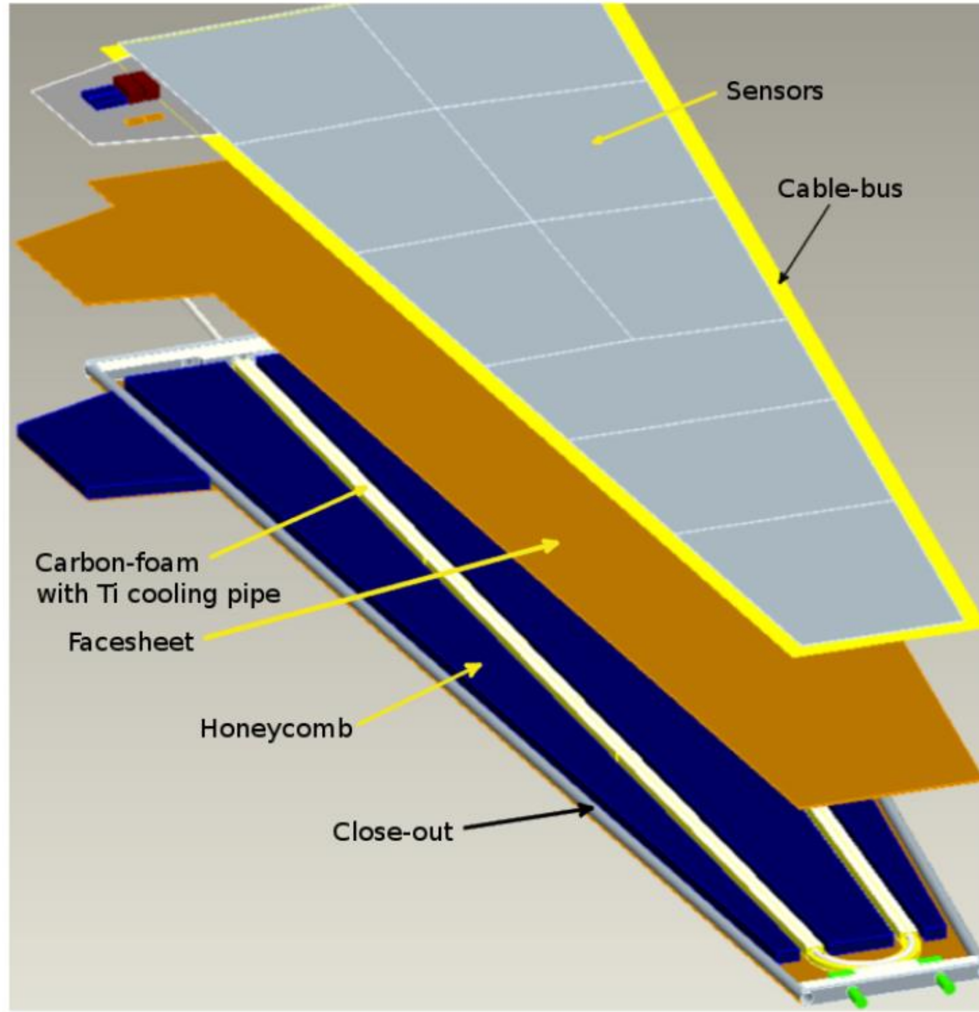
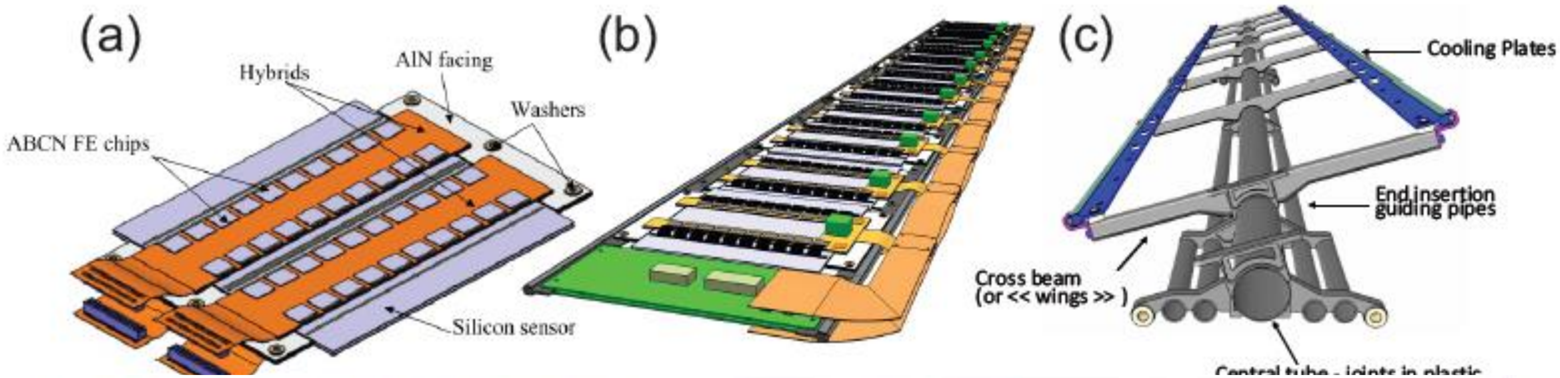


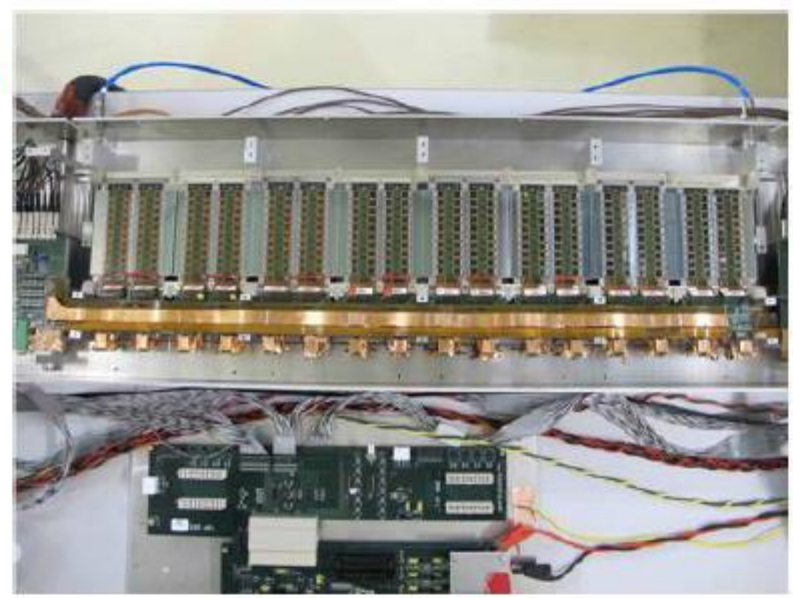
Figure 6.37: Turbofan arrangement of petals.





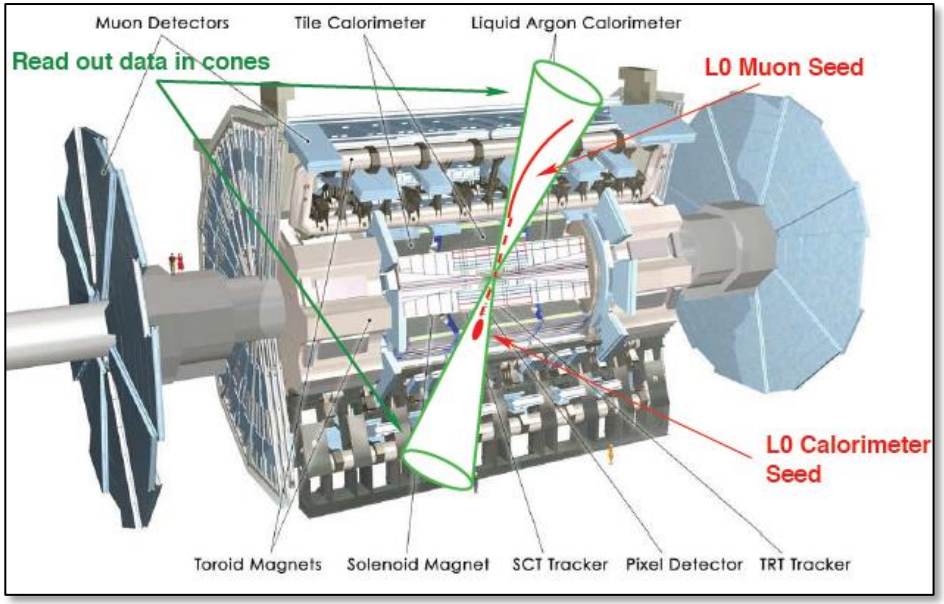
ATLAS Phase II Strips : Barrel Back-Up





ATLAS Phase II : Track Trigger

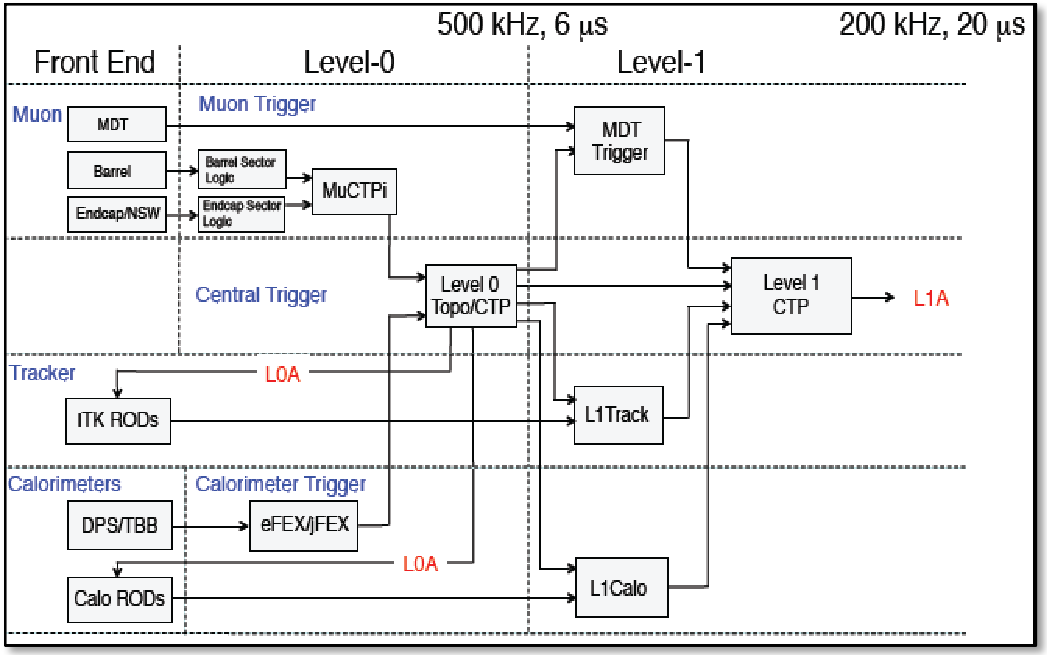
- **L1 Track Trigger**
  - ✓ Aim to keep p_T thresholds and trigger rates low at L1
  - ✓ Part of High Level Trigger reconstruction moved to L1
- **Triggering sequence**
  - **Based on Regions of Interest (RoI)**
  - ✓ L0 trigger (Calorimeter/Muons) reduces rate within 6 µs to ≳ 500 kHz and defines RoIs
  - ✓ L1 track trigger extracts tracking info inside RoIs from detector FEs



Alternate self seeded (a la CMS) approach also being studied.

ATLAS Phase II : Changes to trigger architecture

- New design in time for Phase II
  - 2-level system at Phase II
  - Phase-I L1 becomes Phase-II L0, new L1 includes tracking
  - Make use of improvements made in Phase 1 (NSW, L1Calo) in L0
  - Introduce precision muon and inner tracking information in L1
    - Better muon pT resolution
    - Track matching for electrons,…
  - Requires changes to detector FE electronics feeding trigger system
  - Drives ITk bandwidth requirements.
    - ~3,200 optical links running at 5.6Gb/s



Level-0
Rate ~ 500 kHz, Lat. ~6 μs
Muon + Calo
Level-1
Rate ~200 kHz, Lat. ~20 μs
Muon + Calo + Tracks

ATLAS Phase II : Other Challenges

- Low mass on detector cooling, thermal management, local and global supports and mechanics
- Alignment (with tracks and possibly lasers)
- Integration, decommissioning, installation commissioning and possibilities for access maintenance and repair
- Power supplies, cables, RAD hard fibres
- DAQ, ATCA
- DCS, now becomes part of the detector-data-stream
- Long term reliability issues.
- Logistics ….

ATLAS Phase II : Conclusions

- The HL-LHC physics program will make very stringent demands of the ATLAS tracker beyond phase II
- It will be necessary to replace the existing tracker to meet all of these requirements.
- A baseline option (ITk) has been developed that builds on the performance and experience gained from the existing detector (ID) and our understanding of the harsh tracking environment at HL-LHC.
- We are now moving towards a TDR (2016) and construction in 2017 and we are continuing to develop
- We are continuing to optimize for performance (and cost) and will, where ever possible, exploit emergent technologies.

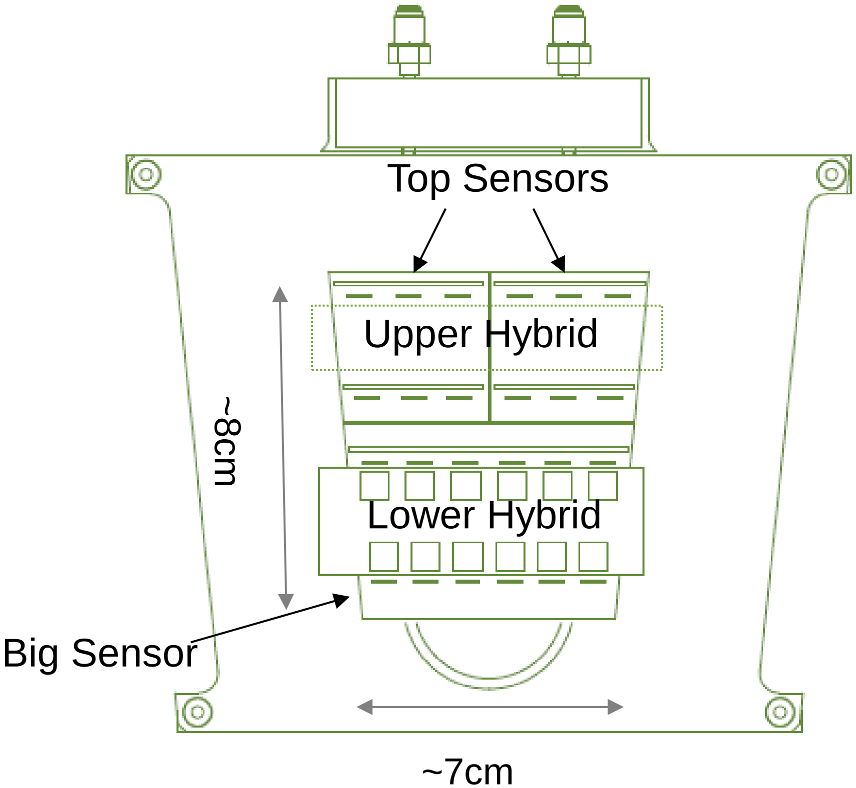
The End

Bonus Material

ATLAS Phase II : Strips Material

Barrel		End-Cap	
Element	% Radiation Length	Element	% Radiation Length
Stave Core	0.55	Petal Core	0.47
Bus Cable	0.30	Bus cables	0.03
Short-Strip Modules	1.07	Modules	1.04
Module Adhesive	0.06	module adhesive	0.06
Total	1.98	Total	1.60

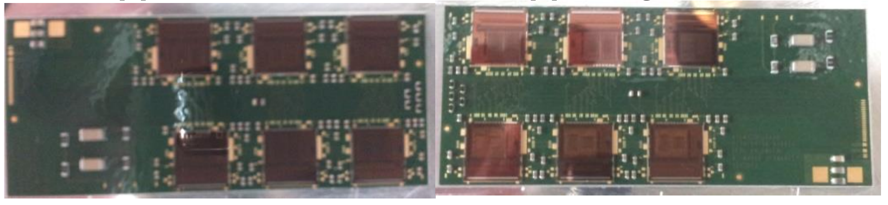
Petalet layout



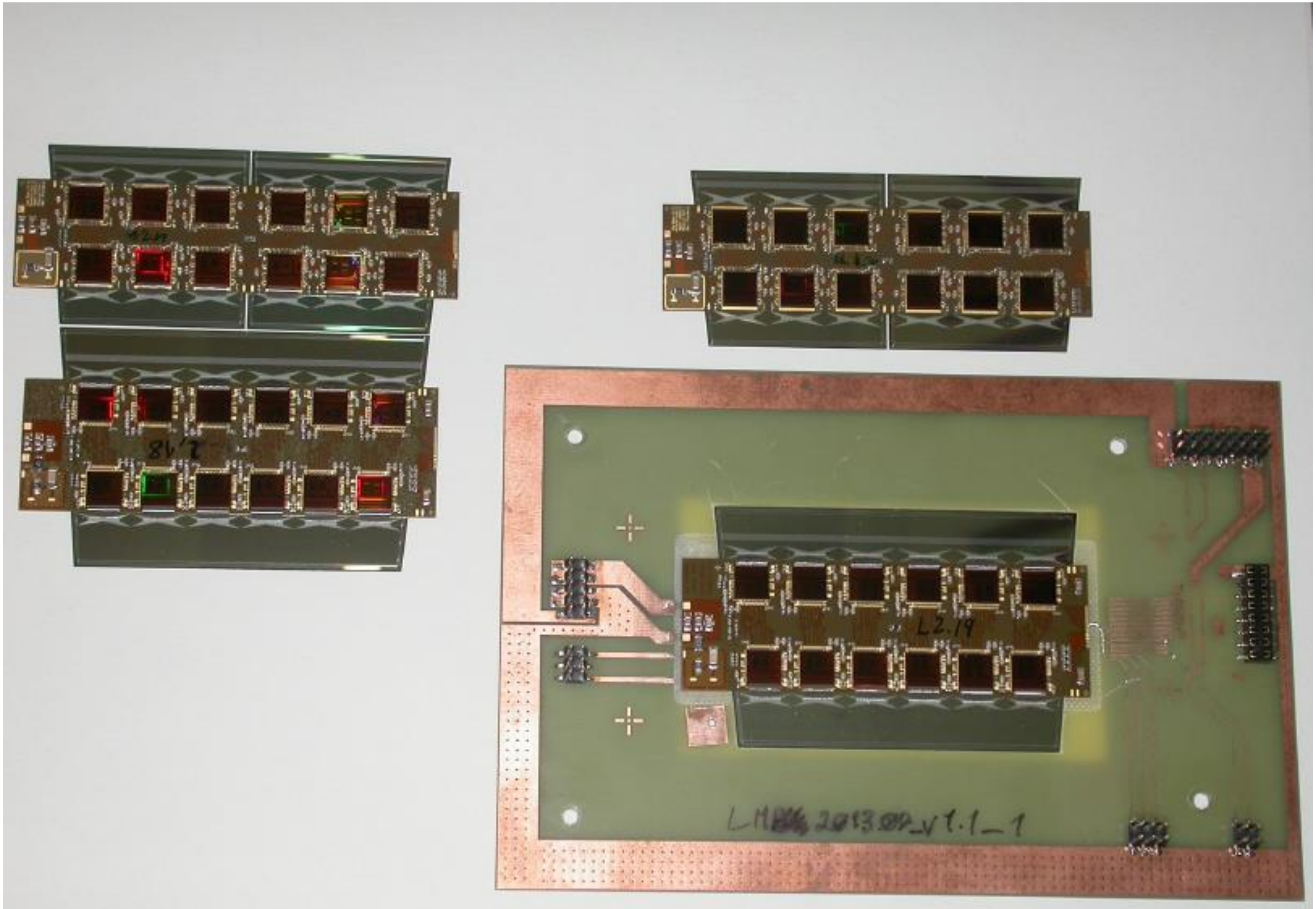
Lamb&Flag upper hybrids

- 1 lower and 2 upper hybrids designed and produced
- Population with passive components
- ASIC assembly with flip-chip bonder
- Tested with low noise of ~380ENC

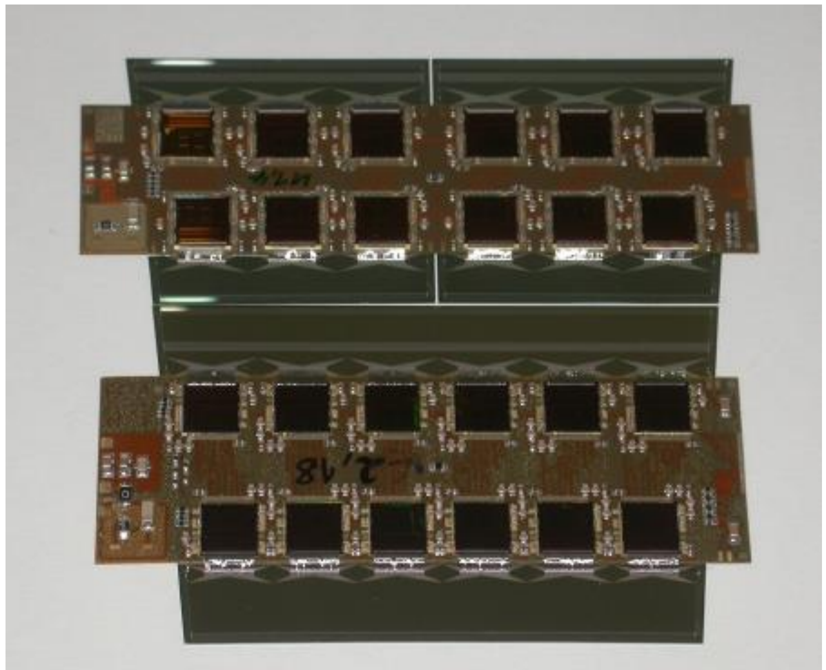
upper left upper right



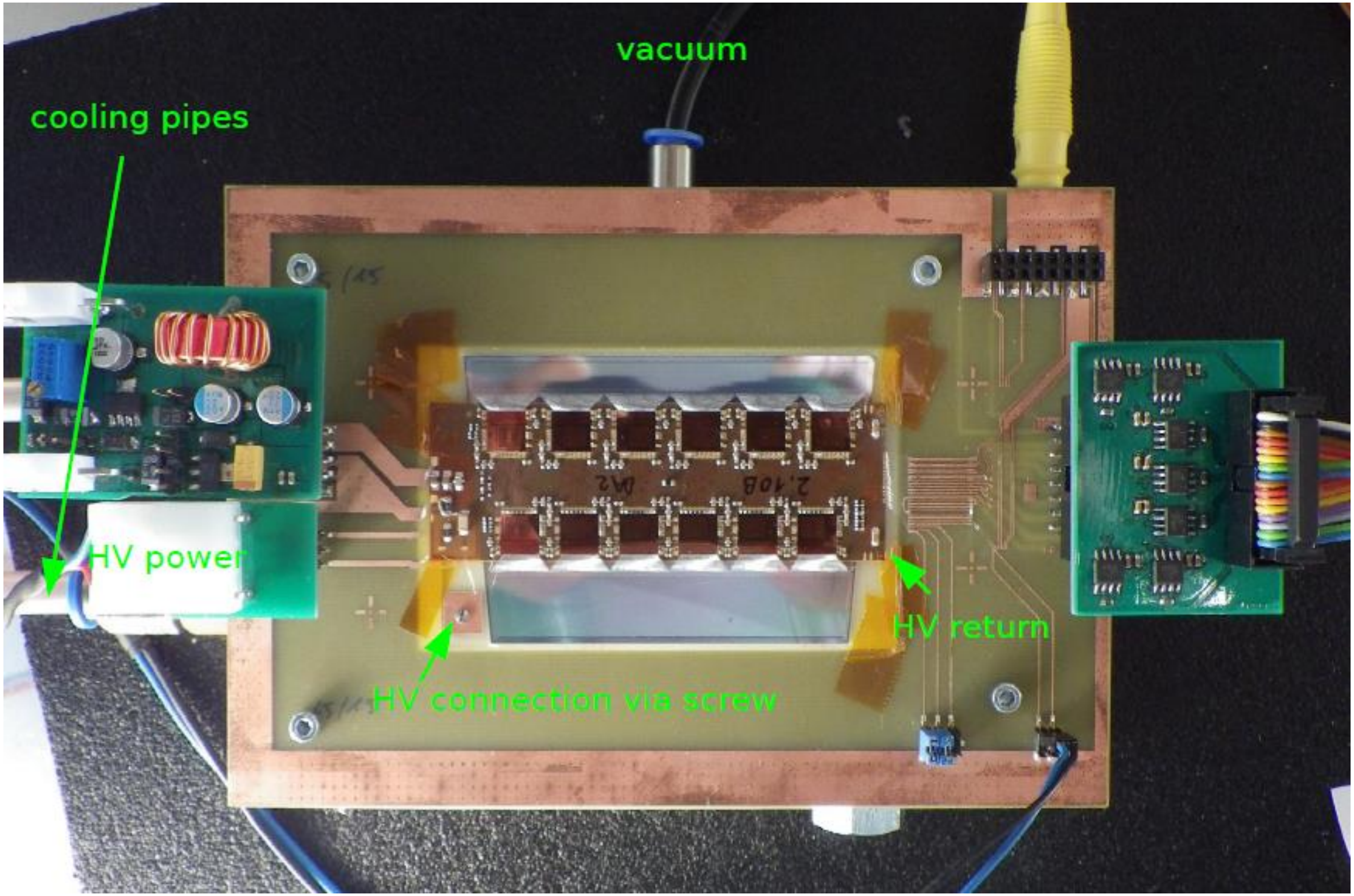
Bear modules for petalet in embedded (straight bonding due to double metal layer on sensor) configuration
lower modules have noise of ~660 ENC upper module to be tested, upper and lower hybrids have noise of ~380ENC



Bear modules for petalet in embedded (straight bonding due to double metal layer on sensor) configuration
lower modules have noise of ~660 ENC upper module to be tested, upper and lower hybrids have noise of ~380ENC

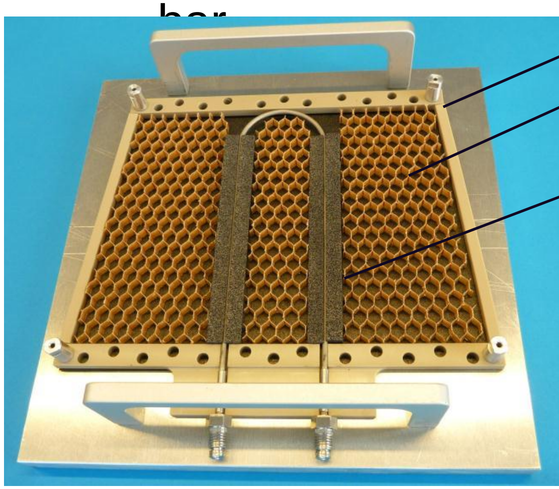


Bear modules for petalet in standard (wire-bonds with different angles) configuration have lower noise of about 560ENC.



Core and bus tape

- Core:
  - Designed and production ongoing
  - Results:
    - Planarity: still low (~250 um flatness).
    - Ti-pipes resistance: more than 200 bar



- Bustape:
  - First designed and produced.