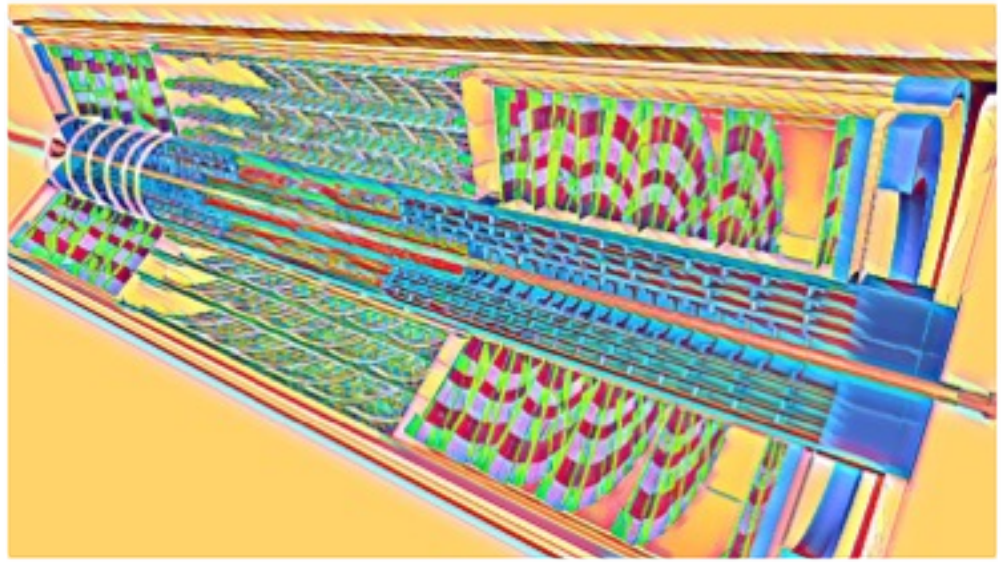


ATLAS Inner Tracker Overview

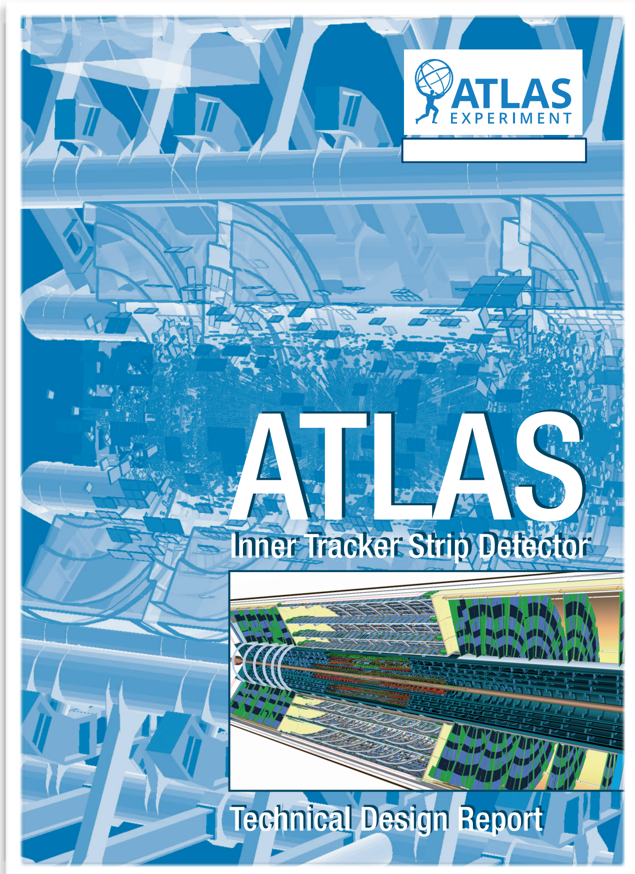
Ingrid-Maria Gregor, DESY

10th Terascale Detector Workshop
10-13 April, 2017
DESY Hamburg

ATLAS EXPERIMENT

DESY

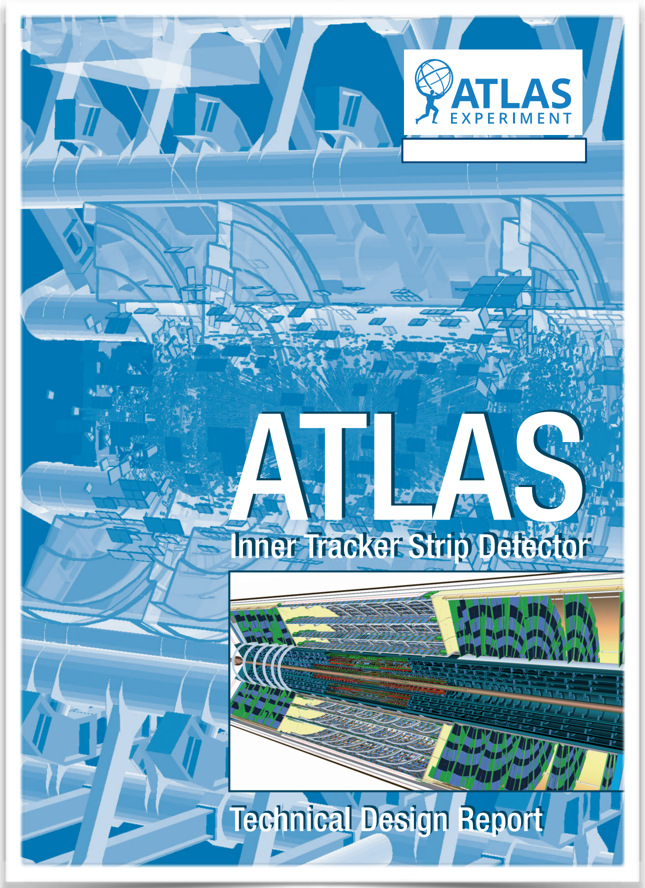
Outline



Public in May

ECFA High Luminosity LHC Experiments Workshop 2016
https://indico.cern.ch/event/524795/

Outline



Public in May

- Introduction
- ITk Layout
- The Strip Detector
  - Concept
  - Modules
  - Some R&D results
  - Towards a full system
- Conclusions

ECFA High Luminosity LHC Experiments Workshop 2016
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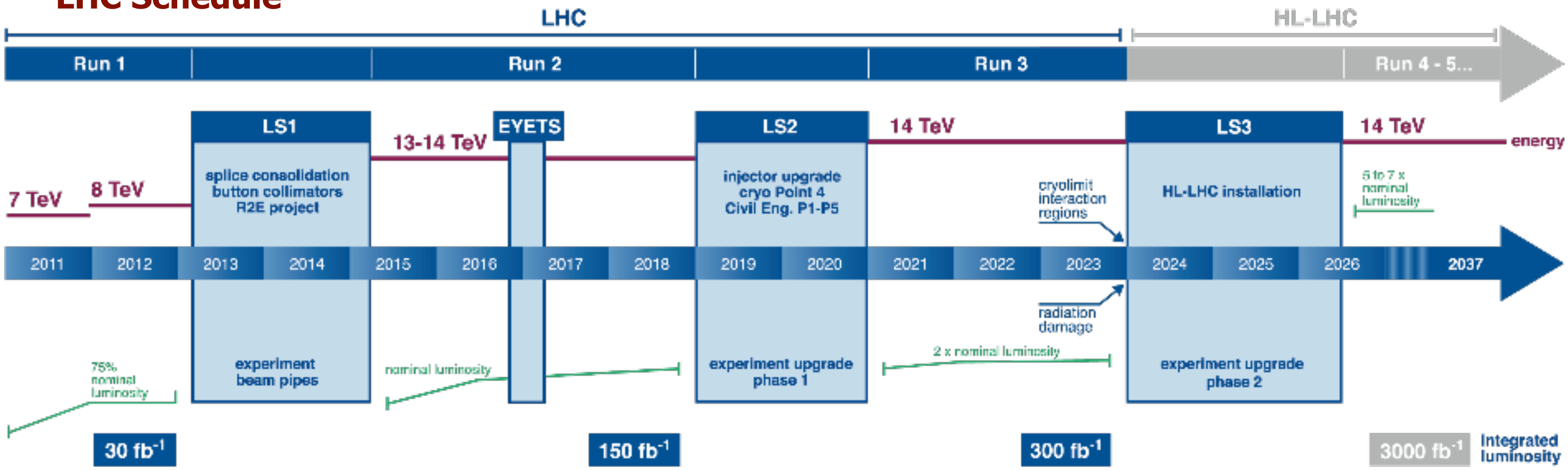
Introduction

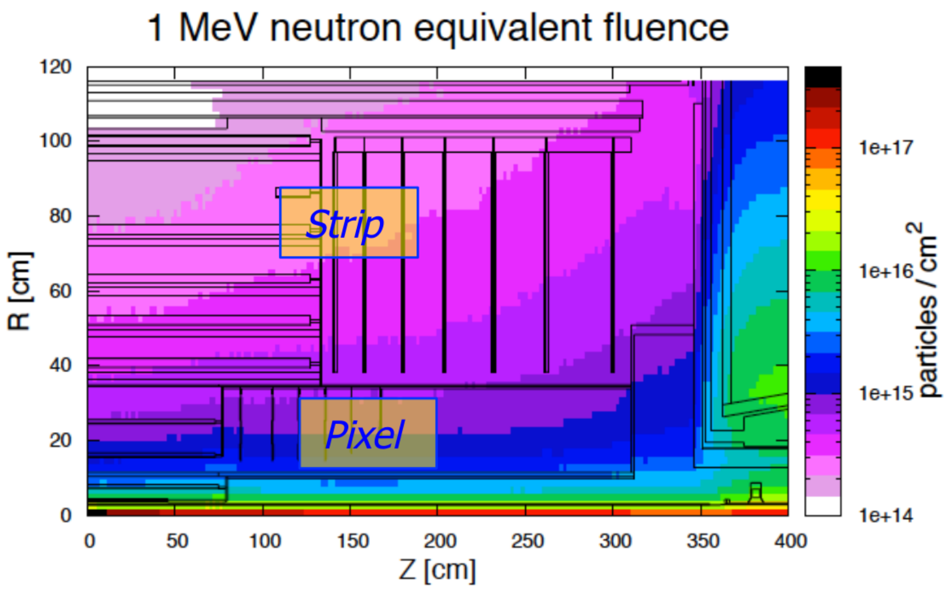
LHC Schedule



Frédérick Bordry, Chamonix Workshop 2017
https://indico.cern.ch/event/580313/

- Primary motivation of all upgrades is to maximise performance
  - Precision measurements of Higgs coupling and other SM processes
  - Make first measurement of Higgs self-coupling (very challenging)
  - Search/investigate for signals of phenomena beyond the Standard Model
- Design choices for detector upgrades driven by physics considerations.

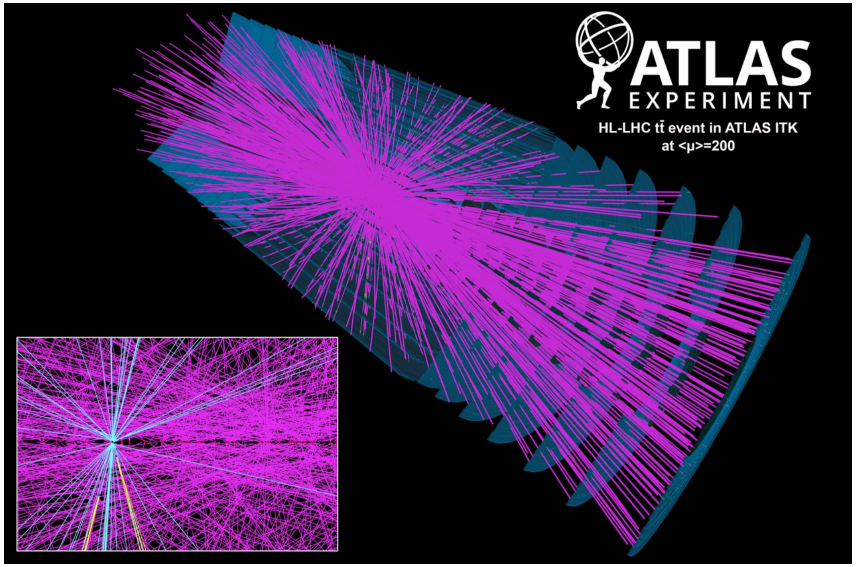
Basic Requirements For The ITk



- Radiation hardness
  - Ultimate integrated luminosity considered ~ 3000 fb^{-1} (original > 400 fb^{-1})
  - Radiation hard sensor material required
  - New readout electronics required
- Granularity
  - Resolve ~200 collisions per bunch crossing
  - Maintain detector occupancy below % level
  - Requires much higher granularity

- Improve tracking performance
  - Reduce material in the tracking volume
  - Reduce rates of nuclear interaction, photon conversions, Bremsstrahlung…
  - Reduce average pitch

- Dream tracking detector:
  - transparent detector with very small pitches
  - super fast
  - radiation hard

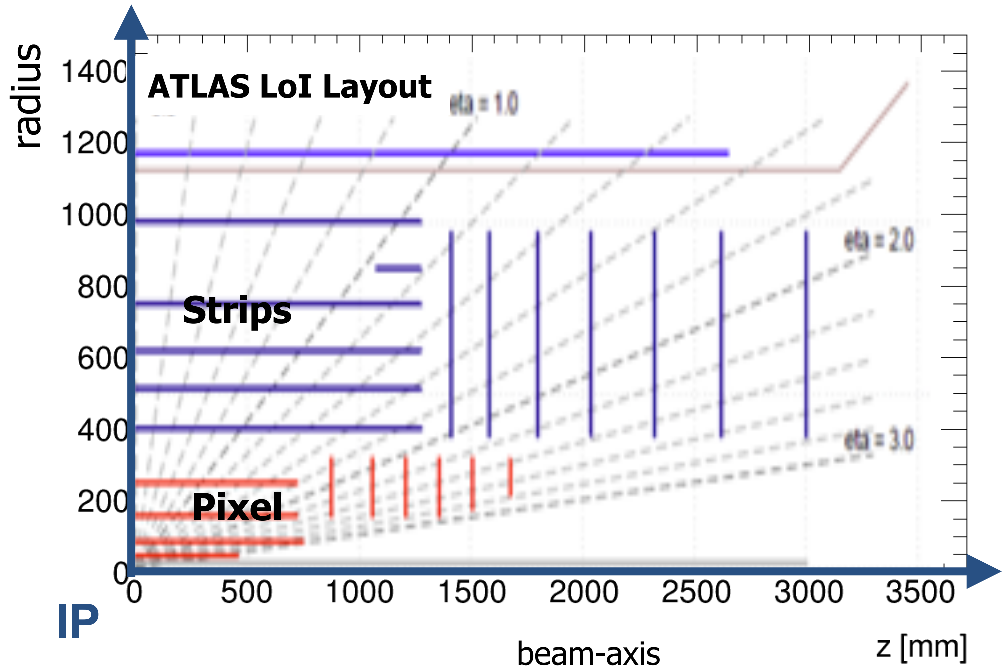


ITk Layout

Key Goals for Tracking @ HL-LHC

- **Sustain** | **improve** excellent performance of ATLAS Run2 also in HL-LHC environment
    - **adapting for the physics goal of HL-LHC**
        - track reconstruction for dense environments, boosted objects (jet core, boosted τ, Z')
        - cope with the higher pile-up environment
        - expanding the η coverage
  - **support excellent physics object reconstruction**
    - highly efficient track reconstruction
    - extremely low fake rates
    - precise impact parameter resolution for vertex reconstruction and b-tagging
    - maintaining acceptable CPU consumption

Recent Changes in Layout



Current ATLAS Inner Detector completely replaced with all-silicon tracker (ITk)

	Silicon Area	Channels [10^6]
Pixel	~13 m^2	580
Strip	160 m^2	50

Changes in the Strip Detector layout

- Reduction to five layers (increase of pixel layers)
- Increase of Strip barrel length from 13 to 14 modules, reduction of Strip end-cap system by on disk (from 7 to 6)
  - momentum resolution sustained by re-arranging the disk positions
- Removal of Stubs
  - longer barrel softens the effect of barrel/end-cap gap

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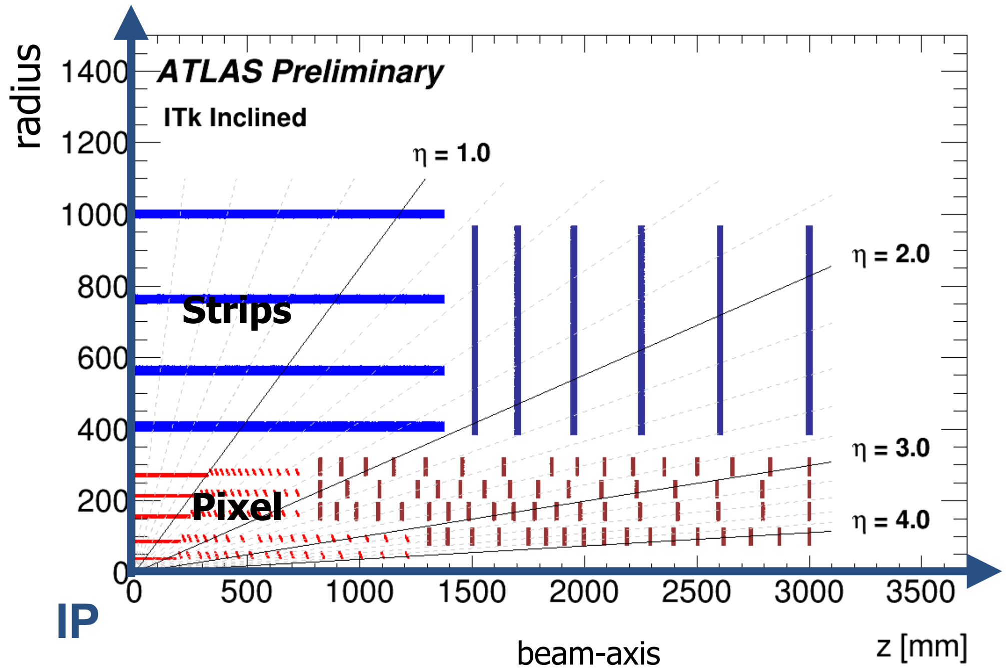

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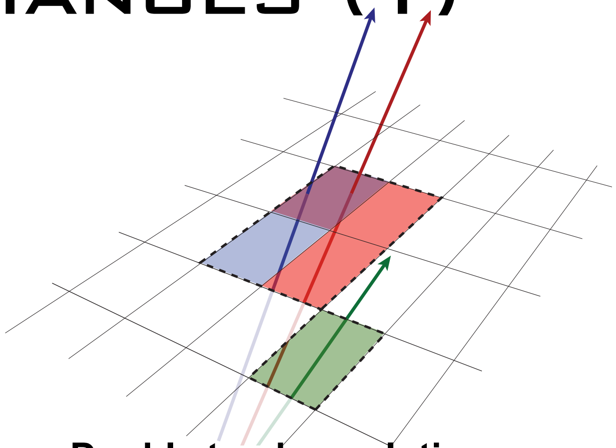
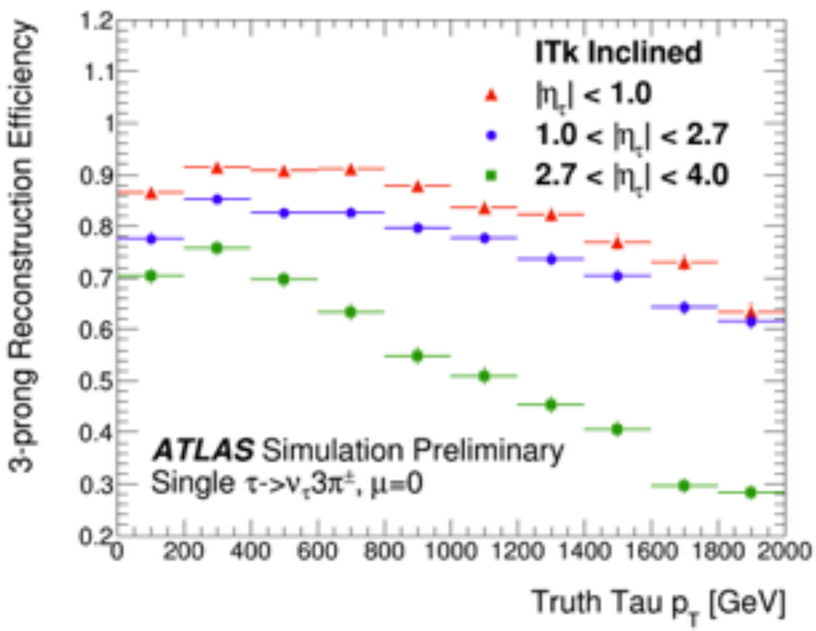
Most Significant Pixel Changes (1)

- Introduced **five layer pixel system** improves performance in key aspects:
  - shows better behaviour in efficiency/fake balance at pile-up of 200
  - significant cluster merging in first four layers in dense environment -> five pixel layer improves ability to resolve nearby tracks significantly
  - possibly improved CPU performance



Double track resolution

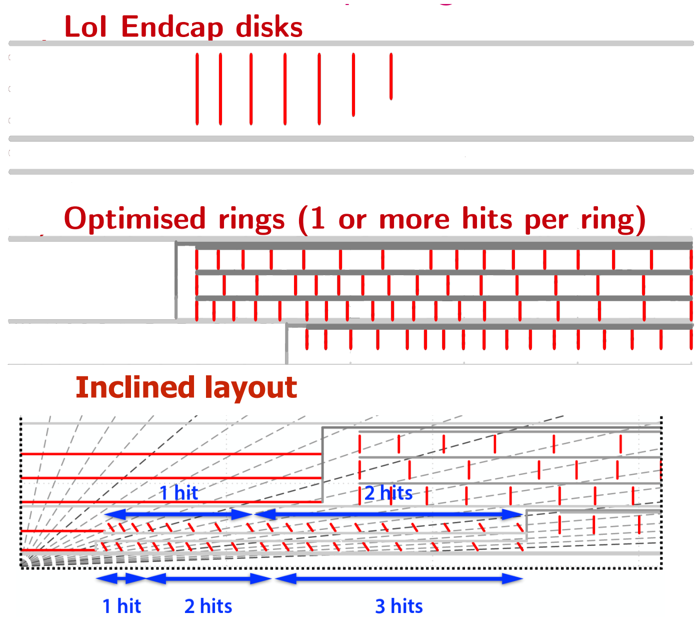
- limited by cluster merging
- use neural networks to identify merged clusters
- needs small segmentation and analog info



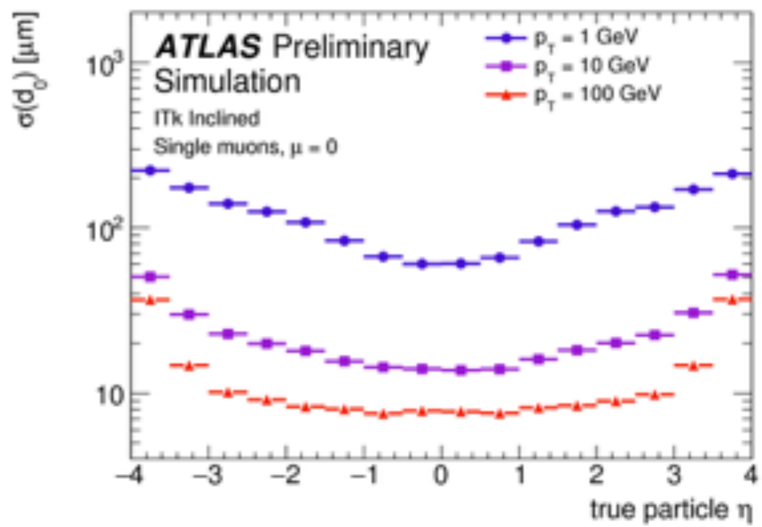
- Dense environment tracking performance studies with 3-prong tau decay
  - Efficiency to reconstruct all 3 tracks from decay

Most Significant Pixel Changes (2)

- **Rings** instead of disks in the pixel end-cap region
  - Services are routed on the support structure
  - Unusual pattern to provide constant number of hits versus η
  - Reduction of the required silicon area compared to LoI-VF
  - Ring positions in *z* can also be easily adapted to the coverage needs of different barrel layouts.

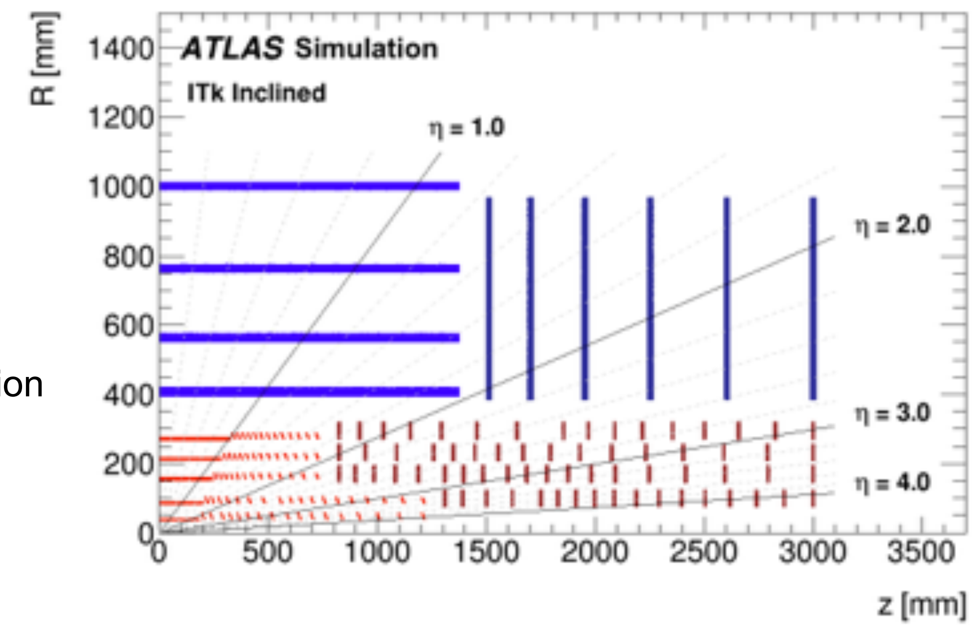


- **Inclined layout**
  - Minimisation of material - better impact parameter resolution
  - Impact parameter resolution comparable or better than Run 2
  - Multiple hits on track in the first layer close to IP facilitates robust track finding - improves tracking efficiency for primaries and reduces fake rates.



|η| Coverage - Pixel Detector

- Benefits of forward tracker extension:
  - Reject pile-up jets
  - Extend lepton coverage
  - Extend b-tagging
  - Better E_T^{miss} resolution
- Improves multiple physics channels
  - Vector-boson scattering, Vector boson fusion
  - High lepton-multiplicity channels
  - ...



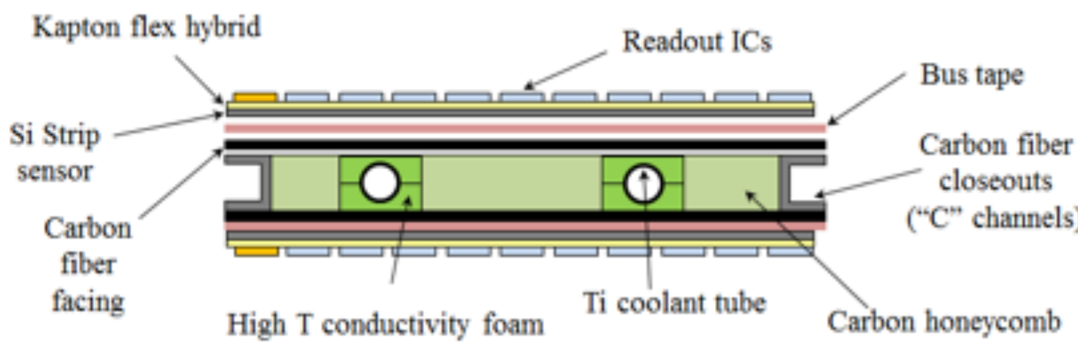
Optimisation of layout for high eta coverage

- Innermost central layer structure needs to cover full pseudo-rapidity range
  - closest possible measurement to IP minimise extrapolation distances
  - for best impact parameter resolution between measurements (hits)
  - minimises passive material before the first two measurements in forward region

Silicon Strips

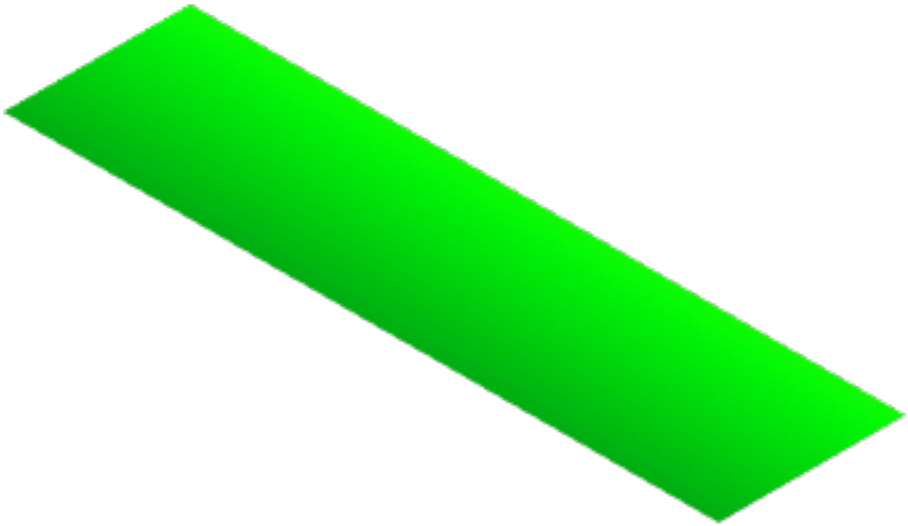
ITK Strips: System Idea

- Developed concept applicable for **barrel and end-cap.**
- Pursuing simplicity for improved producibility:
  - Silicon modules glued directly onto a cooled carbon fibre plank.
  - Designed to reduce radiation length.
  - Kapton service tapes co-cured onto CF skins.
- All components independently testable prior to construction.
  - Leads to early systems-like testing



- Radiation environment
  - Fluence: 1.2×10^{15} 1MeV n_{eq}
  - Dose: ~50MRad
- Chosen strip pitch:
  - 74.5 um in the barrel
  - 60-80um in end-caps

ATLAS Strips: Stave/Petal Concept



- **Hybrid** = kapton board with FE chips (ABC130, connection via wire bonds)
- **Module** = silicon sensor with readout hybrid (connection via wire bonds)
- **Stave/petal** = core structure + cooling + electrical services (power, data, TTC) + modules

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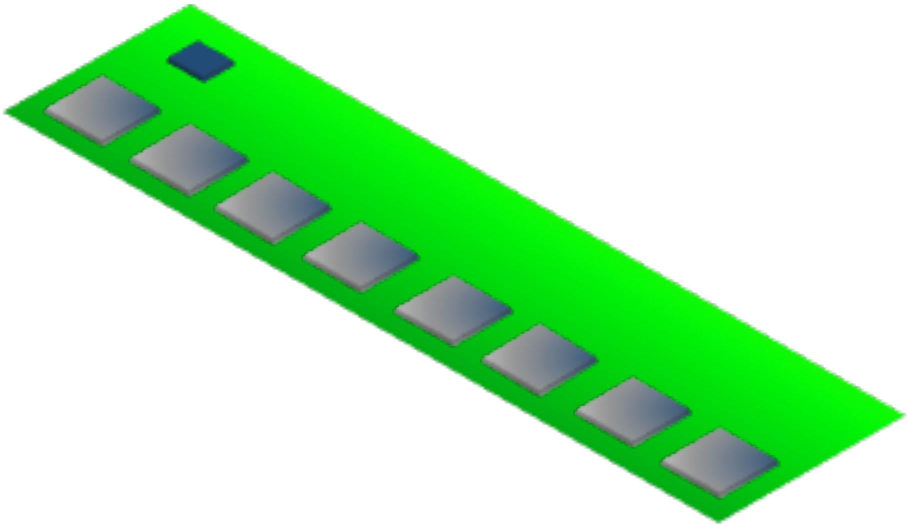

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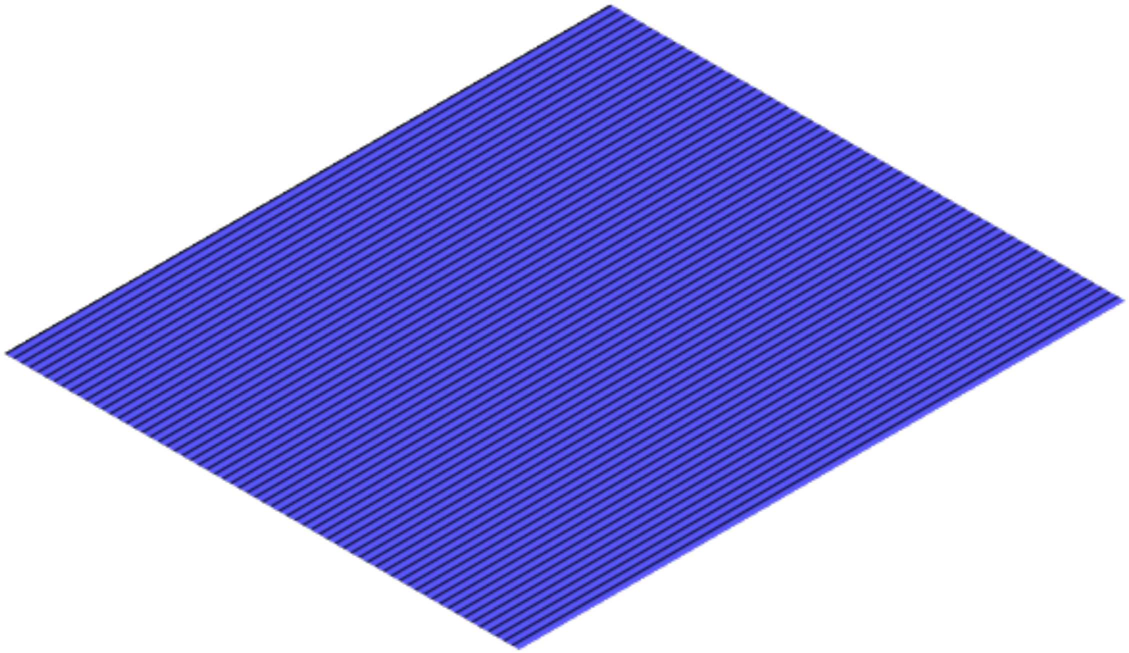

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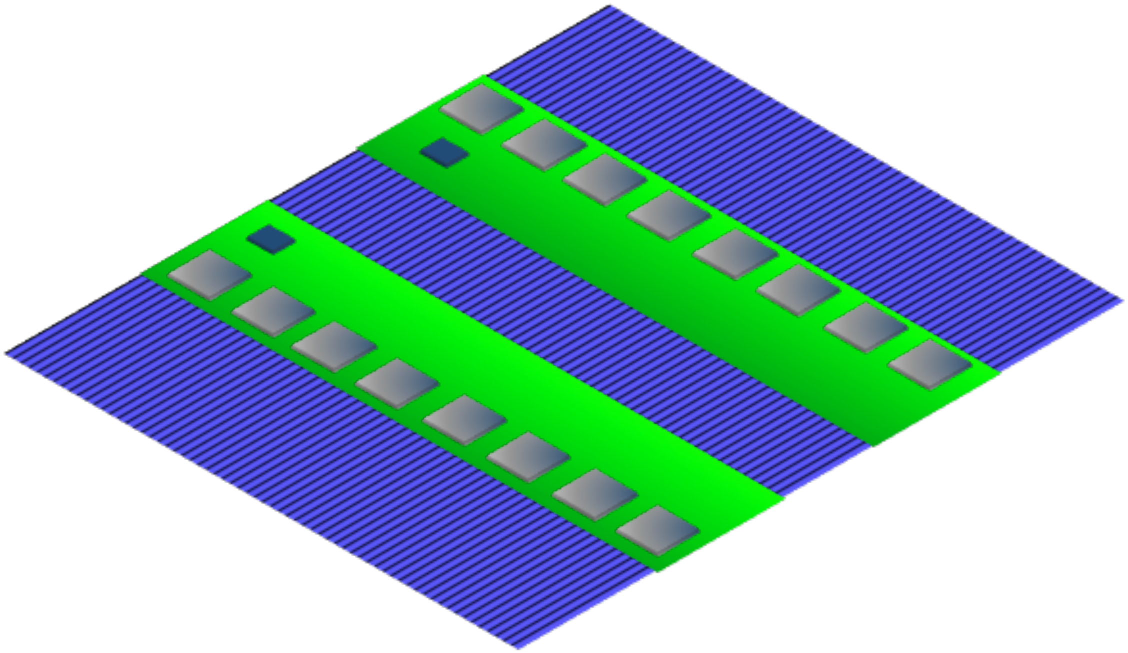

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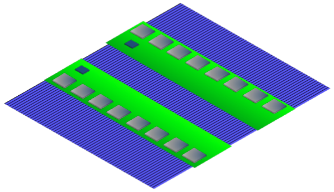

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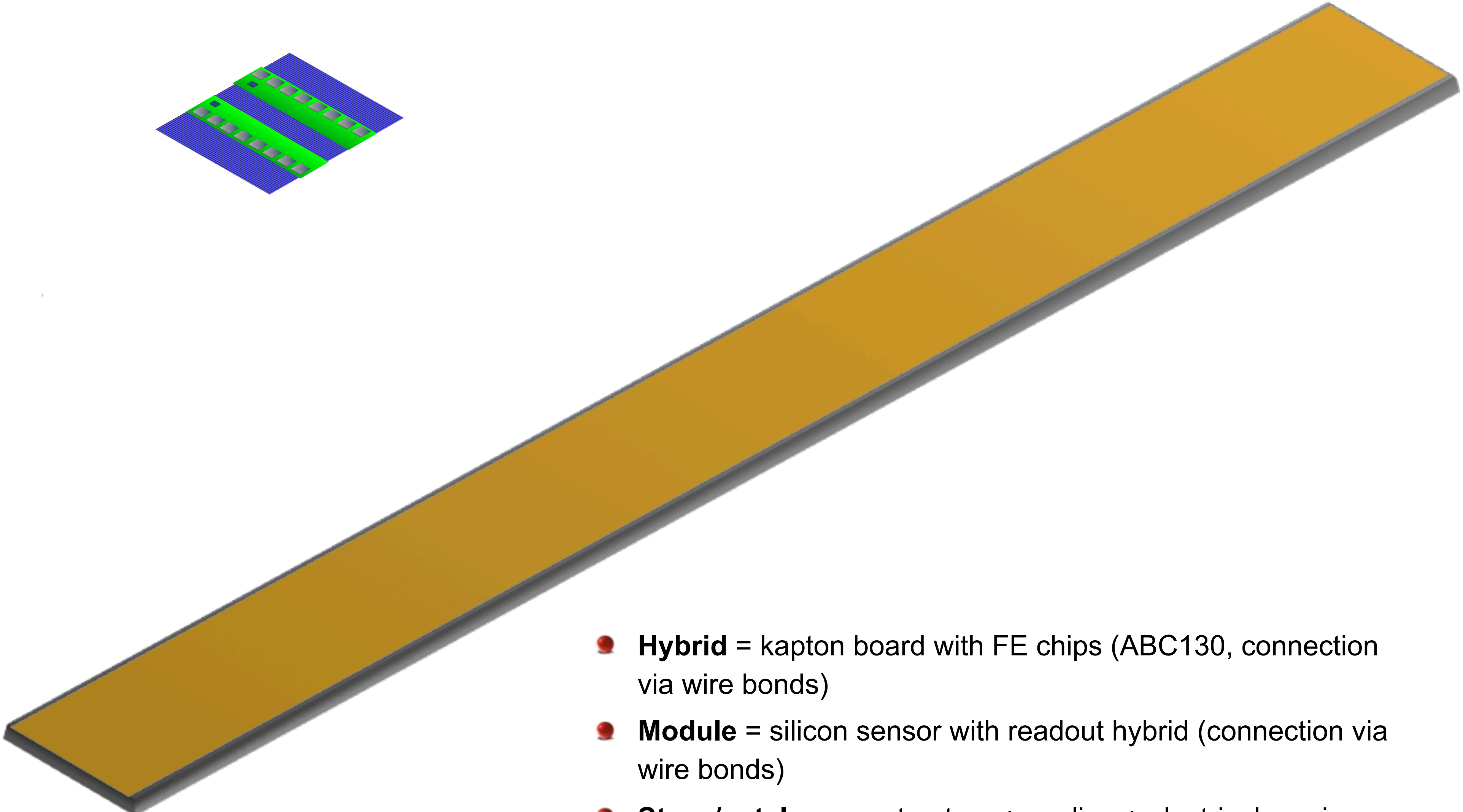

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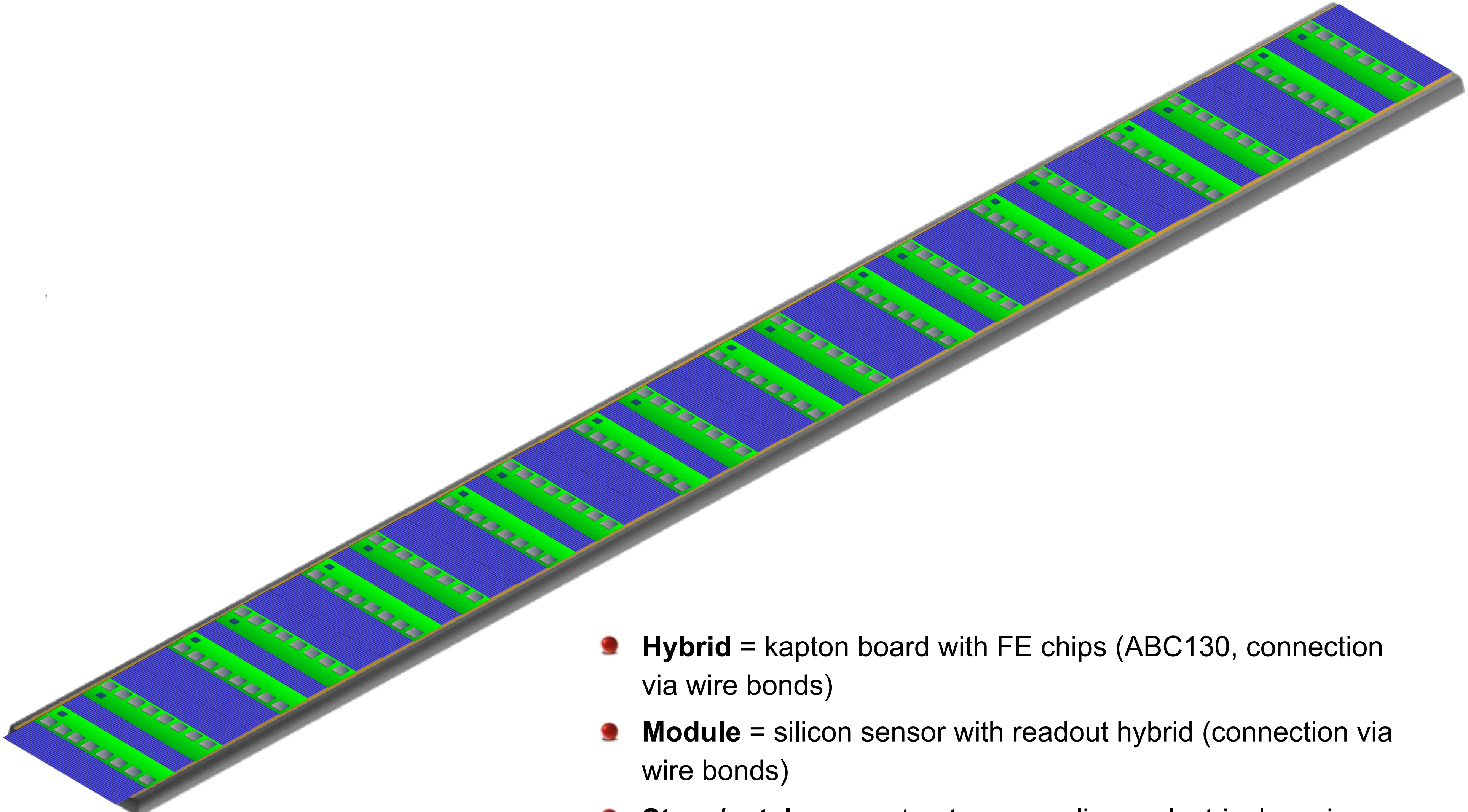

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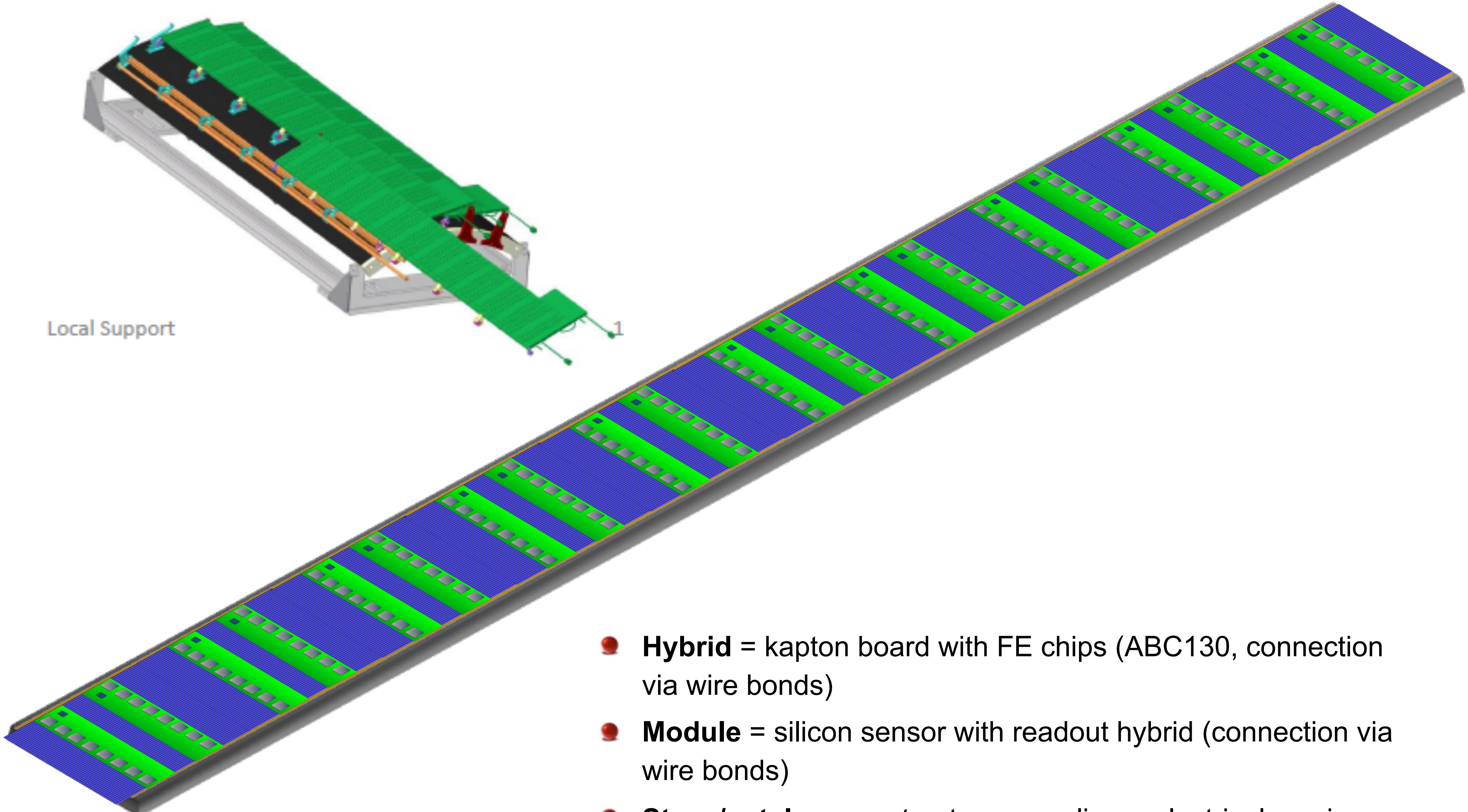

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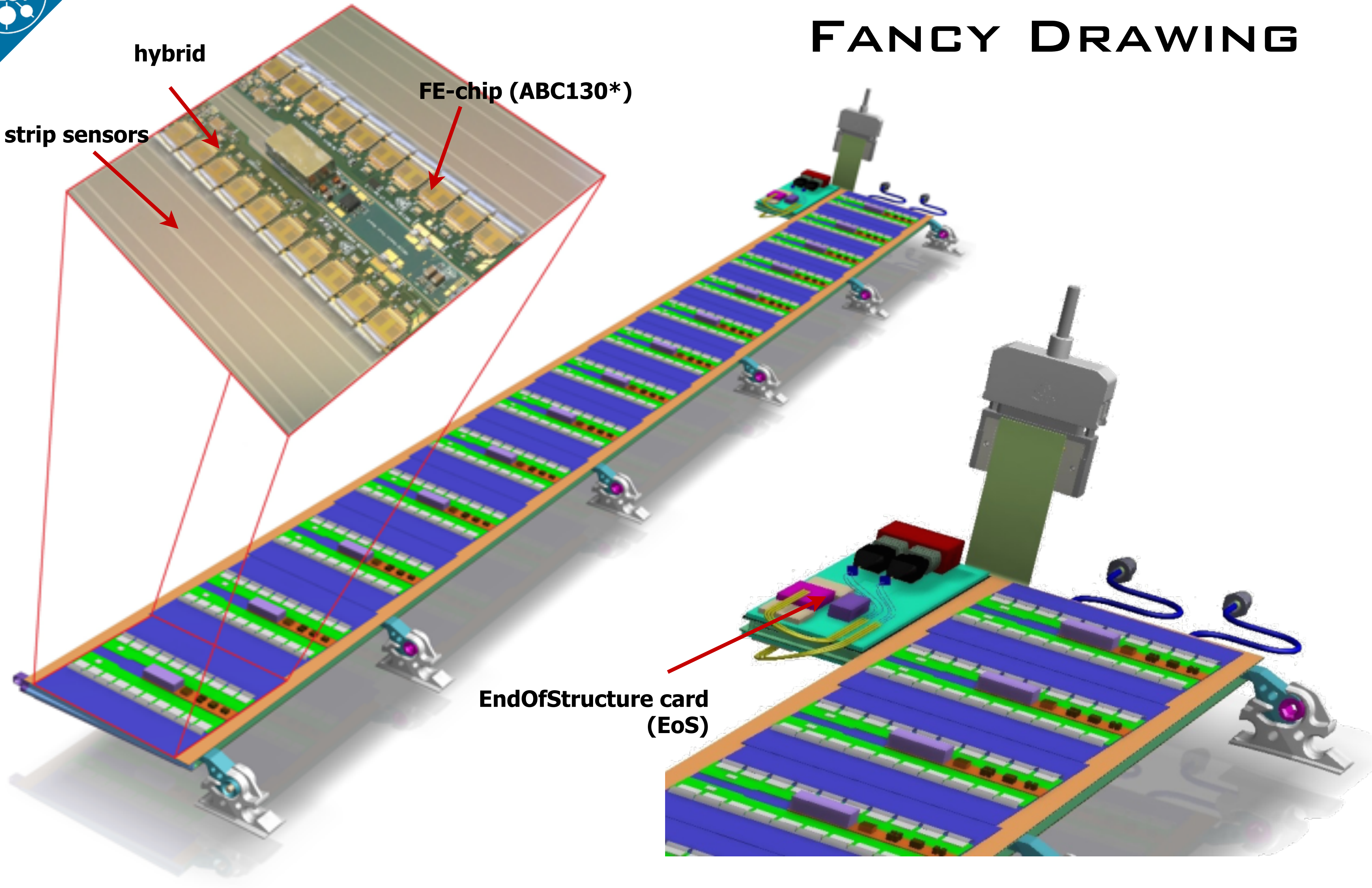
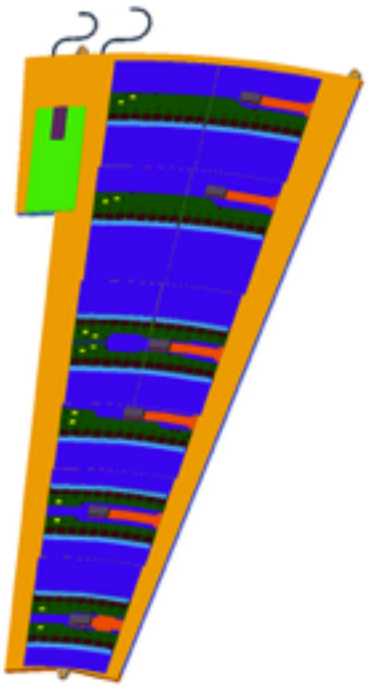
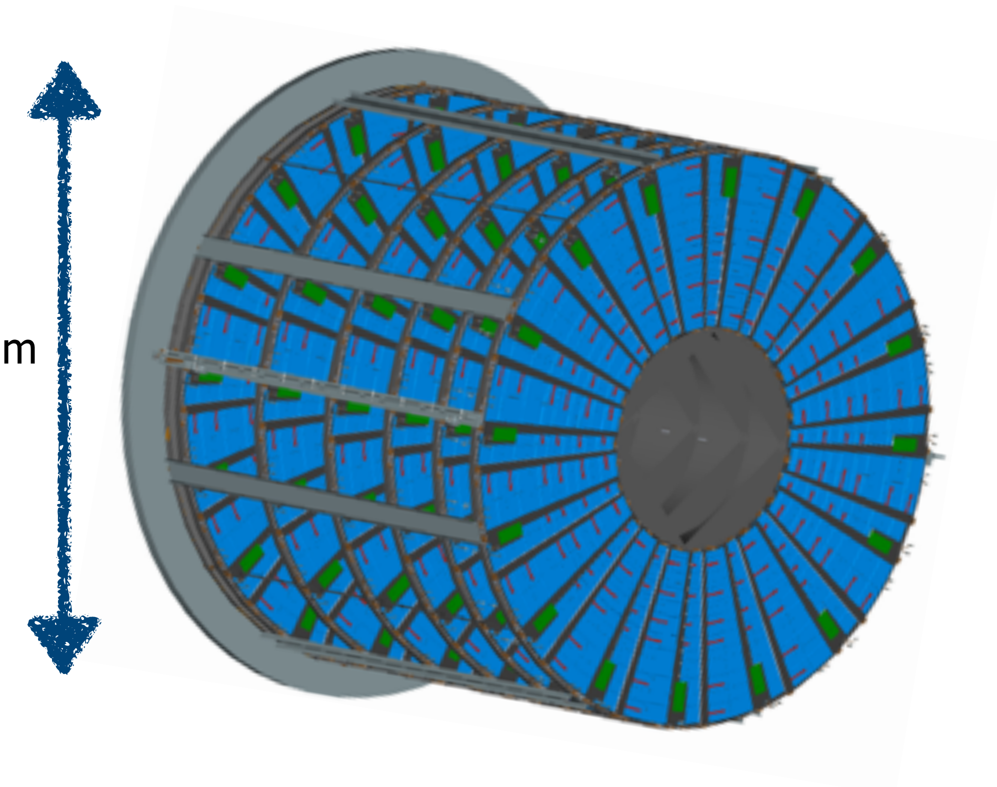
Fancy Drawing



End-caps

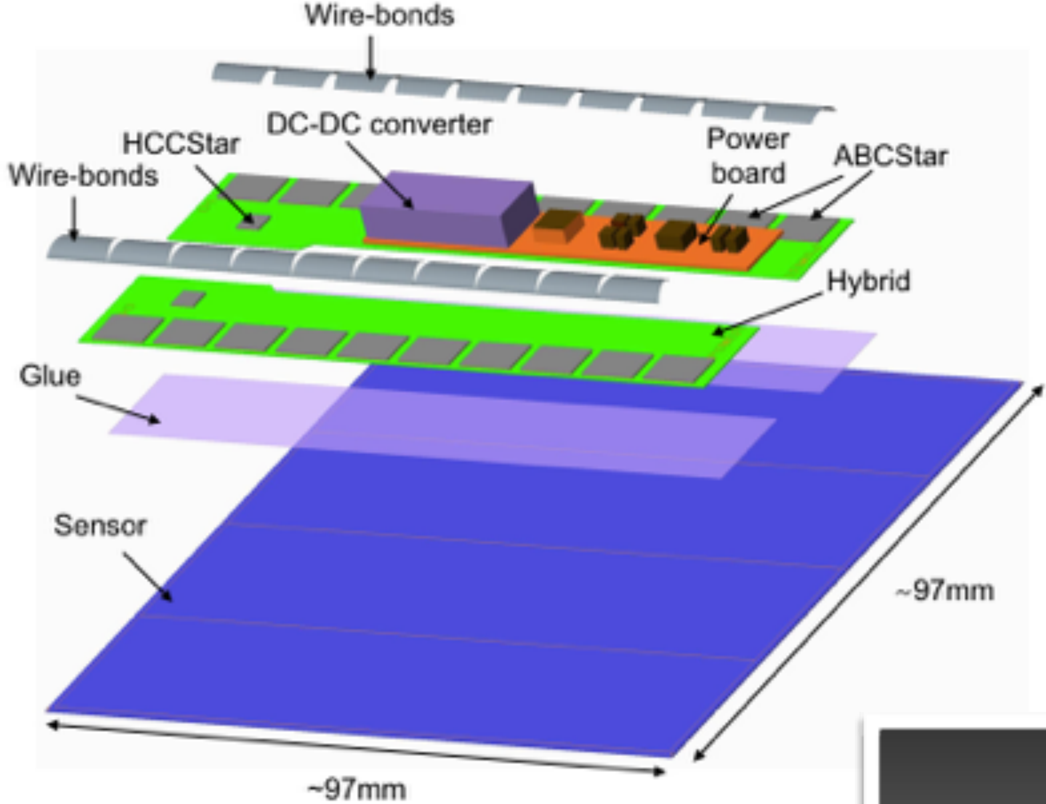




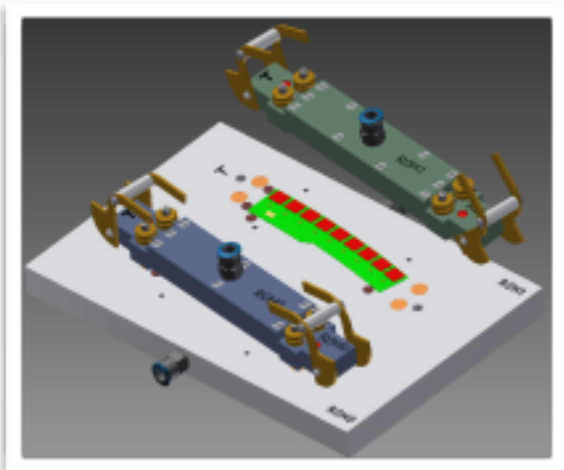
- End-caps are more challenging due to their geometrical constraints
  - pointing strips: same phi coordinate measurement along the strip length
  - same concept as in barrel -> build disks out of wedge shaped petals covered by **six** different sensor shapes
  - more complicated layout for the electronics as we have two modules besides each other
- Advantages:
  - side-insertion - petals accessible for a very long time
  - technical solutions for barrel and end-caps mostly the same
  - especially module production is exactly the same across barrel and end-cap

Modules

The Module

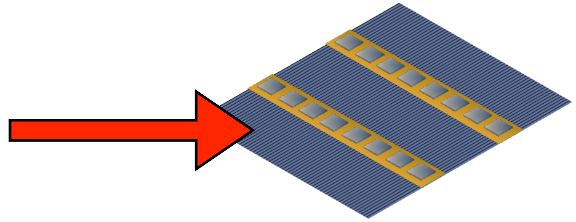


Short Strip module Barrel

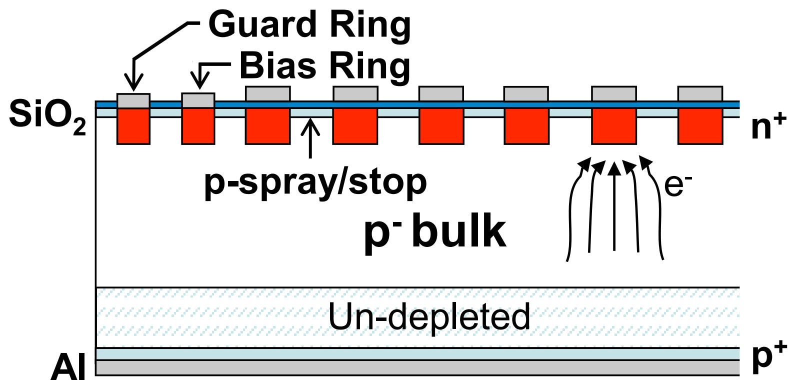


- Even so we have multiple different module “types” they are all based on exactly the same concept and production steps.
- Frame for module production is identical (barrel and end-cap), “just” the tooling has to be switched.

Baseline Sensors

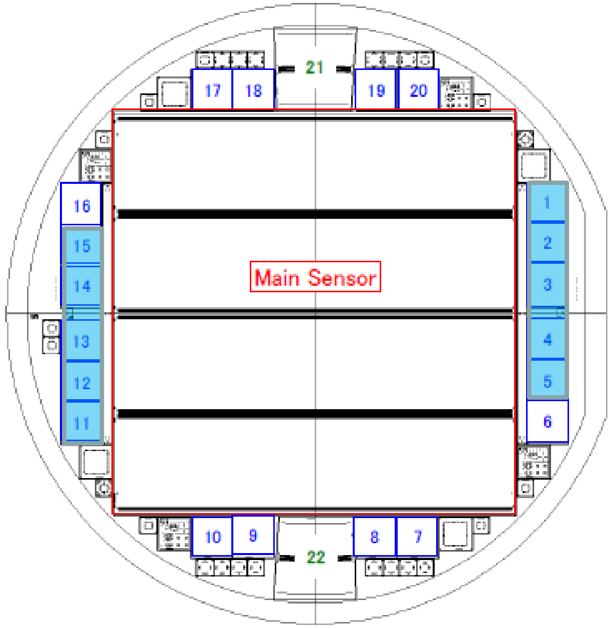


- Sensor parameters basically defined for ATLAS and CMS: **n-in-p with p-stop isolation**
  - Collects electrons like current n-in-n pixels -> faster signal, reduced charge trapping
  - Always depletes from the segmented side: good signal even under-depleted



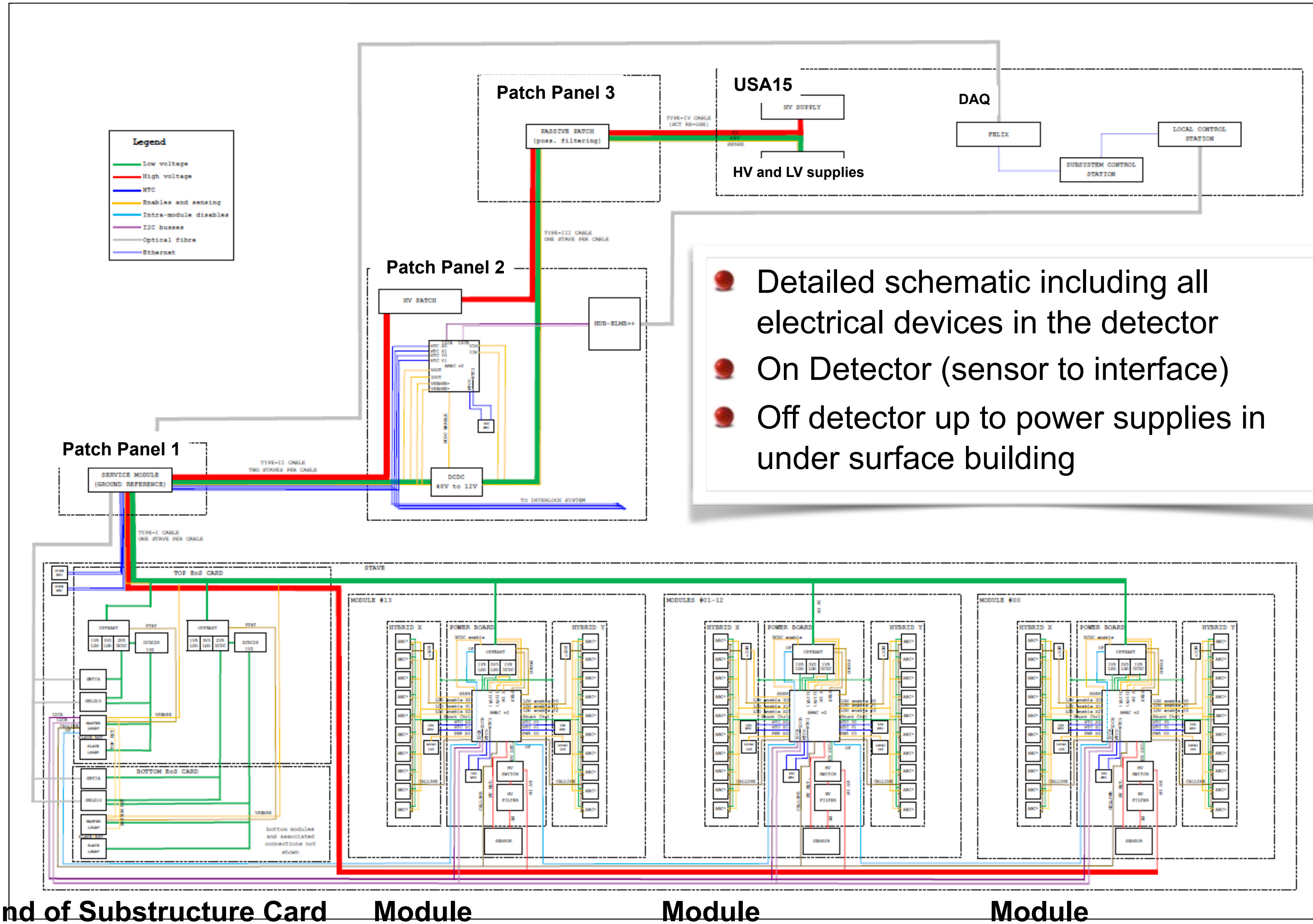
- Single-sided process
  - much cheaper than n-in-n
  - More foundries and available capacity world-wide

- Easier handling/testing due to lack of patterned back-side implant



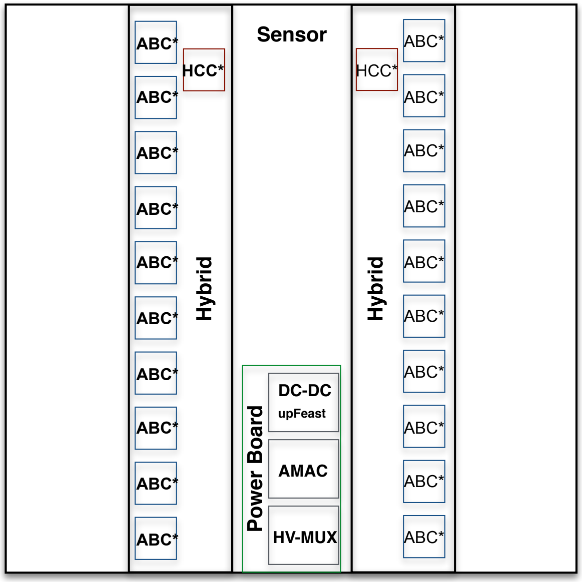
see talk from Marko Dragicevic

Electronics Overview



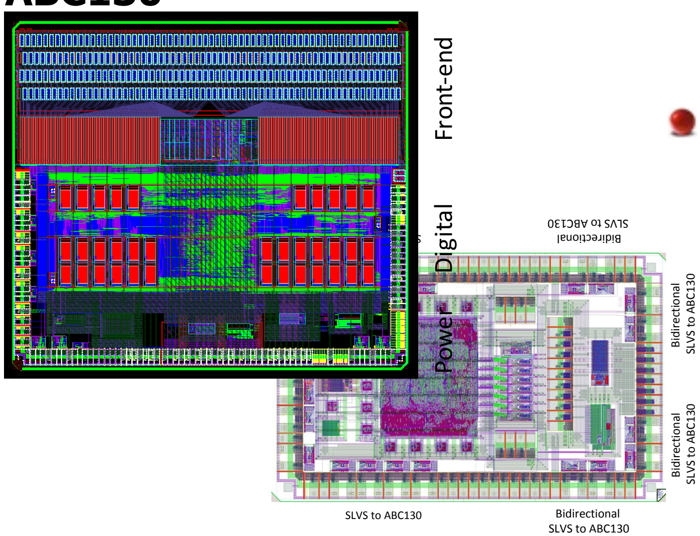
- Detailed schematic including all electrical devices in the detector
- On Detector (sensor to interface)
- Off detector up to power supplies in under surface building

Electronics Overview



Module

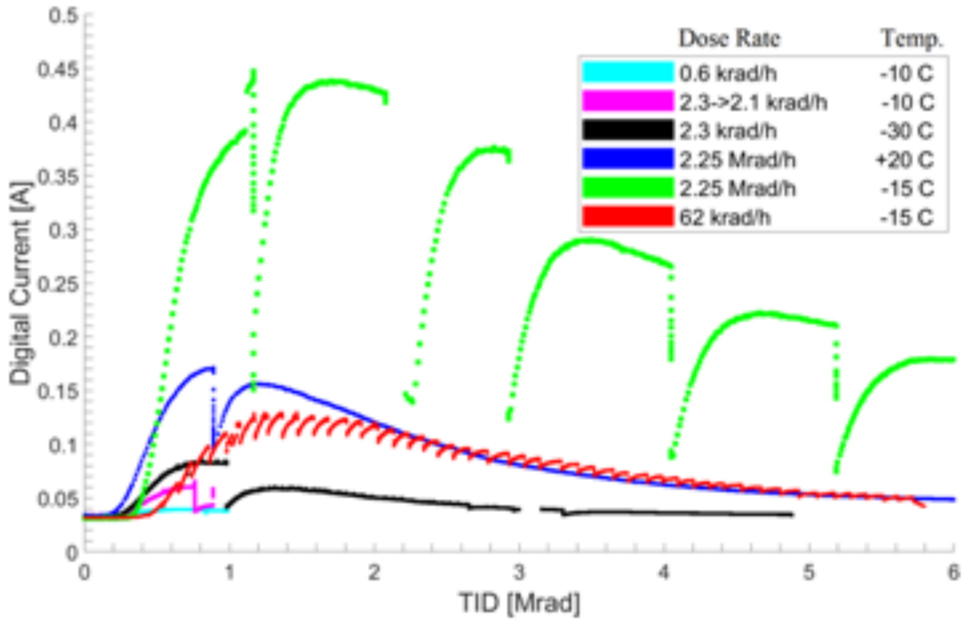
ABC130



- **ABCStar**
  - ATLAS binary chip with 256 channels in 130nm tech.
  - converts incoming charge signal into hit/no-hit information
- **HCCStar**
  - interface between ABC130 and bus-tape
  - collects information from O(10) ABC130 and sends to outside world
- **AMAC**
  - chip for local monitoring - current, voltage, temperature
  - control: HCC, ABC enable; HV switch
- **upFEAST**
  - chip to control the parallel powering (DC-DC)
  - first version (FEAST) worked fine but was not radiation hard
  - upFEAST currently being designed (CERN)

Some R&D Results

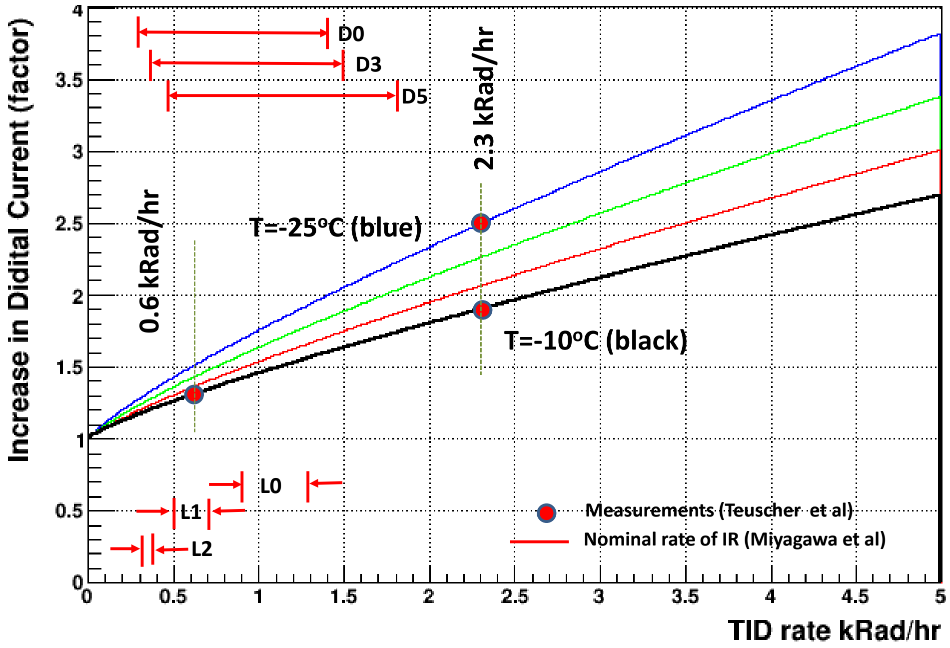
TID induced Current Increase



Surface effects:
Generation of charge traps due to ionising energy loss (Total ionising dose, TID)

- One of the biggest concerns in 2016 in the strip system: TID induced current increase
  - Same effect as observed in ATLAS IBL
- Measurements ongoing of all ASICs at realistic rates and temperatures.
- Increase in current/power during “bump phase” has potential impact on detector design
  - non-standard - running conditions including changing operation temperature over time and/or lowering the voltages serving the front end.
  - impact on mechanical behaviour

TID Bump observed in ABC130

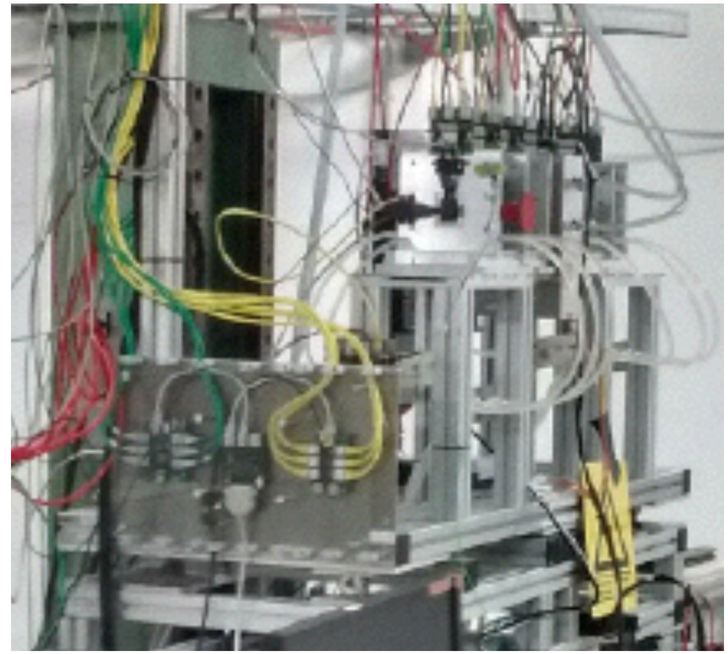


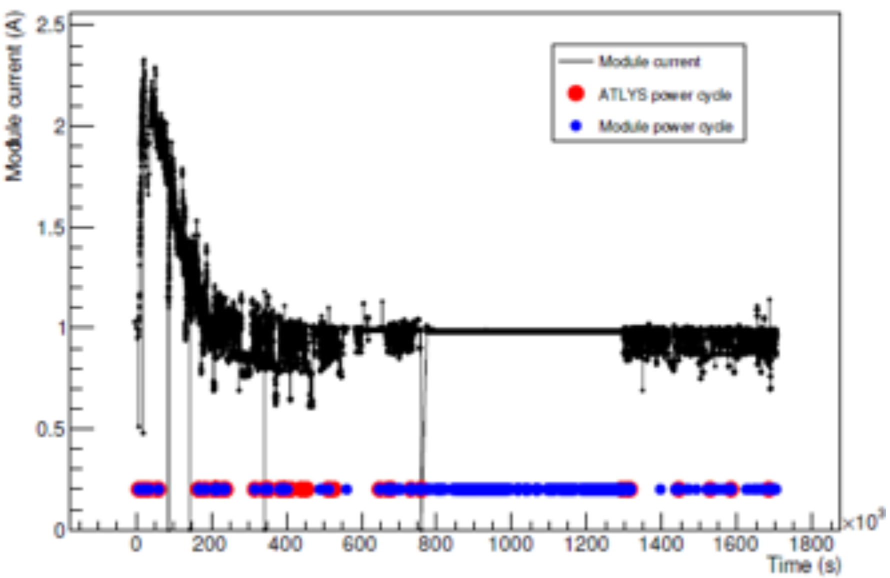
Source	T	Current Increase	Dose Rate (MRad/h)
^{60}Co CERN	-25	2.5	0.0023
^{60}Co CERN	-10	1.9	0.0023
^{60}Co CERN	-10	1.3	0.0006
Birmingham-p	-25	9.7	1.25
X-ray CERN	-15	3.9	62
(extrapolated)	-10	3.5	62
X-ray CERN	-15	13.6	2.25
X-ray CERN	+20	5.2	2.25

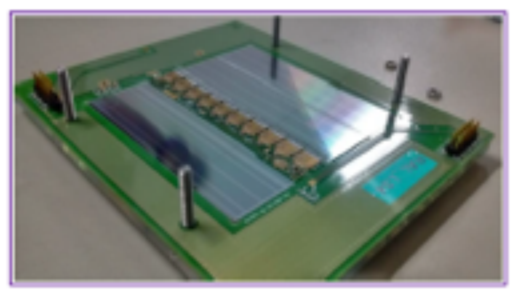
- A model was developed to calculate the power dissipation as a function of the position and the fluence profile.
- Based on this conservative estimates on power dissipation (per position and total) are fed into FEA calculations.
  - assume a power increase of about 20%.
- More detailed studies under way to understand dynamic behaviour.
- Design and layout of the strip detector is sturdy enough to incorporate this feature.

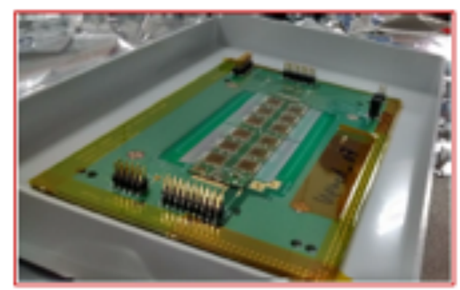
ITk Strips - Test Beam Test Beam Test Beam

- Huge effort at DESY and CERN test beams
  - Barrel long-strip module tested at 11 positions
  - EC module studied (old chip)
  - 130 nm single chip card with irradiation sensor under test
  - Full module irradiated up to 8e14 n_{eq} cm^{-2} at PS



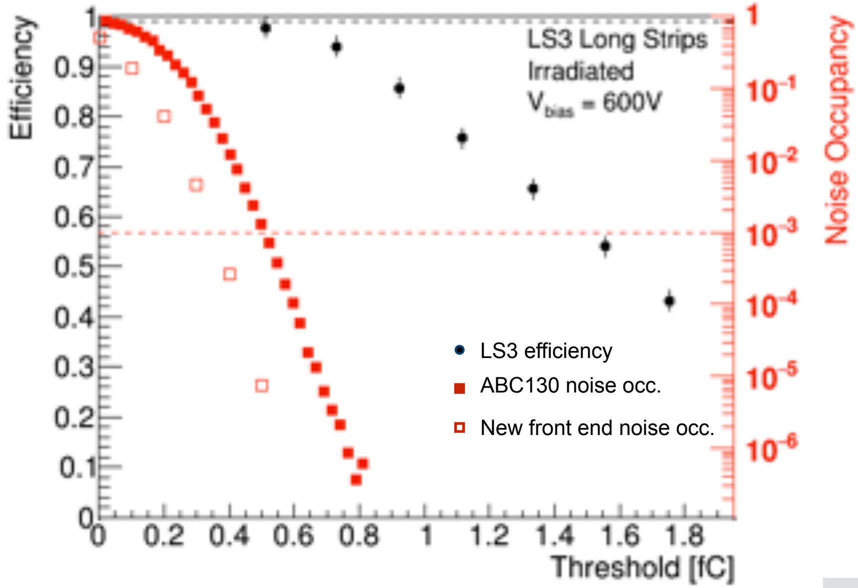






Test Beam Results

most important and most discussed plot ...



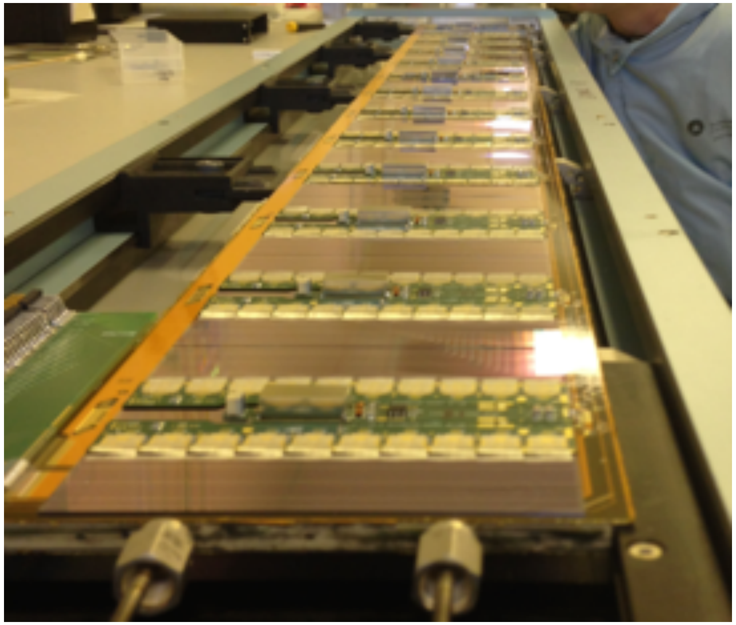
- First measurements of front-end stage prototype for ABCStar indicate much improved noise behaviour

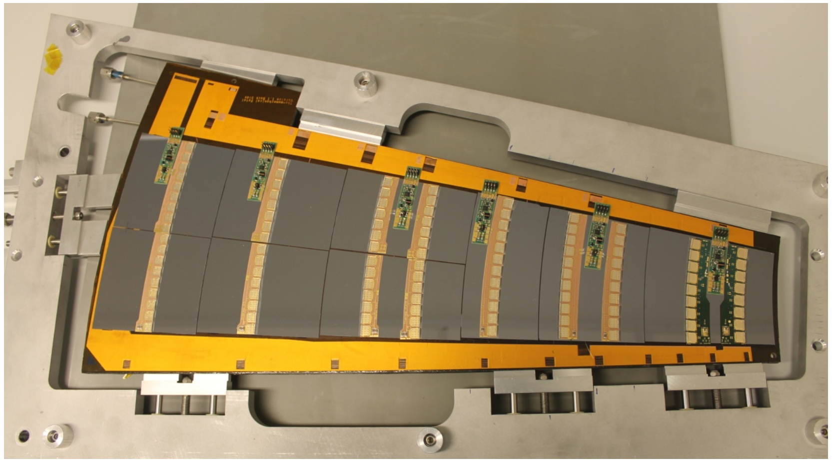
- Performance at end-of-lifetime is marginal with the used prototype components.
- Caveats:
  - Sensors were not annealed (+20% in signal)
  - Final sensor will have higher resistivity (+ 10% in signal)
  - Old front-end stage -> polarity fix (-20% in noise)
  - Enclosed transistors (-30% in noise)
- Extrapolated results to be confirmed with final prototypes

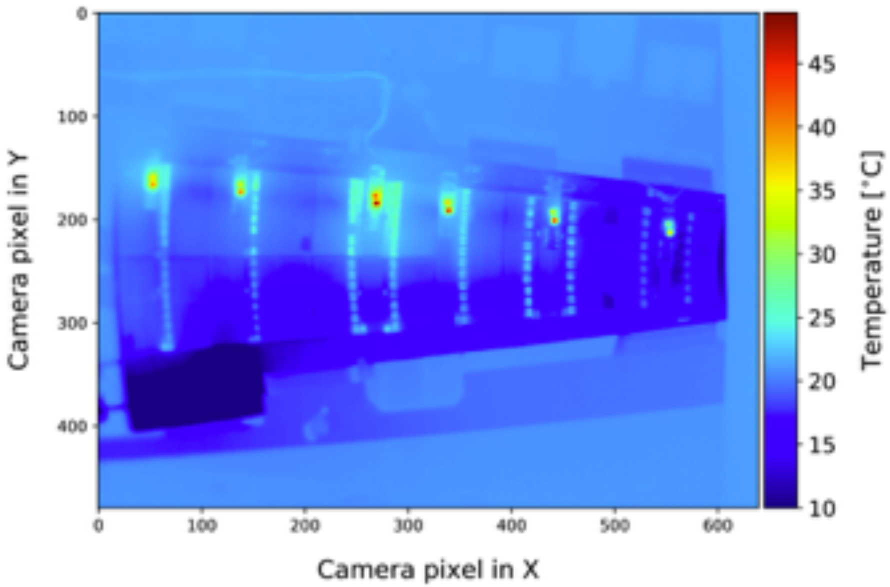
Module Type	Fluence (x E14)	Charge (500 V)	Charge (700V)	Noise (e^-)	S/N (@500 V)	S/N (@700 V)
SS	8,07	13,73	16,12	630,25	21,79	25,58
LS	4,13	17,28	19,47	748,96	23,08	26,00
R0	12,26	11,52	14,04	652,14	17,67	21,53
R1	10,11	12,54	15,00	640,33	19,59	23,43
R2	8,72	13,33	15,74	657,26	20,28	23,95
R3	8,01	13,77	16,16	643,93	21,39	25,10
R4	6,80	14,64	16,98	795,68	18,40	21,34
R5	6,00	15,30	17,60	835,36	18,32	21,07

Towards Full Systems

Staves and Petals



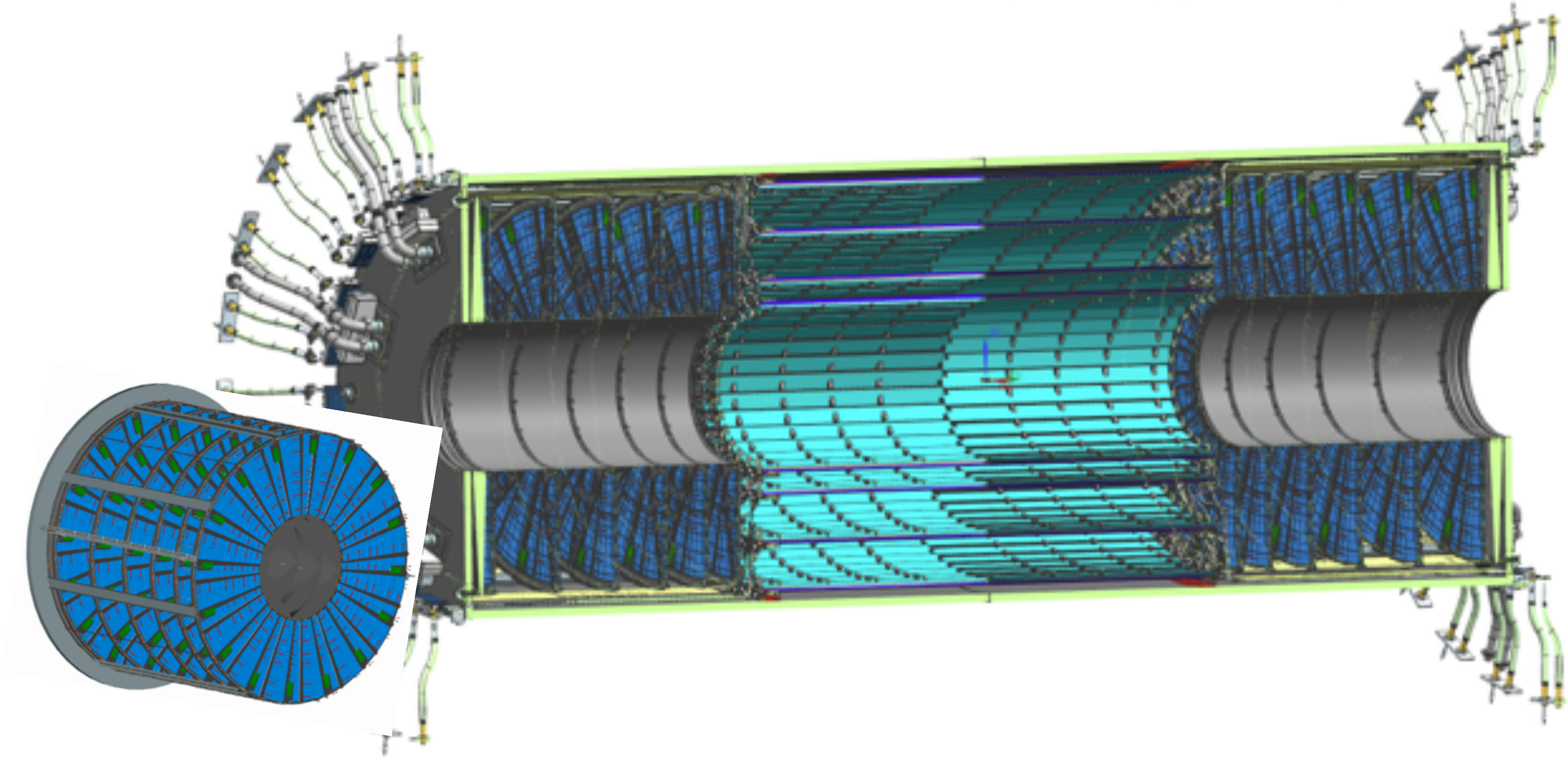




- Prototyping full staves and petals
- Working on detailed quality assurance and control procedures
- FEA calculations and IR measurements
- Readout developments
- ….

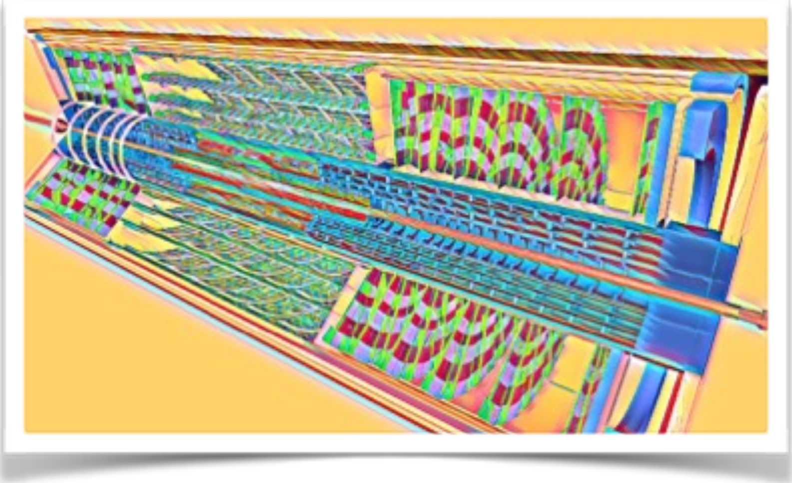
Global Structures

- Barrel staves loaded into shelfs within outer cylinder (@ CERN)



- End-cap petals are loaded into end-cap structures (@DESY and @NIKHEF)
- Services for barrel and end-caps running along outer surface of end-caps
- Barrel and end-caps to be merged and tested at CERN before installation into ATLAS

Conclusions

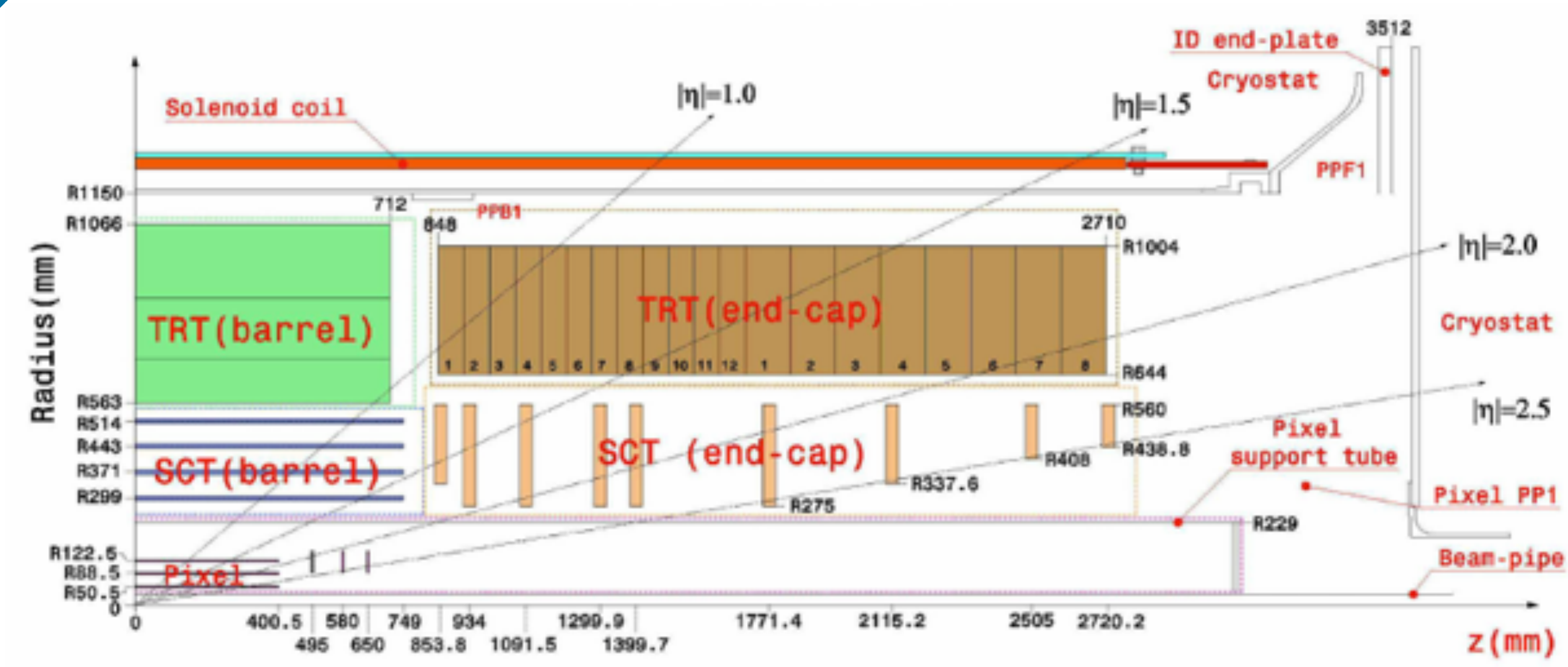


- New tracking detector for the high-luminosity phase of ATLAS taking shape
- Proposed tracker in most areas achieves the same or somewhat better performance as the Run-2 tracker, but with 200 pile-up events.
- Improved performance for boosted objects and extension of tracker acceptance helps the sensitivity in multiple HL-LHC physics analyses.

- Technical Design Report submitted and hopefully published in May.
- The involved German institutes took over the responsibility for the assembly of one full end-cap of the strip detector
  - We will be very busy in the next years !

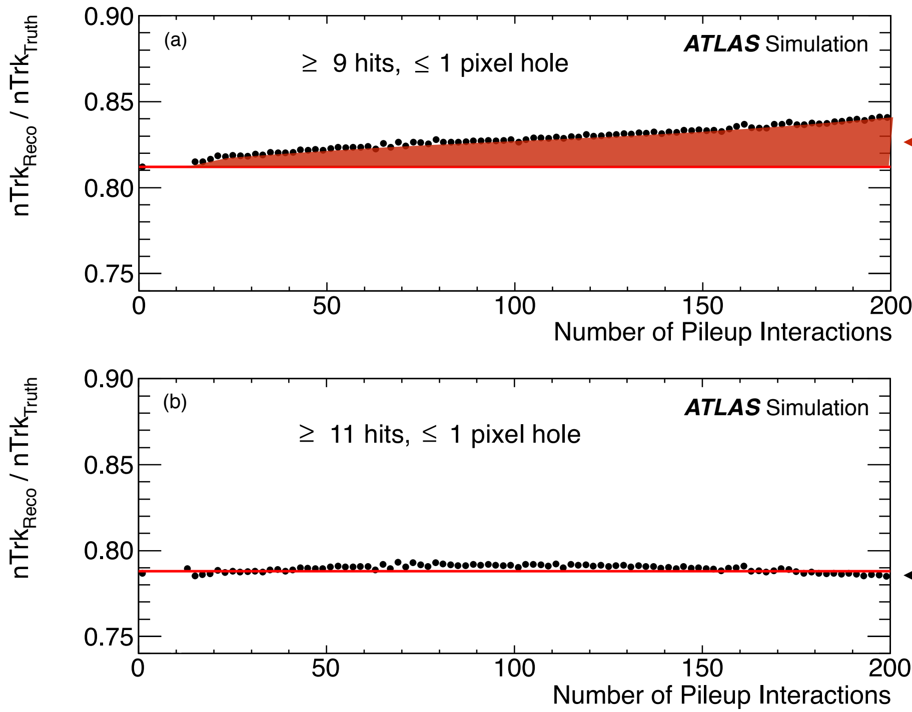
Backup

Inner Tracker Overview



- Increased radiation tolerance and higher granularity to keep occupancies low
- Larger readout bandwidth capabilities
- Reduced material in front of calorimeters
- Extended coverage at high η
- Pixel system extends out to larger radii.
- More pixel hits in forward direction to extend tracking.
- Outer active radius slightly larger to improve momentum resolution.

Number of Hits

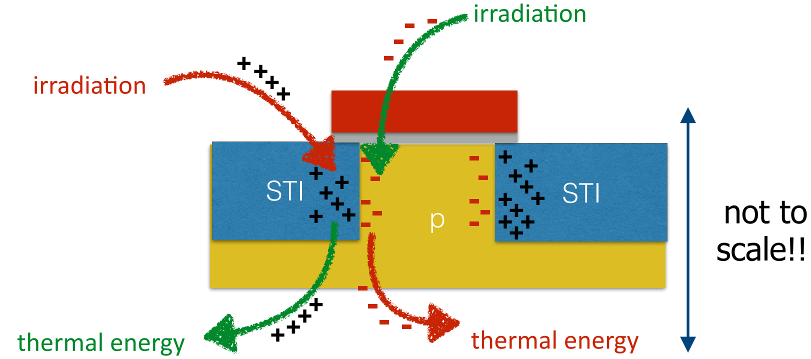


increasing fake component,
additional tracks from hadronic showers

minimum 11/track needed for controlling the pattern recognition at <μ> ~ 200

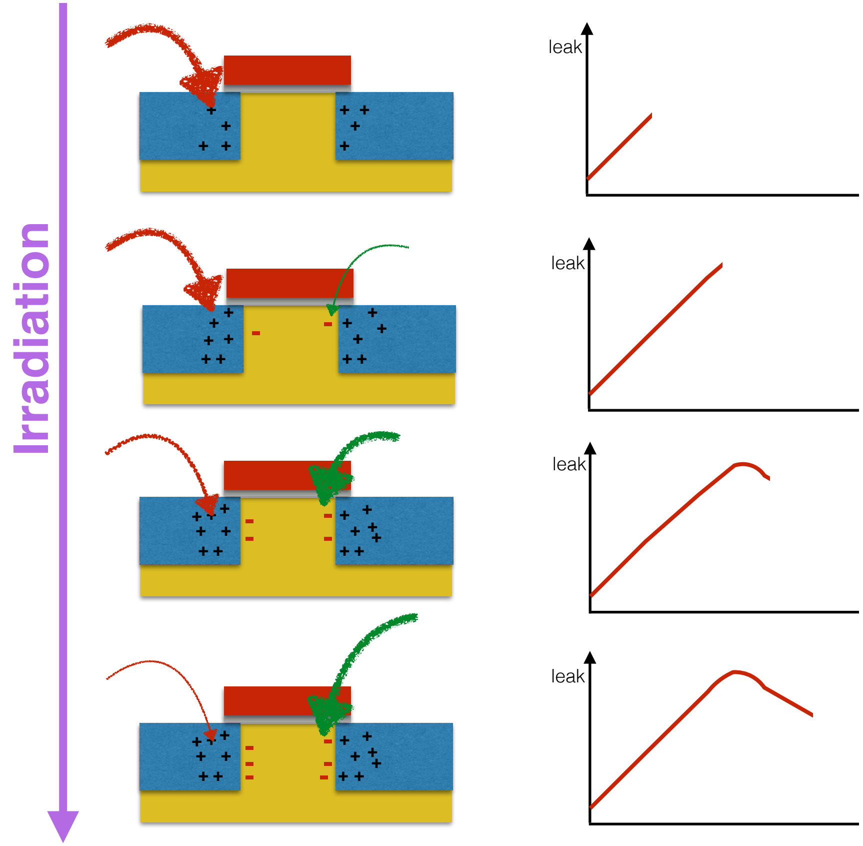
TID Bump

Surface effects: Generation of charge traps due to ionising energy loss (Total ionising dose, TID) **(main problem for electronics).**



- The leakage current is the sum of different mechanisms involving:
  - the creation/trapping of charge (by radiation)
  - its passivation/de-trapping (by thermal excitation)
- These phenomena are dose rate and temperature dependent!

- Charge trapped in the STI oxide
  - +Q charge
  - Fast creation
  - Annealing already at T_{amb}
- Interface states at STI-Silicon interface
  - -Q for NMOS, +Q for PMOS
  - Slow creation
  - Annealing starts at 80-100C



STI = shallow trench interface

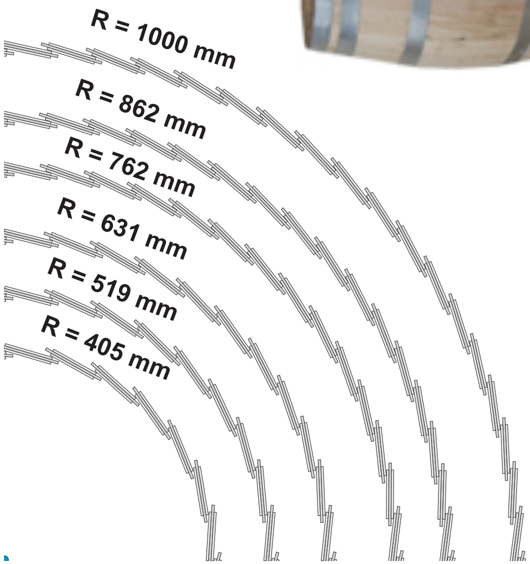
Numbers

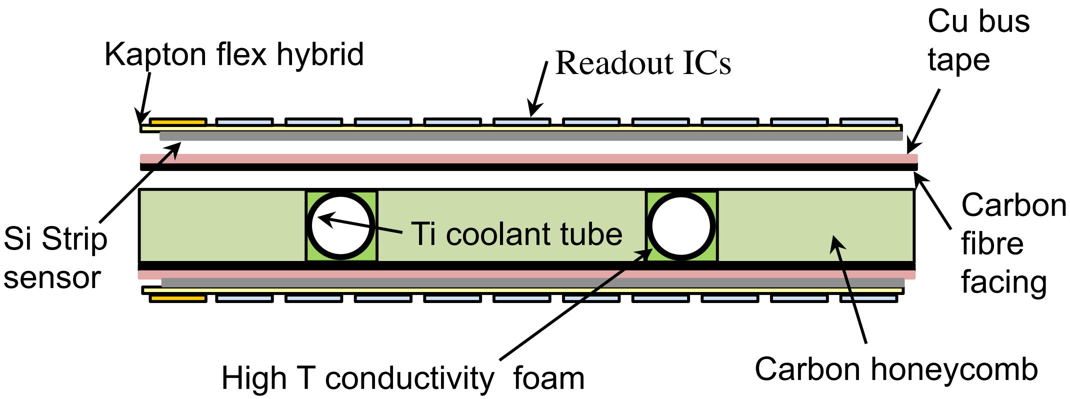
Layer	Radius	staves per layer	# of modules	# of hybrids	# of ABC130	# of channels	m²
0	405	28	784	1568	15680	4,01	7,45
1	562	40	1120	2240	22400	5,73	10,53
2	762	56	1568	1568	15680	4,01	14,75
3	1000	72	2016	2016	20160	5,16	18,96
Total full barrel		**392**	**10976**	**14784**	**147840**	**37,85**	**103,43**
Disk	**z-position**	**petals per disk**	**#modules**	**# of hybrids**	**# of ABC130**	**# of channels**	**m²**
0	1512	32	576	832	7168	1,83	5,03
1	1702	32	576	832	7168	1,83	5,03
2	1952	32	576	832	7168	1,83	5,03
3	2252	32	576	832	7168	1,83	5,03
4	2602	32	576	832	7168	1,83	5,03
5	3000	32	576	832	7168	1,83	5,03
Total end-caps		**384**	**6912**	**9984**	**86016**	**11 Mio**	**60,39**
Total total			**17888**	**24768**	**233856**	**48,9 Mio**	**163,82**

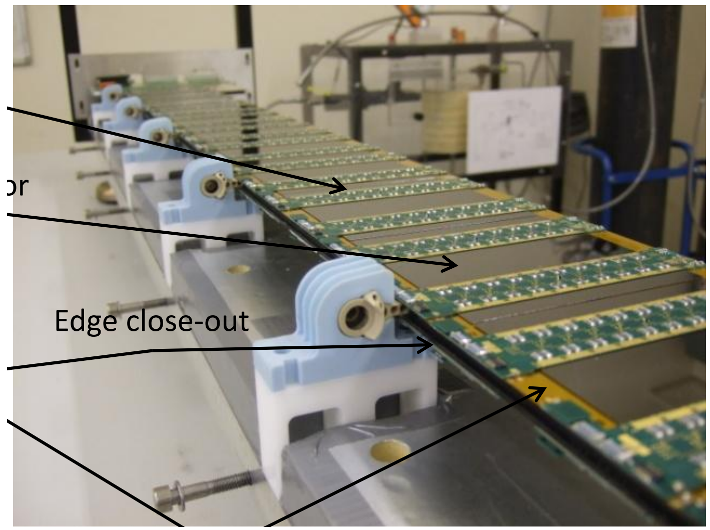
in Germany: ~4000 modules, assembly of 30 m^2 of silicon

Strip Detector

- Staves are arranged in concentric cylinders centred around the beam-line
  - overlap is arranged to make the layer hermetic down to 1 GeV/c tracks
- Double-sided layers with axial strip orientation and rotated by 26 mrad on other side (z-coordinate)
  - A sandwich construction for high structural rigidity with low mass.
  - End insertable (in z) to allow repairs up to the very last moment.
  - Silicon Modules directly bonded to a cooled carbon fibre plate.

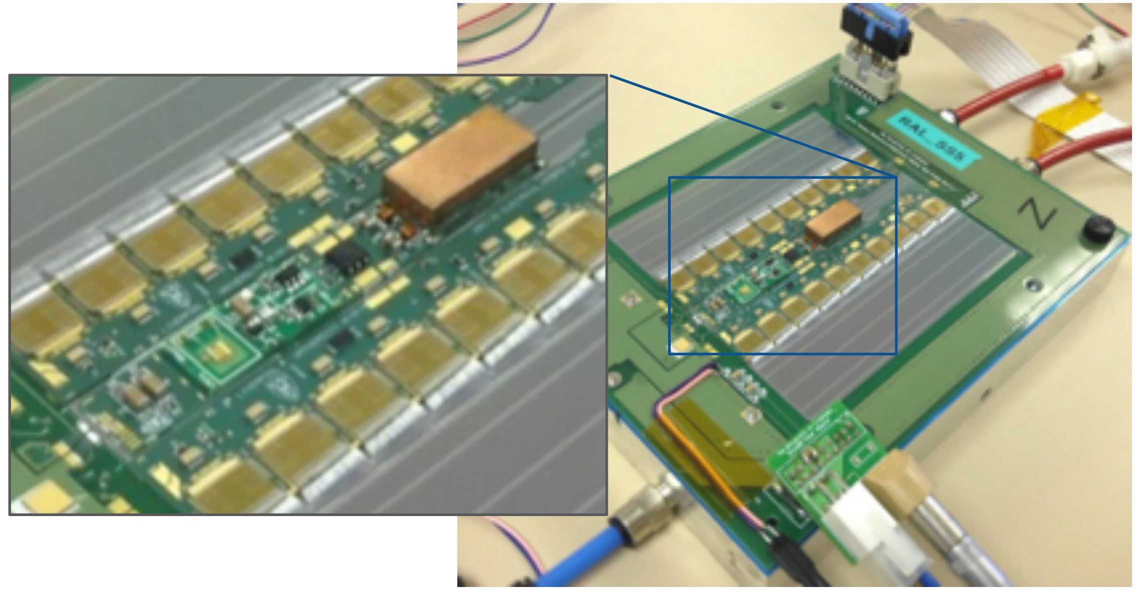






Powering an ATLAS ITk Strips Module

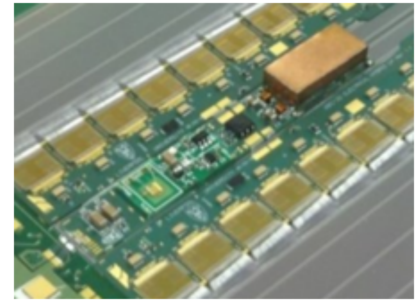
- Power board input
  - 10-12V DC LV
  - Bias voltage (~500-700V)
  - I2C control
- Features
- HV filtering & optional switching
  3 to 4 modules share a
  common HV supply line
- LV
  - conversion 12V → 1.5V
  - switching

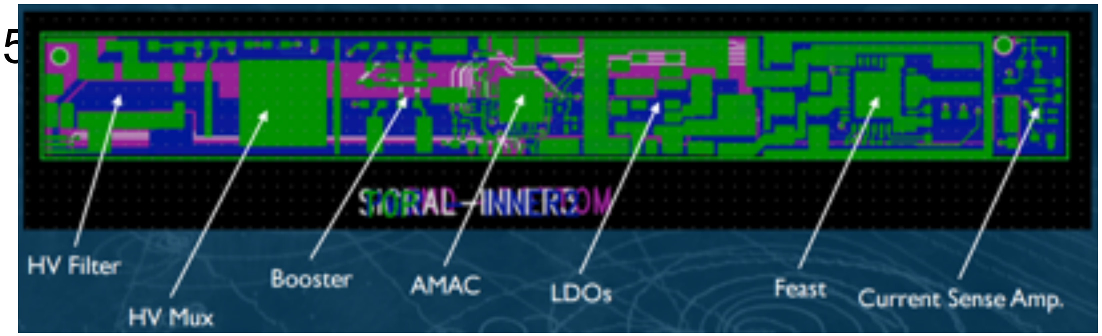


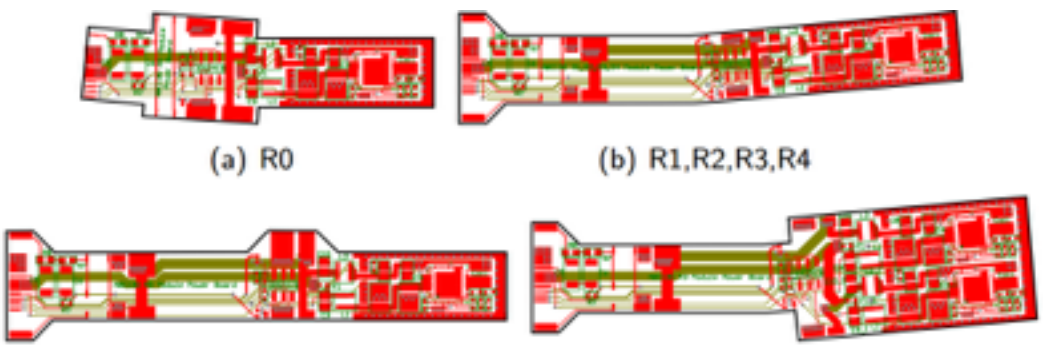
- Control & Monitoring :Dedicated ASIC to the the job:
  - LV on / off
  - Major component in power up sequence
  - LV individual front-end ASIC control, to ensure normalised power consumption in all use states → even temperature → even support strain/deformation
  - Monitoring: LV and HV currents, temperatures, …

Powering an ATLAS ITk Strips Module

- Blue-Black drawing to show where components are located
- Red-White drawing to show different EC shapes
  - R3 is special with 2 DCDC converters (12V → 1.5





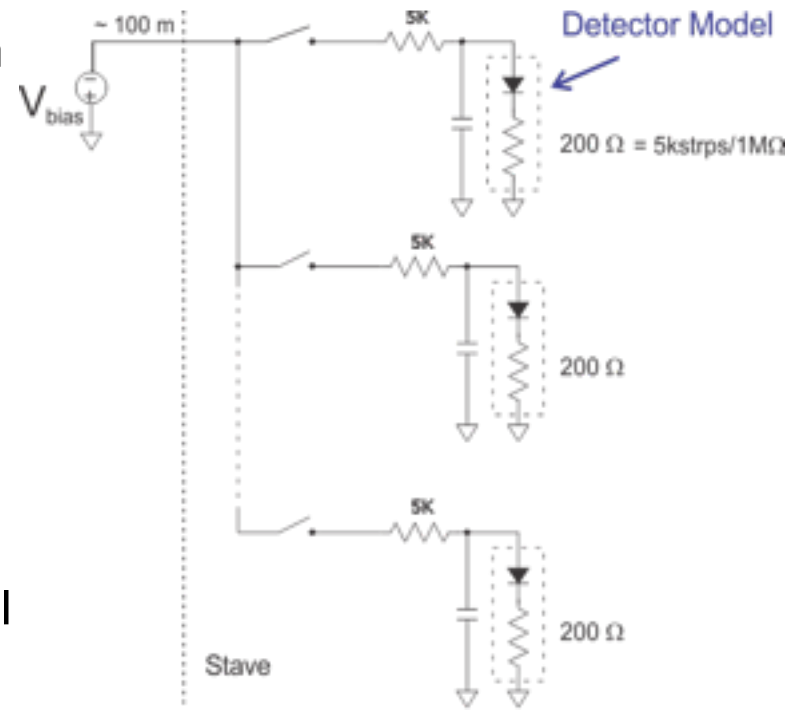


(a) R0
(b) R1,R2,R3,R4
(c) R5
(d) R3

HV Multiplexer

- Not practical to bring individual HV cables to each of the 17888 ITK strip modules
  - Insufficient cables available in type 3-4 services, significant material in service modules, insufficient room on bus tape with current technology/geometry

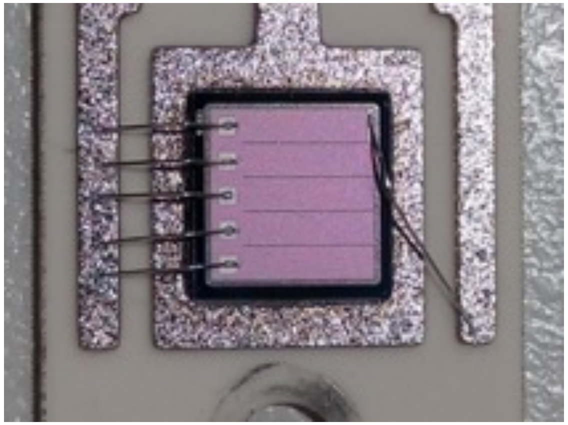
- Two paths studied
  - HV-MUX (baseline): Detector Control System controllable switch which would allow connection/isolation of individual sensors from a common bus
    - Minimises material on local supports and service modules for HV services
    - Requires a rad-hard HV switch transistor
  - Ganging (backup): Connecting 3 - 4 sensors together with four HV sections per stave/petal
    - Implemented in bus-tape designs



HV Switch R&D Results

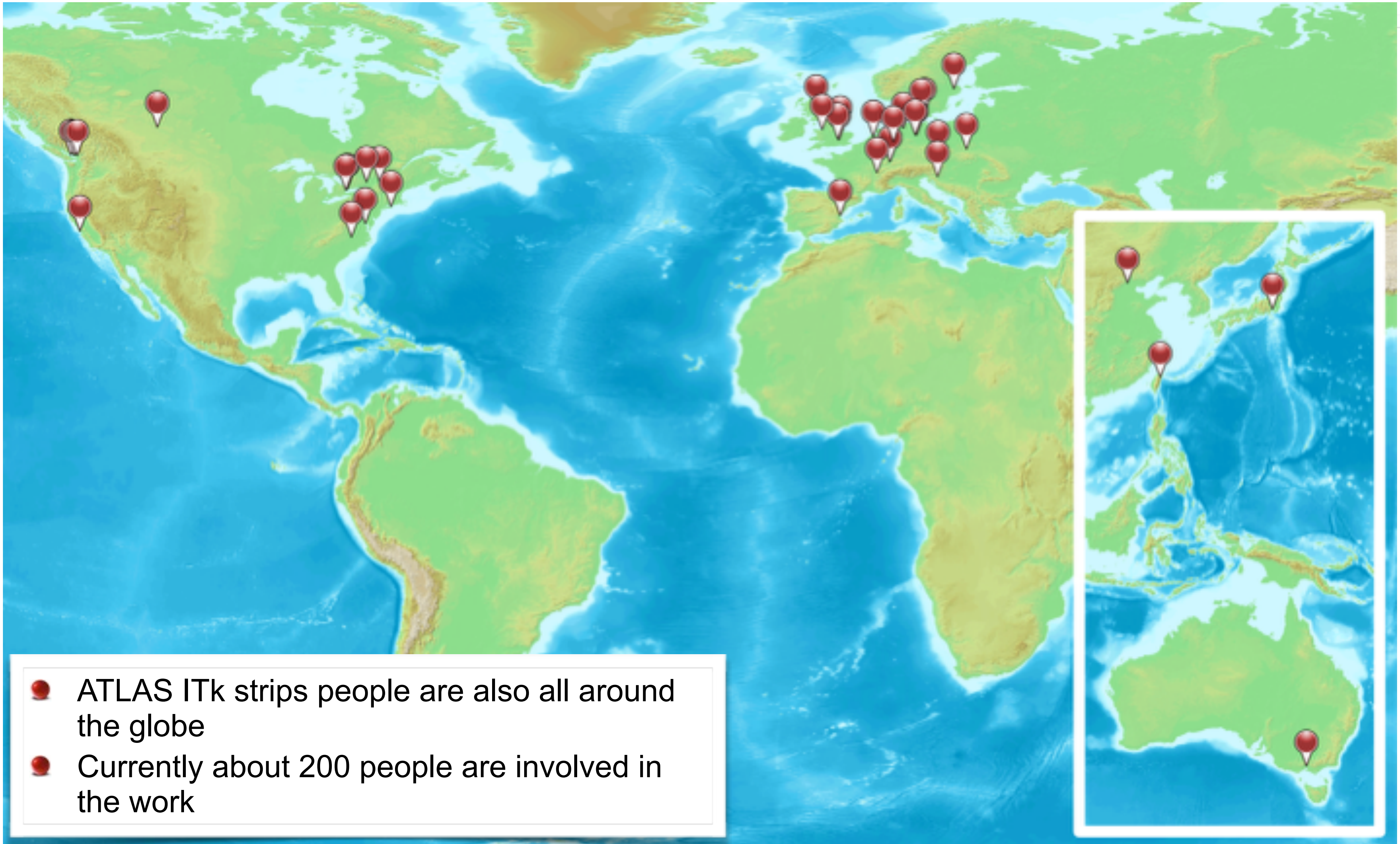
- Many devices types tested, so far with two best potential devices left:
  - 600 V GaN JFET is the best device as of now
    - Shown to be radiation tolerant
    - Larger sample sizes to be tested to show reliability
  - Custom vertical JFET under-development
    - More work needed on radiation tolerance

GaN FET



CNM VJFET

The World of ITk Strips



- ATLAS ITk strips people are also all around the globe
- Currently about 200 people are involved in the work