Upgrade of the ATLAS inner strip detector for the high luminosity LHC

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On behalf of the ATLAS collaboration

Vertex 2014, 12.-19. September 2014, Doksy

LHC Upgrade Plans

2009	LHC	$\sqrt{s}$ = 7~8 TeV
2012	Startup	L = 6 x $10^{33}cm^{-2}s^{-1}$, BS=50 ns

$\int Ldt$~25 fb^{-1}
Discovery of Higgs boson

Phase 0
Go to nominal energy
New beam pipe, additonal b-layer (IBL)

TODAY!

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L~1x10^{34}cm^{-2}s^{-1}, BS=25 ns

$\int Ldt$~75-100 fb^{-1}
Extra dimension@9 TeV
Compositeness@30 TeV
Leptoquarks m=1.5TeV

Phase 1
Injector Upgrade
New Muon Small Wheels, Fast Track Trigger

2019 – 2021 Ultimate Luminosity
$\sqrt{s}$ = 14 TeV
L~2x10^{34}cm^{-2}s^{-1}, BS=25 ns

$\int Ldt$~300 fb^{-1}
Compositeness@40 TeV
TeV resonances
in WW scattering

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TeV resonances in WW scattering

Phase 2
Upgrade, interaction regions, crab cavities?
Replacement of inner detector, calo/muon upgrades, L1 track trigger

2025 2035 High Luminosity $\sqrt{s}$ = 14 TeV
L~5x10^{34} $cm^{-2}s^{-1}$, lumi leveling

$\int Ldt$~3000 fb^{-1}
Z' @ 5 TeV
Ultimate precision of Higgs properties

High luminosity LHC (HL-LHC)

"Europe's top priority should be the exploitation of the full potential of the LHC, including the high-luminosity upgrade of the machine and detectors with a view to collecting ten times more data than in the initial design, by around 2030"

The European Strategy for Particle Physics – March 2013
CERN-Council-S/106 *https://indico.cern.ch/getFile.py/access?resId=0&materialId=0&confId=217656*

→ Simillar statement in the report of the Particle Physics Project Prioritization Panel (P5)

To fully **exploit increase in available integrated luminosity** and decreased statistical uncertainty, try to maintain **same (or better) detector performance**

Fully replace current inner detector tracker (ITK)

Face challenges of HL-LHC: **Radiation damage**
Occupancy

Challenges: Radiation Hardness

- Below < 1 m radius: severe radiation damage to components
- Current ATLAS strip detector can endure
  fluences of only $2 \times 10^{14}\ n_{eq}/cm^2$ (1 MeV neutron equivalent / cm^2)

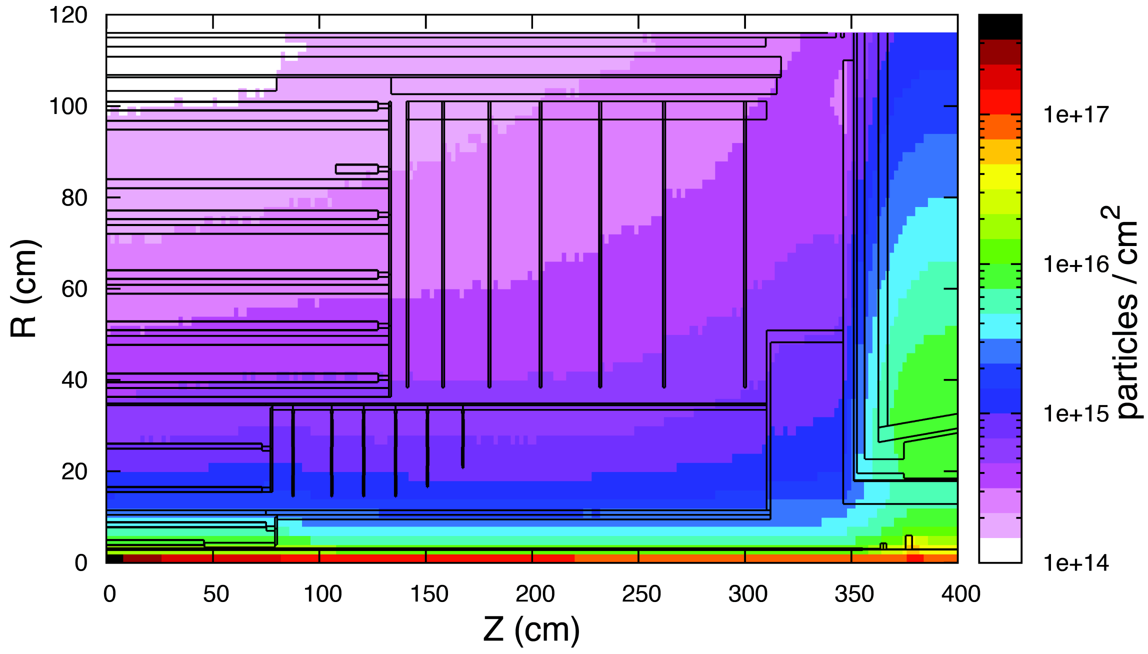
  corresponding to a luminosity of ~700 fb^{-1}

- Required for strip detector
  at the HL-LHC:

  fluence of $2 \times 10^{15}\ n_{eq}/cm^2$
  (expected: $8.1 \times 10^{14}\ n_{eq}/cm^2$, allow for safety margin)

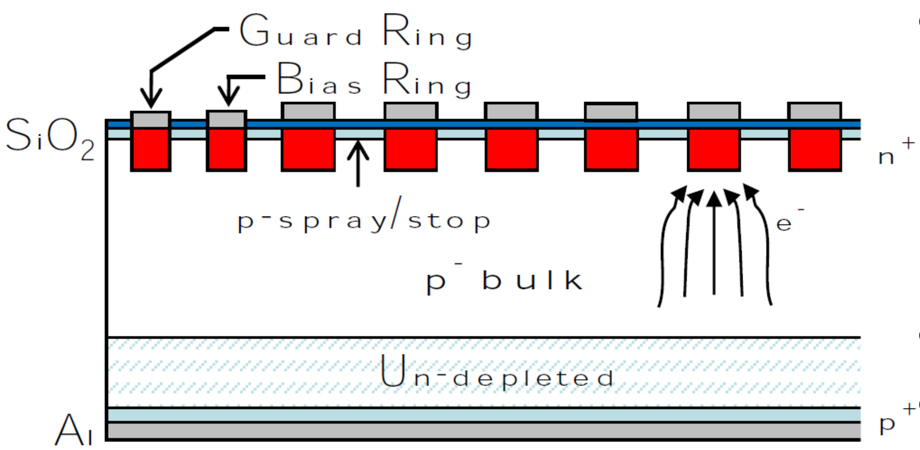
  luminosity of 3000 fb^{-1}
  (or even more)

1 MeV neutron equivalent fluence



Need: Radiation hard detector technology

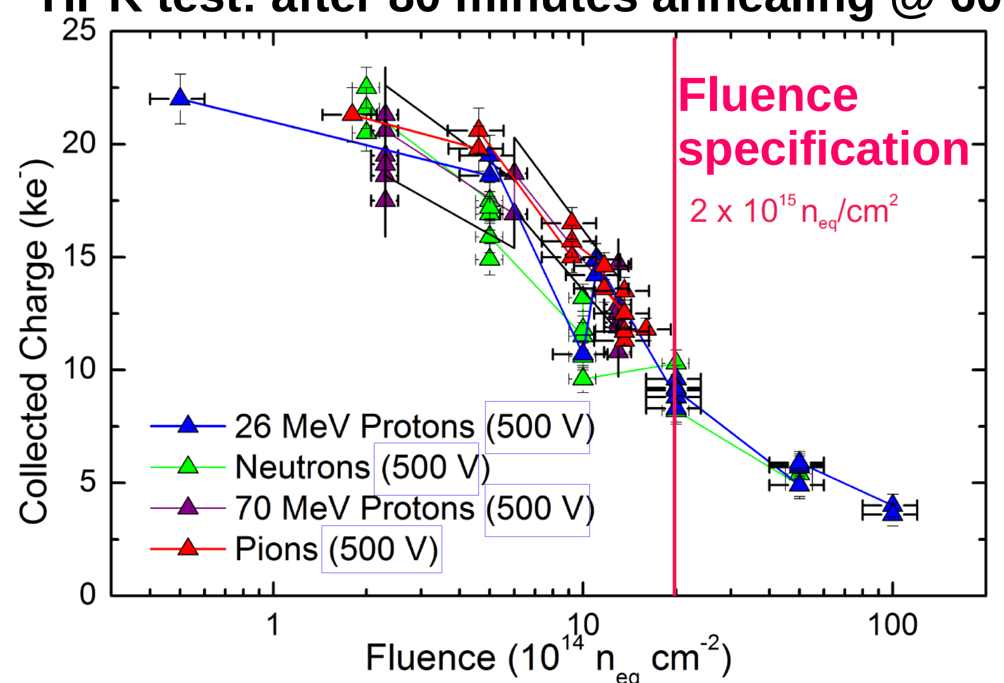
Current Solution: Sensors



- AC-coupled sensors with n-type implants in p-type float zone
  → electron collection, no type inversion
  (single sided process → cheaper)
- Barrel: ~98×98 mm^2 area, 74.5 μm pitch
- Endcap: varying size, similar pitch **(near bond pad)**

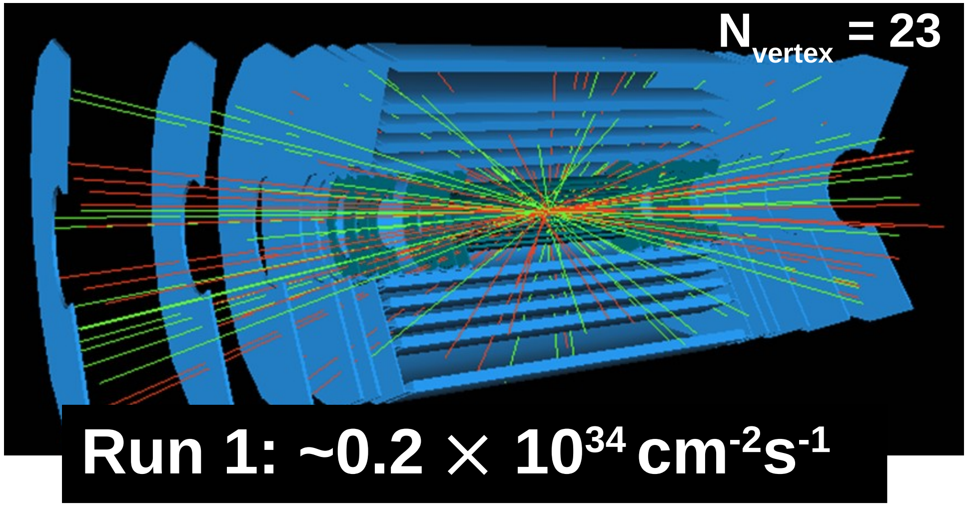
- Thickness: 320 ± 15 μm
  (could be reduced, additional costs)
- Prototype programme **(2008, 2012)**
- Signal to noise better than 10:1
  Barrel: 23-25
  Endcap: 17-26 *(radial strips!!)*
  Module tests: similar results
- Market surveys to investigate alternative suppliers

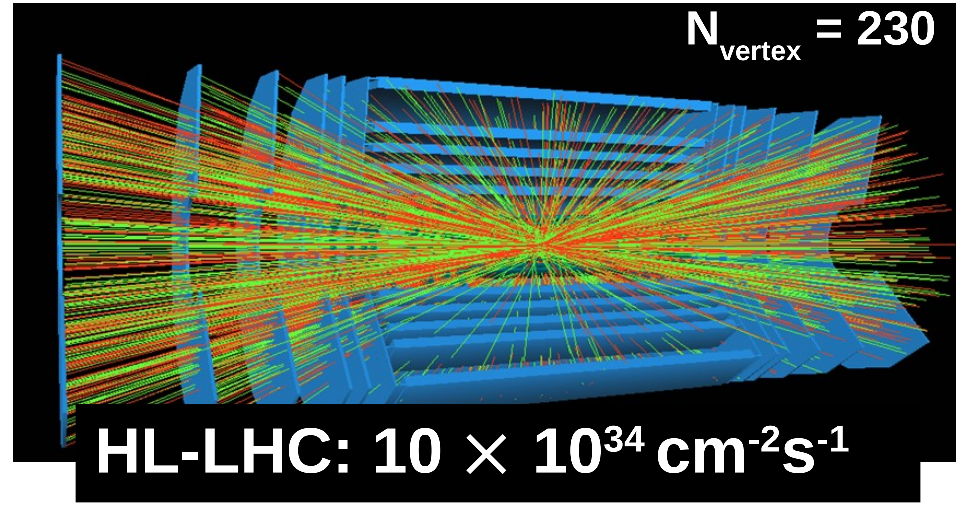
HPK test: after 80 minutes annealing @ 60°C

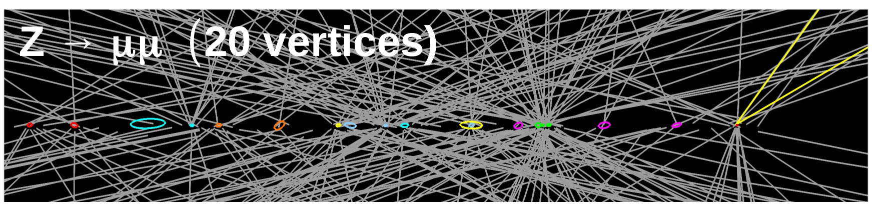


Up to 500 V_{bias} operation required

Challenges: Occupancy







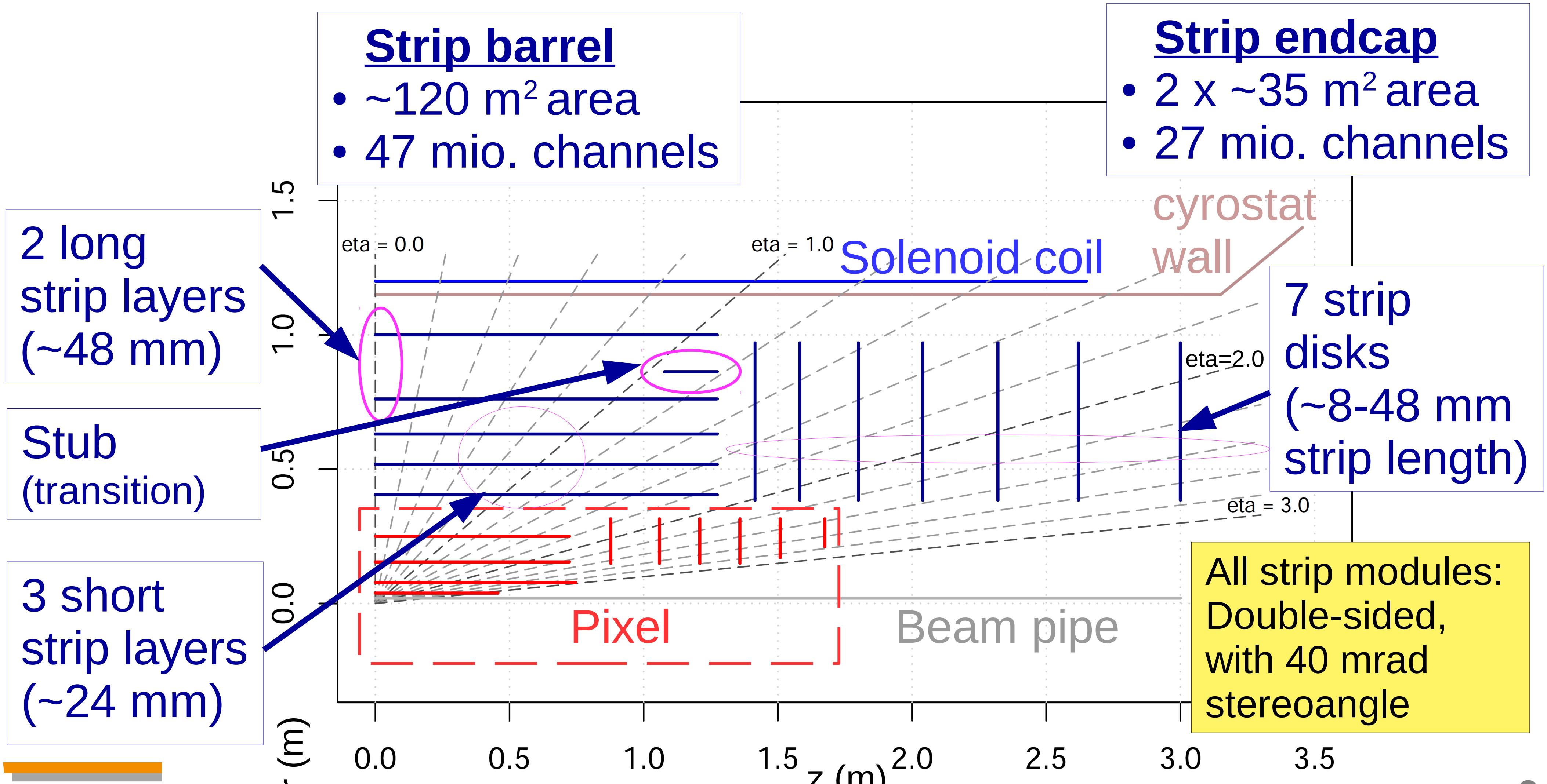
- Average N_{vertex} ~ <20>
- Run 1: Excellent performance
- *Current inner detector* working very well under *current conditions*

- Average N_{vertex} ~ <140> up to 230 multiple interactions, 1000 tracks per $\Delta\eta = 1.0$
- Challenge for > 1m radius are high Pile-up and trigger rates
- Data losses above $3 \times 10^{34}\ cm^{-2}s^{-1}$
  link between ABCD front-end chip and read out driver cards
- Increased reconstruction complexity

Need: High granularity

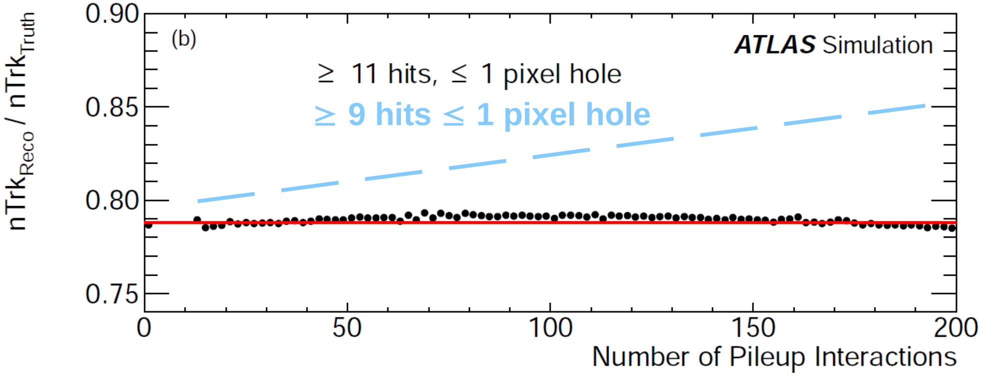
Current Solution: New Layout

- Larger outer active radius → improving momentum resolution
  Outer strip layer and disk are placed at largest possible r / z position
- Re-routing of services out of active area → decreasing dead material
- More layers, shorter strips at smaller radii → increased granularity

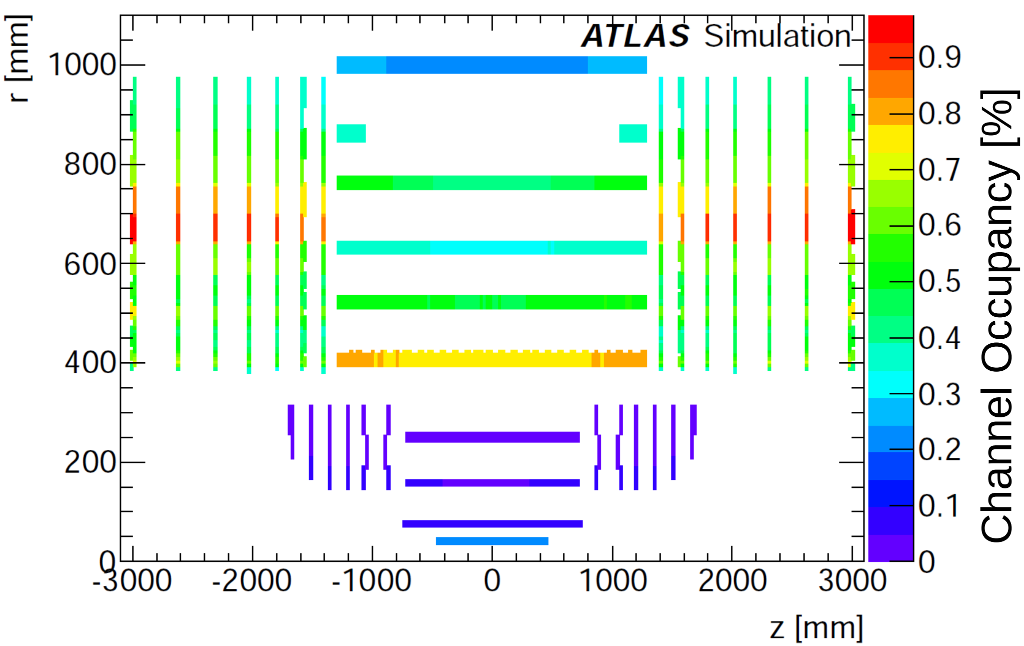


Simulation Results

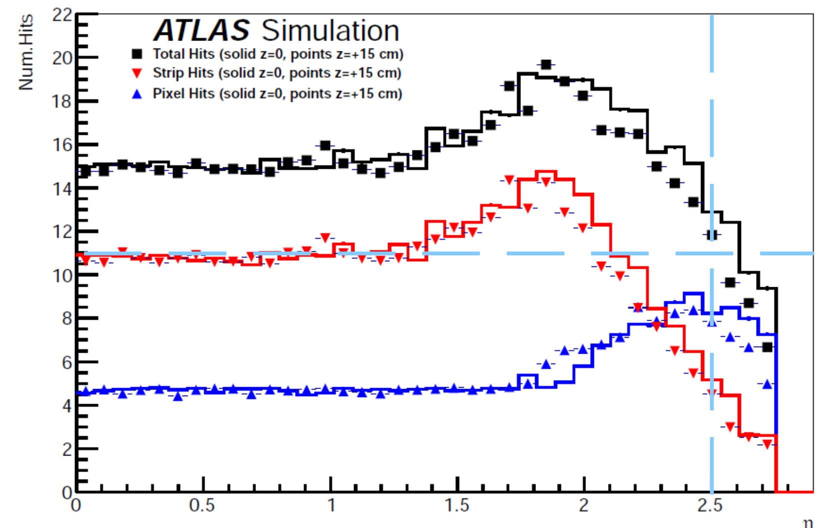
- Pile-up causes fake tracks, removed by requiring ≥ 11 hits



- Occupancy < 1% everywhere, even for 200 pile-up events



- Achieved up to $|\eta| = 2.5$, on average 14 hits in central barrel robust tracking despite dead modules

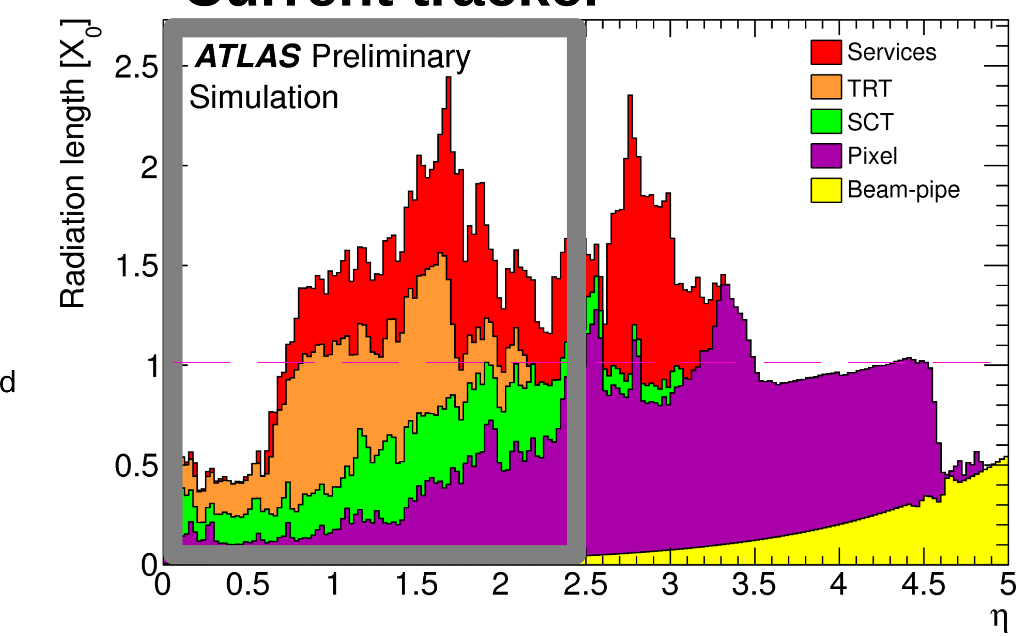


Track parameter (η)	Current tracker (for pT → ∞)	HL-LHC tracker (for pT → ∞)
q/p_T [/TeV]	**0.3**	**0.2**
d_0 [μm]	**8**	**8**
z_0 [μm]	**65**	**50**

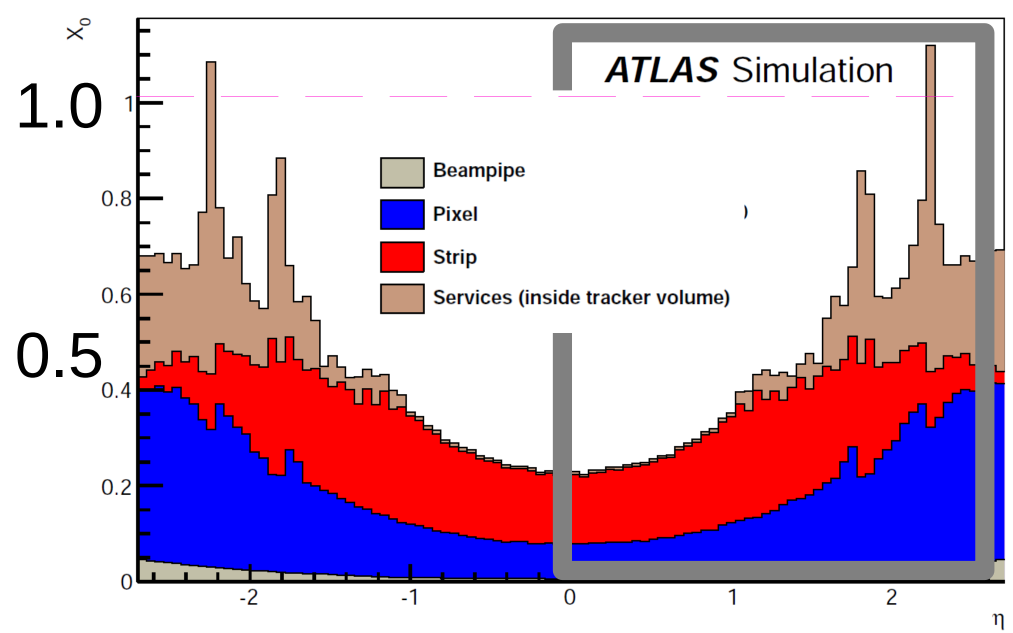
assuming: 200 *pp*-interactions

Material budget

Current tracker



HL-LHC tracker

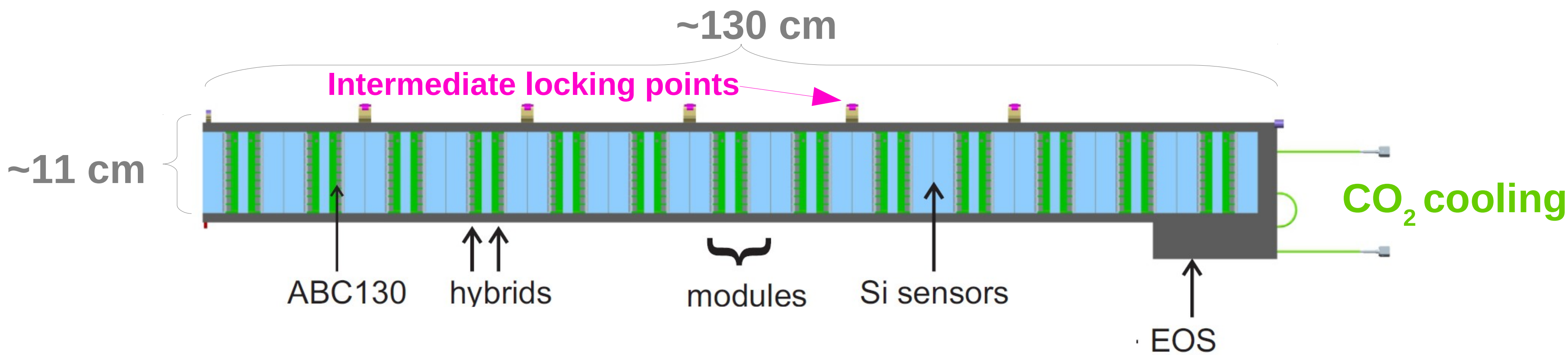


- New support structures (light carbon fibre) → Reduction of material
- Up to a factor of 2-3 for $\eta > 1.0$
- Will greatly reduce bremsstrahlungs losses for electrons, enhances performance

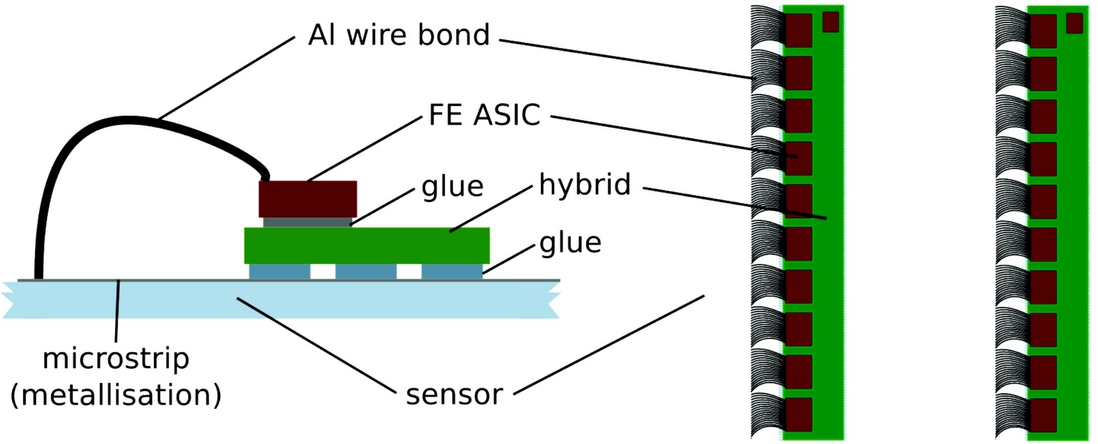
All Requirements are met with current layout
– but can we actually build it?

A closer look: Barrel...

- Barrel detector composed of *staves* (cooling and mechanical support)
- 26 modules (13 per side) glued on carbon composite structure form half-barrel (for A and C side respectively)



- Front-end chips ABC130 nm on kapton circuits → hybrid
- Glued and wire bonded to silicon sensor → module



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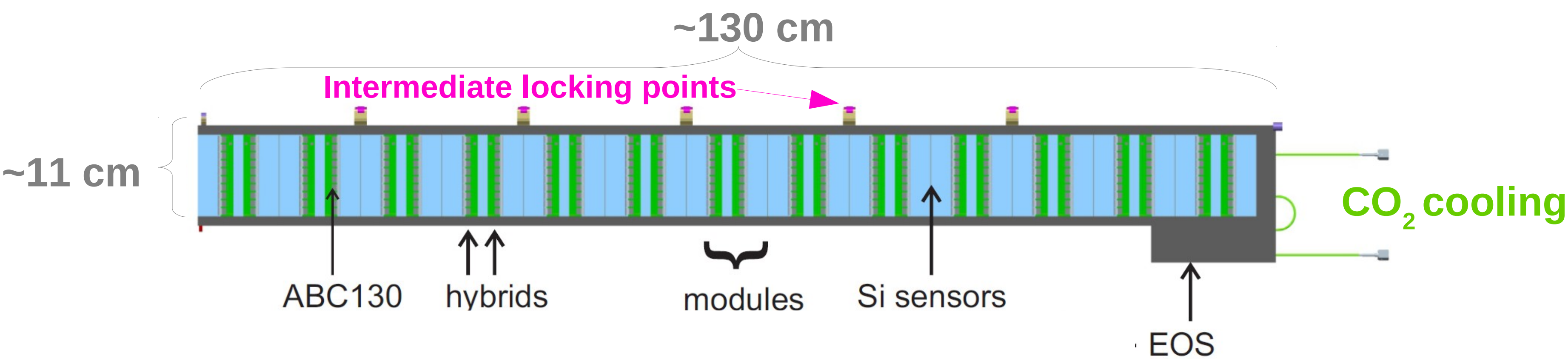
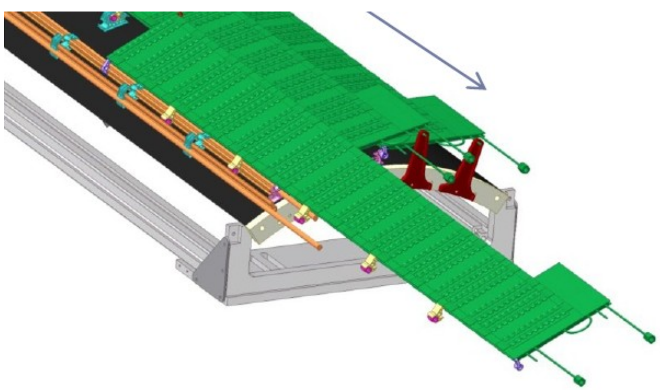
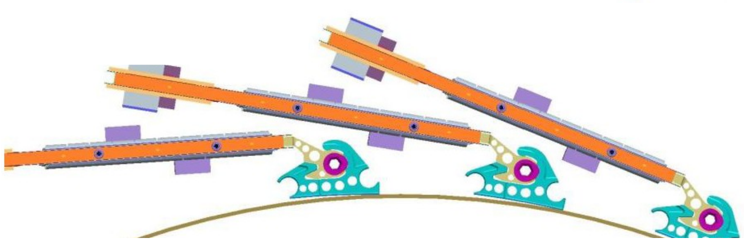






- Emphasis on high modularity, robustness

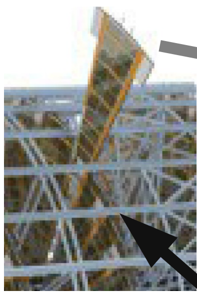
- Insert staves from end of barrel
  in pre-built support structures

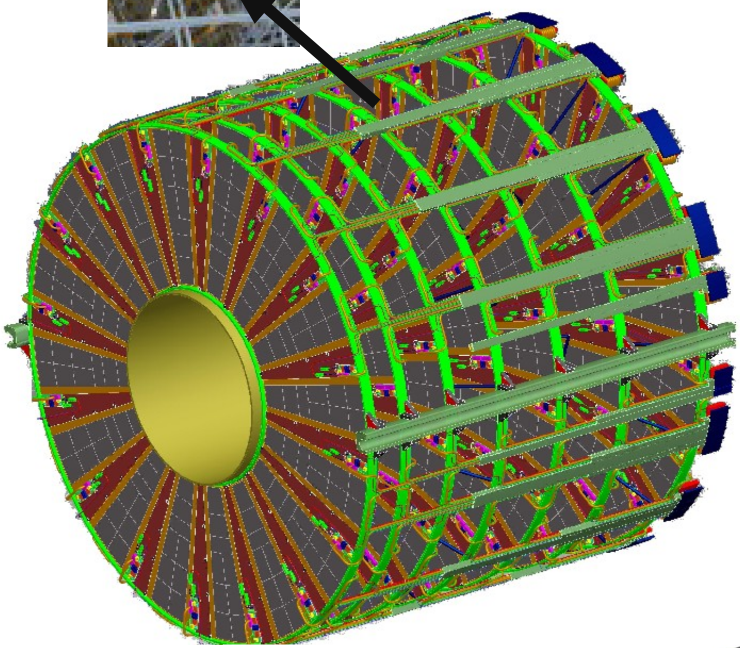
- Total: 472 staves, ~13000 modules

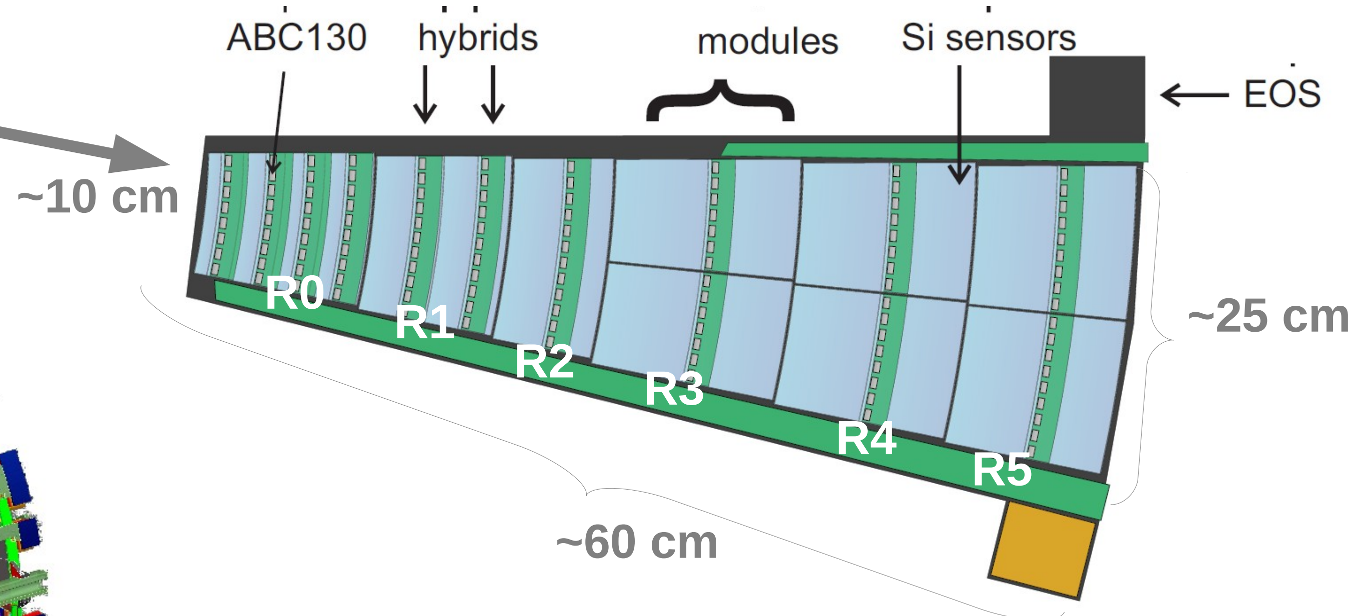
- Tilt angle $\geq 10^{o}$ → hermetic down to 1 GeV,
  minimise charge spread
  due to Lorentz-angle

… and Endcap

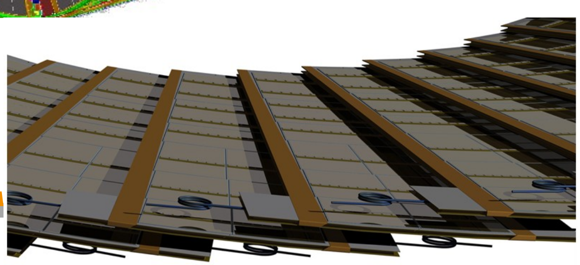
- Endcap detector composed of *petals* (same ideas as for barrel/staves)
- 7 wheels per end-cap, 32 petals per wheel, 18 modules per petal
  4032 modules per endcap



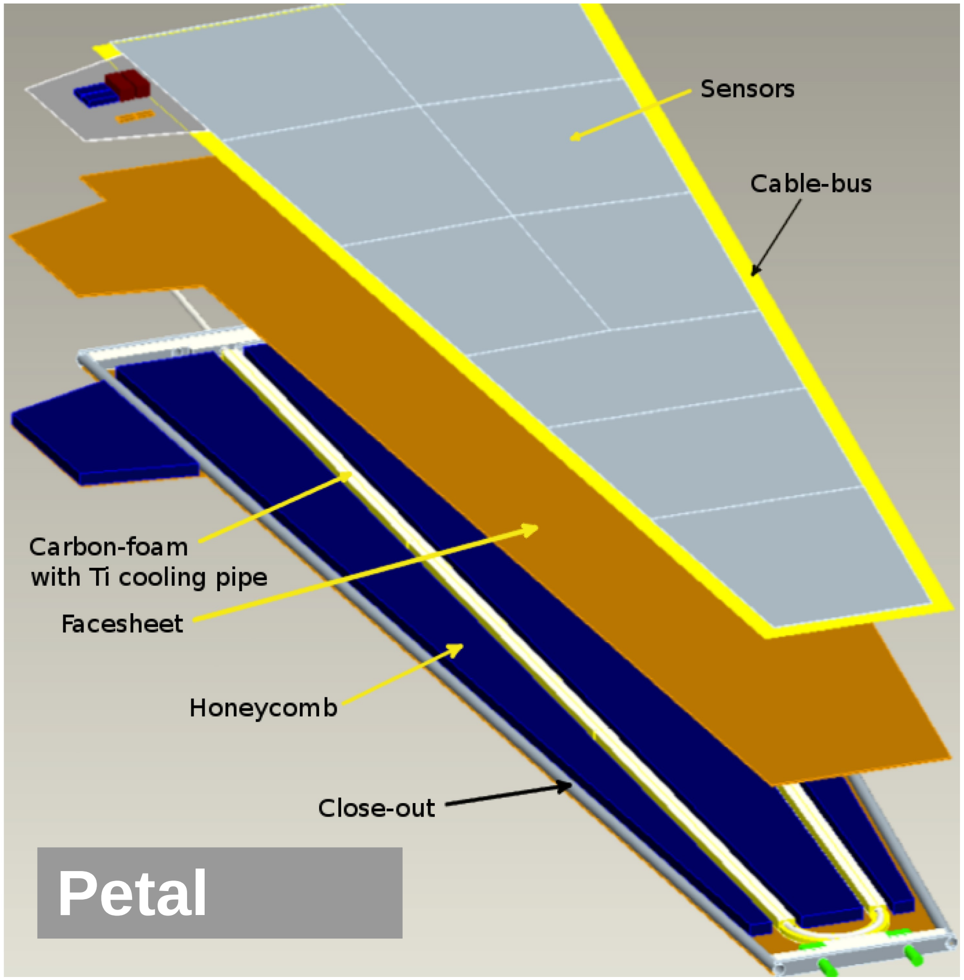




- Petal structures in six rings, R0-R5
- 6 sensor geometries, 14 hybrid variations
- Module arrangement:
  ←turbofan vs. on either side of wheel



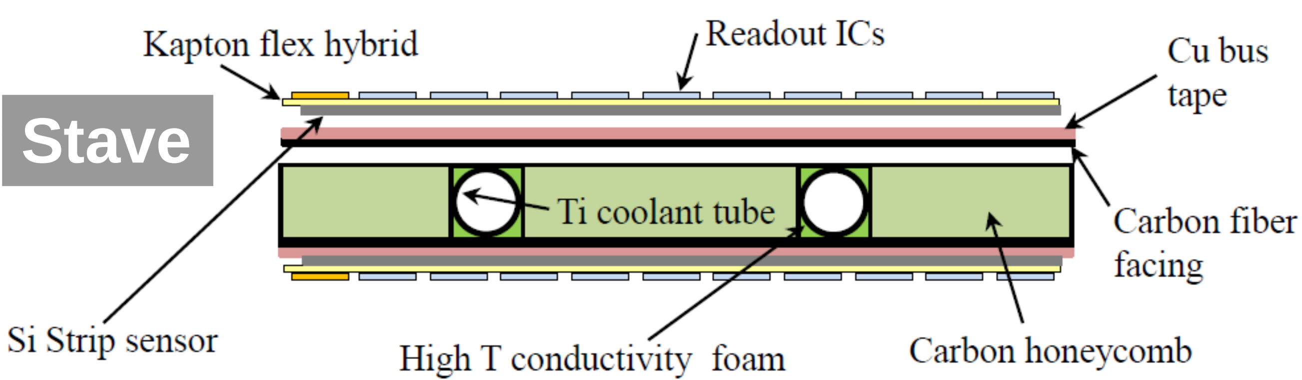
Support and cooling



- Carbon honeycomb + foam with embedded cooling pipe (CO^2)
- Co-cured bus tape for data and power
- Stave production very advanced
  (geometry stable, past R&D,
  ~final procedures in place for full staves)
- Petal core prototyping close to finish
  (need now full design of petal)

Stave: half the X0 is from module

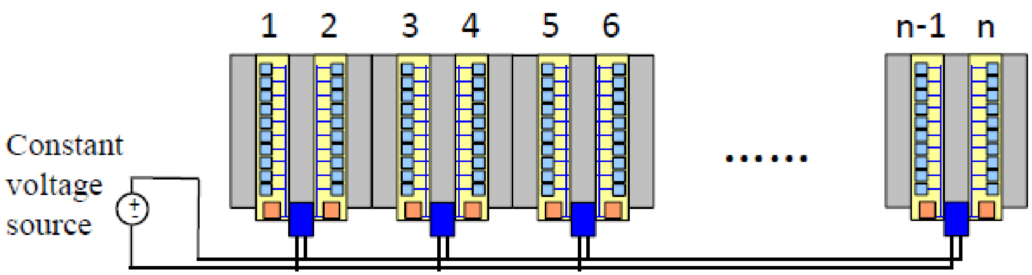
	%X0
Stave core	0.55%
Bus tapes	0.30%
Modules	1.07%
Module to stave adhesives	0.06%
TOTAL	**1.98%**

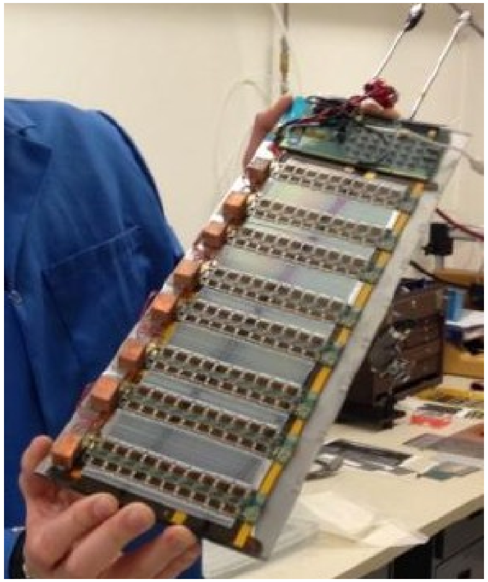


R&D: Small scale prototypes

- Utilize modularity of design → test small scale prototypes **(250nm ASIC)**
- Cost efficient, valuable insights: construction, glueing, tooling

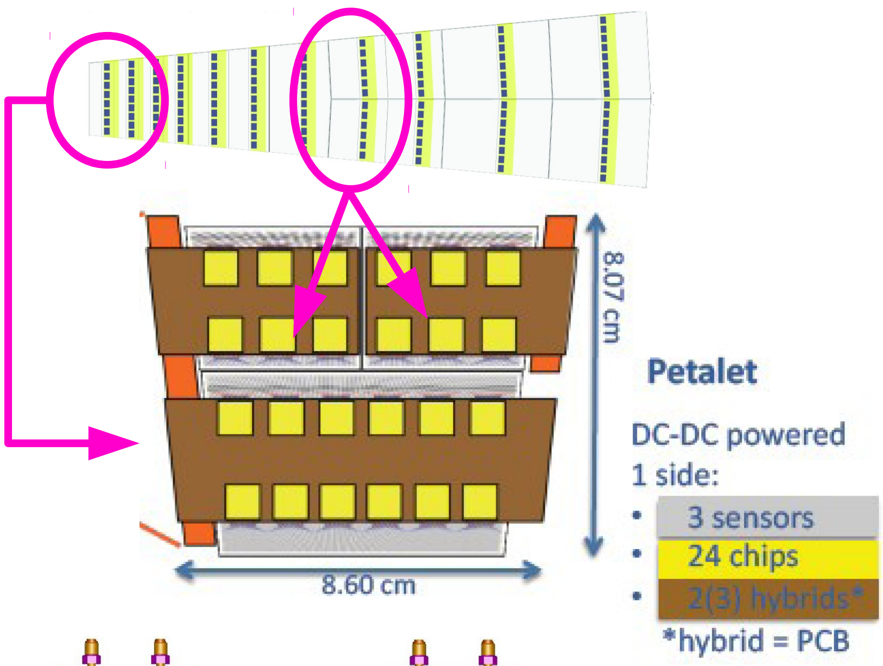
Stave → *Stavelet*

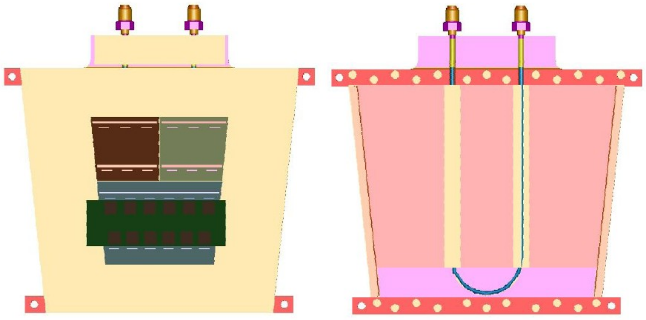




- 4 modules → 1 stavelet
- Full stave in construction

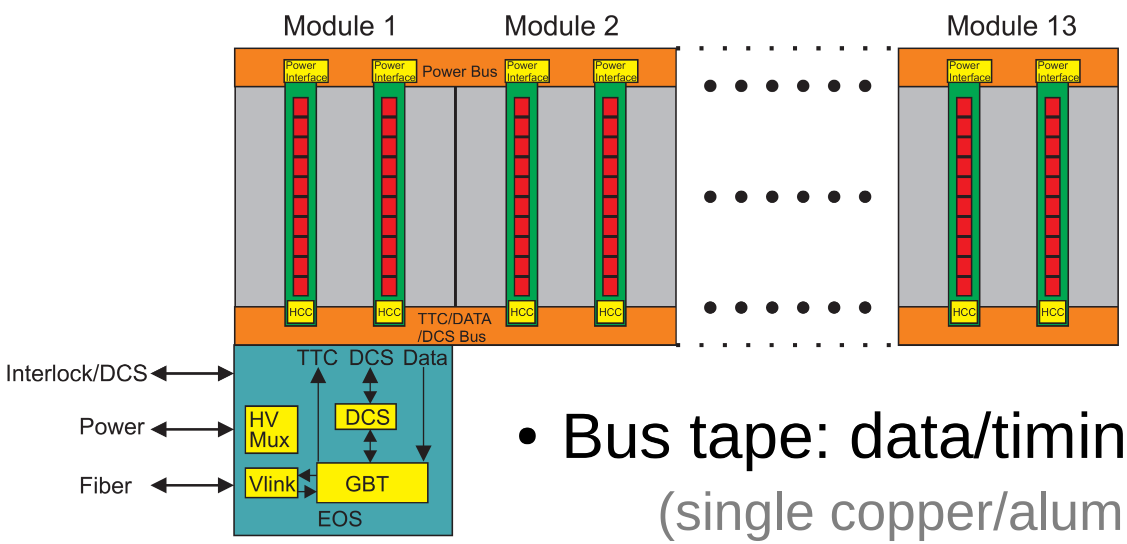
Petal → *Petalet*





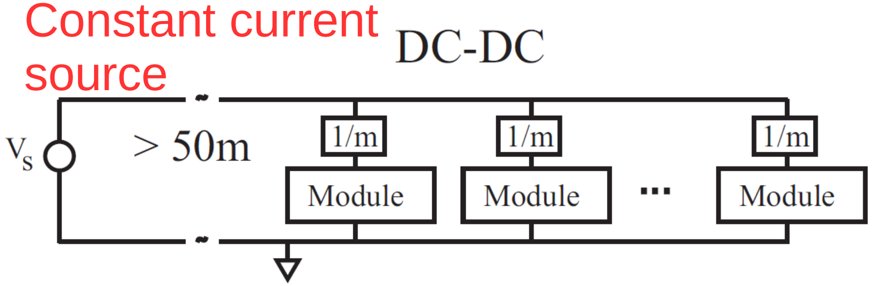
- 1 petalet: smallest module
  + transition of 1 → 2 sensor

Stavelet electrical tests

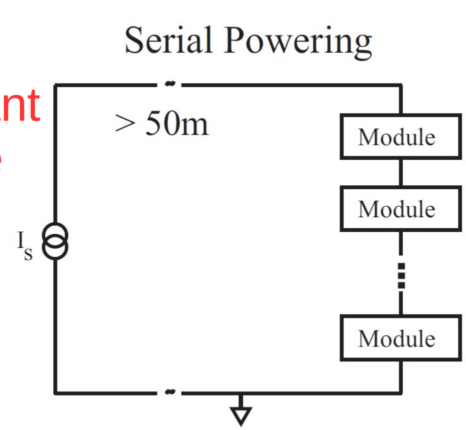


- 2 hybrids with 10 Chips
  (130 nm CMOS ASICs)
- Interfaced to EOS (end-of-stave) board with HCC (Hybrid Control)
- Bus tape: data/timing/trigger and power lines
  (single copper/aluminium/kapton tape laminated on core)

Constant current source

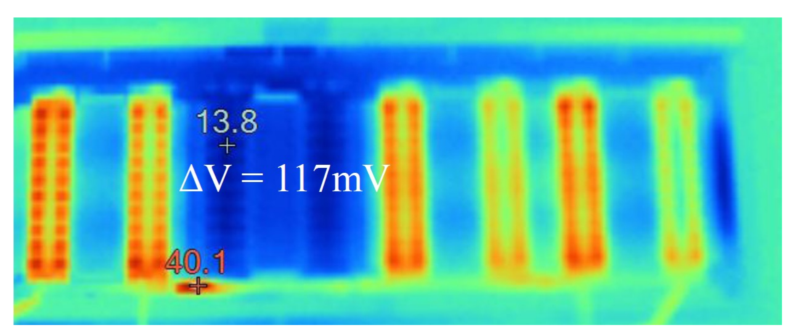


Constant voltage source



- DC-DC vs serial power (two-sided stavelet)
- Noise performance ok - comparable to single module powered by power supply
- Decision after test with proper ABC130 nm

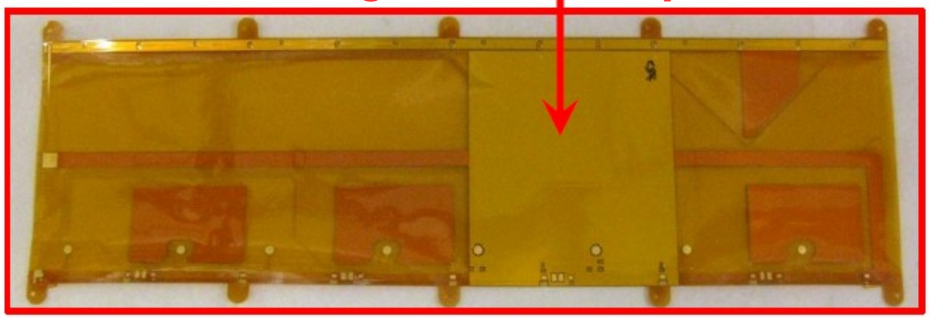
Radiation hard switches to turn off broken modules → *works!*



Stavelets: Materials

- Ideal test bed for for construction and design, e.g.:
  Shieldless bus tape: Remove Al shielding → carbon fibre as shild
  (8-10% material reduction from stave, cost reduction, curing easier)

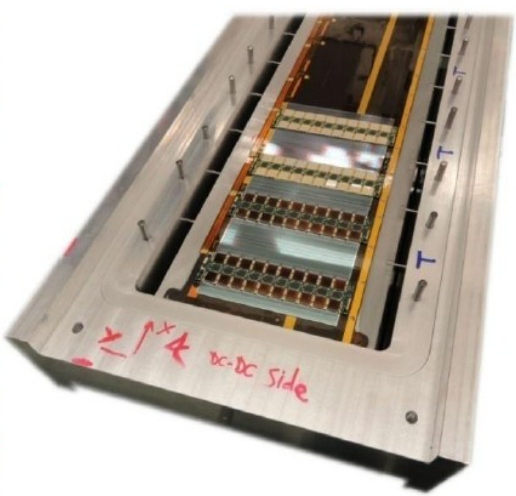
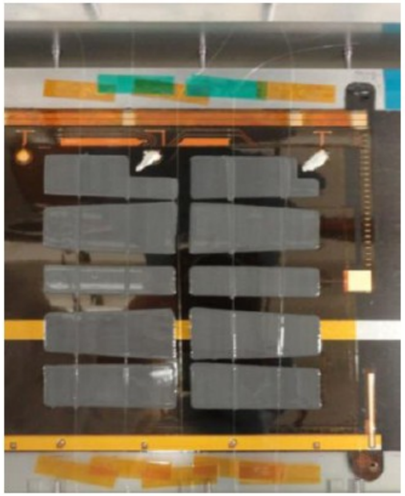
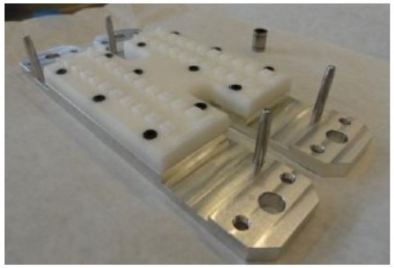
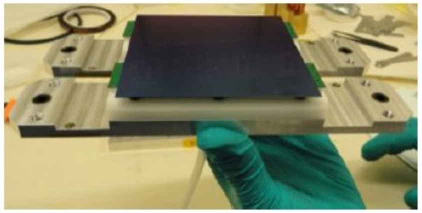
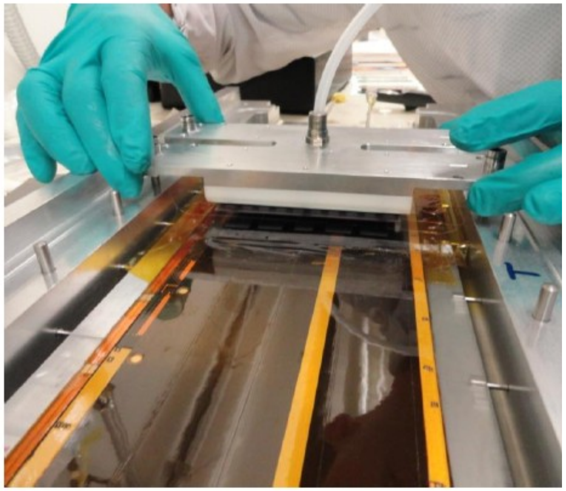
Shielding left for comparison



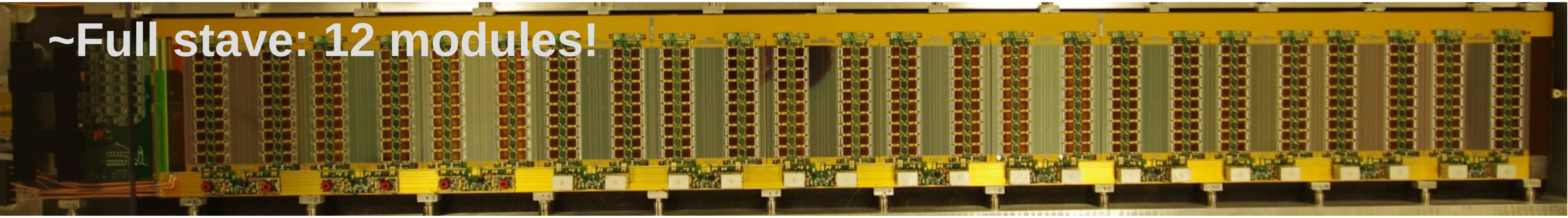
Shield-less tape

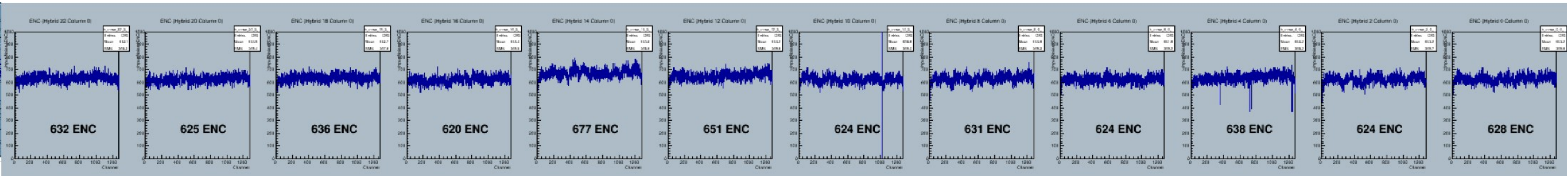
- New precision tools developed:
  Placement with X-Y precision with ~ 150 μm accuracy

- Glue thickness ~175 μm

Stavelets → Staves





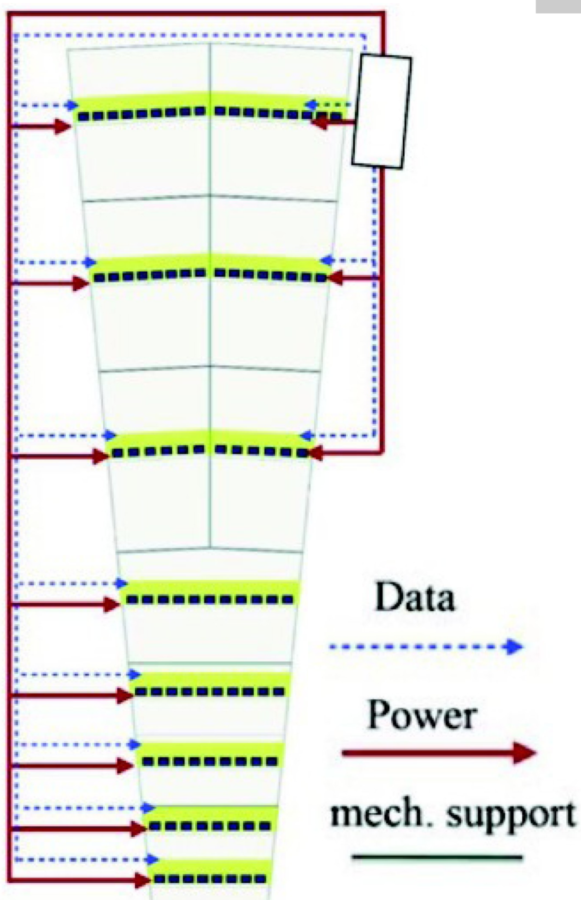
- DC-DC powered
- 4-segment power bus → each segment drives 4 modules
- Good noise behaviour → 600 – 677 ENC (equivalent noise charge)

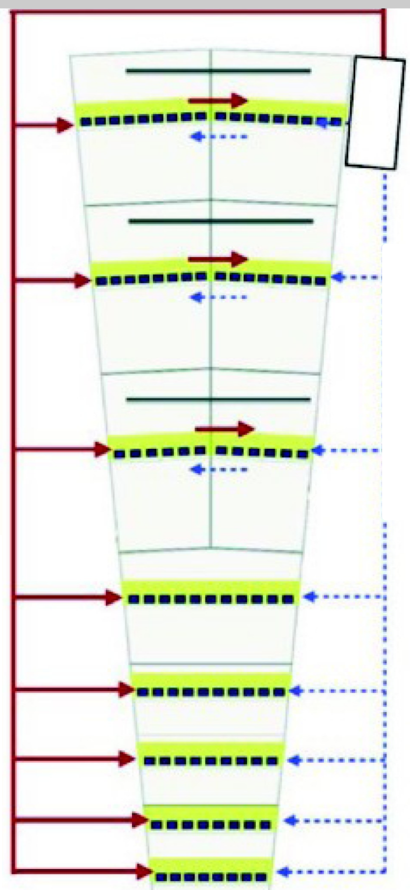
- Work in progress: *Full scale serial powered stave*

Petalet

- Split hybrids
- data/power lines from same end

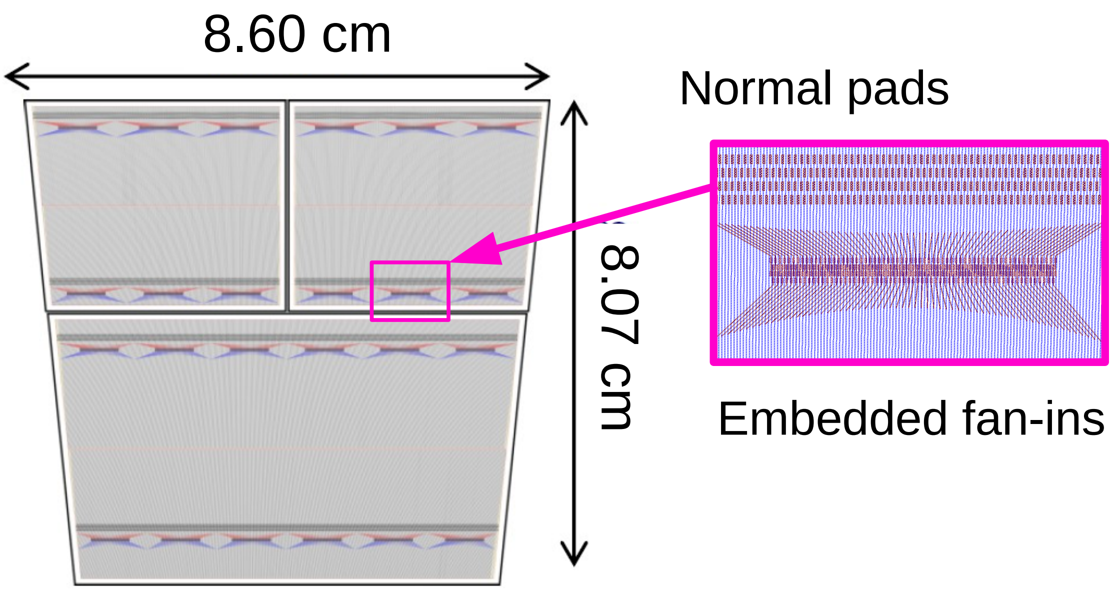
- 1 hybrids for 2 sensors
- data/power lines from two sides





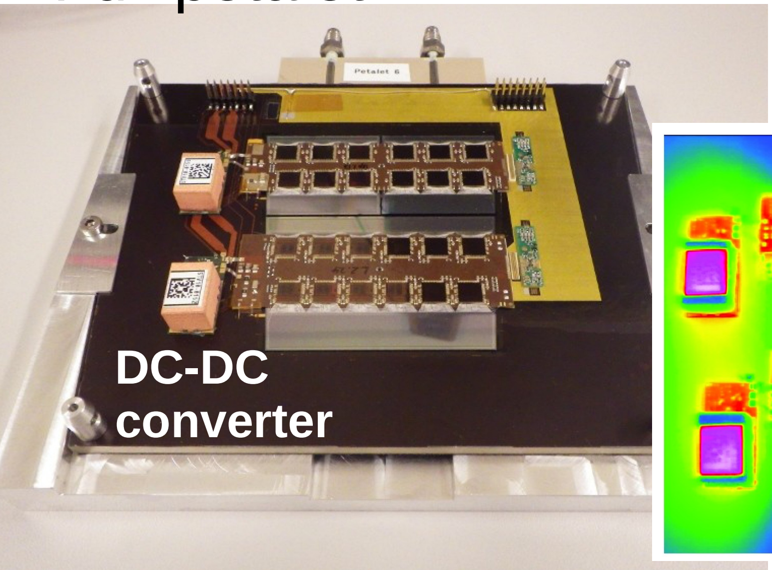
- Two design options: *Lamb&Flag* versus *The Bear*
- 2 neighbour modules: Significant differences to stavelet electrical layout
  (HV routing, DCDC location)
- Plan: → Build 10 petalets with 250 nm ASICs
- DCDC powering prefered: varying number of ABC130 → varying power to be delivered to hybrid
- serial powering requires shunts to dissipate energy

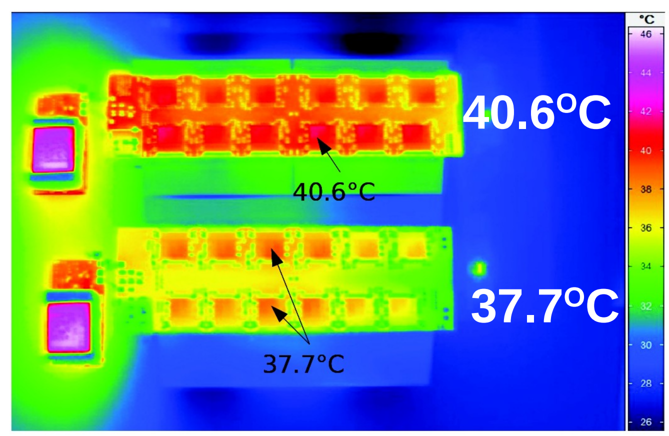
Petalet

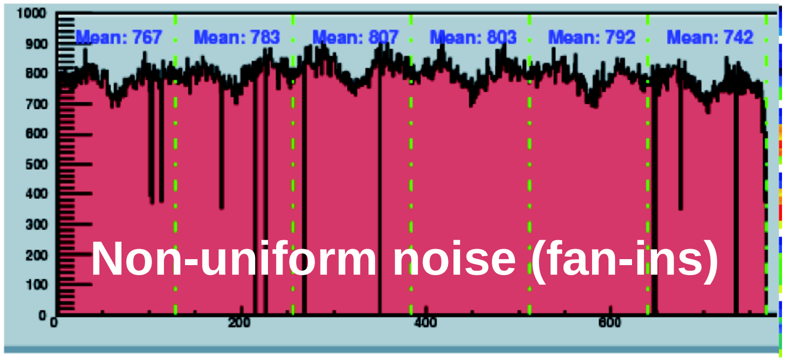


- This year: *First petalet* assembled and tested
- Some differences to stavelet → improved electrical layout
- Built-in stereo angle, fan-ins to bridge different strip pitch align Chip-Sensor pads
- Causes non-uniform noise

Full petalet

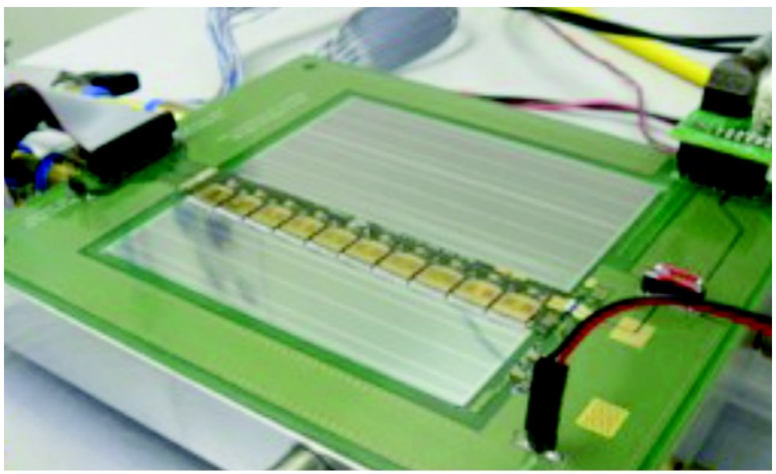




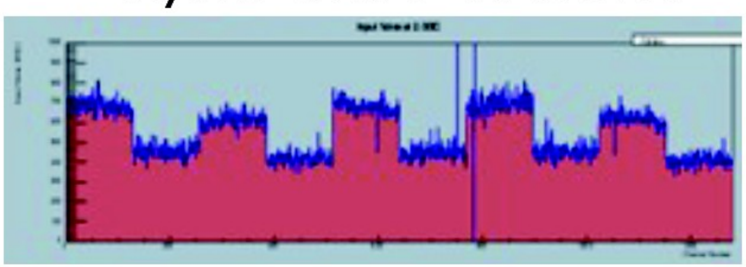


ABC130 nm

- Stavelet/Petalet R&D completed up to 80-90% using 250 nm Chips
- Advantages of 130nm technology: less power consumption
  less cooling needed → less material (cooling pipes/liquid...)



Hybrid with 5+5 ABC130



With one of two columns of strips bonded

- First tests with 130nm vs. 250nm:
  performance mostly as expected
- Hybrid/modules → already built
- Simpler wire-bonding
  → collaboration with chip designers
- Noise as expected, extremely regular

Conclusions

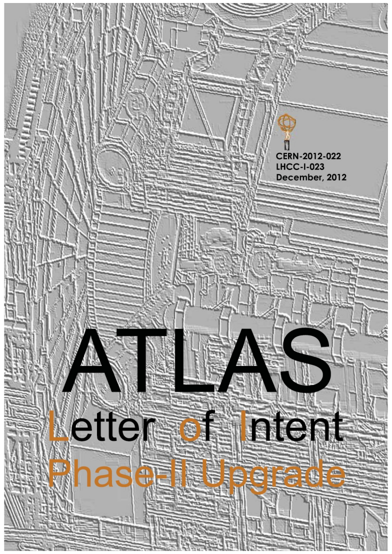
- Significant progress towards
  design and construction of a new inner tracker
  for the ATLAS experiment

- All challenges of the HL-LHC can be met!

- Fully modular approach, allows for substiantial
  testing (and assembly) of ~all components
  before insertion into support structures

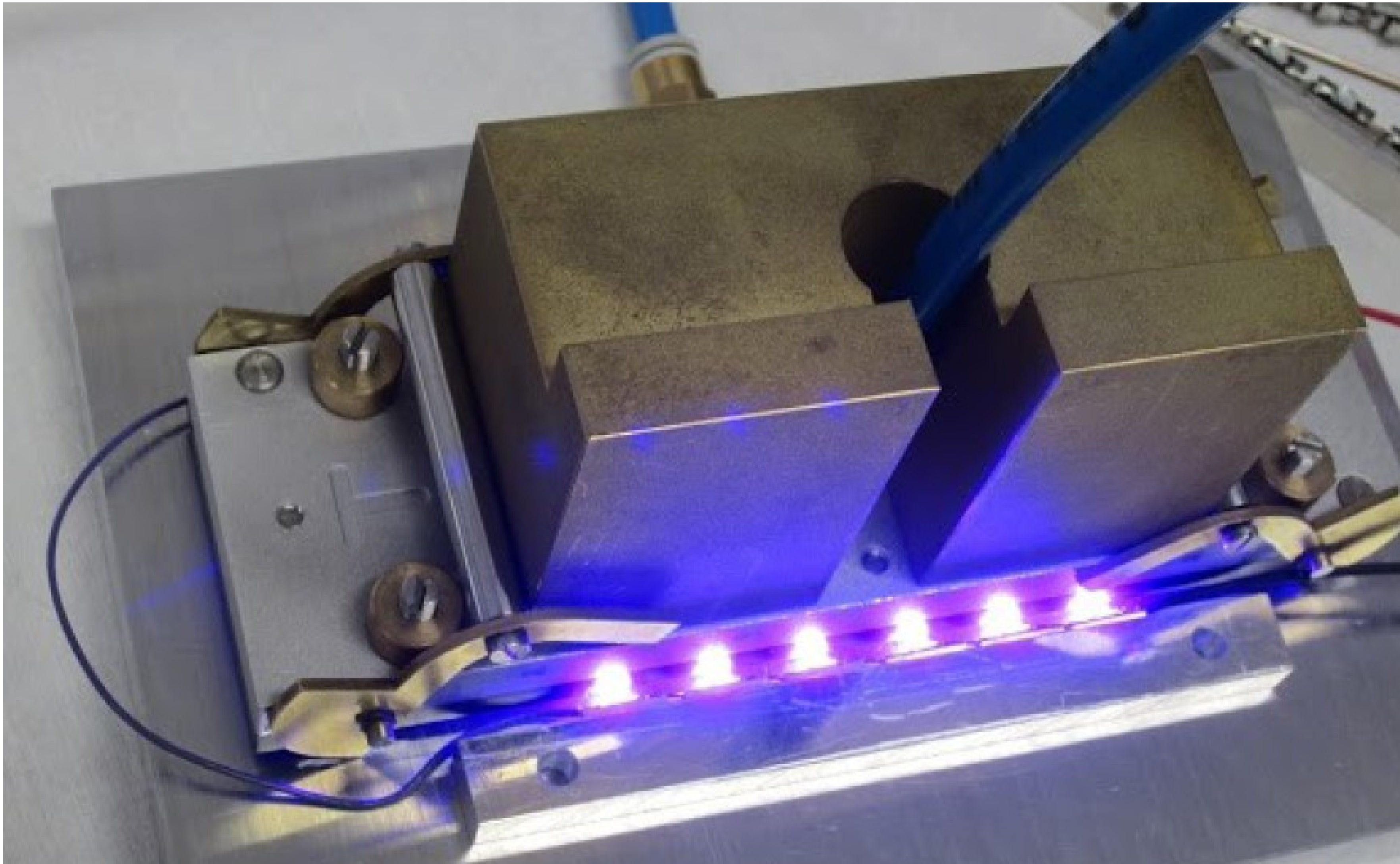
- Successfull R&D programme of small scale structures
  (stavelet and petalet) up to 80-90% completed

- Letter of Intent (2012) will be followed
  by Technical Design Report, envisaged date: 2016



Thank you!

UV Glueing



2015	2016	2017	2018	2019

Design and fabrication of tools

Petal sub assemblys

Petal fabrication

LHC Upgrade Plans

2009 2012	LHC Startup	$\sqrt{s}$ = 7~8 TeV L = 6 x $10^{33}cm^{-2}s^{-1}$, BS=50 ns
Phase 0	Go to nominal energy New beam pipe, additonal b-layer (IBL)	
2015 2018	LHC Design Parameters	$\sqrt{s}$ = 13~14 TeV L~1x$10^{34}cm^{-2}s^{-1}$, BS=25 ns
Phase 1	Injector Upgrade New Muon Small Wheels, Fast Track Trigger	
2019 2021	Ultimate Luminosity	$\sqrt{s}$ = 14 TeV L~2x$10^{34}cm^{-2}s^{-1}$, BS=25 ns
Phase 2	Upgrade, interaction regions, crab cavities? Replacement of inner detector, calo/muon upgrades, L1 track trigger	
2025 2035	High Luminosity	$\sqrt{s}$ = 14 TeV L~5x$10^{34}cm^{-2}s^{-1}$, lumi leveling

$\int Ldt$~25 fb^{-1}
Discovery of Higgs boson

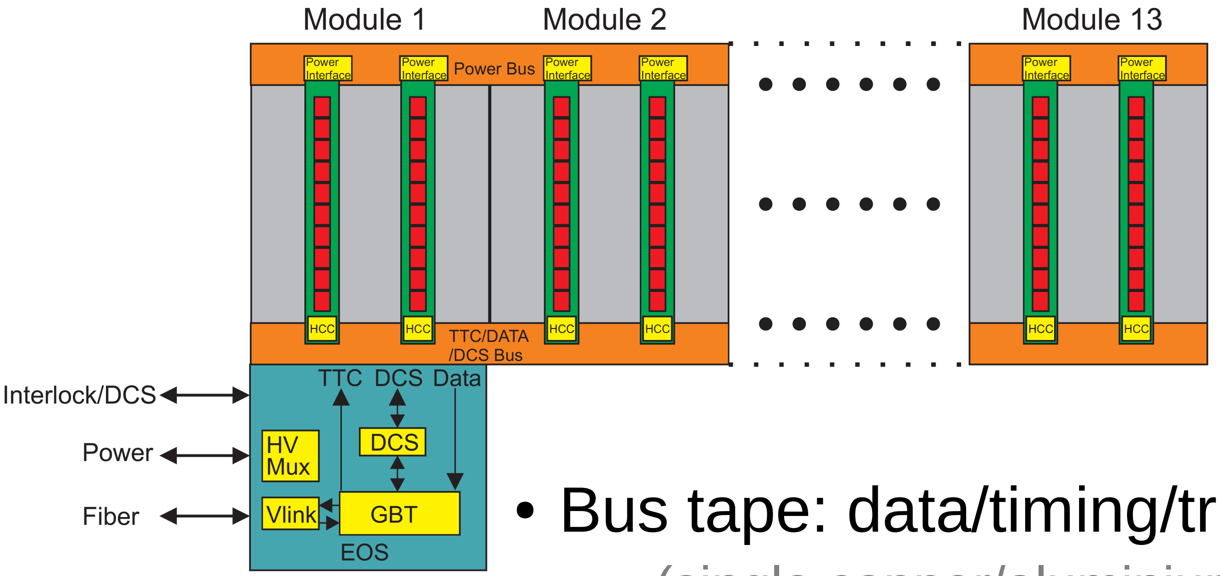
TODAY!

$\int Ldt$~75-100 fb^{-1}
Extra dimension@9 TeV
Compositeness@30 TeV
Leptoquarks m=1.5TeV

$\int Ldt$~350 fb^{-1}
Compositeness@40 TeV
TeV resonances in WW scattering

$\int Ldt$~3000 fb^{-1}
Z' @ 5 TeV
Ultimate precision of Higgs properties

Stavelet electrical tests



- 2 hybrids with 10 Chips (130 nm CMOS ASICs)
- ABC130 interfaced to EOS (end-of-stave) board with HCC (Hybrid Control Card)
- Bus tape: data/timing/trigger and power lines (single copper/aluminium/kapton tape laminated on core)

The EOS has a GigaBit Transceiver (GBT) [31] that interfaces with the HCCs and a Versatile link (Vlink) [71]) fibre optic driver. LV and HV power connect to the EOS and are distributed to each hybrid via a power bus. A power interface connects each hybrid to the power bus. The nature of the power interface will depend upon which power architecture is chosen, either serial power or DC-DC conversion. There may be several detector slow control (DCS) links that communicate with each power interface from the EOS. DCS interlocks will also connect to the EOS from the overall ATLAS DCS system.