ATLAS ITk Strip Detector for High-Luminosity LHC

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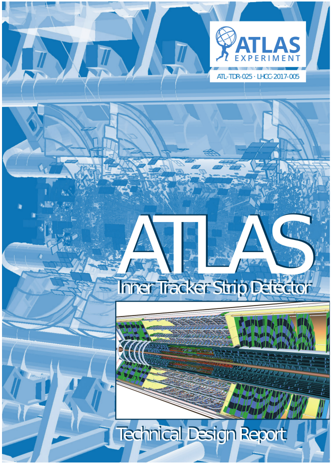
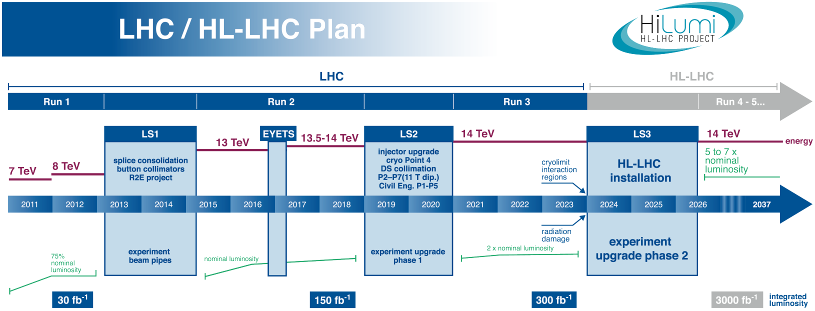
ATLAS ITk Strip project - outline of presentation

- Upgrade of ATLAS inner tracker - motivation and requirements
- ATLAS Inner Tracker (ITk) Strip detector design and components
- Evaluation of individual detector components and structures
- ATLAS Inner Tracker Strip Detector - Technical Design Report (approved public document, link)



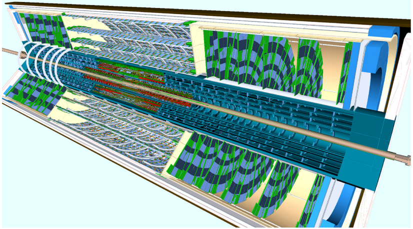
ATLAS Upgrade project

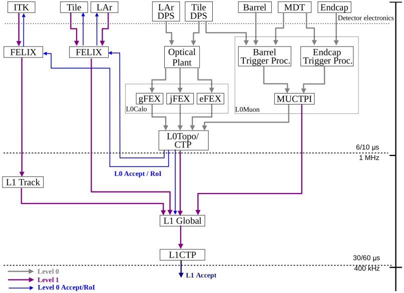


- ATLAS Upgrade is a very complex project planned in 3 phases corresponding to 3 long technical shutdowns of the LHC accelerator
  - LS1 (Q2/2013 - Q1/2014 / 2 years) - ATLAS Upgrade Phase 0
  - LS2 (Q1/2019 - Q4/2020 / 2 years) - ATLAS Upgrade Phase 1
  - LS3 (Q1/2024 - Q2/2026 / 2.5 years) - ATLAS Upgrade Phase 2

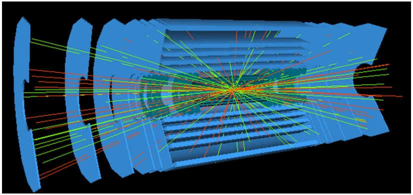
ATLAS Upgrade project - Phase II

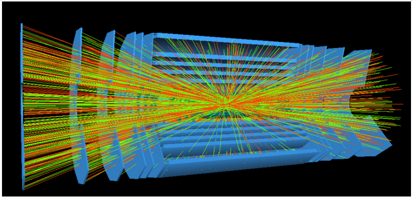
- Upgrade of LHC accelerator to HL-LHC
  - HL-LHC parameters: $\mathcal{L}_{\text{peak}} \sim 5 - 7.5 \times 10^{34}\ \text{cm}^{-2}\text{s}^{-1}$, $\langle \mu \rangle \sim 200$, 25 ns between bunch crossings, $\mathcal{L}_{\text{int}} \sim 3000(4000)\ \text{fb}^{-1}$
- New ATLAS Inner Tracker - current ATLAS Inner Detector (ID) will be replaced with new all-silicon Inner Tracker (ITk)
- Trigger - new design of Phase II Trigger system with L0 trigger layer (including FELIX readout)





ATLAS ITk - motivation and requirements

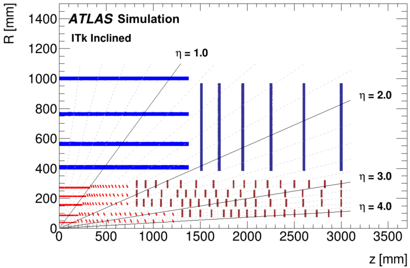


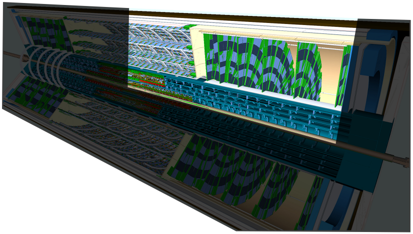


- Radiation damage
  - ID PIX designed for $\sim 400\ \mathrm{fb}^{-1}$, ID SCT $\sim 700\ \mathrm{fb}^{-1}$ and IBL $\sim 850\ \mathrm{fb}^{-1}$
  - HL-LHC should deliver $\sim 3000(4000)\ \mathrm{fb}^{-1}$
- Bandwidth saturation
  - ID designed to accommodate $\langle\mu\rangle \sim 50$ corresponding to $\mathcal{L} = 2 \times 10^{34}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$
- Detector occupancy
  - increased granularity is required for $\langle\mu\rangle \sim 200$ to keep the ITk detector performance at the same level as for current inner detector
- Track Trigger
  - current L1 HW trigger doesn't contain tracking information
  - tracking information added to trigger objects provided by calorimeters and muon system would benefit physics performance

ATLAS EXPERIMENT

ITk Layout



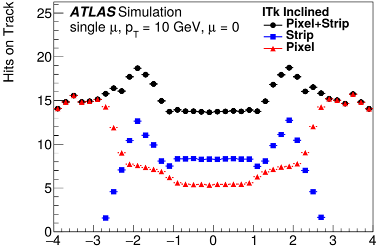


- ITk Pixel detector
  - 5 barrel layers with central sensors placed tangential to a circle of constant radius and inclined sensors in the forward parts of barrel
  - pixel end-cap (EC) system containing individually located rings
- **ITk Strip detector**
  - 4 barrel layers with all sensors placed tangential to a circle of constant radius
  - 6 EC rings on both forward regions

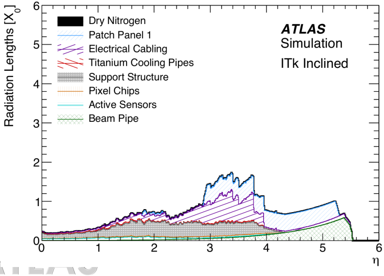
ATLAS EXPERIMENT

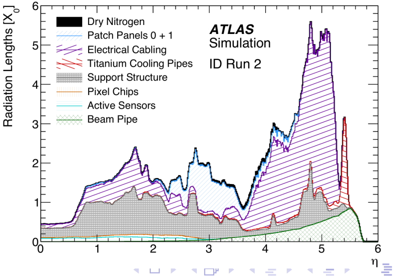
ITk Layout

- designed to satisfy the requirements on tracking performance, material distribution in X_0 and physics studies



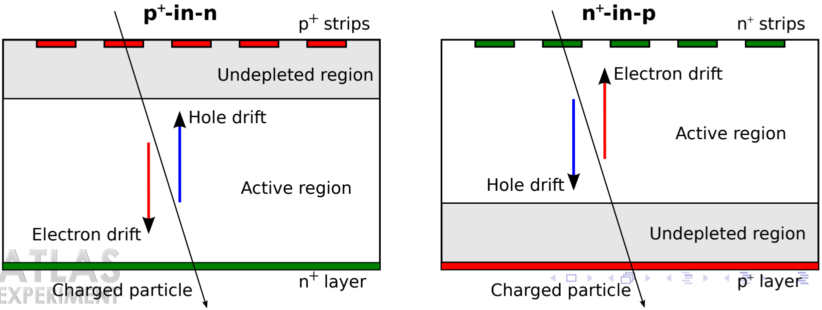
Requirement	Pseudorapidity interval	
	$\|\eta\| < 2.7$	$2.7 < \|\eta\| < 4.0$
Pixel+Strip clusters	≥ 9	≥ 9
Pixel clusters	≥ 1	≥ 1
Holes	< 3	< 3
Pixel holes	< 2	< 2
Strip holes	< 3	< 3
Double Strip holes	< 1	
p_T [MeV]	> 900	> 400
$\|d_0\|$	≤ 2 mm	≤ 10 mm
$\|z_0\|$	≤ 25 cm	≤ 25 cm





ITk Strips: Sensors

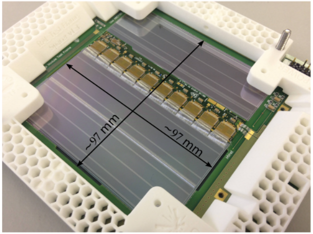
- **(+)** Tolerance against radiation bulk damage - no p-bulk type conversion, partial depletion possible, in the range of $8 - 10 \times 10^{14}\ \mathrm{n_{eq}/cm^2}$ factor of 2 more charge compared to SCT
- **(+)** collecting electrons (fast charge carriers)
- **(+)** single-sided process - easier processing, handling and testing, cheaper and much more available
- **(-)** n-side insulation (p-spray, p-stop) against electron layer in the surface attrated to the positive charges in the Si-SiO$_2$ interface
- **(-)** sensor edges at the bias potential

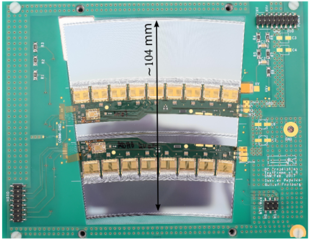


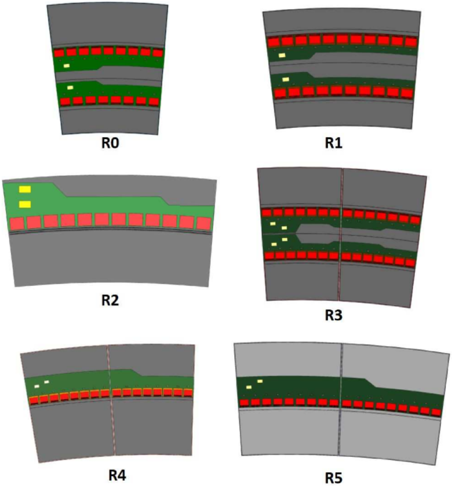
ATLAS EXPERIMENT

ITk Strips: Sensors n^+-in-p FZ

- 2 types of barrel sensors: size $\sim 97 \times 97\ \mathrm{mm}^2$, strip pitch 75.5 $\mu\mathrm{m}$, long strip (LS) with 48.20 mm strips, short strip (SS) with 24.10 mm
- 6 types of EC sensors: variable shapes of R0 - R5 sensors, strip pitch 69 - 84 $\mu\mathrm{m}$

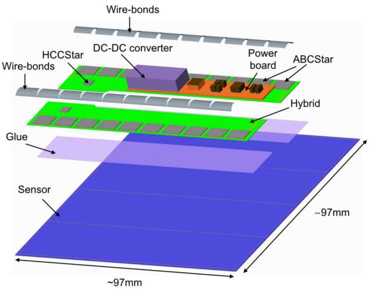


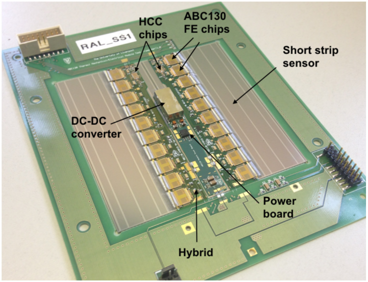




ITk Strips: Module as the basic detector unit

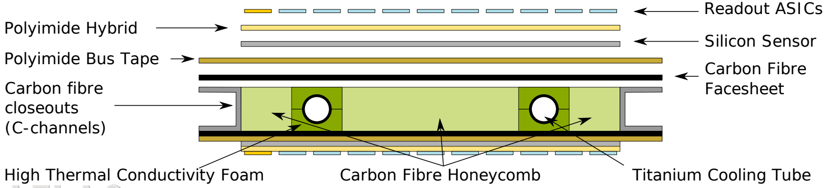
- Strip silicon sensor of n^{+}-in-p FZ type
- low-mass PCB hybrid with ABCStar (ATLAS Binary Chip) and HCCStar (Hybrid Controller Chip) ASICs
- Power-Board including DC-DC LV Power Block controlled witch upFEAST chip, AMAC (Autonomous Monitored and Control Chip) and HV multiplexer with HV filter
- Glues - UV curable glues and (silver) epoxy glues
- Aluminium wire-bonds (thickness of $25\ \mu\text{m}$)



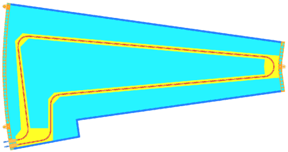


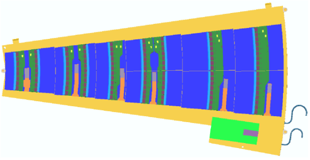
ITk Strips: Local support - Staves and Petals

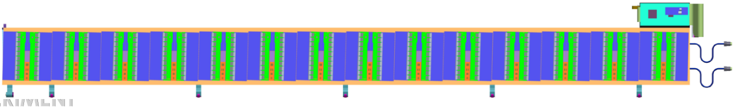
- Staves (barrel) and Petals (EC) provides mechanical, geometric, thermal and electrical support to modules
  - **mechanical and geometric**: local supports interface to global support structures through a series of position locators and locking points
  - **thermal**: titanium cooling tubes connected to CO_2 cooling system working with temperatures between $+20°C$ and $-40°C$
  - **electrical**: electrical power (LV and HV), TTC (Timing, Trigger and Control) data, DCS (Detector Control System) data and measured data transfer services required by the modules are carried by a copper/kapton bus tape mounted on both sides of structure and operated by EoS (End of Substructure) card



- 28 barrel modules on each stave (14 modules per side), short strips on inner two cylinders, modules on each side of the stave are rotated with respect to the beam line by a $\pm 26\ \mathrm{mrad}$ - total rotation of $52\ \mathrm{mrad}$
- 18 EC modules on each petal (9 modules per side, rings R0 - R5), stereo angle of 20 mrad directly implemented in sensor geometry - total stereo angle of 40 mrad

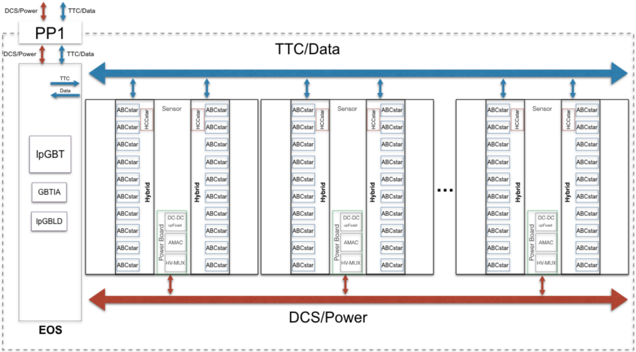




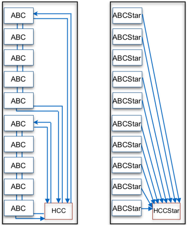


ITk Strip: Electronics Architecture

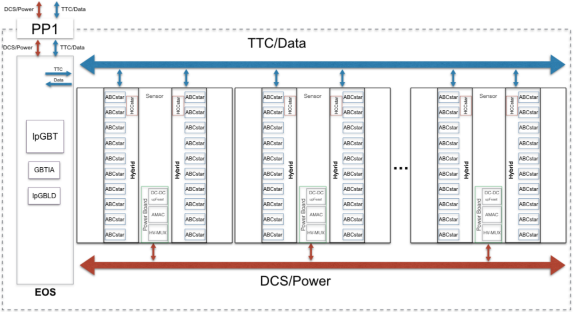
- ITk module: Si Sensor, Hybrid, PowerBoard
  - Hybrid: ABCStar ASIC, hybrid-side bus, HCCStar ASIC
  - PowerBoard: LV DC-DC power block with upFEAST, AMAC, HV Multiplexer
- ITk Stave/Petal: Bus Tape, End-of-Substructure Card
- Barrel/EC global support structure: Patch Panel 1



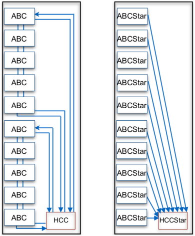
Comparison of daisy chain signal routing of prototype ABC130 ASICs and new ABCStar design

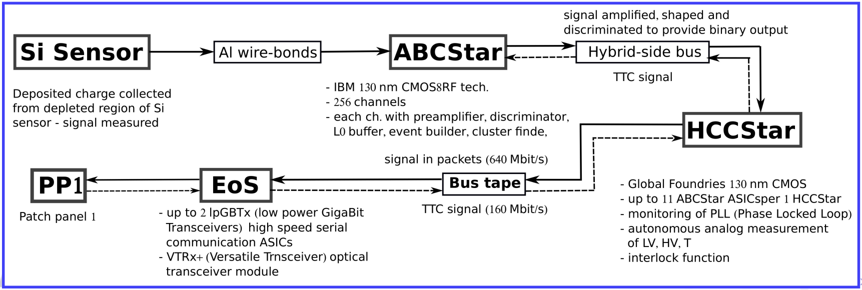


ITk Strip: Electronics Architecture

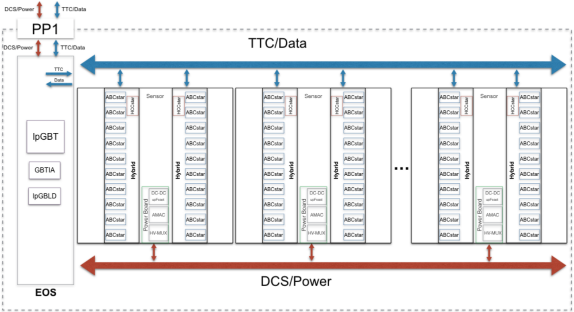


Comparison of daisy chain signal routing of prototype ABC ASICs and new ABCStar design.





ITk Strip: Electronics Architecture



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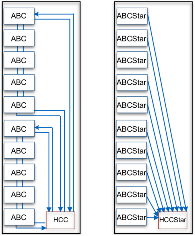


EOS

- lpGBTx (I2C interface) + VTRx+

DC-DC converter

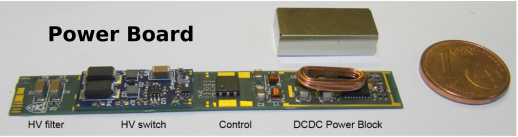
- built around a buck converter **upFEAST chip**
- distribution of LV to module (5-12 V -> 0.6-5 V with FAEST2.1)

AMAC

- monitoring of LV and HV, temperatures and sensor bias current on module (1 sample / ms)

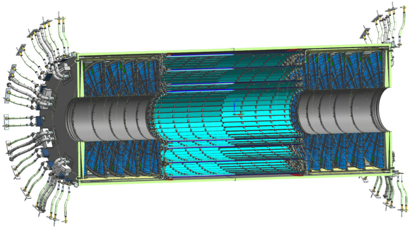
HV-MUX

- controlled HV switch,
- connection/disconection of module from HV,
- GaNFET or 3D Trench Vertical JFET transistor gate controled by HV multiplexer



ITk Strips: Global Support

- primary role of global support structure is to locate robustly staves and petals into barrel and EC structures, respectively
- accurate in-situ track alignment requires a modest initial accuarcy of 100 μm to guarantee mechanical clearance/overlap between active elements
- stability considerations obtained from actual vibrations measurements in ATLAS cavern impose even more stringent requirements



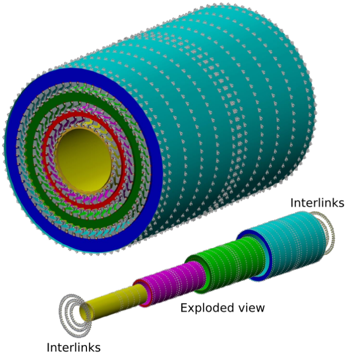
System	Direction	Stability requirement	1 st mode (A) ASD=10^{-7}g^2/Hz	1st mode (B) ASD=10^{-8}g^2/Hz
Strip barrel	z	20 μm	3.2 Hz	6.7 Hz
	R	20 μm	3.2 Hz	6.7 Hz
	φ	2 μm	14.4 Hz	31.6 Hz
Strip end-cap	z	20 μm	3.2 Hz	6.7 Hz
	R	20 μm	3.2 Hz	6.7 Hz
	φ	2 μm	14.4 Hz	31.6 Hz

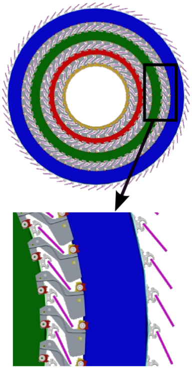
Stability requirements (A - performance, B - design) for vibration modes in the R and ϕ direction - frequencies above which motions will be smaller than the displacement requirements.

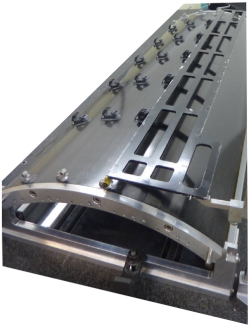
ATLAS EXPERIMENT

ITk Strips: Global Support for barrel

- 4 barrel layers
  - L0: $R = 405$ mm, 28 staves, 784 modules
  - L1: $R = 562$ mm, 40 staves, 1120 modules
  - L2: $R = 762$ mm, 56 staves, 1568 modules
  - L3: $R = 1000$ mm, 72 staves, 2016 modules
- flange-interlink mechanical interface, 1 interlink per stave, 5 identical lock points along a stave - every 3 modules - and a unique lock point at $z = 0$



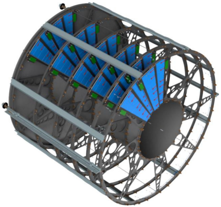




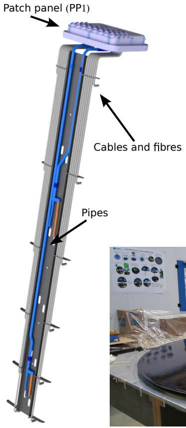
ITk Strips: Global Support for EC

- 6 EC disks on each forward side with 32 petals per disk
  - D0: $z_{\mathrm{pos}} = 1512\ \mathrm{mm}$, D1: $z_{\mathrm{pos}} = 1702\ \mathrm{mm}$, D2: $z_{\mathrm{pos}} = 1952\ \mathrm{mm}$, D3: $z_{\mathrm{pos}} = 2252\ \mathrm{mm}$, D4: $z_{\mathrm{pos}} = 2602\ \mathrm{mm}$, D5: $z_{\mathrm{pos}} = 3000\ \mathrm{mm}$
- 8 service trays for electronics and cooling, 8 EC PP1 patchpannels, EC rail system, first prototypes of disk structure and stiffening disk

EC Global support structure

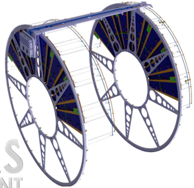


Service tray

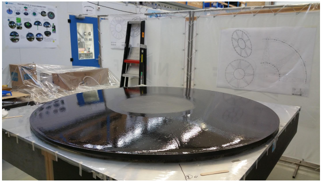


Mock up wheel production

EC disks with service tray



Stiffener disk production

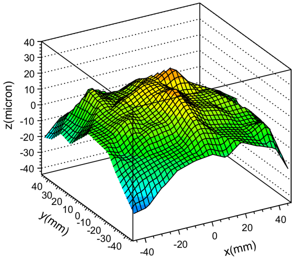


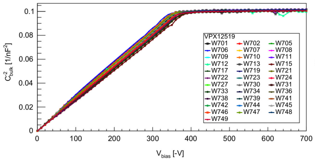
ITk Strips: Total numbers

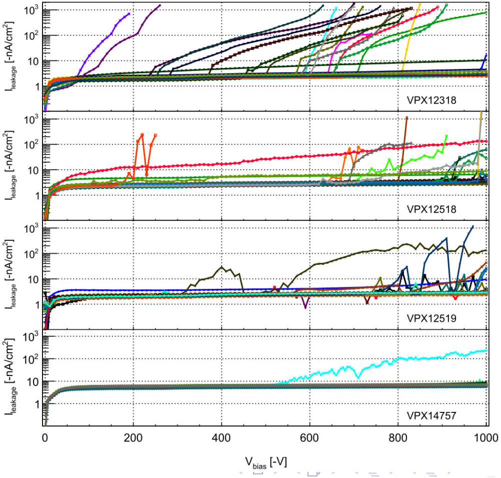
Barrel Layer:	**Radius [mm]**	**# of staves**	**# of modules**	**# of hybrids**	**# of of ABCStar**	**# of channels**	**Area [m^2]**
L0	405	28	784	1568	15680	4.01M	7.49
L1	562	40	1120	2240	22400	5.73M	10.7
L2	762	56	1568	1568	15680	4.01M	14.98
L3	1000	72	2016	2016	20160	5.16M	19.26
Total half barrel		196	5488	7392	73920	18.92M	52.43
Total barrel		392	10976	14784	147840	37.85M	104.86
End-cap Disk:	**z-pos. [mm]**	**# of petals**	**# of modules**	**# of hybrids**	**# of of ABCStar**	**# of channels**	**Area [m^2]**
D0	1512	32	576	832	6336	1.62M	5.03
D1	1702	32	576	832	6336	1.62M	5.03
D2	1952	32	576	832	6336	1.62M	5.03
D3	2252	32	576	832	6336	1.62M	5.03
D4	2602	32	576	832	6336	1.62M	5.03
D5	3000	32	576	832	6336	1.62M	5.03
Total one EC		192	3456	4992	43008	11.01M	30.2
Total ECs		384	6912	9984	86016	22.02M	60.4
Total		**776**	**17888**	**24768**	**233856**	**59.87M**	**165.25**

ITk Strips: sensors evaluation

- Strip sensors are tested against precisely defined specifications
  - visual inspection, sensor bow, I-V, C-V, leakage current stability, inter-strip capacitance, inter-strip resistance, poly-silicon bias resistance, punch-through protection efficiency, etc.

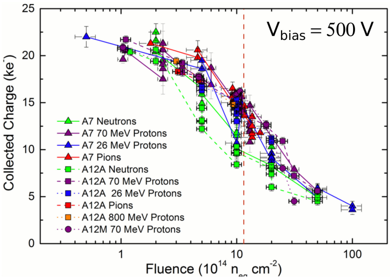


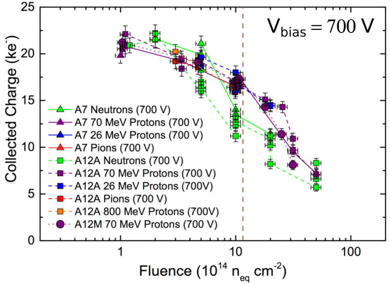


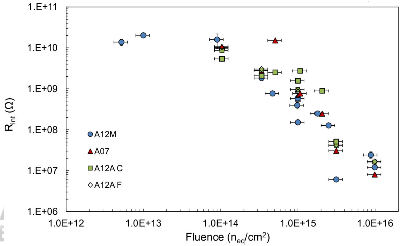


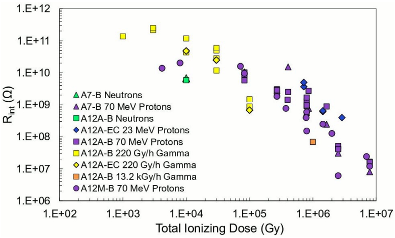
ITk Strips: sensors evaluation

- Studies of irradiation effects on sensors are critical
  - data from prototype sensors are used to estimate the expected signal size in production sensors at the end of detector lifetime



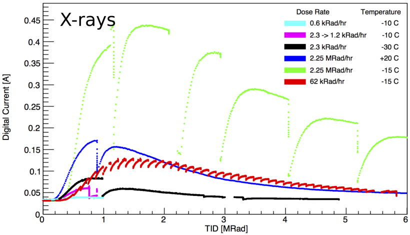


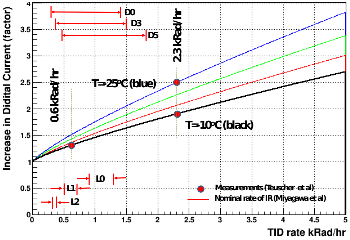


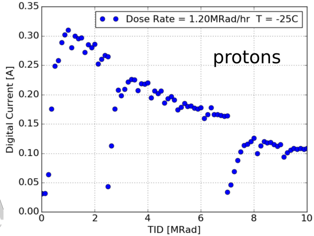


ITk Strips: ABC130 evaluation

- Increase of digital current with delivered total ionization dose
- All studies have been done with prototype ABC130 and HCC130 ASICs, the production ABCStar and HCCStar ASICs will be investigated immediately after they become available



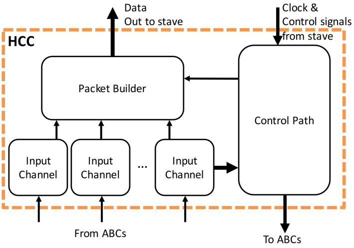


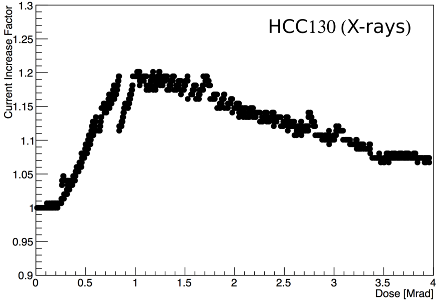


Source	T (°C)	Current Increase	Dose Rate (MRad/h)
^{60}Co CERN	−25	2.5	0.0023
^{60}Co CERN	−10	1.9	0.0023
^{60}Co CERN	−10	1.3	0.0006
Birmingham-p	−25	9.7	1.25
X-ray CERN	−15	3.9	0.062
(extrapolated)	−10	3.5	0.062
X-ray CERN	−15	13.6	2.25
X-ray CERN	+20	5.2	2.25

ITk Strips: HCC130 evaluation

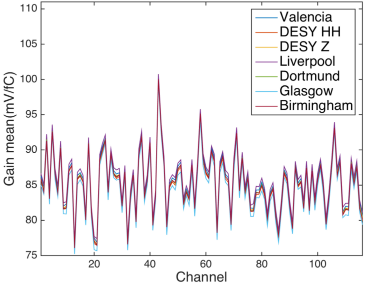
- Increase of digital current in HCC130 ASIC is significantly lower as it contains less digital functionality - fewer memory blocks
- HCCStar will have added memory - higher digital current increase is expected

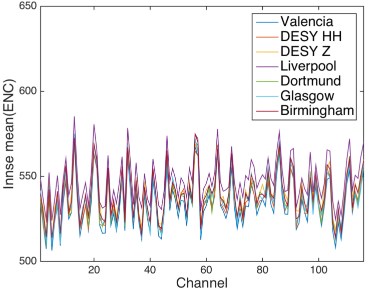


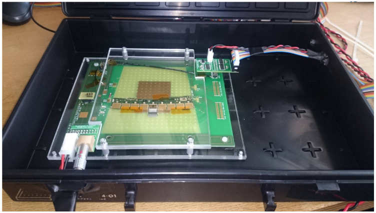


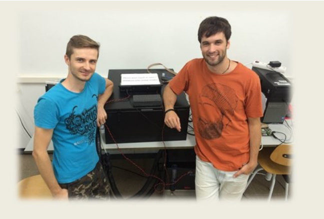
ITk Strips: module evaluation - electrical tests

- Traveling DAQload - prototype module built from 1 ATLAS12 mini-sensor, 1 EC R0H1 hybrid, 1 ABC130 ASIC and 1 HCC130 ASIC mounted on the test frame - was tested at 14 different institutes over the world



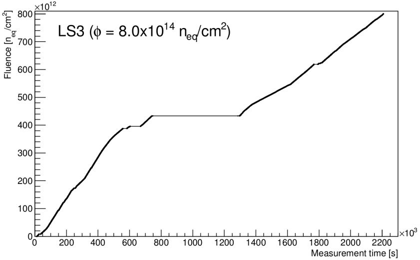


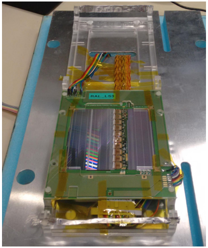


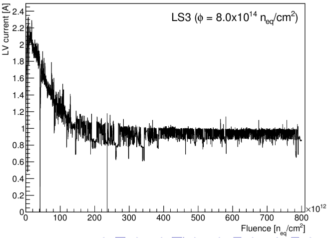


ITk Strips: module evaluation - CERN irradiation 2016

- Irradiation of LS3 barrel module in 2016 to $8.0 \times 10^{14}\ \mathrm{n_{eq}/cm^2}$ = 37.1 Mrad = $0.371 \times 10^6\ \mathrm{Gy}$, which was the highest fluence expected on any part of the Strip EC (without safety factor)[1]



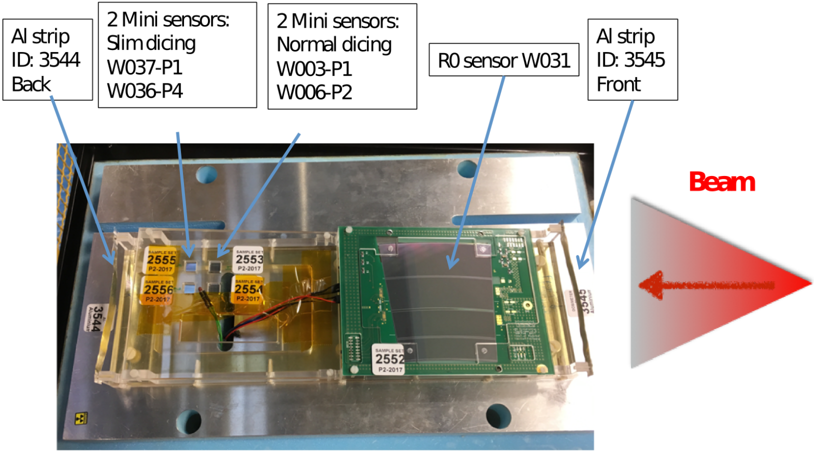




[1] HL-LHC Radiation Background Simulations

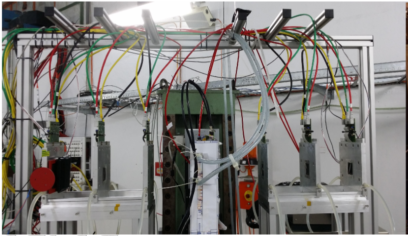
ITk Strips: module evaluation - CERN irradiation 2017

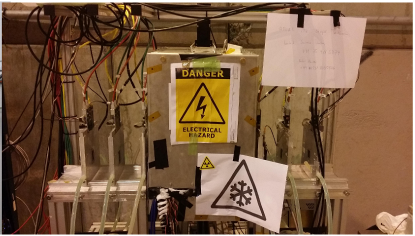
- full-sized R0 sensor + 4 ATLAS12EC minisensors (2 normal dices, 2 slim diced) irradiated in 2017 to the total fluence of $\sim 1.5 \times 10^{15}\ \mathrm{n_{eq}/cm^2}$



ITk Strips: module evaluation - testbeams

- twice a year a testbeam at DESY II testbeam facility
- in 2016 the first ATLAS ITk Strip testbeam at CERN SPS testbeam facility
- Equipment necessary for testbeams
  - EUDET Telescope with 6 cooled Mimosa planes (TLU, cabling, ...), 1 additional pixel layer with FE-I4 readout, scintillators in front of and behind the EUDET Telescope, cooling box + jig + chiller with liquid coolant, nitrogen gas inlet tube for decreasing RH when running cold, XY moving stage with remote control, vacuum for DUT fixing on the dedicated jig, PC with specific version of EUDAQ software, HV/LV power supplies, T/RH monitoring system, DUT :-), PC for DUT operation
- many local and online experts as well as shifters required each testbeam

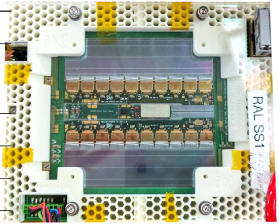


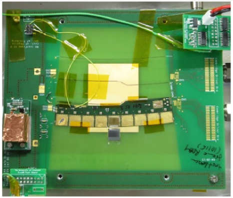


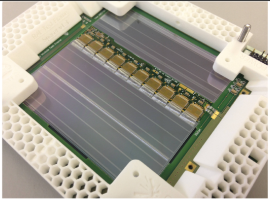
ITk Strips: module evaluation - testbeams

- DUTs tested in years 2015 - 2017
  - DAQload10 (DESY May 2015), LS2 (DESY November 2015)
  - **DAQload13** + LS4 (DESY May 2016), **LS3** (CERN July 2016)
  - R0 + SS1 (DESY May 2017)

Module	Description	Test Beam	Comment
DAQload10	Barrel hybrid with three ABC130s, two wire bonded to mini-sensors.	May-15 DESY	
DAQload13	Two ABC130 and two ATLAS12-mini sensors.	May-16 DESY	Sensors neutron irradiated ($2x10^{15} n_{eq}/cm^2$), ABC130-1 non-irradiated, ABC130-2 X-ray irradiated (4 MRad with 0.85 MRad/hr at RAL at -5°C).
SS1	Full barrel module with ten ABC130, short strips.		
LS2	Full barrel module with ten ABC130, short and long strips.	Nov-15 DESY	
LS3	Full barrel module with ten ABC130, short and long strips.	Jul-16 CERN	Irradiated at PS with protons ($8.0x10^{14} n_{eq}/cm^2$ and TID=37.2 MRad)
LS4	Full barrel module with ten ABC130, short and long strips.	May-16 DESY	



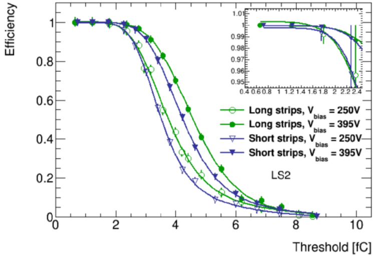


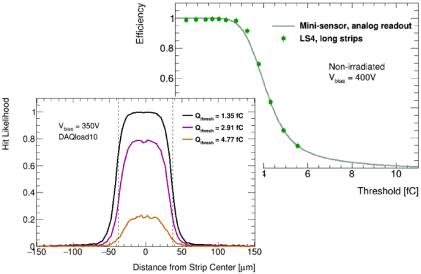


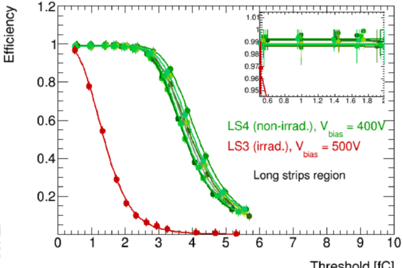
ATLAS EXPERIMENT

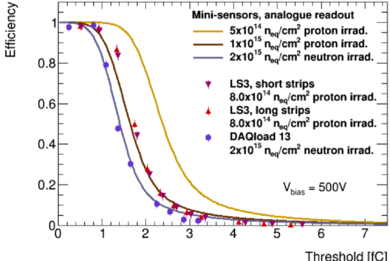
ITk Strips: module evaluation - testbeams

- V_{bias} dependency, hit likelihood as a function of distance from strip, comparison of efficiency of irradiated and unirradiated modules measured with analog and digital readout systems



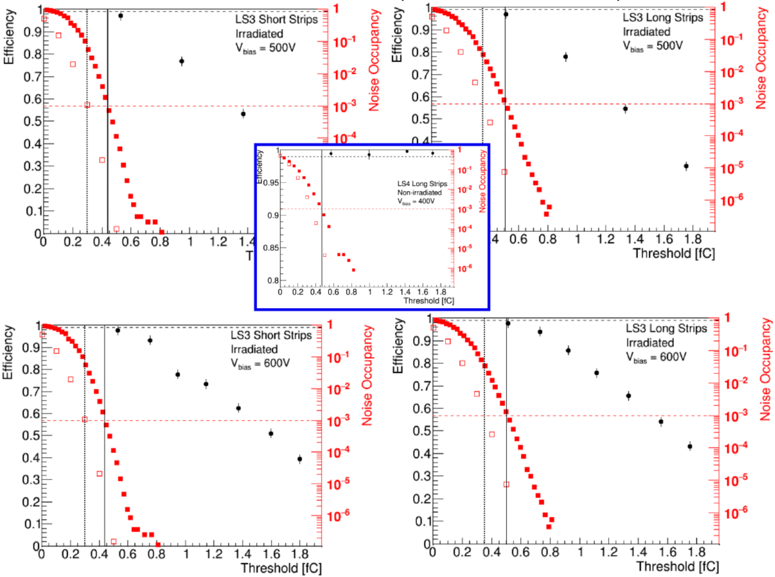




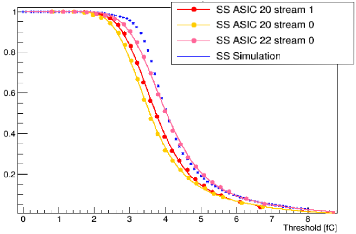


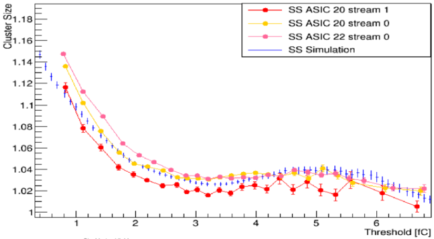
ITk Strips: module evaluation - testbeams

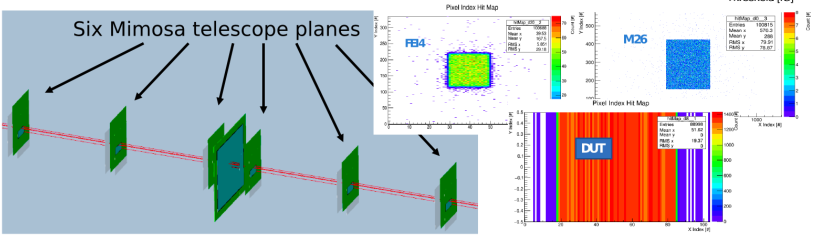
- End-of-Lifetime Performance - detection efficiency $> 99\%$ at thresholds with channel noise occupancy $< 1 \times 10^{-3}$ (ABC130 and ABCStar)



- Testbeam group works also on preparation of DUT and full testbeam simulations in AllPix and AllPix2 frameworks

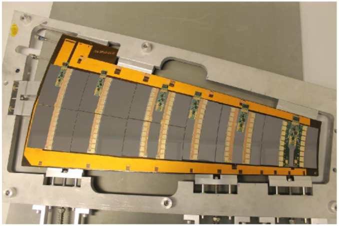


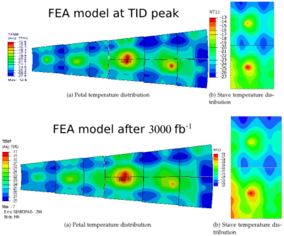


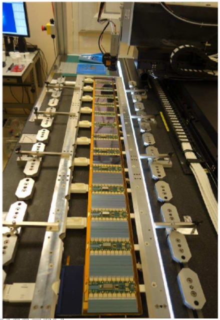


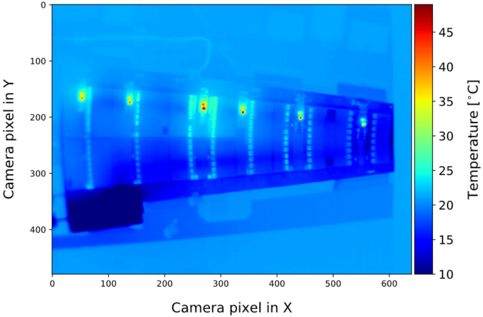
ITk Strips: staves and petals evaluation

- FEA simulation of temperature distribution on stave and petal and its measurement using thermo-mechanical structures



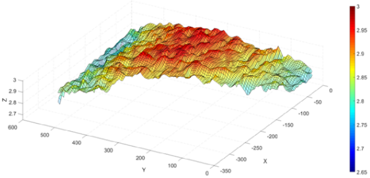


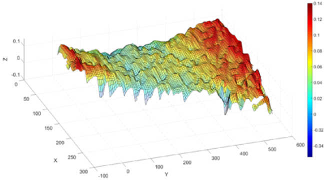


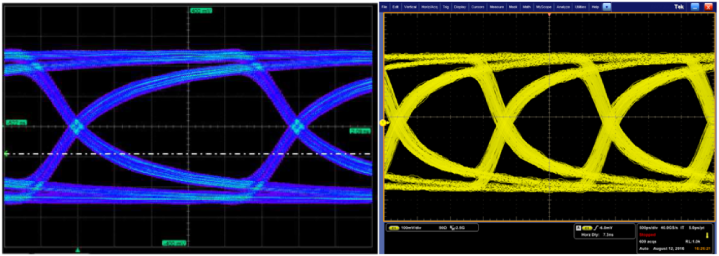


ITk Strips: staves and petals evaluation

- metrology measurements of petal flatness
- Eye diagrams resulting from simulation based on measured S-parameters, for 640 Mbit/s (Data) and for direct measurements on test tape







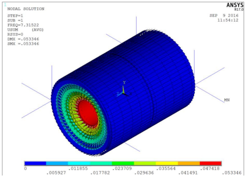
(a) Data eye diagram

(b) TTC eye diagram

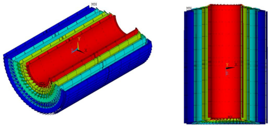
ITk Strips: global structures evaluation

- FEA model analysis of barrel structure - the 1st z mode, the 2nd z mode and the 1st $R\phi$ mode

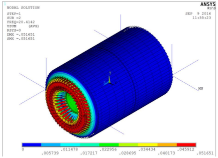
1^{st} Telescoping mode
7.3 Hz



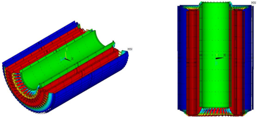
Section views



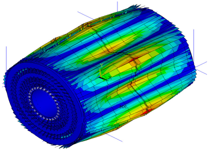
2^{nd} Telescoping mode
20.4 Hz



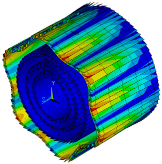
Section views



1^{st} Radial mode
32.1 Hz



Section view through centre

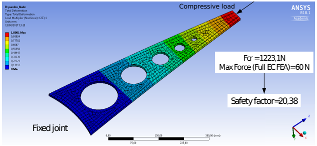


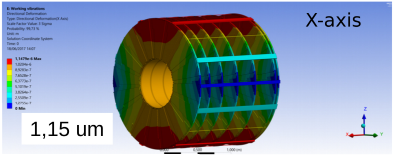
ITk Strips: global structures evaluation

- FEA simulations for EC blade and EC global structure

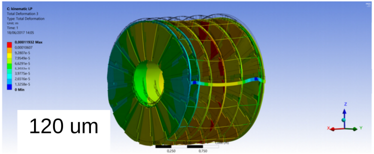
Dynamic deformation in X, Y, Z axis with input parameters from ATLAS cavern measuremet

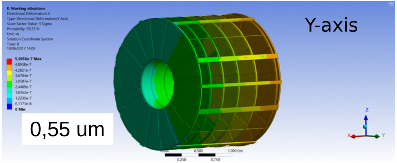
Linear buckling of blade



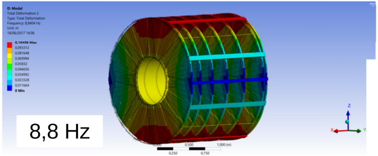


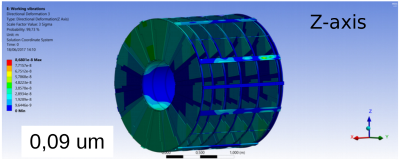
Static total deformation





First frequency mode





ATLAS EXPERIMENT

ATLAS ITk Strip status - summary

- ATLAS Inner Tracker Strip Detector TDR has been approved in Q2 2017 by LHCC and UCG committees
- ATLAS ITk Strip collaboration is in a good shape aiming at milestones scheduled for individual detector components
  - Preliminary Design Reviews
  - Final Design Reviews
  - Production Readiness Reviews
- ATLAS Inner Tracker Pixel Detector TDR to be submitted at the end of 2017

Table 24.1: Milestones for the ITk Strip Detector developments

Milestone	Date
2.2.1 Sensors	
Sensor Preliminary Design Review	Q2-2017
Sensor Final Design Review	Q1-2018
Sensor Production Readiness Review	Q3-2019
2.2.2 Read-out Chips	
Specif cation Review	Q1-2017
ASICs Preliminary Design Review	Q3-2017
Star ASICs submission	Q4-2017
ASICs Final Design Report	Q3-2018
ASICs Production Readiness Review	Q3-2019
2.2.3 Modules	
Specif cation Review	Q2-2017
Modules Preliminary Design Review	Q4-2017
Modules Final Design Report	Q1-2019
Modules Production Readiness Review	Q1-2020
2.2.4 Local Support Electronics	
Specif cation Review	Q2-2017
Preliminary Design Review	Q4-2017
Final Design Report	Q3-2018
Production Readiness Review	Q1-2019
2.2.5 Fully Loaded Local Support	
Specif cations Review	Q2-2017
Local support Preliminary Design Review	Q2-2017
Local support Final Design Review	Q1-2018
Local support Production Readiness Review	Q2-2019
2.2.6 Global Mechanics	
Specif cations and Design Review	Q3-2017
Global support Production Readiness Review	Q4-2018
2.2.7 Services	
Specif cations Review	Q2-2017
Preliminary Design Review	Q4-2017
Final Design Review	Q2-2019
2.2.9 Off-Detector Electronics	
Specif cations Review	Q2-2017
Preliminary Design Review	Q4-2017
Final Design Review	Q2-2019