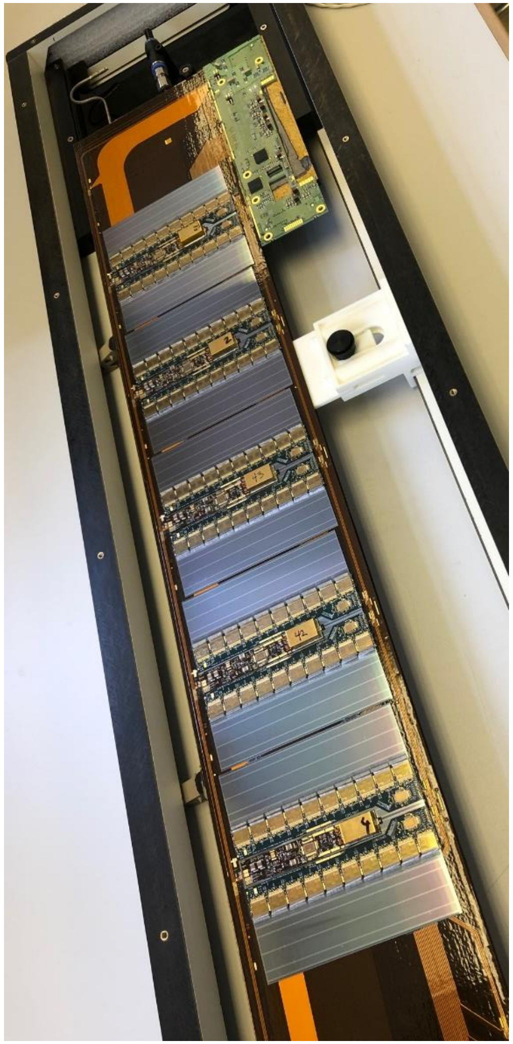
VERTEX 2019

The ATLAS ITk Strip Detector System for the Phase-II LHC Upgrade

Sven Wonsak on behalf of the ATLAS ITk Strip Community

Outline

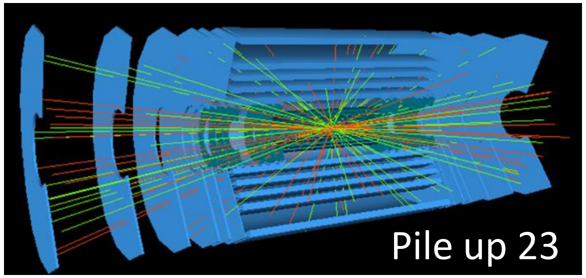
- Overview
  - ATLAS upgrade and ITk
- ITk Strips
  - Sensors
  - Hybrids
  - Powerboard
  - Modules
- Looking Ahead

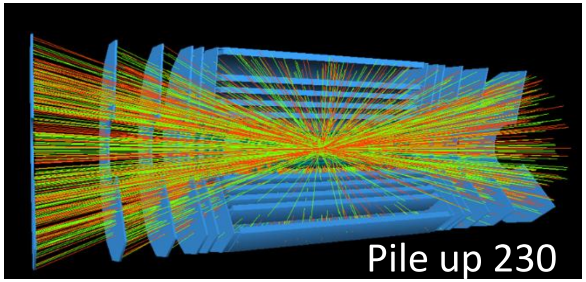


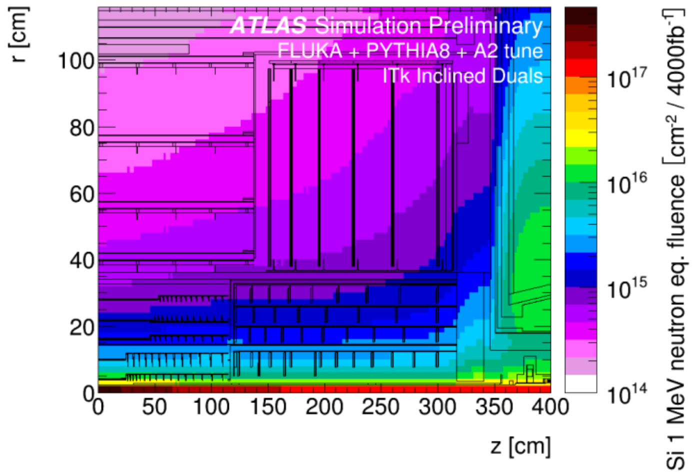
Barrel 5 Short Strip Module Stave

ATLAS Upgrade for HL-LHC

- Upgrade the ATLAS inner detector for the High Luminosity LHC foreseen in 2026
- Operation of the new detector for 10 years with an expected total integrated luminosity of 4000 fb^{-1} and up to 200 interactions per bunch crossing
  - The new detector needs to be radiation hard up to
    - 1.3×10^{16} n_{eq}/cm^2 (inner pixel layer)
    - 1.6×10^{15} n_{eq}/cm^2 (max. strip fluence)



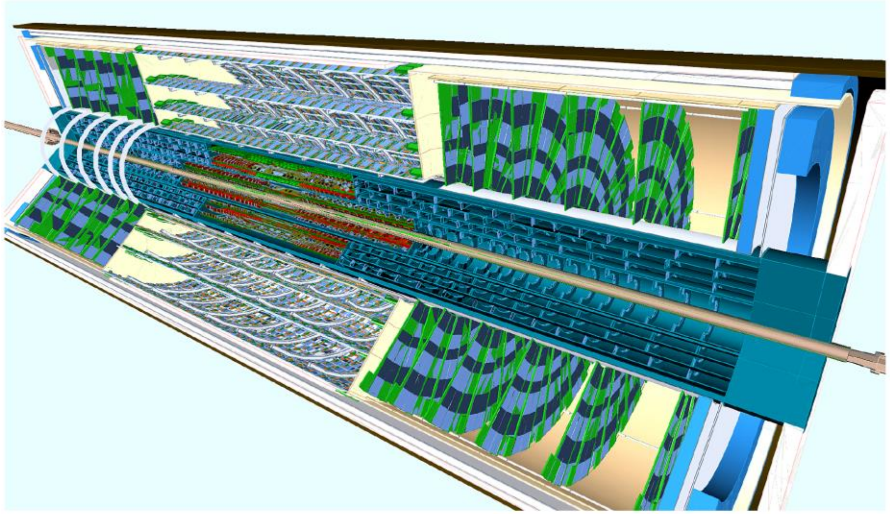


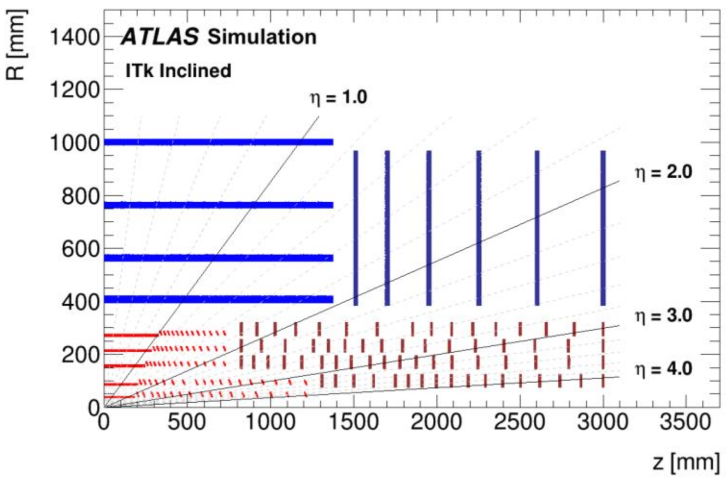


ITk Layout

- Replace the whole inner detector with the all silicon **I**nner **Tr**ac**k**er system
- Pixel region:
  - 5 barrel layers
  - 4 layers of pixel rings in the end-caps
- Strip region:
  - 4 barrel layers
  - 6 strip disks in each end-cap
- Full detector hermeticity up to $|\eta| = 4$
  - 7.5m long within 2T magnetic field

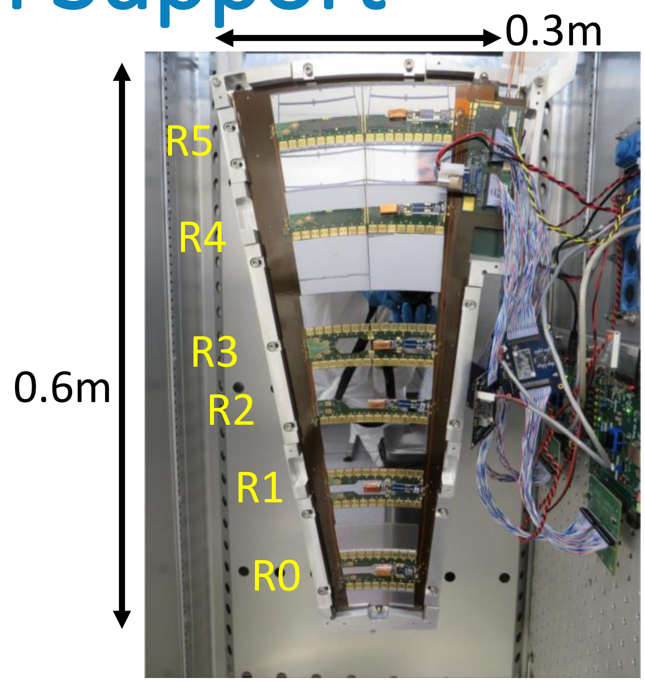
- Strip System:
  - ≈18k modules
  - ≈60 million channels
  - 165m^2 of silicon





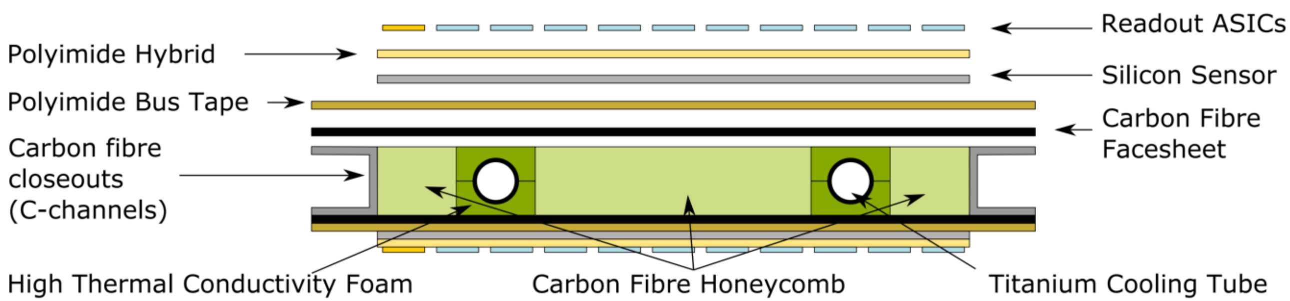
Local Support

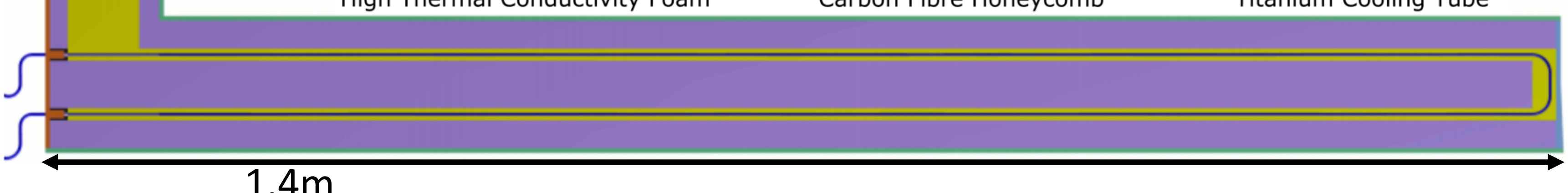
- Carbon-fibre support structures for barrel and endcap that hold multiple modules
  - Titanium cooling pipe in carbon honeycomb core
    - Evaporative CO_2 cooling down to -35°C
  - Polyimide bus tapes for communication and power supply of modules
  - DC-DC powering for all modules
- Barrel: staves with 14 modules on each side
  - Two flavours: short strip for L0 and L1; long strip for L2 and L3
  - 392 staves in the ITk
- Endcap: petals with 6 modules on each side
  - R3 – R5 modules use two sensors
  - 384 petals in both end caps



Endcap Petal

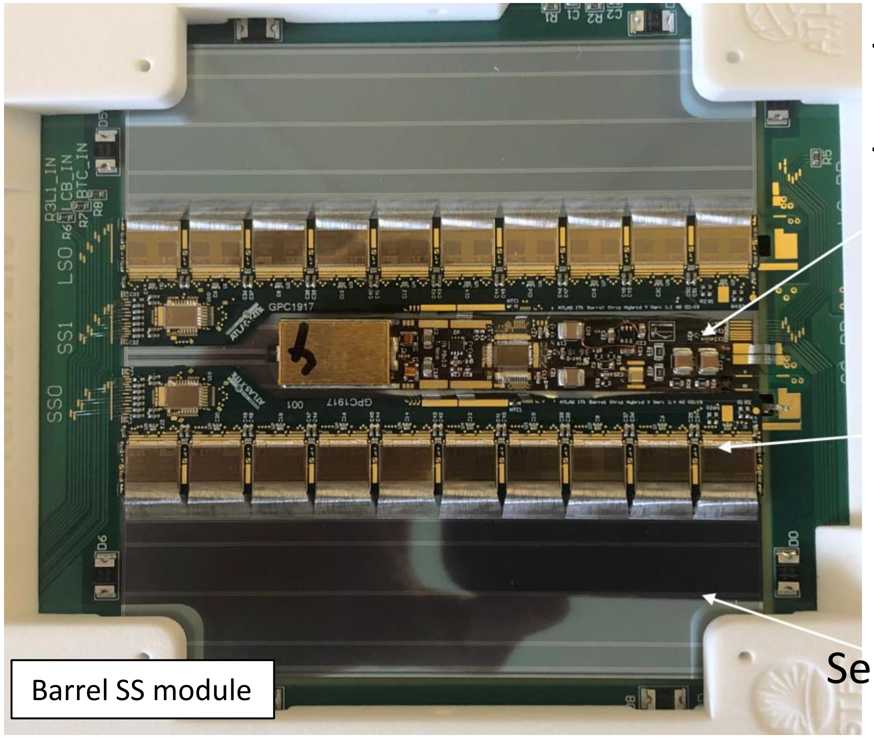
Barrel Stave

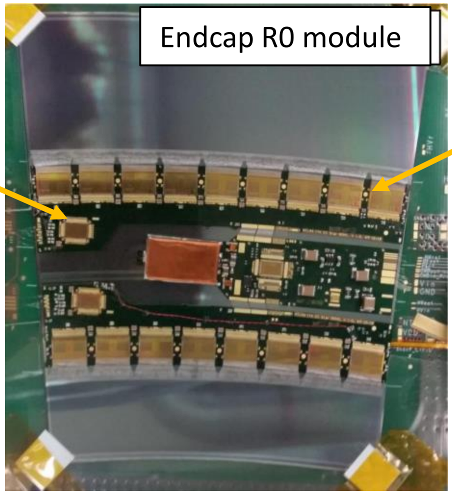


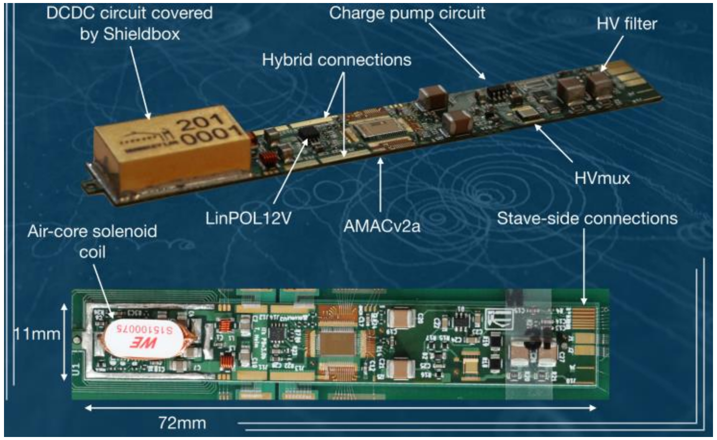


Modules

- Modules consist of:
  - One (or two) silicon sensors
  - Up to four hybrids
    - Binary read-out chips ABCStar
      - 265 front-end channels
    - Hybrid controller chip HCCStar
  - One powerboard to regulate ASIC power
    - Input from stave: 10-11V, output to ASICs: 1.5V
    - Autonomous Monitor And Control chip (AMAC), powered by LinPOL12V
    - DCDC buck converter bPOL12V
    - HVmux to switch sensor high voltage On/Off
  - Data transfer of up to 640 Mbit/s from HCCStar to End-of-Sturcture card
- Hybrids and powerboard glued on sensor





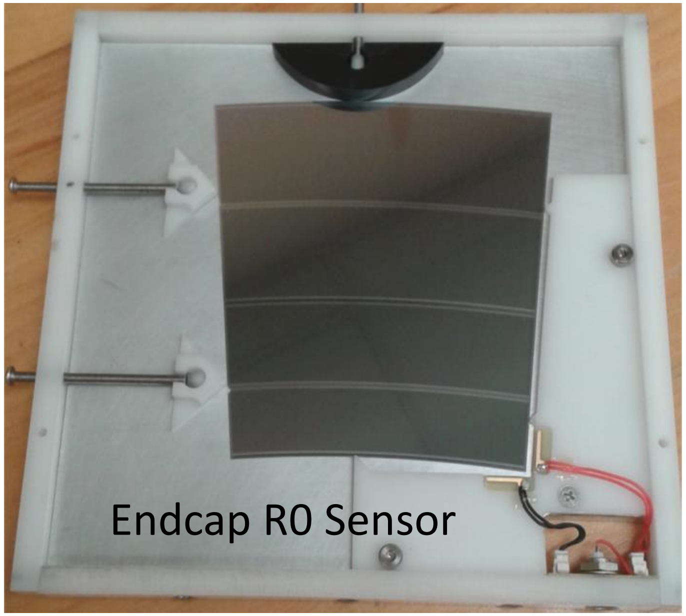


Sensors

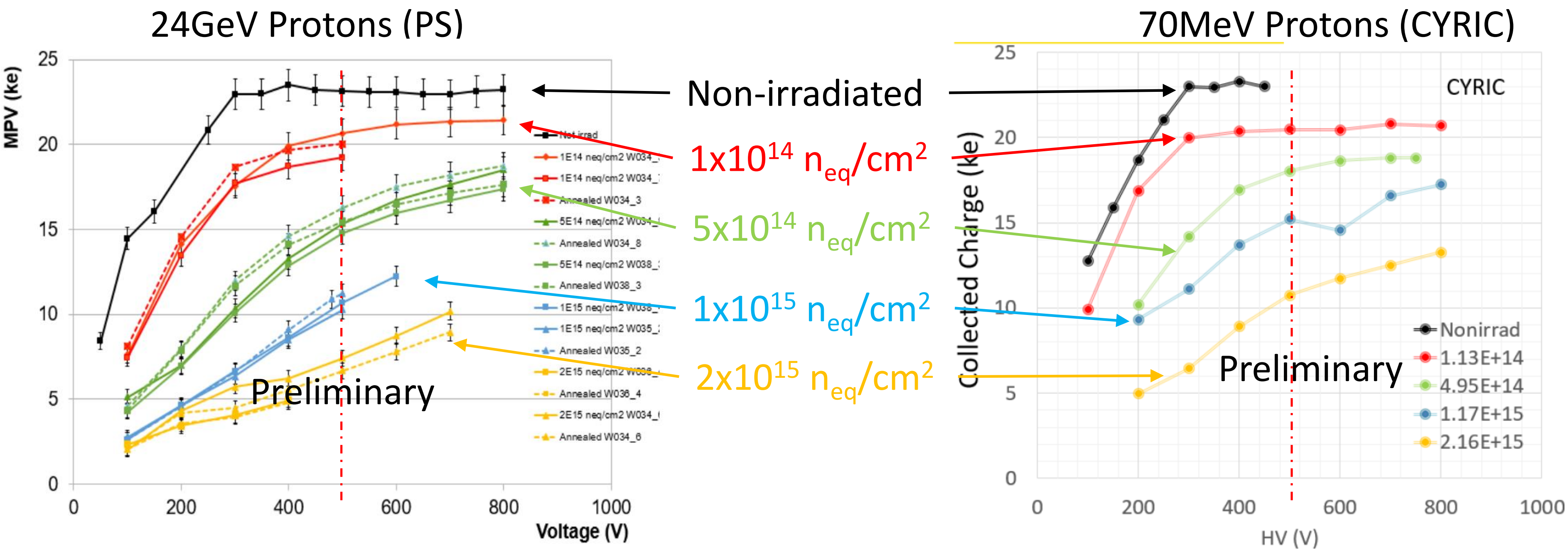
- Produced on 6-in wafers, p-type FZ, <100> orientation
  - Physical thickness: 320µm
  - Barrel: two layouts, ~100x100mm^2
    - Stip pitch: 75.5µm
    - Short Strip (SS): four strip segments, each 24.12mm long
    - Long Strip (LS): two strip segments, each 48.305mm long
    - Sensors rotated on stave by 26 mrad
  - Endcap: six layouts, “stereo-annulus” design
    - Strip pitch from 69.9µm to 80.7µm
    - Strip length from 15.1mm to 60.2mm
    - 20 mrad rotation angle build in sensor design

- Extensive test program to qualify the sensors, using large and mini-sensors from same wafer
  - Irradiations up to 2x10^{15} n_{eq}/cm^2 with protons/neutrons and 70Mrad with gammas, the expected end-of-life dose


Barrel LS Sensor


Endcap R0 Sensor

Sensor Irradiation



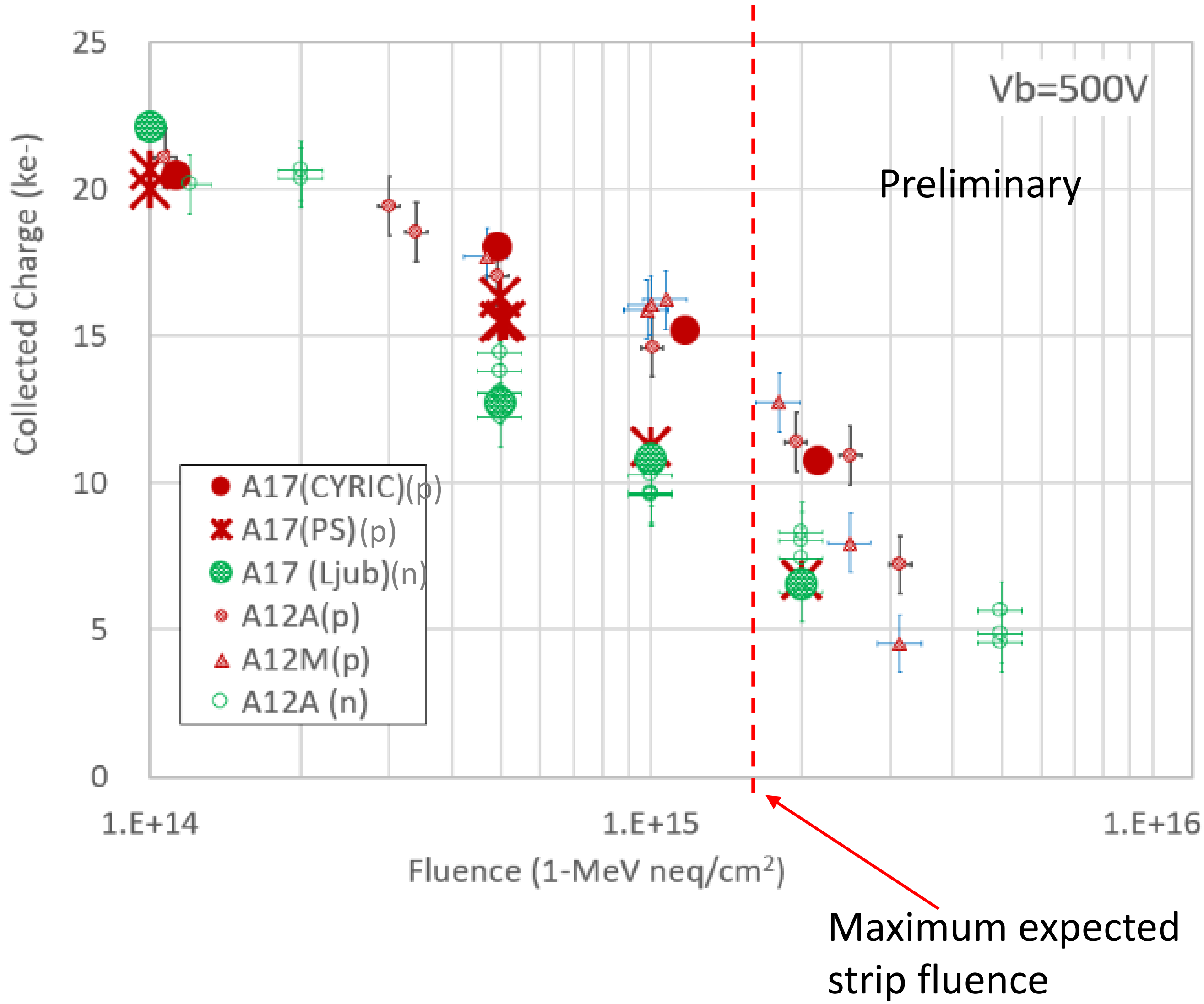
24 GeV Proton irradiation (CERN PS) and 70 MeV protons (Japan CYRIC)

- Good agreement of measurements at different institutes
- Expected charge collection behaviour observed for sensors
- Dashed lines show maximum strip operation voltage of 500V

Gamma irradiation at several dose rates up to 70Mrad show no dose rate dependence of the maximum collected charge

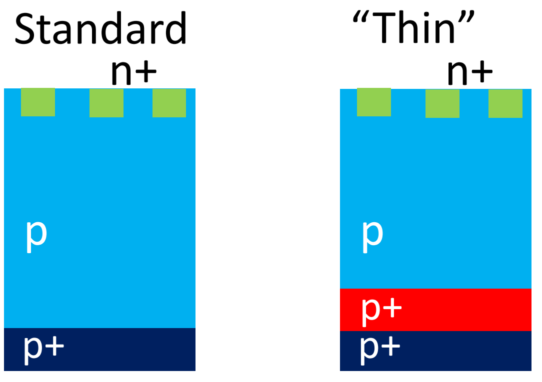
Sensor Irradiation

- Charge collection comparison of ATLAS17LS sensors from the market survey with well known ATLAS12 sensors:
- Good agreement after neutron irradiation
- Fair agreement after proton irradiation (possible deviation for PS irradiation X >1×10^{15} n_{eq}/cm^2, but charge not lower than for neutron irradiation)
  - Use collected charge after neutron irradiation as benchmark



Active Thickness

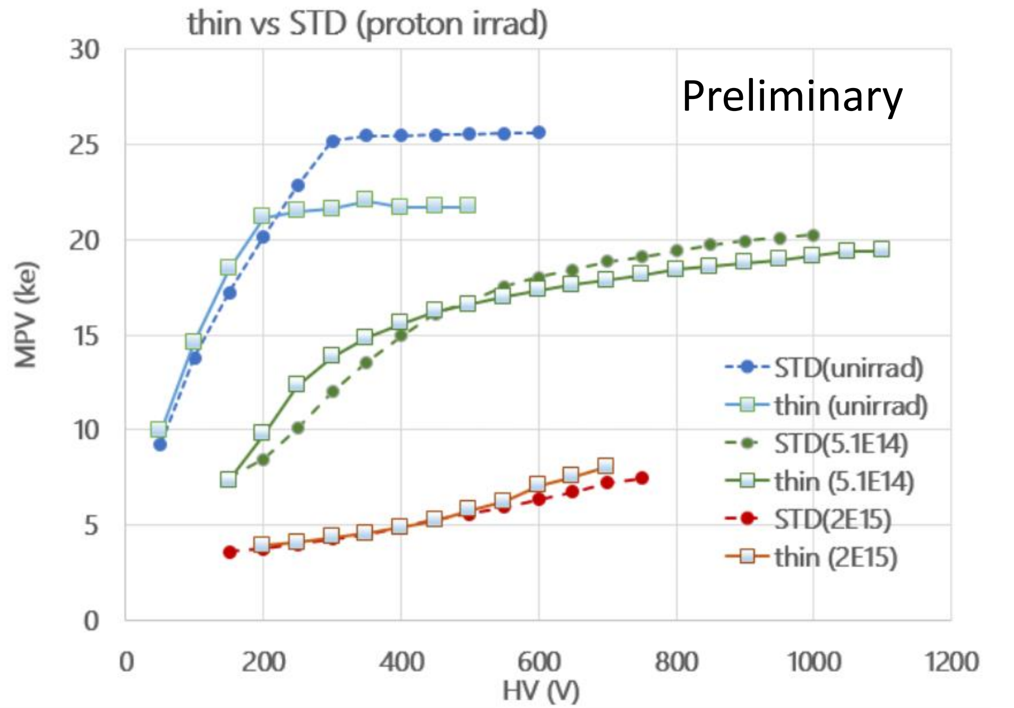
- Sensors have been produced in standard 300µm thickness, but some samples have a thicker backside contact to reduce the active thickness



HPK ATLAS17LS sensors produced in two thicknesses:
300µm (STD) and 240µm ("thin")

- Un-irradiated: lower collected charge for "thin" sensors
- Very similar signal at high fluences for both device types

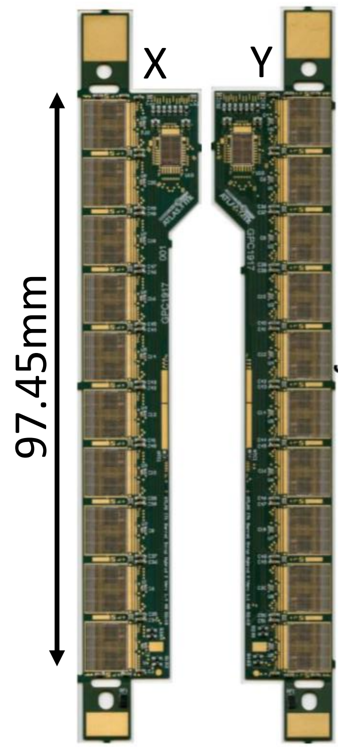
After annealing



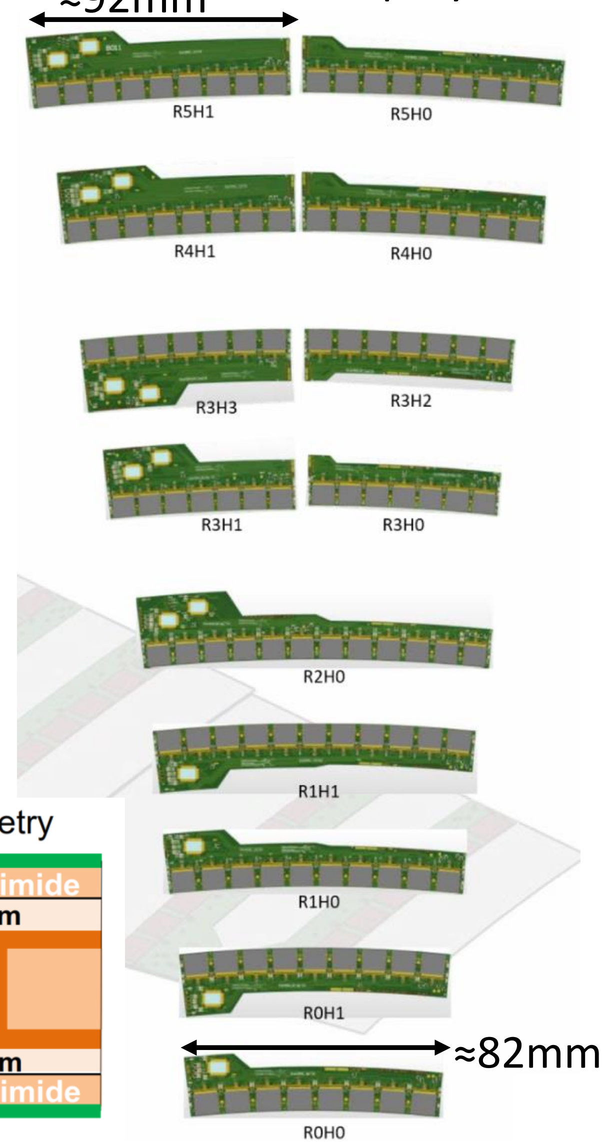
Hybrid Design

- Hybrids:
  - 4 copper layers, controlled impedance
  - Polyimide cores
  - Surface finish is ENIG to IPC Spec 4552 to facilitate aluminium wedge wire-bonding
  - Staggered µ-vias for robust and reliable interconnection between the copper layers
  - Controlled thickness of circuits
    - Barrel: 400µm ± 10%
    - Endcap: 250µm ± 20%
  - 2 barrel & 13 endcap hybrids for the different module types

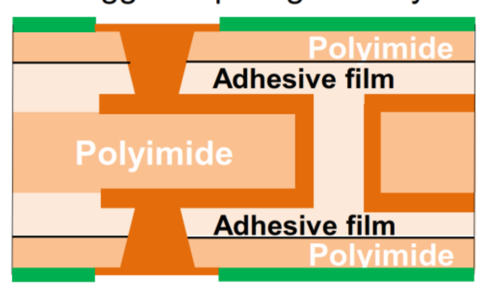
Barrel Hybrids



Endcap Hybrids



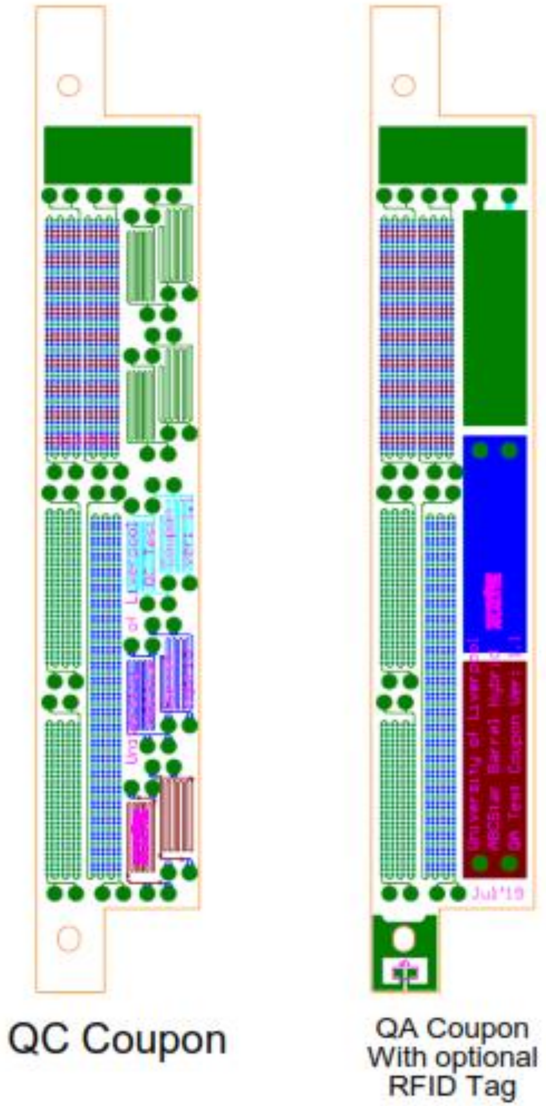
Staggered µvia geometry



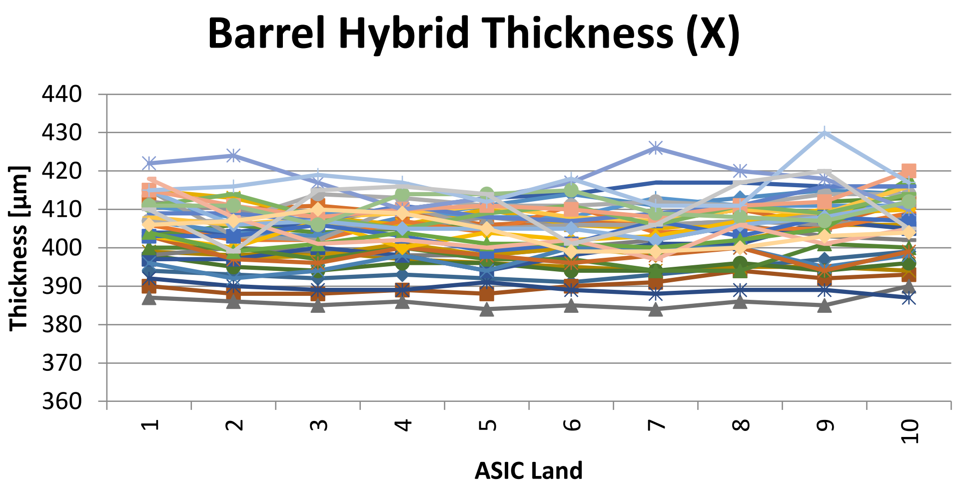
Not to scale

Hybrid QA & QC

- Hybrids are produced on panels
  - Barrel: Segmentation into arrays with at two test coupons and six hybrids each
- Test coupons for quality control and quality assurance during production
- QC Coupon:
  - 15 resistive test structures
  - Layout aligned to automated 4-wire resistance measurement
  - Allows crosscheck of copper weights on all layers
  - Multiple via chains for monitoring their integrity, especially when thermally stressed
  - Bond off pads for pull-tests and thickness measurement
- QA Coupon:
  - Copy of via chains
  - 3 integrated capacitive plate structures for testing construction and material robustness (delamination), as well as dielectric material thickness



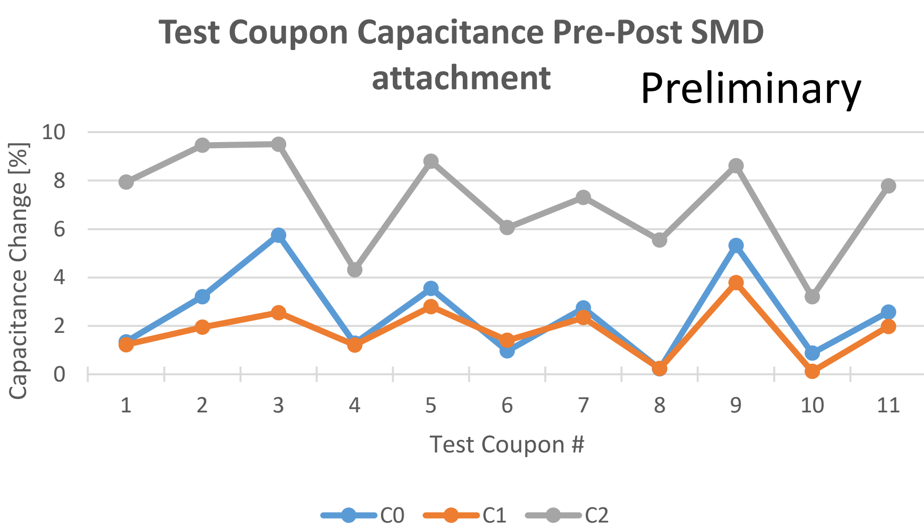
Hybrid QC/QA Test Results



Average thickness: 405±8µm

Thickness relevant for module building

- Tools with fixed geometry require certain hybrid thickness
  - Observed standard deviation smaller than guaranteed 10%

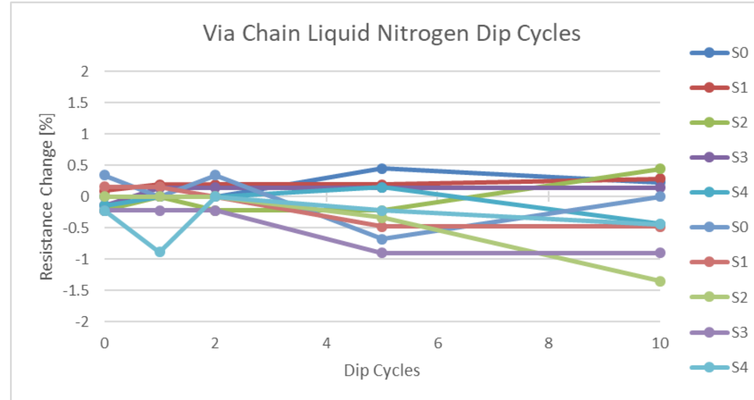


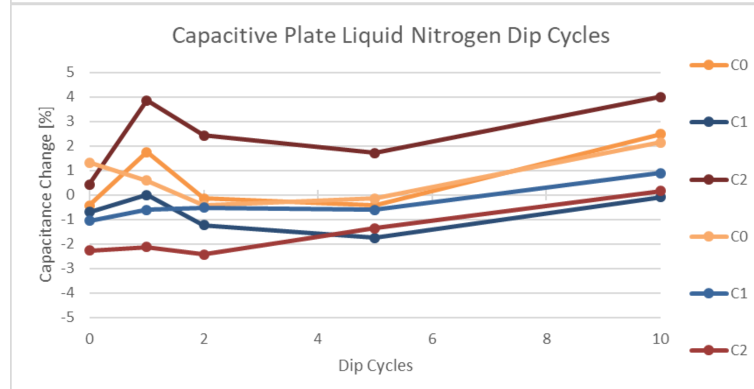
Measure capacitance of test-coupon before and after passive component attachment

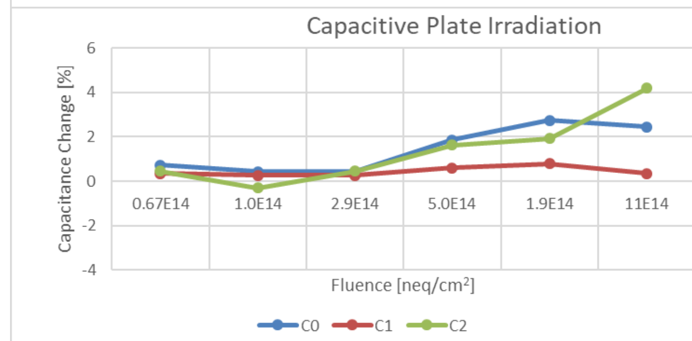
- Change should be less than 10%
- Decrease would indicate delamination => not observed
- Positive change (especially C2) could be a measurement artefact => more statistic required

Hybrid QA Tests

- Nitrogen dip
  - 20°C to -196°C, taking 1, 2, 5 and 10 dips
  - Measure via chains and capacitance after each dip cycle
  - <±2% change in resistance with no breaks and <±4% change in capacitance
- Irradiation of test coupons
  - Irradiation of coupons from 6.7×10^{13} to 1.1×10^{15} n_{eq}/cm^2
  - Compare measurements before and after irradiation: no significant change



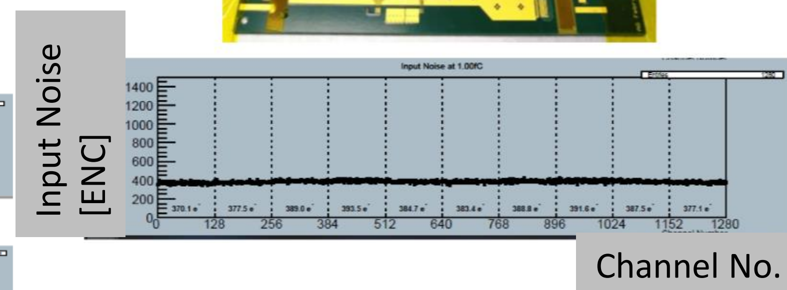


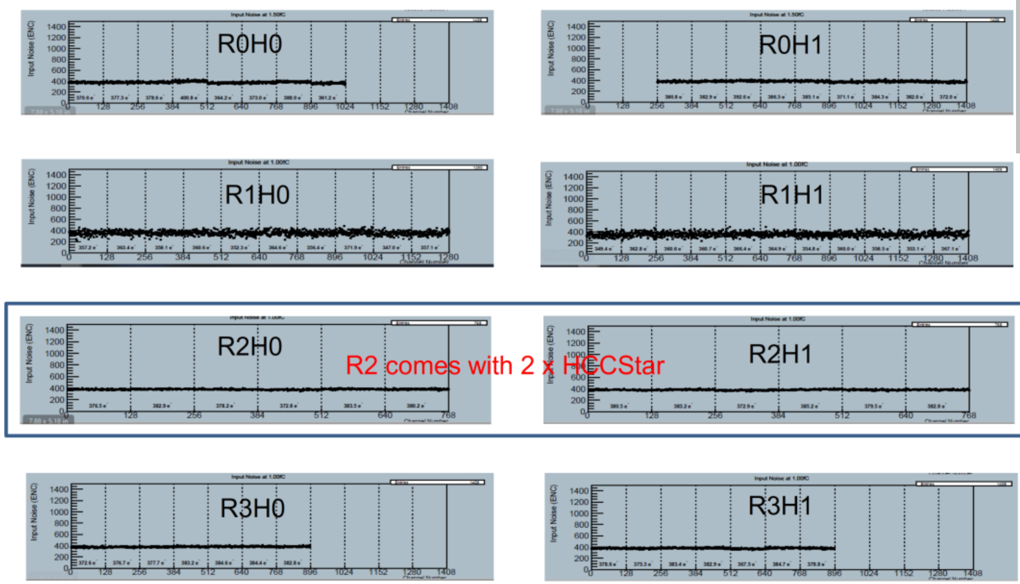


Electrical Hybrid Tests

- First electrical tests of hybrid tests with new front-end ABCStar and controller HCCStar chips show good results
  - Expected noise for ABCStar chip without capacitive load: ≈400ENC
- Hybrids tested on panel
  - Barrel: 6 hybrids and 3 unshielded powerboard plugins
    - Providing hybrid power at 1.5V, monitoring of I/V and hybrid temperature
    - On-hybrid slow-control signalling
    - Allows for controlled power-up sequencing of the hybrids

Barrel Hybrid Test Panel



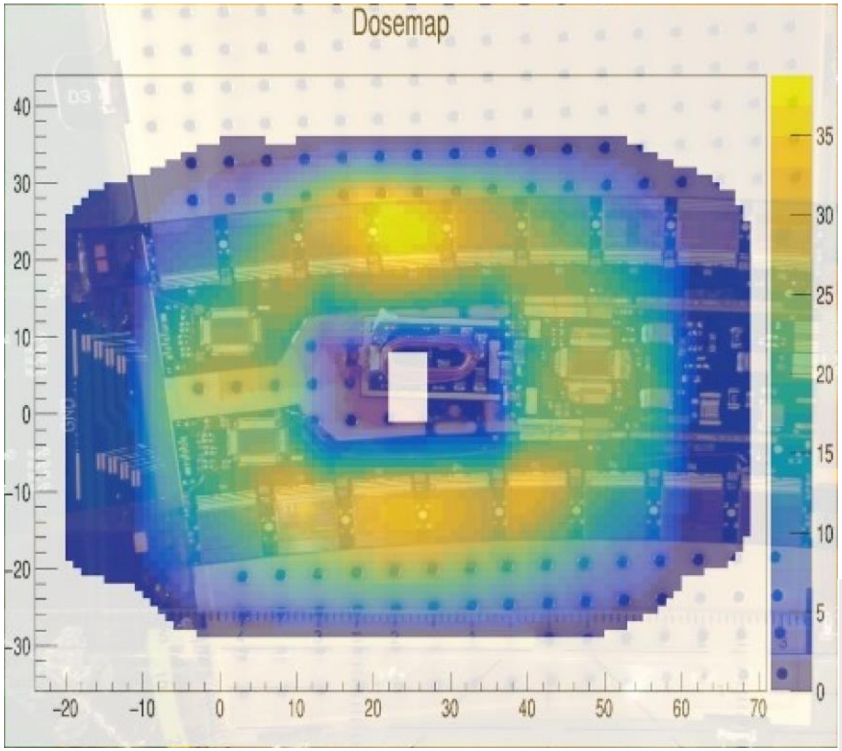


Hybrid	Noise [ENC]	Hybrid	Noise [ENC]
X	384	R2H0	379
R0H0	377	R2H1	381
R0H1	382	R3H0	380
R1H0	359	R3H1	379
R1H1	360		

Irradiated Hybrid

Two Endcap hybrids, R0H0 and R0H1 plus powerboard, irradiated at RAL with X-rays up to 30Mrad

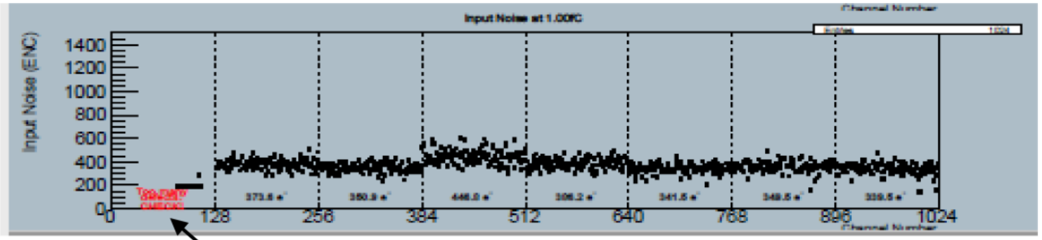
- Dose and irradiation profile driven by available time to get module to test beam



Irradiated hybrids still functioning with front-end input noise mostly unchanged

Likewise a barrel hybrid was irradiated at RAL to ≈25Mrad – remained fully functional and no change in input noise

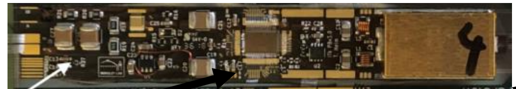
All irradiated hybrids went on to be used successfully as assembled modules at test beams



Input Noise of R0H0

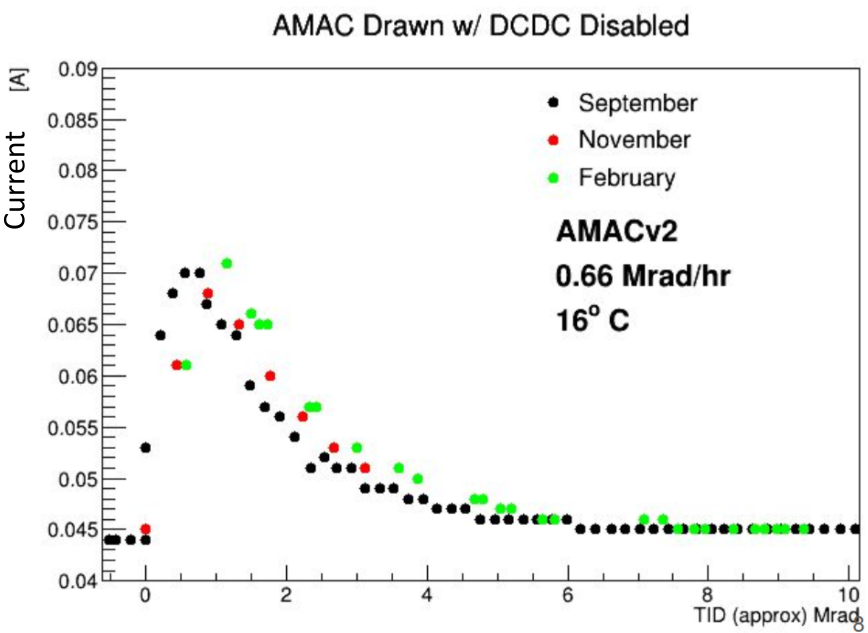
Bad chip due to failed wire-bonds

Powerboard Irradiation



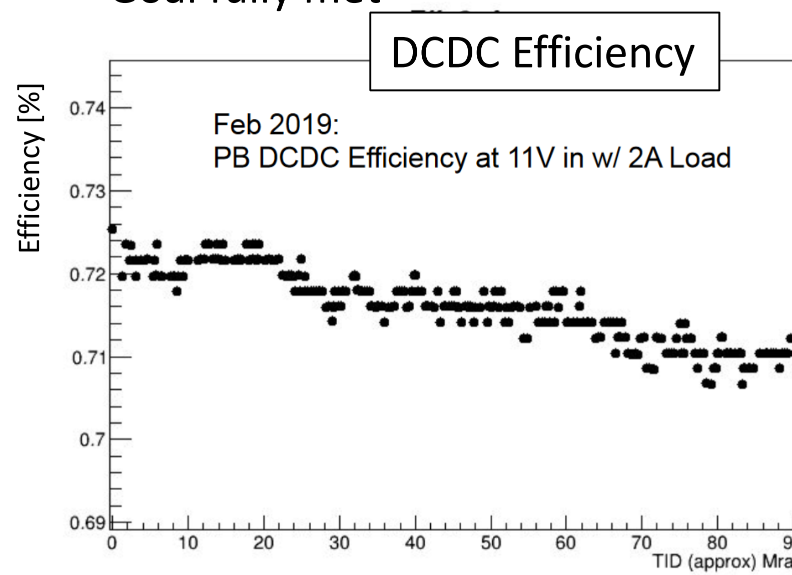
X-Ray Irradiations: Baseline AMAC Current

- Important that AMAC baseline current not exceeds 80mA (linPOL max rating)
- Consistency among results across irradiations



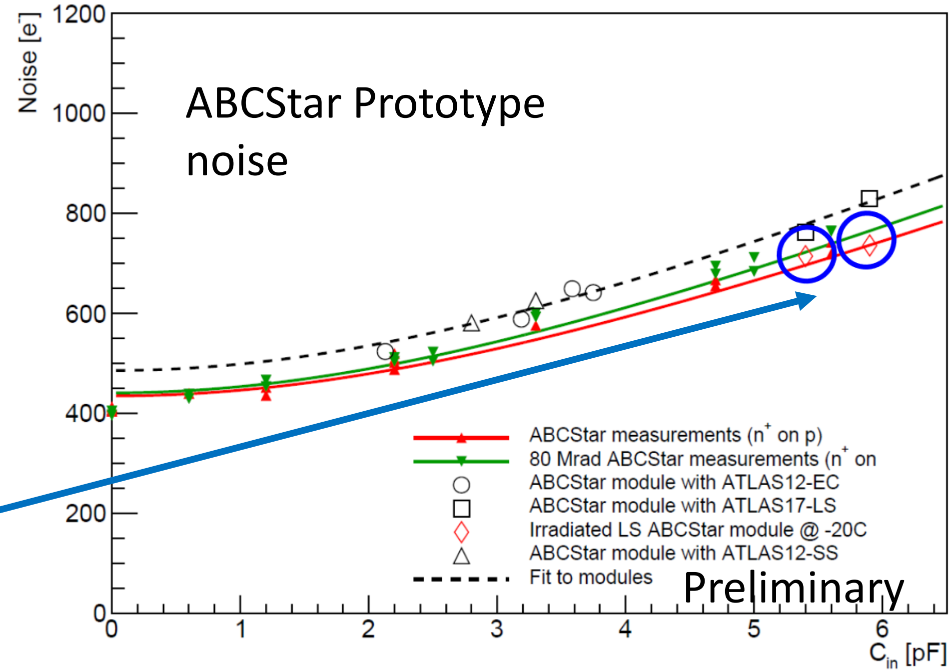
X-Ray Irradiations: DCDC Efficiency

- Cross check for nominal operation
- DCDC output assumed 1.5V, 2A load
- Efficiency: Power Out / Power In
- Efficiency > 70% for entire duration of 90Mrad
- Goal fully met



Module Test Beams And Irradiations

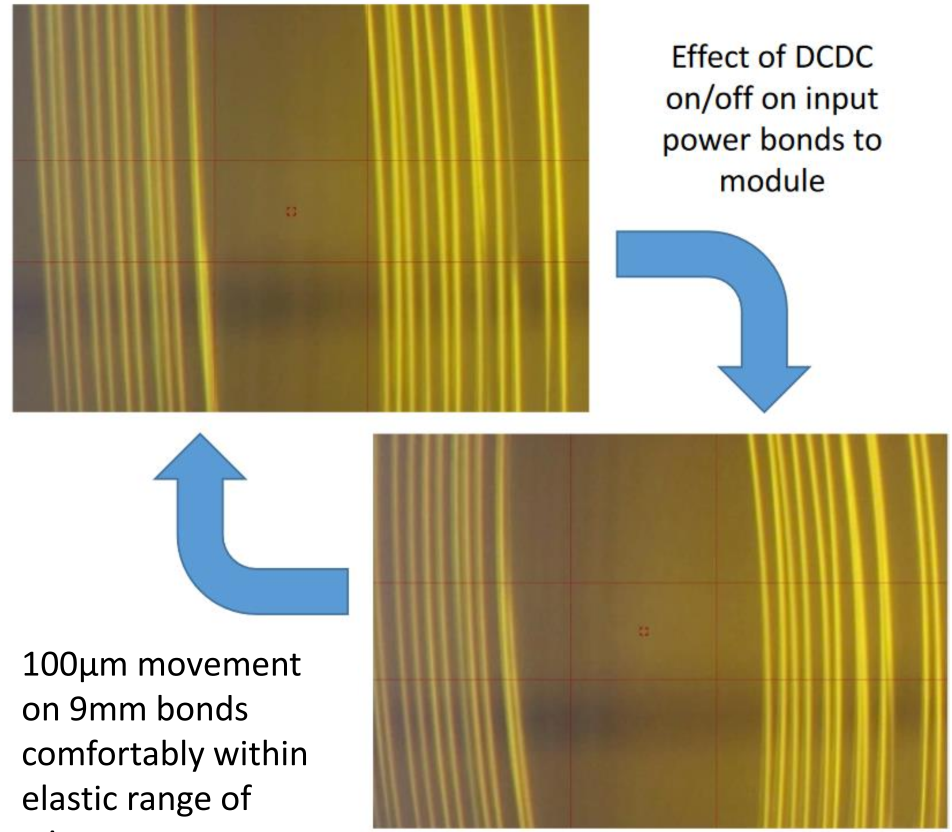
- Several test beam and irradiation campaigns have been performed with ABCStar modules
- Long-strip module irradiated with neutrons to a fluence of 5.1×10^{14} n_{eq}/cm^2 (about maximum fluence expected at end-of-lifetime for this module type) and after standard short term annealing
    - Module performance during testing is within specifications



Noise comparison of ABCStar chips at different conditions (e.g. single chip tests, module tests) well understood and in agreement with expectations

Module testing in magnetic field

- Tested a R0 module in a 1T magnetic field at DESY
  - 2T field not available but not expected to be an issue as resonance independent of B-field
- Fixed frequency triggers between 1kHz and 350kHz (swept up and down)
- Range of trigger frequencies cover the first normal mode frequencies of the wire-bonds of lengths 0.5 – 10mm
- Observed wire-bonds using an optical telescope and camera while module plane perpendicular to the magnetic field



- No broken wire-bonds during tests
- Analysis ongoing for any observed oscillations
- So far, no evidence of decreasing bond strength (pull-tests)

Contract with Hamamatsu Photonics for sensors has been signed 23rd August 2019

Next Steps

- Important ATLAS Final Design Reviews have been passed:
  - Strip Sensor FDR (April 2019)
  - Global Supports and Common Mechanics FDR (June 2019)
  - ASICs FDR Part 1 (July 2019)
  - Bus Tape FDR (September 2019, awaiting feedback)
  - Strip Module FDR (September 2019, awaiting feedback)
- Passing FDRs allow progression to pre-production
- Pre-Production:
  - Produce 5% of total number of ITk modules for site qualification and ramp-up to production
  - First sensors to be delivered January 2020
  - Module site qualification to be completed: November 2020
  - Module Production Readiness Review: December 2020
  - Module pre-production to be completed: February 2021

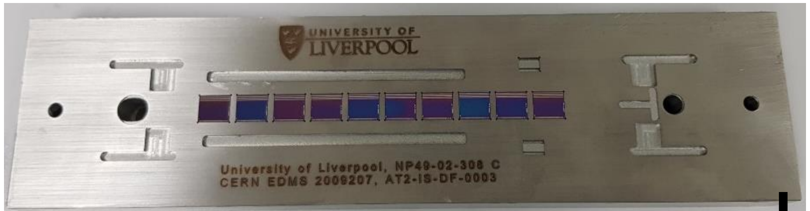
- Full strip production: June 2021 – November 2024
- Strip Barrel and Endcap to be ready for integration: March 2025
- Pixel to be ready for insertion: August 2025
- ITk to be ready for installation: May 2026

BACKUP

	Current ATLAS SCT	ATLAS ITk HL-LHC conditions
Luminosity	1×10^{34} cm^{-2} s^{-1} (2016 1.37×10^{34} cm^{-2} s^{-1})	7.5×10^{34} cm^{-2} s^{-1}
Integrated luminosity	300 fb^{-1}	4000 fb^{-1}
Silicon pseudorapidity Coverage (η)	2.7	4.0
Silicon area (strips)	60 m^2	165 m^2
Expected fluence (innermost strips)	2×10^{14} n_{eq}/cm^2	12×10^{14} n_{eq}/cm^2
Pile-up	23 (peak 40)	≈200

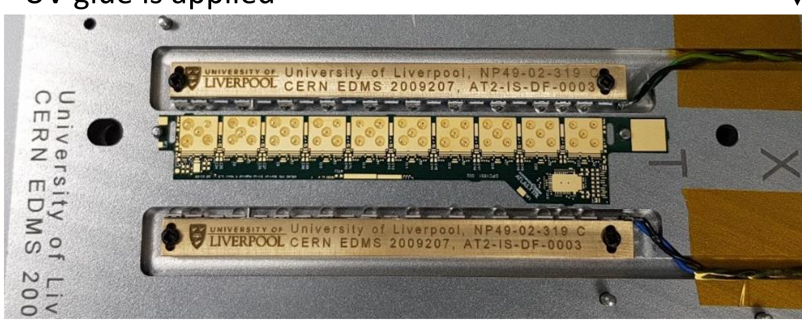
Module Assembly 1

1) ASICs placed in jig



2) Pick up with tool (dowel pins for alignment)

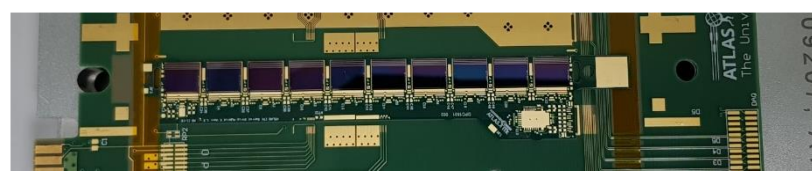
3) Hybrid placed on jig (dowel pins for alignment) and UV glue is applied



4) ASICs placed on hybrid, UV glue cured with LEDs while weight holds ASICs in place

5) Pick hybrid Up with tool

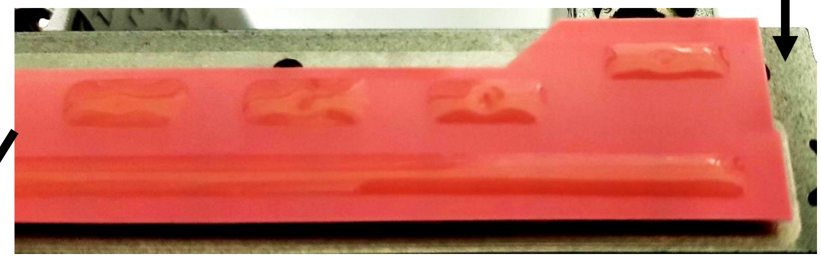
6) Place hybrid on panel for wire-bonding and testing



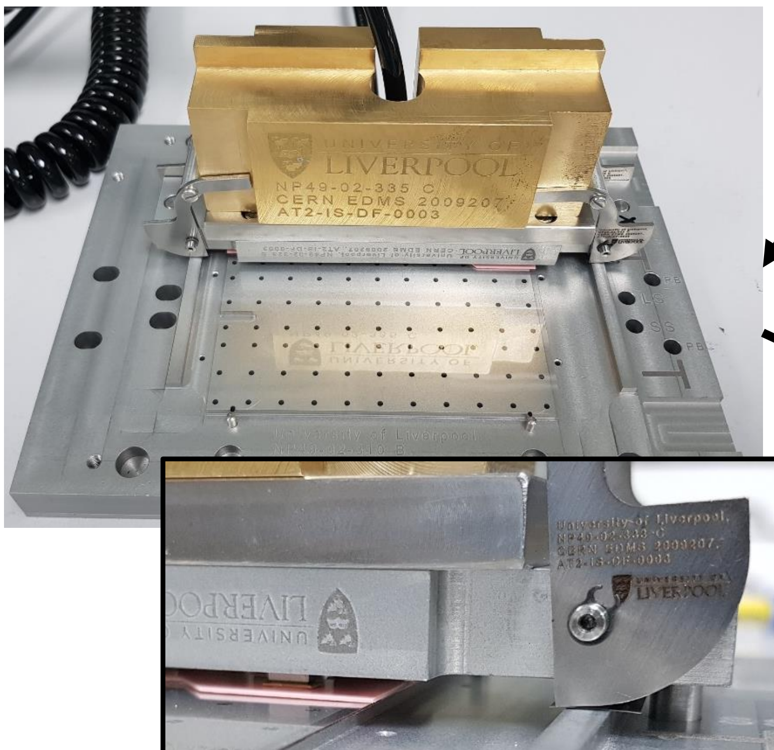
Module Assembly 2

7) Pick up hybrid from panel

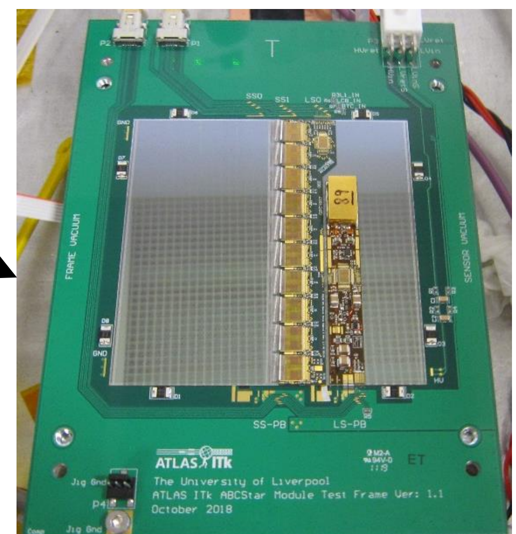
8) Apply glue with stencil



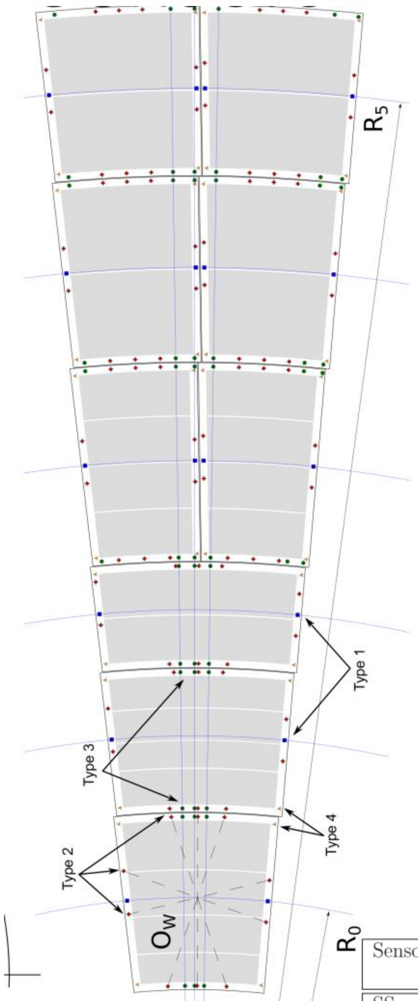
9) Place sensor on jig (dowel pins for alignment); place hybrid on sensor; weight on tool during curing of glue

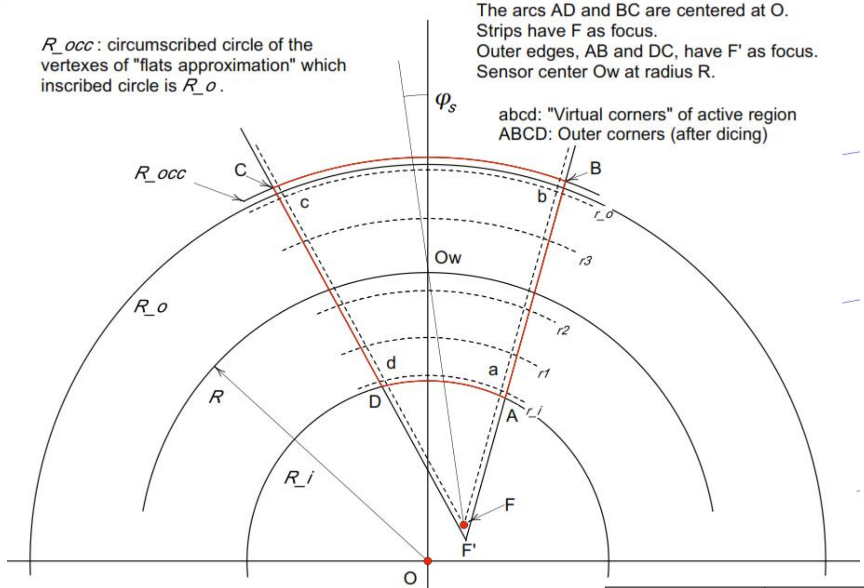


10) Powerboard glued in similar way; then module placed in test frame and wire-bonded



Sensor Details





Sensor	Outer Dimension [µm]	Strip Pitch [µm]	No. readout strips	Thickness [µm]
SS	Width: 97950 ± 20; Length: 97621 ± 20	75.5	4 × 1280	300 to 320 ±15
LS	Width: 97950 ± 20; Length: 97621 ± 20	75.5	2 × 1280	300 to 320 ±15

Ring/Row	Inner Radius [mm]	No. readout strips	Strip Length [mm]	Strip Pitch (inner) [µm]
Ring 0 Row 0	384.5	1024	19.0	75.0
Ring 0 Row 1	403.5	1024	24.0	79.2
Ring 0 Row 2	427.5	1152	29.0	74.9
Ring 0 Row 3	456.4	1152	32.0	80.2
Ring 1 Row 0	489.8	1280	18.1	69.9
Ring 1 Row 1	507.9	1280	27.1	72.9
Ring 1 Row 2	535.0	1408	24.1	75.6
Ring 1 Row 3	559.1	1408	15.1	78.6
Ring 2 Row 0	575.6	1536	30.8	75.7
Ring 2 Row 1	606.4	1536	30.8	79.8
Ring 3 Row 0	638.6	896	26.2	71.1
Ring 3 Row 1	664.8	896	32.2	74.3
Ring 3 Row 2	697.1	896	32.2	77.5
Ring 3 Row 3	729.3	896	26.2	80.7
Ring 4 Row 0	756.9	1024	54.6	75.0
Ring 4 Row 1	811.5	1024	54.6	80.3
Ring 5 Row 0	867.5	1152	40.2	76.2
Ring 5 Row 1	907.6	1152	60.2	80.5

High Voltage Decision

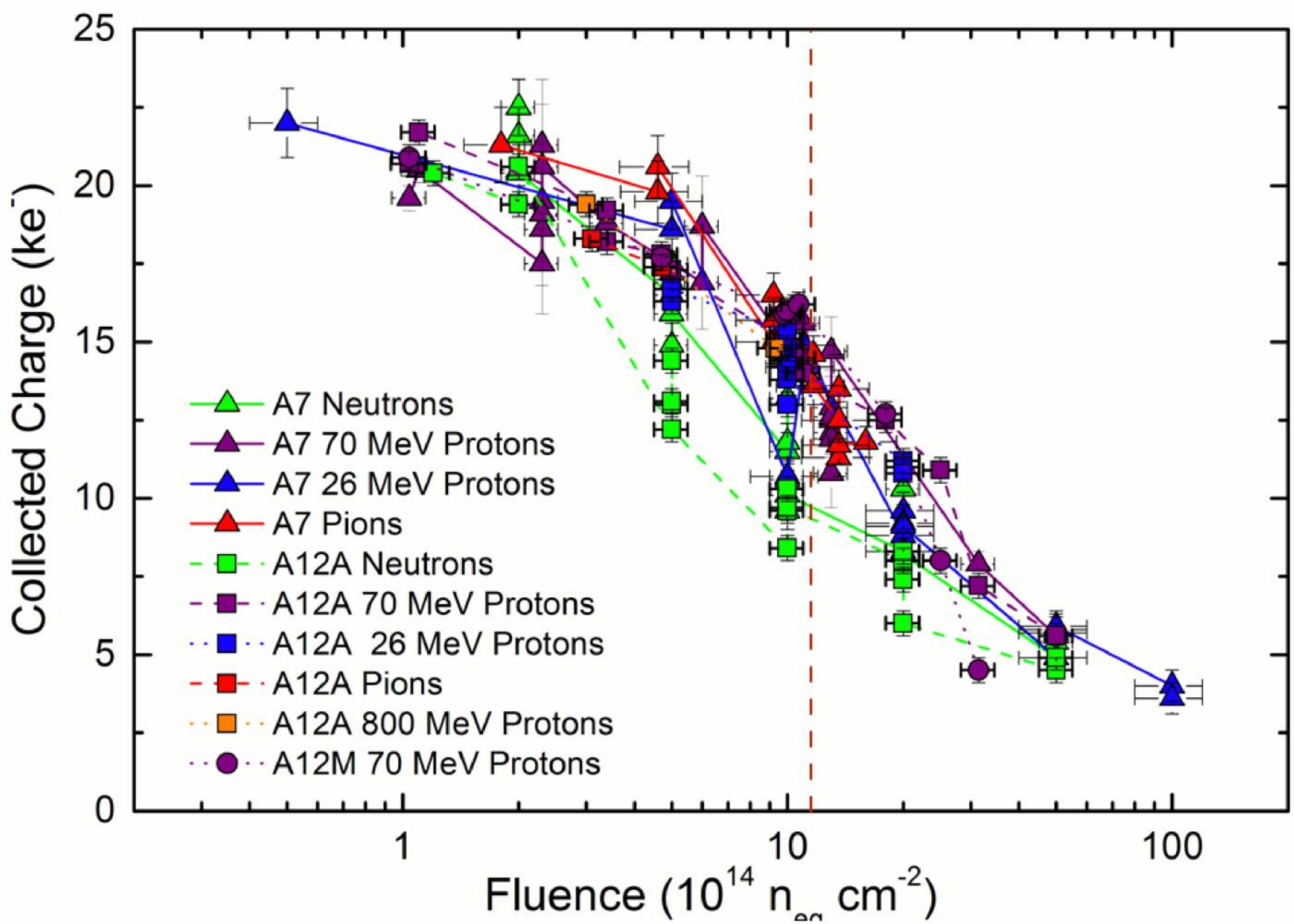
- During TDR test-beam studies, it has been confirmed that
  - the required threshold setting for 99% efficiency can be estimated
  - The required threshold setting for 1×10^{-3} noise occupancy can be predicted from output/input noise
  - A signal-to-noise of 10:1 has a threshold setting that meets both requirements
- It was confirmed that 500V baseline voltage is sufficient to meet the requirements

S/N ratio for different sensor positions within ITk: all are above the 10:1 requirement

Layer/Ring	Barrel	Disk 0	Disk 1	Disk 2	Disk 3	Disk 4	Disk 5
0	15.8	15.1	14.8	14.4	13.9	13.3	12.2
1	-	17.3	17.0	16.5	16.0	15.2	14.1
2	16.2	17.9	17.5	17.0	16.4	15.7	14.8
3	-	19.1	18.7	18.2	17.5	16.7	15.7
4	-	15.1	14.8	14.4	13.9	13.4	12.7
5	-	14.8	14.5	14.1	13.6	13.1	12.5

ATLAS12 Sensor Irradiation

- **Green**: sensors irradiated with neutrons
  - used as conservative signal size



ATLAS ITk TDR (TL-TDR-025 · LHCC-2017-005)
Dashed line: expected end-of-life fluence

Sensor Irradiation

Collected charge comparison for gamma irradiation at various dose rates

Post-anneal 35Mrad charge reduction needs to be investigated further.

All other measurements comparable.

Maximum collected charge independent of irradiation dose.