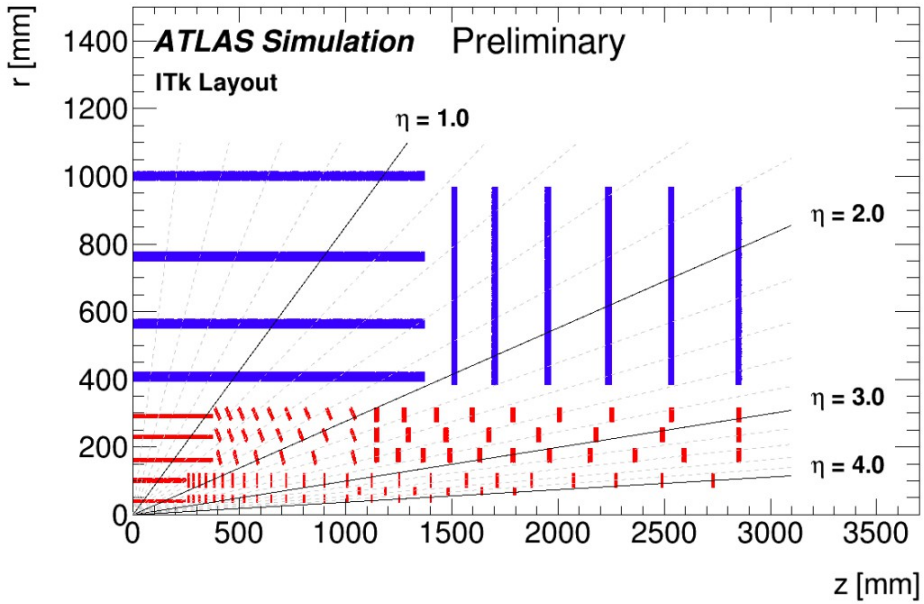
The ATLAS ITk Strip Detector System for the Phase-II LHC Upgrade

Karola Dette on behalf of the ATLAS Collaboration

ITk strip detector introduction



ITk Strip system will consist of:

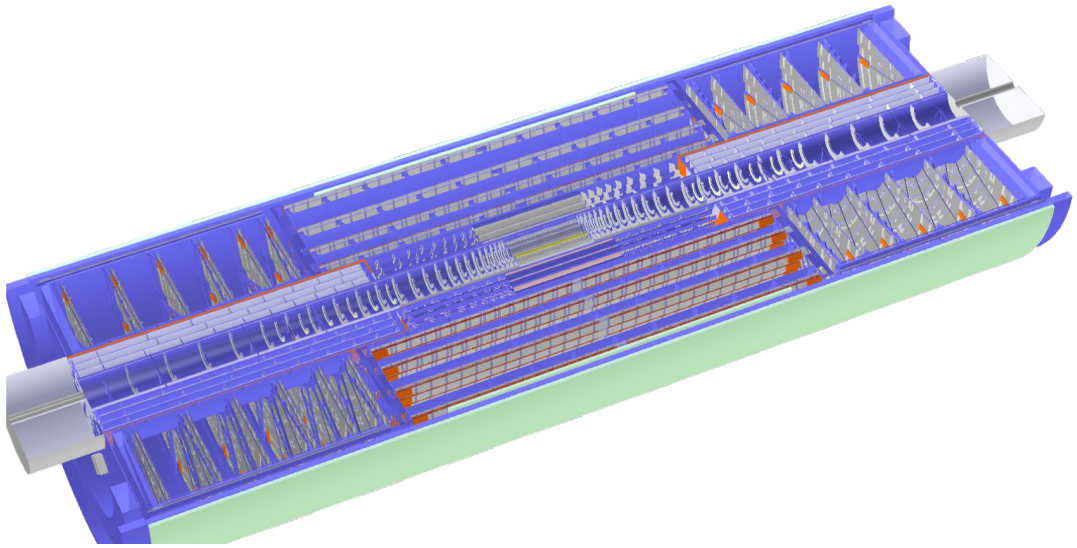
- 4 barrel cylinders and 6 disks per end cap
- 165 m^2 of silicon (current Inner Detector: 61 m^2)
- ~18 k modules (ID: ~4k modules)
- ~60 million channels (ID: ~6 million)

Main requirements for design:

- radiation hardness, high granularity, readout speed that meets increased trigger rates, low material budget

<u>Example of design choices made to meet requirements and schedule:</u>

- Local, on-module DC-DC
- Advanced cooling: Manifolded, CO_2-based
- Honeycomb structures for module support
- Industry standard design rules, simplified construction
- Assembly and testing happening at multiple sites worldwide



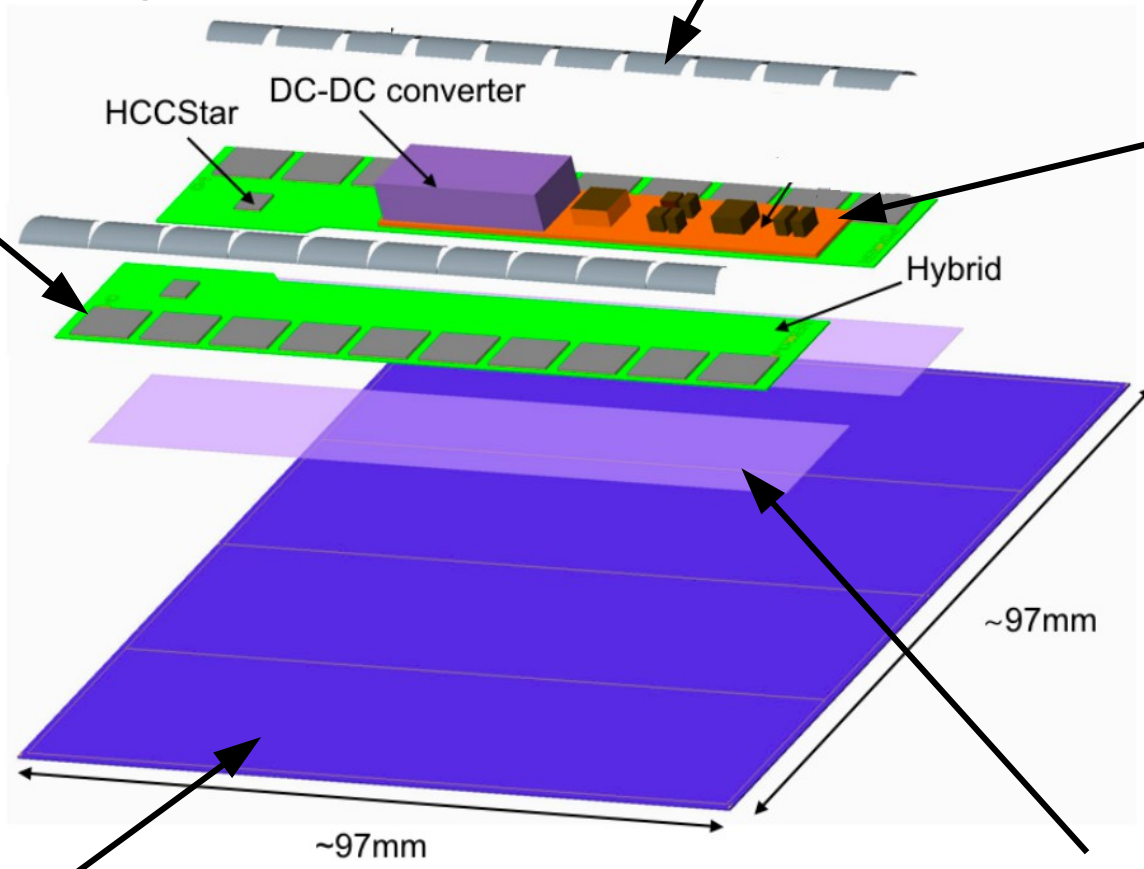
ITk strip detector introduction II

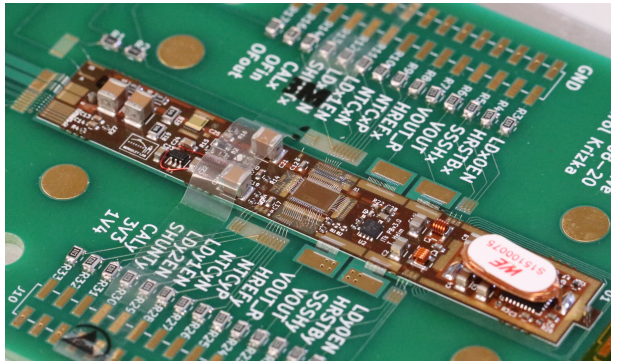
ASICs: 130nm CMOS technology readout chips, attached with UV glue

4 row wirebonding for data readout

Power board: DC-DC converter, dedicated power control ASIC

HV MUX switch for switching off individual modules



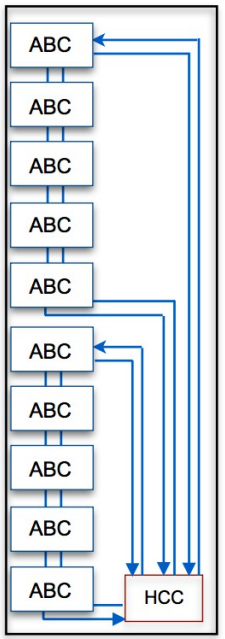


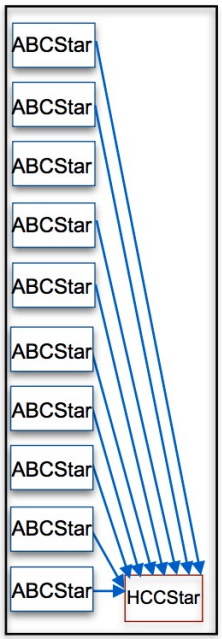
Sensor: AC-coupled n-type strip implants in a p-type float-zone silicon bulk

Radiation hard two component epoxy glue

ASICs

- ABCStar & HCCStar: data readout & control on the hybrids
- AMAC: monitoring and control chip for power board
- Star → latest ASIC generation with central readout scheme for higher trigger rate/bandwidth
- Chips fabricated at Global Foundries in 130 nm CMOS technology
- 640 MHz clock, 256 channel per ASIC, Region Of Interest trigger options, unloaded noise ~400 electrons

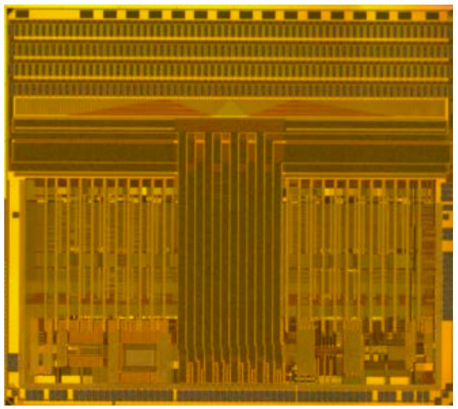




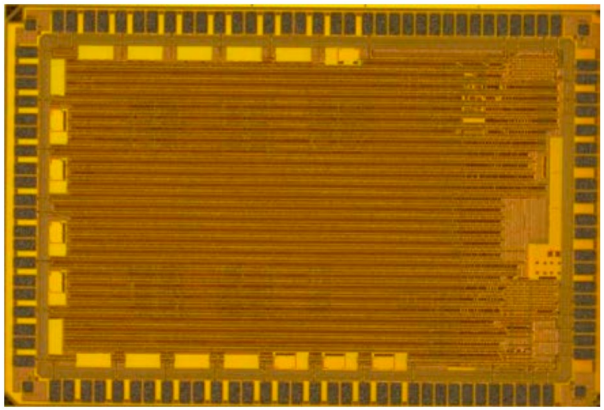
Quality Control/Quality Assurance tasks

- Reception quality control (wafer probing) to identify good dies
- Metrology and visual inspection of diced ASICs
- Irradiation qualification of ASICs for new designs

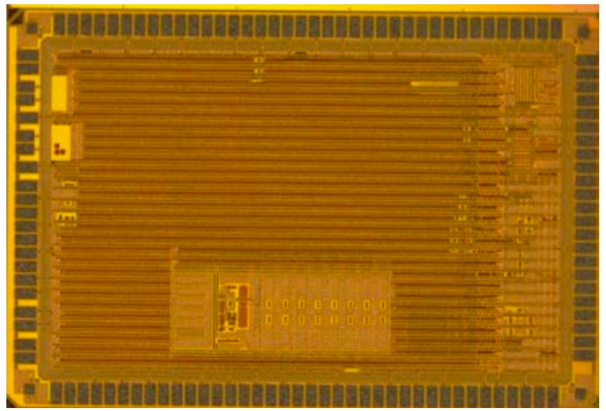
ABCStar



HCCStar



AMACv2a



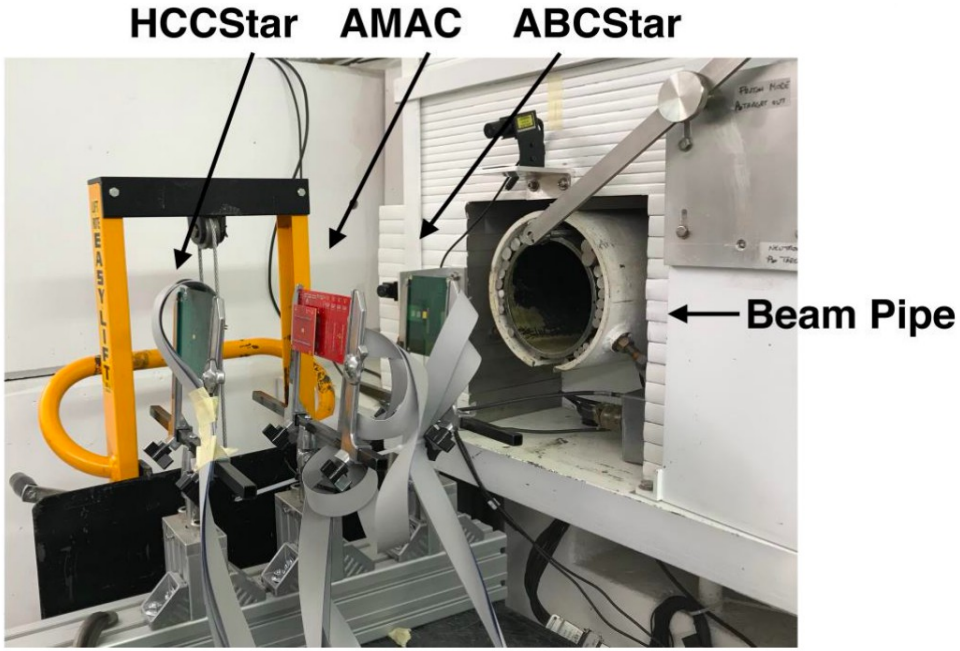
ASICs

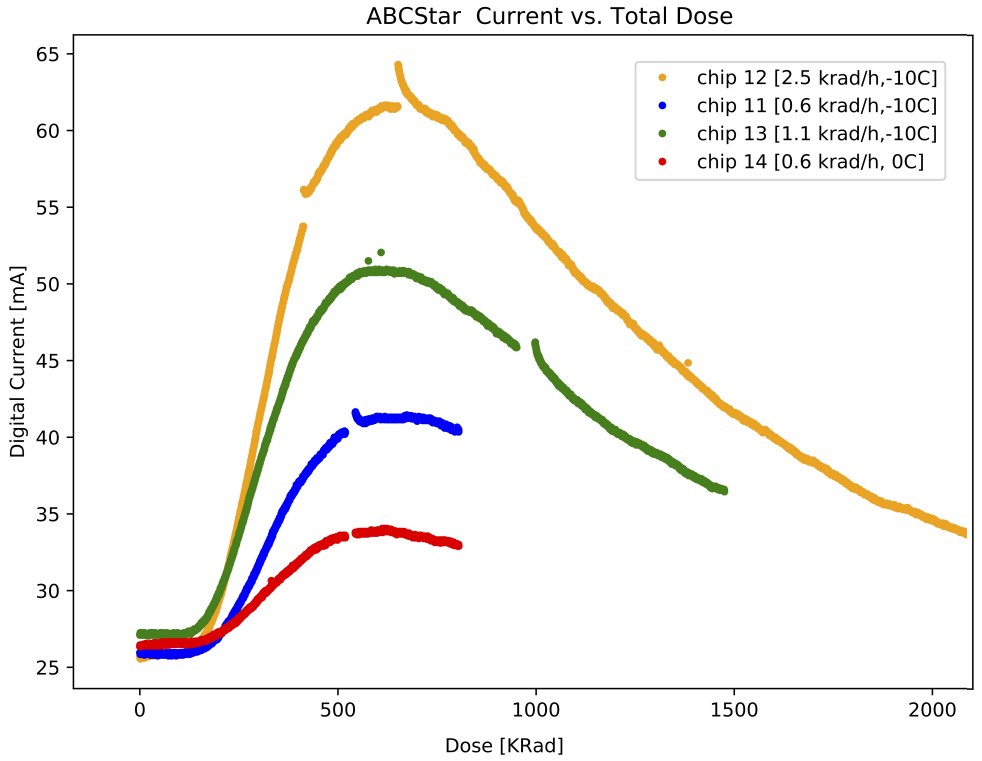
- TID dependent current increase known problem for some non-enclosed transistors (e.g. IBM 130nm)
- IBL (Insertable B-Layer, current innermost tracking layer in ATLAS) detector had to change operation temperature to cope with current increase

→ Extensive irradiation campaign performed on ABCStar chips at different dose rates and temperatures to forecast current maximum

• Input of current estimation important to services specs & design as well as possible operating temperatures

- Expected dose rate during operation up to 2 kRad/h at a temperature of -10 C°

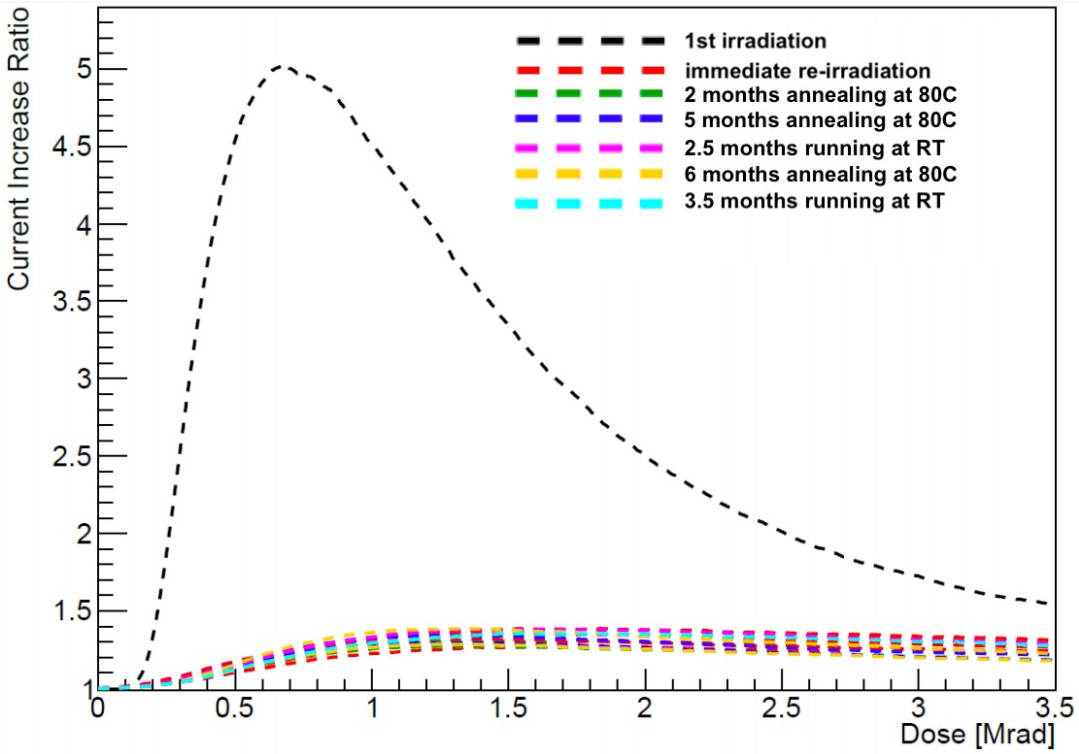


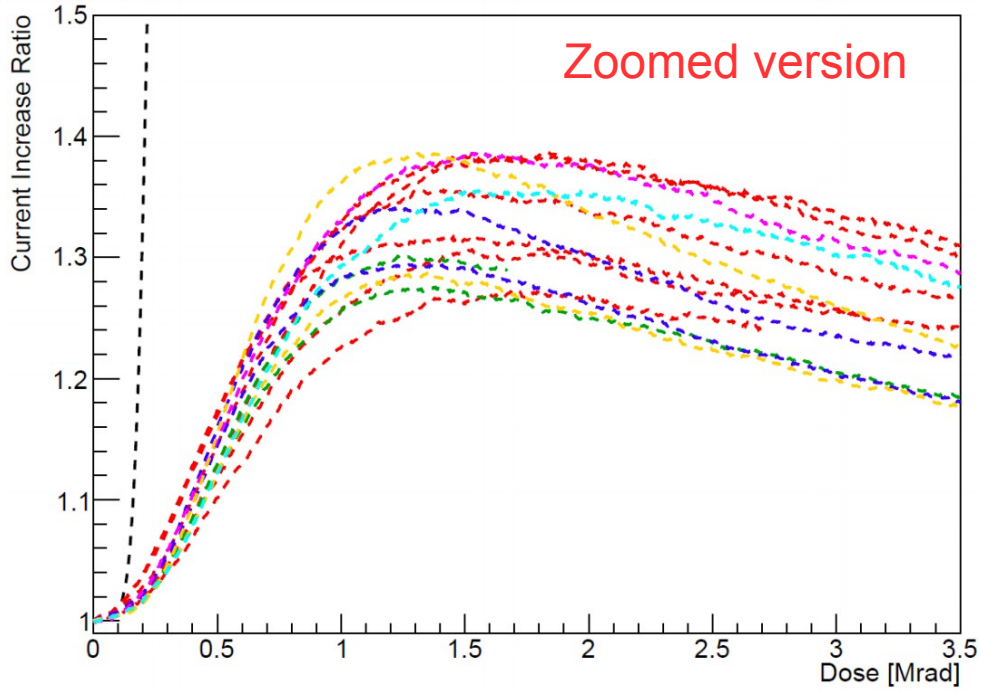


ASICs

Option to cope with TID induced current increase

- Looking at pre-irradiating ASICs to 8 Mrad with Co-60 source before module assembly
- Removes the TID bump and gives us more headroom for system design
- Have pre-irradiated ABC130 at INER in Taiwan with ~350 kRad/hour and re-irradiated after different annealing periods
- So far no significant annealing found
  → confident it also will not occur during detector lifetime, started process of making pre-irradiation the baseline for production





Plot shows current increase, not total current

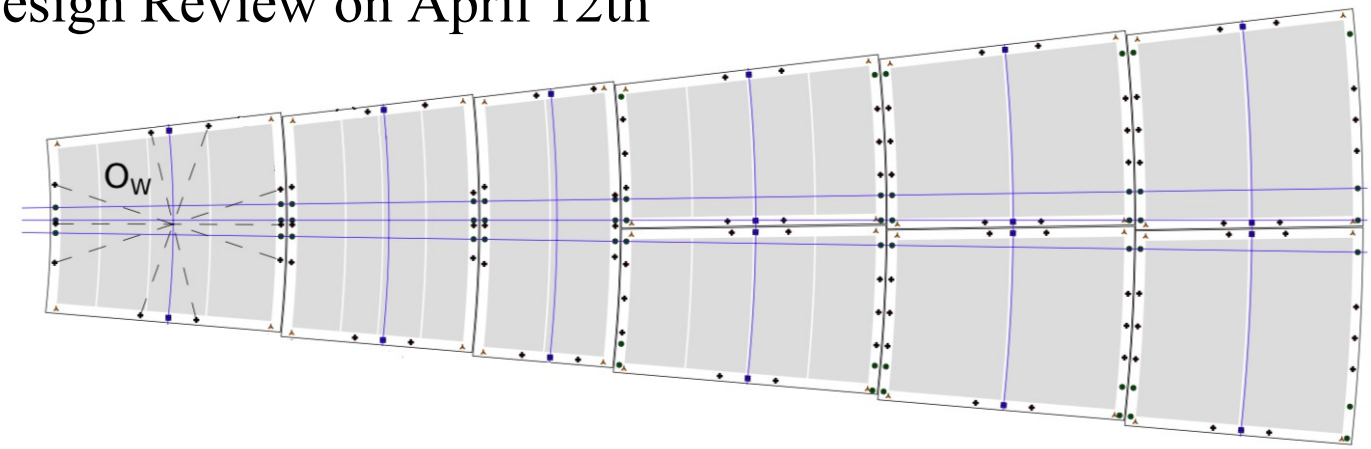
Sensors

- p-type FZ silicon with n-type strip implants
- depletion voltage ≤ 350V, maximum operation voltage 500V, slim edge of ~500 µm for higher track acceptance

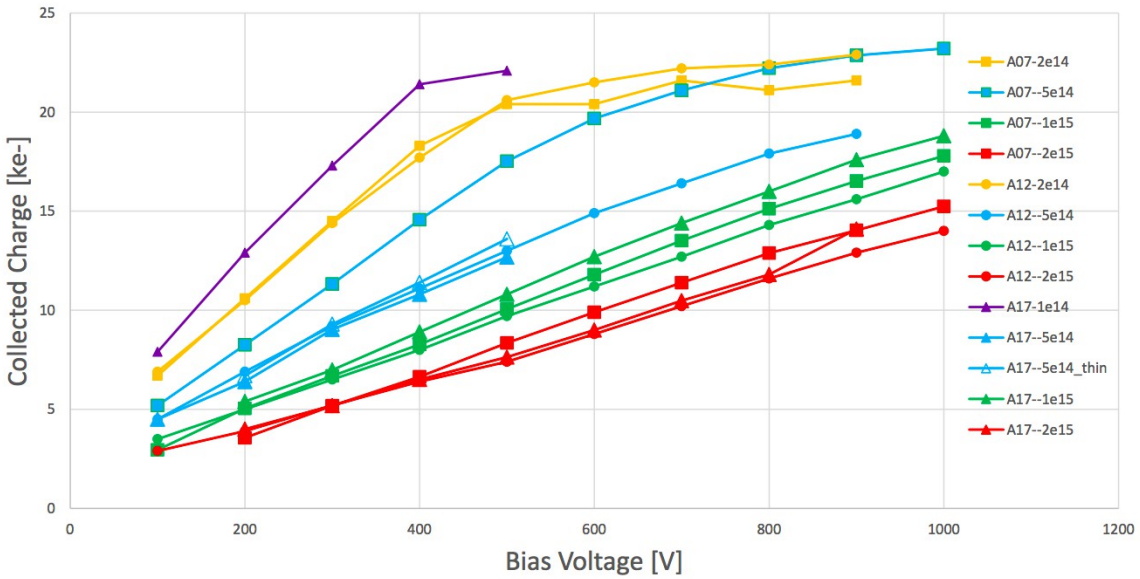
Intensive testing campaign to verify prototype design:

- Testing of various designs developed over more than 10 years
- 5 Irradiation sources, 15 institutes testing the sensors
- 500 devices (miniature sensors, diodes, full size sensors) just in the last iteration
- new max HV spec of 500 V (down from 700 V) due to better post-irradiation performance of Star ASICs, keeping the specified S/N = 10:1 even at lower voltages

Successfully passed Final Design Review on April 12th
and will enter into
pre-production soon!



Sensors



Layer/Ring	Barrel	Disk 0	Disk 1	Disk 2	Disk 3	Disk 4	Disk 5
0	16.4	15.7	15.4	15.0	14.5	13.7	11.8
1		17.9	17.5	17.0	16.4	15.4	13.7
2	15.3	18.1	17.9	17.2	16.6	15.6	14.0
3		19.4	19.2	18.4	17.7	16.6	15.1
4		14.4	14.2	13.6	13.2	12.4	11.5
5		13.9	13.7	13.1	12.7	12.0	11.1

Estimated S/N values for different locations in the strip tracker using CCE values after neutron irradiation

- End-of-life S/N values derived depending on each module's fluence & strip length
- Requirement less than 1×10^{-3} noise occupancy with detection efficiency > 99%

<u>Estimates have inherent safety factors:</u>

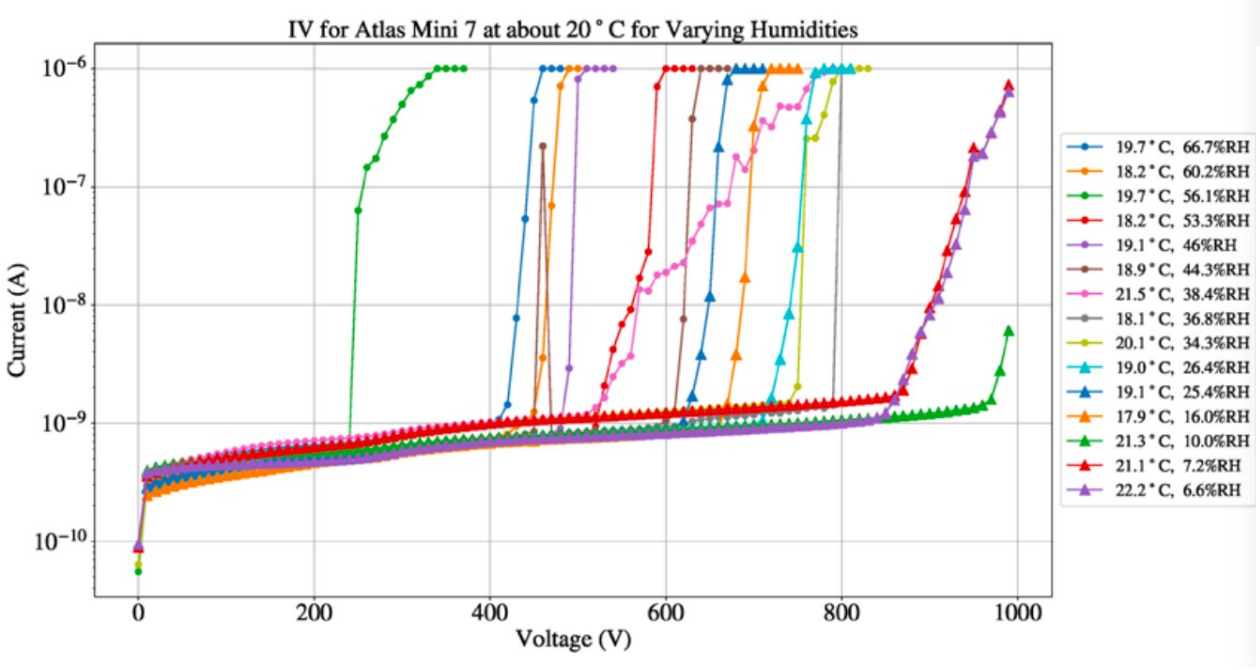
- pessimistic noise parameterization for ABCStar measurements
- 50% fluence safety factor
- Usage of neutrons under-estimates the Charge Collection Efficiency (CCE)
  (about 1/3 of NIEL due to charged hadrons, which have higher CCE for medium-to-high fluences)

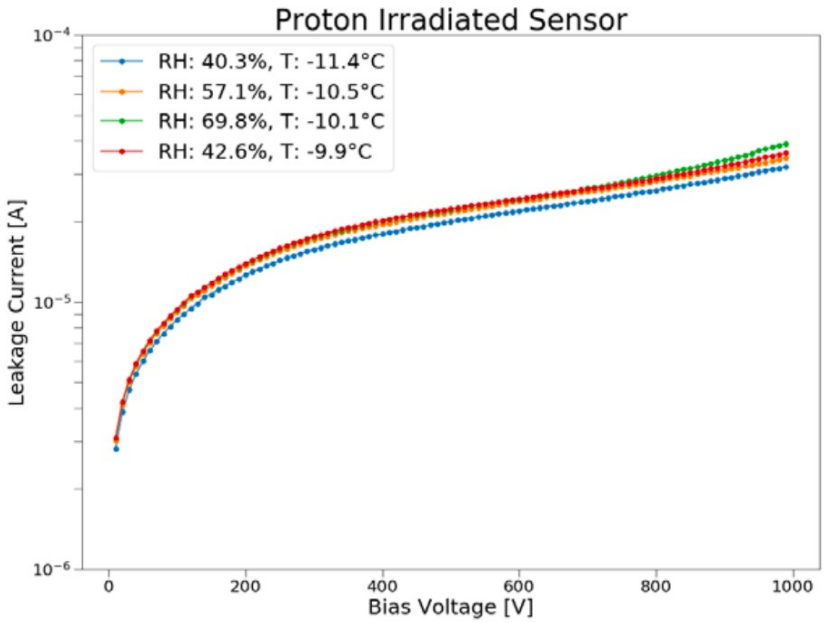
Sensors

- Sensors' breakdown voltage depends on humidity, but this will not affect operation

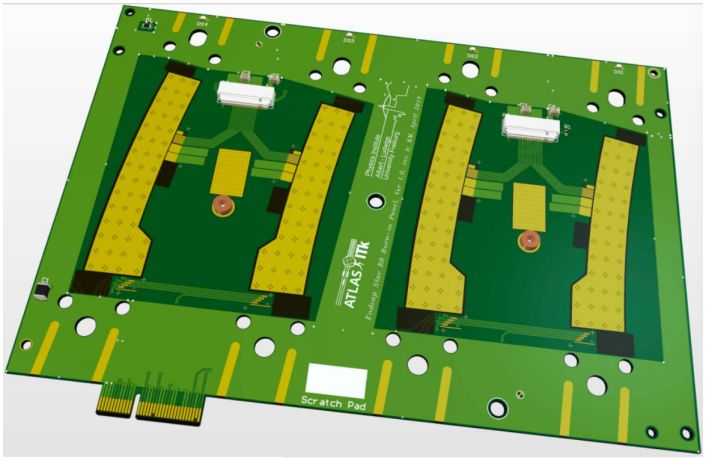
Because:

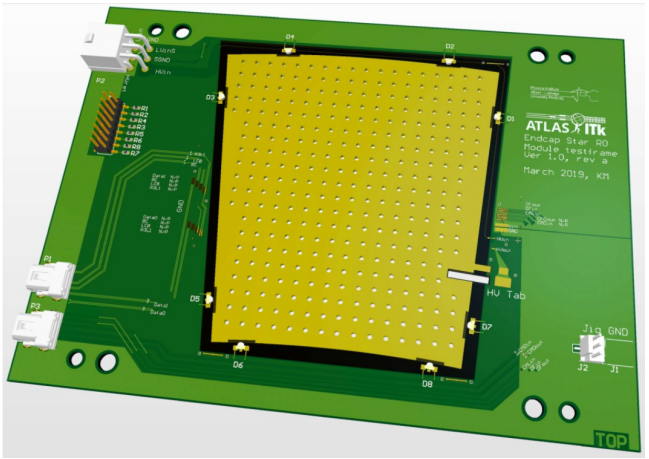
- The operational environment is dry
- Sensors lose the sensitivity after irradiation
- Ensuring dry storage/handling mitigates problem
- IV curves will only be taken in dry environments (= no increased risk of damage)



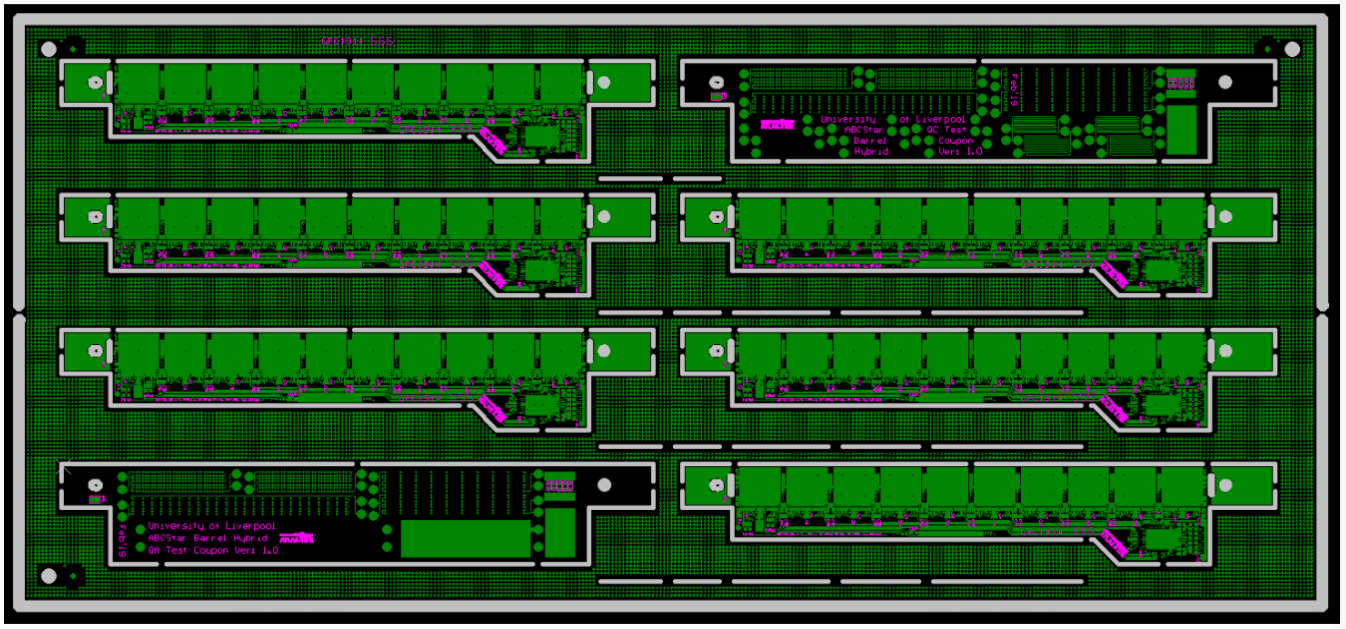


Hybrids and test frames



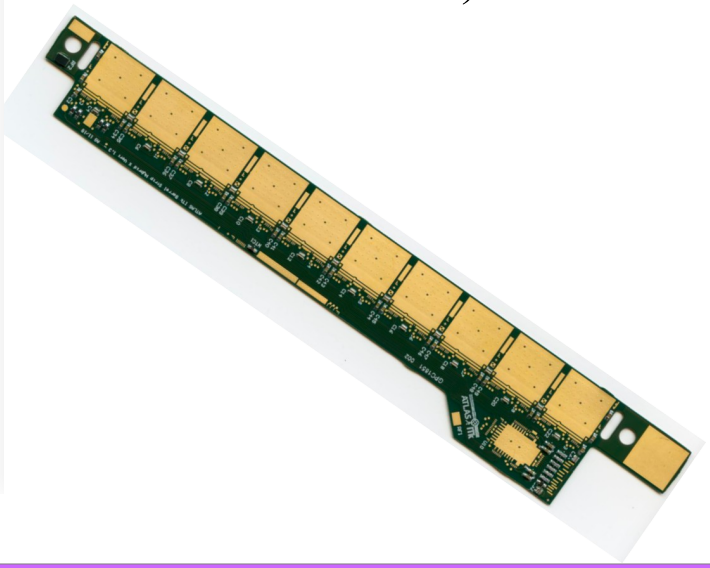


QC Test Coupon



QA Test Coupon

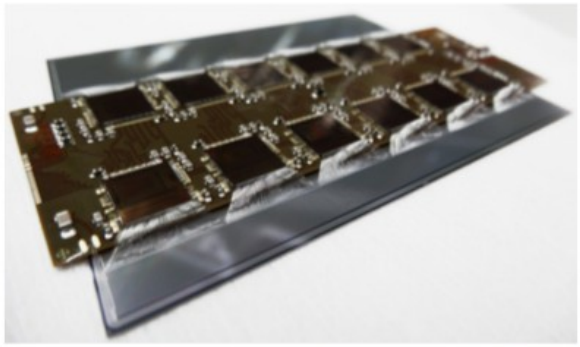
- Hybrid (4 layer flex circuit), test frame and burn-in panel designs are being finalized right now
- 15 different hybrid types in total
- Test coupons will allow thorough QA/QC measurements (thickness, resistance, bond pull tests, thermal cycling, delamination etc.)

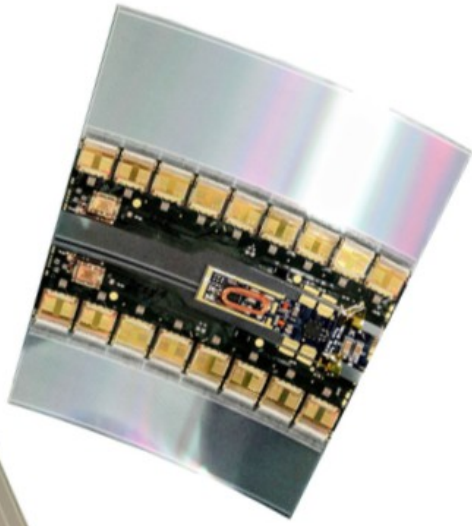


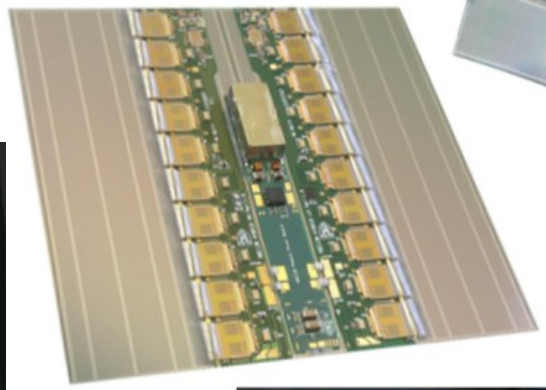
Modules – History of Prototyping

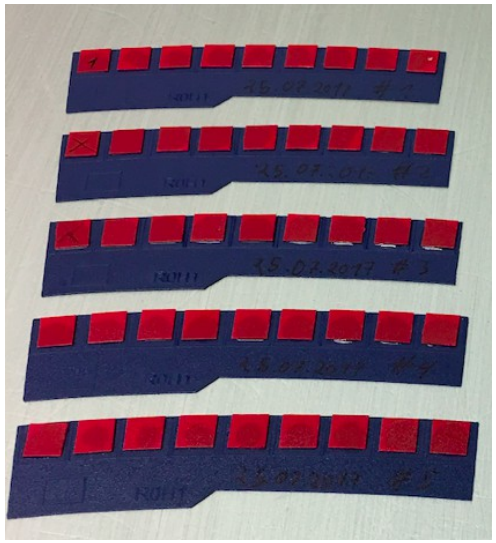
Module assembly has developed over past few years

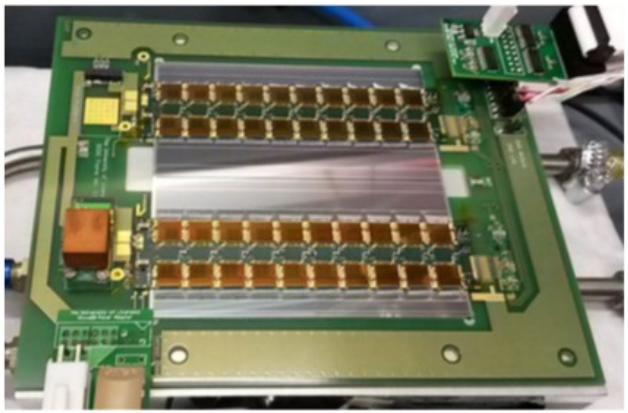
- ABCN modules (2008-2016)
  - ~ 50 barrel modules
  - ~ 30 petalet modules
- ABC130 modules (2015-2019)
  - ~ 80 barrel modules
  - ~ 30 EC modules
- Countless trials with plastic and glass dummies
- ABCStar modules (2019-onwards)
  - 1 LS & 7 SS barrel modules
  - 3 EC modules



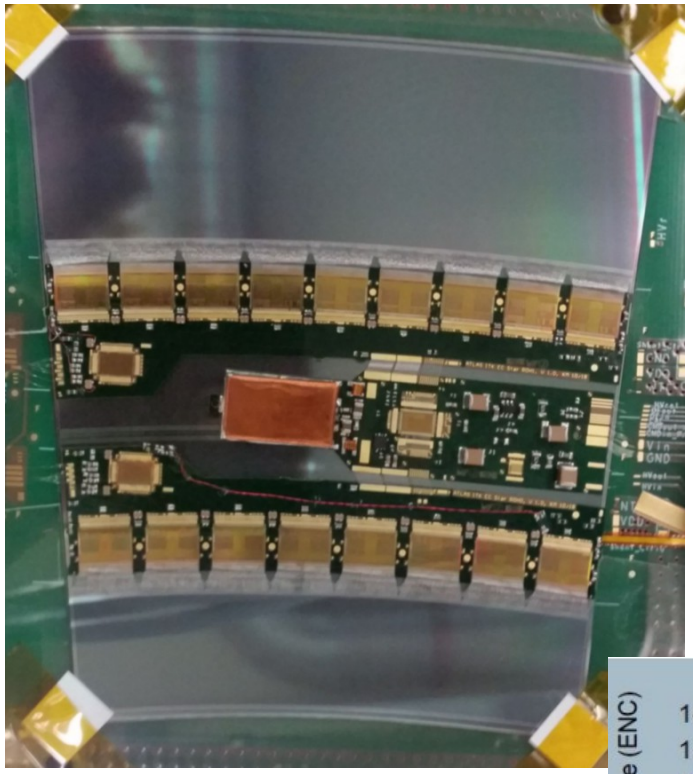




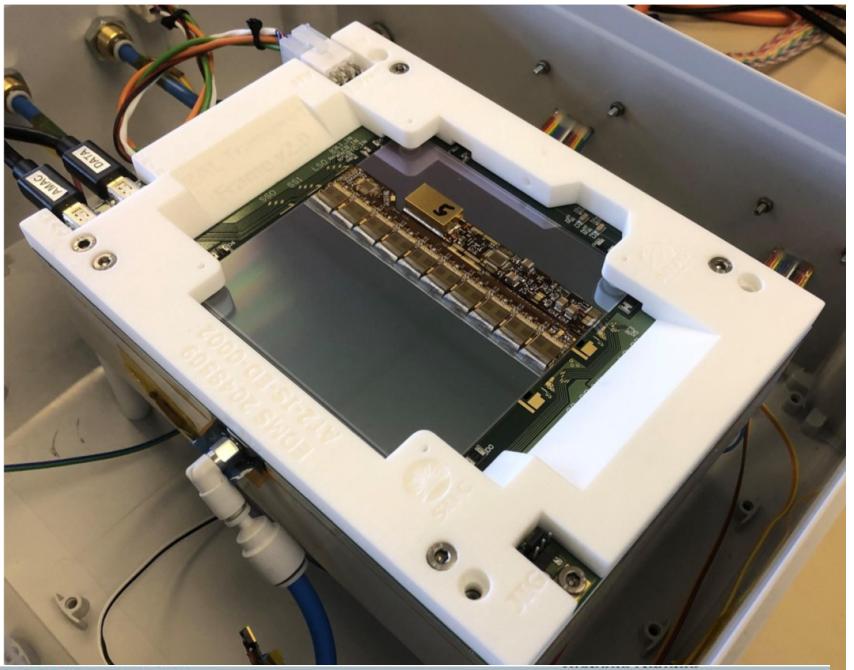




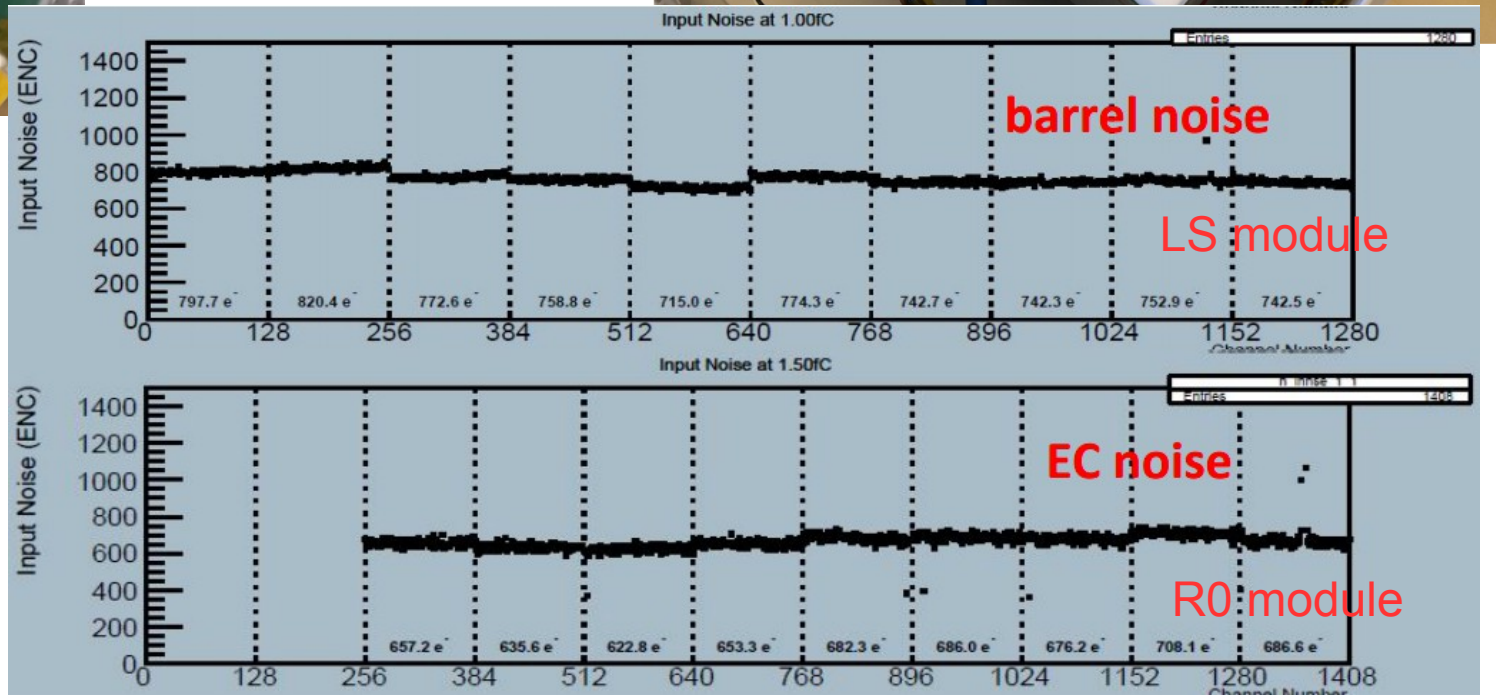
Star Modules



- First Star like modules have been built and tested
- Very promising results consistent with expectation
- Some minor design corrections needed

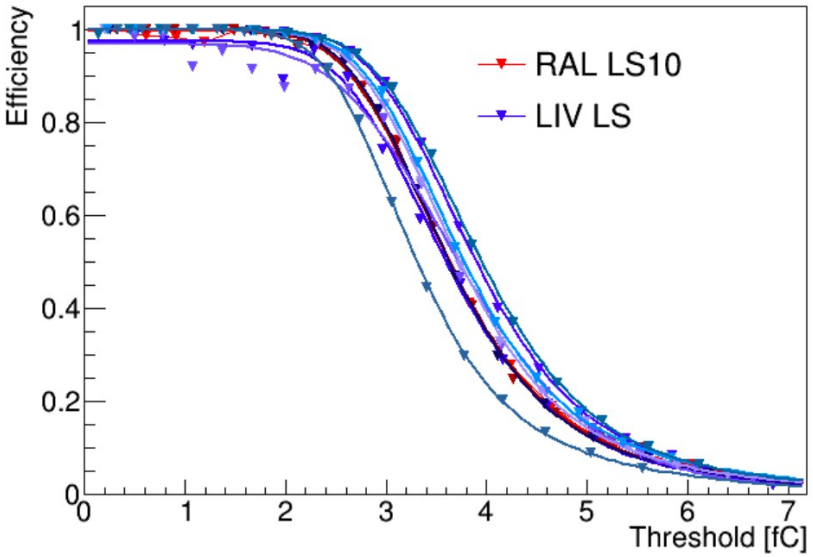


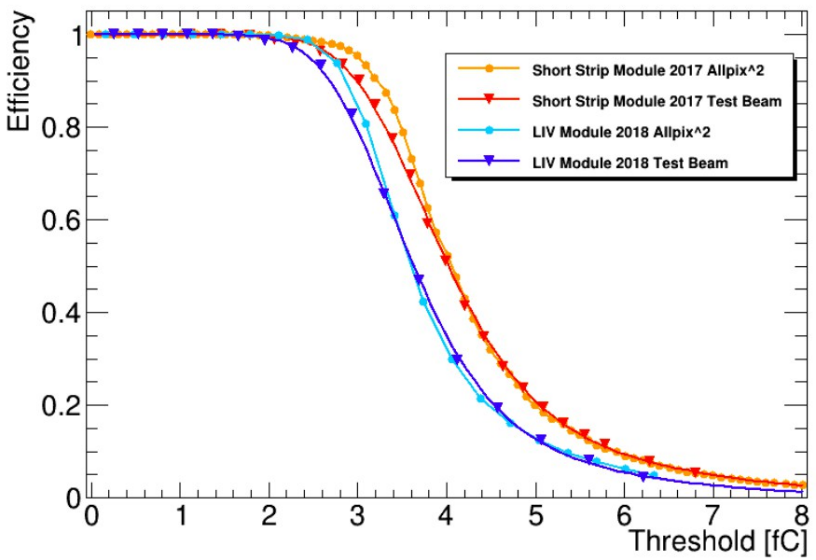
- Full characterisation and testing of these first modules ongoing
- More modules will be built and tested as more components become available



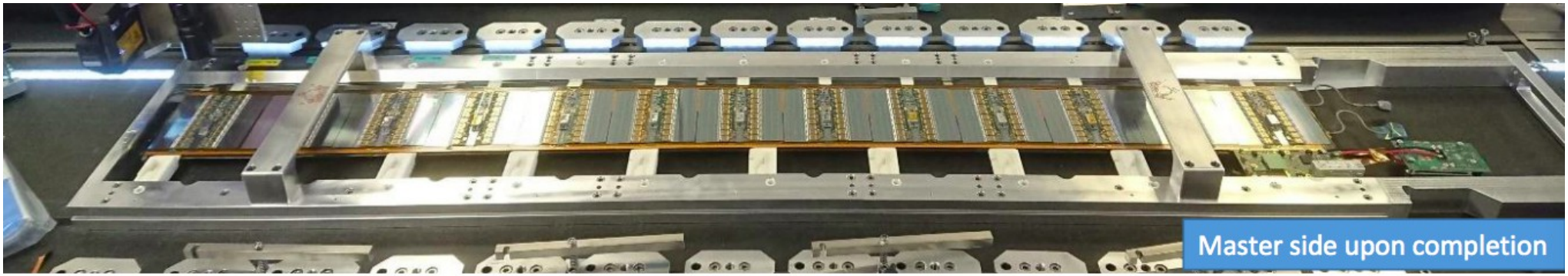
Testbeam results

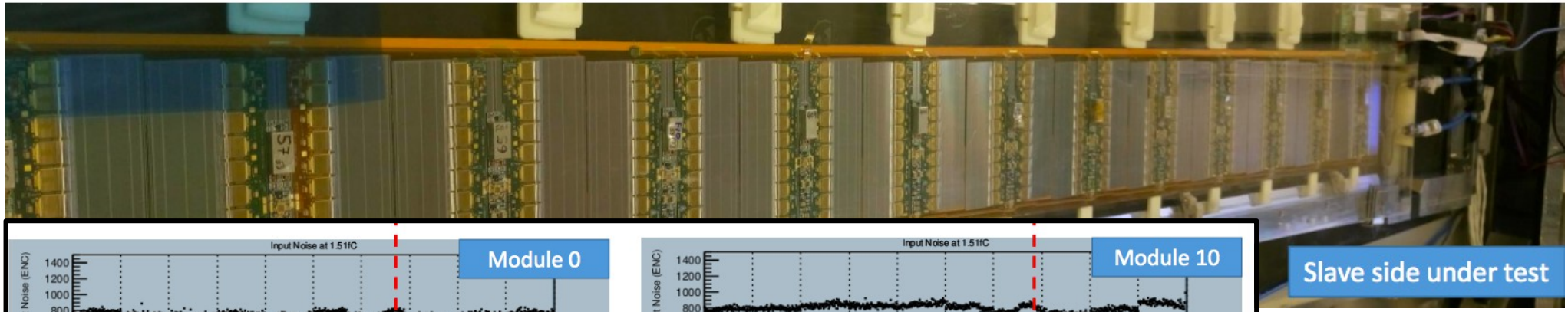
- Latest ITk strip test beam campaigns: two in 2018, two planned for 2019
- Several thousand runs of data-taking
- One campaign at DESY in June, using 4 GeV electrons and an EUDET-type beam telescope
- Tested two long-strip (LS) barrel modules & one double-sided R0 end-cap module
- Simulation generated with Allpix2 using TCAD electric field maps to get estimated results
- Matches well with efficiency measured in test beam
- More measurements with irradiated modules ongoing

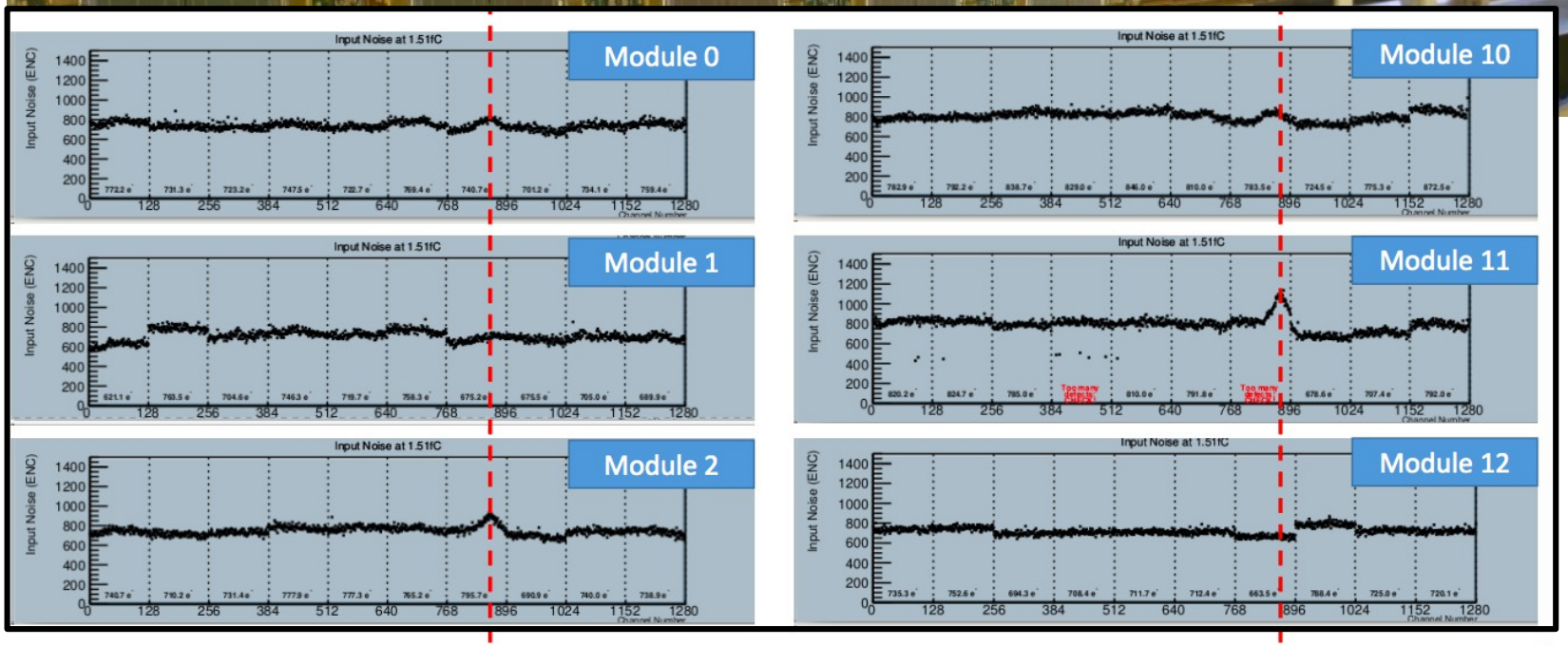




System test







- First double sided stave under test at RAL
- Check: powering, fibre optics, DAQ systems, cooling, mechanical supports, interlocks and control

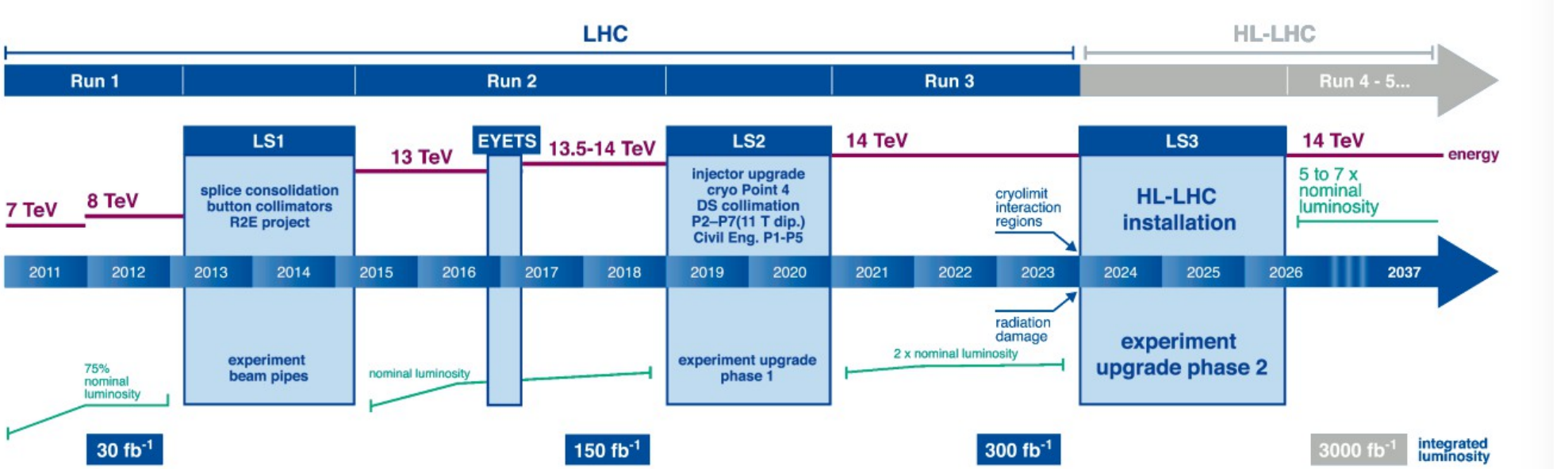
Summary and outlook

- ITk Strip detector is a complex and ambitious project that is on a good path towards success
- Pre-production is scheduled to start in less than a year from now
- Detailed plans for Quality Assurance and Quality Control procedures to test every part of the detector throughout the construction are being defined and documented
- Designs for components, tools and testing equipment are being finalised and reviewed
- Expect to have first final design prototypes of every module type in hand before the end of this year

Thank you for your attention!

Backup

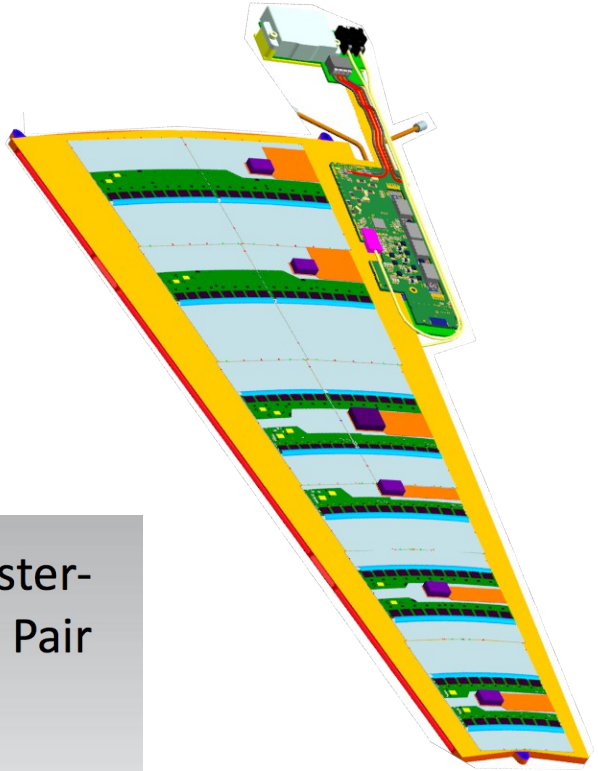
The HL-LHC and it's impact on detector upgrades

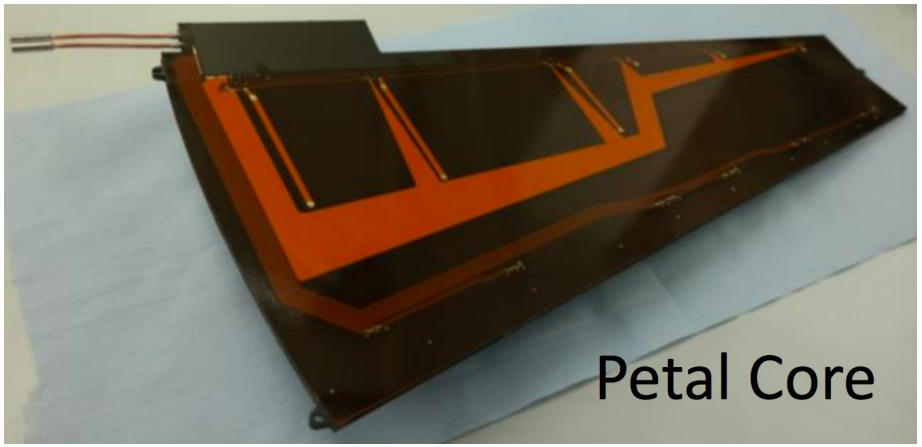


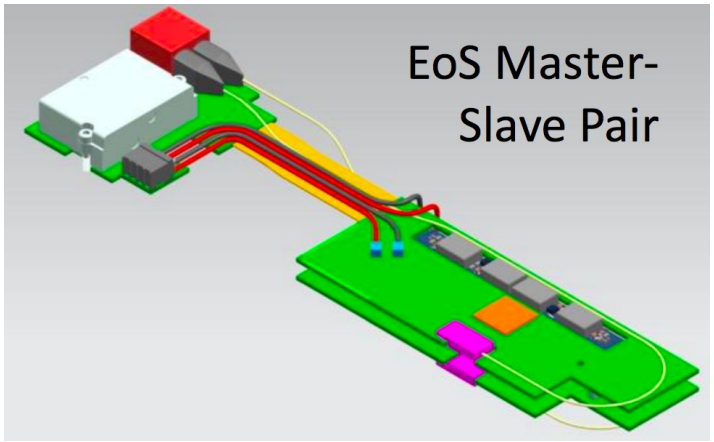
- nominal luminosity of $\mathcal{L} = 5 \times 10^{34} cm^{-2} s^{-1}$ and average pileup of $<\mu> = 140$ present new challenges for detector
- high data rate and expected radiation damage require complete replacement of current tracking system
- ITk Strip Detector will have to withstand radiation levels up to $1.2 \times 10^{15} n_{eq}/cm^2$ and 50 MRad, ten times more than current SCT detector
- ITk will extend to largest radius of inner detector, including radii currently covered by Transition Radiation Tracker system, which will be removed completely

ITk strip detector introduction II

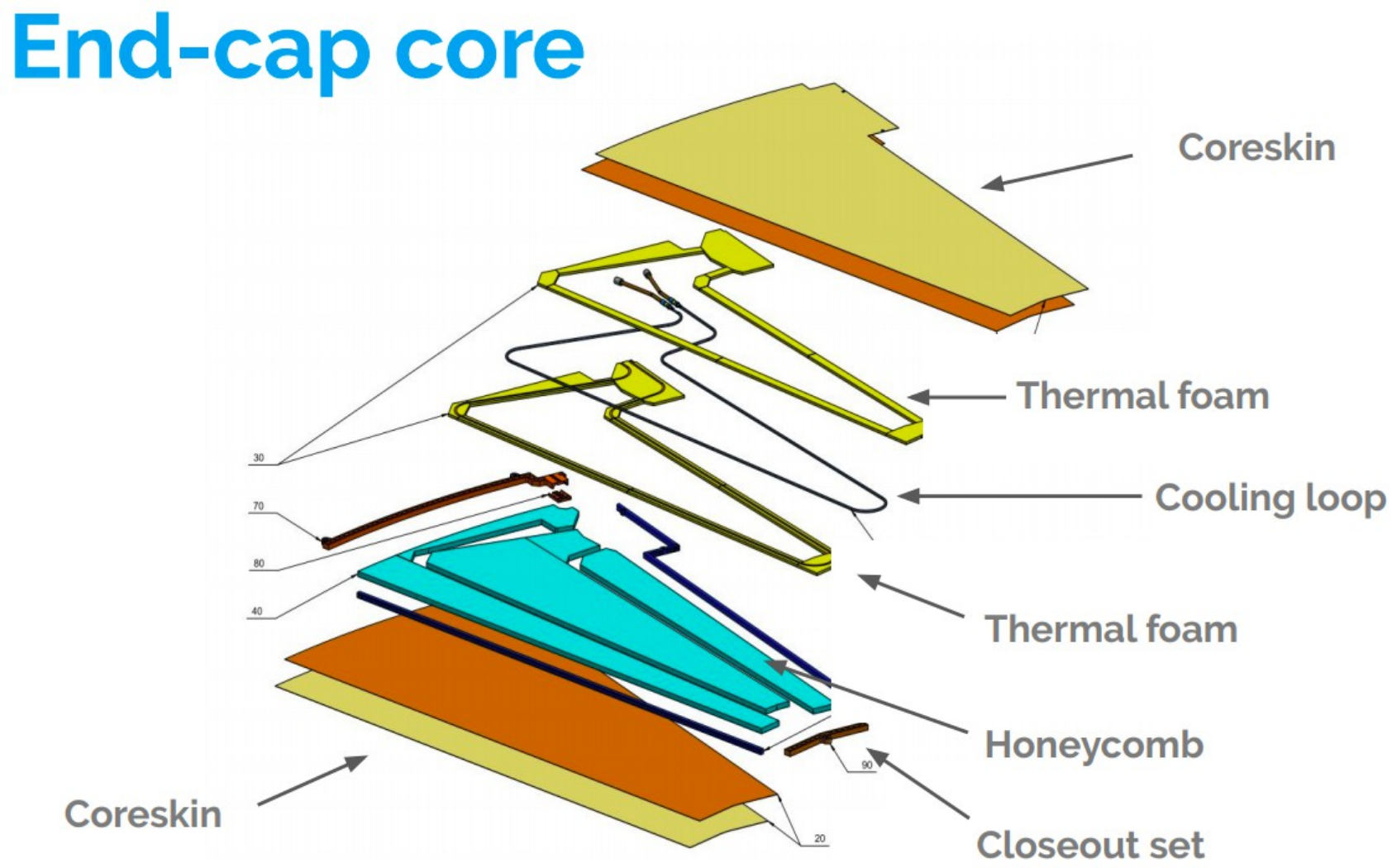
- Substructure for barrel cylinders called staves, endcap disks made of petals
- These local structures (LS) provide mechanical support & cooling (cores) + powering & readout (bus tapes)
- Staves and petals are connected to off-detector electronics through an End-Of-Substructure (EoS) board







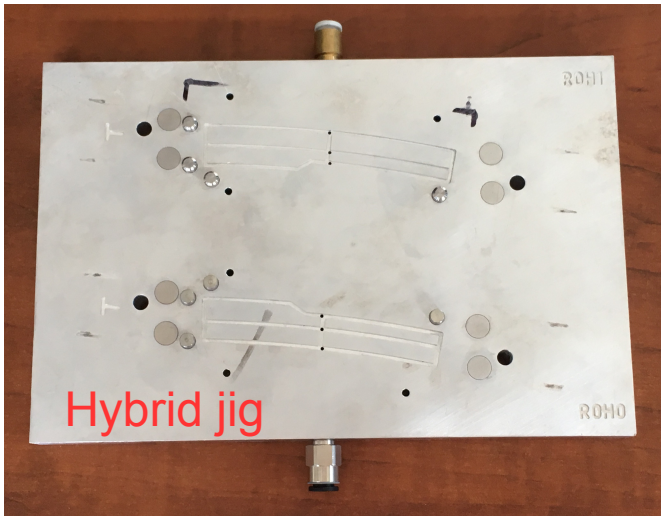
Petal core

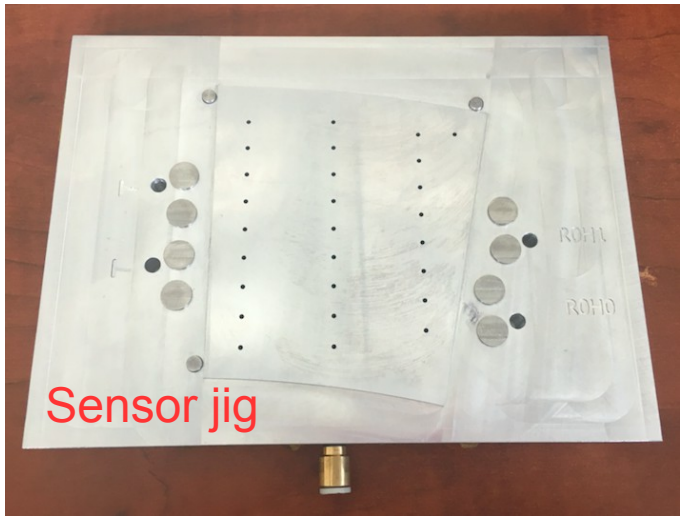

End-cap core
Coreskin
Thermal foam
Cooling loop
Thermal foam
Honeycomb
Closeout set
Coreskin
30
70
80
40
90
20

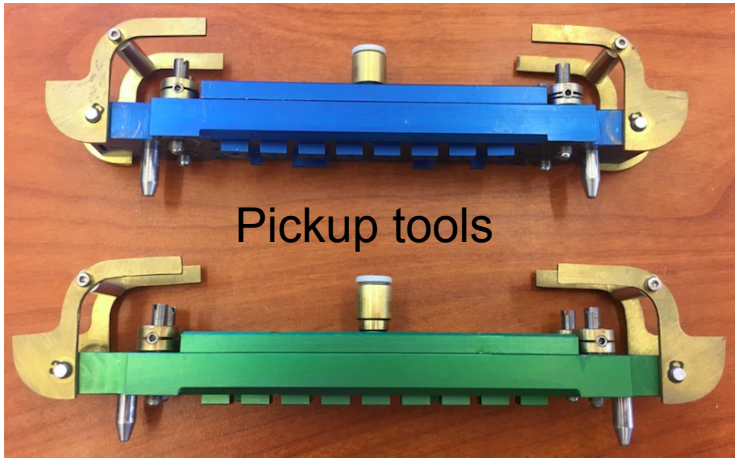
Tooling

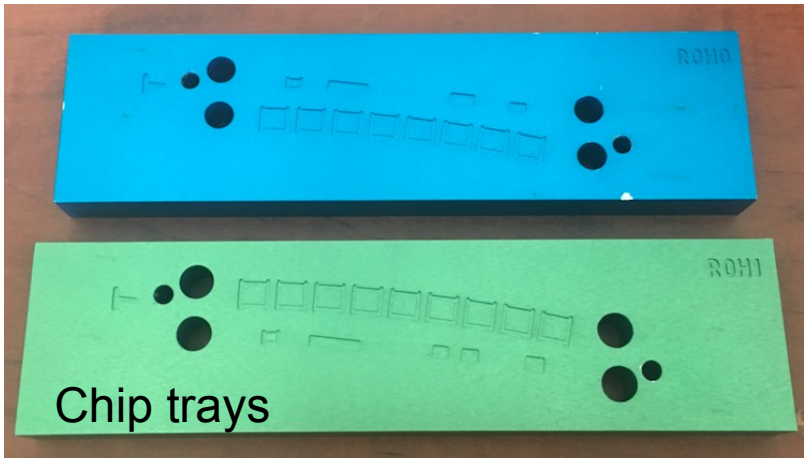
Tooling for module building

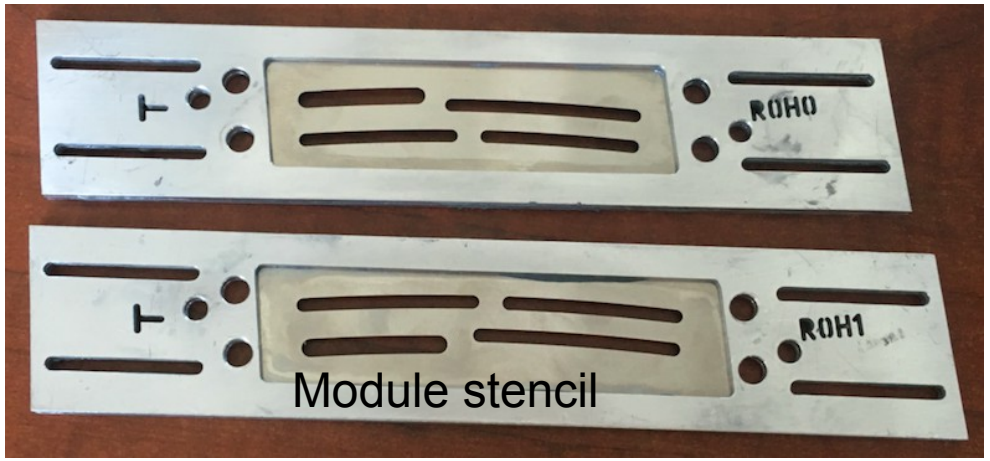
- Drawings for every tool available for ABC130 parts
- Drawing for Star tooling are being finalised
- Shown on this slide are only parts of endcap tooling





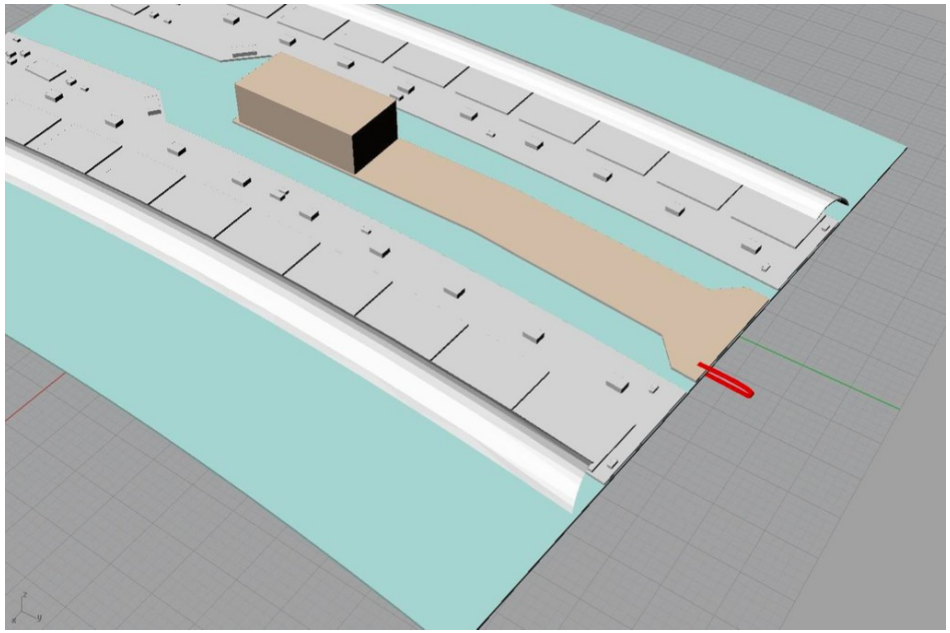


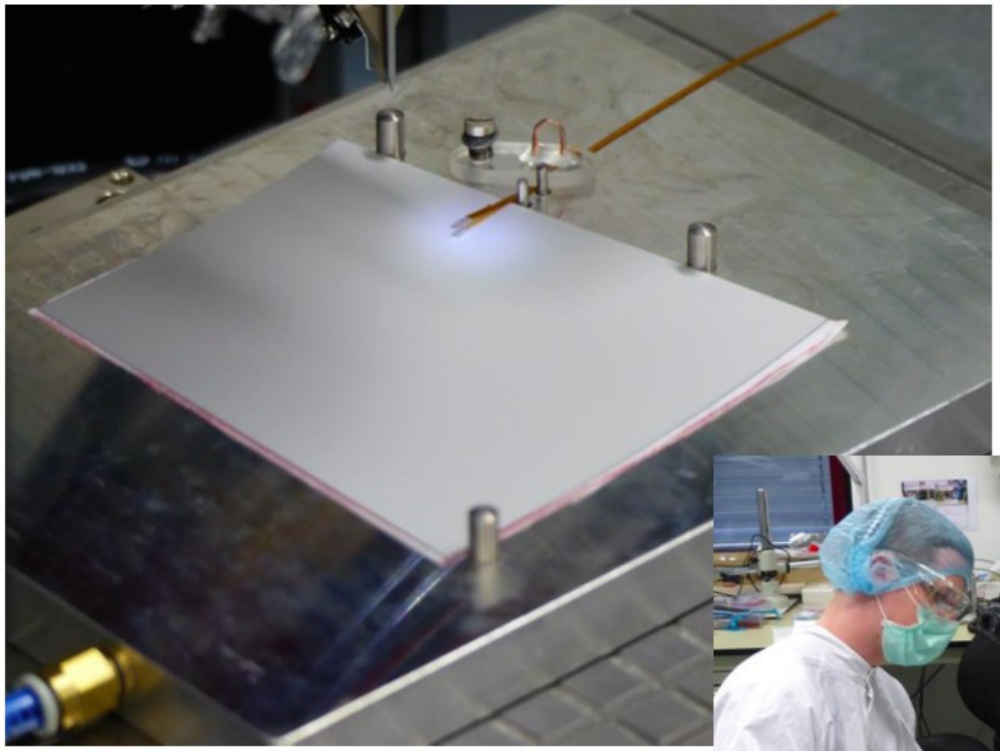


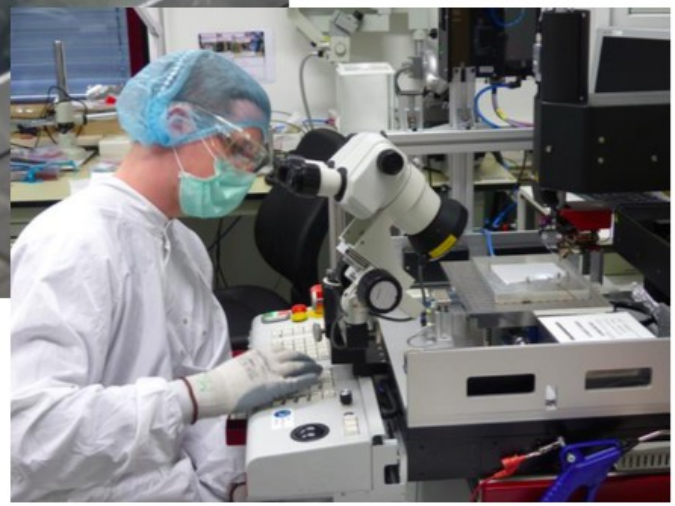


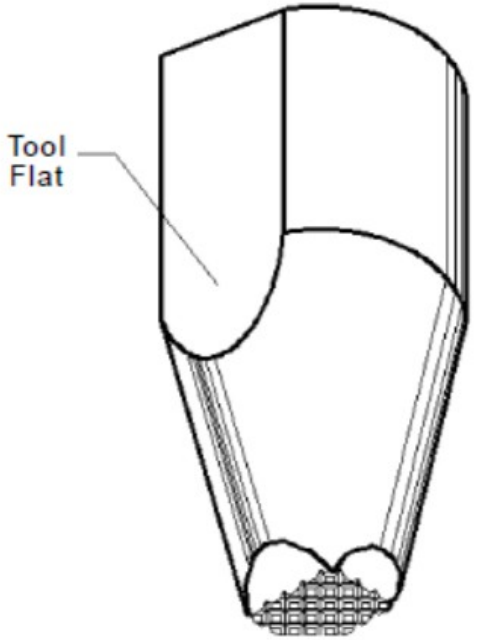
HV Tab

- Mini aluminium Tab, ultrasonic welded to the sensor back plane
- Tab was waffle welded to R0
- Modified version of sensor jig with small clamp to fix the tab in position









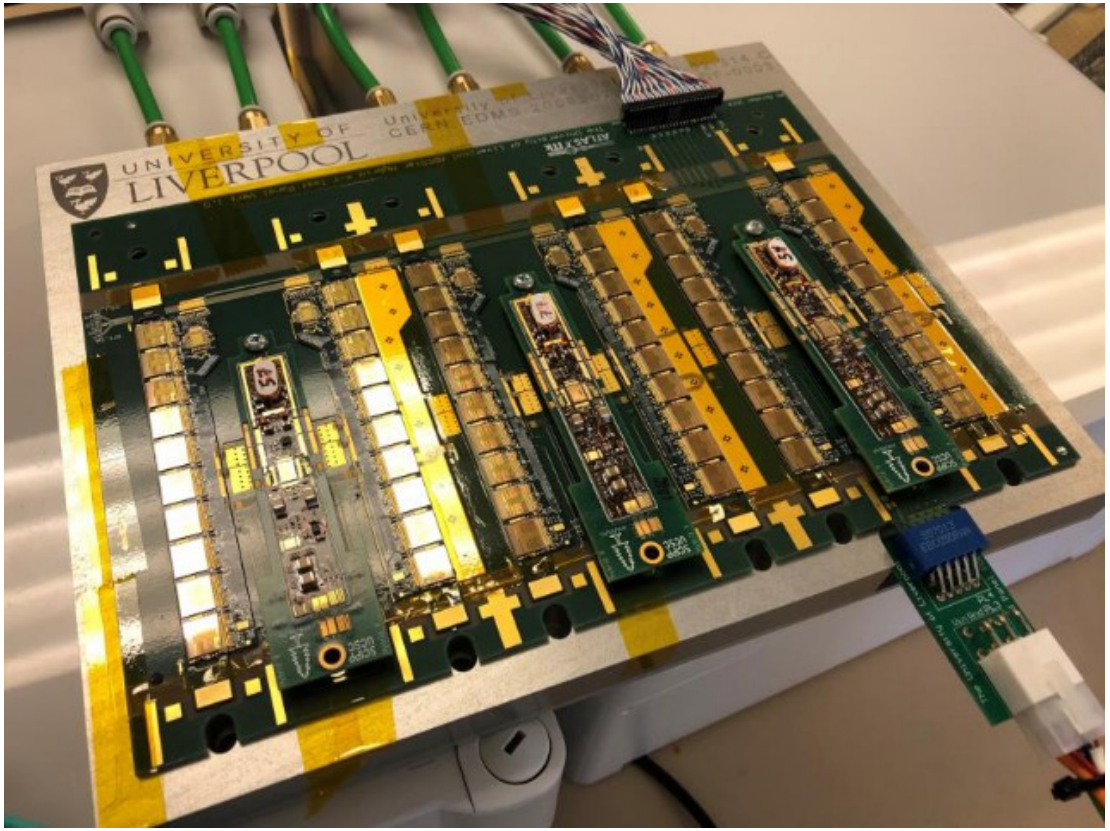
Sensor was flipped upside down and vacuumed down

Cleanroom paper protects front

Martin Stegler, Martin Renzmann

First fully loaded Star hybrid panel

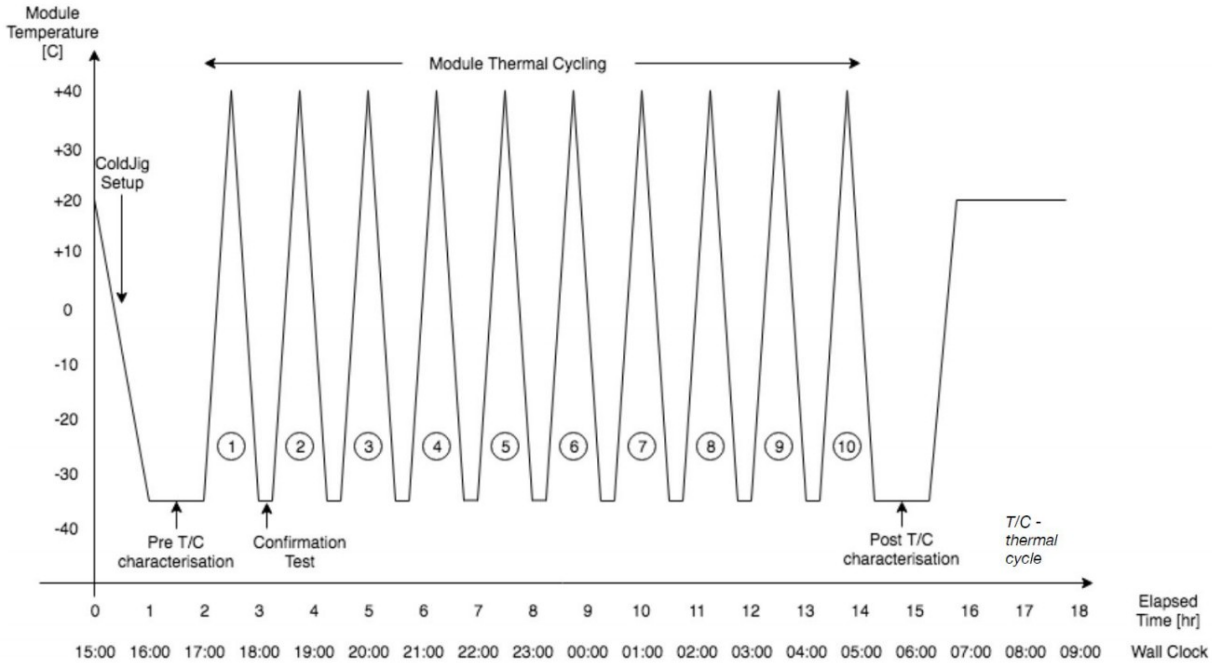
- Latest version of circuits comes with probe points to facilitate ‘spying’ of on-hybrid signals
- Hybrids with Star chips assembled and wire-bonded at Liverpool & RAL
- Test panel with readout capabilities for 6 hybrids in parallel was loaded and bonded
- Uses 3 power boards to power the hybrids
- Power boards share powering across a pair of hybrids and provide access to control signals
- Could be read out successfully w/o the need to adjust any parameters
- Test had being running for 100hrs (as specified for the hybrid burn-in procedure) without problems

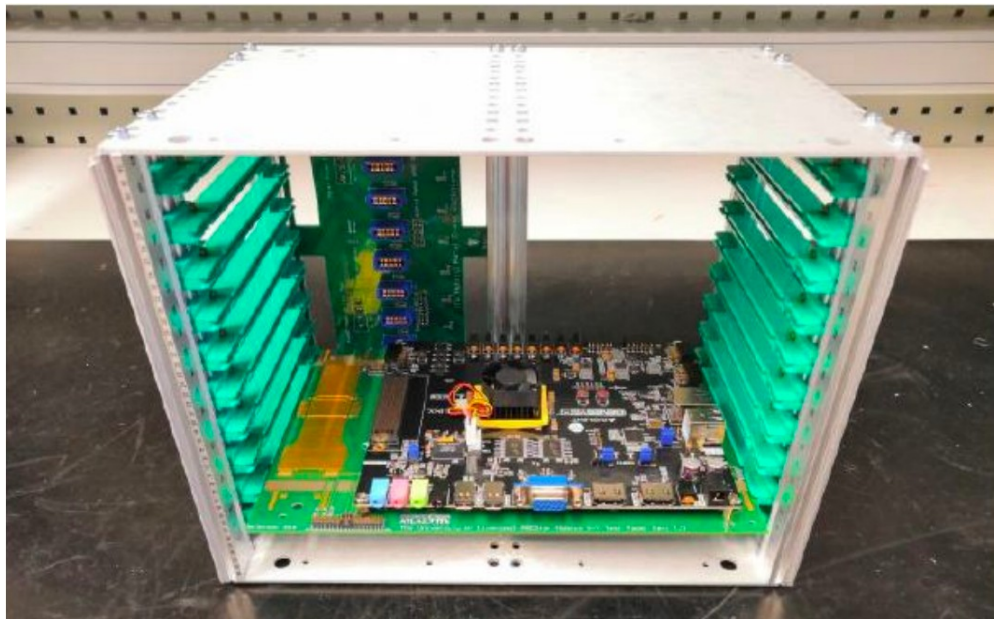


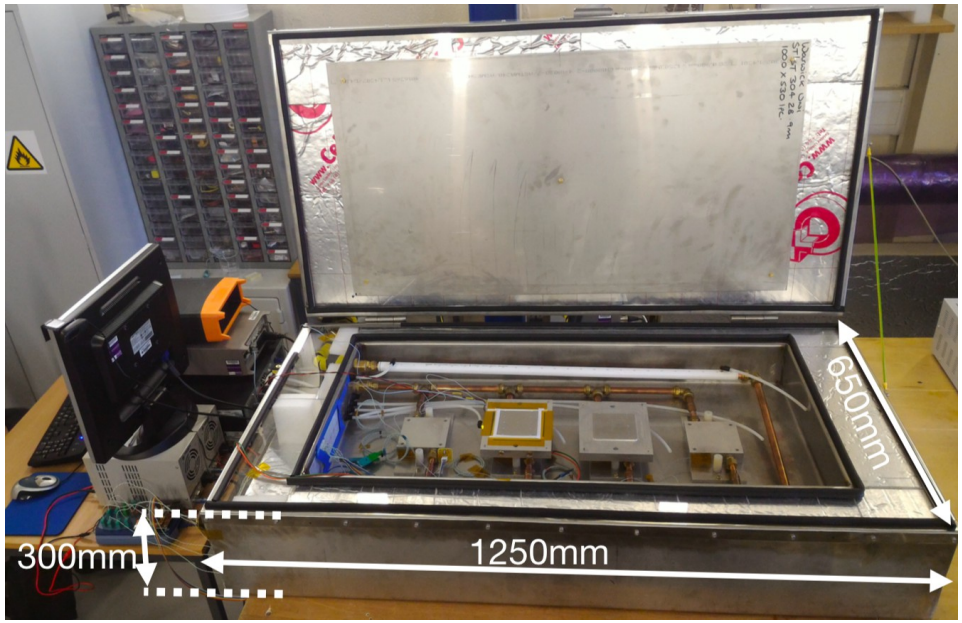
Module QC

QC for modules

- Hybrid crate for 100 hour burn-in
- Module test box for thermal cycling of modules
- First prototypes in hand and being tested
- Designs are being finalised for Final Design Review of modules to demonstrate all steps of QC chain



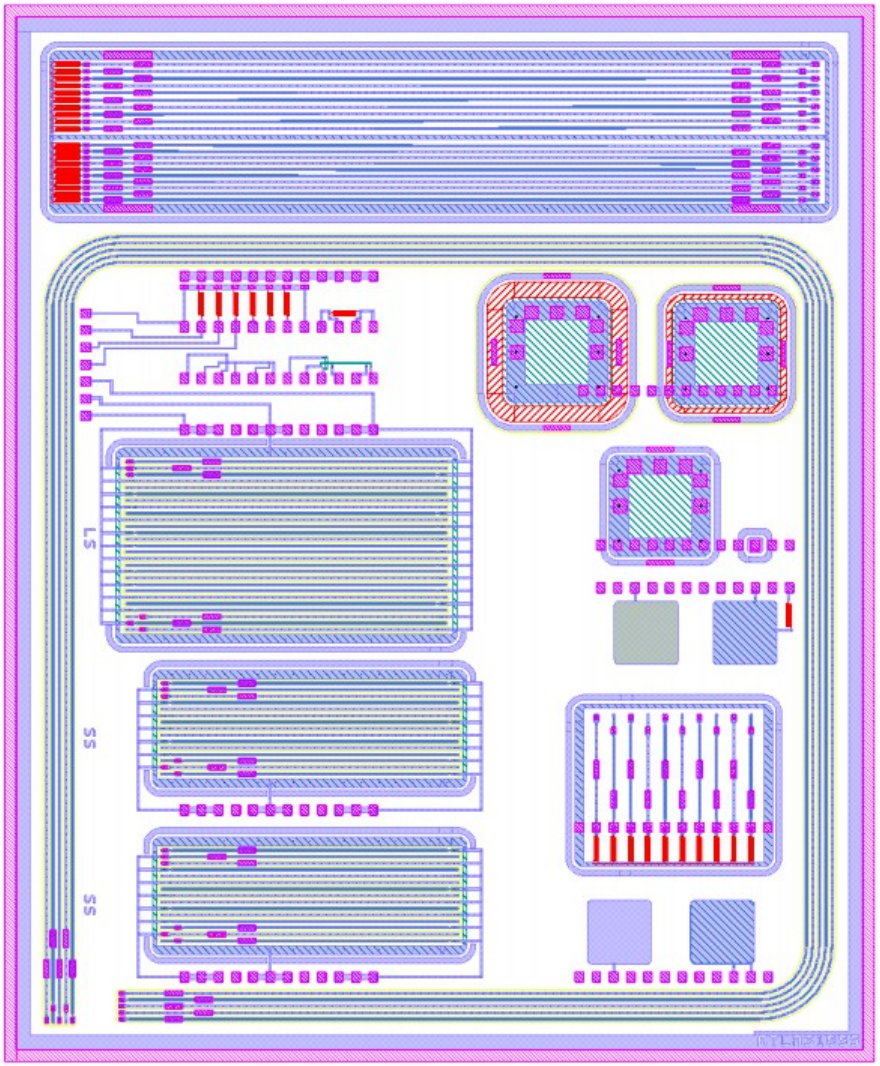




Sensors

Quality Control (QC)

- Detailed visual capture
- Leakage current (plus stability over time) and depletion voltage
- Metrology
- Full strip test (on 2-5%) and stability tests (on 10-20%) are done on a sampling basis



Quality Assurance (QA)

- CCE on mini sensors and diodes after irradiation to $1.6 \times 10^{15}\, n_{eq}/cm^2$ for protons, $1.6 \times 10^{15}\, n_{eq}/cm^2$ & $5 \times 10^{14}\, n_{eq}/cm^2$ for neutrons
- Tests with (standard) ALiBaVa system
- Tests chip to measure: V_{bd}, R_{int}, C_{int}, R_{ptp}, R_{bias}, etc.
- Feedback within 2 months for batch acceptance

Sensor specifications

Parameter	Specification
Process reproducibility	to be controlled and monitored by contractor (e.g. Flat band voltage, Oxide thickness, ...)
Wafer Bulk type	p-type, FZ
- Resistivity	≥3.5 kΩ cm
- Depletion voltage	≤350 V
Max. operating voltage	500 V (at the sensor)
Initial leakage current	<0.1 µA/cm2 @500 V, RH<20% , normalized 20°C
- current stability	<15% @500V, RH<20%, 24 hrs
Polysilicon bias resistor	1.5 ± 0.5 MΩ (R_bias)
Interstrip resistance	>10×R_bias
- capacitance	< 1pF/cm @300V, 100 kHz (1 MHz for mini.)
AC coupling capacitance	≥20 pF/cm @1 kHz
Onset of microdischarge	>500 V
Bad strips	<1% per strip-segment, <1% per sensor, 8 consecutive bad strips

Ring/Row	Inner Radius [mm]	Strip Length [mm]	Strip Pitch [μm]
Ring 0 Row 0	384.5	19	75.0
Ring 0 Row 1	403.5	24	79.2
Ring 0 Row 2	427.5	29	74.9
Ring 0 Row 3	456.4	32	80.2
Ring 1 Row 0	489.8	18.1	69.9
Ring 1 Row 1	507.9	27.1	72.9
Ring 1 Row 2	535	24.1	75.6
Ring 1 Row 3	559.1	15.1	78.6
Ring 2 Row 0	575.6	30.8	75.7
Ring 2 Row 1	606.4	30.8	79.8
Ring 3 Row 0	638.6	32.2	71.1
Ring 3 Row 1	670.8	26.2	74.3
Ring 3 Row 2	697.1	26.2	77.5
Ring 3 Row 3	723.3	32.2	80.7
Ring 4 Row 0	756.9	54.6	75.0
Ring 4 Row 1	811.5	54.6	80.3
Ring 5 Row 0	867.5	40.2	76.2
Ring 5 Row 1	907.6	60.2	80.5

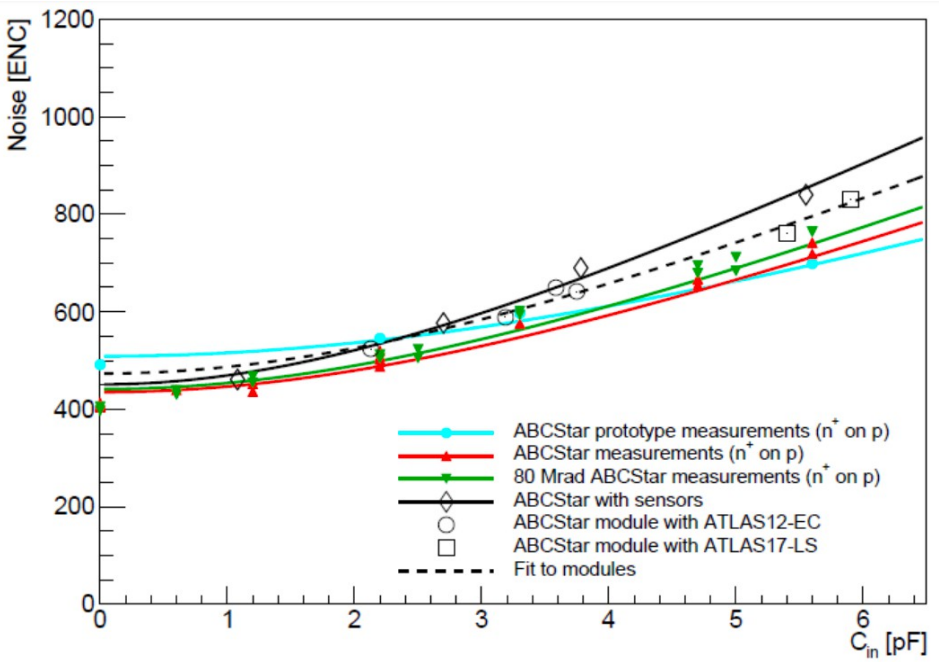
Layer	Radius [mm]	Channels in ϕ	Strip Pitch [μm]	Strip Length [mm]	Tilt Angle [°]	
0	405	28×1280	75.5	24.1	11.5	SS
1	562	40×1280	75.5	24.1	11.0	SS
2	762	56×1280	75.5	48.2	10.0	LS
3	1000	72×1280	75.5	48.2	10.0	LS

- EC strips radially distributed to measure Rφ coordinate
- 40 mrad stereo angle between opposite petal sides achieved by rotating the strips 20 mrad within the sensors

ASICs

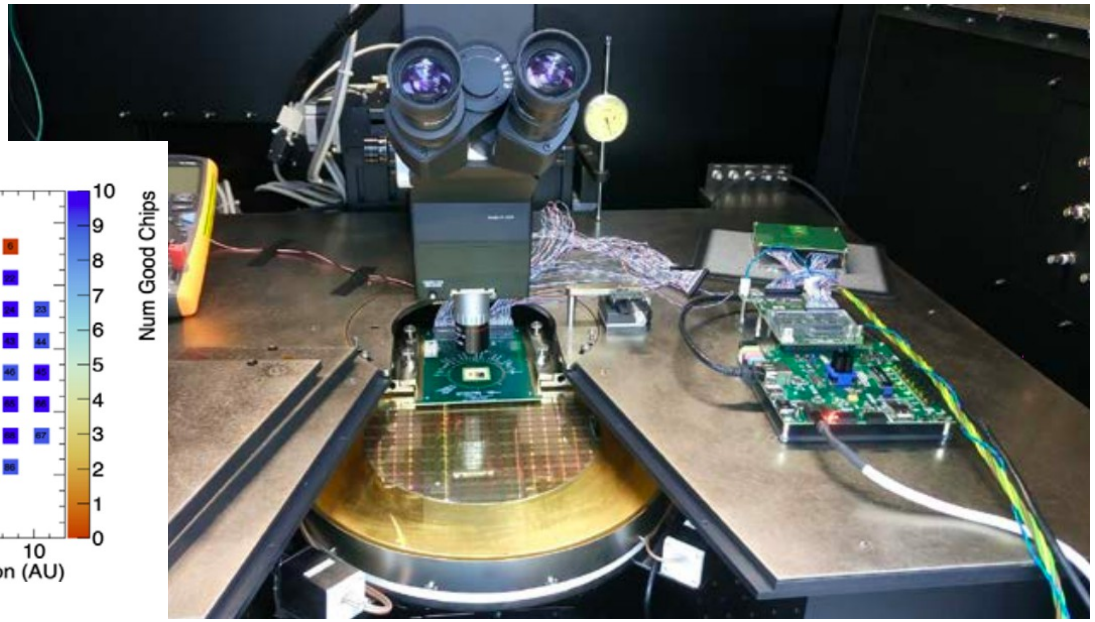
First Star prototypes

- Most functionality tested on SCB and working
- Noise vs capacitance measurements as expected
- ABCStar and HCCStar have been wafer probed on 10 wafers
- ABCStar yield > 90%, HCCStar yield > 95%

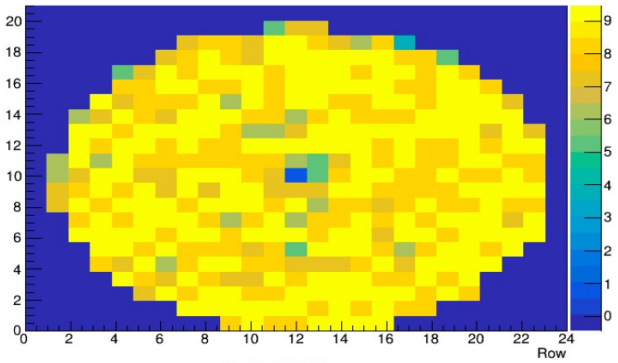


Qualification of designs

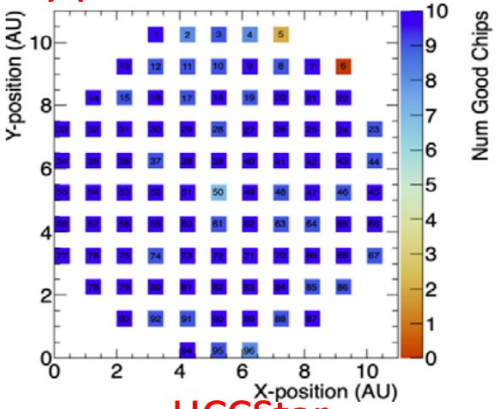
- Low dose rate, low temperature TID irradiations with Co-60 source
- SEE tests with high energy protons and heavy ions



10 Wafers / # good die by position



ABCStar

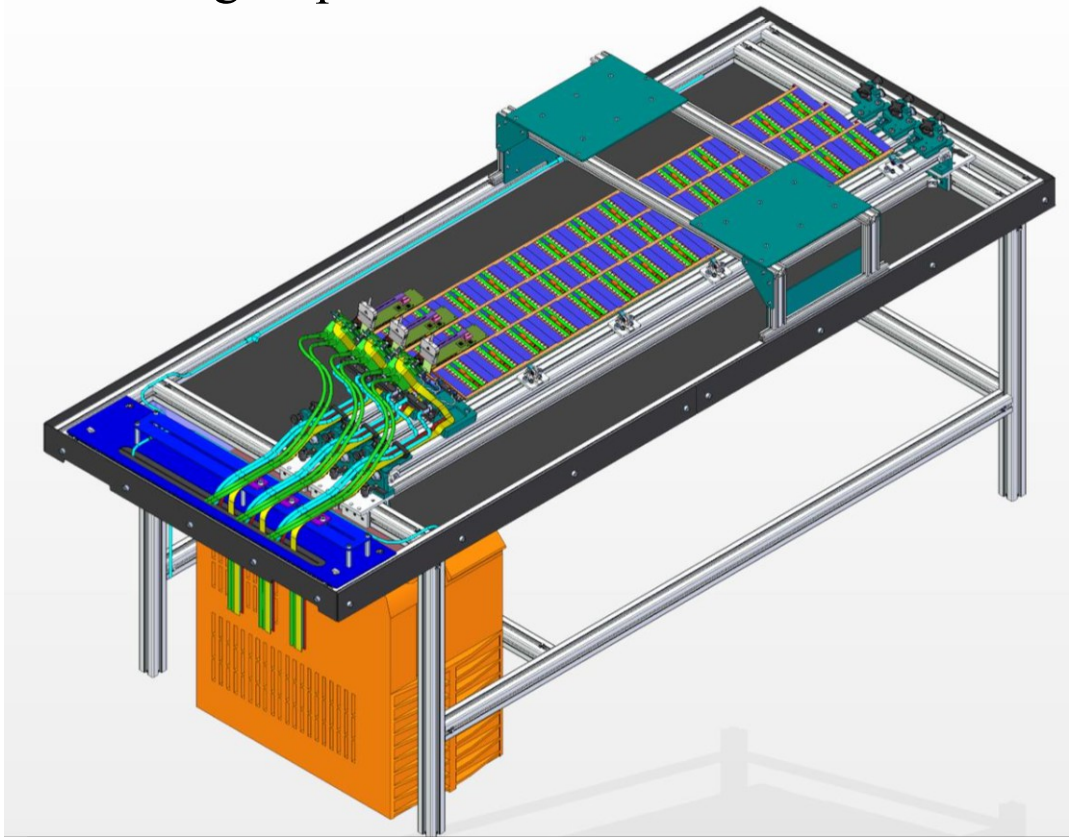


HCCStar

System test

Objective of system test:

- Develop test methodology
- Check: powering, cables, fibre optics, DAQ systems, cooling, mechanical supports, interlocks and control
- Check for change in performance compared to single module/stave results
- Investigate possible inter-stave crosstalk



For Systems FDR: confirm that system performs in accordance with the specs in several key areas, for example:

- FE performance

  → Noise, cross talk etc.

- DAQ

  → Low full system bit error rates and high throughput

  →Successful routing of DCS information

- DCS

  → Reliable control and monitoring of powerboards via FELIX

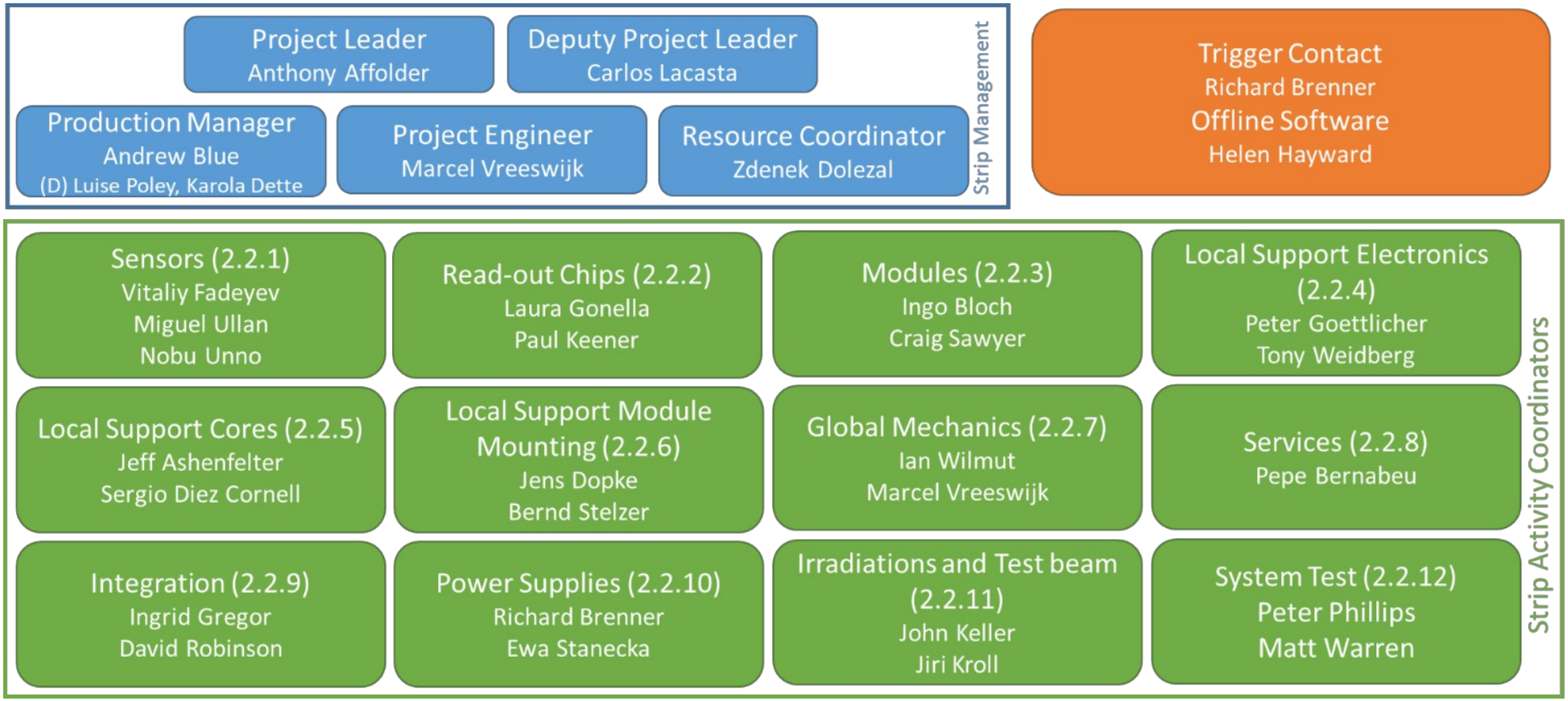
  → Safe operation of power chain from WinCCOA

- Power Chain

  → delivery of LV power within safe limits for BPOL12V under all circumstances

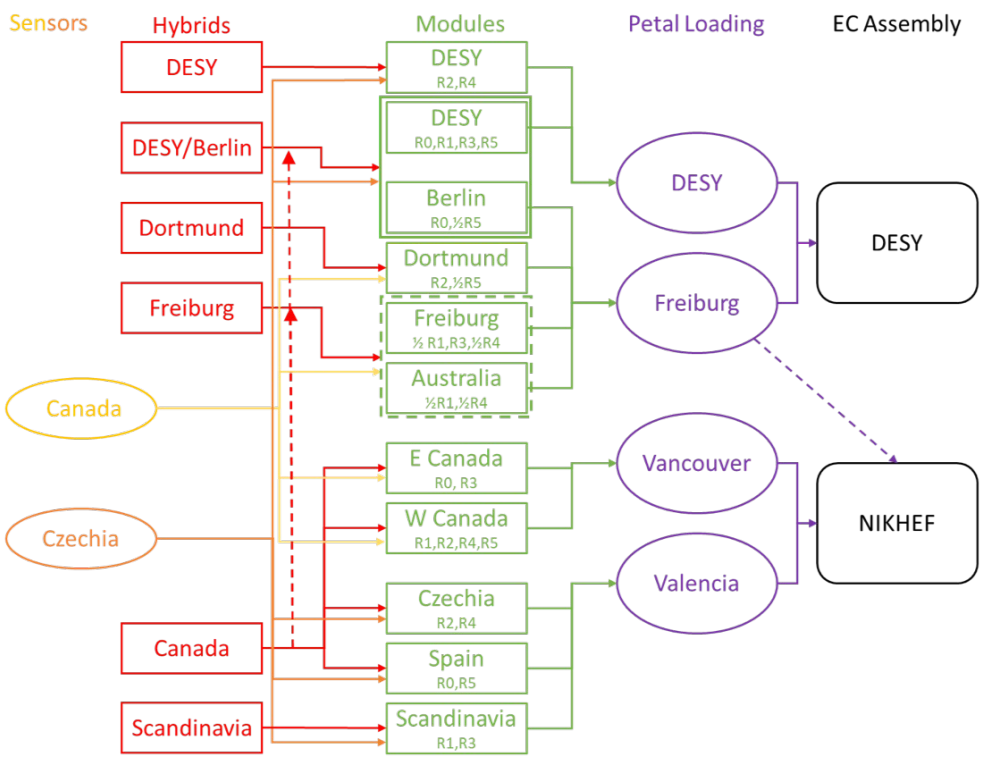
Project organisation

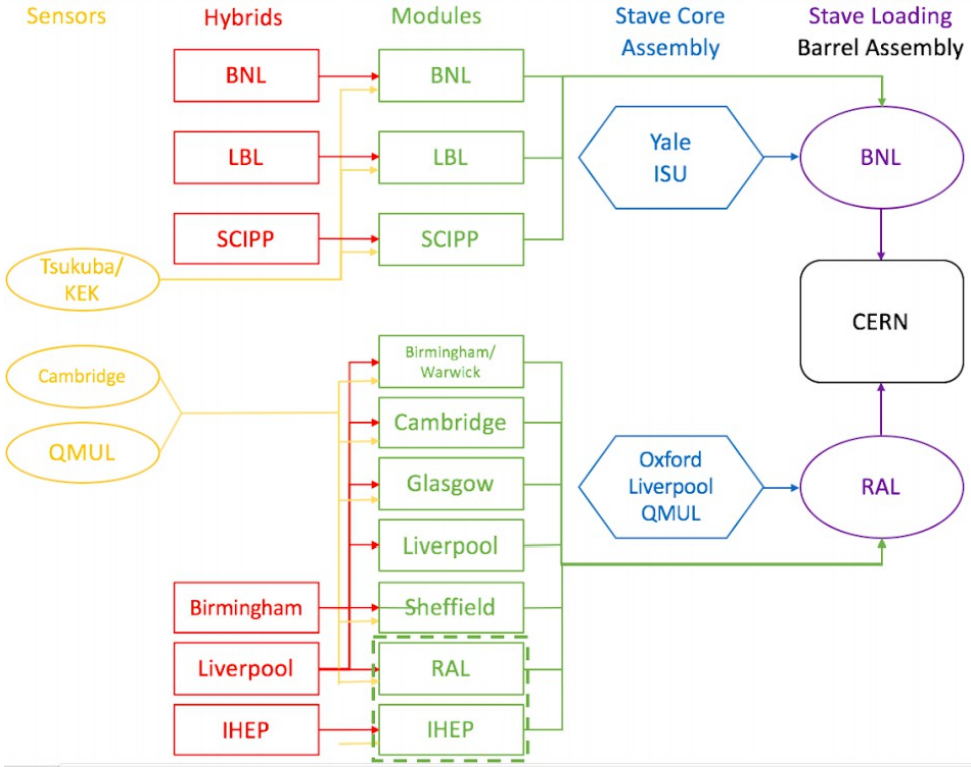
- Complex production model requires tight and consistent methodology and oversight to avoid mismatches/clashes → formation of Production Management team
- Role of production management is (among other things) to:
  - Oversee production logistics for both part production and flow
  - Ensure consistent QA/QC procedures at various sites
  - Monitor production quality
  - Oversee the Production Database work



Project organisation

- Complex production model with 51 institutes worldwide building & testing detector parts
- Need to closely keep track of procedures and scheduling
- Project is currently going through review cycle to allow for the start of pre-production in early 2020
- During pre-production, reviews to allow for production start will take place
- Production scheduled to start one year after beginning of pre-production



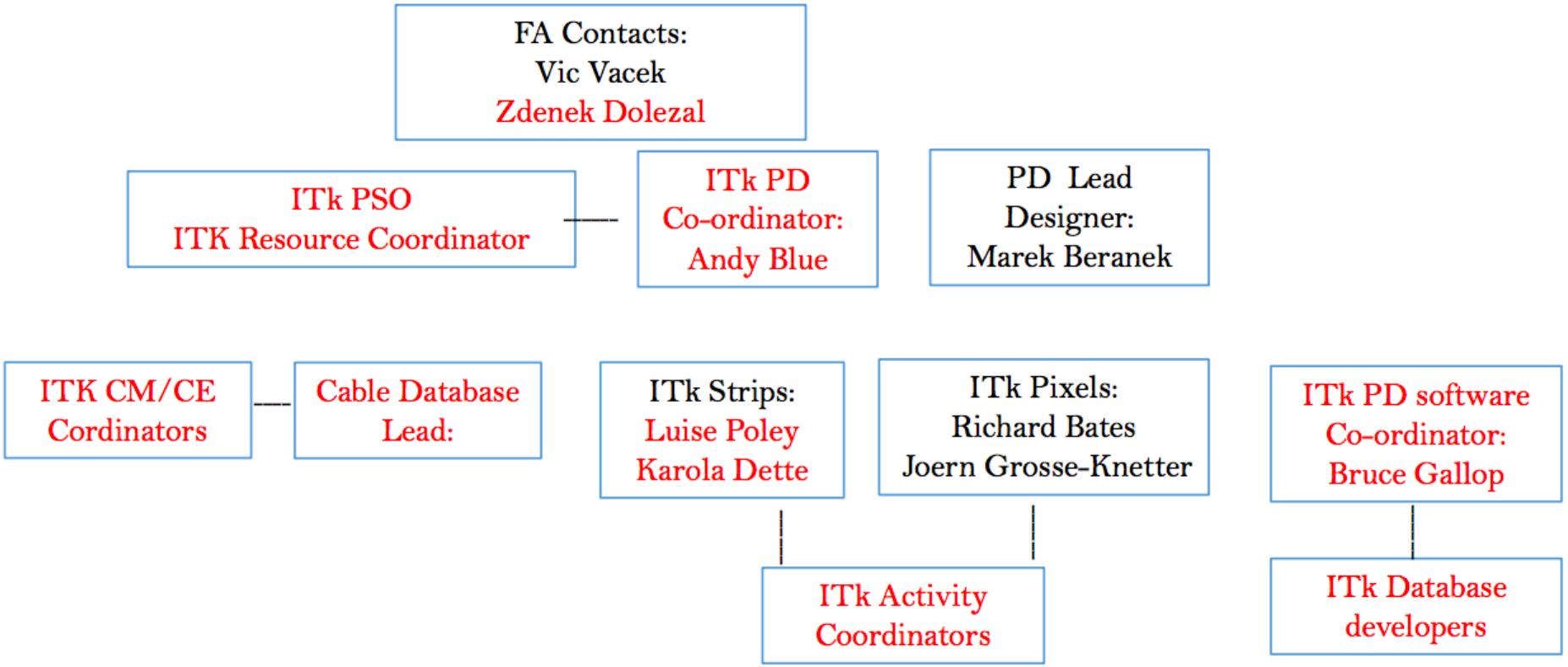


Production Database

- Production Database is combined effort of Strips and Pixel
- Organisational structure similar to overall ITk Strips structure with coordinators for several subcategories to ensure full coverage of needs
- Team is currently being expanded to include even more specialised coordinators for categories like modules/staves etc.

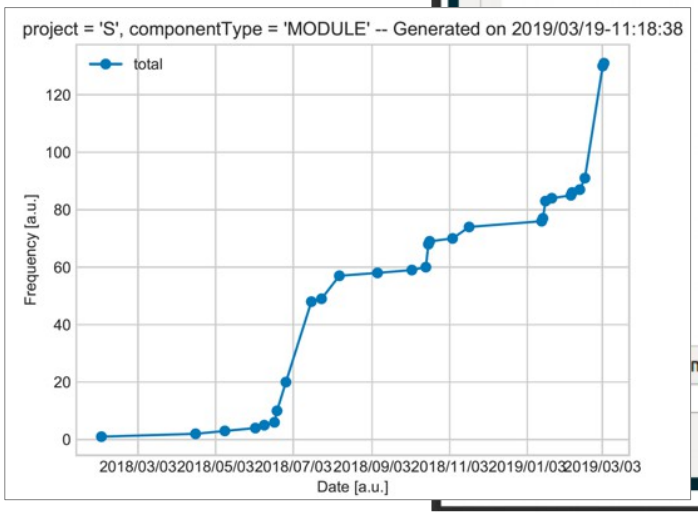
University of Glasgow

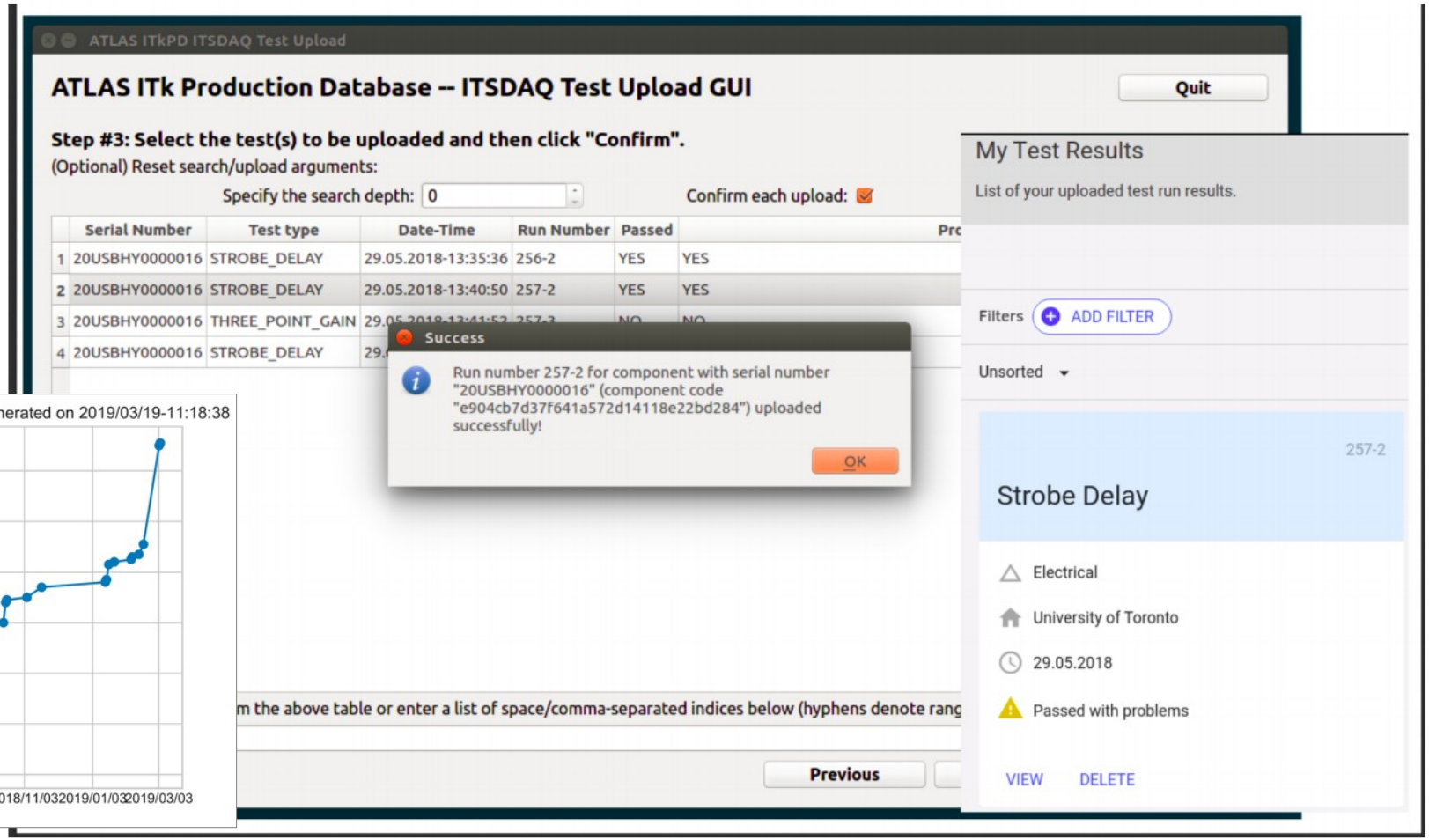
ITK Production Database Organogram



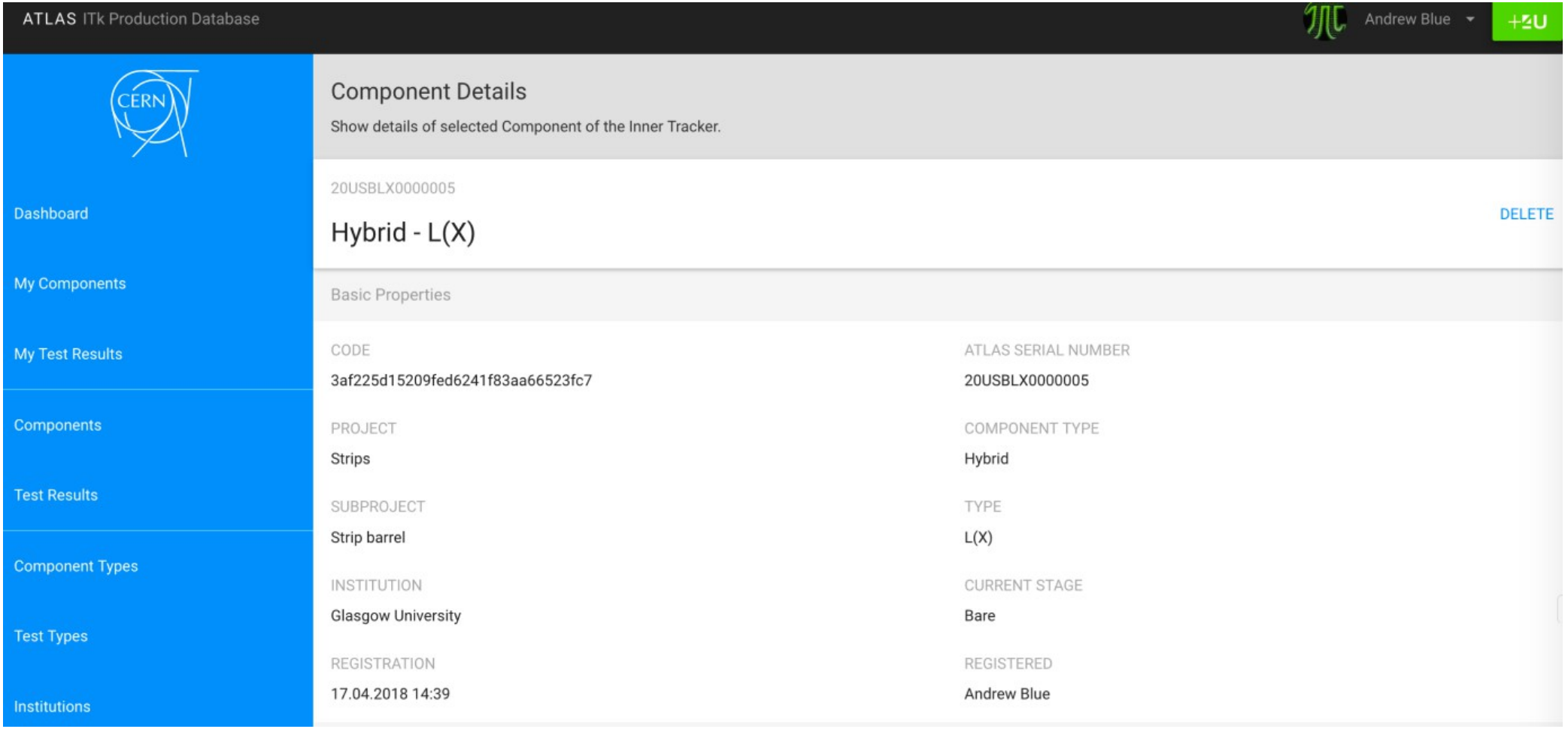
Production Database

- Production Database will keep track of (for example):
  - All components, their properties and history
  - How many modules have been built by institute “x”?
  - Are we on track with schedule? Do we need to procure/ship more parts?
  - What is the yield and where do failures occur?





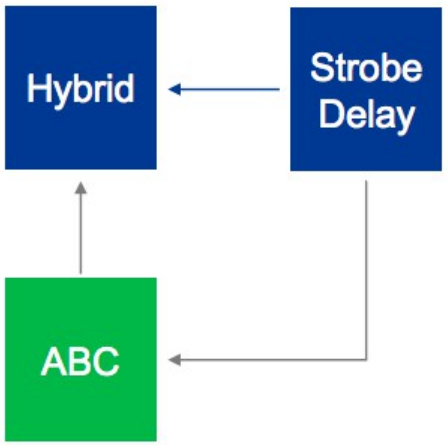
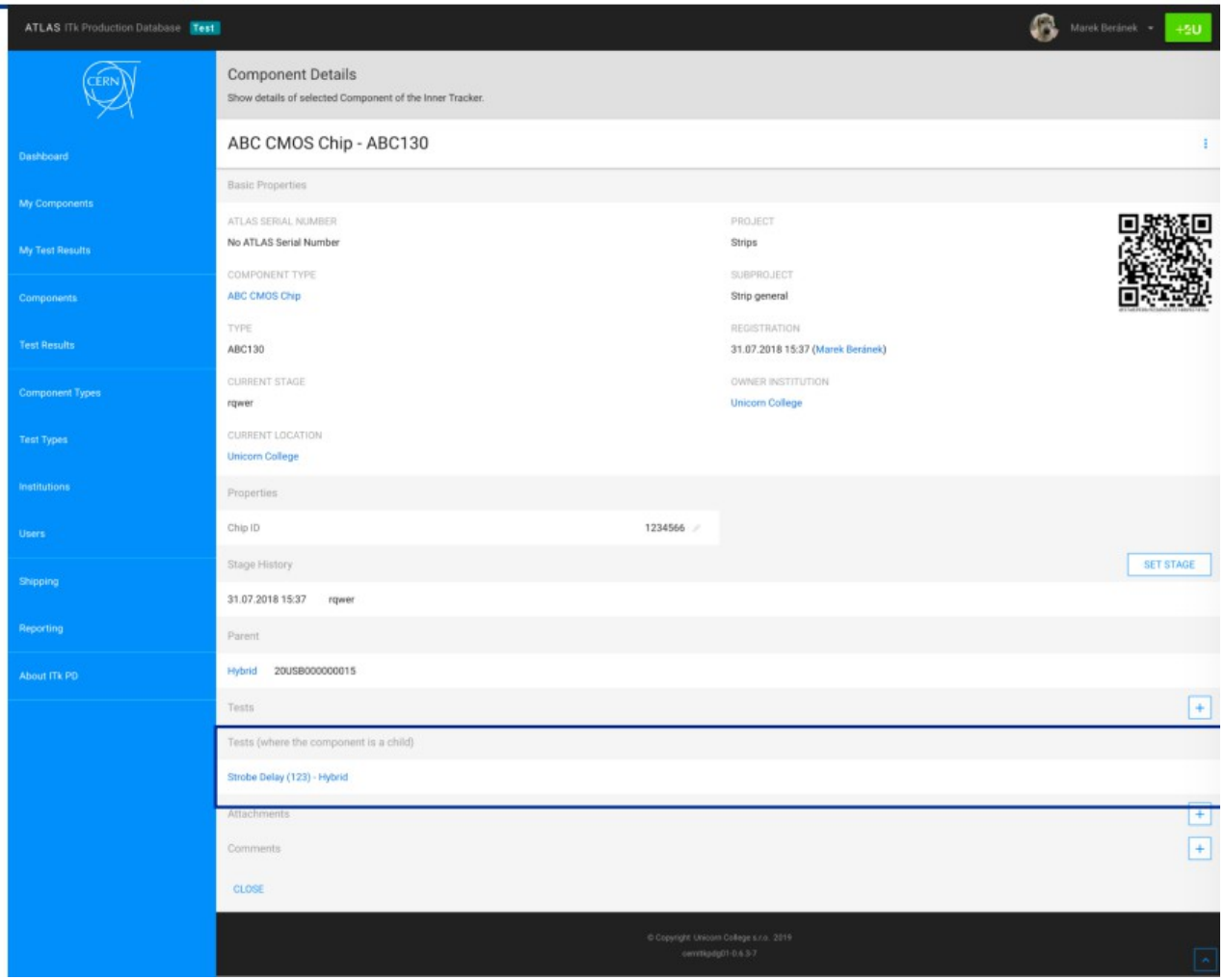
Production Database



- GUI Example for component registration

Production Database

- Database understands relations between components and which parts inherit properties from which parents/childs/batches

List of test runs where the component is a child

- E.g.